Measurements of fiducial differential cross sections for Higgs boson production in the diphoton decay channel at $\sqrt{s} = 8$ TeV with ATLAS
The following evaluators recommend the admission of the dissertation:

Name: Dr. Kerstin Tackmann

Name: Prof. Dr. Peter Schleper
Declaration on oath

I hereby declare, on oath, that I have written the present dissertation by my own and have not used other than the acknowledged resources and aids.


Marco Filipuzzi

Eidesstattliche Erklärung

Hiermit erkläre ich an Eides statt, dass ich die vorliegende Dissertationsschrift selbst verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.


Marco Filipuzzi
Abstract

In this thesis, measurements of fiducial differential cross sections are presented for Higgs boson production in proton-proton collisions at a center-of-mass energy of $\sqrt{s} = 8$ TeV. The analysis is performed in the $H \rightarrow \gamma\gamma$ decay channel using 20.3 fb$^{-1}$ of data recorded by the ATLAS experiment at the CERN Large Hadron Collider. The signal is extracted using a fit to the diphoton invariant mass spectrum, then the signal yields are corrected for the effects of detector inefficiency and resolution. Differential cross sections are presented as a function of variables related to the charged particles and the jet activity produced in the Higgs boson events. The observables considered are derived from the $N$-jettiness inclusive event-shape and build from track and jet information. These observables are sensitive to the distribution of the radiation in the event. Combining jet transverse momentum and jet rapidity information the variables $\tau_1$ and $\sum_i \tau_i$ are defined. These observables can be used as jet vetoes and their cross sections are theoretically well-controlled. The observed spectra are statistically limited but broadly in line with the theoretical expectations.
Zusammenfassung

Diese Arbeit präsentiert Messungen des differenziellen Wirkungsquerschnitts für die Produktion von Higgs-Bosonen in Proton-Proton-Kollisionen bei einer Schwerpunktsenergie von \( \sqrt{s} = 8 \) TeV. Die Analyse nutzt den Zerfallskanal \( H \rightarrow \gamma \gamma \) mit Daten von 20.3 fb\(^{-1}\) gesammelt vom ATLAS-Experiment am Large Hadron Collider am CERN. Das Signal wird mit einer Ausgleichsfunktion extrahiert, die an das Spektrum der invarianten Masse des Zwei-Photonen-Systems angepasst wird. Danach wird die Zahl der Signalereignisse korrigiert, um die Detektorineffizienz und -auflösung zu berücksichtigen. Differenzielle Wirkungsquerschnitte werden gezeigt als Funktion von Observablen zu geladenen Teilchen und zur Jetaktivität produziert in den Ereignissen mit Higgsbosonen. Die berücksichtigten Observablen werden abgeleitet von der “N-jettiness” und werden berechnet mit Informationen von Teilchenspuren und Jets. Diese Observablen hängen von der Verteilung der Strahlung im Ereignis ab. Durch die Kombination aus dem transversalen Impuls von Jets und der Rapidität der Jets werden die Variablen \( \tau_1 \) und \( \sum_i \tau_i \) definiert. Diese Observablen können genutzt werden, um Ereignisse mit Jets zu verwerfen, und sie lassen sich gut theoretisch beschreiben. Die gemessenen Spektren werden in ihrer Präzision durch Statistik limitiert, aber sie sind generell kompatibel mit den Erwartungen aus theoretischen Vorhersagen.
Acknowledgements

I would like to thank first and above all my supervisor Kerstin Tackmann. You trusted me and you gave me this incredible opportunity. From the beginning I understood how lucky I was to be your student. You were always fair, always kind, always honest. It has been an honor for me to work with you. You have been (and will be) a role model to me.

As a caveat when a list of people is made it will be in alphabetical order.

Thanks to Peter Schleper for your interesting questions and for supervising my work. Thanks to Frank Tackmann for the nice collaboration, the detailed explanations and the intriguing chats. Thanks to the members of my PhD examination board, Elisabetta Gallo and Peter Schmelcher, for dedicating me some of their precious time.

I would like to thank all the people that made my year at CERN exciting, pleasant and full of joy. Thanks to the people from the Inner Detector for the work, the help and the company: Gaetano Barone, Alex Kastanas, Priscilla Pani and Adrian Vogel from the Online Monitoring; Saverio D’Auria, Per Johansson, Takahiko Kondo, Steve McMahon and Dave Robinson from the SCT group. Thanks to the friends I made in Rue des Hautains, Giovanni e Michele, to all the laughs that we made and that we will make, there will always be grappa for you. Thanks to Sandro, I was so lucky to meet you again at CERN, your friendly face made everything easier. Thanks to Peter Vankov for all the help and the quiet chats during the first year of my PhD.

Thanks to the whole ATLAS DESY group, starting from the group leaders Ingrid Gregor, Michael Medinnis and Klaus Moenig for showing me how they built and maintained a pleasant work environment where it is so easy to be productive. Thanks to my office mates Chris and Eda, and my office-neighbors Daniel, Martin and Nils who always had a great smile to face the day and were always available for some “German” help that I often needed.

Thanks to Florian Bernlochner, Dag Gillberg and Elisabeth Petit, you were always available for questions, giving me new ideas and new solutions. I learned so much from you.

Thanks to the football friends Alberto, Federico, Timon and many others, it was so nice sweating with you in the sun and (sometimes) in the rain, just for fun, as it should be.

Thanks to my friends here, there and everywhere. To Lorenzo, friend with whom I shared the last 10 years, with all the good and bad moments, you will always be present. Thanks to Andrea, to Cibo and René never too far away to make me feel alone.

Thanks to my “Expat” friends. Alessandro, Francesca, Francesco, Martina, Mauro, Paolo. You helped me in so many things, much more than I did for you. Your smile and your hand was always there for me, my PhD has finished, our friendship continues.

Thanks to my family. Your support is my energy, your hard work and sacrifices my inspiration. Trying to make you feel proud of me is my goal. I hope to be able to give back what you gave me.

Thanks to Chiara, my fiancée. With you I shared most of my PhD and I will share the rest of my life. You comforted and pushed me with the same kindness.
The most I have earned from this experience is the opportunity to have met all these people.

Thanks to you, Hamburg...meine Perle.
# Contents

<table>
<thead>
<tr>
<th>Contents</th>
<th>xi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1 The Standard Model of elementary particles</td>
<td></td>
</tr>
<tr>
<td>1.1 Strong interactions</td>
<td>4</td>
</tr>
<tr>
<td>1.2 Electroweak interactions</td>
<td>6</td>
</tr>
<tr>
<td>1.2.1 The Cabibbo-Kobayashi-Maskawa matrix</td>
<td>7</td>
</tr>
<tr>
<td>1.2.2 Electroweak symmetry breaking</td>
<td>7</td>
</tr>
<tr>
<td>1.3 Standard Model Higgs boson production mechanisms</td>
<td>8</td>
</tr>
<tr>
<td>1.4 Standard Model Higgs boson decay</td>
<td>11</td>
</tr>
<tr>
<td>2 The LHC and the ATLAS experiment</td>
<td>15</td>
</tr>
<tr>
<td>2.1 The Large Hadron Collider</td>
<td></td>
</tr>
<tr>
<td>2.1.1 The accelerators</td>
<td>16</td>
</tr>
<tr>
<td>2.1.2 Coordinate system and kinematic variables</td>
<td>19</td>
</tr>
<tr>
<td>2.2 The ATLAS experiment</td>
<td>20</td>
</tr>
<tr>
<td>2.2.1 The Inner Detector</td>
<td>21</td>
</tr>
<tr>
<td>2.2.2 The calorimeters</td>
<td>22</td>
</tr>
<tr>
<td>2.2.3 The muon spectrometer</td>
<td>25</td>
</tr>
<tr>
<td>2.2.4 Trigger system</td>
<td>26</td>
</tr>
<tr>
<td>2.3 Dataset</td>
<td>28</td>
</tr>
<tr>
<td>3 Simulation of the charge trapping effect in the SCT detector</td>
<td>29</td>
</tr>
<tr>
<td>3.1 Charge trapping</td>
<td></td>
</tr>
<tr>
<td>3.2 SCT digitization</td>
<td>30</td>
</tr>
<tr>
<td>3.3 Results</td>
<td>34</td>
</tr>
<tr>
<td>3.4 Conclusions</td>
<td>44</td>
</tr>
<tr>
<td>4 Physics Objects</td>
<td>45</td>
</tr>
<tr>
<td>4.1 Photons</td>
<td></td>
</tr>
<tr>
<td>4.2 Tracks</td>
<td>46</td>
</tr>
</tbody>
</table>
## Contents

4.3 Primary vertices ................................................. 50
4.4 Jets ................................................................. 50

5 Differential cross section measurements for track-based observables 53
  5.1 Simulated signal samples ........................................ 55
  5.2 Fiducial regions .................................................. 55
  5.3 Observable definitions .......................................... 58
  5.4 Signal model and signal extraction .............................. 62
    5.4.1 Signal model ................................................ 62
    5.4.2 Uncertainties on the signal model ......................... 63
    5.4.3 Signal extraction ........................................... 66
    5.4.4 Systematic uncertainty from the fits ..................... 69
  5.5 Unfolding method ............................................... 72
    5.5.1 Choice of binning .......................................... 73
  5.6 Systematic uncertainties ....................................... 77
    5.6.1 Photon uncertainties ...................................... 77
    5.6.2 Track uncertainties ....................................... 77
    5.6.3 Signal composition uncertainties ......................... 79
    5.6.4 Jet uncertainties .......................................... 80
  5.7 Results .......................................................... 88

6 Fiducial and differential cross sections for jet-based observables 95
  6.1 Fiducial cross section measurements and limits ............... 95
  6.2 Differential cross sections .................................... 98
    6.2.1 $\tau_i$ and $\sum_i \tau_i$ observables ....................... 100
    6.2.2 Moments of the differential cross section distributions . 105
  6.3 Conclusions ..................................................... 109

Summary and conclusions ............................................ 113

Bibliography ........................................................... 115
Introduction

Since its first formulations in the 1960s, the Standard Model of particle physics has been extremely successful in describing the physics of all known particles, and has been tested to remarkable accuracy in several generations of experiments. A foundation of the Standard Model is the existence of a hidden symmetry of the electromagnetic and weak interactions, which is spontaneously broken by the presence of a non-vanishing Higgs boson field. As a consequence of the electroweak symmetry breaking, the weak gauge bosons $W$ and $Z$ acquire masses through their interaction with the Higgs boson field, and their dynamics changes; the masses of quarks and leptons also arise from the same mechanism. After the symmetry breaking, the Higgs boson field manifests itself as a massive neutral scalar particle $H$, the dynamics of which are completely predicted by the theory as function of the unknown Higgs boson mass $m_H$, and of the known masses and couplings to fermions and gauge bosons.

Before 2012, the Higgs boson, was the only unconfirmed element of the Standard Model with $m_H$ the only free parameter of the theory. Giving an answer to the fundamental question about its existence was a one of the main goals of the physics program at the Large Hadron Collider (LHC). For this reason the two general purpose experiments, CMS and ATLAS, have been designed with the detection of a Higgs boson among their primary targets.

In 2012, almost fifty years after the prediction in 1964 of the massive scalar boson the ATLAS and CMS experiments at the LHC at CERN have observed for the first time a new particle with the properties of the Higgs boson [1,2] and have measured its mass to be approximately of 125 GeV/$c^2$. One of the main decay channels in both experiments that lead to the discovery of the new particle was the decay to two photons. Despite the small branching ration of just $\sim 0.2\%$, the diphoton decay channel is well suited for both the discovery and the study of the properties of the Higgs boson. The core of this thesis is focused on analyses that measure fiducial differential cross sections for a Higgs decaying into two photons with data collected by the ATLAS experiment during 2012 operations in proton-proton collisions with center-of-mass energy of 8 TeV at the LHC.

The first chapter of the thesis is a theoretical overview of the Standard Model. Strong and electroweak interactions are shortly described together with the Higgs mechanism. The second chapter is devoted to the LHC and the ATLAS detector main components. Here, the different components of the ATLAS detector are explained. In the third chapter the topic of radiation damage on detector materials is treated. The attention is focused on the SCT detector and
on the particular effect of charge trapping. The implementation of the charge trapping in the simulation of the SCT response allows to study all possible sensitive quantities that might suffer from this defect. Finally results from the simulation assuming even extreme operational scenarios for the LHC and the ATLAS experiment are presented. The forth chapter contains the description and the definition of the physical objects that serve as main ingredients in the measurements of fiducial differential cross section for a Higgs decaying into two photons that follow. Chapter 5 is dedicated to $N$-jettiness fiducial differential cross sections. The observables and the fiducial regions, in which they are measured in, are defined; then the signal parametrization and the yield extraction procedure are explained. The uncertainty sources affecting the measurement are assessed and presented together with the differential distributions. Finally, in the sixth chapter, the contribution to the work of [3] is summarized. A particular set of jet observable is studied and their differential cross section measured.
Chapter 1

The Standard Model of elementary particles

The Standard Model of particle physics (SM) [4–6] is a successful theory that describes all known elementary particles and how they interact. It unifies electromagnetic, weak and strong interactions into a single Quantum Field Theory (QFT) formulation. In this context, matter is described in terms of spin 1/2 particles, called fermions. Each of the 12 fermions, along with the corresponding anti-fermions predicted by the theory, has been observed by experiments. Fermions can be divided in two main groups quarks and leptons, depending on which kind of interaction they are subjected to. Both quarks and leptons can be further categorized in the three doublets often called families or generations. The three quark doublets are: up and down, charm and strange, top and bottom (less commonly also truth and beauty). Up and down quarks have masses of a few MeV/c² and they are the constituents of the atomic nuclei, charm and strange mass is about 1.3 and 0.1 GeV/c², top and bottom have masses of about 172 and 4.2 GeV/c², respectively.

Quarks interact both via electroweak and strong forces. They can have electric charge equal to 2/3 and 1/3 and they do not exist as free states, but only confined in bound states called hadrons. Hadrons made of a combination of three quarks (anti-quarks) are called baryons (anti-baryons), while a bound state of one quark and one anti-quark is called meson. The only exception to this behavior is from the heaviest of the quarks, the top quark, which has an extremely short lifetime that does not allow for the formation of bound states.

Electric charged leptons as the electron, the muon and the tau interact through the electroweak force. For each of these leptons there is an associated neutrino. Neutrinos have zero electric charge and thus are subject to only the weak interaction. Electron, muon and tau have masses of about 0.5 MeV/c², 0.1 GeV/c², 1.8 GeV/c². Neutrinos are known today to be massive even if only upper limits to their masses have been set by recent measurements.

Spin 1 particles called bosons are the mediators through which particles interact. Massless photons (γ) together with the massive $W^+$, $W^-$, Z are responsible for the electroweak interaction, while strong forces exchange massless gluons (g). Finally the Higgs boson field interacts
1.1 Strong interactions

The quantum field theory of the strong interactions is called *Quantum Chromodynamics* (QCD) because the charge to which strong force couples is named *color*. From Noether’s theorem it is known that a conservation law must derive from a local invariance of the Lagrangian. In this case the local gauge transformations form a $SU(3)$ group and the Lagrangian may be written as:

$$\mathcal{L}_{QCD} = -\frac{1}{4} G_{\mu\nu}^a G^{\mu\nu}_a + \sum_{q,a} \bar{\Psi}_{q,a} (i\gamma_{\mu} D^\mu - m_\alpha) \Psi_{q,a},$$
where $\Psi_{q,a}$ are the spinor fields associated to the quarks and the $q, a$ indices are running over the quark flavor and color; $G_{\mu\nu}^a$ the gauge invariant gluonic field tensor:

$$G_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + g_s f_{abc} A_\mu^b A_\nu^c,$$

and $D^\mu$ is the gauge covariant derivative:

$$D_\mu = \partial_\mu - ig_s A_\mu$$

with $A_\mu = \sum_{a=1}^{8} t_a A_\mu^a$.

The $A_\mu^a$ correspond to the 8 bosonic fields, called gluons, which act as force carriers, while $t_a$ are a set of $8 \times 3 \times 3$ matrices corresponding to the generators of $SU(3)_C$ symmetry in the chosen representation. Finally $g_s = \alpha_s/4\pi$ is the strong coupling with $\alpha_s$ the strong coupling constant.

The strong interactions have quite unique properties when compared to electromagnetic and weak interactions, descending from the non-Abelian $SU(3)_C$ group. The principal peculiarities of the QCD are shortly described below:

- **Running of $\alpha_s$** : the first consequence of the different structure of $SU(3)_C$ interactions is evident when computing the running equation for the $\alpha_S$ strong coupling constant:

$$\alpha_s(\mu^2_R) \propto \frac{1}{\log(\frac{\mu^2_R}{\Lambda^2_{QCD}})}.$$

This is a first order solution to the renormalization group equations where $\mu^2_R$ is the renormalization scale (conventionally of the order of the momentum that is transferred in the process) and $\Lambda^2_{QCD}$ the cut-off of the renormalization integrals to prevent soft divergencies; usually $\Lambda_{QCD} \approx 250$ MeV. The strong coupling constant increases at lower energy scales. As a consequence, reliable QCD predictions via perturbation theory are only possible for hard scattering processes where a high momentum transfer is involved.

- **Strong coupling and confinement** : in the low momentum transfer region, close to the energy scale $\Lambda_{QCD}$, interactions between quarks are so strong that the complex dynamics cannot be described anymore as a perturbative expansion around a free theory. It is an experimental fact that all free particles are “colorless” $SU(3)$ singlets, or hadrons: these combinations correspond to scalar $q^a\bar{q}^a$ states, mesons, or to anti-symmetrical $\epsilon^{abc}q^aq^bq^c$ states, baryons. This phenomenon is commonly referred to as confinement, and it affects all the particles carrying color charge. The intuitive explanation for this is that among colored particles there is an attractive force which increases for increasing distance, but there is yet not a well proved and quantitative explanation of this behavior from a theoretical point of view. In the lack of a full understanding of confinement from first principles, predictions for hadron formation are obtained using phenomenological models tuned on experimental results.
• Asymptotic freedom: in the high energy regime the behavior of QCD changes: quantum corrections from vacuum polarization cause the interaction to become weaker with decreasing distance, or increasing energy. This condition is known as asymptotic freedom. The asymptotic freedom is well understood in the context of renormalization, and it is extremely important because it allows a perturbative treatment of the strong interactions.

1.2 Electroweak interactions

Electromagnetic and weak phenomena are explained by imposing the invariance of the fermionic Lagrangian under local transformations of the group $SU(2)_L \times U(1)_Y$. The three generators of $SU(2)_L$ transformation are the three components of the weak isospin operator ($t^a = (1/2)\tau^a$ with $\tau^a$ the Pauli matrices) and the generator of $U(1)_Y$ is the weak hypercharge operator. The weak isospin $I$ and hypercharge $Y$ are related to the electric charge $Q$ by the following equation:

$$Q = I_3 + \frac{Y}{2},$$

with $I_3$ the eigenvalue of the third weak isospin component. This framework inherits the structure of V-A theory of the weak interactions, with quarks and lepton fields organized in left-handed doublets and right-handed singlets:

$$\begin{pmatrix} \nu_{\ell} \\ \ell \end{pmatrix}_L, \begin{pmatrix} u \\ d \end{pmatrix}_L, \begin{pmatrix} u_R \\ d_R \end{pmatrix},$$

where $\ell = e, \mu, \tau$ are the leptons and $u = u, c, t$ and $d = d, s, b$ are the quarks. From the definition of isospin, weak interactions may only occur on left-handed fermionic doublets, thus providing an explanation for the phenomenon of maximal parity violation. The mathematical formulation of the electroweak Lagrangian provides a description of these phenomena in a concise and elegant way:

$$\mathcal{L}_{EW} = -\frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \bar{\Psi} i\gamma_\mu D^\mu \Psi,$$

where the symbols $W^{1,2,3}_\mu$ and $B_\mu$ correspond to the four spin 1 fields, called bosons, associated to the generators of the gauge transformation, $\Psi$ are the fermionic fields described above and $D^\mu$ is the covariant derivative consistent with local gauge transformations:

$$D^\mu = \partial^\mu + igW^\mu_\tau - ig' B_\mu.$$

The mass eigenstates observed in experiments are linear combinations of the electroweak eigenstates. Hence the $W^+$ and $W^-$ bosons are expressed as:

$$W^{\pm}_\mu = \sqrt{\frac{1}{2}} (W^1_{\mu} \mp iW^2_{\mu})$$
and the photon $\gamma$ and the $Z$ bosons as:

$$A_\mu = B_\mu \cos \theta_W + W_\mu^3 \sin \theta_W,$$
$$Z_\mu = -B_\mu \sin \theta_W + W_\mu^3 \cos \theta_W,$$

with $\theta_W$ being the weak mixing angle, or “Weinberg angle”.

### 1.2.1 The Cabibbo-Kobayashi-Maskawa matrix

The actual quark mass eigenstates are a mixture of the flavor eigenstates. The mixing is achieved through a $3 \times 3$ matrix, the Cabibbo-Kobayashi-Maskawa (CKM) matrix [7,8], correlating the three quark doublets, or flavor families:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}.$$

This mechanism provides a natural explanation for the non conservation of the quark flavor under weak interactions mediated by $W^\pm$ bosons, the weak charged currents; at the same time it explains why flavor changing neutral currents mediated by a $Z$ boson are suppressed by the Glashow-Iliopoulos-Maiani mechanism (GIM) [9]. The CKM matrix elements are constrained by the unitarity condition:

$$\sum_k |V_{ik}|^2 = \sum_i |V_{ik}|^2 = 1 \quad \text{and} \quad \sum_k V_{ik}V_{jk} = 0 ;$$

as a consequence the CKM matrix can be parametrized by three real parameters $\theta_{12}, \theta_{13}$ and $\theta_{23}$, called weak mixing angles, and one complex phase $\delta_{13}$ responsible for CP-violating phenomena. The determination of the magnitude of the CKM matrix elements, as of today, is the outcome of several experimental measurements performed over the past 20 years [10].

### 1.2.2 Electroweak symmetry breaking

The bosons and the fermions described by the electroweak theory are massless particles as a consequence of invariance requirements under gauge and chiral transformations respectively. This is in contradiction to the observation of massive particles. A natural way of allowing SM particles to acquire a mass is provided by the existence of a complex scalar field doublet with the following form:

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix},$$

with the doublet structure a consequence of the $SU(2)_L$ representation adopted. The electroweak Lagrangian can be complemented with the potential and the interactions coming from such a scalar field:

$$\mathcal{L} = \mathcal{L}_{EW} + (D^\mu \phi)^\dagger (D_\mu \phi) - V(\phi^\dagger \phi).$$
The potential term has the form:

$$V(\phi^\dagger \phi) = -\mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2.$$ 

It is interesting to notice that with $\mu^2 < 0$ and $\lambda > 0$ the ground state of the system is no more unique and the system is no more invariant under rotations in the $(\phi^+, \phi^0)$ plane:

$$\langle 0 | \phi | 0 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad v^2 \equiv -\frac{\mu^2}{\lambda},$$

with $\langle 0 | \phi | 0 \rangle$ the expectation value of $\phi$ in the ground state. The situation is graphically shown in Figure 1.2. This phenomenon is called *spontaneous symmetry breaking* and in the particular case of electroweak interactions it is commonly referred to as Brout-Englert-Higgs mechanism, from the names of the physicists who first formulated this theory [11,12] in 1964. In the unitary gauge, the $\phi$ doublet can be expressed as:

$$\phi' = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ H + v \end{pmatrix},$$

and is the only real additional degree of freedom introduced by the symmetry breaking term in the Lagrangian, the so called *scalar Higgs field* $H$. The masses of the $W^\pm$, $Z$ vector bosons and of the fermions arise from the interaction terms with the scalar Higgs boson in the symmetry breaking electroweak Lagrangian. Photons continue to be massless, since the breaking of the symmetry only occurs in the weak $SU(2)_L$ sector of the electroweak symmetry.

### 1.3 Standard Model Higgs boson production mechanisms

In the Standard Model, Higgs boson production in proton-proton collisions can happen through five main modes: gluon fusion $gg \rightarrow H$; vector boson fusion $qq \rightarrow H + 2$ jets, associated production of a Higgs boson with a $W$ or $Z$ boson, and associated production with a $t\bar{t}$ pair. The hierarchy of the cross sections and their dependence on the Higgs boson mass is shown in Figure 1.3.
1.3. Standard Model Higgs boson production mechanisms

Figure 1.3: Theoretical predictions for the Higgs boson production cross sections in proton-proton collisions at \( \sqrt{s} = 8 \) TeV. The main five production cross sections, in decreasing order, are gluon fusion, vector boson fusion, \( WH, ZH \) and \( ttH \) [13].

Figure 1.4: Leading diagram for \( gg \rightarrow H \) production.

- **Gluon fusion**: The main Higgs boson production mechanism at the LHC is through gluon fusion (\( ggH \)), for which the leading Feynman diagram involves a quark loop (Figure 1.4). A remarkable property of the amplitude for this process at leading order is that it is zero for massless quarks, and saturates to a constant for increasing \( m_q/m_H \), so that the cross section is proportional to the square of the number of heavy quarks; in the Standard Model, the amplitude is dominated by the contribution from the top quark, the only one with mass scale comparable to the Higgs boson mass, but the production cross section is naturally sensitive to contributions from hypothetical particles with QCD interactions beyond the Standard Model ones at higher energy scales.

- **Vector boson fusion**: With a production cross section of about one-tenth of the gluon fusion one, vector boson fusion (VBF) is the second largest production mode relevant
1.3. Standard Model Higgs boson production mechanisms

Figure 1.5: Leading order Feynman diagrams for $qq \rightarrow H + 2\text{jets}$ production through vector boson fusion.

Figure 1.6: Leading order diagrams for $WH$ and $ZH$ associated production, and higher-order contribution to $ZH$ with gluons in the initial state.

at the LHC. The leading order diagrams for the process are shown in Figure 1.5; in the first, either or both of the incoming quarks can also be replaced by anti-quarks, but the $qq$ initial state gives the largest contribution for proton-proton collisions. As the two outgoing quarks are not connected by any quark or gluon line, QCD radiation in the region between the two jets is suppressed, resulting in final states with two jets at high rapidities.

- **Associated production**: The associated production ($VH$) of a Higgs boson and a $W$ or $Z$ boson is characterized by an even smaller production cross section than vector boson fusion. This mode is experimentally viable since leptons and neutrinos from the $W$ or $Z$ decay can provide handles to select events. The main Feynman diagrams for this process are closely related to the vector boson fusion ones since they both rely on the $WWH$ and $ZZH$ vertices and are shown in Figure 1.6.

- **Associated $t\bar{t}H$**: This is an important channel that allows for a direct measurement of the Yukawa coupling between top quark and Higgs boson. Unfortunately the very low production cross section and the complex final state with a large number of hadronic jets make it very challenging to reconstruct properly. Leading order diagrams for $t\bar{t}H$ production are shown in Figure 1.7.
1.4 Standard Model Higgs boson decay

The Standard Model Higgs boson is an unstable particle with immeasurably short lifetime \( \tau \sim 1.6 \cdot 10^{-22} \text{ s} \) \[10\]), so it can be detected only through its decay products. As for any unstable particle, the branching fractions are determined by the partial widths of the decays into each final state:

\[
\text{BR}(H \rightarrow X) = \frac{\Gamma(H \rightarrow X)}{\sum Y \Gamma(H \rightarrow Y)},
\]

where each partial width depends only on the square of the couplings of the Higgs boson to those specific decay products and on kinematic factors. At leading order in the SM couplings, the Higgs boson can decay into pairs of heavy fermions through Yukawa interactions (Figure 1.9 left), and into pairs of W or Z bosons through SU(2)\(_L\) interactions (Figure 1.9 right). The Yukawa decays have partial widths proportional the square of the ratios between fermion mass and Higgs boson vacuum expectation value \((m_f/v)^2\), so for \(m_H\) below the \(t\bar{t}\) threshold the decays are preferentially to \(b\bar{b}\) pairs, with smaller contributions from \(c\bar{c}\) pairs, \(\tau^+\tau^-\) pairs, and negligible ones from the other fermion pairs. The decays into gauge bosons would be dominant if the Higgs mass was above the \(m_H = 2m_V\) threshold, but can happen if the Higgs boson decays into a pair of off-shell W and Z bosons, which further decay into four fermions. The dependency of the branching fractions on the Higgs boson mass is shown in Figure 1.8.

Loop-induced decays into pairs of photons and gluons are also important. The decay into gluons is the mirror process of the gluon fusion production, happening through a quark loop (Figure 1.4); the large Yukawa coupling of the top quark and the eight-fold color multiplicity of the final state allow this loop decay to be competitive to the tree-level decay into \(\tau^+\tau^-\) pairs. Higgs boson decays into diphotons can happen both through a fermion loop, dominated by the top quark contribution, and through a W boson loop with two \(WW\gamma\) vertices (Figure 1.10). The partial width of the \(H \rightarrow \gamma\gamma\) decay is about a factor 40 smaller than the one for \(H \rightarrow gg\), due to the smaller electroweak couplings. Nevertheless this channel has several unique advantages, playing a major role both in the discovery of the Higgs boson and in the study of its properties. The diphoton final state provides a clean signature that can be exploited already at trigger level while at the same time the strategy of the analysis is simple: a search for a narrow peak in the diphoton invariant mass spectrum over a smooth continuum.

**Figure 1.7:** Leading order diagrams for \(t\bar{t}H\) associated production with gluons and quarks in the initial state.
1.4. Standard Model Higgs boson decay

Figure 1.8: Predicted branching fractions for the Standard Model Higgs boson decays, as function of the Higgs boson mass. The theoretical uncertainties on the predictions is displayed as a band [14].

Figure 1.9: Leading order Feynman diagrams for Higgs boson decays into pairs of fermions (left) and gauge bosons (right).

Figure 1.10: Leading order Feynman diagrams for Higgs boson decays into pairs of photons.
background.
Chapter 2

The LHC and the ATLAS experiment

Particle colliders are among the most efficient tools for the study of high energy particle physics. The essential task of a particle collider is to accelerate two beams of charged particles to high energy and to induce them to collide in well defined interaction points. In this way, it is possible to produce final states with new particles, the only limit being the conservation of quantum numbers and energy in the system. Results from the particle collision can be studied in detail by an appropriate particle detector built around the interaction point (IP) and used to understand the physical processes producing the set of particles measured in final states. The present work is based on a sample of proton-proton collisions produced by the Large Hadron Collider (LHC) at a center-of-mass energy $\sqrt{s} = 8$ TeV during the 2012 data taking period. The description of the ATLAS detector and the LHC machine are based, for consistency, on their status at the time of the 2012 data taking. The first part of this chapter is dedicated to the description of the LHC itself. The collisions produced by the LHC are reconstructed and studied with the ATLAS particle detector in order to produce the data for the physics analysis presented here. In the second part of the chapter, the ATLAS detector is described, with details about the subsystems and the aspects relevant to the measurements later discussed.

2.1 The Large Hadron Collider

The LHC [15–17] is a circular hadron collider currently operated at CERN and it is capable of accelerating particles to the highest energy ever achieved. It occupies a 27 km circular tunnel which previously hosted the Large Electron Positron (LEP) collider, which is situated approximately 100 m underneath the surface across the Swiss-French national border, not far from Geneva. The LHC has been designed to accelerate two circular, opposite beams of protons that collide with a center-of-mass energy of $\sqrt{s} = 14$ TeV ($1$ TeV = $10^{12}$ eV). In addition, LHC can handle beams of heavy ions particles as lead ions.
The particle beams are collimated, focused and brought to collision in four interaction points. These interaction points are located in artificial underground caverns hosting the four major particle detectors of the LHC program: A Thoroidal Lhc ApparatuS (ATLAS) [18], Compact Muon Solenoid (CMS) [19], Large Hadron Collider beauty (LHCb) [20], A Large Ion Collider Experiment (ALICE) [21]. LHC-forward (LHCf) [22] and TOTEM [23] are additional experimental facilities located few hundreds of meters away from the the ATLAS and CMS interaction points, and are dedicated to a complementary physics program based on the study of particles emitted at very low angles with respect to the colliding beams.

The so-called “Run1” data taking period has started with LHC’s first collisions at the end of 2009. During 2010 and 2011 it has produced samples of proton-proton collisions at a center of mass energy of 7 TeV and lead-lead collisions at 2.76 TeV. The largest set of collisions for Run1 has been produced during 2012 at the center of mass energy of 8 TeV; the data collected with these proton-proton collisions has been used for the measurement presented in this thesis. The Run1 of the LHC has ended in early 2013 with proton-lead collisions at 5.02 TeV.

2.1.1 The accelerators

The following section is an overview of the main characteristics of the LHC and its main parameters that are of any relevance to the acquisition of data at the experiments around its collision points.

The chain of accelerators needed to bring the particle beams to the highest energy is presented in Figure 2.1. As described in [16], the path of the accelerated particles goes through several intermediate stages of acceleration before eventually being injected in the LHC main ring:

- **Linac2**, length: 36 m; it is the first and only linear accelerator in the chain. The energy of the output particles is of 50 MeV;
- **Proton Synchrotron Booster**, circumference: 157 m. Nominal energy: 1.4 GeV;
- **Proton Synchrotron (PS)**, circumference: 628 m. Nominal energy: 25 GeV;
- **Super Proton Synchrotron (SPS)**, circumference: 7 km. Nominal energy: 450 GeV.

The circulating particles are kept on a stable and approximately circular orbit by 1232 superconducting 14.2 m long Niobium-Titanium dipole magnets, cooled down at 1.9 K with a liquid $^3$He cooling circuit and capable of producing a magnetic field of about 8.33 T. The two colliding beams that circulate through the LHC in opposite direction are made of particles with the same positive electrical charge. For this reason the dipole magnets are designed to contain two separated cavities filled with an inverse magnetic field. Around each of the four interaction points the circulating particles go through a set of additional magnets with a more complex magnetic field configuration (quadrupolar, sextupolar and octupolar) with the aim of
Figure 2.1: Overview of the LHC accelerator chain [24]. The proton beam enters the LHC from the SPS with an energy of 450 GeV, with collisions happening at four interaction points around the ring, one for each of the main experiments; ATLAS, ALICE, CMS and LHCb.
2.1. The Large Hadron Collider

collimating, focusing and making the beams stable to maximize the probability of interaction between the crossing particles. The particles are grouped in small bunches with a transverse size of around 15 \( \mu \text{m} \) and a longitudinal length of few centimeters, each containing about \( 1.6 \times 10^{11} \) protons. The LHC has been designed to allow a minimum spacing between two consecutive bunches of 25 ns, which corresponds to a bunch crossing frequency of 40 MHz. In this configuration, each beam can be filled with up to 2808 bunches of protons. During the Run1 data taking period a bunch spacing of 50 ns has been adopted instead, corresponding to a maximum of 1404 bunches per beam.

The density of protons in the beam is described by two parameters: the emittance \( \epsilon_n \) and the betatron function \( \beta^* \) (sometimes called amplitude function). The first describes the phase space distribution of particles in the beam: a lower emittance corresponds to bunches of well collimated particles, all with very similar momentum and parallel trajectory. The second corresponds to the width of the beam squared divided by the beam emittance, roughly speaking, this quantity describes how well the beam has been squeezed by the focusing magnets around the crossing point (a small betatron function maximizes the probability of interaction). With all the quantities previously described it is possible to define the particle collider instantaneous luminosity \( \mathcal{L} \):

\[
\mathcal{L} = \frac{\gamma r f_{\text{rev}} n_B N_p^2}{4\pi \epsilon_n \beta^* F}
\]

with \( n_B \) the number of bunches circulating, \( N_p \) the number of protons per bunch, \( \gamma r \) and \( f_{\text{rev}} \) the Lorentz factor and the revolution frequency of the bunches within the orbit respectively. The luminosity is corrected by a geometrical factor \( F \) which depends on the width and the angle of the two colliding beams at the interaction point. The instantaneous luminosity is the parameter of greatest interest for a particle collider because it can be used, along with the theoretical cross section of a given physical process and the acceptance of the particle detector, to compute the expected rate of events for a physical process under study. The higher the luminosity, the higher is the number of events for the same process. The design luminosity for the LHC is \( 10^{34} \) cm\(^{-2}\)s\(^{-1}\). The peak luminosity reached by the machine during Run1 is \( 7.7 \times 10^{33} \) cm\(^{-2}\)s\(^{-1}\), obtained during the 2012 data taking period with a bunch spacing of 50 ns. The total proton-proton cross section at the LHC is of the order of 100 mb [25]. Given the LHC instantaneous luminosity and the beam parameters described above for the 2012 data taking conditions, it is possible to estimate the average number of proton interactions per second to be about \( 10^9 \), i.e. an average of around 20 interactions per bunch crossing. This phenomenon of multiple interactions per bunch crossing is called pileup (PU), and needs to be carefully taken into account when reconstructing a physically interesting event to disentangle the proton interaction generating a process of interest from the decay products of the other interactions. Table 2.1 is a summary of the most relevant LHC parameters.
### 2.1. The Large Hadron Collider

#### 2.1.2 Coordinate system and kinematic variables

The coordinate conventions adopted by the LHC and all of its experiments are described in the following text. For a particular experiment, the center of the laboratory reference frame corresponds to the interaction point and the z-axis corresponds to the tangent line to the beam at the interaction point, in anti-clockwise direction. The x-axis is perpendicular to the z-axis and virtually joins the interaction point with the center of the LHC ring, pointing toward the ring center. The y-axis is perpendicular to the z and x axes and points towards the ground surface. These coordinates are used to define the following quantities:

- $r = \sqrt{x^2 + y^2}$: the distance to the beam line;
- $\phi = \arctan(x/y)$: the azimuthal angle;
- $\theta = \arctan(y/z)$: the polar angle;
- $\eta = -\ln(\tan \theta/2)$: the pseudorapidity.

Every point in space is identified by the $(r, \phi, \eta)$ triplet of coordinates and in particular the $(\phi, \eta)$ coordinate set describes the direction of a particle produced at the interaction point.

Based on these definitions, the momentum of a particle can be divided in two components: the longitudinal momentum $p_z$ and the transverse momentum $p_T$, defined as

$$p_T = \sqrt{p_x^2 + p_y^2} ;$$

while the rapidity of a particle of energy $E$ is defined as

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z} .$$

The rapidity has the property of being additive under Lorentz boosts along the z direction, i.e. it is simply shifted by a constant when subjected to such transformations. For high-energy particles, rapidity can be approximated by pseudorapidity which only depends on the polar angle $\theta$ of the particle momentum.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2011</th>
<th>2012</th>
<th>Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>3.5 TeV</td>
<td>4 TeV</td>
<td>7 TeV</td>
</tr>
<tr>
<td>$\beta^*$</td>
<td>1.0 m</td>
<td>0.6 m</td>
<td>0.55 m</td>
</tr>
<tr>
<td>$1/f_{\text{rev}}$</td>
<td>50 ns</td>
<td>50 ns</td>
<td>25 ns</td>
</tr>
<tr>
<td>$n_b$</td>
<td>1380</td>
<td>1374</td>
<td>2808</td>
</tr>
<tr>
<td>$&lt;N_p&gt;$</td>
<td>$1.45 \times 10^{11}$ protons</td>
<td>$1.65 \times 10^{11}$ protons</td>
<td>$1.10 \times 10^{11}$ protons</td>
</tr>
<tr>
<td>Initial $\epsilon_\eta$</td>
<td>2.5 mm mrad</td>
<td>2.5 mm mrad</td>
<td>3.75 mm mrad</td>
</tr>
<tr>
<td>$\mathcal{L}^{\text{max}}$</td>
<td>$3.7 \times 10^{33}$ cm$^{-2}$ s$^{-1}$</td>
<td>$7.7 \times 10^{33}$ cm$^{-2}$ s$^{-1}$</td>
<td>$1.0 \times 10^{34}$ cm$^{-2}$ s$^{-1}$</td>
</tr>
</tbody>
</table>

**Table 2.1:** Overview of proton proton beam parameters of the LHC during the machine operations of 2011 and 2012. Parameters are compared to their design values.
2.2 The ATLAS experiment

The ATLAS detector is a general purpose detector, situated in one of the four LHC interaction points, as indicated in Figure 2.1. The detector is built with a broad physics program in mind, ranging from searches for the Higgs boson and physics beyond the Standard Model to top physics and precision Standard Model measurements. The ATLAS detector is 44 m long and 25 m tall, its weight is around 7000 tonnes and it has a total of 3000 km of cables.

The ATLAS detector is composed of a range of sub-systems which, ordered from the inside out, are:

- the Inner Detector (ID), which is the innermost tracker for charged particles

- the calorimetry system, comprised of an electromagnetic calorimeter and a hadronic calorimeter measuring respectively energy deposits of particles originated from electromagnetic and from hadronic showers

- the outermost Muon Spectrometer measuring muon trajectories escaping the calorimeter system.

Figure 2.2 shows a schematic view of the detector and its different components. In the following sections the main characteristics for each of the sub-systems are described, for a full detailed description of the ATLAS experiment see [18].
2.2. The ATLAS experiment

Figure 2.3: Overview of the ATLAS inner detector and its parts.

2.2.1 The Inner Detector

The ID [26] is a tracking detector, comprised of three sub-detectors. These are two silicon detectors, the pixel detector (PIXEL) and the SemiConductor Tracker (SCT) and a straw tube detector, the Transition Radiation Tracker (TRT). An overview of the detector layout can be found in Figure 2.3. A solenoid magnet provides a 2 T magnetic field with the field aligned with the beampipe bending the tracks of charged particles in the $x$-$y$ plane allowing for momentum measurements in the tracker. An evaporative cooling system, using $C_3F_8$ as coolant, is used to keep the Pixel and SCT detectors at a temperature of $-7^\circ$C in order to prevent the silicon sensors from operational damage and to slow down the aging degradation.

The PIXEL detector

High granularity tracking detectors near the IP are crucial for a good tracking performance in environments with high track multiplicity, such as the collisions at the LHC. The PIXEL detector [27] consists of 1744 silicon pixel modules arranged in 3 concentric cylindrical barrel layers and 3 disks in each of the two end-caps. The barrel and end-cap modules are identical, with nominal pixel size of $50 \mu m \times 400 \mu m$ and a sensor thickness of $250 \mu m$. Each module has 46080 independent read-out channels, resulting in more than 80 million readout channels for the whole detector. The Pixel sensors are built using an oxygenated n-type bulk material. The detector is situated in the range from $r = 50.5$ mm to $r = 150$ mm from the beam pipe. It provides charged-particle tracking with high efficiency over the pseudorapidity range $|\eta| < 2.5$, with a hit resolution of $10 \mu m$ in the $r - \phi$ plane and $115 \mu m$ along the $z$ direction.
(r in the end-cap). Particles traveling through the detector provide three (two) hits in the barrel (end-cap) for the track measurements.

The Semiconductor Tracker

The SCT [28] is a silicon microstrip detector. It consists of 4088 silicon micro-strip modules arranged in 4 double-sided concentric cylindrical layers in the barrel and 18 single-sided disks, 9 in each of the two end-caps. The whole detector covers the tracking of particles within $|\eta| < 2.5$. The sensors are made using a single sided p-in-n design with each sensor consisting of 768 strips with 12 cm length, 80 $\mu$m strip pitch and a sensor thickness of 285 $\mu$m. In the barrel the strips sensors are glued back-to-back at a stereo angle of 40 mrad providing position information along the strip module direction. The resulting resolution in the $z$ direction is 580 $\mu$m. In the end-cap disks the strips are aligned radially with wedge-shaped modules. The single plane position resolution of the SCT after alignment is very close to 17 $\mu$m in the $r$-$\phi$ direction.

The Transition Radiation Tracker

The TRT [29] is a detector composed of thin-walled proportional drift tubes (so called straws), placed outside the SCT. Each tube has a diameter of 4 mm, a length of 114 cm, and contains a gas mixture of 70% Xe, 27% CO$_2$ and 3% O$_2$. At the center of the tube there is a 31 $\mu$m diameter gold-plated tungsten wire with a read-out on each side of the tube. In the walls of the straws there is an aluminum layer that is held at a potential of -1530 V with respect to the wire that is referenced to ground. The straws are arranged along the $z$ direction in the barrel and radially in the end-caps. The space between the straws is filled with radiator material: polypropylene fibres are used in the barrel and polypropylene foils in the end-caps. The TRT provides coverage for $|\eta| < 1.1$ in the barrel and $1.0 < |\eta| < 2.0$ in the end-cap. When a charged particle goes through the TRT it interacts ionizing the gas-mixture in the straws and emitting transition radiation in the radiator material. The transition radiation is absorbed in the gas inside the straw tubes. The signal from the straw wires is collected, amplified and discriminated against two thresholds, a low threshold at about 300 eV and a high threshold at about 6 keV. The two thresholds are needed both for tracking information and for particle identification (electron/pion separation) [30]. The TRT provides a large number of hits from each straw, typically 36 per track. The spatial resolution for TRT measurements is about 130 $\mu$m.

2.2.2 The calorimeters

The ATLAS calorimetry system is built from five different sub-detectors, split into electromagnetic and hadronic calorimetry.

Calorimeters provide energy and position measurements for neutral and charged particles through energy deposits in absorbing materials. Incoming particles interact with the material
2.2. The ATLAS experiment

Figure 2.4: Overview of the ATLAS calorimeter systems.

and develop showers of secondary particles with gradually reduced energy. Detection is based on the ionization and scintillation processes which originate from the secondary particles produced in the showers. Both longitudinal and later segmentation of the calorimeters allow the determination of the shower characteristics as well as the extraction of position (direction) information. The ATLAS detector uses sampling calorimeters, meaning that the system is designed to have alternating layers of passive and active material, the passive material acts as an absorber while the active one interacts with the event particles and originates cascades of secondary particles.

The ATLAS calorimeters cover a range of $|\eta| < 4.9$. The electromagnetic calorimeter is the closest to the interaction point followed by the hadronic calorimeter. A schematic view of the calorimeter structure can be seen in Figure 2.4. The following paragraphs explain in more details the characteristics of each system.

The electromagnetic calorimeter

The ATLAS electromagnetic calorimeter [31] is a sampling calorimeter using lead absorbers and liquid argon (LAr) as the active material. It is divided into a barrel section, covering the pseudorapidity region $|\eta| < 1.475$, and two end-cap sections, covering the pseudorapidity regions $1.375 < |\eta| < 3.2$. The transition region between the barrel and the end-caps, $1.37 < |\eta| < 1.52$, has a large amount of material upstream of the first active calorimeter layer.

For $|\eta| < 2.5$ the electromagnetic calorimeter has three sampling layers, longitudinal in shower depth, that vary for their different granularity in the $\eta$ direction. The first sampling
layer provides, with its fine $\eta$ granularity of the strips, discrimination between single photon showers and two overlapping showers coming from the decays of neutral hadrons, usually $\pi^0$. The second layer collects most of the energy deposited in the calorimeter by photon and electron showers while the third one is used to correct for leakage beyond the EM calorimeter of high-energy showers. Finally, a thin presampler layer (PS) is placed in front of the calorimeter for $|\eta| < 1.8$ and used to correct for energy loss upstream of the calorimeter. A sketch of a barrel module is shown in Figure 2.5. The energy resolution of the calorimeter can be parametrized as:

$$\sigma(E) / E = a \sqrt{E} + b$$

(2.1)

where the sampling term is $a = 10\% \cdot \sqrt{\text{GeV}}$ and the constant term is $b = 0.17\%$ [18].

The hadronic calorimeter

The ATLAS hadronic calorimeter provides the measurement of the energy for the hadronically interacting particles that transverse the detector. The hadronic calorimeter is composed of the following subsystems: (i) the Tile hadronic calorimeter, covering $|\eta| < 1.7$; (ii) the Hadronic end-cap calorimeter, covering $1.5 < |\eta| < 3.2$; and the (iii) Forward calorimeter which is integrated in the cryostats in the end-caps, covering up to $|\eta| = 4.5$, which also provides an additional measurement for electromagnetic showers.

The Tile calorimeter

The Tile calorimeter (Tile) sits directly outside the electromagnetic calorimeter. It consists of a barrel region covering $|\eta| < 1.0$ and two extended barrel regions,
2.2. The ATLAS experiment

Each covering ranges of $0.8 < |\eta| < 1.7$. It is a sampling calorimeter that uses steel as absorbing material and scintillating tiles as active material. As hadrons transverse the detector they interact with the iron tiles, initiating showers. As the resulting shower goes through the scintillating tiles ultraviolet light is emitted, which is collected at the edge of each scintillating tile through wavelength shifting fibers connected to PhotoMultiplier Tubes (PMTs) at the outer surface of the detector. The collected light is converted into signal and read out. The relative resolution of the Tile calorimeter can be parametrized as in Eq. 2.1 with parameters $a = (56.4 \pm 0.4)\% \cdot \sqrt{\text{GeV}}$ and $b = (5.5 \pm 0.1)\%$.

**The Hadronic End-cap calorimeter**

The Hadronic End-cap Calorimeter (HEC) consists of two wheels, situated at each end-cap. The HEC covers the region of $1.5 < |\eta| < 3.2$ and in part overlaps with the Tile Calorimeter. It uses liquid argon as active material placed between copper plates that act as absorbers.

**The Forward Calorimeter**

The Forward Calorimeter (FCal) is situated in the forwardmost part of the system, specifically covering the region $3.1 < |\eta| < 4.9$, and it is used to provide calorimetry for both electromagnetically and hadronically interacting particles. The detector uses liquid argon as the active material, while a modular design allows for a combination of electromagnetic shower and hadronic shower measurements. Closest to the interaction point, a copper-made module measures electromagnetic deposits. Further away, two modules, made of tungsten, provide hadronic calorimetry and limit punch through to the muon systems.

2.2.3 The muon spectrometer

The Muon Spectrometer (MS) provides a precise (and independent from the ID) momentum resolution for high-$p_T$ muons escaping the inner most detector layers, together with a rapid trigger response.

The detection method is based on bending muon tracks in a large superconducting toroidal magnetic system. The magnetic field in the muon spectrometer volume is provided by an air-core superconducting toroid magnet, consisting of eight toroid coils in the barrel and two magnets in the endcaps built of eight coils. The coils in each endcap are placed inside a common cryostat.

Muons with $|\eta| < 1.4$ and $1.6 < |\eta| < 2.7$ are bent in the toroidal barrel and end-cap magnet systems, respectively. Both the solenoidal magnetic field, and the toroidal system bend muons in the transition region between barrel and end-caps ($1.4 < |\eta| < 1.6$).

The MS, is composed of four detector systems with two different purposes: (i) monitored drift tube chambers and (ii) cathode strip chambers for precision measurements, (iii) resistive plate chambers and (iv) thin gap chambers for triggering. A schematic view of the of the MS is shown in Figure 2.6.
2.2. The ATLAS experiment

Monitored Drift Tube Chambers The Monitored Drift Tube Chambers (MDTs) are used for precision tracking measurements, with coverage for $|\eta| < 2.7$. They are composed by 30 mm diameter drift tubes, filled with a 93% of Ar and 7% of CO$_2$ mixture under 3 bar pressure. At the center of the tubes there is a 50 $\mu$m thick tungsten-rhenium wire. The spatial resolution of the drift chambers is typically 35 $\mu$m.

Cathode Strip Chambers The Cathod Strip Chambers (CSCs) are multi-wire proportional chamber detectors. The CSCs are used for the innermost muon wheel, covering $2.0 < |\eta| < 2.7$. They have very good granularity and timing resolution (the typical response time is 40 ns). The wires run in the radial direction, while the cathode strips run both parallel and perpendicular to the wires. In this way, the CSCs provide coordinate measurements along both the bending plane, with 40 $\mu$m resolution, and along the orthogonal plane, with 5 mm precision.

Resistive Plate Chambers The Resistive Plate Chambers (RPCs) are made of electrode plates with a 2 mm gap. The electric field between the plates induces electron avalanches as muons pass between the plates. The RPCs cover ranges of $|\eta| < 1.05$ and, because of their rapid response time, are used primarily for trigger information. Moreover, they provide additional hits for muon tracking.

Thin Gap Chambers The Thin Gap Chambers (TGCs) are multi-wire proportional chambers. Their defining feature is that the distance between the wires is larger than between the wire and the cathode. The excellent timing resolution of this detector serves perfectly for triggering purposes of high-$p_T$ muons. The TGCs contribute also to track measurements within the range of $1.05 < |\eta| < 2.7$.

2.2.4 Trigger system

As explained in Sec. 2.1.1, the LHC is designed to deliver collisions at the rate of 40 MHz. Detector and computing capabilities do not allow for all the events to be recorded. The computing time required to process and record those events limits the amount of events that can be stored offline for analysis. Moreover, when the event data is retrieved by the readout electronics there is a dead time for the detector while no event can be recorded. For this reasons it is important to select for readout the small fraction of events which are of the most interest for the experiment’s physics program, while the rest, originated from lower energy interactions, are disregarded. The ATLAS trigger system accomplishes this task reducing the event rate from 40 MHz to a few hundreds of Hz, which are written to disk.

The ATLAS trigger system consists of three stages, each successively producing a more refined event selection with a lower output rate. In the first step, the detector response after a collision is buffered in the memory board of the detector. The first trigger stage, named Level 1 (L1), uses reduced information from the muon detectors to identify high-$p_T$ muons and
calorimeter information to identify jets, electrons/photons, taus and events with large missing transverse energy ($E_{\text{miss}}^T$) or total transverse energy to decide if that event should be read out. The L1 trigger selection is designed to use low granularity information, the processing time is as small as possible (2.5 $\mu$s). If the L1 selection criteria are matched, Regions-of-Interest (RoI) within the detector are identified through the corresponding ($\eta, \phi$) coordinates and passed to the next step, the High Level Trigger (HLT). In this first stage, the event rate is reduced from 40 MHz down to 75 kHz.

The HLT is composed of two stages, the Level 2 (L2) trigger and the Event Filter (EF). The L2 trigger looks at the ROI with the full granularity MS and calorimeter information as well as the ID information, using reconstruction algorithms for the objects of interest. With the L2 trigger the event rate is reduced to 3.5 kHz. Finally, in the EF the entire detector data is used at full granularity, producing the final decision on whether the event should be kept. Events selected at this stage are recorded for offline processing. The final event rate after the EF is $\sim$200 kHz.

In the analyses treated in this thesis the events must satisfy the trigger requirement of containing (at least) two photons candidates: the one with the highest transverse momentum (leading) with $p_T > 35$ GeV and the second highest transverse momentum photon (subleading) with $p_T > 25$ GeV and both passing a “loose” photon identification requirement that is based only on shower shapes in the second layer of the electromagnetic calorimeter and on the energy deposited in the hadronic calorimeter [32]. The photons are also required to be within
2.3 Dataset

The analyses presented in this thesis use the full pp collision data recorded by the ATLAS detector during 2012. The center-of-mass energy of the protons at the interaction points was $\sqrt{s} = 8$ TeV and the total integrated luminosity of the measured dataset is 20.3 fb$^{-1}$. The integrated luminosity collected by the ATLAS detector during 2012 is shown in Figure 2.7(a) as a function of time. In Figure 2.7(b) the distribution of the mean number of interactions per bunch-crossing is displayed together with its mean value. For completeness and comparison also data from pp collisions at $\sqrt{s} = 7$ TeV of 2011 is present in Figure 2.7.
Chapter 3

Simulation of the charge trapping effect in the SCT detector

One of the main, macroscopic radiation damage effects in silicon detectors is the charge trapping. It occurs when in the bulk of silicon sensors, after intensive irradiation, defects act as traps for the free carriers (electrons/holes). As a consequence, the charge collection efficiency of the detector is affected. The charge trapping effect has been implemented in the simulation framework of the ATLAS Semiconductor Tracker. This chapter presents the general scheme used for this, together with some results regarding the detector response as a function of the fluence received.

3.1 Charge trapping

During the years of operations at LHC, experiments face detector changing conditions due to the inevitable aging but also to the radiation dose absorbed by the detector materials. For this reason it is fundamental to study, monitor and make predictions about present and future detector response.

Silicon detectors, as the SCT, are subject to different kinds of radiation damage [33–35]. Ionizing radiation (light charged particles or photons), interacting with shell electrons, causes mainly surface damage. Massive hadronic particles as protons, neutron and pions damage mostly the bulk of the sensor, introducing crystal defects, which change the physical properties of the detector:

- Introduction of acceptor centers modifies the doping concentration and lead to type inversion, after which the voltage required to fully deplete the sensor will increase
- Recombination/generation centers increase the leakage current, affecting the power consumption and the signal-to-noise ratio
- Charge trapping centers reduce the charge collection efficiency and hence degrade the hit efficiency, track resolution and e.g. the $b$-tagging performance
The last of the listed effects is the one treated in this chapter.

Charge trapping [36] removes charge carriers from the induced signal through trapping centers in the bulk of the sensor leading to a reduced measured signal $Q_s$,

$$Q_s = Q_0 e^{-\frac{t}{\tau}},$$

with $Q_0$ the ideal signal, without charge trapping, and $t$ the collection time of the signal. Trapping is characterized by the effective trapping time $\tau$, different for electrons and holes, which depends on the fluence received $\Phi$ as:

$$\frac{1}{\tau} = \beta \Phi,$$

where $\beta$ is the trapping constant. In this way the probability of a charge to be trapped after drifting through a sensor thickness $z$ is given by:

$$P_{\text{trap}} = 1 - e^{-\frac{z}{v\tau}} = 1 - e^{-\frac{z}{v\tau}},$$

(3.1)

where the drift velocity $v$ depends on the electric field $E$ and the temperature $T$ inside the sensor through $v = \mu_d(E, T) \cdot E$. The drift velocity is a function of the drift mobility

$$\mu_d = \frac{v_s/E_c}{[1 + (E/E_c)^\eta]^{1/\eta}},$$

where the values for the constants $v_s, E_c, \eta$ can be found in [37]. It is important to say that for holes these values remain almost constant also after high irradiation [38]. However, from the last equations it is obvious how this radiation damage effect is strictly related to and dependent on a good knowledge of the electric field.

### 3.2 SCT digitization

The geometry of the ATLAS detector is implemented in the Geant 4 [39, 40] detector simulation. All the simulated events are processed through Geant 4 simulation. This allows to describe the evolution of the particles generated and their interaction with the detector, including energy and hit positions from particles on the detector modules. The goal of this work is to implement, in an efficient and simple way, the charge trapping effect into the SCT software for the simulation of the detector response, usually called digitization.

In the SCT digitization when a charge particle goes through the sensors the electron-hole pair production is simulated. For simplicity only the holes are taken into account for the signal formation. This is true in first approximation since the SCT sensors are p-on-n and the holes drift from the HV plate to the strips. A simplified scheme of how this part of the SCT digitization works is shown in Figure 3.1. This simulation is modified to include the charge trapping effect. For every free carrier that is generated starting from the Geant 4 hits, a random time $t'$ is generated according to the trapping probability distribution given by the formula $t' = -\tau \log (u)$ that can be easily derived from Eq. 3.1 and where $u$ is a random
3.2. SCT digitization

Figure 3.1: Simplified scheme of the SCT digitization.
number between 0 and 1. The time $t'$ is considered as the trapping time and is compared to the time $t$ that it would take to the charge from the generation point to reach the electrode. If the time $t'$ is long enough to allow the charge to get to the electrode, the usual drifting process is followed and the signal is generated as usual. On the contrary, if the trapping time is smaller than $t$, the charge will be trapped. The trapping position is computed by evolving the charge from the generation point for the time $t'$. Counting the number of charges that reaches a strip could be a good parametrization for the simulation of nonirradiated sensors, but considering a more realistic way of signal generation is fundamental for irradiated ones. In fact free carriers induce a signal while moving in the bulk of the sensor. This process is modeled by Ramo’s potential [41, 42] for the particular geometry of the detector. The Ramo theorem allows to model the signal formation in the electrodes depending on the position of the charge in the detector. A potential map can be then built solving numerically the Laplace equation for a charge with boundary conditions $V_r = 1$ for the electrode subtending the charge, and zero for the rest. Ramo’s potential depends only on the geometry of the detector and position of the charge inside the sensor. For this reason, Ramo’s potential does not change with irradiation. A map for the particular case of the SCT detector modules is computed and can be seen in Figure 3.2. The scheme of the SCT digitization with the charge trapping implemented is shown in Figure 3.3.

![Ramo's potential map](image)

**Figure 3.2:** Ramo’s potential map. It covers 5 strip length with steps of 5 μm, while on $z$ direction the steps are of the size of 2.5 μm. The sensor depth is 285 μm ($z$ direction), the strip pitch is 80 μm ($y$ direction)

Two different electric field parametrizations are considered:
Figure 3.3: Simplified scheme of the SCT digitization with the charge trapping effect implemented.
• the uniform field \( E = \frac{V_b}{d} \)

• and the flat diode model

\[
E = \frac{V_b - V_d}{d} - \frac{2V_d \cdot z}{d^2},
\]

where \( V_b \) and \( V_d \) is the bias and depletion voltage, respectively, \( d \) is the depletion depth and \( z \) is the position in the sensor depth direction. In Figure 3.4 the values for the electric field inside the sensor bulk using the two approximate models seen above are shown for \( V_b = 150 \) V and \( V_d = 70 \) V.

Figure 3.4: Electric field profiles for the two models considered with \( V_B = 150 \) V and \( V_D = 70 \) V. The origin corresponds to the electrode plane, while the HV plane is at 0.285 mm.

3.3 Results

In this section results obtained using the simulation infrastructure described above are shown.

Several different charge trapping constants exist in literature. This can be caused by a large number of reasons as sensor type, type of irradiation used, annealing process \([43–45]\). In the following the value used for \( \beta_{\text{holes}} \) corresponds to \( \beta_{\text{holes}} = 5.1 \cdot 10^{-16} \text{ cm}^{-2} \text{ ns}^{-1} \) for holes \([46]\).

Using FLUKA \([47, 48]\) simulations, it is possible to convert the integrated luminosity delivered by the LHC to the ATLAS detector to radiation dose experienced by the different parts of the detector. Figure 3.5 shows a “radiation map” for a quarter of the ATLAS inner detector \([49]\). From this it is possible to calculate that for the innermost SCT barrel layer, the fluence received at the end of 2012 operations, after 5.61 fb\(^{-1}\) at \( \sqrt{s} = 7 \) TeV and 23.3 fb\(^{-1}\) at
\( \sqrt{s} = 8 \text{ TeV} \), is \( 5.0 \cdot 10^{12}[\text{MeV neq cm}^{-2}] \) (the radiation dose is always converted in 1 MeV neutron equivalent (neq) radiation.). In the following part of this chapter, the attention is focused on the innermost barrel layer since it is the most affected by radiation damage inside the SCT.

![Silicon 1 MeV neutron equivalent fluence, 14 TeV](image)

**Figure 3.5**: Silicon 1 MeV neutron equivalent fluences for 1 fb\(^{-1}\) of pp collisions at \( \sqrt{s} = 14 \text{ TeV} \) in the ATLAS inner detector from FLUKA simulation [49].

Figure 3.6 shows the drift distance for holes before being trapped inside the sensor, for different fluences. For low fluences one can see that these distributions are rather flat while going to higher values of radiation dose leads to more holes trapped at short distances.

Figure 3.7 presents the trapping position inside the sensor for trapped charges where the number of charges is normalized for comparing different fluences. It can be seen that, as one would expect, for low fluences most of the charges are trapped in the region close to the electrode. This is not the case at high fluences, where the distribution becomes more and more flat due to the fact that the trapping times start to be very short so that a uniform distribution of generated free carriers translates into a uniform distribution in trapping position.

Radiation doses considered in these two plots are much higher than what is realistically foreseen for the whole life of the SCT. More realistic fluences for the SCT lifetime are considered from now on.

As seen in Sec. 2.2.1, the SCT plays a crucial role in the track reconstruction of charged particles. To study the impact of charge trapping on tracks, two quantities are investigated: the *cluster size for all hits* and the *cluster size for hits on track* where the cluster size is the number of silicon strips that return a signal after the passage of a charged particle.
3.3. Results

Figure 3.6: Distance that a hole can drift before being trapped inside the sensor. The simulation is performed for different radiation fluences and results are normalized for comparison. The total sensor thickness is 0.285 mm.

Figure 3.7: Position where the hole is trapped with respect to the sensor depth. The origin corresponds to the electrode position while the HV plane is at 0.285 mm. Different radiation doses were used in the simulation, then scaled and compared.
3.3. Results

<table>
<thead>
<tr>
<th>Fluence $\phi$ [1MeV $neq \text{cm}^{-2}$]</th>
<th>All Hits</th>
<th>Hits on Track</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean cluster size</td>
<td>Difference to w/o charge trapping</td>
</tr>
<tr>
<td>0</td>
<td>1.96</td>
<td>-</td>
</tr>
<tr>
<td>$4 \cdot 10^{13}$</td>
<td>1.87</td>
<td>-4.5%</td>
</tr>
<tr>
<td>$7 \cdot 10^{13}$</td>
<td>1.82</td>
<td>-6.8%</td>
</tr>
<tr>
<td>$1 \cdot 10^{14}$</td>
<td>1.77</td>
<td>-9.6%</td>
</tr>
</tbody>
</table>

Table 3.1: Radiation dose and variations on the mean cluster size.

Figure 3.8 shows the cluster size of all reconstructed hits in the innermost SCT barrel layer. In this plot, different fluences are compared. The blue histogram can be used as reference because it considers no charge trapping (or zero radiation dose), while the green, the red and the black distributions correspond to the irradiation after $\sim 200$, $\sim 350$ and $\sim 450 \text{ fb}^{-1}$, respectively. It can be seen that the charge trapping effect reduces the mean cluster size, in the worst case considered by $\sim 10\%$. Figure 3.9 shows results from simulation with the same radiation doses as before, but in this case the cluster size considered is for hits that belong to tracks, which acts as a quality requirement. Similar behavior as in the previous case is seen apart from the fact that the effect of charge trapping in this case is smaller. In fact, for a received fluence of $10^{14}$ [1MeV $neq \text{cm}^{-2}$] the reduction of the mean cluster size is 4%. The results are summarized in Table 3.1.

Figure 3.8: Cluster size for all hits reconstructed on the innermost SCT barrel layer for different radiation doses. Uniform electric field inside the sensor is used with $V_B = 150 \text{ V}$.

Charge trapping is only one of the radiation effects that will rise with time and operation of the detector and even more, different radiation effects can couple. Modifications of the
3.3. Results

Figure 3.9: Cluster size for hits on track on the innermost SCT barrel layer for different radiation doses. Uniform electric field inside the sensor is used with $V_B = 150$ V.

electric field profile in the sensors bulk is one of the most important effects acting against or in favor of charge trapping, mainly because this changes the drift velocity of free carriers inside the sensors resulting in different trapping probabilities. For this reason, changes in the bulk effective doping concentration are taken into account. Figure 3.10 shows the possible behavior of the depletion voltage in the innermost SCT barrel layer sensors given a particular LHC operation and SCT cooling scenario. Probably the conditions are a little bit extreme, but the intention was to study the “worst” case situation. The evolution of $V_d$ [50] is obtained from the effective doping concentration $N_{\text{eff}}$ in the following way

$$V_d = \frac{q |N_{\text{eff}}(\Phi, t, T)| d^2}{2 \epsilon \epsilon_0},$$

where the $N_{\text{eff}}$ depends on fluence, temperature, and aging as given by the Hamburg model [51], $q$ is the unsigned electron charge and $d$ the depletion depth chosen. The silicon electric permittivity is the product of the permittivity in free space $\epsilon_0$ and the dielectric constant of silicon $\epsilon$ and is 1.054 pF/cm.

The integrated luminosity from Figure 3.10 leads to the radiation doses given in Table 3.2, which are used as reference values for the simulations. Phases in the LHC and ATLAS detector can be expressed for simplicity in “run” periods and “shutdown” periods. For this the first data taking period that ended in February 2013 is called Run1, after that during the first long shutdown LS1 from 2013 and 2015 LHC and experiment’s detectors were maintained and partially upgraded. Data taking from 2015 to 2018 is referred to Run2 and from 2019 and 2022 to Run3, while between 2018 and 2019 (LS2) detectors will be further modified and improved.

For the following studies, changes in the electric field inside the bulk are taken into account through the flat diode parametrization, which depends on $V_d$ as in Eq.(3.2). Figure 3.11 shows...
Figure 3.10: Possible scenario for integrated luminosity delivered by the LHC until 2022 and for SCT cooling. These two ingredients lead to depletion voltage evolution shown in blue.

<table>
<thead>
<tr>
<th>LHC evolution</th>
<th>$\Phi$ [1MeV $neq$ cm$^{-2}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>End Run1 (2013) / Start Run2 (2015)</td>
<td>$5 \cdot 10^{13}$</td>
</tr>
<tr>
<td>Run2 (2016)</td>
<td>$1.7 \cdot 10^{13}$</td>
</tr>
<tr>
<td>Run2 (2017)</td>
<td>$3.0 \cdot 10^{13}$</td>
</tr>
<tr>
<td>End Run2 (2018) / Start Run3 (2019)</td>
<td>$4.2 \cdot 10^{13}$</td>
</tr>
<tr>
<td>Run3 (2021)</td>
<td>$7.0 \cdot 10^{13}$</td>
</tr>
<tr>
<td>End Run3 (2022)</td>
<td>$8.7 \cdot 10^{13}$</td>
</tr>
</tbody>
</table>

Table 3.2: Table with dose values extracted from Figure 3.10.
the different electric field profiles given all the conditions seen above.

![Electric field profile diagram]

**Figure 3.11:** Electric field as a function of the sensor bulk position, depletion voltage and bias voltage (expressed in Volts).

The mean cluster size for all hits is shown in Figure 3.12 as a function of “time”, considering evolving operation conditions. This figure shows the combined effect of the charge trapping and electric field modifications in the SCT digitization. As can be easily noticed, the mean cluster size decreases until the end of Run2. In this scenario at the restart of operations after LS2, the change in depletion voltage will require to raise the operational bias voltage. Setting $V_b$ to 300 V leads to a gain in the average cluster size at this point, but then again the decreasing trend continues. The effect seen can be considered rather small since the biggest relative difference is of the order of 6%.

A similar result but for hits on tracks is presented in Figure 3.13, where the following track quality selections are applied (see Sec. 4.2 for the definition of the track parameters):

- $p_T > 500$ MeV
- $|d_0| < 1.5$ mm (w.r.t. PV)
- number of PIXEL hits $> 1$
- number of SCT barrel hits $> 7$

The results show a similar behavior to Figure 3.12 with a progressive decrease of the mean cluster size except for the gain due to raising of the bias voltage, but in this case the effect is smaller, at maximum of the order of 1.5%.

The relative hit efficiency is studied considering the detector before irradiation ($V_d = 70$ V and $\Phi = 0$) and in default operation conditions ($V_b = 150$ V) as 100% in efficient. What is shown in Figure 3.14 is obtained comparing the number of hits obtained from the simulation
3.3. Results

Figure 3.12: Mean cluster size for all hits as a function of time. Charge trapping effect and $V_d$ (expressed in Volts) evolution are taken into account.

Figure 3.13: Mean cluster size for hits on tracks as a function of time. Charge trapping effect and $V_d$ (expressed in Volts) evolution are taken into account.
of the detector before and after irradiation. No significant drop in the number of reconstructed hits on track can be seen. Before the start of Run3 this relative efficiency is stable within 0.2%, while 1% is gained as the bias voltage is raised.

![Figure 3.14: Relative hit efficiency. The number of hits for each case is weighted with the number of hits when no radiation damage is considered (see text for details). In this plot the uncertainties are smaller than the marker size and $V_d$ and $V_b$ are expressed in Volts](image)

Comparing the cluster size as a function of the particle incident angle allows to extract the Lorentz Angle (LA) [37]. For detailed studies on LA in the SCT see [28]. This is done for all the conditions considered in the previous studies, and the result can be seen in Figure 3.15. Here, one can notice a general flat behaviour of this quantity throughout the range considered, with the exception given by the change in $V_b$. One can infer that, within the current simulation, charge trapping and depletion voltage do not affect the LA. Only variations of the bias voltage modify LA.

Trying to separate the effects of charge trapping and the change in the E-field is done considering these effects one at the time. Figure 3.16 shows fits for the cluster size as a function of the particle’s incident angle for four cases: no charge trapping and default operation conditions of $V_b = 150$ V and $V_d = 70$ V (black), only charge trapping (red), only E-field modifications (green), charge trapping and modified electric field (blue). For the effect of charge trapping one can compare the black to the red curve. The minimum of the cluster size sits in the same incident angle position. However the curve has a broader shape and is shifted towards lower values of cluster size. For the impact of a different electric field inside the bulk of the sensors one can focus the attention on the black and green curves. In this case it is clearly visible that the minimum of the fit curve is shifted to a smaller (in terms of absolute value) LA. This minimum is found to be at a smaller cluster size and the shape of the fit curve is steeper. Finally, to see the effect of charge trapping taking into account the change in E-Field, one can compare the case with both radiation effects (blue) with the
3.3. Results

Figure 3.15: Lorentz angle in the SCT innermost barrel layer as a function of time.

one with E-field effect only (green). Turning on charge trapping leads again to a global shift towards smaller values of mean cluster size of the simulated data. Also in this case the LA is found in the same incident angle position, while the broadening effect on the sides is smaller.

Figure 3.16: Lorentz angle fits for different conditions in the simulation: default (black), only charge trapping (red), only modifications on E-Field (green), charge trapping with modified E-field (blue). The values of the fluence $\Phi$ is expressed in 1MeV $neq cm^{-2}$ and $V_d$ and $V_b$ are expressed in Volts.
3.4 Conclusions

In this chapter the implementation of a radiation damage effect, charge trapping, in the full SCT simulation was presented.

The attention was focused on the SCT innermost barrel layer since it is the most affected by radiation damage. Radiation doses up to $10^{14}$ [1 MeV $neq$ cm$^{-2}$], more precisely to $8.7 \cdot 10^{13}$ [1 MeV $neq$ cm$^{-2}$], were considered. This should correspond to the maximum fluence received at the end of Run3 (430 fb$^{-1}$). Depletion voltage and electric field evolution with respect to LHC and SCT changing conditions were also taken into account. Both LHC and SCT cooling scenarios were chosen among the worst possible ones in order to test the most extreme situation.

Using the full simulation chain, the impact of charge trapping was studied on the average cluster size, where it was found to be within 6% for all hits and within 1.5% for hits on tracks. No significant effect can be seen in the hit efficiency throughout the whole time period considered. Lorentz angle results showed dependence only on bias voltage and no dependence at all on charge trapping using this simulation.

Finally, from what seen using the simulation, it is possible to say that the charge trapping effect will have a very small impact on the SCT detector performance.
Chapter 4

Physics Objects

The aim of this chapter is to give a description of the physics objects that are important for the analyses treated in this thesis and to explain how they get reconstructed by the ATLAS detector and software. The first section of this chapter discusses the reconstruction of the photons, which constitute the decay products for the Higgs decay channel that has been taken into account for these analyses. The second and the third section are dedicated to track and vertex reconstruction, with details on the track selection and pileup mitigation. The last section is dedicated to the hadronic jet reconstruction and calibration.

For each of the physics objects, the correspondent definition at particle-level is given. The selections applied at particle-level are chosen to be very similar to the criteria applied at detector-level to ensure minimal model dependence in the final measurement.

4.1 Photons

Photon candidates are reconstructed starting from clusters of energy deposited in the electromagnetic calorimeter.

Both photons that do (called converted photons) or do not convert (called unconverted photons) to electron-positron pairs in the detector material upstream of the ATLAS electromagnetic calorimeter are considered. Converted photons are reconstructed from clusters of energy deposited in the ECAL that can be matched to one or two tracks coming from a conversion vertex in the ID [32]. In the case where there are no tracks that can be associated to a cluster, an unconverted photon candidate is defined.

All photon candidates are required to pass not only the trigger requirements described in Sec. 2.2.4 but also additional isolation and identification criteria:

- isolation:

  - ID: the scalar sum of the $p_T$ of tracks originating from the diphoton vertex (see Sec.4.3 with $p_T > 1$ GeV and lying within a cone of size $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.2$ around the photon direction must be less than 2.6 GeV;
– LAr: the sum of the energy deposited in the topological clusters\(^1\) within \(\Delta R < 0.4\) from the photon direction but excluding the region of size \(0.125 \times 0.175\) in \(\eta \times \phi\) around the barycentre of the photon cluster, corrected for leakage of the photon energy outside of the excluded region and contamination from pileup [53], has to be less than 6 GeV;

- “tight” identification: selection criteria are optimized separately for unconverted and converted photons, making use of all the information from the different layers of the electromagnetic calorimeter, providing good \(\gamma\)-jet and \(\gamma\)-\(\pi^0\) discrimination [32]

The energies of the clusters are calibrated separately for unconverted and converted photon candidates using an MVA calibration trained from dedicated simulated samples [54]. The corrections account for energy losses upstream of the calorimeter as well as for energy leakage outside of the cluster. Correction factors are mainly derived from the study of simulated \(Z \rightarrow ee\) events exploiting similarities between electrons and photons. This approach is validated with photon candidates from \(Z \rightarrow \ell\ell\gamma\) events in data. Photon energy calibration is described with great detail in [54].

At particle-level photons are required to not originate from the decay of a hadron. For particle-level isolation the sum of the transverse momentum of all the particles (excluding muons and neutrinos) within \(\Delta R = 0.4\) from the photon direction must be less than 14 GeV. This criteria is found to be the one that better mimics the detector-level isolation. Photons at particle-level are selected if \(|\eta| < 2.37\), while at detector-level (see Sec. 2.2.4) photons in the region between the barrel and end-cap calorimeters \(1.37 < |\eta| < 1.56\) are excluded.

Both at particle-level and detector-level the two leading photons in the event are considered as the decay products of a Higgs boson candidate.

### 4.2 Tracks

The reconstructed properties of charged particles are essential to this analysis: converted photons are reconstructed from their decay via electrons tracks; the interaction vertex, from which the Higgs is produced (called “primary interaction vertex” or PV), is reconstructed via the tracks in the event; many of the observables studied in this thesis are built starting from tracks.

The algorithm used for track reconstruction is called “inside-out” [55, 56] and uses the information from the entire inner detector. The track reconstruction procedure is iterative and alternates mainly two steps:

- a pattern recognition, which is performed once trying to identify signals from different modules to a single particle in order to get a rough estimate on the charged particle trajectory but also for further refining of particle trajectories;

\(^1\)Three-dimensional clusters, built by associating calorimeter cells on the basis of the signal-to-noise ratio [52]
an actual track-fitting that extracts the parameters necessary to define a particle trajectory;

while the curvature of charged particles induced by the axial magnetic field in which the ID is immersed is used to measure the transverse momentum of the track. In this way it is possible to obtain what is called a “track seed”. The identification of a “track candidate” is performed using a Kalman filter algorithm [57] that tries to associate all compatible hits with the initial “track seed” while iteratively updating the likely trajectory of the charged particle. The next step is to include TRT hits compatible with the initial track candidate in the pattern recognition of the track candidates via fit procedures. Finally, a last application of the Kalman filter to the extended track candidate is used to determine whether the extended or the initial (silicon based) track candidate will be used as the final track and the obtained parameters are used to define the charged particle trajectory. A different method called “back-tracking” or “outside-in” proceeds in the opposite direction. In this case the track reconstruction is seeded from TRT hits and then extrapolated in the direction of the silicon detectors.

For the following selections it is important to define two track parameters: 
\[ d_0 = \sqrt{x_0^2 + y_0^2} \]
the signed distance of the track trajectory to the beam-axis (in the \(x-y\) plane) and \(z_0\), the \(z\)-coordinate of the track at the point of closest approach.

For the following selections it is important to define two track parameters: 
\[ d_0 = \sqrt{x_0^2 + y_0^2} \]
the signed distance of the track trajectory to the beam-axis (in the \(x-y\) plane) and \(z_0\), the \(z\)-coordinate of the track at the point of closest approach.

Only tracks satisfying the following requirements are considered for the purposes of this thesis:

- at least one hit in the pixel subdetector;
- a hit in the innermost pixel layer if the reconstructed trajectory traversed an active pixel module;
- at least six SCT hits;
- the transverse momentum of the track \(p_T > 0.5\) GeV;
- the pseudorapidity of the track \(|\eta| < 2.5\);
- the transverse impact parameter of the track with respect to the PV \(|d_0| < 1.5\) mm;
- the longitudinal impact parameter of the track with respect to the PV \(|z_{PV} - z_0| \sin \theta < 1.5\) mm;

with \(z_{PV}\) the \(z\)-coordinate of the PV vertex. The first two requirements greatly reduce the number of tracks from non-primary particles, which are those originating from particle decays and interactions with material in the inner detector. The third one imposes an indirect constraint on the minimum track length and hence on the precision of the track parameters. The kinematic requirements imposed on the track selection are driven by the \(\eta\)-acceptance of the inner detector and the need for an approximately constant reconstruction efficiency as a function of the track \(p_T\). The last two requirements on the impact parameter aim to suppress tracks not originating from the PV of the event.
4.2. Tracks

Figure 4.1: The distribution of the event track composition for simulated events with a Higgs boson decaying into two photons (a). The event mean track composition as a function of $<\mu>$ (b).

At particle-level a similar selection for the particles is applied. Only stable charge particles (with a mean lifetime of $\tau > 30$ ps) that do not originate from hadron decay are considered. The transverse momentum of the particles must be greater than 0.5 GeV and the pseudorapidity of the particles must be within $|\eta| < 2.5$.

For simulations, it can be useful to distinguish particles with different origins. These are used in the following chapters for a better understanding and control of some observables and their associated uncertainties. At detector-level, tracks from simulated samples can be identified as:

- **fake tracks**, tracks that do not correspond to any particle and originated from a misreconstruction of some ID hits;
- **secondaries**, or non-primary tracks, tracks or charged particles produced at a later point in time after the collision from a decay or from the interaction with the detector material
- **pileup tracks**, tracks not originated from the interaction of interest
- **good tracks**, tracks that can be identified with a counterpart charged particle with a mean lifetime $c\tau > 10$ mm.

Figure 4.1 shows the distribution of the event track composition for the categories described above. The fractions are obtained dividing the number of tracks of one category by the total number of tracks in the event. The dependence of the event mean track composition on the average number of interactions per crossing ($<\mu>$) is shown in Figure 4.1(b). The events used are simulated events for a Higgs boson with diphoton decay. The fraction of tracks around the value of $<\mu> = 20$ can be taken as a reference. The fraction of secondary tracks is $\sim 5\%$, while the fraction of pileup tracks is above $10\%$ and, obviously, has a strong dependence on $<\mu>$. The fraction of fake tracks is negligible with respect to the others.
4.2. Tracks

Figure 4.2: The distribution of the observable $\tau_{0C}$ as a function of the average number of $pp$ interactions per bunch crossing in data (a) and MC (b). In black the distributions without any correction and in blue with the subtraction of the pileup contribution as described in text. For MC (b) the distribution of $\tau_{0C}$ as calculated from only good tracks is also shown in red.

A fundamental aspect for all the observables (Sec. 5.3) built from tracks is their contamination and dependence on pileup tracks. Since it is difficult to exactly reproduce with Monte Carlos the pileup conditions in data, a way of removing the pileup dependence is studied. The method used is simple but very efficient and it has its basis on the “geometrical” nature of the selection of the tracks around the PV:

1. in each event define 4 additional regions centered at $z_{PV} \pm 10(20)$ mm from the PV,
2. in each of these regions apply the same track selections as for the PV,
3. with the selected tracks compute the observable for each of the 1+4 regions per event,
4. for each event subtract from the observable computed with the tracks from the PV the mean of the observable values obtained in the 4 additional “pileup regions”.

The procedure is applied to data and to MC. In Figure 4.2 the effect of the described “pileup subtraction” procedure is shown for the observable $\tau_{0C}$ (Sec. 5.3) in data (a) and MC (b). As can be seen, in both cases when considering the observable without any correction (black dots) a dependence on the number of collisions per event is clearly visible. Applying the simple correction described above (blue) changes completely the picture: the $<\mu>$-dependence of the observable is practically removed. Moreover, in Figure 4.2(b) it is possible to appreciate how the distribution of $\tau_{0C}$ with the pileup subtracted and the one build only from good tracks are similar. Finally it can be noticed that taking into account the beam-spot size in the corrections does not make any significant difference.

For all the other observables considered in Sec. 5.3 the behaviour is very similar to what is shown in Figure 4.2.
4.3 Primary vertices

Vertex reconstruction uses tracks to determine the location of the interaction and the potential presence of decay vertices in the event. In the LHC when two beam bunches collide, the number of interactions can be much greater than one. In 2012, for example, the mean number of interactions per bunch crossing ($\mu$) was around 20 (see Fig. 2.7(b)), requiring many separated vertices to be found.

The reconstruction of vertices is performed using an “adaptive vertex fitting” algorithm [58]. The global maximum of the distribution of the $z$-coordinates of all these tracks is used as seed for the vertex finding as are the tracks in the vicinity of the found maximum. Then, an iterative $\chi^2$ fit of tracks is used to determine the vertex positions by combining nearby tracks. Tracks are added and scored according to their contribution to the $\chi^2$. Tracks that are more than $7\sigma$ away are taken out and used to seed a new vertex candidate. The procedure is repeated until there is no track that can be associated with any vertex.

Usually in analyses that study final states with jets or leptons, the hard interaction vertex is the vertex with the highest $\sum_i |p_{T,i}|$ of all the $i$ tracks associated to the vertex. For a Higgs decaying into two photons this is not only true and given the collection of reconstructed vertices in the event, the one from which the Higgs boson candidate is produced has to be identified. This vertex, usually called “primary interaction vertex” (PV), is selected using a neural network combining the pointing information of the photons in the calorimeters with the $\sum p_T$ and $\sum p_T^2$ of the tracks associated to the vertex, the $\Delta\phi$ between the diphoton system and the sum of the momenta of the tracks, and finally the track information from converted photons.

The efficiency for finding the reconstructed diphoton primary vertex in simulated $H \rightarrow \gamma\gamma$ events from $ggH$ production within 0.3 mm (15 mm) of the true vertex is shown in Figure 4.3 and is around 85% (93%) over the typical range of the number of collision vertices per event observed in the 8 TeV data [59]. The efficiency $\epsilon_{PV}$ increases for large diphoton $p_T$ as the hadron system recoiling against the diphoton evolves into one or more jets, which in turn contain additional higher $p_T$ tracks. These additional tracks make it more likely to reconstruct the diphoton vertex as the vertex with the highest $\sum_i |p_{T,i}|$ in the event.

4.4 Jets

Quarks and gluons hadronize producing bound states of quarks in form of baryons and mesons. These appear in the detector as collimated sprays of particles called jets. In the ATLAS detector, jets are reconstructed primarily using the clusters of energy deposited by the collimated particles in the calorimeters. The method used to combine the energy-deposits in these physics objects defines what a jet is.

The anti-$k_t$ algorithm [60] is used to reconstruct the jets in the analyses presented in this thesis. Starting topological clusters, jets are built by sequentially combining clusters in close
proximity to each other. More precisely, two distance measures are introduced, $d_{ij}$ and $d_{iB}$, between the cluster (or particle) $i$ and the “pseudojet” $j$ or the beam $B$ defined as follows:

$$d_{ij} = \min \left( p_{T_i}^{-2}, p_{T_j}^{-2} \right) \frac{\Delta R(i, j)^2}{R^2},$$  

$$d_{iB} = p_{T_i}^{-2},$$  

with $\Delta R(i, j) = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}$ and $R = 0.4$. The smallest of the distances is considered. If $d_{ij} < d_{iB}$ the entities (particles or topological clusters) $i$ and $j$ are combined and their sum is the new $j$, while if $d_{iB} < d_{ij}$ a new, additional pseudojet is considered and $i$ is removed from the list of entities. The distances are recalculated and the procedure is repeated until there are no entities left. What is called here a psuedojet is just the partial clustering of the entities in the event, starting from any general entity as initial reference. The anti-$k_t$ algorithm ensures infrared and collinear safe jets [60] with a cone-like shape.

The jets are corrected for soft energy deposits originating from pileup by applying an ambient energy correction taken as the event transverse energy density, evaluated event-by-event, multiplied by the jet area [61]. The energy loss in non-compensating regions of the calorimeters is taken into account in the jet energy calibration with a correction on the energy profile and longitudinal shower-depth determined from a combination of simulation and data studies [62,63].

As a general condition for the analyses presented in this thesis, jets are required to have $p_T > 30$ GeV and $|y| < 4.4$. Different selections for jets are also used in this theses, for different purposes, and will be specified for each particular case.
In order to limit the contamination of pileup jets in the selected events, a discriminant variable based on jets, tracks and vertices is defined as:

\[
P_{j,v}^{JVF} = \frac{\sum_i p_{T_i}^{j,v}}{p_{T_{\text{tot}}}^j}
\]

and called jet-vertex fraction (JVF). The scalar sum of the transverse momentum of tracks from all the reconstructed vertices and matched, using ghost-association [64], to the jet \( j \) is \( p_{T_{\text{tot}}}^j \), while \( p_{T_i}^{j,v} \) is the transverse momentum of the \( i \)-th track, coming from the vertex \( v \) and matched to the jet \( j \). For jets with \( p_T < 50 \text{ GeV} \) and \( |\eta| < 2.4 \), the value of JVF is required to be \( P_{j,v}^{JVF} > 0.25 \).

Particle-level jets are reconstructed from all particles with \( \tau_c \lesssim 10 \text{ mm} \), except muons and neutrinos, using the anti-\( k_T \) algorithm. The same selection applied on the jet transverse momentum and (pseudo)rapidity at detector-level is applied also at particle-level.

Finally, jets must be well separated from photons, with a relative distance \( \Delta R > 0.4 \).
Chapter 5

Differential cross section measurements for track-based observables

In this chapter the measurement of differential cross sections as a function of track-based observables for Higgs boson production in the diphoton decay channel is presented.

Measurements of track multiplicity distributions are important for the understanding of soft QCD, underlying events, multi-parton interactions and also pileup effects. Higgs events are of particular interest since they allow to investigate gluon-initiated processes (Sec. 1.3). Other observables can be defined to study the properties of these events, as for example the scalar sum of the transverse momentum of the tracks in the event $H_T^{tracks}$. In this chapter a further step is made and more complex track observables are considered. Event-shape observables are defined based on a slightly modified definition of the inclusive event-shape $N$-jettiness (Sec. 5.3). The $N$-jettiness is define for $N$ jets in the event, and for no jet in the event corresponds to the beam-thrust event-shape. The value of the $N$-jettiness vanishes in the limit of exactly $N$ narrow jets in the event, while it get bigger the more radiation between the $N$ jets is found. Roughly speaking $N$-jettiness can be considered a measure on how much the radiation in the event is concentrated in $N$-regions. For this reason $N$-jettiness can be used as a jet veto to define the inclusive and exclusive $N$-jet cross sections are theoretically well-controlled.

From the original $N$-jettiness definition, several variations can be derived and adapted for the measurement. Differential cross sections for modified versions of the 0-jettiness and 1-jettiness are measured. Different jet fiducial regions are considered for these measurements to study peculiar radiation distributions in the event.

The structure of the chapter reflects the analysis flow and is described below. The dataset used for this analysis is the one described in Sec. 2.3. In the first part of the chapter (Sec. 5.1) the Monte Carlo simulated samples used for the analysis are presented.

In Sec. 5.2 the event selections for several fiducial regions are defined. Section 5.3 is devoted
to the definition of the observables used for the measurements. In this part of the chapter, \( N \)-jettiness is defined, its adaptations for the measurement explained and its peculiarities described.

In Sec. 5.4 the signal parametrization is presented and the procedure for the yield estimation from data is explained. Uncertainties that affect the signal position or shape are described and computed. The observed signal yields are listed for all the differential cross section bins considered.

Section 5.5 is reserved to the description of the method used to correct the yields for detector imperfections in order to be compared with theory predictions. The criteria used to decide the binning for each of the observable is also explained here, while in Sec. 5.6 the uncertainties related to the correction for detector effects are assessed. These include photon, track and jet related uncertainties.

Finally in the last section of the chapter, Sec. 5.7, the results for the differential cross sections measured are presented.
5.1 Simulated signal samples

Higgs boson production and decay are simulated for each of the five production modes: gluon-gluon fusion, VBF, $WH$, $ZH$ and $t\bar{t}H$.

Simulated samples for the gluon-gluon fusion and vector-boson-fusion Higgs production are generated at parton-level with next-to-leading-order (NLO) accuracy in QCD using POWHEG Box [65–69], with the CT10 parton distribution function (PDF) [70]. To go from parton-level events to particle-level events, which include parton showering, hadronization and multiple parton interactions (MPI), PYTHIA8 [71] is used with the AU2 tune for the underlying event [72]. For the gluon fusion process, the total cross section of the POWHEG-PYTHIA sample is normalized to match a prediction from a next-to-next-to-leading order plus next-to-next-to-leading-logarithm (NNLO+NNLL) QCD calculation where also NLO electroweak corrections are applied [73–91]. In the VBF case, the normalization of the total cross section of the POWHEG-PYTHIA sample is taken from an approximate-NNLO QCD calculation with NLO electroweak corrections [73,92–97].

Higgs bosons produced in association with a $W$ or $Z$ boson, or a $t\bar{t}$ pair are fully generated with PYTHIA8 with leading-order (LO) accuracy with the CTEQ6L1 PDF and the 4C tune for the underlying event [98]. The $WH$/$ZH$ simulated samples are normalized to the cross sections calculated at NNLO in QCD and NLO electroweak corrections [73,99–101]. For $t\bar{t}H$ samples the cross section normalization was taken from NLO QCD calculations [73,99–101].

In all the cases, the mass and width of the Higgs boson is chosen to be $m_H = 125$ GeV and $\Gamma_H = 4.07$ MeV.

Inelastic proton-proton collisions produced with PYTHIA8 with the A2 set of parameters [72] are included in the simulation to reproduce the data taking conditions. These collisions are overlaid to Higgs events and represent the effect of pileup.

The simulated samples pass through a GEANT 4 [39,40] simulation of the ATLAS detector [102] and are then treated in the same way as the data.

5.2 Fiducial regions

In this section the fiducial regions which the observables are measured in and unfolded to are defined. The first fiducial region considered is the inclusive (or baseline) fiducial region where the requirements are made on the diphoton mass range and on the two photons transverse momentum. This serves as the general fiducial region from which all the others are included. Three fiducial regions are defined based on the hadron activity in the event: one where at least one jet is required, one that requires an energetic jet vetoing the presence of more than one jet, and the last where only one energetic jet is required at low rapidities, but soft or forward jets are still allowed.

The same selections, described below, are applied respectively to data/detector-level and to particle-level objects (Chapter 4), where the latter effectively defines the fiducial region to
which the measurement is corrected.

Finally also a 2-jet inclusive fiducial region was considered for measuring particular 2-jet observables. However, this was disregarded since the expected available statistics in this fiducial region was too small.

In order to have an idea of how many events are expected to be found in each of these fiducial regions, the predicted number of signal events for a SM Higgs boson for the integrated luminosity of 20.3 fb$^{-1}$ is also given.

**Inclusive**

The inclusive (or baseline) fiducial region is defined as the phase space with events that fulfill the following selection criteria:

- $p_T^{\gamma}/m_{\gamma\gamma} > 0.35$ (0.25) for the leading (subleading) photon,
- $m_{\gamma\gamma} \in [105, 160]$ GeV,

for the photons defined in Sec. 4.1. From Monte Carlo simulation, the number of expected signal events in this fiducial region is approximately 400. All the following additional fiducial regions are a subset of the inclusive fiducial region.

**1-jet inclusive**

The 1-jet inclusive fiducial region requires at least one jet with $p_T^j > 30$ GeV within $|\eta^j| < 2$ in the event, where $\eta^j$ is the pseudorapidity of that jet. The particular $\eta^j$ requirement is needed since the observables, described in the next section (Sec. 5.3), are based on tracks. In this way jets are ensured to be well within the inner detector acceptance where tracks are fully reconstructed up to $|\eta| < 2.5$. The number of expected signal events is approximately 120.

**1-jet exclusive**

Together with the inclusive categories, it is interesting to look at jet exclusive fiducial regions. With the purpose to have just one hard jet in the event, these particular cases are studied:

- 1-jet exclusive: the leading jet has transverse momentum greater than 50 GeV and $|\eta^j| < 2$. No additional jet with $p_T^j > 30$ GeV must be found in the event. From Monte Carlo studies the expected number of signal events that pass this selection is 36.

- 1-jet central exclusive: the leading jet is required to have transverse momentum greater than 50 GeV and $|\eta^j| < 1$. Any additional jet in the event is required to have $p_T^j/(2 \cosh(\eta^j)) < 15$ GeV. In this fiducial region the expected number of signal events is found to be 37.

These two exclusive fiducial regions are quite different from each other. The first one forces the presence of exactly one hard ($p_T^j > 50$ GeV) jet in the region $|\eta^j| < 2$ and vetoes the presence
of any other jet in the event (the $p_T^j < 30$ GeV cut basically corresponds to not having reconstructed any additional jet since the jet definition introduced in Chapter 4 requires $p_T^j > 30$ GeV). The second one requires the presence of one central ($|\eta^j| < 1$) hard jet, but still allowing the possibility to have a soft jet in the same region or a hard jet but in the forward region. This is done with the jet-pseudorapidity dependent $p_T^j$ veto: $p_T^j/(2 \cosh(\eta^j)) < 15$ GeV. For example at $\eta^j = 0$, jets are vetoed if $p_T^j > 30$ GeV, at $|\eta^j| = 1$ jets are allowed if $p_T^j < 46.3$ GeV. In this case the values used to define this phase space were tuned to be a compromise between a stringent central region for the hard jet and still having decent statistics (allowing for other jets in the mentioned way). Simplifying and summarizing, in one fiducial region events contain hard jet activity at low rapidity and only soft radiation in the rest of the space; in the second one the priority is on the separation of the central and forward radiation where both are allowed but well split.

![Figure 5.1](image.png)

**Figure 5.1**: In blue the jet veto function for the 1-jet central exclusive fiducial region. The region below the blue line corresponds to the allowed phase-space for additional jets as $p_T^j/(2 \cosh(\eta^j)) < 15$ GeV. The red represents a flat cut on the jet transverse momentum.

This can be better understood looking at Figure 5.1. Here one can see the effect of this $\eta$-dependent cut in the region of interest, acting exactly as a veto for any additional hard central jet in the event.
5.3 Observable definitions

The observables used for this measurement are mainly based on two works [103], [104]. The global event-shape “N-jettiness” is generally defined in [103] whereas it is operationally described in [104], where several versions of this observable are considered and used in an exclusive cone jet algorithm. N-jettiness is defined as:

\[
\tau_N = \frac{2}{Q^2} \sum_k \min \{ q_a \cdot p_k, q_b \cdot p_k, q_1 \cdot p_k, \ldots, q_N \cdot p_k \} .
\] (5.1)

The index \( k \) represents all the particles in the final state once the signal components are excluded and \( p_k \) is the four momentum of particle \( k \). The \( q_a \) and \( q_b \) are the reference four vectors for the beam axis, once in the positive direction, once in the negative direction. The \( q_1, \ldots, q_N \) are the directions of the \( N \) signal jets present in the event. The scale \( Q^2 \) represents the typical scale of the hard-scattering process. The dot product \( q_a, b \cdot p_k, q_m \cdot p_k \) represents an arbitrary distance measure \( \rho \) of a particle \( k \) with momentum \( p_k \) either from the beam \( \rho_{\text{beam}}(p_k, q_{a,b}) \) (with index \( a \) and \( b \)) or the jets \( \rho_{\text{jet}}(p_k, q_m) \) (with \( m \in N \)). In Eq. (5.1), \( \tau_N \) is dimensionless. The distance measure does not need to be defined in the general formula 5.1, but can be adapted to the particular cases while the general properties of the observable remain unchanged. Once the measure is decided, the closest distance between the generic \( p_k \) and one of the reference objects is the minimum in Eq. (5.1). In the ideal situation where an event contains exactly \( N \) infinitely narrow jets and there is no radiation between jets and beams, \( \tau_N = 0 \). The value for the N-jettiness gets further away from zero the wider the jets are and the more radiation between the reference objects (beams and jets) can be found. In this sense this observable can be considered as an inclusive measure of how \( N \)-jet-like the event looks.

Particles \( k \) are associated to the closest jet or beam, allowing the general \( \tau_N \) to be divided into two (or more) separate components:

\[
\tau_N = \tau_N^{\text{beam}} + \tau_N^{\text{jet}} .
\] (5.2)

In this way, \( \tau_N^{\text{beam}} \) is a measure of the radiation not associated to any of the \( N \) jets, while the measure of \( \tau_N^{\text{jet}} \) represents how collimated the jets are without contamination from the beam region.

Studying these observables can have several advantages: provide an additional way to veto jets and measure inclusive and exclusive jet cross sections; bring new information on soft radiation and underlying event physics. Exclusive jet fiducial regions can give rise to large double logarithms in perturbation theory that must be summed to obtain reliable theory predictions. When using the inclusive variable N-jettiness as a jet veto, especially requiring \( \tau_N \ll 1 \), the phase-space restriction obtained is theoretically well-controlled: resulting logarithms are simple enough to allow their systematic summation to higher orders then leading log (LL), and do not show particular conceptual problems for even higher order resummations. In addition,
jet cross section calculations are greatly simplified in these cases given the factorization properties of \( N \)-jettiness (in the limit \( \tau_N \to 0 \)) that were derived using Soft-Collinear Effective Theory (SCET) [105–108].

A slightly modified version of the definition in Eq. (5.1) of the \( N \)-jettiness is used in this thesis, similar to ones used in [109,110] it is not dimensionless but preserves all the properties described above:

\[
\tau_N = \sum_k \min \{ \rho_{\text{beam}}(p_k), \rho_{\text{jet}}(p_k, n_1), \ldots, \rho_{\text{jet}}(p_k, n_N) \} \tag{5.3}
\]

where the four-momentum of the generic jet \( A \) is \( n_A = \{1, \vec{n}_A\} \) and \( n^2_A = 1 \) is its direction. Three different versions of Eq. 5.3, which differ in the definition of distance measures \( \rho_{\text{beam}} \) and \( \rho_{\text{jet}} \), are considered for the following differential cross section measurements. These are taken from a larger set in [104] and adapted for the current measurement:

- **geometric measure:**

\[
\tau_{N}^{BB} = \sum_k \min \{ \rho_{\text{beam}}^B(p_k), \rho_{\text{jet}}^B(p_k, n_1), \ldots, \rho_{\text{jet}}^B(p_k, n_N) \}
\]

with the distance measures

\[
\rho_{\text{beam}}^B(p_k) = \min\{n_a \cdot p_k, n_b \cdot p_k\} = p_Tk e^{-|\eta_k|} \quad \rho_{\text{jet}}^B(p_k, n_A) = \frac{n_A \cdot p_k}{\rho^2} \tag{5.4}
\]

- **modified geometric measure:**

\[
\tau_{N}^{CB} = \sum_k \min \{ \rho_{\text{beam}}^C(p_k), \rho_{\text{jet}}^B(p_k, n_1), \ldots, \rho_{\text{jet}}^B(p_k, n_N) \}
\]

with the distance measures

\[
\rho_{\text{beam}}^C(p_k) = \frac{p_Tk}{2\cosh \eta_k} \quad \rho_{\text{jet}}^B(p_k, n_A) = \frac{n_A \cdot p_k}{\rho^2} \tag{5.5}
\]

- **conical geometric measure:**

\[
\tau_{N}^{CC} = \sum_k \min \{ \rho_{\text{beam}}^C(p_k), \rho_{\text{jet}}^C(p_k, n_1), \ldots, \rho_{\text{jet}}^C(p_k, n_N) \}
\]

with the distance measures

\[
\rho_{\text{beam}}^C(p_k) = \frac{p_Tk}{2\cosh \eta_k} \quad \rho_{\text{jet}}^C(p_k, n_A) = \frac{\cosh \eta_A}{\rho^2 \cosh \eta_k} n_A \cdot p_k \tag{5.6}
\]

where \( n_{a,b} = \{1, 0, 0, \pm 1\} \) is the beam direction aligned with the \( z \)-direction and \( \rho \) a parameter that allows to control the size of the jet area.

All these distance measures are linear in \( p_k \), since they are defined by the dot product between particles and reference object directions (beam and jets), which is the simplest dependence when making perturbative calculations and for obtaining simple factorization properties of \( \tau_N \).
The three measures differ a little from the point of view of the area that they assign to the jets. The geometric measure is used in [109, 110]. Due to the definition of $\rho_{\text{jet}}^B$, it yields jets with a football-like shape area, especially in the central region and for $\rho > 1$. The modified geometric measure substitutes the term $e^{-|\eta_k|}$ with the term $1/2 \cosh(\eta_k)$. The geometric and modified geometric measures are equal in the limit for large values of $\eta_k$, and thus leading to very similar factorization schemes. This modification, though, regularizes the jet shape towards a conical one but still has a pseudorapidity dependent jet area. The conical geometric measure adds the term $\cosh(\eta_A)/\cosh(\eta_k)$ to the dot product of $n_A \cdot p_k$ for $\rho_{\text{jet}}(p_k, n_A)$. In this way the jet area is uniform and constant for all pseudorapidities and approximately $\pi \rho^2$.

In Figure 5.2 an event is used as example to show the particle distribution given by $\tau_{N}^{BB}$, $\tau_{N}^{BC}$ and $\tau_{N}^{CC}$. The event considered simulates a Higgs boson created through gluon-gluon fusion and in the presence of 3 jets in the final state. The event is used for computing $\tau_3 = \tau_{3}^{\text{beam}} + \tau_{3}^{\text{jet1}} + \tau_{3}^{\text{jet2}} + \tau_{3}^{\text{jet3}}$ for the three different definitions seen above. In this case the geometric measure of Eq.(5.4) is used in Figure 5.2(a), the modified geometric measure of Eq.(5.5) in Figure 5.2(b) and the conical geometric measure of Eq.(5.6) in 5.2(c). The red dots represent all the particles $p_k$ for which the distance $\rho_{\text{beam}}(p_k)$ is smaller than any of the jet counterpart $\rho_{\text{jet}}(p_k, n_{1,2,3})$. These particles are associated to the beams. The blue, magenta and green dots represent the particles associated respectively to one of the 3 jets present in the event. The $\rho^2$ parameter is set to 0.5 as it is fixed to this value for the differential cross section measurements that will follow. The particle transverse momentum is represented by the size of the square dots. Although Figure 5.2(a), 5.2(b) and 5.2(c) look very similar, some difference in the particle association can be seen between the distance measure definitions of Eq.(5.4), (5.5) and (5.6).

The particular case of $\tau_0$ does not contain the jet part, meaning that there is no jet direction considered in the jettness definition, and $\tau_0$ becomes:

$$\tau_0^{B,C} = \tau_0^{B,C,\text{beam}} = \sum_k \rho_{\text{beam}}(p_k)$$

which corresponds exactly to the beam thrust [111,112].

For the fiducial differential cross section measurements of this thesis the set of observables studied are: $\tau_0^B$, $\tau_0^C$, $\tau_1^{BB}$, $\tau_1^{CB}$, $\tau_1^{CC}$, $\tau_1^{BB,\text{beam}}$, $\tau_1^{BB,\text{jet}}$, $\tau_1^{CB,\text{beam}}$, $\tau_1^{CB,\text{jet}}$, $\tau_1^{CC,\text{beam}}$ and $\tau_1^{CC,\text{jet}}$.

Additionally the track multiplicity $N_{\text{tracks}}$ and the scalar sum of the transverse momentum of the tracks $H_T^{\text{tracks}} = \sum_k |p_k|$. 

5.3. Observable definitions
Figure 5.2: Particle $\eta, \phi$ distribution in an example event where the Higgs is produced from a gluon-gluon fusion mechanism and in association with 3 additional jets. The three plots represent the three different definitions for the distance measures (all with $\rho^2 = 0.5$): 5.2(a) the geometric measure (Eq. 5.4), 5.2(b) the modified geometric measure (Eq. 5.5) and 5.2(c) the conical geometric measure (Eq. 5.6). The size of the squared dots is proportional to the particle transverse momentum.
5.4 Signal model and signal extraction

In this section the functional form used to parametrize the signal is described first. Then the uncertainties that affect the signal shape and their estimation are discussed. Next the signal-plus-background function is defined and the procedure for extracting the signal is detailed. Finally the fit results are presented and the method used to disentangle the fit statistical uncertainty from the fit systematic uncertainty is described.

5.4.1 Signal model

The $m_{\gamma\gamma}$ distribution of reconstructed $H \rightarrow \gamma\gamma$ decays is modeled as the sum of a Crystal Ball function and a wide Gaussian function $[1,113]$. The Crystal Ball function captures the majority of the signal events. The wide Gaussian models the outliers of the $m_{\gamma\gamma}$ signal distribution.

The Crystal Ball function has the shape of a narrow Gaussian with an asymmetric tail on the low side and is defined as follows:

$$C(m_{\gamma\gamma}; \mu_{CB}, \sigma_{CB}, \alpha_{CB}, n_{CB}) = N \cdot \begin{cases} \exp\left(-t^2/2\right) & \text{if } t > -\alpha_{CB} \\ \frac{n_{CB}}{\alpha_{CB}} \cdot e^{-\alpha_{CB}^2/2} \cdot \left(\frac{n_{CB}}{\alpha_{CB}} \cdot \alpha_{CB} - t\right)^{-n_{CB}} & \text{otherwise} \end{cases}$$

where $t = (m_{\gamma\gamma} - \mu_{CB})/\sigma_{CB}$, $N$ is a normalization parameter, $\mu_{CB}$ and $\sigma_{CB}$ represent the peak position and the resolution for the Gaussian component, respectively, while $n_{CB}$ and $\alpha_{CB}$ are parameters of the non-Gaussian tail of the Crystal Ball that control where the tail is attached and its shape.

The sum of the above defined Crystal Ball and a Gaussian function forms the signal PDF, which is parametrized as:

$$S(m_{\gamma\gamma}; \theta_{\text{sig}}) = f_{CB} C(m_{\gamma\gamma}; \mu_{CB}, \sigma_{CB}, \alpha_{CB}, n_{CB}) + (1 - f_{CB}) G(m_{\gamma\gamma}; \mu_{GA}, \sigma_{GA}), \quad (5.8)$$

where $f_{CB}$ is the fraction of the Crystal Ball function in the overall PDF, and $\theta_{\text{sig}}$ is a vector of unconstrained shape parameters. The peak position of the Crystal Ball and of the Gaussian is required to be the same, such that the mean and the width of the Gaussian can be written as:

$$\mu_{GA} = \mu_{CB} = m_H + \mu_{\text{offset}}$$
$$\sigma_{GA} = \kappa_{GA} \cdot \sigma_{CB} = \kappa_{GA} \cdot \sigma_{\text{Signal}}. \quad (5.9)$$

This reduces the number of shape parameters to

$$\theta_{\text{sig}} = (f_{CB}, \mu_{CB}, \mu_{\text{offset}}, \sigma_{\text{Signal}}, \alpha_{CB}, n_{CB}, \kappa_{GA}). \quad (5.10)$$

The parameters of the model that define the shape of the signal distribution are determined using simulated $H \rightarrow \gamma\gamma$ decay samples for $m_H = 125$ GeV. The fit range was chosen to be $-20$ GeV to $+15$ GeV around the Higgs mass of the simulated sample neglecting a small fraction of events ($\sim 1\%$) in the high mass tails of the signal distributions that was distorting the
fit shapes. Figure 5.3 shows the fits for each bin for the example of the $\tau_C^0$ observable. These fits are used to fix the parameters of Eq.(5.10) that define the signal probability distribution function of Eq.(5.8).

### 5.4.2 Uncertainties on the signal model

In order to account for uncertainties in the modeling of the shape of the $H \to \gamma\gamma$ decays, nuisance parameters for the photon energy scale and photon energy resolution systematic uncertainty are included to Eq.(5.8). These parameters, defined as $\Theta_{\text{EnScale}}$ and $\Theta_{\text{EnRes}}$, affect the mean and the width, respectively, of the signal PDF as follows:

$$\begin{align*}
\mu_{\text{CB}} &= \mu_{\text{GA}} = (m_H + \mu_{\text{offset}}) \cdot \Theta_{\text{EnScale}}, \\
\sigma_{\text{CB}} &= \sigma_{\text{Signal}} \cdot \Theta_{\text{EnRes}} \\
\sigma_{\text{GA}} &= (\kappa_{\text{GA}} \cdot \sigma_{\text{Signal}}) \cdot \Theta_{\text{EnRes}}
\end{align*}$$

(5.11)

where $\Theta_{\text{EnScale}}$ and $\Theta_{\text{EnRes}}$ parametrize the effect from photon energy scale uncertainties and photon energy resolution uncertainties respectively, which are described below.

For the uncertainties on the photon energy scale, 19 sources of systematic uncertainty are considered ranging from the imperfect knowledge of the material in the detector to the cross-talk between LAr layers. Among these, 8 sources are considered separately for various $\eta$-regions of the detector, leading to a total number of 29 different sources, documented in Ref. [54]. For each source of the photon energy scale uncertainty, a Monte Carlo signal sample is generated where only one single variation is applied. The method used to estimate the uncertainty on the mass of the Higgs (on the peak position of the signal PDF) is to compare the value of the $\mu_{\text{CB}}$ from fitting the signal sample without variation and a sample with variation, for each bin of each observable. The relative uncertainty $\delta_{\text{EnScale}}$, obtained in this way, is then used to define the parameter $\Theta_{\text{EnScale}}$ as:

$$\Theta_{\text{EnScale}} = (1 + \delta_{\text{EnScale}} \theta_{\text{EnScale}}),$$

(5.12)

where $\theta_{\text{EnScale}}$ is the nuisance parameter associated to the photon energy scale systematic uncertainty, constrained by a Gaussian with mean at 0 and $\sigma = 1$. A simplified correlation scheme is used: only the four biggest photon energy scale systematic uncertainties are kept separate while the remaining are merged together by summing them in quadrature. The four single sources are:

- Lateral leakage mis-modelling: electrons and photons deposit about 6% of their energy outside of the calorimeter cluster used in the reconstruction, depending on pseudorapidity and particle type. Imperfect modelling of this effect can lead to a bias in the electron and photon energy calibration due to differences between data and simulation. In the case of electrons this difference was found to be negligible while for the photons $Z \to \ell\ell\gamma$ and $Z \to ee$ samples, selected from data and MC, are compared to estimate this uncertainty.
Figure 5.3: Results from fits of the $m_{\gamma\gamma}$ distribution from simulated $H \rightarrow \gamma\gamma$ for each of the $\tau_C^0$ bins. The bin range for $\tau_C^0$ is listed on Table 5.5. The functional form for the fit is the one in Eq. 5.8 and it is used to constrain the parameters of Eq. 5.10.
5.4. Signal model and signal extraction

- LAr calorimeter electronic calibration: due to the imperfect knowledge of the internal calorimeter geometry and the effect of cross-talk between layers.

- LAr gain miscalibration: the wide range of expected energies in the calorimeter cells needs three different gains for the electronic signals induced. This uncertainty is related to the correction for data-MC differences of the gain dependence of the energy response in high gain and medium gain.

- LAr $E_{1/2}$ electron/unconverted photon: from the differences in the modelling of the ratio of the first-layer energy to the second-layer energy in the longitudinally segmented EM calorimeter for electrons and unconverted photons.

As an example, the values of $\delta_{\text{EnScale}}$ for the five categories described above are collected on Table 5.1 for the measurement of $\tau_{C0}^C$. Similar or smaller uncertainties are estimated for all the other observables considered.

**Table 5.1:** Relative photon energy scale uncertainties $\delta_{\text{EnScale}}$ for $\tau_{C0}^C$, expressed in percent.

<table>
<thead>
<tr>
<th>Bin</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral leakage</td>
<td>0.03</td>
<td>0.02</td>
<td>0.01</td>
<td>0.02</td>
<td>0.06</td>
</tr>
<tr>
<td>LAr calibration</td>
<td>0.02</td>
<td>0.03</td>
<td>0.01</td>
<td>0.02</td>
<td>0.06</td>
</tr>
<tr>
<td>LAr gain</td>
<td>0.01</td>
<td>0.01</td>
<td>0.03</td>
<td>0.01</td>
<td>0.03</td>
</tr>
<tr>
<td>LAr $E_{1/2}$</td>
<td>0.03</td>
<td>0.04</td>
<td>0.01</td>
<td>0.01</td>
<td>0.06</td>
</tr>
<tr>
<td>Merged</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.03</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Photon energy resolution uncertainties include uncertainties in the intrinsic calorimeter resolution as well as effects of the material in front of the calorimeter, imperfections on the calorimeter calibration, contributions from electronics and pile up noise. Samples with a given variation are produced and fitted. The value of the Full Width Half Maximum (FWHM) obtained from a fit of these samples is compared to the one from the nominal case of the same bin and observable. The relative difference between these two values is considered as the relative uncertainty of the photon energy resolution for that variation. A simplified correlation scheme is applied and all the sources of photon energy resolution uncertainty are then added in quadrature. This relative uncertainty $\delta_{\text{EnRes}}$ is used to define the parameter $\Theta_{\text{EnRes}}$ log-normal constrained:

$$\Theta_{\text{EnRes}} = \exp \left( \theta_{\text{EnRes}} \sqrt{\log \left( 1 + \delta_{\text{EnRes}}^2 \right)} \right),$$  \hspace{1cm} (5.13)

where $\theta_{\text{EnRes}}$ is the nuisance parameter associated to the photon energy resolution systematic uncertainty, constrained by a Gaussian with mean at 0 and $\sigma = 1$.

The values for the $\delta_{\text{EnRes}}$ for all measured observables are shown on Table 5.2. They range from 5% to 10% in all cases.
## 5.4. Signal model and signal extraction

### 5.4.1 Signal model

#### 5.4.1.1 Photons

For each event, the photon position is calculated as the weighted average of the hits with a weight equal to the standard deviation of the hit. The energy is determined as the sum of the hits with the same weight. The resolution of the photon energy is then given by

\[ \Delta E_{\text{photon}} = \sqrt{\sum \Delta E_i^2} \]

where \( \Delta E_i \) is the resolution of each hit.

#### 5.4.1.2 QCD Background

The QCD background is modeled by a combination of separate PDFs for each source of QCD radiation. The PDFs are parametrized by different functions for different regions of the spectrum.

### 5.4.2 Signal extraction

For each differential cross section measurement, the signal yields are extracted using a simultaneous unbinned maximum likelihood fit to the \( m_{\gamma\gamma} \) distribution for all bins of the spectrum to be measured. The likelihood function, \( \mathcal{L} \), that is maximized can be written as:

\[
\mathcal{L}(m_{\gamma\gamma}, \nu^\text{sig}, \nu^\text{bkg}) = \prod_i \left\{ e^{-\nu_i} \frac{n_i!}{\nu_i!} \prod_j \left[ \nu_i^{\text{sig}} S_i(m_{\gamma\gamma}^j; m_H) + \nu_i^{\text{bkg}} B_i(m_{\gamma\gamma}^j) \right] \right\} \times \prod_k G_k \quad (5.14)
\]

with \( i \) the bins in the differential cross section, \( \nu_i^{\text{sig}} \) and \( \nu_i^{\text{bkg}} \) the number of signal and background events expected, \( n_i \) the sum of these two numbers, \( n_i \) the total number of events in the \( i \)-th bin, \( m_{\gamma\gamma}^j \) the diphoton invariant mass for the event \( j \), \( S_i(m_{\gamma\gamma}^j; m_H) \) and \( B_i(m_{\gamma\gamma}^j) \) the signal and background PDFs, \( G_k \) the functions used for the uncertainty constraints and \( k \) the index for all the different uncertainties on the signal shape.

The \( m_{\gamma\gamma} \) distribution of the non-resonant background is parametrized, for all the measurements presented in this thesis, with an exponential of a polynomial of second order:

\[
B_i(m_{\gamma\gamma}^j) = N \cdot \exp\left(\frac{m_{\gamma\gamma}^j}{\zeta_0} + \frac{m_{\gamma\gamma}^j}{\zeta_1}\right) \quad (5.15)
\]

where \( N \) is the normalization parameter and \( \zeta_0, \zeta_1 \) fit parameters, independent for each bin, determining the background shape. This functional form is widely used in almost all the previous \( H \rightarrow \gamma\gamma \) ATLAS analyses [1,3,113].
For each observable, the fits are performed simultaneously in all bins with a fixed value for the Higgs mass of $m_H = 125.4$ GeV coming from the combination of ATLAS mass measurements from the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ channels using the full 2011 and 2012 data sets \cite{114}, so that the signal peak position is allowed to float only within the photon energy scale constraints.

Fits for $\tau_C^0$ are presented in Figure 5.4. As already explained in the sections above, the fits are performed simultaneously on all the bins to better constrain the systematic uncertainties from the photon energy scale and resolution. On Figure 5.5(a), the extracted yield with its uncertainty is shown together with the expected signal from Monte Carlo simulation. Both distributions have each bin normalized by their bin-width. This can be used to compare the agreement between data and simulation at detector-level. On Figure 5.5(b), the observed and expected bin significance are presented. The value of the significance in each bin is estimated as $s/\sqrt{b}$, with $s$ the observed or expected number of signal events in a diphoton mass window of $\pm 4$ GeV around the Higgs boson mass and $b$ the corresponding number of background events in the same mass window estimated by a linear extrapolation from data in the range [117,121] GeV and [129,133] GeV.

All the signal yields obtained from the fits, together with their uncertainty, are listed on Table 5.3 for all the available observables.

### Table 5.3: Extracted signal yields with fit uncertainty for all observables considered.

<table>
<thead>
<tr>
<th>Fiducial region</th>
<th>Bin</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive</td>
<td>$N_{\text{tracks}}$</td>
<td>$161 \pm 81$</td>
<td>$272 \pm 82$</td>
<td>$47 \pm 41$</td>
<td>$26 \pm 17$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$H_{\text{tracks}}$</td>
<td>$107 \pm 67$</td>
<td>$176 \pm 81$</td>
<td>$159 \pm 59$</td>
<td>$32 \pm 29$</td>
<td>$45 \pm 16$</td>
</tr>
<tr>
<td></td>
<td>$\tau_C^0$</td>
<td>$142 \pm 80$</td>
<td>$218 \pm 76$</td>
<td>$92 \pm 49$</td>
<td>$80 \pm 27$</td>
<td>$7 \pm 10$</td>
</tr>
<tr>
<td></td>
<td>$\tau_B^0$</td>
<td>$88 \pm 67$</td>
<td>$116 \pm 73$</td>
<td>$227 \pm 61$</td>
<td>$72 \pm 40$</td>
<td>$38 \pm 17$</td>
</tr>
<tr>
<td>1-jet inclusive</td>
<td>$\tau_{1}^{BB}$</td>
<td>$28 \pm 37$</td>
<td>$81 \pm 39$</td>
<td>$22 \pm 31$</td>
<td>$64 \pm 20$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau_{1}^{CB}$</td>
<td>$40 \pm 42$</td>
<td>$52 \pm 40$</td>
<td>$73 \pm 27$</td>
<td>$31 \pm 13$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau_{1}^{CC}$</td>
<td>$43 \pm 42$</td>
<td>$58 \pm 40$</td>
<td>$65 \pm 27$</td>
<td>$34 \pm 14$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau_{1}^{BB,\text{beam}}$</td>
<td>$29 \pm 39$</td>
<td>$81 \pm 40$</td>
<td>$36 \pm 29$</td>
<td>$43 \pm 18$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau_{1}^{CB,\text{beam}}$</td>
<td>$27 \pm 44$</td>
<td>$75 \pm 39$</td>
<td>$63 \pm 26$</td>
<td>$28 \pm 13$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau_{1}^{CC,\text{beam}}$</td>
<td>$36 \pm 44$</td>
<td>$67 \pm 39$</td>
<td>$59 \pm 25$</td>
<td>$29 \pm 13$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau_{1}^{BB,\text{jet}}$</td>
<td>$65 \pm 53$</td>
<td>$94 \pm 33$</td>
<td>$26 \pm 18$</td>
<td>$16 \pm 12$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau_{1}^{CB,\text{jet}}$</td>
<td>$94 \pm 55$</td>
<td>$85 \pm 36$</td>
<td>$22 \pm 13$</td>
<td>$0 \pm 7$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau_{1}^{CC,\text{jet}}$</td>
<td>$75 \pm 53$</td>
<td>$108 \pm 36$</td>
<td>$9 \pm 12$</td>
<td>$2 \pm 8$</td>
<td></td>
</tr>
<tr>
<td>1-jet exclusive</td>
<td>$\tau_{1}^{BB}$</td>
<td>$11 \pm 23$</td>
<td>$15 \pm 21$</td>
<td>$6 \pm 15$</td>
<td>$4 \pm 6$</td>
<td></td>
</tr>
<tr>
<td>1-jet central exclusive</td>
<td>$\tau_{1}^{BB}$</td>
<td>$4 \pm 20$</td>
<td>$27 \pm 20$</td>
<td>$10 \pm 11$</td>
<td>$1 \pm 4$</td>
<td></td>
</tr>
</tbody>
</table>

With the 8 TeV dataset (Sec. 2.3), not all the variables could be measured in all the fiducial regions. In fact, $\tau_1^{CB}$, $\tau_1^{CB,\text{beam}}$, $\tau_1^{CB,\text{jet}}$, $\tau_1^{CC}$, $\tau_1^{CC,\text{beam}}$, $\tau_1^{CC,\text{jet}}$ measured in
Figure 5.4: Signal-plus-background fits for the diphoton invariant mass spectrum for the five bins of the $\tau_C^0$ observable. The solid line represents the results of the single simultaneous fit to data for all the bins. The dashed line is the background-only probability density function. For the signal, the Higgs boson mass was fixed to be $m_H = 125.4$ GeV.
the 1-jet exclusive and 1-jet central exclusive fiducial regions have one bin where the extracted signal yield is negative. As an example of that, the distribution of the extracted yield and of the detector-level prediction for the simulated signal is shown on Figure 5.6 for $\tau_{1}^{CC}$. Here the third bin has a slightly negative extracted signal yield. In the similar analysis [3], the case of finding a bin with a negative yield was treated with merging consecutive bins. This would not make much sense for the measurements considered here because it would imply to reduce the number of bins from four to three, removing the possibility of having a meaningful shape for a distribution of a differential cross section. For this reason the results from $\tau_{1}^{CB}$, $\tau_{1}^{CB,beam}$, $\tau_{1}^{CB,\text{jet}}$, $\tau_{1}^{CC}$, $\tau_{1}^{CC,\text{beam}}$, $\tau_{1}^{CC,\text{jet}}$ in the 1-jet exclusive and 1-jet central exclusive fiducial regions are not presented. Nevertheless, it is worth to say that the just mentioned cases did not show any other particular difference with respect to the other ones in this thesis from the point of bin purity, bin resolution or bin systematic uncertainty.

5.4.4 Systematic uncertainty from the fits

In the simultaneous fit to the diphoton mass spectrum, the photon energy scale and the photon energy resolution nuisance parameters are treated as correlated among all the bins for the particular observable considered. As seen before in Sec. 5.4.2, with Eq.(5.13), the uncertainty associated with the photon energy resolution is floated using a log-normal constraint while for the photon energy scale systematic uncertainty, Eq.(5.12), a simple Gaussian constraint is used. In order to have a better constraint on the nuisance parameters associated to the systematic uncertainties on the signal shape, all the events that passed the baseline selection are included in the fit, and the events that do not fall into any of the bins of the observable under study are merged into a “rest” bin and still considered in the simultaneous fit.

To separate the systematic component of the uncertainty of the fit yield from the statistical one, the following method was used:
5.4. Signal model and signal extraction

Figure 5.6: Detector-level comparison for $\tau_1^{CC}$ between the extracted signal yield, with total fit uncertainty, and prediction from MC simulation. All values are divided by their bin-width.

- the diphoton invariant mass spectrum is fitted
- the obtained form for the signal and background functions, with their profiled parameter values, is used to construct an "Asimov dataset" [115]
- the Asimov dataset is fitted twice, once allowing the nuisance parameters to float and once with the nuisance parameters fixed to their profiled values
- the systematic uncertainty on the extracted yield is defined by subtracting in quadrature the uncertainty on the signal yield obtained with fixed nuisance parameters from the uncertainty on the signal yield obtained with floated nuisance parameters.

The values for the relative systematic uncertainty associated to the fit are listed in Table 5.4. Some of the results are omitted, due to the fact that, given the poor statistic available in each bin, the minimization algorithm of the fits does not converge. In the cases where the whole procedure described in this section met these problems, the decision made was to not split the statistical and systematic component of the uncertainty and just call statistical uncertainty the total uncertainty.
### Table 5.4: Fit systematic uncertainties for all observables considered, expressed in percent.

<table>
<thead>
<tr>
<th>Fiducial region</th>
<th>Bin</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( N_{\text{tracks}} )</td>
<td>3.8</td>
<td>4.4</td>
<td>5.0</td>
<td>4.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( H_{\text{tracks}} )</td>
<td>3.6</td>
<td>3.7</td>
<td>4.9</td>
<td>5.3</td>
<td>4.8</td>
<td></td>
</tr>
<tr>
<td>( \tau_0^C )</td>
<td>3.5</td>
<td>4.0</td>
<td>4.4</td>
<td>4.32</td>
<td>8.0</td>
<td></td>
</tr>
<tr>
<td>( \tau_0^B )</td>
<td>3.4</td>
<td>3.4</td>
<td>3.9</td>
<td>5.0</td>
<td>4.8</td>
<td></td>
</tr>
<tr>
<td>1-jet inclusive</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \tau_1^{BB} )</td>
<td>4.3</td>
<td>4.7</td>
<td>6.2</td>
<td>3.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \tau_1^{CB} )</td>
<td>4.0</td>
<td>5.1</td>
<td>4.0</td>
<td>5.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \tau_1^{CC} )</td>
<td>4.0</td>
<td>5.1</td>
<td>4.2</td>
<td>3.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \tau_1^{BB,\text{beam}} )</td>
<td>4.8</td>
<td>4.7</td>
<td>4.9</td>
<td>5.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \tau_1^{CB,\text{beam}} )</td>
<td>5.2</td>
<td>4.7</td>
<td>4.6</td>
<td>3.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \tau_1^{CC,\text{beam}} )</td>
<td>4.5</td>
<td>4.9</td>
<td>3.8</td>
<td>3.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \tau_1^{BB,\text{jet}} )</td>
<td>4.8</td>
<td>4.3</td>
<td>4.7</td>
<td>4.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \tau_1^{CB,\text{jet}} )</td>
<td>4.5</td>
<td>4.6</td>
<td>4.7</td>
<td>—</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \tau_1^{CC,\text{jet}} )</td>
<td>4.6</td>
<td>4.6</td>
<td>5.4</td>
<td>—</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-jet exclusive</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \tau_1^{BB} )</td>
<td>6.4</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>1-jet central exclusive</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \tau_1^{BB} )</td>
<td>7.5</td>
<td>4.1</td>
<td>4.2</td>
<td>—</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The differential cross section of a generic observable $X$ is defined as:

$$\frac{d\sigma_i}{dX} = \frac{c_i\nu_i^{\text{sig}}}{\Delta_iX \int L \, dt} \quad (5.16)$$

where $\nu_i^{\text{sig}}$ is the fitted number of signal events in the $i$-th bin, $\Delta_iX$ is the width of bin $i$ for variable $X$, $c_i$ is the correction factor that accounts for detector inefficiency and resolution, and $\int L \, dt$ is the integrated luminosity of the available data.

The correction factors $c_i$ are calculated from Monte Carlo simulated signal samples (Sec. 5.1), using a bin-by-bin method. In this approach the correction factor $c_i$ for the bin $i$ can be written as follows:

$$c_i = \frac{n_i^{\text{part}}}{n_i^{\text{det}}} \quad (5.17)$$

with $n_i^{\text{det}}$ the number of signal events at detector-level (Reco) that are found in the $i$-th bin of that distribution and $n_i^{\text{part}}$ the counterpart at particle-level (Truth). These correction factors account for two types of detector effects; the efficiency of reconstructing and identifying the objects used in the analysis (photons, jets, tracks/particles); and detector resolution and miscalibration that causes events to migrate between bins and in/out of the fiducial region. The first one is usually called efficiency and is defined as:

$$\epsilon_i = \frac{n_i^{\text{det,part}}}{n_i^{\text{det}}} \quad (5.18)$$

where $n_i^{\text{det,part}}$ is the number of events in bin $i$ at both particle and detector level. The efficiency reflects the losses in the object reconstruction and identification due to an imperfect detector. On the other hand, the purity, defined as:

$$P_i = \frac{n_i^{\text{det,part}}}{n_i^{\text{det}}} \quad (5.19)$$

accounts for the finite detector resolution or miscalibration that causes events to migrate between bins. The purity also considers the possible presence of events at detector-level that do not have a counterpart at particle level, but come from an imperfect detector reconstruction of an object. These objects/events are sometimes called “fakes”. From definitions (5.18), (5.19) and Eq.(5.17), the correction factors can be expressed in terms of purity and efficiency as $c_i = P_i/\epsilon_i$. In a generic bin, a low value for the purity and a high efficiency suggest the presence of a large “fake” contribution, on the contrary a low efficiency and a high purity indicate a poor object reconstruction/identification. Low values in both purity and efficiency reveal large bin migration as well as a mix of the previous effects.

A few examples for the bin purity and efficiency are presented in Figure 5.7 for $\tau_0^C$ in the inclusive fiducial region and in Figures 5.8 and 5.9 for $\tau_1^{CC,\text{beam}}$ and $\tau_1^{CC,\text{jet}}$ in the 1-jet inclusive fiducial region. In Figure 5.7(a) the diagonal of the 2D-plot shows the values of the
5.5. Unfolding method

![Figure 5.7](image)

**Figure 5.7**: The purity on each bin as defined in Eq.(5.19) for \( \tau_0^C \) (a). Bin efficiency for \( \tau_0^C \) (b) as defined in Eq.(5.18).

![Figure 5.8](image)

**Figure 5.8**: Bin purity (a) and bin efficiency (b) for \( \tau_{1}^{CC,beam} \) in the 1-jet inclusive fiducial region.

The purity defined in Eq.(5.19) for the bins of \( \tau_0^C \) while in Figures 5.8(a) and 5.9(a) events at detector-level that do not have a counterpart at particle-level are not included. Nevertheless that fraction of events is smaller than 1% and the correction is small. The “fake” events are included in the computation of the correction factors. The efficiency computed using Eq.(5.18) is presented on Figures 5.7(b), 5.8(b) and 5.9(b) for the same differential variables.

### 5.5.1 Choice of binning

The binning of the differential variables was chosen before looking at the data in the signal region and was based on two requirements. The first one is the condition that in each bin the purity, defined in Eq.(5.19), should be larger than 60%. This is to limit the biases in the results introduced by the correction for the detector effects especially when using a bin-by-bin unfolding method, which does not take into account corrections from migrations of events between all the bins in the distribution (i.e. off-diagonal elements from Figures 5.8(a)
and 5.9(a)). The second criterion is to aim in each bin for an expected significance, defined as \( s/\sqrt{b} \sim 1 \). The expected number of signal events \( s \) is defined as the number of reconstructed and selected simulated events in a diphoton mass window of \( \pm 4 \) GeV around the Higgs boson mass while \( b \) is the number of background events expected in the same diphoton mass window, estimated with a linear extrapolation from data events observed outside of that mass window. In principle one wants to have more stringent requirements, as also asking for a similar significance in all the bins and to have similar bin-widths for example, but given the available data already the described criteria are difficult to always fully satisfy. Compromises were made and priority was given to the bin purity.

The binning for the differential variables is listed on Table 5.5. The “rest” bin is useful to constrain the nuisance parameters associated to the uncertainties on the signal shape in the fits, as described in Section 5.4.

In all the cases the “bin resolution”, computed as the difference between the observable value in the detector-level case and in the particle-case for the events that fall into the same detector-level and particle-level bin, was checked. As an example, on Figure 5.10 the bin resolution is presented for the case of \( \tau_{1}^{CC,\text{jet}} \) in the 1-jet inclusive fiducial region. Each of these plots shows the distribution of the difference between detector-level and particle-level for the particular \( \tau_{1}^{CC,\text{jet}} \) bin. The values of the mean and the RMS of the resolution can be compared to the particular bin width. In addition to the resolution distribution (black), on the plots are present three more histograms representing what the resolution would look like if, from the differential variable, is subtracted one of the components between the one coming from the good tracks, the pileup tracks or the secondaries tracks. As can be seen pileup tracks and secondaries tracks have little impact on the observable resolution.
Figure 5.10: Bin resolution (black) for $\tau_{1}^{CC,jet}$ in the 1-jet inclusive fiducial region. Blue histogram does not include the contribution from pileup tracks, the pink one does not include secondary tracks and the red one does not include good tracks.
### 5.5. Unfolding method

Table 5.5: Binning for each of the differential cross section measurements presented in this thesis. The “rest” bin indicates a bin that contains all the events that do not pass the event selection requirements for the particular fiducial region but pass the ones from the inclusive case.

<table>
<thead>
<tr>
<th>Fiducial region</th>
<th>Observable</th>
<th>Binning [GeV]</th>
<th>$N_{bins}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive</td>
<td>$N_{tracks}$</td>
<td>{0, 25, 50, 75, 100}</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>$H_{tracks}$</td>
<td>{0, 30, 60, 100, 140, 180}</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>$\tau_0^C$</td>
<td>{0, 10, 20, 35, 65, 100}</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>$\tau_0^B$</td>
<td>{0, 10, 20, 35, 65, 100}</td>
<td>5</td>
</tr>
<tr>
<td>1-jet inclusive</td>
<td>$\tau_1^{BB}$</td>
<td>{0, 10, 20, 35, 65}</td>
<td>4+rest</td>
</tr>
<tr>
<td></td>
<td>$\tau_1^{CB}$</td>
<td>{0, 10, 20, 35, 65}</td>
<td>4+rest</td>
</tr>
<tr>
<td></td>
<td>$\tau_1^{CC}$</td>
<td>{0, 10, 20, 35, 65}</td>
<td>4+rest</td>
</tr>
<tr>
<td></td>
<td>$\tau_1^{BB,\text{beam}}$</td>
<td>{0, 10, 20, 35, 65}</td>
<td>4+rest</td>
</tr>
<tr>
<td></td>
<td>$\tau_1^{CB,\text{beam}}$</td>
<td>{0, 10, 20, 35, 65}</td>
<td>4+rest</td>
</tr>
<tr>
<td></td>
<td>$\tau_1^{CC,\text{beam}}$</td>
<td>{0, 10, 20, 35, 65}</td>
<td>4+rest</td>
</tr>
<tr>
<td></td>
<td>$\tau_1^{BB,\text{jet}}$</td>
<td>{0, 1.5, 3.5, 6, 12}</td>
<td>4+rest</td>
</tr>
<tr>
<td></td>
<td>$\tau_1^{CB,\text{jet}}$</td>
<td>{0, 1.5, 3.5, 6, 12}</td>
<td>4+rest</td>
</tr>
<tr>
<td></td>
<td>$\tau_1^{CC,\text{jet}}$</td>
<td>{0, 1.5, 3.5, 6, 12}</td>
<td>4+rest</td>
</tr>
<tr>
<td>1-jet exclusive</td>
<td>$\tau_1^{BB}$</td>
<td>{0, 10, 20, 40, 65}</td>
<td>4+rest</td>
</tr>
<tr>
<td>1-jet central exclusive</td>
<td>$\tau_1^{BB}$</td>
<td>{0, 12, 25, 45, 65}</td>
<td>4+rest</td>
</tr>
</tbody>
</table>
5.6 Systematic uncertainties

In this section the sources of systematic uncertainties affecting the final results as well as the methods used to estimate them are discussed. Apart from the uncertainty on the integrated luminosity of the data sample, two main categories can be distinguished:

- Signal extraction systematic uncertainties: those are the ones described in section 5.4.2 and affect the signal parametrization and the yield extraction.

- Correction factor systematic uncertainties: all the uncertainties that come from differences between data and Monte Carlo, due to the imperfect simulation of the detector response, and from the particular models used to apply the correction from reconstructed to particle level. Those are related to:
  
  - photon trigger, photon identification, photon isolation
  - tracking efficiency, secondary tracks, pileup tracks
  - signal composition
  - jet energy scale and resolution, jet vertex fraction, pileup jets

and will be described in the following.

5.6.1 Photon uncertainties

The uncertainty in the photon identification and trigger efficiencies have been determined from data [32, 116], and are found to be 1% and 0.5% respectively. The photon isolation selection efficiency depends on the number of jets in the event. The uncertainty associated with the photon isolation is 1% for all the event in the inclusive (baseline) fiducial region and one jet, 2% in the case of two jets in the fiducial region and 4% in the case of three jets [3]. The migration of events in and out of the fiducial regions caused by the uncertainties on the photon energy scale and photon energy resolution were found to be completely negligible.

5.6.2 Track uncertainties

The uncertainties associated with the tracking efficiency of the detector, with the track composition and with the track pileup dependence are detailed here.

For the tracking efficiency one of the most important factors is the precise knowledge and implementation of the material in the detector for a proper simulation of it. To assess to which extent the tracking efficiency is influenced by an imperfect description of the material in front of the detectors, a simulated sample is produced with a conservative variation of the +5% of the material in the inner detector. The tracking efficiency is calculated comparing reconstructed tracks to particles in the simulated sample [117]. From this a map representing the track reconstruction efficiency as a function of the track transverse momentum and the $\eta$ of the track is built. The difference between the efficiency obtained from the sample with the
nominal detector geometry and the one with a 5% variation in the inner detector material corresponds to the fraction of tracks that are randomly removed. The unfolding factors obtained from the nominal simulated sample and the one with a fraction of tracks removed are compared and their difference is considered as the uncertainty associated to the track reconstruction efficiency. The values are listed in Table 5.6.

**Table 5.6:** Relative tracking efficiency systematic uncertainty for all the considered differential variables, expressed in percent.

<table>
<thead>
<tr>
<th>Fiducial region</th>
<th>Bin</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive</td>
<td>$N_{\text{tracks}}$</td>
<td>1.4</td>
<td>0.1</td>
<td>2.1</td>
<td>4.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$H_{\text{tracks}}$</td>
<td>1.3</td>
<td>0.1</td>
<td>1.0</td>
<td>3.1</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>$\tau_0^C$</td>
<td>1.0</td>
<td>0.1</td>
<td>1.0</td>
<td>2.0</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>$\tau_0^B$</td>
<td>1.1</td>
<td>0.2</td>
<td>0.6</td>
<td>1.3</td>
<td>2.0</td>
</tr>
<tr>
<td>1-jet inclusive</td>
<td>$\tau_1^{BB}$</td>
<td>1.1</td>
<td>0.2</td>
<td>0.8</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau_1^{CB}$</td>
<td>1.1</td>
<td>0.2</td>
<td>1.3</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau_1^{CC}$</td>
<td>1.1</td>
<td>0.2</td>
<td>1.3</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau_1^{BB,\text{beam}}$</td>
<td>0.9</td>
<td>0.1</td>
<td>1.0</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau_1^{CB,\text{beam}}$</td>
<td>0.9</td>
<td>0.3</td>
<td>1.4</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau_1^{CC,\text{beam}}$</td>
<td>0.9</td>
<td>0.3</td>
<td>1.5</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau_1^{BB,\text{jet}}$</td>
<td>0.4</td>
<td>0.4</td>
<td>0.7</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau_1^{CB,\text{jet}}$</td>
<td>0.5</td>
<td>0.6</td>
<td>1.0</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau_1^{CC,\text{jet}}$</td>
<td>0.4</td>
<td>0.6</td>
<td>1.2</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>1-jet exclusive</td>
<td>$\tau_1^{BB}$</td>
<td>1.0</td>
<td>0.1</td>
<td>1.4</td>
<td>3.1</td>
<td></td>
</tr>
<tr>
<td>1-jet central exclusive</td>
<td>$\tau_1^{BB}$</td>
<td>1.1</td>
<td>0.2</td>
<td>1.6</td>
<td>3.6</td>
<td></td>
</tr>
</tbody>
</table>

The simulation does not necessarily predict the fraction of non-primary tracks correctly, so that this fraction can be different in data and simulated samples. To take this effect into account the fraction of non-primary tracks in the simulated sample was varied removing randomly 50% of these tracks, using a conservative approach. The unfolding factors of the two simulated samples with nominal and modified secondaries fractions are compared. Their difference is symmetrized and taken as systematic uncertainty. For all the differential variables these values are shown in Table 5.7 for each bin.

Finally a similar scheme is used to estimate the uncertainty on the track pileup subtraction method used. As shown in Section 4.2, Monte Carlo simulations do not reproduce closely the dependence of the observables on the average number of interactions per bunch crossing. The track pileup subtraction method applied flattens out this dependence and decreases this difference on the behavior of data and simulation. The uncertainty related to this effect is computed by randomly removing a fraction of the 30% of the pileup tracks, a fraction that well covers the remaining differences in the pileup dependence between data and simulation.
5.6. Systematic uncertainties

Table 5.7: Secondary track composition systematic uncertainty for all the considered differential variables, expressed in percent.

<table>
<thead>
<tr>
<th>Fiducial region</th>
<th>Bin</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive</td>
<td>$N_{\text{tracks}}$</td>
<td>1.6</td>
<td>0.4</td>
<td>2.5</td>
<td>5.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$H_{\text{tracks}}$</td>
<td>1.3</td>
<td>0.5</td>
<td>1.0</td>
<td>2.4</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>$\tau_{0}^{C}$</td>
<td>1.1</td>
<td>0.03</td>
<td>1.3</td>
<td>2.5</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>$\tau_{0}^{B}$</td>
<td>1.3</td>
<td>0.3</td>
<td>0.6</td>
<td>1.8</td>
<td>2.6</td>
</tr>
<tr>
<td>1-jet inclusive</td>
<td>$\tau_{1}^{BB}$</td>
<td>1.4</td>
<td>0.3</td>
<td>0.9</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau_{1}^{CB}$</td>
<td>1.2</td>
<td>0.1</td>
<td>1.7</td>
<td>3.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau_{1}^{CC}$</td>
<td>1.3</td>
<td>0.02</td>
<td>1.7</td>
<td>3.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau_{1}^{BB,\text{beam}}$</td>
<td>1.2</td>
<td>0.2</td>
<td>1.3</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau_{1}^{CB,\text{beam}}$</td>
<td>1.2</td>
<td>0.3</td>
<td>1.7</td>
<td>3.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau_{1}^{CC,\text{beam}}$</td>
<td>1.2</td>
<td>0.3</td>
<td>1.6</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau_{1}^{BB,\text{jet}}$</td>
<td>0.6</td>
<td>0.4</td>
<td>1.4</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau_{1}^{CB,\text{jet}}$</td>
<td>0.6</td>
<td>0.6</td>
<td>1.6</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau_{1}^{CC,\text{jet}}$</td>
<td>0.6</td>
<td>0.7</td>
<td>1.5</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>1-jet exclusive</td>
<td>$\tau_{1}^{BB}$</td>
<td>1.4</td>
<td>0.1</td>
<td>1.7</td>
<td>5.2</td>
<td></td>
</tr>
<tr>
<td>1-jet central exclusive</td>
<td>$\tau_{1}^{BB}$</td>
<td>1.3</td>
<td>0.1</td>
<td>2.3</td>
<td>5.3</td>
<td></td>
</tr>
</tbody>
</table>

As before, the difference between the unfolding factors from the nominal simulated sample and the one with the variation on the fraction of pileup tracks is symmetrized and considered as systematic uncertainty. The percentage values for this uncertainty source can be found on Table 5.8.

5.6.3 Signal composition uncertainties

The simulated samples for the five main production processes for the Higgs boson, gluon-gluon fusion, vector boson fusion, associated production with a vector boson and finally associated production with a top anti-top pair; are normalized to match the SM production cross sections for a 125 GeV Higgs [13]. To account for the uncertainty associated to the assumption of the SM, the approach was the same as used in [3]: the contribution of the VBF and $VH$ production cross sections was varied once as $\sigma_{VBF+VH} \times 0.5$ and then as $\sigma_{VBF+VH} \times 2$ while for the $t\bar{t}H$ case the cross section was varied from $\sigma_{t\bar{t}H} \times 0$ to $\sigma_{t\bar{t}H} \times 5$. The envelope with the maximum variation on the correction factors from $\sigma_{VBF+VH}$ and $\sigma_{t\bar{t}H}$ variations is taken to be the systematic uncertainty related to the signal composition assumption. The relative uncertainties for each bin for each observable can be found on Table 5.9.
Table 5.8: Pileup tracks systematic uncertainty for all the considered differential variables, expressed in percent.

<table>
<thead>
<tr>
<th>Fiducial region</th>
<th>Bin</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive</td>
<td>$N_{\text{tracks}}$</td>
<td>3.8</td>
<td>0.5</td>
<td>6.7</td>
<td>7.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$H_{\text{tracks}}$</td>
<td>7.6</td>
<td>0.8</td>
<td>5.7</td>
<td>5.2</td>
<td>3.9</td>
</tr>
<tr>
<td></td>
<td>$\tau_0^C$</td>
<td>4.1</td>
<td>2.2</td>
<td>3.2</td>
<td>3.2</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>$\tau_0^B$</td>
<td>5.2</td>
<td>0.3</td>
<td>3.8</td>
<td>3.2</td>
<td>1.1</td>
</tr>
<tr>
<td>1-jet inclusive</td>
<td>$\tau_{BB}$</td>
<td>0.5</td>
<td>1.8</td>
<td>0.8</td>
<td>3.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau_{CB}$</td>
<td>0.3</td>
<td>1.0</td>
<td>2.2</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau_{CC}$</td>
<td>0.3</td>
<td>1.1</td>
<td>2.3</td>
<td>3.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau_{BB, \text{beam}}$</td>
<td>0.1</td>
<td>1.6</td>
<td>1.5</td>
<td>3.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau_{CB, \text{beam}}$</td>
<td>0.5</td>
<td>0.7</td>
<td>2.6</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau_{CC, \text{beam}}$</td>
<td>0.6</td>
<td>0.7</td>
<td>2.5</td>
<td>3.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau_{BB, \text{jet}}$</td>
<td>0.4</td>
<td>0.2</td>
<td>1.2</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau_{CB, \text{jet}}$</td>
<td>0.4</td>
<td>0.5</td>
<td>1.0</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau_{CC, \text{jet}}$</td>
<td>0.3</td>
<td>0.5</td>
<td>0.9</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>1-jet exclusive</td>
<td>$\tau_{BB}$</td>
<td>0.4</td>
<td>1.5</td>
<td>1.3</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>1-jet central exclusive</td>
<td>$\tau_{BB}$</td>
<td>0.1</td>
<td>1.2</td>
<td>2.5</td>
<td>8.0</td>
<td></td>
</tr>
</tbody>
</table>

5.6.4 Jet uncertainties

Jet systematic uncertainties affect observables that depend directly on jet related quantities as well as can cause migration of events in and out of fiducial regions constructed via any jet selection. In the next sections the most important sources of jet systematic uncertainties will be presented.

Jet energy scale uncertainties

The in situ techniques used for the jet energy calibration are based on the balance of physics objects in the transverse plane in $Z$+jet, $\gamma$+jet and multi-jet events. These measurements are combined for the final jet energy calibration, and together with this, also the related uncertainties of the single measurements are propagated [118,119]. The list of jet energy scale uncertainties can be organized as:

- 56 statistical and systematic uncertainty sources directly related to the in situ method applied for the calibration, which only depend on the transverse momentum of the jet
- 2 $\eta$-intercalibration uncertainties that address the MC modelling uncertainty of forward jets and the statistical precision of the in situ derived $\eta$-intercalibration
- 4 uncertainties related to the pileup dependence of the jet energy calibration [120]:
5.6. Systematic uncertainties

Table 5.9: Signal composition systematic uncertainty for all the considered differential variables, expressed in percent.

<table>
<thead>
<tr>
<th>Fiducial region</th>
<th>Bin</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive</td>
<td>$\tau^C_0$</td>
<td>+0.2</td>
<td>+0.4</td>
<td>+1.0</td>
<td>+0.9</td>
<td>+4.4</td>
</tr>
<tr>
<td></td>
<td>$\tau^B_0$</td>
<td>+0.1</td>
<td>+0.3</td>
<td>+0.7</td>
<td>+1.4</td>
<td>+2.0</td>
</tr>
<tr>
<td></td>
<td>$\tau^B_{\text{BB}}$</td>
<td>+5.0</td>
<td>+1.9</td>
<td>+0.2</td>
<td>+2.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^B_{\text{CC}}$</td>
<td>+3.7</td>
<td>+0.8</td>
<td>+0.6</td>
<td>+6.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^B_{\text{CB}}$</td>
<td>+3.7</td>
<td>+0.8</td>
<td>+0.6</td>
<td>+6.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^B_{\text{BB,beam}}$</td>
<td>-2.5</td>
<td>-0.5</td>
<td>-2.1</td>
<td>-14.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^B_{\text{CC,beam}}$</td>
<td>+3.7</td>
<td>+1.4</td>
<td>+0.4</td>
<td>+3.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^B_{\text{BB,jet}}$</td>
<td>+3.7</td>
<td>+1.4</td>
<td>+0.4</td>
<td>+3.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^B_{\text{CC,jet}}$</td>
<td>+3.7</td>
<td>+1.4</td>
<td>+0.4</td>
<td>+3.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^B_{\text{CB,jet}}$</td>
<td>+3.7</td>
<td>+1.4</td>
<td>+0.4</td>
<td>+3.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^{\mu}_{\text{BB}}$</td>
<td>+5.0</td>
<td>+1.9</td>
<td>+0.2</td>
<td>+2.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^{\mu}_{\text{CC}}$</td>
<td>+3.7</td>
<td>+0.8</td>
<td>+0.6</td>
<td>+6.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^{\mu}_{\text{CB}}$</td>
<td>+3.7</td>
<td>+0.8</td>
<td>+0.6</td>
<td>+6.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^{\mu}_{\text{BB,beam}}$</td>
<td>-2.5</td>
<td>-0.5</td>
<td>-2.1</td>
<td>-14.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^{\mu}_{\text{CC,beam}}$</td>
<td>+3.7</td>
<td>+1.4</td>
<td>+0.4</td>
<td>+3.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^{\mu}_{\text{BB,jet}}$</td>
<td>+3.7</td>
<td>+1.4</td>
<td>+0.4</td>
<td>+3.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^{\mu}_{\text{CC,jet}}$</td>
<td>+3.7</td>
<td>+1.4</td>
<td>+0.4</td>
<td>+3.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^{\mu}_{\text{CB,jet}}$</td>
<td>+3.7</td>
<td>+1.4</td>
<td>+0.4</td>
<td>+3.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^{\mu}_{\text{BB}}$</td>
<td>+5.0</td>
<td>+1.9</td>
<td>+0.2</td>
<td>+2.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^{\mu}_{\text{CC}}$</td>
<td>+3.7</td>
<td>+0.8</td>
<td>+0.6</td>
<td>+6.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^{\mu}_{\text{CB}}$</td>
<td>+3.7</td>
<td>+0.8</td>
<td>+0.6</td>
<td>+6.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^{\mu}_{\text{BB,beam}}$</td>
<td>-2.5</td>
<td>-0.5</td>
<td>-2.1</td>
<td>-14.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^{\mu}_{\text{CC,beam}}$</td>
<td>+3.7</td>
<td>+1.4</td>
<td>+0.4</td>
<td>+3.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^{\mu}_{\text{BB,jet}}$</td>
<td>+3.7</td>
<td>+1.4</td>
<td>+0.4</td>
<td>+3.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^{\mu}_{\text{CC,jet}}$</td>
<td>+3.7</td>
<td>+1.4</td>
<td>+0.4</td>
<td>+3.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^{\mu}_{\text{CB,jet}}$</td>
<td>+3.7</td>
<td>+1.4</td>
<td>+0.4</td>
<td>+3.4</td>
<td></td>
</tr>
<tr>
<td>1-jet inclusive</td>
<td>$\tau^B_{\text{BB}}$</td>
<td>+5.0</td>
<td>+1.9</td>
<td>+0.2</td>
<td>+2.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^B_{\text{CC}}$</td>
<td>+3.7</td>
<td>+0.8</td>
<td>+0.6</td>
<td>+6.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^B_{\text{CB}}$</td>
<td>+3.7</td>
<td>+0.8</td>
<td>+0.6</td>
<td>+6.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^B_{\text{BB,beam}}$</td>
<td>-2.5</td>
<td>-0.5</td>
<td>-2.1</td>
<td>-14.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^B_{\text{CC,beam}}$</td>
<td>+3.7</td>
<td>+1.4</td>
<td>+0.4</td>
<td>+3.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^B_{\text{BB,jet}}$</td>
<td>+3.7</td>
<td>+1.4</td>
<td>+0.4</td>
<td>+3.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^B_{\text{CC,jet}}$</td>
<td>+3.7</td>
<td>+1.4</td>
<td>+0.4</td>
<td>+3.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^B_{\text{CB,jet}}$</td>
<td>+3.7</td>
<td>+1.4</td>
<td>+0.4</td>
<td>+3.4</td>
<td></td>
</tr>
<tr>
<td>1-jet exclusive</td>
<td>$\tau^B_{\text{BB}}$</td>
<td>+5.0</td>
<td>+1.9</td>
<td>+0.2</td>
<td>+2.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^B_{\text{CC}}$</td>
<td>+3.7</td>
<td>+0.8</td>
<td>+0.6</td>
<td>+6.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^B_{\text{CB}}$</td>
<td>+3.7</td>
<td>+0.8</td>
<td>+0.6</td>
<td>+6.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^B_{\text{BB,beam}}$</td>
<td>-2.5</td>
<td>-0.5</td>
<td>-2.1</td>
<td>-14.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^B_{\text{CC,beam}}$</td>
<td>+3.7</td>
<td>+1.4</td>
<td>+0.4</td>
<td>+3.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^B_{\text{BB,jet}}$</td>
<td>+3.7</td>
<td>+1.4</td>
<td>+0.4</td>
<td>+3.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^B_{\text{CC,jet}}$</td>
<td>+3.7</td>
<td>+1.4</td>
<td>+0.4</td>
<td>+3.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^B_{\text{CB,jet}}$</td>
<td>+3.7</td>
<td>+1.4</td>
<td>+0.4</td>
<td>+3.4</td>
<td></td>
</tr>
</tbody>
</table>

- $\mu$ dependent uncertainty
- $N_{PV}$ dependent uncertainty
- $p_T$ dependence of the pileup corrections
- mis-modelling of the $\rho$-parameter, defined as the median of the distribution constructed from the ratios of the transverse momentum of the jet and the jet area of all jets in the event

- 2 uncertainties connected to jet flavor: one related to the knowledge of the particular fraction of jets initiated by quarks and gluons, which have different responses in the calorimeter, and another one related to the differences between generators in the modelling of gluon initiated jets
- 1 uncertainty to account for the difference from the Monte Carlo used to derive the uncertainties and the simulated sample used for the particular analysis.

From the first set of 56 uncertainties on the in situ method, that only depend on one parameter ($p_T$), a reduced set of nuisance parameters can be obtained. This combination reduces these uncertainty parameters from 56 to 6.

For each of the listed cases a new simulated signal sample is produced where the energy of the reconstructed jets is shifted by an amount commensurate to the particular uncertainty. The difference in the correction factors from the systematically shifted and the nominal case is taken to be the systematic uncertainty associated to that source. In Table 5.10 an example of
the impact of the jet energy scale systematic uncertainties is presented for the particular case of the variable $\tau_1^{BB}$ evaluated for the 1-jet exclusive fiducial region, where the “BaselineNP” uncertainties are the 6 related to the in situ calibration method.

**Table 5.10:** Breakdown of the jet energy scale systematic uncertainties in the case of $\tau_1^{BB}$ measured in the 1-jet exclusive fiducial region. Values are expressed in percent.

<table>
<thead>
<tr>
<th>Bin</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaselineNP1</td>
<td>0.4</td>
<td>0.3</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>BaselineNP2</td>
<td>0.9</td>
<td>0.7</td>
<td>0.5</td>
<td>1.8</td>
</tr>
<tr>
<td>BaselineNP3</td>
<td>0.7</td>
<td>0.5</td>
<td>0.6</td>
<td>1.7</td>
</tr>
<tr>
<td>BaselineNP4</td>
<td>0.2</td>
<td>0.1</td>
<td>0.3</td>
<td>0.8</td>
</tr>
<tr>
<td>BaselineNP5</td>
<td>0.04</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>BaselineNP6</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>$\eta$-intercalibration modelling</td>
<td>0.04</td>
<td>0.2</td>
<td>1.0</td>
<td>2.1</td>
</tr>
<tr>
<td>$\eta$-intercalibration stat. precision</td>
<td>0.1</td>
<td>0.1</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>$\mu$ offset</td>
<td>0.3</td>
<td>0.2</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>$N_{PV}$ offset</td>
<td>0.03</td>
<td>0.1</td>
<td>0.3</td>
<td>0.8</td>
</tr>
<tr>
<td>$p_T$ pileup correction</td>
<td>0.1</td>
<td>0.1</td>
<td>0.03</td>
<td>0.1</td>
</tr>
<tr>
<td>$\rho$-parameter mis-modelling</td>
<td>0.4</td>
<td>0.1</td>
<td>0.9</td>
<td>2.0</td>
</tr>
<tr>
<td>Flavour composition</td>
<td>3.7</td>
<td>2.2</td>
<td>0.9</td>
<td>6.3</td>
</tr>
<tr>
<td>Flavour response</td>
<td>2.0</td>
<td>1.4</td>
<td>0.4</td>
<td>3.6</td>
</tr>
<tr>
<td>Monte Carlo difference</td>
<td>0.3</td>
<td>0.2</td>
<td>0.04</td>
<td>0.1</td>
</tr>
</tbody>
</table>

The results for all the observables considered in this thesis are listed as a summary in Table 5.11. In this case all the jet energy scale systematic uncertainties are merged into a single value.

**Jet energy resolution uncertainty**

The width of the $p_T$ balance distribution used for the jet energy scale calibration can be used to estimate the jet energy resolution. This measurement is spoiled both by detector implicit imperfection and by the fact that the balance between jets and reference physics objects can be deteriorated by additional QCD radiation, dissipation of particles out of the jet cone and underlying event effects. The data/MC disagreement is considered as systematic uncertainty as well as the difference between the jet energy resolution obtained through in situ techniques and some alternative approach [118, 119]. The expected jet energy resolution obtained using different generator models for Monte Carlo simulation is compared and the discrepancy taken as uncertainty. Finally the contribution of JES uncertainties is determined by re-calculating the jet resolutions after varying the jet energy scale within its uncertainty. In this case a reduced scheme is used with all the sources of the jet energy resolution systematic uncertainties
5.6. Systematic uncertainties

Table 5.11: Jet energy scale systematic uncertainty for all the considered differential variables, expressed in percent.

<table>
<thead>
<tr>
<th>Fiducial region</th>
<th>Bin</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-jet inclusive</td>
<td>$\tau_{BB}$</td>
<td>5.5</td>
<td>5.0</td>
<td>3.7</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>$\tau_{CB}$</td>
<td>5.5</td>
<td>4.7</td>
<td>2.6</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>$\tau_{CC}$</td>
<td>5.5</td>
<td>4.7</td>
<td>2.7</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>$\tau_{BB,,\text{beam}}$</td>
<td>5.3</td>
<td>4.9</td>
<td>3.5</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>$\tau_{CB,,\text{beam}}$</td>
<td>5.4</td>
<td>4.5</td>
<td>2.5</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>$\tau_{CC,,\text{beam}}$</td>
<td>5.4</td>
<td>4.5</td>
<td>2.6</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>$\tau_{BB,,\text{jet}}$</td>
<td>5.0</td>
<td>4.4</td>
<td>3.2</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>$\tau_{CB,,\text{jet}}$</td>
<td>4.9</td>
<td>3.6</td>
<td>1.8</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>$\tau_{CC,,\text{jet}}$</td>
<td>4.9</td>
<td>3.5</td>
<td>1.9</td>
<td>0.7</td>
</tr>
<tr>
<td>1-jet exclusive</td>
<td>$\tau_{BB}$</td>
<td>4.5</td>
<td>2.8</td>
<td>2.0</td>
<td>8.3</td>
</tr>
<tr>
<td>1-jet central exclusive</td>
<td>$\tau_{BB}$</td>
<td>5.7</td>
<td>4.1</td>
<td>0.8</td>
<td>6.7</td>
</tr>
</tbody>
</table>

are merged into one parameter. Jets energies are smeared according to this uncertainty and the difference for each observable bin in the correction factors with the nominal case is the propagated jet energy resolution uncertainty. In Table 5.12 the impact of the jet energy resolution systematic uncertainties is presented. Values are expressed in percent.

**Jet vertex fraction uncertainty**

As seen in Section 4.4 the jet vertex fraction is used to mitigate the presence of pileup jets in the selected events. Due to the imperfect description of the JVF distribution in Monte Carlo compared to data, the impact of the particular JVF cut in the rejection of pileup jets is tested by repeating the analysis with a different JVF selection: once lowering and once increasing the central JVF cut value of 0.25 to 0.22 and 0.28 following the recommendations in [120]. Correction factors for each observable bin are calculated for these alternative samples and the difference to the nominal sample is taken as the uncertainty. In Table 5.13 the impact of the systematic uncertainties associated with the JVF cut is presented for all the observables affected by jet fiducial region restrictions.

**Jet pileup uncertainty**

Jets from additional interactions in the event can be included in the Higgs candidate event selection. The fraction of these pileup jets in the simulated samples can be different from the one in data. Studies of the central jet transverse momentum in a pileup-enhanced sample [121], obtained by using JVF $< 0.1$, and of the transverse energy density in the forward region of the detector [122], indicate that the simulation could be mismodelling the number of pileup
Table 5.12: Jet energy resolution systematic uncertainty for all the considered differential variables, expressed in percent.

<table>
<thead>
<tr>
<th>Fiducial region</th>
<th>Bin</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-jet inclusive</td>
<td>$\tau_1^{BB}$</td>
<td>0.5</td>
<td>0.1</td>
<td>0.6</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>$\tau_1^{CB}$</td>
<td>0.4</td>
<td>0.05</td>
<td>0.9</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>$\tau_1^{CC}$</td>
<td>0.4</td>
<td>0.03</td>
<td>0.8</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>$\tau_1^{BB,\text{beam}}$</td>
<td>0.5</td>
<td>0.1</td>
<td>0.7</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>$\tau_1^{CB,\text{beam}}$</td>
<td>0.4</td>
<td>0.03</td>
<td>1.1</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>$\tau_1^{CC,\text{beam}}$</td>
<td>0.4</td>
<td>0.04</td>
<td>1.1</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>$\tau_1^{BB,\text{jet}}$</td>
<td>0.1</td>
<td>0.9</td>
<td>0.5</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>$\tau_1^{CB,\text{jet}}$</td>
<td>0.2</td>
<td>1.0</td>
<td>1.4</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td>$\tau_1^{CC,\text{jet}}$</td>
<td>0.6</td>
<td>1.7</td>
<td>1.3</td>
<td>3.5</td>
</tr>
<tr>
<td>1-jet exclusive</td>
<td>$\tau_1^{BB}$</td>
<td>0.2</td>
<td>0.2</td>
<td>0.03</td>
<td>2.0</td>
</tr>
<tr>
<td>1-jet central exclusive</td>
<td>$\tau_1^{BB}$</td>
<td>0.5</td>
<td>1.0</td>
<td>0.04</td>
<td>1.6</td>
</tr>
</tbody>
</table>

jets by up to 35%. For this reason, 35% of pileup jets were randomly removed from the signal simulated samples, the correction factor for each observable bin computed again and compared with the one from the nominal case. The difference is symmetrized and considered as the uncertainty associated with the modelling of pileup jets. In Table 5.14 the effect of this systematic uncertainties is presented for all the differential variables considered in jet fiducial regions.

As it can be seen for many of the systematic uncertainties presented in this section, quite big variations on the size of the relative uncertainty between bins are not uncommon. This was investigated, but no trivial explanation was found. However it is without any doubt the fact that the component of statistical uncertainty on the samples used for the systematic uncertainties plays an active role, especially in some particular low statistics bin.

Finally in Figure 5.11 and 5.12 all the uncertainties for the differential cross sections for $\tau_0^C$, $N_{\text{tracks}}$, $H_T^{\text{tracks}}$ in the inclusive fiducial region and $\tau_1^{CC,\text{jet}}$ in the 1-jet inclusive fiducial region are shown as examples. It is clear that in all the cases the statistical uncertainty (gray area) is by far the dominant one. The systematic components are well within 10% and usually around 5% for both the correction factor and signal extraction systematic uncertainties. The size of the systematic uncertainties is usually similar between the different bins of the same variable and in general also between different observables, while this is not true for the statistical uncertainty which fluctuates a lot from bin to bin.

Events in which two or more distinct hard parton interactions occur simultaneously in a single hadron-hadron collision, called Multi-Parton Interactions (MPI) [123, 124], are not uncommon at LHC. One of the consequences is the presence of large hadronic activity characterized by small transverse momentum. As can be seen for example in Figure 5.13, the
Figure 5.11: Fractional uncertainty for each bin of the differential cross section for (a) $\tau^C_0$ in the inclusive fiducial region and (b) $\tau^{CC, jet}_1$ in the 1-jet inclusive fiducial region.

Figure 5.12: Fractional uncertainty for each bin of the differential cross section for (a) $N_{\text{tracks}}$ and $H^\text{tracks}_T$ in the inclusive fiducial region.
Table 5.13: Jet vertex fraction systematic uncertainty for all the considered differential variables, expressed in percent.

<table>
<thead>
<tr>
<th>Fiducial region</th>
<th>Bin</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-jet inclusive</td>
<td>( \tau_1^{BB} )</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>( \tau_1^{CB} )</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>( \tau_1^{CC} )</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>( \tau_1^{BB,\text{beam}} )</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>( \tau_1^{CB,\text{beam}} )</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>( \tau_1^{CC,\text{beam}} )</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>( \tau_1^{BB,\text{jet}} )</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>( \tau_1^{CB,\text{jet}} )</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>( \tau_1^{CC,\text{jet}} )</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>1-jet exclusive</td>
<td>( \tau_1^{BB} )</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>1-jet central exclusive</td>
<td>( \tau_1^{BB} )</td>
<td>0.02</td>
<td>0.03</td>
<td>0.05</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Observables described in Sec. 5.3 are sensitive to this kind of effects and the uncertainties associated to MPI cannot be treated as in [3], where the difference between the observable distribution for turning on and off the MPI effect is taken. Uncertainties from MPI need a dedicated study that, unfortunately, was not possible to threat in the context of this thesis.
Table 5.14: Jet pileup missmodelling systematic uncertainty for all the considered differential variables, expressed in percent.

<table>
<thead>
<tr>
<th>Fiducial region</th>
<th>Bin</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-jet inclusive</td>
<td>$\tau_{1}^{BB}$</td>
<td>0.8</td>
<td>0.9</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>$\tau_{1}^{CB}$</td>
<td>0.8</td>
<td>0.9</td>
<td>0.8</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>$\tau_{1}^{CC}$</td>
<td>0.8</td>
<td>0.9</td>
<td>0.8</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>$\tau_{1}^{BB,\text{beam}}$</td>
<td>0.7</td>
<td>0.9</td>
<td>0.9</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>$\tau_{1}^{CB,\text{beam}}$</td>
<td>0.8</td>
<td>0.9</td>
<td>0.8</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>$\tau_{1}^{CC,\text{beam}}$</td>
<td>0.8</td>
<td>0.9</td>
<td>0.8</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>$\tau_{1}^{BB,\text{jet}}$</td>
<td>0.8</td>
<td>0.9</td>
<td>0.8</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>$\tau_{1}^{BB,\text{jet}}$</td>
<td>0.8</td>
<td>0.9</td>
<td>0.8</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>$\tau_{1}^{CB,\text{jet}}$</td>
<td>0.8</td>
<td>0.9</td>
<td>0.8</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>$\tau_{1}^{CC,\text{jet}}$</td>
<td>0.8</td>
<td>0.9</td>
<td>0.8</td>
<td>0.5</td>
</tr>
<tr>
<td>1-jet exclusive</td>
<td>$\tau_{1}^{BB}$</td>
<td>0.1</td>
<td>0.2</td>
<td>0.2</td>
<td>0.5</td>
</tr>
<tr>
<td>1-jet central exclusive</td>
<td>$\tau_{1}^{BB}$</td>
<td>0.5</td>
<td>0.4</td>
<td>0.3</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Figure 5.13: Distributions of $\tau_{2}^{\text{beams}}$ (a) and $\tau_{2}^{\text{jets}}$ at particle-level for events including or excluding MPI from [125]. The particle selection is the same as in Sec. 4.2 while for the exact definition of $\tau_{2}^{\text{beams}}$ and $\tau_{2}^{\text{jets}}$ see [125].
5.7 Results

In this section the results for measurement of the fiducial differential cross sections for the observables of Sec. 5.3 are presented. These results are obtained for the observables defined in Sec. 5.3 extracting the signal yield from data as described in Sec. 5.4. The extracted yield is then corrected for the detector effects with the bin-by-bin method of Sec. 5.5. The fiducial regions that are considered for the selection of the events and for the unfolding is explained in Sec. 5.2. Finally, as seen in Sec. 5.6, the impact of the main sources of uncertainty are evaluated and propagated to the differential cross section results.

The fiducial differential cross sections measured are shown in Figures 5.14, 5.15, 5.16, 5.17, 5.18 and 5.19.

As can be seen in all the plots, no uncertainty is given on the MC predictions. This is far from ideal but motivated by the fact that this work was more focused on identifying the critical aspects, the problems and the possible limitations in the measurement of $N$-jettiness (and track-based observables) distributions in Higgs events. Uncertainties on theory predictions for these measurements would require particular attention. Apart from the uncertainties related to parton distribution functions, the strong coupling $\alpha_S$ and from the missing higher orders correction terms in QCD-electroweak cross section resummation, these differential cross sections would require proper uncertainty estimation for underlying event and multi-parton interaction, effects to which they are very sensitive to.
5.7. Results

Figure 5.15: The differential cross section for \( pp \rightarrow H \rightarrow \gamma\gamma \) as a function of \( \tau_{BB} \) (a), \( \tau_{BC} \) (b) and \( \tau_{CC} \) (c) in the 1-jet inclusive fiducial region. The data and theoretical predictions are presented the same way as in Figure 5.14.
Figure 5.16: The differential cross section for $pp \rightarrow H \rightarrow \gamma\gamma$ as a function of $\tau_{BB,beam}^1$ (a), $\tau_{BC,beam}^1$ (b) and $\tau_{CC,beam}^1$ (c) in the 1-jet inclusive fiducial region. The data and theoretical predictions are presented the same way as in Figure 5.14.
Figure 5.17: The differential cross section for $pp \rightarrow H \rightarrow \gamma\gamma$ as a function of $\tau_{BB,jet}^1$ (a), $\tau_{BC,jet}^1$ (b) and $\tau_{CC,jet}^1$ (c) in the 1-jet inclusive fiducial region. The data and theoretical predictions are presented the same way as in Figure 5.14.
5.7. Results

**Figure 5.18:** The differential cross section for $pp \to H \to \gamma \gamma$ as a function of $t^{BB}_1$ in the 1-jet exclusive fiducial region (a) and in the 1-jet central exclusive fiducial region (b). The data and theoretical predictions are presented the same way as in Figure 5.14.

**Figure 5.19:** The differential cross section for $pp \to H \to \gamma \gamma$ as a function of track multiplicity $N_{\text{tracks}}$ (a) and the scalar sum of the track transverse momenta $H^\text{tracks}_T$ in the inclusive fiducial region. The data and theoretical predictions are presented the same way as in Figure 5.14.
For the inclusive fiducial region, the differential cross sections as a function of $\tau_B^0$, $\tau_C^0$, $N_{\text{tracks}}$ and $H_T^{\text{tracks}}$ are presented in Figure 5.14 and 5.19 respectively. Within the uncertainties data and predictions agree reasonably with no significant deviations from predictions. Differential cross section in the 1-jet inclusive fiducial region for $\tau_{BB}^1$, $\tau_{CB}^1$, $\tau_{CC}^1$ and their beam and jet component can be found in Figure 5.15, 5.16 and 5.17. In this case in all the distributions present in Figure 5.15 and 5.16 a small excess of data with respect to the prediction in the last bin. However, in all cases this bin corresponds to the one with the smallest expected significance and with the larger statistical uncertainty. For the $\tau_{BB,jet}^1$, $\tau_{CB,jet}^1$, $\tau_{CC,jet}^1$ observables in 5.17 a good agreement between data and Monte Carlo can be seen. Finally for the differential cross section as a function of $\tau_1^{BB}$ measured in the 1-jet exclusive and in the 1-jet central exclusive fiducial regions (Figure 5.18), the large statistical uncertainties can be noted. These two fiducial regions limit even more the number of events expected from simulation and available with the $\sqrt{s} = 8$ TeV data. Differences between the data and the prediction are within uncertainties.

These results show the feasibility of differential cross section measurements for event-shape observables based on tracks or to track related quantities for very particular processes such as the Higgs boson production in the diphoton decay channel, which offers the pretty unique opportunity to study gluon-initiated processes, but also opens up to a wide range of new measurements. The main systematic uncertainties were calculated and, even with a conservative approach, do not represent a limiting factor for the measurements.
Chapter 6

Fiducial and differential cross sections for jet-based observables

In this chapter, results from measurements of fiducial and differential cross sections for Higgs boson production in the diphoton decay channel with the ATLAS detector [3] will be presented, focusing then the attention on two particular observables: $\tau_1$ and $\sum_i \tau_i$. The first section of this chapter is dedicated to the cross section measurement for a number of different fiducial regions defined by jet requirements or by the presence of leptons or by missing transverse energy in the event. The analysis method for these measurements can be considered the same used in Chapter 5.

In the second section the observables $\tau_1$ and $\sum_i \tau_i$, complementary to $p_T^{d1}$ and $H_T$, are defined and their properties described. The analysis strategy used for the differential cross section measurement of $\tau_1$ and $\sum_i \tau_i$ is similar to the one of 5, with the few differences explained. The dataset used is described in Sec. 2.3.

6.1 Fiducial cross section measurements and limits

Cross sections in [3] are probed for the following fiducial regions:

- diphoton baseline: candidate events are required to have two isolated photons (Sec. 4.1), with the leading (subleading) photon satisfying $p_T/m_{\gamma\gamma} > 0.35$ (0.25) and $m_{\gamma\gamma} \in [105, 160]$ GeV, as the inclusive fiducial region in Sec. 5.2

- $N$-jet inclusive: all events that pass the diphoton baseline selection and contain at least $N$ jets, with a jet fulfilling the object definition seen in Sec. 4.4

- VBF-enhanced: all events that pass the diphoton baseline selection and that contain at least two jets that have large dijet invariant mass, $m_{jj} > 400$ GeV, large rapidity separation, $|\Delta y_{jj}| > 2.8$, and where the diphoton-dijet systems are back-to-back in azimuthal angle, $|\Delta \phi_{\gamma\gamma,jj}| > 2.6$
Figure 6.1: The measured cross sections and cross-section limits for $pp \rightarrow H \rightarrow \gamma\gamma$ in seven fiducial regions. The data are shown as filled (black) circles. The error bar on each measured cross section represents the total uncertainty in the measurement, with the systematic uncertainty shown as dark grey rectangles. The error bar on each cross-section limit shows the 95% confidence level. The data are compared to state-of-the-art theoretical predictions for gluon fusion Higgs production (see text for details). The width of each theoretical prediction represents the total uncertainty in that prediction. All gluon fusion Higgs production predictions include the SM prediction arising from VBF, $VH$ and $t\bar{t}H$ production, which are collectively labelled as $XH$.

- lepton inclusive: all events that pass the diphoton baseline selection and that contain an electron or muon with $p_T > 15$ GeV and $|\eta| < 2.47$ (for the definition of electron and muon see [3])

- missing transverse energy: all events that pass the diphoton baseline selection and that have large missing transverse momentum, with magnitude $E_T^{miss} > 80$ GeV, where this is defined at particle-level as the vector sum of neutrino transverse momenta and at detector-level as the missing energy in the transverse plane to balance the vectorial sum of all transverse energies of the objects (photons, electron, muons, jets but also individual calorimeter clusters and tracks) associated with the hard interaction [126].

and where the latest two regions are presented as cross-section limits.

Section 5.4 can be used as a reference for the signal model and the extraction of the signal yield.
Both data and predictions are corrected to particle-level to allow their comparison. In data the extracted yield is unfolded accounting for detector resolution and inefficiencies (Sec. 5.5), while theoretical predictions have to consider the geometrical acceptance of the detector and the effect of hadronization and underlying event activity. The measured cross sections for the described fiducial regions are shown in Figure 6.1. In this plot data is compared to several state-of-the-art theoretical calculations scaled with the $H \rightarrow \gamma\gamma$ branching ratio value of $0.228 \pm 0.011\%$ [73]. The default theoretical prediction for gluon fusion Higgs boson production total cross section used in SM Higgs boson analyses at LHC comes from the LHC Higgs cross section working group (referred as LHC-XS) and it is accurate to NNLO+NNLL in QCD and incorporates NLO electroweak corrections [73]. A number of different predictions, mentioned below, are considered for Higgs boson production via gluon fusion. The theoretical calculation referred as STWZ in Figure 6.1 was performed using soft and collinear effective theory and is also accurate to NNLO+NNLL order in QCD but does not include any electroweak corrections [127]. For the baseline diphoton fiducial region and for the differential distributions that probe the kinematic properties of the diphoton system, the HRES 2.2 calculation [128, 129], also accurate to NNLO+NNLL in QCD and without electroweak corrections, is used as prediction for comparison to data. For the 1-jet inclusive fiducial region a NNLO+NNLL precise prediction based on the zero-jet efficiency is given by JetVHeto [130]. Soft and collinear effective theory based calculation are available for events with at least one jet or at least two jets [131]. This is referred in Figure 6.1 as BLPTW. In the 1-jet inclusive case this prediction is obtained from the combination of NNLO+NNLL zero-jet and NLO+NLL one-jet cross sections. In the 2-jet inclusive case BLPTW calculation is accurate to approximate-NLO+NLL order. A simulated sample of $H + 1$ jet events is produced at NLO accuracy in QCD using the POWHEG BOX, with the MINLO feature [132] applied to include $H + 0$ jet events at NLO accuracy and interfaced to PYTHIA8 to produce the fully hadronic final state (here referred to as MINLO HJ). This can be also used to calculate the cross section for events with one or more jets. Similarly MINLO HJJ, a sample of $H + 2$ jet produced at NLO accuracy, can be used as theoretical prediction in events with at least two jets.

The contributions to the SM predictions from VBF, VH and $t\bar{t}H$ production are determined using the particle-level prediction obtained from POWHEG BOX-PYTHIA8 and PYTHIA8 event generators, with the samples normalized to state-of-the-art theoretical calculations as in Sec 5.1.

The uncertainties on the cross-section predictions include the effect of scale and PDF variation as well as the uncertainties on the $H \rightarrow \gamma\gamma$ branching ratio and non-perturbative modelling factors.

The cross section for $pp \rightarrow H \rightarrow \gamma\gamma$ measured in the baseline fiducial region is

$$\sigma_{\text{fid}}(pp \rightarrow H \rightarrow \gamma\gamma) = 43.2 \pm 9.4 \, (\text{stat.}) \pm^{3.2}_{2.2} \, (\text{syst.}) \pm 1.2 \, (\text{lumi}) \, \text{fb}$$

for a Higgs boson mass $m_H = 125.4$ GeV. This result is slightly larger when compared with the theoretical predictions presented even if the excess can be considered not significant. The
Table 6.1: Measured cross sections in the baseline, $N_{\text{jets}} \geq 1$, $N_{\text{jets}} \geq 2$, $N_{\text{jets}} \geq 3$ and VBF-enhanced fiducial regions, and cross-section limits at 95% confidence level in the single-lepton and high-$E_T^{\text{miss}}$ fiducial regions.

<table>
<thead>
<tr>
<th>Fiducial region</th>
<th>Measured cross section (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>$43.2 \pm 9.4$ (stat.) $^{+3.2}_{-2.9}$ (syst.) $\pm 1.2$ (lumi)</td>
</tr>
<tr>
<td>$N_{\text{jets}} \geq 1$</td>
<td>$21.5 \pm 5.3$ (stat.) $^{+2.4}_{-2.2}$ (syst.) $\pm 0.6$ (lumi)</td>
</tr>
<tr>
<td>$N_{\text{jets}} \geq 2$</td>
<td>$9.2 \pm 2.8$ (stat.) $^{+1.3}_{-1.2}$ (syst.) $\pm 0.3$ (lumi)</td>
</tr>
<tr>
<td>$N_{\text{jets}} \geq 3$</td>
<td>$4.0 \pm 1.3$ (stat.) $\pm 0.7$ (syst.) $\pm 0.1$ (lumi)</td>
</tr>
<tr>
<td>VBF-enhanced</td>
<td>$1.68 \pm 0.58$ (stat.) $^{+0.24}_{-0.25}$ (syst.) $\pm 0.05$ (lumi)</td>
</tr>
<tr>
<td>$N_{\text{leptons}} \geq 1$</td>
<td>$&lt; 0.80$</td>
</tr>
<tr>
<td>$E_T^{\text{miss}} &gt; 80$ GeV</td>
<td>$&lt; 0.74$</td>
</tr>
</tbody>
</table>

maximum tension between data and predictions can be seen in events containing at least three jets in addition to the diphoton system. Comparing this fiducial cross section, a $2.1 \sigma$ significance difference is found between prediction, based on MINLO HJJ, and the data.

All numerical values for measured and predicted cross sections in the fiducial regions defined above are shown respectively in Tables 6.1 and 6.2.

6.2 Differential cross sections

The differential cross sections are measured for four categories of kinematic variables:

1. Higgs boson kinematics: The transverse momentum, $p_T^{\gamma \gamma}$, and absolute rapidity, $|y_{\gamma \gamma}|$, of the diphoton system; $p_T^{\gamma \gamma}$ defined as the magnitude of the transverse momentum of the diphoton system perpendicular to the diphoton thrust axis, $|\Delta y_{\gamma \gamma}|$ the rapidity separation between the two photons. Inclusive Higgs boson production is dominated by gluon fusion for which the transverse momentum of the Higgs boson is largely balanced by the emission of soft gluons and quarks. Measuring $p_T^{\gamma \gamma}$ therefore probes the perturbative-QCD modelling of this production mechanism. The rapidity distribution of the Higgs boson is also sensitive to the modelling of the gluon fusion production mechanism, as well as the parton distribution functions (PDFs) of the colliding protons.

2. Jet activity: The jet multiplicity, $N_{\text{jets}}$, the transverse momentum and absolute rapidity of the leading jet, $p_T^1$ and $|y_1|$, the transverse momentum and absolute rapidity of the subleading jet, $p_T^2$ and $|y_2|$, the third-leading jet transverse momentum, $p_T^3$, the dijet invariant mass, $m_{jj}$, the transverse momentum of the diphoton-dijet system, $p_T^{\gamma \gamma jj}$, the scalar sum of jet transverse momenta, $H_T$, and two inclusive event-shape observables, $\tau_1$ and $\sum_i \tau_i$, that will be defined extensively later. The jet variables are sensitive to the theoretical modelling and relative contributions of the different Higgs boson production mechanisms. In the Standard Model, events with zero or one jet are dominated by
6.2. Differential cross sections

<table>
<thead>
<tr>
<th>Fiducial region</th>
<th>Theoretical prediction (fb)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>30.5 ± 3.3</td>
<td>LHC-XS [73] + XH</td>
</tr>
<tr>
<td></td>
<td>34.1 (\pm 3.6) (-3.5)</td>
<td>STWZ [127] + XH</td>
</tr>
<tr>
<td></td>
<td>27.2 (\pm 3.2) (-1.2)</td>
<td>HRES [129] + XH</td>
</tr>
<tr>
<td>(N_{\text{jets}} \geq 1)</td>
<td>13.8 ± 1.7</td>
<td>BLPTW [131] + XH</td>
</tr>
<tr>
<td></td>
<td>11.7 (\pm 2.0) (-2.4)</td>
<td>JetVHeto [130] + XH</td>
</tr>
<tr>
<td></td>
<td>9.3 (\pm 1.2) (-1.8)</td>
<td>MINLO HJ [132] + XH</td>
</tr>
<tr>
<td>(N_{\text{jets}} \geq 2)</td>
<td>5.65 ± 0.87</td>
<td>BLPTW + XH</td>
</tr>
<tr>
<td></td>
<td>3.99 (\pm 0.56) (-0.59)</td>
<td>MINLO HJJ+ XH</td>
</tr>
<tr>
<td>(N_{\text{jets}} \geq 3)</td>
<td>0.94 ± 0.15</td>
<td>MINLO HJJ + XH</td>
</tr>
<tr>
<td>VBF-enhanced</td>
<td>0.87 ± 0.08</td>
<td>XH</td>
</tr>
<tr>
<td>(N_{\text{leptons}} \geq 1)</td>
<td>0.27 ± 0.02</td>
<td>XH</td>
</tr>
<tr>
<td>(E_T^{\text{miss}} &gt; 80) GeV</td>
<td>0.14 ± 0.01</td>
<td>XH</td>
</tr>
</tbody>
</table>

Table 6.2: Theoretical predictions for the cross sections in the baseline, \(N_{\text{jets}} \geq 1\), \(N_{\text{jets}} \geq 2\), \(N_{\text{jets}} \geq 3\), VBF-enhanced, single-lepton and high-\(E_T^{\text{miss}}\) fiducial regions. The \(XH\) refers to the theoretical predictions for VBF, \(VH\) and \(t\bar{t}H\) derived using the Powheg-Pythia, and Pythia8 event generators.

Theoretical predictions for the cross sections in the baseline, \(N_{\text{jets}} \geq 1\), \(N_{\text{jets}} \geq 2\), \(N_{\text{jets}} \geq 3\), VBF-enhanced, single-lepton and high-\(E_T^{\text{miss}}\) fiducial regions. The \(XH\) refers to the theoretical predictions for VBF, \(VH\) and \(t\bar{t}H\) derived using the Powheg-Pythia, and Pythia8 event generators.

3. Spin–CP sensitive variables: The cosine of the angle between the beam axis and the photons in the Collins–Soper frame [133] of the Higgs boson, \(|\cos \theta^*|\), and the azimuthal angle between the two leading jets, \(|\Delta \phi_{jj}|\), in events containing two or more jets. The \(|\cos \theta^*|\) variable can be used to study the spin of the Higgs boson. The \(|\Delta \phi_{jj}|\) variable is sensitive to the charge conjugation and parity properties of the Higgs boson’s interactions with gluons and weak bosons in the gluon fusion and VBF production channels, respectively [134–136].

4. VBF-sensitive variables for events containing two or more jets: The dijet rapidity separation, \(|\Delta y_{jj}|\), and the azimuthal angle between the dijet and diphoton systems, \(|\Delta \phi_{\gamma\gamma,jj}|\). The distributions of these variables are sensitive to the differences between the gluon fusion and VBF production mechanisms. In vector-boson fusion, the \(t\)-channel exchange of a \(W\) boson typically results in two high transverse momentum jets that are well separated in rapidity. Furthermore, quark/gluon radiation in the rapidity interval between the two jets is suppressed in the VBF process when compared to the gluon fusion process, because there is no colour flow between the two jets. The \(|\Delta \phi_{\gamma\gamma,jj}|\) distribution
for VBF is therefore steeper and more closely peaked at $|\Delta \phi_{\gamma\gamma,jj}| = \pi$ than for gluon fusion.

### 6.2. Differential cross sections

#### 6.2.1 $\tau_1$ and $\sum_i \tau_i$ observables

The test of many Higgs properties relies on the ability of the measurement to efficiently separate events into categories based on the number of hard jets in the final state. Events are classified in inclusive, i.e. with a minimum number of jet, or exclusive, i.e. with an exact number of jets, jet bins given a veto criterion. The default jet variable that is usually used to classify and veto jets is their transverse momentum $p_T^j$. Experimentally, jet vetos are utilized to suppress backgrounds or to enhance the sensitivity to particular production and decay channels, by limiting, or requiring, some hadronic activity in the final state. Theoretically, vetoing jets restricts the phase space for additional emissions making the cross section sensitive to soft and collinear radiation, which causes logarithms in the perturbative expansion that needs to be resummed to obtain precise predictions. The form and structure of this logarithmic series depends on how the veto is imposed. From both experimental and theoretical point of view, the application of a tight jet veto is subject to limitations. In the first case low-$p_T$ jets can be difficult to reconstruct and properly measure, especially at large rapidities where there is no tracking information; in the second case a tight jet veto can lead to increased theoretical uncertainties on cross section predictions.

In the following part a set of jet variables that provide new and complementary information to the measurement of the leading jet $p_T^j$ and the $H_T$ over jets is presented. These variables can be considered and preferred as jet vetos in certain cases for some experimental and theoretical advantages as it is explained in the following.

The proposed jet variables directly depend on the jet transverse momentum $p_T^j$ and some $f(y_j)$ weighting function of the jet rapidity $y_j$ as:

$$
\tau_{fj} = p_T^j f(y_j).
$$

(6.1)

Two particular cases for the weighting function $f(y_j)$ are considered:

$$
\tau_B : \quad f(y_j) = e^{-|y_j - y_{\gamma\gamma}|}
$$

(6.2)

$$
\tau_C : \quad f(y_j) = \frac{1}{2 \cosh(y_j - y_{\gamma\gamma})}
$$

(6.3)

where $y_{\gamma\gamma}$ is the rapidity of the diphoton system. As can be seen, since $\tau_B$ and $\tau_C$ are decreasing functions of $|y_j|$, $\tau_{fj}$ is small if the jet transverse momentum $p_T^j$ is small or if the jet rapidity $|y_j|$ is large. When this observable is used as a jet veto, $\tau_{fj} < \tau_{fj}^\text{cut}$ corresponds to a $p_T^j$-veto which gets tighter at central rapidities and looser at forward rapidities. The presence of the rapidity of the diphoton system $y_{\gamma\gamma}$ in $\tau_B$ and $\tau_C$ just assures the variables to be defined in the diphoton rest frame.

The particular weighting function $\tau_B$ is chosen to be exponential such that the observable $\tau_{Bj}$ corresponds to the small light-cone component of the jet with respect to the beam
6.2. Differential cross sections

Figure 6.2: Weighting functions as defined in 6.2 and 6.3: $\tau_{Bj}$ is in red, $\tau_{Cj}$ in green [138].

In fact it is easy to see:

$$\tau_{Bj} = p^+_j e^{-|y_j|} = |p^2_T| - |p^0_j|$$

(6.4)

that considering a jet with a mass $m_j$ becomes:

$$m_T e^{-|y_j|} = \sqrt{\left(p^2_T\right)^2 + m_j^2} e^{-|y_j|} = E_j - |p_{z_j}| \equiv p^+$$

(6.5)

in the diphoton rest frame and where $p^+$ is the smaller of the two longitudinal components of the jet in light-cone coordinates. At forward rapidities $\tau_B$ and $\tau_C$ are equivalent while the region where they differ is the central one. As can be seen in Figure 6.2, $\tau_{Cj}$, close to values of $|y_j|$ of zero, is smoother then $\tau_{Bj}$ and has its maximum at $p^+_j / 2$.

Observables with a $p^+$-weighting function like $\tau_{Bj}$ and $\tau_{Cj}$ form a class of jet veto variables with cross section resummation properties different than $p^2_T$ ones, but that can be calculated to a similar level of precision, providing in this way complementary information on jet production [138, 139].

In the baseline fiducial region, two differential cross section measurements are considered for observables derived from the previous definitions:

$$\tau_1 = \max_{j \in J} \tau_{Cj}$$

(6.6)

$$\sum_i \tau_i = \sum_{j \in J} \tau_{Cj}$$

(6.7)

where $\tau_{Cj} = m_T / 2 \cosh(y_j - y_{\gamma\gamma})$, $J$ is the collection of jets in the event and the sum on Eq.(6.7) runs over all $\tau_{Cj}$ greater than a cut value $\tau_{Cj}^{cut}$. The motivation for using $\tau_C$ over $\tau_B$ comes purely from an experimental point of view since using $\tau_{Cj}$ a slightly higher purity per bin (see Eq.(5.19)) and a slightly greater expected significance per bin (see Sec. 5.5.1) is found. From the theoretical side, the two definitions with the two rapidity weighting functions, $\tau_C$
and \( \tau_B \), can be treated in a very similar way (together with any function \( f(y) \) that approaches \( e^{-|y|} \) at large rapidities).

The variable \( \tau_1 \) refers to the highest-\( \tau_j \) in the event, and \( \sum_i \tau_i \) is the scalar sum of \( \tau_j \) for all jets with \( \tau_j \) greater than an arbitrary cut value \( \tau_{cut} \), in a completely analogous way to \( p_T^{j} \) and \( H_T \), respectively. Taken together they cover the four main corners of “theory-space” (local vs. global and \( p_T \)-like vs. \( p^+ \)-like sensitivity to soft/collinear radiation) regarding the factorization of the hard Higgs production process from the soft and collinear initial-state radiation [140]. Their measurement therefore allows for a direct and complete test of higher-order jet veto resummations as well as the current description of initial-state radiation in parton-shower Monte Carlos. Furthermore, comparing \( \tau_1 \) and \( \sum_i \tau_i \) give direct insight into underlying event effects and clustering effects in the jet-algorithm. Ultimately, since the initial-state radiation from incoming gluons differs substantially from that of incoming quarks, it is also essential to study these effects directly in Higgs production.

It is also interesting to note how \( \sum_i \tau_i \) can be considered as the jet version of the beam-thrust global event-shape variable [112] or of the \( \tau_C^0 \) observable of Chapter 5, where in this case the ingredients are not particles but jets.

The analysis for the differential cross section measurements of \( \tau_1 \) and \( \sum_i \tau_i \) follows the same structure as in Chapter 5 for the signal parametrization, signal extraction and correction of detector effects. The few differences that exist are explained in the following part of this section.

In order to reach the maximum sensitivity for these observables, the lowest threshold for the transverse momentum of reconstructed jet is used. In contrast with Sec. 4.4, a minimum \( p_T^{j} \) threshold of 25 GeV for jets within \( |\eta_j| < 2.4 \) is required while for jets with \( |\eta_j| > 2.4 \) the usual \( p_T^{j} > 30 \) GeV selection is applied. The same criteria are applied at detector-level and particle-level.

A slightly different signal probability distribution function is used with respect to the one described in Sec. 5.4.1. Here, a whole set of simulated samples produced for different values of \( m_H \) is used to model the dependence of the signal parameters as a function of the Higgs mass.

The \( m_{\gamma\gamma} \) distribution of the non-resonant background decays is parametrized using exponentials of polynomials of the second order (see Eq. (5.15)) in all bins for both \( \tau_1 \) and \( \sum_i \tau_i \). High-statistics MC samples for \( \gamma\gamma, \gamma j \) and \( jj \) events are produced and normalized using data-driven scale factors determined in control regions where the isolation and tight identification criteria for each photon are reversed. The samples are used as background-only \( m_{\gamma\gamma} \) distributions and are fitted with a signal plus background model. Since no signal is present in those background only samples, the resulting number of signal events from the fit is taken as an estimate of the bias in the particular background model considered. This bias is referred to as “spurious signal” [141] and is assigned as the systematic uncertainty on the signal amplitude due to the background modeling.

Since the measurement is performed in the baseline fiducial region while \( \tau_1 \) and \( \sum_i \tau_i \) are
defined in the presence of jets, events with no jets (or in the case of $\sum_i \tau_i$, events with no jet satisfying the condition $\tau_{Cj} > \tau_{Cj}^{cut}$) are included in the first bin of the measured distributions. This first bin edge of the $\tau_1$ distribution can then be considered as the jet veto $\tau_1^{cut}$ that separates data into an exclusive 0-jet fiducial cross section (events with $\tau_1 < \tau_1^{cut}$) and an inclusive 1-jet cross section (events with $\tau_1 > \tau_1^{cut}$). For this reason the value of $\tau_1^{cut}$ is chosen as $\tau_{Cj}^{cut}$ in $\sum_i \tau_i$.

The choice of the binning is based on the same requirements used in Sec. 5.5.1. The correspondent plots of Figures 5.8 and 5.9 for $\tau_1$ and $\sum_i \tau_i$ are shown in Figure 6.3 for the purity and in Figure 6.4 for the efficiency, with $\tau_{Cj}^{cut} = 8$ GeV. Purity and efficiency combined give the bin-by-bin unfolding factor (see Eq.(5.17)) to correct data from detector-level to particle-level.

![Image](image_url)

**Figure 6.3:** The purity on each bin as defined in Eq.(5.19) for $\tau_1$ (left) and $\sum_i \tau_i$ (right).

![Image](image_url)

**Figure 6.4:** Bin efficiency for $\tau_1$ (left) and $\sum_i \tau_i$ (right) as defined in Eq.(5.18).

Sources of uncertainties for these observables that affect the correction factors come from jet energy scale and resolution, pileup mismodelling, signal composition and generator dependence. The procedure to propagate these uncertainties to the measurement is the same as in Sec. 5.6: a MC sample that accounts for a possible source of uncertainty is produced for every variation, the correction factors of the sample with the variation are compared with the
nominal case (no variation applied), the difference is taken as uncertainty.

Jet related uncertainties comprehend discrepancies between data and Monte Carlo on in situ jet energy scale measurements (Baseline in the related Figure 6.5) studied in γ-jet and Z-jet events; η-dependence of the jet calibration (η-Intercalibration), pileup dependence of the jet calibration (NPV+Mu+Pileup), the different response in the calorimeter to gluon or quark jets (Flavour) and jet energy resolution (JER), which were all described in Sec. 5.6.4. The jet related uncertainties are shown in Figure 6.5. The biggest contribution is given by the uncertainties related to the jet flavor composition.

![Figure 6.5](image)

Figure 6.5: Breakdown of jet systematic uncertainties for τ_1 (left) and ∑τ_i (right) expressed in terms of relative fraction.

Uncertainties from theoretical modelling are estimated, in case of gluon fusion modelling, using alternative Monte Carlo generators to the default POWHEG BOX-PYTHIA8 as MINLO HJ, MINLO HJJ and SHERPA [142] and taking the envelope of their difference. Additionally the simulated samples are reweighted in order to reproduce p_{Tγγ} and |y_{γγ}| observed distributions. The difference from the nominal simulated samples and the data-rewighted ones is taken as uncertainty.

A summary of the uncertainties on the τ_1 and the ∑τ_i differential cross sections is shown in Figure 6.6. Uncertainties are split among statistical and systematic ones. The systematic uncertainties are shown separately for signal extraction, correction factors and luminosity. It is easy to note that the statistical uncertainty is the dominant one in all cases. The photon energy resolution systematic uncertainty from the fits is the leading systematic uncertainty component.

Uncertainties for the theoretical predictions comprehend renormalization, factorization and resummation scale variations, as well as uncertainties from PDF variations. The τ_1 and the ∑τ_i differential cross sections are compared with the MINLO HJ theory prediction that is corrected for detector acceptance, photon isolation and non-perturbative effects. Within MINLO HJ, renormalization and factorization scales are varied by a factor of 2 or 0.5 and the envelope is considered as the uncertainty associated to the higher orders of the calculation that are missing. The non-perturbative corrections are obtained using different generator
tunes. The center of the envelope obtained with this variation is the correction factor while the envelope its uncertainty. Different parton distribution functions are used to evaluate in a similar way an additional uncertainty.

The differential cross sections at particle-level for $\tau_1$ and $\sum_i \tau_i$ are shown in Figure 6.7. Even if the measurements are greatly limited by the available amount of data, good agreement within uncertainties can be appreciated. Tabulated results are presented for both $\tau_1$ and $\sum_i \tau_i$ measurements in Table 6.3 and 6.4, respectively. Several theory predictions for these observables can be found in Table 6.5 and 6.6.

A prediction for the differential cross section of $\tau_1$ at NLL$'$+NLO is available in [138] and shown in Figure 6.8. This theory prediction is calculated using soft-collinear effective theory and the NLL$'$ precision includes resummations at the NLL level plus the fixed order one-loop expression for the hard, beam and soft functions in which the cross section factorizes in SCET. An additional correction is applied on data, which corrects for migrations between the first two bins. This extra term effectively expands the fiducial region to which the measurement is unfolded to: jets at particle-level are required to have $p_T > 10$ GeV instead of $p_T > 25$ GeV.

As can be seen in Figure 6.8 good agreement between data and prediction is found. Details on the prediction uncertainties are available in [138].

### 6.2.2 Moments of the differential cross section distributions

As a summary of the results from all the measured differential cross sections in [3], the ratio of the mean and RMS of MC predictions to data are calculated and shown together. The definitions for the moments of the variables that are shown in Figures 6.9 and 6.10 are described below.

The mean value is computed as:

$$\mu = \frac{\sum_i (x_i \cdot y_i)}{N_{\text{tot}}} \quad (6.8)$$
6.2. Differential cross sections

The differential cross section for $pp \rightarrow H \rightarrow \gamma \gamma$ as a function of (a) $\tau_1$ and (b) $\sum \tau_i$. The data are shown as filled (black) circles. The vertical error bar on each data point represents the total uncertainty in the measured cross section, and the shaded (grey) band is the systematic uncertainty component. The SM prediction, using the MINLO HJ prediction for gluon fusion and the default POWHEG BOX-PYTHIA8 samples for the other production mechanisms, is presented as a hatched (blue). The small contribution from VBF, $VH$ and $t\bar{t}H$ is also shown separately as a dashed (green) line and denoted as $XH$. The MINLO HJ prediction is normalized to the LHC-XS prediction using a K-factor of $K_{ggF} = 1.54$.

Figure 6.7: The differential cross section for $pp \rightarrow H \rightarrow \gamma \gamma$ as a function of (a) $\tau_1$ and (b) $\sum \tau_i$. The data are shown as filled (black) circles. The vertical error bar on each data point represents the total uncertainty in the measured cross section, and the shaded (grey) band is the systematic uncertainty component. The SM prediction, using the MINLO HJ prediction for gluon fusion and the default POWHEG BOX-PYTHIA8 samples for the other production mechanisms, is presented as a hatched (blue). The small contribution from VBF, $VH$ and $t\bar{t}H$ is also shown separately as a dashed (green) line and denoted as $XH$. The MINLO HJ prediction is normalized to the LHC-XS prediction using a K-factor of $K_{ggF} = 1.54$. 
6.2. Differential cross sections

\[ \frac{d\sigma}{d\tau_{jet}^C} \text{ [fb/GeV]} \]

**Figure 6.8:** Comparison of the \( gg \rightarrow H \rightarrow \gamma\gamma \) cross section at NLL’+NLO in bins of \( \tau_1 \) [138] (here called \( \tau_{jet}^{C1} \)) to the ATLAS \( H \rightarrow \gamma\gamma \) measurements [3]. Details on corrections are in the text.

**Figure 6.9:** The ratio of the first moment (mean) of each differential distribution predicted by the theoretical models to that observed in the data. The intervals on the vertical axes each represent one of the differential distributions. The band for each theoretical prediction represents the corresponding uncertainty in that prediction. The error bar on the data represents the total uncertainty in the measurement, with the grey band representing the systematic-only uncertainty.
Table 6.3: Summary of results and uncertainties on the particle-level differential cross-sections for $\tau_1$

<table>
<thead>
<tr>
<th>Bin</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal yield/bin width</td>
<td>43.60</td>
<td>7.80</td>
<td>6.21</td>
<td>0.70</td>
</tr>
<tr>
<td>Background PDF</td>
<td>exp2</td>
<td>exp2</td>
<td>exp2</td>
<td>exp2</td>
</tr>
<tr>
<td>Fit: total uncert.</td>
<td>30.2%</td>
<td>73.6%</td>
<td>49.7%</td>
<td>155.4%</td>
</tr>
<tr>
<td>Fit statistical</td>
<td>29.6%</td>
<td>73.2%</td>
<td>49.3%</td>
<td>154.1%</td>
</tr>
<tr>
<td>Fit systematics</td>
<td>6.3%</td>
<td>7.8%</td>
<td>6.8%</td>
<td>9.6%</td>
</tr>
<tr>
<td>Spurious signal</td>
<td>2.1%</td>
<td>2.3%</td>
<td>5.5%</td>
<td>14.0%</td>
</tr>
<tr>
<td>$d\sigma_{fid}/dX$ [fb]</td>
<td>3.39</td>
<td>0.52</td>
<td>0.45</td>
<td>0.05</td>
</tr>
<tr>
<td>Correction factors</td>
<td>1.57</td>
<td>1.36</td>
<td>1.48</td>
<td>1.47</td>
</tr>
<tr>
<td>Purity</td>
<td>0.96</td>
<td>0.65</td>
<td>0.77</td>
<td>0.81</td>
</tr>
<tr>
<td>Luminosity</td>
<td>2.8%</td>
<td>2.8%</td>
<td>2.8%</td>
<td>2.8%</td>
</tr>
<tr>
<td>PID</td>
<td>1.0%</td>
<td>1.0%</td>
<td>1.0%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Isolation</td>
<td>2.0%</td>
<td>2.0%</td>
<td>2.0%</td>
<td>2.0%</td>
</tr>
<tr>
<td>Pileup</td>
<td>0.5%</td>
<td>-1.1%</td>
<td>-0.3%</td>
<td>-0.1%</td>
</tr>
<tr>
<td>Jet energy scale + resolution</td>
<td>2.6%</td>
<td>4.5%</td>
<td>4.5%</td>
<td>5.8%</td>
</tr>
<tr>
<td>Generator modelling</td>
<td>+1.0%</td>
<td>+6.9%</td>
<td>+4.5%</td>
<td>+2.9%</td>
</tr>
</tbody>
</table>

where $x_i$ is the central value of the $i$-th bin, $y_i$ is the $i$-th bin content and $N_{tot}$ is the total number of entries, i.e. $N_{tot} = \sum_i y_i$. The statistical uncertainties are propagated using the formula shown here:

$$\left( \delta \mu_{stat} \right)^2 = \sum_i \left( \frac{x_i - \mu}{N_{tot}} \cdot \delta y_i,stat \right)^2,$$

while for the systematic ones, assumed fully correlated between bins, is used:

$$\left( \delta \mu_{sys} \right)^2 = \sum_{i,j} \left( \frac{x_i - \mu}{N_{tot}} \cdot \frac{x_j - \mu}{N_{tot}} \cdot \delta y_i,sys \cdot \delta y_j,sys \right),$$

with $\delta y_i,stat$ and $\delta y_i,sys$ the statistical and systematic uncertainty associated to the $i$-th bin of the distribution respectively. The total uncertainty is just the sum in quadrature of the two.

The RMS is defined as the square root of the variance ($V$):

$$\text{RMS} = \sqrt{V} = \sqrt{\langle \mu' - \mu^2 \rangle},$$

with $\mu' = \sum_i (x_i^2 \cdot y_i) / N_{tot}$ the second moment. The uncertainty is computed as:

$$\delta \text{RMS} = \frac{\delta V}{2\sqrt{V}},$$

where for the variance the formula that was taken into account is the following:

$$\left( \delta V \right)^2 = \sum_{i,j} \left( \frac{(x_i - \mu)^2}{N_{tot}} - V \right) \cdot \left( \frac{(x_j - \mu)^2}{N_{tot}} - V \right) \cdot c(i,j).$$
Table 6.4: Summary of results and uncertainties on the particle-level differential cross-sections for $\sum_i \tau_i$

<table>
<thead>
<tr>
<th>Bin</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal yield/bin width</td>
<td>43.78</td>
<td>5.88</td>
<td>4.86</td>
<td>1.66</td>
<td>0.59</td>
</tr>
<tr>
<td>Background PDF</td>
<td>exp2</td>
<td>exp2</td>
<td>exp2</td>
<td>exp2</td>
<td>exp2</td>
</tr>
<tr>
<td>Fit: total uncert.</td>
<td>30.2%</td>
<td>92.3%</td>
<td>59.3%</td>
<td>75.1%</td>
<td>37.9%</td>
</tr>
<tr>
<td>Fit statistical</td>
<td>29.5%</td>
<td>91.9%</td>
<td>58.9%</td>
<td>74.7%</td>
<td>37.5%</td>
</tr>
<tr>
<td>Fit systematics</td>
<td>6.5%</td>
<td>8.8%</td>
<td>6.7%</td>
<td>7.6%</td>
<td>5.6%</td>
</tr>
<tr>
<td>Spurious signal</td>
<td>2.1%</td>
<td>2.2%</td>
<td>3.1%</td>
<td>3.3%</td>
<td>3.7%</td>
</tr>
<tr>
<td>$d\sigma_{\text{fid}}/dX$ [fb]</td>
<td>3.40</td>
<td>0.40</td>
<td>0.35</td>
<td>0.12</td>
<td>0.04</td>
</tr>
<tr>
<td>Correction factors</td>
<td>1.57</td>
<td>1.38</td>
<td>1.48</td>
<td>1.44</td>
<td>1.41</td>
</tr>
<tr>
<td>Purity</td>
<td>0.96</td>
<td>0.61</td>
<td>0.71</td>
<td>0.75</td>
<td>0.84</td>
</tr>
<tr>
<td>Luminosity</td>
<td>2.8%</td>
<td>2.8%</td>
<td>2.8%</td>
<td>2.8%</td>
<td>2.8%</td>
</tr>
<tr>
<td>PID</td>
<td>1.0%</td>
<td>1.0%</td>
<td>1.0%</td>
<td>1.0%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Isolation</td>
<td>2.0%</td>
<td>2.0%</td>
<td>2.0%</td>
<td>2.0%</td>
<td>2.0%</td>
</tr>
<tr>
<td>Pileup</td>
<td>0.5%</td>
<td>-0.9%</td>
<td>-0.3%</td>
<td>-0.4%</td>
<td>-0.3%</td>
</tr>
<tr>
<td>Jet energy scale + resolution</td>
<td>2.6%</td>
<td>3.8%</td>
<td>4.0%</td>
<td>6.1%</td>
<td>8.2%</td>
</tr>
<tr>
<td>Generator modelling</td>
<td>$\pm 1.0%$</td>
<td>$\pm 7.5%$</td>
<td>$\pm 4.9%$</td>
<td>$\pm 2.6%$</td>
<td>$\pm 2.6%$</td>
</tr>
</tbody>
</table>

In this case $c(i,j)$ is the covariance matrix built considering the systematic errors fully correlated and the statistical ones uncorrelated.

The MC systematic uncertainties are symmetrized, taking the average from the uncertainty envelope and then using Eq.(6.8) and Eq.(6.9). For the variance, and hence for the RMS, the uncertainty is computed as:

$$(\delta V_{\text{MC}})^2 = \sum_i \left( \frac{(x_i - \mu)^2}{N_{\text{tot}}} \cdot \delta y_i \right)^2.$$

The the first and the second moments of each differential distribution measured in [3] is shown in Figures 6.9 and 6.10, respectively. The measurements are compared to a variety of theoretical predictions and a general good agreement within uncertainties is found.

### 6.3 Conclusions

In this chapter an overview of fiducial cross section measurements for Higgs boson production in the diphoton decay channel at $\sqrt{s} = 8$ TeV from [3] was presented. The measurements were compared to state-of-the-art theoretical predictions and found in good agreement within the uncertainties.

A set of observables that can provide new and complementary information to $p_T^{d1}$ and $H_T$
**Table 6.5**: MC predictions for $\tau_1$. All predictions are at particle-level and normalized to the LCH-XS total cross section. All uncertainties are relative.

<table>
<thead>
<tr>
<th></th>
<th>Bin</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>XH</strong></td>
<td>DiffXS [fb]</td>
<td>0.15</td>
<td>0.09</td>
<td>0.06</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>QCDscale Up</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>QCDscale Down</td>
<td>-0.02</td>
<td>-0.01</td>
<td>-0.02</td>
<td>-0.03</td>
</tr>
<tr>
<td></td>
<td>PDF Up</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>PDF Down</td>
<td>-0.03</td>
<td>-0.03</td>
<td>-0.03</td>
<td>-0.03</td>
</tr>
<tr>
<td><strong>Powheg ggH</strong></td>
<td>DiffXS [fb]</td>
<td>2.29</td>
<td>0.41</td>
<td>0.20</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>QCDscale Up</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>QCDscale Down</td>
<td>-0.15</td>
<td>-0.15</td>
<td>-0.15</td>
<td>-0.15</td>
</tr>
<tr>
<td></td>
<td>PDF Up</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>PDF Down</td>
<td>-0.02</td>
<td>-0.02</td>
<td>-0.02</td>
<td>-0.03</td>
</tr>
<tr>
<td><strong>Minlo HJ</strong></td>
<td>DiffXS [fb]</td>
<td>2.40</td>
<td>0.39</td>
<td>0.19</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>QCDscale Up</td>
<td>0.34</td>
<td>0.29</td>
<td>0.29</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>QCDscale Down</td>
<td>-0.14</td>
<td>-0.15</td>
<td>-0.17</td>
<td>-0.19</td>
</tr>
<tr>
<td></td>
<td>PDF Up</td>
<td>0.03</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>PDF Down</td>
<td>-0.03</td>
<td>-0.02</td>
<td>-0.02</td>
<td>-0.02</td>
</tr>
<tr>
<td><strong>Minlo HJJ</strong></td>
<td>DiffXS [fb]</td>
<td>2.47</td>
<td>0.37</td>
<td>0.17</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>QCDscale Up</td>
<td>0.37</td>
<td>0.24</td>
<td>0.21</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>QCDscale Down</td>
<td>-0.28</td>
<td>-0.23</td>
<td>-0.22</td>
<td>-0.21</td>
</tr>
<tr>
<td></td>
<td>PDF Up</td>
<td>0.03</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>PDF Down</td>
<td>-0.03</td>
<td>-0.02</td>
<td>-0.02</td>
<td>-0.02</td>
</tr>
</tbody>
</table>
### Table 6.6: MC predictions for $\sum_i \tau_i$. All predictions are at particle-level and normalized to the LCH-XS total cross section. All uncertainties are relative.

<table>
<thead>
<tr>
<th></th>
<th>Bin</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>XH</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DiffXS [fb]</td>
<td>0.15</td>
<td>0.08</td>
<td>0.05</td>
<td>0.03</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>QCDscale Up</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>QCDscale Down</td>
<td>-0.02</td>
<td>-0.01</td>
<td>-0.01</td>
<td>-0.02</td>
<td>-0.03</td>
<td></td>
</tr>
<tr>
<td>PDF Up</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>PDF Down</td>
<td>-0.03</td>
<td>-0.03</td>
<td>-0.03</td>
<td>-0.03</td>
<td>-0.03</td>
<td></td>
</tr>
<tr>
<td><strong>Powheg ggH</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DiffXS [fb]</td>
<td>2.29</td>
<td>0.37</td>
<td>0.18</td>
<td>0.07</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>QCDscale Up</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>QCDscale Down</td>
<td>-0.15</td>
<td>-0.15</td>
<td>-0.15</td>
<td>-0.15</td>
<td>-0.15</td>
<td></td>
</tr>
<tr>
<td>PDF Up</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>PDF Down</td>
<td>-0.02</td>
<td>-0.02</td>
<td>-0.02</td>
<td>-0.03</td>
<td>-0.03</td>
<td></td>
</tr>
<tr>
<td><strong>Minlo HJ</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DiffXS [fb]</td>
<td>2.40</td>
<td>0.35</td>
<td>0.17</td>
<td>0.06</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>QCDscale Up</td>
<td>0.34</td>
<td>0.29</td>
<td>0.29</td>
<td>0.29</td>
<td>0.29</td>
<td></td>
</tr>
<tr>
<td>QCDscale Down</td>
<td>-0.14</td>
<td>-0.15</td>
<td>-0.16</td>
<td>-0.19</td>
<td>-0.21</td>
<td></td>
</tr>
<tr>
<td>PDF Up</td>
<td>0.03</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>PDF Down</td>
<td>-0.03</td>
<td>-0.02</td>
<td>-0.02</td>
<td>-0.02</td>
<td>-0.02</td>
<td></td>
</tr>
<tr>
<td><strong>Minlo HJJ</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DiffXS [fb]</td>
<td>2.47</td>
<td>0.34</td>
<td>0.16</td>
<td>0.06</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>QCDscale Up</td>
<td>0.37</td>
<td>0.24</td>
<td>0.21</td>
<td>0.17</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>QCDscale Down</td>
<td>-0.28</td>
<td>-0.23</td>
<td>-0.22</td>
<td>-0.21</td>
<td>-0.19</td>
<td></td>
</tr>
<tr>
<td>PDF Up</td>
<td>0.03</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>PDF Down</td>
<td>-0.03</td>
<td>-0.02</td>
<td>-0.02</td>
<td>-0.02</td>
<td>-0.03</td>
<td></td>
</tr>
</tbody>
</table>
measurements were presented. These variables, defined as $\tau_1$ and $\sum_i \tau_i$ in the text, can be used as jet vetoes with different resummation properties. In this case the Higgs production events allow to study the particular case of gluon initiated interactions. Differential cross sections for $\tau_1$ and $\sum_i \tau_i$ were measured. A good agreement is found between data and theory predictions also in [138].

Finally, as a summary, the first and the second moments were computed for all the distributions considered. Within uncertainties, a good agreement is found between measurements and theory predictions.
Summary and conclusions

This thesis presented the main results obtained during my PhD.

One chapter was dedicated to the implementation and the study of the charge trapping effect in the SCT detector simulation. In irradiated sensors, massive hadronic particles as protons, neutrons and pions damage the bulk of the sensors. As a consequence charge trapping centers can be created and remove some of the free carriers from the signal. This radiation damage effect, known as charge trapping, was implemented in the SCT simulation. Modifications to the electric field induced in the bulk of the sensors are inevitable with the aging of the detector material. Since the electric field plays a crucial role in the strip signal generation, the modifications to the electric field were included in the simulation. The simulation of the response of the innermost barrel layer of the SCT (the most irradiated one) was performed for different conditions of irradiated dose. The cluster size and the Lorentz angle were investigated through simulation. The results showed that there is little impact of the charge trapping effect foreseen on the SCT detector response for the whole LHC operation.

A second chapter was devoted to the contributions to the measurements of fiducial and differential cross sections for Higgs boson production in the diphoton decay channel at $\sqrt{s} = 8$ TeV with the ATLAS detector published in [3]. In this chapter together with presenting the measured fiducial cross sections, a particular set of jet observables were studied for the differential cross section measurement. The event-shape observables $\tau_1$ and $\sum_i \tau_i$ are variables that combine jet transverse momentum and jet rapidity information. Their main characteristic is that they are built from the $p_T$ of the jet weighted by a $y$-dependent function that at forward rapidities scales as $e^{-|y|}$. They provide complementary information to $p_T^{\text{jet}}$ and $H_T$ and the predictions for cross sections that use $\tau_1$ or $\sum_i \tau_i$ as jet vetoes can be calculated to a similar level of precision than the ones calculated for $p_T$-jet vetoes. The study of these observables in Higgs production events allows to directly test radiation from gluon-initiated processes. The differential cross sections for $\tau_1$ and $\sum_i \tau_i$ were measured and found in good agreement with theory predictions.

The central chapter of this thesis was dedicated to the measurement of differential cross sections for track-based observables for Higgs boson production in the diphoton decay channel at $\sqrt{s} = 8$ TeV. The measurements were performed using a procedure as close as possible to the one of the published analysis [3]. The original element of this analysis is the employment of observables based on tracks. Together with the track multiplicity $N_{\text{tracks}}$ and the scalar sum
of the transverse momentum of the tracks $H_T^{tracks} = \sum_k |p_{k,T}|$, a set of variables was derived from the definition of $N$-jettiness. These observables are sensitive to soft radiation, underlying event physics and multi-parton interactions; can be used as a veto for hard radiation or jets, with phase-space restrictions theoretically well-controlled, and can be used as discriminant variables for jet cone algorithms. Moreover, as said above, there is particular interest in studying these observables in Higgs events. A large number of differential cross sections for different track-based observables was measured and the main sources of systematic uncertainty investigated. The results showed good agreement with the theory prediction within the large statistical uncertainty. From the study of the systematic uncertainties no particular obstacle to the measurements was found.
Bibliography


[55] T. Cornelissen, M. Elsing, S. Fleischmann, W. Liebig, E. Moyse, and A. Salzburger, 


[114] ATLAS Collaboration, Measurement of the Higgs boson mass from the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ channels with the ATLAS detector using 25 fb$^{-1}$ of pp collision data, Phys. Rev. D90 (2014), no. 5 052004, [arXiv:1406.3827].


[128] D. de Florian, G. Ferrera, M. Grazzini, and D. Tommasini, *Higgs boson production at the LHC: transverse momentum resummation effects in the $H \rightarrow \gamma\gamma$, $H \rightarrow WW \rightarrow l\nu l\nu$ and $H \rightarrow ZZ \rightarrow 4l$ decay modes*, JHEP **06** (2012) 132, [arXiv:1203.6321].


