

Double Sliced Event Generation

Novel Method for Multijet Background Estimation in Proton-Proton
Collisions in Environments with High Pileup Activity

Methodological Discussion in the Context of Invisible Higgs Boson Decay Searches
in the Vector Boson Fusion channel with ATLAS Detector

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Abstract

In this thesis, a novel method of multijet background estimation in pp collisions in environments sensitive to high pileup activity is introduced. The methodology and development of the method is discussed in the context of searches for invisible Higgs boson decays with vector boson fusion signature using the ATLAS detector. The method aims to decrease the statistical uncertainty of the multijet background in the signal region of the search as well as to enable additional machine learning techniques for the search. The method is based on Monte Carlo simulation of multijet events and their smearing. Additionally, the method employs various statistics and performance improving techniques. The proposed method is validated in a control region using data collected between 2015 and 2018 at centre-of-mass energy of $\sqrt{s} = 13.0$ TeV and between 2022 and 2023 at centre-of-mass energy of $\sqrt{s} = 13.6$ TeV. The multijet background estimation is presented for two signal regions: One signal region represents the signal region used in the previous iteration of the search at $\sqrt{s} = 13.0$ TeV. The other region represents the next iteration of the invisible Higgs decay search's possible signal region definition. When compared with the previous iteration's multijet background prediction based on data-taking conditions between 2015 and 2018, the proposed method's estimation is found to be in agreement.

Zusammenfassung

In dieser Arbeit wird eine neuartige Methode zur Multijet-Untergrundabschätzung bei pp -Kollisionen in Umgebungen mit hoher Aktivität von Pileup. Die Methodik und Entwicklung der Methode wird im Zusammenhang mit der Suche nach unsichtbaren Higgs-Boson-Zerfallsereignissen mit Vektorboson-Fusionssignatur unter Verwendung des ATLAS-Detektors diskutiert. Die Methode zielt darauf ab, die statistische Unsicherheit des Multijet-Beitrags im Signalbereich der Suche zu verringern und zusätzlich maschinelle Lernverfahren für die Suche zu ermöglichen. Die Methode basiert auf einer Monte-Carlo-Simulation von überarbeiteten Ansatz zur Monte-Carlo-basierter Multijetereignissen und deren Verschmierung. Darüber hinaus werden bei diesem Prozess verschiedene statistische Methoden und leistungsverbessernde Techniken eingesetzt. Die vorgeschlagene Methode wird in einem Kontrollbereich mit Daten validiert, die zwischen 2015 und 2018 bei einer Schwerpunktsenergie von $\sqrt{s} = 13.0$ TeV und zwischen 2022 und 2023 bei einer Schwerpunktsenergie von $\sqrt{s} = 13.6$ TeV gesammelt wurden. Die Multijet-Untergrundabschätzung wird für zwei signalangereicherte Selektionen dargestellt: Ein Signalbereich stellt den Bereich dar, der in der vorherigen Iteration der Suche bei $\sqrt{s} = 13.0$ TeV verwendet wurde. Die andere stellt die nächste Iteration der Definition des möglichen Signalbereichs für die Suche nach dem unsichtbaren Higgs-Zerfall dar. Im Vergleich zur Multijet-Untergrundvorhersage der vorherigen Iteration, die auf Datenerfassungsbedingungen zwischen 2015 und 2018 basiert, stimmt die vorgeschlagene Methode überein.

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1. Introduction

Since the start of the 20th century, extensive advancements have been made in various aspects of the fundamental description of nature. From the interactions of the elementary particles to the evolution of the cosmos. However, even with the discovery of the Higgs boson [1, 2], the last missing piece of the Standard Model of particle physics, this description is still not complete. While the discovery and the subsequent property measurements of the boson agreed well with the Standard Model predictions, numerous open question still remain. The identity of dark matter is one of them. The searches for dark matter [3–12] have been an integral part of the physics program of the ATLAS experiment since the start of particle collisions in the Large Hadron Collider at CERN in 2010. The search for a Higgs boson’s, produced through vector boson fusion, invisible decays to dark matter candidates is one of them. The combination of the production method and the background processes results in the most sensitive channel for such detections. Consequently, yielding the most stringent restrictions of the such invisible Higgs boson decays [7]. However, this does not come without a cost. One of which is the complicated nature of the multijet background prediction for such searches. The cause of it is both the abundant occurrence of multijet events in pp collisions and the intrinsic sensitivity of the search to pileup jets with large transverse momentum.

The core of the thesis is the development and deployment of a novel method for estimating and modelling multijet background events for such searches and conditions. The method is presented in the context of the most recent search for invisible Higgs boson decay events with vector boson fusion signatures[7] which used data collected with the ATLAS experiment between 2015 and 2018. The method will be used as the multijet background estimation method for the next iteration of the search with an expanded dataset (including data collected during 2022 and 2023) as well as new machine learning techniques enabled by said method.

Additionally, the thesis covers the development and derivation of simulation-based small-R jet calibrations for the ATLAS experiment. Due to a major update to various components of the central software package used by the experiment, new calibrations needed to be produced to permit small-R jet usage in this and other analyses.

The thesis is structured as follows: Chapter 2 provides the theoretical overview for the Standard Model of Particle Physics, the Standard Model of Cosmology, and theoretical concepts related to invisible Higgs decays and dark matter. In Chapter 3 descriptions of both the Large Hadron Collider and the ATLAS experiment, including all of its primary sub-detector systems, is given. Chapter 4 defines various analysis objects and their reconstruction using the ATLAS experiment. Chapter 5 covers the aforementioned jet calibration derivation needed to enable this work and most other analyses relying on the updated software

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packages and/or data collected after 2022. Chapter 6 introduces the invisible Higgs decay search with vector boson fusion signatures as the context for the method's development. Chapter 7 describes the novel multijet background estimation method, known as Double Sliced Event Generation. This includes both its general methodology and various techniques used to boost its performance and efficiency. Chapter 8 is used for the validation of the newly introduced method. Chapter 9 provides the description and derivation of statistical and systematic uncertainties related to the method. Chapter 10 covers the Double Sliced Event Generation method's application in the context of the invisible Higgs boson decay search introduced previously. In Chapter 11 the summary and outlook for the method are given.

2. Theoretical Overview

2.1. The Standard Model of Particle Physics

The *Standard Model* of particle physics, or *SM* for short, represents the most extensive and rigorously tested theoretical description of the three of the four fundamental forces. The theory had been developed during the latter half of the 20th century through Quantum Field Theory (QFT) mathematical formalisms. The model is composed of various abelian and non-abelian scalar and gauge quantum fields. The fields' excitations correspond to the elementary particles of the theory¹ while their dynamics are described through Lagrangian densities², $\mathcal{L}$, or Lagrangian(s) for short³. The Standard Model Lagrangian is based on $SU(3)_C \times SU(2)_L \times U(1)_Y$ symmetry and can be expressed as

$$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{EW}} + \mathcal{L}_{\text{QCD}} \quad (2.1)$$

where $\mathcal{L}_{\text{EW}}$ represents the $SU(2)_L \times U(1)_Y$ electroweak theory Lagrangian [13–16] and $\mathcal{L}_{\text{QCD}}$ is the Lagrangian for the $SU(3)_C$ based theory of Quantum Chromodynamics, *QCD* [17–19]. The particle content of the theory and each individual Lagrangian densities of Eq. (2.1) are discussed below.

2.1.1. Particle Content of Standard Model

The elementary particle composition of the Standard Model is shown in Figure 2.1 and can be broken down into two categories: *gauge bosons* and *fermions*. Fermions are elementary particles with half-integer spin, described by the Fermi-Dirac statistics⁴, and act as the building blocks of matter. Boson, on the other hand, are full-integer spin particles, described by the Bose-Einstein statistics⁵, and are responsible for the force exchange and mass generation in the theory.

Fermions come in three distinct generations⁶ and are separated into quarks and leptons: Quarks carry both colour and electromagnetic charge as well as participate in the weak

¹According to the second quantisation formalism.

²The Lagrangian density defines action $S = \int \mathcal{L} d^n x$, where $\mathcal{L} \equiv \mathcal{L}(\{x^i\})$. The evolution of the system defined by the Lagrangian density is determined through the stationary action principle, i.e. $\delta S = 0$.

³Even though there is a difference between Lagrangian and Lagrangian density as concepts, in this work as well as in most particle physics descriptions, these terms are used interchangeably.

⁴No two fermions can occupy the same quantum state due to Pauli's exclusion principle [20].

⁵Multiple bosons can occupy the same quantum state,

⁶Ordered according to their rest mass.

2. Theoretical Overview

Standard Model of Elementary Particles

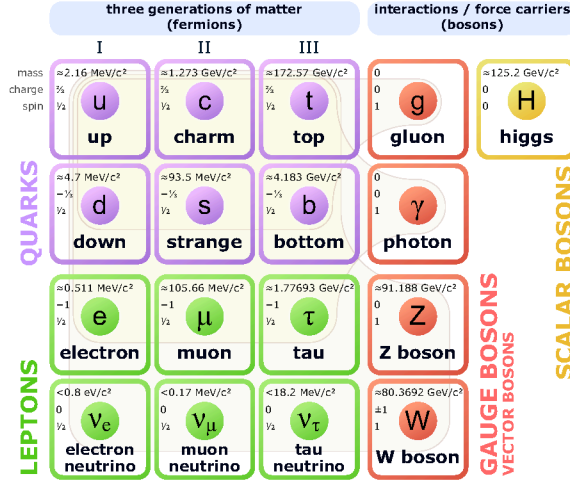


Figure 2.1.: Overview of the elementary particles described in the SM

interaction. Hence, interact with all fundamental forces described by the Standard Model. Additionally, each quark is parametrised by multiple quantum "flavour" numbers shown in Table 2.1. Leptons, on the other hand, are colour-neutral and only the charge leptons (e, μ, τ) interact electromagnetically. Each lepton (group) carries its own leptonic flavour quantum number (breakdown of this is shown in Table 2.2). Quarks are paired in *up-down* fashion, with the *up*-types having EM charge of $\frac{2}{3}$ and being heavier of the two while the *down*-types have EM charge of $-\frac{1}{3}$. Leptons are paired in *charged-neutral* fashion : for each lepton, which all carry an EM charge of -1 , there exists a corresponding neutrino with EM charge of 0. Finally, each fermion has a corresponding anti-particle with the same properties except the inverted electric charge and inverted flavour quantum numbers.

The bosons are separated into vector (gauge) and scalar bosons. The vector bosons act as the force carriers and include : photons, γ , for electromagnetism, gluons, g , for the strong force, and $W^\pm$, Z for the weak nuclear force. Most vector bosons interact only through a singular force they represent, except the $W^\pm$ which interact both weakly and electromagnetically⁷. The only scalar boson in the theory is the Higgs boson, H , which is the excitation of the quantum field responsible for both fermionic and bosonic mass generation.

2.1.2. Electroweak Sector and the Massive Consequences of Spontaneous Symmetry Breaking

The Electroweak sector of the standard model is described by the Glashow, Salam, and Weinberg model of electroweak interaction [13–16]. The theory is based on initially describing the weak and the electromagnetic force as a singular unified electroweak (EW) force which

⁷Indication that they might not necessarily be two separate forces...

2.1. The Standard Model of Particle Physics

Generation	Quark	$Q(e)$	B	I_3	C	S	T	B'
I	u	$+\frac{2}{3}$	$+\frac{1}{3}$	$+\frac{1}{2}$	0	0	0	0
	d	$-\frac{1}{3}$	$+\frac{1}{3}$	$-\frac{1}{2}$	0	0	0	0
II	c	$+\frac{2}{3}$	$+\frac{1}{3}$	0	+1	0	0	0
	s	$-\frac{1}{3}$	$+\frac{1}{3}$	0	0	-1	0	0
III	t	$+\frac{2}{3}$	$+\frac{1}{3}$	0	0	0	+1	0
	b	$-\frac{1}{3}$	$+\frac{1}{3}$	0	0	0	0	-1

Table 2.1.: The Standard Model quark charge and flavour property breakdown. The quarks are listed in generation pairs in the typical *up-down* type association. The properties are as follows: Q is the electromagnetic charge expressed in units electromagnetic unit charge e , B is the baryon number, I_3 is the third component of the (weak) isospin, C - charmness, S - strangeness, T - topness, B' - bottomness. All quantum numbers except the Q and I_3 form the flavour hypercharge $Y = B + C + S + T + B'$ which relates to both the I_3 and electromagnetic charge through the Gell-Mann-Nishijima equation $Q = I_3 + Y/2$ [21, 22].

Generation	Lepton	$Q(e)$	L_e	L_μ	L_τ
I	e	-1	+1	0	0
	ν_e	0	+1	0	0
II	μ	-1	0	+1	0
	ν_μ	0	0	+1	0
III	τ	-1	0	0	+1
	ν_τ	0	0	0	+1

Table 2.2.: The Standard Model lepton charge and flavour property breakdown. The leptons are listed in generation pairs in the typical *charged-neutral* type association. The properties are as follows: Q is the electromagnetic charge expressed in units electromagnetic unit charge e , L_e , L_μ , L_τ are the electronic, leptonic, tauonic lepton numbers.

2. Theoretical Overview

is spontaneously broken through introduction of the scalar Higgs field into the theory. The result of spontaneous symmetry break, or *SSB* for short, is the formation of the observable massive weak and massless electromagnetic gauge bosons, fermionic masses, as well as detectable Higgs field excitation known as the Higgs boson.

The EW theory is formed through the $SU(2)_I \times U(1)_Y$ gauge group with the weak isospin, I_W , and weak hypercharge, Y_W , acting as the generators of each of the component of the group. The group consists of three massless $SU(2)_I$ bosons, W^i where $i \in \{1, 2, 3\}$, and a singular massless $U(1)_Y$ boson B . Similarly to Gell-Mann-Nishijima relation [21, 22], a connection between the observable electromagnetic charge Q and both of the generators can be established as

$$Q = I_W^3 + \frac{1}{2}Y_W \quad (2.2)$$

where I_W^3 is the third component of the weak isospin. The Electroweak Lagrangian prior to SSB can be further separated into individual sectors

$$\mathcal{L}_{EW} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{fermion}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}} \quad (2.3)$$

where the right-hand side consists of the gauge, the fermion, the Higgs, and the Yukawa sector Lagrangian respectively.

The gauge sector defines the interactions of the four massless gauge boson fields associated to $SU(2)_I \times U(1)_Y$ as

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}W_i^{\mu\nu}W_{\mu\nu}^i + \left(-\frac{1}{4}\right)B^{\mu\nu}B_{\mu\nu} \quad (2.4)$$

where $W_i^{\mu\nu}$ and $B^{\mu\nu}$ are their corresponding field strength tensors⁸.

The fermionic sector describes the interaction between the gauge bosons and the (massless) fermions of the theory as

$$\mathcal{L}_{\text{fermion}} = i\bar{\psi}_q \not{D}\psi_q + i\bar{\psi}_l \not{D}\psi_l \quad (2.5)$$

where ψ_q and ψ_l are Dirac spinor representations of quark and lepton fields with the spinor with macron, i.e. $\bar{\psi}$, being their adjoint⁹. Since the (charged) weak interaction is both parity-[23] and CP-violating[24] interaction, the fermion spinors are typically further separated according to their chirality or "handedness" as $SU(2)_I$ is chiral in nature. The chiral decomposed spinor fields are given by

$$\psi_{L,R} = \frac{1}{2}(1 \mp \gamma^5)\psi \quad (2.6)$$

where $\gamma^5 = i \prod_{\mu=0}^3 \gamma^\mu$ and γ^μ are the Dirac γ -matrices, with $\mu \in \{0, 1, 2, 3\}$. The subscripts L and R represent the *left-* and *right-handedness*. Under $SU(2)_I$ the chiral spinor field are

⁸The Einstein summation convention is implied through the $\mu\nu$ super- and subscripts.

⁹ $\bar{\psi} = \psi^\dagger \gamma_0$

2.1. The Standard Model of Particle Physics

grouped according to their handedness with the left-handed fields forming a doublet, L_f , while right-handed field forming a singlet R_f , i.e.

$$L_f = \begin{pmatrix} \psi_L^{up} \\ \psi_L^{down} \end{pmatrix} \quad R_f = \psi_R^{up}, \psi_R^{down} \quad (2.7)$$

where the up and $down$ superscripts indicate the ordering within the generation¹⁰. The doublet fields ψ_L^{up} and ψ_L^{down} have $I_W^3 = +1/2$ and $I_W^3 = -1/2$ respectively, while the singlet fields are given $I_W = 0$ in both cases. Finally, the spinor field interactions in Eq. (2.5) can be decomposed as

$$\mathcal{L}_{\text{fermion}} = i\bar{Q}_j^I \not{D} Q_j^I + i\bar{u}_j^I \not{D} u_j^I + i\bar{d}_j^I \not{D} d_j^I + i\bar{L}_j^I \not{D} L_j^I + i\bar{l}_j^I \not{D} l_j^I \quad (2.8)$$

where Q^I and L^I are the quark and lepton left-handed doublets, u^I and d^I are the up-type and down-type right-handed quark singlets, and l^I is the right-handed non-neutrino lepton singlet. The j subscript runs through all three generations of fermions. Neutrinos, which could be interpreted as the down-type equivalent of leptons do not form a right-handed singlet. The term $\not{D}$ in the Eqs. (2.5) and (2.8) is the contraction of the 4-gradient given by

$$\not{D} \equiv \gamma^\mu D_\mu \quad (2.9)$$

where D_μ is the covariate derivative given by

$$D_\mu = \partial_\mu \left(+ \frac{ig_I \sigma_a}{2} W_\mu^a \right) + \frac{ig_Y}{2} B_\mu \quad (2.10)$$

where σ_a are the Pauli matrices, with $a \in \{1, 2, 3\}$, g_I and g_Y are the dimensionless coupling constants for $SU(2)_I$ and $U(1)_Y$ respectively. Since the $SU(2)_I$ part of the electroweak sector interacts only with the left-handed doublet, the parentheses part of Eq. (2.10) is considered only interacting to the left-handed field doublet.

The Higgs sector, which is responsible for the spontaneous symmetry breaking through the Brout-Englert-Higgs mechanism[25–30], is defined as

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi) \quad (2.11)$$

where Φ is the complex scalar field doublet given by

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} \quad (2.12)$$

and $V(\Phi)$ is the field potential described by

$$V(\Phi) = -\mu_\Phi^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 \quad (2.13)$$

¹⁰For quarks up is associated with the up-type quarks and $down$ - with the down-type quarks; For leptons up is associated with non-neutrino leptons (e.g., e) while $down$ represents neutrinos.

2. Theoretical Overview

where μ_Φ^2 is the field's squared mass and λ is its self-coupling constant restricted to positive values due to renormalisation conditions. Depending on the values that squared mass term takes, two outcomes are possible (both shown in Figure 2.2). If $-\mu_\Phi^2$ is positive, the global minima of the scalar potential is located at the origin and symmetry breaking does not occur; If $-\mu_\Phi^2$ term is negative, SSB will occur as the potential will have infinitely many degenerate minima satisfying

$$2\Phi^\dagger\Phi = \frac{\mu_\Phi^2}{\lambda} = v^2 \quad (2.14)$$

where v is the vacuum expectation value or VEV for short.

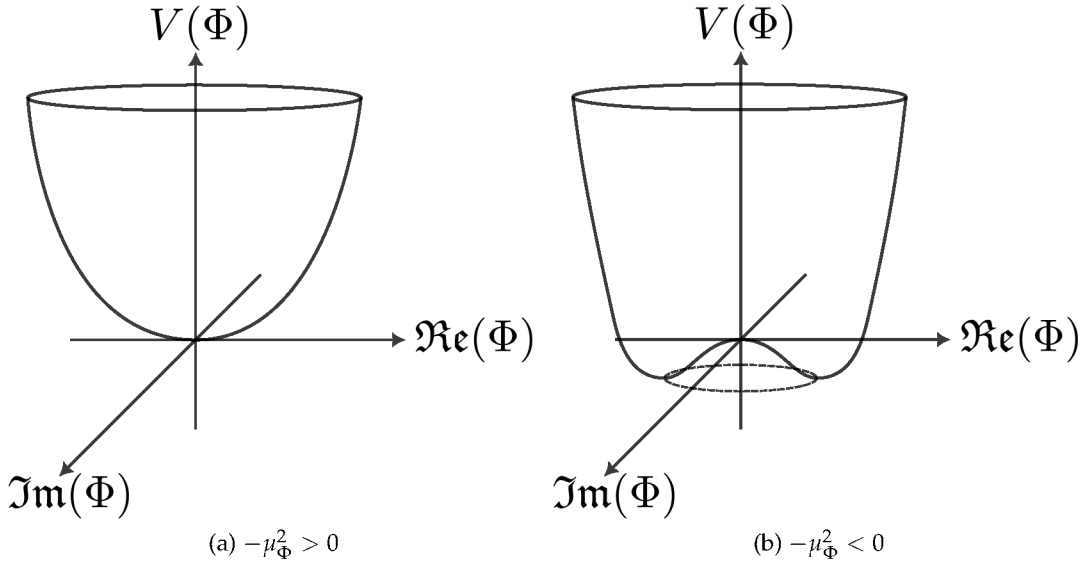


Figure 2.2.: Sketches of complex scalar field potential shapes. The potential is defined as $V(\Phi) = -\mu_\Phi^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$ with $\lambda > 0$. (a) shows the shape of the potential if $-\mu_\Phi^2 > 0$; (b) shows the shape of the potential if $-\mu_\Phi^2 < 0$. Sketches based [31].

If one assumes that VEV is the value that the neutral component of the complex scalar doublet acquires post-symmetry breaking, that is

$$\langle 0|\Phi|0\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \quad (2.15)$$

then the expansion of the Lagrangian around this point causes a spontaneous symmetry breaking resulting in

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1(x) + i\phi_2(x) \\ v + \eta(x) + i\phi_4(x) \end{pmatrix} \quad (2.16)$$

which through simple gauge transformation can be expressed as the unitary gauge

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + \phi_H(x) \end{pmatrix} \quad (2.17)$$

2.1. The Standard Model of Particle Physics

The three "missing" degrees of freedom between Eqs. (2.16) and (2.17), are represented by Goldstone bosons and are identified with the longitudinal polarisation of the physical weak gauge bosons. The physical $W^\pm$ bosons are formed through a linear admixture of the first and second components of the $SU(2)_I$ fields

$$\begin{pmatrix} W_\mu^+ \\ W_\mu^- \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & -1 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} W_\mu^1 \\ W_\mu^2 \end{pmatrix} \quad (2.18)$$

with W mass term given by

$$m_W = \frac{1}{2} g_I v \quad (2.19)$$

The third component of $SU(2)_I$, W_μ^3 , and the $U(1)_Y$ field, B_μ , fuse together through the *weak mixing angle*¹¹ θ_W rotations

$$\cos(\theta_W) = \frac{g_I}{\sqrt{g_I^2 + g_Y^2}} \quad \sin(\theta_W) = \frac{g_Y}{\sqrt{g_I^2 + g_Y^2}} \quad (2.20)$$

to form physical fields Z_μ and A_μ defined by

$$\begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix} = \begin{pmatrix} \cos(\theta_W) & -\sin(\theta_W) \\ \sin(\theta_W) & \cos(\theta_W) \end{pmatrix} \begin{pmatrix} W_\mu^3 \\ B_\mu \end{pmatrix} \quad (2.21)$$

resulting in the field Z_μ acquiring mass of

$$m_Z = \frac{1}{2} (g_I \oplus g_Y) v \quad (2.22)$$

and being identified as the massive weak gauge Z , while the A_μ field acquires no mass

$$m_A = 0 \quad (2.23)$$

and is identified with the $U(1)_{EM}$ gauge boson, the photon. The weak mixing angle also relates the masses of the three physical gauge bosons through

$$m_W = m_Z \cos(\theta_W) \quad (2.24)$$

Finally, since the photon is the gauge boson of the $U(1)_{EM}$ theory of electromagnetism it must couple to all electromagnetically charged particles. The Lagrangian density for a fermion field can be derived from Dirac's equation for free fermion[32] through extension to local gauge-invariance as

$$\mathcal{L}_{QED} = i\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi - g_E\bar{\psi}A_\mu\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} \quad (2.25)$$

¹¹Also known as *Weinberg angle*.

2. Theoretical Overview

where ψ is the free fermionic field with mass m , A_μ is the gauge field, i.e. photon (c.f. Eq. (2.21)), $F_{\mu\nu}$ is the field strength tensor, and g_E is the electromagnetic coupling constant¹² defined as

$$g_E = \sqrt{4\pi\alpha_{EW}} \equiv e \quad (2.26)$$

where α_{EW} is the fine-structure constant, which enters the theory as running coupling constant¹³. Hence, there must also be a relation between the weak mixing angle and the other coupling constants[33]. This relationship can be expressed as

$$g_E = g_I \sin(\theta_W) = g_Y \cos(\theta_W) \quad (2.27)$$

During the spontaneous symmetry breaking, the Higgs field itself acquires mass resulting in formation of the SM Higgs boson. The mass of the boson is defined only through the Higgs potential parameters as

$$m_H = \sqrt{2\lambda v^2} \quad (2.28)$$

hence no *a priori* prediction for the value is provided by the theory, and it enters the theory as a free parameter. On the other hand, the numerical value for the VEV v can be extracted from W mediated muon decays¹⁴. More specifically from the W mass relationship to the very accurately measured Fermi constant G_F . Assuming that the momentum carried by W is negligible compared to its mass,

$$\frac{G_F}{\sqrt{2}} = \frac{g_I^2}{8m_W^2} = \frac{1}{2v^2} \quad \Rightarrow \quad v^2 = \frac{1}{\sqrt{2}G_F} \simeq 246 \text{ GeV} \quad (2.29)$$

given the most precise measurement of $G_F = 1.1663788(7) \times 10^{-5} \text{ GeV}^{-2}$ [34]. Furthermore, numerous (self-)interactions are defined as a consequence of the symmetry breaking. The Higgs sector Lagrangian produces both three- and four-point self interactions of the Higgs boson. The gauge sector contains three- and four-point (self-)interactions between the physical $SU(2)_I$ field bosons and the photon. Combination of both Lagrangians includes direct coupling of the Higgs boson and the massive weak gauge bosons.

The Yukawa sector is responsible for the generation of the fermion masses and describing their interactions with the Higgs boson. After spontaneous symmetry breaking the Yukawa sector Lagrangian consists of

$$\mathcal{L}_{Yukawa} \supset -\frac{g_f v}{\sqrt{2}} (\bar{L}_f R_f + \bar{R}_f L_f) + -\frac{g_f \phi_H}{\sqrt{2}} (\bar{L}_f R_f + \bar{R}_f L_f) \quad (2.30)$$

¹²Canonically identified as the electromagnetic unit charge e (at low energy scales), but expressed as g_E in this section to match the convention used for other gauge field couplings

¹³That means α_{EW} is dependent on the energy scale the process, growing logarithmically as it increases. At zero energy its asymptotic value is approximately 1/137; at scales of Z ($\sim 90 \text{ GeV}$) growing to $\sim 1/127$. Since $\alpha_{EM} \ll 1$, perturbative treatment of QED is possible.

¹⁴ $\mu \rightarrow e \bar{\nu}_e \nu_\mu$

2.1. The Standard Model of Particle Physics

for each fermion f . The first term of Eq. (2.30) can be identified as the mass term for fermion f of mass

$$m_f = \frac{1}{\sqrt{2}} g_f v \quad (2.31)$$

where g_f is the Yukawa coupling for the particular fermion to the Higgs field. The second term can be interpreted as that fermions coupling to the excitation of the field, i.e. the Higgs boson, which is proportional to the fermions mass

$$\frac{g_f \phi_H}{\sqrt{2}} \xrightarrow{\text{Eq. (2.31)}} \frac{m_f \phi_H}{v} \quad (2.32)$$

The electroweak sector of the Standard Model had been rigorously tested since its inception and has produced exceptional results: from agreement between experimental measurements and theoretical calculations in precision measurements (e.g. [35, 36]) to full on discoveries of postulated particles or phenomena (e.g. [37, 38]). The most significant confirmation of the Standard Model was, however, the detection of the Higgs boson in 2012 by ATLAS [1] and CMS [2] experiments at CERN. Event excess in two photon ($\gamma\gamma$) and four lepton ($4l$) final states was observed and matched precisely with the predicted SM Higgs boson with $m_H \approx 125 \text{ GeV}$ decays into these final states (see Figure 2.3). After ten years of intense studying of various properties of the Higgs boson (see Figures 2.4 and 2.5), the SM predictions remain firm.

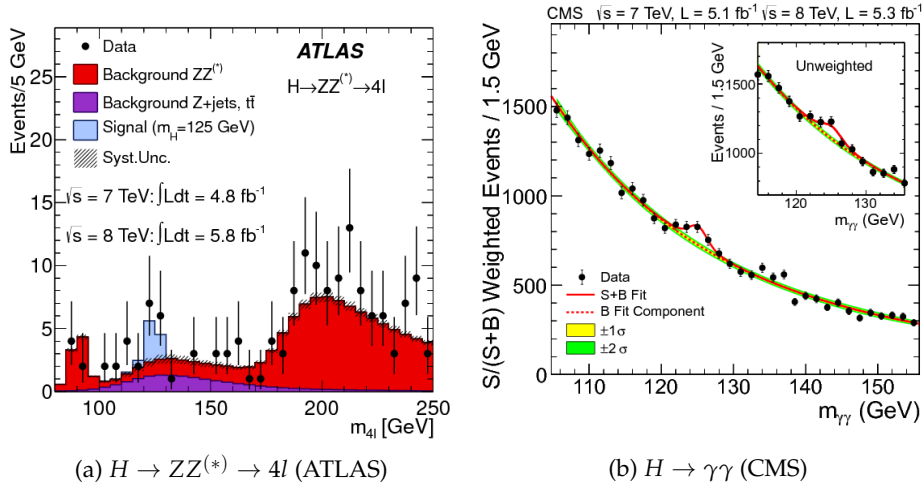


Figure 2.3.: Plots depicting signal event excesses in two possible Higgs decay channels that match the SM prediction. (a) shows excess in the $4l$ decay channel as measured by ATLAS [1]. (b) shows excess in the $\gamma\gamma$ decay channel as measured by CMS [2]. These observations (amongst others) have lead to the confirmation of the Higgs boson discovery announced in 2012.

2. Theoretical Overview

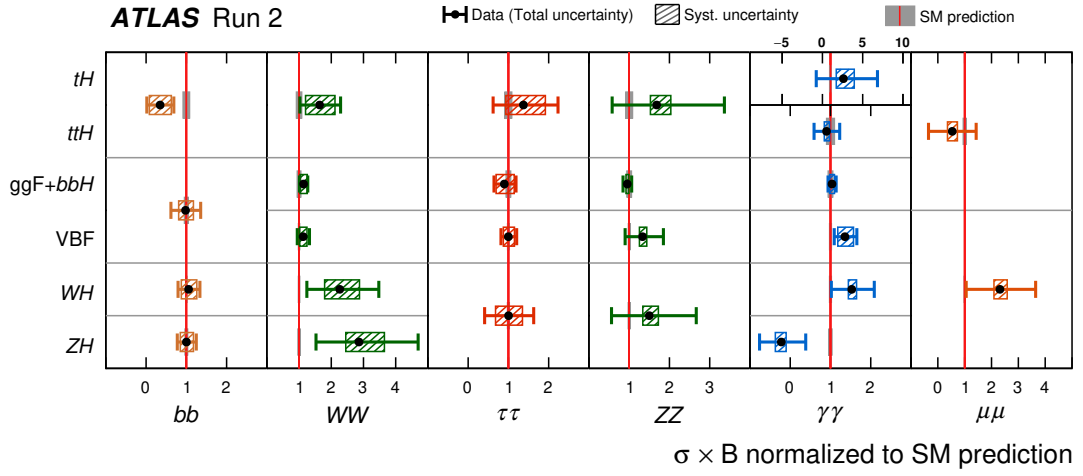


Figure 2.4.: Ratio of observed rate to predicted SM event rate for different combinations of Higgs boson production and decay processes. Figure 3 from [39].

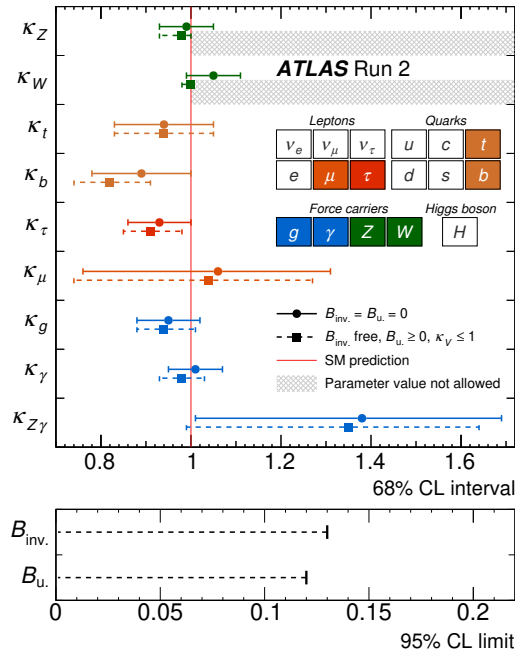


Figure 2.5.: (Top) Reduced coupling strength modifiers and their uncertainties per particle type with effective photon, $Z\gamma$ and gluon couplings. (Bottom) 95% CL upper limits on the invisible, ($B_{inv.}$), and the undetected (B_u) Higgs decay branching ratios. Figure 6 from [39].

2.1.3. Quantum Chromodynamics and the Resulting Complexities of pp Collisions

The second half of Eq. (2.1) encapsulates the strong nuclear force, more precisely the theory of Quantum Chromodynamics [17–19]. QCD finds its origins with quark model for hadron classification proposed independently by Gell-Mann [40] and Zweig [41] in the late 1960s. The theory is based on a $SU(3)_C$ gauge under which each quark carries a colour charge and can be expressed through the three orthogonal colour states. These colour charged states canonically are denominated as *red* (r), *green* (g), and *blue* (b). Similarly to various quark quantum numbers, the anti-quarks carry the opposite charges¹⁵. The generators of the field are 8 massless *gluons*, each representing a different independent linear combination of two out of the three colour states (always colour and anti-colour component). The gauge-invariant Lagrangian of the theory is given by

$$\mathcal{L}_{\text{QCD}} = i\bar{\psi}_a \left(\gamma^\mu D_\mu^{\text{QCD}} - m \right) \psi_b - \frac{1}{4} G_{\mu\nu}^n G_n^{\mu\nu} \quad (2.33)$$

where ψ_a and ψ_b are quark spinor fields in the fundamental $SU(3)_C$ representation, the $G_{\mu\nu}^n$ is the field strength tensor, and the gauge covariant derivative is given by

$$D_\mu^{\text{QCD}} = \partial_\mu + \frac{ig_C \lambda_A}{2} G_\mu^A \quad (2.34)$$

where λ_A with $A \in [1, 8]$ are the Gell-Mann matrices that satisfy the commutation relation of $[\lambda_A, \lambda_B] = 2i \sum_C f_{ABC} \lambda_C$ with f_{ABC} being the asymmetric structure constant of the gauge group. The remaining term in Eq. (2.34) is the coupling constant g_C . Similarly to the electromagnetic coupling, the strong coupling can be rewritten as

$$g_C = \sqrt{4\pi\alpha_S} \quad (2.35)$$

where α_S is the running renormalisation coupling constant for the field, parametrised by the β -function of the renormalisation group

$$\alpha_S(Q^2) = \alpha_S(\mu^2) \left[1 + \frac{\alpha_S \mu^2}{4\pi} \frac{2n_f - 11N_c}{3} \ln \left(\frac{Q^2}{\mu^2} \right) \right] \quad (2.36)$$

where Q is the energy scale (or to be more precise momentum transfer), n_f - number of quarks, N_c - number of colours in the theory, and μ is the mass-dimension renormalisation factor [42]. Since all colour charged objects interact under $SU(3)_C$, this means that gluons also contain self interactions.

The logarithmic decrease with increasing Q of Eq. (2.36) leads to some interesting phenomenological consequences. To begin with, the asymptotic freedom. For high Q , α_S is relatively small and allows perturbative treatment of QCD and higher order calculations of the occurring process. As Q decrease, α_S grows drastically and becomes non-perturbative, hence different treatments of QCD need to be employed. For example, lattice QCD. Moreover,

¹⁵Anti-red ($\bar{r}$), anti-green ($\bar{g}$), and anti-blue ($\bar{b}$)

2. Theoretical Overview

the low Q behaviour, which can also be interpreted as interactions at large distances, results in the colour confinement and hadronisation.

Colour confinement states that no non-zero colour charge can propagate in theory as a free particle. Therefore, all particles with colour-charge must arrange themselves into colour neutral states in one of two ways. If the neutral state is formed through colour anti-colour addition (i.e. $q_{c1}\bar{q}_{c1}$), the resulting state is a *meson*. If the neutral state is formed through addition of all three colour-charges (i.e. $q_{c1}q_{c2}q_{c3}$), the resulting state is *baryon*. Furthermore, if a break-up of a colour neutral system is attempted through provision of (enough) energy, a colour anti-colour quark pair is created from the vacuum, in the large potential between the separating colours, as a response. That is, the initial neutral state forms two new colour neutral systems. Such a process is known as *hadronisation*.

From the perspective of collider based experiments, neither high energy quarks nor gluons travel freely through the detector after the collision. Rather they undergo hadronisation forming a stream of charged and neutral particles known as *jets*. A full theoretical description of hadronisation currently does not exist - it is a non-perturbative process - therefore the modelling of jet evolution is done through phenomenological approaches like the Lund string model[43] or cluster hadronisation[44]. Additionally, colour confinement makes pp collisions more complicated compared to collisions between elementary particles of the Standard Model.

Protons by classification are baryons comprised of two u and single d quarks, known as *valence quarks*. These valence quarks determine the quantum numbers and behaviour of the proton at low energies. However, at high energies, due to colour confinement pairs of quarks and antiquarks of various types can spontaneous be formed from the vacuum¹⁶, resulting in energy dependent structure of the proton during a collision. The fraction of momenta carried by each participating parton in the collision, valence and/or sea, is defined by the Bjorken x_i variable

$$x_i = \frac{p_i}{p_{proton}} \quad (2.37)$$

The probability of a parton carrying a particular x_i at a given energy scale of the process, Q , is then given by the *probability density functions*, $f_i(x_i, Q^2)$, or *PDFs* for short. These PDFs are not theoretically derivable and hence are deduced through fitting of observables to experimental outcomes (example of distributions is shown in Figure 2.6).

Another important role of the Bjorken x_i is the definition of the effective centre-of-mass, $\sqrt{s_{eff}}$, of the process. Given two colliding particles and two out-coming particles, a Lorentz-invariant time-like Mandelstam variable, s , in Minkowski spacetime can be defined as

$$s = (p_1^4 + p_2^4)^2 = (p_3^4 + p_4^4)^2 \quad (2.38)$$

where $p_i^4 = (E_i, \vec{p}_i)$ is the Minkowski spacetime four-momenta for particle i with $i = 1, 2$ colliding and $i = 3, 4$ being the out-coming particles[46]. If particles $i = 1, 2$ have rest mass

¹⁶Such quarks are usually referred *sea-quarks* to differentiate from valence quarks

2.1. The Standard Model of Particle Physics

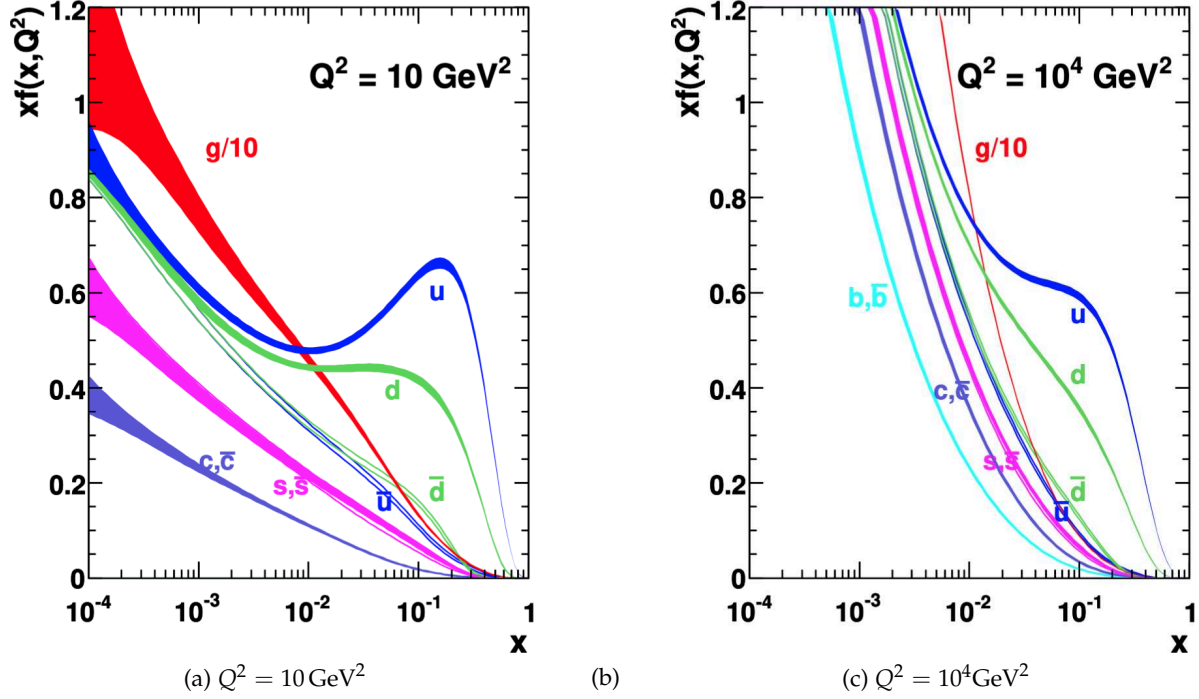


Figure 2.6.: Examples of Parton Distribution Functions of the proton at various energy scales. (a) shows the proton PDF at $Q^2 = 10 \text{ GeV}^2$; (c) shows the proton PDF at $Q^2 = 10^4 \text{ GeV}^2$. Images taken from [45].

of $m_{0,i}$ and follows the energy-momentum relationship¹⁷, then the first part of the Eq. (2.38) definition can be simplified to

$$s = (E_1 + E_2)^2 \stackrel{E_1 \equiv E_2 \equiv E}{=} 4E^2 \quad \Rightarrow \quad \sqrt{s} = 2E \quad (2.39)$$

for head-on collision between particles with opposite but equal magnitude third component of momenta. During a pp collision, between parton i and j the effective centre-of-mass is then defined as

$$s_{eff} = x_i x_j s \quad \Rightarrow \quad \sqrt{s_{eff}} = \sqrt{x_i x_j s} \quad (2.40)$$

Finally, the probability of two partons p_i and p_j , originating from two hadrons h_i and h_j , to undergo a given process with predefined initial and final states, i.e. $ij \rightarrow X$, is described by the process cross-section, $\sigma_{ij \rightarrow X}$, and can be calculated from the matrix element $\mathcal{M}_{ij \rightarrow X}$ via the factorisation theorem

$$\sigma_{ij \rightarrow X} = \sum_{p_i, p_j} \int_0^1 \left[\int \left[f_{p_i}^{h_i}(x_{p_i}, \mu_F) \cdot f_{p_j}^{h_j}(x_{p_j}, \mu_F) \cdot \frac{1}{2s_{eff}} |\mathcal{M}_{ij \rightarrow X}|^2(\Phi_X, \mu_F, \mu_R) \right] d\Phi_X \right] dx_{p_i} dx_{p_j} \quad (2.41)$$

¹⁷ $E_i^2 = \vec{p}_i^2 + m_{0,i}^2$

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where $f_{p_i}^{h_i}(x_{p_i}, \mu_F)$ is the PDF of p_i from hadron h_i with Bjorken x_{p_i} evaluated at the factorisation scale μ_F , μ_R is the renormalisation scale, Φ_X describes the final state phase space. It is important to note, that the integration in Eq. (2.41) over the incoming parton momentum (dx_{p_i}, dx_{p_j}) and the final state phase space ($d\Phi_X$) are carried out in right-to-left fashion¹⁸ as indicated by the overset arrow, rather than left-to-right as often used in literature. An example of the cross-sections relationship on the centre-of-mass, $\sqrt{s}$, is shown in Figure 2.7.

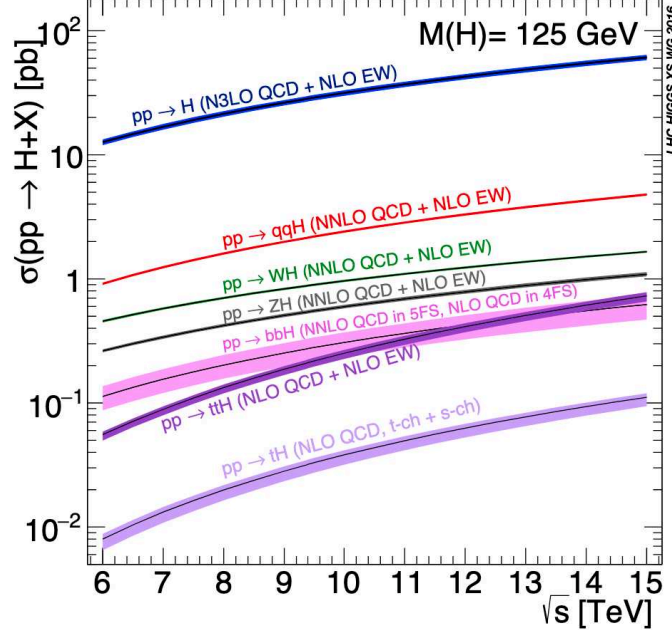


Figure 2.7.: Standard Model Higgs boson ($m_H = 125 \text{ GeV}$) production cross-section as a function of the centre of mass energy[47].

Similarly to the electroweak sector, the QCD sector of the SM has been rigorously investigated and confirmed through various discoveries such as gluon observation by TASSO [48] and PETRA [49] at DESY, as well as exotic meson and baryon states known as tetraquarks (e.g., $Z(4430)$ discovered by Belle experiment [50] in 2007 and later confirmation by the LHCb experiment in 2014 [51]) and pentaquarks (e.g., $P_c(4450)^+$ and $P_c(4380)^+$ detected by the LHCb experiment in 2015 [52]).

2.2. Beyond the Standard Model

While the Standard Model developed in the last half of the century has shown remarkable performance in describing the fundamental behaviour of nature, it is not the proverbial *Theory of Everything*. Despite its great success in both predicting particles, which were only

¹⁸Affecting everything inside corresponding brackets

2.2. Beyond the Standard Model

discovered years later, and providing theoretical descriptions and models, that near perfectly match experimental observations, the Standard Model does not provide specific solutions to some outstanding questions of modern physics. In summary-like fashion, the primary shortfalls of the SM can be described as follows:

- The Gravity question - SM provides no clear inclusion option of the last fundamental force, gravity, into the theory. While the majority of the particle content of the theory acquires mass through the Higgs mechanism during SSB of the electroweak sector and therefore should be affected by the gravitation force, no description of gravity on the quantum level currently exists. While an extension of the SM with a spin-2 graviton has been proposed in the past, the resulting extensions tend to be non-renormalisable.
- The Neutrino question - In Standard Model, neutrinos are massless as they do not have a right-handed representation under $SU(2)_I$ gauge (c.f. Eq. (2.8)), hence cannot form a mass term after SSB. However, the observation of neutrino oscillations [53], indicates that the fundamental eigenstates of the neutrinos mix between themselves into observable mass eigenstates. While multiple solutions have been proposed, for example the seesaw mechanism [54], no permanent agreement of mass origin has been achieved.
- The Hierarchy or the fine-tuning question - While the current observed mass of the Higgs boson, m_H , at the EW energy scale Λ_{EW} is not concerning, when one considers the higher order quantum loop corrections to the observable mass, that is

$$m_H^2 = m_{H0}^2 - \frac{\lambda_f^2 \Lambda^2}{8\pi^2} + \text{h.o.c} \quad (2.42)$$

where m_{H0} is the bare Higgs boson mass, λ_f - fermionic Yukawa coupling, Λ - energy scale, and h.o.c. represents higher order corrections, a clear divergence in Λ is observed. Assuming that no new physics appears between Λ_{EW} and Λ_{Planck} , the energy scale above which SM no longer applies, the divergences would need to be cancelled out by each other through fine-tuning of parameters.

- The baryon asymmetry or baryogenesis question - SM predicts identical production of both matter and anti-matter at the same rate. Hence, nature should be incapable of macroscopic structure formation due to matter and antimatter annihilation. However, the fact that macroscopic structures are abundant in nature, indicates that inherit asymmetry needs to be present during baryogenesis. This is achievable through the Sakharov's conditions : presences of baryon number violation process, C and CP symmetry violation, and interactions out of thermal equilibrium[55]. While these conditions can be realised in SM to some extent, all observed methods of CP symmetry violation are not sufficient to achieve the observed asymmetry.
- The strong CP question - In SM CP symmetry can be violated by both the weak and the strong forces. The QCD sector violation would arise from the phase parameter θ

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of the QCD vacuum and fermion field rotations, resulting in different realised quark masses for the same Lagrangian. Or different Lagrangians for the same realised quark masses. However, since no CP violation is observed in pure QCD focused experiments, the value θ must be unnaturally small [56–58]. There have been attempts to extend the SM to resolve this issue through either modular invariance [59] or introductions of new symmetries resulting in new particles, e.g., axions [60].

- The energy density of the universe question - All the baryonic matter described by the Standard Model can be interpreted as visible matter and, based on the Planck experiment results [61], accounts for about 5% of total energy density of the universe. Another 26% is formed by dark matter - matter that most likely only interacts through the weak force and gravity - without which large galactic structure formation would be impossible. The remaining 69% is comprised by dark energy - a process of unknown nature responsible for accelerating expansion of known universe.
- Recent experimental observation deviations from SM - In 2025 Fermilab's Muon-g2 collaborations has published the most precise measurement of muon's anomalous magnetic moment [62] which confirms the observable deviation between observed and predicted magnetic moments of muons. On the other hand, in 2023 Tevatron's CDF collaborations measured the W mass at around 7σ deviation from the Standard Model prediction[63], which heavily disagreed with both previous measurements and measurements that followed[64]. Both observations remain open questions of active discussion in both theoretical and experimental particle physics.

Various extensions and alterations to the Standard Model had been considered or are under active consideration in an attempt to solve either singular or combination of above listed shortcomings. The proposals range from introduction of individual new symmetries (e.g., Peccei-Quinn $U(1)_{PQ}$ responsible for axions[56]) to inclusion of additional Higgs doublets[33] to unification of the fundamental forces of SM through theories like Supersymmetry[65]. However, no concrete experimental evidence of the proposed solutions' existence (including and not limited to the examples provided) has yet been found. Hence, the topic(s) remain active fields of research to date.

Since the work presented in the thesis has been developed in the context of invisible Higgs decay searches in the interpretation of Higgs Portal, a succinct overview on the concepts of Dark Matter and Higgs portals is provided in the following sections. The topics are covered in order and follow the discussions from [66] and [67] respectively.

2.2.1. Dark Matter : Cosmological Origins and How to Find It

The Standard Model of Cosmology, or Λ CDM for short, represents the best global description of the status and the evolution of the (observable¹⁹) universe. The model is based on the

¹⁹While there exists some cosmological models and theories that separate the definitions between "the observable universe" and "the universe", placing one as the subset of another, for the discussion both terms are treated

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cosmological principle: the universe is homogeneous and isotropic in all directions if (and only if) averaged over sufficiently large regions of space. Additionally, the universe is understood to be expanding with increasing velocity of the expansion. The earliest remnant of the universe formation and indicator of Λ CDM is the cosmic microwave background, or CMB for short (shown in Figure 2.8). CMB was emitted at the time of radiation-matter-decoupling, i.e. when the ambient temperature of the universe dropped below the ionisation level of hydrogen²⁰, consequently forming neutral hydrogen, and allowing photons to radiate freely. Due to the universe expansion, the photons were red-shifted resulting the measurable temperature of CMB today being equal to $T_{CMB}^{today} \sim 2.7\text{ K} \sim 0.2\text{ meV}$ [68] rather than the emittance temperature of $T_{CMB}^{emit} = 0.3\text{ eV}$.

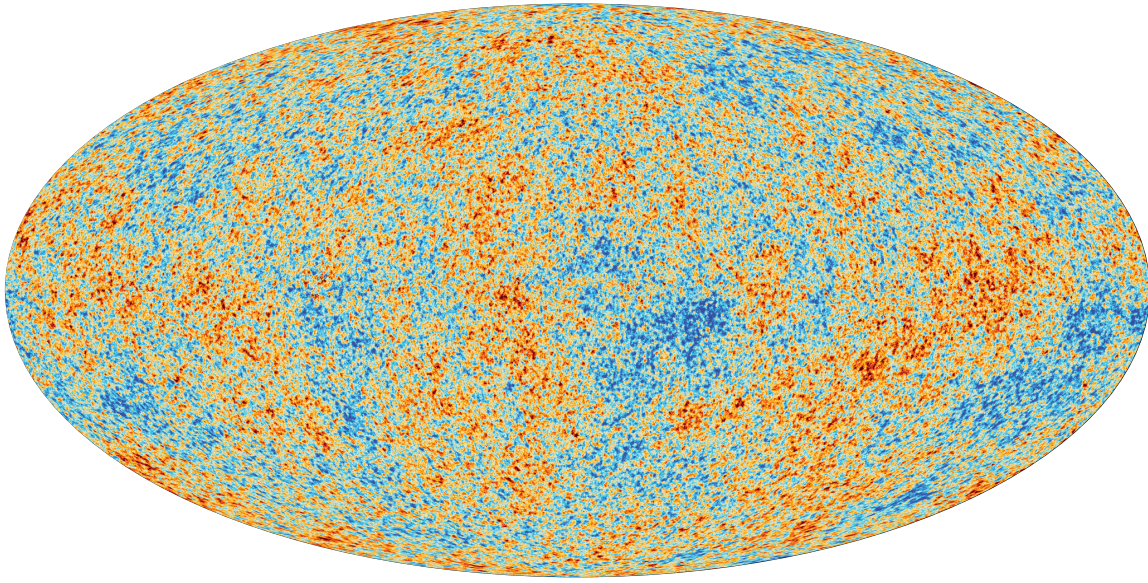


Figure 2.8.: The anisotropies of the cosmic microwave background, or CMB, as observed by ESA's Planck mission. (Credit ESA/Planck Collaboration)

The universe expansion is parametrised through the scale factor $a(t)$, defined as a function of time t . The scale factor links the physical separation between two objects, d_{phys} , at a specific time t_0 to their comoving distance, d_{com} , evaluated at time t_0 through

$$d_{phys}(t) \Big|_{t=t_0} = a(t_0) \cdot d_{com} \Big|_{t=t_0} \quad (2.43)$$

The comoving distance can be interpreted as the distance between the two objects if the universe was not expanding. Hence, it can either be constant if the object have no peculiar motion with respect to each other, or a function of time if they do.

interchangeably.

²⁰Approximately 3.8×10^5 years after Big Bang

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Furthermore, for each component of the universe, i.e. radiation ($i = r$) and baryonic matter ($i = b$), two energy densities can be defined: the average energy density $\bar{\rho}_i(t)$ which is averaged over the whole universe (c.f. cosmological principle) and is only function of time, and the local density around a point in space, $\vec{x}$, given as

$$\rho_i(t, \vec{x}) = \bar{\rho}_i(t) [1 + \delta_i(t, \vec{x})] \quad (2.44)$$

where $\delta_i(t, \vec{x})$ is the density contrast relating whether the local density is larger than the average, hence forms *overdensities* ($\delta_i > 0$), or is smaller and forms *underdensities* ($\delta_i < 0$). The evolution of overdensities is controlled by both gravity, which tends to increase it, and the repulsive pressure of radiation, which tends to decrease it. If overdensities extend through large enough region of space, they pass the *Jeans Collapse Criterion* past which gravitational force always overpowers the radiation pressure. The overdensities continue growing until no more local material can be included, or a new process restores the balance between gravity and radiation pressure (e.g., formation of stars and start of fusion). Based on observation of COBE, WMAP, and Planck, the universe was highly homogeneous at T_{CMB}^{emit} , i.e. $|\delta_i| \ll 1$, and density contrast evolution can therefore be treated perturbatively, with 0^{th} power term being dominant. At $T > T_{CMB}^{emit}$, the baryonic matter δ_b is expected to evolve proportional to $a(t)$,

$$\delta_b(t) \propto a(t) \quad (2.45)$$

while the radiation overdensities δ_r are expected to decrease with t as photons do not interact gravitationally²¹.

Finally, the relative temperature fluctuations in the CMB, $\Delta T/T$, can be expressed as a power spectrum through Fourier transformation of the spherical harmonics. The temperature power spectrum has components sensitive to the baryon density and its relationship with the full energy density of the universe, that is a connection between $\Delta T/T$ and $\delta_b(t_{emit})$ can be established. Assuming that no additional interaction occurs between energy components and that $\bar{\rho}$ is dominated by rest mass, according to Eq. (2.45) the ratio of the density contrast to the scale factor has to be the same for both t_{today} and t_{emit} . That is

$$\frac{\delta_b(t_{today})}{a(t_{today})} \simeq \frac{\delta_b(t_{emit})}{a(t_{emit})} \Rightarrow \delta_b(t_{today}) \simeq \frac{a(t_{today})}{a(t_{emit})} \sim \frac{T_{CMB}^{emit}}{T_{CMB}^{today}} \frac{\Delta T}{T} = 10^{-2} \ll 1 \quad (2.46)$$

where the ratio between the scale factors is replaced by the inverted ratio of the CMB temperatures²² and the observable temperature fluctuations are $\Delta T/T \sim 10^{-5}$ as measured from the CMB[69]. The resulting density contrast at t_{today} implies that no structures should have formed yet, however, the local non-isotropy of the universe indicates otherwise. Hence, the $\delta_b(t)$ needs to grow faster than the expansion scale factor, which is only possible through

²¹Note, this isn't exactly correct as photons are sensitive to the spacetime deformations caused/represented by gravity; In this discussion a more simplified view of interaction is taken: the photon gravitational interaction is assumed to be infinitesimal on the large scale systems and can be treated as non-existing vis-à-vis baryonic interaction with gravity

²²Decrease in temperature is related to the increase of the system

2.2. Beyond the Standard Model

pre-existing gravitation potential presence during matter-radiation decoupling and sustained through new energy density component which primarily interacts gravitationally. That is, dark matter must exist at the time of neutral hydrogen formation.

After the matter-radiation decoupling, overdensities of both baryonic and dark matter begin to form. The dark matter component is the first one to pass the Jeans Collapse Criterion and begins to gravitationally collapse. The resulting structure quickly virializes²³ and forms dark matter halos. The halos are expected to be spherically symmetric, have time-independent phase space distribution, and have radial density profiles described by the Navarro-Frenk-White profile, or NFW profile for short,

$$\rho_{NFW}(r) = \rho_s \frac{r_s}{r} \left(\frac{2}{1 + \frac{r}{r_s}} \right)^2 \quad (2.47)$$

where ρ_s is the normalisation constant and r_s is the scale radius, where the slope of the profile changes. According to NFW profile, the halo density is expected to mimic an isothermal halo behaviour, ($\rho(r) \propto r^{-2}$), but fall less steeply in the inner regions ($\rho(r < r_{inner}) \propto r^{-1}$) and more steeply in the outer regions ($\rho(r > r_{outer}) \propto r^{-3}$). The baryonic component eventually also passes the Jeans Collapse Criterion and galaxy formation occurs within this dark matter halo. The galaxy is typically distributed into two structures: the galactic bulge, concentration of stars around the centre of the galaxy, and the galactic disk, comprised of stars and interstellar material²⁴. The distributions of both visible (baryonic) and dark matter within such systems and the resulting physics effects can be used as useful tools for dark matter detection.

For example, consider galactic rotation curves from the perspective of Newtonian dynamics. For a spherically symmetric mass distribution (e.g., galactic bulge and DM halo), the rotation velocity of objects around the centre of a galactic system at distance r is proportional to the mass within this system,

$$v_{rot}(r) \propto \sqrt{\frac{M(r)}{r}} \quad (2.48)$$

Assuming that the majority of the mass of the system is contained within radius R , the rotational velocity beyond it would experience a Keplerian decline. If DM halo is excluded from the system, the rotational velocity of the galactic bulge would follow Eq. (2.48), while decreasing $v_{rot}(r|_{r>R}) \propto 1/\sqrt{r}$ in the disk. The resulting total curve would be expected to peak around the outer radius of the bulge and drop off as the distance from the centre increases. If the DM halo is included in the system, no drop off would be observed with the curve remaining somewhat flat. The latter option is preferred by to observational data of rotational curves of dwarf spiral galaxies, for example NGC 6503 (shown in Figure 2.9).

Similarly, consider a collision of two galaxy clusters, i.e. groups of above discussed models. During the collision, the interstellar material would be slowed down with respect of the rest of the system due to friction, heat up, and begin emitting X-ray radiation peaking around the

²³I.e. redistribution of potential and kinetic energy occurs within the system

²⁴Gas and/or dust

2. Theoretical Overview

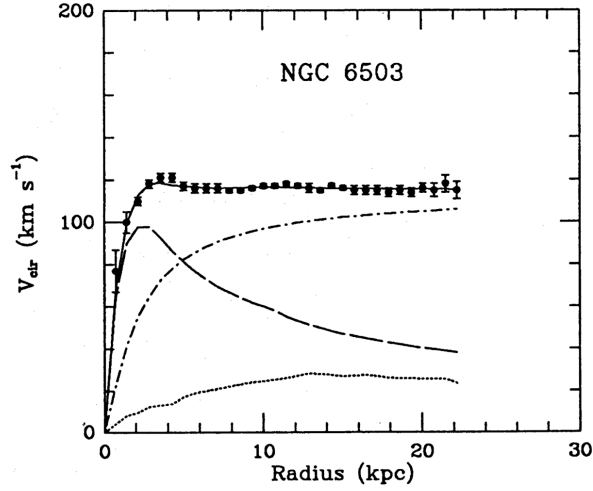


Figure 2.9.: Rotation curve of dwarf spiral galaxy NGC 6503. Individual contribution from the galactic disk (— — —), the dark matter halo (— · —), and the gas (· · ·) to the total rotation curve (solid line) are shown and matched to the observation data (solid points with error bars)[70].

"middle point" of the collision. If DM halo is not part of the colliding systems, then analysis of the gravitational potential of collision²⁵ would indicate a peak of the potential centred around the X-ray emissions. On the other hand, if DM halo is part of the colliding systems, it would remain non-interactive and centred around the galaxies, i.e. outside the "middle point" of the collision. Consequently, the gravitational potential would have a two peak distribution. Observations of such cluster collisions, for example the 1E0657-558 or "Bullet" cluster (shown in Figure 2.10), clearly agree with the latter model.

While cosmological and astronomical observations provide indication that dark matter exists and may even place some restrictions on its properties (see Section 2.3 in [66] and reference therein), they do not provide a concrete answer to what dark matter is. Multiple candidates have been proposed to occupy this description: From aforementioned axions, to weakly interacting massive particles (WIMP's)[73], and even to primordial black holes [74]. However, no clear candidate has yet to emerge victorious. If one considers the DM candidate to be particle-like, then it's observation might be possible through either direct detection (e.g., elastic scattering with target atomic nuclei[75]), indirect detection (e.g., light-shining-through-a-wall experiments [76]), or through production in particle colliders[77]. These possible search paradigms are visualised in Figure 2.11.

²⁵e.g., through gravitational lensing

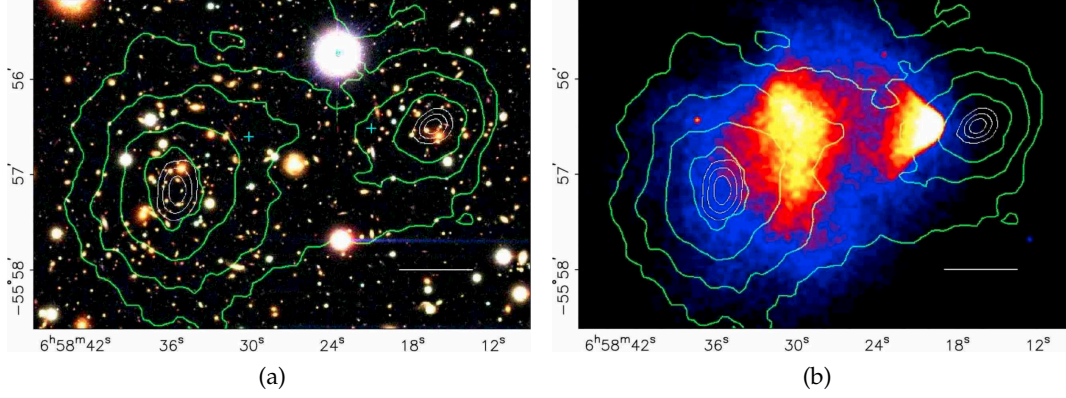


Figure 2.10.: 1E0657-558 ("Bullet") cluster visualisation through various spectra. (a) depict the collision through the visible spectra using Magellan telescope image. (b) depict the collision through the X-ray spectra using Chandra X-ray observatory[71]. In both images, a green contour map is shown indicating gravitation distribution of the system inferred through gravitation lensing. The non coincidence of the gravitation potential peak with the X-ray origins is indicative proof of dark matter existence. Both images taken from [72].

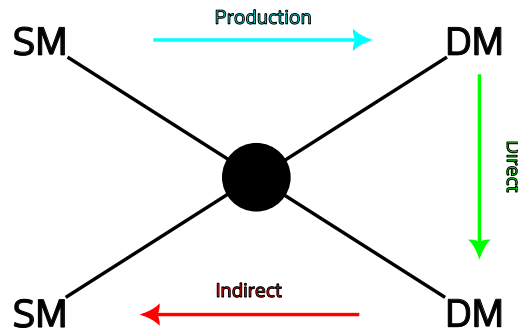


Figure 2.11.: Representative Feynman sketch of particle-like dark matter candidate search paradigm.

2. Theoretical Overview

2.2.2. Higgs portal and the Connection to the Beyond

The Higgs portal model extension of SM relies on introduction of a new Dark Matter sector described by the Lagrangian density, $\mathcal{L}_{\text{DM}}$, and stabilised through unbroken $\mathbb{Z}_2$ symmetry²⁶. The extended Lagrangian for the full theory is given by

$$\mathcal{L}_{\text{BSM}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DM}} \quad (2.49)$$

where $\mathcal{L}_{\text{SM}}$ is identified as Eq. (2.1). Both components of Eq. (2.49) transform under $\mathbb{Z}_2$ as

$$\mathcal{L}_{\text{SM}} \xrightarrow{\mathbb{Z}_2} \mathcal{L}_{\text{SM}} \quad \mathcal{L}_{\text{DM}} \xrightarrow{\mathbb{Z}_2} -\mathcal{L}_{\text{DM}} \quad (2.50)$$

The $\mathbb{Z}_2$ symmetry implies that the physics described by $\mathcal{L}_{\text{SM}}$ is not affected by the physics described by $\mathcal{L}_{\text{DM}}$. The only exception is the Higgs sector as the Higgs field is assumed to couple to the $\mathcal{L}_{\text{DM}}$ defining field and its excitation. Hence, Higgs boson is expected to act as portal between the SM and BSM dark sector.

Following [67], which builds upon [78], three different spin-based scenarios for the introduced dark matter field are considered: spin-0 real scalar, S , spin-half fermion (either Dirac or Majorana²⁷, though for the following discussion Dirac interpretation is used), F , and spin-one Vector, V_μ , fields. Their corresponding Lagrangian (limited to the mass and Higgs coupling terms) are given by

$$\mathcal{L}_{\text{DM},S} \equiv \mathcal{L}_S \supset -\frac{1}{2}M_S^2 S^2 - \frac{1}{4}\lambda_{\text{HSS}}\Phi\Phi^\dagger S^2 \quad (2.51)$$

$$\mathcal{L}_{\text{DM},F} \equiv \mathcal{L}_F \supset -\frac{1}{2}M_F^2 F\bar{F} - \frac{1}{4}\frac{\lambda_{\text{HFF}}}{\Lambda_{\text{DM}}}\Phi\Phi^\dagger F\bar{F} \quad (2.52)$$

$$\mathcal{L}_{\text{DM},V} \equiv \mathcal{L}_V \supset -\frac{1}{2}M_V^2 V_\mu V^\mu - \frac{1}{4}\lambda_{\text{HVV}}\Phi\Phi^\dagger V_\mu V^\mu \quad (2.53)$$

where Φ is the complex Higgs doublet, M_D is the bare mass of the field, λ_{HDD} - the Higgs field coupling, Λ_{DM} is the scale of the new physics ($D = \{S, F, V\}$). After EW spontaneous symmetry breaking and the neutral component Higgs doublet acquiring the VEV, v of 246 GeV, the DM field excitations manifest with real mass, m_D , given by

$$m_S^2 = M_S^2 + \frac{1}{4}\lambda_{\text{HSS}}v^2 \quad (2.54)$$

$$m_F^2 = M_F^2 + \frac{1}{4}\frac{\lambda_{\text{HFF}}}{\Lambda_{\text{DM}}}v^2 \quad (2.55)$$

$$m_V^2 = M_V^2 + \frac{1}{4}\lambda_{\text{HVV}}v^2 \quad (2.56)$$

It is important to note, that while the $\mathcal{L}_{\text{BSM}}$ is based on unbroken $\mathbb{Z}_2$ symmetry and therefore is renormalisable and extrapolative to high energies (assuming no Landau pole is reached),

²⁶Origin of which is dependent on the introduced field's spin

²⁷Primary difference between Dirac fermions and Majorana fermions is that Majorana fermions are their own anti-particles, whereas Dirac fermions and anti-fermions are considered separate

2.2. Beyond the Standard Model

the fermionic interpretation of the DM, shown in Eq. (2.52), is not. Due to dependence of the scale of new physics, i.e. Λ_{DM} , renormalisability can only be achieved through the fermionic coupling redefinition, i.e. $\lambda_{HFF} \rightarrow \lambda_{HFF} \times v / \Lambda_{DM}$. In the following discussion, the pre-redefined version of λ_{HFF} is used for simplicity with the assumption that any process evaluation is done with the redefined coupling at Λ_{DM} . In summary, the Higgs portal extension of the Standard Model only introduces two new free parameters into the theory, the mass of the DM particle, m_D and the coupling constant λ_{HDD}

Based on these two parameters, observables for each of the three dark matter detector approaches described in Section 2.2.1 can be constructed. For direct detection one can utilise the fact that interactions between DM candidate and nuclei are elastic through Higgs boson exchange. The resulting nuclear recoil can then be interpreted in terms of DM candidate mass and the spin-independent DM-nucleon cross-sections, σ_{D-N}^{SI} , given by

$$\sigma_{S-N}^{SI} = \frac{\lambda_{HSS}^2}{16\pi m_H^4} \frac{m_N^4 f_N^2}{(m_S + m_N)^2} \quad (2.57)$$

$$\sigma_{F-N}^{SI} = \frac{\lambda_{HFF}^2}{4\pi m_H^4} \frac{m_N^4 m_F^2 f_N^2}{(m_F + m_N)^2} \frac{1}{\Lambda_{DM}^2} \quad (2.58)$$

$$\sigma_{V-N}^{SI} = \frac{\lambda_{HVV}^2}{16\pi m_H^4} \frac{m_N^4 f_N^2}{(m_V + m_N)^2} \quad (2.59)$$

where m_H is the SM-like Higgs mass, m_N - mass of the nucleon, and f_N parametrises the Higgs-nucleon coupling, either through lattice QCD or individual contributions from heavy and light quarks. For indirect detection purposes the relic abundance of the DM can be used as a measurement and can be inferred through the s-channel annihilation via Higgs boson exchange. The thermally averaged cross-section of such annihilation to a light fermion of mass m_f can be derived through the Boltzmann equation

$$\langle \sigma_{ferm}^S v_r \rangle = \frac{\lambda_{HSS}^2 m_f^2}{16\pi} \frac{1}{(4m_S^2 - m_H^2)^2} \quad (2.60)$$

$$\langle \sigma_{ferm}^F v_r \rangle = \frac{\lambda_{HFF}^2 m_f^2}{32\pi} \frac{1}{(4m_F^2 - m_H^2)^2} \frac{m_F^2 v_r^2}{\Lambda_{DM}^2} \quad (2.61)$$

$$\langle \sigma_{ferm}^V v_r \rangle = \frac{\lambda_{HVV}^2 m_f^2}{48\pi} \frac{1}{(4m_V^2 - m_H^2)^2} \quad (2.62)$$

where v_r is the velocity of the dark matter candidate. Finally, if the DM candidate is light enough, that is $m_D \leq 1/2 m_H$, it can be produced through invisible Higgs decays and escape detection in collider experiments (i.e. appearing as missing energy). The partial invisible

2. Theoretical Overview

Higgs decay widths are given as

$$\Gamma_H^{\text{inv}}(H \rightarrow SS) = \frac{\lambda_{\text{HSS}}^2 v^2 \beta_S}{64\pi m_H} \quad (2.63)$$

$$\Gamma_H^{\text{inv}}(H \rightarrow FF) = \frac{\lambda_{\text{HFF}}^2 v^2 m_H \beta_F^3}{32\pi \Lambda_{DM}} \quad (2.64)$$

$$\Gamma_H^{\text{inv}}(H \rightarrow VV) = \frac{\lambda_{\text{HVV}}^2 v^2 m_H^3 \beta_V}{256\pi m_V^4} \left(1 - 4\frac{m_V^2}{m_H^2} + 12\frac{m_V^4}{m_H^4} \right) \quad (2.65)$$

where $\beta_D = \sqrt{1 - 4m_D^2/m_H^2}$ and v is the Higgs vacuum expectation value. Furthermore, the Eqs. (2.63)–(2.65) are related to the measurable branching ratio for invisible Higgs decay, $\mathcal{B}_{\text{inv}}$, through

$$\Gamma_H^{\text{inv}}(H \rightarrow DD) = \mathcal{B}_{\text{inv}} \cdot \Gamma_H^{\text{total}} \quad (2.66)$$

where Γ_H^{total} is the total decay width of the Higgs boson.

3. LHC and ATLAS experiment

European Organisation for Nuclear Research (*Organisation Européenne pour la Recherche Nucléaire*) (est. 1957) particle physics laboratory CERN¹ has played an integral part in the particle physics research field and yielded numerous achievements. From contributing to quark charge deduction and confirmation[79] and direct evidence of weak neutral currents through the Gargamelle experiment in the 1970s[80, 81] to the discovery of the $W^\pm$ [37, 38] and Z [82] in 1983 by UA1 and UA2 experiments, CERN has been pivotal in forming the current understanding of particle physics. Since 2008, CERN has taken the centre stage of particle physics and its frontier through the operation of the Large Hadron Collider, LHC for short, the most powerful hadron accelerator and collider to date.

3.1. Large Hadron Collider

The Large Hadron Collider is a circular particle accelerator spanning approximately 27 km in circumference. Located at the boarder between Switzerland’s Republic Canton of Genève and France’s commune of Saint-Genis-Pouilly, the acceleration facility lies between 75 m and 125 m under the ground. Numerous bunches of protons (or heavy ions) are accelerated to near the speed of light and collided at predefined four collision points housing the primary LHC experiments, ALICE[83], ATLAS[84], CMS[85], and LHCb[86].

To achieve the high energy frontier, LHC acts as a final stage of a multi-stage acceleration complex, shown in Figure 3.1, and is supplied with proton bunches pre-accelerated to 450 GeV by Super Proton Synchrotron (SPS). The bunches are injected at two separate points and circulated in opposite directions through two independent beamlines. Each beam is further accelerated by 8 dedicated superconducting radiofrequency cavities in one of the straight sections of the accelerator during circulation. Superconducting dipole electromagnets (magnets from here onwards) are used to bend the travelling particle bunches along the beamlines, quadrupoles focus the beam during circulation, while sextuple, octupole, and decapole magnets are used as correctors. When desired centre-of-mass energies and stable beam conditions are achieved, the beams are collided at the interaction points, IP .

The primary LHC experiments can be separated into two categories. Both ATLAS and CMS experiments, located at opposite sided of the accelerator, are general purpose detectors²

¹A name derived from the (provisional) European Council for Nuclear Research *Conseil Européen pour la Recherche Nucléaire* which was superseded by the Organisation; full name European Laboratory for Particle Physics *Laboratoire Européen pour la Physique des Particules*

²Sometimes considered *sister experiments* as both act as each other counter-reference for performance and detection.

3. LHC and ATLAS experiment

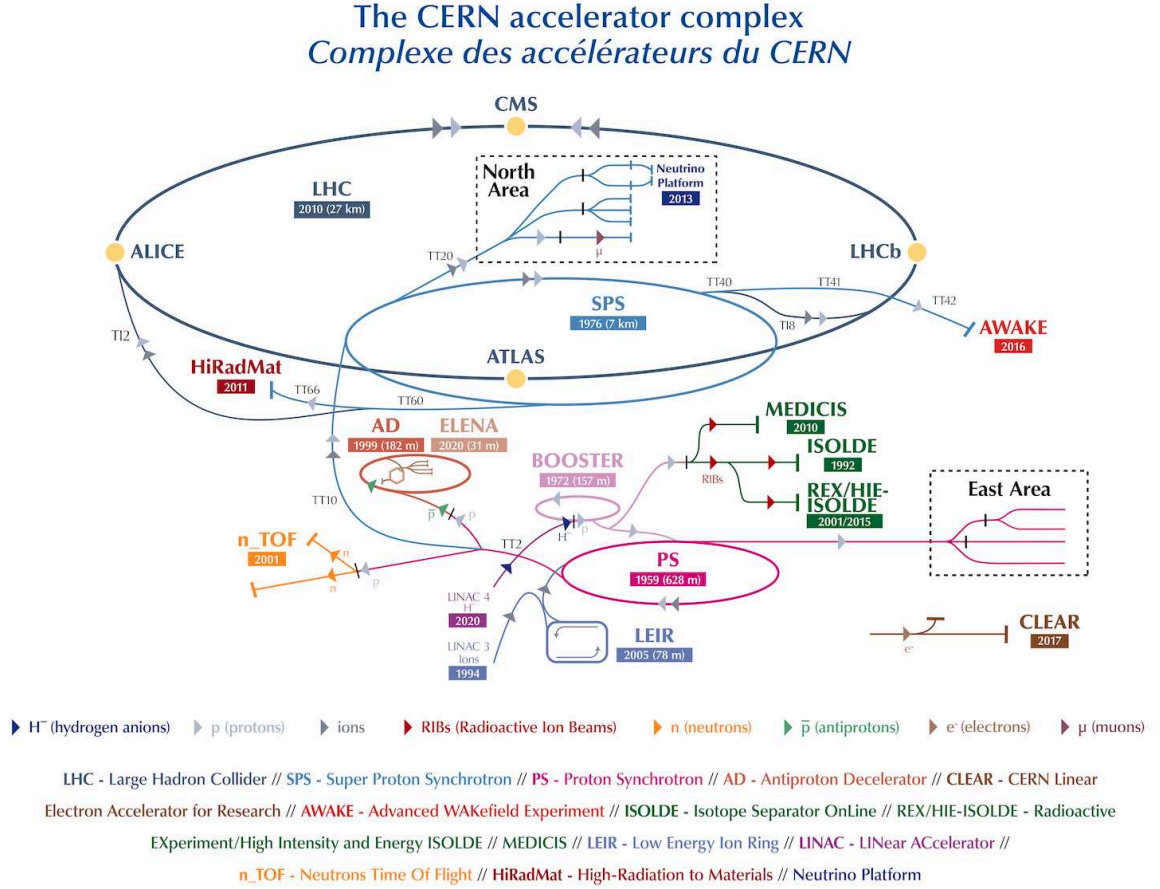


Figure 3.1.: The CERN accelerator complex including the necessary infrastructure for LHC and various experiments [87].

and carry out a diverse physics program. From precision measurements of the Standard Model to searches for physics beyond it. ALICE and LHCb, located near the injection points, on the other hand, are more specialised: ALICE primary research focus is investigation of quark-gluon plasma created during heavy-ion collisions. LHCb focuses on CP violation, baryon asymmetry, and bottom quark related physics.

During nominal LHC operation conditions each of the beamlines is filled with approximately 2000 proton bunches per fill iteration with each bunch being comprised of around 1.2×10^{11} protons³. The number of bunches is different year-to-year, ranging from 2200 in 2016 to 2556 achieved in 2017 and 2018. The parametrisation of bunches is a crucial component needed to describe the instantaneous luminosity of accelerator. Instantaneous luminosity,

³Each fill does not have a predetermined duration, though usually last on $\mathcal{O}(20\text{h})$. Internally (i.e. w.r.t ATLAS) fills are further broken down into smaller sections of data taking known as *runs* (not to be mistaken with Runs as in Run 1, Run 2, or Run 3, which are always capitalised).

3.1. Large Hadron Collider

$\mathcal{L}_{\text{inst}}$, defines the amount of collisions that are delivered to a given experiment. The instantaneous luminosity can be defined as

$$\mathcal{L}_{\text{inst}} = \frac{n_1 n_2 f_r}{2\pi \Sigma_x \Sigma_y} \quad (3.1)$$

where n_1 and n_2 are the number of particles in the colliding bunches, f_r is the revolution frequency, and Σ_x and Σ_y are the convolved horizontal and vertical beam sizes. The total luminosity delivered to the detector during a period of time is then given by the time-integrated luminosity $\mathcal{L}$,

$$\mathcal{L}_{\text{int}} = \int \mathcal{L}_{\text{inst}} dt \quad (3.2)$$

and the event rate produced by the collider is

$$\frac{dN}{dt} = \mathcal{L}_{\text{inst}} \sigma \quad (3.3)$$

where σ is the total cross-section of a particular physics process.

LHC and its corresponding experiment operations are canonically broken down into periods of data taking, known as *Runs*, annual operation stops, *Year End Technical Stops* or *YETS* for short, and periods of extended non-operation, known as *Long Shutdowns* or *LS*. *YETS* are typically used for both detector and accelerator infrastructure maintenance and minor improvements while *Long Shutdowns* are used for major upgrades. During its 27 years of operation, LHC has completed two full *Runs* and is currently approaching the end of the 3rd one. Each data taking period has been marked with both increasing centre-of-mass energy of the collision, $\sqrt{s}$, and increasing amount of data collected (For full breakdown see Table 3.1).

Run	Years	$\sqrt{s}$ [GeV]	$\mathcal{L}_{\text{int}}$ [fb ⁻¹]
Run 1	2009 - 2011	7.0	30
	2012 - 2013	8.0	
Run 2	2015 - 2018	13.0	140
Run 3	2022 - 2026	13.6	300 (planned)
Run 4	2030 - 2034 (planned)	13.6 - 14.0 (planned)	3000 (planned)
Run 5	2036 - 2041 (planned)		

Table 3.1.: LHC Data taking period breakdown by operation years, centre-of-mass collision energy, and (expected) collection of data.

3. LHC and ATLAS experiment

3.2. ATLAS experiment

ATLAS (originally a macronym of **A Toroidal LHC AparatuS**, now just ATLAS) detector is one of the two primary multipurpose experiments based at the LHC [84]. Located at interaction point 1, in a cavern 100 m below the earth surface, the detector measures 46 m in length and 25 m in diameter with an approximate weight of 7×10^6 kg. ATLAS detector is cylindrical in nature with internal subsystems layered in radial fashion. ATLAS detector utilises a forward-backward symmetry and offers near-hermetic (4π) coverage in solid angle. The detector subsystems include: the *Inner Detector* (ID), two calorimeters, *Electromagnetic* (ECAL) and *Hadronic* (HCAL), the *Muon Spectrometer* (MS), and various magnet systems located around the inner detector as well as outside the calorimeters. Detailed description of each subsystem is given in Sections 3.2.2–3.2.4 respectively. Section 3.2.6 is dedicated to describe the ATLAS trigger system and data acquisition process. Additionally, ATLAS operation is also supported with 4 forward detectors : Luminosity Cherenkov Integrating Detector (*LUCID*) [84, 88], The Absolute Luminosity for ATLAS (*ALFA*) Roman Pot detector [89], the Zero Degree Calorimeters (ZDC) [90], and ATLAS Forward Proton (*AFP*) detector [91]. While their functionality covers a wide range topics, their in-depth description is not given in this work. The only exception is the LUCID-2 detector, whose short description is given in Section 3.2.5

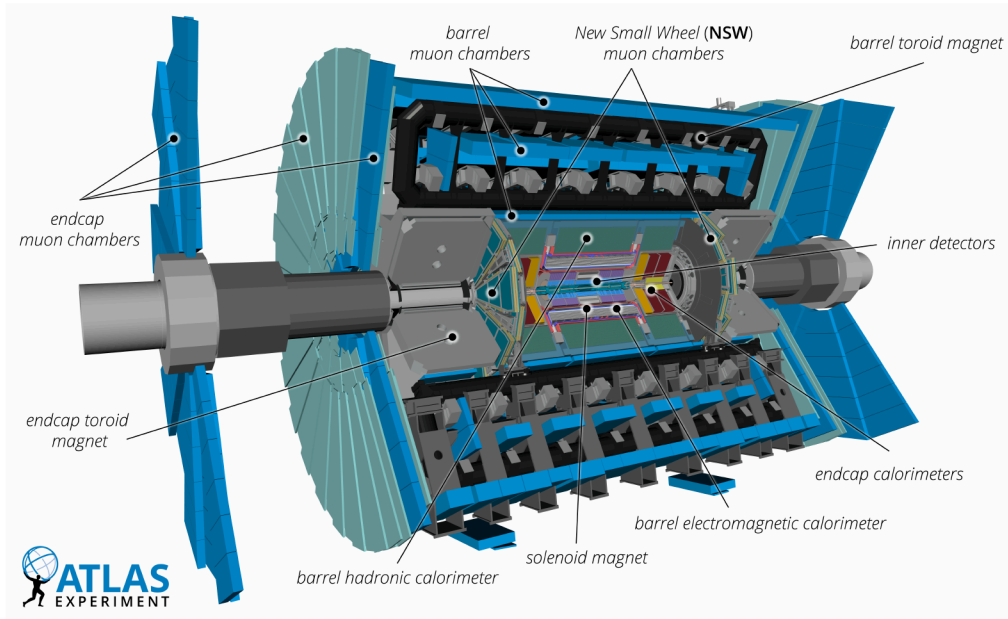


Figure 3.2.: Cut-away view of the Run 3 configuration of the ATLAS detector indicating the locations of the larger detector subsystems. Image from [92]

The ATLAS detector has been initially designed for peak instantaneous luminosity of $10^{34} \text{cm}^{-2} \text{s}^{-1}$ for pp collisions at centre-of-mass energies of $\sqrt{s} = 14 \text{ TeV}$ with about 25

3.2. ATLAS experiment

interaction per bunch crossing, defined as

$$\mu_{vis} = \frac{\mathcal{L}_{inst} \cdot \sigma_{vis}}{f_r} \quad (3.4)$$

where $\mathcal{L}_{inst}$ is the instantaneous luminosity, σ_{vis} - visible cross-section, and f_r the revolution frequency of the accelerator. However, in Run 2 the LHC exceeded its planned design performance and achieved a peak $\mathcal{L}_{inst} = 2.1 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ resulting in average μ_{vis} , $\langle\mu\rangle$, of 33.7 for the period. For Run 3 similar luminosity conditions are expected ($2 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$) with further increase of interaction per bunch crossing ($\langle\mu\rangle \sim 50 - 60$). The distribution of μ_{vis} , including its mean value and total integrated luminosity, for individual years since the start of Run 2 is shown in Figure 3.3. Despite these harsher condition the detector performance remained exceptional. Though, adaptation to analysis and performance techniques was needed in response. Substantial upgrades to the detector during the first two long shutdowns, known as *Phase-I Upgrade*, have also been carried out to handle the harsher environment.

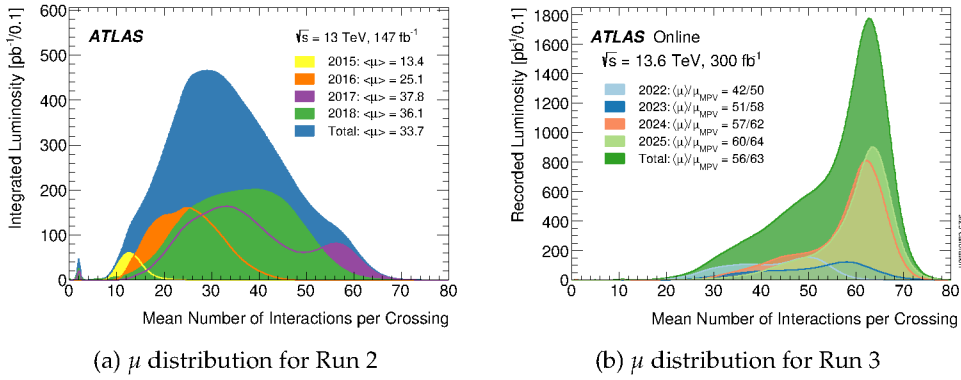


Figure 3.3.: Number of Interactions per bunch crossing distribution for data taking periods of (a) Run 2 [93] and (b) Run 3 [94].

3.2.1. Coordinate Reference System

The three-dimensional Cartesian coordinate systems used in ATLAS is defined with origin of the system located at the interaction point. The x-axis points towards the centre of LHC, the y-axis points towards the sky, and the z-axis is oriented towards the anti-clockwise direction along the LHC beamline. Additionally, two polar coordinates θ and ϕ are used to characterise objects within the detector. The azimuthal angle ϕ defines the rotation in the x – y plane⁴ while θ is the polar angle of the z – y plane. Both angles are bounded to $(-\pi, \pi]$, both $\phi = 0$ and $\theta = 0$ point parallel to their *abscissa* axis (x- and z-axis respectively),

⁴The notation A – B assumes that A is the *abscissa*, while B is the *ordinate*.

3. LHC and ATLAS experiment

while $\phi = \pi/2$ and $\theta = \pi/2$ is oriented identically to their *ordinate* axis (y-axis for both). The rapidity, y , of the object inside the detector is given by

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right) \quad (3.5)$$

where E and p_z are the energy and momentum projection onto the z-axis respectively⁵. More commonly, the pseudo-rapidity of the object, η , defined as

$$\eta = -\ln \left(\tan \left(\frac{\theta}{2} \right) \right) \quad (3.6)$$

is used to approximate y . For low mass approximation ($m \ll |\vec{p}_3|$), where $|\vec{p}_3|$ and m is the magnitude of the three-dimensional Cartesian momentum and mass respectively, $|\eta| \sim |y|$. For more massive objects, the relationship reduces in accuracy as $|\eta| < |y|$.

The final two important quantities used for object description is the transverse momentum of the object, p_T defined by the object's momentum projections along the x- and y-axis

$$p_T = \sqrt{p_x^2 + p_y^2} \quad (3.7)$$

which is related to the energy through hyperbolic cosine relationship as

$$p_T = \frac{\sqrt{E^2 - m^2}}{\cosh \eta} \xrightarrow{E \gg m} \frac{E}{\cosh \eta} \quad (3.8)$$

and the angular separation between two objects defined as

$$\Delta R_{\phi y} = \sqrt{\Delta \phi^2 + \Delta y^2} \quad \text{and} \quad \Delta R_{\phi \eta} = \sqrt{\Delta \phi^2 + \Delta \eta^2} \quad (3.9)$$

where $\Delta \phi$, Δy , $\Delta \eta$ are the objects distance to a reference point in ϕ, y and η respectively. In the low mass interpretation, $\Delta R_{\phi y} \equiv \Delta R_{\phi \eta} \equiv \Delta R$.

3.2.2. Tracking

The Inner Detector, *ID*, is the closest of the detector subsystems to the beamline and serves as the primary charged particle tracking and momenta measurement system for ATLAS. The ID is made of three complimentary subsystems, silicon Pixel detector[95] (with insertable B-layer, *IBL* [96]), Semiconductor tracker (*SCT*) [97, 98], and the Transition Radiation Tracker (*TRT*) [99]. All subsystems are concentrically layered around the beamline and immersed in a 2T uniform⁶ magnetic field created by superconducting solenoidal magnet located outside the TRT [101]. The three subcomponents provide a full coverage in ϕ and partial coverage in η (Pixel and SCT $|\eta| < 2.5$, TRT $|\eta| < 2.0$). The magnetic field is used to bend

⁵Expressed in natural units

⁶To be more precise, the field isn't entirely uniform. There is a drop from 2 T at $|z| = 0$, 1.8 T at $|z| = 1.7$ m, and to 1 T at $|z| = 2.7$ m ($r = 0$ assumed). See [100]

the trajectories of charged particles. The full configuration of the Inner Detector (apart the solenoidal magnet) can be broken down into the central barrel region and two end-cap regions (an end-cap per detector's "end") and is shown in Figure 3.4. Figure 3.5 provides a breakdown of each subcomponents' layout in $r - z$ space with η coverage indication.

The first of the subcomponent of the Inner detector is the silicon Pixel detector. Since Run 1, the silicon Pixel detector has been comprised of three concentric cylindrical barrel layers providing coverage in $|\eta| \lesssim 1.5$ and six disks (3 on each side) extending it to $|\eta| \lesssim 2.5$. All layers are segmented in $r\phi$ and z with identical pixel sensors. During Run 1 and Run 2, the pixel detector has been upgraded through introduction of a fourth cylindrical layer, known as insertable B-layer⁷. The IBL is located 33.5 mm away from the centre of the beamline, has greater granularity pixels, but does not have a disk equivalent. The primary purpose of IBL was to improve vertex and b -quark identification, handle increased luminosity of Run 2, and account for radiation damage to and module failure of the rest of Pixel detector experienced during Run 1.

The middle subcomponent of the Inner detector is the Semiconductor Tracker. The central barrel region of SCT consists four silicon strip layers, each comprised of 12 rings of double-sided rectangular small-angle stereo strip sensors along the z axis. The end cap region consists of 9 disks, each made of three increasing radii rings of similarly double-sided stereo strip sensor. SCT contributes significantly to reconstruction of the charged particles transverse momenta [98].

The outermost layer of the Inner detector is the Transition Radiation Tracker. TRT is based on the gaseous drift strawtube technology and utilises more than 5×10^4 tubes in the barrel region and more than 1.2×10^5 tubes per end-cap. Detection relies on ionisation of the gas inside the strawtube during charged particle transit through it and conversion of the ions and electrons to electrical signal for readout. Additionally, due to transitional radiation dependence on the Lorentz factor γ ⁸, TRT also carries out particle differentiation between electrons and pions[102]. During Run 1, TRT operated using a Xe-based gas mixture. At the start of Run 2, partial substitution to previously tested alternative Ar-based mixture[99] was carried out as some leaks were detected by the end of the previous Run. During Run 3, the alternative is expected to become more prevalent.

During a collision, each charged particle track is expected to cross the 4 layers of the Pixel detector, leave at least 4 space points within SCT, and create around 30 hits within the TRT detector. The readouts from these systems are then used in ATLAS reconstruction software for track (re)construction and transverse momentum calculations. Based on ATLAS inner detector design the p_T resolution is typically parametrised as

$$\sigma_{p_T} \left(\frac{1}{p_T} \right) \cdot p_T \simeq 0.036\% \cdot p_T \oplus 1.3\% \quad (3.10)$$

and ranges between 2% to 12% for $p_T < 100$ GeV tracks depending on their η and p_T [103–105].

⁷While often interpreted as separate systems, the IBL technically is an extension of the Pixel detector.

⁸Which itself is dependent on the ratio of a relativistic particle's momentum to its rest mass.

3. LHC and ATLAS experiment

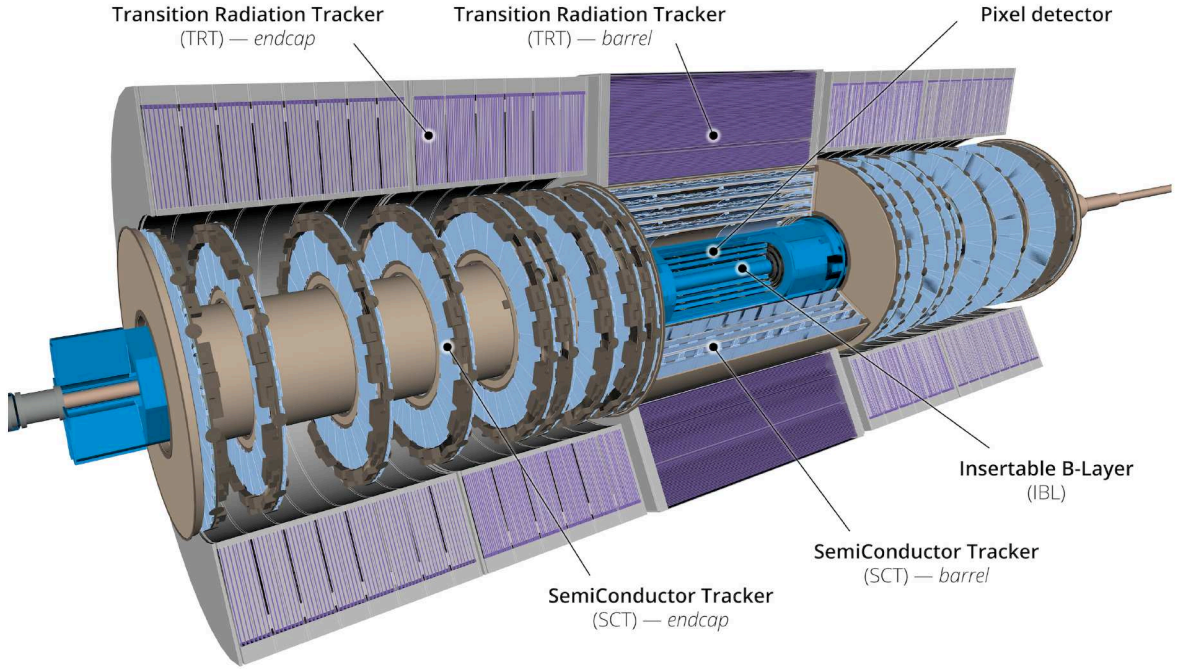


Figure 3.4.: Cut-away view of ATLAS Inner Detector configuration for Run 3. The solenoidal magnet located beyond the TRT and before the calorimeter systems is omitted [92].

3.2.3. Electromagnetic and Hadronic Calorimetry

The ATLAS experiment employs three complimentary calorimeter systems - electromagnetic (*ECal*), hadronic (*HCal*), and forward (*FCal*) - to carry out hermetic energy measurements of both neutral and charged particles. All calorimeters have been designed as sampling calorimeters comprised of active (energy measurement) and absorber (energy deposition) materials. The goal - forcing particles to fully deposit their energy within the absorbers and measure their detector penetration using the active material. Similarly to the Inner Detector, both *ECal* and *HCal* can be separated into the central (barrel) and end-cap regions. The full calorimetry system provides a coverage in $|\eta| < 4.9$ and full coverage in ϕ . The visualisation of the systems is shown in Figure 3.6 while Figure 3.7 provides a more detailed layout and coverage of each subsystem in η . Summary of each calorimeter materials is given in Table 3.2

The closest of subsystems to the interaction point is the Electromagnetic Calorimeter consisting of the Liquid Argon (*LAr*) Electromagnetic Barrel Calorimeter, *EMB*, and the *LAr* Electromagnetic Endcap calorimeter (*EMEC*) [109]. Both calorimeters utilise liquid Ar as the active material while lead (Pb) is used for energy depletion through EM particle shower induction. The *EMB* consists of three concentric barrel layers covering $|\eta| < 1.475$ while *EMEC*, comprised of two coaxial wheels (on both ends), extends the coverage until $|\eta| < 3.2$.

3.2. ATLAS experiment

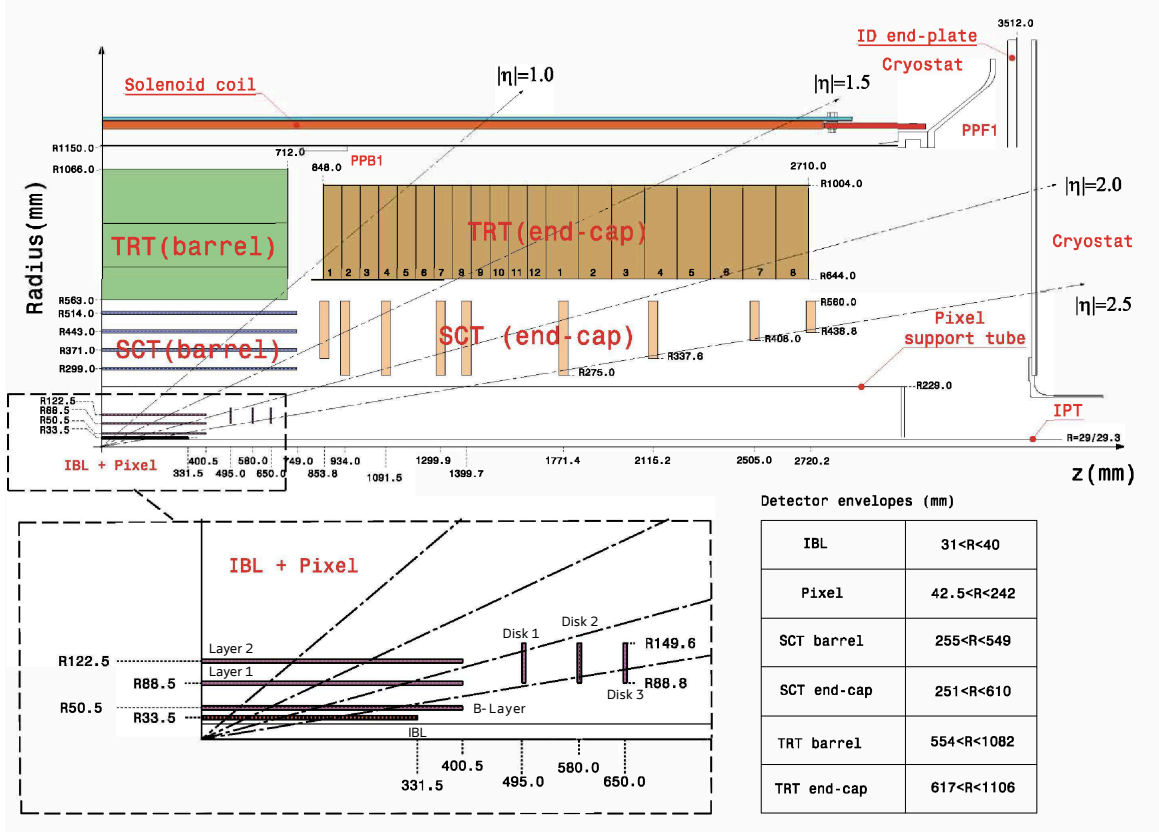


Figure 3.5.: ATLAS Inner Detector subcomponent breakdown in $r - z$ space with η coverage indication. Additionally, various subsystem detector envelopes are also shown [92].

Additionally, a thin LAr presampler is used within $|\eta| < 1.8$ to adjust shower energy due to loss in material upstream. The primary purpose of ECal is the energy measurement of electromagnetically interacting particles through EM shower measurement.

Outside the ECal systems is the Hadronic Calorimeter, made of Tile Calorimeter (*Tile*) in the barrel region and the LAr Hadronic Endcap (*HEC*). The Tile calorimeter is based on scintillating tile technology [110] and differently to other calorimeters is further broken down into the barrel part ($|\eta| < 1.0$) and two extended barrels ($0.8 \leq |\eta| < 1.7$) which cover both EMEC and HEC. All three Tile systems utilise scintillating tiles as the active material and low carbon steel as the absorber. The HEC, similarly to EMEC, extends coverage to ($|\eta| < 3.2$) and is another LAr calorimeter with copper used instead of lead for the absorption. The Hadronic Calorimeter is considered to be a non-compensating calorimeter as no presampler is present between it and ECal. The HCal is used to measure hadronically interacting particle energy using hadronic showers.

The final subsystem is the LAr Forward calorimeter. Comprised of three coaxial rings per

3. LHC and ATLAS experiment

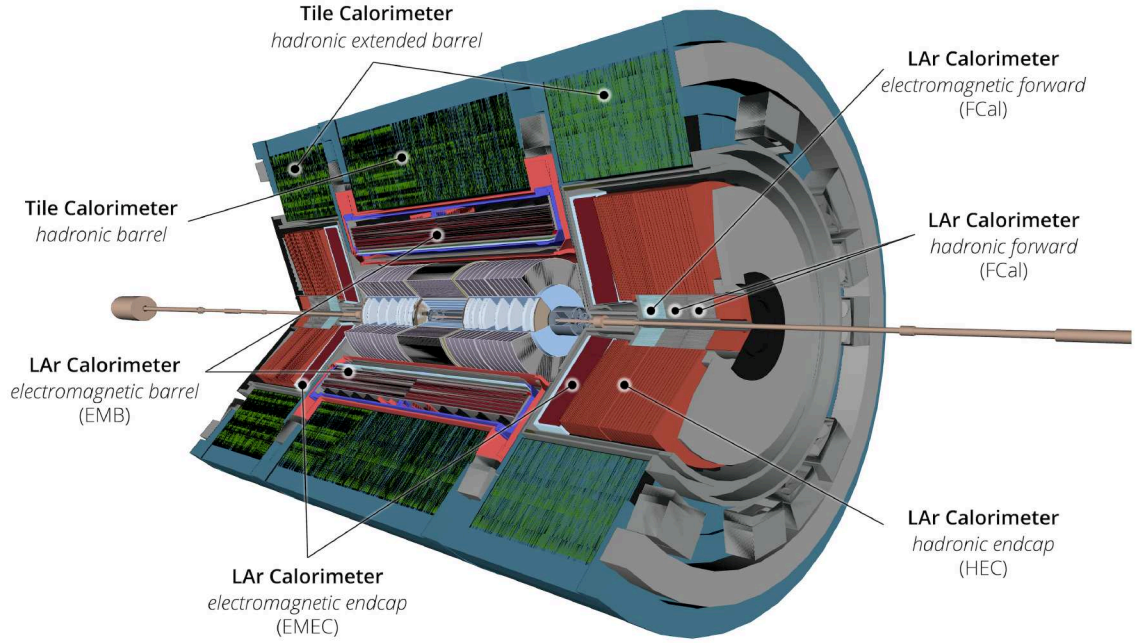


Figure 3.6.: Cut-away view of the ATLAS calorimeter systems [92].

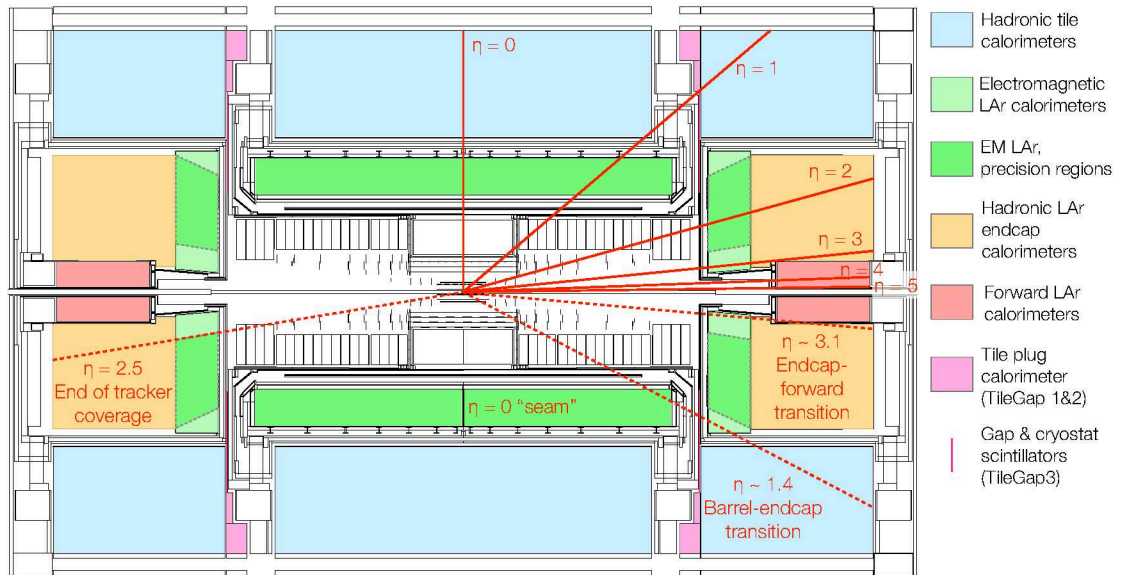


Figure 3.7.: Layout of the ATLAS calorimeters with pseudorapidity η value indications [106].

Calorimeter	$ \eta $ coverage	Active material	Absorber Material	Depth	
EMB	< 1.475	LAr	Pb	$22-33 X_0$	[84]
EMEC	$\in (1.375, 3.2)$	LAr	Pb	$24-38 X_0$	[84]
HEC	$\in (1.5, 3.2)$	LAr	Cu	$103 X_0$	[107]
Tile (barrel)	< 1.0	STile	Steel	11λ	[108]
Tile (extended barrel)	$\in (0.8, 1.7)$	STile	Steel		
FCal (1st ring)	$\in (3.1, 4.9)$	LAr	Cu	$28 X_0$	[84]
FCal (2nd,3rd ring)	$\in (3.1, 4.9)$	LAr	W	$89-91 X_0$	[84]

Table 3.2.: ATLAS Calorimetry system breakdown. Both electromagnetic and hadronic calorimeter systems are parametrised by their coverage in η , materials used for their active (LAr - liquid Argon; STile - scintillating tile) and absorber media, and their depth. Liquid argon based calorimeters' depths are parametrised using the radiation length, X_0 , defined as a mean length of the absorbing medium needed to reduce particle's energy by $1/e$. The depth of scintillating tile based calorimeters is provided through nuclear interaction length, λ , defined as the mean path of the absorber needed to reduce the flux of relativistic particles by a fraction $1/e$. The forward calorimeter system is split into two parts covering both the electromagnetic (1st ring(s)) and hadronic (2nd and 3rd ring(s)) calorimetry functionality.

detector end in increasing $|z|$ distance from the interaction point, FCal encompassing $|\eta|$ ranges between 3.1 and 4.9. Differently to ECal and HCal, FCal is used for both hadronic and electromagnetic calorimetry. The closest ring, which uses copper as the absorber material, is focused on electromagnetic shower measurement, while the remaining two, which use tungsten, are meant to complement the HCal in its functionality.

The granularity of the Calorimeter systems differs depending on their closeness to the interaction point and their purposes. In the η ranges covered by the ID tracking system the electromagnetic calorimeter boasts a very fine granularity due to high resolution requirements for electron and photon measurements. Outside the tracker coverage for ECal and independent of it for HCal, the granularity is coarser, however still sufficient for hadronic jet and missing transverse energy reconstruction and measurement. The relative resolution of the full ATLAS calorimetry system is given by

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E} \quad (3.11)$$

where parameters a, b, c represent the sampling, constant, and noise contributions to relative

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resolution, σ_E/E [111]. The noise contribution, c , originates from the electronic noise of detector front-end electronics (as well as due to pileup) as approximately independent of the energy deposited by the particle. Hence, it is expected to be only significant in low energy regime [106]. The remaining parameter contributions are shown in Table 3.3

Calorimetry System	$a(\sqrt{\text{GeV}})$	b
EMB	10.1%	0.2%
EMEC	12.1%	0.4%
Tile	52.0%	3.0%
HEC	70.6%	5.8%
FCal	94.2%	7.5%

Table 3.3.: ATLAS calorimetry system fractional resolution sampling and constant term breakdown [110, 112, 113].

3.2.4. Muon Spectrometer

The outermost subsystem of the ATLAS detector is the Muon Spectrometer (MS) [114]. MS primary purpose is detection and momentum measurement of particles escaping the calorimetry system - primarily muons - within pseudorapidity range of $|\eta| < 2.7$. Additionally, MS has a dedicated muon triggering system based on high-precision tracking chambers that covers $|\eta| < 2.4$. To further improve its performance, magnetic deflection is provided by the air-core toroid magnet system. Same as ID, ECal, and HCal, MS can be separated into barrel and endcap regions. Full breakdown of spatial layout of the muon spectrometer as well as the toroid magnet system is shown in Figure 3.8.

The barrel region ($|\eta| < 1.0$) consists of three concentric layers of muon detection stations around the beam axis and has remained relatively unchanged since the start of ATLAS operation. All three layers of barrel use multilayered Monitored Drift Tubes, *MDT*, for precision track measurement. For triggering purpose, the two most outer-layers are also equipped with Resistive Plate Chambers, *RPCs*.

The endcap region ($1 < |\eta| < 2.7$) on both sides of the detector is split to 3 Endcap disk, inner, middle, and outer wheels. An additional disk, Extended Endcap ring, located between the inner and middle wheels, provides coverage in $|\eta| \in [1.05, 1.3]$ that is not covered by the outer wheel. Extended endcap ring, outer, and middle wheels have not experience major changes compared to Run 1 and Run 2 data taking periods. Similar to the barrel, the three disks are equipped with MDT for precision measurements but triggering capability is provided by Thin Gap Chambers, *TGCs*, which are only located near the middle wheel. The inner wheel of MS, on the other hand, has been a major focus of upgrade during the

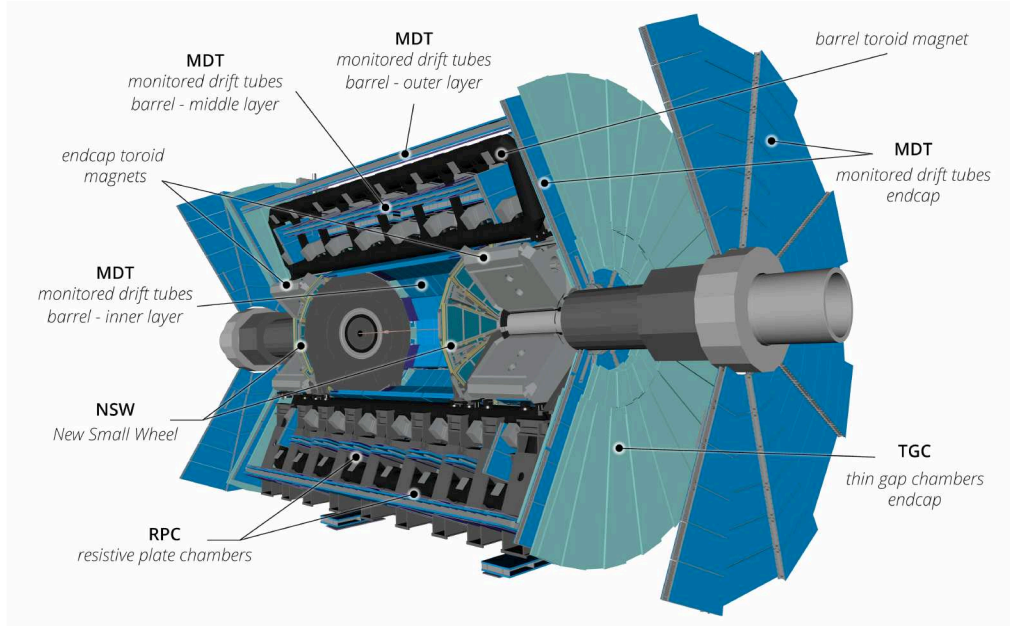


Figure 3.8.: Cut-away view of the ATLAS muon spectrometer system including the air-core toroid magnets as of Run 3 data taking period. The primary change to MS implemented during Long Shutdown 2, New Small Wheels (NSW) which replaced the previous inner (endcap) wheels, are also shown [92].

Long Shutdown 2. Initially, based on combination of MTDs and Cathode Strip Chambers (CSC), the inner wheels have been fully replaced by the new small wheels (NSW) [115]. The NSW utilise two new subdetector types: small-strip TGC (*sTGC*) and micro-mesh gaseous structure (*Micromegas*) which are able to participate in both precision measurements and triggering. With the implementation of NSW, MS is expected to have an overall 15% momentum resolution for 1 TeV muons and greater than 95% tracking efficiency for muons with p_T of 10 GeV or greater [116].

The magnetic deflection needed for MS operation is provided by air-core toroidal magnet system located outside the ATLAS Calorimeters. In the barrel region of $|\eta| < 1.4$, large barrel air-core toroid comprised of 8 individual coils is used [117]. In the end cap region of $|\eta| \in (1.6, 2.7)$, magnetic deflection is created by two endcap toroid magnets at each end of the detector [118]. In the transitional region of $1.4 < |\eta| < 1.6$ the bending of the muons is a consequence of both the barrel and the endcap toroid magnetic fields. The field integral of the toroids is 2-6 T across most of the detector.

3.2.5. Forward Detectors: LUCID 2

Apart from the three primary subsystems described in Sections 3.2.2–3.2.4, the ATLAS experiment also includes four forward detector systems located at various distances away

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from the interaction point along the LHC beamline. Each of the detector systems participates in different parts of the ATLAS physics program and utilise particles that escape detection by ATLAS at high ($|\eta| > 4.9$) pseudorapidity.

The only forward detector relevant for the presented work is the Luminosity Cherenkov Integrating Detector, *LUCID* [84, 88], located around 17 m away⁹ from the interaction point. *LUCID* (or to be more precise *LUCID-2*) acts as the primary reference ATLAS luminometer able to assist in *online* and *offline*¹⁰ per-bunch luminosity deduction. The former is useful for stable beam condition and detector performance monitoring. The latter is crucial for the physics program of ATLAS, for example allowing comparison between simulated Monte Carlo sample and recorded ATLAS data. The expected luminosity at typical ATLAS pp collision conditions is extrapolated from data collected during dedicated low luminosity runs. These runs are optimised to reduce systematic uncertainties of luminosity measurements [119–121] carried out through van der Meer (*vdM*) scans [122]. The collected data is then used as a basis of the extrapolation through a transfer factor application.

3.2.6. ATLAS Trigger, Data Acquisition and Processing

During nominal LHC operations around 4×10^7 bunch crossings per second are expected to occur at ATLAS interaction point. Due to physical limitations of the soft-, firm-, and hardware utilised in the ATLAS detector and its associated data storage systems, it is impossible to save all the generated information. Hence, a two-level Trigger and Data Acquisition (*TDAQ*) system is utilised by the ATLAS experiment [123–125]. The primary purpose of the trigger system is to select events with particular characteristics, e.g. hadronic jets or larger missing transverse energy, and using the DAQ system record the measurements from different ATLAS detector systems for offline processing and analysis. Elements participating in triggering decisions and the general data flow for *TDAQ* configuration for Run 2 and Run 3 are shown in 3.9(a) and 3.9(b) respectively.

The first level of the trigger system, known as *level-1* or *L1* for short, is a hardware-based trigger [126]. *L1* uses custom electronics with reduced granularity inputs from the calorimetry systems and MS to identify Regions of Interest (*RoI*) as preliminary event selection. This reduces the event rate from 40 MHz to 100 kHz with the decision made within 2.5 μ s latency window[125].

The second level of the trigger system is the software-based *High Level Trigger*, or *HLT* for short [127]. *HLT* uses *online* algorithms, which are based on *offline* algorithms used for analysis, to reconstruct physics objects in greater detail than *L1* in either *L1*'s *RoIs* or in full detector range to further select events of interest. During Run 2 data taking period, *HLT* would further reduce event rate down to 1 kHz [124]. However, due to *TDAQ* system upgrades¹¹ carried out during Long Shutdown 2, for the period of Run 3 the acceptance and

⁹In both directions.

¹⁰*Online* refers to processes carried out specifically during active data taking; *Offline* refers to processes carried out without active data taking. For example, object reconstruction from already recorded data.

¹¹As well as changes to detector system and central ATLAS software.

recording rate has been increased to 3 kHz [125]

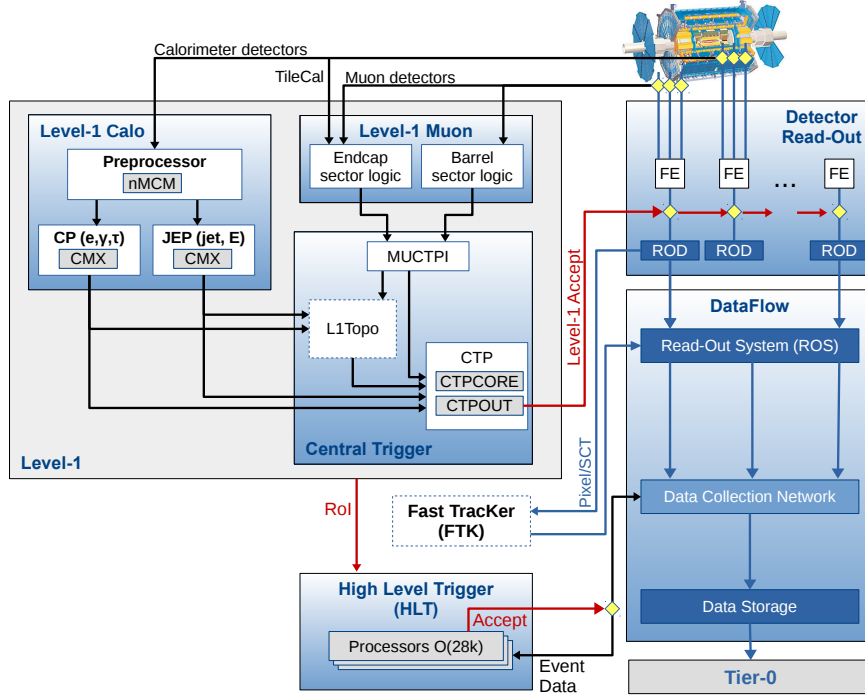
To better manage computation resources needed for trigger operation, the rate of accepted events can be adjusted through trigger prescaling factors. If a trigger has a prescale factor n , it is assumed that the probability for an event, that meets the trigger criteria, to pass it is $1/n$. A trigger that has a prescale factor of $n = 1$, is assumed to be *unprescaled*. The majority ($\sim 85\%$) of ATLAS triggers during Run 2 data collection were operated as unprescaled triggers [125].

Offline object reconstruction and analysis¹² using real and simulated data is carried out using a specialised central ATLAS software framework, *Athena*¹³ [128]. For real data the general processing chain is as follows: post-trigger the raw collected data (*RAW*) is reconstructed into analysis object data (*AOD*/*xAOD*) which is then transformed through derivation to derived analysis objects (*DAOD*) which are either used directly in the analysis or refined further to other formats. For simulated data, the event generator outputs (*EVNT*) are used as inputs for detector interaction simulation, which outputs (*HITS*) are then digitised to simulated detector outputs (*RDO*) [129, 130]. *RDO*'s are then further reconstructed and derived to *DAOD* in similar fashion to real data.

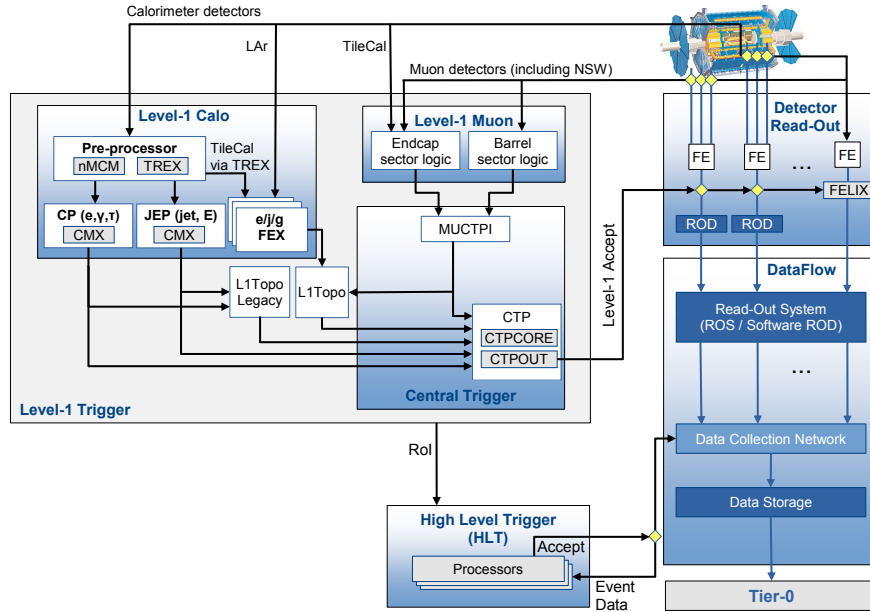
¹²As well as online for HLT, though the following description does not apply fully.

¹³Which from Run 3 period supports multithreading capabilities[92].

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(a) ATLAS TDAQ during Run2 [124]



(b) ATLAS TDAQ during Run3 [125]

Figure 3.9.: ATLAS Trigger and Data Acquisition (TDAQ) system visualisation for (a) Run 2 and (b) Run 3. Elements relevant to triggering, detector read-out, and data flow are primarily shown. The post-HLT event rate for Run 2 is 1 kHz [124] and 3 kHz for Run 3 [125]

4. Object and Event reconstruction

4.1. Tracks

Tracks, defined as reconstructed charged particle trajectories, are one of the most crucial elements in correctly reconstructing a particle collision event. As mentioned in Sections 3.2.2 and 3.2.4, tracks are build using subdetector readings from all layers of the ID and tracking-capable layers of the MS using a dedicated suite of algorithms[131–133]. A general track reconstruction strategy follows a two-fold approach: the *inside-out* reconstruction, which starts from the precision layers of the ID detectors and builds outwards towards the TRT, followed by backtracking or *outside-in* reconstruction. The former focuses primarily on particles produced close to the pp interaction point, while the latter is used to increase sensitivity to tracks for particles produced further away from the beamline (e.g., e from γ conversion in detector material). While tracks are build for all physics objects in the detector¹, muonic track reconstruction is carried out in inverted order with differing methods. The general tracks are reconstructed with $p_T > 500$ MeV (limitation through track curvature in the solenoid's magnetic field) within $|\eta| < 2.5$ (the ID geometry). Muonic tracks are reconstructed with $p_T > 3$ GeV (limitation from energy loss in calorimetry systems) within $|\eta| < 2.7$ (the MS geometry). In both cases, a track is parametrised by the following set of variables

$$\left\{ d_0, z_0, \phi, \theta, \frac{q}{p_T^{\text{track}}} \right\} \quad (4.1)$$

where d_0 and z_0 are the transverse and longitudinal impact parameters, defined as distances between track perigee² and beamline in $x - y$ and $r - z$ planes respectively, ϕ is the azimuthal angles between p_T^{track} and x-axis, θ - polar angle between $\vec{p}_{\text{track}}$ and the z-axis, q is the charge, and $\vec{p}_{\text{track}}$ and p_T^{track} is the full and transverse momentum of the track respectively.

The (general) *inside-out* procedure begins with a *track seed* construction which is made up of three *space-points* or hits³ from three consecutive layers of either Pixel, the SCT, or both. The seeds are then expended to *track candidates* using combinatorial Kalman filter[134] through inclusion of remaining Pixel and/or SCT layers that match the seed's trajectory. Following the extension ambiguity solver algorithm is run to remove possible overlaps between the candidates and reject (possibly) fake tracks. The algorithm scores each candidate based on quality criteria⁴ with lower score candidates possibly being fully rejected versus a high

¹Exceptions are neutrally charged particles, e.g., ν

²Closest orbital approach with respect to a reference.

³Formed by charged particle traversing the active material of a detector.

⁴e.g., p_T^{track} or hits within precision ID detectors

4. Object and Event reconstruction

score track candidate if too many clusters formed through the Kalman filter are shared. Some hit sharing is tolerated for compatibility with expected dense topologies, e.g., high energy jets, where separation between individual charged particles might not be possible. In such situations, the shared hits are distributed between the candidates using an additional neural network based algorithm[135, 136]. A track candidate is considered appropriate during Run 2 (Run 3) if it has at least 7 (8) hits and $|d_0| < 10$ mm(5 mm) and is then further extrapolated to the TRT. The extrapolation includes TRT drift circles⁵ close to track candidates trajectory through iterative χ^2 -based re-fit approach. The final TRT extensions are selected by a dedicated ambiguity solver similar to the one used for precision ID detectors.

Following the *inside-out* procedure, a back-tracking reconstruction is carried out. The procedure is only done where depositions in the electromagnetic calorimeter (see Section 3.2.3) have compatible segments within the TRT. In such regions, the requirement for the Pixel and SCT based seed is lowered to two points, which are then extended to candidates using Kalman filter, ambiguity solved, and extrapolated to the TRT segment through similar procedure as before. It is important to note, that for the *outside-in* reconstruction, only hits that have not been used or included during *inside-out* are considered.

For muon track reconstruction the order is reversed and combination of information from all ATLAS primary detector systems is used[137]. The muonic *outside-in* reconstruction begins with muon system tracks through various MS tracking detector output aggregation in similar steps to the general *inside-out* procedure⁶. After formation, the MS track trajectories are then globally extrapolated back to the beamline through a re-fit procedures needed to account for energy loss in the calorimetry systems. If the muonic track lies within $|\eta| < 2.5$, a procedure to combine it with an ID track is carried out. Following the muonic *outside-in* procedure, an *inside-out* equivalent is done. If there exists a full ID-based track or partial track compatible with a short-lived charged particle decay with extrapolated trajectory intersecting activity in the MS which had not been used or has been omitted during MS track formation, a similar ID and MS track combination procedure is done. In both *outside-in* and *inside-out* cases, based on the joining procedures results, muons in ATLAS are separated into different groups (for more details see Section 4.5).

4.2. Vertices

A primary vertex, PV_i , is defined by a three dimension space position of inelastic proton-proton collision[138–140]. As discussed in Section 3.2, multiple pp collisions are expected to occur during each bunch crossing. Only one of such interaction is expected to yield insight into interesting physics, referred to as *hard scatter* or *HS*. The remaining interactions are referred to as *pile-up* (or *PU*) and their associated activity tends to obfuscate HS. Hence, detectable object association to their corresponding primary vertices of origin is paramount in reconstructing the event's full kinematic properties. The differentiation between hard

⁵Hit equivalent for the TRT.

⁶Seed $\rightarrow$ candidate $\rightarrow$ ambiguity solver $\rightarrow \chi^2$ fit

scatter and pile-up vertices is done using the scalar sum of their associated track momenta. The vertex with the greatest sum is identified as the hard scatter vertex while the remaining are treated as pileup. That is

$$\text{vtx}_i \equiv \text{HS} \iff \sum_{\text{track} \in \text{vtx}_i} \left(p_T^{\text{track}}\right)^2 \equiv \max \left\{ \sum_{\text{track} \in \text{vtx}} \left(p_T^{\text{track}}\right)^2 \right\} \quad (4.2)$$

During Run 1 and Run 2, the vertex assignment was carried out using the *Iterative Vertex Finder*, or *IVF*, procedure [138]. IVF reconstructs individual vertices on individual basis through a four step routine. To begin with, a vertex seed is formed by impact parameter z_0 scan of all tracks not associated to a vertex and locating a point along the beamline with the greatest (not assigned) track density. All (unassigned) tracks that are nearby the seed are associated to it based on their impact parameter significance⁷. Following association, an iterative χ^2 fit of track's compatibility to a vertex seed is carried out. During each cycle the outliers weights are systematically reduced. At the end of the fit, tracks falling outside 7σ acceptance are removed from association to a given vertex and may be reused for future vertex reconstruction. A reconstructed vertex is considered viable if it has at least two tracks that pass this criterion. Once the vertex is constructed, the process continues until either less than two tracks remain for seeding, less than two tracks can be associated to a vertex, or the maximum number of vertices has been reconstructed.

With the increasing luminosity and increasing $\langle \mu \rangle$ the performance of the IVF has experienced consistent degradation and is not expected to be sufficient for Run 4 and Run 5 high pile-up conditions. Hence, as a preparation for future Runs, a new method had been deployed during Run 3⁸ - the *Adaptive Multi-Vortex Fitter*, or *AMVF* for short. While both the IVF and the AMVF follow the same general procedure outline, there are some crucial differences. To begin with, the AMVF utilises a new seed finding approach, known as *Gaussian Track Density Seed Finder* (GS) [140]. Similarly to the IVF, the AMVF selects a possible primary vertex position using track density of tracks unassociated to any previous vertex through longitudinal Gaussian function for density deduction. Differently to the IVF, the AMVF allows tracks associated to already reconstructed vertices to be also associated to the new vertex candidate. Similarly to the IVF, a χ^2 -fitting is carried out in an iterative approach with outlier weight reduction procedure as before. Differently to the IVF, during the fit all other vertices linked to the candidate (e.g., through a track) are also simultaneously refitted. Finally, the acceptance/rejection stage. A new vertex candidate is accepted if it contains at least two tracks with χ^2 probability greater than 10^{-4} after the final iteration fit that have not been previously associated to any other vertex, the separation between the new vertex and any other is greater than 3σ , and the weighted average of the track weights in the fit is greater than $2/3$. Based of this criterion either all associated tracks (in case of passing) or only the most compatible (in case of failure) are removed from the seed formation group.

⁷Defined as $d_0/\sigma(d_0)$ and $z_0/\sigma(z_0)$.

⁸Interesting to note, that the method has been in development stages already before the start of Run 1 data taking.

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The AMVF procedure is terminated in similar fashion to the IVF. Based on various quality performance studies, the AMVF performs either as well as or better than the IVF [140].

4.3. Topological Clusters

Another crucial element in both object and event reconstruction in ATLAS are the *Topological Clusters* or *Topo-Clusters*. The 3D noise-suppressed energy deposits located within the highly granular ATLAS calorimetry volume (see Section 3.2.3) encapsulate the energy-flow of the particles passing through it. Depending on various traversing particles properties, an individual topo-cluster can represent either full (full shower) or partial (shower fragment) response of the particle, merged response of several particles, or combination of all the above.

Each topo-cluster is created through the growing-volume algorithm controlled by a set of three parameters $\{S, N, P\}$ known as primary seed threshold, growth control threshold, and principal cell filter respectively[141]. The driving variable of the algorithm is the cell signal significance, $c_{\text{cell}}^{\text{EM}}$, defined as

$$c_{\text{cell}}^{\text{EM}} = \frac{E_{\text{cell}}^{\text{EM}}}{\sigma_{\text{noise, cell}}^{\text{EM}}} \quad (4.3)$$

where $E_{\text{cell}}^{\text{EM}}$ and $\sigma_{\text{noise, cell}}^{\text{EM}}$ are cell signal energy and average (expected) noise in the cell, both measured at the electromagnetic (EM) scale. The EM scale is the baseline calorimeter scale that correctly measures energy deposition from electromagnetic showers⁹. Each step of the construction algorithm is run until a given cell's significance falls below a specified threshold, that is until $c_{\text{cell}}^{\text{EM}} \leq \chi$ where $\chi \in \{S, N, P\}$.

The first step, controlled by S , is the seed selection step. Each cell who's measured absolute signal energy, including those with a negative energy, exceed the expected noise by a factor of S are designated as seed cells or *proto-clusters* and are ordered according to their significance. Each proto-cluster is then further iteratively expanded by including neighbouring cells whose significance is greater than N . This includes cells who are adjacent the seed cell in the same calorimeter layer or cells from adjacent layers if they have partial overlap in $\eta - \phi$ plane. The included cells are also considered to be part of the proto-cluster, hence extend the number of proto-cluster neighbouring cells. If a neighbouring cell is a seed cell of a proto-cluster, both proto-clusters are merged. If a neighbouring cell is already associated to a proto-cluster, both proto-clusters are merged into one. The iterative inclusion lasts until the outermost layer of cells only pass $c_{\text{cell}}^{\text{EM}} > P$, but not $c_{\text{cell}}^{\text{EM}} > N$. Finally, if the proto-cluster contains more than one local maxima, defined by $E_{\text{cell}}^{\text{EM}} > 500 \text{ MeV}$ measured in the ECal sampling layers¹⁰, it is split between these maxima. The new local-maxima-centred

⁹Energy depositions by electrons and photons is reconstructed correctly, however, the hadronic signals are not due to non-compensation of the hadronic calorimeters.

¹⁰2nd and 3rd barrel layer and 2nd and 3rd rings for barrel calorimeter and endcap calorimeter respectively.

topo-clusters are required to have at least four neighbours with neither of them having a signal greater than the local maxima.

The resulting topo-clusters differ quite significantly in their geometry and energy density based on what kind showers they encapsulate. The EM showers tend to be denser and highly compact resulting in formation of an individual topo-clusters with relatively small shower-to-shower geometric differences¹¹. The hadronic showers, on the other hand, have greater shape variance and can often form multiple topo-clusters. Both cases are crucial in reconstruction of various analysis object, such as electrons, photons, jets, and missing transverse energy. For the ATLAS experiment purposes, the topo-cluster reconstruction algorithm has been optimised with the threshold and filter parameters set to $S = 4$, $N = 2$, $P = 0$ [141].

In Run 3, the procedure of topo-cluster formation has been improved to handle its sensitivity to *out-of-time* pileup interactions¹² through introduction of calorimeter-cell timing cut. For a cell to be considered a seed cell during the seeding procedure, it must not only satisfy $c_{\text{cell}}^{\text{EM}} > S$, but also fall within the collision time window, i.e.

$$|t_{\text{cell}}| < 12.5 \text{ ns} \quad (4.4)$$

where t_{cell} is the cell time measured by LAr or Tile calorimeters. Seed cells failing this cut are also not included during the topo-cluster growing step. Eq. (4.4) is ignored if $c_{\text{cell}}^{\text{EM}}$ is greater than 20 [142].

4.4. Electrons and Photons

While electrons and photons are intrinsically two different components of the Standard Model, their detection and reconstruction in ATLAS is heavily intertwined and follows a near identical procedure. Electrons are spin-half fermions carrying a unitary electromagnetic charge, have a rest mass of $m_e \sim 0.510 \text{ MeV}$, participate in both electromagnetic and weak interactions, and cannot decay to other leptons¹³. Their ATLAS detector signature is expected to be comprised of tracks left in the ID and formation of electromagnetic calorimeter topo-clusters. Photons, on the other hand, are spin-one bosons that are electromagnetically neutral, massless, but couple to other particles with EM charge. Their expected signature in the detector would be only an ECal-level topo-cluster as they are not expected to leave tracks in the ID. However, the differences in expected signatures is not foolproof. Due to electrons low mass, they loose significant amount of energy due to bremsstrahlung radiation in the form of photons. On the other hand, photons can be converted into electron-positron pairs. Furthermore, both signatures can be mimicked by other object detected by the ATLAS detector, e.g., muon bremsstrahlung, non-prompt photons from hadronic decays in jets.

¹¹Extension in directions along and perpendicular to their path of flight

¹²Collisions that happen outside the 25 ns proton-bunch-crossing time window. See Section 3.2.6.

¹³Due to mass and charge conservation restrictions.

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Hence, the reconstruction of both types of object is similar in nature and specialises in their correct identification[143, 144].

The first step of electron and photon reconstruction is the EM topo-cluster creation. The EM topo-clusters are formed using the general topo-cluster (see Section 4.3) as a basis and requiring them to be primarily comprised of EM showers. This selection is enforced through a requirement that more than 50% of cluster's energy is contained within the three layers of the electromagnetic calorimeter and within the presampler and the EMEC if the cluster is within the transition region of $|\eta| \in (1.37, 1.63)$. The contributions stemming from the hadronic calorimeters for these EM topo-cluster candidates are also removed[143]. These EM clusters then form *Region-of-Interest*, or *RoI* for short, in which ID tracks are loosely matched to these EM clusters. The candidate tracks are also refitted to account for possible energy loss due to bremsstrahlung. Additionally, *conversion vertices* from two matched tracks or a singular matched track with missing hits in the innermost ID layer are built and matched to the EM shower. The primary idea for conversion vertices is to match an EM shower captured in the calorimeters to a possible *photon conversion* occurring in the ID. To better encapsulate the EM shower progression, the EM topo-clusters are expanded through inclusion of secondary satellite clusters, found within a specific $\Delta\eta \times \Delta\phi$ window around the original one, forming a *supercluster*. The superclusters undergo positional correction and calibrations of energy scale and resolution to account for simulation mismodelling. This process utilises comparisons between data and Monte Carlo simulations in $Z \rightarrow ee$ and $J/\psi \rightarrow e^+e^-$ decays. Finally, the tracks and conversion vertices are rematched to the calibrated superclusters and depending on the result may be reconstructed to be either an electron or a photon candidate.

If ID tracks are matched to the supercluster within stringent restriction in $\eta - \phi$ plane, the object could be reconstructed as an *electron candidate*. If a conversion vertex is matched to an EM topo-cluster the object could be identified as *converted photon candidate*. Finally, if no tracks or conversion vertex can be matched to an EM topo-cluster, the object could be considered to be an *unconverted photon candidate*. Even though the reconstructed object can be identified as either an electron or photon, a strict binary differentiation is not imposed in this stage to ensure a high reconstruction efficiency of both objects[143]. Furthermore, similar signature can be produced by other physics objects. For example, non-prompt electrons stemming from heavy flavour hadron decays or misidentified hadrons with unusually short and narrow hadronic showers. For this purpose, identification and isolation of the candidate is carried out using a combination of tracks and/or calorimeter-level measurements. Prompt electron are identified in $|\eta| < 2.47$ using likelihood discriminator resulting in three identification or *working points* (*loose, medium, tight*) with different electron reconstruction efficiencies for different electron energies [144, 145]. Photon identification uses a sliding window in $\Delta\eta \times \Delta\phi$ resulting in only two working points - loose and tight [146, 147]. For both objects the isolation is defined using the cone isolation approach with the cone radius in $\eta - \phi$ plane changing according to the desired isolation level. The isolation can be carried out using calorimeter level or tracking level information.

4.5. Muons

Muons are the second-generation leptons in the SM, identical to electrons spin- and EM-charge-wise, and play a crucial role in the event reconstruction in ATLAS. Due to their heavy mass ($m_\mu \sim 200 \cdot m_e$), muons lose less energy through bremsstrahlung¹⁴. Therefore, they can escape the ATLAS Calorimeter systems with little energy deposition while leaving clear tracks in the ID. To account for this difficult detector signature, a dedicated sub-detector system, the Muon Spectrometer, is used to capture the muonic tracks outside the calorimeters (see Section 3.2.4 and Section 4.1).

For muon reconstruction, all main ATLAS detector systems are utilised in an attempt to match the tracks in the ID to tracks in the MS as well as incorporating minimal energy signatures in the calorimeters. Based on track availability and matching success, five muon candidate types are possible[137]. *Combined* (CB) muons are defined by a successful ID and MS track matching through a combined track fit that accounts for energy loss in the calorimeters. *Muon spectrometer extrapolated* (ME) muons are formed when an MS track cannot be matched to an ID track and hence is extrapolated to the beamline. This ensures muon reconstruction in $|\eta|$ range covered by MS but not ID. *Inside-out combined* (IO) muons, are formed from ID tracks extrapolated to three loosely-aligned MS hits (that do not form a muonic track). This improves reconstruction efficiency in limited-MS-coverage regions as well as low p_T muon reconstruction. *Segment-tagged* (CT) muons are created from ID tracks that have been extrapolated to the MS and matched to at least one MS segment within stringent angular criteria. *Calorimeter-tagged* (CT) muons are identified through ID track extrapolation to calorimeter energy deposits matching minimum-ionising particles. In all reconstructions cases, the p_T of the muon is expressed at the interaction point.

Similarly to electrons and photons, muon candidates have multiple selection and isolation working points to support a wide range of analyses carried by the ATLAS collaboration. Different selection WPs utilising different candidates as inputs (from only CB+IO combination to full inclusion) promote these candidates to a reconstructed muon at different identification efficiencies based on their properties like p_T , η , and charge-to-momentum ratio. Muon isolation is carried out using the $\eta - \phi$ cone approach like before using tracking-level and/or calorimeter-level objects and measurements for the decision[137].

4.6. Tau Leptons

Tau lepton is the heaviest of the Standard Model leptons with the same electromagnetic charge and spin as an electron or muon. Due to their very short lifetime ($\mathcal{O}(10^{-13})$ s) taus tend to decay before reaching active detector regions into specific combination of electrons, muons, pions, and neutrinos. The leptonic modes, i.e. $\tau \rightarrow l \bar{\nu}_l \nu_\tau$, represent $\sim 17\%$ of decays for both $l = e, \mu$. The rest are hadronic decays, appearing in the detector as jets. Hadronically

¹⁴Bremsstrahlung radiation is inversely proportional to particle's mass.

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decaying τ s, or to be more precise jets produced from such decays, are differentiated from quark and gluon initiated jets through a dedicated RNN algorithm [148].

4.7. Jets

Jets are inseparable part of any detector-based physics involving hadronic collisions. While not a part of the Standard Model as for example photons, jets rather represent a collimated stream of hadrons (mesons and baryons) within the detector originating as a consequence of QCD colour confinement. During a collision, the stable colour-neutral state of a hadron is disturbed and individual quarks (valence or sea) and/or gluons can act as the starting points for the parton shower leading to hadronisation. Modelling and capturing the progression and evolution of the shower is a difficult task both theoretically and by using detectors. Since the process is non-perturbative in nature, complicated phenomenological models like the Lund string model [43] are used during simulations. From detector perspective, both charged and neutral hadrons formed during hadronisation deposit energy within the calorimetry system (sometimes even escaping it) and leave tracks in the ID if they are charged. In either case, jets are complex objects and are typically described through the choice of clustering and reconstruction algorithms as well as their "flavour"¹⁵.

There are two approaches to jet reconstruction utilised by ATLAS. The first one, known as *EMTopo* utilises topo-clusters as building blocks and was dominant during Run 1. Since Run 2, the primary jet reconstruction approach is the *Particle Flow* algorithm, or *PFlow* for short. The algorithm combines both information from ID tracks and topo-clusters to reconstruct jets and their resolutions with greater precision than the individual components could (like it was done in Run 1). Recall the relative track p_T resolution of the ID given by Eq. (3.10)

$$\sigma_{p_T} \left(\frac{1}{p_T} \right) \cdot p_T \simeq 0.036\% \cdot p_T \oplus 1.3\%$$

and the relative calorimeter energy resolution given by Eq. (3.11)

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

where $a \in [10.1\%, 70.6\%]$, $b \in [0.2\%, 5.8\%]$, and c is $\mathcal{O}(1\%)$ in the central region of the detector. In the low p_T regime, the ID has a better resolution than calorimeters, while the opposite is true for the high p_T regime¹⁶. The PFlow algorithm uses cell-based subtraction to remove the overlaps between track momentum and calorimeter energy measurements and then combines both to form a PFlow object used for jet clustering [103]. The algorithm's flow chart is given Figure 4.1 with each step described a bit more in depth below.

¹⁵Here flavour more refers to particular originator of the jet, e.g., b or c quarks.

¹⁶Note, even though calorimeter resolution is expressed in terms of energy, a linear relationship to transverse momentum exists. See Eq. (3.9).

4.7.1. PFlow algorithm

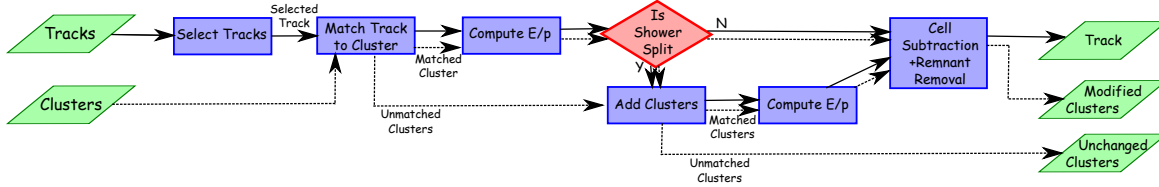


Figure 4.1.: ATLAS Particle Flow algorithm flow chart. The algorithm aims to match selected tracks to topo-clusters, remove former's associated energy from the latter's, and use the remaining full track, modified and unmodified (in case of match failure) energy clusters to form jets [103].

The PFlow object construction algorithm begins with the selection of ID tracks. The tracks are required pass stringent selection criteria, known as "tight selection"¹⁷, be within $|\eta| < 2.5$ and have $p_T > 0.5$ GeV, though no association to a primary vertex is required. An additional restriction of $p_T < 40$ GeV is also enforced as such track inclusion in PFlow objects does not benefit the reconstruction. In addition, tracks matched to electron candidates and muon candidates are also omitted. Following the selection, the tracks are extrapolated to the second layer of the EM calorimeter and a matchable topo-cluster is searched for through $\Delta R'$ metric given by

$$\Delta R' = \frac{\Delta\eta}{\sigma_\eta} \oplus \frac{\Delta\phi}{\sigma_\phi} \quad (4.5)$$

where $\Delta\eta$ and $\Delta\phi$ are distances between the extrapolated track and the barycentre of the topo-cluster in the $\eta - \phi$ plane, while σ_η and σ_ϕ represent the angular topo-cluster widths. The track is matched to the topo-cluster with the smallest $\Delta R'$ within $\Delta R' < 1.64$ requiring the energy cluster ratio to track momentum, i.e. $E^{\text{clus}}/p^{\text{track}}$, to be greater than 0.1. If no such cluster exists, it is assumed the track did not form one and the track is not included as a PFlow object. Similarly, if no track is matched to the topo-cluster, the topo-cluster is assumed to have been formed from a neutral hadron and is included as a PFlow object. In the situation where a track has been matched to a topo-cluster, a split shower recovery procedure might need to be carried out as particles are not expected to deposit their energy within a singular topo-cluster. The decision is based on the $S(E^{\text{clus}})$ discriminant, which is given by

$$S(E^{\text{clus}}) = \frac{E^{\text{clus}} - \langle E_{\text{dep}} \rangle}{\sigma(E_{\text{dep}})} \quad (4.6)$$

where E^{clus} is the energy of the matched topo-cluster, $\langle E_{\text{dep}} \rangle$ is the expected energy deposition of track within the calorimeter modelled through single-pion deposition, and $\sigma(E_{\text{dep}})$

¹⁷The selection requires at least nine hits in silicon detectors and no missing Pixel hits when they would be expected [149].

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represents the spread of $\langle E_{dep} \rangle$ (also evaluated with single-pion modelling). If the discriminant is less than -1 , then the recovery procedure is carried out and all topo-clusters within $\Delta R < 0.2$ of the extrapolated track are also assumed to be matched. Following the matching, the overlap between the track momentum and topo-cluster energy depositions is carried out based on the track's $\langle E_{dep} \rangle$. If it exceeds the total energy of all matched topo-clusters, then all associated clusters are removed and the PFlow object is formed from the track. If it does not exceed, then a cell-by-cell subtraction is carried out. For the subtraction, rings are formed in $\eta - \phi$ space around the extrapolated track. The rings must include at least one calorimeter cell, are confined to an individual calorimeter layer, and are equidistantly spaced out within that layer. The rings are then ranked according to the average energy density contained within them and irrespective of their layer position. The subtraction process begins from the highest density ring and proceeds descendingly. If the ring contains less energy than it is needed for $\langle E_{dep} \rangle$, the cells in that ring are subtracted and the $\langle E_{dep} \rangle$ is decreased by the total energy of the ring. If the ring contains more, then each cell in that ring is scaled accordingly to equate to the (reduced) $\langle E_{dep} \rangle$. Finally, if the remaining energy within the topo-cluster is less than $1.5\sigma(E_{dep})$, it is assumed that this cluster was formed by a singular particle and the remaining signature stems from shower fluctuations. Hence, the remaining cells are also removed. If the energy is greater, then the topo-cluster was most likely formed by multiple particles and no further subtraction is done. In the end, the matched tracks and full or augmented topo-clusters form the full set of PFlow objects used in jet clustering.

4.7.2. Jet Clustering

Jet clustering is carried out through specialised algorithms [150] which need to adhere to strict standards set out in the Snowmass accord of 1990[151]. A proper algorithm is required to produce well-defined jet boundaries, even in jet overlap cases, and be infrared and collinear safe, or *IRC safe* for short. IRC safety ensures that the collection of the jets reconstructed in an event remains the same after collinear splitting of the event or soft emission inclusion. According to Les Houches convention [152], jet clustering algorithm is defined by its merging scheme, which defines the distance condition for two objects to be included in a jet, and a recombination scheme, which defines how the momentum is assigned during a merger of two objects. The most common jet clustering algorithms can be roughly separated into two categories: cone and sequential recombination algorithms. Cone algorithms, e.g., UA1 cone algorithm [153], construct jets by grouping objects around a specific seed within specified geometrical cones defined in $\eta - \phi$ space. On the other hand, the sequential recombination algorithms utilise a semi-recursive spatial distance calculation between two objects and a distance cut-off point below which these two objects are recombined into a new one. For example, the Cambridge–Aachen [154], k_t [155], and anti- k_t [156] algorithms all share a generalised form for of the spatial distance between object i and j , d_{ij}

$$d_{ij} = \min \left\{ p_{T,i}^{2p}, p_{T,j}^{2p} \right\} \frac{\Delta y_{ij}^2 \oplus \Delta \phi_{ij}^2}{R^2} \quad (4.7)$$

4.7. Jets

where p_T is the transverse momentum of the object, Δy_{ij} and $\Delta\phi_{ij}$ - distance between i and j in rapidity and ϕ respectively, R is the size parameter, and p - the power parameter. For Cambridge–Aachen $p = 0$, for k_t $p = 1$, and for anti- k_t $p = -1$. The cut-off spatial distance, known as *jet axis* or *beam*, is given as

$$d_{iB} = p_{T,i}^{2p} \quad (4.8)$$

If $d_{ij} < d_{iB}$ then the two objects are clustered together and the process repeats; If $d_{ij} > d_{iB}$, the object i is considered to be a fully built jet and is removed from the pool of possible objects to merge. The process continues until no objects are left, that is everything has been clustered into a jet. An example demonstrating the difference between these three algorithm clustering outcomes is shown in Figure 4.2.

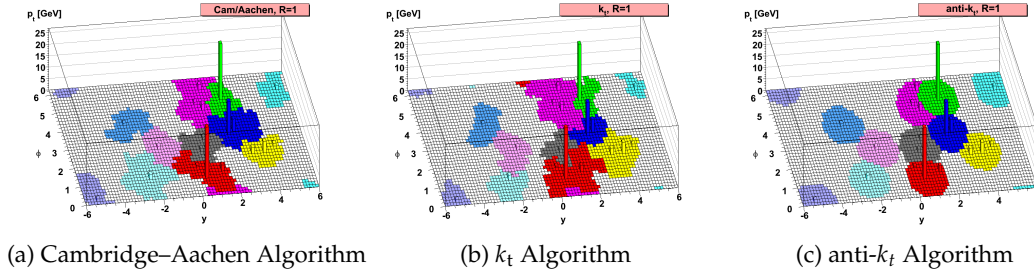


Figure 4.2.: Visualisation of three sequential recombination algorithm clustering outcomes in y , ϕ , and p_T . In all three cases the same sample HERWIG [157] parton-level event is clustered together with many random soft "ghosts". The clustering is carried out according to comparison between Eq. (4.7) with $R = 1.0$ and Eq. (4.8) where different values of p define the following algorithms: (a) shows Cambridge–Aachen algorithm with $p = 0$, (b) shows k_t algorithm with $p = 1$, and (c) demonstrates anti- k_t with $p = -1$ [156].

4.7.3. Jets In ATLAS

ATLAS primarily uses the anti- k_t algorithm due to its insensitivity to soft radiation (the highest p_T objects act as starting point) as well as the resulting circular shape of the jets post clustering. Two different clustering size parameter R options are typically used: $R = 0.4$ which forms the *small- R jets*, the standard collection of jets in ATLAS, and $R = 1.0$ which forms the *large- R jets*, which are used to capture hadronic decays of massive gauge bosons or the t quark. The anti- k_t clustering uses the PFlow objects defined in the previous subsection with an additional requirement imposed on the tracks. To participate in the anti- k_t clustering, the track is required to be matched to a hard-scatter vertex, i.e. have $|z_0 \sin(\theta)| < 2$ mm. Furthermore, the PFlow topo-cluster's η and ϕ is calculated with respect to the primary vertex rather than detector origin ($z = 0$). During clustering, the momenta between the

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objects is combined through the standard *E-scheme*¹⁸[158]. The clustering procedure in ATLAS is implemented through the FASTJET package [159]. The clustered jet is required to have $p_T > 7$ GeV and be within detectors detectable range, i.e. $|\eta| < 4.9$, for the object to be differentiable from the irreducible background signatures, e.g., comic radiation.

After clustering, multiple classifications of the jets are made. To begin with, differentiation whether the jet has been initiated by a quark or a gluon is made using a constituent-based transformers[160]. Furthermore, the jet is also classified between light or heavy flavour jet¹⁹ through flavour tagging algorithms. The algorithms rely on impact parameters, secondary vertex reconstruction, and decay chain reconstruction to form low-level taggers which are then combined into high level taggers through either Boosted Decision Tree (MV2 class)[161] or using neural network (DL1 class)[162] based approaches²⁰. In recent years, graph neural network based tagging using low level tracking information (GN2 class) has also been explored and is becoming more prevalent[163].

For jets to be usable in analysis they must undergo a two stage calibration process during which the jet energy scale and jet energy resolution measured by the ATLAS detector is corrected to match the one expected at the truth-level. The calibrations of the jets is presented in greater detail in Section 5 with particular focus on enabling early Run 3 ATLAS analyses. After calibration, only jets with $p_T > 20$ GeV are accepted as well calibrated jets.

During the calibration, hard-scatter jets are corrected for the effects of both in-time and out-of-time pile-up. However, this does not remove jets originating from pile-up vertices themselves. In general, pile-up jets can be separated into two categories: stochastic pile-up jets, which are comprised of multiple pile-up vertices' contributions, and QCD pile-up jets, which are dominated by single pile-up vertex contribution (see Figure 4.3). Since ATLAS does not have a full $|\eta|$ tracking coverage, discrimination between hard scatter and pile-up jets is done in two separate approaches based on whether the ID provides coverage or not.

In the central region (covered by the ID), two track-level and primary vertex information based variables are used to carry out differentiation through a discriminant known as *Jet-Vertex-Tagger*, or JVT for short [165]. The first of such variables is the *pileup-corrected Jet Vertex Fraction*, or corrJVF for short, given by

$$\text{corrJVF} = \frac{\sum_k p_T^{\text{trk}_k}(\text{PV}_0)}{\sum_l p_T^{\text{trk}_l}(\text{PV}_0) + (k \cdot n_{\text{trk}}^{\text{PU}})^{-1} \cdot (\sum_{n \geq 1} \sum_l) p_T^{\text{trk}_l}(\text{PV}_n)} \quad (4.9)$$

The $\sum_k p_T^{\text{trk}_k}(\text{PV}_i)$ is the scalar p_T sum of the tracks associated with the jet and originating from a primary vertex PV_i ($i = 0$ implies HS; $i > 0$ implies PU), $n_{\text{trk}}^{\text{PU}}$ - total number of pileup tracks per event²¹, k is the scaling factor used to correct for linear increase of $\langle p_T^{\text{PU}} \rangle$ with increasing $n_{\text{trk}}^{\text{PU}}$. The corrJVF ranges between 0 and 1, with corrJVF = -1 assigned to jets with no associated tracks. While the value of k can be empirically deduced²², the

¹⁸Simple addition of the four-momenta.

¹⁹Initiated by c - or b -hadrons.

²⁰Majority of Run2 analyses have relied on or rely on the DL1r flavour tagger.

²¹Computed from all tracks associated with vertices other than the HS.

²²Slope of $\langle p_T^{\text{PU}} \rangle$ vs $n_{\text{trk}}^{\text{PU}}$.

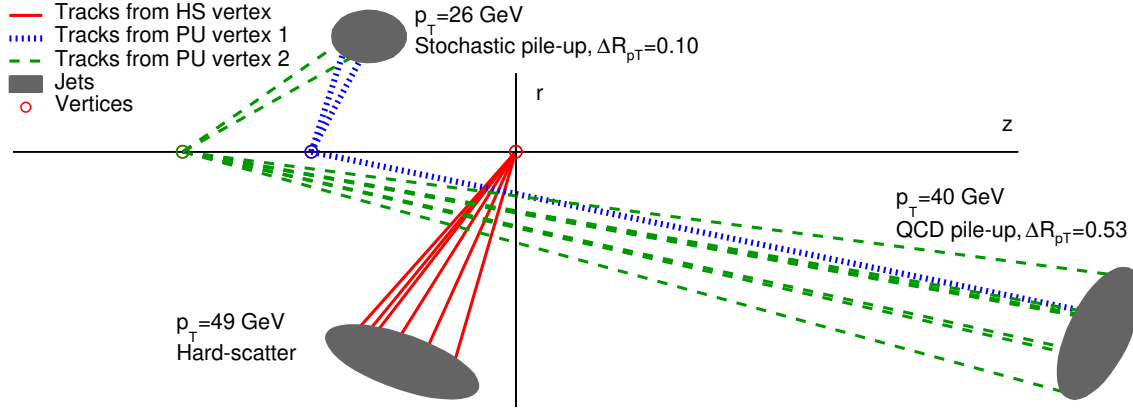
ATLAS Simulation

Figure 4.3.: Display of a simulated event in the $r - z$ plane containing a hard-scatter, QCD pile-up, and stochastic pile-up jets. The difference between the dominant and average values of $R_{p_T}^i$ (see Eq. (4.10)) is shown for both types of pileup jets. Image taken from [164].

discriminant's performance is k -independent[165]. Hence, the scaling factor is set to $k = 0.01$ in order to mimic the performance of a similar discriminant used in Run 1, JVF²³. The second parameter, $R_{p_T}^i$, represents the fraction of scalar p_T sum of the tracks that are associated with the jet and stem from PV_i versus the fully calibrated jet's p_T . That is

$$R_{p_T}^i = \sum_{\text{trk}} \frac{p_T^{\text{trk}}(PV_i)}{p_T^{\text{jet}}} \quad (4.10)$$

Both corrJVF and R_{p_T} of the HS primary vertex, $R_{p_T}^0$, are used to form a 2-dimensional likelihood based discriminant using k-nearest neighbour (kNN) algorithm [166]. Based on this discriminant value and the chosen work point, the jet is classified as either hard scatter or pileup in the central region during reconstruction.

In the forward region, where there is no tracking provided by the ID, a method based on transverse momentum balance in a hadronic system²⁴ known as forward Jet-Vertex-Tagger, or FJVT [164, 167], is employed. If a hadronic system has no jets in the forward region and the vectorial sum of the $\vec{p}_T$ is calculated in the centre region of the detector, the hadronic system should have little to no $\vec{p}_T$ imbalance. If a forward jet does exist in such hadronic system, $\vec{p}_T$ imbalance of the system will be noticeably higher. Hence, a forward jet that improves the imbalance or fully removes it, has most likely originated from such system. The forward jet's "balancing power" for each PV_i (with $i > 0$) is quantified through

$$\text{FJVT}_i = \frac{\vec{p}_{T, PV_i}^{\text{miss}} \cdot \vec{p}_T^{\text{fwd jet}}}{\vec{p}_T^{\text{fwd jet}} \cdot \vec{p}_T^{\text{fwd jet}}} \quad (4.11)$$

²³Which is corrJVF with $(k \cdot n_{\text{trk}}^{\text{PU}}) = 1$.

²⁴Activity stemming from an individual primary vertex.

4. Object and Event reconstruction

where $\vec{p}_T^{\text{fwd jet}}$ is the vectorial transverse momentum of the forward jet, $\vec{p}_{T, \text{PV}_i}^{\text{miss}}$ is the missing transverse momentum associated with PV_i (i.e. the momentum imbalance), and the full discriminant is taken as

$$\text{FJVT} = \max \{ \text{FJVT}_i \} \quad (4.12)$$

As forward pile-up jets are expected to balance their corresponding vertex $\vec{p}_{T, \text{PV}_i}^{\text{miss}}$, their FJVT is expected to be close to 1. On the other hand, a hard scatter jet should not balance any vertex's $\vec{p}_{T, \text{PV}_i}^{\text{miss}}$, hence $\text{FJVT} \sim 0$. To further improve FJVT performance, stochastic pile-up jets are excluded from the hadronic system formation. Since stochastic pile-up jets contain contributions from multiple pileup vertices, the difference between $\max \{ R_{p_T}^i \}$ and $\langle R_{p_T} \rangle$ is expected to be small, hence a restriction based on either the former or the difference between the two

$$\Delta R_{p_T} = \max \{ R_{p_T}^i \} - \langle R_{p_T} \rangle \quad (4.13)$$

is imposed. Depending on what type of jet reconstruction is being considered (EMTopo or PFlow), the momentum imbalance is evaluated differently. For EMTopo jets, the missing transverse momentum is given by

$$\vec{p}_{T, \text{PV}_i}^{\text{miss, EMTopo}} = -\frac{1}{2} \left(\sum_{\text{tracks} \in \text{PV}_i} [k \cdot \vec{p}_T^{\text{track}}] + \sum_{\text{jets} \in \text{PV}_i} [\vec{p}_T^{\text{jet}}] \right) \quad (4.14)$$

where $\vec{p}_T^{\text{track}}$ and $\vec{p}_T^{\text{jet}}$ are the vector transverse momenta of track and jets associated to a given PV_i respectively, and factor k accounts for intrinsic differences between these two terms and is set to $k = 2.5$ through optimisation. The stochastic pile-up jet restriction is set through $\Delta R_{p_T} < 0.2$ for all jet with $p_T > 35 \text{ GeV}$ ²⁵ [164]. For PFlow jets, the missing transverse momentum is given by

$$\vec{p}_{T, \text{PV}_i}^{\text{miss, PFlow}} = - \left(\sum_{\text{jets}}^{p_T^{\text{jet}} > 20 \text{ GeV}} [\vec{p}_T^{\text{jet}}] + \sum_{\text{tracks}}^{p_T^{\text{jet}} < 20 \text{ GeV}} [\vec{p}_T^{\text{track}}] + \sum_{\text{tracks}}^{\text{jets fail } R_{p_T}^i \text{ cut}} [\vec{p}_T^{\text{track}}] \right) \quad (4.15)$$

The stochastic pile-up jets are rejected by requiring all jets to have $\max \{ R_{p_T}^i \} > 0.1$. The first term of Eq. (4.15) includes jets associated with PV_i that pass the R_{p_T} and p_T restrictions, the second and third term includes tracks from jets that fail either of the restrictions [167].

4.7.4. Dijet System

Another important concept related to jets, VBF topology, and multijet backgrounds is the *Dijet system*. In ATLAS, hard-scatter jets in the event are ordered according to their p_T . Jets with the highest and the second highest p_T are identified as *leading* and *subleading* jets

²⁵Above this p_T the fraction of stochastic pile-up jets is found to be negligible.

respectively and form the events dijet system. The dijet system is parametrised by the absolute angular distance between the jets in η

$$\Delta\eta_{jj} = |\eta_{j0} - \eta_{j1}| \quad (4.16)$$

and in ϕ

$$\Delta\phi_{jj} = |\phi_{j0} - \phi_{j1}| \quad (4.17)$$

where in both cases $j0$ and $j1$ represent the leading and subleading jets respectively. Another important parametrisation is the invariant mass of the system, defined as

$$m^2 = \left(\sum_i^{\{j\}} E_i \right)^2 - \left(\sum_i^{\{j\}} \vec{p}_i \right)^2 \quad (4.18)$$

which in the low mass regime, i.e. $m_i \ll E_i$, can be expressed as

$$m_{jj}^2 = 2p_T^{j0} p_T^{j1} (\cosh(\Delta\eta_{jj}) - \cos(\Delta\phi_{jj})) \quad (4.19)$$

4.8. Neutrinos

Neutrinos are near massless electromagnetically neutral spin-half fermions. Neutrinos only interact via the weak force²⁶ and exist within the Standard Model in three generations that match the lepton generations. From detector perspective, they leave no signature in any of the subsystems, hence are in essence the only known invisible particle class in the Standard Model. However, they are still detectable through recoil reconstruction and contribute to missing transverse energy of the event.

4.9. Missing Transverse Energy and Hadronic Activity

Since the pp collision occurs between two protons that have little to no momentum along the x or y axis, the measurement of the energy and momentum (im)balance in the transverse plane act as important observables indicating how well the event could be reconstructed from the visible objects due to four-momentum conservation during the collision. As discussed in Section 4.8, while neutrinos do not leave any signatures within the detector, they do create imbalance in both transverse energy and recoil in momentum systems because of it. Hence, can be detected. The same argument can also be extended to any other invisible final state BSM particle. Therefore, these missing quantities are both paramount probes in BSM searches and event reconstruction quality criteria.

²⁶Theoretically speaking, they also interact gravitationally since they do have mass.

4. Object and Event reconstruction

Starting from the energy perspective, the *missing transverse energy*, $\vec{E}_T$, is defined as the negative vectorial sum of all fully reconstructed visible objects. That is

$$\vec{E}_T = - \underbrace{\sum_e \vec{p}_T^e - \sum_\gamma \vec{p}_T^\gamma - \sum_\tau \vec{p}_T^\tau - \sum_\mu \vec{p}_T^\mu - \sum_j \vec{p}_T^j}_{\text{hard terms}} - \vec{p}_T^{\text{soft}} \quad (4.20)$$

where $\{e\}$ is the set of selected electrons, $\{\gamma\}$ - accepted photons, $\{\tau\}$ - accepted τ -leptons, $\{\mu\}$ - selected muons, $\{j\}$ - accepted jets after JVT and FJVT, and the last term represents soft objects. The hard terms are assumed to be fully calibrated while the soft terms are build from tracks or clusters that are not associated to any of the reconstructed object. Additionally, the hard terms are required to be non-ambiguous with respect to each other to avoid double-counting within the detector. Hence, only objects passing the overlap removing criteria are included in the calculations (see Table 4.1). The magnitude of $\vec{E}_T$ is given as $E_T = |\vec{E}_T|$ while the azimuthal direction, $\phi_{\vec{E}_T}$ is given by

$$\phi_{\vec{E}_T} = \text{atan} \left(\frac{\vec{E}_y}{\vec{E}_x} \right) \quad (4.21)$$

Based on how the soft terms are modelled, two versions of $\vec{E}_T$ can be formed. If unassociated tracks are used as the soft representation, a *Track Soft Term* or *TST* $\vec{E}_T$ is formed:

$$\vec{E}_T^{\text{TST}} \equiv \vec{E}_T \quad \text{with} \quad \vec{p}_T^{\text{soft}} = \sum_{\text{trk}}^{\{\text{utrk}\}} \vec{p}_T^{\text{trk}} \quad (4.22)$$

where $\{\text{utrk}\}$ - unassociated tracks. If soft terms are measured in the calorimeters, then *Cluster Soft Term* or *CST* missing transverse momentum is formed:

$$\vec{E}_T^{\text{CST}} \equiv \vec{E}_T \quad \text{with} \quad \vec{p}_T^{\text{soft}} = \sum_{\text{cls}}^{\{\text{ucls}\}} \vec{p}_T^{\text{cls}} \quad (4.23)$$

and $\{\text{ucls}\}$ - unassociated topo-clusters.

A similar quantity to E_T can also be formed purely from jets, both hard scatter and pileup, known as *missing hadronic activity*, $\vec{H}_T$, through the negative vectorial sum of their transverse momenta

$$\vec{H}_T = - \sum_j^{\text{HS \& PU jets}} \vec{p}_T^j \Rightarrow H_T = |\vec{H}_T| \quad (4.24)$$

while the scalar sum results in the *total hadronic activity*, H_T ,

$$H_T = \sum_j^{\text{HS \& PU jets}} p_T^j \quad (4.25)$$

4.9. Missing Transverse Energy and Hadronic Activity

Object	Reference	Object removal criteria
e	e	shared ID track (assumes $p_T^{\text{Obj}} < p_T^{\text{Ref}}$)
μ	e	shared ID track and μ with calorimeter energy deposit
e	μ	shared ID track
γ	e	$\Delta R < 0.4$
γ	μ	$\Delta R < 0.4$
jet	e	$\Delta R < 0.2$
e	jet	$\Delta R < \min \{0.4, 0.04 + 10 \text{ GeV} / p_T^e\}$
jet	μ	$N_{\text{tracks}}^{\text{jet}} < 3$ and $\Delta R < 0.2$
μ	jet	$\Delta R < \min \{0.4, 0.04 + 10 \text{ GeV} / p_T^\mu\}$
jet	γ	$\Delta R < 0.2$

Table 4.1.: ATLAS overlap removal procedure in descending priority. The procedure dictates under what conditions any given object (electron (e), muon (μ), photon (γ), or jet) needs to be removed if overlapped with the reference object. The summarised overview is based on the one presented in [7].

Both variables are useful in order to understand how well the hadronic activity is measured within the event. Since $\vec{H}_T$ includes pile-up jets, it is naturally more sensitive to pile-up compared to $\vec{E}_T$. However, it is insensitive to any failures in pile-up tagging that might compromise $\vec{E}_T$. Another important relation that needs to be stressed is that $H_T \geq \cancel{H}_T$.

5. Jets calibration for Run 2 and early Run 3 analyses

Jets are one of the primary objects reconstructed within the ATLAS detector and play a crucial role in most if not all analyses. Particularly for the invisible Higgs decay searches with VBF signature, the leading jets and their dijet system define the signal regions. However, jets are complex reconstructed objects interacting with all primary ATLAS detector subsystems. The observed clusters of particles within the detector and the collimated products of quark and or gluon hadronisation, decay, and showering of the theory are not the same. In order to compare one with the other, a transformation method between them has to be made in the form of jet calibration.

Jet calibration in ATLAS can be divided into two broad sections: The Monte Carlo based calibration tries to understand how jet interaction with the detector changes its kinematics. Ideally, through the calibration one should be able to restore the reconstructed jet in the detector to a scale it would have had if the interaction had not occurred. The second - residual *in situ* calibration which is only applied to data - aims to adjust for the imperfect simulation and detector response through comparison with well measured dijet events. The full calibration chain is shown in Figure 5.1.

Around 2022, the central ATLAS software packages had undergone major update known as *Release 22*. Since the changes affected numerous algorithms utilised in object identification and event reconstruction, a new reprocessing campaign of all Run 2 Monte Carlo samples was initiated. Naturally this included the multijet samples. Additionally, during the same time the Run 3 of data taking had begun with its conditions represented by different set of MC samples¹. In order to enable analyses to utilise the newest software version and the benefits it offered as well as permit usage of data collected in the first year of Run 3, new jet calibrations and recommendations on how to use them needed to be produced for both situations. The task was split into two stages, known as *Phases*, and was broken down as follows: *Phase 1* focused on Run 2 MC samples and utilised all available MC campaigns, representing data taking conditions between 2015 and 2018, known as *MC20*² and derived a singular form of recommendations for all years with the expectation that the full Run 2 dataset would be used. *Phase 2* focused on 2022 data taking period and aimed to produce early pre-recommendations that would enable early Run 3 analyses. The *Phase*

¹Due to higher centre of mass energy and increased average number of interactions per bunch crossing.

²To provide a bit more context, the original Run 2 campaign is MC16; MC20 is MC16 processed with the updated software suite. That is, no new event generation took place.

5.1. Simulated Event and Jet Selection for MC-based Calibrations

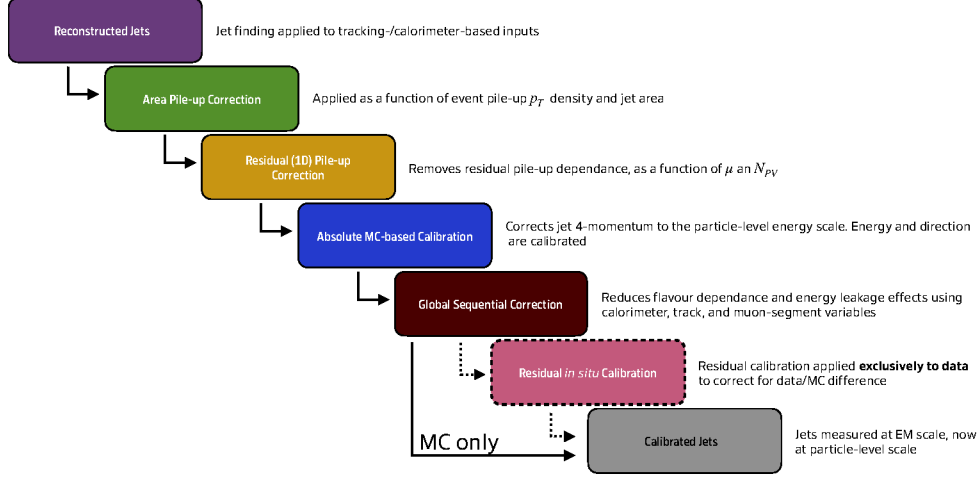


Figure 5.1.: ATLAS PFlow small-R jet calibration chain.

2 calibrations were based on MC23 samples³ generated and simulated using data-taking conditions of 2022. Later on, these 2022 pre-recommendations were also tested with MC samples representing conditions of 2023 for compatibility and were found to be sufficient requiring no additional calibrations for 2023 specifically.

In this section, individual steps of both *Phase 1* and *Phase 2* pre-recommendations are presented and discussed with particular focus on the Monte Carlo part of the calibration which is based on the consolidated jet calibration recommendations from the end of Run 2 [106, 168].

5.1. Simulated Event and Jet Selection for MC-based Calibrations

The Monte Carlo based calibrations are derived using dijet or multijet events with clearly identified dijet systems. The $2 \rightarrow 2$ events are generated using PYTHIA 8 [169–171] event generator with the A14 tune [172] with NNPDF2.3 LO set of parton distribution functions (PDFs) [173]. The heavy-flavour hadron decays are additionally modelled using EVT-GEN (v1.6) [174]. The effects of pile-up are simulated by PYTHIA 8 minimum bias inelastic pp collisions (A3 tune [175]), that are overlaid with the hard scatter process [176]. To ensure

³Differently to MC20, these were generated from "scratch" due to different conditions between Run 2 and Run 3.

5. Jets calibration for Run 2 and early Run 3 analyses

enough statistics over the wide range of possible p_T values of jets, the samples are generated in sliced fashion according to the leading jet p_T . The correct modelling of the steeply falling p_T spectrum is achieved through the appropriate weighting procedure. The weight can be broken down to

$$w = \frac{\sigma \cdot w_{MC} \cdot \epsilon \cdot k \cdot w_{bs} \cdot \mathcal{L}_{int}}{\sum [w_{MC}]} \quad (5.1)$$

where σ is the cross-section of the process, w_{MC} is the generator level event weight, ϵ - filter efficiency, k factor is used for higher order corrections, w_{bs} - beamspot weight. The sample is scaled according to their representative year's $\mathcal{L}_{int}$ and normalised to the total sum of weight of the sample, i.e. $\sum [w_{MC}]$.

Each data taking Run is represented by a dedicated MC campaign group: Run 2 by MC20 and Run 3 by MC23. These campaigns are further broken down into sub-campaigns for each data taking year in order to encapsulate the changing accelerator and detector conditions. The groups are as follows: MC20a, MC20d, MC20e represent conditions for years 2015+2016, 2017, and 2018 respectively. MC23a, MC23d represent conditions for years 2022 and 2023. The sliced generation space breakdown is shown in Table 5.1 for both campaign groups.

As mentioned in Section 3.2.6, these simulated events are used as inputs for detector interaction simulation whose digitised outputs are used to reconstruct detector objects in identical fashion to the real detector readout. For example, formation of PFlow objects (see Section 4.7.1) for jet clustering. Similarly, stable⁴ final state particles, excluding muons and neutrinos, are used to construct generator-level jets, known as *truth jets*. These jets represent jets that would be measured by an ideal detector with perfect object reconstruction and property measurement. Both truth and reconstructed (or *reco*) jets are clustered using the anti- k_t algorithm with radius parameter $R = 0.4$ using the FASTJET software package [159] as described in Section 4.7.2.

To participate in the calibration both tracks and reconstructed jets are required to pass the criteria listed in Section 4.7.3 except for jets the $|\eta|$ acceptance window is decreased from 4.9 to 4.5 and no p_T limitation is imposed. The omission of p_T selection of jets is motivated by the following: the primary purpose of the cut is to remove signature from irreducible backgrounds which are not present during simulation. Furthermore, as the kinematics of the jet are expected to change during calibration pre-emptive cut on variables sensitive to it would decrease the calibration precision. Truth jets, on the other hand, are selected with $p_T > 7 \text{ GeV}$ and $|\eta| < 4.5$ requirements.

For an event to be used for the simulation based calibrations, it is required to have at least one reconstructed primary vertex with two matched ID tracks (see Sections 4.1 and 4.2). Furthermore, the reconstructed and truth-level primary vertices (i.e. the simulated hard scatter process) are required to be within $\Delta z < 0.2 \text{ mm}$ of each other. Each event is required to have at least two reconstructed jets and one truth jet. All truth jets are required to be matched with a reconstructed jet through $\Delta R = \Delta\eta \oplus \Delta\phi < 0.3$ (see Eq. (3.9)) criteria. All reconstructed jets need to be isolated from other reconstructed jets with p_T^{reco} greater than

⁴Defined as $c\tau > 10 \text{ mm}$ where c is the speed of light and τ the particle's lifetime.

5.2. Pileup corrections

Slice	$\hat{p}_T$ [GeV]	$\sigma_{\sqrt{s}=13.0 \text{ GeV}}$ [pb]	$\sigma_{\sqrt{s}=13.6 \text{ GeV}}$ [pb]	Comment
Slice 0	[0, 20)	7.8050×10^{10}	7.8050×10^{10}	
Slice 1	[20, 60)	7.8050×10^{10}	8.9549×10^{10}	
Slice 2	[60, 160)	2.4330×10^9	2.4329×10^9	
Slice 3	[160, 400)	2.6450×10^7	2.6456×10^7	
Slice 4	[400, 800)	2.5461×10^5	2.5463×10^5	
Slice 5	[800, 1300)	4.5332×10^3	4.5541×10^3	
Slice 6	[1300, 1800)	2.5754×10^2	2.5756×10^2	
Slice 7	[1800, 2500)	1.6215×10^1	1.6218×10^1	
Slice 8	[2500, 3200)	6.2506×10^{-1}	6.2501×10^{-1}	
Slice 9	[3200, 3900)	1.9639×10^{-2}	N/A	Run 2 only
	[3200, ∞)	N/A	1.9636×10^{-2}	Run 3 only
Slice 10	[3900, 4600)	1.1962×10^{-3}	N/A	Run 2 only
Slice 11	[4600, 5300)	4.2263×10^{-5}	N/A	Run 2 only
Slice 12	[5300, ∞)	1.0367×10^{-6}	N/A	Run 2 only

Table 5.1.: Sliced Pythia generation space definitions for ATLAS MC samples. Each slice is defined by leading jet p_T ranges, and cross-sections for both $\sqrt{s} = 13.0 \text{ TeV}$ (MC20) and $\sqrt{s} = 13.6 \text{ TeV}$ (MC23). Note, for MC samples covering Run 3 (MC23), the last four slices had been merged into one, hence extending its range from [3200, 3900) to [3200, ∞) GeV.

7 GeV by at least 1.5 times the jet size parameter, i.e. $\Delta R < 0.6$. Similarly, no truth jets with $p_T^{\text{truth}} > 7 \text{ GeV}$ can be within $\Delta R < 1.0$ (2.5 times the size parameter) of any other truth jet. Finally, the reconstructed dijet system's average energy cannot exceed the leading truth jet's p_T by more than 40%. That is

$$\frac{p_T^{1st \text{ reco}} + p_T^{2nd \text{ reco}}}{2} < 1.4 p_T^{1st \text{ truth}} \quad (5.2)$$

5.2. Pileup corrections

One of the first things that needs to be adjusted in MC-based calibration, are the effects of pileup activity. Since multiple protons are collided during each bunch interaction, jets originating from other primary vertices than the hard scatter interaction will leave signatures

5. Jets calibration for Run 2 and early Run 3 analyses

inside the ATLAS detector. There is a chance that during jet reconstruction these contributions will be included into the hard scatter jet resulting in artificial increase of its energy. To account for these effects, a two-step approach is used.

To begin with, pileup contributions are expected to be deposited within the detector uniformly and should be relative soft. Therefore, an area-based subtraction of such contributions is carried out for each hard scatter jet. The correction is known as "pileup area correction" or "pileup density correction" as it relies on both the median p_T density of pile-up activity in the event, ρ , and the area of any given jet, A_{jet} . The area of the jet is deduced using ghost association method [177, 178]: Each event is overlaid with numerous infinitesimally soft massless ghost particles randomly distributed in the $y - \phi$ plane and actively participate during jet clusterings⁵. If the number of ghost per unit area is defined as n_g and the number of ghost clustered within jet j is $N_g(j)$, then the jet area of j , $A_{\text{jet}}(j)$, is defined as

$$A_{\text{jet}}(j) = \frac{N_g(j)}{n_g}. \quad (5.3)$$

and the median p_T density of the event, ρ , is calculated by

$$\rho = \text{median} \left\{ \frac{p_{T,i}^{\text{jet}}}{A_{\text{jet},i}} \right\}, \quad (5.4)$$

where the index i implies iteration over all jets in the event. It is important to note that for the evaluation of ρ , jets are clustered using the k_t algorithm rather than anti- k_t clustering algorithm as the former tends to better reconstruct jets with a uniform soft background. Additionally, jets only found within $|\eta| < 2.0$ are used due to ρ 's tendency to drop towards zero in more forward detector regions. Under the assumption that pileup activity contribution is uniform and diffuse in nature, the correction for it can be expressed as

$$p_T^{\text{area}} := p_T^{\text{det}} - \rho \times A \quad (5.5)$$

where p_T^{det} is the jet transverse momentum measured at detector reconstruction level, p_T^{area} - after calibration and A represents jet area in the $\eta - \phi$ space. For Phase 1, ρ was calculated using the same PFlow objects that are used to build the jets. That is, both neutral and charged PFlow objects that satisfied $|z_0 \sin(\theta)| < 2$ mm. For Phase 2, ρ was calculated using neutral PFlow objects and charged PFlow objects with $|z_0 \sin(\theta)| \in (2, 4)$ mm [168].

While Eq. (5.5) corrects the average increase in jet energy due to pileup activity, it does not account for it fully. After the area correction, the jet is still affected by pileup activity from the same event, known as *in-time pileup*, which is sensitive to N_{PV} . Similarly, due to the high event interaction rate at the LHC, jet reconstruction is also susceptible to both previous and following bunch crossings, resulting in *out-of-time pileup*, which is dependent on $\langle \mu \rangle$. In

⁵This area definition is known as the *active jet area* and is expanded more on in [177] Section 3. Inclusion of ghost during clustering is permitted as jet algorithms are required to be IRC safe see Section 4.7.2 for more details.

5.3. Monte Carlo Based Jet Energy Scale Correction

ATLAS there are two methods to accommodate for these residual effects: 1D and 3D residual pileup corrections [168]. For the purposes of the pre-recommendations, the 1D residual pileup correction was chosen as the point of focus.

The 1D residual corrections adjust the jet's four-momentum for in-time and out-of-time pileup effects

$$P_{\text{PUcorr}}^4 = P_{\text{det}}^4 \cdot \frac{p_{\text{T}}^{\text{corr}}}{p_{\text{T}}^{\text{det}}} \quad (5.6)$$

where P_{det}^4 and $p_{\text{T}}^{\text{det}}$ are the jet's four momentum and transverse momentum at detector reconstruction level, P_{PUcorr}^4 is the PU corrected four momentum and $p_{\text{T}}^{\text{corr}}$ is defined as

$$p_{\text{T}}^{\text{corr}} := p_{\text{T}}^{\text{area}} - \alpha(|\eta_{\text{det}}|) \cdot (N_{\text{PV}} - 1) - \beta(|\eta_{\text{det}}|) \cdot \langle \mu \rangle \quad (5.7)$$

where $|\eta_{\text{det}}|$ is absolute value of the jets pseudorapidity measured at the detector reconstructed level⁶, $\alpha(|\eta_{\text{det}}|)$ and $\beta(|\eta_{\text{det}}|)$ are scaling functions for in-time and out-of-time pileup components respectively. Both α and β are derived in near identical fashion with jet energy scale after the area correction acting as the starting point. In order to derive α , a linear slope of the area corrected p_{T} vs $p_{\text{T}}^{\text{truth}}$, i.e. $\Delta p_{\text{T}} = p_{\text{T}}^{\text{area}} - p_{\text{T}}^{\text{truth}}$, is binned in $p_{\text{T}}^{\text{truth}}$, η , and μ . The average of these slopes in μ are fitted with a logarithmic function in each η bin for $p_{\text{T}}^{\text{truth}} \in [20, 200]$ GeV. The logarithmic fit evaluated at $p_{\text{T}}^{\text{truth}} = 25$ GeV is taken to be the nominal value for a given η bin and a piecewise linear function is fitted through the whole η range to provide full η coverage. This piecewise linear function is equated to the α scaling factor. For β factor derivation, the same procedure is undertaken with N_{PV} and μ switching places. If during the application of the calibration the $p_{\text{T}}^{\text{corr}}$ ever becomes negative, it is automatically set to 10 MeV. However, for calibration derivation purposes this behaviour is turned off to ensure proper jet energy response non-Gaussian tail modelling (see Section 5.3).

The distributions of both factors before and after the correction (i.e. Eq. (5.6)) are shown in Figures 5.2 and 5.3 for both Phases of the calibration. It can be seen, that after calibration the resulting values converge towards 0, indicating removal of the residual pileup contribution, particularly within ID and tracking coverage $|\eta| < 2.5$. The negative dependence of the out-of-time correction, i.e. β , is attributed the pulse shape of the LAr calorimeter, which is negative during the short period after registering a signal [106].

5.3. Monte Carlo Based Jet Energy Scale Correction

The following step in the calibration chain aims to restore the reconstructed jet energy scale back to the generator/constituent level. That is to account for jet energy scale changing effects due to non-compensating calorimeter response, out-of-cone effects, different calorimeter response and changes to their granularity. For this calibration step - known as absolute MC JES calibration - jets clustered with anti- k_t $R = 0.4$ are used after the pileup corrections have

⁶Measured with respect to the primary vertex, not detector origin.

5. Jets calibration for Run 2 and early Run 3 analyses

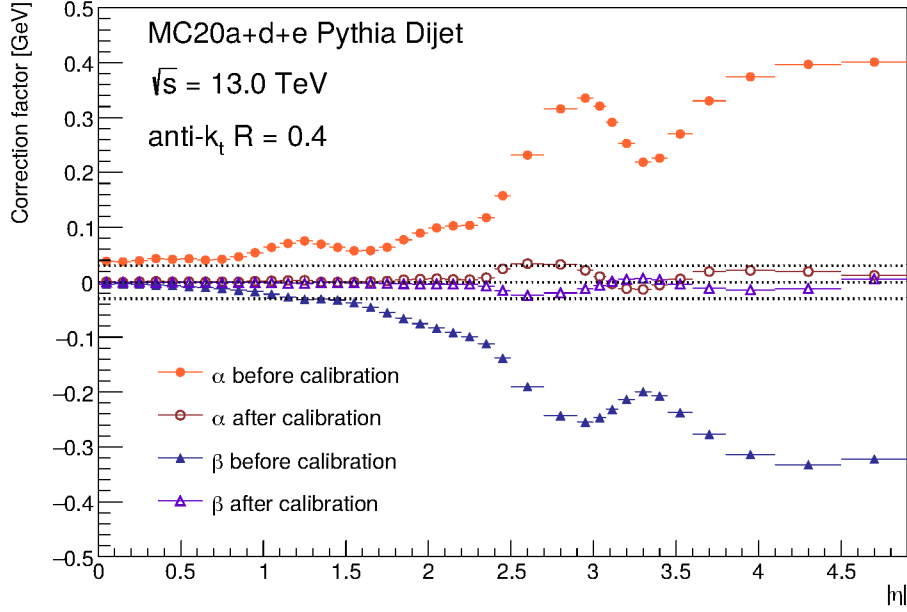


Figure 5.2.: 1D Residual pileup calibration factor distribution in $|\eta|$ before and after correction application for Phase 1 calibration (MC20). The in-time pileup correction is shown in orange and circles. The out-of-time pileup correction is shown in blue and triangles. Filled marks indicate the actual correction factor values while open symbols show their values derived after the calibration. This acts as a closure check of the correction where factor value of 0 is associated with full residual pileup contribution removal.

been applied⁷. The primary goal of the absolute MC JES calibration is to derive a calibration function parametrised only in reconstructable quantities, that would, on average, rescale the jet such that its response is as close as possible to unity without affecting the jet energy resolution.

Jet energy response, $\mathcal{R}$, can be defined as

$$\mathcal{R} = \frac{E_{\text{rec}}}{E_{\text{true}}} \quad (5.8)$$

where E_{rec} and E_{true} are the reconstructed and truth jet energies respectively for a given truth-reco jet pair. For a given truth energy range, a well calibrated response is expected to be Gaussian-like, centred around unity, with the width of the distribution being defined by the jet energy resolution, of JER for short. The jet energy scale, or JES , can be interpreted as

⁷It is important to note, that counter-argumentatively the JES after PU corrections is allowed to become non-positive (i.e. unphysical) to ensure as precise energy response modelling at this state.

5.3. Monte Carlo Based Jet Energy Scale Correction

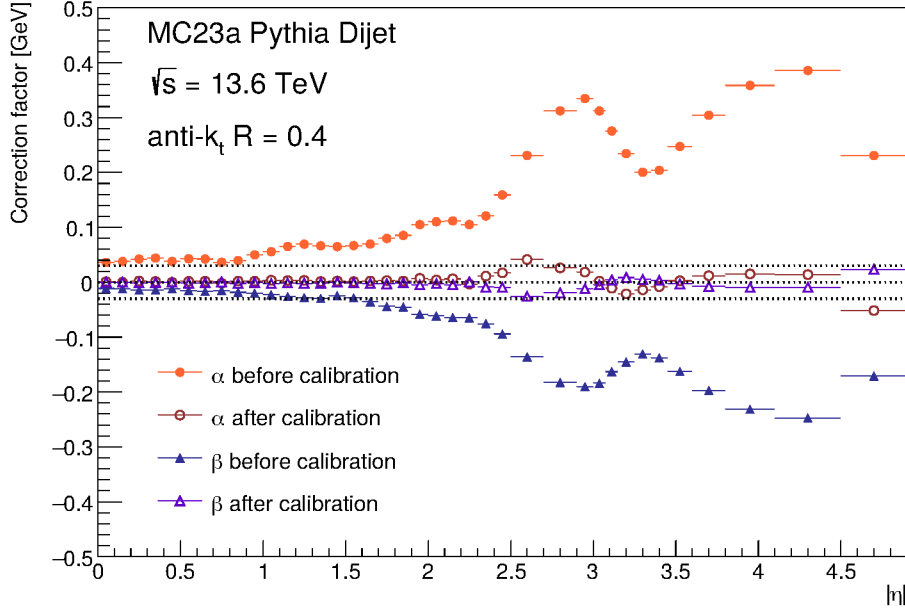


Figure 5.3.: 1D Residual pileup calibration factor distribution in $|\eta|$ before and after correction application for Phase 2 calibration (MC23a). The in-time pileup correction is shown in orange and circles. The out-of-time pileup correction is shown in blue and triangles. Filled marks indicate the actual correction factor values while open symbols show their values derived after the calibration. This acts as a closure check of the correction where factor value of 0 is associated with full residual pileup contribution removal.

the distribution's deviation from unity. Hence, an ideal absolute MC JES calibration function, C , is defined such that

$$E_{\text{calib}} := E_{\text{rec}} \cdot C(E_{\text{rec}}, \{\dots\}) \Rightarrow \mathcal{R}_{\text{calib}} := \frac{E_{\text{calib}}}{E_{\text{true}}} = 1 \quad (5.9)$$

The underlying principle of C deduction is the numerical inversion technique, whose generalised case and mathematical proof is provided by [179]. The step-by-step implementation of it for both phases of the calibrations is summarised below.

In order to obtain the numerical expression of C , a multistep process is carried out. To begin with, jet energy response is initially binned in E_{true} and η_{det} , η with respect to detector's geometric origin. Then through a Gaussian core fit, the mean $\mathcal{R}$ is deduced for all bins of E_{truth} and η_{det} (See Figures 5.4(a) and 5.5(a)). The means are fitted as a function of E_{truth} for every bin of η_{det} resulting in a set of response functions $\{\mathcal{R}(E_{\text{true}})\}$. The response functions are then used to calculate the numerically inverted energy,

$$E_{\text{NI}}(\eta_{\text{det}}) = E_{\text{truth}} \cdot \mathcal{R}(E_{\text{true}}, \eta_{\text{det}}) \quad (5.10)$$

5. Jets calibration for Run 2 and early Run 3 analyses

The jet response is once again rebinned in E and η_{det} with E_{NI} being used instead of E_{truth} . The mean response is again obtained through Gaussian core fit and consequently the set of response functions $\{\mathcal{R}(E_{\text{NI}})\}$ are formed like before (See Figures 5.4(b) and 5.5(b)). The inversion of these functions act as the calibration function $C(E_{\text{reco}})$ (Eq. (5.9)) and test of calibration closure is carried out. According to Eq. (5.9), if the jet response is calculated using the calibrated jet energy, the mean of its distributions for each η_{det} bin in E_{calib} will be around unity (See Figures 5.4(c) and 5.5(c)). It is important to note, that during calibration the correction is not applied just to the energy, but rather is used to scale the full 4-momenta of the jet.

In all steps, the mean responses are fitted with penalised splines method developed for Run 2 consolidated recommendations[168]. A spline, $S(x)$, of order N is a piecewise polynomial function of degree N , built up from b-spline basis functions, $B_i(x, t)$

$$S(x) = \sum_i^{n-1} a_i B_i(x, t) \quad (5.11)$$

where a_i are the control points for the individual basis functions, B_i , t - are knots (points where two bases are joint), and n are the fit points [180]. The $S(x)$ is continuous differentiable across $\{t\}$ for its first $N - 1$ derivatives. The function is fit using least square, χ^2 method with an added penalisation term, P . That is, $S(x)$ is derived through minimisation of

$$L = \chi^2 + \alpha P = \sum_{i=0}^n (y_i - S(x_i))^2 + \alpha \int_a^b \left[(S''(x))^2 \right] dx \quad (5.12)$$

where x and y are identified as jet energy and jet responses during various stages of the calibration, $[a, b]$ the domain over which the penalisation is applied⁸. α is the penalisation parameter dynamically defined for each η bin as

$$\alpha = \frac{\lambda}{n} \cdot \sum_{i=0}^n w_i \quad (5.13)$$

where λ is the regulative parameter, n is the number of data points per given η bin, $\{w_i\} = \{\sigma_y^{-1/2}\}$ is the set of point weights with σ_y representing the Gaussian fit uncertainty of the jet response. For x (i.e. energy) outside the domain covered by knots, i.e. (where $S(x) = 0$), the function is linearly extrapolated towards the lower (higher) energy values using the first (last) five points of the spline. For the calibrations, a 3rd order spline with $\lambda = 0.1$ was used, and the spline functionality was implemented using the Splinter framework[181].

The effectiveness of the calibration through the whole η scope of the detector is visualised in Figures 5.6 and 5.7 for differing values of jet energies, separated into two arbitrary categories of low and high jet energies. The right-hand side plots for both shows the jet energy response after calibration, which converges towards unity. The slight non-closure⁹ at

⁸Note: $a < x_i < b$

⁹Deviation from 1.0.

5.4. Monte Carlo Based η Correction

large values of $|\eta|$ for all energies is explained due to decreasing number of jets populating those specific (E, η) bins. The greatest non-closure is achieved when the combination E and η would result in jet's p_T approaching the $p_T > 20$ GeV boundary conditions (c.f. Section 4.7.3). The slightly worse performance of the Phase 2 calibration (Figure 5.7) compared to Phase 1 (Figure 5.6) is motivated by the fact that Phase 2 calibration was derived with only MC23a samples, whereas Phase 1 used all the Run 2 MC20 campaigns. No changes to methodology have been made between Phase 1 and Phase 2, except for slight redefinition of some of lower energy bins to account for the decrease in statistics between the phases (compare Figures 5.4(a) and 5.5(a)).

5.4. Monte Carlo Based η Correction

Similarly to the full jet momentum calibration defined above, an additional correction is derived for the jet's pseudorapidity to correct for the η reconstruction bias due to calorimeter system geometry and differing technologies. This is particularly needed in the geometry transition regions: barrel-to-endcap ($|\eta| \sim 1.4$) or endcap-to-forward ($|\eta| \sim 3.1$). A similar approach to one described in Section 5.3 is used, except the η response is defined as the difference between reconstructed and the truth, that is

$$\mathcal{R}_\eta = \langle \eta_{\text{reco}} - \eta_{\text{truth}} \rangle \quad (5.14)$$

with closure condition defined as $\mathcal{R}_\eta = 0$. As before, the Gaussian means in each energy bin are fitted to produce the calibration function, however, this time a 3rd degree polynomial is used instead of a penalised spline. During calibration, the correction is performed simultaneously with the MC JES correction and is applied on jet-by-jet basis

$$\eta_{\text{calib}} = \eta_{\text{reco}} - \mathcal{R}_\eta \quad (5.15)$$

Differently to the absolute MC JES calibration, the correction only affects the η (and conversely p_T) of the jet and is expected to be far smaller compared to the energy-based correction. The performance of the calibration is visualised with particular focus on the transition regions for both Phase 1 and Phase 2 of the calibration in Figures 5.8 and 5.9 respectively.

5.5. Global Sequential Correction

The following and final step of the MC-based corrections are the *Global Sequential Corrections*, or GSC. Differently to MC JES and η corrections discussed in previous sections, GSC aims to improve the jet resolution without changing the average jet energy response (as it assumed to be fully calibrated at this point). The corrections are comprised of 6 individual and independent corrections which rely on global jet observables and adjust misconstruction effects caused by differing jet flavours and their interactions with the calorimeter systems. Each jet correction is linked to the normalised jet p_T response parametrised by a corresponding observable and their application is multiplicative in nature.

5. Jets calibration for Run 2 and early Run 3 analyses

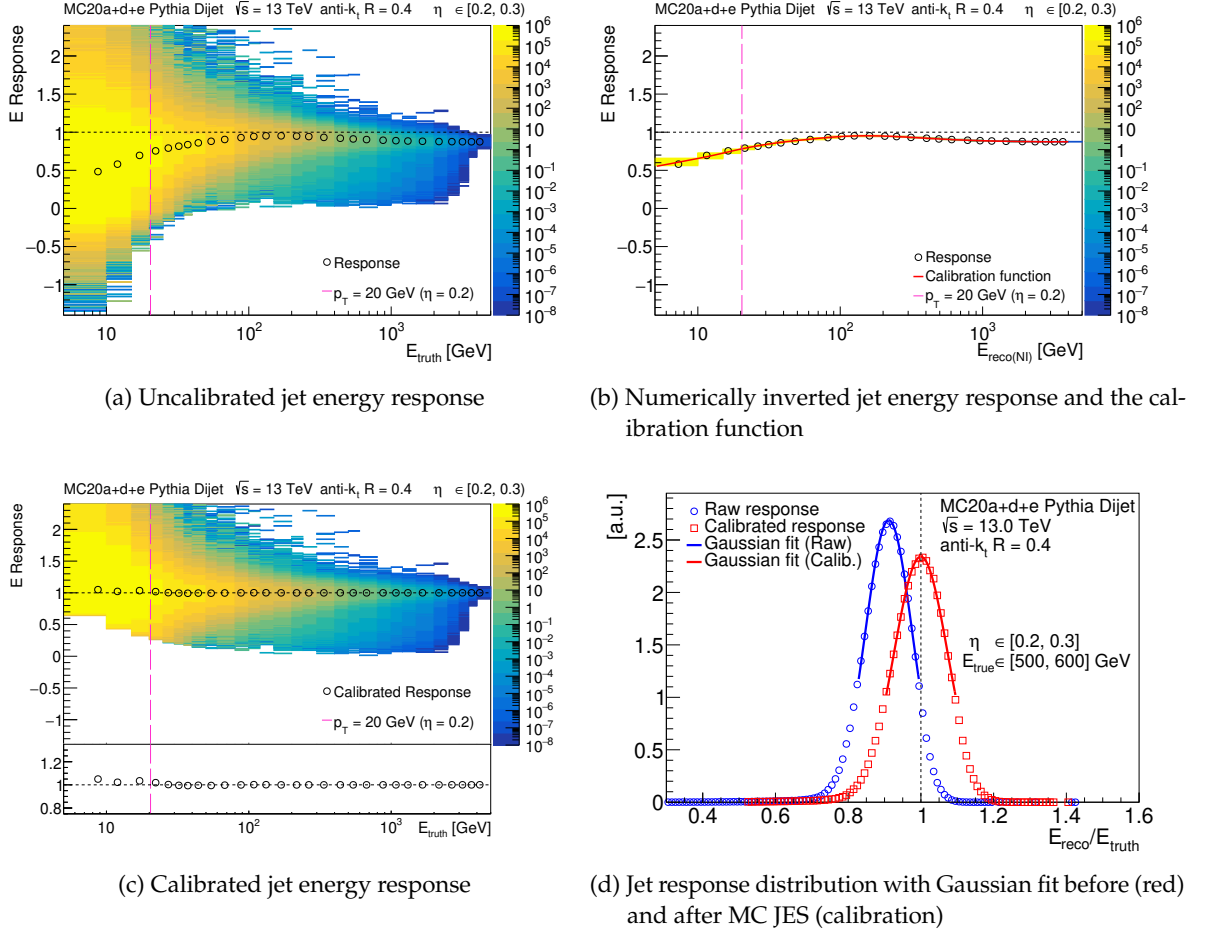


Figure 5.4.: Performance of $|\eta| \in [0.2, 0.3]$ bin in various stages of the MC JES calibration for Phase 1 (MC20a+d+e) calibration. (a) shows the (uncalibrated) jet energy response ($E_{\text{reco}}/E_{\text{truth}}$) as a function of E_{truth} . (b) shows the (intermediate) jet energy response ($E_{\text{reco}}/E_{\text{NI}}$) as a function of E_{NI} ($E_{\text{truth}} = E_{\text{truth}} \cdot f_{\text{truth}}(E_{\text{truth}})$, where f_{truth} is the response function from (a)). The inverse of the response function, $f_{\text{NI}}(E_{\text{NI}})$, shown in red, derived from this distribution is identified as the calibration function, $C(E_{\text{reco}}) \equiv f_{\text{NI}}^{-1}(E_{\text{reco}})$. (c) shows the calibrated jet energy response ($(E_{\text{reco}} \cdot C(E_{\text{reco}}))/E_{\text{truth}}$) as a function of E_{truth} . Convergence around unity indicates correct calibrations performance. In all three plots, the open circles indicate the response means (calculated through Gaussian fit) in each energy bin. Penalised-spline fit is used for all response function fitting. The dashed pink vertical line indicates the reconstructed jet's minimum p_T . (d) shows the normalised jet response distributions before (blue) and after (red) application of the calibration function for $E_{\text{truth}} \in [500, 600]$ GeV as well as their Gaussian core fits.

5.5. Global Sequential Correction

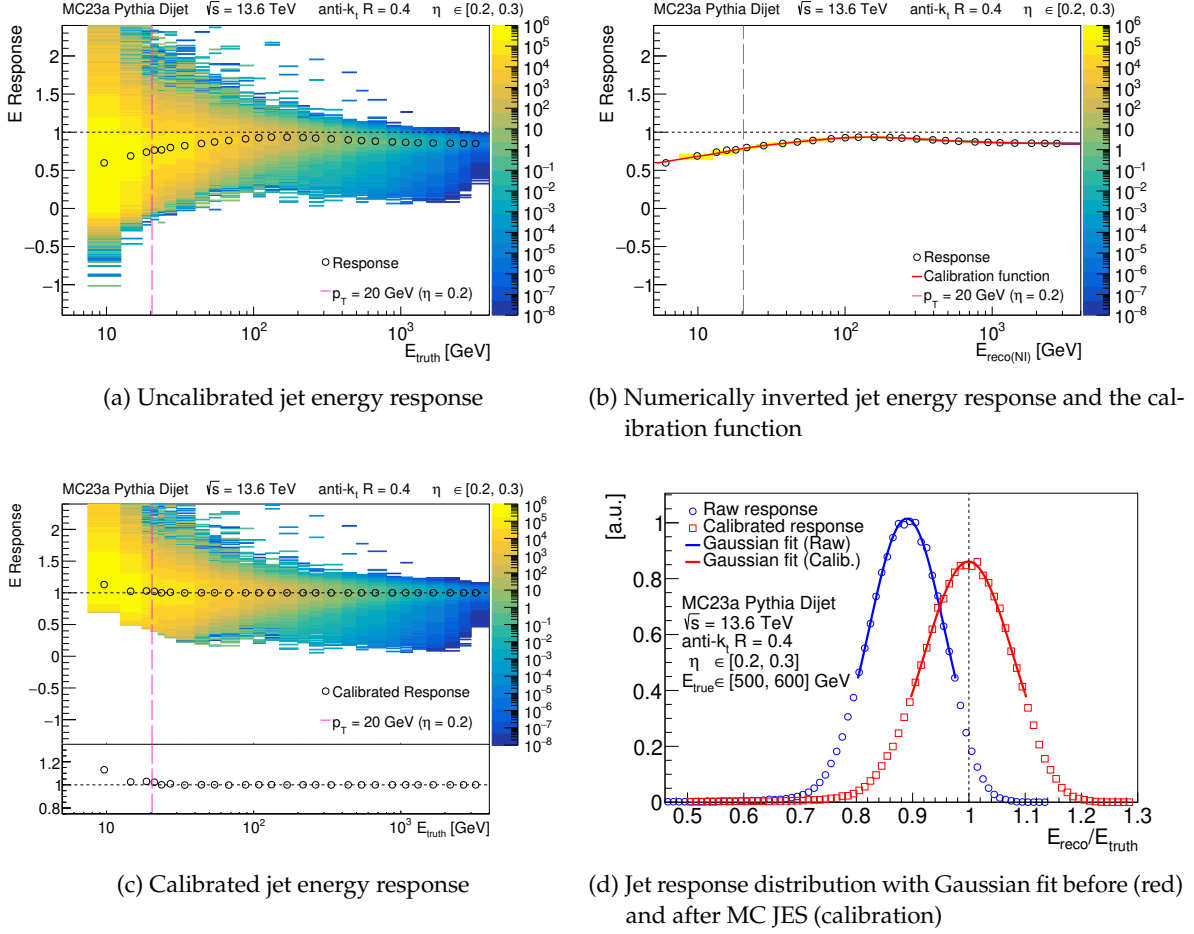


Figure 5.5.: Performance of $|\eta| \in [0.2, 0.3]$ bin in various stages of the MC JES calibration for Phase 2 (MC23a) calibration. (a) shows the (uncalibrated) jet energy response ($E_{\text{reco}}/E_{\text{truth}}$) as a function of E_{truth} . (b) shows the (intermediate) jet energy response ($E_{\text{reco}}/E_{\text{NI}}$) as a function of E_{NI} ($E_{\text{truth}} \cdot f_{\text{truth}}(E_{\text{truth}})$), where f_{truth} is the response function from (a). The inverse of the response function, $f_{\text{NI}}(E_{\text{NI}})$, shown in red, derived from this distribution is identified as the calibration function, $C(E_{\text{reco}}) \equiv f_{\text{NI}}^{-1}(E_{\text{reco}})$. (c) shows the calibrated jet energy response ($(E_{\text{reco}} \cdot C(E_{\text{reco}}))/E_{\text{truth}}$) as a function of E_{truth} . Convergence around unity indicates correct calibrations performance. In all three plots, the open circles indicate the response means (calculated through Gaussian fit) in each energy bin. Penalised-spline fit is used for all response function fitting. The dashed pink vertical line indicates the reconstructed jet's minimum p_T . (d) shows the normalised jet response distributions before (blue) and after (red) application of the calibration function for $E_{\text{truth}} \in [500, 600]$ GeV as well as their Gaussian core fits.

5. Jets calibration for Run 2 and early Run 3 analyses

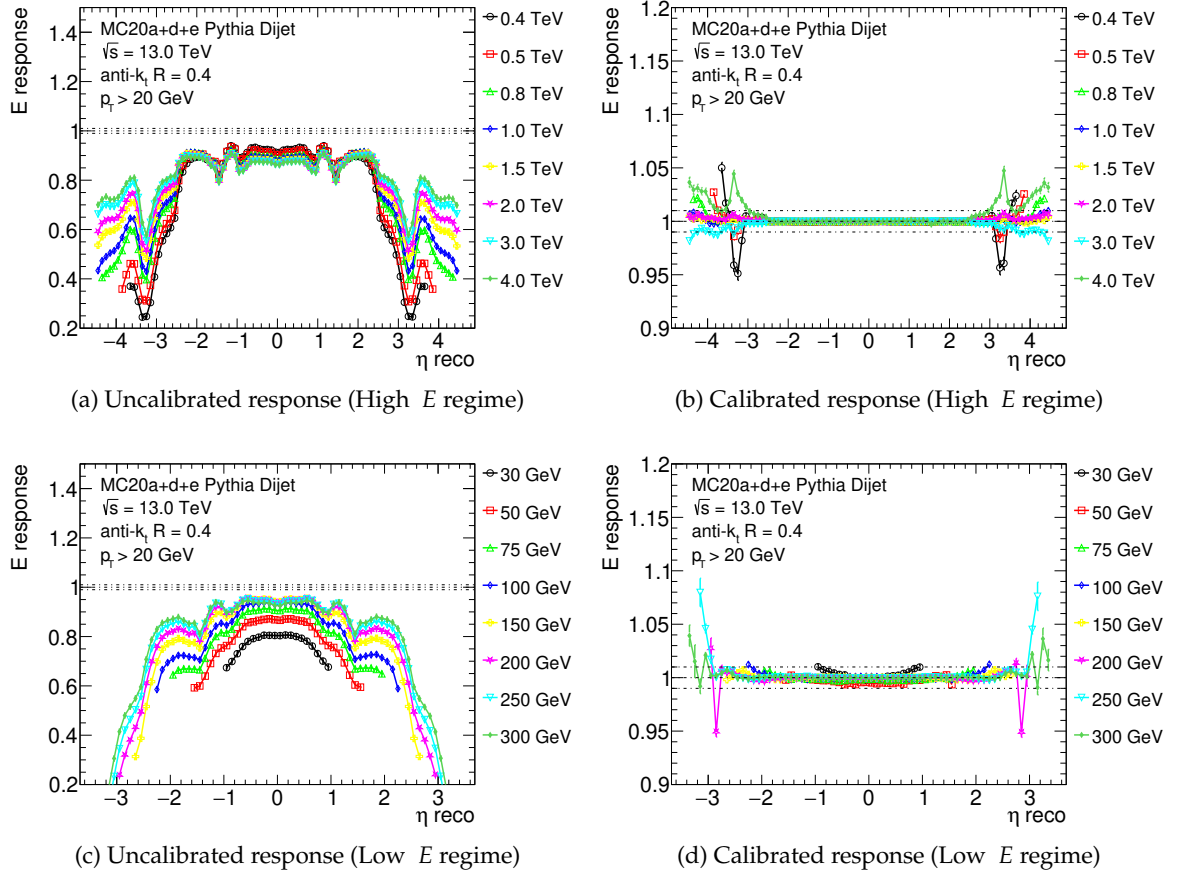


Figure 5.6.: Jet response distribution as a function of η for Phase 1 Calibration (MC20a+d+e). (a) shows uncalibrated jet response for higher p_T jets. (b) shows calibrated jet response for higher p_T jets. (c) shows uncalibrated jet response for lower p_T jets. (d) shows calibrated jet response for lower p_T jets.

5.5. Global Sequential Correction

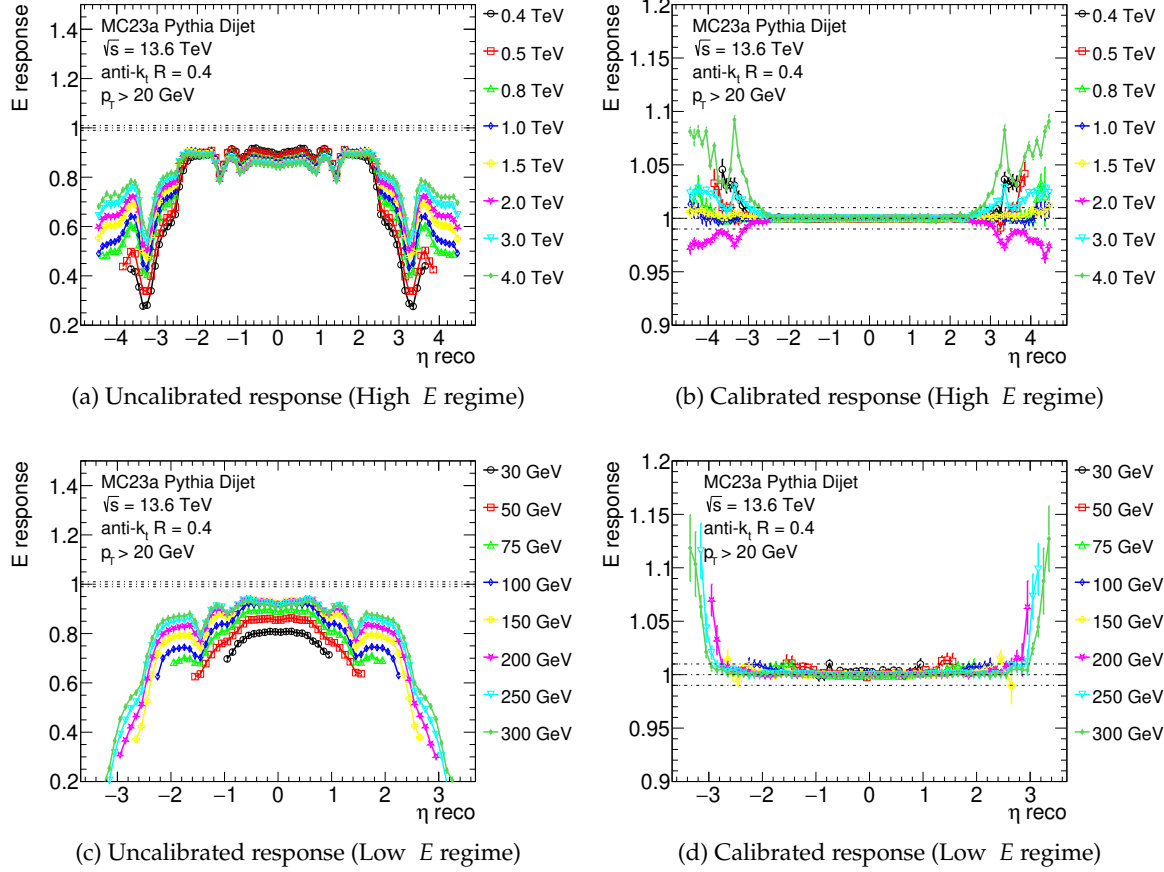


Figure 5.7.: Jet response distribution as a function of η for Phase 2 Calibration (MC23a). (a) shows uncalibrated jet response for higher E jets. (b) shows calibrated jet response for higher E jets. (c) shows uncalibrated jet response for lower E jets. (d) shows calibrated jet response for lower E jets.

5. Jets calibration for Run 2 and early Run 3 analyses

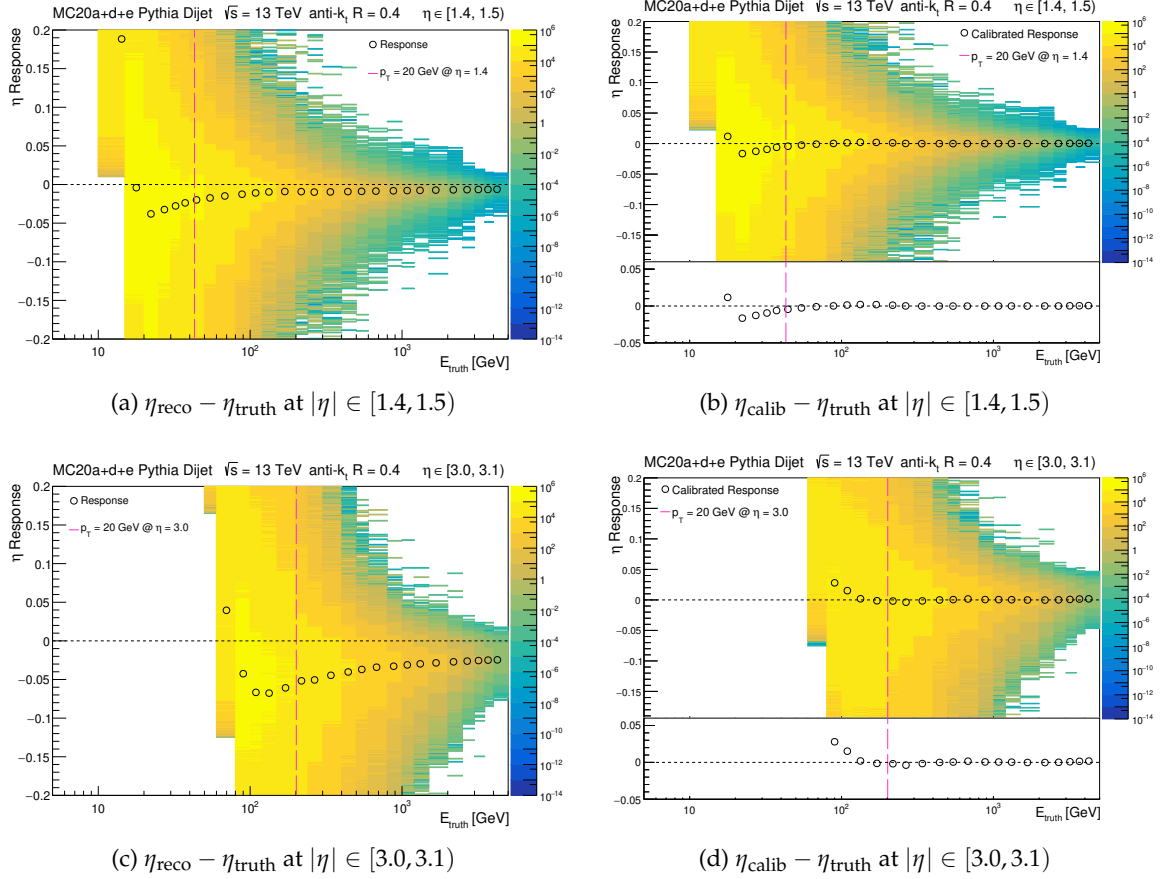


Figure 5.8.: Performance of the MC η calibration for Phase 1 (MC20a+d+e) in various η bins: (a) shows the uncalibrated jet η response function of E_{truth} in the barrel-to-endcap transition region. (b) shows the calibrated jet η response function of E_{truth} in the barrel-to-endcap transition region. (c) shows the uncalibrated jet η response function of E_{truth} in the endcap-to-forward transition region. (d) shows the calibrated jet η response function of E_{truth} in the endcap-to-forward transition region. For all plots, the open circles indicate the response means (calculated through Gaussian fit) in each energy bin. The dashed pink vertical line indicates the reconstructed jet's minimum p_T .

5.5. Global Sequential Correction

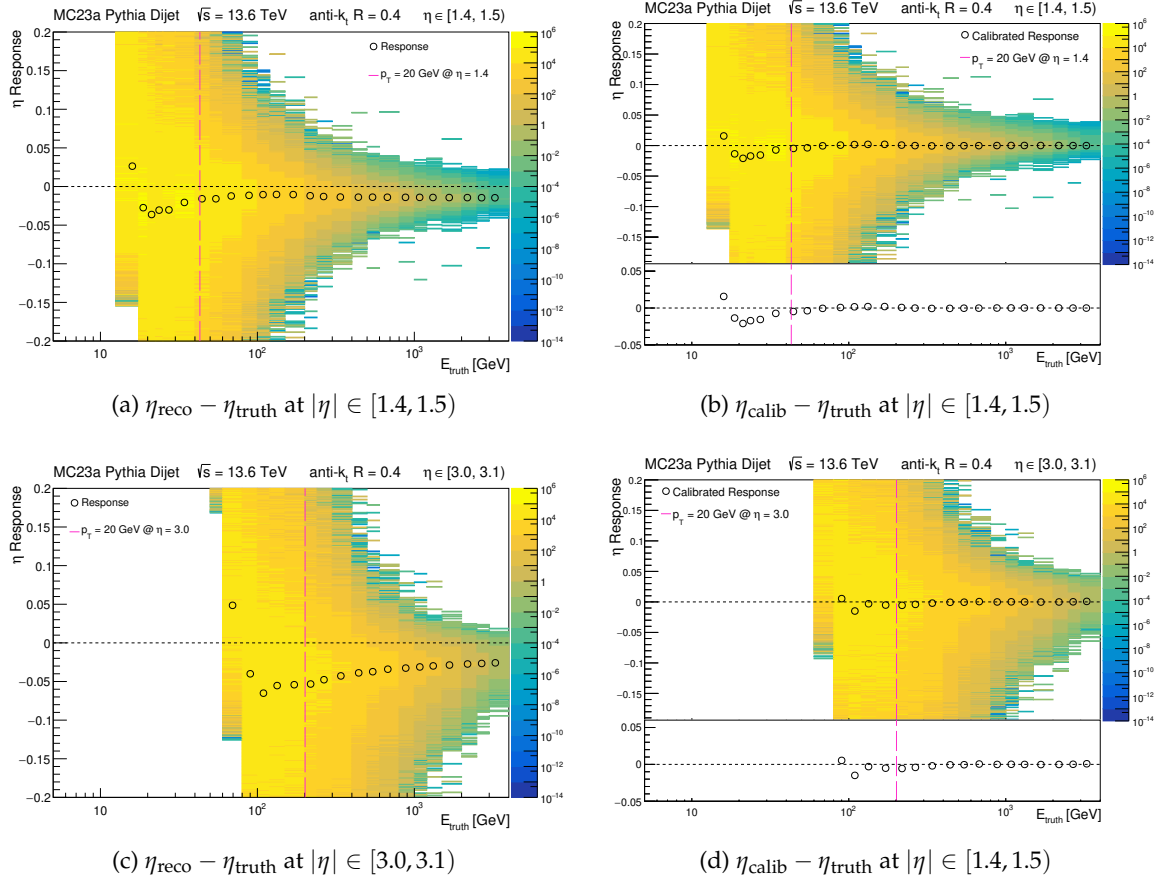


Figure 5.9.: Performance of the MC η calibration for Phase 2 (MC23a) in various η bins: (a) shows the uncalibrated jet η response function of E_{truth} in the barrel-to-endcap transition region. (b) shows the calibrated jet η response function of E_{truth} in the barrel-to-endcap transition region. (c) shows the uncalibrated jet η response function of E_{truth} in the endcap-to-forward transition region. (d) shows the calibrated jet η response function of E_{truth} in the endcap-to-forward transition region. For all plots, the open circles indicate the response means (calculated through Gaussian fit) in each energy bin. The dashed pink vertical line indicates the reconstructed jet's minimum p_T .

5. Jets calibration for Run 2 and early Run 3 analyses

For a given correction variable, x_i , the correction is defined as follows. To begin with, jet p_T response, defined as p_T / p_T^{truth} , is parametrised in bins of $|\eta|$, p_T^{truth} , and x_i . The responses are then fitted in a procedure similar to ones described in Sections 5.3–5.4 and are normalised by the inclusive response in each $(|\eta|, p_T^{\text{truth}})$ bin and linearly smoothed. The normalisation is necessary to ensure that the correction does not change JES during calibration. After the linear smoothing, numerical inversion is once again utilised to acquire the response in each x_i bin in terms of the reconstructed jet's transverse momentum. The response is then refilled in bins of $(|\eta|, p_T^{\text{NI}}, x_i)$. Finally, a Gaussian kernel smoothing in (p_T^{NI}, x_i) is carried out for each $|\eta|$. The variables in question are:

- f_{charged} - fraction of jet p_T carried by charged particles. Measured through ghost-associated tracks with $p_T^{\text{track}} > 500$ MeV within tracking system ($|\eta_{\text{det}}| < 2.5$). Applicable only to PFlow jets.
- f_{Tile0} - fraction of jet energy measured in the first layer of the hadronic tile calorimeter ($|\eta_{\text{det}}| < 1.8$).
- f_{LAr3} - fraction of jet energy measured in the third layer of the electromagnetic liquid argon calorimeter ($|\eta_{\text{det}}| < 3.5$).
- N_{tracks} - number of ghost-associated tracks with $p_T^{\text{track}} > 1$ GeV ($|\eta_{\text{det}}| < 2.5$).
- w_{track} - average p_T -weighted transverse difference in $\eta - \phi$ plane between the jet axis and above described tracks. This is also known as the *track width*.
- N_{segments} or $N_{\text{punch-through}}$ - number of ghost associated muon track segments ($|\eta_{\text{det}}| < 2.8$). The only correction that is applied/derived in terms of energy rather than momentum as it accounts for the effects of punch-through, which is the amount of escaping jet energy.

The corrections are assumed to be independent of one another, hence are applied multiplicatively without a strict order enforcement¹⁰. That is, the full GSC calibration can be expressed as

$$\vec{p}_T^{\text{post-GSC}} := \vec{p}_T^{\text{post-EtaJES}} \cdot \prod_{x_i}^{\{\text{corr}\}} [\mathcal{R}(x_i)^{-1}] \quad (5.16)$$

Note, the response $\mathcal{R}(x_i)$ enters as an inverse due to numerical inversion (c.f. Eq. (5.9)).

The effects of the Global Sequential corrections of the Phase 1 and Phase 2 calibrations is shown in Figures 5.10 and 5.11 respectively. As expected, jet energy resolution is improved with consecutive application of the corrections with little to no change in the jet energy response. It is important to note, that for the Phase 2 corrections, the last step is skipped due to a faulty calculation of number of muon segments associated to jet during jet reconstruction.

¹⁰The corrections are applied in order they are listed. Differing application ordering have been investigated in the past and their effect have been found to be negligible.

5.6. Data Only *In situ* Calibration

The omission of this step is not expected to introduce major effects of the total calibration (compare Figures 5.10(b) and 5.11(b)). Furthermore, as mentioned in the introduction of this section, the Phase 2 calibrations which were developed using MC23a samples, have also been tested with MC23d samples representing the data taking conditions of 2023. The difference between the application to the two collections is shown in Figure 5.12. The behaviour difference at low p_T^{truth} is attributed to differing pileup conditions between the years. The effect of this was deemed not significant enough to warrant new calibration. Rather, a slight increase in the calibration uncertainties was used to cover this change.

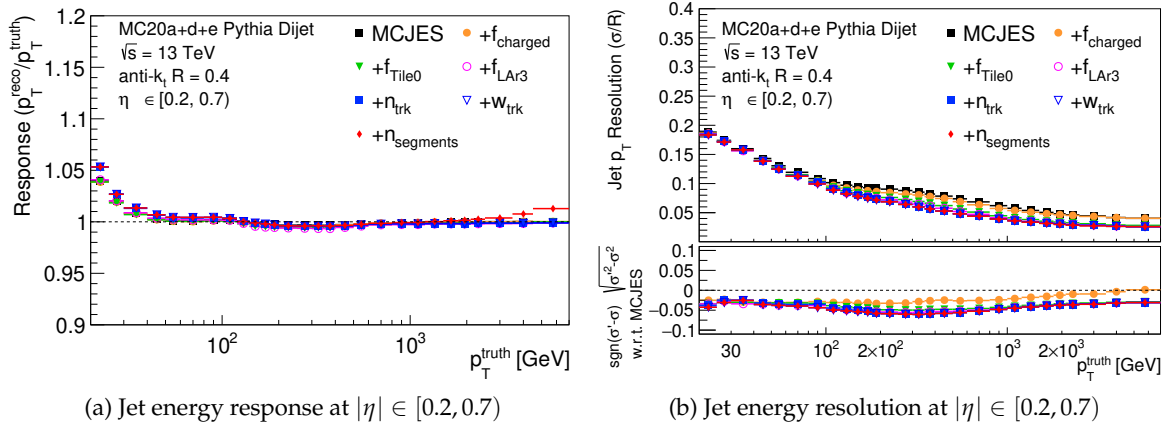


Figure 5.10.: Iterative jet energy response and resolution change during Phase 1 GSC calibration visualised in $|\eta| \in [0.2, 0.7]$. (a) shows how the Jet energy response changes between various steps of GSC calibration. (b) shows how the jet energy resolution improvement between various steps of GSC calibration (top) and relative improvement before any GSC calibration is carried out (bottom). All correction discussed in Section 5.5 are applied in interactive and multiplicative fashion.

5.6. Data Only *In situ* Calibration

The calibrations discussed in Sections 5.2–5.5 are applicable to both data and Monte Carlo backgrounds as their primary goal is to restore the detector reconstruction to theoretical simulation level. The final step of the calibration, known as *in situ calibration*, is applied only to data and addresses the imperfections of the simulations with respect to the physics processes and the detector performance.

The *in situ* correction group consists of three individual corrections [106]. To begin with, the η -intercalibration, which relies on dijet momentum asymmetry, $\mathcal{A}$, defined as

$$\mathcal{A} := \frac{p_T^{\text{jetA}} + p_T^{\text{jetB}}}{p_T^{\text{avg}}}$$

5. Jets calibration for Run 2 and early Run 3 analyses

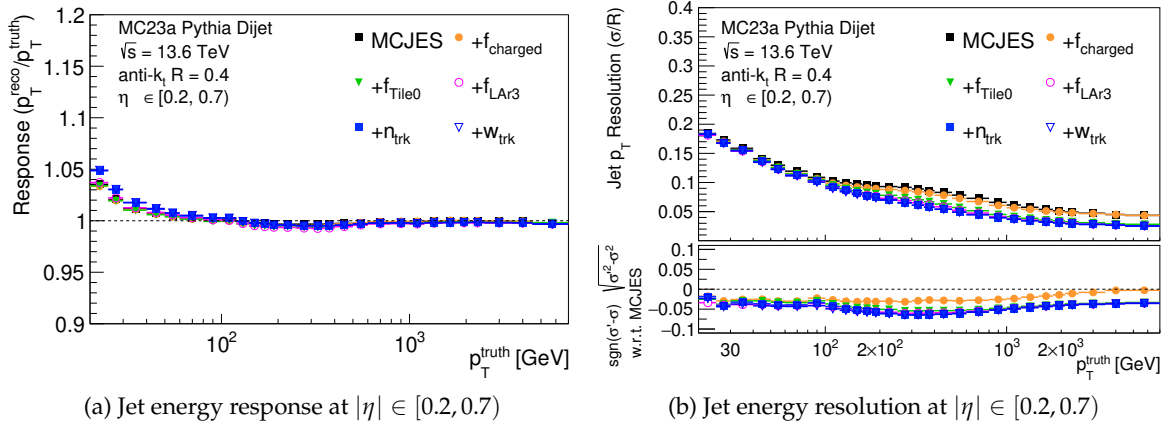


Figure 5.11.: Iterative jet energy response and resolution change during Phase 2 GSC calibration visualised in $|\eta| \in [0.2, 0.7]$. (a) shows how the Jet energy response changes between various steps of GSC calibration. (b) shows how the jet energy resolution improvement between various steps of GSC calibration (top) and relative improvement before any GSC calibration is carried out (bottom). All correction discussed in Section 5.5 apart N_{segments} based one are applied in interactive and multiplicative fashion. The last correction was skipped due to faulty muon segment associated to jet calculation during jet reconstruction.

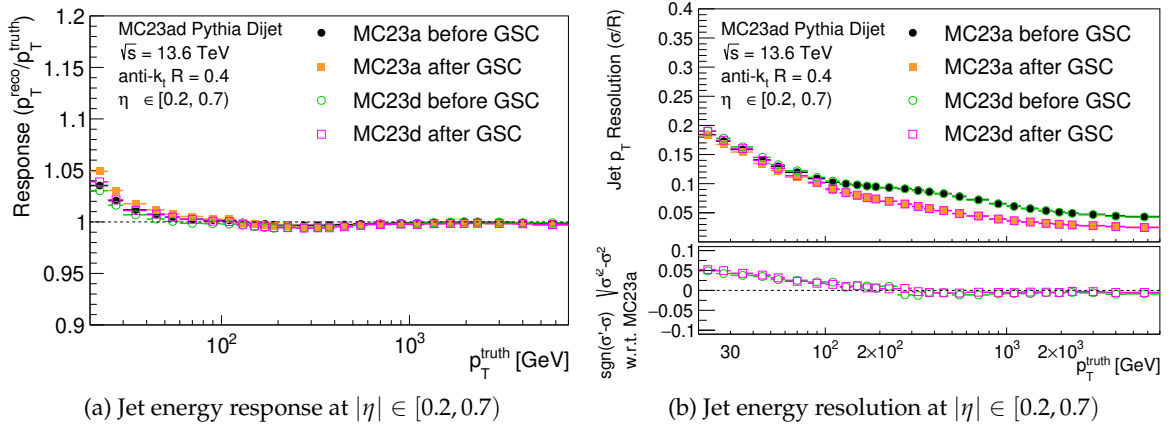


Figure 5.12.: Comparison of MC23a-based calibration application to MC23a and MC23d at $|\eta| \in [0.2, 0.7]$. (a) shows comparison between MC23a and MC23d jet energy response before and after GSC calibration. (b) shows comparison between MC23a and MC23d jet energy resolution before and after GSC calibration (top) and relative difference with respect to MC23a for both stages (bottom). The observed behaviour divergence at low p_T^{truth} is attributed to changes in pile-up conditions between 2022 and 2023 data taking periods.

5.6. Data Only In situ Calibration

It calibrates forward jets found in $|\eta_{\text{det}}| \in [0.8, 4.5)$ to the same jet energy scale as central jets with $\eta_{\text{det}} < 0.8$. Following this, a correction based on momentum balance between the central jet p_T and p_T of well measured objects (e.g. Z, γ) is derived using $Z + \text{jets}$ and $\gamma + \text{jets}$ events. Finally, a correction for jets with p_T greater than those used in previous step is derived. This correction also relies on momentum balance, however now the calibration target is the singular high p_T jet and the reference is the remaining hadronic activity.

The absolute in situ measurements from last two steps derived in the central region ($\eta_{\text{det}} < 0.8$) are then combined into a singular correction factor through a procedure detailed in [182]. The resulting double ratio

$$c^{\text{in situ}} := \frac{\mathcal{R}_{\text{in situ}}^{\text{data}}}{\mathcal{R}_{\text{in situ}}^{\text{MC}}} \quad (5.17)$$

where $\mathcal{R}_{\text{in situ}}^{\text{data}}$ and $\mathcal{R}_{\text{in situ}}^{\text{MC}}$ are data's and Monte Carlo sample's in situ responses respectively, both defined as

$$\mathcal{R}_{\text{in situ}} := \left\langle \frac{p_T^{\text{jet}}}{p_T^{\text{ref}}} \right\rangle,$$

is the in-situ correction factor which thanks to the η -intercalibration can be applied to both central and forward jets.

6. Development Context: Invisible Higgs Decay searches in VBF topologies

As discussed in Section 2.2.2, invisible Higgs boson decays may provide a way of inferring information about dark matter and physics related to it. The Higgs boson can decay invisibly in SM without DM presence through $H \rightarrow ZZ^* \rightarrow 4\nu$ channel in about 0.1% of all its decays[47]. Excess decay over this limit would be indicative of BSM physics. However, detection of such events is particularly complicated. The short life-time of the Higgs boson would make only its decay products detectable if not for the fact that said products are invisible by nature, hence, escape detection. As a result, missing transverse energy, $\cancel{E}_T$, (see Section 4.9) is a signature part of such an event. Furthermore, particular care needs to be taken to differentiate DM-originated decay events from other events with similar signatures using available¹ information from the detector. In this chapter, one such search is presented as a case study and as the motivational background for which the novel multijet estimation method had been developed.

6.1. Recent Results

Searches for invisible Higgs decays exceeding the SM have been a crucial part of the Dark Matter physics searches carried out by both ATLAS [3–12] and CMS [183–186] experiments since the start of LHC operation. Up to the writing of this work, there have been no excess events exceeding this limit by over 5σ , hence, only more stringent upper limits on the observed invisible branching ratio could be placed. By the end Run 2, a combination of searches in various topologies at $\sqrt{s} = 7, 8, 13$ TeV had placed the observed (expected) invisible Higgs branching ratio, $\mathcal{B}_{\text{inv}}$, to 0.107 (0.077) at 95% confidence level[187] (see Figure 6.1). The most sensitive search contributing to the precision of this limit, is based on the vector boson fusion (VBF) channel with individually set limit of 0.145 (0.103) for the expected (observed) $\mathcal{B}_{\text{inv}}$ [7]. From CMS side, the vector boson fusion channel is also the most sensitive in such searches and results in 0.18 (0.12) limit at 95% confidence level (see Figure 6.2) [185]. While VBF channel is the second most dominant Higgs boson production channel (Figure 2.7), the invisible Higgs decay searches based on it show the greatest sensitivity. This stems purely from the better signal-to-background (S/B) ratio, where background is assumed to be the most dominant process mimicking the signal's end state. For vector boson fusion, with the production cross-section ($\sigma_{\text{VBF}}(H + qq) = 3.781^{+0.079}_{-0.079}$ pb at $\sqrt{s} = 13$ TeV [47]), the S/B is

¹detectable

6.2. Major Backgrounds, their Predictions, and Region Definitions

given by

$$\frac{\sigma_{VBF}(H + qq)}{\sigma_{VBF}(Z + q) \cdot \mathcal{B}(Z \rightarrow \nu\nu)} \sim \frac{4}{3} \quad (6.1)$$

while for the most dominant production channel, gluon-gluon fusion, with production cross-section $\sigma_{ggF}(H + jet) = 48.57^{+2.22}_{-3.27}$ at $\sqrt{s} = 13$ TeV[47], the ratio is

$$\frac{\sigma_{ggF}(H + jet)}{\sigma(Z + jet) \cdot \mathcal{B}(Z \rightarrow \nu\nu)} \sim \frac{1}{300} \quad (6.2)$$

That is, even if Higgs bosons are produced more than order of magnitude less often through VBF than through ggF, the former is more sensitive to invisibly decaying Higgs bosons. Hence, the ATLAS search for invisibly decaying Higgs boson in VBF topology [7] is chosen as the context for the new model development.

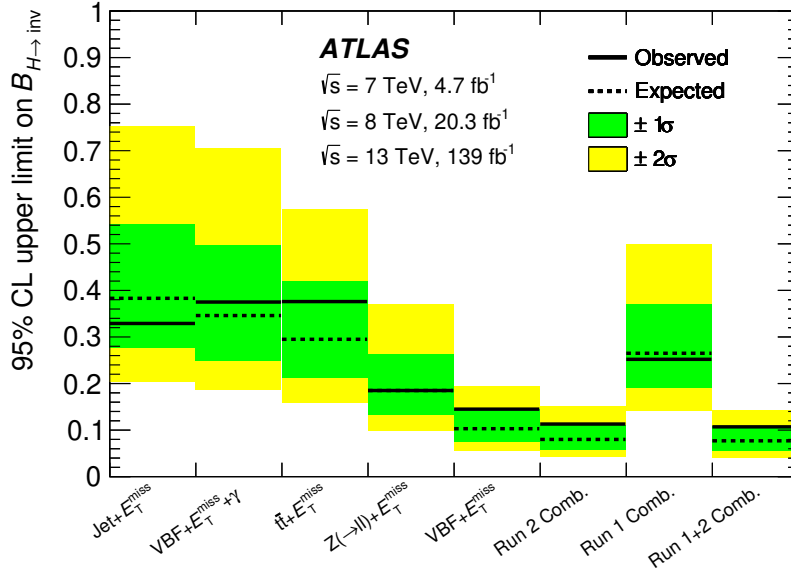


Figure 6.1.: ATLAS observed and expected upper limits on B_{inv} at 95% CL for the Run 2 analyses targeting various final states and their combination, the Run 1 combination, and the full Run 1+2 result; the 1σ and 2σ contours of the expected limit distribution are also shown [187].

6.2. Major Backgrounds, their Predictions, and Region Definitions

The vector boson fusion event topology is characterised by an energetic dijet system with a wide pseudorapidity gap ($\Delta\eta_{jj}$) and consequently a large invariant mass (m_{jj}). The invisible Higgs decay is expected to introduce a large amount of E_T to the event. As a result, the dijet system will not be back-to-back² and little to no visible activity is expected in the central

²i.e. $\Delta\phi_{jj}$ is expected to be small.

6. Development Context: Invisible Higgs Decay searches in VBF topologies

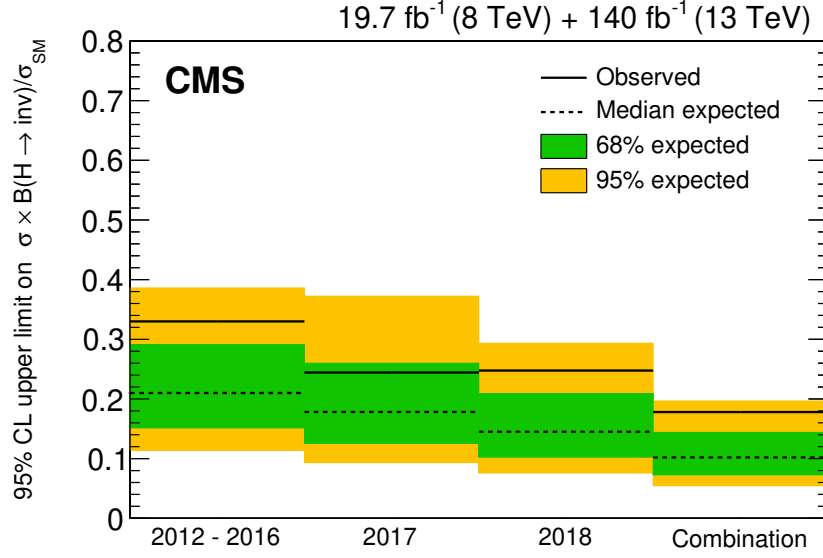


Figure 6.2.: Observed and expected 95% CL upper limits on $(\sigma_H/\sigma_H^{SM})\mathcal{B}(H \rightarrow \text{inv})$ for data taking periods covering from 2012 to 2016, 2017, 2018, as well as their combination, assuming an SM Higgs boson with a mass of 125.38 GeV[185].

region. The only permitted activity would need to be compatible with FSR³. This is enforced through additional restrictions on non-dijet jets: The first one is centrality [188] given by

$$C_i = \exp \left(-\frac{4}{\Delta\eta_{jj}^2} \left(\eta_{ji} - \frac{\sum \eta_{jj}}{2} \right)^2 \right) \quad (6.3)$$

where subscript i refers to a non-dijet jet, $\Delta\eta_{jj}$ is given by Eq. (4.16), and $\sum \eta_{jj} = \eta_{j0} + \eta_{j1}$ is defined in similar fashion. The value of C_i can provide separation between QCD processes (whose tend accumulate around $C_i \sim 1$) and VBF processes ($C_i < 1$). The second criterion is the invariant mass of the dijet systems formed by the non dijet jet (j_i) with the leading (j_0) or subleading (j_1) jet, whichever is smaller, versus the actual invariant mass of the proper dijet system. That is

$$m_i^{rel} = \frac{\min \{m_{j_0 j_i}, m_{j_1 j_i}\}}{m_{jj}} \quad (6.4)$$

where the invariant masses $m_{j_0 j_i}$ and $m_{j_1 j_i}$ are calculated according to Eq. (4.19).

The full Run 2 analysis [7] divided the signal region into 16 search bins based on all the above discussed parameters with C_i and m_i^{rel} being applied only when more than 3

³Compatibility with ISR could also be permitted, however, since ATLAS detector's ability to distinguish ISR is not as good as FSR's, only FSR is considered.

6.2. Major Backgrounds, their Predictions, and Region Definitions

jets were being considered. In each bin signal yield is extracted through a simultaneous maximum-likelihood fit which takes into account contributions from various backgrounds that might obfuscate it. The backgrounds in the searches can be roughly grouped into three categories: V+jets, multijet, and other. The latter only contributes less than 1% of all events in the signal region, hence their contributions are model through Monte Carlo simulations. The former two require dedicated estimation methods which are summarised below for context. For the purposes of this work, the 16 search bins have been grouped into 3 categories for simplicity and the group definitions (from now *Signal Regions* or just *SR*) given in Table 6.1.

Requirement	HighMET	HighNJet	LowMET
N_γ	0	0	0
N_e	0	0	0
N_μ	0	0	0
$N_{\text{jet}}(p_T^{\text{jet}} > 25 \text{ GeV})$	2	{3,4}	2
N_{bjet}	< 2	< 2	< 2
$p_T(j_0)$	> 80 GeV	> 80 GeV	> 80 GeV
$p_T(j_1)$	> 50 GeV	> 50 GeV	> 50 GeV
$\eta(j_0) \cdot \eta(j_1)$	< 0.0	< 0.0	< 0.0
$\text{fJVT}(j_0)$	< 0.5	< 0.5	< 0.2
$\text{fJVT}(j_1)$	< 0.5	< 0.5	< 0.2
$\Delta\eta_{jj}$	> 3.8	> 3.8	> 3.8
$\Delta\phi_{jj}$	< 2.0	< 2.0	< 2.0
m_{jj}	> 800 GeV	> 1.5 TeV	> 1.5 TeV
$\cancel{E}_T$	> 200 GeV	> 200 GeV	$\in [160, 200] \text{ GeV}$
$\cancel{E}_T^{\text{soft}}$	< 20 GeV	< 20 GeV	< 20 GeV
$C(j_i)$	N/A	< 0.6	N/A
$m^{\text{rel}}(j_i)$	N/A	< 0.05	N/A

Table 6.1.: Invisible Higgs decay search signal region group definitions based on [7]. The term (j_i) indicates which jet is used as a reference, with j_0 and j_1 identified as leading and subleading jets respectively, and j_i refers to jet of i^{th} order. The $C(j_i)$ is the centrality of the jet given by Eq. (6.3). The $m^{\text{rel}}(j_i)$ is defined in Eq. (6.4). Both only applicable for the 3^{rd} and 4^{th} jets in the hadronic system.

6. Development Context: Invisible Higgs Decay searches in VBF topologies

The majority of the backgrounds in invisible Higgs decay searches originate from the vector boson decays. That is, through $Z \rightarrow \nu\nu(+\text{jets})$ and $W \rightarrow \nu l(+\text{jets})$, where the lepton l is lost in reconstruction. In the Run 2 analysis, these contributions, are divided into strong (or QCD) and electroweak (or EW) components based on the α_{EW} order of their process diagrams. The QCD components are associated with α_{EW}^2 diagrams (examples shown Figures 6.3(b) and 6.3(d)), while the EW components are based on α_{EW}^4 processes (examples shown Figures 6.3(c) and 6.3(e)). Due to high theoretical uncertainties of Monte Carlo modelling of these decays, in SR their contributions are derived using a data-driven transfer factor techniques. For each vector boson a dedicated control regions, CRs for short, are established by inverting specific SR requirements listed in Table 6.1, mainly the lepton number requirements. The $W \rightarrow l + \nu(+\text{jets})$ decays' MC SR prediction is normalised by a normalisation factor derived in W_{lv} CR's. For $Z \rightarrow \nu\nu$ a similar approach is not feasible due to low statistics of $Z \rightarrow ll$ in various SRs. Hence, the W_{lv} CR predictions with an additional double-ratio factor are used. The former is justified through $W+\text{jets}$ and $Z+\text{jets}$ processes similarities in the topology⁴ while the latter address the differences arising from distinctions in mass, spin and flavour structures. For the Run 2 search a dedicated Next-to-Leading (NLO) QCD and NLO electroweak calculations of corresponding process cross-section ratios [189] was used for this purpose.

The multijet background poses its own set of challenges. While in general a multijet event is expected to have a well-balanced hadronic system, some $\cancel{E}_T$ can be introduced through b - and c -hadron decays to neutrinos. Additionally, $\cancel{E}_T$ may also arise from experimental detector effects, e.g., fluctuations in jet response or their misclassification between hard scatter and pile-up, or even from highly energetic jets punching through the detector (c.f. Section 5.5 N_{segments} based correction). The situation is further complicated by the presence of the high pile-up jet activity. It is possible to form a dijet system where both jets stem from different scattering processes due failure of PU tagging. As a result such a dijet system, comprised from two uncorrelated hadronic systems, could have a small $\Delta\phi_{jj}$ separation between the two leading jets. While each of the hadronic systems might have additional reconstructed jets balancing it out⁵, in the situations where such jets are lost, either due to reconstruction or misidentification, the dijet system would also contain artificially large $\cancel{E}_T$. Therefore, could enter the SRs. This is further exacerbated by the fact that in the VBF topology, the leading jets are typically found in the forward regions of the detector where the PU tagging is less efficient.

The region definitions shown in Table 6.1 had been developed to suppress the multijet background through the $\Delta\phi_{jj}$ and $\cancel{E}_T$ restrictions due to the high multijet production cross-section⁶. However, the suppression isn't 100% nor is able to fully reject events with combinatorial dijet systems. Furthermore, due to the high suppression factor⁷ such contributions to the SR cannot be inferred from pure MC simulations. Hence, since the start of Run 1

⁴Identical QCD couplings for the hadronic part of the process.

⁵Hence, failing SR requirements

⁶ $\sigma_{MJ} \sim 100 \text{ mb}$ at $\sqrt{s} = 13 \text{ TeV}$.

⁷Using typical Pythia simulation multijet events, the suppression factor is $\sim \mathcal{O}(10^8)$.

6.2. Major Backgrounds, their Predictions, and Region Definitions

era the multijet background has been estimated through different data-based techniques[3, 7, 190]. The latest invisible Higgs decay search in VBF channel relied on two such methods, the *Rebalance and Smear*, or R+S for short, (used previously in [191, 192]) and *pile-up-CR method*, or PU-CR for short. The R+S method initially constructs a momentum balance exhibiting multijet sample from either simulated event or single jet triggered data. The detector response and event reconstruction is then emulated multiple times using this sample as input resulting in some of these emulated events entering the SR. The R+S method is run using both types of inputs (and consequently making different assumptions on jet classification and methodology), the resulting prediction is then normalised to single jet triggered data in multijet enriched CRs, and the normalisation factor is transferred to the SR prediction. The PU-CR is an independent method from R+S, specifically developed for the full Run 2 search [7]. The method relies on estimating the multijet background through extrapolation of multijet background prediction in pile-up enriched multijet control region. The control region for PU-CR is formed by inverting the fJVT requirement of the SR definitions of the leading jet (i.e. requiring it to be PU) and making no cuts on the subleading jet's fJVT. The transfer factor is evaluated in lower E_T regions and is binned in m_{jj} and $\Delta\phi_{jj}$. The factor is then applied to the difference between data and all other non-multijet backgrounds in the pile-up enriched CR to estimate the multijet background in the SR. Both methods were found to be in agreement with each other (within their respective uncertainties) for the multijet background prediction in the inclusive signal region. For the final prediction used in the analysis, the more precise of the two or a combination of both has been used for each individual signal search bin.

The signal yield is extracted from the observed event counts through a simultaneous maximum-likelihood fit in both signal and control regions. The likelihood is defined through the product of Poissonian observations of specific number of events occurring in a given region. The full expression is given by

$$L(\mu, \vec{\beta}_V, \{\vec{n}_X\}, \vec{\theta}) = L_{SR} \cdot L_{PU-CR} \cdot L_{V+jets-CR} \cdot L_{fake-CR} \cdot L_{NP} \quad (6.5)$$

where μ is the signal strength, $\vec{\beta}_V$ are the V+jets scaling parameters, $\vec{n}_X$ is a set of different free fit parameters for a different context X , and $\vec{\theta}$ are the nuisance parameters. The full likelihood is made of individual likelihoods for the signal region, pileup-enriched CR, V+jets CR, fake lepton CR⁸, and a nuisance parameter constraining likelihood. For the scope of this thesis only the first two are of relevance. The signal region likelihood is defined as

$$L_{SR} = \prod_i \text{Poisson}(N_i^{SR} | \beta_i \cdot B_{Z,i}^{SR} + \beta_i \cdot B_{W,i}^{SR} + B_{MJ,i}^{SR} + B_{other}^{SR} + \mu \cdot S_i^{SR}) \quad (6.6)$$

where i represent the individual signal bin⁹, N_i^{SR} - observed number of events in the SR, $B_{Z,i}^{SR}$ and $B_{W,i}^{SR}$ - corresponding V+jets predictions in the SR, B_{other}^{SR} - SR contribution from non-V+jets and non-MJ backgrounds, S_i^{SR} - simulated yield for invisible Higgs boson decay with

⁸Not discussed in this work.

⁹One of the original sixteen as defined in [7]

6. Development Context: Invisible Higgs Decay searches in VBF topologies

a 100% branching fraction to invisible, and $B_{MJ,i}^{SR}$ is the multijet background prediction based on R+S and PU-CR methods. The multijet background prediction is evaluated differently based of which of the 16 signal bins are considered:

$$B_{MJ,i}^{SR} = \begin{cases} n_{PU-MJ,i} \cdot R_{MJ,i} & \text{for } i \in [1, 5] \\ n_{PU-MJ,i} \cdot R_{MJ,i} \cdot f_{R+S,i} & \text{for } i \in [6, 10] \\ B_{MJ-R+S,i}^{SR} & \text{for } i \in [11, 13] \\ n_{PU-MJ,i} \cdot R_{MJ,i} & \text{for } i \in [14, 16] \end{cases} \quad (6.7)$$

where

$$\begin{aligned} i \in [1, 5] & : N_{\text{jet}}^{25} = 2, \quad \Delta\phi_{jj} \in [0, 1), \quad m_{jj} > 0.8 \text{ TeV}, \quad E_T > 200 \text{ GeV} \\ i \in [6, 10] & : N_{\text{jet}}^{25} = 2, \quad \Delta\phi_{jj} \in [1, 2), \quad m_{jj} > 0.8 \text{ TeV}, \quad E_T > 200 \text{ GeV} \\ i \in [11, 13] & : N_{\text{jet}}^{25} \in [3, 4], \quad \Delta\phi_{jj} \in [0, 2), \quad m_{jj} > 1.5 \text{ TeV}, \quad E_T > 200 \text{ GeV} \\ i \in [14, 16] & : N_{\text{jet}}^{25} = 2, \quad \Delta\phi_{jj} \in [0, 2), \quad m_{jj} > 1.5 \text{ TeV}, \quad E_T \in [160, 200) \text{ GeV} \end{aligned}$$

and N_{jet}^{25} represents the number of reconstructed jets with $p_T > 25 \text{ GeV}$, R_{MJ} is the transfer factor for the PU-CR multijet prediction, $B_{MJ-R+S,i}^{SR}$ is the multijet prediction from R+S method. The $n_{PU-MJ,i}$ is the free parameter restrained in the pileup enriched multijet region through

$$L_{PU-CR} = \prod_i \text{Poisson}(N_i^{PU-CR} | B_{non-MJ,i}^{PU-CR} + n_{PU-MJ,i}) \quad (6.8)$$

where N_i^{PU-CR} is the event yield observed in the pileup enriched control region and $B_{non-MJ,i}^{PU-CR}$ is the contribution from all non-MJ backgrounds to this CR. The bins $i \in [6, 10]$ in Eq. (6.7) are assumed to be merged with their yield being calculated by the PU-CR method and adjusted by the shape function $f_{R+S,i}$ derived from the R+S method in the same bins.

The final fitted value of the signal strength has been found to be $\mu = 0.053 \pm 0.052$ with the multijet background estimation providing one of the largest systematic uncertainties to the fit¹⁰ despite being the 5th largest background[7]. Furthermore, the complicated treatment of the multijet SR contribution estimation through the mixture of two methods has prevented deployment and development of machine learning based approaches in the past. These two facts are the primary motivators for a new method of multijet background estimation.

6.3. Object and Event Selection

For the development and evaluation of the effectiveness of the method described in Section 7, a facsimile of the analysis described in [7] is used. The recreation is based on a full Run 2 ATLAS data set collected between 2015 and 2018 at $\sqrt{s}$ of 13 TeV with $\mathcal{L}_{\text{int}} = 139 \text{ fb}^{-1} \pm 0.83\%$

¹⁰Contribution of 0.021 to the 68% confidence level of the fitted signal strength μ . For more details see Table 8 of [7].

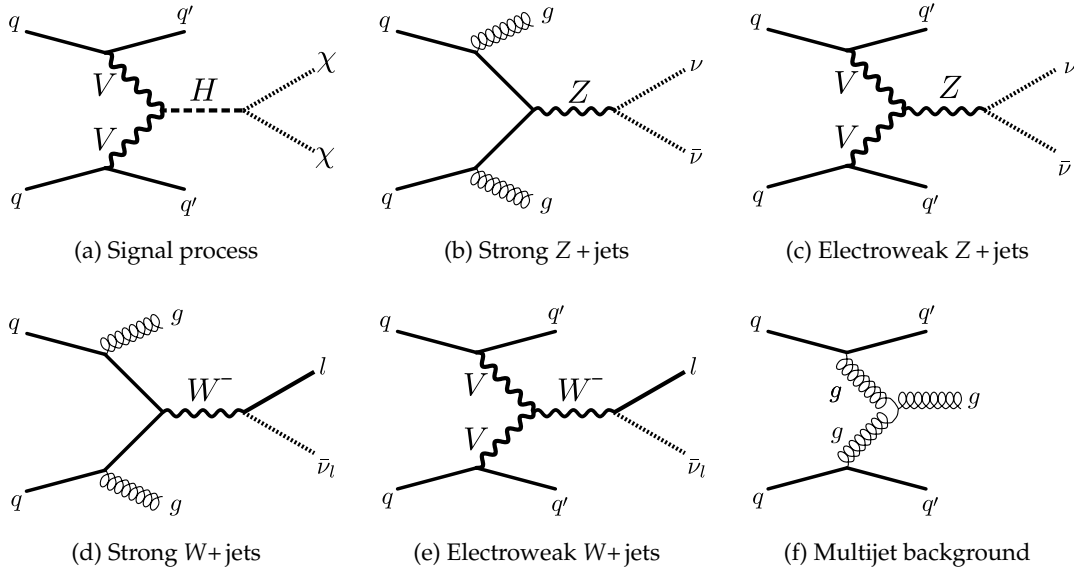


Figure 6.3.: Representative Feynman diagrams for the invisible Higgs decay (signal) and the main five backgrounds: **(a)** Invisible Higgs decay to dark sector under the assumption $m_H \geq 2m_\chi$, **(b)** Strong Z + jets background produced as $\mathcal{O}(\alpha_S^2)$, **(c)** Electroweak Z + jets background produced as $\mathcal{O}(\alpha_S^4)$, **(d)** Strong W + jets background produced as $\mathcal{O}(\alpha_S^2)$, **(e)** Electroweak W + jets background produced as $\mathcal{O}(\alpha_S^4)$, **(f)** General Multijet background. W-based decays are shown for W^- though the same holds for W^+ . For simplicity, no distinction between different quark flavours is shown.

[193]. Additionally, partial Run 3 dataset covering 2022 ($\mathcal{L}_{\text{int}} = 26.1 \text{ fb}^{-1} \pm 2.19\%$ [194]) and 2023 ($\mathcal{L}_{\text{int}} = 25.59 \text{ fb}^{-1} \pm 2.04\%$ [195]) data taking periods with $\sqrt{s}$ of 13.6 TeV are used to investigate the method's viability in the next generation of the invisible Higgs decay searches in VBF channel. In all cases, the data had been collected during stable beam conditions.

The recreation uses inclusive jet-triggered data recorded with a set of single-jet triggers. The set is build from triggers with varying jet p_T thresholds, ranging from 15 GeV up to ~ 460 GeV, with lower p_T triggers having significant prescaling factors. Data taken during Run 2, is recorded using both central ($|\eta| < 3.2$) and forward ($|\eta| \in (3.2, 4.5)$) single-jet triggers; Data taken during Run 3 uses only the central triggers. In order to ensure a smoothly falling jet p_T distribution¹¹, each event is weighted according to the highest p_T -threshold trigger that was triggered by the leading jet in the event. Full list of triggers and their 99% efficiency points are given in Tables 6.2 and 6.3. The effects of the unpre-scaling can be seen in Figure 6.4. Since in the reference analysis the signal region candidate events had been collected with unpre-scaled $\cancel{E}_T$ triggers (with the lowest threshold) [196], the decision on

¹¹Expected behaviour if data was recorded with unpre-scaled triggers.

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whether a given event would have passed such a trigger is also stored. The full list of $\cancel{E}_T$ triggers used can be found in Table 6.4. Additionally, decisions for the unprescaled single and unprescaled dilepton triggers [197, 198] that would be used for W and Z control regions are recorded but not used in the recreation. The triggers are listed in Tables 6.5 and 6.6 and Tables 6.7 and 6.8 respectively.

Trigger Name	2016		2017		2018	
	$p_{T,99\%}^{\text{cnt}}$	$p_{T,99\%}^{\text{fwd}}$	$p_{T,99\%}^{\text{cnt}}$	$p_{T,99\%}^{\text{fwd}}$	$p_{T,99\%}^{\text{cnt}}$	$p_{T,99\%}^{\text{fwd}}$
HLT_j25	42.5	47	37.5	44	38.5	45
HLT_j35	56.5	60	57.5	57	54.5	56
HLT_j45	67.5	84	66.5	95	67.5	95
HLT_j60	82.5	93	81.5	104	81.5	104
HLT_j85	110.5	123	106.5	112	106.5	112
HLT_j110	141.5	153	133.0	143	133.0	143
HLT_j175	217.5	222	205.5	222	205.5	219
HLT_j260	317.5	322	287.5	328	297.5	320
HLT_j360	430.5	N/A	409.5	N/A	409.5	N/A
HLT_j380	452.0	N/A	N/A	N/A	N/A	N/A
HLT_j420	N/A	N/A	472.5	N/A	472.5	N/A

Table 6.2.: Single jet triggers with their 99% efficiency turn-on point expressed in offline jet p_T (in GeV) for data taking periods covering 2015 to 2018. Triggers are based on Run 2 trigger configuration [124] and both central (denoted by ^{cnt}) and forward (denoted by ^{fwd}) triggers are shown.

Lepton and photon candidate reconstruction follows Sections 4.4 and 4.5 and their selection criteria are given in Tables 6.9 and 6.10. An additional requirement of $p_T > 30$ GeV is placed on leading lepton in the event. Depending on whether the lepton enters either of the vector boson control regions, their identification is altered appropriately to *tight* (for W_{CR}) or *loose* (for Z_{CR}).

Jets are reconstructed as described in Section 4.7 and have their energy scale calibrated using techniques described in Section 5. The resulting jets are required to have $p_T > 20$ GeV and $|\eta| < 4.5$. If the jet is located within the central region of the detector (i.e. $|\eta| < 2.5$) and its $p_T \in [20, 60)$ GeV, the jet is also required to pass the JVT selection. All jets used in this work are b-tag using GN2 class taggers (c.f. Section 4.7.3 and [163]).

The event is only considered in the analysis, if it has a reconstructed primary vertex with at least two associated tracks with $p_T^{\text{trk}} > 500$ MeV. If the event contains any *signal* photons, it is vetoed to ensure orthogonality with other VBF channel searches (e.g., [9]). Additionally, a jet cleaning procedure, based on calorimeter signal quality, shape of energy depositions within the calorimetry systems, and track properties, is carried out to remove jets from

6.3. Object and Event Selection

Trigger Name	2022	2023
	$p_{T,99\%}^{\text{cnt}}$	$p_{T,99\%}^{\text{cnt}}$
HLT_j25_pf_ftf_L1RD0_FILLED	41	41
HLT_j35_pf_ftf_L1RD0_FILLED	55	56
HLT_j45_pf_ftf_preselj20_L1RD0_FILLED	64	65
HLT_j85_pf_ftf_preselj50_L1J20	95	98
HLT_j110_pf_ftf_preselj80_L1J30	152	155
HLT_j175_pf_ftf_preselj140_L1J50	192	195
HLT_j260_pf_ftf_preselj200_L1J75	280	285
HLT_j360_pf_ftf_preselj225_L1J100	388	391
HLT_j420_pf_ftf_preselj225_L1J100	455	455

Table 6.3.: Single jet triggers with their 99% efficiency turn-on point expressed in offline jet p_T (in GeV) for data taking periods covering 2022 and 2023. Triggers are based on Run 3 trigger configuration [125] and only central (denoted by $^{\text{cnt}}$) triggers are shown.

Period	E_T trigger
2015	HLT_xe70_mht
2016 (runs ≤ 302872)*	HLT_xe90_mht_L1XE50
2016 (runs > 302872)*	HLT_xe110_mht_L1XE50
2017	HLT_xe110_pufit_L1XE55
2018	HLT_xe110_xe70_L1XE50
2015 to 2018	HLT_noalg_J400
2022	HLT_xe65_cell_xe90_pfopufit_L1XE50
2023	HLT_xe65_cell_xe90_pfopufit_L1XE50

Table 6.4.: E_T triggers used for data taking periods from 2015 to 2018, for 2022 and 2023. Trigger used between 2015 and 2018 are based on Run 2 trigger system configuration [124] while from 2022 triggers are based on Run 3 trigger system configuration [125]. * differentiates between data taking period before (runs ≤ 302872) and after (runs > 302872) increase of HLT threshold in 2016.

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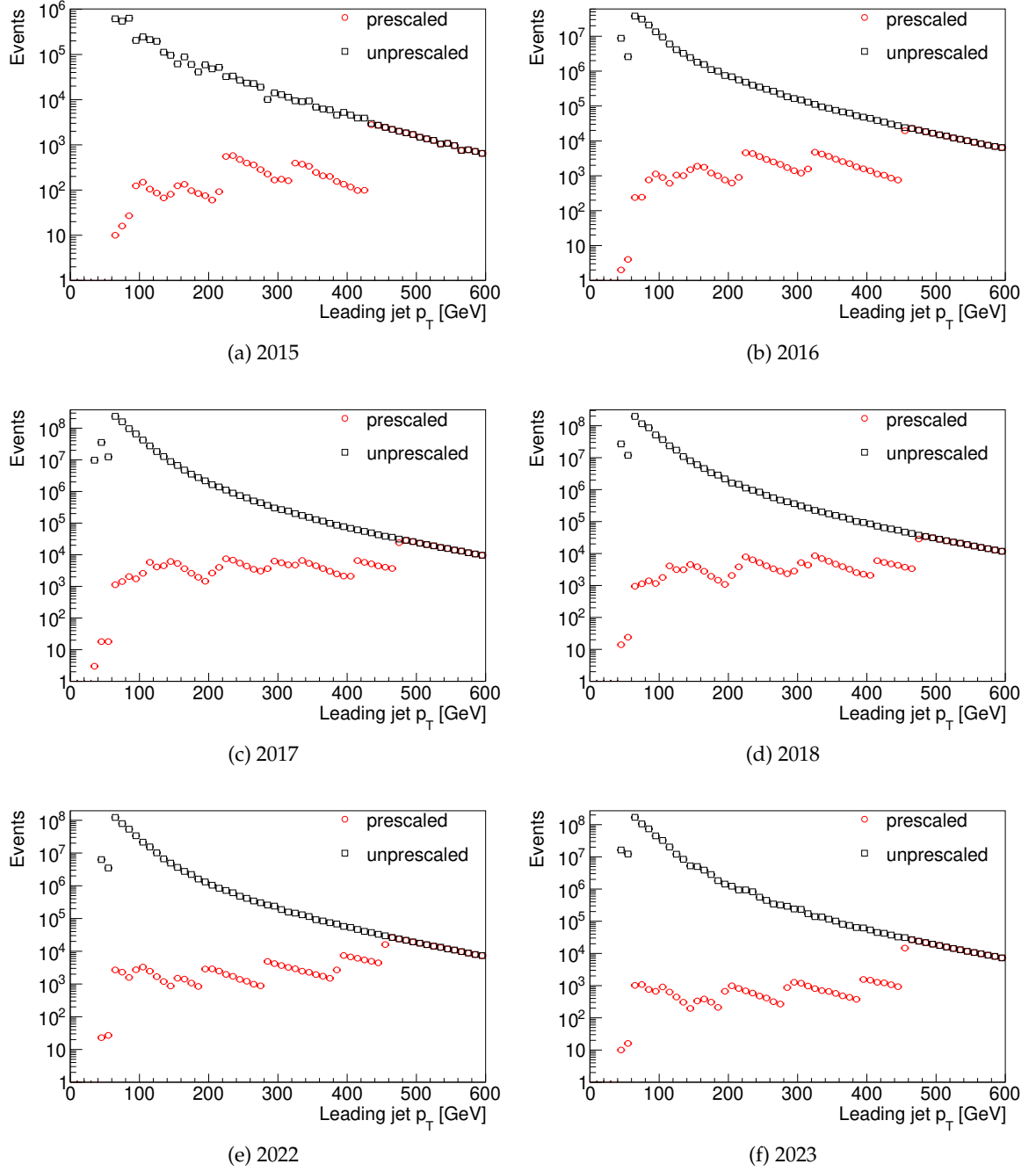


Figure 6.4.: Leading jet p_T spectrum comparison between prescaled and unprescaled single jet trigger events from individual data taking years. The prescale factor for each event is taken from the highest triggered p_T^{online} -based single jet trigger that is found to be efficient given the leading jet p_T^{offline} . The prescaled p_T spectrum is shown in black, while unprescaled one is shown in red. The unprescaling performance is shown for individual data taking years.

6.3. Object and Event Selection

Period	Single electron trigger name
2015 (all runs)	HLT_e24_lhmedium_L1EM20VH HLT_e60_lhmedium HLT_e120_lhloose
2016 (runs ≤ 302872)*	HLT_e24_lhtight_nod0_ivarloose
2016 (runs > 302872)*	HLT_e26_lhtight_nod0_ivarloose
2016 (all runs)	HLT_e60_lhmedium_nod0 HLT_e140_lhloose_nod0 HLT_e300_etcut0
2017 (all runs)	HLT_e26_lhtight_nod0_ivarloose HLT_e60_lhmedium_nod0 HLT_e140_lhloose_nod0 HLT_e300_etcut
2018 (all runs)	HLT_e26_lhtight_nod0_ivarloose HLT_e60_lhmedium_nod0 HLT_e140_lhloose_nod0 HLT_e300_etcut
2022 (all runs)	HLT_e26_lhtight_ivarloose_L1EM22VHI HLT_e60_lhmedium_L1EM22VHI HLT_e140_lhloose_L1EM22VHI HLT_e300_etcut_L1EM22VHI
2023 (runs ≤ 450894) ⁺	HLT_e26_lhtight_ivarloose_L1EM22VHI HLT_e60_lhmedium_L1EM22VHI HLT_e140_lhloose_L1EM22VHI HLT_e300_etcut_L1EM22VHI
2023 (runs > 450894) ⁺	HLT_e26_lhtight_ivarloose_L1eEM26M HLT_e60_lhmedium_L1eEM26M HLT_e140_lhloose_L1eEM26M HLT_e300_etcut_L1eEM26M

Table 6.5.: Single lepton triggers used for SR and lepton CR definition. Triggers used between 2015 and 2018 are based on Run 2 trigger system configuration [124] while from 2022 onwards triggers are based on Run 3 trigger system configuration[125]. Periods denoted by * differentiate between data taking before (runs ≤ 302872) and after (runs > 302872) increase of HLT threshold in 2016; Periods denoted by ⁺ differentiates between data taking with smaller than 400 bunches per fill (runs ≤ 450894) and larger than 400 bunches per fill (runs > 450894) conditions.

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Period	Single muon trigger name
2015	HLT_mu20_loose_L1MU15 HLT_mu50
2016	HLT_mu26_ivarmedium HLT_mu50
2017	HLT_mu26_ivarmedium HLT_mu50
2018	HLT_mu26_ivarmedium HLT_mu50
2022	HLT_mu24_ivarmedium_L1MU14FCH HLT_mu50_L1MU14FCH
2023	HLT_mu24_ivarmedium_L1MU14FCH HLT_mu50_L1MU14FCH

Table 6.6.: Single muon triggers used for SR and lepton CR definition. Triggers used between 2015 and 2018 are based on Run 2 trigger system configuration [124] while from 2022 onwards triggers are based on Run 3 trigger system configuration[125].

non-collision backgrounds¹²[199, 200]. If any selected jet fails the *tight* cleaning working point conditions, the event is also vetoed. All reconstructed objects in the event are required to pass the overlap procedure described in Table 4.1. Finally, missing transverse energy, $\cancel{E}_T$, is calculated according to Eq. (4.20) using all jets with $p_T > 20$ GeV within $|\eta| < 4.5$, except central jets tagged as pile-up by JVT. An alternative version of $\cancel{E}_T$ is calculated without the usage of leptons, known as $\cancel{E}_T^{\text{no-lep}}$. It is used to model the $\cancel{E}_T$ behaviour in W_{CR} and Z_{CR} regions under the assumption that the visible leptons are lost, hence could enter the SR. In analysis regions where there are no leptons, both of these forms of the missing transverse momentum are identical.

Various background processes needed for the analysis recreation are simulated with various MC event generators and summarised in Tables 6.11 and 6.12 with particle interactions with the detector simulated with GEANT4 [201]. As discussed in Section 6.2, the $V + \text{jets}$, as well as the minor $VV + \text{jets}$ background, are generated in separate QCD and EW components based on their $\mathcal{O}(\alpha_{EW})$. The hard scatter process interaction with the ATLAS detector is then simulated and digitised as discussed in Section 3.2.6. The effects of pileup are simulated through MC overlay technique, where digitised hard scatter event is overlaid with pre-digitised inelastic minimum bias pp events [176]. The digitised detector readouts (RDO) are then used to reconstruct various analysis object candidates which have to satisfy

¹²E.g., comic radiation, beam-halo proton interactions, or noisy calorimeter cells.

6.3. Object and Event Selection

Period	Dielectron trigger name
2015	HLT_2e12_lhvloose_L12EM10VH HLT_e17_lhloose_2e9_lhloose
2016(runs $\leq$ 302872)*	HLT_e17_lhloose_nod0_2e9_lhloose_nod0 HLT_2e15_lhvloose_nod0_L12EM13VH
2016(runs $>$ 302872)*	HLT_2e17_lhvloose_nod0 HLT_e17_lhloose_nod0_2e9_lhloose_nod0 HLT_e17_lhloose_nod0_2e10_lhloose_nod0_L1EM15VH_3EM8VH HLT_e20_lhmedium_nod0_2g10_loose HLT_e20_lhmedium_nod0_2g10_loose_L1EM15VH_3EM8VH
2017	HLT_2e17_lhvloose_nod0_L12EM15VHI HLT_2e24_lhvloose_nod0
2018	HLT_2e17_lhvloose_nod0_L12EM15VHI HLT_2e24_lhvloose_nod0
2022	HLT_2e17_lhvloose_L12EM15VHI HLT_2e24_lhvloose_L12EM20VH
2023 (runs $\leq$ 450894) [†]	HLT_2e17_lhvloose_L12EM15VHI HLT_2e24_lhvloose_L12EM20VH
2023 (runs $>$ 450894) [†]	HLT_2e17_lhvloose_L12eEM18M HLT_2e24_lhvloose_L12eEM24L

Table 6.7.: Dielectron triggers used for SR and lepton CR definition. Triggers used between 2015 and 2018 are based on Run 2 trigger system configuration [124] while from 2022 onwards triggers are based on Run 3 trigger system configuration[125]. Periods denoted by * differentiate between data taking before (runs $\leq$ 302872) and after (runs $>$ 302872) increase of HLT threshold in 2016; Periods denoted by [†] differentiates between data taking with smaller than 400 bunches per fill (runs $\leq$ 450894) and larger than 400 bunches per fill(runs $>$ 450894) conditions.

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Period	Dimuon trigger name
2015	HLT_mu18_mu8noL1 HLT_2mu10
2016	HLT_mu22_mu8noL1 HLT_2mu14
2017	HLT_mu22_mu8noL1 HLT_2mu14
2018	HLT_mu22_mu8noL1 HLT_2mu14
2022	HLT_2mu10_l2mt_L1MU10BOM HLT_2mu14_L12MU8F HLT_mu20_ivarmedium_mu8noL1_L1MU14FCH HLT_mu22_mu8noL1_L1MU14FCH
2023	HLT_2mu10_l2mt_L1MU10BOM HLT_2mu14_L12MU8F HLT_mu20_ivarmedium_mu8noL1_L1MU14FCH HLT_mu22_mu8noL1_L1MU14FCH

Table 6.8.: Dimuon triggers used for SR and lepton CR definition. Triggers used between 2015 and 2018 are based on Run 2 trigger system configuration [124] while from 2022 onwards triggers are based on Run 3 trigger system configuration [125].

the above described selection criteria to be considered *analysis* or *signal* objects.

6.3. Object and Event Selection

Object	ID WP	p_T [GeV]	$ \eta $	Iso	$ z_0 \sin(\theta) $ [mm]	$ d_0 /\sigma(d_0)$
e_c	Loose*	> 4.5	< 2.47	N/A	0.5	N/A
e_a	Tight	> 7.0	< 2.47	Loose [†]	0.5	5
e_W	Tight	> 30.0	< 2.47	Loose [†]	0.5	5
e_Z	Very loose	> 7.0	< 2.47	Loose [†]	0.5	5
μ_c	Very loose	> 4.0	< 2.7	N/A	0.5	N/A
μ_a	Medium	> 7.0	< 2.7	Loose	0.5	3
μ_W	Medium	> 30.0	< 2.7	Loose	0.5	3
μ_Z	Very loose	> 7.0	< 2.7	Loose	0.5	3
γ_c	Loose	> 15.0	< 2.37	N/A	N/A	N/A
γ_a	Tight	> 15.0	< 2.37	FixedCutTight	N/A	N/A

Table 6.9.: Run 2 lepton and photon definitions used in the analysis. Subscripts in the first column indicates the category of the object: $_c$ - candidate, $_a$ - analysis, $_W$ - originating from W , and $_Z$ - originating from Z . "ID WP" reflects the identification working point with * requiring a hit in the insertable B-layer. "Iso" represents the object's isolation criterion with [†] being used up to ($p_T \leq 200$ GeV); above that a specific high p_T isolation *HighPtCaloOnly* criterion is used.

Object	ID WP	p_T [GeV]	$ \eta $	Iso	$ z_0 \sin(\theta) $ [mm]	$ d_0 /\sigma(d_0)$
e_c	Loose*	> 4.5	< 2.47	N/A	0.5	N/A
e_a	Tight	> 7.0	< 2.47	Tight	0.5	5
e_W	Tight	> 30.0	< 2.47	Tight	0.5	5
e_Z	Loose*	> 7.0	< 2.47	Tight	0.5	5
μ_c	Loose	> 5.0	< 2.7	N/A	0.5	N/A
μ_a	Medium	> 7.0	< 2.7	Loose	0.5	3
μ_W	Medium	> 30.0	< 2.7	Loose	0.5	3
μ_Z	Loose	> 7.0	< 2.7	Loose	0.5	3
γ_c	Loose	> 15.0	< 2.37	N/A	N/A	N/A
γ_a	Tight	> 15.0	< 2.37	FixedCutTight	N/A	N/A

Table 6.10.: Run 3 lepton and photon definitions used in the analysis. Subscripts in the first column indicates the category of the object: $_c$ - candidate, $_a$ - analysis, $_W$ - originating from W , and $_Z$ - originating from Z . "ID WP" reflects the identification working point with * requiring a hit in the insertable B-layer. "Iso" represents the object's isolation criterion.

Process	Generator	ME order	PDF	Parton Shower	Tune
V+jets (QCD)	SHERPA 2.2.11	NLO (0,1,2) LO (3,4,5)	NNPDF3.0 _{NNLO}	SHERPA 2.2.11	SHERPA
	SHERPA 2.2.14 [†]	NLO (0,1,2) LO (3,4,5)	NNPDF3.0 _{NNLO}	SHERPA 2.2.14	SHERPA
V+jets (EWK)	SHERPA 2.2.11	LO (2,3)	NNPDF3.0 _{NNLO}	SHERPA 2.2.11	SHERPA
QCD Multijet	PYTHIA 8(v.235) ^{††}	LO	NNPDF2.3 _{LO}	PYTHIA 8(v.235) ^{††} (LO)	A14
VV+jets (QCD ^{**})	SHERPA 2.2.12	NLO (0,1) LO (2,3)	NNPDF3.0 _{NNLO}	SHERPA 2.2.12	SHERPA SHERPA
VV+jets (QCD [*])	SHERPA 2.2.12	LO (0,1)	NNPDF3.0 _{NNLO}	SHERPA 2.2.12	SHERPA
VV+jets (EWK)	SHERPA 2.2.12	LO (0,1)	NNPDF3.0 _{NNLO}	SHERPA 2.2.12	SHERPA
$t\bar{t}$	POWHEG BOX v2	NLO	NNPDF3.0 _{NNLO}	PYTHIA 8(v.230) ^{††} (LO)	A14
Pileup	PYTHIA 8(v.186)	LO	NNPDF2.3 _{LO}	PYTHIA 8(v.186)	A3

Table 6.11.: Summary of generators used for simulating the major and (some) minor backgrounds in Run 2 conditions. The *Matrix Element*, or *ME* for short, refers to the order of the perturbation theory at which the cross-sections of the process are computed. Number in parentheses indicate up to how many additional partons are included under given precision. The [†] indicates generation of $Z \rightarrow \tau\tau$ samples which are based on SHERPA 2.2.14 rather than SHERPA 2.2.11 due to τ polarisation error within the latter version of the samples. The ^{††} implies additional heavy flavour hadron decay modelling using EVTGEN v1.6 [174]. * indicates a specific QCD decay of $VV \rightarrow ll\nu\nu$ which is modelled on LO level, compared to remaining VV QCD decays which are modelled at NLO level and indicated by **. The effect of pile-up is modelled by adding detector signals from simulated inelastic pp events (*Pileup*) to the original hard-scattering event. References in the order of appearance: SHERPA 2.2 [202], PYTHIA 8.2 [170], POWHEG BOX v2 [203–206], PYTHIA 8.1 [207], NNPDF3.0 [208], NNPDF2.3 [173], Tunes A14[172] and A3[175].

Process	Generator	ME order	PDF	Parton Shower	Tune
V+jets (QCD)	SHERPA 2.2.14	NLO (0,1,2) LO (3,4,5)	NNPDF3.0 _{NNLO}	SHERPA 2.2.14	SHERPA
V+jets (EWK)	SHERPA 2.2.14p1	LO (2,3)	NNPDF3.0 _{NNLO}	SHERPA 2.2.14p1	SHERPA
QCD Multijet	PYTHIA 8(v.308) ^{††}	LO	NNPDF2.3 _{LO}	PYTHIA 8(v.308) ^{††} (LO)	A14
VV+jets (QCD ^{**})	SHERPA 2.2.16	NLO (0,1) LO (2,3)	NNPDF3.0 _{NNLO}	SHERPA 2.2.16	SHERPA
VV+jets (QCD [*])	SHERPA 2.2.14	LO (0,1)	NNPDF3.0 _{NNLO}	SHERPA 2.2.14	SHERPA
VV+jets (EWK)	SHERPA 2.2.14	LO (0,1)	NNPDF3.0 _{NNLO}	SHERPA 2.2.14	SHERPA
$t\bar{t}$	POWHEG BOX v2	NLO	NNPDF3.0 _{NNLO}	PYTHIA 8(v.308) ^{††} (LO)	A14
Pileup	PYTHIA 8(v.186)	LO	NNPDF2.3 _{LO}	PYTHIA 8(v.186)	A3

Table 6.12.: Summary of generators used for simulating the major and (some) minor backgrounds in Run 3 conditions. The *Matrix Element*, or *ME* for short, refers to the order of the perturbation theory at which the cross-sections of the process are computed. Number in parentheses indicate up to how many additional partons are included under given precision. The ^{††} implies additional heavy flavour hadron decay modelling using EVTGEN v2.1.1 [174]. * indicates a specific QCD decay of $VV \rightarrow ll\nu\nu$ which is modelled on LO level, compared to remaining VV QCD decays which are modelled at NLO level and indicated by **. The effect of pile-up is modelled by adding detector signals from simulated inelastic pp events (*Pileup*) to the original hard-scattering event. References in the order of appearance: SHERPA 2.2 [202], PYTHIA 8.3 [171], POWHEG BOX v2 [203–206], PYTHIA 8.1 [207], NNPDF3.0 [208], NNPDF2.3 [173], Tunes A14[172] and A3[175].

7. Double Sliced Event Generation

As discussed in Section 6.2, the multijet background poses numerous and complex challenges for invisible Higgs decay searches. Events with dijet system formed by jets coming from two separate primary vertices are one of them. While the signal region is designed to suppress the multijet background with jets from the same vertex, due to its high production cross-section in pp collisions the background is irreducible. If MC generated event with a combinatorial dijet system would pass the filter¹, it would enter the signal regions with unphysically large event weight. Consequently, rendering the background prediction technically infeasible. For an example of such an event, see Table 7.1. While different data-driven methods of multijet background estimation had been used in the past [3, 7, 191, 192, 209] to varying degrees of success, none came without shortcomings. Hence, a new method of multijet background estimation has been developed and is presented in this work.

The Double Sliced Event Generation, or *DSEG* for short, is a novel method for estimating the multijet background in phase spaces sensitive to high pile-up jet activity. The method merges benefits from both Monte Carlo based generators and techniques used in the data-driven approaches. From the generation side, full access to underlying event kinematics (and other information) is available from the start of the generation to the final dijet system formation. Ergo, precise identification of combinatorial dijet system is possible. From the data-driven method side, various technique, e.g., jet smearing, allows precise emulation of jet interactions with the detector without the need for complicated simulations (e.g., GEANT4 [201]) or exorbitant amount of generated event statistics. While the underlying methodology of DSEG is detector and search agnostic in nature, the method has been developed in the context of the invisible Higgs decay search in VBF channel using the ATLAS experiment. Therefore, the following discussion will rely on this context.

7.1. Event generation with DSEG

Similarly to traditional Monte Carlo based background generation, the Double Sliced Event Generation method generates its hard interactions in a sliced generation space while the minimum bias interactions are generated inclusively. PYTHIA v8.312 [171] with NNPDF2.3 LO set of parton distribution functions (PDFs)[173] has been chosen as the event generator of choice for the method's development and implementation. The choice is motivated as follows: Firstly, the commonly used multijet background in ATLAS is generated using

¹See Section 6.2 for explanation how this could happen.

7.1. Event generation with DSEG

Generator Level Interaction					
vertex (by $\hat{p}_T$)	vertex (by $\sum p_T^{trk}$)	p_T^{jet} [GeV]	η_{jet}	ϕ_{jet}	m_{jet} [GeV]
0	1	82.55	1.34	0.16	19.45
		41.60	0.37	-3.07	6.93
		17.66	0.63	-1.98	5.75
		9.81	-0.27	-1.86	4.82
		8.23	-0.36	2.41	4.38
1	2	51.30	-3.15	0.48	9.32
		30.87	1.80	-2.28	6.04
		12.55	-2.03	-2.28	3.36
		8.14	1.17	2.29	1.32
2	0	29.74	2.71	2.63	6.21
		24.39	-1.52	0.17	8.79
		19.23	-1.61	-1.23	6.29
		15.28	1.34	-2.53	5.04
< ... > (jets with $p_T^{\text{jet}} < 15 \text{ GeV}$)					
Generator Level Hadronic Systems					
vertex (by $\hat{p}_T$)	vertex (by $\sum p_T^{trk}$)	E_T [GeV]	$\Delta\eta_{\text{jj}}$	$\Delta\phi_{\text{jj}}$	m_{jj} [GeV]
0	1	26.07	3.05	0.97	133.69
1	2	12.14	2.76	4.95	476.55
2	0	4.76	2.45	4.23	227.24
Reconstruction Level Interaction					
HS ID Cause		p_T^{jet} [GeV]	η_{jet}	ϕ_{jet}	m_{jet} [GeV]
$p_T > 60 \text{ GeV}$		84.70	1.34	0.16	19.96
$p_T > 60 \text{ GeV}$		66.01	-3.21	0.46	15.02
FJVT (= 0.34) dependent		29.98	2.71	2.63	6.26
$\max(\sum p_T^{trk})$ vertex		29.25	-1.52	0.17	10.54
pile-up tagging failure		26.99	1.80	-2.28	5.28
Reconstruction Level Hadronic Systems					
		E_T [GeV]	$\Delta\eta_{\text{jj}}$	$\Delta\phi_{\text{jj}}$	m_{jj} [GeV]
		134.64	4.55	0.30	720.35
Generated event weight $w = 1.9832994 \times 10^8$					

Table 7.1.: Example of combinatorial multijet background event. Event generated with Double Sliced Event Generation mimicking ATLAS multijet background generation strategy (see *Basic Mode* in Section 8.2). Event generated from inclusive Run 2 pile-up profile with $\sqrt{s} = 13 \text{ TeV}$. No normalisation to N_{gen} (as per Eq. (7.35)) or scaling by $\mathcal{L}_{\text{int}}$ is applied.

7. Double Sliced Event Generation

the Pythia event generator. PYTHIA also provides dedicated tunes² based on collected ATLAS data that aim to encapsulate physics aspects that cannot be fully derived from first principle. Therefore, this choice provides a direct venue for comparison between DSEG and the ATLAS MC samples without the need to account for possible systematic differences between generators. Secondly, PYTHIA provides the option to specify the minimum invariant p_T (denoted as $\hat{p}_T$) range for interaction generation. This permits the generation space to be split in a manner that enhances generation of events of interest³. The full breakdown of the "sliced" generation domain is given in Table 7.2. Each slice is handled by a unique instance of a PYTHIA generator, each of which is set to use the ATLAS A14 tune [172]. Each generator is initialised with the same RNG⁴ seed except the "Inclusive" whose RNG seed is offset by a predefined value.

Slice	$\hat{p}_T$ [GeV]	$\sigma @ \sqrt{s} = 13.0 \text{ TeV}$ [mb]	$\sigma @ \sqrt{s} = 13.6 \text{ TeV}$ [mb]
Inclusive	$[0, \infty)$	100.3	101.0
Slice 1	$[5, 10)$	79.55	83.61
Slice 2	$[10, 20)$	8.925	9.425
Slice 3	$[20, 40)$	8.051×10^{-1}	8.539×10^{-1}
Slice 4	$[40, 80)$	6.002×10^{-2}	6.425×10^{-2}
Slice 5	$[80, 160)$	3.681×10^{-3}	3.991×10^{-3}
Slice 6	$[160, 320)$	1.828×10^{-4}	2.019×10^{-4}
Slice 7	$[320, \infty)$	7.147×10^{-6}	8.007×10^{-6}

Table 7.2.: Double Sliced Event Generation generation domain's slice definitions, their corresponding $\hat{p}_T$ ranges, and cross-sections. Interactions from numbered slices are generated with `HardQCD : all` option, whereas "Inclusive" slice - with `SoftQCD : all` option. Note: there is no "Slice 0" with $\hat{p}_T \in [0, 5]$ GeV as interaction generated in this slice would not be able to produce a jet with p_T passing the minimum jet clustering requirements.

Differently to traditional Monte Carlo based generated background, generation of interactions in Double Sliced Event Generation method follows a particular order. To begin with, a total number of interactions in the event, N_{vtx} , is randomly chosen from mean number of interactions per bunch crossing distribution (also referred to as *interaction profile*). This can either be a Poisson distribution with its mean set to $\langle \mu \rangle$ (i.e. averaged value of Eq. (3.4)) or the actual interaction per bunch crossing distribution observed by ATLAS (see Figure 3.3). The latter is used for the following discussion. Following this, N_{vtx} number of minimum bias interactions are independently generated from the "Inclusive" slice. The generated interactions are sorted by their $\hat{p}_T$ and the two hardest interactions are then removed. The

²Set of internal Pythia parameter variations.

³Similar splitting is also done for ATLAS MC multijet samples, See Table 5.1.

⁴Random Number Generation

7.1. Event generation with DSEG

remaining collection of $N_{vtx} - 2$ interactions forms one of the event basis in DSEG known as, *Soft Pileup*, or *SoftPU* for short. Following this, two independent hard interactions are generated from the sliced generation domain. One of the interactions is randomly generated between slice 3 and the final slice, while the other - from a slice 1 and the final slice. The interaction with the greater $\hat{p}_T$ is assumed to be *Hard Scatter* interaction (or *HS* for short) while the other is given the *Leading Pileup* interaction (or *LPU* for short) designation. The allowed combinations are visualised in Figure 7.1(b). The combination of *HS*, *LPU*, and *SoftPU* interactions forms a full DSEG event candidate - the *Base Event*.

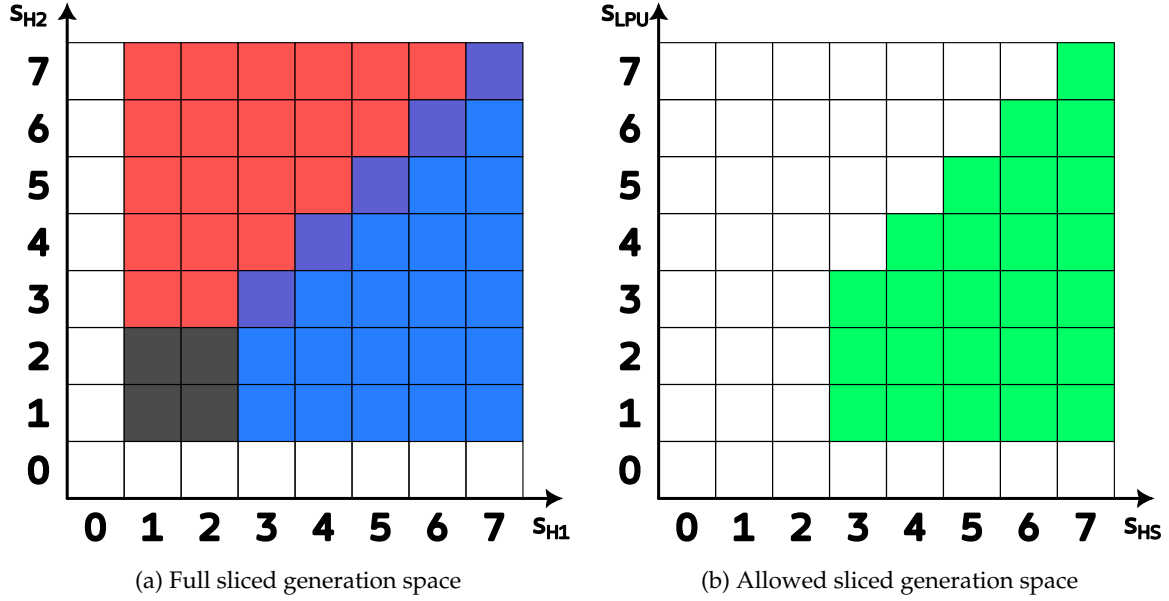


Figure 7.1.: Visualisations of sliced generation space(s) described in Table 7.2. Note, numerical binning rather than $\hat{p}_T$ ranges are shown on all axes. Slice 0 is included for completion but is never sampled. Inclusive slice is assumed to cover the full space. (a) shows the full sliced sampling space where the two hard scatter interactions have been sampled independently. Blue represents the cases where s_{H1} is identified as s_{HS} ; Red - where s_{H2} is identified as s_{HS} ; Purple - shared overlap between Blue and Red; Gray - part of domain which will never be sampled as either s_{H1} or s_{H2} has to be greater than 3. (b) shows all allowed Hard Scatter and Leading Pileup interaction slice combinations which are indicated by shaded area.

The motivation for the differing slice random choice ranges is the following: as described in Section 4.7.3, only jets with $p_T > 20$ GeV are considered in the analysis. The softest slice that could generate such jets is slice 3 (c.f. Table 7.2). Hence, the underlying assumption is that the softest *HS* interaction can only stem from slice 3 and the first of hard interactions is generated as a prototype of *HS*. Furthermore, DSEG assumes that *LPU* interaction is softer

7. Double Sliced Event Generation

than HS , hence it should be generated anywhere from slice 1 up to the slice the HS interaction has been generated from. However, since both interactions are generated independently of one another, the second hard interaction is generated in the full sliced space as a prototype of LPU . In the situation where the second interaction stems from a higher slice than the first, the interaction from the second slice becomes the true HS and the HS prototype is assigned as LPU ; Otherwise, each interaction takes on their prototype designations.

Since the greatest contribution to the signal regions is expected to come from interactions with moderate p_T jets, the generation phase space is correspondingly sliced more granularly towards lower $\hat{p}_T$. Additionally, multiple "final" slice options have been considered to ensure that events coming from jets from high p_T tail are also modelled appropriately. Eventually, 7 slice configuration presented in Table 7.2 was found to be optimal.

Similarly to the traditional approach, both HS and LPU interactions contribute a probabilistic factor to the final event weight based on the cross-section of their corresponding slice. One would naïvely expect the generated event weight, w to be directly proportional to the ratio of the hard slice production cross-section versus the total production cross-section of the process. That is

$$w \propto \frac{\sigma_k}{\sigma_{tot}} \quad (7.1)$$

where σ_k is the cross-section of a slice k and σ_{tot} is the total multijet production cross-section. However, this does not account for the fact that all three HS , LPU , and $SoftPU$ interactions stem from the same physics process - multijet production. Primarily Eq. (7.1) does not reflect the probability of a minimum bias interaction which is replaced by either of the hard interactions would originally come from the $\hat{p}_T$ range of the hard interaction slice. The probability for one of these interactions to originate from slice k 's $\hat{p}_T$ range is given by the difference between generating the interaction from slice k or lower and generating from slice $k - 1$ or lower. Since there is no difference which of the soft interactions is replaced⁵, such abjunctious⁶ probability is given by

$$p_{\neg}(k, N) := \left[\sum_{i=0}^k \frac{\sigma_i}{\sigma_{tot}} \right]^N - \left[\sum_{i=0}^{k-1} \frac{\sigma_i}{\sigma_{tot}} \right]^N \quad (7.2)$$

where N is the total number of interactions under consideration. Therefore, the final event weight w is proportional to

$$w \propto \mathcal{L} \cdot \sigma_{tot} \cdot \frac{n_{sLPU}^2 - (n_{sLPU} - n_{sHS})^2}{N_{gen}} \cdot w_{\neg}^{HS} \cdot w_{\neg}^{LPU} \quad (7.3)$$

where $\mathcal{L}$ is the luminosity, N_{gen} is the total number of events generated⁷, n_{sHS} and n_{sLPU} number of slices for HS and LPU interaction generation respectively, and $w_{\neg}^{HS}$ and $w_{\neg}^{LPU}$ are

⁵Even though DSEG replaces the hardest by $\hat{p}_T$ standard, the probability of this interaction being the first one generated is as high as it being the last one generated.

⁶Material nonimplication, or abjunction, is negation of the material implication logic operation. That is given proposition P and Q , material nonimplication from P to Q is true only if P is true and Q is false.

⁷To be more precise, pairs of HS and LPU , i.e. "seed events", generated.

7.2. Jet clustering and jet property definitions

known as their corresponding abjunctious weights, given by

$$w_{\cancel{\nearrow}}^{\text{HS}} \equiv p_{\cancel{\nearrow}}(s_{\text{HS}}, N_{\text{vtx}}) \quad \text{and} \quad w_{\cancel{\nearrow}}^{\text{LPU}} \equiv p_{\cancel{\nearrow}}(s_{\text{LPU}}, N_{\text{vtx}} - 1) \quad (7.4)$$

where N_{vtx} is the total number of vertices⁸, s_{HS} and s_{LPU} are the slices from which *HS* and *LPU* have been generated. DSEG assumes that the *HS* interaction is generated prior to the *LPU* interaction, therefore $w_{\cancel{\nearrow}}^{\text{LPU}}$ is calculated with $N_{\text{vtx}} - 1$ rather than N_{vtx} .

The fraction part of Eq. (7.3) arises as a consequence of how the *HS* and *LPU* are generated and identified. As discussed above, s_{HS} is allowed to be randomly chosen from $[3, 7]$ while s_{LPU} is randomly chosen from $[1, 7]$. The event is considered valid as long as $s_{\text{HS}} \geq s_{\text{LPU}}$. If the inequality is implemented into sampling directly, a complicated probabilistic event distribution calculation becomes necessary for correct event weight normalisation. For example, when $s_{\text{HS}} = 4$, 25% of all events originating from this hard scatter slice should be sampled from $s_{\text{LPU}} = 3$, but only 20% would be sampled from the same leading pileup slice when $s_{\text{HS}} = 5$. However, since both hard interactions are generated independently and differentiation between *HS* and *LPU* only becomes important during weight calculation, a more simplistic approach can be deployed to estimate the total fractional fill of each (HS, LPU) combination. Consider the total sampling space (shown in Figure 7.1(a)) in which all sampled events are distributed equally. The space can be deconstructed into four regions: one where the first sampled interaction, s_{H1} , is identified as *HS*; one where the second interaction, s_{H2} , will be *HS*; an overlap region where $s_{H1} = s_{H2}$; and a subspace which will never be sampled as it cannot satisfy the *HS* domain requirements and hard interaction ordering requirement at the same time. The allowed sampling space (see Figure 7.1(b)) is then the projection of the general sampling space with separation between *HS* and *LPU* slices implemented. As a result, the total number of generated (HS, LPU) pairs should be equally⁹ distributed/sampled from the general space. The space is hence defined by the total number of possible generation slices - the sampling domain of s_{LPU} - without the region where no physical event can be sampled - the difference between s_{LPU} and s_{HS} sampling domains. That is, each (s_{H1}, s_{H2}) combination is expected to be sampled $N_{\text{gen}} / (n_{s_{\text{LPU}}}^2 - (n_{s_{\text{LPU}}} - n_{s_{\text{HS}}})^2)$ number of times. Each resulting generated event is hence normalised to the inversion of this ratio.

7.2. Jet clustering and jet property definitions

During generation of each interaction, both visible and invisible final state particles are clustered into truth jet equivalents in DSEG, known as *Base Jet*. The clustering procedure mimics the one used in ATLAS (c.f. Sections 4.7.1–4.7.2 and Section 5.1). The particles are clustered using the anti- k_t clustering algorithm [156] with radius parameter of 0.4. The

⁸In ATLAS, this would be equivalent to number of primary vertices. However, since DSEG does not explicitly emulate or consider displaced vertex events, the "primary" epithet is omitted for simplicity.

⁹It is important to note that each pair is not as equally to happen from physics point of view. The physics probability of this is given by the abjunctious weight product.

7. Double Sliced Event Generation

clustering is carried out through the anti- k_t algorithm's implementation using FASTJET [159] (release 3.4.1) and its interfacing with PYTHIA generator. The clustered *Base Jet* are required to have $p_T > 7 \text{ GeV}$ to reflect the kinematic boundary between reconstructable jets in ATLAS and various irreducible backgrounds as well as requiring the jets to be detectable by the detector, i.e. $|\eta| < 4.5$. No additional restriction on number of reconstructed jets is placed on the interactions.

Differently to ATLAS event reconstruction, the only objects present in DSEG events are jets. That is, Double Sliced Event Generation does not differentiate between different physics objects, e.g., γ are treated as jets, nor contain detector specific object, e.g., tracks. Rather, DSEG describes its jets through various *fractional jet properties* - fraction of total jet's p_T carried by its partons matching particular conditions. For example, the *electromagnetic fraction* of the jet is defined as

$$f_{\text{EM}} := \frac{\sum_{e \in \text{jet}} p_T^e + \sum_{\gamma \in \text{jet}} p_T^\gamma}{p_T^{\text{jet}}} \quad (7.5)$$

that is jet's p_T fraction carried by photons and (anti-)electrons that had been clustered into the jet.

Since DSEG does not use tracks as independent objects, all jet properties and behaviours stemming from them are described through the *charged fraction*

$$f_{\text{ch}} := \frac{\sum_{\theta \in \text{jet}} p_T^\theta}{p_T^{\text{jet}}} \quad \text{where} \quad \theta \Rightarrow \text{charged}, p_T^\theta > 0.5 \text{ GeV} \quad (7.6)$$

and the *track fraction* (also referred to as *charged fraction within limit*)

$$f_{\text{trk}} \equiv f_{\text{ch}\chi} := \frac{\sum_{\theta \in \text{jet}} p_T^\theta}{p_T^{\text{jet}}} \quad \text{where} \quad \theta \Rightarrow \text{charged}, p_T^\theta > 0.5 \text{ GeV}, |\eta_\theta| < |\chi| \quad (7.7)$$

where in both cases the partons are required to be charged, to have p_T greater than the smallest possible track p_T in the ATLAS detector, and, for f_{trk} case, to be located within the ATLAS tracker system (see Section 3.2.2), i.e. $|\eta| < 2.5$.

Additionally, each jet's composition is also described by the *invisible fraction*, f_{inv} , defined as the sum of p_T carried by invisible final state particles. The origin of these invisible particles is primarily heavy flavoured hadron decays through electroweak channel(s). Similarly, jet's *heavy flavour fraction*, f_{HF} , is defined as the sum of p_T carried by final state particles originating from b hadron and meson decays. Such origin is determined by going backwards in the PYTHIA event record until a b hadron or meson is encountered as the mother particle or the original pp beam is reached.

Muons and their momentum contributions can and have been excluded from fractional property calculations. DSEG operates under the assumption that μ are identifiable by the ATLAS Muon system (Section 3.2.4) and would be removed/not considered during jet reconstruction.

7.3. Interaction with ATLAS Detector Emulation

DSEG *Base Jet* is also assigned two vertex indices. One according to interaction's position in the ordering by $\hat{p}_T$, which acts as the truth vertex. Another according to the interaction's contribution to the tracking system

$$p_{T,vtx}^{track} := \sum_{j \in vtx} p_T^j \cdot f_{trk}^j \quad (7.8)$$

which acts more akin to reconstructed vertex during ATLAS reconstruction (see Section 4.1). Hence, two possible collections of hard scatter jets could be formed: one stemming from the highest $\hat{p}_T$ interaction, another from highest $p_{T,vtx}^{track}$. If otherwise unspecified, in the following discussions the general term of "vertex" refers to vertex index by tracking system contribution.

7.3. Interaction with ATLAS Detector Emulation

The discussion up to this point regarding *Base Event* generation primarily accounted for physics at truth level. However, in order to use DSEG events for comparison with data, one needs to account for the effects the ATLAS detector has on the generated interactions. The detector has a limited energy resolution and is unable to measure particle and jet energies with limitless precision: The tracking system of ATLAS does not cover the full η range of the interaction which can lead to pile-up identification and tagging inefficiencies. If a jet is energetic enough, it may not be fully contained by the detector calorimetry systems. It can also be lost due to inactive or dead detector material. The anti- k_t clustering algorithm may omit partons from the correct shower or include ones from different shower. In either case, introducing p_T imbalance into the reconstructed hard scatter interaction. Additionally, $\cancel{E}_T$ may be introduced through heavy quark decays to neutrinos. All of these effects have to be accounted for either through jet calibration or emulation.

Normally, one would use a truth-level base as an input for full detector interaction simulation using GEANT4 [201] or similar software programs. However, this is both computationally and time-wise expensive procedure that would still be afflicted with the same downsides that prevent current MC-based multijet samples from being used. DSEG neither aims to be a full simulation replacement nor could be used in suites like GEANT4 to begin with. Rather detector interaction is implemented through parametrised emulation maps and various other statistic boosting techniques aimed at improving the statistical precision of the sample.

7.3.1. Jet Response and Jet Energy Resolution

One of the most crucial jet-level properties that needs to be accounted during this emulation is the jet energy response, $\mathcal{R}$, within the ATLAS detector. The response is related to the jet energy resolution of the detector, JER, and can be expressed as a convolution of a Gaussian-like core with non-Gaussian tails. As per Eq. (3.11), the Gaussian core can be parametrised

7. Double Sliced Event Generation

in terms of its three components: the stochastic term, S , the noise term, N , and the constant term, C . Both S and N terms being p_T dependent while the C term is not.

For the purposes of jet response emulation within Double Sliced Event Generation, jet response is drawn from a Gaussian centred around unity with its standard deviation equated to JER. However, ATLAS jet energy resolution is not a constant nor a uniform function in η -space. It's dependent on both jet p_T and differing resolutions between detector parts. Therefore, JER is (re)calculated on jet-by-jet basis, and for each jet the response is sampled from an independent Gaussian core. For the purposes of JER calculation, the three components - S , N , and C - are parametrised using Run2 data as functions of jet $|\eta|$. The JER in DSEG is calculated as:

$$\sigma_{JER}^2(p_T^{\text{vis}}, |\eta|) := \text{sgn}(N) \cdot \left[\frac{N(|\eta|)}{p_T^{\text{vis}}} \right]^2 + \frac{S(|\eta|)^2}{p_T^{\text{vis}}} + C(|\eta|)^2 \quad (7.9)$$

where σ_{JER} is the calculated jet energy resolution and p_T^{vis} is the visible fraction of jet p_T . Example of possible values of σ_{JER} for given p_T^{vis} and $|\eta|$ are shown in Figure 7.2.

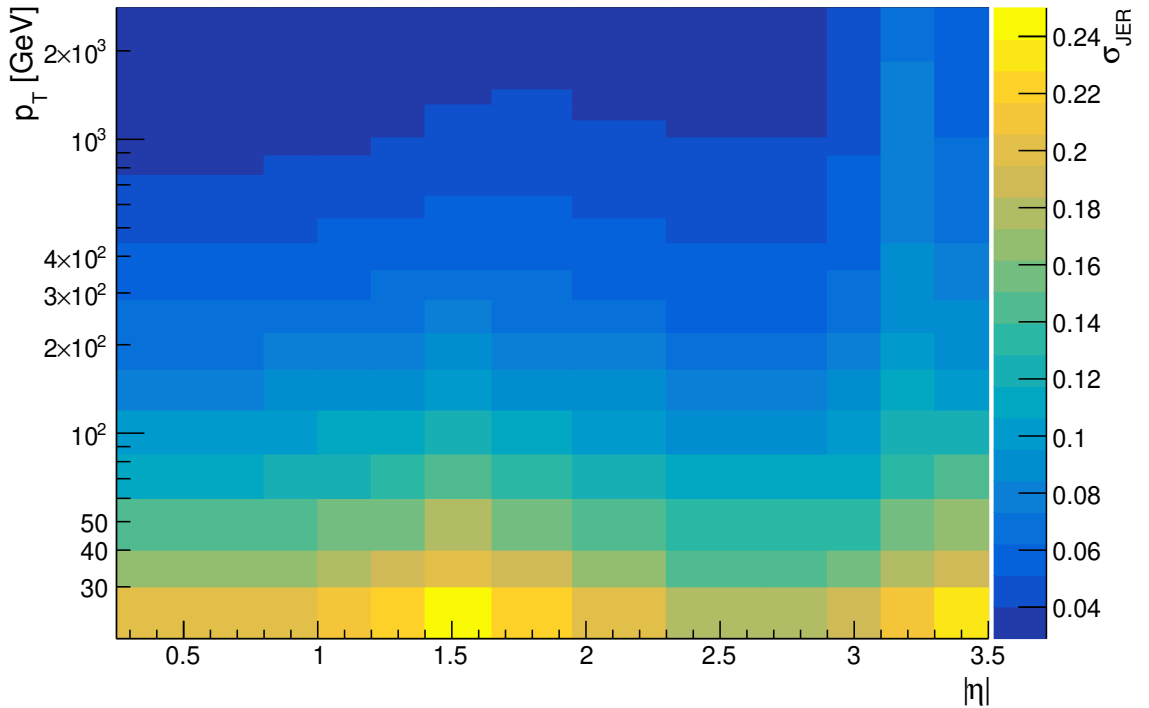


Figure 7.2.: Jet Energy Resolution distribution for PFlow jets with $\mu = 33$. Based on [210]

7.3. Interaction with ATLAS Detector Emulation

The drawn $\mathcal{R}$ is then used to smear the truth jet kinematics as follows:

$$p_T \rightarrow p_T \cdot \mathcal{R} \qquad p_x \rightarrow p_x \cdot \mathcal{R} \qquad (7.10)$$

$$\eta \rightarrow \eta \qquad p_y \rightarrow p_y \cdot \mathcal{R} \qquad (7.11)$$

$$\phi \rightarrow \phi \qquad p_z \rightarrow p_z \cdot \mathcal{R} \qquad (7.12)$$

$$m \rightarrow m \cdot \mathcal{R} \qquad E \rightarrow E \cdot \mathcal{R} \qquad (7.13)$$

No additional smearing in either η or ϕ plane is considered at the current iteration of the method. Jet fractional properties, discussed in Section 7.2, are not changed or altered during the smearing. This jet smearing procedure is also the origin of the two of the 6 systematic uncertainty categories considered for method: the jet energy scale uncertainty, representing response deviation from unity, as well as jet energy resolution uncertainty, representing broadening and narrowing of the Gaussian core that is used to sample the response.

7.3.2. Smeared Jet Merging : Hard Scatter and Pileup jet overlap in DSEG

After all *Base Event* comprising interaction jets have been smeared according to their jet response, an additional jet merging step takes place. Up to this point, the interactions have been treated as independent and no overlap between their jets has been considered. Post smearing, the jets are treated as a singular collection, i.e. no longer isolated by their interactions and can overlap in the $\eta - \phi$ space. As a result, a reconstructed jet may now contain contributions from multiple vertices, including "tracks"¹⁰, and "classification" similar to one shown in Figure 4.3 comes into play.

The smeared jet merging follows a similar logic implemented in general anti- k_t algorithms: Starting from the highest p_T jet each subsequent jet is checked if the distance in the angular space is smaller than specified merge radius parameter R_{merge} . That is if

$$\Delta R(j_A, j_B) = \Delta\eta(j_A, j_B) \oplus \Delta\phi(j_A, j_B) < R_{\text{merge}} \qquad (7.14)$$

then j_B is merged into j_A , assuming $p_T^{j_B} < p_T^{j_A}$, and j_B is removed from the smeared jet collection¹¹. In order to ensure that jet merging is carried out correctly, the merging follows the E-scheme, i.e. is done in the p_x, p_y, p_z, E frame of reference. Similarly to the EMTopo [141] and PFlow [103, 106] jet merging algorithms, Double Sliced Event Generation has the ability to either merge j_B fully or only its neutral part. As the analysis for which this method has been developed uses PFlow for the analysis jet object reconstruction, Double Sliced Event Generation uses the PFlow-like merging approach as well to maintain consistency.

¹⁰Or Double Sliced Event Generation equivalent of track representation.

¹¹To be more precise, the jet is internally tagged as Merged and Removed and not considered in further discussion. The jet is still recoverable for the purposes of systematic uncertainty derivation. See discussion in Section 9.2.

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That is

$$\begin{aligned} p'_x &= p_x^{jA} + (1.0 - f_{\text{trk}}^{jB}) \cdot p_x^{jB} \\ p'_y &= p_y^{jA} + (1.0 - f_{\text{trk}}^{jB}) \cdot p_y^{jB} \\ p'_z &= p_z^{jA} + (1.0 - f_{\text{trk}}^{jB}) \cdot p_z^{jB} \\ E' &= E^{jA} + (1.0 - f_{\text{trk}}^{jB}) \cdot E^{jB} \end{aligned}$$

where p'_x, p'_y, p'_z, E' is the merged jet momentums and energy and f_{trk} is the charged fraction of the jet that would detectable by the ATLAS detector's tracking system as per Section 7.2. Consequently, identifiable as not belonging to the jet during reconstruction.

Differently to smearing, the *jet fractional properties* will change during jet merging. The change is based on additional partons contributing to said quantity inclusion into the merged jet composition. In order to correctly account for this, at each instance of jet merging the fractional properties are recalculated with respect to the updated merged jet p_T, p'_T ,

$$f'_X = \frac{p_T^{jA} \cdot f_X^{jA} + p_T^{jB} \cdot f_X^{jB}}{p'_T} \quad (7.15)$$

where f_X represents any of the fractional properties. When neutral only merging is considered, f_{ch} and f_{trk} are not incremented by merged jet's corresponding fractions. Rather, they are simply rescaled to the newly increased jet p_T . Similarly, f_{HF} remains unchanged. Specifically, it is not even rescaled to the new p_T as the partons that form it are either charged (leptons) or invisible (neutrinos). In either case - omitted.

During jet merging there is a possibility that a softer jet stemming from a different vertex will be merged into the harder jet. Consequently, such jet four momentum after smearing will not only be distorted (with respect to the truth jet four momentum) by detector emulation but also due to pile-up jet inclusion. In order to account for such effects, ATLAS uses pileup area correction during jet calibration (see Section 5.2). Double Sliced Event Generation accounts for the increase in energy in similar fashion. Figure 7.3 depicts the average increase of jet energy during merging as a function of the number of interactions, N_{vtx} , and jet pseudorapidity, η . After smearing and merging has been completed, each jet's four momentum is corrected for the expected average increase of its energy through rescaling. The rescaling factor for each jet is given as

$$R_\rho(N_{\text{vtx}}, \eta) = \frac{p_T - \rho(N_{\text{vtx}}, \eta) \cdot r^2 \pi}{p_T} \quad (7.16)$$

where $r = 0.4$ and a procedure similar to Eqs. (7.10)–(7.13) is carried out with R_ρ instead of $\mathcal{R}$.

7.3.3. Jet Vertex Fraction: Jet-Vertex Association

Each merged jet keeps track of the total p_T deposited in the tracking system by its "constituent" jets with the recording done in a by-vertex basis. For example, given a set of jets, all of

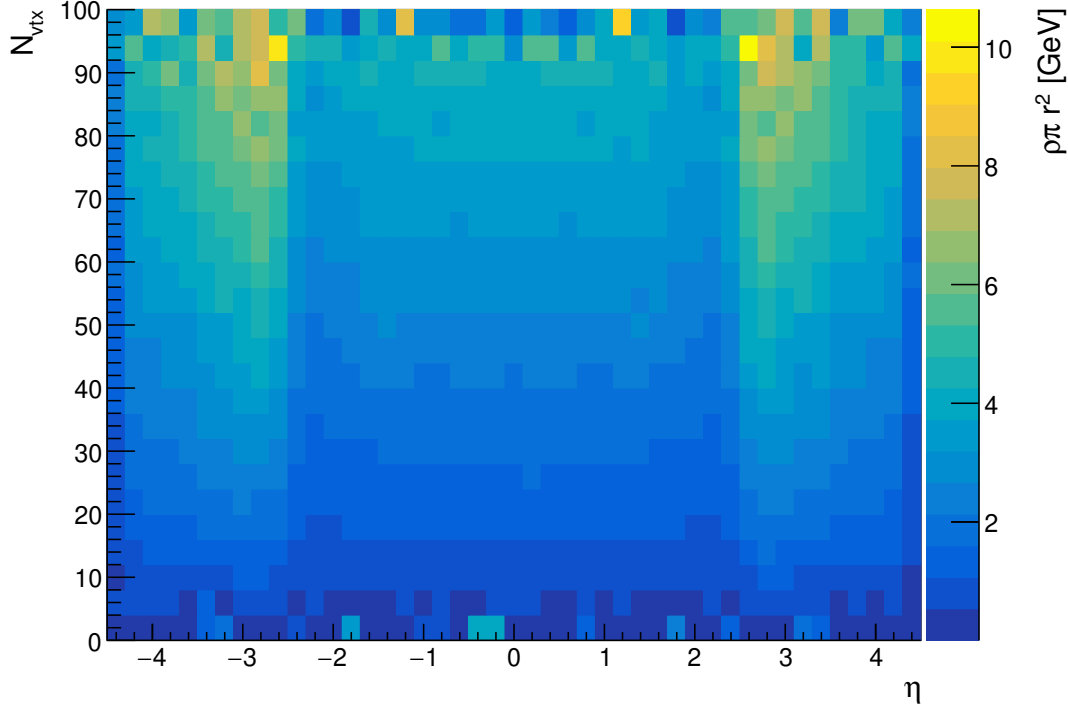


Figure 7.3.: Average energy increase acquired by jets from soft pileup jets during jet merging. The map is parametrised in number of (primary) vertices, N_{vtx} and jet (to which soft pileup jet is merged into) η . The ρ is the average PFlow jet density (c.f. Eq. (5.4)), and r on the z axis is identified as the clustering size parameter.

which originate from the same vertex, i.e. $j \in vtx_A$, and have been merged into the same jet, j_{ref} , the total p_T deposited in the tracking system by this vertex that is associated to j_{ref} would be given by

$$p_T^{track}(vtx_A) = \sum_{j \in vtx_A \subset j_{ref}} p_T^j \cdot f_{trk}^j \quad (7.17)$$

It is important to note, that even though Eq. (7.8) and Eq. (7.17) are nearly identical, they represent two distinctly different variables. Eq. (7.8) is an interaction-level quantity and is vertex-centric, while Eq. (7.17) is a jet-level quantity and is jet-centric.

After the merging procedure, each jet is further described by vertex fraction. A general vertex fraction is given by

$$VF_j(vtx_A) = \frac{p_T^{track}(vtx_A)}{\sum_{\{vtx_i\} \in j} p_T^{track}(vtx_i)} \quad (7.18)$$

and is defined as the ratio of a p_T deposition of a given vertex (partially or fully comprising a jet) over the total sum of such depositions (c.f. Eq. (4.10)). The dominant vertex fraction, DVF,

7. Double Sliced Event Generation

is the largest of such fractions and defines to which vertex (and consequently interaction) a merged jet is assigned to¹². Primary vertex fraction, PVF, is the vertex fraction stemming from the hard scatter interaction¹³. The modelling differences between PVF for hard scatter and pile-up jets between Double Sliced Event Generation and ATLAS data is shown in Figure 7.4. The PVF performance as a discriminant between these two jet categories is given in Figure 7.5. It can be seen that for the more simplistic case of vertex fraction assignment to jets, DSEG's PVF modelling agrees well with the one observed in data.

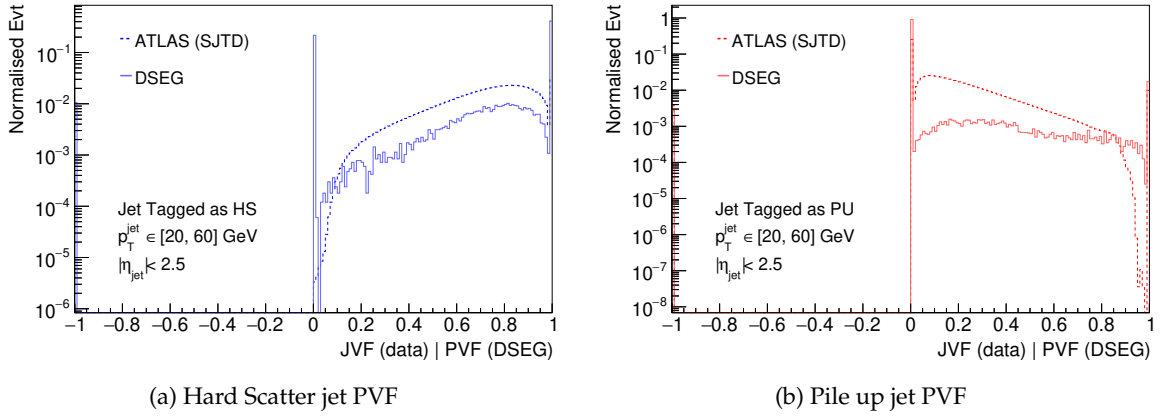


Figure 7.4.: PVF modelling similarities between Double Sliced Event Generation and 2018 (single jet triggered) data for Hard Scatters (HS) and Pileup (PU) jets. Showing inclusive jets with $p_T \in [20, 60]$ GeV and $|\eta| < 2.5$. For single jet triggered 2018 data (dashed line), differentiation decision is made based NNJVT algorithm outcome. For Double Sliced Event Generation (solid line), decision is based on generator level vertex: if a jet stems from the highest $\hat{p}_T$ slice it is assumed to be a hard scatter jet. DSEG samples produced with 2018 interaction profile using 5×10^4 HS and LPU combinations with DSEG *Basic Mode* (see Section 8.2).

Additionally, a *corrected* version of PVF, corrPVF is also calculated in near identical procedure to corrJVF calculation in ATLAS JVT algorithm (c.f. Eq. (4.9)). The corrected primary vertex fraction for Double Sliced Event Generation is given by

$$\text{corrPVF} := \frac{p_T^{\text{track}}(\text{vt}x_0)}{p_T^{\text{track}}(\text{vt}x_0) + (k \cdot n_{\text{trk}}^{\text{PU}})^{-1} \cdot \sum_{\{\text{vt}x_i\} \in j}^{\text{vt}x_i \neq \text{vt}x_0} [p_T^{\text{track}}(\text{vt}x_i)]} \quad (7.19)$$

where in DSEG's case $n_{\text{trk}}^{\text{PU}}$ is the total number of charged hadrons contributing to all f_{trk} calculations and the rest stay the same as for Eq. (4.9). In the ATLAS case, the discriminating power of corrJVF has been found to be insensitive to the choice of k and an empirical value

¹²In a situation where a jet has no DVF, the merged jet is given the jet's with the highest p_T interaction's vertex by track contribution, see Section 7.2.

¹³see Section 7.2. for a discussion on hard scatter interaction assignment in DSEG.

7.3. Interaction with ATLAS Detector Emulation

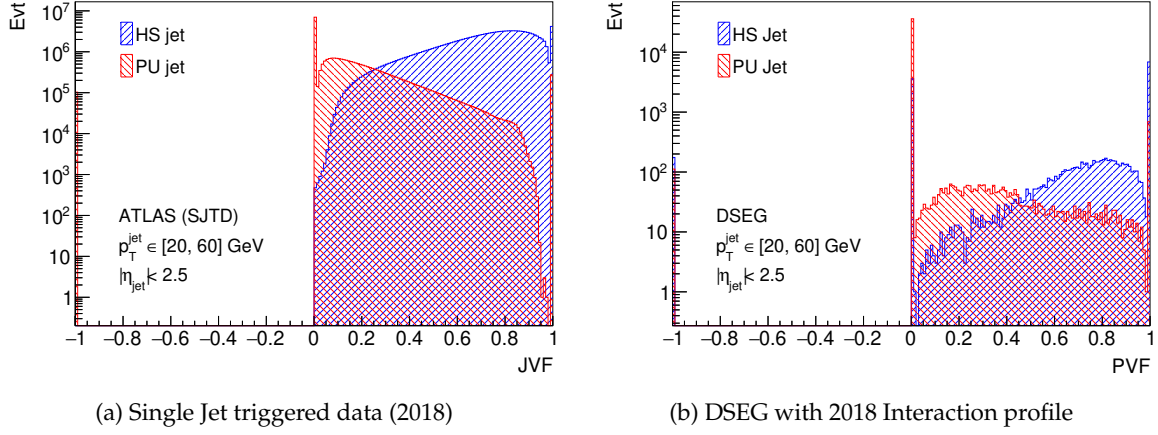


Figure 7.5.: Comparison between Double Sliced Event Generation and 2018 (single jet triggered) data for PVF-based differentiation between Hard Scatter jet (blue) and Pileup jets (red). Showing inclusive jets with $p_T \in [20, 60]$ GeV and $|\eta| < 2.5$. For single jet triggered 2018 data, differentiation decision is made based NNJVT algorithm outcome. For Double Sliced Event Generation, decision is based on generator level vertex: if a jet stems from the highest $\hat{p}_T$ slice it is assumed to be a hard scatter jet. DSEG samples produced with 2018 interaction profile using 5×10^4 HS and LPU combinations with DSEG *Basic Mode* (see Section 8.2).

of 0.01 is chosen. This choice results in corrJVF distribution behaviour similarity to JVF counterpart's [165]. For DSEG's corrPVF, multiple options for k-value have been considered in an attempt to optimise its modelling power. The modelling differences between Double Sliced Event Generation corrPVF and ATLAS corrJVF for hard scatter and pile-up jets is shown in Figure 7.6. While, the k-value for DSEG could be deduced numerically from the linear increase of $\langle p_T^{\text{PU}} \rangle$ with increasing $n_{\text{trk}}^{\text{PU}}$, due to different interpretation and modelling of tracks, this would be unreliable. Furthermore, as it will be discussed in Section 7.3.4, it is far more important to model the shape-behaviour of corrJVF in ATLAS, rather than its methodology. Therefore, a pragmatic check (for consistency) has been done with the ATLAS k-value of 0.01 and the best-shape-match of $k = 0.05$ is chosen. The discriminatory behaviour of both is shown in Figure 7.7 from which it can be seen that the latter choice is more optimal.

7.3.4. Pileup Tagging in DSEG

Similarly to ATLAS pile-up tagging procedure described in Section 4.7.3, Double Sliced Event Generation pile-up tagging differentiates between the central and forward regions of the detector. However, since DSEG does not contain objects mimicking tracks¹⁴, including

¹⁴Recall that from DSEG perspective "tracks" is an electrically charged parton which $p_T > 500$ MeV that is within ATLAS tracker acceptance and has been clustered into jet or has been merged through jet merging

7. Double Sliced Event Generation

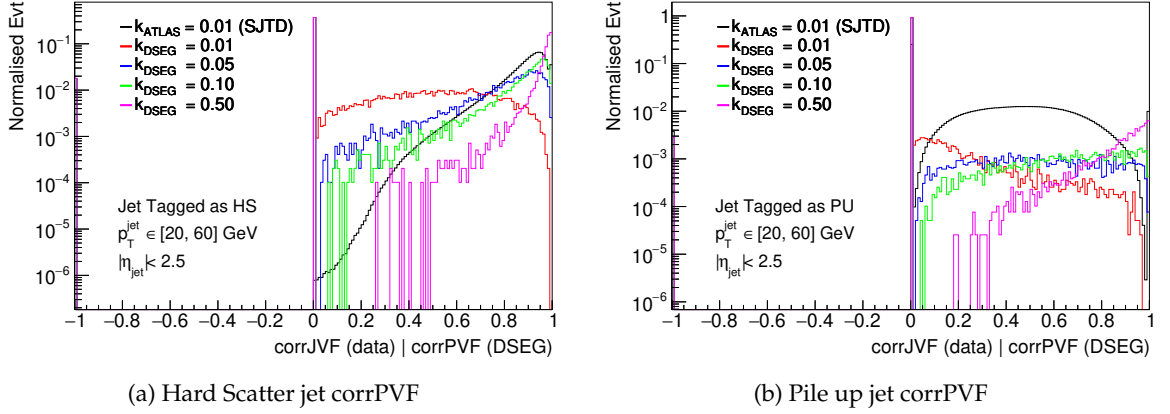


Figure 7.6.: corrPVF modelling similarities between Double Sliced Event Generation and 2018 (single jet triggered) data for Hard Scatters (HS) and Pileup (PU) jets. Showing inclusive jets with $p_T \in [20, 60]$ GeV and $|\eta| < 2.5$. For single jet triggered 2018 data (dashed line), differentiation decision is made based NNJVT algorithm outcome. For Double Sliced Event Generation (solid line), decision is based on generator level vertex: if a jet stems from the highest $\hat{p}_T$ slice it is assumed to be a hard scatter jet. DSEG samples produced with 2018 interaction profile using 5×10^4 HS and LPU combinations with DSEG *Basic Mode* (see Section 8.2). Multiple DSEG corrPVF distributions are shown for different k_{DSEG} values. $k_{DSEG} = 0.01$ mimics k -value used by ATLAS. $k_{DSEG} = 0.05$ chosen as the one that represents ATLAS corrPVF variables distribution the closest.

their resolution or reconstruction efficiencies, direct application of JVT and FJVT, as used in ATLAS, is impossible. As a result two methods with similar design philosophy had been developed and implemented in DSEG.

Central region: Probability Maps

In the central region of the ATLAS detector, the pileup tagging algorithm relies on two variables: corrJVF (Eq. (4.9)) and R_{p_T} (Eq. (4.10)). While Double Sliced Event Generation has their equivalents in corrPVF (Eq. (7.19)) and VF_j (Eq. (7.18)), replication of JVT algorithm based on them would not be reliable. Hence, an alternative approach using a probability map has been chosen. The probability for a given jet to be tagged as pileup is constructed for every single year of ATLAS data taking. The map is based on data collected using single jet triggers during that year and is parametrised in p_T , $|\eta|$, and a chosen vertex fraction. Two versions of the map have been investigated: one based on PVF (see Figures 7.8 and 7.9) and another based on corrPVF (see Figures 7.10 and 7.11). The maps cover the full $|\eta|$ range of the ATLAS tracking system and are only valid within $p_T \in [20, 60]$ GeV. If jet p_T is greater

procedure into the jet.

7.3. Interaction with ATLAS Detector Emulation

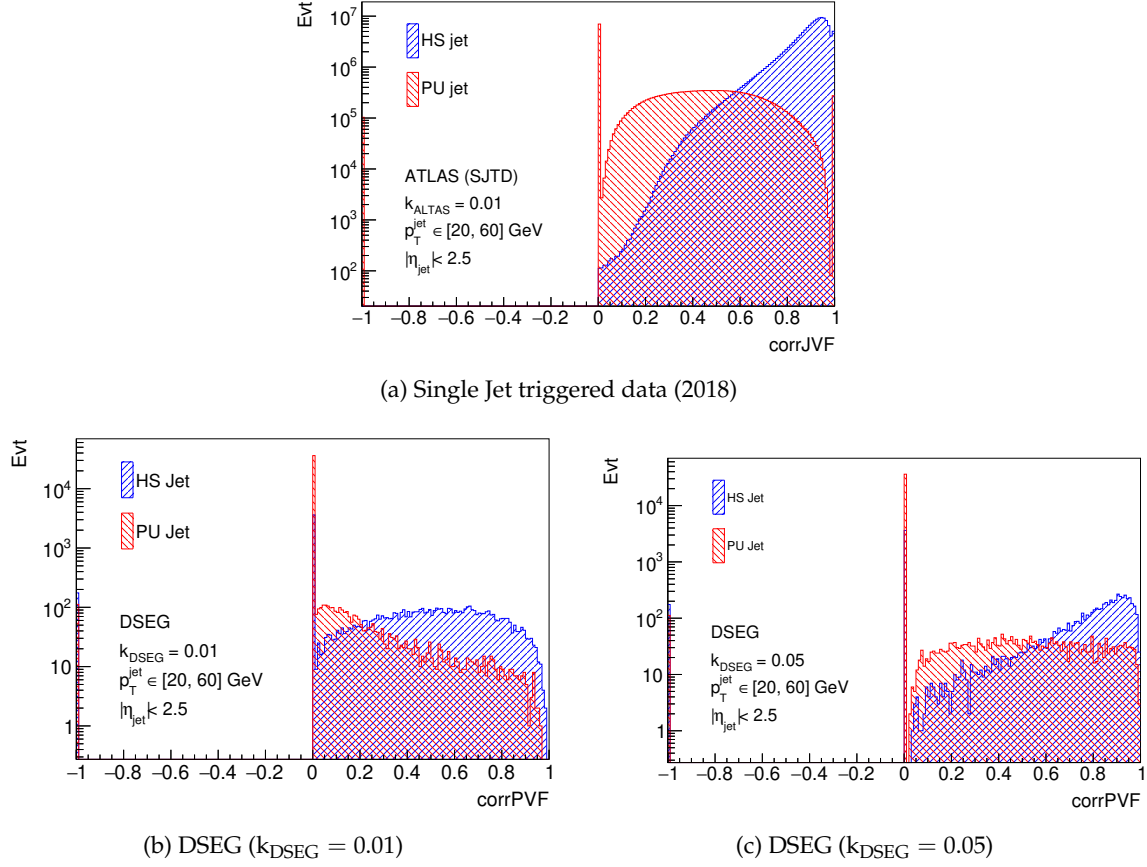


Figure 7.7.: Comparison between Double Sliced Event Generation and 2018 (single jet triggered) data for corrPVF-based differentiation between Hard Scatter jet (blue) and Pileup jets (red). Showing inclusive jets with $p_T \in [20, 60] \text{ GeV}$ and $|\eta| < 2.5$. For single jet triggered 2018 data, the differentiation decision is made based on NNJVT algorithm outcome. For Double Sliced Event Generation, the decision is based on generator level vertex: if a jet stems from the highest $\hat{p}_T$ slice it is assumed to be a hard scatter jet. DSEG samples produced with 2018 interaction profile using 5×10^4 HS and LPU combinations with DSEG Basic Mode (see Section 8.2). Two corrPVF values considered for DSEG's case : $k_{\text{DSEG}} = 0.01$ shown in (b) and $k_{\text{DSEG}} = 0.05$ shown in (c)

7. Double Sliced Event Generation

than 60 GeV, it is assumed to be a hard scatter jet.

At first glance the corrJVF version of the map seems to be more reasonable (c.f. at $\text{corrJVF} \sim 0.5$ pileup tagging probability is also around 50%). However, as described in Section 7.3.3, corrPVF is not an identical match to corrJVF due to different k value choices and track modelling differences. Furthermore, PVF and JVF pair is far less sensitive to the differences of track modelling as it can be seen in Figures 7.4 and 7.5. Therefore, the JVF-based pileup tagging is used as the nominal approach and the corrJVF-based map is utilised to deduce systematic uncertainty for pileup tagging. Since corrPVF would be used instead of corrJVF by DSEG to check the probability from the map for a given jet, the corrPVF k_{DSEG} value has been optimised to mimic corrJVF distributions between hard scatter and pile-up jets as close as possible.

Double Sliced Event Generation also includes a simplistic jet vertex based pile-up tagging. If a jet is located within tracker acceptance and applicable p_T range, it is assigned a pileup probability, $\mathbb{P}_{\text{PU}}$, based on pileup tagging efficiency or miss-tagging probability for pile-up and hard scatter jets respectively, that is

$$\mathbb{P}_{\text{PU}}(\text{vtx}_{\text{HS}}) = 0.08 \quad \text{and} \quad \mathbb{P}_{\text{PU}}(\text{vtx}_{\text{PU}}) = 0.98 \quad (7.20)$$

where vtx_{HS} and vtx_{PU} indicates the hard scatter and pileup interaction vertices respectively. As this approach is quite simplistic, it is included only as a component in pileup tagging systematic uncertainty deduction.

Forward Region: Hadronic Balance

Since the ATLAS tracking system does not extend beyond $|\eta| > 2.5$, one cannot rely on track matching to energy deposits for jet assignment to reconstructed vertices. Rather a method based on transverse momentum (im)balance in a hadronic system is employed known as forward Jet-Vertex-Tagger, or FJVT [164, 167] (see Section 4.7.3). Two different methods of calculating each primary vertex's momentum imbalance are used depending on whether jets in ATLAS are build as EMTopo (Eq. (4.14)) or PFlow jets (Eq. (4.15)). In either case, the maximum of the momentum imbalance projection onto the jet (Eq. (4.11)) is used as the discriminator.

For Double Sliced Event Generation, the underlying strategy remains the same. However, the FJVT score calculation has to be augmented to account for the lack of tracks as individual objects within the method. To begin with, each jet tracks which vertices and by how much contribute to the jets f_{trk} . Hence, one can form momentum imbalance for each vertex by summing each of its contributions to all jets present in the event

$$\vec{p}_T^{\text{track}}(\text{vtx}) = \sum_{\{j\} \in \text{vtx}} \left[-\vec{j} \cdot \frac{p_T^{\text{trk} \in \text{vtx} \subset j}}{p_T^j} \right] \quad (7.21)$$

The missing transverse track momentum is calculated for each vertex, vtx , from all jets, $\{j\}$, to which it contributes. It is important to note that this quantity will be formed from all jets.

7.3. Interaction with ATLAS Detector Emulation

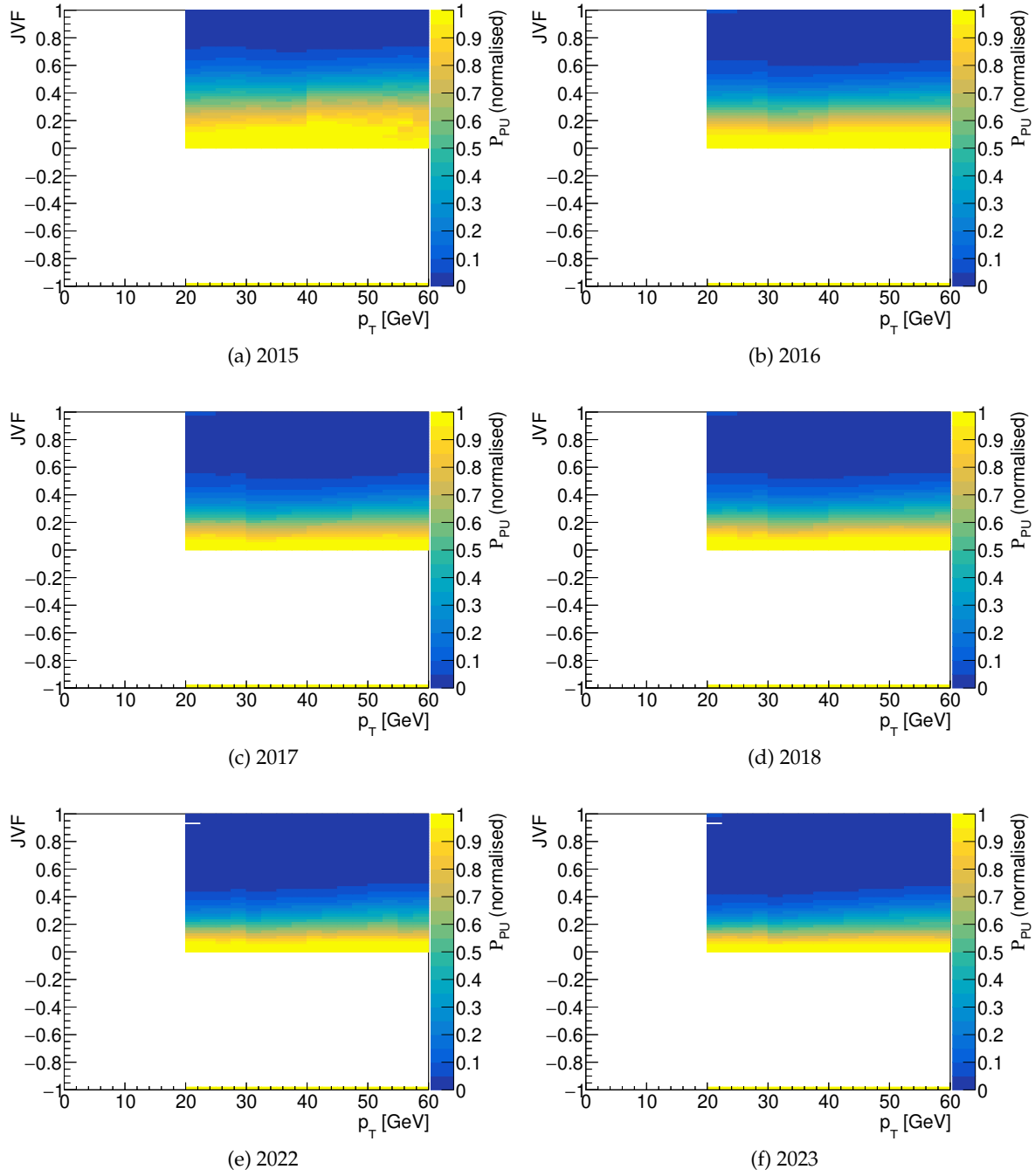


Figure 7.8.: JVF-based pileup probability 3D map projections on to JVF – p_T plane of all data taking years. The has been filled by full single jet triggered data with events passing the most basic event cleaning cuts. The negative corrJVF values are representative of jets that left no tracks in the tracking system.

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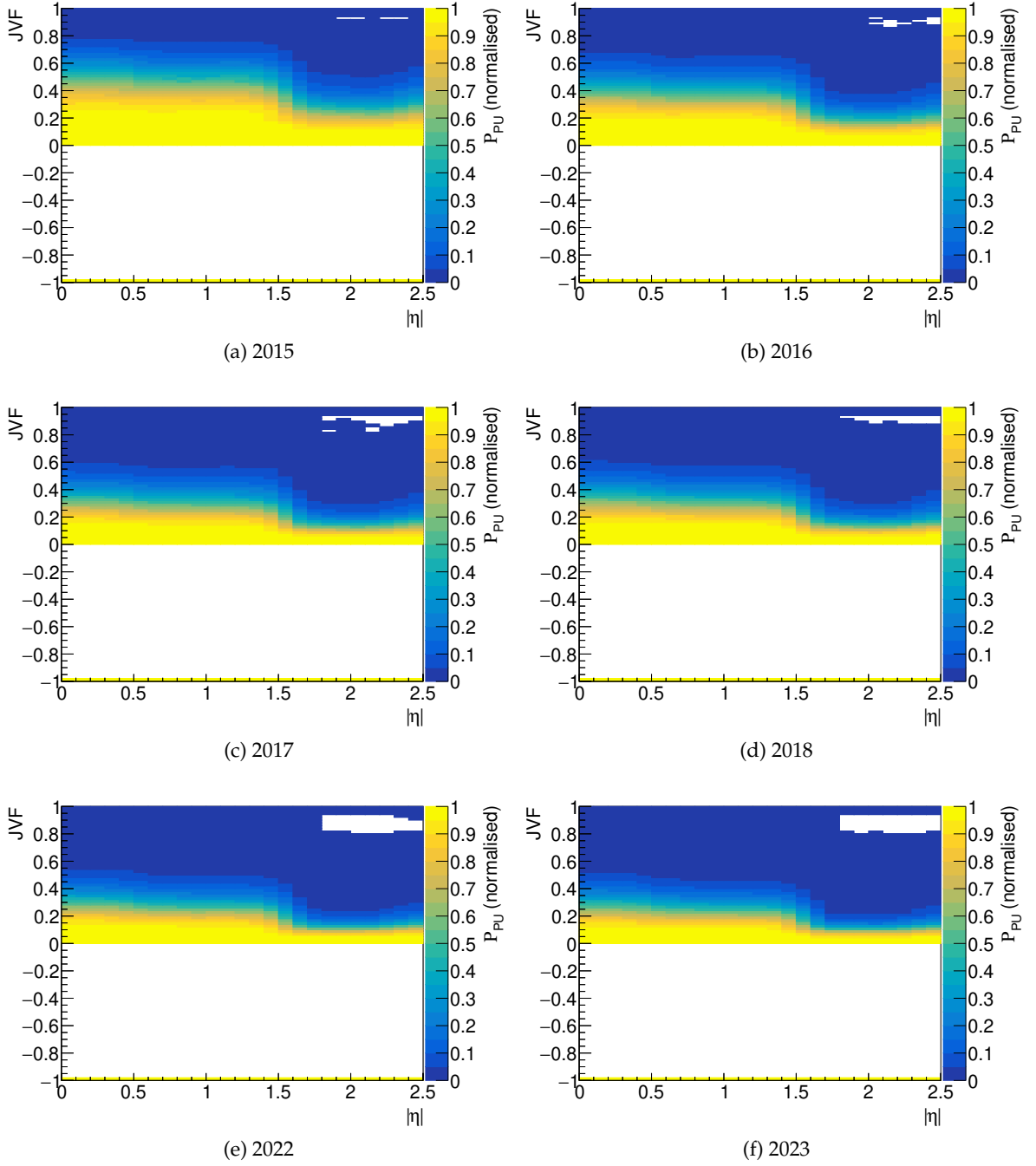


Figure 7.9.: JVF-based pileup probability 3D map projections on to JVF – $|\eta|$ plane of all data taking years. The has been filled by full single jet triggered data with events passing the most basic event cleaning cuts. The negative corrJVF values are representative of jets that left no tracks in the tracking system.

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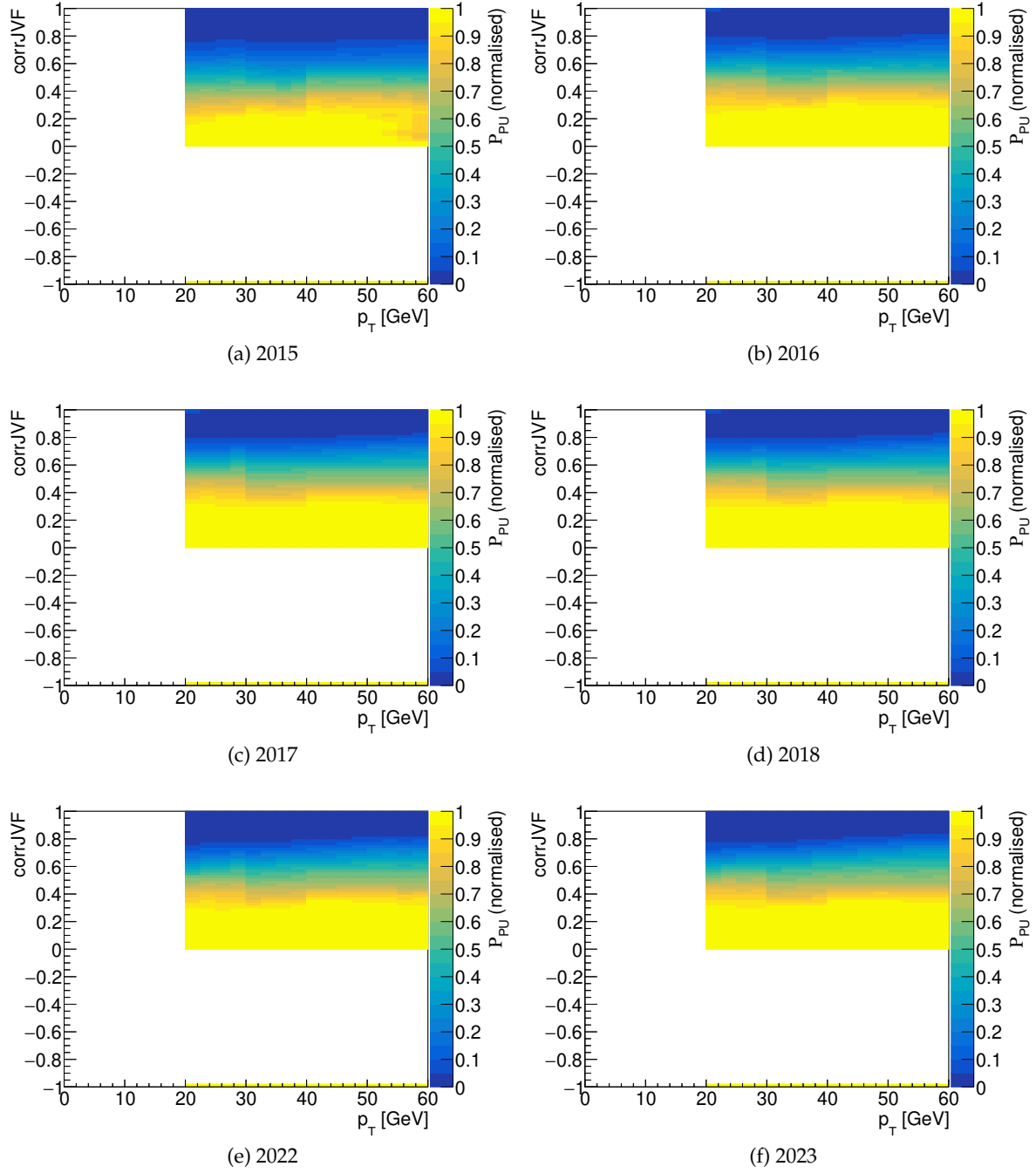


Figure 7.10.: corrJVF-based pileup probability 3D map projections on to $\text{corrJVF} - p_T$ plane of all data taking years. The has been filled by full single jet triggered data with events passing the most basic event cleaning cuts. The negative corrJVF values are representative of jets that left no tracks in the tracking system.

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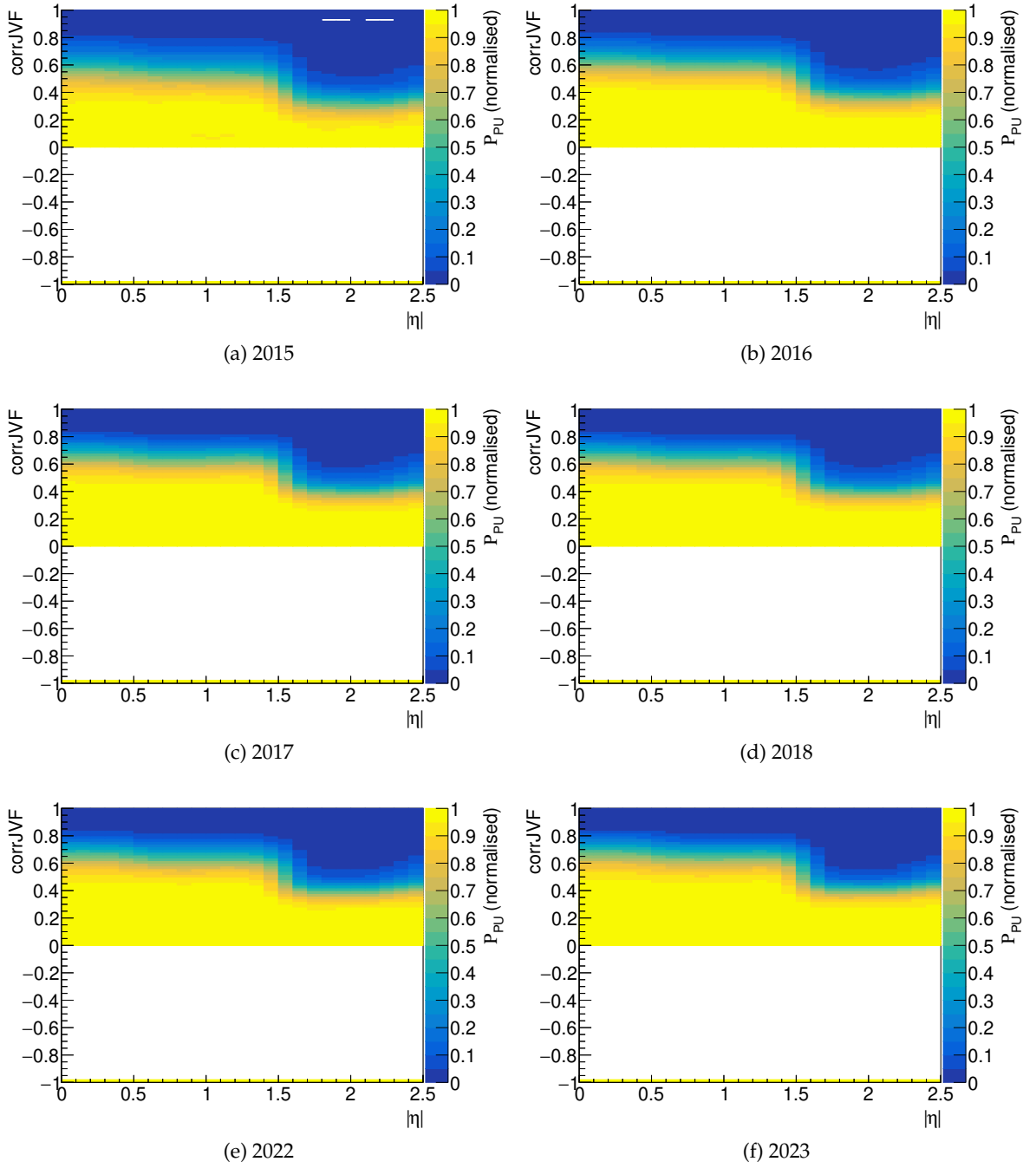


Figure 7.11.: corrJVF-based pileup probability 3D map projections on to $\text{corrJVF} - |\eta|$ plane of all data taking years. The has been filled by full single jet triggered data with events passing the most basic event cleaning cuts. The negative corrJVF values are representative of jets that left no tracks in the tracking system.

7.3. Interaction with ATLAS Detector Emulation

That includes central jets that have not been tagged as pileup - they might have absorbed a pileup jet or their p_T is greater than the threshold - as well as forward jets - soft assumption that the forward jet is close to the η boundary and has absorbed a pileup jet.

Similarly, as the vertex of origin/assignment is always known for every jet, a missing transverse pile-up jet momentum is calculated as

$$\vec{p}_T^{\text{PU}}(\text{vtx}) = \sum_{\{j\} \in \text{vtx}} [-\vec{j}] \iff j \equiv \text{PU}, \eta_j < \eta_{\text{JV T max}} \quad (7.22)$$

The quantity is formed on a per-vertex basis and includes all central pile-up tagged jets $\{j\}$ which has been associated to a given vertex, vtx.

Then both Eq. (7.21) and Eq. (7.22) are combined similarly to Eq. (4.14) into EMTopo-like missing transverse momentum

$$\vec{p}_T^{\text{EMTP}}(\text{vtx}) = \frac{1}{2} \cdot [k \cdot \vec{p}_T^{\text{track}} + \vec{p}_T^{\text{PU}}] \quad (7.23)$$

The scaling parameter k is also set to 2.5 to match the methodology described by [141]. It is important to note that Eq. (7.23) does not contain a negative sign explicitly compared to the ATLAS counterpart (Eq. (4.14)).

Similarly to its EMTopo-based counterpart, the PFlow-like missing transverse momentums is also adjusted. Using the Eq. (4.15) as the reference, the PFlow-based missing transverse momentum is calculated as

$$\begin{aligned} \vec{p}_T^{\text{PF}}(\text{vtx}) = -(& \sum \vec{j} \quad \text{if } j \text{ is PU tagged and } \text{VF}_j(\text{vtx}) > 0.1 \\ & + \sum \left[\vec{j} \cdot \frac{p_T^{\text{track} \in \text{vtx} \subset j}}{p_T^j} \right] \quad \text{if } j \text{ is PU tagged and } \text{VF}_j(\text{vtx}) < 0.1 \\ & + \sum \left[\vec{j} \cdot \frac{p_T^{\text{track} \in \text{vtx} \subset j}}{p_T^j} \right] \quad \text{if } j \text{ is not PU tagged} \\ &) \end{aligned} \quad (7.24)$$

The summation breaks down as follows: The first term includes all central jets with $p_T > 20 \text{ GeV}$ that have been tagged as pile-up and have more than 10% of their momenta detectable by the tracking system and are associated to the vertex under consideration. Their four-momenta is included fully into the imbalance calculation. The second term includes pile-up tagged jet contributions to the tracking system if they fail the VF_j criteria. Finally, tracking contributions of the remaining jets are also added. This may include central jets which are too soft to be tagged as pileup, or forward jets if they are located close to the tracking cut-off point in η and have been merged with a central jet.

Since Eq. (4.15) is more heavily reliant on direct integration of tracks as objects into its methodology, for Double Sliced Event Generation $\vec{p}_T^{\text{EMTP}}$ based FJVT tagging is used as

7. Double Sliced Event Generation

the nominal approach with $\vec{p}_T^{\text{PF}}$ used for systematical uncertainty evaluation. However, the choice between Eq. (7.23) and Eq. (7.24) as the nominal is not expected to have a major influence in the end, as the requirements of FJVT defined in Table 6.1 is only applicable to the softest of the sub-leading jets and with a very narrow p_T range between 50 GeV and 60 GeV.

7.3.5. b -jet and DSEG

Most b -jets decay (semi-)leptonically resulting in detectable lepton within the detector. Since all three signal regions include a lepton veto (c.f. Table 6.1), b -jets are not expected to heavily contribute to neither the signal region nor to the multijet control region that would be based on signal regions. Therefore, a simplistic approach to b -tagging is used within Double Sliced Event Generation. Recall that each reconstructed jet in DSEG is parametrised by the heavy flavour fraction, f_{HF} . Hence, if this fraction exceeds more than half of the total momentum content of the jet, the jet is assumed to be a b -jet.

7.3.6. Missing Transverse Energy Trigger Emulation

As discussed in Section 6.3, the reference analysis uses $\cancel{E}_T$ triggers to select signal event candidates. Therefore, the final component of emulation that needs to be included in Double Sliced Event Generation is the $\cancel{E}_T$ trigger performance and modelling. ATLAS $\cancel{E}_T$ triggers only become fully efficient around 250 GeV. Prior to that, their efficiency increases in Gaussian error function fashion [196]. As all previous and possibly future signal regions are defined below this threshold, the trigger inefficiency needs to be incorporated into the final DSEG event weight. This poses a couple of challenges: reference and parametrisation.

To begin with, the reference question. The $\cancel{E}_T$ trigger inefficiency effects are present in both data (recorded with actual triggers) and Monte Carlo samples (trigger decision inferred from detector interaction simulation). However, their turn on function behaviour is slightly different: triggers used to record data tend to become efficient at lower $\cancel{E}_T$ compared to their MC counterparts. For this reason as well as for closer comparison between DSEG and data, the $\cancel{E}_T$ trigger efficiency weight factor, w_{trig} , is defined using data, not Monte Carlo simulation.

Secondly, the parametrisation of the trigger efficiency. Per Section 3.2.6, the $\cancel{E}_T$ trigger decision is made using online quantities, primarily reduced granularity readouts from the calorimetry systems and MS to make the decision. Double Sliced Event Generation does not contain such equivalent level variables as it does not simulate interaction with the detector on an individual subdetector level. The closest approximation for such quantities are the hadronic activities. As mentioned in Section 4.9, two versions of the hadronic activity can be defined: total transverse hadronic activity, H_T , defined as the scalar sum of jet transverse momentum, and the missing transverse hadronic activity, $\cancel{H}_T$, which is defined similarly to other missing transverse quantities as a magnitude of the negative vectorial sum of all jets. For both versions of the hadronic activity, no differentiation between hard scatter and pileup

7.3. Interaction with ATLAS Detector Emulation

jet is made¹⁵. Due to differing approaches to jet reconstruction and missing independent objects (e.g., tracks), Double Sliced Event Generation's definition of $\cancel{H}_T$ is closer in nature to $\cancel{E}_T$ that is calculated using soft terms originating from clusters, $\cancel{E}_T^{\text{CST}}$, rather than tracks, $\cancel{E}_T^{\text{IST}}$, which is more commonly used (see Eqs. (4.22) and (4.23) respectively and the discussion surrounding them).

Therefore, the $\cancel{E}_T$ trigger efficiency, ε_{MET} , is parametrised in data through H_T and $\cancel{E}_T^{\text{CST}}$, and is defined as

$$\varepsilon_{\text{MET}}(H_T, \cancel{E}_T^{\text{CST}}) = \frac{N_{\text{SJT}+\text{MET}}(H_T, \cancel{E}_T^{\text{CST}})}{N_{\text{SJT}}(H_T, \cancel{E}_T^{\text{CST}})} \quad (7.25)$$

where $N_{\text{SJT}+\text{MET}}$ are the number of events from single jet triggered data that would also trigger the $\cancel{E}_T$ trigger and N_{SJT} is the total number of events that triggered the single jet trigger. As single jet triggered data is insensitive to $\cancel{E}_T$ trigger inefficiencies at low $\cancel{E}_T$ ranges, constructing the map based on the data allows the parametrised to fully encode $\cancel{E}_T$ inefficiencies without being exposed to them performance-wise. To further ensure the precision of the map, each event participating in the map construction is required to pass loose event selection requirements show in Table 7.3. The resulting $\cancel{E}_T$ trigger efficiency maps for individual data taking years are shown in Figure 7.12.

Selection	Requirement	Condition
Good Run List	pass	
Detector Cleaning cuts	pass	
Event Cleaning cuts	pass	
Jet Cleaning cuts	pass	
$N_{\text{baseline lepton}}$	0	
$\cancel{E}_T^{\text{soft}}$	$< 20 \text{ GeV}$	
p_T^0	$> 80 \text{ GeV}$	if $n_{\text{jet}} > 1$
p_T^1	$> 50 \text{ GeV}$	if $n_{\text{jet}} > 1$
$\Delta\phi_{jj}$	< 2.5	if $n_{\text{jet}} > 1$

Table 7.3.: $\cancel{E}_T$ trigger efficiency map production event selection. The event selection is based on the expected signal region definition. The inclusion of zero base leptons is used to suppress non-multijet background contributions. However, single jet events are permitted as the trigger should not differentiate between pure multijet and V +jet events

For application to Double Sliced Event Generation events the equivalence between $\cancel{E}_T^{\text{CST}}$ and $\cancel{H}_T$ is assumed, i.e. $\varepsilon_{\text{MET}}(H_T, \cancel{E}_T^{\text{CST}}) = \varepsilon_{\text{MET}}(H_T, \cancel{H}_T)$. The resulting trigger efficiency is not binary in nature as compared to the trigger decision itself¹⁶, all the Double Sliced

¹⁵Note, in ATLAS this is not entirely true. The local pileup suppression algorithm, `pufit`, used in online $\cancel{E}_T$ construction carries out rudimentary rejection from pile-up contributions [196].

¹⁶The event either passes the trigger or it does not.

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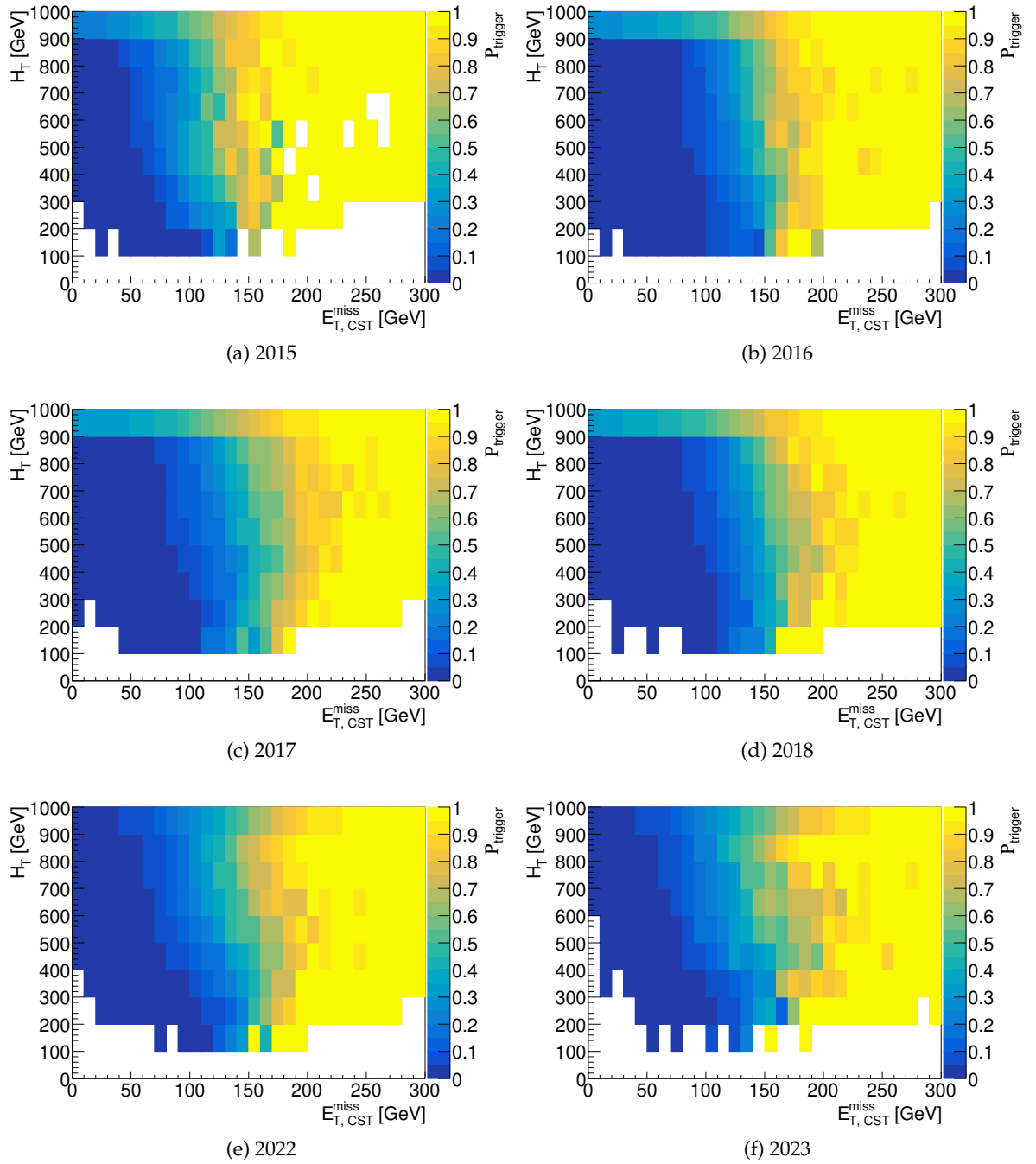


Figure 7.12.: E_T trigger efficiency maps for individual years of data taking: The efficiency map parametrised in E_T calculated using soft terms from calorimeter systems, $E_T^{\text{CST}} \equiv E_{T, \text{CST}}^{\text{miss}}$, and scalar sum of all hadronic activity in the event. For Double Sliced Event Generation, E_T^{CST} is represented as the magnitude of the negative vectorial sum of all hadronic activity in the event, $\cancel{H}_T$.

Event Generation event weights need to be adjusted for the probabilistic nature of the trigger efficiency implementation. Consequently

$$w_{\text{trig}} = \varepsilon_{\text{MET}}(H_T, \cancel{H}_T) \quad (7.26)$$

7.4. Statistics Boosting Techniques

Similarly to other data driven techniques, Double Sliced Event Generation aims to extract more than a singular reconstructed final event from each of its generated truth events, or *Base Events* in DSEG's case. Hence, different statistics boosting technique are employed within DSEG. Additionally, the method aims to avoid introduction of bias through such statistics boosting. Therefore, multiple techniques aimed at decreasing homogeneity and interrelation between produced final state events are also used. The collection of these techniques as well as methods of increasing the computation-wise performance of Double Sliced Event Generation are presented in this section.

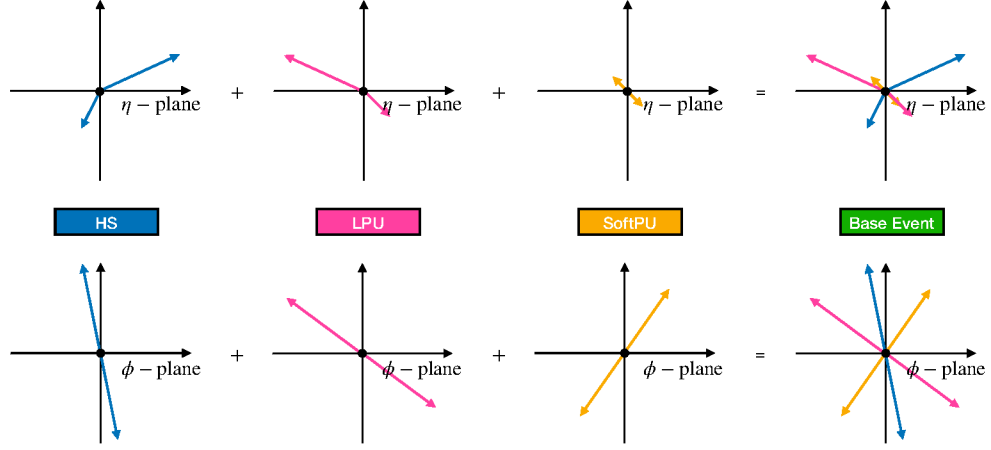
7.4.1. Soft Pileup Reuse and $\eta - \phi$ plane scrambling

As mentioned before, the greatest amount of jet activity is expected to originate from the two hardest interactions. However, from the generation viewpoint this only comprise a fraction of interactions generated. These two facts provide an avenue for boost in performance: Rather than regenerating *HS*, *LPU*, and *SoftPU* between consecutive *Base Event* generation cycles, only the two hardest $\hat{p}_T$ -wise interactions are replaced, while the rest is kept. In order not to introduce a bias through such reuse, a scrambling of the *SoftPU* interactions is done in the $\eta - \phi$ plane with respect to each other. After the two hardest interactions are removed, each of the *SoftPU* hadronic systems are rotated by random amount in the ϕ and have a random chance of their η sign inverting. Consequently, the physics within individual hadronic systems remains the same, but the combination of them differs cycle-by-cycle. An example of such procedure is shown in Figure 7.13. To further decrease the possibility of a bias as well as provide some variation w.r.t. to the soft jets, *SoftPU* is reused only limited number of times, before a remake of *HS*, *LPU*, and *SoftPU* is done.

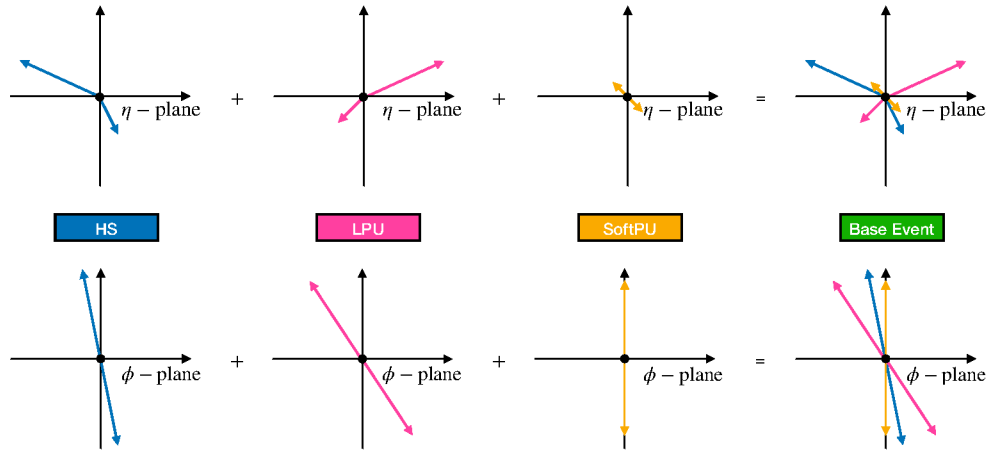
7.4.2. Dynamical Smearing

One benefit of jet smearing over full detector emulation is the possibility of creating multiple reconstructed/smeared events from an individual truth-level event. As long as the jet response is drawn at random from the Gaussian distribution, resulting smeared jets stemming from the same truth jet would be kinematically different providing a statistics boost. However, this may lead to possible overbiasing problem. If all *Base Events* are smeared a fixed amount of times, the resulting sample will be dominated by high generation weight

7. Double Sliced Event Generation



(a) Before $\eta - \phi$ scrambling



(b) After $\eta - \phi$ scrambling

Figure 7.13.: Visualisation of the $\eta - \phi$ scrambling procedure. A simplistic *Base Event*, comprised of a *HS* (blue), *LPU* (pink), and a single *SoftPU* (yellow) interactions, is shown before (a) and after (b) the $\eta - \phi$ scrambling procedure. The jets associated to each interaction are represented by arrows of differing length and the dijet system is assumed to be balanced in all interactions. The *HS* interaction experience only the η -flip, the *SoftPU* interaction experience only the ϕ -rotation, and *LPU* experiences both.

events (c.f. Eq. (7.3)) in a non-physical manner. Therefore, a dynamical smearing based on the generation weight is employed.

Each event is expected to be smeared between $n_{\text{smeared}}^{\min}$ and $n_{\text{smeared}}^{\max}$ amount of times with the actual number of smears being calculated as

$$n_{\text{smeared}} := n_{\text{smeared}}^{\min} \cdot n_{\text{smeared}}^{\max} \cdot w_{\text{HS}}^{\text{HS}} \cdot w_{\text{LPU}}^{\text{LPU}} \quad (7.27)$$

where w_{HS} are abjunction weights as defined in Eq. (7.4) and $n_{\text{smeared}} \in [n_{\text{smeared}}^{\min}, n_{\text{smeared}}^{\max}]$. If n_{smeared} is greater or smaller than its corresponding boundary, the boundary is used. All smeared events stemming from the same truth interaction collection are hence normalised by the number of times that truth interaction collection has been smeared, i.e. $w \propto n_{\text{smeared}}^{-1}$. For the purposes of this project, the smearing boundaries had been set to 500 and 10^5 respectively. Similarly to *SoftPU* reuse, the particular boundaries and their differences have been found to have a negligible systematic effect, however they do provide a drastic computational performance boost.

To further reduce the homogeneity between smeared event, both *HS* and *LPU* interactions are scrambled in $\eta - \phi$ space with respect to the *SoftPU* interactions. This is done in identical manner that had been described in Section 7.4.1.

7.4.3. Visible Fraction Smearing

While the smearing procedure is beneficial in boosting the statistical size of the sample, it only affects the visible fraction of the jet properties. During smearing, the invisible fraction remains constant therefore the contribution to E_T from invisible particles remains unchanged. This contribution plays crucial role for large values of E_T modelling and signal region differentiation. Therefore, an increased number of *Base Event* sampling would not yield corresponding increase in statistical precision in the signal region by itself. Hence, invisible fraction is also smeared prior to jet response calculation.

The invisible fraction is primarily comprised of neutrinos stemming from semi-leptonic heavy flavour hadron decays. Therefore, the f_{inv} can be parametrised as a function of f_{HF} with the underlying assumption that $f_{\text{inv}} < f_{\text{HF}}$ as part of the momentum needs to be carried out by the visible lepton partner of the ν . A 2D histogram binned in f_{inv} and f_{HF} is filled using simulated events generated with PYTHIA and is shown in Figure 7.14. During each smearing iteration, the invisible fraction of the jet is randomly chosen based on its f_{HF} . The f_{inv} is uniformly sampled from all bins with non-zero contribution in corresponding f_{HF} bin of the map. The only exception are jets with $f_{\text{HF}} < 0.05$. In this situation, the invisible fraction is set to f_{HF} . Consequently, each jet suppresses the smeared event weight by the probability to sample a particular f_{inv} given a specific f_{HF} . That is,

$$w_{\text{smeared}} = \prod_j P(f_{\text{inv}}^j | f_{\text{HF}}^j > 0.05) \quad (7.28)$$

where w_{smeared} is provided by the integral normalised f_{HF} slice of the map (see Figure 7.14(b)). The aforementioned limitation of $f_{\text{HF}} < 0.05$ is pragmatically motivated by the drastic difference between the weight factor associated to the dominant bin of f_{inv} and the rest.

7. Double Sliced Event Generation

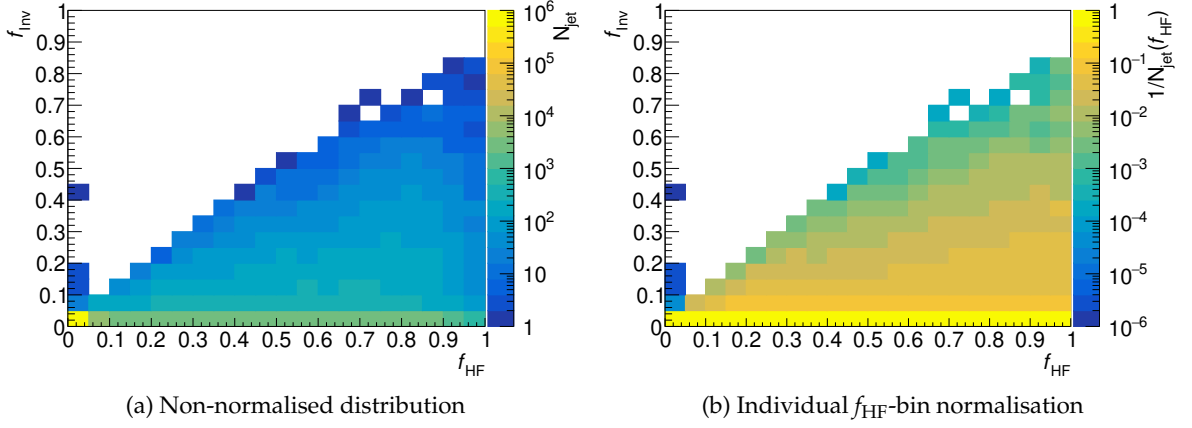


Figure 7.14.: Distribution of jet momentum fraction carried particles from b-meson and b-hadron decays, f_{HF} , versus momentum fraction carried by invisible particles, f_{inv} . (a) Shows non-normalised jet counting-based map. (b) Shows normalisation carried out in individual f_{HF} bins. The latter version is used in DSEG, while the former is provided for context. Jets have been generated with PYTHIA 8 generator at $\sqrt{s} = 13$ TeV.

7.4.4. Pileup combinatorics

Another major boost in statistical power of Double Sliced Event Generation stems from the combinatorial treatment of pile-up jets. In full detector simulation approach, a singular input event can only yield a singular pile-up background outcome. Each jet will be tagged as either pileup or hard scatter jet based on their location in the detector and the results of an appropriate algorithm. DSEG, on the other hand, does not have such a limitation.

After the smearing process is completed, each central jet with p_{T} within $[20, 60]$ GeV is given a probability to be tagged as a pile-up jet based on their kinematics and the chosen vertex fraction as described in Section 7.3.4. Following this, every single possible pile-up tagging combination of these central jets is considered. Starting from all jets not being tagged as pile-up and finishing with all jets tagged as pileup. Since FJVT algorithm is dependent on balancing the pile-up hadronic systems, each forward jets' FJVT (discriminant) has to be reevaluated during each combination. To ensure that such combinatorial event remains physical, the final event weight is suppressed by each central jet pileup tagging probability

$$w \propto w_{\text{PU}} := \prod_{j_{\text{C}}} w_{\text{PU}, j_{\text{C}}} \quad \text{where} \quad w_{\text{PU}, j_{\text{C}}} = \begin{cases} (1 - \mathbb{P}_{\text{PU}}) & \text{if } j_{\text{C}} \text{ is not PU tagged} \\ \mathbb{P}_{\text{PU}} & \text{if } j_{\text{C}} \text{ is PU tagged} \end{cases} \quad (7.29)$$

where j_{C} represents a central jet and $\mathbb{P}_{\text{PU}}$ is its probability to be tagged as a pileup jet. As a consequence, Double Sliced Event Generation is able to produce $2^{n_{j_{\text{C}}}}$ number of events from a singular smeared *Base Event*. The most probable of them being interpreted as the singular outcome one would expect from the full detector simulation.

7.4.5. Leptons veto emulation

As discussed in Section 7.2, the primary origin of the invisible fraction in jets are neutrinos produced from electroweak heavy flavour hadron decays. In order to suppress events with such decays entering the signal region, a lepton veto is typically implemented in analyses relying on $\cancel{E}_T$ and jets. In ATLAS analyses, electrons and muons are differentiated from jets through the overlap removal (OR) procedure. If a candidate electron or a candidate muon overlaps with a candidate jet, the jet is rejected in either case in favour of a well reconstructed lepton candidate (c.f. Table 4.1). In combination with signal region definition (Table 6.1), a multijet event entering the signal region should not contain any leptons as its components. Therefore, it is important for DSEG to be able to emulate lepton contamination within the jet and reject the event if such contamination occurs. This is done in two ways.

One option is to check each parton during jet clustering as described in Section 7.2. If a jet contains an electron or muon passing identification criteria described in Tables 6.9 and 6.10, the jet and subsequently the interaction can be tagged as containing (identifiable) leptons. Then during event selection¹⁷, a veto can be implemented utilising this tag. However, this approach drastically decreases the "seed event" statistics and prevents¹⁸ invisible fraction sampling as described in Section 7.4.3.

Another option is to determine the probability that no jet in the event contains a lepton based on their observables. The probability of an electron or a muon satisfying the veto criteria to appear inside a jet is parametrised as two-dimensional map and given in Figure 7.15. The map is parametrised in jet p_T and f_{inv} . As only neutrinos can contribute to the invisible fraction of the jet, map parametrisation in f_{inv} provides the cleanest method of probability description. While electrons and muons can contribute to other jet fractional properties defined in Section 7.2, there is no such property where only these leptons would contribute to it in a non ad-hoc manner. Similarly to Eq. (7.29), the probability to find a lepton within a given event is jet-cumulative. Hence, each pileup combination of each smeared *Base Event* will have an associated probability to contain a soft lepton given by

$$\mathbb{P}_{\text{lep}} = \prod_{\{j\}} \mathbb{P}_{\text{lep}}^j(p_T^j, f_{\text{inv}}^j) \quad (7.30)$$

where $\{j\}$ represents all selected jets in the event (i.e. signal jets). Since no lepton contamination is expected in the selected event, the final event weight is appropriately suppressed by the improbability of finding a lepton within any of the jets. That is,

$$w_{\text{lep}} = (1 - \mathbb{P}_{\text{lep}}) \quad (7.31)$$

¹⁷Or during event recording to output/storage/disk decision.

¹⁸Or would at minimum force an adjustment to.

7. Double Sliced Event Generation

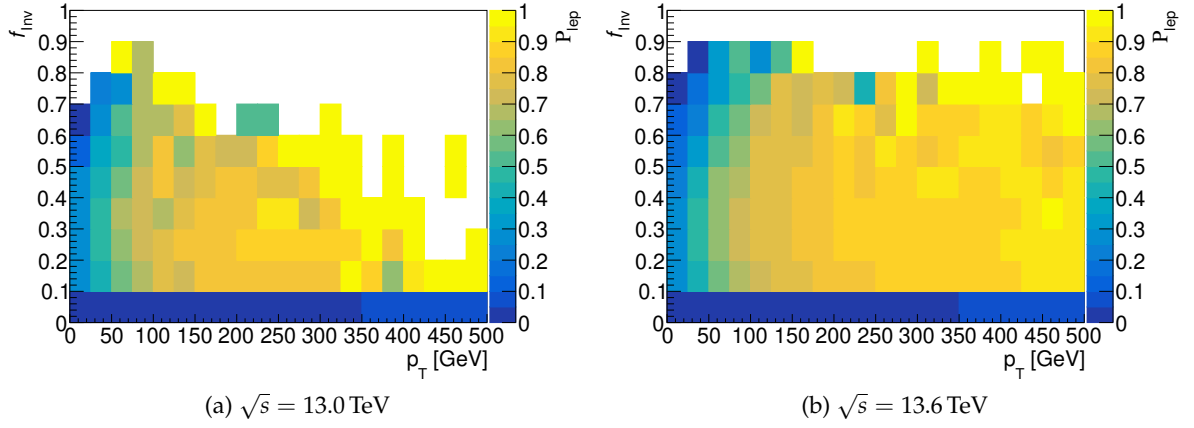


Figure 7.15.: Probability map of finding a *veto* lepton inside a jet. The map is parametrised in jet p_T and the momentum fraction carried by invisible partons, mainly neutrinos, f_{inv} .

7.5. Fraction Fit

Every multijet event generated by Double Sliced Event Generation can be classified into two groups based on their leading jet origin relationship. If both jets originate from the same vertex, the event is considered to be a true hard scatter event, or HS + HS for short; If the jets stem from different vertices, then this event is considered to be a combinatorial background event and is denoted as HS + PU for short. It is important to note, that for the differentiation for both cases, neither of the vertices are required to be the leading one. That is, it is possible to have HS + HS event where both jets originate from a non-leading vertex. Such combination would represent a hard scatter event that left little to no deposition in the hypothetical tracking system during emulation. Since the signal region definitions have been optimised for multijet background suppression, HS + HS events are expected to enter them only in the case where the dijet event is actually a multijet event with its central activity being "lost"¹⁹. On the other hand, the HS + PU background is of greater interest as it represents the conditions where pileup tagging has failed for one of the leading jets. This typically results in events with significant event weight due to incorrect hadronic system reconstruction (See Table 7.1 for an example). Additionally, this background also includes events where one the leading jets is a pileup jet with momentum exceeding the FJVT or JVT tagging thresholds. In both cases, correct modelling of the contribution behaviour is crucial as signal region definition in tandem with the detector tracking system limitation in η are only able to suppress the multijet background, not fully eliminate it.

The focus on correct modelling of the contribution behaviour is one of the strengths of Double Sliced Event Generation as well as one of its shortcomings. The proposed method

¹⁹Recall multiple possible causes for this : jet misreconstruction, detector inefficiencies, incorrect pile-up tagging.

is an emulation based background generator. Through *Base Event* smearing, pileup combinatorics, and other statistics boosting methods DSEG is able to deduce the behaviour of HS + HS and HS + PU events in a given phasespace. Even if, such behaviour is unlikely. However, Double Sliced Event Generation is reliant on many assumptions about jet and detector interactions through their emulation. To overcome this limitation, a normalisation to data procedure - known as fraction fit [211] - is implemented to circumvent this shortcoming.

For the purposes of the fraction fit, consider a multijet enriched phase space close to the signal region but still perpendicular to it. The multijet background contribution in such region should be equivalent to the difference between observed data and the remaining backgrounds. If one assumes that the multijet contribution is comprised from both HS + HS and HS + PU events, then the following equation should hold true for any given region i

$$N_{\text{data}, i} - \sum_{\text{bkg}}^{\text{Non-MJ MC}} [N_{\text{bkg}, i}] - [\alpha_{\text{HSHS}, i} \cdot N_{\text{HS+HS}, i}] - [\beta_{\text{HSPU}, i} \cdot N_{\text{HS+PU}, i}] = 0 \quad (7.32)$$

where N_{data} is the number of data events, N_{bkg} number of non-multijet background events, $N_{\text{HS+HS}, i}$ and $N_{\text{HS+PU}, i}$ number of events from HS + HS and HS + PU contributions, while α_{HSHS} and β_{HSPU} are their corresponding scaling factors in the region. Assuming that there is no kinematic-space-dependence on HS + HS or HS + PU event production, both the scaling factors can be treated as constants. Consequently, Eq. (7.32) can be generalised to a linear equation and both factors can be derived from two independent regions with no overlap.

For the purposes of α_{HSHS} and β_{HSPU} derivation, the azimuthal distance between the two leading jets, $\Delta\phi_{jj}$, is incredibly useful (see Figure 7.16). Since HS + HS are formed from the correct hadronic system, the leading jets are expected to be more back-to-back and $\cancel{E}_T$ would be formed from missed central activity. Hence, such events would accumulate towards larger values of $\Delta\phi_{jj}$. On the other hand, HS + PU event jets are independent in ϕ due to unrelated hadronic system origins. However, in order for such event to enter the signal (or adjacent) region, significant $\cancel{E}_T$ needs to be produced, which is more likely to occur for events with $\Delta\phi_{jj} \rightarrow 0$. Hence, by dividing the resulting $\Delta\phi_{jj}$ region in two in a multijet enriched control region, the scale factors can be given by

$$\alpha_{\text{HSHS}} = \frac{P_A \cdot \Delta_B - P_B \cdot \Delta_A}{H_B \cdot P_A - H_A \cdot P_B} \quad (7.33)$$

and

$$\beta_{\text{HSPU}} = \frac{H_B \cdot \Delta_A - H_A \cdot \Delta_B}{H_B \cdot P_A - H_A \cdot P_B} \quad (7.34)$$

where $H_i \equiv N_{\text{HS+HS}, i}$, $P_i \equiv N_{\text{HS+PU}, i}$, and Δ_i is the difference between N_{data} and all other non multijet backgrounds, N_{bkg} , in a given region i . Note, it is possible to express either of Eqs. (7.33)–(7.34) in terms of the other scalar parameter, e.g., $\alpha_{\text{HSHS}} = \Delta_B - \beta_{\text{HSPU}} \cdot P_B / H_B$. However, the presented definitions are preferred as their uncertainties are fully originating from statistical uncertainties of event count in each $\Delta\phi_{jj}$ region.

7. Double Sliced Event Generation

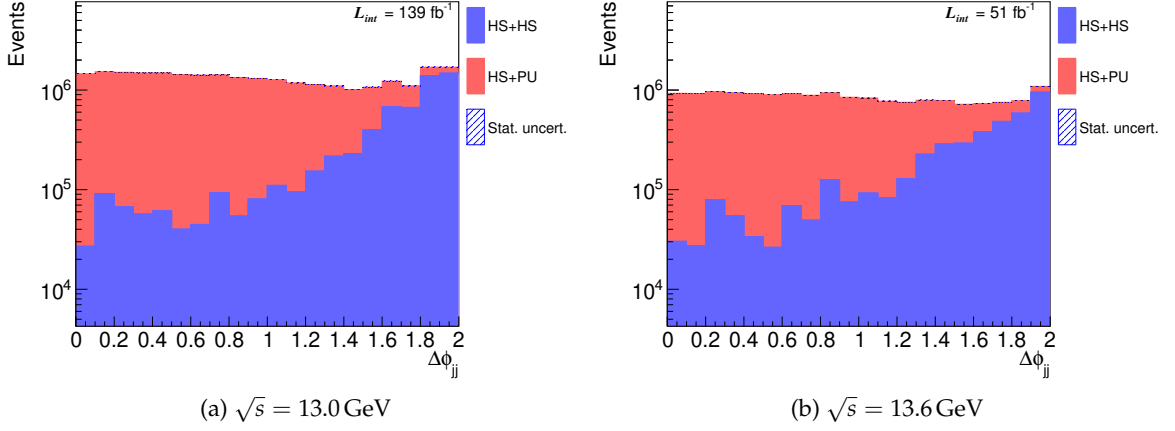


Figure 7.16.: $\Delta\phi_{jj}$ distribution of HS + HS and HS + PU components in *MJCR* (see Section 8.1 for definition) prior to fraction fitting. (a) shows a DSEG dataset covering the full Run 2 data taking period consisting of three sets of 1×10^8 *Base Events* each produced at $\sqrt{s} = 13.0 \text{ GeV}$ and using interaction profiles of 2015+2016, 2017, and 2018 respectively. (b) shows a DSEG dataset covering data taking periods of 2022 and 2023. Each data taking year is represented by a 1×10^8 *Base Events* each produced at $\sqrt{s} = 13.6 \text{ GeV}$ and using the year’s interaction profile.

7.6. Final event weight calculation

The event generation procedure described in Section 7.1 in combination with various statistics boosting techniques discussed in Section 7.4 allow DSEG to drastically increase the statistical size of the generated sample. As a consequence, these changes need to be incorporated into the final event weight to ensure that the weight remains physical. Furthermore, the final Double Sliced Event Generation event weight must also incorporate the $\cancel{E}_T$ trigger emulation (Section 7.3.6) as well as prediction’s normalisation to data through fraction fit (Section 7.5). Therefore, the final event weight for DSEG event is given as

$$w_{\text{DSEG}} = \frac{\sigma_{\text{incl}} \cdot (n_{s\text{LPU}}^2 - (n_{s\text{LPU}} - n_{s\text{HS}})^2) \cdot w_{\cancel{E}_T}^{\text{HS}} \cdot w_{\cancel{E}_T}^{\text{LPU}} \cdot w_{\text{smear}} \cdot w_{\text{PU}} \cdot w_{\text{lep}} \cdot w_{\alpha\beta} \cdot w_{\text{trig}}}{N_{\text{gen}} \cdot n_{\text{smear}} \cdot N_{\text{vtx}}} \quad (7.35)$$

Each component of the weight is broken down as such: σ_{incl} represents the total productions cross-section of the multijet event at any given centre-of-mass energy. Additionally, it is also the cross-section of a general minimum bias interaction production that forms the *SoftPU* basis of the event. The N_{vtx} in the denominator represents the total number of interactions (or (primary) vertices) generated for the event from the interaction profile. The fraction $(n_{s\text{LPU}}^2 - (n_{s\text{LPU}} - n_{s\text{HS}})^2) / N_{\text{gen}}$ is the normalisation factor arising from the hard scatter, *HS*, and leading pileup, *LPU*, interaction distribution in the sampling space (see

7.6. Final event weight calculation

Section 7.1 for the explanation). $w_{\nearrow}^{\text{HS}}$ and $w_{\nearrow}^{\text{LPU}}$ are the abjunction weights for *HS* and *LPU* interactions respectively. They are defined by Eq. (7.4) and represent the probability for each of the hard interactions to be generated with a specific $\hat{p}_T$ range. The normalisation factor n_{smear} accounts for the number of times the *Base Event*, comprised of the *HS*, *LPU*, and *SoftPU* interactions, has been smeared. Its definition is given by Eq. (7.27) and is dynamically dependent on the particular generation slice (i.e. $\hat{p}_T$ range) of the hard interaction pair. Additionally, the w_{smear} term accounts for the invisible fraction sampling carried out between each cycle of smearing (see Section 7.4.3).

Since Double Sliced Event Generation considers every single possible central jet pileup combination, the remaining weight factors in Eq. (7.35) specifically target the properties of such combinations. The probability for such combination to occur is given by w_{PU} (see Eq. (7.29)). w_{lep} , defined in Eq. (7.31), describes the probability of no leptons being included in the selected final state jets. The fraction fit weight, $w_{\alpha\beta}$, adjusts the general Double Sliced Event Generation prediction to the observed data in $\cancel{E}_T$ trigger inefficiency insensitive region. The weight is equivalent to α_{HSHS} or β_{HSPU} depending on whether the event considered matches the *HS* + *HS* or *HS* + *PU* topology respectively (see Section 7.5 for more in-depth discussion). While w_{trig} reflects the probability of such combination to pass the $\cancel{E}_T$ trigger. Most importantly, it also includes the $\cancel{E}_T$ trigger inefficiency slope that is included in the signal region definitions due to relatively low $\cancel{E}_T$ cut (see Section 7.3.6 for an extended discussion).

8. Validation of the Method

In the previous chapter, the methodology for Double Sliced Event Generation method has been presented. The method relies on a reworked approach to simulated background generation using Monte Carlo generators as well as integrates numerous methods commonly used in data-driven approaches. The method also includes different statistics boosting techniques meant to take advantage of this unique combination (described in Section 7.4). Double Sliced Event Generation is able to predict the approximate distribution of multijet events classified according to their dijet systems. If the dijet system is formed by two jets originating from the same vertex, it is assumed to be a true hard scatter interaction and is tagged HS + HS; If the dijet system is formed by jets from different vertices, then the event is presumed to be of combinatorial nature and is denoted as HS + PU. Irrespectively, the prediction needs to be normalised to data through fraction fit procedure (Section 7.5) to be usable in the signal regions of the search. Prior to the method's application to the invisible Higgs decay searches in events with VBF signature (see Section 6), validation of both the statistics boosting techniques and the fraction fit procedure is presented in this chapter.

8.1. Multijet Enriched Control Region

For the purpose of validation and the α_{HSHS} and β_{HSPU} derivation, a multijet enriched control region, *MJCR*, is used. The control region is based on the most populous signal regions used in the previous analysis [7], now represented by the HighMET signal region group (see Table 6.1). The perpendicularity of the control region to the signal region(s) is achieved through the following variable changes: the E_T requirement of $E_T > 200$ GeV is inverted to $E_T \in [100, 200]$ GeV. The E_T lower bound for *MJCR* is not set to 0 as E_T is expected in the signal regions and the *MJCR* is required to be similar to them for fraction fitting. The $\Delta\eta_{jj}$ cut is lowered from 3.8 to 2.5 and the p_T boundary for jet counting is increased from 25 GeV to 35 GeV¹ to boost multijet statistics. Additionally, a more stringent FJVT discriminant, fJVT, cut (0.5 $\rightarrow$ 0.2) is used similarly to LowMET signal region group. Finally, for comparison with data, events triggered by the single jet triggers, rather than E_T based triggers, are used. The full breakdown of the *MJCR* and its comparison to HighMET signal region group is given in Table 8.1.

¹To be more precise a new cut on 3rd jet p_T is used for this purpose instead of the jet counting cut.

8.1. Multijet Enriched Control Region

Requirement	<i>MJCR</i>	HighMET
trigger type	Single Jet Trigger	$\cancel{E}_T$ trigger
N_γ	0	0
N_e	0	0
N_μ	0	0
N_{bjet}	< 2	< 2
$N_{\text{fwd. jet}}$	1	N/A
$p_T(j_0)$	$> 80 \text{ GeV}$	$> 80 \text{ GeV}$
$p_T(j_1)$	$> 50 \text{ GeV}$	$> 50 \text{ GeV}$
$p_T(j_2)$	$< 35 \text{ GeV}$	$< 25 \text{ GeV}$
$\eta(j_0) \cdot \eta(j_1)$	< 0.0	< 0.0
$\text{fJVT}(j_0)$	< 0.2	< 0.5
$\text{fJVT}(j_1)$	< 0.2	< 0.5
$\Delta\eta_{jj}$	> 2.5	> 3.8
$\Delta\phi_{jj}$	< 2.0	< 2.0
m_{jj}	$> 500 \text{ GeV}$	$> 800 \text{ GeV}$
$\cancel{E}_T$	$\in [100, 200] \text{ GeV}$	$> 200 \text{ GeV}$
$\cancel{E}_T^{\text{soft}}$	$< 20 \text{ GeV}$	$< 20 \text{ GeV}$

Table 8.1.: Multijet enriched control region, *MJCR*, comparison with the HighMET signal region. The term (j_i) indicates which jet is used as a reference with jet counting starting from 0, i.e. j_0 identified as leading jet, j_1 identified as subleading jets. The $N_{\text{jet}}(p_T^{\text{jet } i} > 25 \text{ GeV})$ requirement from Table 6.1, has been replaced with a 3rd jet p_T cut

8. Validation of the Method

8.2. Operation Modes

For the purposes of validation, different multijet background samples have been produced with different configurations of the Double Sliced Event Generation technique. In order to facilitate the upcoming discussion, these configurations are classified into three categories which are described below.

To begin with, the *Plain Mode*. The *Plain Mode* describes Double Sliced Event Generation event generation relying only on technique described in Sections 7.1–7.3. That is, operating with no statistics boost. Consequently, the Eq. (7.35) is altered accordingly: the w_{smear} and n_{smear} are set to 1.0 as no dynamic smearing is done and therefore the original invisible fraction for each jet is used. The w_{PU} is set to 1.0 as no pileup combinatorics is carried out and only the most probable outcome is considered: For each jet a real² random number between 0 and 1 is draw from a uniform distribution. If that number is smaller than the probability for the jet to be tagged as pile-up, the jet is tagged as pileup. The w_{lep} is also set to 1.0 as the soft lepton veto is carried out based on the constituent check method described in Section 7.4.5. The values of the remaining two terms of Eq. (7.35) numerator depend on whether the fraction fit and/or the E_T trigger emulation is carried out.

Following this, the *Boosted Mode* builds upon the *Plain Mode*. Depending on which technique described in Section 7.4 is used, its corresponding weight factor begins playing an active role in Eq. (7.35). While each of the statistics boosting techniques in Double Sliced Event Generation can be activated independently of each other, there is a caveat. If one wishes to sample the invisible fraction during smearing, then one must carry out the soft lepton veto through the parametrised map approach. Recall that at generator-level, the invisible fraction of the jet is formed from neutrinos originating from the electroweak decay of b- and c-hadrons. If the invisible fraction is sampled, then the momentum fraction associated to neutrinos in the event is no longer the same as the invisible fraction contained within all jets. Hence, an artificial miscounting of leptons is irrevocably and artificially introduced. For the purposes of signal region estimation, the *Boosted Mode* with all techniques activated is considered to be the default working point.

Finally, the *Basic Mode*. The *Basic Mode* acts as the simplification of the *Plain Mode*. The primary change is that instead of replacing the two $\hat{p}_T$ -wise hardest *SoftPU* interactions, only the hardest one is replaced. That is, *LPU* is kept as *SoftPU*. Consequently, $w_{\text{LPU}}^{\text{LPU}} = 1$ and $(n_{s\text{LPU}}^2 - (n_{s\text{LPU}} - n_{s\text{HS}})^2) = n_{s\text{HS}}$ in Eq. (7.35). The purpose of the *Basic Mode* is to mimic the tradition MC-based background generation approach used in ATLAS (see Section 5.1) as close as possible. Since the methodology of traditional MC background generation differs quite significantly from the one employed in Double Sliced Event Generation, partial comparison between the datasets is impossible. That is, one cannot take a subset of events from PYTHIA 8 multijet background and compare it to some subset of DSEG generated events. Particularly, when one tries to consider the changes between predictions at fine methodological granularity. For example, if one wished to compare 20% of MC20e Pythia

²as in $\mathbb{R}$.

multijet sample with DSEG prediction, how many unique *HS* and *LPU* pairs would need to be generated from the corresponding (2018) average number of interactions per bunch crossing profile? Would it be more correct to compare the same number of pairs as Pythia events before any DSEG event selection? Or is it more correct to continue generating the pairs ad infinitum until the same number of DSEG events pass the selection criteria as Pythia's? Would this number need to change as different statistic boosting techniques are "turned on"? How about the differing event weight calculations (c.f. Eqs. (5.1) and (7.35))? In either of the cases, the comparison between the nominal Pythia multijet and DSEG subsamples would be near impossible. However, it is still of interest to know how different configurations of Double Sliced Event Generation performs against the nominal sample. For this purpose, DSEG can be run in a *Basic Mode* to acquire a prediction of what the nominal generation approach could have yielded given the same conditions³. Additionally, the *Basic Mode* provides a probe to compare DSEG's modelling of various event- or jet-level quantities (e.g., primary vertex fraction (see Section 7.3.3)) versus either simulated or real data.

8.3. Statistics Boost Validation

For the purposes of validating the effectiveness of the statistics boosting techniques described in Section 7.4, 7 sets of 5 million *Base Events* each has been generated using the combined mean number of interactions per bunch crossing profile of all data taking periods covering Run 2 (see Figure 3.3(a)): 1 set has been generated using the *Basic Mode*, 1 set has been generated with the *Plain Mode*, and 5 sets have been generated using the *Boosted Mode* with each individual techniques turned one after another in cumulative fashion. Each set is made off 100 "batches" of 5×10^4 *Base Events* each with each batch being generated using a different RNG seed. All sets have been generated using the same list of unique 100 seeds, hence observed changes between them stem fully from the methodological implementation. Figures 8.1–8.8 provide comparisons between two modes. Figure 8.9 shows computational performance difference between the modes.

Prior to event selection, each generated (final) event is expected to have a $E_T > 100$ GeV, leading jet with $p_T > 60$ GeV, subleading jet with $p_T > 40$ GeV, and no additional jets with $p_T > 50$ GeV. Additionally, the dijet system is expected to have $\Delta\eta_{jj} > 2.0$, $\Delta\phi_{jj} < 2.5$, and $m_{jj} > 200$ GeV. After the event selection, the events are further expected to fulfil the *MJCR* criteria described in Section 8.1. If otherwise unspecified, the soft lepton veto and pileup tagging approach follows the *Plain Mode* approach described in the previous section.

Figure 8.1 shows the comparison between the *Basic Mode* and the *Plain Mode* of Double Sliced Event Generation event generation. The former is used as a substitute for a "traditional" MC-based background, while the latter represents the most simplistic implementation of DSEG methodology. It can be seen that the *Plain Mode* approach is able to produce events spanning a wider variable-space compared to its *Basic Mode* counterpart. Additionally, the

³Though it is still important to note, that this is not 1-to-1 comparison as DSEG does not utilise detector interaction simulation through GEANT4 as it is done during the nominal MC background generation.

8. Validation of the Method

Plain Mode is already showing statistical uncertainty improvement for some variable modelling. For example, for $\Delta\phi_{jj}$ distribution (Figure 8.2(c)) $\delta_{\text{stat}}^{\text{Plain}} \sim 50\%$ while $\delta_{\text{stat}}^{\text{Basic}} \sim 100\%$. However, the *Plain Mode* still exhibits the large generated event weight problem as discussed in Section 6.2 as the majority of variable distribution bins seem to be filled by individual events (e.g., $m_{jj} > 1.5 \text{ TeV}$ in Figure 8.1(a)).

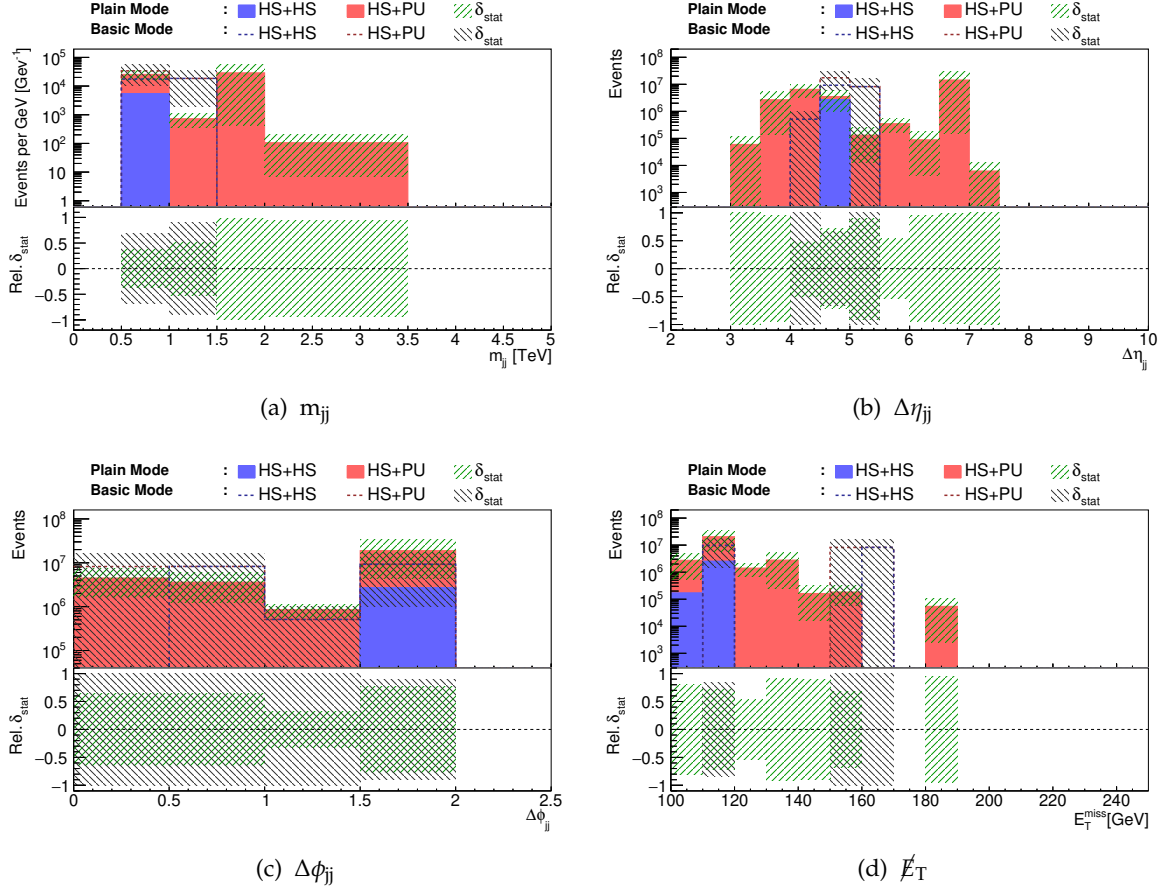


Figure 8.1.: Comparison between DSEG *Basic Mode* (dashed lines) and DSEG *Plain Mode* (solid lines) multijet background estimation in MJCR. Both estimations are produced from 5×10^6 Base Events generated using the full Run 2 interaction profile (with the same list of RNG seeds). No Luminosity scaling, fraction fit, nor $\cancel{E}_T$ trigger emulation is applied. Events are separated into HS + HS (blue) and HS + PU (red) contributions. The *Plain Mode* statistical uncertainty is shown in green, while the *Basic Mode* statistical uncertainty is shown in grey.

Figure 8.2 compares the effect of reusing *SoftPU* between each *HS* and *LPU* generation cycle. Note, during each of these cycles the *SoftPU* interaction collection remains unaltered. Hence, some biasing of the events is expected. However, the effect should be minimal as the

majority of the jets should stem from the two hardest $\hat{p}_T$ interactions. Comparing it with *Plain Mode*, it can be seen that some changes in variable distribution have occurred as either new heavily weighted generated events were formed ($\Delta\phi_{jj} \in [1.0, 1.5]$ in Figure 8.2(c)) or previously generated ones could no longer be formed ($\cancel{E}_T \in [180, 200]$ GeV in Figure 8.2(d)). The primary benefit of the *SoftPU* reuse is the increase in event generation speed which can be easily seen in Figure 8.9(c).

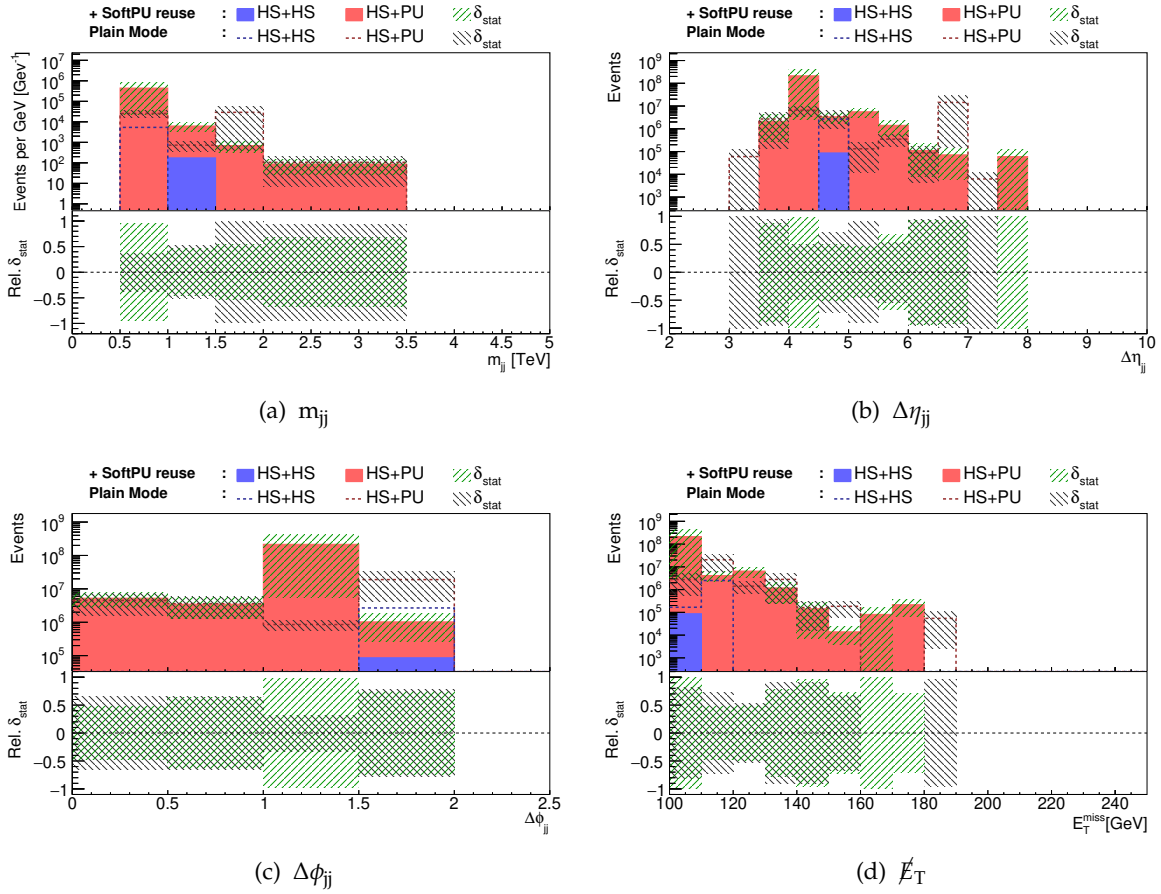


Figure 8.2.: Comparison between DSEG *Plain Mode* (dashed lines) and DSEG *Boosted Mode* (solid lines) with *SoftPU* reused during hard interaction generation (solid lines) multijet background estimations in *MJCR*. The *Boosted Mode* consists of *SoftPU* reuse during hard interaction generation (Section 7.4.1). Both estimations are produced from 5×10^6 *Base Events* generated using the full Run 2 interaction profile (with the same list of RNG seeds). No Luminosity scaling, fraction fit, nor $\cancel{E}_T$ trigger emulation is applied. Events are separated into HS + HS (blue) and HS + PU (red) contributions. The *Boosted Mode* statistical uncertainty is shown in green, while the *Plain Mode* statistical uncertainty is shown in grey.

8. Validation of the Method

The primary boost in both statistical precision and distribution modelling extension is expected from dynamical smearing described in Section 7.4.2. The jump in pure event count due to dynamical smearing can be clearly observed in Figure 8.9(a). On the other hand, Figure 8.3 shows the variable modelling and precision changes when this is implemented in tandem with already discussed improvements of DSEG. The statistical uncertainty drops to percent-level precision with a wider range of possible variable values now being well modelled. Additionally, the expected $\Delta\phi_{jj}$ behaviour of the two multijet background component⁴ can be seen in Figure 8.3(c).

To further ensure that dynamical smearing is not biased by a particular combination of *HS* and *LPU* interactions, the $\eta - \phi$ scrambling procedure (described in Sections 7.4.1 and 7.4.2) is included into the *Boosted Mode*. The effects of this change can be seen in Figure 8.4. Similarly to *SoftPU* reuse, some shape differences between the *HS + HS* and *HS + PU* contribution modelling is expected and can be observed. The cause of this is the fact that each *Base Events* before smearing is guaranteed to be different to its predecessor as well as its successor. Consequently, a slight (indirect) boost in statistical precision can also be observed.

To introduce variance to $\cancel{E}_T$ modelling, the invisible fraction of the jet, f_{inv} , is additionally sampled during smearing as described in Section 7.4.3. Consequently, the soft lepton veto implementation is also changed from constituent-check to probabilistic map implementation⁵. These additional changes versus previously discussed ones are visualised in Figure 8.5. As expected, no major improvements or changes in statistical precision is observed. The greatest modelling change is seen in the $\cancel{E}_T$ distribution (Figure 8.5(d)).

The final component needed to reach the full *Boosted Mode* of Double Sliced Event Generation is activation of pileup combinatorics. As discussed in Section 7.4.4, rather than considering the most probable pileup tagging combination of central jets, all possible combinations are considered. Hence, a possible 2^n , where n is the number of central jets, boost to event count is possible. The effects of this change are shown in Figure 8.6.

Figure 8.8 compares the full *Boosted Mode* of DSEG with the *Plain Mode* version of estimation. Similarly, Figure 8.7 carries out the same comparison with *Basic Mode*. In both cases, the drastic difference in statistical precision and variable-space modelling is observed when *Boosted Mode* is used. Furthermore, a direct improvement of both generated (and selected) event count as well as the generation frequency can be seen in Figure 8.9 when the three primary modes are compared.

8.4. Fraction Fit Validation

Since *MJCR* is defined by low $\cancel{E}_T$ events with the cut placed below the $\cancel{E}_T$ trigger efficiency plateau, $\cancel{E}_T$ triggered data cannot be used for fraction fit parameter deduction (Eqs. (7.33) and (7.34)). Hence, the scale factors are derived using single jet triggered data. While the

⁴See discussion on *HS + HS* and *HS + PU* identification in Sections 6.2 and 7.5

⁵For more details about implementation see Section 7.4.5. For why, see Section 8.2.

8.4. Fraction Fit Validation

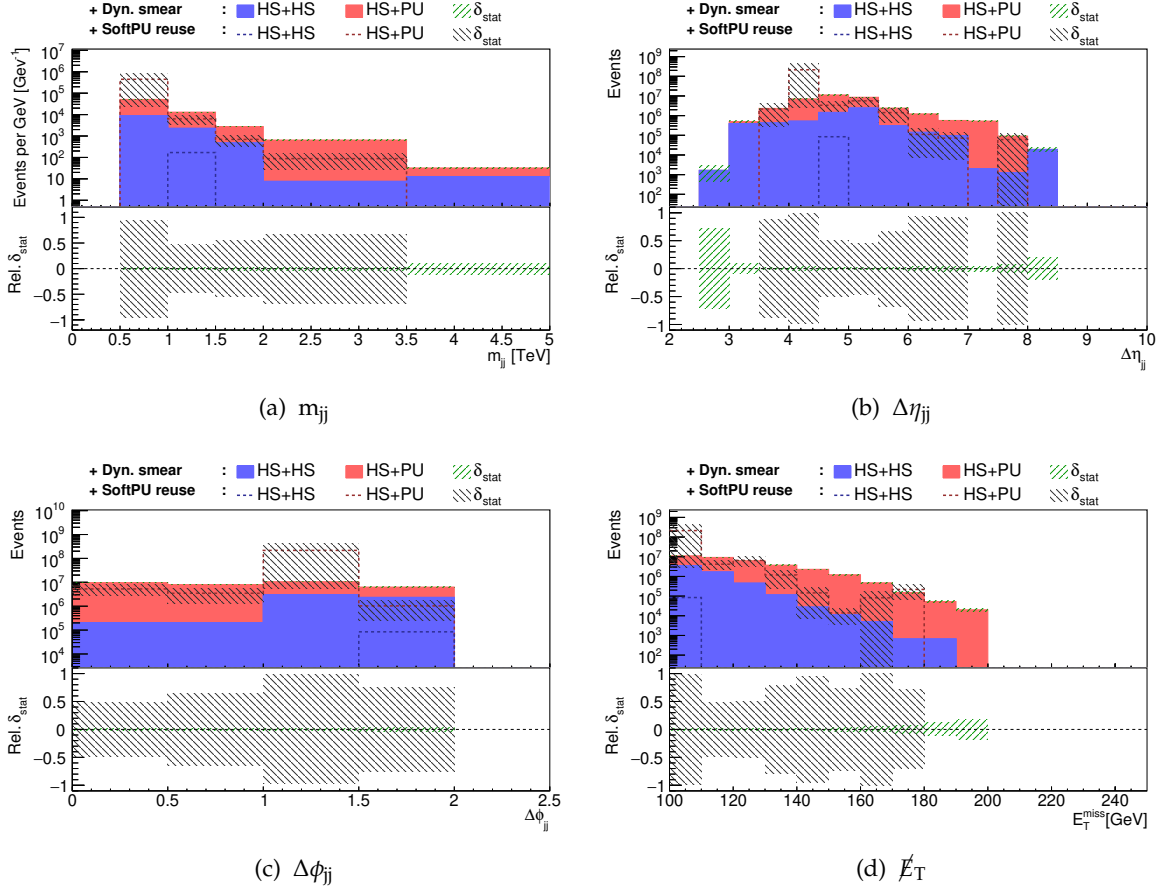


Figure 8.3.: Comparison between DSEG *Boosted Mode* multijet background estimation in MJCR with (solid) and without (dashed lines) dynamical smearing being applied. Apart from the dynamical smearing (Section 7.4.2), the *Boosted Mode* is also made of *SoftPU* reuse during hard interaction generation (Section 7.4.1). Both estimations are produced from 5×10^6 *Base Events* generated using the full Run 2 interaction profile (with the same list of RNG seeds). No Luminosity scaling, fraction fit, nor E_T trigger emulation is applied. Events are separated into HS + HS (blue) and HS + PU (red) contributions. The statistical uncertainty for dynamical smearing application is shown in green, while the statistical uncertainty of *Boosted Mode* without it is shown in grey.

8. Validation of the Method

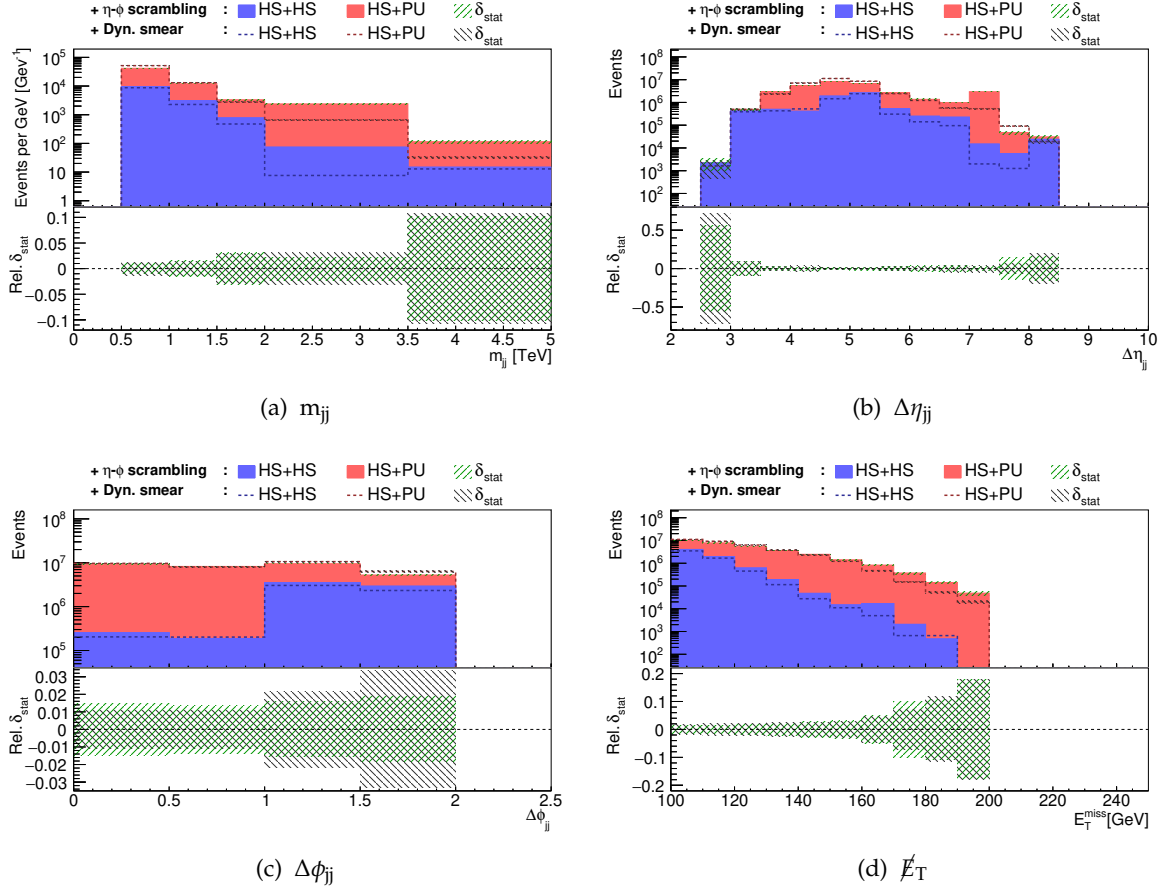


Figure 8.4.: Comparison between DSEG *Boosted Mode* multijet background estimation in MJCR with (solid) and without (dashed lines) $\eta - \phi$ scrambling. Apart from the $\eta - \phi$ scrambling (Section 7.4.1), the *Boosted Mode* is additionally comprised of *SoftPU* reuse during hard interaction generation (Section 7.4.1) and dynamical smearing (Section 7.4.2). Both estimations are produced from 5×10^6 *Base Events* generated using the full Run 2 interaction profile (with the same list of RNG seeds). No Luminosity scaling, fraction fit, nor E_T trigger emulation is applied. Events are separated into HS + HS (blue) and HS + PU (red) contributions. The statistical uncertainty for method with $\eta - \phi$ scrambling is shown in green, while the statistical uncertainty of *Boosted Mode* without it is shown in grey.

8.4. Fraction Fit Validation

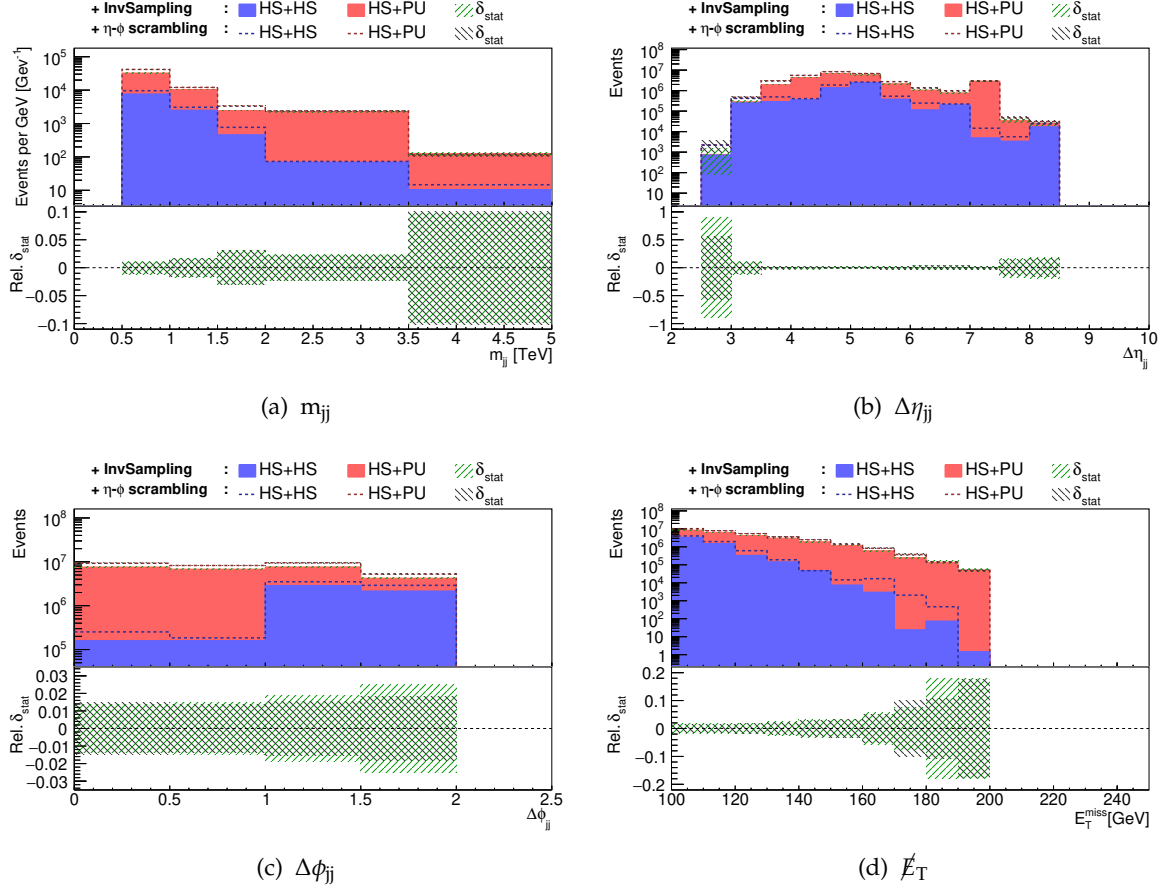


Figure 8.5.: Comparison between DSEG *Boosted Mode* multijet background estimation in MJCR with (solid) and without (dashed lines) invisible fraction sampling during smearing and map-based soft lepton veto application. Apart from the invisible fraction sampling (Section 7.4.3) and the soft lepton veto emulation through probability map (Section 7.4.5), the *Boosted Mode* is additionally comprised of *SoftPU* reuse during hard interaction generation, $\eta - \phi$ scrambling (Section 7.4.1) and dynamical smearing (Section 7.4.2). Both estimations are produced from 5×10^6 *Base Events* generated using the full Run 2 interaction profile (with the same list of RNG seeds). No Luminosity scaling, fraction fit, nor E_T^{miss} trigger emulation is applied. Events are separated into HS + HS (blue) and HS + PU (red) contributions. The statistical uncertainty for method with invisible fraction sampling and soft lepton veto is shown in green, while the statistical uncertainty of *Boosted Mode* without it is shown in grey.

8. Validation of the Method

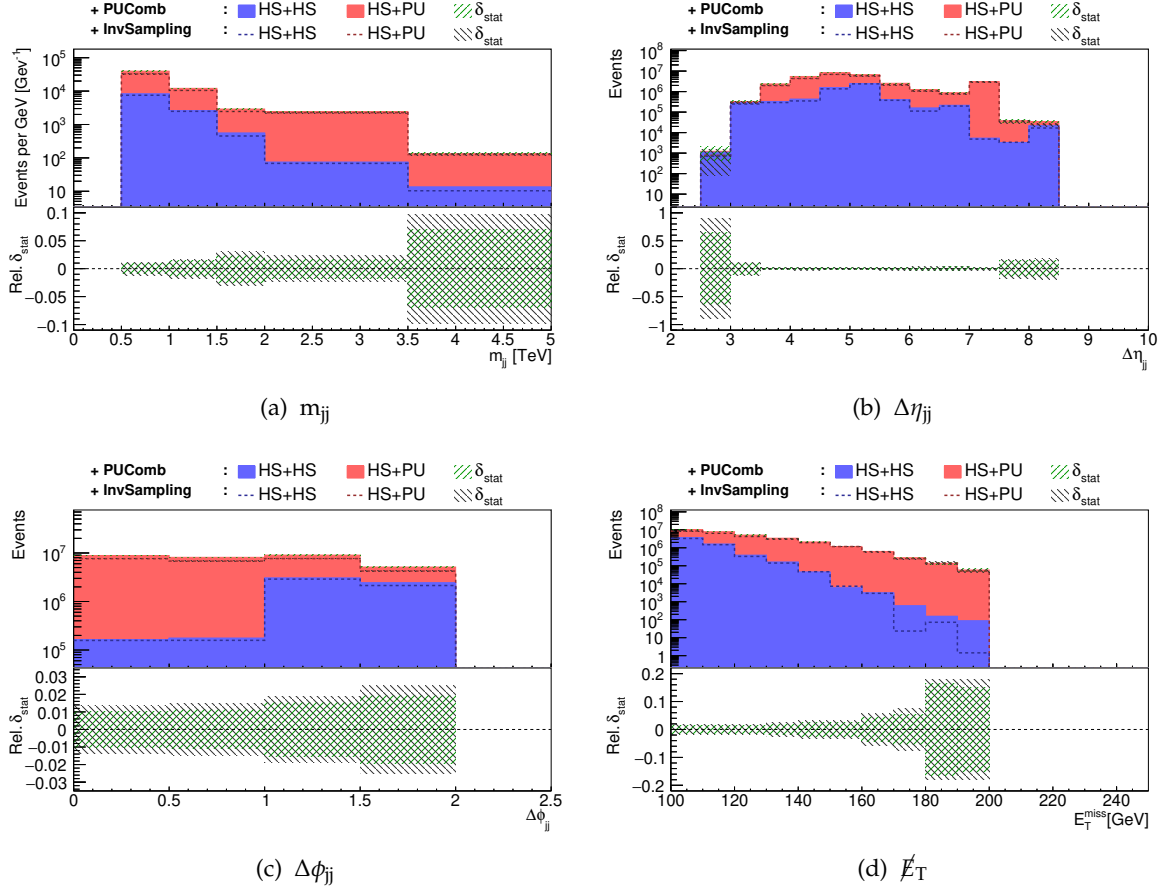


Figure 8.6.: Comparison between DSEG *Boosted Mode* multijet background estimation in MJCR with (solid) and without (dashed lines) pileup combinatorics. Apart from the pile-up combinatorics (Section 7.4.4), the *Boosted Mode* is additionally comprised of *SoftPU* reuse during hard interaction generation, $\eta - \phi$ scrambling (Section 7.4.1), dynamical smearing (Section 7.4.2), invisible fraction sampling during it (Section 7.4.3), and probabilistic soft lepton veto (Section 7.4.5). Both estimations are produced from 5×10^6 *Base Events* generated using the full Run 2 interaction profile (with the same list of RNG seeds). No Luminosity scaling, fraction fit, nor E_T trigger emulation is applied. Events are separated into HS + HS (blue) and HS + PU (red) contributions. The statistical uncertainty for method with pileup combinatorics is shown in green, while the statistical uncertainty of *Boosted Mode* without it is shown in grey.

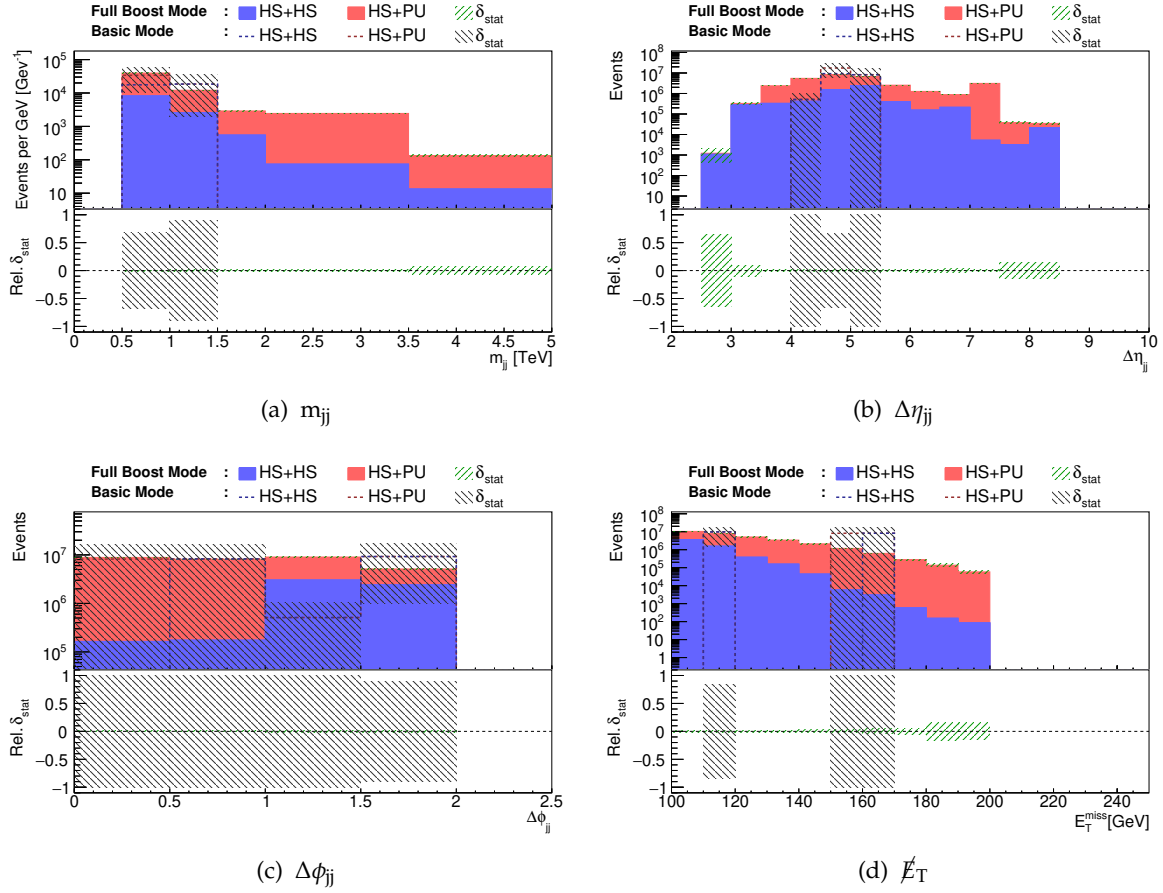


Figure 8.7.: Comparison between DSEG *Basic Mode* (dashed lines) and the full *Boosted Mode* (solid lines) multijet background estimation in MJCR. The full *Boosted Mode* includes all statistics boosting techniques described in Section 7.4. Both estimations are produced from 5×10^6 *Base Events* generated using the full Run 2 interaction profile (with the same list of RNG seeds). No Luminosity scaling, fraction fit, nor E_T trigger emulation is applied. Events are separated into HS + HS (blue) and HS + PU (red) contributions. The statistical uncertainty for full *Boosted Mode* is shown in green, while the statistical uncertainty for *Basic Mode* is shown in grey.

8. Validation of the Method

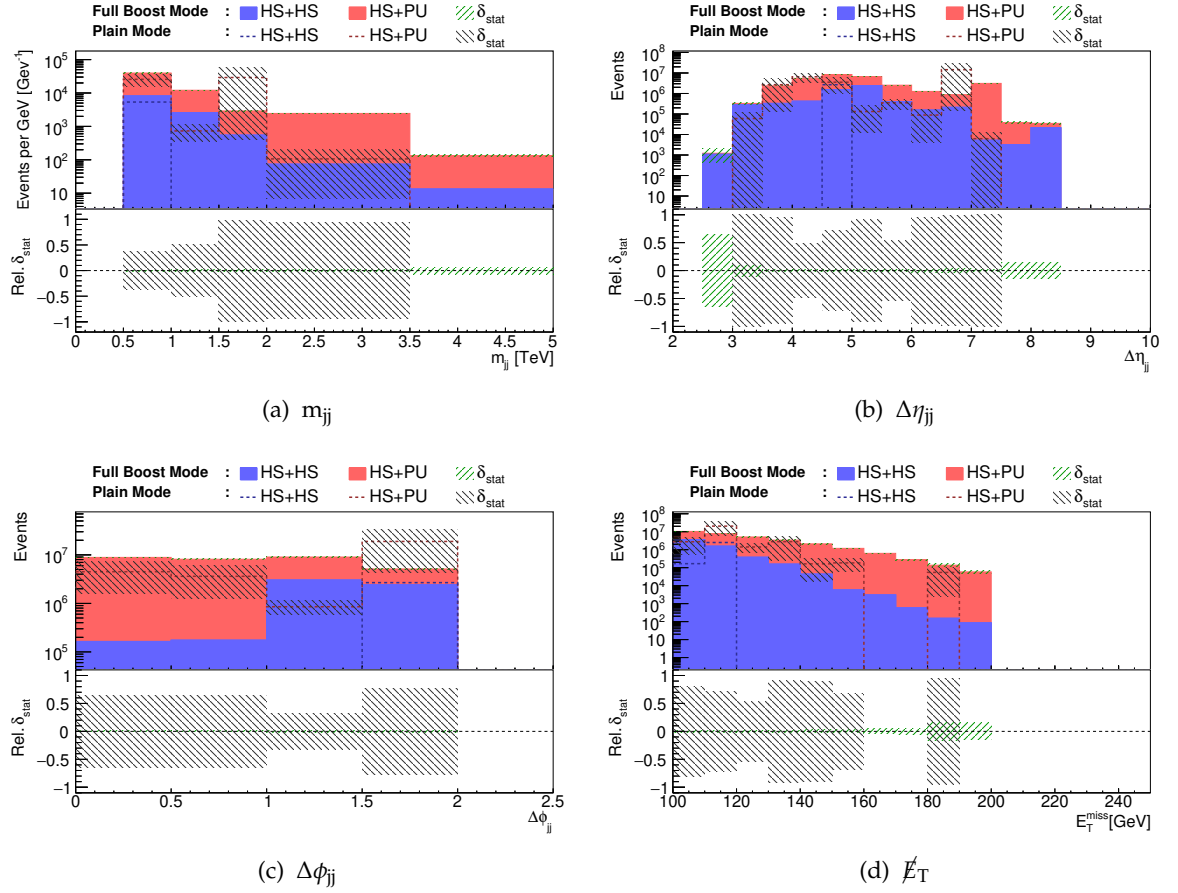


Figure 8.8.: Comparison between DSEG *Plain Mode* (dashed lines) and the full *Boosted Mode* (solid lines) multijet background estimation in MJCR. The full *Boosted Mode* includes all statistics boosting techniques described in Section 7.4. Both estimations are produced from 5×10^6 *Base Events* generated using the full Run 2 interaction profile (with the same list of RNG seeds). No Luminosity scaling, fraction fit, nor $\cancel{E}_T$ trigger emulation is applied. Events are separated into HS + HS (blue) and HS + PU (red) contributions. The statistical uncertainty for full *Boosted Mode* is shown in green, while the statistical uncertainty for *Plain Mode* is shown in grey.

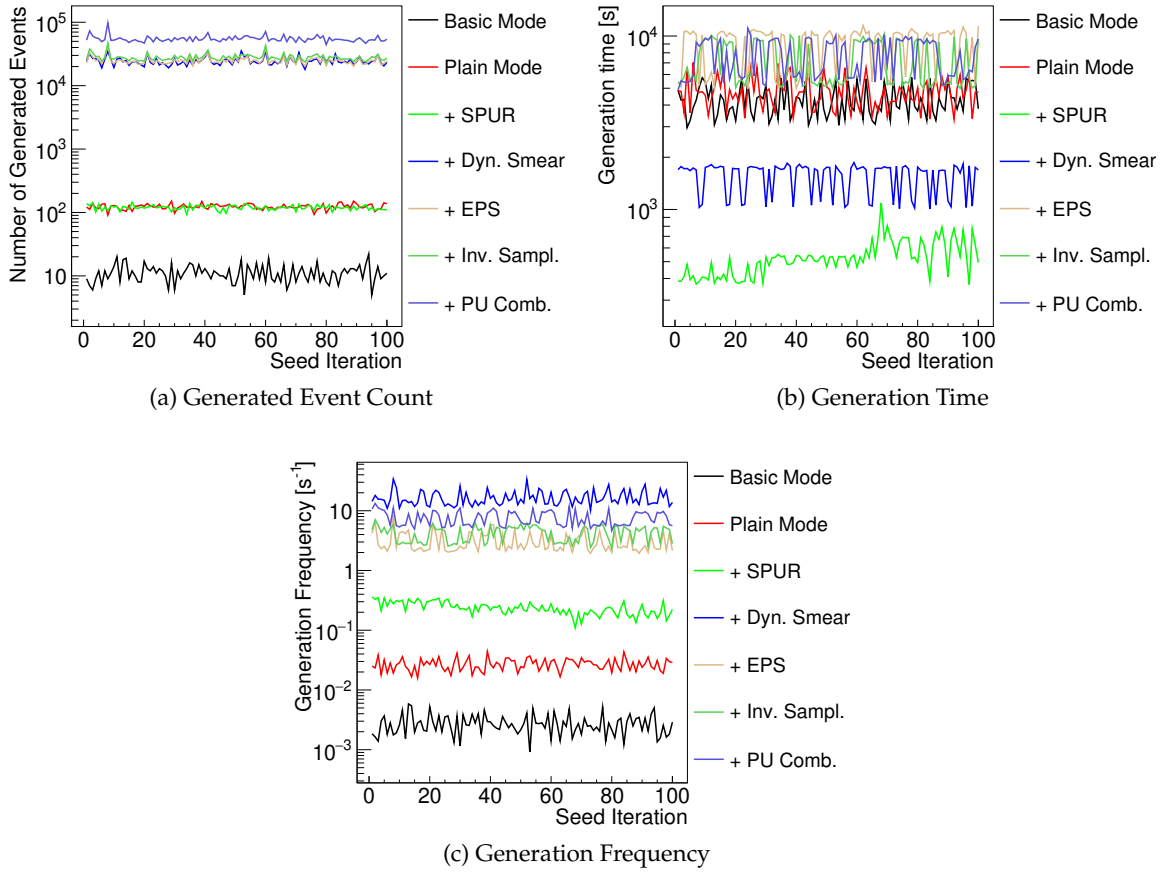


Figure 8.9.: Computational performance comparison between different DSEG operation modes and various statistics boosting techniques. 100 batches of 5×10^4 *Base Events* were generated using the full Run 2 interaction profile (with the same list of RNG seeds) for each mode under consideration. The *Boosted Mode* is split into individual boosting techniques (as described in Section 7.4): *SoftPU* reuse (+ *SPUR*), dynamical smearing (+ *Dyn. Smear*), $\eta - \phi$ scrambling (+ *EPS*), invisible fraction sampling and soft lepton veto emulation (+ *Inv. Sampl.*), and pileup combinatorics (+ *PU Comb.*). All boosting techniques are applied in cumulative fashion. Computation performance is evaluated using three basic metrics: (a) shows the (unweighted) number of events generated by each batch. No Luminosity scaling, fraction fit, nor E_T trigger emulation scaling is applied. (b) shows the total time needed for each version of the estimation process to finish to completion. (c) shows the generation frequency of the modes. The frequency is pragmatically defined as Figure (a) / Figure (b). The methods in the legends are listed in descending order of complexity from the least complex, *Basic Mode*, to the most complex mode, full *Boosted Mode* (indicated by + *PU Comb.*).

8. Validation of the Method

resulting dataset is comparatively lower in statistical power, it is insensitive to the MET trigger inefficiencies and differing inefficiency behaviour between data and MC samples. That is, perfectly suited for both scale factor derivation and Double Sliced Event Generation performance comparison.

For the purposes of validating of the fraction fit method and deriving the α_{HSHS} and β_{HSPU} parameters for signal region estimation, a set of multijet events for each year of data taking⁶ have been generated. Each set consists of 500 batches of 2×10^5 *Base Events* (1×10^8 in total) with each batch generated using a different RNG seed with no seed sharing between the sets. Each set has been generated using its corresponding mean number of interaction per bunch crossing profile, except for 2015 and 2016, which have been merged into a singular profile (vis-à-vis MC20a c.f. Section 5.1).

Prior to event selection, each generated (final) event is expected to have a $E_T > 100$ GeV, leading jet with $p_T > 80$ GeV, subleading jet with $p_T > 50$ GeV, and no additional jets with $p_T > 50$ GeV. Additionally, the dijet system is expected to have $\Delta\eta_{jj} > 2.0$, $\Delta\phi_{jj} < 2.5$, and $m_{jj} > 200$ GeV. After the event selection, the events are further expected to fulfil the enriched multijet control region selection criteria. Each event is also scaled by luminosity, $\mathcal{L}_{\text{int}}$, corresponding to the data taking period for which it has been generated.

Two approaches to deriving α_{HSHS} and β_{HSPU} have been considered : fitting-by-year, where for each data taking period a corresponding set of parameters would be derived, and fitting-by-run, where the parameters are derived for full data taking periods, i.e. Run 2 and Run 3. Furthermore, multiple variations of *MJCR* have been considered for this by varying the third jet p_T requirement from 25 GeV to 50 GeV in steps of 5 GeV. Eventually, combination of the *MJCR* definition given in Section 8.1 and fitting-by-run has been selected as the optimal one. The control region is as similar to signal region as possible, α_{HSHS} and β_{HSPU} never become negative after the fit⁷, and the single jet trigger data is not depleted of statistics. The results of the fraction fit procedure are shown in Figures 8.10 and 8.11 for full Run 2 and partial Run 3 respectively.

⁶2015-2018 + 2022 + 2023

⁷Which while mathematically would be correct, would not make sense from physics perspective.

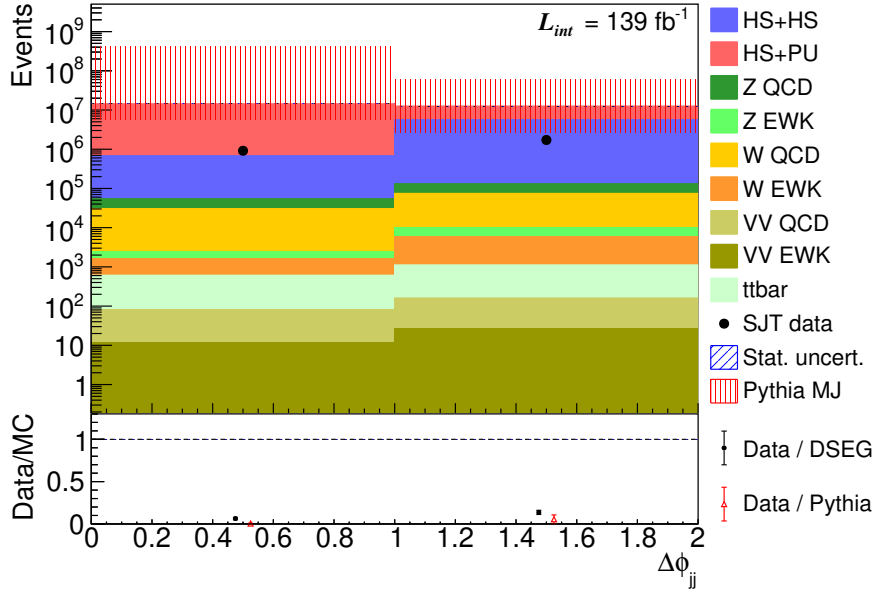
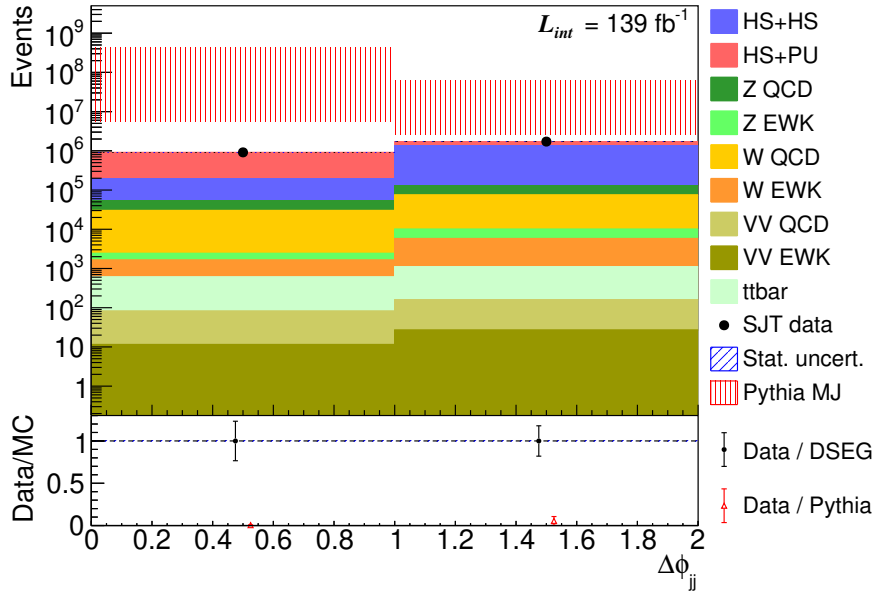
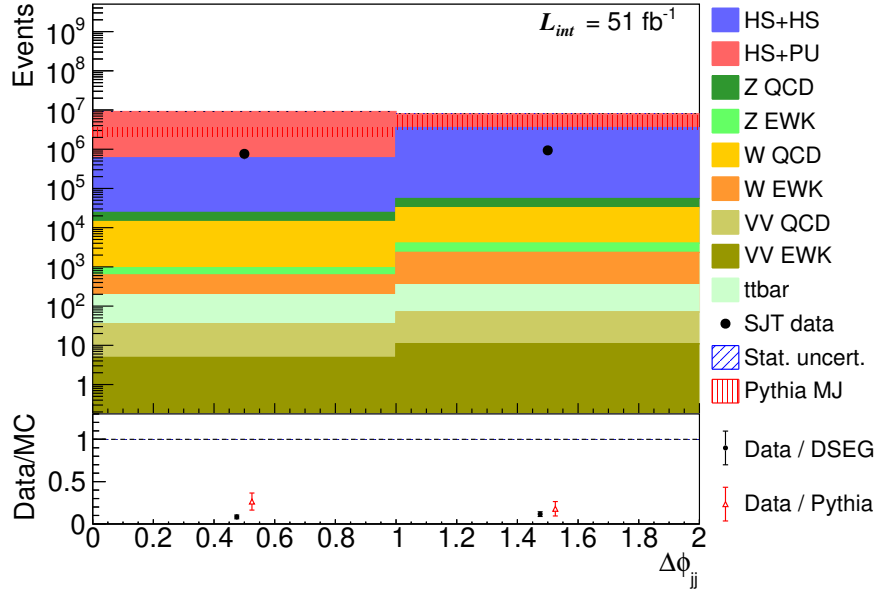
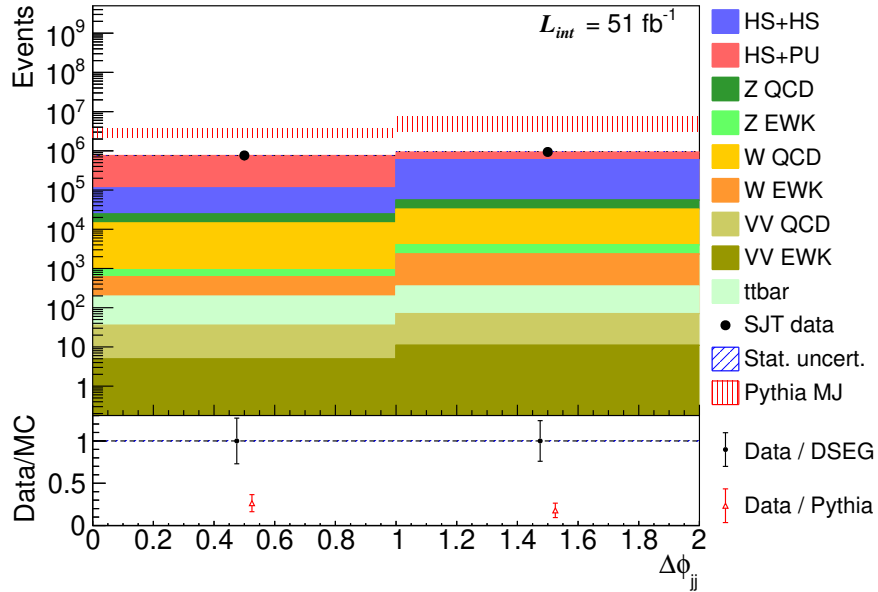
(a) $\Delta\phi_{jj}$ comparison prior to fraction fit(b) $\Delta\phi_{jj}$ comparison post fraction fit

Figure 8.10.: $\Delta\phi_{jj}$ distribution comparison between single jet triggered data (full Run 2), MC backgrounds, and Double Sliced Event Generation events. (a) shows variable distributions before fraction fitting. (b) shows variable distributions after fraction fitting. Both multijet background modelling options are shown: using DSEG (solid colours and individual distributions) and nominal PYTHIA 8 based multijet background (inclusive strike through fill). Regarding the latter, the DSEG component is replaced by the PYTHIA MC prediction and the total event count is shown.

8. Validation of the Method



(a) $\Delta\phi_{jj}$ comparison prior to fraction fit



(b) $\Delta\phi_{jj}$ comparison post fraction fit

Figure 8.11.: $\Delta\phi_{jj}$ distribution comparison between single jet triggered data (2022+2023), MC backgrounds, and Double Sliced Event Generation events. (a) shows variable distributions before fraction fitting. (b) shows variable distributions after fraction fitting. Both multijet background modelling options are shown: using DSEG (solid colours and individual distributions) and nominal PYTHIA 8 based multijet background (inclusive strike through fill). Regarding the latter, the DSEG component is replaced by the PYTHIA MC prediction and the total event count is shown.

9. Statistical and Systematic Uncertainties of Double Sliced Event Generation

In order to have confidence in the predicted contribution of the multijet background to the signal region, it is important to understand the uncertainties introduced by the method. Two types of uncertainties are typically used to define the precision of any measurement or predictions. The statistical uncertainty represents the limitations introduced by the finite size of the data sample. On the other hand, limitations introduced due to experimental setup (e.g., finite precision on jet energy resolution measurement) or theoretical assumptions of the underlying physics are encompassed by the systematic uncertainties. Naïvely one would expect that Double Sliced Event Generation would not require a dedicated statistical uncertainty handling procedure and only the systematic uncertainties need to be addressed. While it is true, that the latter plays a crucial role due to DSEG's employment of probabilistic and in some aspects simplified approach to detector interaction emulation, due to the multijet background separation into HS + HS and HS + PU categories and the stringent definitions of the signal region, the former also requires attention. Hence, in total, Double Sliced Event Generation contains two statistical uncertainties, one for each type of category, and five types of systematic uncertainties related to the 5 primary steps in emulation: jet energy resolution, δ_{JER} , jet energy scale, δ_{JES} , pileup tagging, δ_{PU} , fraction fit, $\delta_{\alpha\beta}$, and MET trigger emulation, δ_{trigger} .

9.1. Statistical uncertainty evaluation

Given a large sample of independent event statistics, one can estimate the uncertainty of a measurement from such sample simply through

$$\delta_{\text{(stat.)}} = \sqrt{\sum_i w_i^2} \quad (9.1)$$

where w_i is the individual event weight. While Double Sliced Event Generation, differently to its predecessors, is not limited in statistics it can utilise per-say, the stringent signal region selection in combination with how DSEG operates gives rise to an interesting niche case that needs to be addressed. Consider a *Base Event* entering the signal region twice at different dynamical smearing cycles. If in both cases, the dijet system is formed from different hadronic systems, i.e. the event is considered to be of HS + PU category, then the two states of the *Base Event* during different smearing cycles can be thought as independent events. Recall, that before each cycle both hard interactions are scrambled in the $\eta - \phi$ space

9. Statistical and Systematic Uncertainties of Double Sliced Event Generation

and the resulting overlay of the interaction will be different (c.f. Figure 7.13). Hence, it is possible to form different dijet systems at each smearing cycle. However, if the dijet system is formed from the same interaction, i.e. it's a HS + HS event, then neither $\eta - \phi$ scrambling nor any other procedure will fundamentally change the *Base Event*. That means, that near identical *Base Event* can enter the signal region multiple times. Furthermore, since the signal region definitions aim to suppress particular category of events, the resulting population of this contribution might be only comprised of few unique *Base Events*. While this does not pose a problem with unphysically large event weights that one would expect from HS + PU combinations, the underlying assumption of independent events of Eq. (9.1) no longer applies. Hence, each category of multijet events requires an independent statistical uncertainty. Since the same HS + PU *Base Event* at different smearing cycles can be treated as independent events, the statistical uncertainty for HS + PU events follows Eq. (9.1) as before. On the other hand, the HS + HS statistical uncertainty needs to be evaluated using the bootstrapping method [212] with the proposed implementation.

Rather than filling a one-dimensional histogram after the event selection, a two dimension histogram is filled instead. Assuming that the $x - y$ plane represents the original one-dimensional histogram, the z-axis then becomes the bootstrapping axis consisting of N number of bins with the 0th bin¹ identified with the original histogram². When a new HS + HS *Base Event* would fill the original histogram, the 0th bin of the z-axis is filled with w_{DSEG} (Eq. (7.35)). Then the remaining $N - 1$ bins are then filled consecutively with $N - 1$ independent (bootstrap) augmentations of w_{DSEG} , i.e. $w_{\text{DSEG}} \cdot z_i$. Each factor $z_i \in \mathbb{Z}$ is drawn from a Poissonian distribution centred on unity and represents an independent recreation of the estimation using a replicated identical dataset. If $z_i = 1$, the *Base Event* is interpreted to have entered the region only once (as it expected in the nominal prediction or the 0th bin); If $z_i = 2$, the event enters an additional time; If $z_i = 0$ the event does not enter and so on. When all HS + HS events have been selected, then for each x-bin, the average value of the corresponding $z - y$ plane distribution should be centred on w_{DSEG} in a Poissonian fashion with the standard deviation identified as the statistical uncertainty of the prediction for that x-bin.

9.2. Systematic uncertainty evaluation

In order to evaluate the systematic uncertainties, the most straightforward approach would be to run multiple instance of the Double Sliced Event Generation generator with the slight change in configuration reflecting the systematic variation. However, considering that neither of the systematic uncertainties is affecting the event, interaction, or *Base Jet* kinematics before the ATLAS detector interaction emulation, this is not the most efficient method. For example, consider the JER systematic uncertainty, δ_{JER} . From the perspective

¹Assuming standard array counting, i.e. starting from 0.

²Operating under the assumption that HS + HS and HS + PU fill their own 1D histograms independently.

9.2. Systematic uncertainty evaluation

of the method it only enters in Eqs. (7.10)–(7.13) through alteration of $\mathcal{R}$

$$\mathcal{R}_{\text{Nominal}} \subset \text{Gaus}(1, \sigma_{\text{JER}}) \quad \mathcal{R}_{\text{Syst}} \subset \text{Gaus}(1, \sigma_{\text{JER}} + \delta_{\text{JER}}) \quad (9.2)$$

Similarly, the jet energy scale uncertainty would be interpreted as

$$\mathcal{R}_{\text{Nominal}} \subset \text{Gaus}(1, \sigma_{\text{JER}}) \quad \mathcal{R}_{\text{Syst}} \subset \text{Gaus}(1 + \delta_{\text{JES}}, \sigma_{\text{JER}}) \quad (9.3)$$

In all three cases, the (p_x, p_y, p_z, E) base that would be smeared according to any $\mathcal{R}$ would be identical. In the straightforward approach, this would lead to wasted computational time and storage resources. Hence, Double Sliced Event Generation employs a different approach to systematic evaluation based on *TruthBasis*

***TruthBasis* systematic variation**

As described in Section 7.3.1, after the generator level *Base Event* is formed from the combination of the *HS*, *LPU*, *SoftPU* interactions all the individual interaction jets are treated as belonging to the same event, are smeared (including *HS* and *LPU* interaction jet $\eta - \phi$ scrambling), and merged. During this procedure three important aspects are to be noted:

- During $\eta - \phi$ scrambling, the alteration is applied to the generator level (p_x, p_y, p_z, E) basis³. That is given two iterations of scrambling, the resulting jets have the same generator basis.
- During dynamical smearing, the $\mathcal{R}$ scaling (Eqs. (7.10)–(7.13)) is applied to the scrambled (p_x, p_y, p_z, E) basis. That is given two iterations of smearing, during smearing the jets will have differing smeared and scrambled bases, but the same generator basis.
- If this smeared and scrambled basis is identified as the "truth" basis, then the resulting event can be treated as independent even if it shares a generator basis with another event.

That is, after smearing but before the jet merging, the smeared jets have their truth momenta set to their scrambled basis. The scrambled basis jet fractional properties are also recorded as truth level properties (i.e. are not altered during merging). Additionally, both the truth, $\mathcal{R}_{\text{truth}}$, and the visible⁴, $\mathcal{R}_{\text{vis}}$, responses are also associated to each jet. The combination of the (new) truth momenta, jet fractional properties, and $\mathcal{R}_{\text{truth}}$ is identified as the *TruthBasis* of the smeared jet.

Following jet smearing and merging, the resulting merged jets are pile-up tagged and undergo pile-up combinatorics as per Section 7.3.4. If any of the central-jet pileup combination is able to produce an event that satisfies predefined event selection criteria, the full *TruthBasis* of all the jets (including the ones that had been merged into other jets) is saved for systematic evaluation. If more than one such combination produces the applicable event,

9. Statistical and Systematic Uncertainties of Double Sliced Event Generation

Selection	<i>MJCR</i>	Systematic Evaluation
p_T^{j0}	$> 80 \text{ GeV}$	$> 60 \text{ GeV}$
p_T^{j1}	$> 50 \text{ GeV}$	$> 40 \text{ GeV}$
E_T	$\in [100, 200] \text{ GeV}$	$> 100 \text{ GeV}$
$\Delta\phi_{jj}$	< 2.0	< 2.0
$\Delta\eta_{jj}$	> 2.5	> 2.5
n_{lep}	0	0
Opp. hemispherity dijet system formed by	leading jets	any two jets

Table 9.1.: Double Sliced Event Generation Event for systematic evaluation selection criteria and *MJCR* comparison. Note, while for the systematic evaluation selection the criteria is shown as complete, for *MJCR* the comparison is not fully extensive. For more details please see Table 8.1.

the full *TruthBasis* is not saved additional times. For the purposes for this analysis, the selection criteria are similar to Table 8.1 and are shown in Table 9.1.

After the nominal production is completed, the various *TruthBases* comprising the final event selection are used to derive the systematic uncertainties for the method. During the procedure, for each saved *TruthBasis* a jet collection is created. Then, for each systematic uncertainty, an independent smeared jet set is formed from the *TruthBasis* jet collection with the smearing being carried out as a scaling operation between the Truth momenta, invisible fraction, and the truth response (c.f. Eqs. (7.10)–(7.13))

$$p_T^{\text{sys}} \rightarrow p_T^{\text{truth}} \cdot \mathcal{R}_{\text{truth}} \cdot (1 - f_{\text{inv}}^{\text{truth}}) \quad p_x^{\text{sys}} \rightarrow p_x^{\text{truth}} \cdot \mathcal{R}_{\text{truth}} \cdot (1 - f_{\text{inv}}^{\text{truth}}) \quad (9.4)$$

$$\eta^{\text{sys}} \rightarrow \eta^{\text{truth}} \quad p_y^{\text{sys}} \rightarrow p_y^{\text{truth}} \cdot \mathcal{R}_{\text{truth}} \cdot (1 - f_{\text{inv}}^{\text{truth}}) \quad (9.5)$$

$$\phi^{\text{sys}} \rightarrow \phi^{\text{truth}} \quad p_z^{\text{sys}} \rightarrow p_z^{\text{truth}} \cdot \mathcal{R}_{\text{truth}} \cdot (1 - f_{\text{inv}}^{\text{truth}}) \quad (9.6)$$

$$m^{\text{sys}} \rightarrow m^{\text{truth}} \cdot \mathcal{R}_{\text{truth}} \cdot (1 - f_{\text{inv}}^{\text{truth}}) \quad E^{\text{sys}} \rightarrow E^{\text{truth}} \cdot \mathcal{R}_{\text{truth}} \cdot (1 - f_{\text{inv}}^{\text{truth}}) \quad (9.7)$$

The resulting jets are then merged, pileup-tagged, undergo pileup combinatorics, and probabilistic soft lepton veto like before forming an independent systematic event. The resulting events are then fraction fitted in *MJCR* and compared to the nominal variation⁵ in the *MJCR*. The only exception to this are the fraction fit and E_T trigger emulation uncertainties which are evaluated using independent method.

³Here *basis* refers equivalently to either (p_x, p_y, p_z, E) or (p_T, η, ϕ, m) basis.

⁴Evaluated as $\mathcal{R} \times (1 - f_{\text{inv}})$.

⁵Note: for the purposes of full comparison an independent nominal variation is constructed from *TruthBases* and used for comparison.

9.2.1. Jet Energy Scale Uncertainty

As described in Section 7.3.1, the jet response, $\mathcal{R}$, is randomly drawn from a Gaussian distribution centred on unity with its standard deviation set to σ_{JER}

$$\mathcal{R} \subset \text{Gaus}(\mu, \sigma) \Big|_{\mu=1, \sigma=\sigma_{\text{JER}}} \quad (9.8)$$

The effects of the JES uncertainty, δ_{JES} , can be thought of as the offset of the Gaussian from unity. Hence, in the context of Eqs. (9.4)–(9.7), the Jet energy scale uncertainty enters as an additional modification parameter for the visible response calculation

$$\mathcal{R}_{\text{JES UP}} = \mathcal{R}_{\text{truth}} \cdot (1 - f_{\text{inv}}^{\text{truth}}) \cdot (1 + \delta_{\text{JES}}) \quad (9.9)$$

$$\mathcal{R}_{\text{JES DOWN}} = \mathcal{R}_{\text{truth}} \cdot (1 - f_{\text{inv}}^{\text{truth}}) \cdot (1 - \delta_{\text{JES}}) \quad (9.10)$$

During Run2 the jet energy scale systematic uncertainty for central jets $|\eta| < 1.2$ has been found to vary between 1% to 5% from very low p_{T} (20 GeV) to very high p_{T} (< 2 TeV) jets [106]. The distribution of the total fractional δ_{JES} for data taking periods between 2015 and 2017 is shown in Figure 9.1. For the purposes of estimating effects of δ_{JES} , the JES uncertainty has been conservatively set to 4% for samples created using interaction profiles covering Run 2. Similar uncertainty is also applied to samples produced using year 2022 and 2023 interaction profiles as specific uncertainty measurement for these years has not yet been made public.

9.2.2. Jet Energy Resolution Uncertainty

In a similar approach as above, the uncertainty in jet energy resolution shown in Eq. (9.3) can be reinterpreted as a broadening augmentation factor to the visible response calculations

$$\mathcal{R}_{\text{JER UP}} = (\mathcal{R}_{\text{visible}} - 1) \cdot (1 + \delta_{\text{JER}}) + 1 \quad (9.11)$$

$$\mathcal{R}_{\text{JER DOWN}} = (\mathcal{R}_{\text{visible}} - 1) \cdot (1 - \delta_{\text{JER}}) + 1 \quad (9.12)$$

where $\mathcal{R}_{\text{visible}}$ is the visible response given by $\mathcal{R}_{\text{truth}} \cdot (1 - f_{\text{inv}}^{\text{truth}})$. During Run 2, the difference between jet energy response in MC and data has been found to around 10% [106] (see Figure 9.2). Hence, for the purposes of systematic uncertainty derivation for DSEG, δ_{JER} is also set to 0.1 for samples covering all data taking periods under consideration.

9.2.3. Pileup tagging uncertainties

As described in Section 7.3.4, Double Sliced Event Generation handles jet pileup tagging based on the differentiation if the jet is considered to be central or not. Subsequently, this gives rise to two categories of uncertainties: The central pileup tagging uncertainty, δ_{PU} , covers uncertainties introduced by pileup tagging of the central jets. The FJVT uncertainty, δ_{FJVT} , covers the forward jet tagging. However, due to pile-up combinatorics of the central

9. Statistical and Systematic Uncertainties of Double Sliced Event Generation

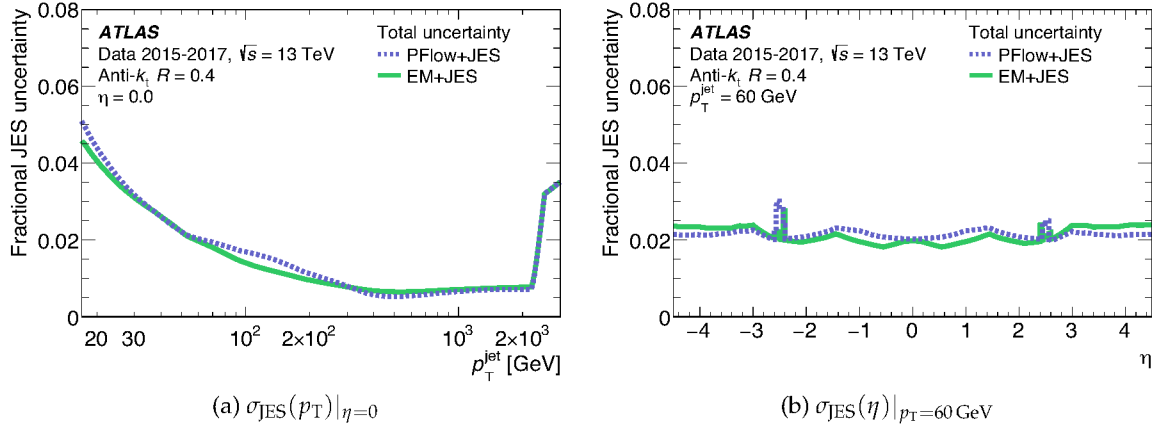


Figure 9.1.: Total fractional jet energy scale systematic uncertainty for PFlow and EMTopo jets. Uncertainty includes all JES uncertainty components for anti- k_t $R = 0.4$ jets with topology-dependent components calculated assuming a dijet flavour composition. (a) shows the total fractional uncertainty as a function of jet's p_T evaluated at the centre of the detector ($\eta = 0$). (b) shows the total fractional uncertainty as a function of jet's η for jets with ($p_T = 60$ GeV). Plots taken from [106].

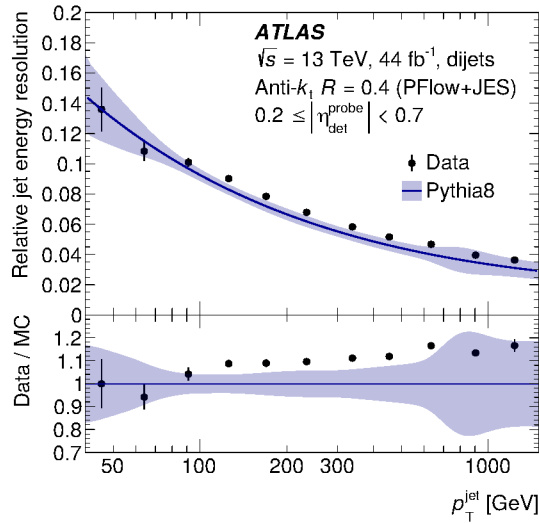


Figure 9.2.: Relative jet energy resolution for PFlow jets in the central region of the detector measured using the dijet balance method. Plots taken from [106].

9.2. Systematic uncertainty evaluation

jets and consequential changes in the fJVT score because of it, these uncertainties cannot be treated as typical *up-down* uncertainties, rather they are included as *multipoint* uncertainties.

For central jet tagging, these uncertainty points are represented by the three options provided in Section 7.3.4: vertex-, PVF-, and corrPVF-based tagging with PVF-based tagging assumed to be nominal. During estimation, the largest and the smallest (including non-existent) deviation from the nominal are recorded for each bin for each variable distribution being considered. Then the symmetrised uncertainty centred around the nominal value is evaluated as the averaged quadrature sum of the deviations for each bin.

For forward jet tagging, only two methods based on different ways of reconstructing the missing transverse momentum for a given vertex are considered. Both FJVT methods are build as close equivalents to ones applied in ATLAS. However, due to $\vec{p}_T^{\text{PF}}$ (or to be more precise Eq. (4.15)) being more sensitive to track modelling, the $\vec{p}_T^{\text{EMTP}}$ based approach is taken as nominal value with $\vec{p}_T^{\text{PF}}$ used for systematic variation evaluation. Similarly to δ_{PU} , δ_{fJVT} is evaluated as a multipoint variation around nominal estimation. However, since only a singular point of reference is used, no symmetrisation is carried out.

The distributions and expected impact of both systematic uncertainties for all campaigns is shown in Figures 9.3 and 9.4 in the context of the enriched multijet control region defined in Table 8.1. As it can be seen, the greatest impact is expected from the central pileup tagging, particularly for modelling of E_T . On the other hand, the effects of the uncertainty associated with fJVT modelling, δ_{fJVT} , are miniscule. This minimal impact is associated to the very narrow window where the FJVT cut is applied at all in both signal and *MJCR*. Recall that FJVT is only applicable to jets with $p_T < 60$ GeV and due to the leading jet p_T requirements, only the subleading jet is sensitive to this cut at a narrow 10 GeV window. Hence, in the current iteration of the method, the δ_{fJVT} is neglected and only δ_{PU} is considered and propagated.

9.2.4. Fraction Fit Uncertainty

As mentioned in Section 7.5, the systematic uncertainty for the derived fraction fit parameters fully originates from the individual events count terms of Eqs. (7.33) and (7.33). If the α_{HSHS} and β_{HSPU} were expressed in the general function form of $c(\{N_i\})$, where $\{N_i\}$ is the set of event count terms defining the parameter, then the uncertainty for said parameter would be simply given by

$$\delta_c = \sqrt{\sum_{N_i}^{\{N_i\}} \left[\left(\frac{\partial c(\{N_i\})}{\partial N_i} \delta_{\text{stat}}^{N_i} \right)^2 \right]} \quad (9.13)$$

where $\delta_{\text{stat}}^{N_i}$ is the statistical uncertainty associated with the event count N_i and δ_c is assumed to be symmetrical. Since α_{HSHS} and β_{HSPU} are evaluated in separate regions and all event count terms N_i are expected to be independent of one another, no correlation between the terms in Eq. (9.13) is expected. However, since Double Sliced Event Generation is a newly developed method, the systematic uncertainties associated to the fraction fit parameters are

9. Statistical and Systematic Uncertainties of Double Sliced Event Generation

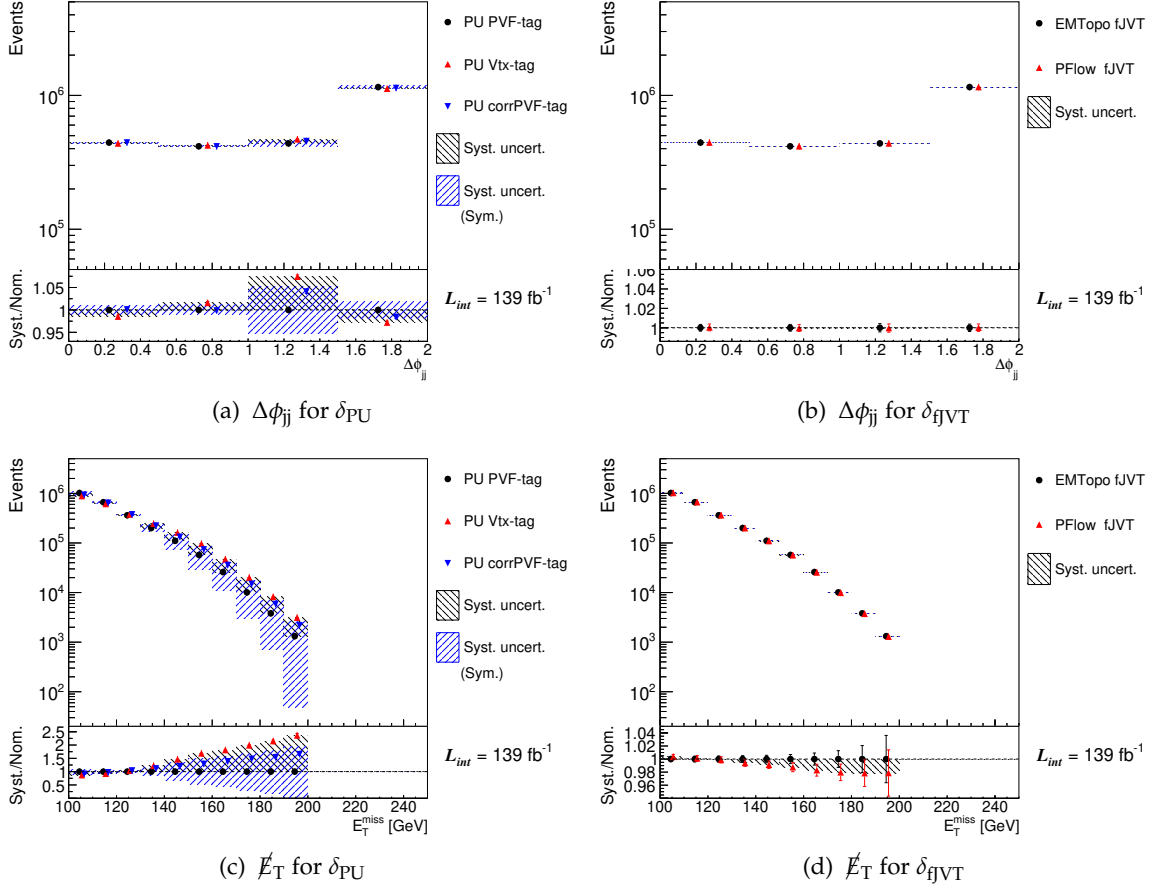


Figure 9.3.: Multipoint systematic uncertainties associated to pileup tagging of Run 2-based DSEG samples in MJCR. Independent DSEG samples have been generated for each individual data taking years spanning Run 2 (except 2015 and 2016, which have been merged). Each sample is scaled according to corresponding year's $\mathcal{L}_{\text{int}}$ and all samples are fraction fit as described in Section 8.4. (a) and (c) show the systematic uncertainty related to central jet pile-up tagging for $\Delta\phi_{jj}$ and $\cancel{E}_T$ distributions respectively; (b) and (d) show the systematic uncertainty related to forward jet pile-up tagging for $\Delta\phi_{jj}$ and $\cancel{E}_T$ distributions respectively; Both individual and symmetrised systematic uncertainties are shown for δ_{PU} while only non-symmetrised uncertainty is shown for δ_{fJVT} .

9.2. Systematic uncertainty evaluation

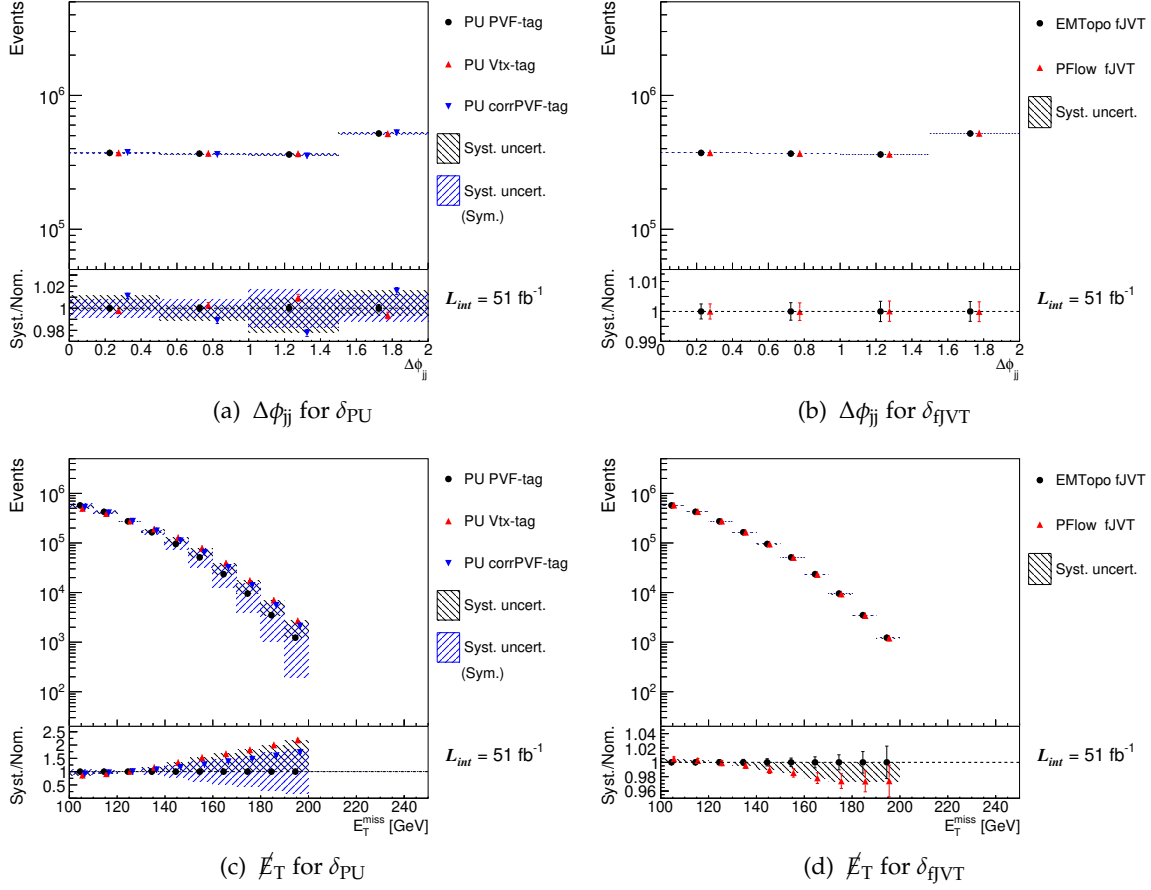


Figure 9.4.: Multipoint systematic uncertainties associated to pileup tagging of Run 3-based DSEG samples in MJCR. Independent DSEG samples have been generated for each individual data taking years comprising partial Run 3. Each sample is scaled according to corresponding year's $\mathcal{L}_{int}$ and all samples are fraction fit as described in Section 8.4. (a) and (c) show the systematic uncertainty related to central jet pile-up tagging for $\Delta\phi_{jj}$ and $\cancel{E}_T$ distributions respectively; (b) and (d) show the systematic uncertainty related to forward jet pile-up tagging for $\Delta\phi_{jj}$ and $\cancel{E}_T$ distributions respectively; Both individual and symmetrised systematic uncertainties are shown for δ_{PU} while only non-symmetrised uncertainty is shown for δ_{fjVT} .

9. Statistical and Systematic Uncertainties of Double Sliced Event Generation

conservatively assumed to be fully correlated. That is,

$$\delta_{\alpha\beta}^{\text{UP}} \Rightarrow \alpha_{\text{HSHS}} + \delta_{\alpha_{\text{HSHS}}}^{\text{UP}} \quad \text{and} \quad \beta_{\text{HSPU}} + \delta_{\beta_{\text{HSPU}}}^{\text{UP}} \quad (9.14)$$

The derived numerical values and their associated uncertainties are shown in Table 9.2. The dominant contribution to the uncertainty is the statistical limitation of the data sample.

Normalisation Period	α_{HSHS}	β_{HSPU}
Run 2	0.22522 ± 0.06424	0.05249 ± 0.01671
Run 3	0.15377 ± 0.07752	0.07570 ± 0.02660

Table 9.2.: Fraction fit parameters for Run 2 and Run 3 normalisation-by-run fraction fitting. The parameters have been derived in *MJCR* using single jet triggered data as described in Section 8.4. The dominant contribution to the uncertainty is the statistical limitation of the data sample. Both parameters are conservatively assumed to be fully correlated

9.2.5. Missing Transverse Energy Trigger Emulation Uncertainty

The emulation maps and their corresponding MET trigger efficiencies presented in Section 7.3.6 are not dependent on $\cancel{E}_T$ but rather attempt to approximate it through H_T and $\cancel{H}_T$ ⁶. Consequently, this will not result in a one-to-one mapping from data to DSEG events. The uncertainty of such two-dimensional parametrisation is assumed to be symmetric and is defined as a function of offline $\cancel{E}_T$:

$$\delta_{\text{trigger}}(\cancel{E}_T) = \frac{|\epsilon_{\text{real}}(\cancel{E}_T^{\text{TST}}) - \epsilon_{\text{map}}(\cancel{E}_T^{\text{TST}})|}{\epsilon_{\text{map}}(\cancel{E}_T^{\text{TST}})} \quad (9.15)$$

where ϵ_{real} is the actual missing transverse energy trigger efficiency calculated as

$$\epsilon_{\text{real}}(\cancel{E}_T) = \frac{N_{\text{SJT} + \text{MET}}(\cancel{E}_T^{\text{TST}})}{N_{\text{SJT}}(\cancel{E}_T^{\text{TST}})} \quad (9.16)$$

and ϵ_{map} represents the mapped efficiency performance, i.e.

$$\epsilon_{\text{map}}(\cancel{E}_T) = \frac{N_{\text{SJT}}(\cancel{E}_T^{\text{TST}}) \cdot \epsilon_{\text{trigger}}(H_T, \cancel{E}_T^{\text{CST}})}{N_{\text{SJT}}(\cancel{E}_T^{\text{TST}})} \quad (9.17)$$

That is the ratio of all single jet triggered events scaled by their probability to pass the trigger versus their unscaled count. Note, simplification $\epsilon_{\text{map}}(\cancel{E}_T) \equiv \epsilon_{\text{trigger}}(H_T, \cancel{E}_T^{\text{CST}})$ is

⁶Or $\cancel{E}_T^{\text{CST}}$ in case for data.

9.2. Systematic uncertainty evaluation

not possible. Though $\cancel{E}_T$ is approximated through $(H_T, \cancel{E}_T^{\text{CST}})$, events with the same $\cancel{E}_T$ may have differing $(H_T, \cancel{E}_T^{\text{CST}})$ combinations. The trigger systematic uncertainties have been evaluated using single jet triggered data and are shown in Figure 9.5. The uncertainty acts as an augmentation of the trigger emulation weight factor in Eq. (7.35). That is

$$w_{\text{trig}}^{\text{syst}}(\cancel{E}_T) = w_{\text{trig}}(\cancel{E}_T) \cdot (1 \pm \delta_{\text{trigger}}(\cancel{E}_T)) \quad (9.18)$$

9. Statistical and Systematic Uncertainties of Double Sliced Event Generation

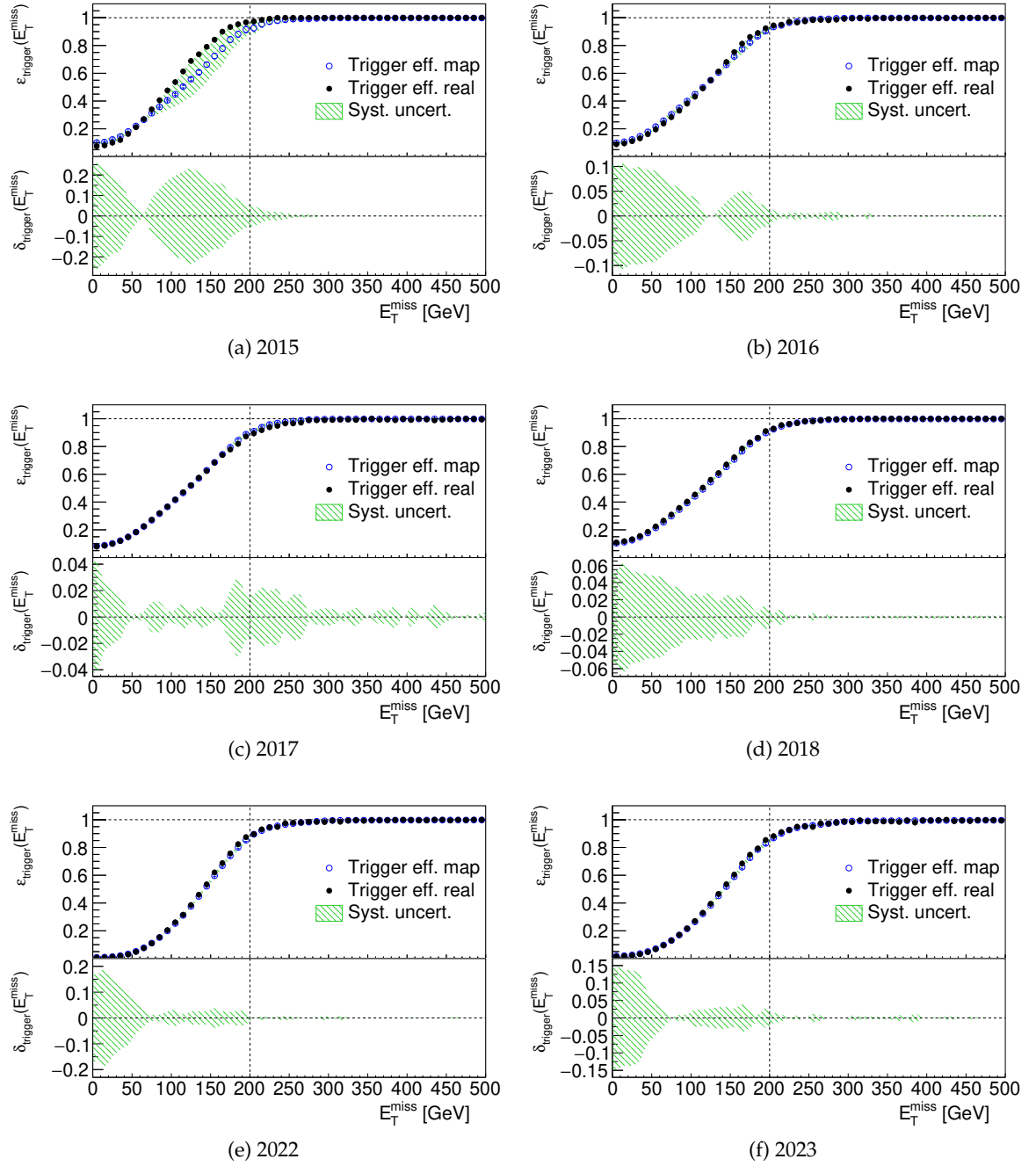


Figure 9.5.: E_T trigger modelling efficiency and systematic uncertainty for individual data taking years: 2015 (a), 2016 (b), 2017 (c), 2018 (d), 2022 (e), 2023 (f). The map modelling efficiency and associated uncertainty shown for single jet triggered data using E_T^{TST} .

10. Performance and Results : Multijet Background Estimation in the Signal Regions

Similarly to fraction fit validation described in Section 8.4, the Double Sliced Event Generation prediction of multijet background in the signal region is formed from individual dataset representing each data taking year, except 2015 and 2016 which have been merged together. Each set consists of 500 batches of 2×10^5 *Base Events*. Each batch is generated using a unique RNG seed and uses its corresponding year's mean number of interactions per bunch crossing profile (see Figure 3.3) to draw a random number of interactions per *Base Event*.

These *Base Events* are then used to form *TruthBases* as described in Section 9.2. These *TruthBases* are then used to derive both the nominal prediction and the six systematically varied predictions described in Sections 9.2.1–9.2.3. All the derived variations are then independently fraction fitted in the *MJCR* as per Sections 7.5 and 8.4 to ensure that any modelling difference between the nominal and each systematically varied prediction is fraction fit independent. Consequently, the systematical uncertainty relating to fraction fit (Section 9.2.4) is assumed to be fully uncorrelated with the other systematical uncertainties, hence is only applicable to the nominal sample. For the fitting procedure, the $\cancel{E}_T$ trigger emulation is turned off and the w_{trig} in Eq. (7.35) is set to 1.0.

The final *MJCR* predictions for Run 2, Run 3, and the systematical variation effects on them are given in Figures 10.1 and 10.2 respectively. From Figures 10.1(d) and 10.2(d) it can be seen that the independently applied fraction fit procedure ensures that modelling differences observed between nominal and systematical variation (e.g., Figures 10.1(e) and 10.2(e)) are fit independent. The only systematical variation observed in the $\Delta\phi_{jj}$ distributions shown in Figures 10.1(c) and 10.2(c) stems primarily from $\delta_{\alpha\beta}$. Note, the slight deviation between the single jet triggered data and inclusive prediction using DSEG in $\Delta\phi_{jj}$ (c.f. Figures 8.10(b) and 10.1(c) and Figures 8.11(b) and 10.2(c)) is attributed to the changed binning strategy¹.

For an event to contribute to any of the signal regions, it must satisfy the corresponding signal region groups requirements which are given in Table 6.1. Since one of the requirements is passing the $\cancel{E}_T$ trigger², the $\cancel{E}_T$ trigger emulation, described in Section 7.3.6, is applied. The trigger emulation's implementation into the method also introduces two additional systematical variations for the signal region prediction. These systematically varied datasets

¹The binning strategy is now mimicking the one used in the reference analysis. See [7].

²See Table 6.4 for details.

10. Performance and Results : Multijet Background Estimation in the Signal Regions

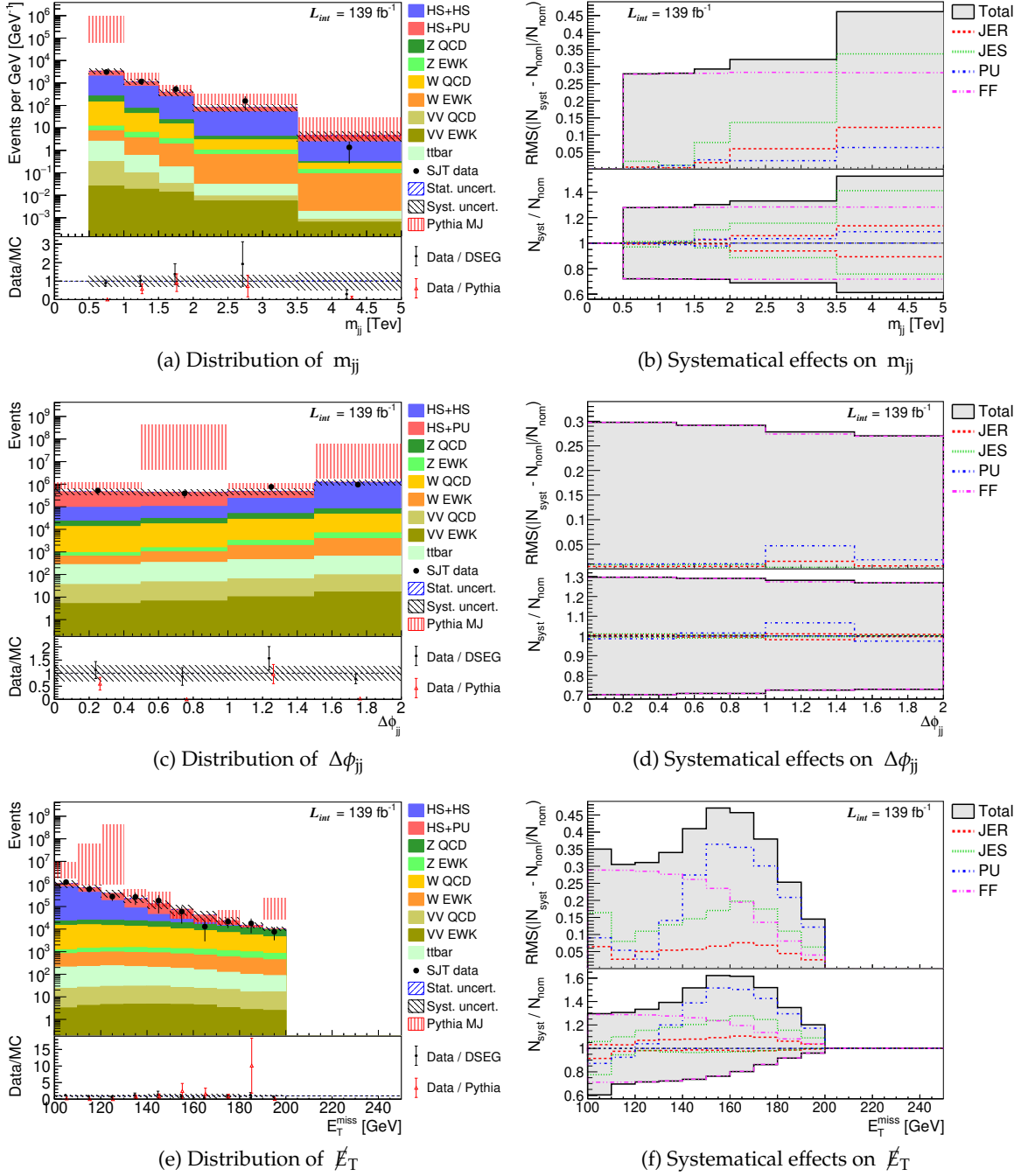


Figure 10.1.: Systematical variation effects on full fraction fitted Run 2 multijet background estimation in *MJCR*. The uncertainties (and their labels) are as follows: JER (JER), JES (JES), Pileup tagging (PU), and Fraction Fit (FF). The uncertainty effects are shown with respect to the full event yield. Red thatched area depicts prediction where PYTHIA MJ prediction is used instead of DSEG.

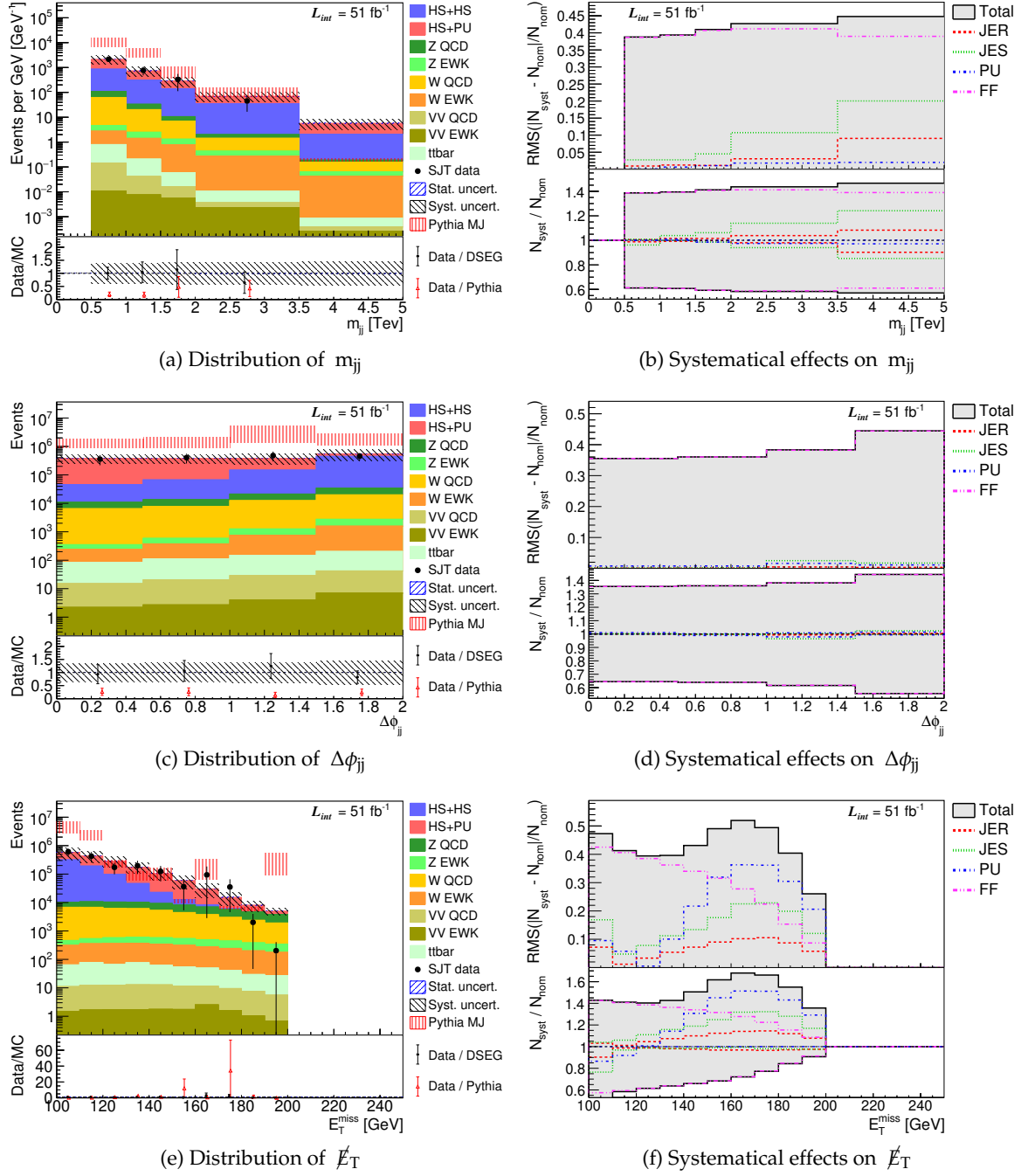


Figure 10.2.: Systematical variation effects on full fraction fitted Run 3 multijet background estimation in $MJCR$. The uncertainties (and their labels) are as follows: JER (JER), JES (JES), Pileup tagging (PU), and Fraction Fit (FF). The uncertainty effects are shown with respect to the full event yield. Red thatched area depicts prediction where PYTHIA MJ prediction is used instead of DSEG.

10. Performance and Results : Multijet Background Estimation in the Signal Regions

are formed from the nominal prediction with the systematical adjustment to the associated weight factor as per Eq. (9.18).

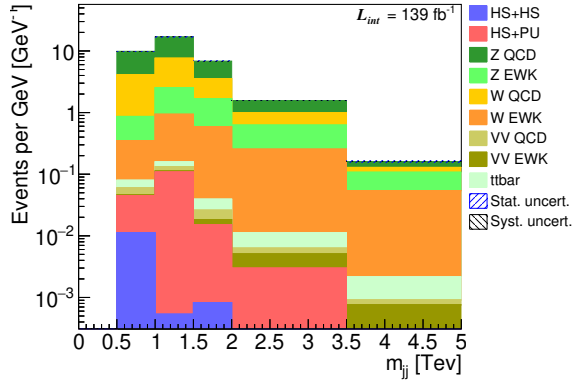
The Run 2 Double Sliced Event Generation multijet background contributions (along with other major backgrounds described in Section 6.2) in various signals regions are shown in the following: HighMET in Figure 10.3, HighNJet in Figure 10.4, and LowMET in Figure 10.5. The Run 3 predictions are shown in Figures 10.6–10.8 respectively. It is important to note, that for these plots the bootstrapping procedure for HS + HS events described in Section 9.1 has not been applied. In all signal region cases, it can be seen that the dominant multijet background contribution is originating from the combinatorial component (i.e HS + PU). Additionally, the expected separation between HS + PU and HS + HS in $\Delta\phi_{jj}$ is clearly observable in all plots with both contributions (e.g., Figure 10.5(c)). The HS + HS components are heavily suppressed as expected by the signal region definitions leading to miniscule contribution in high $\cancel{E}_T$ based regions. However, due to this suppression, a similar problem to typical MC-based background generation is introduced. The HS + HS component is statically limited due to a very small number of events entering these regions. Therefore, providing an additional motivation to the aforementioned bootstrapping method.

Finally, the comparison between the Double Sliced Event Generation multijet background estimation and the prediction used in the reference analysis is shown in Figure 10.9. Both estimation and the prediction are shown for the three signal region groups described in Table 6.1 individually as well as inclusively and cover all the 16 search bins used in [7] as described in Section 6.2. The combined systematic uncertainty for the DSEG estimation is rudimentally evaluated through summation in quadrature of the difference between the systematically varied and nominal prediction under the assumption that none of the uncertainty groups are correlated. Similarly, the total uncertainty for Double Sliced Event Generation is evaluated as $\delta_{\text{stat.}} \oplus \delta_{\text{syst.}}$ and the inclusive estimation can be broken down as

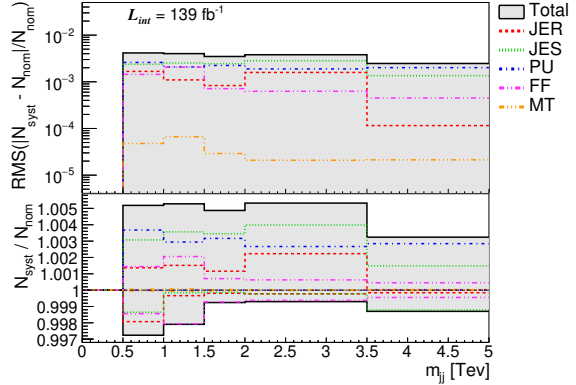
$$544 \pm 16 (\delta_{\text{stat.}}) {}^{+402}_{-97} (\delta_{\text{JES}}) {}^{+208}_{-93} (\delta_{\text{JER}}) + 114 (\delta_{\text{PU}}) \pm 175 (\delta_{\alpha\beta}) \pm 11 (\delta_{\text{trigger}})$$

where δ_{JES} represents the jet energy scale modelling uncertainty (Section 9.2.1), δ_{JER} - jet energy resolution modelling uncertainty (Section 9.2.2), δ_{PU} - the central pileup tagging uncertainty (Section 9.2.3), $\delta_{\alpha\beta}$ - the fraction fit uncertainty (Section 9.2.4), and δ_{trigger} represents the $\cancel{E}_T$ trigger emulation uncertainty (Section 9.2.5)³. The significant variations associated to JES and JER uncertainties can be attributed to their very conservative modelling in DSEG. For example, the δ_{JES} is set to constant 4% irrespective of the jet's p_T , however, from the detector's perspective the uncertainty is not static and primarily decreases with increasing p_T (see Figure 9.1). The asymmetric nature of the pile-up tagging uncertainty originates from its multipoint nature with the simplistic vertex-based tagging more often than not being the dominant contribution to the upward fluctuation (see Figures 9.3(c) and 9.4(c) for an example). For comparison with the reference analysis, the inclusive multijet

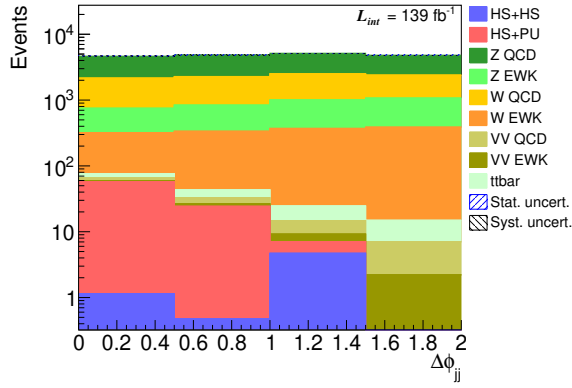
³In Figures 10.1–10.8 they are shown as JES, JER, PU, FF, MT respectively.



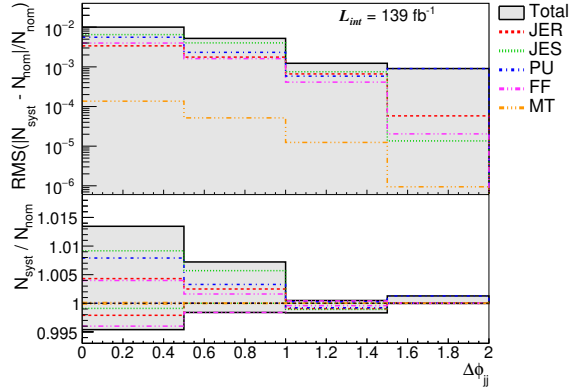
(a) Distribution of m_{jj}



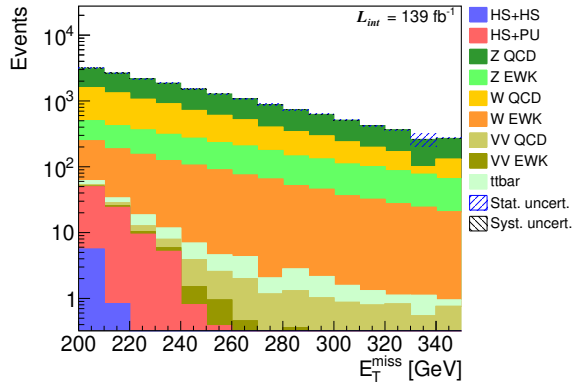
(b) Systematic effects on m_{jj}



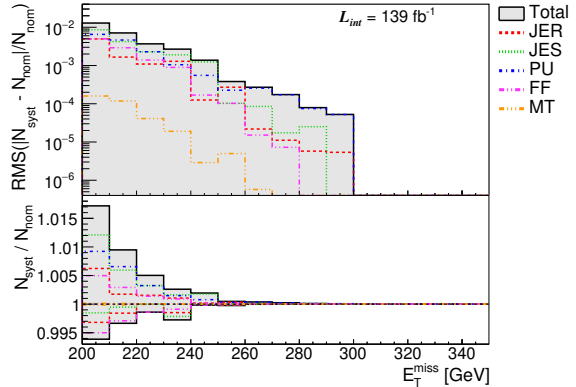
(c) Distribution of $\Delta\phi_{jj}$



(d) Systematical effects on $\Delta\phi_{jj}$



(e) Distribution of $\cancel{E}_T$



(f) Systematical effects on $\cancel{E}_T$

Figure 10.3.: Systematical variation effects on full fraction fitted Run 2 multijet background estimation in HighMET SR group. The uncertainties (and their labels) are as follows: JER (JER), JES (JES), Pileup tagging (PU), Fraction Fit (FF), $\cancel{E}_T$ trigger emulation (MT). The uncertainty effects are shown with respect to the full event yield.

10. Performance and Results : Multijet Background Estimation in the Signal Regions

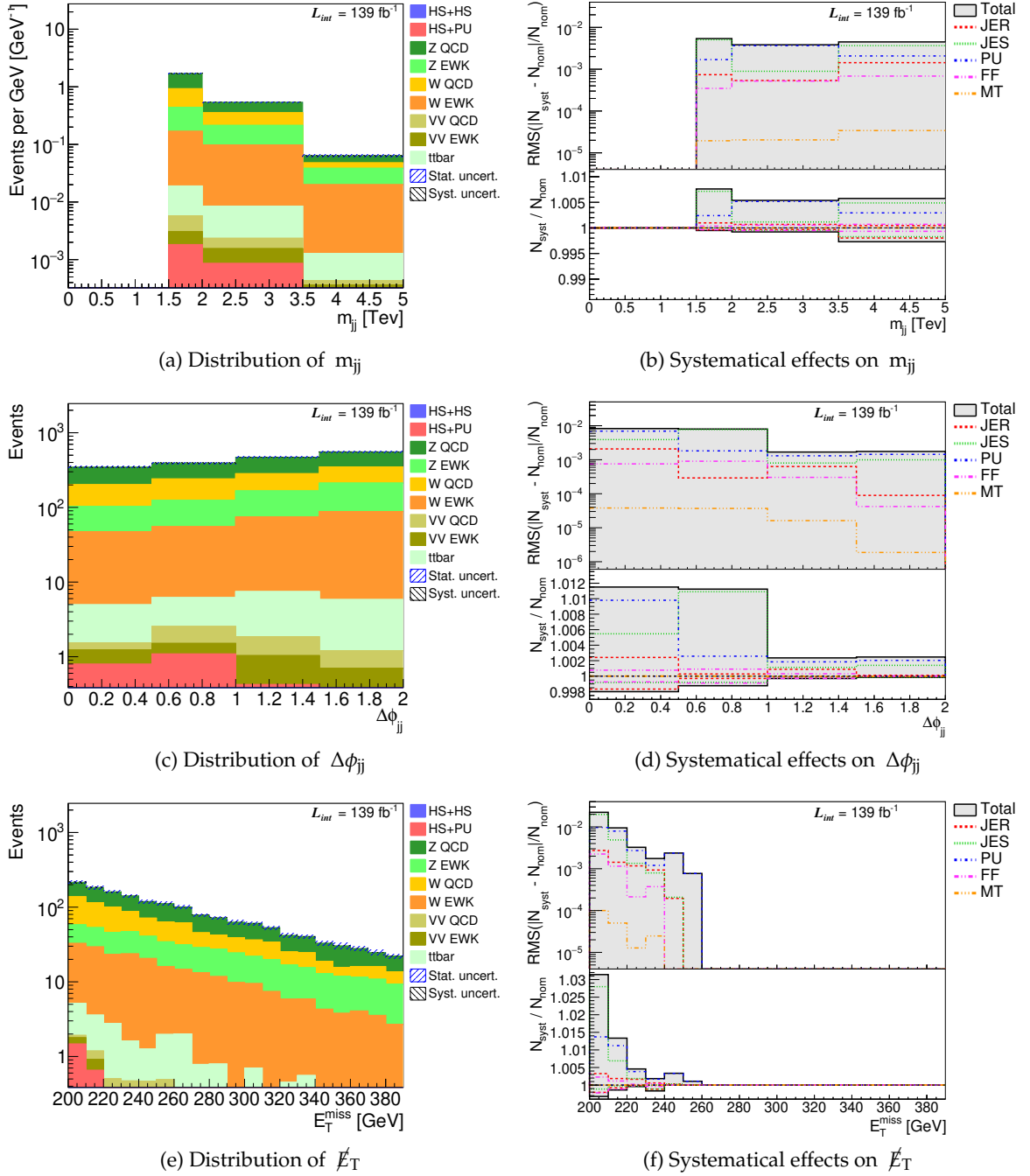
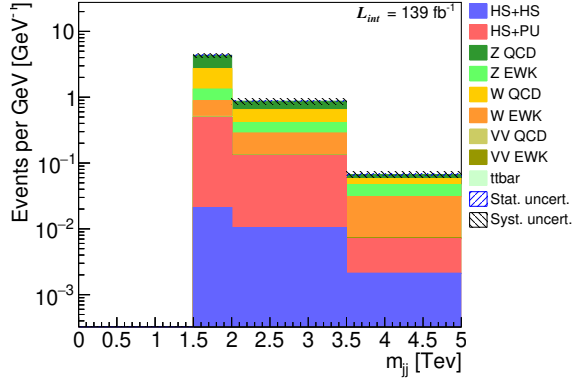
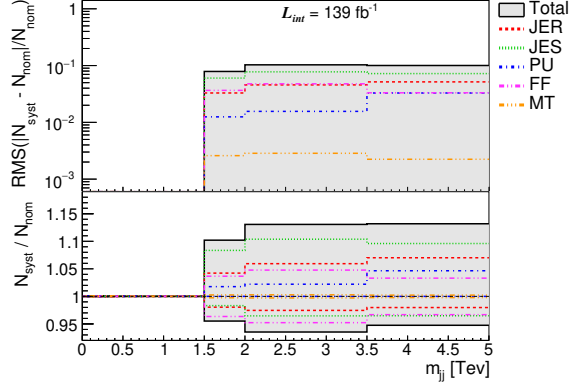


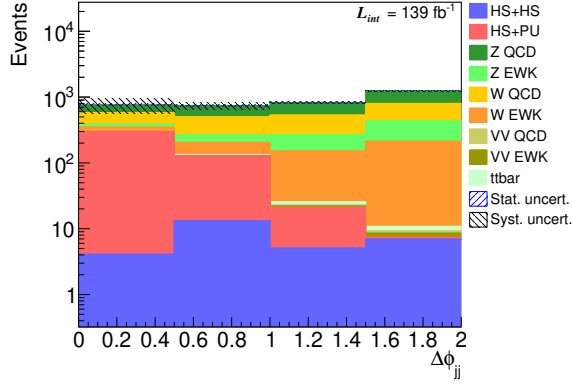
Figure 10.4.: Systematical variation effects on full fraction fitted Run 2 multijet background estimation in HighNJet SR group. The uncertainties (and their labels) are as follows: JER (JER), JES (JES), Pileup tagging (PU), Fraction Fit (FF), E_T^{miss} trigger emulation (MT). The uncertainty effects are shown with respect to the full event yield.



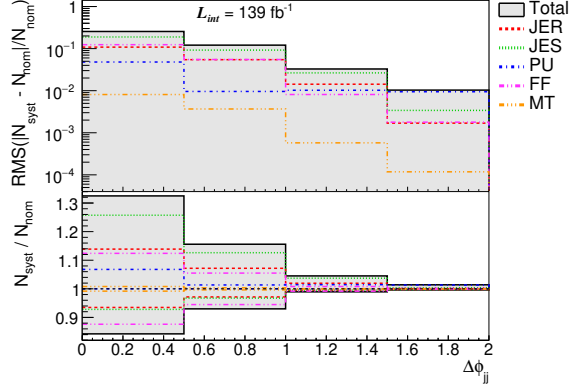
(a) Distribution of m_{jj}



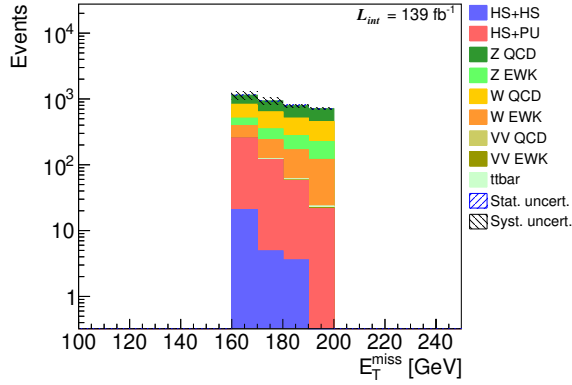
(b) Systematical effects on m_{jj}



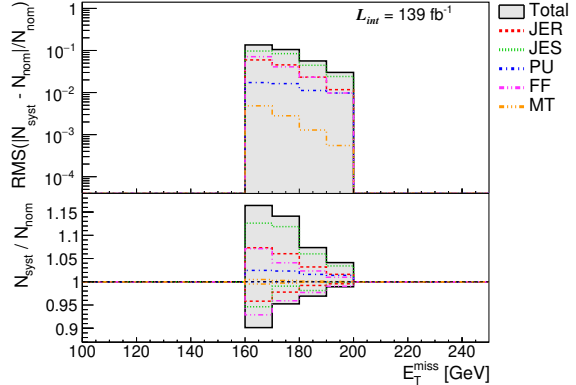
(c) Distribution of $\Delta\phi_{jj}$



(d) Systematical effects on $\Delta\phi_{jj}$



(e) Distribution of $\cancel{E}_T$



(f) Systematical effects on $\cancel{E}_T$

Figure 10.5.: Systematical variation effects on full fraction fitted Run 2 multijet background estimation in LowMET SR group. The uncertainties (and their labels) are as follows: JER (JER), JES (JES), Pileup tagging (PU), Fraction Fit (FF), $\cancel{E}_T$ trigger emulation (MT). The uncertainty effects are shown with respect to the full event yield.

10. Performance and Results : Multijet Background Estimation in the Signal Regions

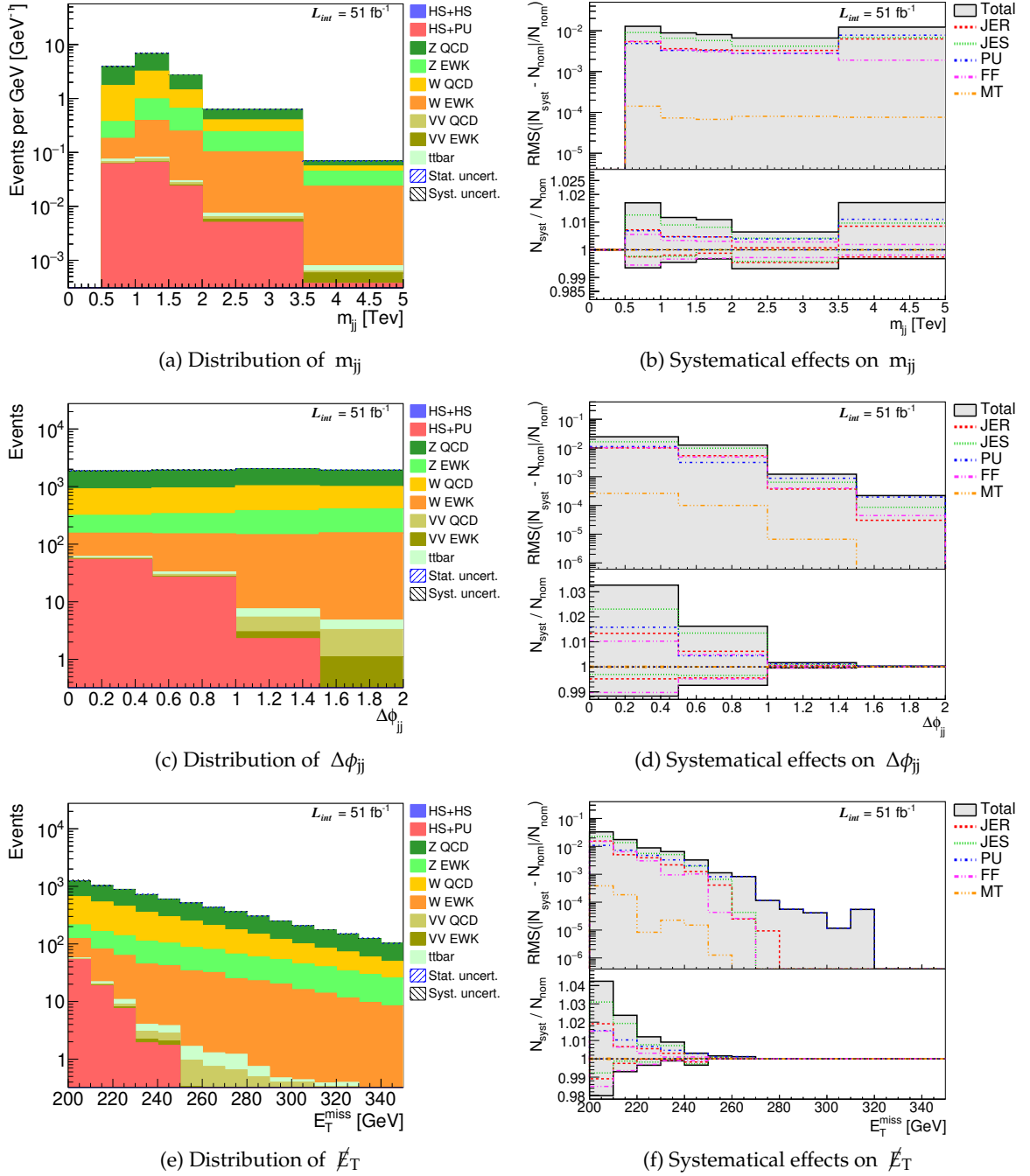
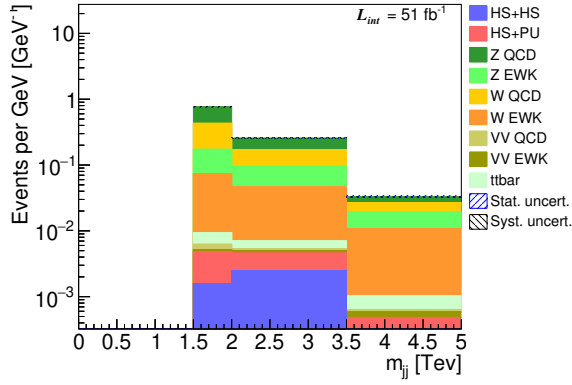
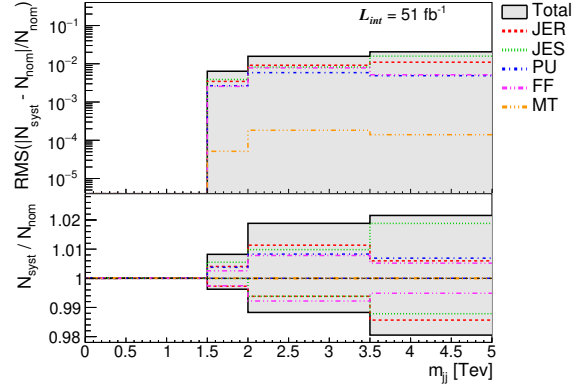


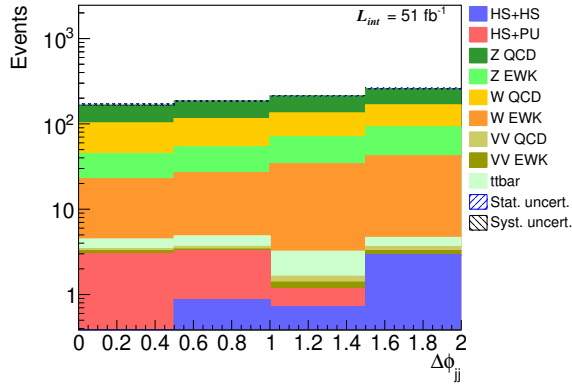
Figure 10.6.: Systematical variation effects on full fraction fitted Run 3 multijet background estimation in HighMET SR group. The uncertainties (and their labels) are as follows: JER (JER), JES (JES), Pileup tagging (PU), Fraction Fit (FF), E_T trigger emulation (MT). The uncertainty effects are shown with respect to the full event yield.



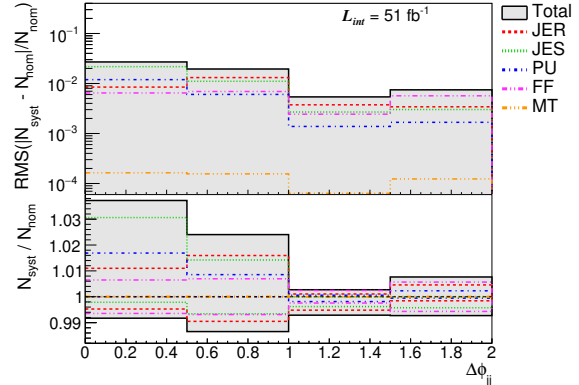
(a) Distribution of m_{jj}



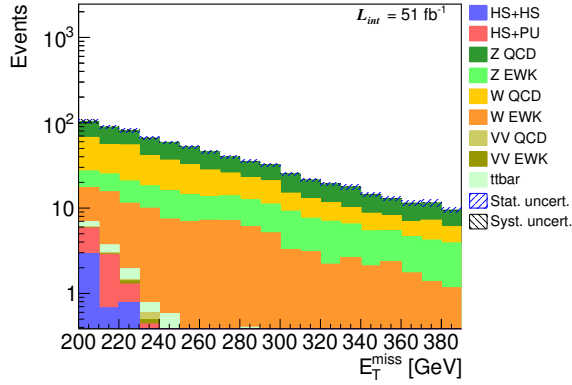
(b) Systematical effects on m_{jj}



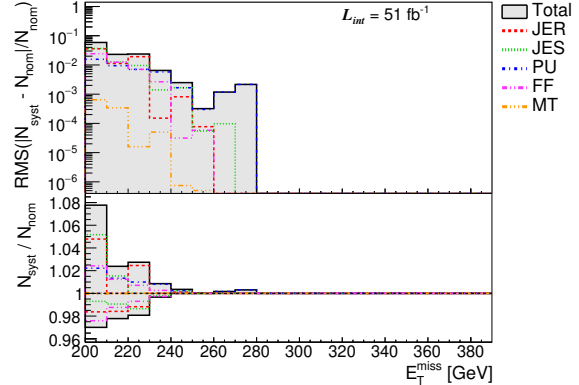
(c) Distribution of $\Delta\phi_{jj}$



(d) Systematical effects on $\Delta\phi_{jj}$



(e) Distribution of E_T^{miss}



(f) Systematical effects on E_T^{miss}

Figure 10.7.: Systematical variation effects on full fraction fitted Run 3 multijet background estimation in HighNJet SR group. The uncertainties (and their labels) are as follows: JER (JER), JES (JES), Pileup tagging (PU), Fraction Fit (FF), E_T trigger emulation (MT). The uncertainty effects are shown with respect to the full event yield.

10. Performance and Results : Multijet Background Estimation in the Signal Regions

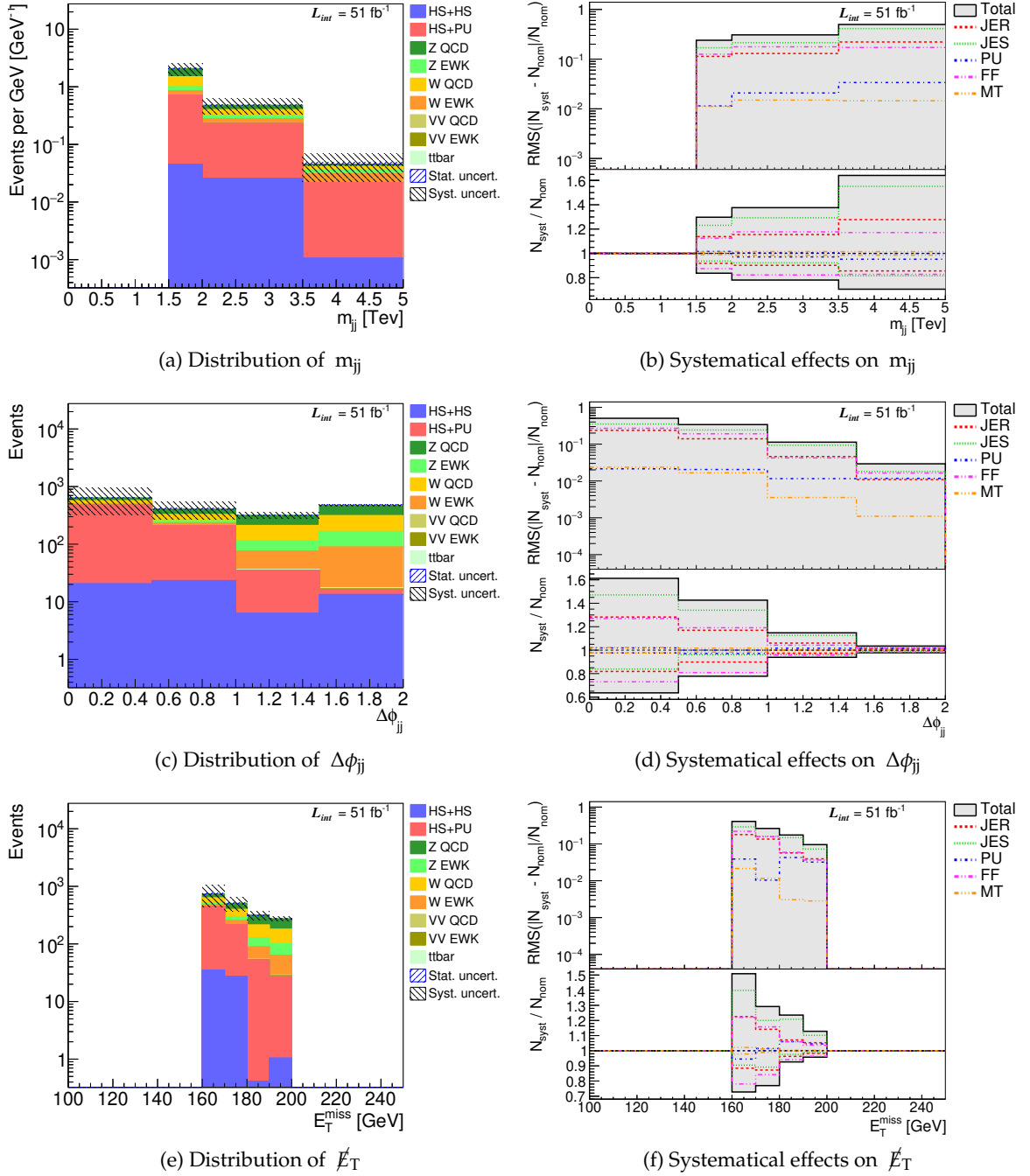


Figure 10.8.: Systematical variation effects on full fraction fitted Run 3 multijet background estimation in LowMET SR group. The uncertainties (and their labels) are as follows: JER (JER), JES (JES), Pileup tagging (PU), Fraction Fit (FF), E_T trigger emulation (MT). The uncertainty effects are shown with respect to the full event yield.

background prediction acquired from the combined R+S and PU-CR methods is

$$830 \pm 190 \text{ (syst.)}$$

As it can be seen in Figure 10.9 both the prediction and the estimation overlap with the uncertainty ranges for the inclusive signal region. However, some disagreement between the approaches exists. This can be attributed to various factors: To begin with, the reference analysis prediction is shown after the signal likelihood fit, where the multijet contribution is estimated through a complicated admixture of both R+S and PU-CR methods (see Eq. (6.7)); Double Sliced Event Generation estimation on the other hand is shown prior to the likelihood fit. Furthermore, the PU-CR multijet estimation relies on the assumption that the multijet background behaviour is identical in both the signal region and the pile-up enriched control regions; Double Sliced Event Generation estimation does not need to rely on such assumption. Finally, all three methods utilise different jet objects: R+S utilises EMTopo-like jets for its estimation. PU-CR is reliant on jets from data which are build as PFlow jets. DSEG jets are based on PFlow jet reconstruction algorithm with significantly different track modelling in DSEG compared to the former two, and an assumption that muons do not participate in jet reconstruction (an alternative approach to muon-in-jet handling is presented in Appendix A).

10. Performance and Results : Multijet Background Estimation in the Signal Regions

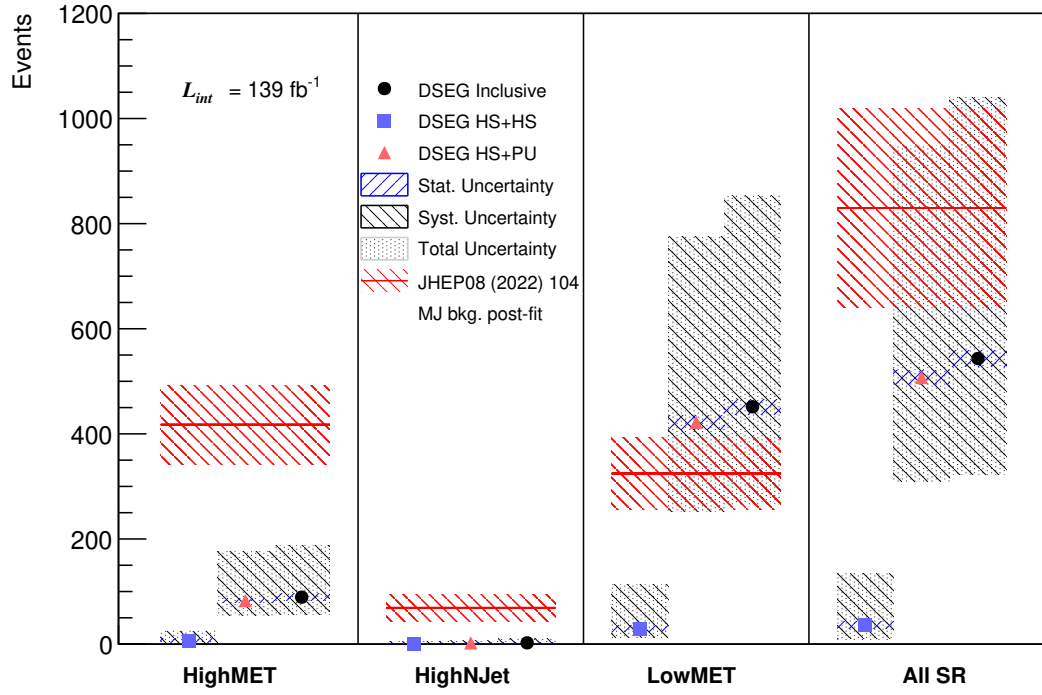


Figure 10.9.: Double Sliced Event Generation multijet background contribution prediction to all signal region comparison with reference analysis. The prediction is shown in all three signal region groups and inclusively. The reference analysis prediction and associated uncertainty post-fit is shown red (based on Tables 5–7 in [7]). In both cases, the "Total uncertainty" represents the signal likelihood fitting domain for Double Sliced Event Generation.

11. Summary and Outlook

The thesis focuses on a novel multijet background estimation method, known as Double Sliced Event Generation. The method has been developed, validated, tested, and introduced in the context of invisible Higgs boson decay event searches with VBF signature in the ATLAS detector. The combination of the Higgs boson production channel and the dominant background processes yields the largest signal-to-noise ratio for event detection. However, due to the search's sensitivity to high p_T pileup jets and the generally large cross-section for a multijet event in pp collisions, estimating the multijet background contribution to the signal region is difficult. The signal events for this search are defined by opposite hemisphere dijet system with large m_{jj} , little to no central activity (apart from ISR and FSR), and significant E_T in the central region. While the multijet background is heavily suppressed by this selection, it is not eliminated. Furthermore, one of the two jets forming the dijet system can be faked by a pileup jet due to various detector effects, including (but not limited to) detector resolution or incorrect pileup tagging, and still pass the selection criteria. Consequently, such events typically have significant event weights when generated using Monte Carlo based simulations. Hence, a new approach to the multijet background estimation was needed.

The core of the Double Sliced Event Generation method relies on a reworked approach to Monte Carlo-based event generation and its integration with various data-driven techniques for detector emulation. During each event generation cycle, the two hardest interactions from the event are replaced with a new pair generated from a sliced generation domain. The resulting collection of the interaction jets are then smeared according to each jet's visible fraction and merged if overlap between them exists. The interaction between the jet collection and the detector is carried out through various data-based emulation maps. The generated events are then scaled to the difference between data and remaining background estimations in a control region to derive the multijet estimation for the signal region. The prediction is divided into two components: true multijet events (HS + HS), where jets originate from the same interaction, and combinatorial background (HS + PU), where they do not. Furthermore, numerous statistics and efficiency boosting techniques (e.g., dynamical smearing, pileup combinatorics) are employed by DSEG to improve the method's and its generated samples' performance. Finally, statistical and systematical uncertainties related to interaction emulation and scaling have been presented, discussed, and derived.

Various aspects of the method had been tested and validated in a multijet enriched control region, defined similarly to the signal regions. The orthogonality of the control region to signal region is primarily achieved through inversion of E_T criteria. However, since at that point the ATLAS E_T triggers are not yet fully efficient, the validation as well as

11. Summary and Outlook

data-based emulation map creation has been carried out using data collected with single jet triggers. During the relevant data taking periods, these triggers operated in a prescaled mode. This resulted in a limited statistics dataset that is not affected by the $\cancel{E}_T$ trigger inefficiencies, but requires an unprescaling procedure to restore the leading jet's p_T spectrum. During the validation, Double Sliced Event Generation showed great performance with its generated events demonstrating the expected behaviours of the multijet background. Furthermore, clear increase in the computation efficiency in the form of increased event generation frequency of the method has been observed when comparing with traditional MC-based background estimation in near identical conditions.

For the purposes of signal region background estimation, 5 datasets have been produced. The datasets are based on data taking years covering both the Run 2 period, upon which the context search is based, and partial Run 3, which is planned as the dataset expansion for the next iteration of the search. Each dataset's interaction with the detector had been emulated using year-dependent maps, however, the scaling to data had been carried out based on full data taking periods, i.e. Runs. As expected, the resulting signal region prediction is dominated by the combinatorial background, while the HS + HS component is heavily suppressed by the signal region definition. Furthermore, due to stringent requirements, the latter, while low in total yield, tends to be dominated by individual final events. Consequently, requiring an introduction of a bootstrapping technique specifically for this contribution (implementation of which is not covered by the scope of the work). Nonetheless, the final signal region prediction (prior to likelihood fit) already matches, within uncertainties, with the post-fit background estimation of the previous search iteration's prediction. Moreover, the unique combination of MC-based event generation with integrated data-driven techniques for various emulations simplifies the multijet background inclusion into the final likelihood fit. In previous iterations of the invisible Higgs boson decay searches, the multijet background contribution would either be fully deduced prior to the fit or partially fitted with the remaining backgrounds. The Double Sliced Event Generation estimation can be fitted in all signal regions like other MC-based background estimations. In addition, this also allows DSEG samples to be used in machine learning based techniques and their implementation.

While the current version of the method has already achieved a mature state, this does not mark the end of its (possible) development. The results of Double Sliced Event Generation application to the facsimile of the last invisible Higgs boson decay search are promising. However, prior to the final fit in the signal region, the bootstrapping procedure for the HS + HS component should be implemented to ensure a proper handle on the statistical uncertainty for the component. Likewise, there are other aspects of the method that could be improved. For example, handling of tracks. Currently, tracks in DSEG are representative of jet constituents with $p_T > 0.5$ GeV located within ATLAS ID tracking coverage. Alternatively, tracks could be modelled as an intermediate object between final state particles from a Monte Carlo generator and a fully clustered jet. This would allow not only a more precise merging of objects after smearing, but could also allow incorporation of the magnetic field bending effects to object reconstruction or more precise modelling of vertex assignment and variables related to it (e.g., corrPVF). On the other hand, this would come at a significant

computational cost and (possibly) increased size of the dataset. Similarly, a more robust approach of jet-kinematic dependent JES and JER uncertainty modelling could also lead to improved precision of the method. Additionally, investigation of Double Sliced Event Generation interaction with other Monte Carlo generators than PYTHIA could also yield interesting insight into multijet background modelling and possible improvements.

Moreover, from the start of Run 4 the LHC is expected to operate in increased luminosity mode, known as High-Luminosity LHC (or *HL-LHC*). Consequently, the ATLAS detector is also expected to receive major upgrades to its hardware during the Long Shutdown 3¹[213]. Most notably, the ID will be replaced with full-silicon tracker known as *ATLAS Inner Tracker*, or *ITk* for short [214]. As a result, track reconstruction capabilities of ATLAS are expected to extend from $|\eta| < 2.5$ to approximately $|\eta| < 4.0$. However, an increase in pileup tagging efficiency is not guaranteed. The average number of interactions per bunch crossing is expected to increase up to $\langle \mu \rangle \sim 200$, hence possibly increasing the contribution of HS + PU events to the signal region for the Run 4 iteration of the search. Further pileup tagging improvements, particularly in the forward region, are expected from the inclusion of the *High-Granularity Timing Detector*[215] (HGTD) which is planned to cover $|\eta| \in (2.4, 4.0)$ and be installed in front of the LAr calorimeter. The HGTD is designed as a charged particle time-of-flight detector and will provide additional venue for pileup mitigation. For Double Sliced Event Generation to remain competitive during Run 4, the planned upgrades to ATLAS would need to be incorporated.

In summary, a novel method for multijet background estimation in pp collision in environments sensitive to high p_T pileup jets has been presented. The method relies on combination of reworked Monte Carlo based event generation and data-driven emulation technique integration. The method has been tested and validated using a facsimile analysis based of the most precise search for invisible decaying Higgs boson events with VBF signatures and performed well. Its multijet background estimation is expected to be as reliable as previously tested methods while enabling other analysis technique usage. However, the method could still be further improved and will require readjustments for the HL-LHC period.

¹Period of approximately 3 yr between Run 3 and Run 4.

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Finally, you, dear reader, be you driven by innate curiosity of new methods of estimating multijet background in events with high pileup activity or simply intrigued by what lied at

Bibliography

the end of this work, thank you for reading up until now.

Appendices

A. Alternative handling of muons in jet for Double Sliced Event Generation

As discussed in Section 7.2, the muons are excluded and do not contribute to the *fractional jet properties*' calculation during jet clustering procedure in DSEG¹. This approach, denoted in this appendix as μExcl for short, has yielded inclusively good prediction for the hypothetical Run 2 analysis case (see Section 10). However, the predictions for the HighMET and HighNJet signal region groups still showed noticeable disagreement on individual level. Hence, an alternative approach to *muon-in-jet* handling has also been investigated to some extent. In the alternative, muons are additionally² allowed to contribute to the invisible fraction, f_{inv} , calculation during jet clustering. However, the "muons-as-invisible" (or μInv for short) approach introduces additional complications to fraction property definitions and methods that rely on them. Consequently, requiring strong *ad hoc* assumptions during jet reconstruction for the method to work.

To begin with, consider the definition of the invisible fraction, f_{inv} , given in Section 7.2. The fraction is normally formed by ν originating from the leptonic W decays in heavy flavoured hadron decays. Therefore, f_{inv} can be thought as the p_T fraction of the jet carried by neutrinos. Under the μInv assumption the definition is ambivalent and depends on which of the charged electroweak boson decay channel forms this fraction. If the f_{inv} is formed through the $W \rightarrow e\nu$ decay, then the definition of the fraction remains the same as before and

$$f_{\text{inv}}^{W \rightarrow e\nu} = \frac{\sum p_T^\nu}{p_T^{\text{jet}}} \Rightarrow \sum p_T^\nu \sim p_T^{\text{jet}} \cdot f_{\text{inv}}^{W \rightarrow e\nu} \quad (\text{A.1})$$

holds. If the fraction is formed through the muonic W decay, the above relationship is no longer valid as both leptons are now treated as invisible. Hence, the invisible fraction is now comprised of both lepton momenta sums

$$f_{\text{inv}}^{W \rightarrow \mu\nu} = \frac{\sum p_T^\nu + \sum p_T^\mu}{p_T^{\text{jet}}} \Rightarrow \sum p_T^\nu \sim \frac{1}{2} \cdot p_T^{\text{jet}} \cdot f_{\text{inv}}^{W \rightarrow \mu\nu} \quad (\text{A.2})$$

The $W \rightarrow \tau\nu$ decay channel is not considered due τ lepton short lifetime as per Section 4.6. The relationship between $\sum p_T^\nu$ and f_{inv} becomes even more complicated if one considers a situation where a reconstructed jet contains constituents from two separate W decays

¹To be more precise, muons failing applicable identification and reconstruction criteria listed in Tables 6.9 and 6.10 contribute only to the track fraction calculation, Eq. (7.7)

²See previous footnote

A. Alternative handling of muons in jet for Double Sliced Event Generation

through two different lepton channels. Hence, for the simplicity of the discussion (and the method) the following *ad hoc* assumption is imposed: A (DSEG) jet can only contain a singular leptonic type of W decay in all of its constituents.

Consequently, the ambivalence of f_{inv} definitions propagates to statistics boosting techniques reliant on it. Specifically, the *visible fraction smearing* described in Section 7.4.3 and *leptons veto emulation* described in Section 7.4.5. The former samples the invisible fraction of the jet based on jet's heavy flavour fraction, f_{HF} , using a normalised two-dimensional map. The latter parametrises³ the probability of finding a lepton passing "candidate" lepton definitions (see Tables 6.9 and 6.10) within the jet based on the jet's transverse momenta and f_{inv} . In both cases, the maps are now dependent on the invisible fraction definition. Hence, a second *ad hoc* assumption is imposed: the leptonic W decay channel chosen for invisible fraction definition is identical between the f_{inv} smearing and lepton veto procedure. That is, if the jet's invisible fraction has been sampled assuming that W decayed to an e and ν , only the probability to find an electron within the jet is used in *lepton veto emulation* procedure. The comparison between the universal and discerning f_{inv} -reliant maps is shown in Figure A.1.

Both of the assumptions are implemented as follows: During the *visible fraction smearing* procedure, before the invisible fraction is sampled according to the jet's f_{HF} the jet is assigned one of the two W leptonic decay modes with equal probability. The choice is made through a random "coin flip" due to near identical branching ratios between the two modes[216]. According to this choice, the appropriate maps are used during the *visible fraction smearing* and *leptons veto emulation* procedures.

To test the performance of the μInv approach, a set of multijet events for each data taking period comprising Run 2 has been created as described in Section 7 and with the above changes. Each of these test datasets consists of 100 "batches" of 10^5 *Base Events*⁴ with each batch generated with a unique RNG seed. Following Section 7.5 and Section 8.4, the fraction fit procedure is carried out to derive the α_{HSHS} and β_{HSPU} parameters. The resulting values and their associated uncertainties are listed in Table A.1. The changes in the fraction fit parameters, particularly in β_{HSPU} , is primarily attributed to the relatively smaller size of the total DSEG dataset used for this comparison. While Eq. (7.35) does account for the pure statistical decrease of dataset through the N_{gen} parameter, the decrease of kinematic variance of events⁵ still remains.

The resulting estimation of the multijet background's contribution to all signal region groups (vis-à-vis Figure 10.9) is shown in Figure A.2. The μInv -based prediction shows clear improvements in both HighMET and LowMET region modelling with a slight boost to

³In the form of a two-dimensional map

⁴Note, this is order of magnitude smaller compared to the datasets used in the main body (c.f. Section 8.4 and Section 10)

⁵A decreased number of generated events implies decreased number of "applications" of various statistic boosting techniques described in Section 7.4. This will result in the decreased number of *Base Events* passing stringent event selection criteria while still pertaining interesting kinematic properties (e.g., high $\cancel{E}_T$ with small $\Delta\phi_{jj}$).

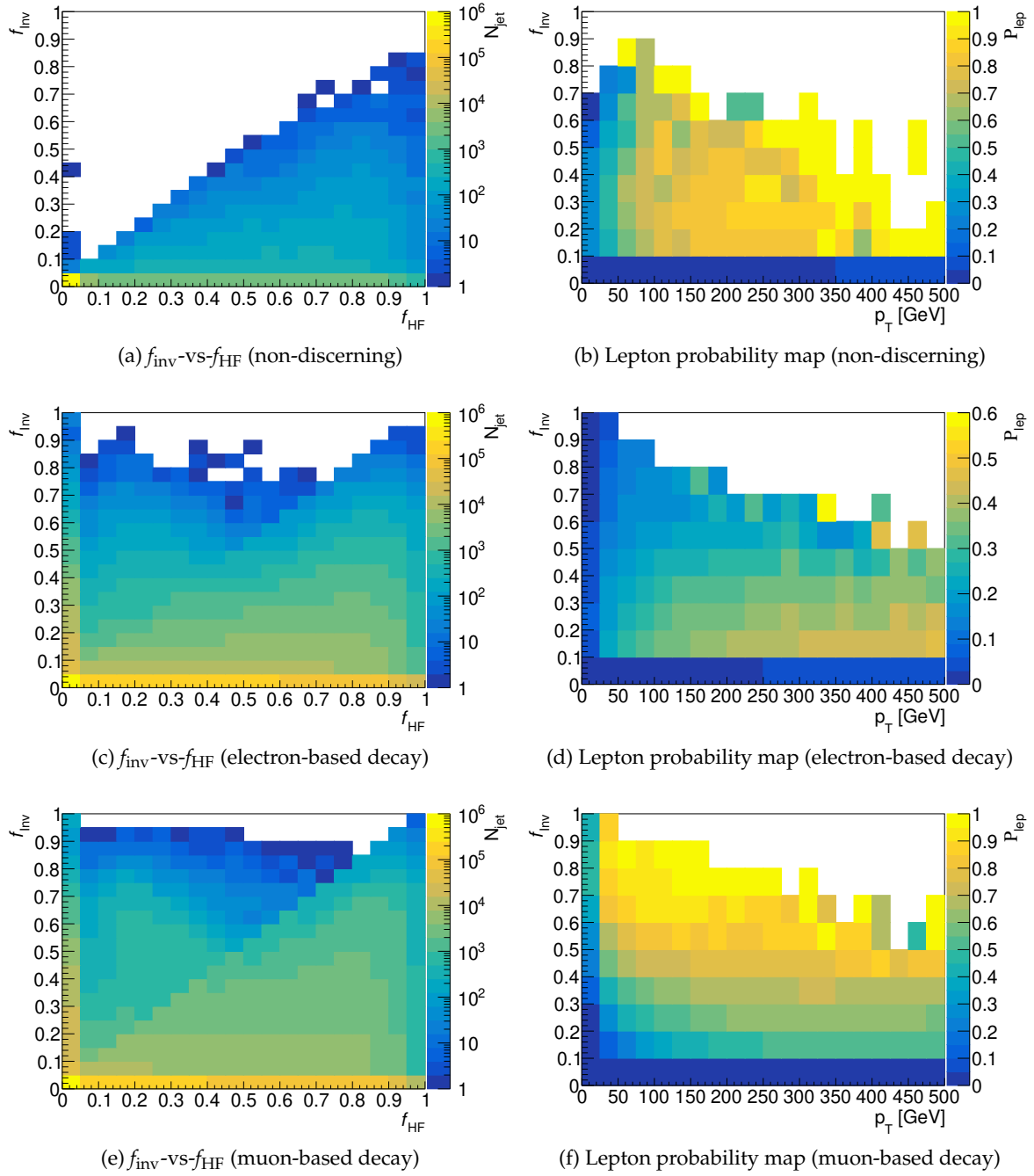


Figure A.1.: Comparison of the invisible fraction based maps between different f_{inv} definition approaches. Left column shows the f_{inv} -vs- f_{HF} map (c.f. Figure 7.14). Right column shows the lepton probability as a function of p_T and f_{inv} (c.f. Figure 7.15) (a) and (b) shows maps produced with the universal or non-discerning definition of the invisible fraction which is used in the main body of this work. (c) and (d) shows maps produced with the $W \rightarrow e\nu$ definition of f_{inv} . (e) and (f) shows maps produced with the $W \rightarrow \mu\nu$ definition of f_{inv} .

A. Alternative handling of muons in jet for Double Sliced Event Generation

Normalisation Period	α_{HSHS}	β_{HSPU}
Run 2 (μInv)	0.29859 ± 0.07637	0.15260 ± 0.09965
Run 2 (μExcl)	0.22522 ± 0.06424	0.05249 ± 0.01671

Table A.1.: Fraction fit parameter comparison for Run 2 normalisation-by-run fraction fitting between μInv and μExcl approaches. The parameters have been derived in *MJCR* using single jet triggered data as described in Section 8.4. The "Run 2 (μExcl)" is identified as the default approach of handling muons as described in the main body of the work and is taken from Table 9.2. The "Run 2 (μInv)" is identified as the alternative approach of treating muons as invisible particles. The dominant contribution to the uncertainty is the statistical limitation of the data sample. Both parameters are conservatively assumed to be fully correlated.

HighNJet signal region group estimation. These improvements could be explained by the expanded sampling range of the f_{inv} . Particularly for the muonic decay based definition of the fraction. Since the upper value of it is no longer constraint by the heavy flavour fraction of the jet (see Figure A.1), a low f_{HF} jet can have a high f_{inv} . This naturally increases the total E_{T} of the event, resulting in more events having the chance to pass the stringent event selection criteria. This effect is further compounded by the fact that majority of the jets tend to have low f_{HF} to begin with (see Figures A.1(a) and A.1(e)). The clear increase in statistical uncertainty (compared to Figure 10.9) is primarily explained by the difference of magnitude between the dataset sizes used between estimations. Similarly to μExcl , the μInv prediction is also significantly affected by systematic uncertainties described in Section 9. While the impact is partially caused by the statistical limitation of the samples⁶, the μInv would still require additional constraintment in dedicated E_{T} -triggered control region before proper application in the analysis. Furthermore, the difference between DSEG, R+S, and PU-CR methods discussed in Section 10 are still applicable. Most importantly, the approach is heavily reliant on the *ad hoc* assumptions to work and introduces an irreducible difference between jet description and modelling in the method. Hence, the μInv succession over μExcl is not straightforward and would require a deeper investigation before implementation.

⁶Recall that uncertainties are derived using the same *TruthBases* that are used for Nominal variation. Hence, statistical limitation on Nominal prediction is also expected to affect the systematically varied prediction.

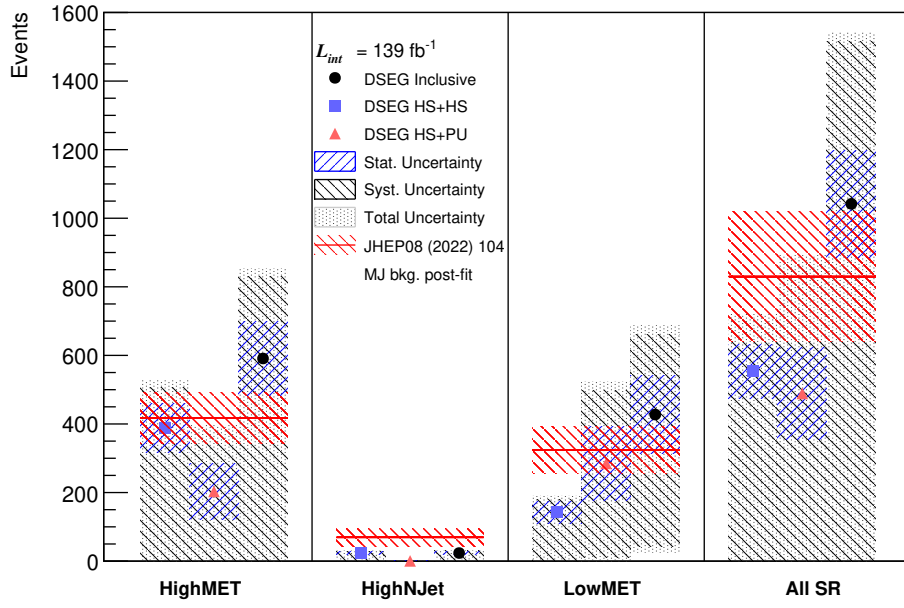


Figure A.2.: Multijet background contribution prediction by DSEG to all signal region comparison with reference analysis for μInv approach. The prediction is based on 3×10^7 Base Events with muons additionally contributing to invisible fraction calculations. The prediction is shown in all three signal region groups and inclusively. The reference analysis prediction and associated uncertainty post-fit is shown red (based on Tables 5–7 in [7]).

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Declaration on oath

I hereby declare and affirm that this doctoral dissertation is my own work and that I have not used any aids and sources other than those indicated.

If electronic resources based on generative artificial intelligence (gAI) were used in the course of writing this dissertation, I confirm that my own work was the main and value-adding contribution and that complete documentation of all resources used is available in accordance with good scientific practice. I am responsible for any erroneous or distorted content, incorrect references, violations of data protection and copyright law or plagiarism that may have been generated by the gAI.

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