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Search for squarks and gluinos in final states with jets and missing transverse momentum using 36 fb⁻¹ of $\sqrt{s} = 13$ TeV pp collision data with the ATLAS detector

The ATLAS Collaboration

A search for the supersymmetric partners of quarks and gluons (squarks and gluinos) in final states containing hadronic jets and missing transverse momentum, but no electrons or muons, is presented. The data used in this search were recorded in 2015 and 2016 by the ATLAS experiment in $\sqrt{s} = 13$ TeV proton–proton collisions at the Large Hadron Collider, corresponding to an integrated luminosity of 36.1 fb⁻¹. The results are interpreted in the context of various models where squarks and gluinos are pair-produced and the neutralino is the lightest supersymmetric particle. An exclusion limit at the 95% confidence level on the mass of the gluino is set at 2.03 TeV for a simplified model incorporating only a gluino and the lightest neutralino, assuming the lightest neutralino is massless. For a simplified model involving the strong production of mass-degenerate first- and second-generation squarks, squark masses below 1.55 TeV are excluded if the lightest neutralino is massless. These limits substantially extend the region of supersymmetric parameter space previously excluded by searches with the ATLAS detector.

1 Introduction

Supersymmetry (SUSY) [1–6] is a generalization of space-time symmetries that predicts new bosonic partners for the fermions and new fermionic partners for the bosons of the Standard Model (SM). If R -parity is conserved [7], SUSY particles, called sparticles, are produced in pairs and the lightest supersymmetric particle (LSP) is stable and represents a possible dark-matter candidate. The scalar partners of the left- and right-handed quarks, the squarks \tilde{q}_L and \tilde{q}_R , mix to form two mass eigenstates \tilde{q}_1 and \tilde{q}_2 ordered by increasing mass. Superpartners of the charged and neutral electroweak and Higgs bosons also mix, producing charginos ($\tilde{\chi}^\pm$) and neutralinos ($\tilde{\chi}^0$). Squarks and the fermionic partners of the gluons, the gluinos (\tilde{g}), could be produced in strong-interaction processes at the Large Hadron Collider (LHC) [8] and decay via cascades ending with the stable LSP, which escapes the detector unseen, producing substantial missing transverse momentum (\vec{E}_T^{miss}).

The large cross-sections predicted for the strong production of supersymmetric particles make the production of gluinos and squarks a primary target in searches for SUSY in proton–proton (pp) collisions at a center-of-mass energy of 13 TeV at the LHC. Interest in these searches is motivated by the large available choice of parameters for R -parity-conserving models in the Minimal Supersymmetric Standard Model (MSSM) [9, 10] where squarks (including anti-squarks) and gluinos can be produced in pairs ($\tilde{g}\tilde{g}$, $\tilde{q}\tilde{q}$, $\tilde{q}\tilde{g}$) and can decay through $\tilde{q} \rightarrow q\tilde{\chi}_1^0$ and $\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$ to the lightest neutralino, $\tilde{\chi}_1^0$, assumed to be the LSP. Additional decay modes can include the production of charginos via $\tilde{q} \rightarrow q\tilde{\chi}^\pm$ (where \tilde{q} and q are of different flavor) and $\tilde{g} \rightarrow qq\tilde{\chi}^\pm$, or neutralinos via $\tilde{g} \rightarrow qq\tilde{\chi}_2^0$. Subsequent chargino decay to $W^\pm\tilde{\chi}_1^0$ or neutralino decay to $Z\tilde{\chi}_1^0$ or $h\tilde{\chi}_1^0$, depending on the decay modes of W , Z and h bosons, can increase the jet multiplicity and missing transverse momentum.

This paper presents two approaches to search for these sparticles in final states containing only hadronic jets and large missing transverse momentum. The first is an update of the analysis [11] (referred to as ‘Meff-based search’ in the following). The second is a complementary search using the recursive jigsaw reconstruction (RJR) technique [12–14] in the construction of a discriminating variable set (‘RJR-based search’). By using a dedicated set of selection criteria, the RJR-based search improves the sensitivity to supersymmetric models with small mass splittings between the sparticles (models with compressed spectra). Both searches presented here adopt the same general approach as the analysis of the 7 TeV, 8 TeV and 13 TeV data collected during Run 1 and Run 2 of the LHC, described in Ref. [11]. The CMS Collaboration has set limits on similar models in Refs. [15–18].

In the searches presented here, events with reconstructed electrons or muons are rejected to avoid any overlap with a complementary ATLAS search in final states with one lepton, jets and missing transverse momentum [19], and to reduce the background from events with neutrinos ($W \rightarrow e\nu, \mu\nu$). The selection criteria are optimized in the $m_{\tilde{g}}, m_{\tilde{\chi}_1^0}$ and $m_{\tilde{q}}, m_{\tilde{\chi}_1^0}$ planes, (where $m_{\tilde{g}}$, $m_{\tilde{q}}$ and $m_{\tilde{\chi}_1^0}$ are the gluino, squark, and LSP masses, respectively) for simplified models [20–22], and in the $m_{\tilde{g}}, m_{\tilde{q}}$ plane for the simplified phenomenological MSSM (pMSSM) models [23, 24] in which the number of MSSM parameters is reduced using existing experimental and theoretical constraints. Although interpreted in terms of SUSY models, the results of this analysis could also constrain any model of new physics that predicts the production of jets in association with missing transverse momentum.

The paper is organized as follows. Section 2 describes the ATLAS experiment and data samples used, and Section 3 Monte Carlo (MC) simulation samples used for background and signal modeling. Event reconstruction and identification are presented in Section 4. The analysis strategy used by both searches is given in Section 5. Since the RJR technique is a new approach for this search, Section 6 is dedicated

to the description of the technique and associated variables. Searches are performed in signal regions that are defined in Section 7. Summaries of the background estimation methodology and corresponding systematic uncertainties are presented in Sections 8 and 9, respectively. Results obtained using the signal regions optimized for both searches are reported in Section 10. Section 11 is devoted to conclusions.

2 The ATLAS detector and data samples

The ATLAS detector [25] is a multipurpose detector with a forward-backward symmetric cylindrical geometry and nearly 4π coverage in solid angle¹. The inner detector (ID) tracking system consists of pixel and silicon microstrip detectors covering the pseudorapidity region $|\eta| < 2.5$, surrounded by a transition radiation tracker, which improves electron identification over the region $|\eta| < 2.0$. The innermost pixel layer, the insertable B-layer [26], was added between Run 1 and Run 2 of the LHC, at a radius of 33 mm around a new, narrower and thinner beam pipe. The ID is surrounded by a thin superconducting solenoid providing an axial 2 T magnetic field and by a fine-granularity lead/liquid-argon (LAr) electromagnetic calorimeter covering $|\eta| < 3.2$. A steel/scintillator-tile calorimeter provides hadronic coverage in the central pseudorapidity range ($|\eta| < 1.7$). The endcap and forward regions ($1.5 < |\eta| < 4.9$) are made of LAr active layers with either copper or tungsten as the absorber material for electromagnetic and hadronic measurements. The muon spectrometer with an air-core toroid magnet system surrounds the calorimeters. Three layers of high-precision tracking chambers provide coverage in the range $|\eta| < 2.7$, while dedicated chambers allow triggering in the region $|\eta| < 2.4$.

The ATLAS trigger system [27] consists of two levels; the first level is a hardware-based system, while the second is a software-based system called the high-level trigger. The events used by the searches described in this paper were selected using a trigger logic that accepts events with a missing transverse momentum above 70 GeV (for data collected during 2015) or above 90–110 GeV (depending on data-taking period for data collected in 2016) calculated using a vectorial sum of the jet transverse momenta. The trigger is 100% efficient for the event selections considered in these analyses. Auxiliary data samples used to estimate the yields of background events were selected using triggers requiring at least one isolated electron ($p_T > 24$ GeV), muon ($p_T > 20$ GeV) or photon ($p_T > 120$ GeV) for data collected in 2015. For the 2016 data, the events used for the background estimation were selected using triggers requiring at least one isolated electron or muon ($p_T > 26$ GeV) or photon ($p_T > 140$ GeV).

The data were collected by the ATLAS detector during 2015 with a peak delivered instantaneous luminosity of $L = 5.2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$, and during 2016 with a maximum of $L = 1.37 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. The mean number of pp interactions per bunch crossing in the dataset was 14 in 2015 and 24 in 2016. Application of beam, detector and data-quality criteria resulted in a total integrated luminosity of 36.1 fb^{-1} . The uncertainty in the integrated luminosity averaged over both years is 3.2%. It is derived, following a methodology similar to that detailed in Ref. [28], from a preliminary calibration of the luminosity scale using a pair of x – y beam-separation scans performed in August 2015 and May 2016.

¹ ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the center of the detector. The positive x -axis is defined by the direction from the interaction point to the center of the LHC ring, with the positive y -axis pointing upwards, while the beam direction defines the z -axis. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z -axis. The pseudorapidity η is defined in terms of the polar angle θ by $\eta = -\ln \tan(\theta/2)$ and the rapidity is defined as $y = (1/2) \ln[(E + p_z)/(E - p_z)]$ where E is the energy and p_z the longitudinal momentum of the object of interest. The transverse momentum p_T , the transverse energy E_T and the missing transverse momentum E_T^{miss} are defined in the x – y plane unless stated otherwise.

3 Monte Carlo samples

A set of simulated MC event samples was used to optimize the selections, estimate backgrounds and assess the sensitivity to specific SUSY signal models.

Simplified models and pMSSM models are both used as SUSY signals in this paper. Simplified models are defined by an effective Lagrangian describing the interactions of a small number of new particles, assuming one production process and one decay channel with a 100% branching fraction. Signal samples are used to describe squark and gluino pair production, followed by the direct ($\tilde{q} \rightarrow q\tilde{\chi}_1^0$) or one-step ($\tilde{q} \rightarrow qW\tilde{\chi}_1^0$) decays of squarks and direct ($\tilde{g} \rightarrow qq\tilde{\chi}_1^0$) or one-step ($\tilde{g} \rightarrow qqW/Z/h\tilde{\chi}_1^0$) decays of gluinos as shown in Figure 1. Direct decays are those where the considered SUSY particles decay directly into SM particles and the LSP, while the one-step decays refer to the cases where the decays occur via one intermediate on-shell SUSY particle, as indicated in parentheses. In pMSSM models, gluino and first- and second-generation squark production are considered inclusively, followed by direct decays of squarks and gluinos, or decays of squarks via gluinos ($\tilde{q} \rightarrow q\tilde{g}$) and decays of gluinos via squarks ($\tilde{g} \rightarrow q\tilde{q}$) if kinematically possible. All other supersymmetric particles, including the squarks of the third generation, have their masses set such that the particles are effectively decoupled. These samples were generated with up to two (simplified models) or one (pMSSM models) extra partons in the matrix element using the MG5_aMC@NLO 2.2.2 or 2.3.3 event generator [29] interfaced to PYTHIA 8.186 [30]. The CKKW-L merging scheme [31] was applied with a scale parameter that was set to a quarter of the mass of the gluino for $\tilde{g}\tilde{g}$ production or of the squark for $\tilde{q}\tilde{q}$ production in simplified models. In pMSSM models, a quarter of the smaller of the gluino and squark masses was used for CKKW-L merging scale. The A14 [32] set of tuned parameters (tune) was used for initial/final-state radiation (ISR/FSR) and underlying-event parameters together with the NNPDF2.3LO [33] parton distribution function (PDF) set. The signal cross-sections were calculated at next-to-leading order (NLO) in the strong coupling constant, adding the resummation of soft gluon emission at next-to-leading-logarithmic accuracy (NLO+NLL) [34–38]. The nominal squark and gluino cross-sections were taken from an envelope of predictions using different PDF sets and factorization and renormalization scales, as described in Ref. [39], considering only first- and second-generation squarks ($\tilde{u}, \tilde{d}, \tilde{s}, \tilde{c}$). Eightfold degeneracy of first- and second-generation squarks is assumed for the simplified models with direct decays of squarks and pMSSM models while fourfold degeneracy is assumed for the simplified models with one-step decays of squarks. In the case of gluino pair (squark pair) production in simplified models, cross-sections were evaluated assuming arbitrarily high masses of 450 TeV for the first- and second-generation squarks (gluinos) in order to decouple them. The free parameters are $m_{\tilde{\chi}_1^0}$ and $m_{\tilde{q}} (m_{\tilde{g}})$ for squark pair (gluino pair) production in simplified models, while both $m_{\tilde{q}}$ and $m_{\tilde{g}}$ are varied in pMSSM models with $m_{\tilde{\chi}_1^0}$ fixed.

In the simulation of the production of W or Z/γ^* bosons in association with jets [40] using the SHERPA 2.2.1 event generator [41], the matrix elements were calculated for up to two partons at NLO and up to two additional partons at leading order (LO) using the COMIX [42] and OPEN LOOPS [43] matrix-element generators, and merged with the SHERPA parton shower [44] using the ME+PS@NLO prescription [45]. Simulated events containing a photon in association with jets were generated requiring a photon transverse momentum above 35 GeV. For these events, matrix elements were calculated at LO with up to three or four partons depending on the p_T of the photon, and merged with the SHERPA parton shower using the ME+PS@LO prescription [46]. The $W/Z + \text{jets}$ events were normalized using their NNLO cross-sections [47] while for the $\gamma + \text{jets}$ process the LO cross-section, taken directly from the SHERPA MC event generator, was multiplied by a correction factor as described in Section 8.

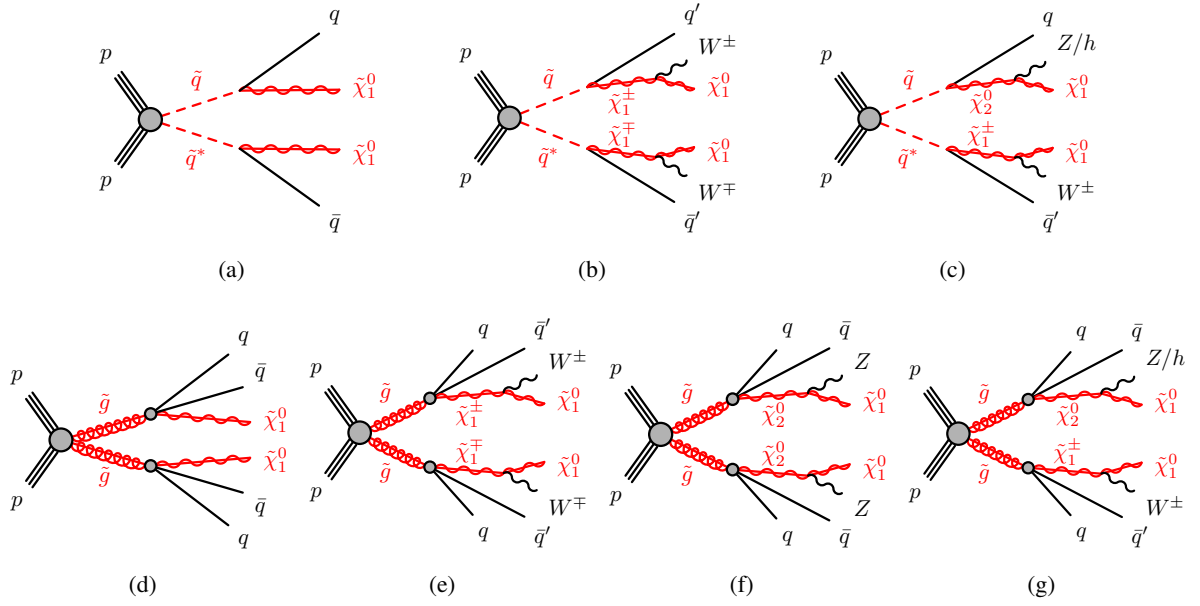


Figure 1: The decay topologies of (a,b,c) squark pair production and (d, e, f, g) gluino pair production in the simplified models with (a) direct or (b,c) one-step decays of squarks and (d) direct or (e, f, g) one-step decays of gluinos.

For the generation of $t\bar{t}$ and single-top processes in the Wt and s -channel [48], the POWHEG-Box v2 [49] generator was used, while electroweak (EW) t -channel single-top events was modeled using POWHEG-Box v1. This latter generator uses the four-flavor scheme for the NLO matrix-element calculations together with the fixed four-flavor PDF set CT10f4 [50]. For each of these processes, the decay of the top quark was simulated using MadSpin [51] preserving all spin correlations, while for all processes the parton shower, fragmentation, and the underlying event were generated using PYTHIA 6.428 [52] with the CTEQ6L1 [53] PDF set and the corresponding Perugia 2012 tune (P2012) [54]. The top quark mass was set to 172.5 GeV. The h_{damp} parameter, which controls the p_T of the first additional emission beyond the Born configuration, was set to the mass of the top quark in the $t\bar{t}$ process. The main effect of this parameter is to regulate the high- p_T emission against which the $t\bar{t}$ system recoils [48]. The $t\bar{t}$ events were normalized using cross-sections calculated at NNLO+NNLL [55, 56] accuracy, while s - and t -channel single-top events were normalized using the NLO cross-sections [57, 58], and the Wt -channel single-top events were normalized using the NNLO+NNLL cross-sections [59, 60]. Production of a top quark in association with a Z boson is generated with the MG5_aMC@NLO 2.2.1 generator at LO with CTEQ6L1 PDF set.

For the generation of $t\bar{t} + \text{EW}$ processes ($t\bar{t} + W/Z/WW$) [61], the MG5_aMC@NLO 2.2.3 generator at LO interfaced to the PYTHIA 8.186 parton-shower model was used, with up to two ($t\bar{t} + W$, $t\bar{t} + Z(\rightarrow \nu\nu/qq)$), one ($t\bar{t} + Z(\rightarrow \ell\ell)$) or no ($t\bar{t} + WW$) extra partons included in the matrix element. The events were normalized using their respective NLO cross-sections [62, 63] and the top quark mass was set to 172.5 GeV.

Diboson processes (WW , WZ , ZZ) [64] were simulated using the SHERPA 2.1.1 generator. For processes with four charged leptons (4ℓ), three charged leptons and a neutrino ($3\ell + 1\nu$) or two charged leptons and two neutrinos ($2\ell + 2\nu$), the matrix elements contain all diagrams with four electroweak couplings, and were calculated for up to one (4ℓ , $2\ell + 2\nu$) or no partons ($3\ell + 1\nu$) at NLO. For processes in which one

Table 1: The SUSY signals and the SM background MC simulation samples used in this paper. The generators, the order in α_s of cross-section calculations used for yield normalization, PDF sets, parton showers and tunes used for the underlying event are shown.

| Physics process | Generator | Cross-section normalization | PDF set | Parton shower | Tune |
|--|-------------------------|-----------------------------|--------------|---------------|----------------|
| SUSY processes | MG5_aMC@NLO 2.2.2–2.3.3 | NLO+NLL | NNPDF2.3LO | PYTHIA 8.186 | A14 |
| $W(\rightarrow \ell\nu) + \text{jets}$ | SHERPA 2.2.1 | NNLO | NNPDF3.0NNLO | SHERPA | SHERPA default |
| $Z/\gamma^*(\rightarrow \ell\bar{\ell}) + \text{jets}$ | SHERPA 2.2.1 | NNLO | NNPDF3.0NNLO | SHERPA | SHERPA default |
| $\gamma + \text{jets}$ | SHERPA 2.1.1 | LO | CT10 | SHERPA | SHERPA default |
| $t\bar{t}$ | Powheg-Box v2 | NNLO+NNLL | CT10 | PYTHIA 6.428 | PERUGIA2012 |
| Single top (Wt -channel) | Powheg-Box v2 | NNLO+NNLL | CT10 | PYTHIA 6.428 | PERUGIA2012 |
| Single top (s -channel) | Powheg-Box v2 | NLO | CT10 | PYTHIA 6.428 | PERUGIA2012 |
| Single top (t -channel) | Powheg-Box v1 | NLO | CT10f4 | PYTHIA 6.428 | PERUGIA2012 |
| Single top (Zt -channel) | MG5_aMC@NLO 2.2.1 | LO | CTEQ6L1 | PYTHIA 6.428 | PERUGIA2012 |
| $t\bar{t} + W/Z/WW$ | MG5_aMC@NLO 2.2.3 | NLO | NNPDF2.3LO | PYTHIA 8.186 | A14 |
| WW, WZ, ZZ | SHERPA 2.1.1 | NLO | CT10 | SHERPA | SHERPA default |

of the bosons decays hadronically and the other leptonically, matrix elements were calculated for up to one (ZZ) or no (WW, WZ) additional partons at NLO. All diboson samples also simulated up to three additional partons at LO using the COMIX and OPENLOOPS matrix-element generators, and were merged with the SHERPA parton shower using the ME+PS@NLO prescription.

A summary of the SUSY signals and the SM background processes together with the MC event generators, cross-section calculation orders in α_s , PDFs, parton shower and tunes used is given in Table 1.

For all SM background samples the response of the detector to particles was modeled with a full ATLAS detector simulation [65] based on GEANT4 [66]. Signal samples were prepared using a fast simulation based on a parameterization of the performance of the ATLAS electromagnetic and hadronic calorimeters [67] and on GEANT4 elsewhere. The EvtGen v1.2.0 program [68] was used to describe the properties of the b - and c -hadron decays in the signal samples, and the background samples except those produced with SHERPA [41].

All simulated events were overlaid with multiple pp collisions simulated with PYTHIA 8.186 using the A2 tune [32] and the MSTW2008LO parton distribution functions [69]. The MC samples were generated with a variable number of additional pp interactions (pileup), and were reweighted to match the distribution of the mean number of interactions observed in data.

4 Event reconstruction and identification

The reconstructed primary vertex of the event is required to be consistent with the luminous region and to have at least two associated tracks with $p_T > 400$ MeV. When more than one such vertex is found, the vertex with the largest $\sum p_T^2$ of the associated tracks is chosen.

Jet candidates are reconstructed using the anti- k_r jet clustering algorithm [70, 71] with a jet radius parameter of 0.4 starting from clusters of calorimeter cells [72]. The jets are corrected for energy from pileup using the method described in Ref. [73]: a contribution equal to the product of the jet area and the median energy density of the event is subtracted from the jet energy [74]. Further corrections, referred to as the jet energy scale corrections, are derived from MC simulation and data, and are used to calibrate the average energies of jets to the scale of their constituent particles [75]. Only corrected jet candidates with

$p_T > 20$ GeV and $|\eta| < 2.8$ are retained. An algorithm based on boosted decision trees, ‘MV2c10’ [76, 77], is used to identify jets containing a b -hadron (b -jets), with an operating point corresponding to an efficiency of 77%, and rejection factors of 134 for light-quark jets and 6 for charm jets [77] for reconstructed jets with $p_T > 20$ GeV and $|\eta| < 2.5$ in simulated $t\bar{t}$ events. Candidate b -jets are required to have $p_T > 50$ GeV and $|\eta| < 2.5$. Events with jets originating from detector noise and non-collision background are rejected if the jets fail to satisfy the ‘LooseBad’ quality criteria, or if at least one of the two leading jets with $p_T > 100$ GeV fails to satisfy the ‘TightBad’ quality criteria, both described in Ref. [78]. The application of these requirements reduces the data sample by less than 1%. In order to reduce the number of jets coming from pileup, a significant fraction of the tracks associated with each jet must have an origin compatible with the primary vertex. This is enforced by using the jet vertex tagger (JVT) output using the momentum fraction of tracks [79]. The requirement $\text{JVT} > 0.59$ is only applied to jets with $p_T < 60$ GeV and $|\eta| < 2.4$.

Two different classes of reconstructed lepton candidates (electrons or muons) are used in the analyses presented here. When selecting samples for the search, events containing a ‘baseline’ electron or muon are rejected. The selections applied to identify baseline leptons are designed to maximize the efficiency with which W +jets and top quark background events are rejected. When selecting ‘control region’ samples for the purpose of estimating residual W +jets and top quark backgrounds, additional requirements are applied to leptons to ensure greater purity of these backgrounds. These leptons are referred to as ‘high-purity’ leptons below and form a subset of the baseline leptons.

Baseline muon candidates are formed by combining information from the muon spectrometer and inner detector as described in Ref. [80] and are required to have $p_T > 7$ GeV and $|\eta| < 2.7$. High-purity muon candidates must additionally have $p_T > 27$ GeV and $|\eta| < 2.4$, the significance of the transverse impact parameter with respect to the primary vertex $|d_0^{\text{PV}}|/\sigma(d_0^{\text{PV}}) < 3$, and the longitudinal impact parameter with respect to the primary vertex $|z_0^{\text{PV}}\sin(\theta)| < 0.5$ mm. Furthermore, high-purity candidates must satisfy the ‘GradientLoose’ isolation requirements described in Ref. [80], which rely on tracking-based and calorimeter-based variables and implement a set of η - and p_T -dependent criteria.

Baseline electron candidates are reconstructed from an isolated electromagnetic calorimeter energy deposit matched to an ID track and are required to have $p_T > 7$ GeV, $|\eta| < 2.47$, and to satisfy ‘Loose’ likelihood-based identification criteria described in Ref. [81]. High-purity electron candidates additionally must satisfy ‘Tight’ selection criteria described in Ref. [81], and the leading electron must have $p_T > 27$ GeV. They are also required to have $|d_0^{\text{PV}}|/\sigma(d_0^{\text{PV}}) < 5$, $|z_0^{\text{PV}}\sin(\theta)| < 0.5$ mm, and to satisfy isolation requirements similar to those applied to high-purity muons [81].

After the selections described above, ambiguities between candidate jets with $|\eta| < 2.8$ and leptons are resolved as follows: first, any such jet candidate that is not tagged as b -jet, lying within a distance $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.2$ of a baseline electron is discarded. If a jet candidate is b -tagged it is interpreted as a jet and the overlapping electron is ignored. Additionally, if a baseline electron (muon) and a jet passing the JVT selection described above are found within $0.2 \leq \Delta R < 0.4$ ($< \min(0.4, 0.04 + 10 \text{ GeV}/p_T^\mu)$), it is interpreted as a jet and the nearby electron (muon) candidate is discarded. Finally, if a baseline muon and jet are found within $\Delta R < 0.2$, it is treated as a muon and the overlapping jet is ignored, unless the jet satisfies $N_{\text{trk}} < 3$, where N_{trk} refers to the number of tracks with $p_T > 500$ MeV that are associated with the jet, in which case the muon is ignored. This criterion rejects jets consistent with final-state radiation or hard bremsstrahlung.

Additional ambiguities between electrons and muons in a jet, originating from the decays of hadrons, are resolved to avoid double counting and/or remove non-isolated leptons: the electron is discarded if a

baseline electron and a baseline muon share the same ID track.

Reconstructed photons are used in the missing transverse momentum reconstruction as well as in the control region used to constrain the Z +jets background, as explained in Section 8. These latter photon candidates are required to satisfy $p_T > 150$ GeV and $|\eta| < 2.37$, photon shower shape and electron rejection criteria, and to be isolated [82]. The reduced η range for photons is chosen to avoid a region of coarse granularity at high η where photon and π^0 separation worsens. Ambiguities between candidate jets and photons (when used in the event selection) are resolved by discarding any jet candidates lying within $\Delta R = 0.4$ of a photon candidate. Additional selections to remove ambiguities between electrons or muons and photons are applied such that a photon is discarded if it is within $\Delta R = 0.4$ of a baseline electron or muon.

The measurement of the missing transverse momentum vector \vec{E}_T^{miss} (and its magnitude E_T^{miss}) is based on the calibrated transverse momenta of all electron, muon, jet candidates, photons and all tracks originating from the primary vertex and not associated with such objects [83].

Initial jet-finding is extended using an approach called jet reclustering [84]. This allows the use of larger-radius-jet algorithms while maintaining the calibrations and systematic uncertainties associated with the input jets. Jets with a radius parameter 0.4 described above surviving the resolution of ambiguities and having $p_T > 25$ GeV are used as input to an anti- k_t algorithm with a jet radius parameter 1.0. A grooming scheme called “reclustered jet trimming” is applied to remove any small-radius jet constituent j of a large-radius reclustered jet J if $p_T^j < f_{\text{cut}} \times p_T^J$ where the parameter f_{cut} is set to be 0.05.

Corrections derived from data control samples are applied to account for differences between data and simulation for the lepton and photon trigger and reconstruction efficiencies, the lepton momentum/energy scale and resolution, and for the efficiency and mis-tag rate of the b -tagging algorithm.

5 Analysis strategy and background prediction

This section summarizes the common analysis strategy and statistical techniques that are employed in the searches presented in this paper.

To search for a possible signal, selection criteria are defined to enhance the expected signal yield relative to the SM backgrounds. Signal regions (SRs) are defined using the MC simulation of SUSY signals and the SM background processes. They are optimized to maximize the expected discovery sensitivity for each model considered. To estimate the SM backgrounds in an accurate and robust fashion, control regions (CRs) are defined for each of the signal regions. They are chosen to be orthogonal to the SR selections in order to provide independent data samples enriched in particular backgrounds, and are used to normalize the background MC simulation. The CR selections are optimized to have negligible SUSY signal contamination for the models near the previously excluded boundary [11], while minimizing the systematic uncertainties arising from the extrapolation of the CR event yields to estimate backgrounds in the SR. Cross-checks of the background estimates are performed with data in several validation regions (VRs) selected with requirements such that these regions do not overlap with the CR and SR selections, and also have a low expected signal contamination.

In order to ensure sensitivity to the variety of squark and gluino production signals targeted in this search, a collection of inclusive SRs is considered. Each of the SR selection requirements is optimized to exploit expected differences in masses, kinematics, and jet multiplicities, and each represents its own counting

experiment. Two different approaches are used in defining these SRs, with Meff-based and RJR-based selection criteria described in Sections 7.1 and 7.2, respectively. These two approaches are complementary because of differences in selected event populations and the strategy for balancing the signal-to-background ratio against systematic uncertainties. A discussion of differences in these approaches is provided in Section 7.3.

To extract the final results, three different classes of likelihood fits are employed: background-only, model-independent and model-dependent fits [85]. A background-only fit is used to estimate the background yields in each SR. The fit is performed using the observed event yields in the CRs associated with the SR as the only constraints, but not the yields in the SR itself. It is assumed that signal events from physics beyond the Standard Model (BSM) do not contribute to these CR yields. The scale factors represent the normalization of background components relative to MC predictions ($\mu(W+\text{jets})$, $\mu(Z+\text{jets})$, $\mu(\text{Top})$), and are simultaneously determined in the fit to all the CRs associated with a SR. The expected background in the SR is based on the yields predicted by simulation for $W/Z+\text{jets}$ and background processes containing top quarks, corrected by the scale factors derived from the fit. In the case of multi-jet background, the estimate is based on the data-driven method described in Section 8. The systematic and MC statistical uncertainties in the expected values are included in the fit as nuisance parameters that are constrained by Gaussian distributions with widths corresponding to the sizes of the uncertainties considered and by Poisson distributions, respectively. The background-only fit is also used to estimate the background event yields in the VRs.

A model-independent fit is used to quantify the level of agreement between background predictions and observed yields and to set upper limits on the number of BSM signal events in each SR. This fit proceeds in the same way as the background-only fit, where yields in the CRs are used to constrain the predictions of backgrounds in each SR, while the SR yield is also used in the likelihood with an additional nuisance parameter describing potential signal contributions. The observed and expected upper limits at 95% confidence level (CL) on the number of events from BSM phenomena for each signal region (S_{obs}^{95} and S_{exp}^{95}) are derived using the CL_s prescription [86], neglecting any possible signal contamination in the CRs. These limits, when normalized by the integrated luminosity of the data sample, may be interpreted as upper limits on the visible cross-section of BSM physics ($\langle\epsilon\sigma\rangle_{\text{obs}}^{95}$), where the visible cross-section is defined as the product of production cross-section, acceptance and efficiency. The model-independent fit is also used to compute the one-sided p -value (p_0) of the background-only hypothesis, which quantifies the statistical significance of an excess.

Finally, a model-dependent fit is used to set exclusion limits on the signal cross-sections for specific SUSY models. Such a fit proceeds in the same way as the model-independent fit, except that both the signal yield in the signal region and the signal contamination in the CRs are taken into account. Correlations between signal and background systematic uncertainties are taken into account where appropriate. Signal-yield systematic uncertainties due to detector effects and the theoretical uncertainties in the signal acceptance are included in the fit.

6 The Recursive Jigsaw Reconstruction technique

The RJR technique [12–14] is a method for defining kinematic variables event by event. While it is straightforward to fully describe an event’s underlying kinematic features when all objects are fully reconstructed, events involving invisible weakly interacting particles present a challenge, as the loss of information from escaping particles constrains the kinematic variable construction to take place in the

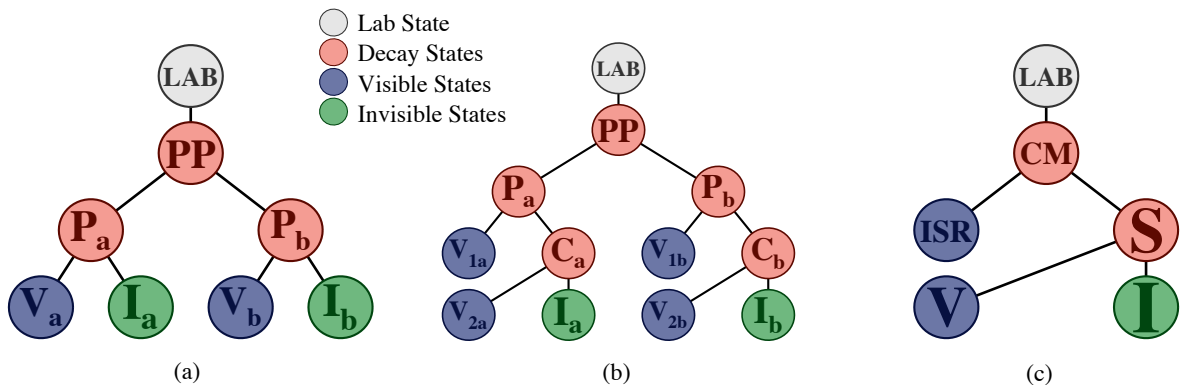


Figure 2: (a) Inclusive strong sparticle production decay tree. Two sparticles (P_a and P_b) are non-resonantly pair-produced with each decaying to one or more visible particles (V_a and V_b) that are reconstructed in the detector, and two systems of invisible particles (I_a and I_b) whose four-momenta are only partially constrained. (b) An additional level of decays can be added when requiring more than two visible objects. This tree is particularly useful for the search for gluino pair production described in the text. The di-sparticle production frame is denoted PP . Intermediate decay states are labelled C . (c) Strong sparticle production with ISR decay tree for use with small mass splitting spectra. CM refers to the center-of-mass of the whole reaction. A signal sparticle system S decays into visible particles (V) and a system of invisible particles (I) that recoil from a jet radiation system ISR .

lab frame instead of the more physically natural frames of the hypothesized decays. The RJR method partially mitigates this loss of information by determining approximations of the rest frames of intermediate particle states in each event. This reconstructed view of the event gives rise to a natural basis of kinematic observables, calculated by evaluating the momenta and energy of different objects in these reference frames.

All jets with $p_T > 50$ GeV and $|\eta| < 2.8$ and the missing transverse momentum are used as input to the RJR algorithm. Motivated by searches for strong production of sparticles in R -parity-conserving models, a decay tree, shown in Figure 2(a), is used in the analysis of events. Each event is evaluated as if two sparticles (the intermediate states P_a and P_b) were produced and then decayed to the particles observed in the detector (the collections V_a and V_b). The benchmark signal models probed in this search give rise to signal events with at least two weakly interacting particles associated with two systems of invisible particles (I_a and I_b), the respective children of the initially produced sparticles.

This decay tree includes several kinematic and combinatoric unknowns. In the final state with no leptons, the objects observed in the detector are exclusively jets and it is necessary to decide how to partition these jets into the two groups V_a and V_b in order to calculate the observables associated with the decay tree. In this analysis, the grouping that minimizes the masses of the four-momentum sum of group constituents is chosen.

More explicitly, the collection of reconstructed jet four-momenta, $V \equiv \{p_i\}$ and their four-momentum sum p_V are considered. Each of the four-momenta is evaluated in the rest frame of p_V (V frame) and different partitions of these jets $V_i = \{p_1, \dots, p_{N_i}\}$ are considered such that $V_a \cap V_b = 0$ and $V_a \cup V_b = V$. For each partition, the sum of four-momenta $p_{V_i} = \sum_{j=1}^{N_i} p_j$ is calculated and the combination that maximizes the sum of momentum of the two groups, $|\vec{p}_{V_a}| + |\vec{p}_{V_b}|$, is chosen. The axis that this partition implicitly defines in the V rest frame is equivalent to the thrust axis of the jets, and the masses $M_{V_i} = \sqrt{p_{V_i}^2}$ are

simultaneously minimized.

When the decay tree shown in Figure 2(b) is used to analyze events, each of the groups V_a and V_b are further subdivided, with each group undergoing exactly the same partitioning algorithm (based on selecting the combination maximizing the scalar sum of the momentum of the two partitions), resulting in a finer partition with subgroups $V_{1a/2a}$ and $V_{1b/2b}$. Similarly, the same algorithm is used to decide which jets are assigned to the groups V and ISR when analyzing events according to the decay tree shown in Figure 2(c), where the E_T^{miss} , represented as I , is treated as an additional, massless jet in the partitioning algorithm. The reconstruction code for the algorithm can be found in Ref. [87].

The remaining unknowns in the event are associated with the two collections of weakly interacting particles: their masses, longitudinal momenta and information about how the two groups contribute to the \vec{E}_T^{miss} . The RJR algorithm determines these unknowns through subsequent minimizations of the intermediate particle masses appearing in the decay tree. In each of these newly constructed rest frames, all relevant momenta are defined and can be used to construct any variable – multi-object invariant masses, angles between objects, etc. The primary energy-scale-sensitive observables used in the search presented here are a suite of variables denoted by H . These H variables denote *hemispheres*, with the H suggesting similarities with H_T , the scalar sum of visible transverse momenta. However, in contrast to H_T , these H variables are constructed using different combinations of objects’ momenta, including contributions from the invisible four-momenta, and are not necessarily evaluated in the lab frame, nor only in the transverse plane.

The H variables are labeled with a superscript F and two subscripts n and m , $H_{n,m}^F$. The F represents the rest frame in which the momenta are evaluated. In this analysis, this may be the lab frame, the proxy frame for the sparticle–sparticle frame PP , or the proxy frame for an individual sparticle’s rest frame P . The subscripts n and m represent the number of visible and invisible momentum vectors considered, respectively. This means, given the number of visible momentum vectors in the frame, these are summed until only n distinct vectors remain. The choice for which vectors are summed is made by finding jets with smallest mutual four vector dot products, using the minimization procedure described above. The same is done for the invisible system so that only m distinct vectors remain. For events with fewer than n visible objects, the sum only runs over the available vectors. The additional subscript “T” can denote a transverse version of the variable, where the transverse plane is defined in a frame F as follows: The Lorentz transformation relating F to the lab frame is decomposed into a boost along the beam axis, followed by a subsequent transverse boost. The transverse plane is defined to be normal to the longitudinal boost. In practice, this is similar to the plane transverse to the beam-line.

The variables that are used to define the signal and control regions are listed below. As few requirements are placed on dimensionful variables as possible, in order to increase the generality of the signal regions’ sensitivity. Additional discrimination is achieved through a minimal set of dimensionless variable requirements with selections imposed on unit-less quantities exploiting common mass-independent features of the signals considered.

To select signal events in models with squark pair production, the following variables are used:

- $H_{1,1}^{PP}$: scale variable as described above. Measures the momentum of missing particles in the PP frame and behaves similarly to E_T^{miss} .
- $H_{T,2,1}^{PP}$: scale variable as described above. Behaves similarly to effective mass, m_{eff} (defined as the scalar sum of the transverse momenta of the two leading jets and E_T^{miss}) for squark pair production signals with two-jet final states.

- $H_{1,1}^{PP}/H_{2,1}^{PP}$: provides additional information in testing the balance of the two scale variables, where in the denominator the $H_{2,1}^{PP}$ is no longer solely transverse. This provides excellent discrimination against unbalanced events where the large scale is dominated by a particular object p_T or by high E_T^{miss} .
- $p_{PP,z}^{\text{lab}}/(p_{PP,z}^{\text{lab}} + H_{T,2,1}^{PP})$: compares the z -momentum of all the objects associated with the PP system in the lab frame ($p_{PP,z}^{\text{lab}}$) to the overall transverse scale variable considered. This variable tests for significant boost in the z direction.
- $p_{Tj2}^{PP}/H_{T,2,1}^{PP}$: the ratio of the p_T of the second leading jet, evaluated in the PP frame (p_{Tj2}^{PP}) to the transverse scale variable, with small values generally more background-like.

For signal topologies with higher jet multiplicities, there is the option to exploit the internal structure of the hemispheres by using a decay tree with an additional decay. For gluino pair production, the tree shown in Figure 2(b) can be used and the variables used by this search are:

- $H_{1,1}^{PP}$: described above.
- $H_{T,4,1}^{PP}$: analogous to the transverse scale variable described above but more appropriate for four-jet final states expected from gluino pair production.
- $H_{1,1}^{PP}/H_{4,1}^{PP}$: analogous to $H_{1,1}^{PP}/H_{2,1}^{PP}$ for the squark search.
- $H_{T,4,1}^{PP}/H_{4,1}^{PP}$: a measure of the fraction of the momentum that lies in the transverse plane.
- $p_{PP,z}^{\text{lab}}/(p_{PP,z}^{\text{lab}} + H_{T,4,1}^{PP})$: analogous to $p_{PP,z}^{\text{lab}}/(p_{PP,z}^{\text{lab}} + H_{T,2,1}^{PP})$ above.
- $\min_i (p_{Tj2i}^{PP}/H_{T,2,1i}^{PP})$: represents the fraction of a hemisphere's overall scale due to the second-highest- p_T jet (in the PP frame) compared to the overall scale, independently for each hemisphere. The smaller of the values in the two hemispheres is used, corresponding to the index i .
- $\max_i (H_{1,0}^{P_i}/H_{2,0}^{P_i})$: testing balance of solely the jets momentum in a given hemisphere's approximate sparticle rest frame (P_i , index i indicating each hemisphere) provides additional discrimination against a small but otherwise signal-like subset of background events with a vector boson and associated jets.

In order to reject events where the E_T^{miss} results from mismeasurements of jets, the E_T^{miss} is attributed to one or more jets using a transverse clustering scheme. The transverse components of reconstructed jet four vectors and the E_T^{miss} , treated as massless, are organized into a binary decay tree by choosing associations through the recursive minimization of subgroup masses at each decay step using the previously described algorithm. The jet(s) appearing in the decay step where the E_T^{miss} appears alone are those that have the smallest inner product with the system of invisible particles in the event, and their mutual transverse momentum is compared with the E_T^{miss} using the ratio R_{QCD} :

$$R_{\text{QCD}} = \frac{\max(\vec{p}_T^{\text{jets}} \cdot \vec{E}_T^{\text{miss}}, 0)}{(E_T^{\text{miss}})^2 + \max(\vec{p}_T^{\text{jets}} \cdot \vec{E}_T^{\text{miss}}, 0)}, \quad (1)$$

where \vec{p}_T^{jets} is the transverse momentum of the E_T^{miss} -associated jet(s) or system of jets in the lab frame. Alternatively, the magnitude and direction of these jets can be compared with the E_T^{miss} by considering the

“decay angle” of the jet(s)/ E_T^{miss} system, $\cos(\phi_{j, E_T^{\text{miss}}})$, defined using the transverse jet(s) and E_T^{miss} four vectors of the binary decay tree. These quantities are combined into a discriminant Δ_{QCD} , defined as

$$\Delta_{\text{QCD}} = \frac{1 + \cos(\phi_{j, E_T^{\text{miss}}}) - 2R_{\text{QCD}}}{1 + \cos(\phi_{j, E_T^{\text{miss}}}) + 2R_{\text{QCD}}} . \quad (2)$$

This observable is used to quantify the likelihood that mismeasurements of these jets were responsible for the E_T^{miss} . Multi-jet events with severe jet mismeasurements tend to have Δ_{QCD} values in the interval $[-1, 0]$ while events with E_T^{miss} from weakly interacting particles are more likely to have values in the interval $[0, 1]$.

In addition to trying to resolve the entirety of the signal event, it can be useful for sparticle spectra with smaller mass splittings and lower intrinsic E_T^{miss} to instead select events with a partially resolved sparticle system recoiling from a high- p_T jet from initial-state radiation (ISR). To target such topologies, a separate tree for compressed spectra is shown in Figure 2(c). This tree is somewhat simpler and attempts to identify visible (V) and invisible (I) systems that are the result of an intermediate state corresponding to the system of sparticles and their decay products (S). As the E_T^{miss} is used to choose which jets are identified as ISR, a transverse view of the reconstructed event is used which ignores the longitudinal momentum of the jets. The reference frames appearing in the decay tree shown in Figure 2(c), such as the estimate of the center-of-mass frame (CM), are then approximations in this transverse projection. This tree yields a slightly different set of variables:

- p_{TS}^{CM} : the magnitude of the vector-summed transverse momenta of all S -associated jets ($|\vec{p}_{TS}^{\text{CM}}|$) and E_T^{miss} evaluated in the CM frame.
- $R_{\text{ISR}} \equiv \vec{p}_I^{\text{CM}} \cdot \hat{p}_{TS}^{\text{CM}} / p_{TS}^{\text{CM}}$: serves as an estimate of $m_{\tilde{\chi}}/m_{\tilde{q}/\tilde{q}}$. This is the fraction of the momentum of the S system that is carried by its invisible system I , with momentum \vec{p}_I^{CM} in the CM frame. As p_{TS}^{CM} grows it becomes increasingly hard for backgrounds to possess a large value in this ratio – a feature exhibited by compressed signals.
- M_{TS} : the transverse mass of the S system.
- N_{jet}^V : number of jets assigned to the visible system (V) and not associated with the ISR system.
- $\Delta\phi_{\text{ISR}, I}$: the azimuthal opening angle between the ISR system and the invisible system in the CM frame.

7 Event selection and signal regions definitions

Following the event reconstruction described in Section 4, in both searches documented here, events are discarded if a baseline electron or muon with $p_T > 7$ GeV remains, or if they contain a jet failing to satisfy quality selection criteria designed to suppress detector noise and non-collision backgrounds (described in Section 4). Events are rejected if no jets with $p_T > 50$ GeV are found. The remaining events are then analyzed in two complementary searches, both of which require the presence of jets and significant missing transverse momentum. The selections in the two searches are designed to be generic enough to ensure sensitivity in a broad set of models with jets and E_T^{miss} in the final state.

In order to maximize the sensitivity in the $m_{\tilde{q}}, m_{\tilde{q}}$ plane, a variety of signal regions are defined. Squarks typically generate at least one jet in their decays, for instance through $\tilde{q} \rightarrow q\tilde{\chi}_1^0$, while gluinos typically

generate at least two jets, for instance through $\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$. Processes contributing to $\tilde{q}\tilde{q}$ and $\tilde{g}\tilde{g}$ final states therefore lead to events containing at least two or four jets, respectively. Decays of heavy SUSY and SM particles produced in longer \tilde{q} and \tilde{g} decay cascades (such as those involving chargino production with subsequent decays e.g. $\tilde{\chi}_1^\pm \rightarrow qq'\tilde{\chi}_1^0$) tend to further increase the jet multiplicity in the final state. To target different scenarios, signal regions with different jet multiplicity requirements (in the case of Meff-based search) or different decay trees (in the case of RJR-based search) are assumed. The optimized signal regions used in both searches are summarized in the following.

7.1 The jets+ E_T^{miss} Meff-based search

Due to the high mass scale expected for the SUSY models considered in this study, the ‘effective mass’, m_{eff} [88], is a powerful discriminant between the signal and SM backgrounds. When selecting events with at least N_j jets, $m_{\text{eff}}(N_j)$ is defined to be the scalar sum of the transverse momenta of the leading N_j jets and E_T^{miss} . Requirements placed on $m_{\text{eff}}(N_j)$ and E_T^{miss} form the basis of the Meff-based search by strongly suppressing the multi-jet background where jet energy mismeasurement generates missing transverse momentum. The final signal selection uses a requirement on $m_{\text{eff}}(\text{incl.})$, which sums over all jets with $p_T > 50$ GeV and E_T^{miss} to suppress SM backgrounds, which tend to have low jet multiplicity.

Twenty-four inclusive SRs characterized by increasing the minimum jet multiplicity, from two to six, are defined in Table 2: eight regions target models characterized by the squark pair production with the direct decay of squarks, seven regions target models with gluino pair production followed by the direct decay of gluinos and nine regions target squark pair or gluino pair production followed by the one-step decay of squarks/gluinos via an intermediate chargino or neutralino. Signal regions requiring the same jet multiplicity are distinguished by increasing the threshold of the $m_{\text{eff}}(\text{incl.})$ and $E_T^{\text{miss}}/m_{\text{eff}}(N_j)$ or $E_T^{\text{miss}}/\sqrt{H_T}$ requirements. This ensures the sensitivity to a range of sparticle masses for each decay mode. All signal regions corresponding to the Meff-based approach are labeled with the prefix ‘Meff’. For SR’s with a low number of hard jets, $E_T^{\text{miss}}/\sqrt{H_T}$ is found to be more discriminant than $E_T^{\text{miss}}/m_{\text{eff}}(N_j)$.

In each region, different requirements are applied for jet momenta and pseudorapidities. These thresholds are defined to reduce the SM background while keeping high efficiency for targeted signal events. Signal regions with high $m_{\text{eff}}(\text{incl.})$ thresholds are optimized for large mass differences, leading to hard jets in the central region of the detector. For the SRs Meff-2j-2100, Meff-3j-1300 (and Meff-5j-1700) that are optimized for small mass differences between \tilde{q} (\tilde{g}) and $\tilde{\chi}_1^0$, a very high p_T threshold is applied to the leading jet in order to explicitly tag a jet originating from initial-state radiation, which results in asymmetric p_T requirements on the leading jet and the other jets.

Two signal regions, Meff-2jB-1600/2400, optimized for one-step decay models are designed to improve the sensitivity to models with the cascade squark decay via $\tilde{\chi}^\pm$ to $qW\tilde{\chi}_1^0$ (Figure 1(b)) or gluino decay via $\tilde{\chi}^\pm$ ($\tilde{\chi}_2^0$) to $qqW\tilde{\chi}_1^0$ (or $qqZ\tilde{\chi}_1^0$) (Figures 1(e) and 1(f)), in cases where the $\tilde{\chi}^\pm$ ($\tilde{\chi}_2^0$) is nearly degenerate in mass with the squarks or the gluino. These signal regions place additional requirements on the mass of the large-radius jets to select the candidate hadronically decaying W or Z bosons that, due to the small mass difference between the parent SUSY particles and intermediate chargino or neutralino, can have significant transverse momentum and appear as a single high-mass jet. The signal regions Meff-5j-2000/2600 target similar models and have similar $E_T^{\text{miss}}/\sqrt{H_T}$ and $m_{\text{eff}}(\text{incl.})$ selections to the 2jB signal regions, filling the coverage gaps between the 2jB SRs and the other non-boosted SRs. In the other regions with at least four jets in the final state, jets from signal processes are distributed isotropically. Additional

suppression of background processes is based on the aplanarity variable, which is defined as $A = 3/2\lambda_3$, where λ_3 is the smallest eigenvalue of the normalized momentum tensor of the jets [89].

To reduce the background from multi-jet processes, requirements are placed on two variables: $\Delta\phi(\text{jet}, \vec{E}_T^{\text{miss}})_{\text{min}}$ and $E_T^{\text{miss}}/m_{\text{eff}}(N_j)$. The former is defined to be the smallest azimuthal separation between \vec{E}_T^{miss} and the momentum vector of any of the reconstructed jets with $p_T > 50$ GeV. The exact requirements, which depend on the jet multiplicity in each SR, are summarized in Table 2, where the criteria for all the Meff-based signal regions can also be found.

| Targeted signal | $\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$ | | | | | | | |
|--|---|---------|---------|---------|---------|---------|---------|---------|
| Requirement | Signal Region [Meff-] | | | | | | | |
| | 2j-1200 | 2j-1600 | 2j-2000 | 2j-2400 | 2j-2800 | 2j-3600 | 2j-2100 | 3j-1300 |
| E_T^{miss} [GeV] > | 250 | | | | | | | |
| $p_T(j_1)$ [GeV] > | 250 | 300 | 350 | | | 600 | | 700 |
| $p_T(j_2)$ [GeV] > | 250 | 300 | 350 | | | 50 | | |
| $p_T(j_3)$ [GeV] > | - | | | | | | | |
| $ \eta(j_{1,2}) <$ | 0.8 | 1.2 | | | 2.8 | | | |
| $\Delta\phi(\text{jet}_{1,2,(3)}, \vec{E}_T^{\text{miss}})_{\text{min}} >$ | 0.8 | | | 0.4 | | | | |
| $\Delta\phi(\text{jet}_{i>3}, \vec{E}_T^{\text{miss}})_{\text{min}} >$ | 0.4 | | | 0.2 | | | | |
| $E_T^{\text{miss}} / \sqrt{H_T}$ [GeV ^{1/2}] > | 14 | 18 | | | | 26 | 16 | |
| $m_{\text{eff}}(\text{incl.})$ [GeV] > | 1200 | 1600 | 2000 | 2400 | 2800 | 3600 | 2100 | 1300 |

| Targeted signal | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$ | | | | | | |
|--|--|---------|---------|---------|---------|---------|---------|
| Requirement | Signal Region [Meff-] | | | | | | |
| | 4j-1000 | 4j-1400 | 4j-1800 | 4j-2200 | 4j-2600 | 4j-3000 | 5j-1700 |
| E_T^{miss} [GeV] > | 250 | | | | | | |
| $p_T(j_1)$ [GeV] > | 200 | | | | | 700 | |
| $p_T(j_4)$ [GeV] > | 100 | | | 150 | | 50 | |
| $p_T(j_5)$ [GeV] > | - | | | | | | |
| $ \eta(j_{1,2,3,4}) <$ | 1.2 | 2.0 | | | | 2.8 | |
| $\Delta\phi(\text{jet}_{1,2,(3)}, \vec{E}_T^{\text{miss}})_{\text{min}} >$ | 0.4 | | | | | | |
| $\Delta\phi(\text{jet}_{i>3}, \vec{E}_T^{\text{miss}})_{\text{min}} >$ | 0.4 | | | | | 0.2 | |
| $E_T^{\text{miss}} / m_{\text{eff}}(N_j) >$ | 0.3 | 0.25 | | | 0.2 | 0.3 | |
| Aplanarity > | 0.04 | | | | | | |
| $m_{\text{eff}}(\text{incl.})$ [GeV] > | 1000 | 1400 | 1800 | 2200 | 2600 | 3000 | 1700 |

| Targeted signal | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}W\tilde{\chi}_1^0$ and $\tilde{q}\tilde{q}, \tilde{q} \rightarrow qW\tilde{\chi}_1^0$ | | | | | | | |
|--|--|---------|---------|---------|---------|---------|---------|--|
| Requirement | Signal Region [Meff-] | | | | | | | |
| | 5j-1600 | 5j-2000 | 5j-2600 | 6j-1200 | 6j-1800 | 6j-2200 | 6j-2600 | |
| E_T^{miss} [GeV] > | 250 | | | | | | | |
| $p_T(j_1)$ [GeV] > | 200 | | | | | | | |
| $p_T(j_5)$ [GeV] > | 50 | | | | 100 | | | |
| $p_T(j_6)$ [GeV] > | - | | | 50 | 100 | | | |
| $ \eta(j_{1,\dots,6}) <$ | 2.8 | | | 2.0 | | | 2.8 | |
| $\Delta\phi(\text{jet}_{1,2,(3)}, \vec{E}_T^{\text{miss}})_{\text{min}} >$ | 0.4 | | 0.8 | 0.4 | | | | |
| $\Delta\phi(\text{jet}_{i>3}, \vec{E}_T^{\text{miss}})_{\text{min}} >$ | 0.2 | 0.4 | | | 0.2 | | | |
| $E_T^{\text{miss}} / m_{\text{eff}}(N_j) >$ | 0.15 | - | | | 0.25 | 0.2 | 0.15 | |
| $E_T^{\text{miss}} / \sqrt{H_T}$ [GeV ^{1/2}] > | - | 15 | 18 | - | | | | |
| Aplanarity > | 0.08 | - | | | 0.04 | 0.08 | | |
| $m_{\text{eff}}(\text{incl.})$ [GeV] > | 1600 | 2000 | 2600 | 1200 | 1800 | 2200 | 2600 | |

| Targeted signal | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}W\tilde{\chi}_1^0$ and $\tilde{q}\tilde{q}, \tilde{q} \rightarrow qW\tilde{\chi}_1^0$ | |
|--|--|----------|
| Requirement | Signal Region [Meff-] | |
| | 2jB-1600 | 2jB-2400 |
| E_T^{miss} [GeV] > | 250 | |
| $p_T(\text{large-}R j_1)$ [GeV] > | 200 | |
| $p_T(\text{large-}R j_2)$ [GeV] > | 200 | |
| $m(\text{large-}R j_1)$ [GeV] | [60,110] | |
| $m(\text{large-}R j_2)$ [GeV] | [60,110] | |
| $\Delta\phi(\text{jet}_{1,2,(3)}, \vec{E}_T^{\text{miss}})_{\text{min}} >$ | 0.6 | |
| $\Delta\phi(\text{jet}_{i>3}, \vec{E}_T^{\text{miss}})_{\text{min}} >$ | 0.4 | |
| $E_T^{\text{miss}} / \sqrt{H_T}$ [GeV ^{1/2}] > | 20 | |
| $m_{\text{eff}}(\text{incl.})$ [GeV] > | 1600 | 2400 |

Table 2: Selection criteria and targeted signal models from Figure 1 used to define signal regions in the Meff-based search, indicated by the prefix ‘Meff’. The first block of SRs targets Figure 1(a), the second block of SRs targets Figure 1(d). The third and fourth blocks of SRs target Figures 1(b) and 1(e). Each SR is labeled with the inclusive jet multiplicity considered (‘2j’, ‘3j’ etc.) together with the the m_{eff} requirement. The $E_T^{\text{miss}}/m_{\text{eff}}(N_j)$ cut in any N_j -jet channel uses a value of m_{eff} constructed from only the leading N_j jets ($m_{\text{eff}}(N_j)$). However, the final $m_{\text{eff}}(\text{incl.})$ selection, which is used to define the signal regions, includes all jets with $p_T > 50$ GeV. Large-radius reclustered jets are denoted by large- $R j$.

7.2 The jets+ E_T^{miss} RJR-based search

The procedure adopted is such that, as the mass splitting between parent sparticle and the LSP increases, the criteria applied to the scale variables are tightened, while the criteria for dimensionless variables are loosened. In searching for the squark pair production, the overall balance of the events is studied with $H_{1,1}^{PP}/H_{2,1}^{PP}$. The range selected in this ratio rejects those events where the missing transverse momentum dominates the scale (upper bound) and ensures the sufficient balance between the scales of visible and invisible particles (lower bound). The selection on the $p_{Tj2}^{PP}/H_{T2,1}^{PP}$ ratio serves to ensure that each of the jets contributes to the overall scale significantly. This particular ratio is a powerful criterion against imbalanced events with W/Z +jets, where one of the jets has a much higher momentum than the subleading jet.

For signals of gluino pair production, the same principles are followed. Tight requirements are placed on $H_{1,1}^{PP}/H_{4,1}^{PP}$ and $H_{T4,1}^{PP}/H_{4,1}^{PP}$ to target scenarios with more compressed spectra. A selection is applied to the ratio $p_{PP,z}^{\text{lab}}/(p_{PP,z}^{\text{lab}} + H_{T4,1}^{PP})$ to test the size of the total z -component of momentum relative to the overall scale, requiring that it should be small. A lower bound is placed on $p_{Tj2}^{PP}/H_{T2,1}^{PP}$. This provides a very strong constraint against events where the two hemispheres are well balanced but one of the jets dominates the scale variable contribution. In order to reject events where the E_T^{miss} results from mismeasurements of jets a requirement on the variable Δ_{QCD} is applied, rejecting events where this is deemed likely.

Additionally, separate SRs are defined for models with extremely compressed spectra. Following the pattern of successive SRs targeting larger mass splitting scenarios, several regions designed to be sensitive to various mass splittings utilize the ISR-boosted compressed decay tree described in Section 6. These regions target mass splittings between parent squarks and gluinos and $\tilde{\chi}_1^0$ from roughly 25 GeV to 200 GeV.

The selection criteria of the resulting 19 signal regions are summarized in Table 3. The entries for $|\eta_{j1,j2}|$ and $|\eta_{j1,2,a,b}|$ correspond to upper bounds on the pseudorapidities of the leading two jets in each event and the leading two jets in each hemisphere a, b , respectively, while $|\eta_{jV}|$ corresponds to the jets associated with the system V . All signal regions included in the RJR-based search have an ‘RJR’ prefix.

| Targeted signal | $\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$ | | | | | | |
|--|---|---------|---------|---------|---------|---------|--------|
| Requirement | Signal Region | | | | | | |
| | RJR-S1 | RJR-S2 | RJR-S3 | RJR-S4 | | | |
| $H_{1,1}^{PP}/H_{2,1}^{PP} \geq$ | 0.55 | 0.5 | 0.45 | – | | | |
| $H_{1,1}^{PP}/H_{2,1}^{PP} \leq$ | 0.9 | 0.95 | 0.98 | – | | | |
| $p_{Tj2}^{PP}/H_{T2,1}^{PP} \geq$ | 0.16 | 0.14 | 0.13 | 0.13 | | | |
| $ \eta_{j1,j2} \leq$ | 0.8 | 1.1 | 1.4 | 2.8 | | | |
| $\Delta_{\text{QCD}} \geq$ | 0.1 | 0.05 | 0.025 | 0 | | | |
| $p_{PP,T}^{\text{lab}} / (p_{PP,T}^{\text{lab}} + H_{T2,1}^{PP}) \leq$ | 0.08 | | | | | | |
| | RJR-S1a | RJR-S1b | RJR-S2a | RJR-S2b | RJR-S3a | RJR-S3b | RJR-S4 |
| $H_{T2,1}^{PP}$ [GeV] > | 1000 | 1200 | 1400 | 1600 | 1800 | 2100 | 2400 |
| $H_{1,1}^{PP}$ [GeV] > | 800 | 1000 | 1200 | 1400 | 1700 | 1900 | 2100 |

| Targeted signal | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$ | | | | | | |
|--|--|---------|---------|---------|---------|---------|--------|
| Requirement | Signal Region | | | | | | |
| | RJR-G1 | RJR-G2 | RJR-G3 | RJR-G4 | | | |
| $H_{1,1}^{PP}/H_{4,1}^{PP} \geq$ | 0.45 | 0.3 | 0.2 | – | | | |
| $H_{T4,1}^{PP}/H_{4,1}^{PP} \geq$ | 0.7 | 0.7 | 0.65 | 0.65 | | | |
| $\min(p_{Tj2i}^{PP}/H_{T2,1i}^{PP}) \geq$ | 0.12 | 0.1 | 0.08 | 0.07 | | | |
| $\max(H_{1,0}^{Pi}/H_{2,0}^{Pi}) \leq$ | 0.96 | 0.97 | 0.98 | 0.98 | | | |
| $ \eta_{j1,2,a,b} \leq$ | 1.4 | 2.0 | 2.4 | 2.8 | | | |
| $\Delta_{\text{QCD}} \geq$ | 0.05 | 0.025 | 0 | 0 | | | |
| $p_{PP,z}^{\text{lab}} / (p_{PP,z}^{\text{lab}} + H_{T4,1}^{PP}) \leq$ | 0.5 | 0.55 | 0.6 | 0.65 | | | |
| $p_{PP,T}^{\text{lab}} / (p_{PP,T}^{\text{lab}} + H_{T4,1}^{PP}) \leq$ | 0.08 | | | | | | |
| | RJR-G1a | RJR-G1b | RJR-G2a | RJR-G2b | RJR-G3a | RJR-G3b | RJR-G4 |
| $H_{T4,1}^{PP}$ [GeV] > | 1200 | 1400 | 1600 | 2000 | 2400 | 2800 | 3000 |
| $H_{1,1}^{PP}$ [GeV] > | 700 | | 800 | | 900 | | 1000 |

| Targeted signal | compressed spectra in $\tilde{q}\tilde{q} (\tilde{q} \rightarrow q\tilde{\chi}_1^0); \tilde{g}\tilde{g} (\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0)$ | | | | |
|--|---|--------|--------|--------|--------|
| Requirement | Signal Region | | | | |
| | RJR-C1 | RJR-C2 | RJR-C3 | RJR-C4 | RJR-C5 |
| $R_{\text{ISR}} \geq$ | 0.95 | 0.9 | 0.8 | 0.7 | 0.7 |
| $p_{TS}^{\text{CM}} [\text{GeV}] \geq$ | 1000 | 1000 | 800 | 700 | 700 |
| $\Delta\phi_{\text{ISR}, l/\pi} \geq$ | 0.95 | 0.97 | 0.98 | 0.95 | 0.95 |
| $\Delta\phi(\text{jet}_{1,2}, \vec{E}_T^{\text{miss}})_{\text{min}} >$ | – | – | – | 0.4 | 0.4 |
| $M_{TS} [\text{GeV}] \geq$ | – | 100 | 200 | 450 | 450 |
| $N_{\text{jet}}^V \geq$ | 1 | 1 | 2 | 2 | 3 |
| $ \eta_{jV} \leq$ | 2.8 | 1.2 | 1.4 | 1.4 | 1.4 |

Table 3: Selection criteria and targeted signal model from Figure 1 used to define signal regions in the RJR-based search, indicated by the prefix ‘RJR’. Each SR is labeled with the targeted SUSY particle or the targeted region of parameter space, such that ‘S’, ‘G’ and ‘C’ denote search regions for squark pairs, gluino pairs, or compressed spectra, respectively.

7.3 Meff-based and RJR-based signal region comparison

Even though the selection requirements that define the Meff-based and RJR-based SRs use different sets of kinematic observables, the regions are not necessarily orthogonal. The fraction of events common to different regions, for both the SM backgrounds and the SUSY signals, reflects the complementarity of using these two approaches. For models with large \tilde{q}/\tilde{g} masses, the signal efficiency is prioritized due

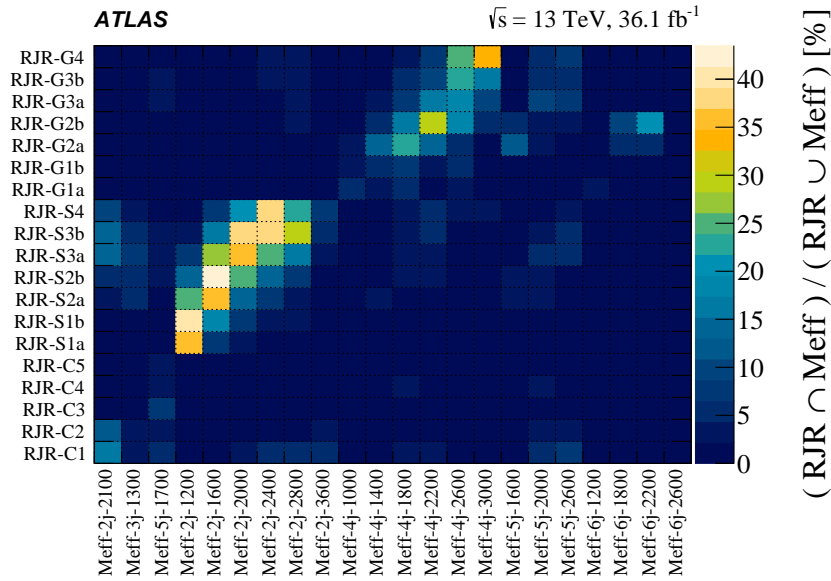


Figure 3: Fractional overlap of data events selected in Meff-based and RJR-based SRs. Meff-based SRs are listed along the x -axis with RJR-based regions on the y -axis. The intersection events falling in each pair of regions, normalized by the union, is shown on the z -axis. The Meff-based boosted boson SRs (Meff-2jB-1600, Meff-2jB-2400) are not included as they have negligible overlap with other regions due to their unique requirements.

to low production cross-sections. In these cases, stringent requirements on the similarly behaving m_{eff} and $H_{T 2,1}^{PP}/H_{T 4,1}^{PP}$ variables result in a larger overlap between the Meff-based and RJR-based signal regions. Conversely, signal regions designed for increasingly compressed mass spectra have looser m_{eff} and $H_{T 2,1}^{PP}/H_{T 4,1}^{PP}$, and backgrounds must be suppressed with other, complementary, kinematic requirements. As these additional kinematic observables can be quite different between Meff-based and RJR-based approaches, the orthogonality of these respective SRs increases with decreasing sparticle mass splittings.

This behavior can be observed in Figure 3, which shows the fractional overlap of selected events in data between the Meff-based and RJR-based SRs. Each of the axes listing the various SRs are organized in the same order, with SRs targeting compressed mass spectra in the lower left of the figure, followed by squark regions with increasing sparticle masses, and then gluinos with increasing mass. This ordering results in a diagonal pattern of larger overlap, as SRs targeting the same signals are more similar. The SRs searching for evidence of squark production (RJR-Sx and Meff-2j-x) have fractions of overlapping events between 25% and 45%, while those targeting gluino production (RJR-Gx and Meff-4j-x) have smaller intersections, ranging from a few percent to 35%. This decrease in overlap for gluino SRs follows from increasing differences between the selections used in the Meff-based and RJR-based approaches. While observables such as $E_{\text{T}}^{\text{miss}}/m_{\text{eff}}(N_j)$ and aplanarity are sensitive to global event properties, the RJR-based analysis for gluinos attempts to decompose the event into two hemispheres representing each gluino. Kinematic variables used in the definitions of SRs are calculated from each hemisphere independently, providing complementarity to those describing the total event. Using this additional information in the RJR-based selections leads to generally tighter SRs, adding increased sensitivity for intermediate mass splittings.

Similar trends in event overlaps between SRs are expected for signal contributions, as shown in Figures 4(a) and 4(b) where a simulated squark signal with $m_{\tilde{q}} = 1.5$ TeV and massless $\tilde{\chi}_1^0$, and a gluino signal with $m_{\tilde{g}} = 2$ TeV and massless $\tilde{\chi}_1^0$ are used as examples. In these cases, the SRs targeting squarks

and gluinos share a large fraction of their events, with the RJR-S4 and Meff-2j-2800 regions best suited to this squark signal having 45% of selected events in common and the analogous gluino SRs (RJR-G4 and Meff-4j-3000) having an overlap of 40%. In the case of a squark signal, the largest overlap of 65% is seen with the RJR-S2a and Meff-2j-1600, with smaller overlap between tighter SRs favored for this signal point.

The RJR-Cx SRs targeting signals with the most compressed mass spectra ($0 < m_{\tilde{q}/\tilde{g}} - m_{\tilde{\chi}_1^0} \lesssim 200$ GeV) are the most dissimilar from their Meff-based analogs. They attempt to explicitly identify the strong initial-state radiation system that provides the escaping $\tilde{\chi}_1^0$ pair the E_T^{miss} needed to satisfy trigger and selection requirements and use kinematic requirements based on this interpretation of the event. The Meff-based SRs designed for these signals (Meff-2j-2100/3j-1300/5j-1700) exploit this compressed-mass-spectra event topology by requiring large $E_T^{\text{miss}}/\sqrt{H_T}$ or large $E_T^{\text{miss}}/m_{\text{eff}}(N_j)$ and a hard leading jet corresponding to the ISR system, and the modest m_{eff} requirements result in SRs with relatively large expected background yields and low systematic uncertainties. The RJR-Cx SRs take a more restrictive approach, using observables designed specifically for this ISR event topology, with the corresponding SRs having much lower event yields, higher signal-to-background ratios, but larger uncertainties. This results in much smaller event overlap for both signal and background, as seen in Figures 4(c) and 4(d) for an example simulated squark signal with $m_{\tilde{q}} = 700$ GeV and $m_{\tilde{\chi}_1^0} = 600$ GeV, and a gluino signal with $m_{\tilde{g}} = 1$ TeV and $m_{\tilde{\chi}_1^0} = 800$ GeV. For these signals, the overlap between the best-suited SRs (RJR-C3 and Meff-3j-1300 for the squark signal, RJR-C5 and Meff-5j-1700 for the gluino) is only about 10%. On the other hand, 65% (35%) of the signal events in RJR-C3 (RJR-C4) are also selected in Meff-3j-1300 (Meff-5j-1700). The more stringent selection strategy employed in the RJR-Cx regions leads to increased sensitivity for compressed mass spectra for each of the signal variants considered in this analysis.

8 Background estimation

Standard Model background processes contribute to the event counts in the signal regions. The largest backgrounds in both searches presented here are: Z +jets, W +jets, top quark pair, single top quark, diboson and multi-jet production. Non-collision backgrounds are negligible.

Generally, the largest background results from an irreducible component of Z +jets events in which $Z \rightarrow \nu\bar{\nu}$ decays generate large E_T^{miss} . Similarly, most of the W +jets background is composed of $W \rightarrow \tau\nu$ events in which the τ -lepton decays to hadrons, with additional contributions from $W \rightarrow e\nu, \mu\nu$ events in which no baseline electron or muon is reconstructed, with E_T^{miss} due to neutrinos. Top quark pair production, followed by semileptonic decays, in particular $t\bar{t} \rightarrow b\bar{b}\tau\nu qq'$ (with the τ -lepton decaying to hadrons), as well as single-top-quark events, can also generate large E_T^{miss} and satisfy the jet and lepton-veto requirements. Each of these primary backgrounds is estimated using dedicated control regions, as described in the following section, while diboson production is estimated with MC simulated data normalized using NLO cross-section predictions, as described in Section 3.

The multi-jet background in the signal regions is due to missing transverse momentum from misreconstruction of jet energies in the calorimeters, jets misidentified as electrons, jets lost due to the JVT requirement, as well as neutrinos from semileptonic decays of heavy-flavor hadrons. After applying the requirements based on $\Delta\phi(\text{jet}, \vec{E}_T^{\text{miss}})_{\text{min}}$ and $E_T^{\text{miss}}/m_{\text{eff}}(N_j)$ in the Meff-based search, or $\Delta_{\text{QCD}}, p_{Tj2}^{PP}/H_{T2,1}^{PP}$ and $\Delta\phi(\text{jet}, \vec{E}_T^{\text{miss}})_{\text{min}}$ in the RJR-based search, as indicated in Tables 2 and 3, the remaining multi-jet background is negligible.

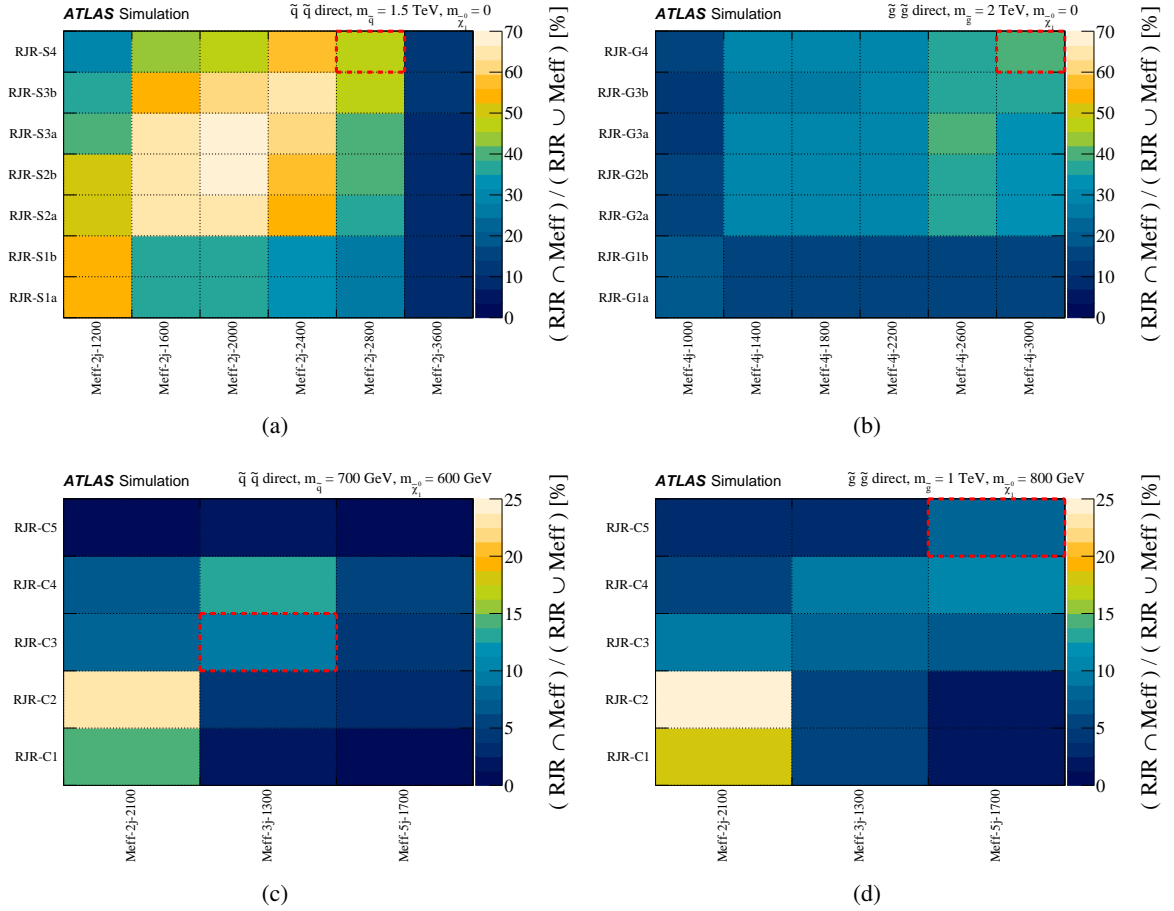


Figure 4: Fractional overlap of simulated squark and gluino pair events selected in Meff-based and RJR-based SRs. For these signals each squark (gluino) decays to one (two) quarks and a $\tilde{\chi}_1^0$. Figures correspond to simulated signals with (a) $m_{\tilde{q}} = 1.5 \text{ TeV}$, $m_{\tilde{\chi}_1^0} = 0$, (b) $m_{\tilde{g}} = 2 \text{ TeV}$, $m_{\tilde{\chi}_1^0} = 0$, (c) $m_{\tilde{q}} = 700 \text{ GeV}$, $m_{\tilde{\chi}_1^0} = 600 \text{ GeV}$, and (d) $m_{\tilde{g}} = 1 \text{ TeV}$, $m_{\tilde{\chi}_1^0} = 800 \text{ GeV}$. These selected signal points are near the limit of expected sensitivity for these SRs. Meff-based SRs are listed along the x -axis with RJR-based regions on the y -axis. The intersection events falling in each pair of regions, normalized by the union, is shown on the z -axis. The Meff- and RJR-based SRs best suited to each signal, respectively, are indicated by dashed red boxes.

8.1 Control regions

In order to estimate the expected background yields, control regions are defined for each of the signal regions in four different final states. In the Meff-based search, each SR has its own set of four CRs, while in the RJR-based search, a common set of CRs is used for all SRs in every targeted signal category (RJR-S, RJR-G or RJR-C). The CR selections are optimized to maintain adequate statistical precision while minimizing the systematic uncertainties arising from the extrapolation of the CR event yield to estimate the background in the SR. The latter is addressed through the fact that the jet p_T thresholds and $m_{\text{eff}}(\text{incl.})$ selections in the CRs are the same as used for the SR in the Meff-based search. In the RJR-based search, requirements on discriminating variables are chosen to match those used in the SRs as closely as possible. The basic CR definitions in both searches are listed in Table 4.

| CR | SR background | CR process | CR selection (Meff-based) | CR selection (RJR-based) |
|----------------------|-------------------------------------|---|--|---|
| Meff/RJR-CR γ | $Z(\rightarrow \nu\bar{\nu})$ +jets | γ +jets | Isolated photon | Isolated photon |
| Meff/RJR-CRQ | Multi-jet | Multi-jet | SR with reversed requirements on (i) $\Delta\phi(\text{jet}, \vec{E}_T^{\text{miss}})_{\text{min}}$ and (ii) $E_T^{\text{miss}}/m_{\text{eff}}(N_j)$ or $E_T^{\text{miss}}/\sqrt{H_T}$ | $\Delta_{\text{QCD}} < 0$ reversed requirement on $H_{1,1}^{PP}$ (RJR-S/G) or $R_{\text{ISR}} < 0.5$ (RJR-C) |
| Meff/RJR-CRW | $W(\rightarrow \ell\nu)$ +jets | $W(\rightarrow \ell\nu)$ +jets | $30 \text{ GeV} < m_T(\ell, E_T^{\text{miss}}) < 100 \text{ GeV}$, b -veto | |
| Meff/RJR-CRT | $t\bar{t}$ (+EW) and single top | $t\bar{t} \rightarrow b\bar{b}q q' \ell\nu$ | $30 \text{ GeV} < m_T(\ell, E_T^{\text{miss}}) < 100 \text{ GeV}$, b -tag | |

Table 4: Summary of CRs for the Meff-based and RJR-based searches. Also listed are the main targeted SR backgrounds in each case, the process used to model the background, and the main CR requirement(s) used to select this process. The transverse momenta of high-purity leptons (photons) used to select CR events must exceed 27 (150) GeV. The jet p_T thresholds and m_{eff} (incl.) selections match those used in the corresponding SRs of the Meff-based search. For the RJR-based search, selections are based on the discriminating variables used in the SRs, as described in the text.

The γ +jets region in both searches (labeled as Meff/RJR-CR γ in Table 4) is used to estimate the contribution of $Z(\rightarrow \nu\bar{\nu})$ +jets background events to each SR by selecting a sample of γ +jets events with $p_T(\gamma) > 150$ GeV and then treating the reconstructed photon as invisible in the E_T^{miss} calculation. For $p_T(\gamma)$ significantly larger than m_Z the kinematic properties of such events strongly resemble those of Z +jets events [90]. In order to reduce the theoretical uncertainties associated with the Z/γ^* +jets background predictions in SRs arising from the use of LO γ +jets cross-sections, a correction factor is applied to the Meff/RJR-CR γ events as a function of the requirement on the number of jets. This correction factor, κ , ranges from 1.41 to 2.26 for two to six jets, and is determined by comparing Meff-CR γ observations with those in a highly populated auxiliary control region defined by selecting events with two electrons or muons for which the invariant mass lies within 25 GeV of the mass of the Z boson, satisfying $E_T^{\text{miss}} > 250$ GeV, $E_T^{\text{miss}}/\sqrt{H_T} > 14$ GeV $^{1/2}$ and $m_{\text{eff}}(\text{incl.}) > 1200$ GeV where two leptons are treated as contributing to E_T^{miss} .

The W and top regions in both searches (labeled as Meff/RJR-CRW and Meff/RJR-CRT in Table 4) aim to select samples rich in $W(\rightarrow \ell\nu)$ +jets and semileptonic $t\bar{t}$ background events, respectively. They use events with one high-purity lepton with $p_T > 27$ GeV and differ in their number of b -jets (zero or ≥ 1 , respectively). In both searches, the requirement on the transverse mass m_T formed by the E_T^{miss} and a selected lepton is applied, as indicated in Table 4. The lepton is treated as a jet with the same momentum to model background events in which a hadronically decaying τ -lepton is produced. This estimation procedure is used to try to get a better idea of the $W(\rightarrow \ell\nu)$ +jets and $t\bar{t}$ cross section in a restricted kinematic phase space, by normalizing the MC to the data for the electron and muon channels, respectively. The propagation of the number of background events from the control region to the signal region is done purely by Monte Carlo which takes into account the impact of all the differences in selection criteria between the control and signal regions. The Meff-CRW and Meff-CRT criteria omit the SR selection requirements on $|\eta_{\text{jet}}|$, $\Delta\phi(\text{jet}, \vec{E}_T^{\text{miss}})_{\text{min}}$ and aplanarity for all SRs, while for the SRs requiring $m_{\text{eff}}(\text{incl.}) > 2200$ GeV the requirements on $E_T^{\text{miss}}/m_{\text{eff}}(N_j)$ are not applied. This is done in order to increase the number of CR data events without significantly increasing the theoretical uncertainties associated with the CR-to-SR extrapolation in the background estimation procedure.

The multi-jet background in both searches is estimated using a data-driven technique [90], which applies a resolution function to well-measured multi-jet events in order to estimate the impact of jet energy mis-

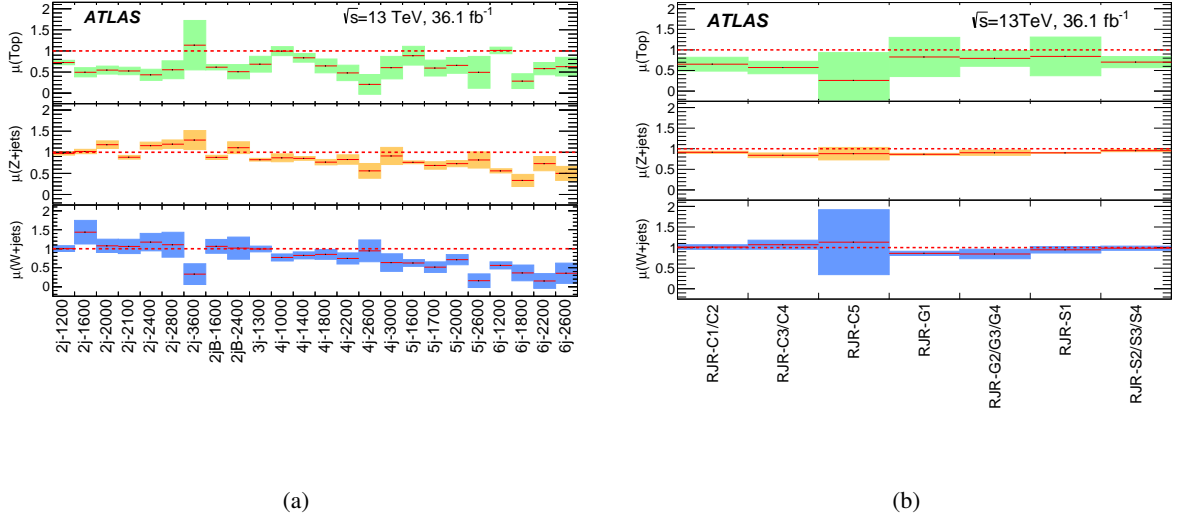


Figure 5: Fitted normalization factor per process as a function of the channel considered in the (a) m_{eff} -based and (b) RJR-based searches. The dashed horizontal lines at 1 correspond to pure MC estimates with the vertical size of the colored regions corresponding to the total uncertainty in each background source.

measurement and heavy-flavor semileptonic decays on $E_{\text{T}}^{\text{miss}}$ and other variables. The resolution function of jets is initially estimated from MC simulation by matching ‘truth’ jets reconstructed from generator-level particles including muons and neutrinos to detector-level jets with $\Delta R < 0.1$ in multi-jet samples, and then is modified to agree with data in dedicated samples to measure the resolution function. The m_{eff} -CRQ region uses reversed selection requirements on $\Delta\phi(\text{jet}, \vec{E}_{\text{T}}^{\text{miss}})_{\text{min}}$ and on $E_{\text{T}}^{\text{miss}}/m_{\text{eff}}(N_{\text{j}})$ (or $E_{\text{T}}^{\text{miss}}/\sqrt{H_{\text{T}}}$ where appropriate) to produce samples enriched in multi-jet background events.

In the RJR-based search, all CRs corresponding to RJR-S (RJR-G) SRs are required to satisfy $H_{1,1}^{PP} > 800$ (700) GeV. Additionally, $H_{2,1}^{PP} > 1000$ GeV (for RJR-S), $H_{4,1}^{PP} > 1200$ GeV (for RJR-G) and $M_{\text{T}S} > 0$ (for RJR-C) are required for RJR-CRW, RJR-CRT and RJR-CRQ regions. In RJR-CRW and RJR-CRT, the requirements on all the other variables used for the RJR-SR selections are chosen such that the loosest value in the SR category (RJR-S, RJR-G or RJR-C) indicated in Table 3 is used. No requirement on $p_{PP,z}^{\text{lab}}/(p_{PP,z}^{\text{lab}} + H_{\text{T},N,1}^{PP})$ is used for the RJR-CRQ selections in all RJR-SRs, where $N = 2$ or 4.

The normalization factors determined from the background-only fits in each CR for each background process are shown in Figure 5. Some trends in these factors are observed, with the normalization factors for top background becoming smaller with increasingly tight m_{eff} requirements for the m_{eff} -based regions. Similarly, the measured top normalization factors decrease with increasingly tight $M_{\text{T}S}$ and $N_{\text{jet}}^{\text{V}}$ requirements in the RJR-based search. This behavior follows from the simulated top MC samples exhibiting generally harder kinematics than observed in data, as seen in Figures 6(d) and 7(d). The normalization factors for W +jets and Z +jets processes are generally stable with changing kinematic selections but with a clear indication that they become systematically smaller with increasingly strict requirements on the jet multiplicity. This is due to the MC simulation predicting jet multiplicities higher than observed in data events.

Example m_{eff} (incl.) distributions in control regions associated with m_{eff} -4j-2200 selections are shown in Figure 6. Figure 7 shows the $p_{\text{T}S}^{\text{CM}}$ discriminating variable distributions in control regions corresponding to RJR-C1 signal region selections. In all CRs, the data distributions are consistent with the MC

background prediction within uncertainties after normalizing the dominant process in each CR.

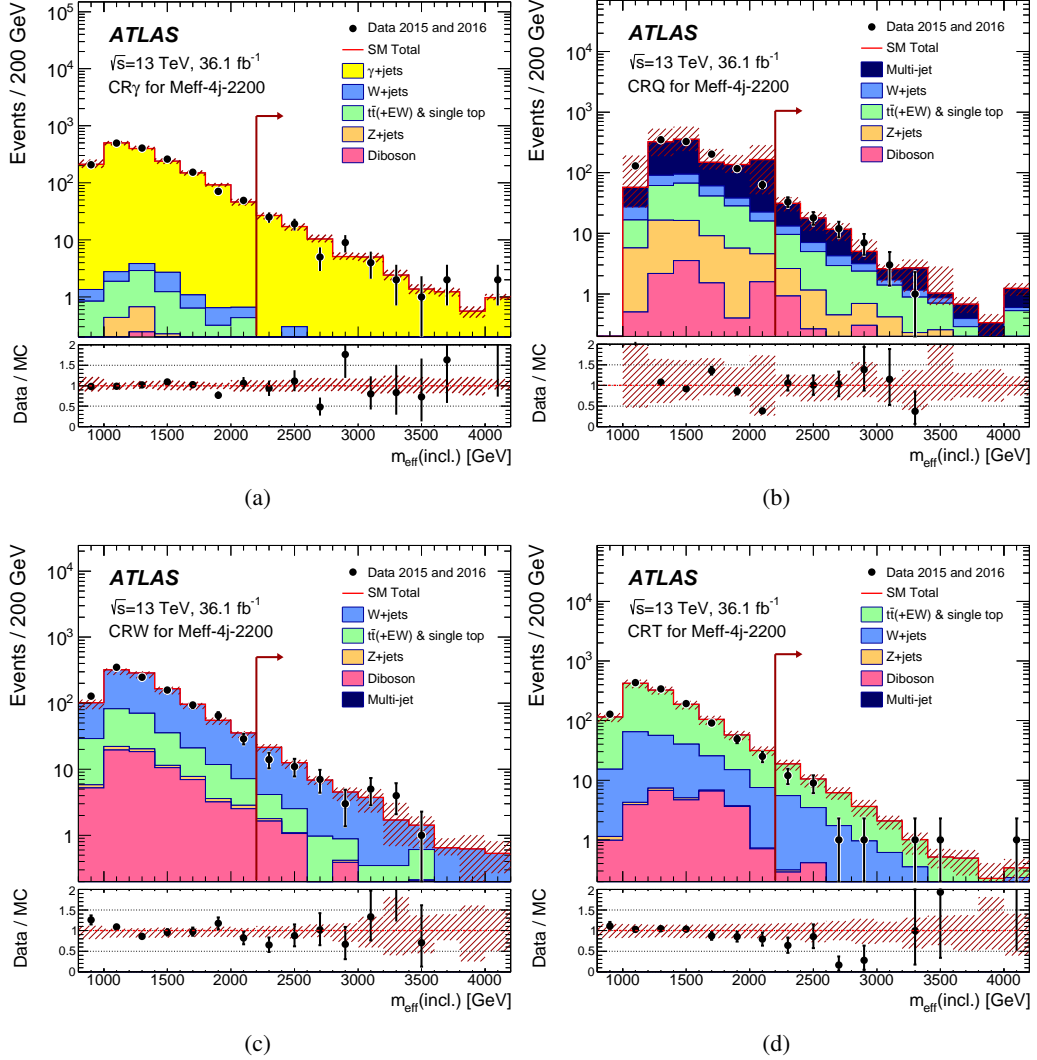


Figure 6: Observed $m_{\text{eff}}(\text{incl.})$ distributions in control regions (a) Meff-CR γ , (b) Meff-CRQ, (c) Meff-CRW and (d) Meff-CRT after applying the Meff-4j-2200 selection requirements listed in Table 2, except those on the plotted variable. No selection requirements on $\Delta\phi(\text{jet}, \vec{E}_T^{\text{miss}})_{\text{min}}$ are applied in Meff-CRW and Meff-CRT regions. The arrows indicate the values at which the requirements on $m_{\text{eff}}(\text{incl.})$ are applied. The histograms show the MC background predictions, normalized using cross-section times integrated luminosity and the dominant process in each CR is normalized using data. In the case of the γ +jets background, a κ factor described in the text is applied. The last bin includes overflow events. The hatched (red) error bands indicate the combined experimental, MC statistical and theoretical modeling uncertainties.

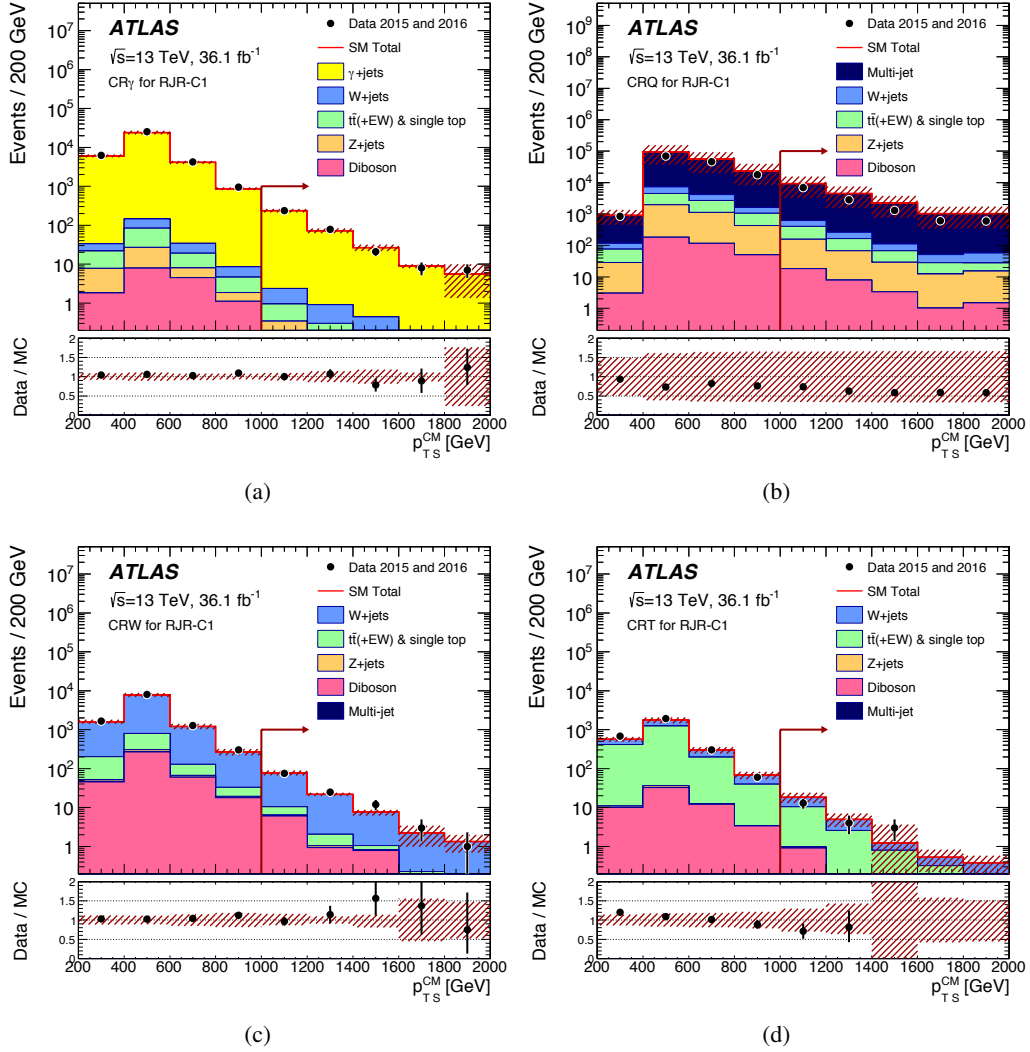


Figure 7: Observed p_{TS}^{CM} distribution in control regions (a) RJR-CR γ , (b) RJR-CRQ, (c) RJR-CRW and (d) RJR-CRT after selecting events for the corresponding control regions as explained in the text for RJR-C1 region and after applying all selection requirements except those on the plotted variable. The arrows indicate the values at which the requirements are applied. The histograms show the MC background predictions, normalized using cross-section times integrated luminosity and the dominant process in each CR is normalized using data. In the case of γ +jets background, a κ factor described in the text is applied. The last bin includes overflow events. The hatched (red) error bands indicate the combined experimental, MC statistical and theoretical modeling uncertainties.

8.2 Validation regions

The background estimation procedure is validated by comparing the numbers of events observed in the VRs to the corresponding SM background predictions obtained from the background-only fits. Several VRs are defined in both searches, with requirements distinct from those used in the CRs and that maintain low expected signal contamination. Like the CRs, the majority of the VRs are defined in final states with leptons and photons, allowing the different expected background contributions to the SRs to be validated

almost separately with high-purity selections.

The Meff/RJR-CR γ estimates of the $Z(\rightarrow \nu\bar{\nu})$ +jets background are validated using samples of $Z(\rightarrow \ell\bar{\ell})$ +jets events selected by requiring high-purity lepton pairs of opposite sign and identical flavor for which the dilepton invariant mass lies within 25 GeV of the Z boson mass (Meff/RJR-VRZ). In Meff/RJR-VRZ regions, the leptons are treated as contributing to E_T^{miss} . Additional VRs designed to validate the $Z(\rightarrow \nu\bar{\nu})$ +jets estimate in the RJR-based search are also used: the VRZc region, which selects events with no leptons but inverts the $\Delta\phi_{\text{ISR}, l}$ requirement of the SR selection (Table 3) and VRZca, which further loosens some other criteria to match the RJR-CRW and RJR-CRT regions. The VRZc regions have a purity of $Z(\rightarrow \nu\bar{\nu})$ +jets of 50%–70%. In order to increase yields in the dilepton final state RJR-VRZ regions, two additional regions, RJR-VRZa and RJR-VRZb are constructed with $H_{1,1}^{PP}$ and $H_{T 2,1}^{PP}$ (or $H_{T 4,1}^{PP}$ where appropriate) loosened, respectively, relative to the values used for the RJR-CRW and RJR-CRT regions.

The Meff-CRW and Meff-CRT estimates of the W +jets and top quark background are validated with the same Meff-CRW and Meff-CRT selections, but applying the $\Delta\phi(\text{jet}, \vec{E}_T^{\text{miss}})_{\text{min}}$ requirement and treating the lepton as a jet (Meff-VRW, Meff-VRT). To further validate the extrapolation over the $\Delta\phi(\text{jet}, \vec{E}_T^{\text{miss}})_{\text{min}}$ and aplanarity variables from the dedicated W +jets and top quark CRs to the SRs, additional validation regions Meff-VRW $\Delta\Phi$ and Meff-VRT $\Delta\Phi$ as well as Meff-VRWap and Meff-VRTap are defined by relaxing $\Delta\phi(\text{jet}, \vec{E}_T^{\text{miss}})_{\text{min}}$ and aplanarity requirements, respectively, relative to Meff-VRW and Meff-VRT.

Similarly, the RJR-CRW and RJR-CRT estimates of the W +jets and top quark backgrounds are validated using the same selections as for the corresponding CRs, except that the requirements on $H_{1,1}^{PP}$ and $M_{T S}$ (RJR-VRWa, RJR-VRTa) or $H_{T 2,1}^{PP}$ and $H_{T 4,1}^{PP}$ (RJR-VRWb, RJR-VRTb) are omitted. Two additional VRs that require the presence of a high-purity lepton and either veto (RJR-VRW) or require the presence of at least one b -jet (RJR-VRT), and require no additional SR selection criteria, are also used in the analysis.

The Meff-CRQ estimates of the multi-jet background are validated with VRs for which the Meff-CRQ selection is applied, but with the SR $E_T^{\text{miss}}/m_{\text{eff}}(N_j)$ ($E_T^{\text{miss}}/\sqrt{H_T}$) requirement reinstated (Meff-VRQa), or with a requirement of an intermediate value of $\Delta\phi(\text{jet}, \vec{E}_T^{\text{miss}})_{\text{min}}$ applied (Meff-VRQb). The RJR-VRQ regions use the same selection as the corresponding RJR-CRQ, except that the requirements on $H_{1,1}^{PP}$, $H_{T 2,1}^{PP}$ (or $H_{T 4,1}^{PP}$ where appropriate) and $M_{T S}$ are omitted depending on the region. Additional VRs with inverted Δ_{QCD} (RJR-VRQa), $H_{1,1}^{PP}$ (RJR-VRQb) for RJR-S and RJR-G signal regions, and with $0.5 < R_{\text{ISR}} < \text{SR requirement}$ (RJR-VRQc) for the RJR-C region (Table 3), are also used.

The results of the validation procedure are shown in Figure 8, where the difference in each VR between the numbers of observed and expected events, expressed as fractions of the one-standard deviation (1σ) uncertainties in the latter, are summarized. No significant systematic biases are observed for both searches, with the largest discrepancies being 1.9σ in the Meff-VRZ associated with the SR Meff-2j-3600 out of 190 VRs and 2.3σ in RJR-VRW associated with the SR RJR-G1b out of 194 VRs.

9 Systematic uncertainties

Systematic uncertainties in background estimates arise from the use of extrapolation factors that relate observations in the control regions to background predictions in the signal regions, and from the MC modeling of minor backgrounds.

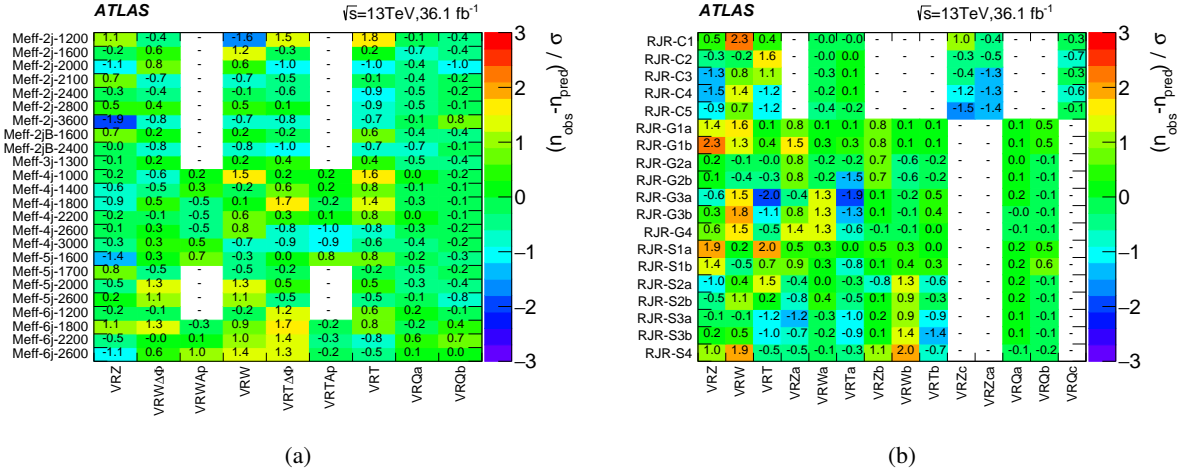


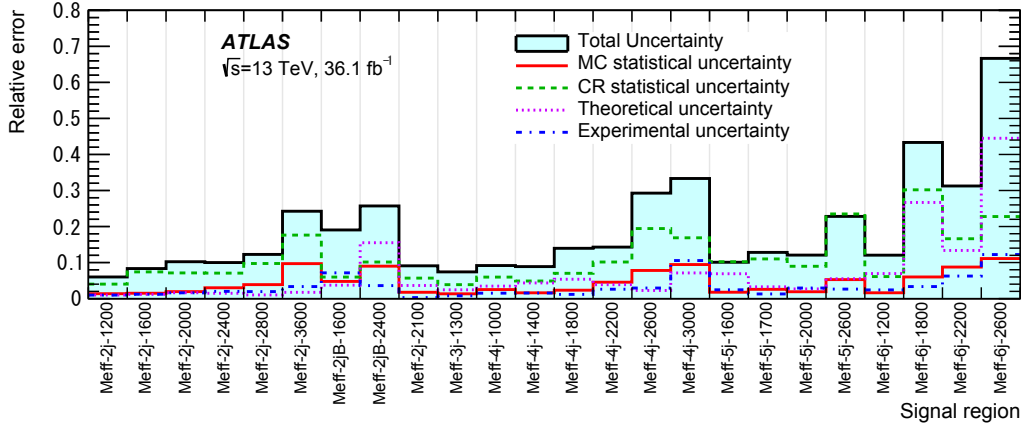
Figure 8: Differences between the numbers of observed events in data and the SM background predictions for each VR used in the (a) Meff-based and (b) RJR-based searches, expressed as a fraction of the total uncertainty, which combines the uncertainty in the background predictions, and the expected statistical uncertainty of the test obtained from the number of expected events. Empty boxes (indicated by a ‘-’) are when the VR is not used for the corresponding SR selection.

The overall background uncertainties, detailed in Figure 9, range from 6% in SR Meff-2j-1200 to 67% in SR Meff-6j-2600 and from 10% in SRs RJR-S1a, RJR-S2a, RJR-G1a and RJR-C2 to 30% in SR RJR-G4.

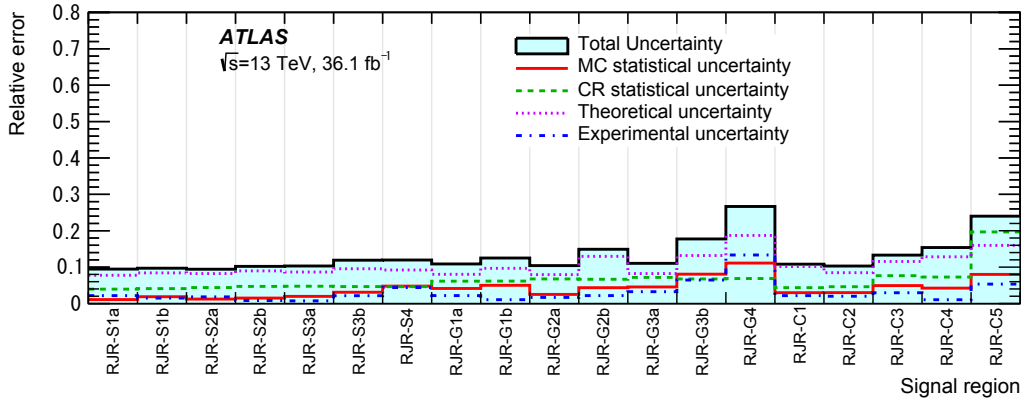
For the backgrounds estimated with MC simulation-derived extrapolation factors, the primary common sources of systematic uncertainty are the jet energy scale (JES) calibration, jet energy resolution (JER), theoretical uncertainties, and limited event yields in the MC samples and data CRs. Correlations between uncertainties (for instance between JES or JER uncertainties in CRs and SRs) are taken into account where appropriate.

The JES and JER uncertainties are estimated using the methods discussed in Refs. [75, 91, 92]. An additional uncertainty in the modeling of energy not associated with reconstructed objects, used in the calculation of E_T^{miss} and measured with unassociated charged tracks, is also included. The combined JES, JER and E_T^{miss} uncertainty ranges from 1% of the expected background in 2-jet Meff-SRs to 12% in SR Meff-6j-2600. In the RJR-based search, the same uncertainties range from 1% in RJR-C4 to 14% in RJR-G4. Uncertainties in jet mass scale (JMS) and jet mass resolution (JMR) are additionally assigned to SR Meff-2jB-1600 and Meff-2jB-2400, which have requirements on the masses of large-radius jets. The JMS uncertainty is estimated using the same methodology as Ref. [93]. A 20% uncertainty is conservatively assigned to the JMR. The combined JMS and JMR uncertainty is 3.2% of the expected background in Meff-2j-1600 and 5.1% in Meff-2j-2400.

Uncertainties arising from theoretical modeling of background processes are estimated by comparing samples produced with different MC generators or by varying the scales. Uncertainties in W/Z +jets production are estimated by increasing and decreasing the renormalization, factorization and resummation scales by a factor of two, and by increasing and decreasing the nominal CKKW matching scale, 20 GeV, by 10 GeV and 5 GeV, respectively. Uncertainties in the modeling of top quark pair production are estim-



(a)



(b)

Figure 9: Breakdown of the largest systematic uncertainties in the background estimates for the (a) M_{eff} -based and (b) RJR-based searches. The individual uncertainties can be correlated, such that the total background uncertainty is not necessarily their sum in quadrature.

ated by comparing samples generated with POWHEG-Box and MG5_aMC@NLO, and by comparing the nominal sample with samples generated using different shower tunes. Uncertainties associated with PDF modeling of top quark pair production are found to be negligible. Uncertainties in diboson production due to PDF, renormalization and factorization scale uncertainties (estimated by increasing and decreasing the scales used in the MC generators by a factor of two for all combinations and taking the envelope of them) are accounted for. The combined theoretical uncertainty ranges from 1% in $M_{\text{eff}}-2j-1200$ to 45% in $M_{\text{eff}}-6j-2600$ for M_{eff} SRs. In the RJR-based search, the same uncertainties range from 8% in RJR-S1a to 18% in RJR-G4, with the smaller range largely due to the absence of 6-jet SRs. Uncertainties associated with the modeling of Z +jets production are largest in the 2-jet M_{eff} -SRs (7%). In the RJR-based search, these uncertainties are largest in RJR-S2b and RJR-S3b SR (8%). The impact of lepton reconstruction uncertainties, and of the uncertainties related to the b -tag/ b -veto efficiency, on the overall background uncertainty is found to be negligible for all SRs.

The uncertainties arising from the data-driven correction procedure applied to events selected in the CR γ region, described in Section 8, are included in Figure 9 under ‘CR statistical uncertainty’. Other uncertainties due to CR data sample size range from 4% to 30% for Meff SRs and from 4% to 20% for RJR SRs. The statistical uncertainty arising from the use of MC samples is largest in SRs Meff-6j-2600 (11%) and RJR-G4 (12%). Uncertainties related to the multi-jet background estimates are taken into account by applying a uniform 100% uncertainty to the multi-jet yield in all SRs. In most of the SRs these uncertainties are negligible, and the maximum resulting contribution to the overall background uncertainty is less than 1%.

Experimental uncertainties (JES, JER, JMS, JMR and E_T^{miss}) and MC statistical uncertainty in the SUSY signals are estimated in the same way as for the background and are less than a few percent for most of the signals, except that 7% is assigned as JMS and JMR uncertainties in Meff-2jB-1600 and Meff-2jB-2400. The signal cross-section uncertainty is estimated by computing the changes when the renormalization and factorization scale, PDF and the strong coupling constant (α_s) are varied. The uncertainties in the amount of ISR and FSR in the SUSY signals are estimated by varying generator tunes in the simulation as well as scales used in the matrix-element generator as a function of the mass difference, Δm , between gluino (or squark) and $\tilde{\chi}_1^0$. This uncertainty reaches 20% in the limit of no mass difference and is negligible for $\Delta m > 200$ GeV.

10 Results, interpretation and limits

Distributions of $m_{\text{eff}}(\text{incl.})$ from the Meff-based search for selected signal regions, obtained before the final selections on this quantity (but after applying all other selections), are shown in Figure 10 for data and the different MC samples normalized using the theoretical cross-sections. Similarly, distributions of the final discriminating variables used in the RJR-based search, $H_{T,2,1}^{PP}$ ($H_{T,4,1}^{PP}$ where appropriate) in selected RJR-S and RJR-G regions, and $p_{T,S}^{\text{CM}}$ in selected RJR-C regions, after applying all other selection requirements except those based on the plotted variable, are shown in Figure 11. Examples of SUSY signals are also shown for illustration. These signals correspond to the processes to which each SR is primarily sensitive: $\tilde{q}\tilde{q}$ production for the lower jet-multiplicity SRs and $\tilde{g}\tilde{g}$ production for the higher jet-multiplicity SRs. In these figures, data and background distributions largely agree within uncertainties.

The number of events observed in the data and the number of SM events expected to enter each of the signal regions, determined using the background-only fit, are shown in Tables 5 and 6 and in Figure 12. The pre-fit background predictions are also shown in Tables 5 and 6 for comparison.

The background normalizations for each SR are fit to reproduce the event yields observed in the CRs. This is in particular seen in Figure 5, leading to agreement between data and post-fit background predictions in most of the SRs. The most significant observed excess in the signal regions for the Meff-based search, with a p -value for the background-only hypothesis of 0.02, corresponding to a significance of 2.0 standard deviations, occurs in SR Meff-2j-1200 and Meff-2j-2100 (Table 5). The most significant observed excess across the signal regions for RJR-based search, with a p -value for the background-only hypothesis of 0.01, corresponding to a significance of 2.5 standard deviations, occurs in SR RJR-S1a (Table 6).

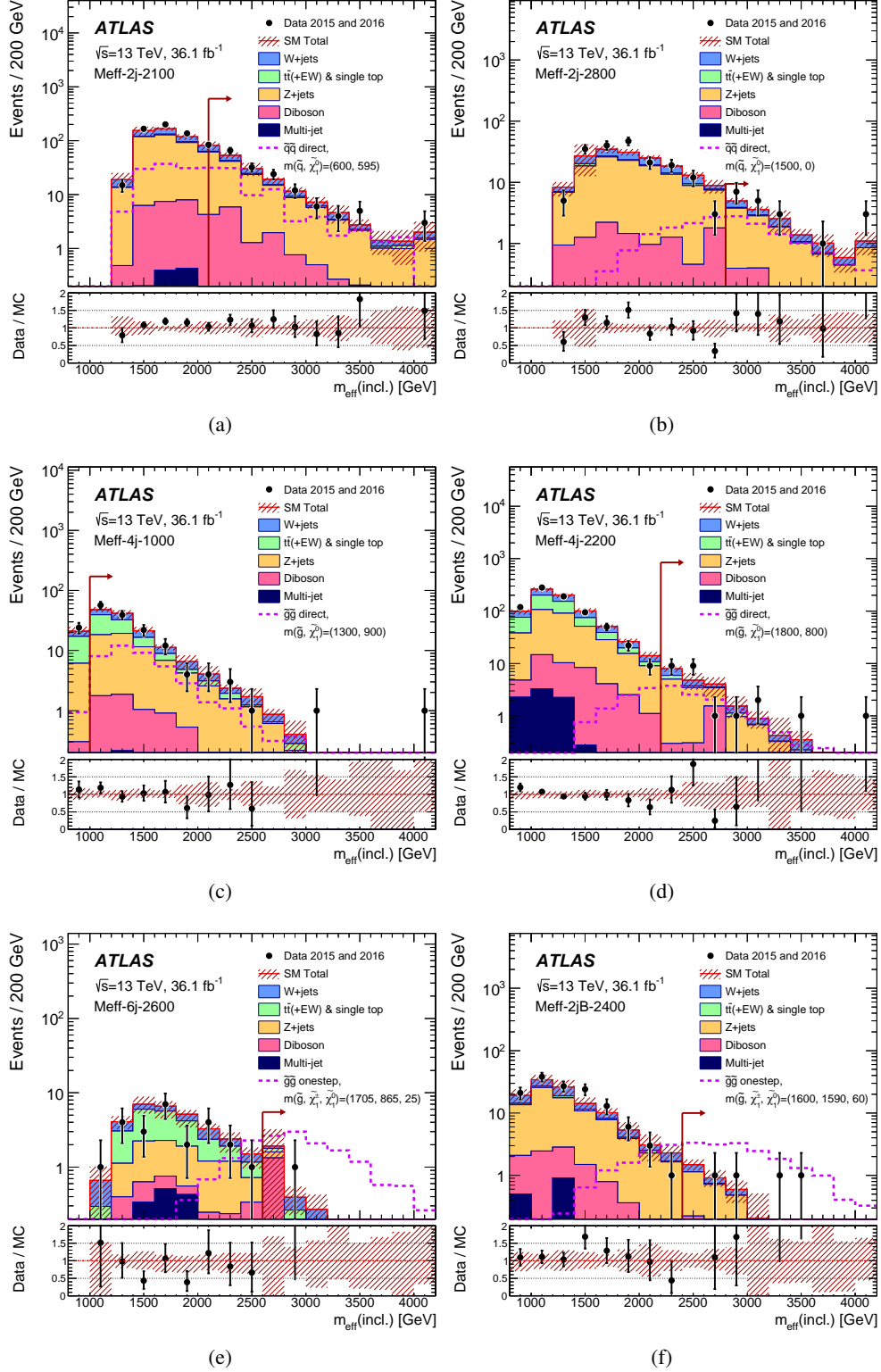


Figure 10: Observed $m_{\text{eff}}(\text{incl.})$ distributions for the (a) Meff-2j-2100, (b) Meff-2j-2800, (c) Meff-4j-1000, (d) Meff-4j-2200, (e) Meff-6j-2600 and (f) Meff-2jB-2400 signal regions, after applying all selection requirements except those on the plotted variable. The histograms show the MC background predictions prior to the fits described in the text, normalized using cross-section times integrated luminosity. The last bin includes the overflow. The hatched (red) error bands indicate the combined experimental and MC statistical uncertainties. The arrows indicate the values at which the requirements on $m_{\text{eff}}(\text{incl.})$ are applied. Expected distributions for benchmark signal model points, normalized using NLO+NLL cross-section (Section 3) times integrated luminosity, are also shown for comparison (masses in GeV).

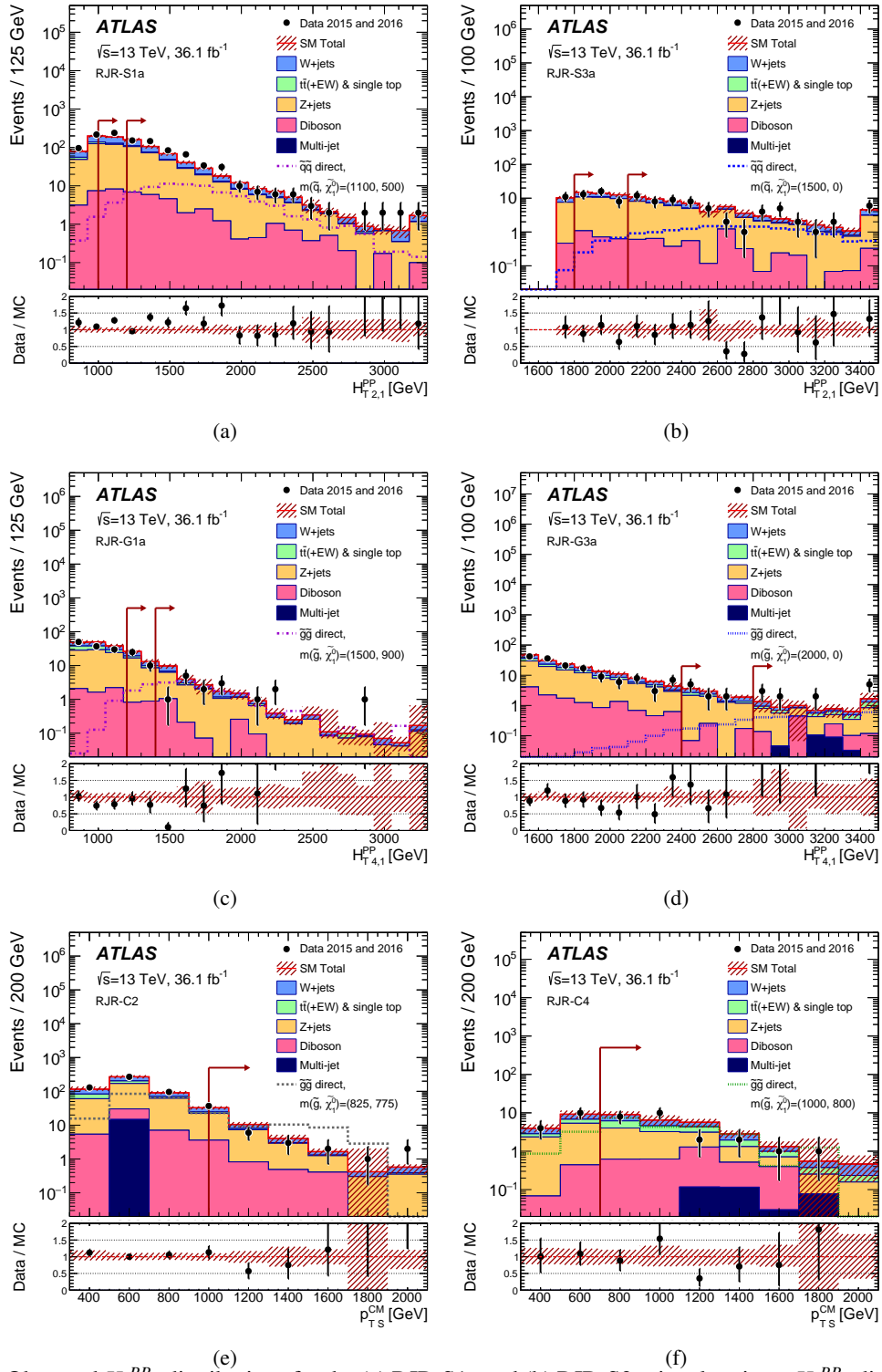


Figure 11: Observed $H_{T,2,1}^{PP}$ distributions for the (a) RJR-S1a and (b) RJR-S3a signal regions, $H_{T,4,1}^{PP}$ distributions for the (c) RJR-G1a and (d) RJR-G3a signal regions, and $p_{T,S}^{CM}$ distributions for the (e) RJR-C2 and (f) RJR-C4 signal regions, after applying all selection requirements except those on the plotted variable. The histograms show the MC background predictions prior to the fits described in the text, normalized using cross-section times integrated luminosity. The last bin includes the overflow. The hatched (red) error bands indicate the combined experimental and MC statistical uncertainties. The arrows indicate the values at which the requirements on the plotted variable are applied. When two arrows are shown, these correspond to the looser SR variation ‘a’ and the tighter variation ‘b’. Expected distributions for benchmark signal model points, normalized using NLO+NLL cross-section (Section 3) times integrated luminosity, are also shown for comparison (masses in GeV).

| Signal Region [Meff-] | 2j-1200 | 2j-1600 | 2j-2000 | 2j-2400 | 2j-2800 | 2j-3600 | 2j-B1600 | 2j-B2400 |
|---|----------------------------------|----------------------------------|--------------------------------------|--------------------------------------|--------------------------------------|--|--------------------------------------|--|
| MC expected events | | | | | | | | |
| Diboson | 28 | 14.8 | 5.6 | 3.4 | 1.2 | 0.21 | 1.9 | 0.41 |
| Z/ γ^* +jets | 345 | 140 | 54 | 24.2 | 10.2 | 2.3 | 16.6 | 2.5 |
| W+jets | 141 | 47 | 18 | 8.2 | 3.4 | 1.11 | 5.2 | 0.7 |
| $t\bar{t}$ (+EW) + single top | 21.0 | 5.8 | 2.48 | 1.13 | 0.32 | 0.04 | 0.80 | 0.03 |
| Fitted background events | | | | | | | | |
| Diboson | 28 \pm 4 | 14.8 \pm 2.3 | 5.5 \pm 1.2 | 3.4 \pm 0.7 | 1.2 \pm 0.2 | 0.21 \pm 0.07 | 1.9 \pm 0.5 | 0.41 \pm 0.07 |
| Z/ γ^* +jets | 336 \pm 19 | 143 \pm 11 | 64 \pm 8 | 28.0 \pm 3.3 | 12.2 \pm 1.5 | 2.9 \pm 0.8 | 14.6 \pm 1.9 | 2.8 \pm 0.6 |
| W+jets | 141 \pm 24 | 68 \pm 16 | 20 \pm 4 | 9.6 \pm 2.6 | 3.7 \pm 1.2 | 0.37 \pm 0.32 | 5.5 \pm 3.1 | 0.7 \pm 0.7 |
| $t\bar{t}$ (+EW) + single top | 15 \pm 4 | 2.9 \pm 1.6 | 1.36 \pm 1.0 | 0.5 \pm 0.5 | 0.18 \pm 0.15 | 0.04 ^{+0.05} _{-0.04} | 0.5 \pm 0.5 | 0.02 ^{+0.67} _{-0.02} |
| Multi-jet | 6 \pm 6 | 0.3 \pm 0.3 | 0.07 \pm 0.07 | 0.02 \pm 0.02 | < 0.004 | – | 0.03 \pm 0.03 | < 0.002 |
| Total MC | 538 | 208 | 80 | 37 | 15.1 | 3.6 | 24 | 3.6 |
| Total bkg | 526 \pm 31 | 228 \pm 19 | 90 \pm 10 | 42 \pm 4 | 17.3 \pm 2.0 | 3.6 \pm 0.9 | 22 \pm 4 | 3.9 \pm 1.2 |
| Observed | 611 | 216 | 73 | 34 | 19 | 5 | 26 | 4 |
| $\langle \epsilon\sigma \rangle_{\text{obs}}^{95}$ [fb] | 4.14 | 1.03 | 0.47 | 0.32 | 0.33 | 0.20 | 0.46 | 0.17 |
| S_{obs}^{95} | 149 | 37 | 17.0 | 11.4 | 11.9 | 7.2 | 16.7 | 6.1 |
| S_{exp}^{95} | 81 ⁺³¹ ₋₂₅ | 44 ⁺¹⁸ ₋₁₂ | 25.2 ^{+9.0} _{-7.8} | 15.3 ^{+5.7} _{-3.9} | 10.6 ^{+3.9} _{-2.8} | 5.5 ^{+2.5} _{-1.4} | 13.1 ^{+5.5} _{-3.4} | 5.7 ^{+2.3} _{-1.2} |
| p_0 (Z) | 0.02 (2.03) | 0.50 (0.00) | 0.50 (0.00) | 0.50 (0.00) | 0.31 (0.50) | 0.21 (0.81) | 0.28 (0.57) | 0.32 (0.47) |

| Signal Region [Meff-] | 2j-2100 | 3j-1300 | 4j-1000 | 4j-1400 | 4j-1800 | 4j-2200 | 4j-2600 | 4j-3000 |
|---|----------------------------------|----------------------------------|---------------------------------------|----------------------------------|--------------------------------------|--------------------------------------|--|-------------------------------------|
| MC expected events | | | | | | | | |
| Diboson | 12 | 37 | 6.4 | 18.1 | 6.0 | 2.4 | 1.8 | 0.24 |
| Z/ γ^* +jets | 116 | 268 | 60 | 100 | 33 | 12.0 | 4.1 | 1.4 |
| W+jets | 34 | 107 | 29 | 52 | 15 | 4.5 | 1.66 | 0.6 |
| $t\bar{t}$ (+EW) + single top | 5.0 | 36 | 43 | 42 | 7.7 | 1.6 | 0.64 | 0.21 |
| Fitted background events | | | | | | | | |
| Diboson | 12 \pm 5 | 37 \pm 6 | 6.4 \pm 1.1 | 18.1 \pm 3.0 | 6.0 \pm 1.1 | 2.4 \pm 0.7 | 1.8 \pm 0.8 | 0.24 \pm 0.07 |
| Z/ γ^* +jets | 102 \pm 8 | 221 \pm 20 | 52 \pm 7 | 85 \pm 10 | 25 \pm 4 | 9.9 \pm 2.0 | 2.3 \pm 0.9 | 1.2 \pm 0.5 |
| W+jets | 35 \pm 10 | 106 \pm 19 | 22 \pm 7 | 42 \pm 10 | 12 \pm 6 | 3.3 \pm 1.1 | 1.57 \pm 1.0 | 0.39 \pm 0.3 |
| $t\bar{t}$ (+EW) + single top | 2.6 \pm 1.4 | 25 \pm 9 | 43 \pm 8 | 35 \pm 10 | 5.0 \pm 3.3 | 0.8 \pm 0.4 | 0.13 ^{+0.17} _{-0.13} | 0.12 \pm 0.11 |
| Multi-jet | 0.11 \pm 0.11 | 1.4 \pm 1.4 | 0.39 \pm 0.39 | 0.5 \pm 0.5 | 0.10 \pm 0.10 | 0.02 \pm 0.02 | 0.03 \pm 0.03 | 0.01 \pm 0.01 |
| Total MC | 167 | 449 | 138 | 212 | 61 | 20.5 | 8.2 | 2.4 |
| Total bkg | 153 \pm 14 | 390 \pm 29 | 124 \pm 12 | 182 \pm 16 | 49 \pm 7 | 16.5 \pm 2.7 | 5.8 \pm 2.0 | 2.0 \pm 0.6 |
| Observed | 190 | 429 | 142 | 199 | 55 | 24 | 4 | 2 |
| $\langle \epsilon\sigma \rangle_{\text{obs}}^{95}$ [fb] | 1.98 | 2.84 | 1.40 | 1.76 | 0.79 | 0.49 | 0.16 | 0.12 |
| S_{obs}^{95} | 72 | 103 | 50.6 | 64 | 28.3 | 17.6 | 5.8 | 4.5 |
| S_{exp}^{95} | 38 ⁺¹⁶ ₋₁₀ | 72 ⁺²⁹ ₋₂₁ | 37.1 ^{+12.5} _{-9.1} | 45 ⁺¹⁵ ₋₁₂ | 22.2 ^{+6.9} _{-7.0} | 11.3 ^{+4.8} _{-2.7} | 6.7 ^{+2.7} _{-1.9} | 4.6 ^{+1.6} _{-1.2} |
| p_0 (Z) | 0.02 (2.03) | 0.13 (1.12) | 0.10 (1.26) | 0.08 (1.39) | 0.18 (0.90) | 0.09 (1.34) | 0.50 (0.00) | 0.50 (0.00) |

| Signal Region [Meff-] | 5j-1600 | 5j-1700 | 5j-2000 | 5j-2600 | 6j-1200 | 6j-1800 | 6j-2200 | 6j-2600 |
|---|---------------------------------|--|--------------------------------------|--|--|-------------------------------------|--|--|
| MC expected events | | | | | | | | |
| Diboson | 10.8 | 6.6 | 8.9 | 2.6 | 20.5 | 1.9 | 1.7 | 1.3 |
| Z/ γ^* +jets | 56 | 31 | 50 | 7.4 | 109 | 3.3 | 1.3 | 0.76 |
| W+jets | 42 | 15.5 | 18.6 | 2.57 | 81 | 2.2 | 0.67 | 0.44 |
| $t\bar{t}$ (+EW) + single top | 45 | 12.0 | 9.9 | 0.8 | 144 | 4.3 | 0.63 | 0.39 |
| Fitted background events | | | | | | | | |
| Diboson | 10.8 \pm 1.8 | 6.6 \pm 1.1 | 8.9 \pm 1.5 | 2.6 \pm 0.7 | 20.5 \pm 3.5 | 1.9 \pm 0.7 | 1.7 \pm 0.8 | 1.3 \pm 0.9 |
| Z/ γ^* +jets | 42 \pm 5 | 21 \pm 4 | 37 \pm 6 | 6.0 \pm 1.7 | 61 \pm 11 | 1.1 \pm 0.7 | 0.9 \pm 0.5 | 0.38 \pm 0.29 |
| W+jets | 26 \pm 7 | 8.0 \pm 2.6 | 13.3 \pm 3.3 | 0.41 ^{+0.45} _{-0.41} | 46 \pm 22 | 0.8 ^{+1.1} _{-0.8} | 0.10 ^{+0.16} _{-0.10} | 0.16 ^{+0.24} _{-0.16} |
| $t\bar{t}$ (+EW) + single top | 40 \pm 9 | 7.1 \pm 2.8 | 6.5 \pm 2.6 | 0.4 \pm 0.4 | 145 \pm 25 | 1.2 \pm 1.0 | 0.37 \pm 0.27 | 0.24 ^{+0.41} _{-0.24} |
| Multi-jet | 9 \pm 9 | 0.08 ^{+0.09} _{-0.08} | 0.09 \pm 0.09 | 0.01 \pm 0.01 | 1.29 ^{+1.30} _{-1.29} | 0.12 \pm 0.12 | 0.02 ^{+0.03} _{-0.02} | 0.06 \pm 0.06 |
| Total MC | 158 | 65 | 88 | 13.3 | 355 | 11.7 | 4.3 | 2.9 |
| Total bkg | 128 \pm 14 | 43 \pm 5 | 65 \pm 7 | 9.4 \pm 2.1 | 274 \pm 32 | 5.1 \pm 1.8 | 3.1 \pm 1.3 | 2.2 \pm 1.4 |
| Observed | 135 | 49 | 59 | 10 | 276 | 9 | 3 | 1 |
| $\langle \epsilon\sigma \rangle_{\text{obs}}^{95}$ [fb] | 1.26 | 0.64 | 0.49 | 0.24 | 2.19 | 0.33 | 0.15 | 0.11 |
| S_{obs}^{95} | 45.4 | 23.0 | 17.8 | 8.8 | 79 | 11.9 | 5.4 | 3.8 |
| S_{exp}^{95} | 39 ⁺¹⁴ ₋₈ | 18.2 ^{+6.7} _{-5.6} | 20.7 ^{+8.6} _{-5.3} | 8.5 ^{+3.0} _{-2.1} | 70 ⁺¹⁹ ₋₂₀ | 8.2 ^{+3.6} _{-1.7} | 5.4 ^{+1.8} _{-1.2} | 4.3 ^{+1.8} _{-0.6} |
| p_0 (Z) | 0.32 (0.46) | 0.21 (0.82) | 0.50 (0.00) | 0.46 (0.09) | 0.50 (0.00) | 0.11 (1.25) | 0.50 (0.00) | 0.50 (0.00) |

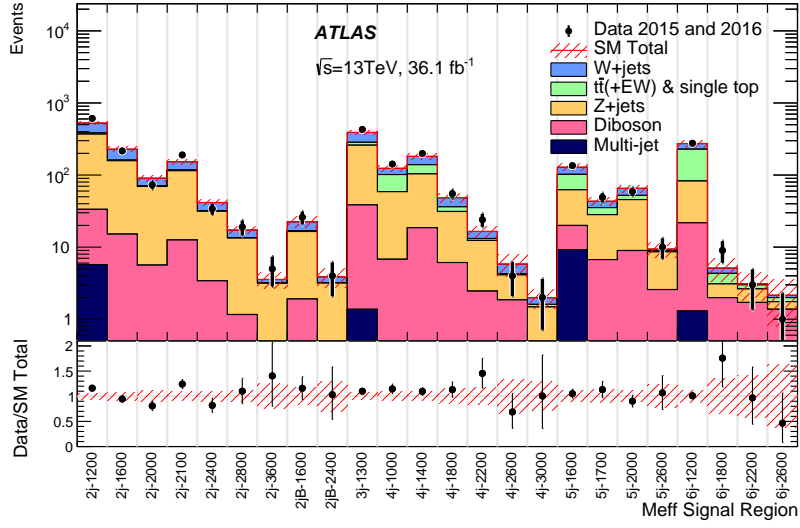
Table 5: Numbers of events observed in the signal regions used in the Meff-based analysis compared with background predictions obtained from the fits described in the text. The p -values (p_0) are the probabilities to obtain a value equal to or larger than that observed in the data. For an observed number of events lower than expected, the p -value is truncated at 0.5. In addition to p -values, the number of equivalent Gaussian standard deviations (Z) is given in parentheses. Also shown are 95% CL upper limits on the visible cross-section ($\langle \epsilon\sigma \rangle_{\text{obs}}^{95}$), the visible number of signal events (S_{obs}^{95}) and the number of signal events (S_{exp}^{95}) given the expected number of background events (and $\pm 1\sigma$ excursions of the expected number).

| Signal Region | RJR-S1a | RJR-S1b | RJR-S2a | RJR-S2b | RJR-S3a | RJR-S3b | RJR-S4 |
|---|--------------------|-------------------|-------------------|------------------|------------------|-----------------------|-------------------------|
| MC expected events | | | | | | | |
| Diboson | 37 | 17 | 23 | 10.3 | 7.2 | 3.5 | 2.0 |
| Z/ γ^* +jets | 495 | 189 | 222 | 102 | 70 | 30.5 | 17.9 |
| W+jets | 220 | 77 | 84 | 36 | 22.6 | 9.2 | 5.3 |
| $t\bar{t}$ (+EW) + single top | 32 | 9.2 | 10.9 | 4.7 | 2.6 | 1.17 | 0.68 |
| Fitted background events | | | | | | | |
| Diboson | 37 \pm 8 | 17 \pm 4 | 23 \pm 5 | 10.3 \pm 2.6 | 7.2 \pm 1.5 | 3.5 \pm 1.1 | 2.0 \pm 0.5 |
| Z/ γ^* +jets | 450 \pm 40 | 170 \pm 14 | 211 \pm 17 | 97 \pm 8 | 67 \pm 5 | 29.0 \pm 2.4 | 17.0 \pm 1.5 |
| W+jets | 208 \pm 27 | 73 \pm 9 | 83 \pm 12 | 35 \pm 5 | 22.3 \pm 3.0 | 9.0 \pm 1.3 | 5.2 \pm 0.9 |
| $t\bar{t}$ (+EW) + single top | 27 \pm 26 | 7.4 \pm 2.0 | 7.6 \pm 3.2 | 3.3 \pm 1.2 | 1.9 \pm 0.5 | 0.82 \pm 0.34 | 0.49 $^{+0.51}_{-0.49}$ |
| Multi-jet | 18 \pm 17 | 1.3 \pm 1.3 | 0.6 \pm 0.6 | 0.31 \pm 0.31 | 0.27 \pm 0.27 | 0.03 \pm 0.03 | 0.03 \pm 0.03 |
| Total MC | 1830 | 370 | 378 | 172 | 120 | 45.9 | 27.7 |
| Total bkg | 740 \pm 50 | 268 \pm 18 | 326 \pm 22 | 146 \pm 10 | 98 \pm 6 | 42.4 \pm 3.0 | 24.7 \pm 2.1 |
| Observed | 880 | 325 | 365 | 170 | 102 | 46 | 23 |
| $\langle\epsilon\sigma\rangle_{\text{obs}}^{95}$ [fb] | 6.45 | 2.76 | 1.89 | 1.38 | 0.69 | 0.51 | 0.30 |
| S_{obs}^{95} | 233 | 99.5 | 68.3 | 49.9 | 24.7 | 18.3 | 10.7 |
| S_{exp}^{95} | 120 $^{+44}_{-34}$ | 50 $^{+18}_{-13}$ | 50 $^{+14}_{-10}$ | 32 $^{+14}_{-8}$ | 24 $^{+11}_{-6}$ | 15.5 $^{+5.9}_{-3.4}$ | 11.6 $^{+4.5}_{-3.9}$ |
| p_0 (Z) | 0.01 (2.52) | 0.01 (2.34) | 0.14 (1.07) | 0.10 (1.30) | 0.50 (0.00) | 0.50 (0.00) | 0.50 (0.00) |

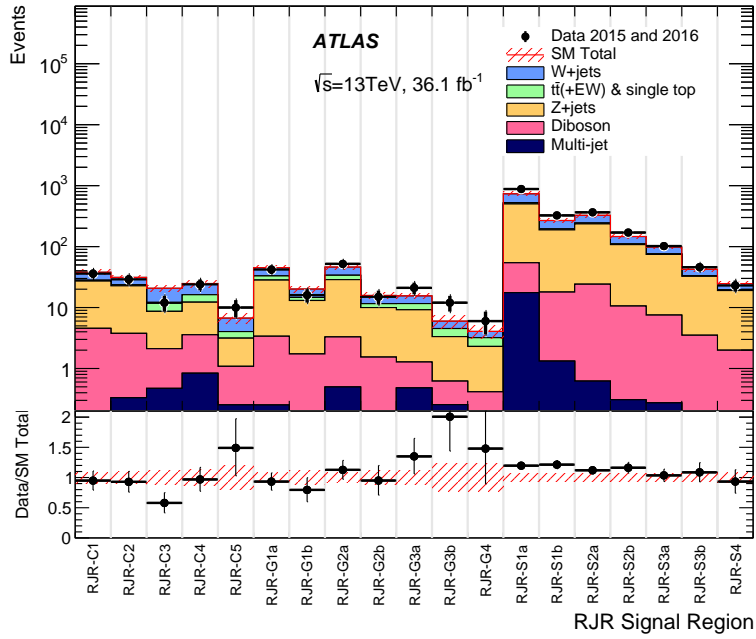
| Signal Region | RJR-G1a | RJR-G1b | RJR-G2a | RJR-G2b | RJR-G3a | RJR-G3b | RJR-G4 |
|---|-----------------------|-----------------------|-----------------------|----------------------|-----------------------|-----------------------|-------------------------|
| MC expected events | | | | | | | |
| Diboson | 3.1 | 1.6 | 2.8 | 1.34 | 0.80 | 0.37 | 0.24 |
| Z/ γ^* +jets | 28.7 | 13.1 | 28.1 | 9.4 | 8.8 | 3.0 | 2.09 |
| W+jets | 14.0 | 6.4 | 14.6 | 5.0 | 4.7 | 1.7 | 1.0 |
| $t\bar{t}$ (+EW) + single top | 6.0 | 2.0 | 6.5 | 2.0 | 3.1 | 1.5 | 1.1 |
| Fitted background events | | | | | | | |
| Diboson | 3.1 \pm 0.7 | 1.6 \pm 0.5 | 2.8 \pm 0.8 | 1.34 \pm 0.33 | 0.80 \pm 0.27 | 0.36 \pm 0.29 | 0.24 \pm 0.11 |
| Z/ γ^* +jets | 24.8 \pm 2.7 | 11.3 \pm 1.4 | 25.4 \pm 2.9 | 8.4 \pm 1.2 | 7.9 \pm 1.1 | 2.7 \pm 0.7 | 1.89 \pm 0.35 |
| W+jets | 12.0 \pm 1.7 | 5.5 \pm 0.9 | 12.3 \pm 2.1 | 4.2 \pm 0.8 | 3.9 \pm 0.7 | 1.5 \pm 0.6 | 0.85 \pm 0.29 |
| $t\bar{t}$ (+EW) + single top | 4.8 \pm 0.9 | 1.6 \pm 1.4 | 5.2 \pm 1.9 | 1.6 \pm 0.6 | 2.4 \pm 0.9 | 1.2 \pm 1.0 | 0.9 \pm 0.8 |
| Multi-jet | 0.25 \pm 0.25 | 0.13 \pm 0.13 | 0.5 \pm 0.5 | 0.2 \pm 0.2 | 0.5 \pm 0.5 | 0.26 \pm 0.25 | 0.18 $^{+0.18}_{-0.18}$ |
| Total MC | 66.8 | 30.9 | 80.4 | 28.9 | 44.4 | 21.1 | 14.4 |
| Total bkg | 45 \pm 4 | 20.1 \pm 2.3 | 46 \pm 4 | 15.8 \pm 1.8 | 15.6 \pm 1.7 | 6.0 \pm 1.4 | 4.1 \pm 0.9 |
| Observed | 42 | 16 | 52 | 15 | 21 | 12 | 6 |
| $\langle\epsilon\sigma\rangle_{\text{obs}}^{95}$ [fb] | 0.44 | 0.25 | 0.63 | 0.26 | 0.42 | 0.38 | 0.22 |
| S_{obs}^{95} | 15.9 | 8.9 | 22.7 | 9.4 | 15.2 | 13.9 | 7.8 |
| S_{exp}^{95} | 16.6 $^{+6.7}_{-5.0}$ | 11.0 $^{+4.1}_{-2.7}$ | 16.7 $^{+6.8}_{-4.8}$ | 9.9 $^{+4.1}_{-2.5}$ | 10.7 $^{+3.4}_{-3.1}$ | 10.3 $^{+2.7}_{-2.1}$ | 6.3 $^{+1.9}_{-2.1}$ |
| p_0 (Z) | 0.50 (0.00) | 0.50 (0.00) | 0.19 (0.89) | 0.50 (0.00) | 0.11 (1.21) | 0.07 (1.50) | 0.24 (0.72) |

| Signal Region | RJR-C1 | RJR-C2 | RJR-C3 | RJR-C4 | RJR-C5 |
|---|-------------------------|-----------------------|-----------------------|-----------------------|-------------------------|
| MC expected events | | | | | |
| Diboson | 4.5 | 3.4 | 1.6 | 2.7 | 0.8 |
| Z/ γ^* +jets | 24.8 | 20.7 | 7.8 | 10.3 | 2.3 |
| W+jets | 9.8 | 7.4 | 8.3 | 8.0 | 2.4 |
| $t\bar{t}$ (+EW) + single top | 1.32 | 1.6 | 5.5 | 6.9 | 3.39 |
| Fitted background events | | | | | |
| Diboson | 4.5 \pm 1.0 | 3.4 \pm 0.8 | 1.6 \pm 0.5 | 2.7 \pm 0.7 | 0.8 \pm 0.5 |
| Z/ γ^* +jets | 22.6 \pm 2.3 | 18.9 \pm 2.0 | 6.5 \pm 1.2 | 8.6 \pm 1.2 | 2.1 \pm 0.6 |
| W+jets | 9.9 \pm 1.9 | 7.5 \pm 1.4 | 8.9 \pm 1.4 | 8.6 \pm 1.4 | 2.7 \pm 2.1 |
| $t\bar{t}$ (+EW) + single top | 0.86 $^{+1.00}_{-0.86}$ | 1.0 \pm 0.7 | 3.2 \pm 1.5 | 4.0 \pm 2.4 | 0.89 $^{+2.17}_{-0.89}$ |
| Multi-jet | 0.06 \pm 0.06 | 0.33 \pm 0.33 | 0.5 \pm 0.5 | 0.8 \pm 0.8 | 0.25 $^{+0.26}_{-0.25}$ |
| Total MC | 43.9 | 53.3 | 54.8 | 84.0 | 28.0 |
| Total bkg | 37.9 \pm 3.5 | 31.2 \pm 2.9 | 20.7 \pm 2.6 | 24.8 \pm 3.3 | 6.7 \pm 1.3 |
| Observed | 36 | 29 | 12 | 24 | 10 |
| $\langle\epsilon\sigma\rangle_{\text{obs}}^{95}$ [fb] | 0.38 | 0.35 | 0.18 | 0.42 | 0.30 |
| S_{obs}^{95} | 13.8 | 12.7 | 6.4 | 15.2 | 10.7 |
| S_{exp}^{95} | 15.3 $^{+5.7}_{-4.7}$ | 14.0 $^{+5.0}_{-4.2}$ | 11.2 $^{+4.4}_{-3.5}$ | 15.2 $^{+4.5}_{-3.5}$ | 7.8 $^{+2.7}_{-2.0}$ |
| p_0 (Z) | 0.50 (0.00) | 0.50 (0.00) | 0.50 (0.00) | 0.50 (0.00) | 0.14 (1.06) |

Table 6: Numbers of events observed in the signal regions used in the RJR-based analysis compared with background predictions obtained from the fits described in the text. The p -values (p_0) are the probabilities to obtain a value equal to or larger than that observed in the data. For an observed number of events lower than expected, the p -value is truncated at 0.5. In addition to p -values, the number of equivalent Gaussian standard deviations (Z) is given in parentheses. Also shown are 95% CL upper limits on the visible cross-section ($\langle\epsilon\sigma\rangle_{\text{obs}}^{95}$), the visible number of signal events (S_{obs}^{95}) and the number of signal events (S_{exp}^{95}) given the expected number of background events (and $\pm 1\sigma$ excursions of the expected number).



(a)



(b)

Figure 12: Comparison of the observed and expected event yields as a function of signal region in the (a) Meff-based and (b) RJR-based searches. The background predictions are those obtained from the background-only fits, presented in Tables 5 and 6. The bottom graph shows the ratio of observed data yields to the total predicted background. The hatched (red) error bands indicate the combined experimental and MC statistical uncertainties.

In the absence of a statistically significant excess, limits are set on contributions to the SRs from BSM physics. Upper limits at 95% CL on the number of BSM signal events in each SR and the corresponding visible BSM cross-section are derived from the model-independent fits described in Section 5 using the CL_S prescription. Limits are evaluated using MC pseudo-experiments. The results are presented in Tables 5 and 6.

The model-dependent fits in all the SRs are used to set limits on specific classes of SUSY models using asymptotic formulae [94]. The two searches presented in this paper are combined such that the final observed and expected 95% CL exclusion limits are obtained from the signal regions with the best expected CL_S value. Fine structures in the limit lines arise due to transitions between best SR's which then also have an impact on the interpolations between grid points.

In Figure 13, limits are shown for two classes of simplified models in which only direct production of first- and second-generation mass-degenerate squark or gluino pairs are considered. Limits are obtained by using the signal region with the best expected sensitivity at each point. In these simplified-model scenarios, the upper limit of the excluded first- and second-generation squark mass region is 1.55 TeV assuming massless $\tilde{\chi}_1^0$, as obtained from the signal region RJR-S4. The observed exclusion limit is worse than the expected limit in the region with squark ($\tilde{\chi}_1^0$) mass of 1 TeV (500 GeV) due to a 2σ excess in SR Meff-2j-1200. The corresponding limit on the gluino mass is 2.03 TeV, if the $\tilde{\chi}_1^0$ is massless, as obtained from the signal region Meff-4j-3000. The best sensitivity in the region of parameter space where the mass difference between the squark (gluino) and the lightest neutralino is small, is obtained from the dedicated RJR-C signal regions. In these regions with very compressed spectra and where the mass difference is less than 50 GeV, squark (gluino) masses up to 650 GeV (1 TeV) are excluded. In Figure 13(b), the compressed-mass region with a gluino mass below 700 GeV is fully excluded by this analysis; small deviations in the exclusion contour in this region, suggesting non-excluded areas, are due to interpolation effects. The observed exclusion limit is worse than the expected limit in the region with gluino ($\tilde{\chi}_1^0$) mass of 1800 (700) GeV due to a moderate excess (1.3σ) in SR Meff-4j-2200.

In Figure 14, limits are shown for pair-produced first- and second-generation squarks or gluinos each decaying via an intermediate $\tilde{\chi}_1^\pm$ to a quark (for squarks) or two quarks (for gluinos), a W boson and a $\tilde{\chi}_1^0$. Two sets of models of mass spectra are considered for each case. One is with a fixed $m_{\tilde{\chi}_1^\pm} = (m_{\tilde{q}} + m_{\tilde{\chi}_1^0})/2$ (or $(m_{\tilde{g}} + m_{\tilde{\chi}_1^0})/2$), the other is with a fixed $m_{\tilde{\chi}_1^0} = 60$ GeV. In the former models with squark pair production, $m_{\tilde{q}}$ up to 1.15 TeV are excluded for a massless $\tilde{\chi}_1^0$, as is $m_{\tilde{g}}$ up to 1.98 TeV with gluino pair production. These limits are obtained from the signal region RJR-G2b and Meff-6j-2600, respectively. In the regions with very compressed spectra with mass difference between the gluino (or squark) and $\tilde{\chi}_1^0$ less than 50 GeV, RJR-C signal regions also exclude squark (gluino) masses up to 600 GeV (1 TeV). In the latter models, Meff-2jB-1600 and Meff-2jB-2400 extend the limits on squark (gluino) masses up to 1.1 TeV (1.85 TeV) in the regions with small mass difference between the squark (gluino) and $\tilde{\chi}_1^\pm$.

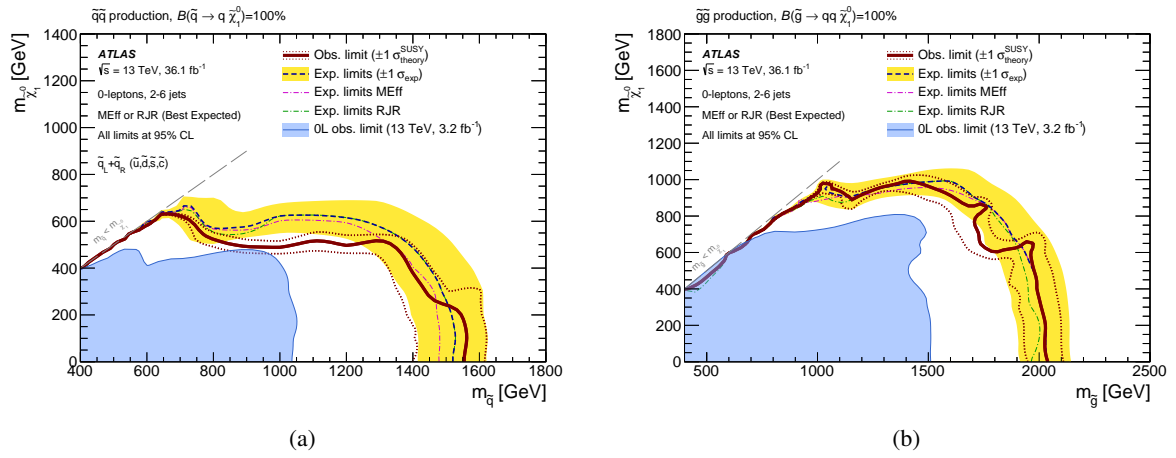


Figure 13: Exclusion limits for direct production of (a) first- and second-generation squark pairs with decoupled gluinos and (b) gluino pairs with decoupled squarks. Gluinos (first- and second-generation squarks) are required to decay to two quarks (one quark) and a neutralino LSP. Exclusion limits are obtained by using the signal region with the best expected sensitivity at each point. Expected limits from the Meff- and RJR-based searches separately are also shown for comparison. The blue dashed lines show the expected limits at 95% CL, with the light (yellow) bands indicating the 1σ excursions due to experimental and background-only theoretical uncertainties. Observed limits are indicated by medium dark (maroon) curves where the solid contour represents the nominal limit, and the dotted lines are obtained by varying the signal cross-section by the renormalization and factorization scale and PDF uncertainties. Results are compared with the observed limits obtained by the previous ATLAS searches with jets, missing transverse momentum, and no leptons [11].

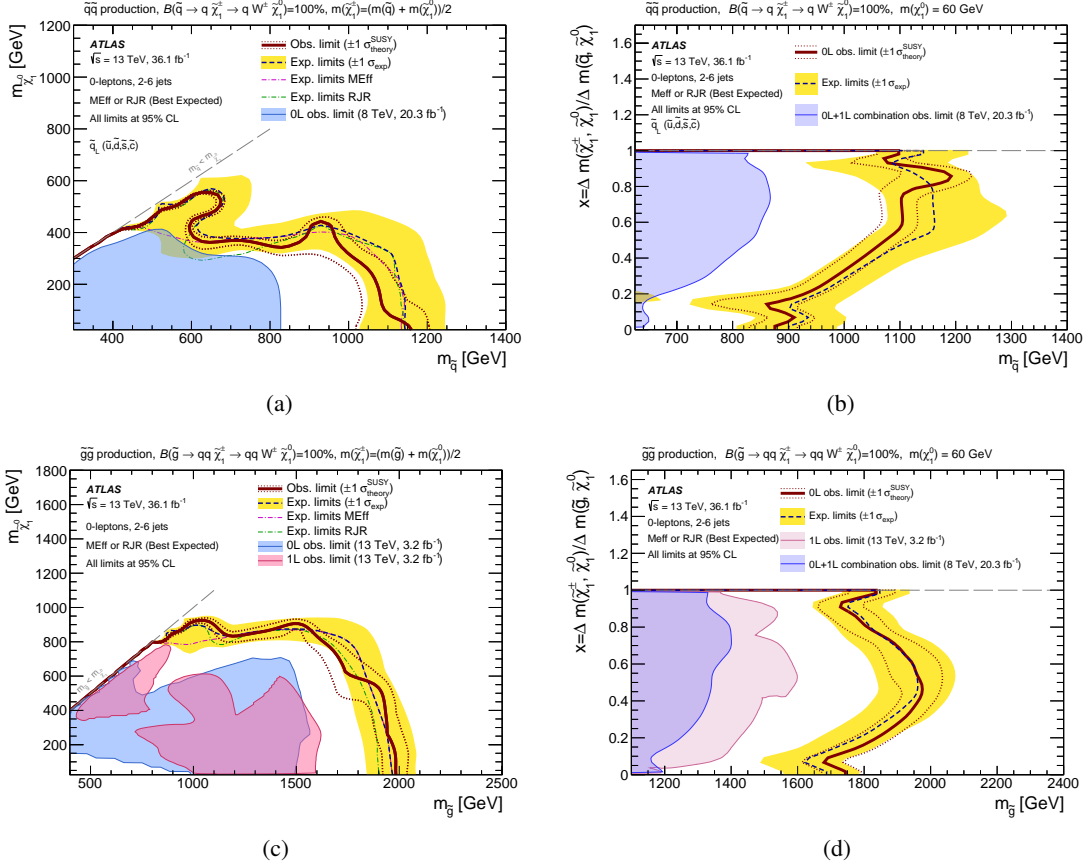


Figure 14: Exclusion limits for direct production of (a,b) first- and second-generation left-handed squark pairs with decoupled gluinos and (c,d) gluino pairs with decoupled squarks. Gluinos (first- and second-generation squarks) are required to decay to two quarks (one quark) and an intermediate $\tilde{\chi}_1^\pm$, decaying to a W boson and a $\tilde{\chi}_1^0$. Models with (a,c) a fixed $m_{\tilde{\chi}_1^\pm} = (m_{\tilde{g}} + m_{\tilde{\chi}_1^0})/2$ (or $(m_{\tilde{q}} + m_{\tilde{\chi}_1^0})/2$) and varying values of $m_{\tilde{g}}$ (or $m_{\tilde{q}}$) and $m_{\tilde{\chi}_1^0}$, and (b,d) a fixed $m_{\tilde{\chi}_1^0} = 60$ GeV and varying values of $m_{\tilde{g}}$ (or $m_{\tilde{q}}$) and $m_{\tilde{\chi}_1^\pm}$ are considered. Exclusion limits are obtained by using the signal region with the best expected sensitivity at each point. Expected limits from the Meff- and RJR-based searches separately are also shown for comparison in (a,c). The blue dashed lines show the expected limits at 95% CL, with the light (yellow) bands indicating the 1σ excursions due to experimental and background-only theoretical uncertainties. Observed limits are indicated by medium dark (maroon) curves where the solid contour represents the nominal limit, and the dotted lines are obtained by varying the signal cross-section by the renormalization and factorization scale and PDF uncertainties. Results are compared with the observed limits obtained by the previous ATLAS searches with one or no leptons, jets and missing transverse momentum [11, 19, 95].

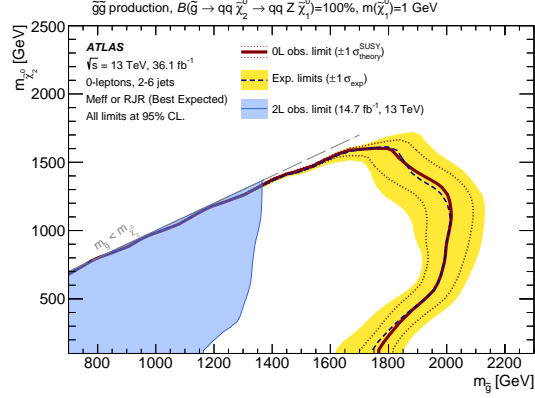


Figure 15: Exclusion limits for pair-produced gluinos each decaying via an intermediate $\tilde{\chi}_2^0$ to two quarks, a Z boson and a $\tilde{\chi}_1^0$ for models with a fixed $m_{\tilde{\chi}_1^0} = 1$ GeV and varying values of $m_{\tilde{g}}$ and $m_{\tilde{\chi}_2^0}$. Exclusion limits are obtained by using the signal region with the best expected sensitivity at each point. The blue dashed lines show the expected limits at 95% CL, with the light (yellow) bands indicating the 1σ excursions due to experimental and background-only theoretical uncertainties. Observed limits are indicated by medium dark (maroon) curves where the solid contour represents the nominal limit, and the dotted lines are obtained by varying the signal cross-section by the renormalization and factorization scale and PDF uncertainties. Results are compared with the observed limits obtained by the previous ATLAS search in events containing a leptonically decaying Z boson, jets and missing transverse momentum [96].

In Figure 15, limits are shown for gluino pair production decaying via an intermediate $\tilde{\chi}_2^0$ to two quarks, a Z boson and a $\tilde{\chi}_1^0$. The mass of the $\tilde{\chi}_1^0$ is set to 1 GeV. In these models, gluino masses below 2.0 TeV are excluded for $\tilde{\chi}_2^0$ masses of ~ 1 TeV, as obtained from the signal region Meff-6j-2600.

In Figure 16, results are presented in the models with mixed decays of intermediate $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ for squark pair and gluino pair production. The highest limits on the squark mass are 1.34 TeV and on the gluino mass are 2.02 TeV, which are similar to the models with 100% branching fraction for $\tilde{\chi}_1^\pm$ ($\tilde{\chi}_2^0$) to a W (Z) boson and $\tilde{\chi}_1^0$. In Figure 16(b), the limits are extended by the SR Meff-2jet in the region with small mass differences between the gluino and $\tilde{\chi}_2^0$.

In Figure 17, results are interpreted in simplified pMSSM models assuming only first- and second-generation squarks, gluino and $\tilde{\chi}_1^0$. The $\tilde{\chi}_1^0$ is assumed to be purely bino. Models with a fixed $m_{\tilde{\chi}_1^0} = 0, 695, 995$ GeV are considered while varying $m_{\tilde{g}}$ and $m_{\tilde{q}}$. In the limit of high squark mass, gluino masses up to 2 TeV are excluded for massless $\tilde{\chi}_1^0$, which is consistent with the simplified models of gluino pair production with decoupled squarks. With a gluino mass of 6 TeV, squark masses up to 2.2 TeV are excluded for a massless $\tilde{\chi}_1^0$, much higher than in the simplified models of squark pair production with decoupled gluinos. This is due to the large cross-section of squark pair production via gluino exchange diagrams.

A comparison of the Meff-based and RJR-based results highlights some notable features. The RJR-Cx signal regions provide additional sensitivity in the most compressed mass regions beyond their Meff-based counterparts, extending exclusion limits up to 200 GeV in $\tilde{\chi}_1^0$ mass for the smallest mass splitting, as is the case in Figure 14(a) for first- and second-generation squarks decaying via an intermediate $\tilde{\chi}_1^\pm$. In general, the RJR-Cx regions are only mildly sensitive to the specific decays of squarks and gluinos,

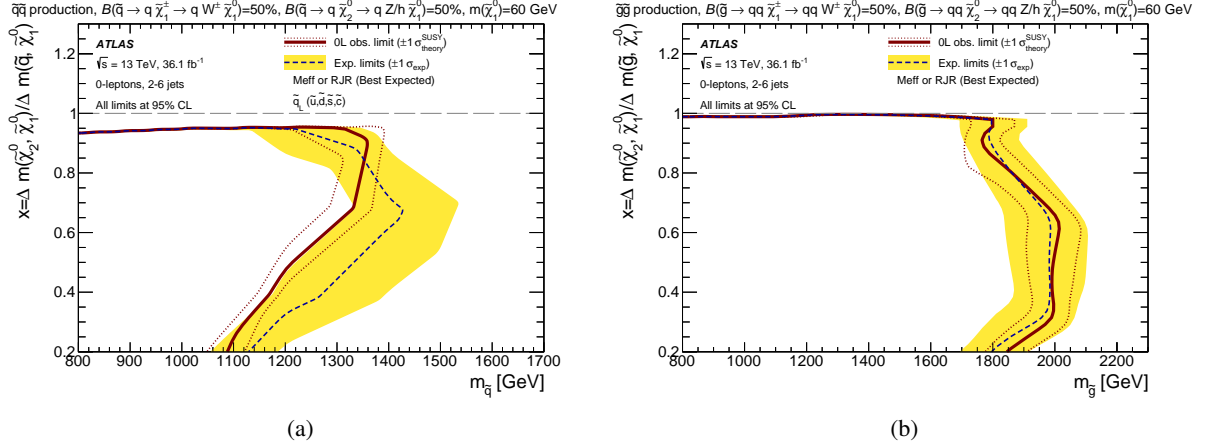


Figure 16: Exclusion limits for direct production of (a) first- and second-generation left-handed squark pairs with decoupled gluinos and (b) gluino pairs with decoupled squarks. Gluinos (first- and second-generation squarks) are required to decay to two quarks (one quark) and an intermediate $\tilde{\chi}_{1^\pm}^\pm$ or $\tilde{\chi}_2^0$ with a 50% branching fraction, respectively, with $\tilde{\chi}_1^\pm$ decays to a W boson and a $\tilde{\chi}_1^0$, and $\tilde{\chi}_2^0$ decays to a Z or a h boson and $\tilde{\chi}_1^0$. Models with fixed $m_{\tilde{\chi}_1^0} = 60$ GeV are considered while varying $m_{\tilde{g}}$ (or $m_{\tilde{q}}$) and $m_{\tilde{\chi}_1^0}$. Exclusion limits are obtained by using the signal region with the best expected sensitivity at each point. The blue dashed lines show the expected limits at 95% CL, with the light (yellow) bands indicating the 1σ excursions due to experimental and background-only theoretical uncertainties. Observed limits are indicated by medium dark (maroon) curves where the solid contour represents the nominal limit, and the dotted lines are obtained by varying the signal cross-section by the renormalization and factorization scale and PDF uncertainties.

resulting in similar sensitivity as a function of \tilde{q}/\tilde{g} and $\tilde{\chi}_1^0$ masses between signal models with direct decays in Figure 13 and those with intermediate sparticle decays as in Figure 14.

Despite being largely orthogonal, the RJR-based and Meff-based SRs targeting squark and gluino direct decay signals tend to result in similar sensitivity, with the RJR-based regions generally performing better for intermediate mass splittings. This is the result of tighter restrictions placed on dimensionless variables in the RJR-based regions, resulting in generally lower background yields.

For models with additional jets in the final state expected from intermediate sparticle decays, the Meff-5j-x and Meff-6j-x provide significant additional sensitivity with respect to lower multiplicity SRs, extending exclusion limits by close to 100 GeV in gluino mass when intermediate $\tilde{\chi}_1^\pm$ decays are considered. These more stringent jet multiplicity requirements compensate for the modest $E_T^{\text{miss}}/m_{\text{eff}}(N_j)$ values characteristic of these models.

With requirements aimed at tagging hadronic decays of W/Z bosons, the Meff-2jB-x SRs provide higher sensitivity to models with intermediate $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ decays when these sparticles are almost degenerate in mass with their parent squarks and gluinos, corresponding to Figures 14(b), 14(d), 15, and 16. In these cases, the sensitivity of the Meff-2jB-x regions far surpasses those of the RJR-based and other Meff-based SRs.

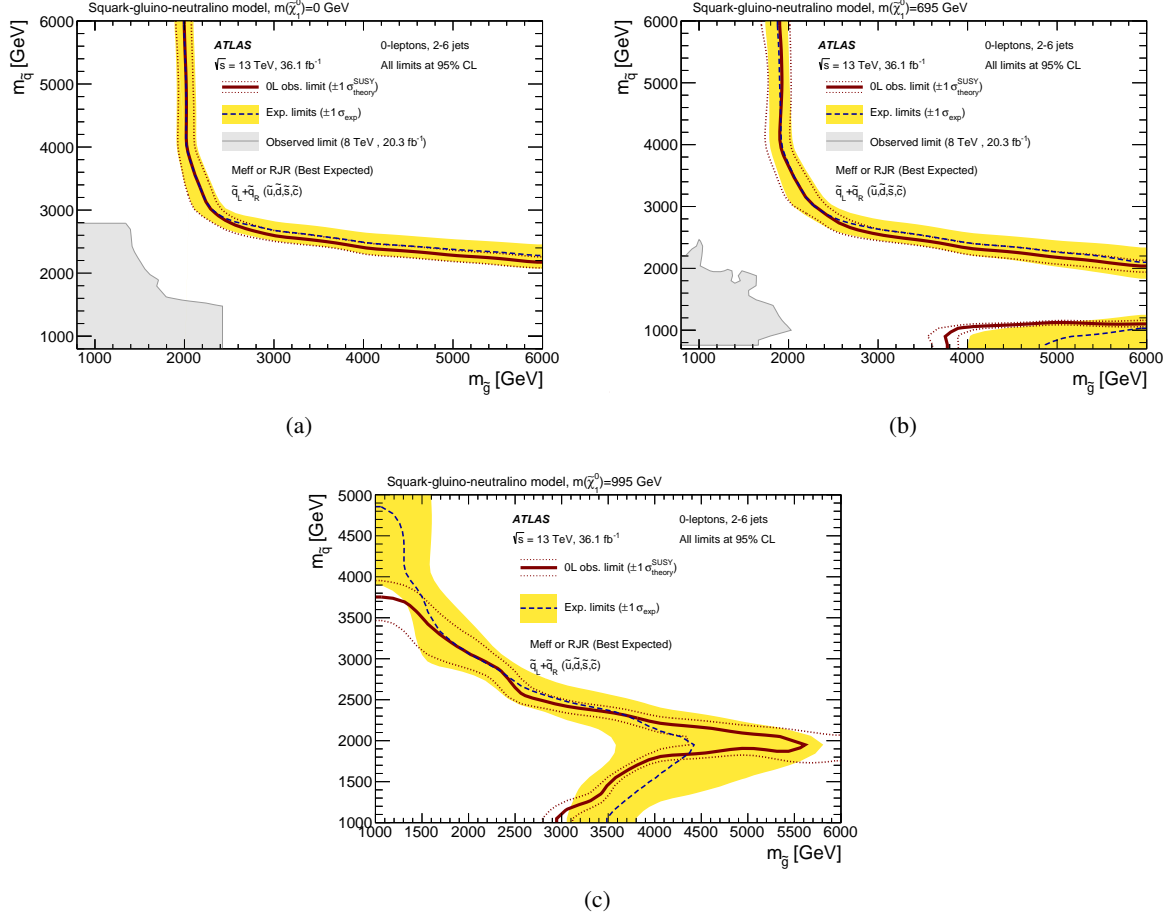


Figure 17: Exclusion limits for inclusive squark–gluino production in pMSSM models with (a) $m_{\tilde{\chi}_1^0} = 0$ GeV, (b) $m_{\tilde{\chi}_1^0} = 695$ GeV and (c) $m_{\tilde{\chi}_1^0} = 995$ GeV varying values of $m_{\tilde{g}}$ and $m_{\tilde{q}}$ and assuming purely bino $\tilde{\chi}_1^0$. Exclusion limits are obtained by using the signal region with the best expected sensitivity at each point. The blue dashed lines show the expected limits at 95% CL, with the light (yellow) bands indicating the 1σ excursions due to experimental and background-only theoretical uncertainties. Observed limits are indicated by medium dark (maroon) curves where the solid contour represents the nominal limit, and the dotted lines are obtained by varying the signal cross-section by the renormalization and factorization scale and PDF uncertainties. Results (a,b) are compared with the observed limits obtained by the previous ATLAS searches with no leptons, jets and missing transverse momentum [97].

11 Conclusion

This paper presents results of two selection strategies to search for squarks and gluinos in final states containing high- p_T jets, large missing transverse momentum but no electrons or muons, based on a 36.1 fb^{-1} dataset of $\sqrt{s} = 13$ TeV proton–proton collisions recorded by the ATLAS experiment at the LHC in 2015 and 2016. No significant deviation from the background expectation is found.

Results are interpreted in terms of simplified models or pMSSM models with only first- and second-generation squarks, or gluinos, together with a neutralino LSP, with the masses of all the other SUSY particles set such that the particles are effectively decoupled. For a massless lightest neutralino, gluino

masses below 2.03 TeV are excluded at the 95% confidence level in a simplified model with only gluinos and the lightest neutralino. For a simplified model involving the strong production of squarks of the first and second generations, with decays to a massless lightest neutralino, squark masses below 1.55 TeV are excluded, assuming mass-degenerate squarks of the first two generations. No exclusion is obtained for simplified models of squark (gluino) pair production with lightest neutralino masses above 630 GeV (970 GeV). In simplified models with pair-produced squarks and gluinos, each decaying via an intermediate $\tilde{\chi}_1^\pm$ to one quark or two quarks, a W boson and a $\tilde{\chi}_1^0$, squark masses below 1.15 TeV and gluino masses below 1.98 TeV are excluded for massless $\tilde{\chi}_1^0$. In pMSSM models assuming squarks, gluinos and $\tilde{\chi}_1^0$, gluino masses below 2.0 TeV are excluded for a squark mass of 6 TeV or squark masses below 2.2 TeV are excluded for a gluino mass of 6 TeV for massless $\tilde{\chi}_1^0$.

These results substantially extend the region of supersymmetric parameter space previously excluded by ATLAS searches.

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