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A search for an unexpected asymmetry in the production of $e^+\mu^-$ and $e^-\mu^+$ pairs in proton–proton collisions recorded by the ATLAS detector at $\sqrt{s} = 13$ TeV

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ABSTRACT

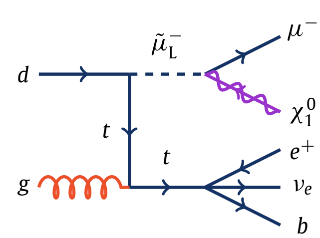
This search, a type not previously performed at ATLAS, uses a comparison of the production cross sections for $e^+\mu^-$ and $e^-\mu^+$ pairs to constrain physics processes beyond the Standard Model. It uses 139 fb^{-1} of proton–proton collision data recorded at $\sqrt{s} = 13$ TeV at the LHC. Targeting sources of new physics which prefer final states containing $e^+\mu^-$ to $e^-\mu^+$, the search contains two broad signal regions which are used to provide model-independent constraints on the ratio of cross sections at the 2% level. The search also has two special selections targeting supersymmetric models and leptoquark signatures. Observations using one of these selections are able to exclude, at 95% confidence level, singly produced smuons with masses up to 640 GeV in a model in which the only other light sparticle is a neutralino when the R-parity-violating coupling λ'_{231} is close to unity. Observations using the other selection exclude scalar leptoquarks with masses below 1880 GeV when $g^{eu}_{1R} = g^{\mu c}_{1R} = 1$, at 95% confidence level. The limit on the coupling reduces to $g^{eu}_{1R} = g^{\mu c}_{1R} = 0.46$ for a mass of 1420 GeV.

1. Introduction

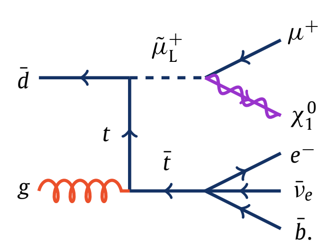
Under the Standard Model of particle physics, the ratio of the production cross section of a positron and muon together in a proton–proton interaction is expected to be very similar to the production cross section for an electron and anti-muon. This similarity is a consequence of the lepton flavour universality of the electroweak boson interactions that produce these leptons, in combination with charge conservation and the relatively low mass of these leptons with respect to the mass of the electroweak bosons. As was explored in Ref. [1], measuring the ratio of these cross sections can serve as an experimental test of this aspect of the Standard Model (SM) and could have sensitivity to physics Beyond the Standard Model (BSM). Specifically, the ratio:

$$\rho \equiv \frac{\sigma(pp \to e^+\mu^- + X)}{\sigma(pp \to e^-\mu^+ + X)} \qquad (1)$$

is defined, where the leptons are all taken to be promptly produced in the primary interaction.[1] Scenarios are considered where the presence of a BSM process would bias ρ to be significantly greater than one (more $e^+\mu^-$ than $e^-\mu^+$). Two concrete examples of such BSM models are considered in this Letter. The first is an R-parity-violating supersymmetry model. As was noted in Ref. [1], a non-zero R-parity-violating λ'_{231} coupling (defined in Refs. [2–4]) linking smuons to top and down quarks could easily drive $\rho > 1$ as the proton's down quarks would result in



(and related s-channel processes) occurring more frequently than the charge conjugate process:



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[1] The X in Eq. (1) contains no further prompt leptons.

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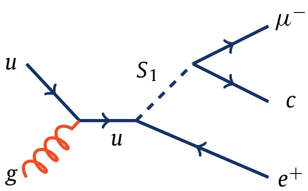
The second model considered to drive $\rho > 1$ is a scalar leptoquark with couplings permitting $S_1 \to ue^-$ and $S_1 \to c\mu^-$. In that case, processes such as



would be favoured over charge conjugates.

This Letter describes a measurement of ρ using the ATLAS detector at the LHC, which is used as a test for the existence of BSM physics that would bias ρ above one. While related BSM processes could also bias ρ to be significantly less than one, sensitivity to such processes are not considered in this Letter because of the existence of experimental effects that predominantly bias the measured ratio downwards. Examples of these effects are explored further in Ref. [1], but one such example is the presence of hadronic jets being incorrectly reconstructed as an electron more frequently than as a muon. This bias for fake electrons over fake muons, in combination with the predominance of W^+ over W^- bosons from the $(pp)^{2+}$ initial state [5,6], would manifest as a bias for $e^-\mu^+$ (with a fake e^-) over $e^+\mu^-$ (with a fake μ^-), and hence bias the measured ρ downwards. The analysis strategy presented in this Letter includes estimating corrections to account for *some* of these biasing experimental effects, the primary motivation for which is the enhancement of sensitivity to BSM physics that increases ρ rather than to improve the accuracy of the ρ measurement, and estimating systematic uncertainties to account for any remaining biases. In particular, for the model-independent statistical analysis of the measured ρ in this Letter it is assumed that the SM hypothesis covers values of ρ less than or equal to one, an assumption that is checked in data in the analysis event selections.[2] Thus evidence for new physics would only be claimed if the BSM contribution is strong enough to overcome any residual biases that have not been accounted for. For calculating limits on signal model parameters the strength of the residual biases are estimated from an SM-enriched control region.

The structure of this Letter is as follows: in Section 2 the ATLAS detector is described and Section 3 details the datasets used in the analysis. Section 4 describes the object reconstruction and Section 5 defines the regions of phase space that ρ is measured in and how experimental effects that could impact its measurement are corrected for, including the verification of these corrections with the measurement of ρ in SM-enriched control regions. Section 6 presents the measurement of ρ in generic signal regions designed to have broad sensitivity to BSM physics that would bias ρ upwards, then in optimised signal regions designed to have sensitivity to the two BSM models described above, alongside a statistical interpretation of the result in the parameter space of these models.

2. ATLAS detector

The ATLAS experiment [7] at the LHC is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and a near 4π coverage in solid angle.[3] It consists of an inner tracking detector surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadron calorimeters, and a muon spectrometer. The inner tracking detector covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity. A steel/scintillator-tile hadron calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The endcap and forward regions are instrumented with LAr calorimeters for both the EM and hadronic energy measurements up to $|\eta| = 4.9$. The muon spectrometer surrounds the calorimeters and is based on three large superconducting air-core toroidal magnets with eight coils each. The field integral of the toroids ranges between 2.0 and 6.0 T·m across most of the detector. The muon spectrometer includes a system of precision chambers for tracking and fast detectors for triggering. A two-level trigger system is used to select events. The first-level trigger is implemented in hardware and uses a subset of the detector information to accept events at a rate below 100 kHz. This is followed by a software-based trigger that reduces the accepted event rate to 1 kHz on average depending on the data-taking conditions.

An extensive software suite [8] is used in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

3. Data and Monte Carlo samples

The proton–proton collisions analysed in this Letter are those collected at a centre-of-mass energy of $\sqrt{s} = 13$ TeV and a 25 ns interbunch spacing between 2015 and 2018. They correspond to an integrated luminosity of 139 fb^{-1}. The uncertainty in the combined 2015–2018 integrated luminosity is 1.7% [9], obtained using the LUCID-2 detector [10] for the primary luminosity measurements. In any given data-taking period the unprescaled two-lepton triggers (specifically ee, $e\mu$ or $\mu\mu$) with the lowest per-lepton p_{T} thresholds were used [11–13]. These thresholds ranged from 10 GeV to 24 GeV.

R-parity-violating (RPV) [14] models of supersymmetry [15–20] were tested using simulated events with $\mu^-\tilde{\chi}_1^0 t$ or $\mu^+\tilde{\chi}_1^0\bar{t}$ in the final state, where $\tilde{\chi}_1^0$ is the lightest neutralino. This neutralino is considered stable enough on detector scales that it can only be detected through missing transverse momentum, unless it approaches or exceeds the top-quark mass, when it can decay through the RPV coupling. These events were generated at leading order using the Monte Carlo (MC) program MadGraph5_aMC@NLO [21] version 2.61 together with the RPV MSSM UFO model [22]. Shower evolution and hadronisation was performed by Pythia 8 [23] version 8.23. The NNPDF2.3lo [24] PDF was used with a set of tuned parameters called the A14 tune [25]. All RPV couplings except λ'_{231} were set to zero, so only the smuon RPV interaction is considered. Supersymmetric particles other than the neutralino and smuon were decoupled by setting their masses to a large value. The MadGraph hard processes permitted at most one additional light parton in the final state, and they were matched to the Pythia parton shower using the CKKW-L [26] merging scheme. Use of the matching scale $Q_{\mathrm{MS}} = \frac{1}{4}\left(m(t) + m(\tilde{\chi}_1^0)\right)$ gives a smooth transition between the matrix-element and parton-shower regimes, and distributions with little dependence on the exact scale value. Event samples were generated for a two-dimensional grid of points, distributed in a plane of smuon and neutralino masses, all with a coupling of

[2] See definitions of cr-ratio and cr-jet in Section 5, and the estimates of fake-lepton contributions to Standard Model expectations.

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

$\lambda'_{231} = 1.0$. Samples for other values of the coupling were obtained by weighting the cross sections of the first set in proportion to the square of the desired value of λ'_{231} and changing the branching ratio for the smuon decay. The branching ratio for the desired smuon to muon decay is 2% (70%) at $\lambda'_{231} = 1$ (0.1), whilst the remaining smuons decay via the RPV vertex.

Leptoquark events were generated at leading order using MADGRAPH5_AMC@NLO 2.61 together with the 'S_1' model of Ref. [27], which is implemented as a Feynrules [28] package named 'LO_LQ_S1' available online [29] and described in Ref. [30]. Shower evolution and hadronisation were performed by PYTHIA 8.23. The NNPDF2.3LO PDF was used with the A14 tune. All leptoquark couplings were set to zero, apart from two flavours of the g_{1R} coupling of Ref. [27] which couples leptoquarks to leptons and quarks in weak singlet states. Specifically, g^{eu}_{1R} and $g^{\mu c}_{1R}$ were assigned a common non-zero value simply denoted 'λ'. The leptoquark signal events were generated for a set of leptoquark masses, all with a coupling of $\lambda = 1.0$. Charm-quark-initiated processes are neglected since they provide no charge–flavour asymmetry, and their cross section is only $\mathcal{O}(5\%)$ of that for up-quark-initiated processes. The hard processes specified no additional light jets in the final state and they were matched to the PYTHIA parton shower using the CKKW-L [31] merging scheme. The merging scale Q_{MS} was chosen to be $\frac{1}{4}\big(m(t) + m(S_1)\big)$, where $m(S_1)$ is the mass of the leptoquark.

Next-to-leading order (NLO) cross sections are used for the samples and were calculated using MADGRAPH5_AMC@NLO 2.94 with a narrow-width (nw) approximation and the NNPDF2.3NLO PDF set. To include the effect of the finite-width (fw) approximation in the samples, the cross sections are corrected thus:

$$\sigma^{\text{NLO,fw}}_{\text{Total}} = \frac{\sigma^{\text{NLO,nw}}_{e^+\mu^-}}{\sigma^{\text{LO,nw}}_{e^+\mu^-}} \sigma^{\text{LO,fw}}_{e^+\mu^-} + \frac{\sigma^{\text{NLO,nw}}_{e^-\mu^+}}{\sigma^{\text{LO,nw}}_{e^-\mu^+}} \sigma^{\text{LO,fw}}_{e^-\mu^+}, \tag{2}$$

following an approach similar to that used in Ref. [32]. The narrow-width leading order (LO) cross sections are calculated using MADGRAPH5_AMC@NLO 2.94 and the NNPDF2.3LO PDF set. The finite-width LO cross sections are calculated using the same setup as the generated samples described above. Theoretical uncertainties in the NLO cross sections are calculated by MADGRAPH5_AMC@NLO using an envelope of nine variations of the renormalisation and factorisation scales, each taking values of either 0.5, 1,0 or 2.0 times their nominal value.

Samples for other values of the coupling λ were obtained by weighting the cross sections of the first set in proportion to the square of the desired value of λ and accounting for the change in leptoquark width. A two-dimensional grid of samples for a variety of leptoquark masses and couplings was thereby obtained. All signal sample events were then simulated using ATLFASTII [33], a fast simulation of the ATLAS detector.

MC simulations of SM processes are not used in the final result of this analysis, but were used to guide the signal-region choices, to study the validity of the analysis strategy, to assist in deriving efficiencies and uncertainties for the fake-lepton background estimate, and to perform cross-checks (see Appendix A for MC sample details). Instead, measurements of ρ are based entirely on comparisons between $e^+\mu^-$ and $e^-\mu^+$ data, and contributions from jets misidentified as leptons, muon corrections and even expected SM yields (see Section 6) are also estimated primarily from data.

4. Reconstructed objects

Reconstructed objects (electrons, muons, jets, missing transverse momentum) are the building blocks of any analysis. In this analysis, leptons and jets exist in two forms: 'BASELINE' and 'SIGNAL'. The former are used to define missing transverse momentum and the procedure to resolve ambiguities between objects with overlapping constituents, otherwise the analysis regions are built exclusively on the latter.

BASELINE electrons are required to have $|\eta| < 2.47$ and $p_{\text{T}} >$ 10 GeV, and to pass the `Loose` likelihood-based identification working point defined in Ref. [34]. The same p_{T} and $|\eta|$ demands are placed on BASELINE muons, which are also required to pass the `Medium` identification working point as defined in Ref. [35]. The anti-k_t algorithm [36,37] with a radius parameter of $R = 0.4$ is used to reconstruct jets with a four-momentum recombination scheme, using 'particle-flow' objects [38] as inputs. BASELINE jets are required to have $p_{\text{T}} > 20$ GeV and $|\eta| < 4.5$. The missing transverse momentum, $\vec{p}^{\,\text{miss}}_{\text{T}}$, is calculated from the BASELINE leptons and jets as described in Ref. [39] using the `Tight` working point and 'particle-flow track-based soft term' defined therein.

An overlap removal procedure is applied to BASELINE jets and BASELINE leptons to avoid double-counting. Firstly, any electron which shares a track with a muon is rejected. Any jet whose angular distance ΔR from an electron is less than 0.2 is removed, as is any which has fewer than three tracks lying within $\Delta R = 0.4$ of a muon. Finally, electrons and muons within $\Delta R = 0.4$ of the remaining jets are then discarded.

The 'jet vertex tagger' (JVT) [40] is applied to jets with $|\eta| < 2.4$ and $p_{\text{T}} < 120$ GeV, and helps to veto jets that are likely to have originated from pile-up (additional pp collisions from the same or nearby bunch crossings). A similar 'forward jet vertex tagger' (fJVT) is used to help identify and remove pile-up jets with $|\eta| > 2.5$ [41]. Jets surviving the overlap removal procedure are deemed SIGNAL if they pass the JVT or fJVT, and have $|\eta| < 2.8$.

Those leptons which remain are then given a status of SIGNAL if they meet the following five criteria: (i) they must have $p_{\text{T}} > 25$ GeV and $|\eta| < 2.47$, and (ii) be consistent with the hard-scatter vertex, through $|d_0/\sigma(d_0)| < 3$ and $|z_0 \sin(\theta)| <$ 0.3 mm, where d_0 and z_0 are their transverse and longitudinal impact parameters; (iii) electrons must pass the `Tight` likelihood-based identification working point defined in Ref. [34], and have charge misidentification suppressed through the use of the boosted-decision-tree-based discriminant described in Ref. [34]; (iv) electrons with $p_{\text{T}} < 200$ GeV ($p_{\text{T}} > 200$ GeV) are required to pass the `Tight` (`HighPtCaloOnly`) isolation working point of Ref. [34] to reduce contamination by electrons from heavy-flavour decays or misidentified light hadrons; and (v) muons with $p_{\text{T}} < 200$ GeV ($p_{\text{T}} > 200$ GeV) are required to pass the `Tight` (`FixedCutHighPtTrackOnly`) isolation working point of Ref. [35] to reduce contamination by muons from semileptonic heavy-flavour and hadron decays.

In the rest of this Letter, leptons and jets are assumed to be only those with SIGNAL status, unless stated otherwise.

5. Analysis

The tests of whether ρ is significantly greater than one are made in four signal regions. Two of them, (SR-MET and SR-JET) aim to provide sensitivity to general sources of charge–flavour violation, while the other two (SR-RPV and SR-LQ) are less inclusive versions of their partners[4] and target specific RPV supersymmetry and leptoquark theories mentioned in the introduction. These regions are summarised in Fig. 1.

The PRELIMINARY selection common to all signal regions requires the presence of exactly one electron and exactly one muon, of opposite charge. As there are few other constraints on the forms

[4] Every event in SR-RPV is also in SR-MET, and every event in SR-LQ is also in SR-JET.

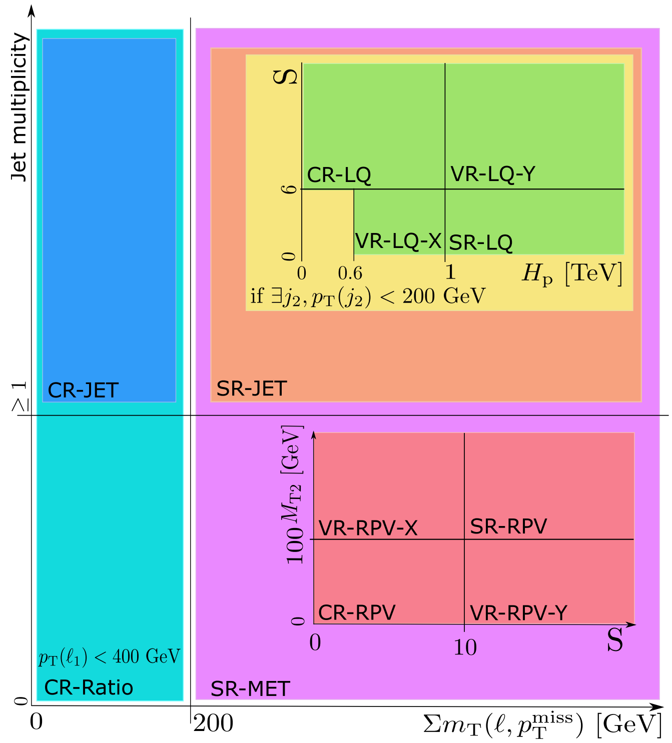


Fig. 1. Summary of the regions used in the analysis. ℓ_1 refers to the lepton with the largest p_T in each event. j_2 refers to the jet with the second-largest p_T in each event. SR-MET and SR-JET are used for the ρ measurement. CR-RATIO and CR-JET are used to check the SM expectation of $\rho \le 1$, and CR-RATIO is used to derive the residual-bias uncertainty included in the ratio measurement. CR-RPV is used to derive the SM background expectation used to set limits on RPV supersymmetry models in SR-RPV, after being validated in VR-RPV-X and VR-RPV-Y. CR-LQ is used to derive the SM background expectation used to set limits on scalar leptoquark models in SR-LQ, after being validated in VR-LQ-X and VR-LQ-Y. Note that the horizontal positions of the boxes do not denote $\Sigma(m_\mathrm{T})$ thresholds beyond the 200 GeV cut.

that the signal regions should take, and as the ATLAS experiment has not previously published a charge–flavour asymmetry search, the approach taken in this first search is to prioritise simple selections over complex ones. With this principle in mind:

- when defining SR-MET, the only requirement which is added to the PRELIMINARY selection is that $\Sigma(m_\mathrm{T}) > 200$ GeV, where $\Sigma(m_\mathrm{T}) \equiv m_\mathrm{T}(e, \vec{p}_\mathrm{T}^{\,\mathrm{miss}}) + m_\mathrm{T}(\mu, \vec{p}_\mathrm{T}^{\,\mathrm{miss}})$ and m_T is the usual transverse mass:

$$m_\mathrm{T}(\ell, \vec{p}_\mathrm{T}^{\,\mathrm{miss}}) \equiv \sqrt{2|\vec{p}_\mathrm{T}^{\,\ell}||\vec{p}_\mathrm{T}^{\,\mathrm{miss}}| - 2\vec{p}_\mathrm{T}^{\,\ell} \cdot \vec{p}_\mathrm{T}^{\,\mathrm{miss}}},$$

- and when defining SR-JET (a subset of SR-MET) the only additional requirement is that events must contain at least one jet with transverse momentum greater than 20 GeV.

The primary purpose of the $\Sigma(m_\mathrm{T})$ requirement is to allow for the low $\Sigma(m_\mathrm{T})$ region to be available for studying the SM behaviour before unblinding the data in the signal regions. The benchmark BSM models have a low yield in $\Sigma(m_\mathrm{T}) < 200$ GeV, and it can be assumed that they are representative of other general sources of charge–flavour violation, so BSM sensitivity is not reduced substantially by excluding this region from SR-MET or SR-JET. As shown in Fig. 1, the region $\Sigma(m_\mathrm{T}) < 200$ GeV is designated as CR-RATIO. If the further requirement of at least one jet with $p_\mathrm{T} > 20$ GeV is placed, the region is designated CR-JET, used to study the SM behaviour in a region more kinematically similar to SR-JET.

The signal-optimised regions make use of three more flavour-symmetric event variables: $\mathcal{S}$, M_{T2} and H_P.

- $\mathcal{S}$ is the so-called 'object-based $\vec{p}_\mathrm{T}^{\,\mathrm{miss}}$ significance' defined in Eq. (15) of Ref. [42]. It is a dimensionless measure of the degree to which the apparent missing transverse momentum in the event is 'real' (i.e. attributable to momentum carried away by invisible particles) rather than due to object mismeasurement or pile-up.
- $M_{\mathrm{T2}} \equiv \min_{\vec{a}+\vec{b}=\vec{p}_\mathrm{T}^{\,\mathrm{miss}}} \max\left[m_\mathrm{T}(e,\vec{a}), m_\mathrm{T}(\mu,\vec{b})\right]$ was proposed in Ref. [43], where $\vec{a}$ and $\vec{b}$ represent the contributions to $p_\mathrm{T}^{\mathrm{miss}}$ from each semi-leptonic decay of a pair-produced particle, and all possible values that sum to the observed $p_\mathrm{T}^{\mathrm{miss}}$ are minimised over. It is evaluated using the algorithm of Ref. [44].
- $H_\mathrm{P} \equiv |\vec{p}_\mathrm{T}^{\,e}| + |\vec{p}_\mathrm{T}^{\,\mu}| + |\vec{p}_\mathrm{T}^{\,j_1}|$ is a simple sum of the magnitudes of the transverse momenta of the two leptons and the most energetic jet in the event.

SR-RPV is defined to require $\mathcal{S} > 10$ and $M_{\mathrm{T2}} > 100$ GeV. The first requirement anticipates that neutralinos ($\tilde{\chi}_1^0$) of the supersymmetric signals should carry away missing transverse momentum, while the second suppresses SM W^+W^- backgrounds. In all other respects, SR-RPV is identical to SR-MET.

In contrast, the targeted leptoquark model processes have no invisible particles in the final state, so SR-LQ requires $\mathcal{S} < 6$. Furthermore, SM backgrounds in this region are suppressed by requiring events to have $H_\mathrm{P} > 1$ TeV. In all other respects, SR-LQ is the same as SR-JET.

Once the analysis regions are defined, potential biases to the measurement must be considered. The largest source of strictly one-sided charge–flavour bias in the ratio measurement is the misreconstruction of jets as light leptons in W+jet events. In particular: (i) more W^+ than W^- are produced in LHC proton collisions, and (ii) jets misreconstructed as 'fake' leptons are more likely to appear to be electrons than muons. If uncorrected, these two factors would cause $e^-_{\mathrm{fake}}\mu^+_{\mathrm{real}}$ to be more prevalent than $e^+_{\mathrm{fake}}\mu^-_{\mathrm{real}}$ and therefore the so-called 'fake' background would favour $\rho < 1$. To remove the bias, a data-driven estimate of the number of fake-lepton events passing any particular selection is determined, separately for each charge combination, and is subtracted from the raw data counts before the ratio ρ of $e^+\mu^-$ to $e^-\mu^+$ counts is calculated.

The fake-lepton estimate itself is determined using a Likelihood Matrix Method approach of the form described in Ref. [45] or 'Method B' of Ref. [46]. This method predicts the fake lepton background where either one or both leptons is fake, and relies on two lepton definitions with different stringencies. The tighter selection corresponds to the SIGNAL definition used in the rest of the analysis, and the looser 'LOOSE' definition relaxes this by removing the isolation requirements, vertex requirements, and loosening the electron identification requirement to the Loose likelihood-based working point defined in Ref. [34]. Real-lepton efficiencies are derived in $e^\pm e^\mp$ and $\mu^\pm\mu^\mp$ regions, dominated by $Z \to \ell\ell$ events, as the number of events with two SIGNAL leptons divided by the number of events with a given lepton loosened to pass the LOOSE requirements. The fake-lepton efficiencies are derived using a muon tag-and-probe method, using $\mu^\pm\mu^\pm$ pairs for the muon efficiency and $e^\pm\mu^\pm$ pairs for the electron efficiency. The 'tag' lepton must pass the SIGNAL requirements as well as $p_\mathrm{T} > 50$ GeV, and the efficiency is defined as the fraction of LOOSE probe leptons also passing the SIGNAL requirements, once the small SM real-lepton background (estimated from MC) has been subtracted. The requirement for same-charge-sign rather than opposite-charge-sign increases the contribution from events with fake leptons relative to real SM processes, dominantly W+jets events. The efficiencies are calculated separately for each lepton flavour and charge (such that the flavour and charge match the lepton that has its selection loosened), and are binned in lepton p_T. These efficiencies, together with event counts in regions orthogonal to the signal regions and where one lepton is required to pass the Loose selection, are used to calculate a prediction for the yield of fake-lepton events in the signal regions. The fake-lepton estimate accounts for $\mathcal{O}(2\%)$ of the events in the signal regions used for the ratio measurement, and $\mathcal{O}(6\%)$ or $\mathcal{O}(17\%)$ of the events in the signal region used for the RPV supersymmetry or leptoquark interpretation, respectively. As can be seen in Fig. 2, the fake-lepton estimate in $e^-\mu^+$ events is indeed generally higher than in $e^+\mu^-$ events.

The uncertainty in the fake-lepton estimate includes two uncertainties: one propagated from uncertainty in the values of the efficiencies, and a 'non-closure' uncertainty. The non-closure uncertainty is derived in the region used to calculate electron fake efficiencies: an $e^\pm\mu^\pm$ region (with the electron failing the Signal selection but passing the Loose selection, and the muon passing the 'tag' selection described above), which – like the signal regions – has fake leptons originating mostly from W+jet events. The region is split into two bins, with either $\Sigma(m_\mathrm{T}) < 200$ GeV or $\Sigma(m_\mathrm{T}) > 200$ GeV. The non-closure uncertainty is taken as the fractional difference in event counts in these bins between the total background estimate and the data. Here, the total background estimate includes the Likelihood Matrix Method fake-background estimate, as well as the real-lepton background estimated using SM MC. It was checked that the real-lepton background contamination in this region has no significant impact on the uncertainty value. The non-closure uncertainty has a magnitude of 21% (13%) for events with $\Sigma(m_\mathrm{T}) > 200$ GeV ($\Sigma(m_\mathrm{T}) < 200$ GeV), which is applied to the signal (control) region.

Only two other sources of potential charge–flavour bias motivate application of an explicit correction to data. Firstly, in certain regions of the detector there are small differences between the reconstruction (and trigger) efficiencies for positively and negatively charged muons. These are largely a result of the toroidal magnetic field that the muons move in while traversing the muon spectrometer, increasing the relative acceptance of muons of one charge in certain regions, usually anti-symmetrically in η. To remove these differences, weights (depending on muon charge, transverse momentum and pseudorapidity, and derived from $Z \to \mu\mu$ samples following the tag-and-probe approach described in Ref. [35]) are applied to events after data-taking but before any other use in the analysis. These weights correct for the bias by taking the efficiency values back to the charge-averaged values. Approximately two thirds of these weights have values within 1% of unity. In addition to introducing an overall acceptance change of $\sim$0.05%, these weights are responsible for event yields acquiring non-integer values. Uncertainties associated with this correction are obtained by propagating the statistical uncertainty of the charge-bias measurement. Secondly, a small correction is applied to data to account for the muon sagitta bias, which is derived in accord with Ref. [47], and comes with associated uncertainties which are also applied to data. This charge-dependent bias in muon momentum is caused by misalignment of the detector, and is found to be very minor: 68% of muons have a bias of less than 0.2% of the muon p_T.

Before unblinding the signal regions, the hypothesis that the proton–proton initial state and experimental effects lead to a bias favouring $\rho \leq 1$ in the SM was confirmed by measuring ρ, binned in 'stransverse mass' M_T2 [43], in cr-ratio. Whilst the ratio is consistent with one within uncertainties, the maximal deviation from one is used to define a 2% 'residual-bias' uncertainty encompassing small remaining uncorrected detector biases. The extrapolation of the uncertainty to high $\Sigma(m_\mathrm{T})$ was validated by inspecting its impact on the ρ measurement in cr-ratio and cr-jet when binned in $\Sigma(m_\mathrm{T})$.

6. Results

The observed data and fake-lepton background estimate in the $e^+\mu^-$ and $e^-\mu^+$ channels of sr-met and sr-jet are shown in bins of M_T2 and H_P respectively in Fig. 2. Benchmark RPV-supersymmetry or leptoquark signal yields are included to demonstrate that these BSM models favour $e^+\mu^-$ over $e^-\mu^+$. In the lower panels of Fig. 2, an estimate of the proportion of SM background processes in each bin is given, showing that $t\bar{t}$ is expected to dominate in most bins apart from the tails, where the fake-lepton, diboson, and single-top backgrounds become proportionally more important.

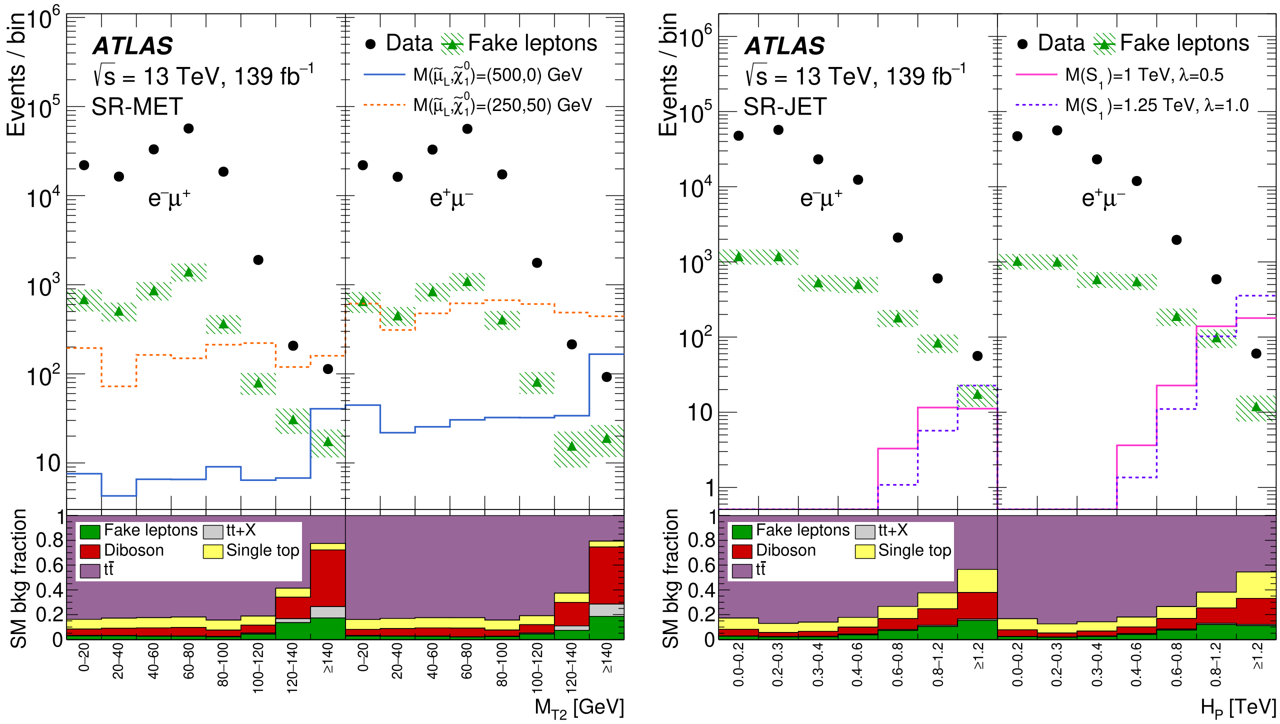
The ratio, ρ, is measured in bins, i, of M_T2 (H_P) in the sr-met (sr-jet) by maximising a parameterised likelihood model of the observed yields, $\tilde{N}^{+-/-+}_{\mathrm{obs,i}}$. The likelihood model assumes an independent Poisson distribution for the yield in each bin of the charge–flavour channels ($e^+\mu^-$ or $e^-\mu^+$):

$$\begin{aligned}\mathcal{L}(\vec{N}^{+-/-+}_{\mathrm{obs}}|\vec{\theta},\vec{\alpha},\vec{\rho}) \\ = \prod_{i\in\mathrm{bins}}\Big[\mathrm{Pois}(N^{-+}_{\mathrm{obs},i}|w_i^{-+}(\vec{\theta})N_{\mathrm{exp},i}+F_i^{-+}(\vec{\alpha})) \\ \times\,\mathrm{Pois}(N^{+-}_{\mathrm{obs},i}|\rho_i w_i^{+-}(\vec{\theta})N_{\mathrm{exp},i}+F_i^{+-}(\vec{\alpha}))\Big] \\ \times\prod_{k\in\text{ fake lepton uncertainties}}\mathrm{Gaus}(0|\alpha_k,1) \\ \times\prod_{j\in\text{ data uncertainties}}\mathrm{Gaus}(0|\theta_j,1),\end{aligned} \quad (3)$$

where the expectation in each bin is the combination of a fake-lepton background estimate, $F_i^{+-/-+}$, and a total irreducible (real-lepton) SM expectation, $N_{\mathrm{exp},i}$, which is a floating parameter in the likelihood. Uncertainties associated with the Likelihood Matrix Method estimate and the non-closure uncertainty in the fake-lepton background estimate are included by parameterising $F_i^{+-/-+}$ with Gaussian-constrained nuisance parameters, α. Muon charge and sagitta-bias corrections are already applied to the observed yields,[5] $\tilde{N}^{+-/-+}_{\mathrm{obs,i}}$, with the relative uncertainties on these corrections included in the $w_i^{+-/-+}(\vec{\theta})$ term and corresponding Gaussian-constrained nuisance parameters on the expected yields, θ_j. The 'residual-bias' uncertainty is included in the same manner. A global ratio measurement from combining all bins in a region gives $\rho = 0.987^{+0.022}_{-0.021}$ for sr-met and sr-jet. The binned measured ratios (maximum-likelihood estimators of ρ_i) are shown in Fig. 3. In the lower bins of these variables the residual-bias uncertainty dominates; in the final two bins of M_T2 and three bins of H_P the fake-lepton and statistical uncertainties dominate. Fig. 3 also shows *one-sided* p-values for a hypothesis test of $\rho = 1$ using a modified profile-likelihood-ratio test statistic that equals zero when $\rho_i \leq 1$, calculated using asymptotic approximations [48]. No significant upward deviation from one is seen in any bin, meaning that the SM hypothesis of $\rho \leq 1$ is not excluded anywhere. The largest upward deviation of ρ from one has a local significance of 1σ. The largest downward deviation from one is $\rho = 0.929^{+0.023}_{-0.022}$, in the $80-100$ GeV bin of M_T2, with a local significance of 3.1σ. The goodness-of-fit significance to the model that $\rho = 1$ in all bins is 1.6σ, estimated using a likelihood ratio test statistic with the asymptotic approximation.

The $\mathrm{CL_s}$ method [49] is used to obtain 95% confidence level (CL) upper limits on the number of possible signal events S entering sr-met and sr-jet, with a fraction z entering the $e^+\mu^-$ channel,

[5] These corrections are sufficiently close to unity to support the Poisson modelling assumption for the corrected yields (further evidence can be seen in Table 1).



(a) SR-MET (b) SR-JET

Fig. 2. Distributions of data in the $e^+\mu^-$ and $e^-\mu^+$ channels of the model-independent signal regions, binned in M_{T2} for SR-MET, and H_P for SR-JET, to correspond to the ratio measurement binning. The data has the muon charge and sagitta-bias corrections applied and corresponding uncertainties are added in quadrature in the error bar with the statistical uncertainty of the data. The fake-lepton background estimate is also shown, along with its uncertainty components added in quadrature, illustrating larger yields in the $e^-\mu^+$ channel as expected. The lower panel shows the fraction that each SM process contributes to the total SM background in each bin, estimated using standard MC simulations. The dominant background is $t\bar{t}$, whilst the importance of the fake-lepton background increases in higher bins of each variable. Benchmark RPV-supersymmetry signal models are shown for SR-MET, and benchmark scalar leptoquark models are shown for SR-JET, which all strongly favour the $e^+\mu^-$ final state over $e^-\mu^+$, as expected.

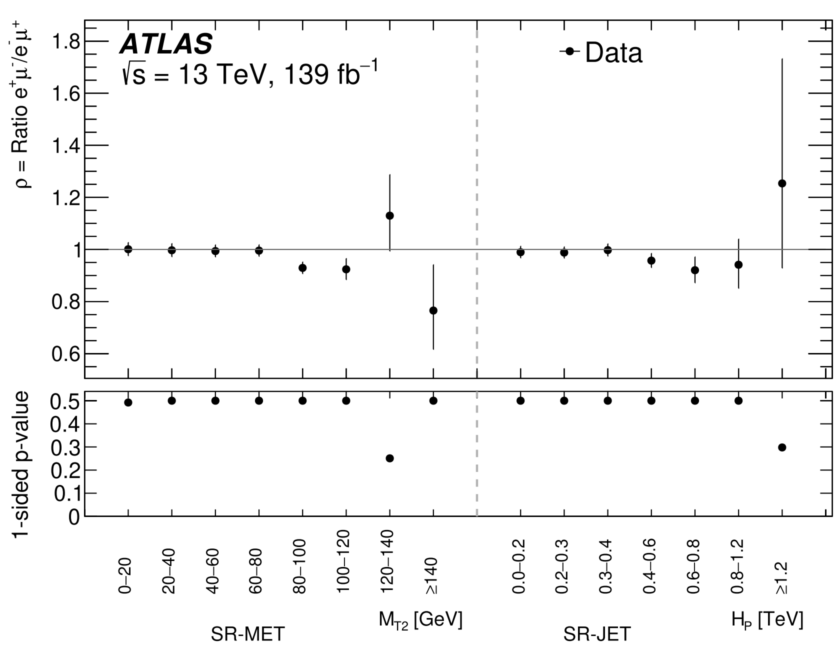


Fig. 3. A summary of the ratio ρ measurement in the full Run-2 data for SR-MET binned in M_{T2}, and SR-JET binned in H_P. Muon charge and sagitta-bias corrections are applied to data along with corresponding uncertainties, and the likelihood matrix method is used to estimate the charge–flavour-biased fake-lepton background such that it can be subtracted from the data. A 2% uncertainty in ρ, encompassing remaining observed detector biases, is also included. The lower panel shows the p-value for a one-sided discovery test to reject the SM hypothesis that $\rho \leq 1$.

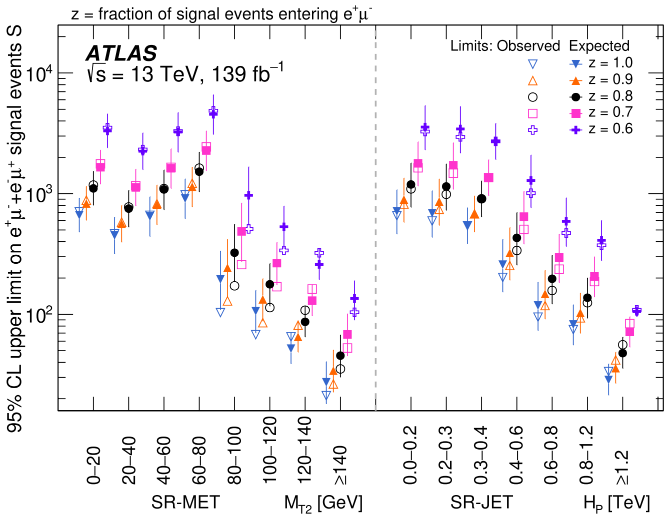


Fig. 4. Observed and expected 95% CL upper limits on the total number of signal events entering the $e^+\mu^-$ and $e^-\mu^+$ channels in each bin of SR-MET and SR-JET. The regions are binned in the same way as the ratio (ρ) measurement. The limits are shown for a selection of 'z' values, where 'z' is the fraction of the total number of signal events entering the $e^+\mu^-$ channel. The expected limit is calculated with the asymptotic approximation, by considering when there is a 50% chance of exclusion at 95% CL$_s$, under the hypothesis that $S = 0$ and $\rho_i = 1$.

and these are shown in Fig. 4 for a range of z values. These limits are calculated using a profile-likelihood-ratio test statistic with the likelihood function from Eq. (3) after fixing the ratio values to $\rho_i = 1$ and adding signal components to the Poisson expectations: Sz in the $e^+\mu^-$ channel, and $S(1-z)$ in the $e^-\mu^+$ channel, where S is the parameter of interest.

Having seen consistency with the SM hypothesis in the ratio measurement, limits are placed on parameters of the two benchmark BSM models. RPV-supersymmetry model exclusion limits are calculated with a one-sided profile-likelihood-ratio test statistic, where a likelihood function is defined for the observed yields in the $e^+\mu^-$ and $e^-\mu^+$ channels of both SR-RPV and a corresponding control region CR-RPV. This likelihood function is similar to Eq. (3) with signal yield terms added to the Poisson expectations (these signal terms are scaled by a signal strength parameter μ_{sig}) and i labelling the regions instead of the bins (each region in this model has a single bin). The ρ_i are also replaced by a single ρ that is common to both regions. In this respect, the control region drives the measurement of ρ and the signal region determines the value of μ_{sig}, which is used as the parameter of interest in the test statistic. The variance of ρ across the $(\mathcal{S}, M_{\text{T2}})$-plane ('RPV-plane') outside of the signal region is estimated with measurements of the ratio in bins of the plane axis observables: the binning was chosen to approximately match the statistical precision of the signal region. The estimated variance of 6% is added to the likelihood model as an uncertainty in ρ to cover the modelling assumption that ρ is invariant across the plane. This uncertainty covers both statistical and systematic sources of variance. The model is validated by finding good agreement between the observed and post-fit expected yields in the $e^+\mu^-$ channel of validation regions orthogonal to SR-RPV and CR-RPV (defined in Fig. 1), where the $e^-\mu^+$ channel of these regions is included in the fit along with both channels of CR-RPV. These validation regions are not included for the test statistic calculations when calculating the limits. Fig. 5(a) shows the observed and expected yields after the fit in the RPV-plane, demonstrating good agreement in the validation regions. This analysis is repeated in the $(H_{\text{P}}, \mathcal{S})$-plane ('LQ-plane') for leptoquark benchmark models (see Fig. 1), with an estimated 9% variance of ρ across the plane. Fig. 5(b) shows the fit result in the LQ-plane, demonstrating again good agreement in the validation regions. Uncertainties are included in the signal terms for lepton reconstruction efficiency, energy scale and resolution, and trigger efficiency differences between MC simulation and data; uncertainties in the jet-energy scale and resolution [50], the modelling of the $\vec{p}_{\text{T}}^{\text{miss}}$ soft term [39], and electron charge identification [51] are also included. The RPV signal model yields include theoretical uncertainties in the signal acceptance due to the choice of parton shower model and factorisation and renormalisation scales. The LQ signal models include effects of factorisation and renormalisation scale uncertainties on the NLO cross-section prediction, which form the $\pm 1\sigma_{\text{theory}}$ band on the observed limit.

As shown in Table 1, no statistically significant deviations of the data from the total SM background prediction are seen in the $e^+\mu^-$ channels of either signal region. By construction, since $N_{\text{exp,i}}$ is a freely floating parameter, good agreement is seen between the data and SM prediction in the $e^-\mu^+$ channels after the fit excluding the $e^+\mu^-$ channels. These are included in the Table 1 for completeness and comparison with the benchmark signal yields.

The observed and expected RPV-supersymmetry limits are shown in Fig. 6 for the case where the λ'_{231} coupling is fixed at one, and in Fig. 7 where the coupling takes values between 0.1 and 1.5. The perturbative upper limit for the λ'_{231} coupling is 1.12 at the Z-boson mass [53], and increases with the energy scale. For coupling values above 1, the limit at high smuon mass becomes constant since the cross-section increase and the branching-ratio decrease cancel each other out. Neutralino masses near and above the top-quark mass are not excluded, as here the neutralino can decay through the RPV coupling and no real $\vec{p}_{\text{T}}^{\text{miss}}$ remains in the final state. For the largest coupling value considered, smuon masses up to 650 GeV are excluded.

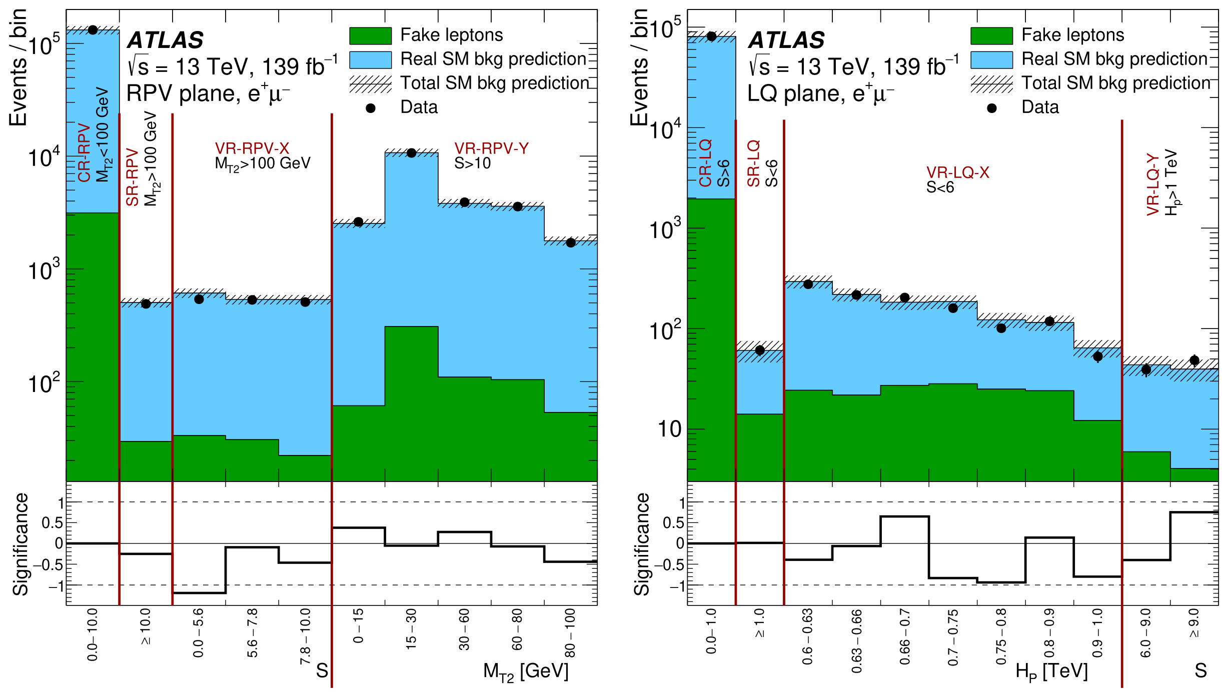
Fig. 8 shows the observed and expected limits on the leptoquark models considered. Since the energy required to produce a pair of leptoquarks is always double that required to make a single one, the suppression of high centre-of-mass energies by steeply falling parton distribution functions naturally leads to places where this analysis has better reach in leptoquark mass than analyses which have targeted pair production.[6] Notably, leptoquark couplings of $g^{eu}_{1\text{R}} = g^{\mu c}_{1\text{R}} > 0.46$ are newly excluded for masses above 1420 GeV, up to a value of unity (the largest coupling considered) for a leptoquark mass of 1880 GeV.

7. Conclusion

To search for evidence of new physics, this analysis compares the production cross sections for $e^+\mu^-$ and $e^-\mu^+$ by investigating the ratio $\rho = \frac{\sigma(pp \to e^+\mu^- + X)}{\sigma(pp \to e^-\mu^+ + X)}$ in a variety of signal regions. New physics processes could potentially raise or lower ρ from one, but even though the largest Standard Model effect known to lower ρ was subtracted, the model-independent tests presented in the first half of this analysis look only for evidence of the 'unexpected' scenario of $\rho > 1$. No significant model-independent evidence for $\rho > 1$ was seen when analysing 139 fb^{-1} of proton–proton collision data recorded at $\sqrt{s} = 13$ TeV by the ATLAS detector at the LHC.

Further observations were conducted in more exclusive regions optimised for particular signals beyond the Standard Model. These regions targeted: (i) R-parity-violating supersymmetric models with non-zero λ'_{231} couplings, with smuons and stable neutralinos, and (ii) scalar leptoquark models with $g^{eu}_{1\text{R}} = g^{\mu c}_{1\text{R}}$. The secondary measurements were then used to create exclusions in planes in

[6] This benefit comes, though, at the cost of requiring two non-zero leptoquark couplings $g^{eu}_{1\text{R}} \neq 0 \neq g^{\mu c}_{1\text{R}}$ rather than just the one assumed by existing pair–production searches.



(a) RPV-plane (b) leptoquark plane

Fig. 5. Distributions of data in the $e^+\mu^-$ channel of the signal, control, and validation regions, used for the R-parity-violating supersymmetry model and leptoquark model limit fits. Note that 'VR-LQ-x' has a lower bound of $H_P > 600$ GeV, as it is not necessary to validate the ratio extrapolation any further away, kinematically, from the signal region. The data has the muon charge and sagitta-bias corrections applied. The fake-lepton background estimate and data-driven real SM background prediction derived from the fit are also shown. The sum of these is the total SM background estimate, and its error bar includes contributions from the fake-lepton background estimate, muon charge-bias and sagitta-bias uncertainties on the denominator data yields used to fit the SM background estimate. The lower panel shows the significance of any deviation between the observed data yields and total SM background prediction in each bin, defined in Ref. [52].

Table 1
Observed yields, and (post-fit) expected yields for the data-driven SM estimates in the case where $\mu_{\text{sig}} = 0$ and the fit excludes the $e^+\mu^-$ signal region; in such a fit the post-fit expected yields in the $e^-\mu^+$ channel are constrained to match the data exactly. Additionally, signal yields are shown for the benchmark RPV-supersymmetry signal points in SR-RPV and the leptoquark signal points in SR-LQ obtained from a fit excluding the $e^+\mu^-$ signal region and setting $\mu_{\text{sig}} = 1$. Small weights correcting for muon charge biases affect all rows except that containing the fake-lepton estimate. These weights, w_i, cause non-integer yields. The uncertainties, $\sqrt{\sum_i w_i^2}$, are given for data to support the choice made to model the yields with a Poisson distribution.

	SR-RPV		SR-LQ	
	$e^+\mu^-$	$e^-\mu^+$	$e^+\mu^-$	$e^-\mu^+$
$M(\tilde{\chi}_1^0, \tilde{\mu}) = (0, 500)$ GeV, $\lambda'_{231} = 1$	191 ± 23	46.8 ± 7.7		
$M(\tilde{\chi}_1^0, \tilde{\mu}) = (50, 250)$ GeV, $\lambda'_{231} = 1$	1160 ± 130	361 ± 97		
$M(S_1)$ = 1 TeV, λ = 0.5			214 ± 15	14.5 ± 1.8
$M(S_1)$ = 1.25 TeV, λ = 1.0			356 ± 53	22.9 ± 3.7
Data	489 ± 22	510 ± 23	60.9 ± 7.8	69.1 ± 8.3
Total SM expectation	503 ± 48	510 ± 26	61 ± 15	69 ± 12
• part due to real leptons	473 ± 47	479 ± 24	47 ± 13	47 ± 11
• part due to fake leptons	29.4 ± 8.2	30.3 ± 8.3	14.1 ± 6.5	22.1 ± 6.6

sparticle or leptoquark model spaces. The search was able to exclude singly produced smuons in certain models in which the only other light sparticle is a neutralino, albeit with those exclusions dependent on the existence of λ'_{231} R-parity-violating couplings. Scalar leptoquarks with $g^{eu}_{1R} = g^{\mu c}_{1R} \leq 1$ were excluded for masses below 1880 GeV. This value reduces to $g^{eu}_{1R} = g^{\mu c}_{1R} = 0.46$ for 1420 GeV (close to the limits obtained in analyses based on leptoquark pair production).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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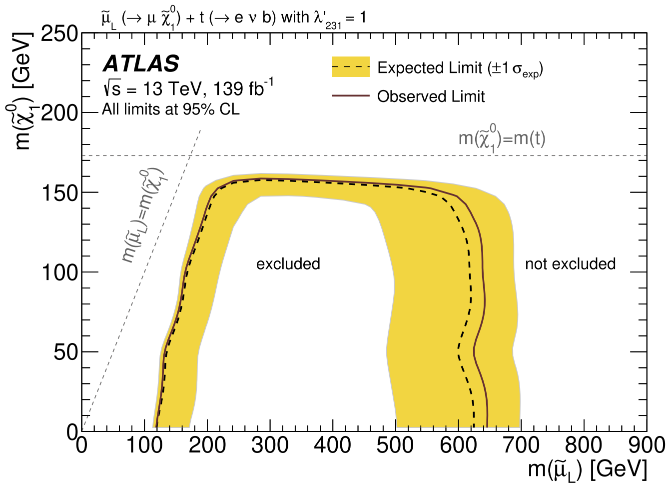

Fig. 6. Expected and observed exclusion limits are shown for RPV-supersymmetry models which allow for production of a single smuon (decaying into a muon and neutralino) in association with a top quark (decaying leptonically). The expected limit is calculated with the asymptotic approximation, by considering when there is a 50% chance of exclusion at 95% CL$_s$, under the SM-only hypothesis. The smuon is produced through the λ'_{231} coupling, which is fixed at unity. All limits are computed at 95% CL and all uncertainties are included. Also shown are dotted lines to indicate the two kinematic limits for the RPV process considered.

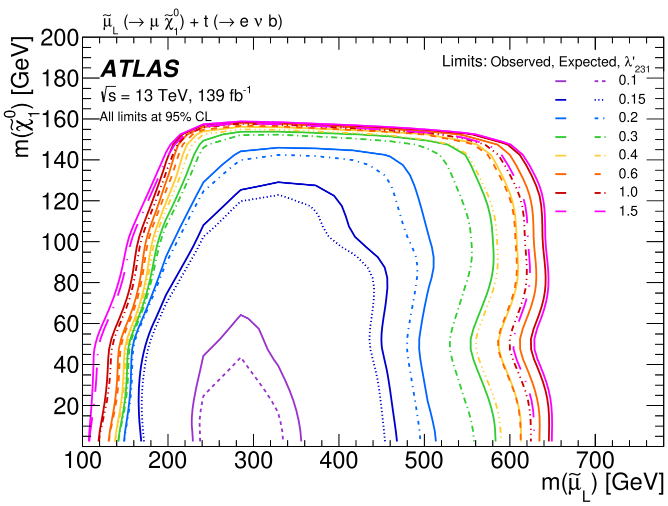

Fig. 7. Expected and observed exclusion limits are shown for RPV-supersymmetry models which allow for production of a single smuon (decaying into a muon and neutralino) in association with a top quark (decaying leptonically). The expected limits is calculated with the asymptotic approximation, by considering when there is a 50% chance of exclusion at 95% CL$_s$, under the SM-only hypothesis. The smuon is produced through the λ'_{231} coupling, which takes values up to 1.5. All limits are computed at 95% CL and all uncertainties are included.

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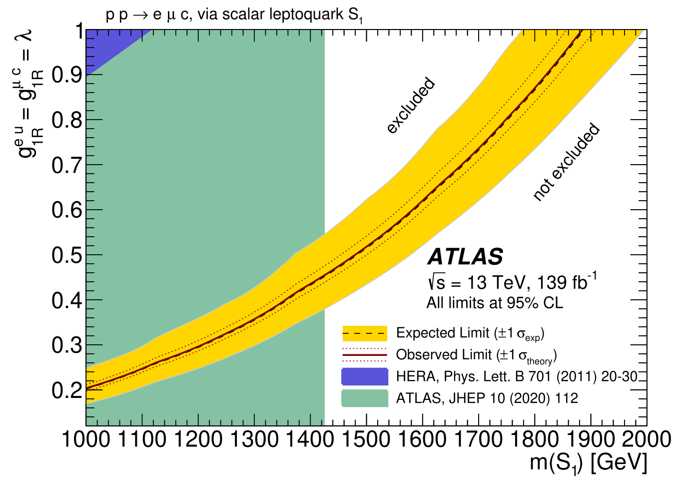

Fig. 8. Expected and observed exclusion limits are shown for models featuring production of a single scalar leptoquark which decays into a muon and charm quark. All limits are computed at 95% CL and all uncertainties are included. The $\pm 1\sigma_{\text{theory}}$ band considers the theoretical uncertainty of the NLO cross section used for the leptoquark signals. The expected limit is calculated with the asymptotic approximation, by considering when there is a 50% chance of exclusion at 95% CL$_s$, under the SM-only hypothesis. The underlaid exclusion is derived from a previous ATLAS leptoquark pair-production search [54], considering the result from μc final states. Since the model in this analysis requires leptoquarks to have two decay modes while that of Ref. [54] assumes only one, a branching ratio of 50% into μc was used when determining the position of the exclusion boundary. The interpretation of Ref. [54] also assumes that the narrow-width approximation is valid for leptoquarks over the range of coupling values shown.

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Appendix A

The top pair and single-top backgrounds were modelled using Powheg Box [56] v2 interfaced to Pythia 8 [23] and EvtGen [57] and the NNPDF2.3lo [24] PDF. A dilepton filter was applied to the $t\bar{t}$ and tW processes.

The diboson backgrounds were modelled using Sherpa [58]. Hard processes with no or one additional jet in the final state were simulated at NLO, while up to three additional jets were included at LO. Sherpa 2.2.2 was used for the fully leptonic final states ($\ell\ell\ell\ell$, $\ell\ell\ell\nu$, $\ell\ell\nu\nu$ and $\ell\nu\nu\nu$) together with the CT10 PDF [59]. For the semileptonic final states ($\ell\ell qq$ and $\ell\nu qq$), Sherpa 2.2.1 was used with the NNPDF [24] PDF. The loop-induced processes ($gg\ell\ell\ell\ell$, $gg\ell\ell\nu\nu$, $\ell\ell\ell\ell jj$, $\ell\ell\ell\nu jj$ and same-sign $\ell\ell\nu\nu jj$) were generated using Sherpa 2.1.1 and the CT10 PDF.

The $Z+$jets background was modelled using Sherpa 2.2.1 with the NNPDF PDF. Up to two jets were generated at NLO and up to four at LO.

The $t\bar{t}+X$ processes were simulated using MadGraph5_aMC@NLO + Pythia 8. The EvtGen program was used for properties of the bottom and charm hadron decays. The events are normalised to their respective NLO cross sections.

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