EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Submitted to: PRD

CERN-EP-2023-147
July 28, 2023

Pursuit of paired dijet resonances in the Run 2 dataset with ATLAS

The ATLAS Collaboration

New particles with large masses that decay into hadronically interacting particles are predicted by many models of physics beyond the Standard Model. A search for a massive resonance that decays into pairs of dijet resonances is performed using 140 fb^{-1} of proton–proton collisions at $\sqrt{s} = 13$ TeV recorded by the ATLAS detector during Run 2 of the Large Hadron Collider. Resonances are searched for in the invariant mass of the tetrajet system, and in the average invariant mass of the pair of dijet systems. A data-driven background estimate is obtained by fitting the tetrajet and dijet invariant mass distributions with a four-parameter dijet function and a search for local excesses from resonant production of dijet pairs is performed. No significant excess of events beyond the Standard Model expectation is observed, and upper limits are set on the production cross-sections of new physics scenarios.

Contents

1 Introduction

New massive particles that decay into hadronically interacting quarks and gluons are predicted in many scenarios of physics beyond the Standard Model (BSM) accessible at the Large Hadron Collider (LHC), including well-motivated models of particle dark matter [1–8] and models with large extra spatial dimensions [9–15]. Quarks and gluons produced at high energies fragment and hadronize into collimated *jets* of particles [16], observable in particle detectors like ATLAS [17]. The majority of Standard Model (SM) multijet event production occurs via *nonresonant* quantum chromodynamics (QCD) processes, resulting in multijet systems with smoothly falling invariant mass distributions. The large production cross-section of multijet processes can make searching for fully hadronic BSM signatures challenging, especially without the presence of other distinguishing feaures like leptons and/or missing transverse momentum [18]. However, when massive particles decay into pairs of jets ('dijets') via s-channel interactions, the invariant mass spectrum of the dijet system exhibits the signature of the massive particle as a *resonance* around its mass value. While the rate of new particle production may be too low that no resonance is obvious, such models may be detected using data-driven techniques analyzing the smoothly-falling invariant mass distribution of the SM background. Searches for dijet resonances have been a cornerstone of collider physics at the LHC [19–36] and at earlier colliders [37–40].

This paper presents a search for a generic massive resonance Y that decays into two pairs of intermediate resonances X with the same mass, each decaying into two partons and so typically producing a pair of dijet systems. This decay structure is represented schematically in Figure 1. Examples of exotic physics models that could produce such a final state topology include scalar diquark [41–44] and coloron states [45–48], and additional new particle content such as a vector-like quarks that interact in pairs with the massive diquark or coloron and decay hadronically [49–51]. The analysis is performed on the Run 2 proton–proton

(pp) collision data recorded by the ATLAS experiment. Previous searches for signals with this resonance structure have been performed by the ATLAS [52–55] and CMS [56–58] collaborations at the LHC. Most recently, in Ref. [58], the CMS Collaboration studied final states where pairs of dijet resonances are collimated but insufficiently boosted to be reconstructed in a single large-radius jet (*e.g.* a jet reconstructed with radius parameter R=1.0 [59, 60]). A small, locally significant excess of events (3.6 standard deviations from two events, corresponding to a 2.5 standard deviation global significance) was observed with tetrajet resonance masses around $m_{4\mathrm{j}} \sim 8$ TeV producing dijet resonances with average masses around $m_{2\mathrm{j}} \sim 2$ TeV. This prompted an investigation of such final state configurations using ATLAS data.

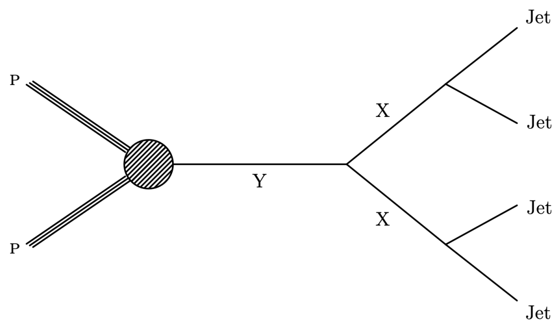


Figure 1: A schematic representation of the signal topology studied in this analysis: a massive new particle Y decays into two new particles with intermediate mass X, each decaying into a dijet system.

As there are two resonances with different masses involved in the final state topology (Y and X), both the tetrajet system and the average dijet system invariant masses are separately studied using the BumpHunter algorithm [61–65]. A data-driven background estimate is obtained by fitting these invariant mass distributions with a functional form.

An outline of the remainder of this paper is as follows. Section 2 provides overviews of the ATLAS detector, the Run 2 pp data sample and the signal and background Monte Carlo (MC) simulations used in this search. This is followed in Section 3 by a description of the analysis methodology including jet reconstruction, event selection, the data-driven background estimation procedure and the systematic uncertainties considered. The main results are presented in Section 4, interpreting the observed data in terms of upper limits on the production cross-sections of new physics scenarios. Concluding remarks are made in Section 5.

2 ATLAS, the Run 2 data, and simulation

2.1 The ATLAS detector

The ATLAS detector [17] at the LHC covers nearly the entire solid angle around the collision point.[1] It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the center of the LHC ring, and the y-axis points upwards. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta y)^2 + (\Delta\phi)^2}$, where $y = (1/2)[(E + p_z)/(E - p_z)]$ is the object's rapidity defined by its energy and longitudinal momentum.

hadron calorimeters, and a muon spectrometer incorporating three large superconducting air-core toroidal magnets.

The inner-detector system is immersed in a 2 T axial magnetic field and provides charged-particle tracking in the range of $|\eta| < 2.5$. The high-granularity silicon pixel detector covers the vertex region and typically provides four measurements per track, the first hit normally being in the insertable B-layer installed before Run 2 [66, 67]. It is followed by the silicon microstrip tracker , which usually provides eight measurements per track. These silicon detectors are complemented by the transition radiation tracker (TRT), which enables radially extended track reconstruction up to $|\eta| = 2.0$. The TRT also provides electron identification information based on the fraction of hits (typically 30 in total) above a higher energy-deposit threshold corresponding to transition radiation.

The calorimeter system covers the pseudorapidity range of $|\eta| < 4.9$. Within the region $|\eta| < 3.2$, electromagnetic calorimetry is provided by barrel and endcap high-granularity lead/liquid-argon (LAr) calorimeters, with an additional thin LAr presampler covering $|\eta| < 1.8$ to correct for energy loss in material upstream of the calorimeters. Hadron calorimetry is provided by the steel/scintillator-tile calorimeter, segmented into three barrel structures with $|\eta| < 1.7$, and two copper/LAr hadron endcap calorimeters. The solid angle coverage is completed with forward copper/LAr and tungsten/LAr calorimeter modules optimized for electromagnetic and hadronic energy measurements respectively.

The muon spectrometer comprises separate trigger and high-precision tracking chambers measuring the deflection of muons in a magnetic field generated by the superconducting air-core toroidal magnets. The field integral of the toroids ranges between 2.0 and 6.0 T m across most of the detector. Three layers of precision chambers, each consisting of layers of monitored drift tubes, cover the region $|\eta| < 2.7$, complemented by cathode-strip chambers in the forward region, where the background is highest. The muon trigger system covers the range of $|\eta| < 2.4$ with resistive-plate chambers in the barrel, and thin-gap chambers in the endcap regions.

Interesting events are selected by the first-level trigger system implemented in custom hardware, followed by selections made by algorithms implemented in software in the high-level trigger [68]. The first-level trigger accepts events from the 40 MHz bunch crossings at a rate below 100 kHz, which the high-level trigger further reduces to record events to disk at about 1 kHz.

An extensive software suite [69] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

2.2 The Run 2 data sample

This analysis is performed using data from LHC pp collisions with $\sqrt{s} = 13$ TeV, collected during 2015–2018 with the ATLAS detector. The total integrated luminosity of this data sample is 140 fb^{-1}. The uncertainty in the combined 2015–2018 integrated luminosity is 0.83% [70], obtained using the LUCID-2 detector [71] for the primary luminosity measurements. Due to the high instantaneous luminosity and the large total inelastic pp cross-section, there are, on average, 33.7 simultaneous collisions (‘pileup’) in each bunch crossing. Data are required to satisfy certain quality requirements [72] to be included in the analysis.

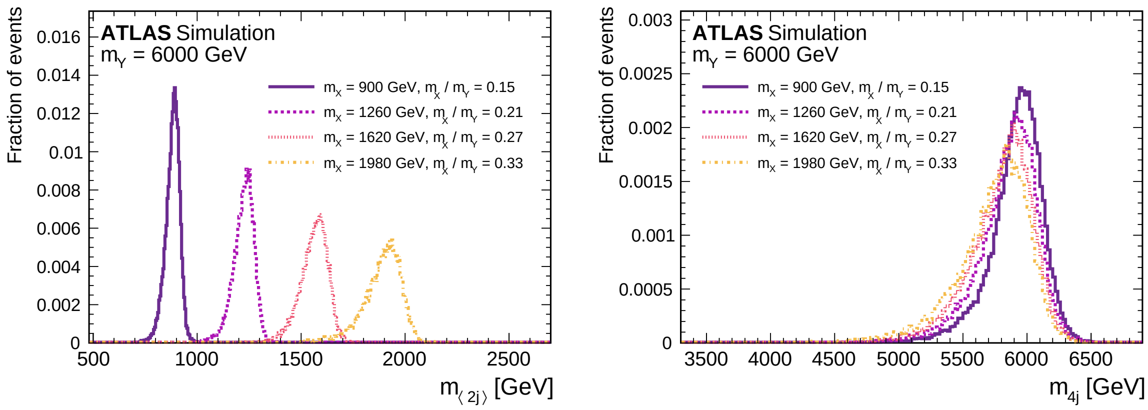
During certain data-taking periods, modules of the tile calorimeter were disabled. A study of the impact of vetoing these disabled modules in MC and data was performed, and found to have a negligible impact on the background shape modeling and expected limits.

2.3 Simulated event samples

Samples of MC simulated signal and background (multijet) events are used for optimisation, estimation of possible signal contributions, and validation of background estimation strategies.

Pythia 8.230 [73, 74] was used as the nominal MC generator for both the signal and the background events. Events were simulated using the A14 set of tuned parameters ('tune') [75], the Lund string hadronization model and the NNPDF2.3lo [76] leading-order (LO) parton distribution function (PDF) set. The Pythia parton shower algorithm uses a dipole-style transverse momentum (p_{T}) ordered evolution, and its renormalization and factorization scales were set to the geometric mean of the squared transverse masses of the outgoing particles. EvtGen [77] was used to model decays of heavy flavor hadrons.

Signal samples were generated with Pythia 8.230 using the process $W' \to WZ$, where the mass of the W' corresponds to the Y mass, and the W/Z masses were both set to be equal to the X mass. The W and Z full widths at half maximum of a relativistic Breit–Wigner were set to 0.1 GeV, so that the width of the resonance is determined by the detector resolution (typically ranging between 1-4% for both $m_{4\mathrm{j}}$ and $\langle m_{2\mathrm{j}} \rangle$). These exotic X bosons were forced to decay into quark–antiquark pairs, and decays into top–antitop quark pairs were disabled. Representative $m_{4\mathrm{j}}$ and $\langle m_{2\mathrm{j}} \rangle$ distributions are shown in Figure 2 for several different choices of $\alpha = \langle m_{2\mathrm{j}} \rangle / m_{4\mathrm{j}}$ (see Section 3.2) with $m_Y = 6000$ GeV. The signal distributions have clear peaks near the generated signal masses.



(a) (b)

Figure 2: Examples of (a) $\langle m_{2\mathrm{j}} \rangle$ and (b) $m_{4\mathrm{j}}$ distributions for $m_Y = 6000$ GeV with $m_X/m_Y = 0.15$, 0.21, 0.27, and 0.33.

Background samples of 'hard-QCD' multijet processes were simulated using the same Pythia settings. These samples were used to optimize aspects of the analysis in early stages, although they are not used for the final background estimate. Additional background multijet samples were simulated with Sherpa 2.2.5 [78] to test the robustness of the background estimation procedure, using the default AHADIC cluster hadronization model [79]. This sample includes LO matrix element calculations for $2 \to 2$ processes, and used the Sherpa parton shower algorithm based on Catani–Seymour dipole subtraction [80]. It used the CT14nnlo next-to-next-to-leading-order (NNLO) PDF [81] set for matrix element calculations and CT10 for multi-parton interactions [82].

Simulated background events were passed through a detailed detector simulation [83] based on Geant4 [84], while simulated signal events were reconstructed with a fast simulation that uses a parameterisation of the ATLAS calorimeter response [85]. In both cases, the samples were overlayed with minimum-bias interactions simulated using Pythia 8 with the A3 tune [86] and the NNPDF2.3lo PDF set to represent pileup interactions. The distribution of the average number of pileup interactions in simulation is reweighted during data analysis to match that observed in Run 2 data.

Additional details of the MC samples used in this measurement may be found in Ref. [87].

3 Methodology

3.1 Particle flow jets

Jets are reconstructed from particle flow objects [88] using the anti-k_t algorithm [89] as implemented in FastJet [90], using a jet radius parameter $R = 0.4$. The ATLAS particle flow algorithm combines measurements from the ATLAS inner detector and calorimeter systems [91] to improve the jet energy resolution (JER), reduce sensitivity to pileup effects, and improve the jet reconstruction efficiency (especially at low jet p_{T}) relative to the jet reconstruction based on calorimeter signals alone. Jets are required to have a $p_{\mathrm{T}} > 60$ GeV and a rapidity y satisfying $|y| < 2.4$. The jet energy scale (JES) of particle flow jets is calibrated using a combination of simulation-based and *in situ* corrections [92].

3.2 Event selection

To be considered for analysis, all detector-level events are required to have at least one primary vertex reconstructed from two or more inner-detector tracks with $p_{\mathrm{T}} > 500$ MeV. Events are required to have at least four jets, from which two dijet pairs are reconstructed. In the selected events, an event selection similar to that of Ref. [58] is applied to allow direct comparisons of the two searches. The two dijet pairs are determined by minimizing the ΔR between the jets, defined as

$$\Delta R = |\Delta R_{\mathrm{AB}} - 0.8| + |\Delta R_{\mathrm{CD}} - 0.8|,$$

where A, B, C, and D are the ordering of the four highest-p_{T} jets in the event that minimizes ΔR. The value of 0.8 ensures that the reconstructed pair of dijet systems are collimated, but not so boosted that they will be reconstructed as a large-R jet. Once the two dijet pairs AB and CD are selected, the dijet systems are required to satisfy angular requirements

$$\Delta R_{\mathrm{AB}} < 2.0,\ \Delta R_{\mathrm{CD}} < 2.0$$

and

$$\Delta\eta = |\eta_{\mathrm{AB}} - \eta_{\mathrm{CD}}| < 1.1.$$

In addition, the mass asymmetry between the two dijet pairs is required to satisfy

$$\frac{m_{\mathrm{AB}} - m_{\mathrm{CD}}}{m_{\mathrm{AB}} + m_{\mathrm{CD}}} < 0.1.$$

After the event selection procedure is complete, the observables of interest are the invariant mass of the tetrajet system, $m_{4\mathrm{j}}$ (a proxy for m_Y), and the average invariant mass of the two dijet systems, $\langle m_{2\mathrm{j}} \rangle$ (a proxy

Table 1: Table of selections for the minimum $\langle m_{2j} \rangle$ and m_{4j} values considered when selecting events for a given α bin. These selections are based on a requirement that the single-jet triggers used in the search are at least 99.5% efficient in the selected region.

α bin	Minimum $\langle m_{2j} \rangle$	Minimum m_{4j}
$0.10 < \alpha < 0.12$	230 GeV	1775 GeV
$0.12 < \alpha < 0.14$	250 GeV	1775 GeV
$0.14 < \alpha < 0.16$	270 GeV	1725 GeV
$0.16 < \alpha < 0.18$	330 GeV	1825 GeV
$0.18 < \alpha < 0.20$	370 GeV	1875 GeV
$0.20 < \alpha < 0.22$	430 GeV	1875 GeV
$0.22 < \alpha < 0.24$	430 GeV	1875 GeV
$0.24 < \alpha < 0.26$	490 GeV	1875 GeV
$0.26 < \alpha < 0.28$	510 GeV	1925 GeV
$0.28 < \alpha < 0.30$	570 GeV	1975 GeV
$0.30 < \alpha < 0.32$	630 GeV	1975 GeV
$0.32 < \alpha < 0.34$	730 GeV	2175 GeV

for m_X). The ratio of these quantities, $\alpha = \langle m_{2j} \rangle / m_{4j}$, is used to parameterize the kinematic space studied in this search in terms of the Lorentz boost of the X decay products. The correlations between m_{4j} and $\langle m_{2j} \rangle$ are shown in Figures 3(a) and 3(b) after the event selection for the Run 2 data and for a simulated signal sample with $m_Y = 6$ TeV and $m_X = 2$ TeV, respectively. As shown, requirements on $\langle m_{2j} \rangle$ are correlated with m_{4j} and therefore they can sculpt the background mass distribution. Figures 3(c)–3(f) illustrate the correlation between m_{4j}, $\langle m_{2j} \rangle$ and α. For the background distribution, α is less correlated with m_{4j} than $\langle m_{2j} \rangle$. The analysis is performed in regions of α rather than $\langle m_{2j} \rangle$, to reduce background sculpting in the tetrajet and average dijet invariant mass spectra due to the selection criteria. Twelve different α regions are used, evenly spaced to cover $0.10 < \alpha < 0.34$. For each α region, separate fits are performed for m_{4j} and $\langle m_{2j} \rangle$.

The combined acceptance times efficiency of all analysis selections is between 12%–45% for signal events as a function of the signal particle masses m_Y and m_X for 2000 GeV $< m_Y <$ 10000 GeV, and 500 GeV $< m_X <$ 3300 GeV.

Events in data are required to have been selected by one of several single-jet triggers, whose thresholds varied depending on the data-taking period during Run 2. The particular triggers used to select events in a given run period were always the lowest unprescaled triggers recording data during that time. The single jet triggers become fully efficient for different values of m_{4j} and $\langle m_{2j} \rangle$, depending on the α bin that is selected. To use fully efficient triggers while also retaining sensitivity to the widest range of values, different minimum m_{4j} and $\langle m_{2j} \rangle$ thresholds are imposed on the data and simulated signal events used in the interpretation of the search (see Section 4). The trigger thresholds were optimised such that they were at least 99.5% efficient for each trigger, and are listed in Table 1 for the various α regions used in the search. Over 220 000 events in the Run 2 data sample satisfy the analysis selections.

3.3 Signal templates

The results are interpreted using model-independent and model-dependent strategies. For the model-independent results, the signal templates are modeled as Gaussian distributions, with a mean equal to m_Y and m_X for the m_{4j} and $\langle m_{2j} \rangle$ distributions respectively. The template widths range from 5% to 15% for

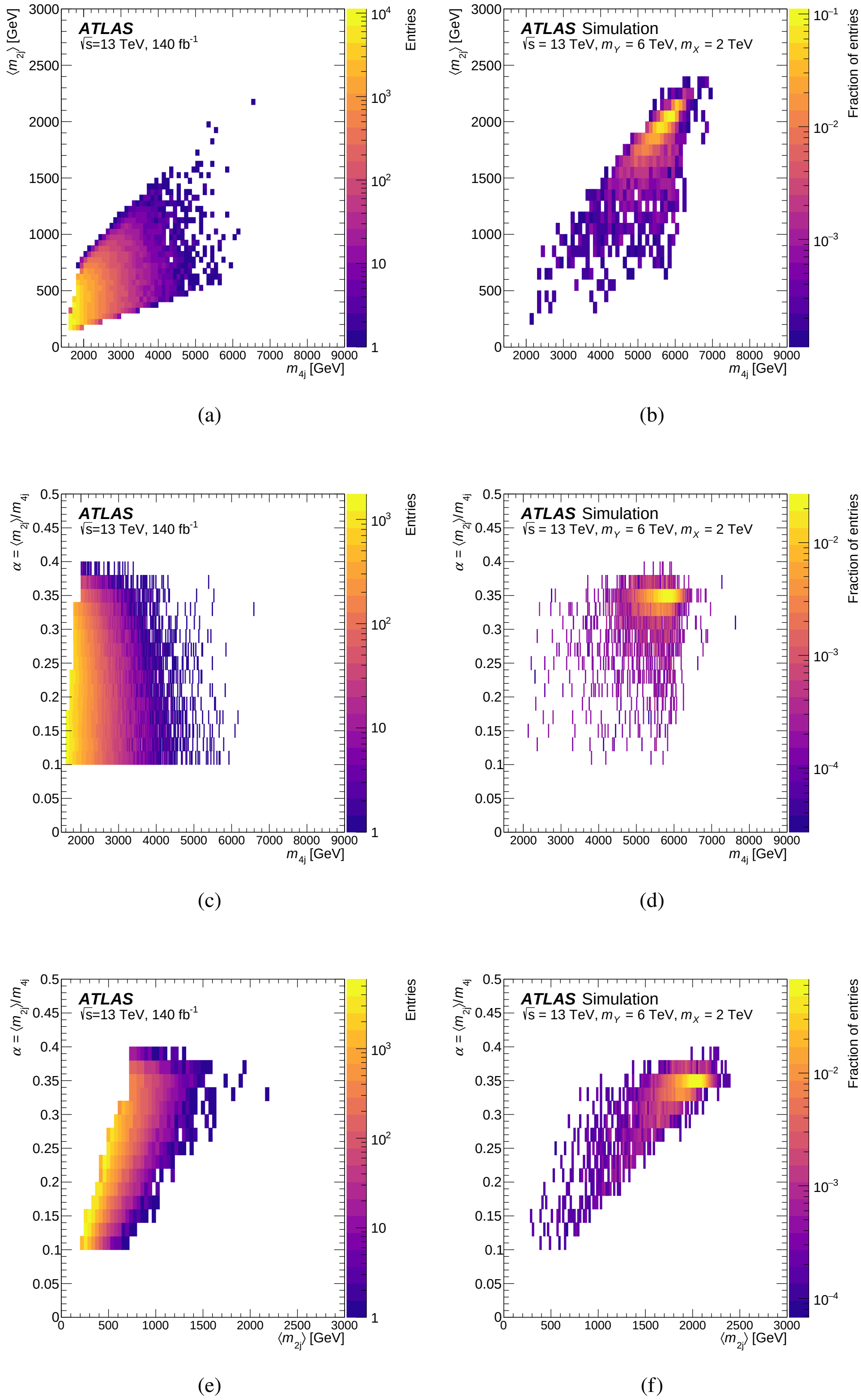


Figure 3: Two-dimensional histograms of (a, b) $\langle m_{2\mathrm{j}} \rangle$ *vs.* $m_{4\mathrm{j}}$, (c, d) α *vs.* $m_{4\mathrm{j}}$ and (e, f) α *vs.* $\langle m_{2\mathrm{j}} \rangle$. The left column shows the distributions in data, the right column shows the distributions for a simulated signal sample with $m_Y = 6$ TeV and $m_X = 2$ TeV.

both m_{4j} and $\langle m_{2j} \rangle$. The upper end of the template width is determined from the results of the spurious signal test described in Section 3.4.

For the model-dependent limits, the shape of the m_{4j} and $\langle m_{2j} \rangle$ distributions are parameterized using a Crystal Ball function [93], which provides a good description of the shape of mass distribution. Signal samples are produced with a limited set of signal masses, and these templates are used as inputs to interpolation between mass points to provide a finer signal grid. The interpolation is done separately for each α region by morphing the parameterized Crystal Ball fits of the signal shape.

3.4 Background estimation

Non-resonant QCD processes, which constitute the SM background for this search, result in multijet systems with smoothly falling invariant mass distributions. To estimate this background in the search regions, a parametric function is fit to the observed data distributions in 1 GeV bins:

$$f(x) = p_1(1-x)^{p_2} x^{p_3 + p_4 \ln(x) + p_5 \ln(x)^2}, x = m/\sqrt{s};$$

where p_1, p_2, p_3, p_4, and p_5 are the fitted parameters, and m is either m_{4j} or $\langle m_{2j} \rangle$. This function has been succesfully used in a wide variety of resonance dijet and multijet searches by the CDF, CMS, and ATLAS experiments [19, 22, 27, 30, 32, 35, 39, 58, 94]. For the background estimation, a 4-parameter fit is used, where p_5 is set to zero, while the 5-parameter fit is used to produce pseudodata to validate the fit strategy. Three-parameter fit functions were also studied but did not have sufficient flexibility to describe the background.

The background distribution is fit using a binned, maximum-likelihood fit. In background-only fits, the signal strength is set to zero, while in the signal-plus-background fits, the signal strength is left as a free parameter. For the model-dependent interpretation, the signal probability density function is defined as the Crystal Ball function fit to the simulated signal events. For the model-independent interpretations, the signal is parameterized as a Gaussian distribution, where the signal width is set to be a fixed fraction of the signal peak.

The data-driven background fitting procedure was validated with MC simulation using several cross-checks, including 'spurious signal tests' and 'signal injection tests'. Tests involving signal-plus-background fits are performed using both templates derived from the simulated signal samples described in Section 2.3, and for model-independent Gaussian signal shapes, using signal widths of 5%, 10%, and 15% of the signal peak.

The spurious signal test evaluates whether the fitting procedure is biased in a manner that will produce a non-zero extracted signal when fitting a data sample with no true signal. This test is performed for a 4-parameter fit function by performing a signal plus background fit with a Gaussian signal hypothesis of a specified width to 100 pseudodata distributions that are generated from background-only fits to the data distribution with an 5-parameter function, to provide more flexibility to the background distribution than to the fit function. Signal widths for both the X and Y ranging from 5% to 15% of the signal mean are tested, as well as using the signal templates directly. For each pseudodata distribution, the number of extracted signal events, n_S, is determined, and the median value and standard deviation of n_S across all pseudodata distributions are taken to be S_{spur} and σ_{spur} respectively. To satisfy the spurious signal requirements, $S_{\text{spur}}/\sigma_{\text{spur}}$ is required to be less than 0.5. For m_{4j} and $\langle m_{2j} \rangle$, all α regions satisfy this criterion for the signal templates, and for Gaussian signals with widths of 5%, 10%, and 15%.

The signal injection test is performed to ensure that the background fit is able to extract a signal component with the expected signal strength. Simulated signal models with the Gaussian templates with signal widths of 5% to 15% and signal templates are included in the fitted background distribution with a given signal cross-section selected to be in the range of 0–5σ, where $\sigma = n_S/\sqrt{n_B}$ and the number of signal and background events are determined using a 2σ window around the injected signal peak in each test. For these studies, the extracted signal strength is scaled to be the number of signal events within a 2σ window around the injected signal peak, to match the definition used for the injection. The injected signals in this study were extracted for 100 pseudodata distributions, with the requirement that the median extracted significance is within 0.5σ of the injected significance for fits to both the $m_{4\mathrm{j}}$ and $\langle m_{2\mathrm{j}} \rangle$ distributions in all analysis α regions. All signal templates and Gaussian signals that passed the spurious signal tests also passed the signal injection tests.

3.5 Systematic and statistical uncertainties

When interpreting the analysis in terms of candidate signal models, the impact of various experimental and theoretical sources of uncertainty is considered. The uncertainties in the luminosity and parton distribution functions are included as Gaussian constraints on the yield, while the uncertainties in the jet energy scale, jet energy resolution, tune, and theoretical renormalization and factorization scale are included as Gaussian constraints on the shape of the distribution. The uncertainty in the background modeling is implemented as an additional 'spurious' signal-like contribution.

Luminosity. The uncertainty in the combined 2015–2018 integrated luminosity is 0.83% [70], obtained using the LUCID-2 detector [71] for the primary luminosity measurements. It is treated as a single normalization uncertainty applied as a scale factor to the signal models.

Parton distribution functions. The theoretical uncertainty envelope associated with the NNPDF 2.3 LO set of PDFs is propagated through the analysis, where their impact is primarily on the normalization of the signal events. The change in analysis selection efficiency is recalculated for each provided PDF variation, and the standard deviation of all such variations is taken as a measure of the systematic uncertainty due to the PDFs. This uncertainty is a sub-1% effect for all signal models considered.

Jet energy scale and resolution. Systematic uncertainties in the $R = 0.4$ JES and JER are evaluated using a series of *in situ* measurements and simulation-based techniques, documented in Ref. [92]. Improvements have been made to the component of the jet energy scale uncertainty related to the extrapolation of single-hadron response measurements [95, 96] and combined test-beam results [97, 98] into jets. These uncertainties are reduced by roughly a factor of two compared to those reported in Ref. [92]. Uncertainties due to differences between the gluon-initiated jet energy response of different MC generator setups have also been reduced ('jet flavor response' in Ref. [92]), by performing more granular comparisons of the effect of different parton shower and hadronization models on the jet response using the samples documented in Ref. [87]. Following the improved procedure compared with that documented in Ref. [92], the most significant source of uncertainty in the JES now originates from the absolute *in situ* JES calibration.

Variation of initial-state α_S value in the A14 set of tuned parameters. The A14 set of tuned parameters used in the Pythia 8 signal simulation includes a pair of 'eigentune variations' that can be used to assess the sensitivity of an analysis to the value of the QCD coupling, α_S, in initial-state radiation (ISR) [75]. The value of α_S was varied between $0.115 - 0.140$ from its initial value of 0.127. The impact of this variation is negligible compared with other systematic variations.

Theoretical renormalization and factorization scale variations. The QCD renormalization and factorization scales (μ_R, μ_F) used in the parton shower of the Pythia 8 signal samples are each varied up and down by a factor of two, via weights provided by the Pythia event generator [99]. These variations assess the sensitivity of the analysis to parton shower configurations that contain branchings that may compromise the Pythia parton shower's underlying assumptions. Scale variations for such configurations will result in a large variation for that shower. The theoretical uncertainties resulting from these scale variations in the mean of the signal distribution are typically less than 0.5%, and are smaller than the JES uncertainties.

Background modeling A systematic uncertainty to cover potential modeling biases is accounted for using the spurious signal S_{modeling}. The value of S_{modeling} is determined as the envelope of $|S_{\text{spur}}|$ over $m_{4\text{j}}$ and $\langle m_{2\text{j}} \rangle$ respectively. This is implemented as an additional signal contribution, such that

$$N_{\text{signal}}(m_{X,Y}) = \sigma_{\text{signal}} \mathcal{L} A \epsilon + S_{\text{modeling}}(m_{X,Y}) \theta_{\text{modeling}},$$

where $N_{\text{signal}}(m_{X,Y})$ is the number of extracted signal events at a given m_X or m_Y, $\mathcal{L}$, A, and ϵ are the integrated luminosity, acceptance, and efficiency factors respectively and θ_{modeling} is a nuisance parameter associated with the modeling uncertainty. The acceptance is defined as the fraction of simulated events at generator level passing the analysis selection cuts, while the efficiency is the fraction of reconstructed events passing the selection.

4 Results

4.1 Model-independent search

Example tetrajet and average dijet invariant mass distributions in data, together with the corresponding fitted background estimates, are shown in Figure 4 for two representative α regions. The example α regions are selected to show the highest tetrajet invariant mass, and the most significant localized excess observed in data. The data are well-described by the 4-parameter fit function in all α regions, and the global χ^2 p-value ranges from 0.74 to 1.00 for the $m_{4\text{j}}$ spectra, and from 0.08 to 1.00 for the $\langle m_{2\text{j}} \rangle$ spectra. The BumpHunter [62, 63] algorithm, as implemented in pyBumpHunter [64, 65], is used to quantify the statistical significance of possible resonant signals that may be present in the $m_{4\text{j}}$ and $\langle m_{2\text{j}} \rangle$ distributions. This is performed using mass bins where the bin width is determined by the mass resolution of $m_{4\text{j}}$ or $\langle m_{2\text{j}} \rangle$ as a function of the mass, where the mass resolution is determined using a Gaussian fit to the mass response distribution. The width of the invariant mass window scanned by BumpHunter is varied between two and six resolution bins, and all possible windows of the $m_{4\text{j}}$ and $\langle m_{2\text{j}} \rangle$ distributions are scanned, in each α region. For each scanned window, BumpHunter evaluates the statistical significance of the observed difference between the data distribution and the background fit. The BumpHunter p-value is defined as the smallest observed probability for the data in a given window to deviate from the background prediction by the observed amount due to a Poissonian fluctuation of the background, using pseudo-experiments generated from the background prediction. The most significant localized excesses identified by the BumpHunter algorithm are found at 3200 GeV in the α region from $0.24 < \alpha < 0.26$ for the $m_{4\mathrm{j}}$ spectra with a global significance of 0.53 standard deviations, and at 800 GeV in the α region from $0.26 < \alpha < 0.28$ for the $\langle m_{2\mathrm{j}} \rangle$ spectra with a global significance of 1.98 standard deviations.

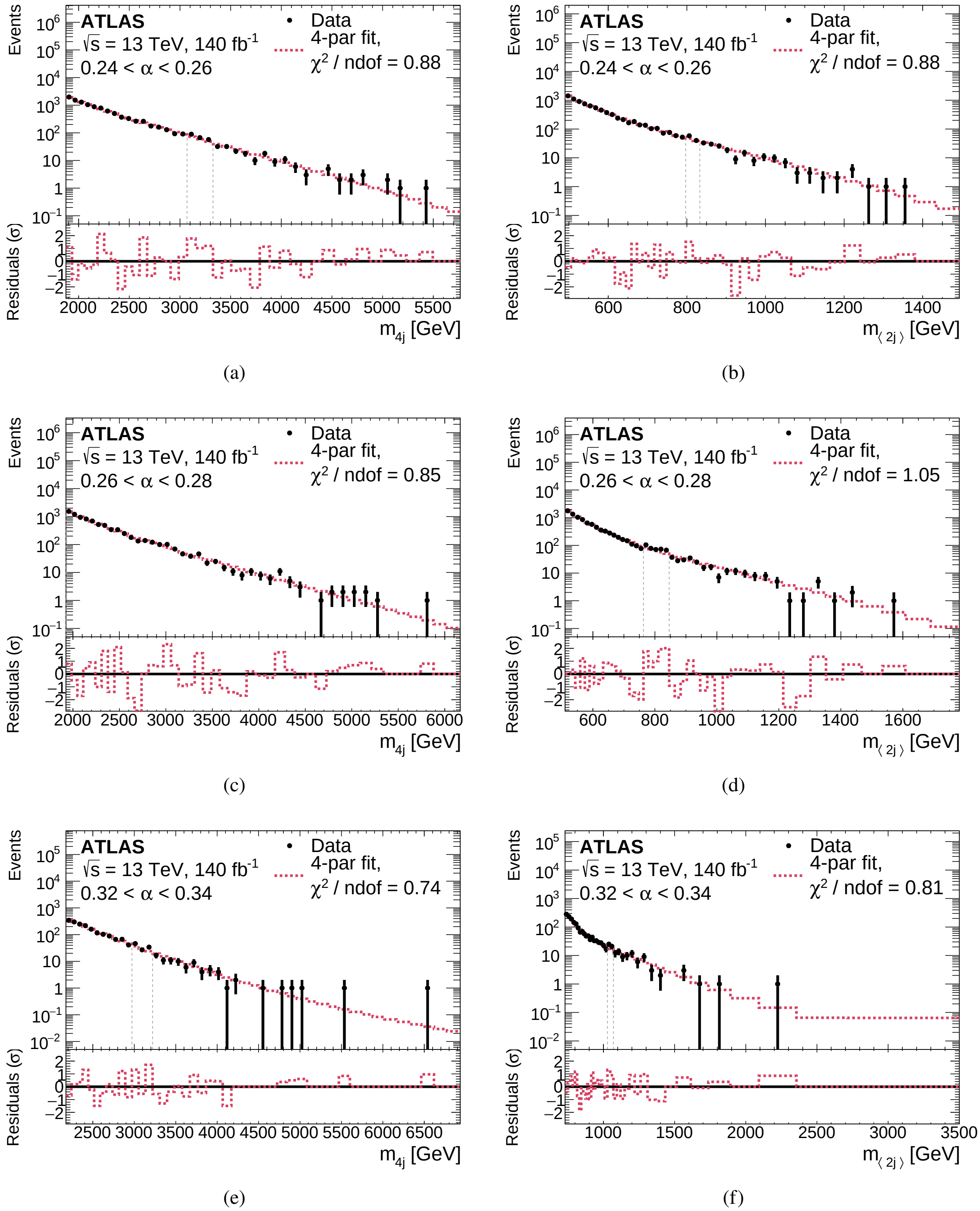


Figure 4: The (a, c, e) tetrajet and (b, d, f) average dijet invariant mass distributions in data are shown, along with the fitted background estimates for (a, b) $0.24 < \alpha < 0.26$, (c, d) $0.26 < \alpha < 0.28$, and (e, f) $0.32 < \alpha < 0.34$. The bottom panel of each figure illustrates the fit residuals in terms of standard deviations (σ).

4.2 Cross-section limits

As no signal is observed, limits can be placed on the range of possible production cross-sections for the hypothetical Y and X bosons.

The numbers of signal and background events are estimated from maximum-likelihood fits of the signal-plus-background models to the corresponding $m_{4\text{j}}$ and $\langle m_{2\text{j}} \rangle$ distributions. Systematic uncertainties described in Section 3.5 are included in the fits via nuisance parameters constrained by Gaussian penalty terms. The p-value is determined from a profile-likelihood-ratio test statistic [100]. The local p-value for compatibility with the background-only hypothesis when testing a given signal hypothesis (p_0) is evaluated based on the asymptotic approximation. Global significance values are computed from background-only pseudo-experiments to account for the trial factors due to scanning both the signal mass and the width hypotheses. The expected and observed 95% confidence level (CL) exclusion limits on the product of the cross-section, branching ratio and acceptance are computed using a modified frequentist-approach CL_s [101], in an asymptotic approximation to the test-statistic distribution.

Figure 5 shows the 95% CL upper limits on the allowed cross-sections of these particles as a function of their mass, derived using the signal templates used to optimize the analysis for two representative α regions. Results are interpolated linearly in the logarithm of the cross-section. Similar results are shown in Figure 6 for the Gaussian signal templates with 5%, 10%, and 15% signal widths. A summary of the limits for all generated signal masses is shown in Figure 7 for m_Y and m_X as a function of α. Overall, the limits are smooth as a function of the mass and α, and flatten out in the high-mass region where the background estimation predicts significantly less than one event.

The relative contribution of statistical and systematic uncertainties (see Section 3.5) on the final analysis sensitivity was assessed by repeating the limit-setting procedure while including only statistical sources of uncertainty. The analysis sensitivity was not observed to significantly differ during this test.

To better illustrate different types of events passing the event selection, two event displays are shown in Figure 8. The first shows the event with the highest four-jet mass, with a value of $m_{4\text{j}} = 6.6$ TeV and corresponding $\langle m_{2\text{j}} \rangle = 2.2$ TeV, while the second shows the event with the highest-p_T fourth jet that is selected ($m_{4\text{j}} = 5.2$ TeV, $\langle m_{2\text{j}} \rangle = 0.90$ TeV).

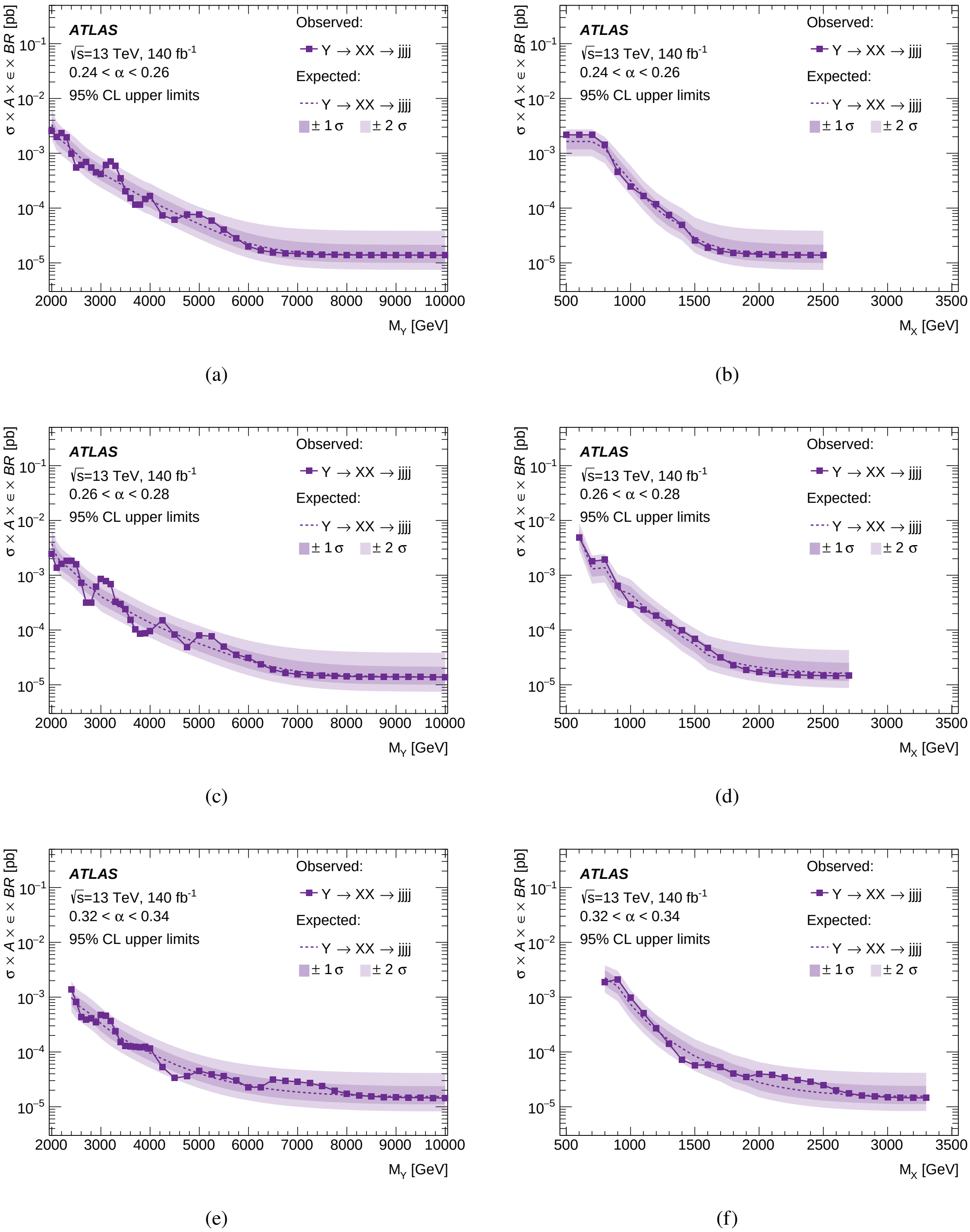


Figure 5: The expected and observed 95% confidence exclusion limits on the signal cross-section times acceptance (A), efficiency (ε), and branching ratio (BR) as a function of (a, c, e) m_Y and (b, d, f) m_X using the signal templates and a 4-parameter fit function for (a, b) $0.24 < \alpha < 0.26$, (c, d) $0.26 < \alpha < 0.28$, and (e, f) $0.32 < \alpha < 0.34$. Observed and expected limits are indicated with markers or a dashed line, respectively. The shaded bands around the expected limit indicates the (darker band) 1σ and (lighter band) 2σ uncertainty range.

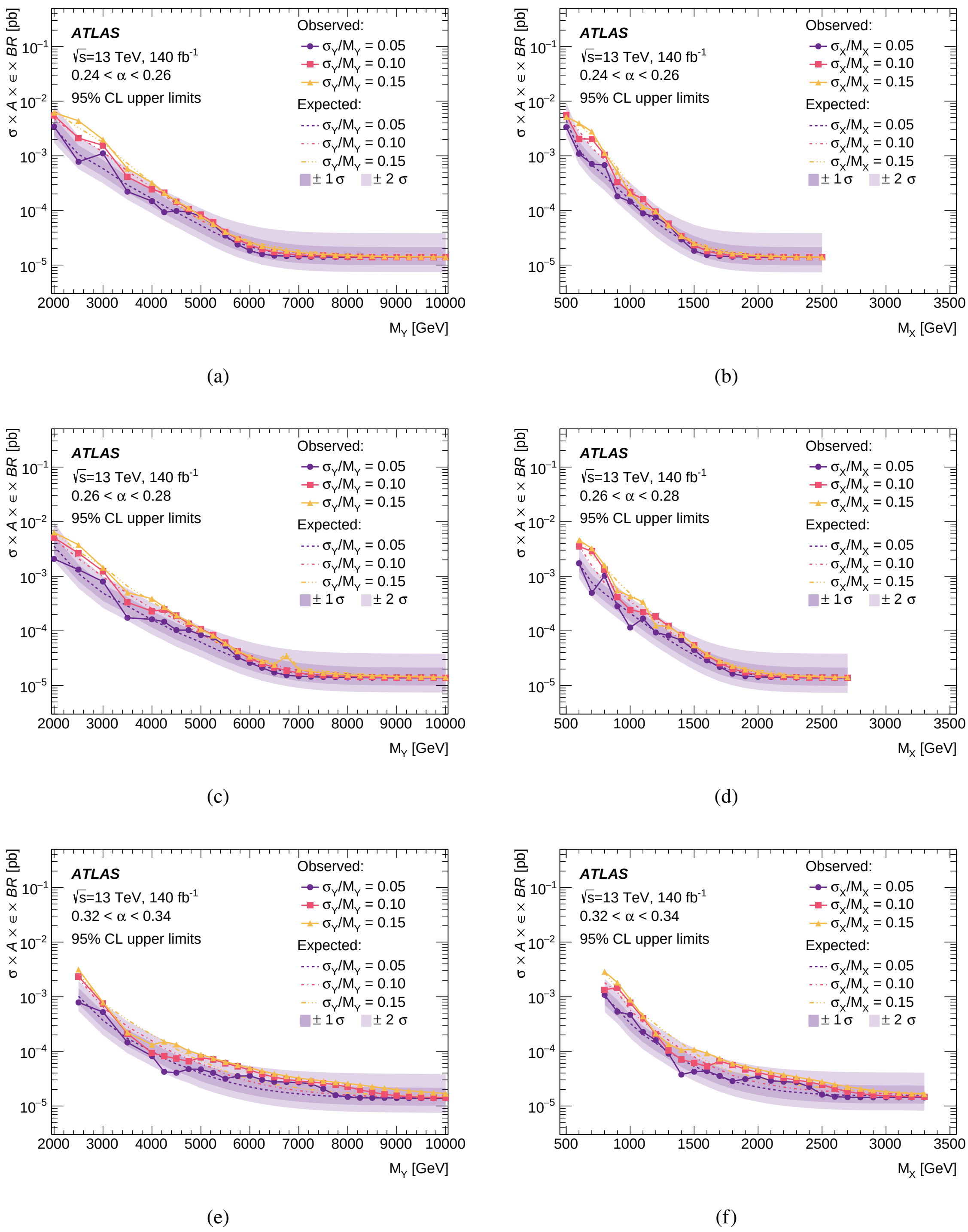
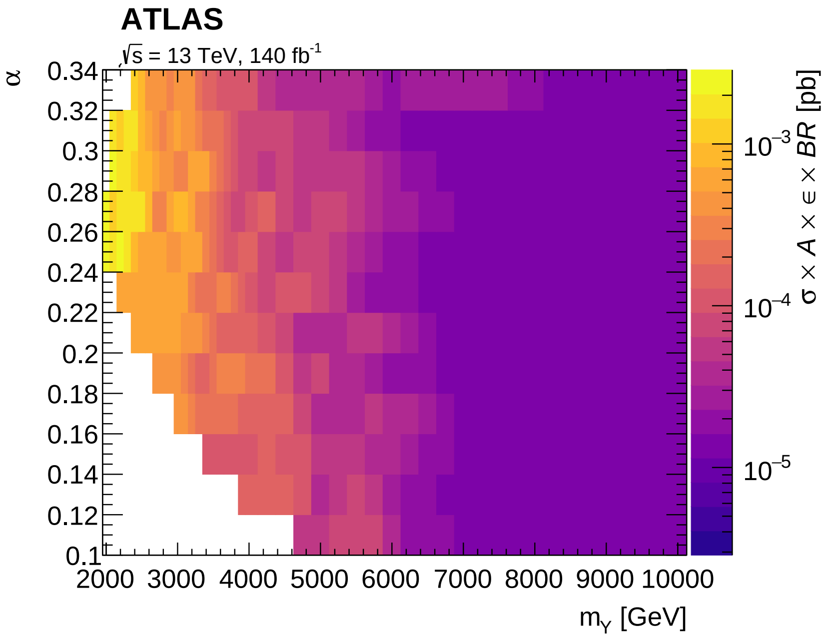
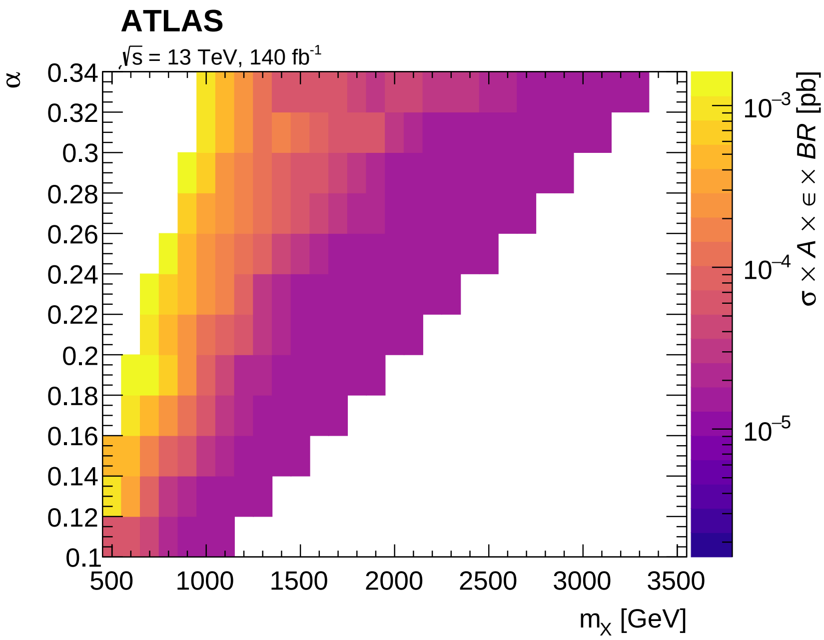


Figure 6: The expected and observed limits on the signal cross-section times acceptance (A), efficiency (ε), and branching ratio (BR) as a function of (a, c, e) m_Y and (b, d, f) m_X for Gaussian signal templates using a 4-parameter fit function for (a, b) $0.24 < \alpha < 0.26$, (c, d) $0.26 < \alpha < 0.28$, and (e, f) $0.32 < \alpha < 0.34$. Observed and expected limits corresponding to different choices of template widths (5%, 10% and 15%) are indicated as different sets of markers or line styles, respectively. The shaded bands around the expected limit for templates with 5% width indicate the (darker band) 1σ and (lighter band) 2σ uncertainty range.

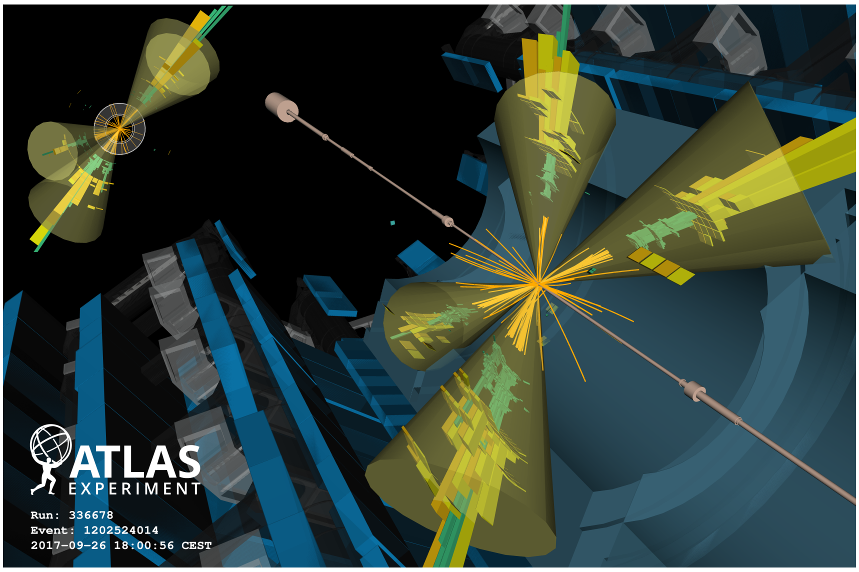


(a)

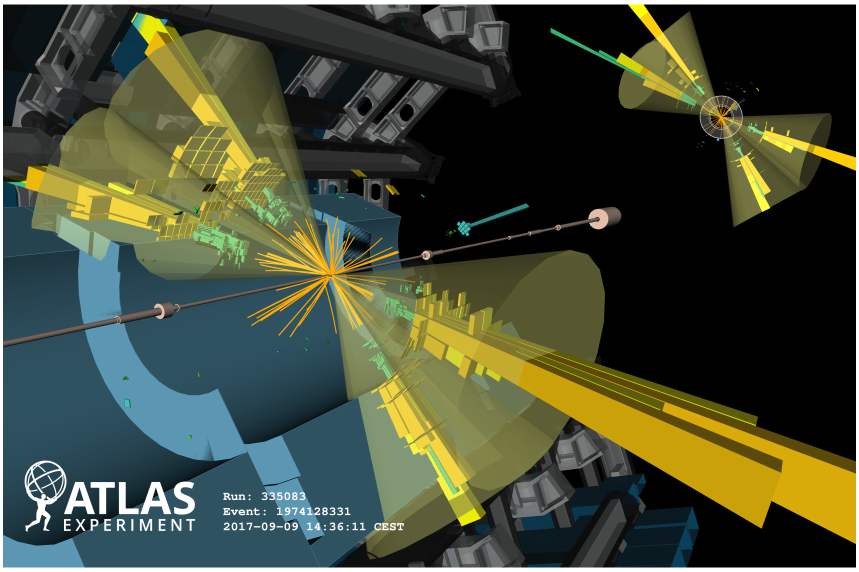


(b)

Figure 7: The observed 95% confidence exclusion limits on the signal cross-section times acceptance (A), efficiency (ε), and branching ratio (BR) as a function of (a) m_Y, and (b) m_X for signals templates using a 4-parameter fit function.



(a)



(b)

Figure 8: Event display of multijet events (a) Run 336678, Event 1202524014 and (b) Run 335083, Event 1924128331 from proton–proton collisions recorded by ATLAS with LHC stable beams at a collision energy of 13 TeV. The former event is displayed from a side-view where the beamline runs horizonally across the image, while the latter event is displayed in a transverse view, down the beamline. Event (a) possesses the largest tetrajet invariant mass observed in the search (m_{4j} = 6.6 TeV, $\langle m_{2j} \rangle$ = 2.2 TeV), and the p_T values of the four selected jets are 2 TeV, 1.2 TeV, 1.2 TeV and 0.5 TeV. Event (b) is the event with the highest-p_T fourth-jet passing the event selection (m_{4j} = 5.2 TeV, $\langle m_{2j} \rangle$ = 0.90 TeV), and the p_T values of the four selected jets are 1.6 TeV, 1.3 TeV, 1.2 TeV and 1.0 TeV. Tracks with momenta greater than 1 GeV are shown as yellow lines, and energy depositions in the Liquid Argon and Tile calorimeters cells are displayed, respectively, as green and yellow boxes.

5 Conclusion

A search for the production of a generic massive resonance Y that decays into two pairs of intermediate resonances X, each decaying into two jets, is performed using 140 fb^{-1} of proton–proton collisions with $\sqrt{s}$ = 13 TeV collected with the ATLAS Detector during Run 2 of the LHC. Such a resonant signal in multijet events could be manifested in many models of physics beyond the Standard Model, including in well-motivated models of particle dark matter and models with large extra spatial dimensions.

A data-driven background estimate is obtained by fitting these invariant mass distributions with a functional form. The tetrajet system and average dijet system invariant masses are then studied using the BumpHunter algorithm. No significant excess of events beyond the Standard Model expectation is observed. The most significant localized excesses are found at 3200 GeV in the α region from $0.24 < \alpha < 0.26$ for the m_{4j} spectra (global significance of 0.53 standard deviations), and at 800 GeV in the α region from $0.26 < \alpha < 0.28$ for the $\langle m_{2j} \rangle$ spectra (global significance of 1.98 standard deviations). The highest tetrajet invariant mass observed is m_{4j} = 6.6 TeV, with a corresponding $\langle m_{2j} \rangle$ value of 2.2 TeV. Using the observed data, upper limits are set on the production cross-sections of new physics scenarios as a function of the Y and X masses in both the model-dependent and model-independent interpretations.

Data distributions from this search are openly available on the HEPData platform [102] for use in future reinterpretations.

Acknowledgments

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; ANID, Chile; CAS, MOST and NSFC, China; Minciencias, Colombia; MEYS CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS and CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF and MPG, Germany; GSRI, Greece; RGC and Hong Kong SAR, China; ISF and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MEiN, Poland; FCT, Portugal; MNE/IFA, Romania; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DSI/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TENMAK, Türkiye; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, CANARIE, Compute Canada and CRC, Canada; PRIMUS 21/SCI/017 and UNCE SCI/013, Czech Republic; COST, ERC, ERDF, Horizon 2020 and Marie Skłodowska-Curie Actions, European Union; Investissements d'Avenir Labex, Investissements d'Avenir Idex and ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF, Greece; BSF-NSF and MINERVA, Israel; Norwegian Financial Mechanism 2014-2021, Norway; NCN and NAWA, Poland; La Caixa Banking Foundation, CERCA Programme Generalitat de Catalunya and PROMETEO and GenT Programmes Generalitat Valenciana, Spain; Göran Gustafssons Stiftelse, Sweden; The Royal Society and Leverhulme Trust, United Kingdom.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3

(France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [103].

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