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Search for resonant leptoquark production via lepton–jet signatures in pp collisions at $\sqrt{s}$ = 13 TeV and $\sqrt{s}$ = 13.6 TeV with the ATLAS detector

The ATLAS Collaboration

This paper presents a search for physics beyond the Standard Model targeting a heavy resonance visible in the invariant mass of the lepton–jet system. The analysis focuses on final states with a high-energy lepton and jet, and is optimised for the resonant production of leptoquarks—a novel production mode mediated by the lepton content of the proton originating from quantum fluctuations. Four distinct and orthogonal final states are considered: e+light jet, μ+light jet, e+b-jet, and μ+b-jet, constituting the first search at the Large Hadron Collider for resonantly produced leptoquarks with couplings to electrons and muons. Events with an additional same-flavour lepton, as expected from higher-order diagrams in the signal process, are also included in each channel. The search uses proton–proton collision data from the full Run 2, corresponding to an integrated luminosity of 140 fb^{-1} at a centre-of-mass energy of $\sqrt{s}$ = 13 TeV, and from a part of Run 3 (2022–2023), corresponding to 55 fb^{-1} at $\sqrt{s}$ = 13.6 TeV. No significant excess over Standard Model predictions is observed. The results are interpreted as exclusion limits on scalar leptoquark ($\tilde{S}_1$) production, substantially improving upon previous ATLAS constraints from leptoquark pair production for large coupling values. The excluded $\tilde{S}_1$ mass ranges depend on the coupling strength, reaching up to 3.4 TeV for quark–lepton couplings y_{de} = 1.0, and up to 4.3 TeV, 3.1 TeV, and 2.8 TeV for $y_{s\mu}$, y_{be}, and $y_{b\mu}$ couplings set to 3.5, respectively.

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Contents

1 Introduction

While the discovery of the Higgs boson [1, 2] and subsequent precision measurements of its properties [3, 4] remain landmark achievements, an equally fundamental scientific motivation for the Large Hadron Collider (LHC) [5] is the search for physics beyond the Standard Model (BSM). Numerous BSM theories predict the existence of new massive states that could be produced resonantly in proton–proton (pp) collisions at the TeV scale, provided their masses lie within the experimentally accessible range of the LHC. When produced through resonant mechanisms, these states would manifest as localised excesses in the invariant mass spectra of their decay products. Such distinctive peaks superimposed on the smoothly falling background predicted by the Standard Model (SM) would constitute an unambiguous signature of new physics. Consequently, resonance searches constitute a cornerstone of the research programs for both the ATLAS and CMS experiments.

Leptoquarks (LQs) represent a prominent category of hypothetical heavy states predicted by various grand unified theories featuring extended gauge groups [6–8]. These colour-charged particles carry both baryon and lepton numbers, naturally reflecting the underlying symmetry between the two sectors as predicted by unifying theories and suggested by observed patterns in nature. Characterised by fractional electric charges and postulated in either scalar or vector forms, LQs decay into distinctive lepton–quark pairs whose flavour composition depends on the LQs' coupling parameters.

Extensive investigations of LQ signatures were conducted using the datasets collected during the LHC Run 1 and Run 2 data-taking periods. Previous LHC searches have primarily focused on two production

mechanisms: pair production (PP) [9] mediated by quantum chromodynamics (QCD) and coupling-dependent single production (SP) in association with a lepton [10], as illustrated in Figure 1 (a) and (b), respectively. While PP cross-sections depend predominantly on the strong coupling constant and remain largely independent of LQ coupling parameters, production via SP becomes more and more relevant with increasing coupling values due to its direct dependence on these parameters. Additional LQ sensitivity also arises from non-resonant contributions to dilepton production via t-channel processes (Drell–Yan, DY) seen in Figure 1 (c).

This paper introduces a novel probe of s-channel resonant LQ production shown in Figure 1 (d) and (e), enabled by recent advancements in understanding the proton's lepton content that arises from quantum fluctuations. State-of-the-art next-to-leading-order (NLO) calculations of lepton parton distribution functions (PDFs) [11] show that, despite the relative scarcity of leptonic constituents of the proton compared to quarks and gluons, this previously unexplored production channel offers competitive sensitivity relative to established search strategies [12]. The resonant production mechanism yields a relatively clean final state comprising a lepton–jet system whose invariant mass distribution could reveal a characteristic resonance peak, similar to single LQ production. This distinctive signature motivates the development of dedicated search algorithms within the ATLAS experimental programme.

The analysis employs a $\tilde{S}_1$ LQ with absolute electric charge $\frac{4}{3}e$ as a benchmark signal. This LQ is a singlet under the $SU(2)$ SM gauge group, with purely right-handed Yukawa couplings to down-type quarks and leptons. Therefore, it is characterised by a simple, exclusive decay topology into a down-type quark and a charged lepton, with no additional competing decay channels into neutral leptons. Four distinct coupling scenarios are investigated where the LQ exclusively interacts through single non-zero coupling parameters: y_{de}, $y_{s\mu}$, y_{be} and $y_{b\mu}$, corresponding to first/second-generation lepton (e, μ) couplings with d/s- or b-quark partners. Alternative models featuring couplings to u/c-quark flavours show detector-level signatures kinematically indistinguishable with the studied scenarios, permitting phenomenological re-interpretation through coupling parameter rotation in the quark flavour space. The ATLAS Collaboration has performed a pair-production search focusing on scalar LQ decays into quark–lepton ($q\ell$) final states with $\ell = e, \mu$, establishing mass exclusion limits up to 1.8 TeV (electron channel) and 1.7 TeV (muon channel) assuming a branching ratio into a charged lepton and a quark of 100%, with minimal dependence on the quark flavour [13]. These results also served as input for a statistical combination of LQ searches [14] to enhance sensitivity across different decay modes. Searches for LQ pair-production from the CMS Collaboration constrain scalar LQ masses up to 1.4 TeV and 1.5 TeV for couplings to electrons and muons, respectively [15, 16]. For couplings to muons and b-quarks, these constraints extend up to 1.8 TeV [17]. A recent search by the CMS Collaboration for t-channel LQ exchange strengthens the constraints on large couplings involving up- and down-type quarks and electrons or muons, probing LQ masses up to 5 TeV [18]. The CMS Collaboration also conducted a search for resonant LQs with couplings to a τ-lepton and a $u/d/s/b$ quark using data collected in 2016–2018 [19].

The present analysis introduces the first dedicated exploration of resonant LQ production mechanisms coupling to first- and second-generation leptons (e/μ). It is conducted using $\sqrt{s} = 13$ TeV and $\sqrt{s} = 13.6$ TeV pp collision data collected with the ATLAS experiment from 2015 to 2018 in LHC Run 2 (140 fb^{-1}) and from 2022 to 2023 in Run 3 (55 fb^{-1}), respectively.

The analysis incorporates four mutually exclusive detection channels: e + light-jet, μ + light-jet, e + b-jet, and μ + b-jet, where light-jet refers to jets that are not tagged as containing a b-hadron decay. To ensure methodological consistency, a similar analysis strategy is implemented across all channels while preserving channel-specific optimisations. Each channel features dedicated 1-lepton (1L) and 2-lepton (2L) signal regions (SRs), where the 2L topology is specifically designed to account for the NLO diagram shown

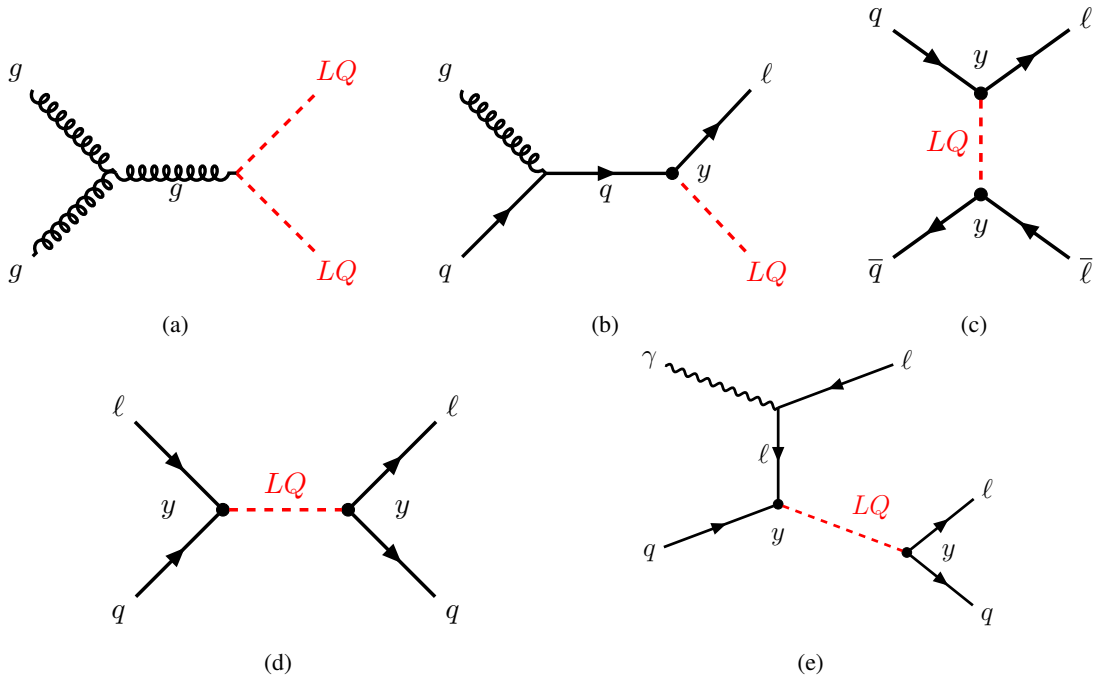


Figure 1: Example Feynman diagrams for the (a) pair, (b) single, (c) Drell–Yan, as well as (d) leading-order and (e) next-to-leading-order resonant LQ production modes. The symbol y marks interactions mediated by a LQ Yukawa coupling to quarks and leptons.

in Figure 1 (e). These diagrams are mediated via the photon constituent of the proton which is less suppressed than the lepton content and therefore their contributions are approximately on equal footing with the ones from the s-channel LQ production. Signal extraction employs a shape-based discrimination strategy through a multi-bin template likelihood analysis of the lepton–jet invariant mass ($m_{\ell j}$) spectrum. This approach combines channel-specific background modelling, kinematic selection thresholds, and independent treatments of systematic uncertainties, enabling simultaneous constraints on potential signals across the full $m_{\ell j}$ phase space covered in this analysis. Backgrounds with prompt, genuine leptons are constrained using dedicated control regions (CRs), complemented with data-driven techniques to estimate contributions from misidentified (*"fake"*) or non-prompt (FNP) leptons. An individual analysis selection is developed for each channel and is applied separately on the Run-2 and Run-3 datasets, enabling cross-validation between the two data-taking periods. For the interpretation of results, the observed $m_{\ell j}$ spectra from Run 2 and Run 3 are fitted simultaneously to maximise the sensitivity to the benchmark signal.

The rest of this paper is organised as follows. A brief description of the ATLAS detector is given in Section 2, and the data and simulation samples used are discussed in Section 3. Overviews of the reconstruction of physics objects and the event selection are presented in Sections 4 and 5, respectively. The background estimation strategy is described in Section 6. The systematic uncertainties related to this search are described in Sections 7. The results of the search are given in Section 8. Finally, Section 9 presents the conclusions.

2 ATLAS detector

The ATLAS detector [20, 21] at the LHC covers nearly the entire solid angle around the collision point.[1] It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer incorporating three large superconducting air-core toroidal magnets.

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

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

The muon spectrometer (MS) comprises separate trigger and high-precision tracking chambers measuring the deflection of muons in a magnetic field generated by the superconducting air-core toroidal magnets. The field integral of the toroids ranges between 2.0 and 6.0 T m across most of the detector. Three layers of precision chambers, each consisting of layers of monitored drift tubes, cover the region $|\eta| < 2.7$. These were complemented in the innermost layer of the endcap region by cathode-strip chambers in Run 2, which were replaced in Run 3 by layers of small-strip thin-gap chambers and Micromegas chambers, both providing precision tracking in the region $1.3 < |\eta| < 2.7$. The muon trigger system covers the range $|\eta| < 2.4$ with resistive-plate chambers in the barrel region, thin-gap chambers in the endcap regions, and, in Run 3, the aforementioned small-strip thin-gap chambers and Micromegas chambers in the innermost layer of the endcap.

The luminosity is measured mainly by the LUCID–2 detector that records Cherenkov light produced in the quartz windows of photomultipliers located close to the beampipe.

Events were selected by the first-level trigger system implemented in custom hardware, followed by selections made by algorithms implemented in software in the high-level trigger [22, 23]. The first-level trigger accepted events from the 40 MHz bunch crossings at a rate close to 100 kHz, which the high-level trigger further reduced in order to record complete events to disk at about 1.25 kHz and 3 kHz in Run 2 and Run 3, respectively.

[1] 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. Polar 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 $\eta = -\ln\tan(\theta/2)$ and is equal to the rapidity $y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$ in the relativistic limit. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta y)^2 + (\Delta\phi)^2}$.

The Run-3 detector configuration benefits from several upgrades compared with that of Run 2 to maintain high detector performance at the higher pile-up levels of Run 3. The improvements include a new innermost layer of the muon spectrometer in the endcap region, which provides higher redundancy and a large reduction in fake muon triggers. The trigger system also benefits from new digital electronics readout of the LAr calorimeters with significantly increased granularity. Other updates and further details are provided in Ref. [21].

A software suite [24] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

3 Data and simulated event samples

The data used in this analysis were collected using a set of single-electron and single-muon triggers [25, 26]. The transverse momentum thresholds of the online leptons vary across data-taking periods and depend on whether isolation requirements are applied at the trigger level. For electrons (muons), the p_{T} thresholds range from 24–26 (20–24) GeV for triggers with isolation, and increase up to 120–140 (50) GeV for those without isolation requirements. Application of data-quality requirements [27] results in data samples corresponding to integrated luminosities of 140 fb^{-1} and 55 fb^{-1} for Run 2 and Run 3, respectively.

While background contributions from misidentified or non-prompt leptons are mainly estimated by using data-driven techniques, Monte Carlo (MC) simulations are used to estimate the event yields and systematic uncertainties for both the signal processes and SM backgrounds featuring prompt-lepton production. These simulated event samples include the effect of multiple pp interactions in the same or neighbouring bunch crossings (pile-up), as well as the effect on the detector response due to interactions from bunch crossings before or after the one containing the hard interaction. All MC events were then re-weighted to match the pile-up distribution observed in the data. To simulate the detector response, background and signal MC samples were processed through the ATLAS simulation framework [28] in GEANT4 [29].

Simulated signal samples of resonant LQ production are used to optimise the event selection and interpret the results. Events are generated with an implementation of this process in POWHEG BOX RES at NLO [30] with the LUXlep-NNPDF3.1NLO PDF set[2] [11] and are interfaced with HERWIG 7.2.3 for parton shower, hadronisation, and underlying event using the H7.2-Default set of tuned parameters [31]. This implementation models both the LQ production and subsequent decay. Decays of bottom and charm hadrons are performed by EVTGEN 2.1.1 [32].

The 2L selections of the analysis are sensitive to the photon-induced diagrams of resonant LQ production but also to other LQ production modes that feature a second lepton in the final state such as DY and single production. Therefore, dedicated combined DY+SP LQ samples are generated with a POWHEG BOX implementation at NLO [33] and used additionally in the interpretation of the results. These samples use the same PDF set as the resonant LQ samples and are similarly interfaced to HERWIG 7.2.3 for the parton shower. These samples also take the interference from DY LQ production with SM DY $Z/\gamma^* \to \ell\ell$ into account. As the latter is estimated from dedicated samples, the LQ signal samples only include the interference but not the SM contribution. The DY+SP samples include a $m_{\ell\ell} > 100$ GeV requirement at matrix-element level to increase the acceptance of the generated events for the signal selections in this analysis.

[2] This PDF set includes both leptons and photons in the proton content.

The $\tilde{S}_1$ LQ is used as benchmark and four different types of minimal LQ scenarios are considered. Only one LQ coupling is considered at a time while all other couplings are set to zero. The couplings considered are y_{de}, $y_{s\mu}$, y_{be} and $y_{b\mu}$ that result in an e + light-jet, μ + light-jet, e + b-jet and μ + b-jet signature, respectively. For the scenarios with y_{de} and $y_{s\mu}$ couplings, samples with LQ masses between 1 and 5 TeV are generated. Models with couplings to b-quarks have lower production cross-sections due to the smaller b-quark PDF, hence the generated samples cover LQ masses between 1 and 3.5 TeV. The signal samples cover the LQ coupling range from 0.1–1.0 for y_{de} and from 0.5–3.5 for the other scenarios. The ranges of the signal parameters are motivated by the expected sensitivity of the search, taking into account existing constraints from collider and low-energy (for y_{de}) experiments, and restricting to the perturbative regime of the theory [8]. The signal production cross-sections and uncertainties are taken from the POWHEG BOX RES implementations and evaluated according to prescriptions from Ref. [34]. As an example, the production cross-section for a 2 TeV LQ at $\sqrt{s}$ = 13 TeV for y_{de} couplings between 0.1 and 1.0 range from 0.024 fb to 2.5 fb. At $\sqrt{s}$ = 13.6 TeV these cross-sections increase by approximately 16%.

A variety of MC generators is utilised to model the SM backgrounds involving the production of prompt leptons. The event generator configurations for SM processes are mostly identical between the Run 2 and Run 3 MC samples, except that more recent generator versions are used for some of the latter. Table 1 provides a comprehensive overview of the SM background samples utilised in the analysis. Additional information regarding ATLAS simulations of W+jets, Z+jets, $t\bar{t}$, single-top (Wt, t-channel, s-channel), and diboson processes is available in Refs. [35–38]. The decays of bottom and charm hadrons are performed by EVTGEN versions 1.2.0, 1.6.0 and 2.1.1 [32], except for the backgrounds modelled using SHERPA, for which the decays are performed internally.

In addition to the hypothesized resonant LQ production, taking into account the lepton PDF in the proton also predicts a SM ℓj scattering process at the LHC. Such a process has not been observed yet but features the same lepton–jet signature as the targeted LQ model. To take this contribution into account, an ℓj scattering sample is generated at leading-order using MADGRAPH 3.3.4 [39] and interfaced with HERWIG 7.2.3 and the LUXlep-NNPDF3.1NLO PDF set. To enrich the sample in events with large $m_{\ell j}$, the transverse momentum (p_{T}) of the lepton is required to be greater than 50 GeV and the generation is performed in bins of lepton p_{T}.

4 Object reconstruction

Events are required to contain a primary vertex built from at least two associated tracks with $p_{\mathrm{T}} > 0.5$ GeV. The primary vertex with the highest sum of squared transverse momenta $\sum p_{\mathrm{T}}^2$ of its associated tracks [67] is identified as the hard-scatter vertex of interest in each event. A set of basic data-quality requirements is applied to ensure a fully operating detector and to suppress contributions from detector noise or non-collision backgrounds [68].

Two categories of analysis objects are defined and utilised to define the search regions. Leptons and jets are first "preselected" using loose selection criteria; those that satisfy additional, tighter requirements are designated as "signal" objects. For electrons, also an intermediate category—falling between the preselected and signal definitions—is introduced which is employed in the data-driven estimate of the FNP electron background, as detailed in Section 6.

Preselected electrons are reconstructed using ID tracks matched to energy clusters in the electromagnetic calorimeter. These satisfy $p_{\mathrm{T}} > 10$ GeV and $|\eta| < 2.47$ with a *LooseAndBLayerLLH* identification [69, 70].

Table 1: Simulated signal and background event samples with the corresponding matrix element and parton shower (PS) generators, cross-section order in α_s used to normalise the event yield, set of tuned parameters (tune) for the underlying-event and the generator PDF sets used. For diboson samples, $V \in \{W, Z\}$. "Default" refers to the default tune of the SHERPA generator. When different, the settings used for the simulation of samples compared with Run-3 data are mentioned in parentheses. Abbreviations used are defined as: leading-order (LO), next-to-leading-order (NLO), next-to-next-to-leading-order (NNLO), next-to-leading-logarithmic (NLL), next-to-next-to-leading-logarithmic (NNLL). The PDF set employed in the PS is generally the same as in the generator except for the $t\bar{t}$, single-top and the MG5_aMC@NLO $t\bar{t}$+Z and $t\bar{t}$+W samples where the NNPDF2.3LO [40] set is used.

Physics process	Generator	Parton shower	Normalisation	Tune	PDF (generator)
Resonant LQ signal	POWHEG BOX RES [30]	HERWIG 7.2.3 [31]	NLO	H7.2-Default [31]	LUXlep-NNPDF3.1NLO [11]
DY+SP LQ signal	POWHEG BOX v2 [33]	HERWIG 7.2.3	NLO	H7.2-Default	LUXlep-NNPDF3.1NLO
$Z/\gamma^*(\to \ell\ell)$+jets	SHERPA 2.2.11 [41, 42] (SHERPA 2.2.14)	SHERPA 2.2.11 [43] (SHERPA 2.2.14)	NNLO [44]	Default [38]	NNPDF3.0NNLO [45]
$Z/\gamma^*(\to \tau\tau)$+jets	SHERPA 2.2.14	SHERPA 2.2.14	NNLO [44]	Default	NNPDF3.0NNLO
$W(\to \ell\nu, \tau\nu)$+jets	SHERPA 2.2.11 [41] (SHERPA 2.2.14)	SHERPA 2.2.11 (SHERPA 2.2.14)	NNLO [44]	Default	NNPDF3.0NNLO
$t\bar{t}$	POWHEG BOX v2 [46–49]	PYTHIA 8.230 [50]	NNLO+NNLL [51–57]	A14 [58]	NNPDF3.0NLO
Single-top	POWHEG BOX v2 [47–49, 59]	PYTHIA 8.230	NLO+NNLL [60]	A14	NNPDF3.0NLO
Diboson VV	SHERPA 2.2.11, 2.2.12 (SHERPA 2.2.14, 2.2.16)	SHERPA 2.2.11, 2.2.12 (SHERPA 2.2.14, 2.2.16)	LO–NLO [61–64]	Default	NNPDF3.0NNLO
$t\bar{t}$+Z	MG5_aMC@NLO 2.3.3 [39, 65]	PYTHIA 8.210 [50]	NLO [39]	A14	NNPDF3.0NLO
$t\bar{t}$+W	MG5_aMC@NLO 2.3.3 (SHERPA 2.2.14)	PYTHIA 8.210 (SHERPA 2.2.14)	NLO	A14 (Default)	NNPDF3.0NLO
Multijet	PYTHIA 8.230 (PYTHIA 8.308)	PYTHIA 8.230 (PYTHIA 8.308)	LO [66]	A14	NNPDF2.3LO
ℓj scattering	MADGRAPH 3.3.4 [39]	HERWIG 7.2.3	LO	H7.2-Default	LUXlep-NNPDF3.1NLO

Electrons reconstructed in the calorimeter transition region, $1.37 < |\eta| < 1.52$, are not considered. The longitudinal impact parameter z_0 of preselected electron tracks is required to satisfy $|z_0 \sin\theta| < 0.5$ mm. Signal electrons must also satisfy $p_T > 25$ GeV, the *Tight* likelihood-based identification criteria and have a transverse impact parameter d_0 with uncertainty $\sigma(d_0)$ satisfying $|d_0/\sigma(d_0)| < 5$. To further reject FNP electrons, the *HighPtCaloOnly* isolation discriminant [70] is employed that is calculated from energy deposits in the calorimeter cells in a cone around the electron candidate.

Preselected muons are reconstructed by combining tracks from the ID and the muon spectrometer subsystems. These are required to have $p_T > 10$ GeV, $|\eta| < 2.5$, satisfy the *High-p_T* identification criteria [71] and $|z_0 \sin\theta| < 0.5$ mm. Signal muons must have $p_T > 25$ GeV, impact parameter significance $|d_0/\sigma(d_0)| < 3$ and must satisfy an isolation requirement with a similar performance to the *PflowTight* criterion described in Ref. [71].

Hadronic jets are reconstructed using the anti-k_t algorithm [72] as implemented in `FastJet` [73] with a jet radius parameter of $R = 0.4$. The inputs to this algorithm are particle-flow objects [74] that combine measurements from the ATLAS inner detector and calorimeters [75]. The jet energy scale and resolution are calibrated using simulations, with in situ corrections obtained from data [76]. Preselected jets are required to satisfy $p_T > 20$ GeV and $|\eta| < 4.5$. Signal jets are required to have $|\eta| < 2.5$ and must additionally satisfy a pile-up jet rejection criterion based on a neural-network variant of the jet vertex tagger [77] if they have $p_T < 60$ GeV. Signal jets that satisfy the 85% efficiency working point of the *GN2* algorithm [78] are considered to likely contain b-hadrons and are referred to as b-tagged jets.

The missing transverse momentum $p_{\mathrm{T}}^{\mathrm{miss}}$ is calculated as the magnitude of the negative vector sum of the transverse momenta of all identified hard physics objects (preselected leptons and jets) calibrated to their respective energy scales, with a contribution from an additional soft term [79]. This soft term is constructed from ID tracks matched to the hard-scatter vertex but not associated with any of the hard reconstructed objects.

Since the object reconstruction algorithms are applied independently, lepton and jet candidates may share contributions from the same detector signals. To resolve such ambiguities, an overlap removal procedure is applied to the preselected leptons and signal jets in the following order. First, any electron sharing an ID track with a muon is removed. Next, jets are removed if they are within $\Delta R < 0.2$ from a remaining electron. After this, electrons are in turn rejected if they are within $\Delta R < 0.4$ of any remaining jet. Subsequently, jets with any ghost-associated [80] muon or within $\Delta R < 0.2$ are removed if the jet has fewer than three associated tracks with $p_{\mathrm{T}} > 500$ MeV. Finally, any muon within $\Delta R < 0.4$ of a jet is removed. Only objects that satisfy this overlap removal procedure are retained for the event selection.

5 Event selection

A set of analysis variables is derived from the physics objects that satisfy the identification criteria and are used in the event selections. These are briefly summarised below, where the leading lepton (jet) refers to the lepton (jet) with the largest p_{T} in the event:

$m_{\ell j}$: Invariant mass of the system built from the leading lepton and leading jet in the event to reconstruct the LQ mass.

$p_{\mathrm{T}}^{\ell}/m_{\ell j}$: Ratio of the p_{T} of the leading lepton and the invariant mass of the lepton–jet system $m_{\ell j}$.

$\Delta R(\ell, j)$: Angular separation $\Delta R(\ell, j) = \sqrt{\Delta\phi(\ell, j)^2 + \Delta\eta(\ell, j)^2}$ between the leading lepton and leading jet .

$\Delta\phi(\ell, p_{\mathrm{T}}^{\mathrm{miss}})$: Azimuthal angle between the leading lepton and $p_{\mathrm{T}}^{\mathrm{miss}}$.

$m_{\ell\ell}$: Invariant mass of the lepton pair in the 2L selections.

$\mathcal{S}(p_{\mathrm{T}}^{\mathrm{miss}})$: Object-based $p_{\mathrm{T}}^{\mathrm{miss}}$ significance [79] that provides a measure for the likelihood of the reconstructed $p_{\mathrm{T}}^{\mathrm{miss}}$ to originate from real invisible particles instead of from detector effects.

All four channels share a common preselection designed to enrich the selected events in the kinematic phase space of interest and to serve as basis to define signal, control, and validation regions. Each event must contain at least one signal lepton (electron or muon) and at least one jet, both with $p_{\mathrm{T}} > 130$ GeV. The invariant mass of the lepton–jet system, $m_{\ell j}$, is required to exceed 700 GeV. Although the leptons and jets from the LQ decays of interest typically have transverse momenta of several hundreds of GeV, the p_{T} requirements at the preselection level are relaxed to retain a sufficiently large sample of events for reliable background estimation.

The 1L selection requires exactly one signal lepton, while the 2L selection requires exactly two same-flavour signal leptons (ee or $\mu\mu$). Events with additional preselected leptons beyond those satisfying the signal lepton criteria are vetoed. For the 2L selections, an additional requirement of $m_{\ell\ell} > 70$ GeV is imposed, as the signal of interest with a resonantly produced LQ does not contribute much at low $m_{\ell\ell}$.

Table 2: Definitions of the preselection together with the 1L and 2L SRs for the e + light-jet, μ + light-jet, e + b-jet and μ + b-jet channels. The lepton requirements indicate an additional veto of preselected leptons, e.g. $N_e = 1$ requires the presence of exactly one signal electron but no other preselected lepton in the event.

Preselection								
$m_{\ell\ell} > 700$ GeV	$p_{\mathrm{T}}^{\ell_1} > 130$ GeV	$p_{\mathrm{T}}^{j_1} > 130$ GeV	$m_{\ell\ell} > 70$ GeV (if $N_\ell = 2$)					
Region	e + light-jet		μ + light-jet		e + b-jet		μ + b-jet	
	SR-1L-ej	SR-2L-ej	SR-1L-μj	SR-2L-μj	SR-1L-eb	SR-2L-eb	SR-1L-μb	SR-2L-μb
$m_{\ell j}$ [GeV]	≥ 950		≥ 900		≥ 900		≥ 900	
N_e	1	2	0		1	2	0	
N_μ	0		1	2	0		1	2
$N_{b\text{-jets}}$	0		0		1		1	
$\mathcal{S}(p_{\mathrm{T}}^{\mathrm{miss}})$	< 3.5		< 3.5		< 3.0	< 5.0	< 3.0	< 5.0
$\Delta R(\ell, j)$	< 3.7	–	[2.9, 3.6]	–	–		[2.4, 4.2]	
$p_{\mathrm{T}}^{\ell}/m_{\ell j}$	> 0.4	> 0.3	> 0.4	> 0.3	> 0.3	> 0.25	> 0.3	> 0.2
$m_{\ell\ell}$ [GeV]	–	> 160	–	> 160	–	> 150	–	> 120

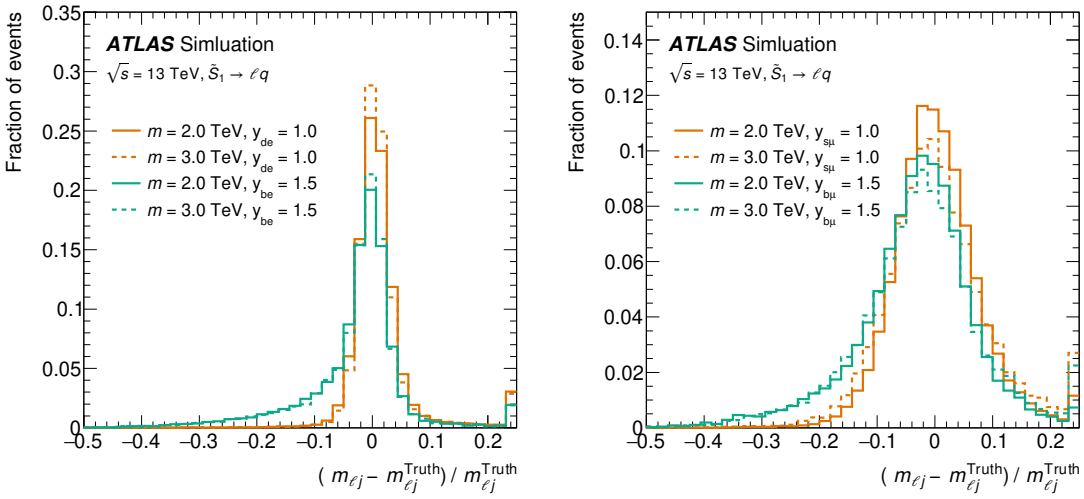
To ensure that events are selected in the plateau region of the trigger efficiency, a reconstructed lepton is required to be matched to the trigger-level lepton and to have a sufficiently high p_{T} above the corresponding online threshold, as described in Section 3. For muons, the p_{T} requirement of the event preselection alone guarantees that the single-muon triggers operate within their efficiency plateau. For electrons, the required p_{T} reaches up to 141 GeV in events selected by single-electron triggers that employ only a loose identification and no isolation criteria at the trigger level.

Events satisfying this preselection are then assigned to one of four analysis channels based on the lepton flavour and the number of b-tagged jets $N_{b\text{-jets}}$. The electron-based (muon-based) channels are restricted to events with either one or two electrons (muons). The e + light-jet and μ + light-jet channels require the absence of any b-tagged jet (b-veto) while the e + b-jet and μ + b-jet channels require the leading jet to be b-tagged.

Building on the preselection, additional requirements are applied—individually optimised for each channel and for the 1L and 2L selections—to enhance the separation between signal and background events. The resulting signal regions are referred to as SR-1L and SR-2L, respectively.

A summary of the SR definitions for each channel is provided in Table 2. Since the LQ signal does not produce genuine missing transverse momentum, an upper requirement on $\mathcal{S}(p_{\mathrm{T}}^{\mathrm{miss}})$ is applied to efficiently suppress W+jets and top-related backgrounds while retaining most of the signal events. The lepton and jet originating from a LQ decay are typically produced back-to-back in the detector, motivating a selection on their angular separation $\Delta R(\ell, j)$. In addition, the LQ decay products are expected to share the parent particle's energy approximately equally, resulting in similar lepton and jet momenta. Therefore, each channel imposes a lower bound on $p_{\mathrm{T}}^{\ell}/m_{\ell j}$ to reject SM events with a large p_{T} imbalance between the leading lepton and jet. Finally, in the SR-2L selections, a lower requirement on $m_{\ell\ell}$ is applied to suppress Z + jets events.

To maximise sensitivity across a broad range of potential LQ masses, the SRs are further binned in $m_{\ell j}$,



(a) (b)

Figure 2: Relative difference between the reconstructed $m_{\ell j}$ and particle-level $m_{\ell j}^{\text{Truth}}$ invariant mass of the lepton–jet system for selected example LQ scenarios in the (a) e + light-jet and e + b-jet, and (b) μ + light-jet and μ + b-jet channels using Run 2 MC simulation. The dashed lines correspond to an LQ scenario with a larger mass but the same coupling as the one shown by the solid lines. The particle-level invariant mass is calculated using the particle-level four-momenta of the reconstructed lepton and jet. The last bin contains the overflow.

targeting LQ masses of approximately 1 TeV and above. The binning choice is derived by the experimental resolution in $m_{\ell j}$, defined by the relative difference between the invariant mass of the lepton–jet system at reconstruction- and at particle-level. This resolution is evaluated using LQ signal samples and found to be largely independent of the LQ coupling, with only a mild dependence on the LQ mass. Figure 2 shows the relative difference between the reconstructed and the particle-level $m_{\ell j}$ for example LQ signals after application of the preselection requirements. Since the absolute $m_{\ell j}$ resolution worsens with increasing LQ mass, the $m_{\ell j}$ bin widths are gradually broadened across the spectrum. Binning continues until the SM background expectation falls below approximately one event, with the final bin in both SR-1L and SR-2L being inclusive and capturing all overflow events. No substantial difference between the $m_{\ell j}$ resolution between Run 2 and Run 3 is observed; therefore, the same binning strategy is applied to both data-taking periods.

Table 3 provides an overview of how the individual $m_{\ell j}$ SR bins are defined for each channel. In the e + light-jet channel, the $m_{\ell j}$ resolution is found to be approximately 5%, motivating bin widths of 100 GeV for LQ masses around 1 TeV and 200 GeV for masses near 2 TeV. The first bin in the e + light-jet SRs begins at $m_{\ell j}$ = 950 GeV, while the final bin in SR-1L-ej (SR-2L-ej) includes events with $m_{\ell j} \geq 3100$ (2300) GeV.

In the μ + light-jet channel, the $m_{\ell j}$ resolution is approximately 10%, due to the worsened momentum resolution for high-p_{T} muons compared with electrons. This suggests a bin width of 200 GeV for a LQ mass of 1 TeV and therefore the SRs in this channel begin at $m_{\ell j}$ = 900 GeV with the final bin in both SR-1L-μj and SR-2L-μj includes events with $m_{\ell j} \geq 2300$ GeV.

In the b-tagged channels, the $m_{\ell j}$ resolution is slightly worse than in the corresponding light-jet channels due to the possible presence of neutrinos in b-hadron decays, and is determined to be approximately 8% in the e + b-jet channel and 13% in the μ + b-jet channel. Both SR-1L-eb and SR-1L-μb begin at $m_{\ell j}$

Table 3: Binning of the $m_{\ell j}$ distribution used for SR-1L and SR-2L of the e + light-jet, μ + light-jet, e + b-jet and μ + b-jet channels, respectively.

SR		Binning in $m_{\ell j}$ [GeV]
e + light-jet	SR-1L-ej	[950, 1050, 1150, 1250, 1350, 1450, 1600, 1750, 1900, 2100, 2300, 2550, 2800, 3100, ∞)
	SR-2L-ej	[950, 1050, 1150, 1250, 1350, 1450, 1600, 1750, 1900, 2100, 2300, ∞)
μ + light-jet	SR-1L-μj	[900, 1100, 1300, 1600, 1900, 2300, ∞]
	SR-2L-μj	[900, 1100, 1300, 1600, 1900, 2300, ∞]
e + b-jet	SR-1L-eb	[900, 1100, 1300, 1550, 1850, 2200, ∞]
	SR-2L-eb	[900, 1100, 1300, 1550, ∞]
μ + b-jet	SR-1L-μb	[900, 1175, 1550, 2025, ∞]
	SR-2L-μb	[900, 1175, 1550, ∞]

= 900 GeV, while the final bin in SR-1L-eb (SR-1L-μb) and SR-2L-eb (SR-2L-μb) includes events with $m_{\ell j} \geq 2200$ (2025) GeV and $m_{\ell j} \geq 1550$ (1550) GeV, respectively.

Therefore, the LQ decay width[3] remains well below the experimental resolution for couplings up to about 1.5, corresponding to a width of approximately 80 GeV for a 2 TeV LQ. For the largest couplings considered, the effects of the intrinsic width and the detector resolution on the reconstructed LQ mass peak become comparable.

The signal composition in the SR-2L regions varies across the parameter space. For coupling values below 0.5, resonant LQ production accounts for approximately 70–80% of the total signal in these regions. As the coupling strength increases, the DY+SP production mode becomes increasingly relevant, reaching comparable levels to resonant production at couplings around 3.5. Within the DY+SP sample, the SP component, which also produces a peak in the $m_{\ell j}$ spectrum at the LQ mass, dominates for low couplings and LQ masses up to roughly 2 TeV. In contrast, the non-resonant DY contribution, which decreases steeply with $m_{\ell j}$ and thus has a comparable low selection efficiency in the SRs, gains in relative importance at larger couplings and LQ masses.

The overall signal efficiencies for resonant LQ production, including the detector acceptance, for the SR-1L and SR-2L selections in the e + light-jet channel assuming a LQ with mass of 2 TeV and coupling of 1.0 are approximately 30% and 15%, respectively. In the μ + light-jet channel these selection efficiencies for a LQ of the same mass and a coupling of 1.5 are approximately 17% and 10%, respectively. The selection efficiencies in the b-tagged channels are smaller than in the light-jet channels and are 17% (12%) and 7% (7%) in the e + b-jet (μ + b-jet) channel, for a LQ signal with mass of 2 TeV and a coupling of 1.5.

6 Background estimation

The SM processes contributing to the phase space targeted by this analysis can be broadly classified into reducible and irreducible backgrounds. Reducible backgrounds include events containing at least one FNP lepton, originating from misidentified detector signatures such as jets, or from non-prompt leptons produced

[3] The partial decay width Γ_{LQ} of a scalar LQ with mass m_{LQ} corresponding to coupling $y_{q\ell}$ is given at LO by $\Gamma_{\mathrm{LQ}} = \frac{|y_{q\ell}|^2}{16\pi} m_{\mathrm{LQ}}$ in the limit of large LQ masses [12].

in hadron decays involving heavy-flavour quarks. Irreducible backgrounds arise from processes with prompt, genuine leptons that produce final states resembling the target signal. The dominant irreducible contributions come from $W+$ jets and $Z+$ jets production, with top-quark processes providing an additional source in the b-tagged channels.

A combination of data-driven and MC-based techniques is used to estimate these SM backgrounds, as detailed in the following sections. The resulting predictions are validated in dedicated validation regions (VRs), which are typically enriched in specific background processes.

6.1 Reducible backgrounds

The particle-level information available in simulation samples enables a study of the origins of reconstructed leptons, allowing a distinction between genuine and misidentified objects. In the 1L selections of the e + light-jet and $e + b$-jet channels, a non-negligible fraction of the SM background is predicted to arise from FNP electrons. The most common origins of these misidentified electrons are prompt photons, arising from e.g. initial- and final-state radiation, and light-hadron decays. To estimate this contribution, a data-driven technique known as the fake-factor method [81] is employed in the 1L selections of the electron channels. In contrast, the selections requiring two electrons and all selections in the μ + light-jet and $\mu + b$-jet channels receive only a small contribution from FNP leptons. In these cases, the FNP background is instead estimated directly from MC simulation.

In the fake-factor method, the number of FNP leptons entering an analysis region—i.e., those satisfying the "tight", signal selection criteria for leptons, $N^{\text{FNP}}_{\text{signal}}$—is estimated using a separate, independent data sample of "loose" leptons in the same region that meet a relaxed set of selection requirements. The ratio to extrapolate from the loose to the signal lepton sample is referred to as the "fake factor" (FF) and is derived from data, as described below. To isolate the FNP contribution, any contamination from real, genuine leptons in the loose lepton sample is estimated by using MC simulation and subtracted from the data. The resulting estimate of the number of signal FNP leptons $N^{\text{FNP}}_{\text{signal}}$ in a given region is computed as

$$N^{\text{FNP}}_{\text{signal}} = \text{FF} \cdot (N^{\text{data}}_{\text{loose}} - N^{\text{MC, real}}_{\text{loose}}) \, .$$

Here, $N^{\text{data}}_{\text{loose}}$ and $N^{\text{MC, real}}_{\text{loose}}$ are the numbers of loose leptons observed in data and the estimated number of genuine loose leptons from simulation, respectively. The fake factor is typically parameterised in bins of relevant kinematic variables to account for dependencies in the extrapolation. These are derived as the ratio of signal to loose electrons in data, using a region enriched in FNP leptons and orthogonal to all other selections used in the analysis. The contamination from genuine leptons in both the loose and signal samples within the fake factor measurement region is estimated from MC simulation and again subtracted accordingly:

$$\text{FF} = \frac{N^{\text{data}}_{\text{signal}} - N^{\text{MC, real}}_{\text{signal}}}{N^{\text{data}}_{\text{loose}} - N^{\text{MC, real}}_{\text{loose}}} \, .$$

Loose electrons are defined as preselected electrons that fail to satisfy any of the signal electron selection criteria. They are further required to satisfy the *Medium* identification and *IsoLoose_VarRad* isolation working points [70] to match the associated online criteria and avoid any bias originating from the trigger

Table 4: Overview of the definitions for the regions employed to derive and validate the FNP electron estimate.

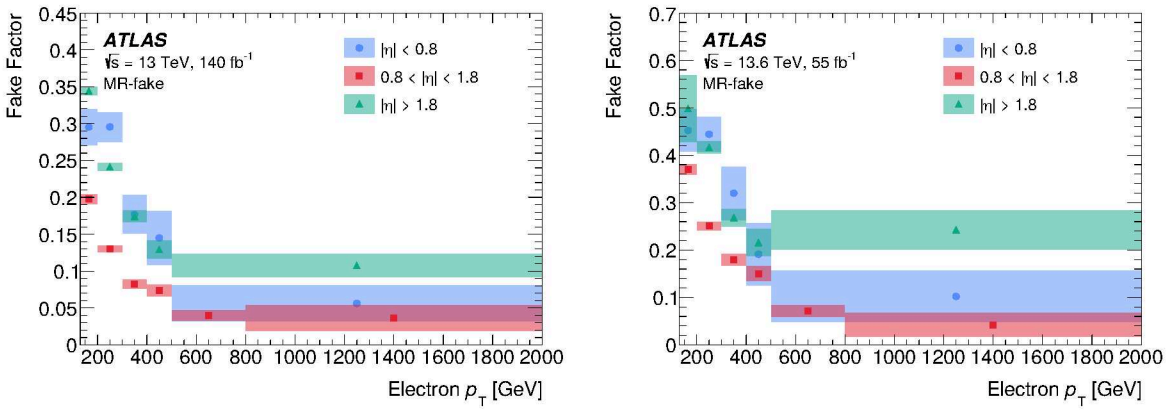
Region	FNP estimation		
	MR-fake	VR-fake	CR-W-fake
$m_{\ell j}$ [GeV]		> 700	
N_e		1	
N_μ		0	
$N_{b\text{-jets}}$		0	
$\Delta R(\ell, j)$		> 3.7	
$\mathcal{S}(p_{\mathrm{T}}^{\mathrm{miss}})$	< 3	3–5	> 5.0

requirements in the measured fake factors. Moreover, applying these requirements brings the loose electron definition closer to the signal one, reducing the size of the extrapolation between them while maintaining a sufficiently large number of events in the loose electron sample.

Fake factors are measured in events that satisfy the preselection described in Section 5. Such events must contain exactly either one loose or signal electron, no additional preselected leptons, and no b-tagged jets. To ensure orthogonality with the selections in the e + light-jet channel, a requirement of $\Delta R(\ell, j) > 3.7$ is imposed. An additional $\mathcal{S}(p_{\mathrm{T}}^{\mathrm{miss}}) < 3$ requirement suppresses contributions from W+jets events. This selection is referred to as fake factor measurement region, denoted by MR-fake. Events featuring $3 < \mathcal{S}(p_{\mathrm{T}}^{\mathrm{miss}}) < 5$ instead define the validation region VR-fake, which is used to assess the performance of the measured fake factors. While the loose electron samples in MR-fake and VR-fake are very pure in FNP leptons, the purity decreases to approximately 40% and 20% for signal electrons due to significant contamination from the W+jets process. To constrain the W+jets normalisation when validating the FNP estimate in VR-fake, events with $\mathcal{S}(p_{\mathrm{T}}^{\mathrm{miss}}) > 5$ are used to define a control region, CR-W-fake. A summary of the region definitions is provided in Table 4.

The fake factors are parameterised as a function of the electron p_{T} in three bins of $|\eta|$, and are shown separately for Run 2 and Run 3 in Figure 3. In Run 2, the fake factors range from 0.2 to 0.35 at $p_{\mathrm{T}} \sim 130$ GeV, depending on $|\eta|$, and typically decrease to values between 0.05 and 0.1 for $p_{\mathrm{T}} > 800$ GeV. In Run 3, higher values are observed, with fake factors ranging from approximately 0.35 to 0.5 at low p_{T} and from 0.05 to 0.25 at high p_{T}. This difference between Run 2 and Run 3 is consistently observed in both data and simulation. The $\Delta R(\ell, j) > 3.7$ requirement in the MR-fake region biases the selected electrons towards the more forward direction, limiting the available number of events in the central region and allowing only a coarser binning at high electron p_{T}. Although the fake factors are measured in events without b-tagged jets, they are applied in both the e + light-jet and e + b-jet channels. A b-tagged counterpart to MR-fake cannot be defined due to low FNP purity and limited number of events. Since MC simulation shows no strong dependence of the fake factors on the b-jet multiplicity, an additional uncertainty is assigned when applying them to events with b-tagged jets instead to cover this dependence, see Section 7.

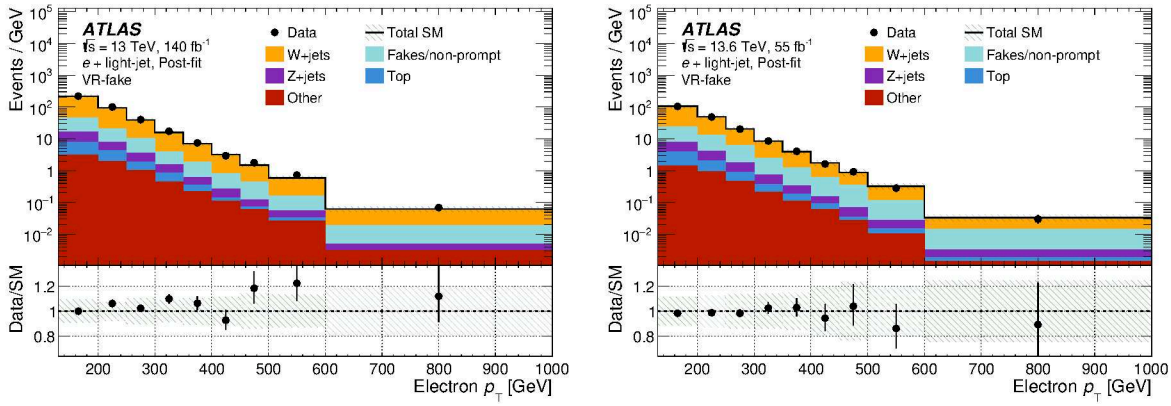
Figure 4 shows the electron p_{T} distributions in VR-fake separately for Run 2 and Run 3, with the FNP background estimated by using the derived fake factors. The normalisation of W+jets in this region is constrained by performing a background-only fit (see Section 8) to the corresponding CR-W-fake region. The extracted normalisation factors for W+jets in the CR-W-fake regions are found to be compatible with unity. These fit results are used solely to validate the FNP estimate in VR-fake; the following section



(a) (b)

Figure 3: Measured electron fake factors in MR-fake for (a) Run 2 and (b) Run 3 with respect to p_{T} in the three $|\eta|$ bins. The uncertainty bands represent the statistical uncertainties in the fake factors. The last bin is inclusive in the electron p_{T}.

introduces the dedicated CRs used to constrain the W+jets normalisation in the SRs. Good agreement between data and the SM predictions is observed across the p_{T} spectrum in both data-taking periods within systematic uncertainties (see Section 7), giving confidence in the procedure used to derive the fake factors.



(a) (b)

Figure 4: Post-fit distributions of the electron p_{T} in VR-fake for (a) Run 2 and (b) Run 3 using a background-only fit of CR-W-fake. The error bands include statistical and systematic uncertainties, with correlations between uncertainties taken into account. The last bin contains the overflow.

6.2 Irreducible backgrounds

Irreducible backgrounds are estimated from MC simulation, with the dominant processes being constrained to data through dedicated control regions. These CRs are individually optimised for each channel and enriched in a specific background process. The W+jets and Z+jets backgrounds are constrained in CR-W and CR-Z, respectively. The e + b-jet and μ + b-jet channels define additional CR-T regions to normalise

Table 5: Definitions of the CRs and VRs for the e + light-jet and μ + light-jet channels. The requirements listed are placed on top of the preselection introduced in the main text. The lepton requirements indicate an additional veto of preselected leptons, e.g. $N_e = 1$ requires the presence of exactly one signal electron but no other preselected lepton in the event. The VR-W and VR-Z regions follow the $m_{\ell j}$ binning of the associated SRs as described in the main text. The suffixes -ej (e.g. in CR-W-ej) and $-\mu j$ of each region name are dropped in the table for brevity, respectively.

Region	e + light-jet						μ + light-jet			
	CR-W	VR-W	VR-$\mathcal{S}(p_{\mathrm{T}}^{\mathrm{miss}})$	CR-Z	VR-Z	VR-$m_{\ell\ell}$	CR-W	VR-W	CR-Z	VR-Z
$m_{\ell j}$ [GeV]	[700, 950]	> 950	[700, 950]	[700, 950]	> 950	[700,950]	[700, 900]	> 900	[700, 900]	> 900
N_e	1		1	2		2	0		0	
N_μ	0		0	0		0	1		2	
$N_{b\text{-jets}}$	0		0	0		0	0		0	
$\Delta R(\ell, j)$	< 3.7		< 3.7	–		–	[2.9, 3.6]		–	
$m_{\ell\ell}$ [GeV]	–		–	[70, 160]		[160, 250]	–		[70, 160]	
$\mathcal{S}(p_{\mathrm{T}}^{\mathrm{miss}})$	> 3.5		< 3.5	< 3.5		< 3.5	> 3.5		< 3.5	
$p_{\mathrm{T}}^{\ell}/m_{\ell j}$	> 0.4		> 0.4	> 0.3		> 0.3	> 0.4	> 0.2	> 0.3	

Table 6: Definitions of the CRs and VRs for the e + b-jet channel. The requirements listed are placed on top of the preselection introduced in the main text. The lepton requirements indicate an additional veto of preselected leptons, e.g. $N_e = 1$ requires the presence of exactly one signal electron but no other preselected lepton in the event. The VR-W, VR-Z and VR-T-high regions follow the $m_{\ell j}$ binning of the associated SRs as described in the main text. The suffix -eb (e.g. in CR-W-eb) of each region name is dropped in the table for brevity.

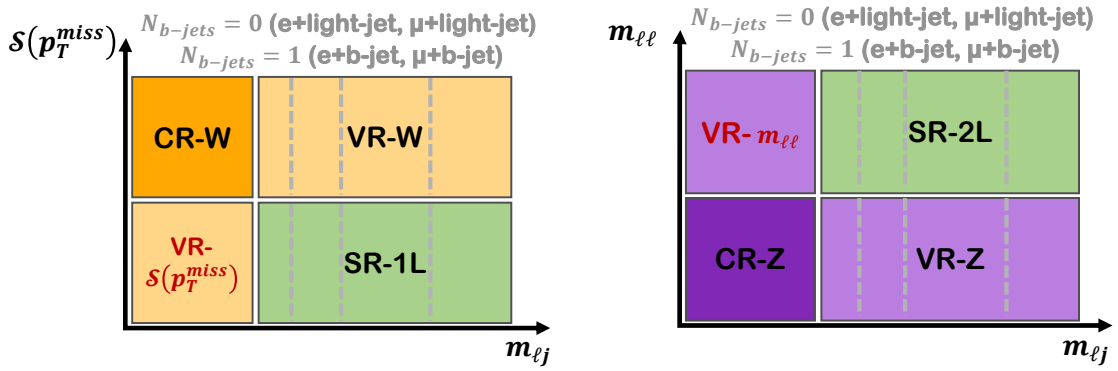
Region	e + b-jet							
	CR-W	VR-W	CR-Z	VR-Z	CR-T-high	VR-T-high	CR-T-low	VR-$\mathcal{S}(p_{\mathrm{T}}^{\mathrm{miss}})$
$m_{\ell j}$ [GeV]	[700, 900]	> 900	[700, 900]	> 900	[900, 1300]	> 1300	[700, 900]	[700, 900]
N_e	1		2		1		1	1
N_μ	0		0		0		0	0
$N_{b\text{-jets}}$	1		1		≥ 2		≥ 2	1
$m_{\ell\ell}$ [GeV]	–		[70, 110]		–		–	–
$\mathcal{S}(p_{\mathrm{T}}^{\mathrm{miss}})$	> 3.0		< 5.0		< 4.0		> 3.0	< 3.0
$p_{\mathrm{T}}^{\ell}/m_{\ell j}$	> 0.3		> 0.25		> 0.3		> 0.3	> 0.3
$\Delta\phi(\ell, p_{\mathrm{T}}^{\mathrm{miss}})$	< 1.0		–		< 1.0		< 1.0	< 1.0

backgrounds containing top quarks. Events from $t\bar{t}$ and single-top production are therefore grouped into a common category labelled "Top" and constrained using a common normalisation factor. Other, rarer processes involving genuine leptons—such as diboson production, $t\bar{t}V$, and ℓj scattering —are estimated from MC simulation and grouped into a category labelled "Others". MC events used to estimate the irreducible backgrounds are required to contain only genuine leptons to avoid double-counting with the FNP estimate described in the previous subsection. The extracted background normalisations are validated in the corresponding VRs which also adopt the $m_{\ell j}$ binning of the SRs. Summaries of the CR and VR definitions are provided in Table 5 for the light-jet and Tables 6 and 7 for the $e + b$-jet and $\mu + b$-jet channels, respectively.

All four channels follow a similar strategy to derive and validate the normalisations for W+ jets and Z + jets

Table 7: Definitions of the CRs and VRs for the and $\mu + b$-jet channel. The requirements listed are placed on top of the preselection introduced in the main text. The lepton requirements indicate an additional veto of preselected leptons, e.g. $N_e = 1$ requires the presence of exactly one signal electron but no other preselected lepton in the event. The VR-W, VR-Z and VR-T-high regions follow the $m_{\ell j}$ binning of the associated SRs as described in the main text. The suffix -μb (e.g. in CR-W-μb) of each region name is dropped in the table for brevity.

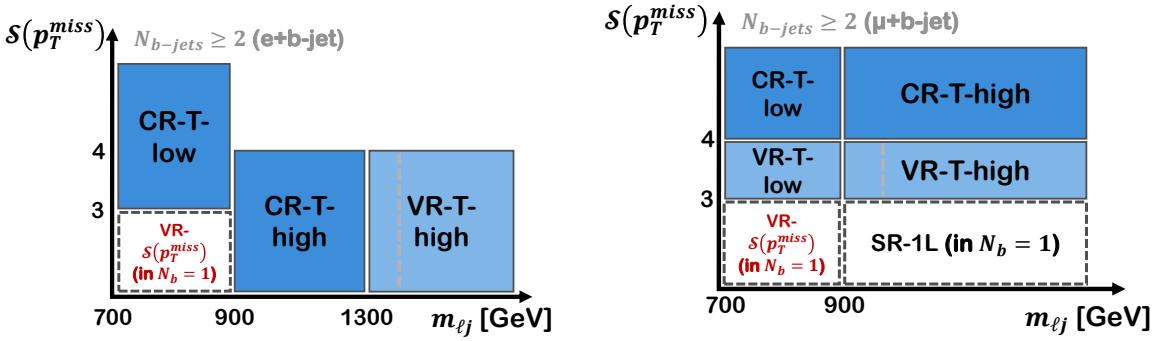
Region	$\mu + b$-jet								
	CR-W	VR-W	CR-Z	VR-Z	CR-T-high	VR-T-high	CR-T-low	VR-T-low	VR-$\mathcal{S}(p_{\mathrm{T}}^{\mathrm{miss}})$
$m_{\ell j}$ [GeV]	[700, 900]	> 900	[700, 900]	> 900	> 900	> 900	[700, 900]		[700, 900]
N_e	0		0		0		0		0
N_μ	1		2		1		1		1
$N_{b\text{-jets}}$	1		1		≥ 2		≥ 2		1
$\Delta R(\ell, j)$	[2.4, 4.2]		[2.4, 4.2]		[2.4, 4.2]		[2.4, 4.2]		[2.4, 4.2]
$m_{\ell\ell}$ [GeV]	–		[70, 120]		–		–		–
$\mathcal{S}(p_{\mathrm{T}}^{\mathrm{miss}})$	> 3.0		< 5.0		> 4.0	[3.0, 4.0]	> 4.0	[3.0, 4.0]	< 3.0
$p_{\mathrm{T}}^{\ell}/m_{\ell j}$	> 0.2		> 0.2		> 0.3		> 0.3		> 0.3



(a) (b)

Figure 5: Illustrations of the CRs and VRs definitions for the (a) W+jets and (b) Z+jets backgrounds. The phase space of SR-1L and SR-2L is also indicated, respectively. Grey vertical dashed lines indicate that a region is binned in $m_{\ell j}$.

backgrounds. Both the CR-W and CR-Z are defined at lower $m_{\ell j}$ values than the SRs to ensure sufficiently large event counts in these regions. Illustrations showing the region layout of the CR-W and CR-Z are presented in Figure 5. These CRs span the $m_{\ell j}$ range from 700 GeV up to the start of the SRs, which begins at either 900 or 950 GeV depending on the channel. The VR-W and VR-Z regions apply the same selection as their respective CRs but cover the $m_{\ell j}$ range used in the SRs. To maintain kinematic similarity to the SRs, the CRs and VRs mirror the SR requirements on $\Delta R(\ell, j)$, $m_{\ell\ell}$, $\mathcal{S}(p_{\mathrm{T}}^{\mathrm{miss}})$, and $p_{\mathrm{T}}^{\ell}/m_{\ell j}$ as closely as possible, with one selection inverted to ensure orthogonality. In some of these CRs and VRs, additional or relaxed requirements relative to the SRs are applied to ensure that the contamination from signals not already excluded by previous ATLAS searches remains below 10%. CR-W and VR-W replicate the SR-1L selection but invert the $\mathcal{S}(p_{\mathrm{T}}^{\mathrm{miss}})$ requirement to enrich W+jets events. Similarly, CR-Z and VR-Z mimic the SR-2L selection but require $m_{\ell\ell}$ to lie within a window around the Z boson mass. To facilitate a



(a) (b)

Figure 6: Illustrations of the CRs and VRs definitions for the top background in the (a) $e + b$-jet and (b) $\mu + b$-jet channel, respectively. The phase spaces of VR-$\mathcal{S}(p_{\mathrm{T}}^{\mathrm{miss}})$ and SR-1L which select event with exactly one b-tagged jet are indicated as hatched boxes. The phase space SR-1L is only indicated in (b) as it overlaps with the phase space of CR/VR-T-high in (a) in the $m_{\ell j}$–$\mathcal{S}(p_{\mathrm{T}}^{\mathrm{miss}})$ plane. Grey vertical dashed lines indicate that a region is binned in $m_{\ell j}$.

validation of the background normalisations across $m_{\ell j}$, VR-W and VR-Z adopt the same $m_{\ell j}$ binning as SR-1L and SR-2L, respectively. If the expected number of events in a VR bin falls below approximately 10, the corresponding bin is made inclusive in $m_{\ell j}$ to ensure adequate event counts for validation.

The estimation strategy for the top background is adapted relative to that for the V+jets processes, as its normalisation is found to depend on $m_{\ell j}$. The associated CR-T and VR-T regions select 1L events with two or more b-tagged jets, with the b-jet requirement ensuring orthogonality with the SRs. Both the $e + b$-jet and $\mu + b$-jet channels define a CR-T-high region at $m_{\ell j} > 900$ GeV to normalise top events in the high-$m_{\ell j}$ regime.

Since top-quark decays involving leptons yield genuine $p_{\mathrm{T}}^{\mathrm{miss}}$, CR-T-high-$\mu b$ applies the same kinematic selections as SR-1L-μb but requires $\mathcal{S}(p_{\mathrm{T}}^{\mathrm{miss}}) > 4.0$ to enhance the top fraction while suppressing signal contamination. Events with $3.0 < \mathcal{S}(p_{\mathrm{T}}^{\mathrm{miss}}) < 4.0$ define VR-T-high-μb, which otherwise matches the CR selection and is binned in $m_{\ell j}$ for validation.

In contrast, CR-T-high-eb applies $\mathcal{S}(p_{\mathrm{T}}^{\mathrm{miss}}) < 4.0$, i.e. an upper requirement on this variables similar as in the SRs, since the top normalisation also shows some dependence on $\mathcal{S}(p_{\mathrm{T}}^{\mathrm{miss}})$ in the e + light-jet channel. CR-T-high-eb extends up to $m_{\ell j} = 1300$ GeV, while higher-$m_{\ell j}$ events are covered by VR-T-high-eb, which otherwise mirrors the CR selection and is binned in $m_{\ell j}$.

The CR-W regions in both the $e + b$-jet and $\mu + b$-jet channels, which cover $m_{\ell j}$ values below 900 GeV, receive substantial contributions from top-quark backgrounds. To ensure proper normalisation of these events, dedicated CR-T-low regions are defined to normalise top events in the low-$m_{\ell j}$ regime. CR-T-low-eb adopts the same requirements as CR-W-eb, differing only in the b-jet multiplicity. CR-T-low-μb reflects the kinematic selections of SR-1L-μb but enforces $\mathcal{S}(p_{\mathrm{T}}^{\mathrm{miss}}) > 4.0$. An illustration of the CRs and VRs definitions for the top background is shown in Figure 6.

A set of additional VRs is defined to test the robustness of the background normalisations when extrapolated over variables other than $m_{\ell j}$. The VR-$\mathcal{S}(p_{\mathrm{T}}^{\mathrm{miss}})$ regions invert the $\mathcal{S}(p_{\mathrm{T}}^{\mathrm{miss}})$ requirement of the corresponding CR-W selections to test the modelling of W+jets at low $\mathcal{S}(p_{\mathrm{T}}^{\mathrm{miss}})$. The extrapolation of the Z+jets normalisation across $m_{\ell\ell}$ is validated with VR-$m_{\ell\ell}$. This validation region is defined only for the e + light-jet channel, as the other three channels show significant signal contamination that precludes

its use. The $\mu + b$-jet channel defines VR-T-low-μb, to validate the low-$m_{\ell j}$ top background normalisation across $\mathcal{S}(p_{\mathrm{T}}^{\mathrm{miss}})$ as the associated VR-$\mathcal{S}(p_{\mathrm{T}}^{\mathrm{miss}})$ receives a substantial contribution from this background.

7 Systematic uncertainties

While this search is predominantly limited by statistical constraints, experimental, theory, and modelling uncertainties have non-negligible contributions to the total uncertainty. These systematic effects are quantified and incorporated into the statistical model (see Section 8), with their key components detailed below. The overall effect of systematic uncertainties in the LQ mass sensitivity reach is found to be below 5%.

Figure 7 shows a decomposition into individual categories of the systematic uncertainties in the total SM predictions for the SRs in Run 2 of each channel, with a similar breakdown observed for the corresponding Run 3 regions. This decomposition is obtained by performing a series of fits in which the parameters associated with a given category are fixed to their best-fit values and held constant, effectively removing their contribution from the systematic model. The systematic uncertainty attributed to each category is then computed as the quadratic difference between the total background uncertainty in the nominal fit and that in the fit with the category fixed [82].

A detailed evaluation of detector-related systematic uncertainties is performed. These include uncertainties in lepton performance, covering trigger, reconstruction, identification, and isolation efficiencies for electrons [83] and muons [71], along with momentum calibration uncertainties for both lepton species. Jet energy calibration uncertainties are also considered, including those in the jet energy scale (JES) and jet energy resolution (JER) [76]. Additional jet-related uncertainties arise from efficiency corrections applied to pile-up jet tagging [77] and b-jet identification [84–86]. Missing transverse momentum uncertainties originate from the propagation of JES and JER uncertainties to the $p_{\mathrm{T}}^{\mathrm{miss}}$ calculation, supplemented by uncertainties related to tracks associated with the primary vertex but unmatched to reconstructed objects [79]. The uncertainties in the combined 2015–2018 and 2022–2023 integrated luminosities are 0.83% [87] and 2.0% [88, 89], respectively, obtained using the LUCID-2 detector [90] for the primary luminosity measurements, complemented by measurements using the inner detector and calorimeters. Additionally, a dedicated uncertainty accounts for discrepancies between data and simulation in pile-up profile modelling.

The treatment of FNP background employs distinct strategies across analysis channels. Simulated samples directly model these backgrounds in the μ + jet and $2e$ electron channels, with a conservative 80% normalisation uncertainty applied to account for potential mismodelling. In the $1e$ selections of the e + light-jet and $e + b$-jet channels, systematic uncertainties associated with the data-driven FNP estimate (Section 6) are characterised through multiple dedicated studies. The dominant uncertainty originates from the subtraction of the prompt-lepton contamination in the loose and tight electron samples, originating in particular from W+jets events. Therefore, ±15% variations in the MC-derived real lepton fractions are propagated through the fake-factor calculation, with the variation magnitude chosen to cover the size of the W+jets normalisation factors observed in the e + light-jet channel, see Section 8. To account for the reduced binning granularity in p_{T} for central electrons with $p_{\mathrm{T}} > 800$ GeV in the fake-factor measurements, an additional 70% uncertainty, based on the p_{T} dependence of the fake factors observed in MC simulation, is assigned on the FNP estimate from such electrons. A non-negligible dependence of the fake factors on $\Delta R(\ell, j)$ is observed. Comparing fake factors from MC simulation from events with $\Delta R(\ell, j)$ smaller and larger than 3.7, results in uncertainties of 50% ($p_{\mathrm{T}} < 200$ GeV) and 25% ($p_{\mathrm{T}} > 200$ GeV), respectively.

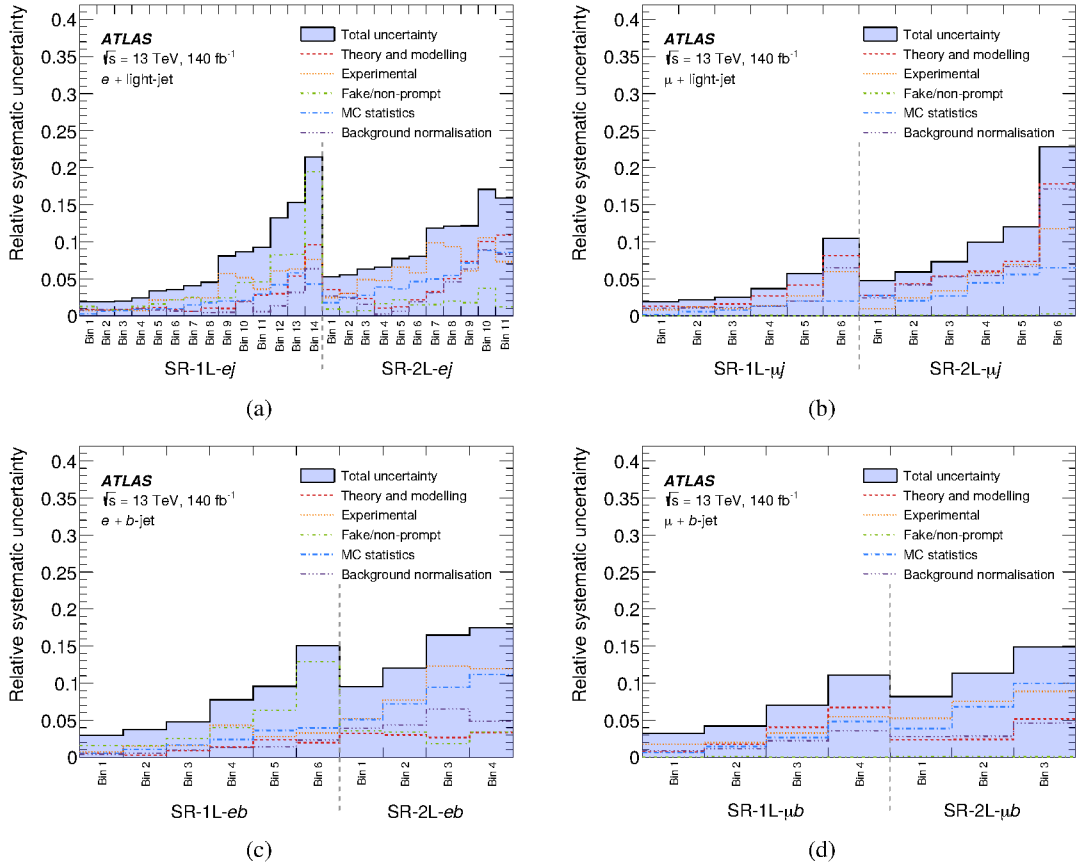


Figure 7: Relative systematic uncertainties in the post-fit SM background estimates in the (a) e + light-jet, (b) μ + light-jet, (c) e + b-jet and (d) μ + b-jet channels obtained from a background-only fit to the respective CRs and SRs. The "Fake/non-prompt" category reflects uncertainties impacting the FNP background estimate. Uncertainties originating from the limited size of the MC samples used to model the irreducible background contributions are contained in the "MC statistics" category. The "Background normalisation" category reflects uncertainty in normalisation factors for the W+jets, Z + jets and top backgrounds extracted from the respective CR-W, CR-Z and CR-T regions. The "Theory and modelling" category includes the different sources of theory modelling uncertainties for the W+ jets, Z + jets and top backgrounds. The "Experimental" category covers detector related uncertainties from the reconstruction and selection of objects in the analysis. The individual uncertainties are correlated and do not necessarily add up in quadrature to the total uncertainty.

Differences between the FNP composition between the fake-factor measurement and application domains are evaluated using MC simulation and translated into an additional 50% uncertainty in the FNP estimate. Furthermore, potential b-jet induced modifications to the fake factors were investigated through dedicated simulation studies comparing b-jet enriched and depleted phase spaces in the e+b-jet channel. The observed weak correlation between fake factor magnitudes and b-jet presence was conservatively accommodated through an additional 25% uncertainty component in the FNP estimates derived for the e + b-jet channel.

The background composition exhibits a strong channel dependence, with W+ jets production constituting the dominant contribution in SR-1L and Z + jets prevailing in SR-2L. Systematic uncertainties in these V+ jets processes incorporate three principal components: variations of the QCD renormalisation μ_R and factorisation μ_F scales by a factor two evaluated through the envelope of seven μ_R–μ_F combinations, PDF eigenvector variations using the NNPDF3.1 NNLO set, and α_S variations. Additional uncertainties are

applied to take into account electroweak corrections on the V+jets samples [91].

Top-quark backgrounds, while small in b-vetoed regions, are subleading contributions in the $e + b$-jet and $\mu + b$-jet channels. Their theory uncertainties mirror the V+jets framework in scale and PDF treatment, augmented by process-specific considerations including parton shower modelling differences quantified via Pythia 8.230 versus Herwig 7.2.1 (for $t\bar{t}$) or Herwig 7.1.6 (for single top) generator comparisons. Uncertainties associated with the level of initial- (ISR) and final-state radiation (FSR) are estimated by variations of α_S in the A14 tune [58] and variations of the renormalization scale for FSR branchings, respectively. The matrix element-parton shower interface uncertainty is assessed through a variation of the $p_{\mathrm{T}}^{\mathrm{hard}}$ parameter that regulates how the radiation phase space of the parton shower is determined, following the prescription in Ref. [92]. Interference effects between $t\bar{t}$ and Wt processes are evaluated through diagram subtraction/removal scheme comparisons [93].

Similarly, uncertainties in the signal predictions from scale and PDF variations were evaluated using generator-level reweighting, focusing on $m_{\ell j}$ spectrum distortions in both the SR-1L and SR-2L regions. These uncertainties were found to have a negligible impact on the results and were therefore neglected.

As seen in Figure 7, the dominant sources of systematic uncertainties vary depending on the channel and signal region. In the SR-1L selections of the e + light-jet and $e + b$-jet channels, the leading uncertainty arises from the estimate of backgrounds with FNP electrons. Other major experimental uncertainties are associated with the jet energy scale and resolution, as well as the b-jet identification efficiency in the $e + b$-jet and $\mu + b$-jet channels. Among the modelling uncertainties, the most significant contributions come from QCD scale variations and electroweak corrections to the V+jets backgrounds.

8 Results

Observed data in the CRs, VRs, and SRs are compared with the SM predictions using a profile likelihood method [94]. The statistical model is constructed using the `cabinetry` [95] package, which interfaces with `pyhf` [96], a Python-based implementation of the HistFactory [97] template. Parameters of interest, such as the signal strength, along with other floating parameters like normalisation factors, are determined via a maximum-likelihood fit to data. In each region, the expected event yield is modelled as the sum of contributions from the individual physics processes (samples). The predicted rate for each sample may depend on a set of free parameters $\boldsymbol{\psi}$ such as normalisation factors and the signal strength, and a set of constrained nuisance parameters $\boldsymbol{\theta}$, which encode the effect of systematic uncertainties.

The probability density function for bin b in region r is modelled as a Poisson distribution, $\mathrm{Pois}(n_{rb} \mid \nu_{rb}(\boldsymbol{\psi}, \boldsymbol{\theta}))$, where n_{rb} is the observed number of events and $\nu_{rb}(\boldsymbol{\psi}, \boldsymbol{\theta})$ is the predicted event yield. To account for systematic uncertainties, additional constraint terms are introduced, which control the allowed deviations of the nuisance parameters from their nominal values. These constraints are interpreted as auxiliary measurements, with associated global observables $\boldsymbol{a}$, such that the full set of observations is denoted by $\boldsymbol{x} = (\boldsymbol{n}, \boldsymbol{a})$, where $\boldsymbol{n} = n_{rb}$ represents the set of observed yields across all bins and regions. The full likelihood function is then constructed as the product of the Poisson likelihoods for each bin and region and the constraint terms for each nuisance parameter:

$$L(\boldsymbol{x} \mid \boldsymbol{\psi}, \boldsymbol{\theta}) = \prod_{r \in \text{regions}} \prod_{b \in \text{bins}} \mathrm{Pois}(n_{rb} \mid \nu_{rb}(\boldsymbol{\psi}, \boldsymbol{\theta})) \prod_{\theta \in \boldsymbol{\theta}} f_\theta(a_\theta \mid \theta)\,, \tag{1}$$

where $f_\theta(a_\theta \mid \theta)$ is the constraint term associated with nuisance parameter θ, typically modelled as a Gaussian distribution centred on the nominal value with a width reflecting the corresponding uncertainty.

Different fit configurations are employed to derive the results presented below. All fits are performed independently for each channel and for the validation of the FNP background estimate, and generally also individually for the Run 2 and Run 3 datasets.

The first configuration, referred to as *CR-only fit*, is a background-only fit to the CR-W and CR-Z regions to validate the background estimates by extracting normalisation factors μ_W and μ_Z for the W+jets and Z+jets backgrounds, respectively. In the $e + b$-jet and $\mu + b$-jet channels, the CR-T-low and CR-T-high regions are additionally included to extract normalisation factors $\mu_\mathrm{top}^{\text{low-}m_{\ell j}}$ and $\mu_\mathrm{top}^{\text{high-}m_{\ell j}}$ for top backgrounds in the low- and high-$m_{\ell j}$ regimes, respectively. The results of the CR-only fit are extrapolated to the corresponding VRs to compare the post-fit SM predictions with the observed data. For the validation of the FNP estimate, a separate CR-only fit is performed using only the CR-W-fake region to derive predictions in VR-fake, see Section 6 This CR is not included in any other fit.

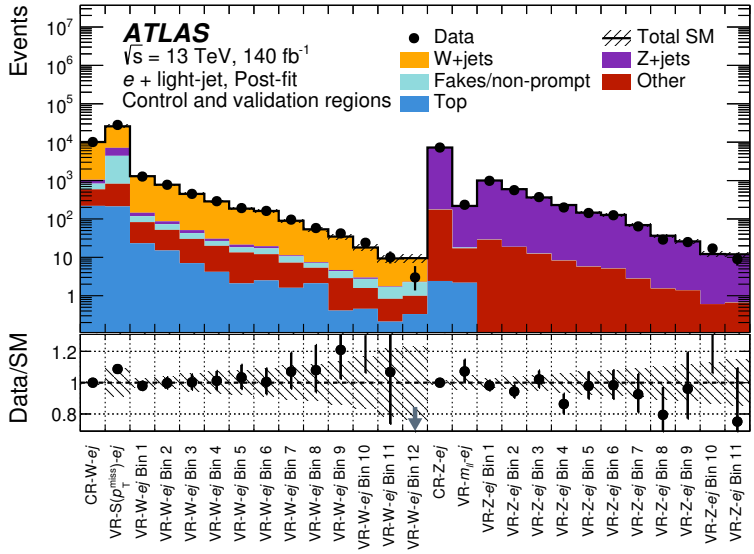
The second configuration, referred to as *CR+SR fit*, simultaneously fits the $m_{\ell j}$ distributions in SR-1L and SR-2L along with the associated CRs. This configuration probes for potential BSM contributions while constraining the background components, and is also used to evaluate the compatibility of the observed data with specific signal hypotheses. The normalisation factors derived in this configuration are found to be compatible with the ones from a CR-only fit.

A third configuration, the *Run 2+3 combination*, maximizes sensitivity to a given signal model by fitting the $m_{\ell j}$ spectra in the SRs of both Run 2 and Run 3 simultaneously. In this configuration, all CRs and SRs from both data-taking periods are included, with independent normalisation factors for the backgrounds in Run 2 and Run 3. All nuisance parameters are treated as uncorrelated between the two data-taking periods, except for most of the JES and JER variations, which are derived from a shared set of in situ calibrations. Treating all nuisance parameters as fully correlated between Run 2 and Run 3 was not found to have a notable impact on the final sensitivity reach of the search.

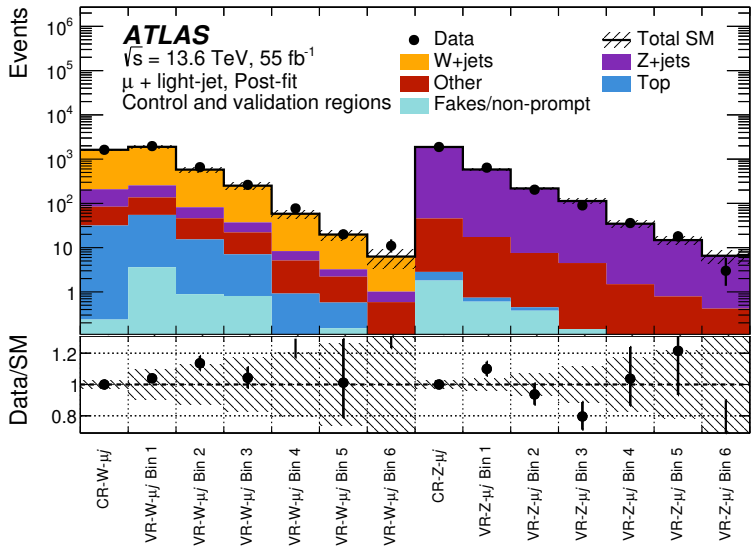
8.1 Results for control and validation regions

The agreement between observed data and SM predictions in the e + light-jet VRs after a fit to CR-W-ej and CR-Z-ej for Run 2 is shown in Figure 8(a). Overall, the data are consistent with the SM predictions within the associated uncertainties. A notable deficit is observed in the last bin of VR-W-ej in Run 2, which is not reproduced in the corresponding Run 3 region and is therefore attributed to a statistical fluctuation. Overall, the observations support the robustness of the W+jets and Z+jets normalisation extrapolation over $m_{\ell j}$.

Similar conclusions are drawn from the CR-only fit results in the VRs of the μ + light-jet, $e + b$-jet, and $\mu + b$-jet channels. As an example, the Run 3 VR results for the μ + light-jet channel are shown in Figure 8(b), while Figure 9 presents the corresponding VRs for the $e + b$-jet and $\mu + b$-jet channels. The data generally agree with the SM predictions within uncertainties, and no consistent mis-modelling is observed between Run 2 and Run 3. Table 8 reports the extracted normalisation factors for all channels.

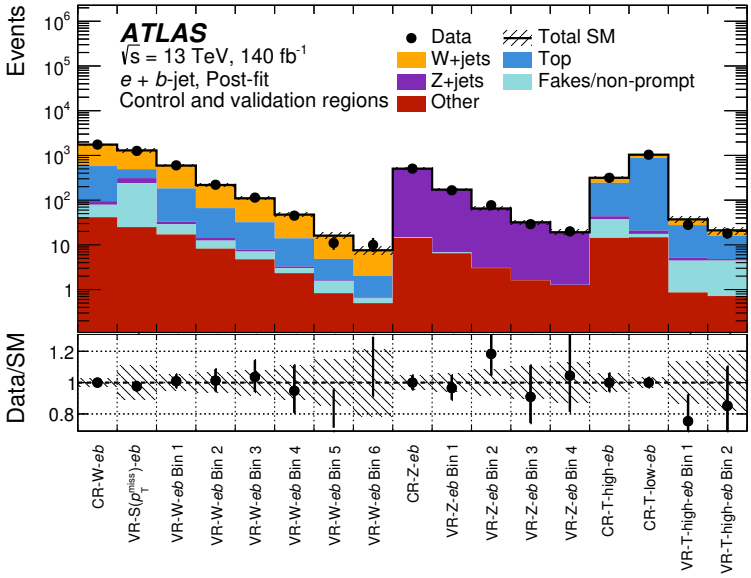


(a)

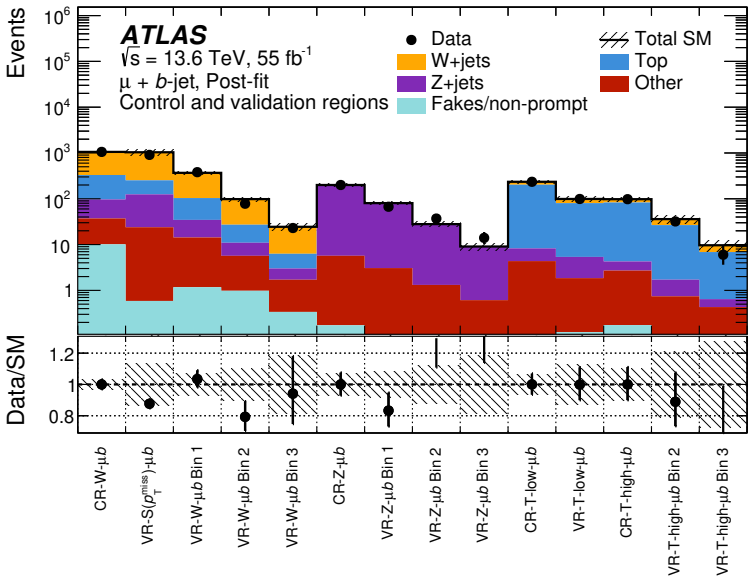


(b)

Figure 8: Data (dots) and post-fit SM predictions (histograms) in the VRs for (a) Run 2 of the e + light-jet and (b) Run 3 of the μ + light-jet channels obtained by a CR-only fit. The lower panel shows the ratio of observed data to the total post-fit SM prediction. Uncertainties in the background estimates include both the statistical and systematic uncertainties, with correlations between uncertainties taken into account. A grey arrow in the lower panel indicates a data point outside the vertical range shown.



(a)



(b)

Figure 9: Data (dots) and post-fit SM predictions (histograms) in the VRs for (a) Run 2 of the e + b-jet and (b) Run 3 of the μ + b-jet channels obtained by a CR-only fit. The lower panel shows the ratio of observed data to the total post-fit SM prediction. Uncertainties in the background estimates include both the statistical and systematic uncertainties, with correlations between uncertainties taken into account.

Table 8: Normalisation factors μ_W, μ_Z, $\mu_{top}^{\text{high-}m_{\ell j}}$ and $\mu_{top}^{\text{low-}m_{\ell j}}$ for the W+jets, Z+jets and top backgrounds, respectively, extracted from CR-only fits using the respective CRs of each channel. The associated uncertainties include all statistical and systematic contributions.

Norm. factor	e + light-jet		μ + light-jet		e + b-jet		μ + b-jet	
	Run 2	Run 3	Run 2	Run 3	Run 2	Run 3	Run 2	Run 3
μ_W	1.08 ± 0.21	1.13 ± 0.25	1.04 ± 0.18	1.05 ± 0.21	1.21 ± 0.28	1.22 ± 0.33	1.24 ± 0.27	1.24 ± 0.31
μ_Z	1.14 ± 0.25	1.20 ± 0.23	1.08 ± 0.20	1.20 ± 0.22	1.24 ± 0.28	1.19 ± 0.26	1.11 ± 0.23	1.31 ± 0.29
$\mu_{top}^{\text{high-}m_{\ell j}}$	–		–		0.74 ± 0.17	0.79 ± 0.26	0.55 ± 0.13	0.71 ± 0.27
$\mu_{top}^{\text{low-}m_{\ell j}}$	–		–		0.75 ± 0.12	0.77 ± 0.23	0.71 ± 0.12	0.69 ± 0.21

8.2 Results for signal regions

The observed and predicted $m_{\ell j}$ distributions in SR-1L-ej and SR-2L-ej of the e + light-jet channel for Run 2 and Run 3 are shown in Figure 10. The SM predictions agree well with the data within their uncertainties, and no significant excess of events is observed. Among the selections, SR-2L provides the strongest sensitivity to the LQ signals of interest due to its much higher signal to background ratio, as illustrated by the overlaid nominal predictions of two example signal models in Figure 10.

Figure 11 presents the results of SR-1L-μj and SR-2L-μj of the μ + light-jet channel for both Run 2 and Run 3. The data agree well with the SM predictions within uncertainties in the SR-1L-μj regions. Deficits of approximately 50% are observed in the last two bins of SR-2L-μj in Run 2, although compatible with the predictions within uncertainties.

The results of SR-1L-eb and SR-2L-eb of the e + b-jet channel for both data-taking periods are shown in Figure 12, while Figure 13 presents the corresponding SRs, SR-1L-eb and SR-2L-eb, of the μ + b-jet channel. In both channels no significant excesses are observed and the SM predictions generally agree with the data within uncertainties.

To quantitatively probe the observed $m_{\ell j}$ spectra in each channel for a new-physics signal, the p_0 value of the background-only hypothesis is evaluated relative to each signal model and translated into a discovery significance. No deviations above the 1σ level are observed in any channel.

8.3 Interpretations

In the absence of any significant indications for new-physics contributions in the SRs, the observations are interpreted as constraints on minimal LQ production models featuring $\tilde{S}_1$ with either y_{de}, $y_{s\mu}$, y_{be}, or $y_{b\mu}$ couplings as benchmark scenarios. To evaluate the compatibility of the observed data with a given $\tilde{S}_1$ model, a combined fit to the Run-2 and Run-3 datasets is performed, effectively fitting the $m_{\ell j}$ spectra from both data-taking periods simultaneously. In these fits, the signal strength is a free parameter and coherently scales the nominal signal predictions across all regions, accounting for the difference of the $\tilde{S}_1$ production cross-sections between Run 2 and Run 3. The CL_s prescription [98] is used to perform hypothesis tests and set exclusion limits at 95% confidence level (CL), employing the asymptotic approximation [94] for the calculation of the CL_s values. The results were cross-checked using pseudo experiments and found to agree within 10%. In each channel the constraints are dominated by the Run-2 results due to the larger

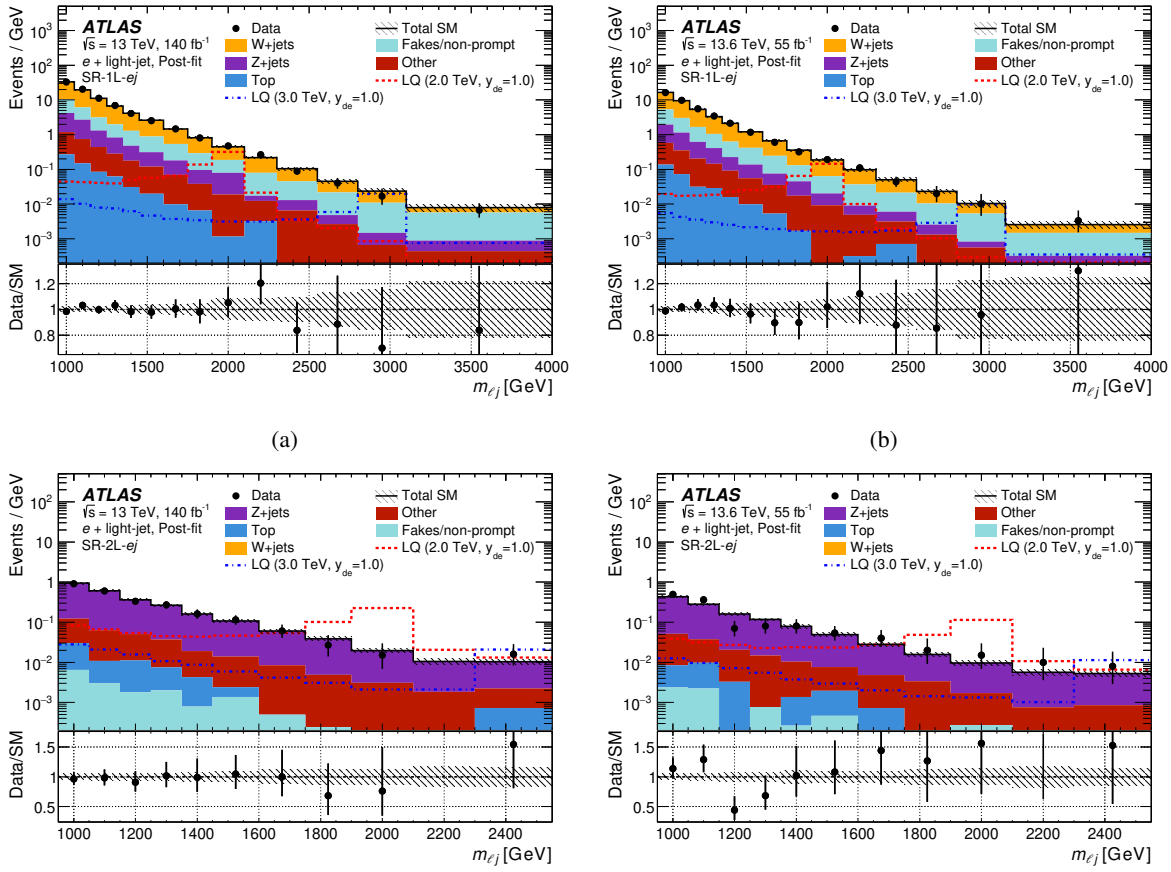


Figure 10: Data (dots) and post-fit SM distribution (histograms) of $m_{\ell j}$ in (a, b) SR-1L-ej and (c, d) SR-2L-ej of the e + light-jet channel obtained by a CR+SR background-only fit for Run 2 and Run 3, respectively. The lower panel shows the ratio of observed data to the total post-fit SM prediction. The last bin includes the overflow. Uncertainties in the background estimates include both the statistical and systematic uncertainties, with correlations between uncertainties taken into account. The dashed lines show the predicted yields for two benchmark signal models corresponding to $\tilde{S}_1(m, y_{de}) = (2.0\ \text{TeV}, 1.0)$ and $\tilde{S}_1(m, y_{de}) = (3.0\ \text{TeV}, 1.0)$, respectively.

dataset size and the SR-2L regions which are significantly more sensitive to the signal of interest than their respective SR-1L counterparts.

Figure 14 shows the observed and expected exclusion limits for the e + light-jet channel. The contours are presented in the $m(\tilde{S}_1)$–y_{de} plane, with couplings ranging from 0.1 to 1.0. In this minimal LQ model, $\tilde{S}_1$ masses up to approximately 3.4 TeV are excluded for a coupling value of $y_{de} = 1.0$. For couplings larger than roughly 0.25, this search surpasses the limits set by a previous ATLAS search for LQ pair production [13], which are independent of the coupling strength. Strong indirect constraints on y_{de} arise from weak charge measurements of protons and nuclei [10], which impose $y_{de} \leq 0.17 \frac{m(S)}{[\text{TeV}]}$, where $m(S)$ denotes the scalar LQ mass. The results from this search exceed those limits in a small region of parameter space below approximately 2.3 TeV. Although the weak charge constraints dominate across most of the parameter space, they may be relaxed or even vanish in scenarios with more than one LQ present in the mass range of interest [99], rendering the constraints from this search complementary.

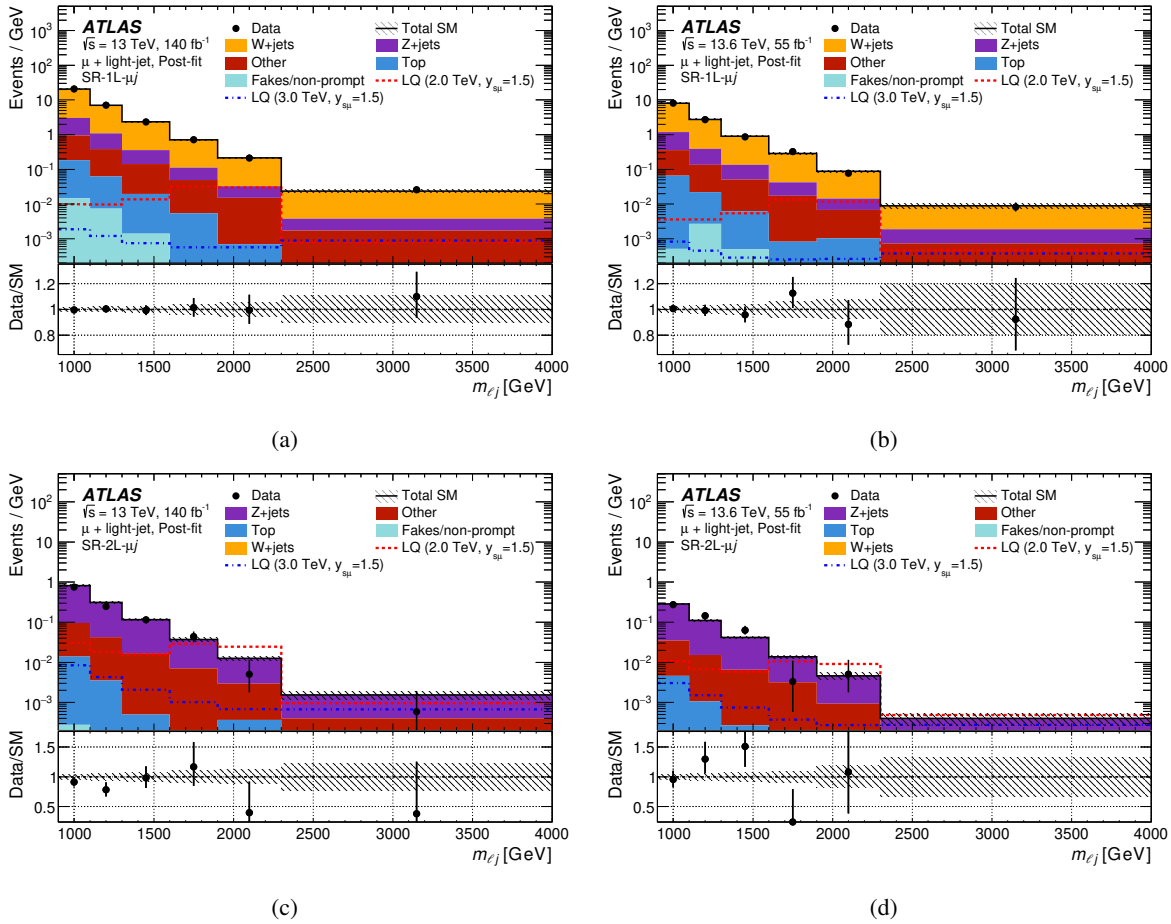


Figure 11: Data (dots) and post-fit SM distribution (histograms) of $m_{\ell j}$ in (a, b) SR-1L-μj and (c, d) SR-2L-μj of the μ + light-jet channel obtained by a CR+SR background-only fit for Run 2 and Run 3, respectively. The lower panel shows the ratio of observed data to the total post-fit SM prediction. The last bin includes the overflow. Uncertainties in the background estimates include both the statistical and systematic uncertainties, with correlations between uncertainties taken into account. The dashed lines show the predicted yields for two benchmark signal models corresponding to $\tilde{S}_1(m, y_{s\mu}) = (2.0\ \text{TeV}, 1.5)$ and $\tilde{S}_1(m, y_{s\mu}) = (3.0\ \text{TeV}, 1.5)$, respectively.

The observed and expected exclusion contours for the μ + light-jet channel are shown in Figure 15. The deficits observed in the highest $m_{\ell j}$ bins of SR-2L-μj for Run 2 shift the observed limits beyond the 1σ uncertainty band, though they are found to remain well within the 2σ band. $\tilde{S}_1$ masses up to approximately 4.3 TeV are excluded assuming coupling values of 3.5.

Figure 16 shows the observed and expected exclusion limits for the $e+b$-jet channel. The derived constraints on the $\tilde{S}_1$ mass depend again on the coupling and range up to 3.1 TeV for $y_{be} = 3.5$. The mild excess observed in the third $m_{\ell j}$ bin of SR-2L-eb in Run 2 slightly weakens the observed limit relative to the expected one for masses below approximately 2 TeV.

Exclusion contours for the $\mu + b$-jet channel are presented in Figure 17 where constraints on the $\tilde{S}_1$ mass extend up to 2.8 TeV at couplings of 3.5.

In summary, all channels improve upon existing ATLAS constraints for scalar LQ models at large coupling values—approximately above 0.25 in the e + light-jet channel, above 0.7 in the μ + light-jet channel and

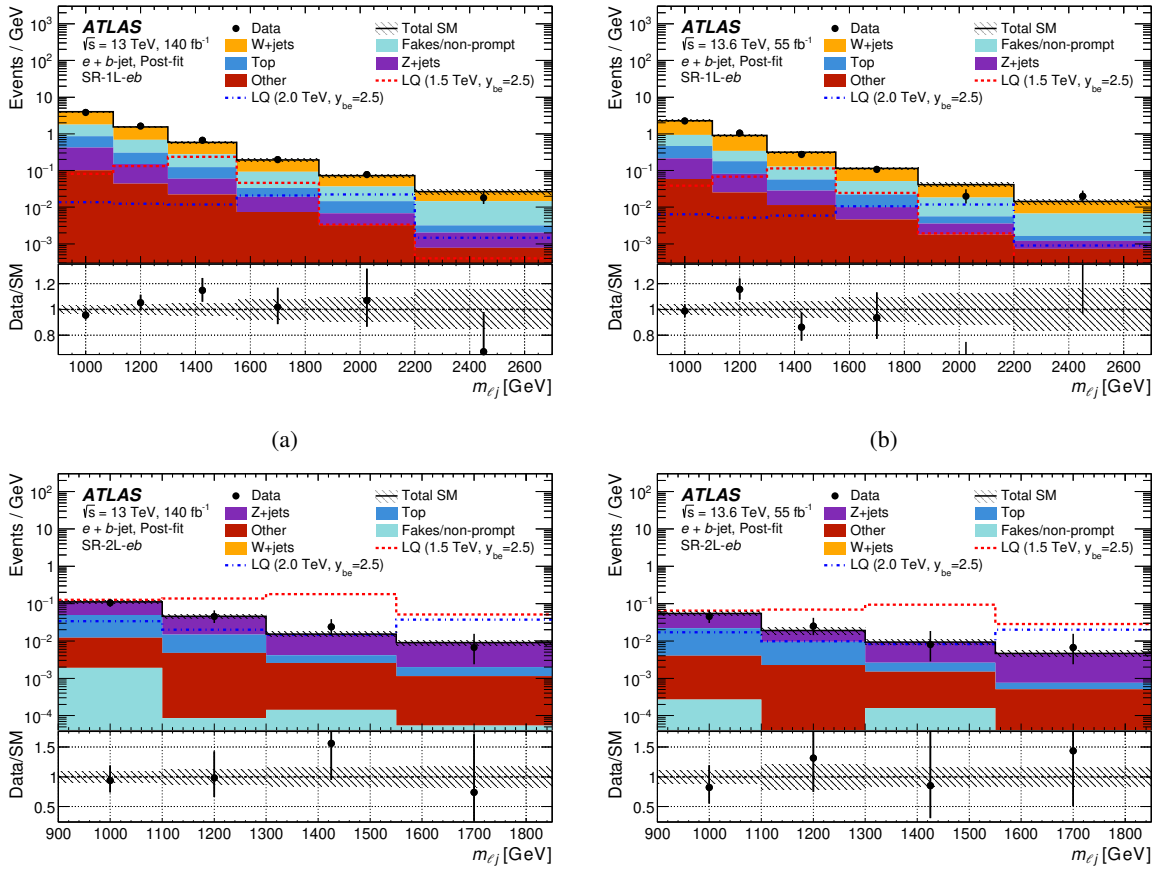


Figure 12: Data (dots) and post-fit SM distribution (histograms) of $m_{\ell j}$ in (a, b) SR-1L-eb and (c, d) SR-2L-eb of the $e+b$-jet channel obtained by a CR+SR background-only fit for Run 2 and Run 3, respectively. The lower panel shows the ratio of observed data to the total post-fit SM prediction. The last bin includes the overflow. Uncertainties in the background estimates include both the statistical and systematic uncertainties, with correlations between uncertainties taken into account. The dashed lines show the predicted yields for two benchmark signal models corresponding to $\tilde{S}_1(m, y_{be}) = (1.5\ \text{TeV}, 2.5)$ and $\tilde{S}_1(m, y_{be}) = (2.0\ \text{TeV}, 2.5)$, respectively.

above 1.0 in the other channels. At lower couplings, the LQ pair production searches remain more sensitive due to their independence from the LQ coupling strength.

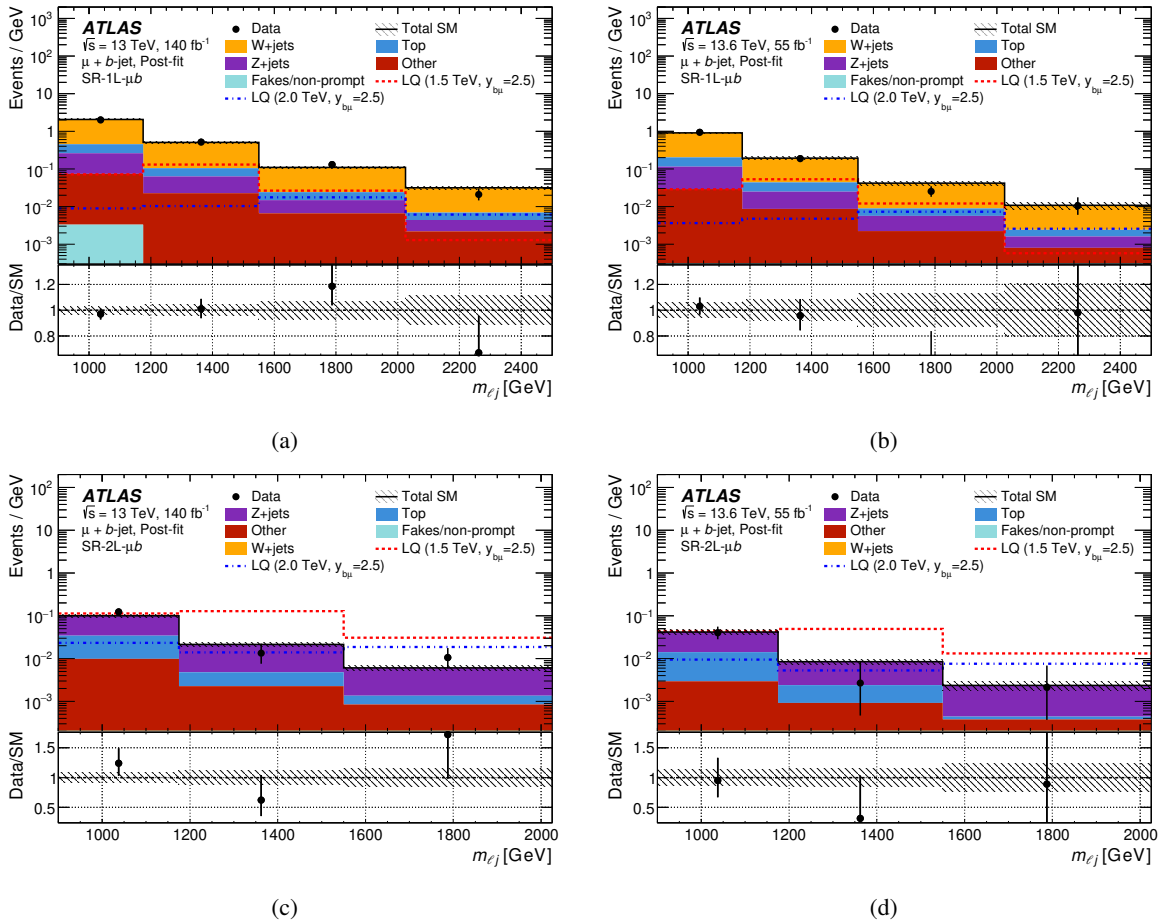


Figure 13: Data (dots) and post-fit SM distribution (histograms) of $m_{\ell j}$ in (a, b) SR-1L-μb and (c, d) SR-2L-μb of the $\mu + b$-jet channel obtained by a CR+SR background-only fit for Run 2 and Run 3, respectively. The lower panel shows the ratio of observed data to the total post-fit SM prediction. The last bin includes the overflow. Uncertainties in the background estimates include both the statistical and systematic uncertainties, with correlations between uncertainties taken into account. The dashed lines show the predicted yields for two benchmark signal models corresponding to $\tilde{S}_1(m, y_{b\mu}) = (1.5\ \text{TeV}, 1.5)$ and $\tilde{S}_1(m, y_{b\mu}) = (2.0\ \text{TeV}, 1.5)$, respectively.

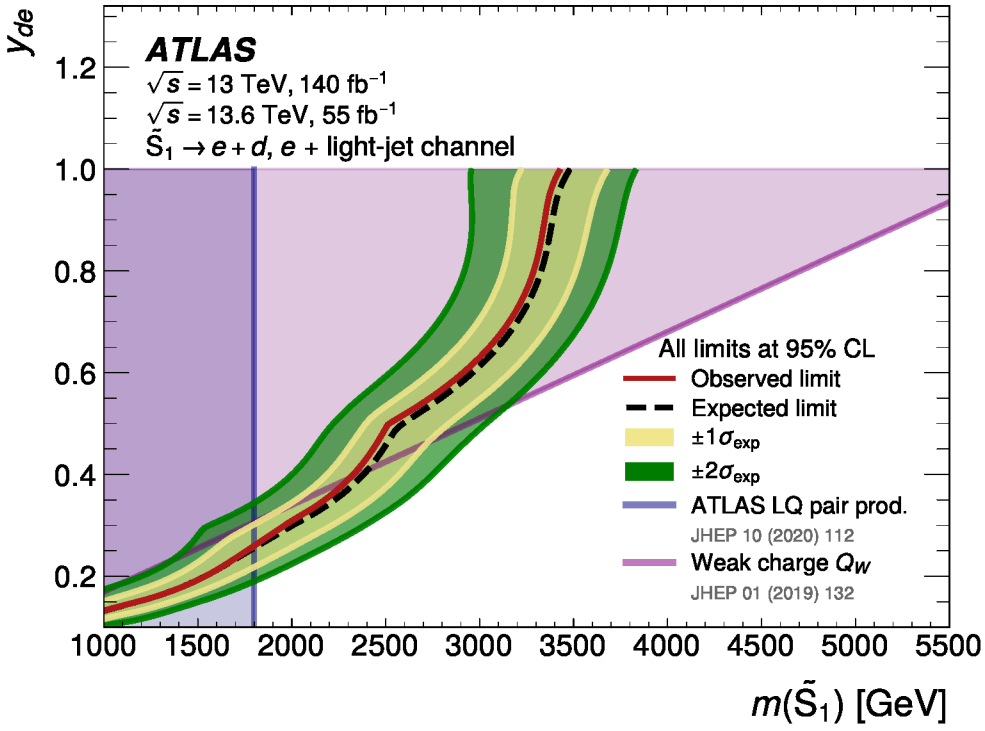


Figure 14: Exclusion limits for minimal models of $\tilde{S}_1$ production with only y_{de} being non-zero obtained from a simultaneous fit to SR-1L and SR-2L of the e + light-jet channel combining Run-2 and Run-3 data. All limits are computed at 95% CL and the observed (red solid lines) and expected (black dashed lines) exclusion limits are shown in the $m(\tilde{S}_1) - y_{de}$ plane. The observed exclusion should be interpreted as the region above the red line. The yellow inner (green outer) shaded band around the expected limits corresponds to the $\pm 1\,\sigma$ ($\pm 2\,\sigma$) variations of the expected limit, accounting for all uncertainties. The observed limit obtained from ATLAS searches for LQ pair production is also shown as dark blue line [13]. Constraints from weak charge measurements of protons and nuclei on y_{de} couplings derived by Ref. [10] are shown as light magenta line.

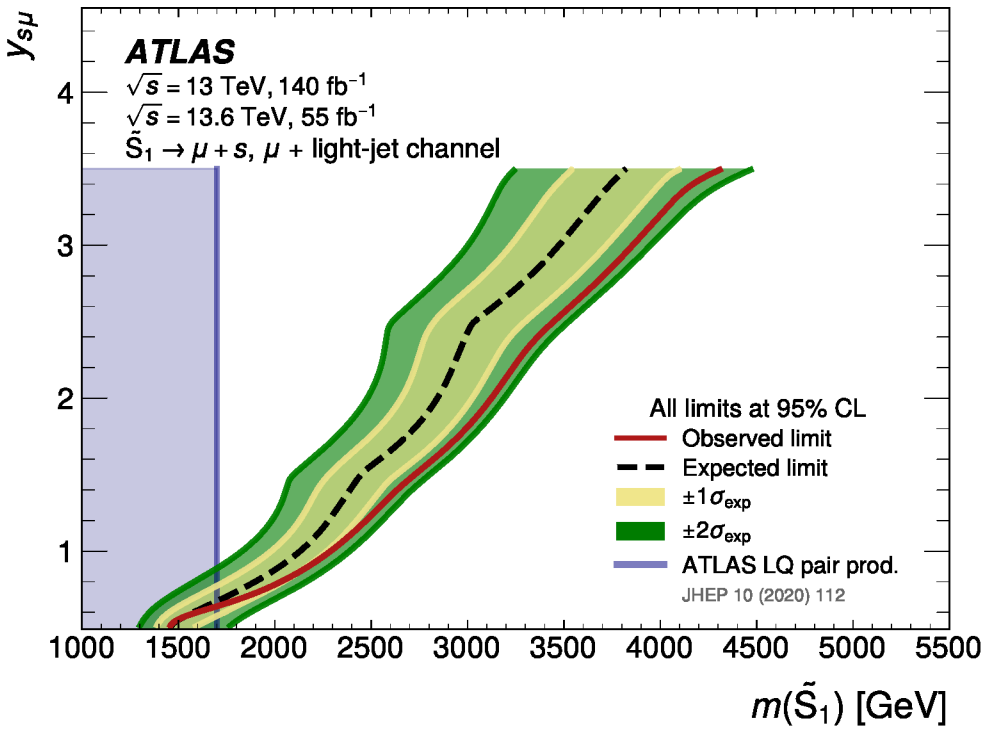


Figure 15: Exclusion limits for minimal models of $\tilde{S}_1$ production with only $y_{s\mu}$ being non-zero obtained from a simultaneous fit to SR-1L and SR-2L of the μ + light-jet channel combining Run-2 and Run-3 data. All limits are computed at 95% CL and the observed (red solid lines) and expected (black dashed lines) exclusion limits are shown in the $m(\tilde{S}_1) - y_{s\mu}$ plane. The observed exclusion should be interpreted as the region above the red line. The yellow inner (green outer) shaded band around the expected limits corresponds to the $\pm 1\,\sigma$ ($\pm 2\,\sigma$) variations of the expected limit, accounting for all uncertainties. The observed limit obtained from ATLAS searches for LQ pair production is also shown as dark blue line [13].

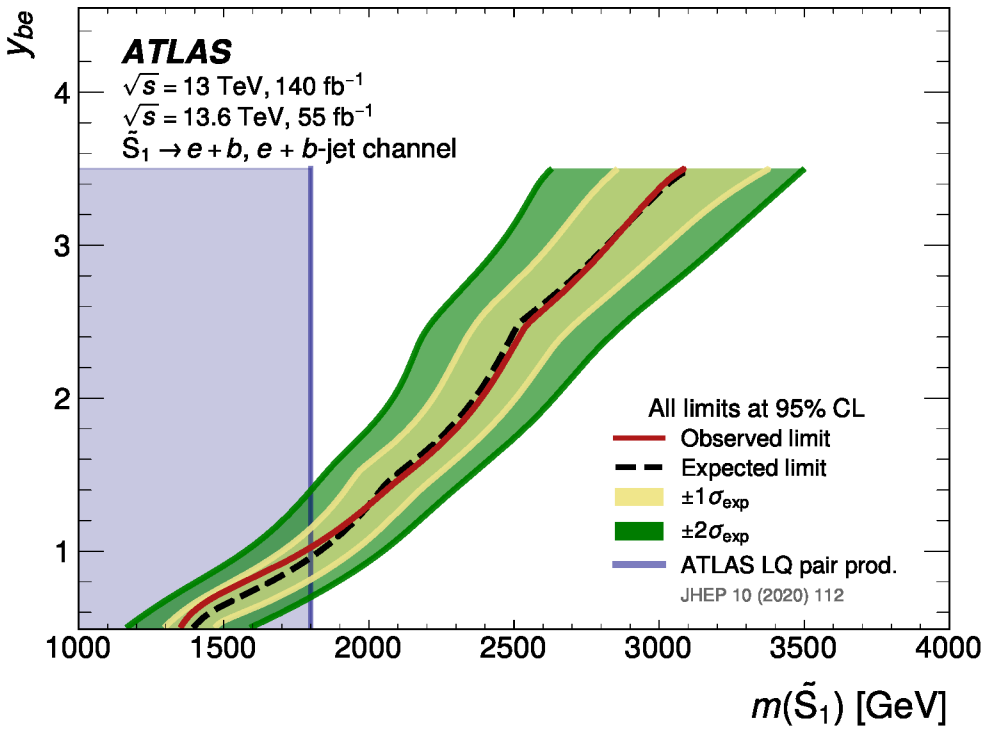


Figure 16: Exclusion limits for minimal models of $\tilde{S}_1$ production with only y_{be} being non-zero obtained from a simultaneous fit to SR-1L and SR-2L of the e + b-jet channel combining Run-2 and Run-3 data. All limits are computed at 95% CL and the observed (red solid lines) and expected (black dashed lines) exclusion limits are shown in the $m(\tilde{S}_1) - y_{be}$ plane. The observed exclusion should be interpreted as the region above the red line. The yellow inner (green outer) shaded band around the expected limits corresponds to the $\pm 1\,\sigma$ ($\pm 2\,\sigma$) variations of the expected limit, accounting for all uncertainties. The observed limit obtained from ATLAS searches for LQ pair production is also shown as dark blue line [13].

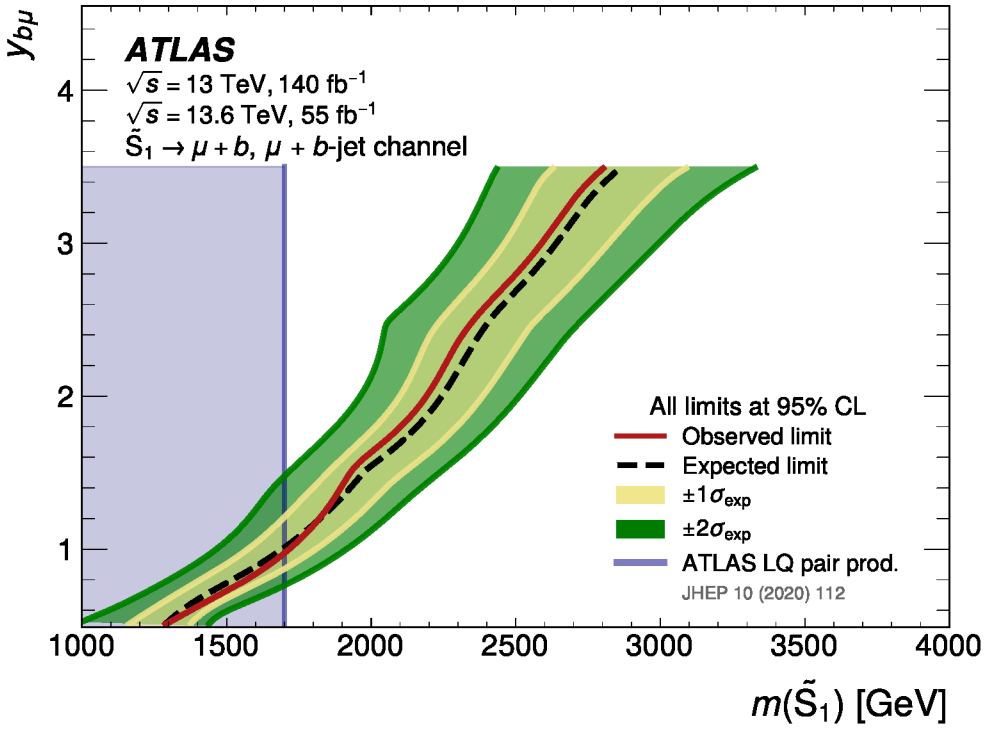


Figure 17: Exclusion limits for minimal models of $\tilde{S}_1$ production with only $y_{b\mu}$ being non-zero obtained from a simultaneous fit to SR-1L and SR-2L of the $\mu + b$-jet channel combining Run-2 and Run-3 data. All limits are computed at 95% CL and the observed (red solid lines) and expected (black dashed lines) exclusion limits are shown in the $m(\tilde{S}_1) - y_{b\mu}$ plane. The observed exclusion should be interpreted as the region above the red line. The yellow inner (green outer) shaded band around the expected limits corresponds to the $\pm 1\,\sigma$ ($\pm 2\,\sigma$) variations of the expected limit, accounting for all uncertainties. The observed limit obtained from ATLAS searches for LQ pair production is also shown as dark blue line [13].

9 Conclusion

This paper reports a search for resonantly produced LQs using proton–proton collision data from the full Run-2 (2015–2018) and partial Run-3 (2022–2023) datasets at the LHC. The analysis probes the s-channel production of LQs, which exploits the lepton content of the proton to yield a distinctive lepton+jet final state. The signal topology features a narrow $m_{\ell j}$ peak near the LQ mass, and the inclusion of 2-lepton+jet final states—motivated by NLO contributions to resonant LQ production—is crucial for maximizing the analysis sensitivity as it also provides acceptance for additional LQ production modes beyond the lepton- and photon-induced processes.

Four orthogonal channels—e + light-jet, μ + light-jet, e + b-jet, and μ + b-jet—are analysed, each with individually optimised SRs binned in $m_{\ell j}$ to maximize coverage across a broad range of LQ masses. Dominant SM backgrounds, including W+ jets and Z + jets, are constrained through dedicated CRs at low $m_{\ell j}$, with extrapolations validated in VRs. For b-jet channels, the top background is further controlled using two CRs spanning distinct kinematic regimes of $m_{\ell j}$, addressing observed dependencies in top processes modelling.

No significant excesses beyond SM predictions are observed in any of the SRs. The results are interpreted within a minimal $\tilde{S}_1$-model framework, where only a single LQ coupling is non-zero. Combining Run-2 and partial Run-3 data, the analysis achieves stringent exclusion limits on LQ masses: for electron+jet channels (e + light-jet and e + b-jet), LQ masses below 3.4 TeV (coupling $y_{de} = 1.0$) and 3.1 TeV ($y_{be} = 3.5$) are excluded at 95% CL. For muon+jet channels (μ+light-jet and μ+b-jet), exclusion reaches extend to 4.3 TeV ($y_{s\mu} = 3.5$) and 2.8 TeV ($y_{b\mu} = 3.5$), respectively. These limits surpass those from previous ATLAS searches for LQ pair production for sufficiently large couplings ($y_{de} \gtrsim 0.25, y_{s\mu} \gtrsim 0.7, y_{be,b\mu} \gtrsim 1.0$). By establishing robust exclusion limits for LQ masses and couplings beyond the reach of pair-production searches, this work underscores the critical role of resonant production as a complementary probe of TeV-scale LQ scenarios. The results also highlight the potential of early Run-3 data to constrain exotic physics, paving the way for future high-luminosity LHC analyses to explore uncharted parameter space in LQ models.

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