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# Search for pair production of first-generation scalar leptoquarks at $\sqrt{s} = 13$ TeV

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## Abstract

A search for the pair production of first-generation scalar leptoquarks is performed using proton-proton collision data recorded at 13 TeV center-of-mass energy with the CMS detector at the LHC. The data correspond to an integrated luminosity of  $35.9 \text{ fb}^{-1}$ . The leptoquarks are assumed to decay to a quark, and either an electron or a neutrino with branching fractions  $\beta$  and  $1 - \beta$ , respectively. The search targets the decay final states comprising two electrons, or one electron and large missing transverse momentum, along with two quarks that are detected as hadronic jets. First-generation scalar leptoquarks with masses below 1435 (1270) GeV are excluded for  $\beta = 1.0$  (0.5). These are the most stringent limits on the mass of first-generation scalar leptoquarks to date. The data are also interpreted to set exclusion limits in the context of an  $R$ -parity violating supersymmetric model, predicting promptly decaying top squarks with a similar dielectron final state.

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# 1 Introduction

The quark and lepton sectors of the standard model (SM) [1–3] are similar: both have the same number of generations composed of electroweak doublets. This could indicate the existence of an additional fundamental symmetry linking the two sectors, as proposed in many scenarios of physics beyond the SM. These include grand unified theories with symmetry groups  $SU(4)$  of the Pati–Salam model [4, 5],  $SU(5)$ ,  $SO(10)$ , and  $SU(15)$  [6–11]; technicolor [12–14]; superstring-inspired models [15]; and models exhibiting quark and lepton substructures [16]. A common feature of these models is the presence of a new class of bosons, called leptoquarks (LQs), that carry both lepton ( $L$ ) and baryon numbers ( $B$ ). In general, LQs have fractional electric charge and are color triplets under  $SU(3)_C$ . Their other properties, such as spin, weak isospin, and fermion number ( $3B + L$ ), are model dependent.

Direct searches for LQs at colliders are usually interpreted in the context of effective theories that impose constraints on their interactions. In order to ensure renormalizability, these interactions are required to respect SM group symmetries, restricting the couplings of the LQs to SM leptons and quarks only. A detailed account of LQs and their interactions can be found in Ref. [17]. Results from experiments sensitive to lepton number violation, flavor changing neutral currents, and proton decay allow the existence of three distinct generations of LQs with negligible intergenerational mixing for mass scales accessible at the CERN LHC [18, 19]. Indirect searches for new physics in rare B meson decays [20–24] by LHCb and Belle suggest a possible breakdown of lepton universality. These anomalies, if confirmed, could provide additional support for LQ-based models [25]. A comprehensive review of LQ phenomenology and experimental constraints on their properties is given in Ref. [26].

We search for the pair production of first-generation scalar LQs. The final state arising from each LQ decay comprises a quark that is detected as a hadronic jet, and either an electron or a large missing transverse momentum attributed to the presence of an undetected neutrino. For light-quark final states, the quark flavors cannot be determined from the observed jets. We assume the LQs decay only to  $e(\nu_e)$  and up or down quarks. The LQ decay is expressed in terms of a free parameter,  $\beta$ , which denotes the branching fraction to an electron and a quark. Consequently, the branching fraction of the decay to a neutrino and a quark is  $1 - \beta$ . For pair production of LQs, we consider two decay modes. The first arises when each LQ decays to an electron and a quark, having an overall branching fraction of  $\beta^2$ . In the second mode one LQ decays to an electron and a quark, and the other to a neutrino and a quark. This mode has a branching fraction of  $2\beta(1 - \beta)$ . We therefore utilize final states with either two high transverse momentum ( $p_T$ ) electrons and two high- $p_T$  jets, denoted as  $eejj$ ; or one high- $p_T$  electron, large missing transverse momentum, and two high- $p_T$  jets, denoted as  $e\nu jj$ .

Previous experiments at the LEP [27], HERA [28, 29], and Tevatron [30, 31] colliders have searched for LQ production and placed lower limits of several hundreds of GeV on allowed LQ masses ( $m_{LQ}$ ) at 95% confidence level (CL). The CMS experiment at the LHC has extended the limits on pair production of first-generation scalar LQs using proton-proton (pp) collision data recorded during 2012 at a center-of-mass energy of  $\sqrt{s} = 8$  TeV. Based on a sample corresponding to an integrated luminosity of  $19.7 \text{ fb}^{-1}$ , the lower limit obtained on  $m_{LQ}$  was 1010 (850) GeV for  $\beta = 1.0$  (0.5) [32]. The CMS Collaboration has also published results on a search for singly produced LQs with the final states of either two electrons and one jet, or two muons and one jet [33]. Recently, using a data set of  $3.2 \text{ fb}^{-1}$  collected at  $\sqrt{s} = 13$  TeV, the ATLAS experiment has placed a lower limit on  $m_{LQ}$  of 1100 GeV [34] for  $\beta = 1.0$ .

This analysis is based on data recorded in pp collisions at  $\sqrt{s} = 13$  TeV with the CMS detector,

corresponding to an integrated luminosity of  $35.9 \text{ fb}^{-1}$ . At LHC energies, the pair production of LQs would mainly proceed via gluon-gluon fusion with a smaller contribution from quark-antiquark annihilation. The corresponding Feynman diagrams are shown in Fig. 1. The production cross section as a function of  $m_{\text{LQ}}$  has been calculated at next-to-leading order (NLO) in perturbation theory [35]. At the LHC, the LQ-lepton-quark Yukawa coupling has negligible effect on the production rate for promptly decaying LQs, which are the focus of our search.

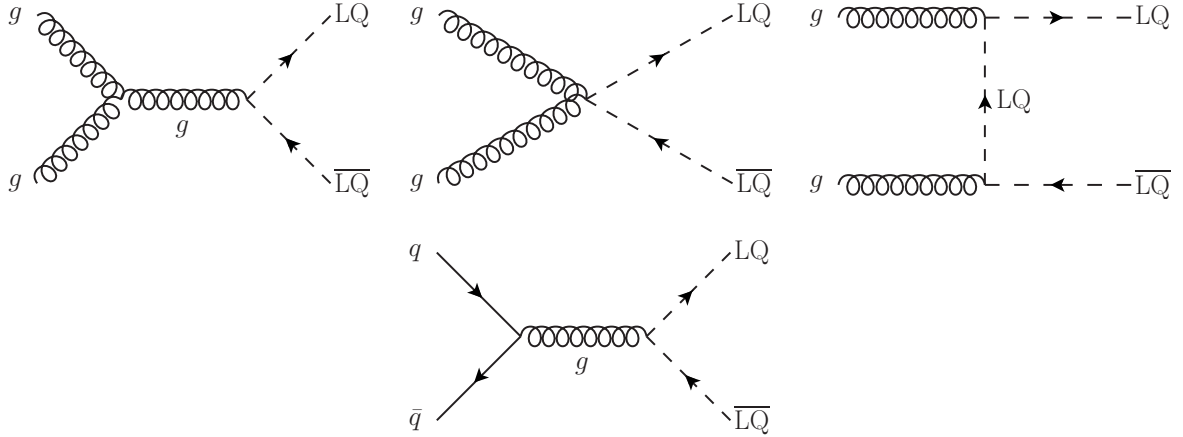


Figure 1: Leading order Feynman diagrams for the scalar LQ pair production channels at the LHC.

The paper is organized as follows. Section 2 introduces the CMS detector, and Section 3 describes the data and simulated samples used in the search. The core of the analysis in terms of event reconstruction and selection is discussed in Section 4, while the background estimation is presented in Section 5. Section 6 deals with the systematic uncertainties affecting this analysis. Sections 7 and 8 describe the results of the LQ search and its interpretation in an exotic scenario of supersymmetry, respectively. We conclude with a summary of the main results in Section 9.

## 2 The CMS detector

The key feature of the CMS apparatus is a superconducting solenoid of 6 m diameter, providing a magnetic field of 3.8 T. Within the solenoid volume lie a silicon pixel and microstrip tracker, a lead-tungstate crystal electromagnetic calorimeter (ECAL), and a brass-scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity ( $\eta$ ) coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. The first level of the trigger system [36], composed of custom electronics, uses information from the calorimeters and muon detectors to select the most interesting events in an interval of less than  $4 \mu\text{s}$ . The high-level trigger processor farm further reduces the event rate from around 100 to 1 kHz, before data storage. A detailed description of the CMS detector, along with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [37].

## 3 Data and simulated samples

Events are selected using a combination of triggers requiring either a single electron or a single photon. Electron candidates are required to have a minimum  $p_{\text{T}}$  of 27 (115) GeV for the low (high) threshold trigger. Each of these triggers examines clusters of energy deposited in

the ECAL that are matched to tracks reconstructed within a range  $|\eta| < 2.5$ . Cluster shape requirements as well as calorimetric and track-based isolation (only for the low threshold trigger) are also applied. By comparison, the photon trigger requires  $p_T > 175$  GeV without any requirements on track-cluster matching, cluster shape, or isolation. The latter three criteria are applied to electron triggers to reduce background rates and are not necessary at high  $p_T$ . Therefore, the single photon and electron triggers are combined to improve efficiency at high electron  $p_T$ . Events selected using other single-photon triggers with lower thresholds are used for determining the multijet background.

Monte Carlo (MC) simulation samples of scalar LQ signals are generated using PYTHIA version 8.212 [38] at leading order (LO) with the NNPDF2.3LO parton distribution function (PDF) set [39]. Samples are generated for  $m_{LQ}$  ranging from 200 to 2000 GeV in 50 GeV steps. The LQ is assumed to have quantum numbers corresponding to the combination of an electron ( $L = 1$ ) and an up quark ( $B = 1/3$ ), implying it has an electric charge of  $-1/3$ . The cross sections are normalized to the values calculated at NLO [35, 40] using the CTEQ6L1 PDF set [41].

The main backgrounds for searches in the  $eejj$  and  $evjj$  channels include Drell–Yan ( $Z/\gamma^*$ ) production with jets, top quark pair production ( $t\bar{t}$ ), single top quark and diboson ( $VV = WW, WZ$ , or  $ZZ$ ) production. Additional background contributions arise from  $W$ +jets,  $\gamma$ +jets, and multijet production, where jets are misidentified as electrons. The  $t\bar{t}$  background in the  $eejj$  channel as well as the multijet background in both channels are estimated from data, while MC simulated events are used to calculate all other backgrounds. The  $Z/\gamma^*$ +jets,  $W$ +jets, and  $VV$  samples are generated at next to leading order (NLO) with MADGRAPH5\_aMC@NLO version 2.3.3 using the FxFx merging method [42, 43]. Both  $t\bar{t}$  and single top quark events are generated at NLO using MADGRAPH5\_aMC@NLO, and POWHEG v2 complemented with MADSPIN [44], except for single top quark production in association with a  $W$  boson, where events are generated with POWHEG v1 at NLO [45–50], and  $s$ -channel single top quark production, where MADGRAPH5\_aMC@NLO at NLO is used. The  $\gamma$ +jets events are generated with MADGRAPH5\_aMC@NLO at LO with MLM merging [51]. The NNPDF3.0 at NLO [52] PDF set is used, except for  $\gamma$ +jets events that are generated using the LO PDF set.

The  $W$ +jets and  $Z/\gamma^*$ +jets samples are normalized to next-to-NLO (NNLO) inclusive cross sections calculated with FEWZ versions 3.1 and 3.1.b2, respectively [53]. Single top quark samples are normalized to NLO inclusive cross sections [54, 55], except for the  $tW$  production, where the NNLO calculations of Refs. [56] are used. The calculations from Refs. [57–63] with TOP++2.0 are used to normalize the  $t\bar{t}$  sample at NNLO in quantum chromodynamics (QCD) including resummation of the next-to-next-to-leading-logarithmic soft gluon terms.

PYTHIA 8.212 with the CUETP8M1 underlying event tune [64] is used for hadronization and fragmentation in all simulated samples, with the exception of a dedicated tune used for the  $t\bar{t}$  sample [65]. All samples include an overlay of minimum bias events (pileup), generated with an approximate distribution for the number of additional pp interactions expected within the same or nearby bunch crossings, and reweighted to match the distribution observed in data. In all cases, the GEANT4 software v.10.00.p02 [66, 67] is used to simulate the response of the CMS detector.

## 4 Event reconstruction and selection

A particle-flow (PF) algorithm [68] aims to reconstruct and identify each individual particle in a given event, by optimally combining information from the various elements of the CMS detector. The energy of photons is directly obtained from the ECAL measurement. On the other

hand, the energy of electrons is determined from a combination of their momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL clusters, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the associated track. The momentum of muons is obtained from the curvature of the corresponding track. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for zero suppression effects as well as for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energy.

Electrons are identified by spatially matching a reconstructed charged-particle track to a cluster of energy deposits in the ECAL. The ECAL cluster is required to have longitudinal and transverse profiles compatible with those expected from an electromagnetic shower. Electrons used in this analysis are required to have  $p_T > 50 \text{ GeV}$  and  $|\eta| < 2.5$ , excluding the transition regions between barrel and endcap detectors  $1.4442 < |\eta| < 1.5660$ . Additional selection criteria are applied to electron candidates in order to reduce backgrounds while maintaining high efficiency for identification of electrons with large  $p_T$  [69]. The absolute difference in  $\eta$  between the ECAL cluster seed and the matched track is required to be less than 0.004 (0.006) in the barrel (endcap), and the corresponding quantity in the azimuthal angle,  $\phi$ , must be less than 0.06 rad. Leptons resulting from the decay of LQs are expected to be isolated from hadronic activity in the event. Requirements are therefore applied based on calorimeter energy deposits and tracks in the vicinity of electron candidates. The scalar sum of  $p_T$  associated with calorimeter clusters in a cone of radius  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$  centered on the electron candidate must be less than 3% of the electron  $p_T$ . A correction to the isolation sum accounts for contributions from pileup interactions. The track-based isolation, calculated as the scalar  $p_T$  sum of all tracks in the cone defined above, must be less than 5 GeV to reduce misidentification of jets as electrons. At most one layer of the pixel detector may have missing hits along the trajectory of the matched track. The track must also be compatible with originating from the primary pp interaction vertex, which is taken to be the reconstructed vertex with the largest value of summed physics-object  $p_T^2$ . Here the physics objects are the jets, reconstructed using the algorithm [70, 71] with the tracks assigned to the vertex as inputs, and the negative vector sum of the  $p_T$  of those jets. To correct for the possible difference of electron reconstruction and identification efficiencies between collision and simulated data, appropriate corrections or scale factors are applied to the simulated samples.

Muons are used in defining a control region to estimate the  $t\bar{t}$  background contribution. They are identified as tracks in the central tracker consistent with either a track or several hits in the muon system [72]. These muon candidates must have  $p_T > 35 \text{ GeV}$  and  $|\eta| < 2.4$ , and are required to pass a series of identification criteria designed for high- $p_T$  muons as follows. Segments in at least two muon stations must be geometrically matched to a track in the central tracker, with at least one hit from a muon chamber included in the muon track fit. In order to reject muons from decays in flight and increase momentum measurement precision, at least five tracker layers must have hits associated with the muon, and there must be at least one hit in the pixel detector. Isolation is imposed by requiring the  $p_T$  sum of tracks in a cone of  $\Delta R = 0.3$  (excluding the muon itself) divided by the muon  $p_T$  to be less than 0.1. For rejection of cosmic ray muons, the transverse impact parameter of the muon track with respect to the primary vertex must be less than 2 mm and the longitudinal distance of the track formed from tracker system only to the primary vertex must be less than 5 mm. Finally, the relative uncertainty on the  $p_T$  measurement from the muon track must be less than 30%.

Jets are reconstructed using the anti- $k_T$  algorithm [70, 71] with a distance parameter of 0.4.

Their momentum is determined as the vectorial sum of all particle momenta in the jet, and is found in simulation to be within 5–10% of the true momentum [73] over the entire  $p_T$  spectrum and detector acceptance. Pileup interactions can contribute spurious tracks and calorimeter energy deposits to the jet momentum. To mitigate this effect, tracks identified to be originating from pileup vertices are discarded, while a correction [74] is applied to compensate for the remaining contributions. Jet energy corrections are extracted from simulation to compensate for differences between the true and reconstructed momenta of jets. In situ measurements of the momentum balance in dijet,  $\gamma$ +jets,  $Z/\gamma^*$ +jets, and multijet events are used to estimate and correct for any residual differences in jet energy scale between data and simulation [74]. Additional selection criteria are applied to all jets to remove those potentially affected by spurious energy deposits originating from instrumental effects or reconstruction failures [75]. Jets must have  $p_T > 50$  GeV and  $|\eta| < 2.4$ , and only jets separated from electrons or muons by  $\Delta R > 0.3$  are retained.

The missing transverse momentum ( $\vec{p}_T^{\text{miss}}$ ) is given by the negative vector sum of  $p_T$  of all PF candidates in the event. The magnitude of  $\vec{p}_T^{\text{miss}}$  is referred to as  $p_T^{\text{miss}}$ .

To identify b jets arising from top quark decays in the determination of the  $e\nu jj$  background control regions, the combined secondary vertex algorithm is used with the loose working point of Ref. [76]. Based on simulation, the corresponding b-jet identification efficiency is above 80% with a probability of 10% of misidentifying a light-flavor jet.

#### 4.1 The eejj channel

For the eejj analysis, we select events with at least two electrons and at least two jets passing the criteria described above. When additional objects satisfy these requirements, the two highest  $p_T$  electrons and jets are considered. Further, there should not be any muon fulfilling the requirements mentioned earlier in this section. The dielectron invariant mass  $m_{ee}$  is required to be greater than 50 GeV. The  $p_T$  of the dielectron system must be greater than 70 GeV. The scalar  $p_T$  sum over the electrons and two jets,  $S_T = p_T(e_1) + p_T(e_2) + p_T(j_1) + p_T(j_2)$ , must be at least 300 GeV. This initial selection is used for the determination of backgrounds in control regions, as explained in Section 5.

Final selections are then optimized by maximizing the Punzi criterion for observation of a signal at a significance of five standard deviations [77]. These selections are determined by examining three variables:  $m_{ee}$ ,  $S_T$ , and  $m_{ej}^{\text{min}}$ . The electron-jet pairing is chosen to minimize the difference in the invariant mass of the LQ candidates, and the quantity  $m_{ej}^{\text{min}}$  is defined as the smaller of the two masses. Thresholds for the three observables are varied independently, and the Punzi criterion is then calculated at each set of thresholds as well as for each  $m_{LQ}$  hypothesis. The optimized thresholds as a function of  $m_{LQ}$  are shown in Fig. 2 (left). For the  $m_{LQ}$  hypotheses above 1050 GeV the statistical uncertainty in the background becomes large and the thresholds for the 1050 GeV hypothesis are applied.

#### 4.2 The $e\nu jj$ channel

In the  $e\nu jj$  channel, we select events containing exactly one electron, at least two jets, and  $p_T^{\text{miss}} > 100$  GeV. The electron and jets must pass the aforementioned identification criteria. Events with isolated muons are rejected, applying the same criteria as for the eejj channel. The absolute difference in the angle between the  $\vec{p}_T^{\text{miss}}$  and the leading  $p_T$  jet,  $\Delta\phi(\vec{p}_T^{\text{miss}}, j_1)$ , is required to be larger than 0.5 rad. This helps reject events with  $p_T^{\text{miss}}$  arising primarily from instrumental effects. The  $\Delta\phi(\vec{p}_T^{\text{miss}}, e)$  must be greater than 0.8 rad for similar reasons. The  $p_T$  and transverse mass of the  $\vec{p}_T^{\text{miss}}$ -electron system must be greater than 70 and 50 GeV, respectively. Here and

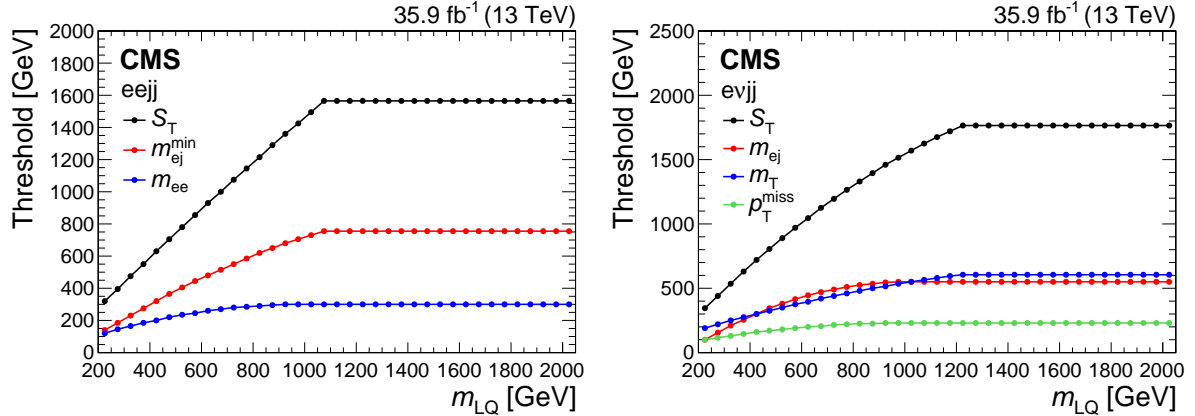


Figure 2: Optimized threshold values applied for the selection variables in the eejj (left) and evjj (right) channels as a function of  $m_{LQ}$ .

later, the transverse mass of a two-object system is given by  $m_T = \sqrt{2p_{T,1}p_{T,2}(1 - \cos \Delta\phi)}$ , with  $\Delta\phi$  being the angle between the  $p_T$  vectors of two objects, namely  $\vec{p}_T^{\text{miss}}$ , electron and jet. The  $m_T$  criterion helps suppress the W+jets contribution. Finally, selected events must have  $S_T > 300$  GeV, where  $S_T = p_T(e) + p_T^{\text{miss}} + p_T(j_1) + p_T(j_2)$ .

The selection criteria are then optimized in a similar fashion as for the eejj channel, except that four observables are considered for final selections at each  $m_{LQ}$  hypothesis:  $S_T$ ,  $m_T$  of the  $\vec{p}_T^{\text{miss}}$ -electron system,  $p_T^{\text{miss}}$ , and the electron-jet invariant mass  $m_{ej}$ . The  $\vec{p}_T^{\text{miss}}$ -jet and electron-jet pairing is chosen to minimize the difference in  $m_T$  between the two LQ candidates. The optimized thresholds as a function of  $m_{LQ}$  are shown in Fig. 2 (right). For the  $m_{LQ}$  hypotheses above 1200 GeV, the thresholds for the 1200 GeV hypothesis are used owing to the statistical uncertainty in the background becoming large, as for the eejj channel.

## 5 Background estimation

The SM processes that produce electrons and jets can have final states similar to those of an LQ signal and are therefore considered as backgrounds for this search. These include dilepton events from  $Z/\gamma^*$ +jets,  $t\bar{t}$ , and  $VV$ ; single top quark production; and W+jets. Another background arises from multijet production in which at least one jet is misidentified as an electron.

The major backgrounds in the eejj channel are  $Z/\gamma^*$ +jets and  $t\bar{t}$  production. The  $Z/\gamma^*$ +jets background is estimated from simulation and normalized to the data in a control region that comprises the initial selection plus a window of  $80 < m_{ee} < 100$  GeV around the nominal Z boson mass; the latter criterion is applied to enrich the sample with  $Z/\gamma^*$ +jets events. The  $m_{ee}$  distribution is corrected for the presence of non- $Z/\gamma^*$ +jets events in the data control region using simulation. The resulting normalization factor applied to the  $Z/\gamma^*$ +jets simulated events is  $R_Z = 0.97 \pm 0.01$  (stat).

The contribution from  $t\bar{t}$  events containing two electrons is estimated using a control region in data, which consists of events containing one electron and one muon, to which all applicable eejj selection criteria are applied. Residual backgrounds from other processes are subtracted using simulated event samples. Corrections for the branching fractions between the two states as well as for the differences in electron/muon identification and isolation efficiencies and acceptances are determined using simulation. The difference in the trigger efficiency between the one- and two-electron final states is corrected by reweighting each event in the  $e\mu$  sample with the calculated efficiencies for the single electron final state.



After application of event selection requirements, the background contribution to the eej channel arising from single top quark production, W+jets, and VV is found to be small and is estimated from simulations.

The multijet background in the eej channel is estimated using control samples in data. The electron identification requirements for the calorimeter shower profile and track-cluster matching are relaxed to define a loose selection. The events are required to have exactly one loose electron, at least two jets, and low  $p_T^{\text{miss}} (< 100 \text{ GeV})$ . This sample is dominated by QCD multijet events. The probability that an electron candidate passing loose requirements also satisfies the electron identification and isolation criteria used in the analysis is measured as a function of the candidate  $p_T$  and  $\eta$ . The distribution of multijet events in the eej channel following final selections is obtained by applying this probability twice to an event sample with two electrons passing loose electron requirements, and two or more jets that satisfy all the requirements of the signal selection. The normalization is obtained by scaling the weighted multijet sample to an orthogonal control region defined by inverting track-isolation requirement for electrons.

Distributions of kinematic variables for the eej channel in data, including those used in the final selections, have been studied at the initial selection level, and are found to agree with the background models within background estimation uncertainties. The distributions of  $S_T$ ,  $m_{ej}^{\text{min}}$ , and  $m_{ee}$  are shown in Fig. 3.

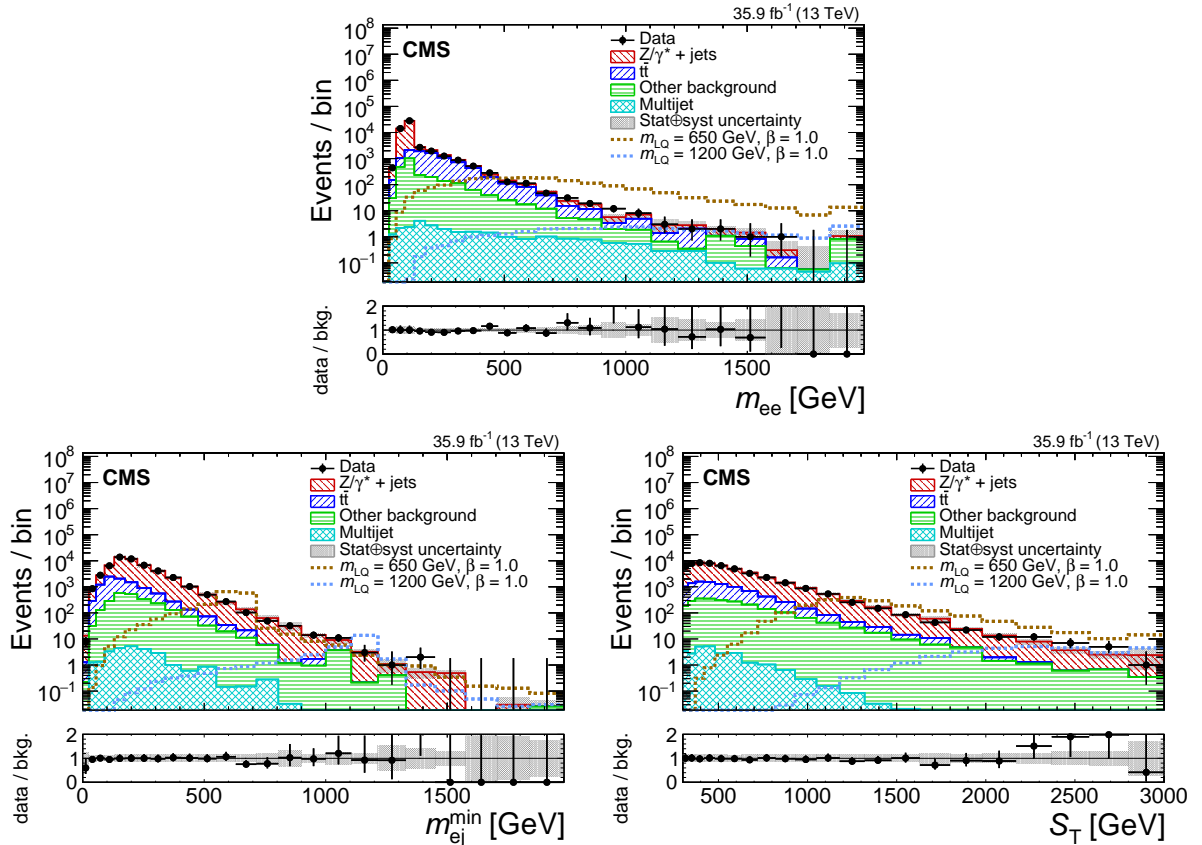


Figure 3: Data and background comparison for events passing the initial selection requirements for the eej channel, shown for the variables used for final selection optimization:  $m_{ee}$  (upper),  $m_{ej}^{\text{min}}$  (lower left), and  $S_T$  (lower right). “Other background” includes diboson, single top quark, and W+jets. Signal predictions for  $m_{LQ} = 650$  and  $1200 \text{ GeV}$  hypotheses are overlaid on the plots. The last bin includes all events beyond the upper  $x$ -axis boundary.

The largest background in the  $evjj$  channel comes from  $W$ +jets and  $t\bar{t}$  production. Single top quark,  $VV$ , and  $Z/\gamma^*$ +jets backgrounds have small contributions and are estimated from simulations. The QCD multijet background is estimated from control samples in data using the same probability for jets to be misidentified as electrons as is used in the background estimation for the  $eejj$  channel. The number of multijet events at the final selection is obtained by selecting events having exactly one loose electron, large  $p_T^{\text{miss}}$ , and at least two jets satisfying the signal selection criteria, and weighting these with the probability of a jet being misidentified as an electron.

The background contributions from  $W$ +jets and  $t\bar{t}$  are estimated from simulation, and normalized to the data in a control region defined by requiring  $50 < m_T < 110$  GeV after the initial selection. Then b-tagging information is used to distinguish  $W$ +jets from  $t\bar{t}$  in the control region. The  $W$ +jets contribution is enhanced by requiring zero b-tagged jets in the event, while the  $t\bar{t}$  control region is defined by requiring at least one b-tagged jet in the event. These regions have a purity of about 75%. The normalization factors for the two backgrounds are determined from these control regions using:

$$\begin{aligned} N_1 &= R_{t\bar{t}}N_{1,t\bar{t}} + R_WN_{1,W} + N_{1,O} \\ N_2 &= R_{t\bar{t}}N_{2,t\bar{t}} + R_WN_{2,W} + N_{2,O}, \end{aligned} \quad (1)$$

where  $N_{1(2)}$  is the number of events in the  $t\bar{t}$  ( $W$ +jets) control region in data. The terms  $N_{i,t\bar{t}}$  and  $N_{i,W}$  are the numbers of  $t\bar{t}$  and  $W$ +jets events in the simulated samples, while  $N_{i,O}$  is the number of events arising from other background sources, namely diboson, single top quark,  $Z/\gamma^*$ +jets and multijet. The subscript  $i = 1, 2$  refers to the two control regions described above. The background normalization factors  $R_{t\bar{t}} = 0.92 \pm 0.01$  (stat) and  $R_W = 0.87 \pm 0.01$  (stat) are then determined by solving Eq. (1).

The observed distributions of kinematic variables for the  $evjj$  channel following the initial selection are found to agree with the background prediction within estimation uncertainties. The distributions of  $m_T$ ,  $m_{ej}$ ,  $S_T$ , and  $p_T^{\text{miss}}$  are shown in Fig. 4.

## 6 Systematic uncertainties

The sources of systematic uncertainties considered in this analysis are listed in Table 1. Uncertainties in the reconstruction of electrons, jets and  $p_T^{\text{miss}}$  affect the selected sample of events used in the analysis. The uncertainty due to the electron energy scale is obtained by shifting the electron energy up and down by 2%. The uncertainty in the electron energy resolution is measured by smearing the electron energy by  $\pm 10\%$  [78]. The uncertainties due to electron reconstruction and identification efficiencies are obtained by varying the corresponding scale factors applied to simulated events by  $\pm 1$  standard deviation with respect to their nominal values. The trigger efficiency for electrons is measured by utilizing the tag-and-probe method [79] in data, and parametrized as a function of electron  $p_T$  and  $\eta$ . The corresponding uncertainty depends on the number of data events and is almost entirely statistical in origin for the kinematic range studied in this analysis.

The uncertainty due to the jet energy scale is obtained by varying the nominal scale correction by  $\pm 1$  standard deviation and taking the maximum difference with respect to the nominal event yield. The jet energy resolution models the variation between the reconstructed and generated jets. The corresponding uncertainty is obtained by modifying the parametrization of this difference [74].

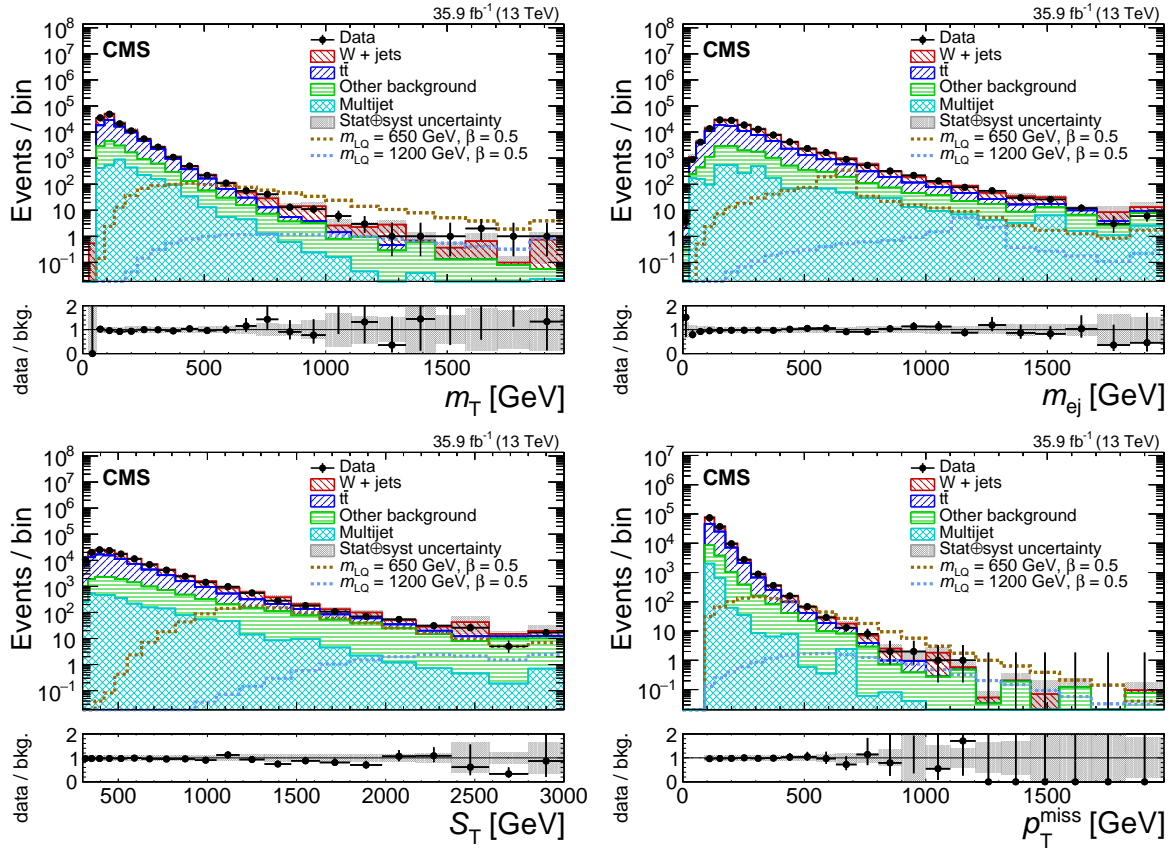


Figure 4: Data and background for events passing the initial selection requirements in the  $e\nu jj$  channel, shown for the variables used for final selection optimization:  $m_T$  (upper left),  $m_{ej}$  (upper right),  $S_T$  (lower left), and  $p_T^{\text{miss}}$  (lower right). “Other background” includes diboson, single top quark, and  $Z/\gamma^* + \text{jets}$ . Signal predictions for  $m_{LQ} = 650$  and  $1200 \text{ GeV}$  hypotheses are overlaid on the plots. The last bin includes all events beyond the upper  $x$ -axis boundary.

To determine uncertainties in  $p_T^{\text{miss}}$ , we consider up and down shifts in the jet energy scale and resolution, electron energy correction, and the scale corrections applied to the energy not associated with any PF candidates. For each variation, a new  $p_T^{\text{miss}}$  vector is computed for each event. The uncertainties corresponding to different variations in the quantities are then added in quadrature to determine the variation in  $p_T^{\text{miss}}$ , and the maximum difference of the event yield with respect to nominal is taken as the uncertainty.

Variations in the shape of the  $Z/\gamma^* + \text{jets}$  (eejj channel only),  $W + \text{jets}$  and  $t\bar{t}$  (evjj channel only), and diboson (both channels) backgrounds are determined using simulated samples with renormalization and factorization scales independently varied up and down in the matrix element by a factor of two, yielding eight different combinations. The event yields are then calculated for each of these variations and the maximum variation with respect to nominal is taken as the systematic uncertainty. The corresponding normalization uncertainties are evaluated from the statistical uncertainties in the scale factors obtained while normalizing these backgrounds to data in the control regions. In the evjj channel, an additional uncertainty of 10% is included to account for the observed differences associated with the choice of the  $m_T$  range, defining the control region used to calculate the normalization scale factors. As described above, b-tagging is used to define the control region for  $W + \text{jets}$  and  $t\bar{t}$  normalization in the evjj channel; therefore an uncertainty in the b-tagging efficiency is taken into account.

The uncertainty in the QCD multijet background is assessed by using an independent data sample. This sample is required to have exactly two electron candidates satisfying loosened criteria applied to the track-cluster matching, the isolation (both track-based and calorimetric), and the shower profile. We compare the number of events in this sample, where one candidate satisfies the electron selection requirements, to that predicted by the multijet background method. This test is repeated on a subsample of the data after applying an  $S_T$  threshold of 320 GeV, which corresponds to the optimized final selection for an LQ mass of 200 GeV. The relative difference of 25% observed between the results of the two tests is taken as the systematic uncertainty in the probability for a jet to be misidentified as an electron and applied in the evjj channel. For the eejj case, we assume full correlation between the two electrons and take 50% as the uncertainty.

The uncertainty in the integrated luminosity is 2.5% [80]. An uncertainty in the modeling of pileup is evaluated by reweighting the simulated events after varying the inelastic pp cross section by  $\pm 4.6\%$  [81]. The acceptance for both signal and backgrounds, and the expected background cross sections are affected by PDF uncertainties. We estimate this effect by evaluating the complete set of NNPDF 3.0 PDF eigenvectors, following the PDF4LHC prescription [52, 82–85].

## 7 Results of the leptoquark search

After applying the final selection criteria shown in Fig. 2, the data are compared to SM background expectations for both channels and each  $m_{\text{LQ}}$  hypothesis. Distributions of  $m_{\text{ej}}^{\text{min}}$  and  $S_T$  are shown in Fig. 5 for the eejj channel with the selections applied for the 650 and 1200 GeV  $m_{\text{LQ}}$  hypotheses. Figure 6 shows the corresponding distributions of  $m_{\text{ej}}$  and  $S_T$  for the evjj channel for the same mass hypotheses.

Figure 7 shows background, data, and expected signal for each LQ mass point after applying the final selection criteria. Signal efficiency times acceptance, along with tables listing event yields for signal, background, and data are provided in Appendix A. The data are found to be in agreement with SM background expectations in both channels. We set upper limits on

Table 1: Systematic uncertainties for the eejj and evjj channels. The values shown are calculated for the selections used in the  $m_{\text{LQ}} = 1000 \text{ GeV}$  search hypothesis and reflect the variations in the event yields due to each source. Major backgrounds, namely  $Z/\gamma^* + \text{jets}$  (eejj),  $W + \text{jets}$  and  $t\bar{t}$  (evjj), are normalized at the initial selection level when calculating the effect of shifts for various systematics.

Source of the uncertainty	eejj		evjj	
	Signal (%)	Background (%)	Signal (%)	Background (%)
Electron energy scale	1.5	2.5	1.9	6.9
Electron energy resolution	0.2	5.3	0.1	4.9
Electron reconstr. efficiency	3.0	3.0	0.6	0.8
Electron identif. efficiency	1.3	0.3	0.6	0.1
Trigger	1.1	1.4	9.5	7.6
Jet energy scale	0.5	0.9	0.5	2.3
Jet energy resolution	0.1	1.7	0.1	2.4
$p_{\text{T}}^{\text{miss}}$	—	—	0.8	13.1
$Z/\gamma^* + \text{jets}$ shape	—	5.6	—	—
$Z/\gamma^* + \text{jets}$ normalization	—	1.0	—	—
$W + \text{jets}$ shape	—	—	—	7.1
$W + \text{jets}$ normalization	—	—	—	1.1
$W + \text{jets}$ sideband selection	—	—	—	10.0
$W + \text{jets}$ b tagging	—	—	—	3.0
$t\bar{t}$ shape	—	—	—	10.4
$t\bar{t}$ normalization	—	1.0	—	1.0
$t\bar{t}$ b tagging	—	—	—	3.0
Diboson shape	—	3.4	—	3.2
QCD multijet	—	$<0.1$	—	2.6
Integrated luminosity	2.5	0.6	2.5	0.5
Pileup	0.2	1.0	0.4	1.4
PDF	2.8	3.0	2.9	4.7

the product of the cross section and branching fraction for scalar LQs as a function of  $m_{\text{LQ}}$  and  $\beta$ . The limits are calculated using the asymptotic approximation [86] of the  $\text{CL}_s$  modified frequentist approach [87–89]. Systematic uncertainties described in Section 6 are modeled with log-normal probability density functions, while statistical uncertainties are modeled with gamma functions whose widths are calculated from the number of events in the control regions or simulated samples.

We set upper limits on the production cross section multiplied by the branching fraction  $\beta^2$  or  $2\beta(1 - \beta)$  at 95% CL as a function of  $m_{\text{LQ}}$ . The expected and observed limits are shown with NLO predictions for the scalar LQ pair production cross section in Fig. 8 for both eejj and evjj channels. The observed limits are within two standard deviations of expectations from the background-only hypothesis. The uncertainty in the theoretical prediction for the LQ pair production cross section is calculated as the quadrature sum of the PDF uncertainty in the signal cross section and the uncertainty due to the choice of renormalization and factorization scales. The latter is estimated by independently varying the scales up and down by a factor of two.

Under the assumption  $\beta = 1.0$ , where only the eejj channel contributes, first-generation scalar LQs with masses less than 1435 GeV are excluded at 95% CL compared to a median expected limit of 1465 GeV. For  $\beta = 0.5$ , using the evjj channel alone, LQ masses are excluded below

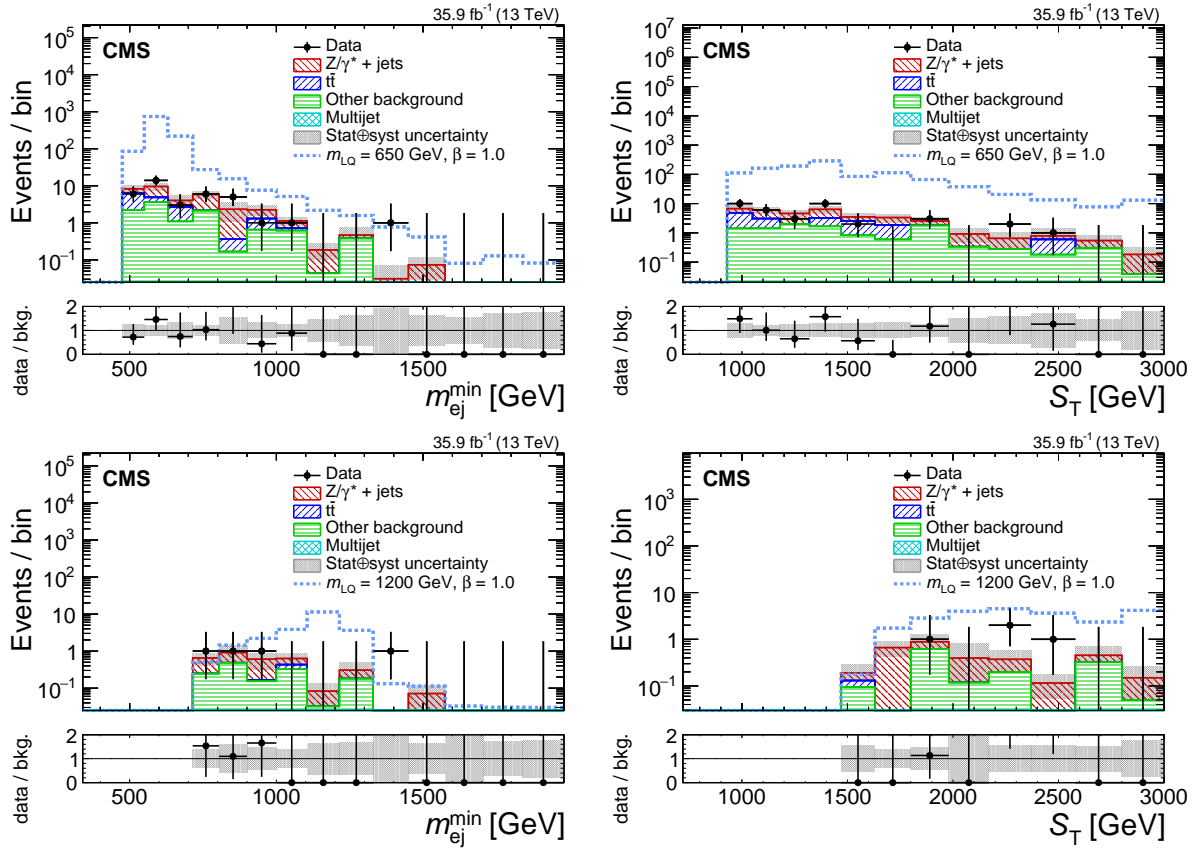


Figure 5:  $m_{ej}^{\min}$  (left) and  $S_T$  (right) distributions for events passing the eejj final selection for LQs of mass 650 (upper) and 1200 (lower) GeV. The predicted signal model distributions are shown, along with major backgrounds and “other background” which consists of the sum of the  $W$ +jets, diboson, single top quark, and  $\gamma$ +jets contributions. The background contributions are stacked, while the signal distributions are plotted unstacked. The dark shaded region indicates the statistical and systematic uncertainty in the total background. The last bin includes all events beyond the upper  $x$ -axis boundary.

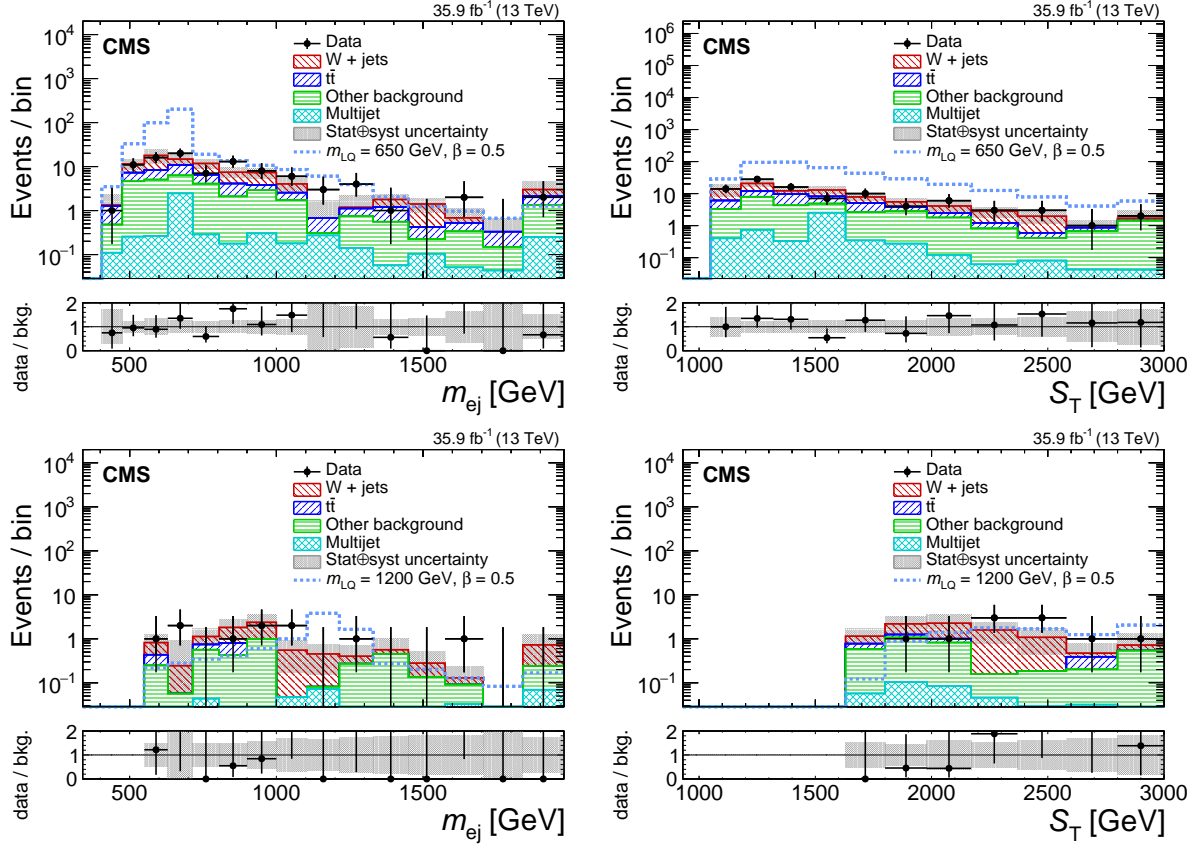


Figure 6:  $m_{ej}$  (left) and  $S_T$  (right) distributions for events passing the  $evjj$  final selection for LQs of mass 650 (upper) and 1200 (lower) GeV. The predicted signal model distributions are shown, along with major backgrounds and “other background” which consists of the sum of  $Z/\gamma^*$ +jets, diboson, single top quark, and  $\gamma$ +jets contributions. The background contributions are stacked, while the signal distributions are plotted unstacked. The dark shaded region indicates the statistical and systematic uncertainty in the total background. The last bin includes all events beyond the upper  $x$ -axis boundary.

1195 GeV with the corresponding expected limit being 1210 GeV. As both  $eejj$  and  $evjj$  decays contribute at  $\beta$  values smaller than 1, the LQ mass limit is improved using the combination of the two channels. In this combination, systematic uncertainties are considered to be fully correlated between the channels, while statistical uncertainties are treated as fully uncorrelated. Limits for a range of  $\beta$  values from 0 to 1 are set at 95% CL for both  $eejj$  and  $evjj$  channels, as well as for their combination, as shown in Fig. 9. In the  $\beta = 0.5$  case, the combination excludes first-generation scalar LQs with masses less than 1270 GeV, compared to a median expected value of 1285 GeV.

## 8 $R$ -parity violating supersymmetry interpretation

Many new physics models predict the existence of particles with couplings of the type expected for LQs. One such model is  $R$ -parity violating supersymmetry (RPV SUSY) [90, 91], where the superpartners of quarks or ‘squarks’ can decay into LQ-like final states. For example, the top squark ( $\tilde{t}$ ) can decay to a bottom quark and an electron. The topology of the resulting events is similar to an LQ decay and hence these events will pass our nominal selection for the  $eejj$  channel.

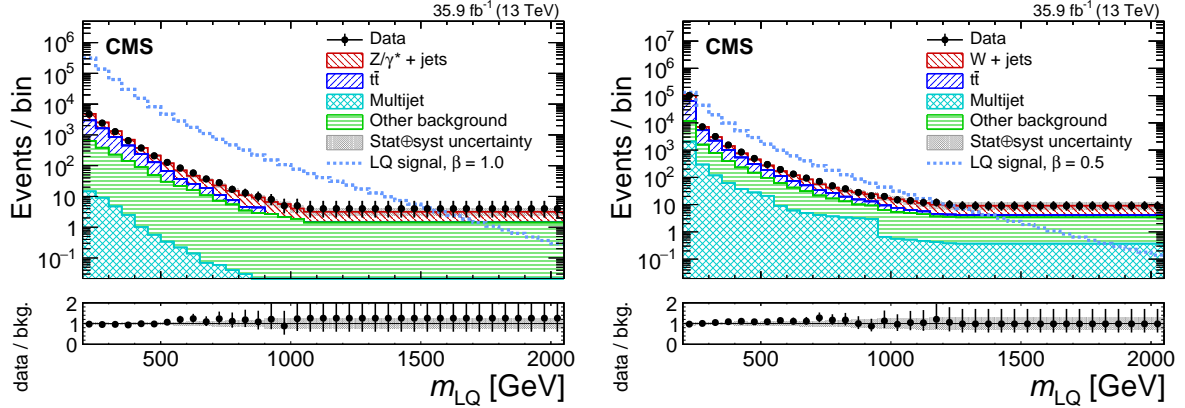


Figure 7: Data, background, and expected signal yields after applying the final selection criteria for the  $eejj$  (left) and  $evjj$  (right) channels. “Other background” includes diboson, single top quark, and  $W$ +jets (for the  $eejj$  channel) or  $Z/\gamma^*$ +jets (for the  $evjj$  channel). The bin contents are correlated, because events selected for higher-mass LQ searches are a subset of those selected for lower mass searches.

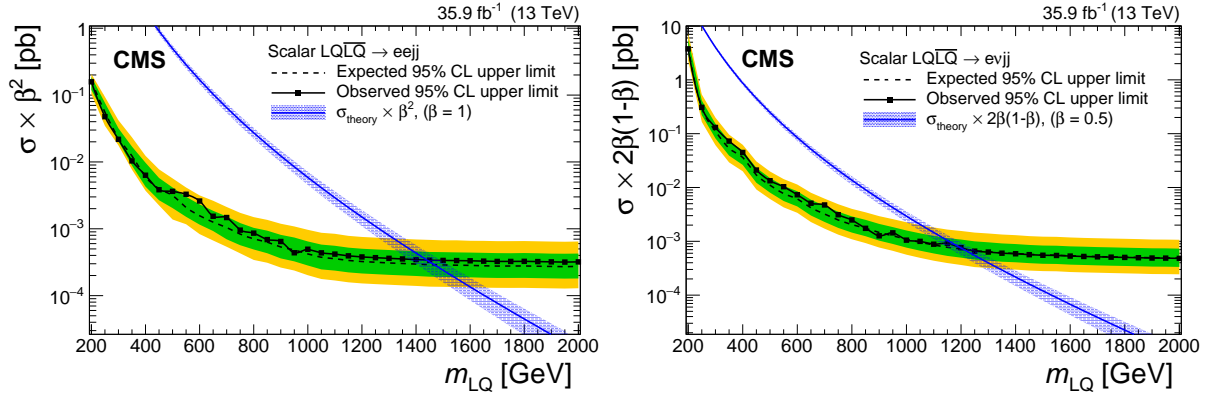


Figure 8: Observed upper limits for scalar LQ pair-production cross section times  $\beta^2$  (left) and  $\beta(1 - \beta)$  (right) at 95% CL obtained with the  $eejj$  (left) and  $evjj$  (right) analysis. The median (dashed line), 68% (inner green band) and 95% (outer yellow band) confidence-interval expected limits are also shown.

The analysis is recast in terms of the possible production of prompt top-squark pairs ( $c\tau = 0$  cm), with each  $\tilde{t}$  subsequently decaying to a bottom quark and an electron. Limits on the production cross section for  $\tilde{t}$  pairs are calculated from the  $eejj$  data, accounting for the difference in branching fractions of LQ and  $\tilde{t}$  decays to electrons.

Figure 10 shows the expected and observed 95% CL upper limits on the RPV SUSY  $\tilde{t}$  pair production cross section as a function of the  $\tilde{t}$  squark mass ( $m_{\tilde{t}}$ ). The observed exclusion limit is 1100 GeV for  $c\tau = 0$  cm.

## 9 Summary

A search has been performed for the pair production of first-generation scalar leptoquarks in final states consisting of two high-momentum electrons and two jets, or one electron, large missing transverse momentum and two jets. The data sample used in the study corresponds to an integrated luminosity of  $35.9 \text{ fb}^{-1}$  recorded by the CMS experiment at  $\sqrt{s} = 13 \text{ TeV}$ . The data



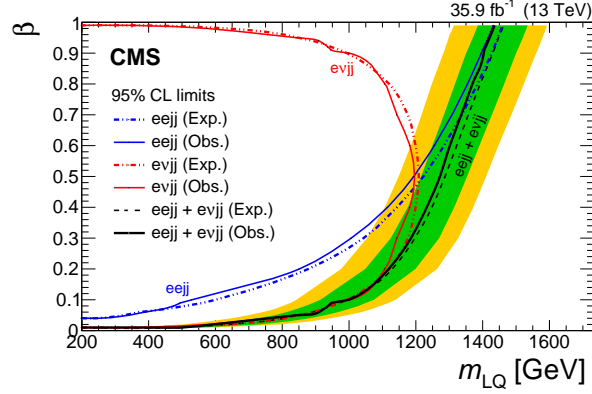


Figure 9: Expected and observed exclusion limits at 95% CL for pair production of first-generation scalar LQ shown in the  $\beta$  versus  $m_{LQ}$  plane for the individual  $eejj$  and  $evjj$  channels and their combination. The inner green and outer yellow bands represent the 68% and 95% confidence intervals on the expected limits.

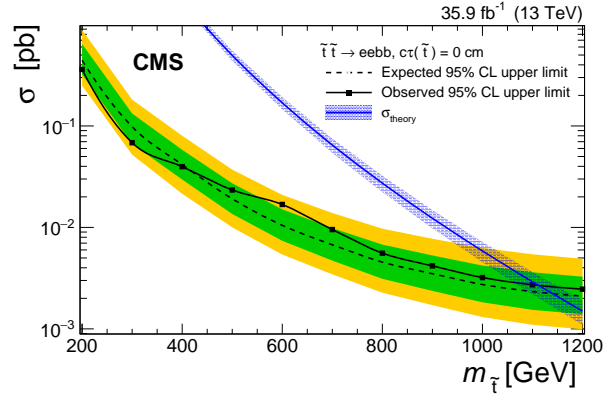


Figure 10: Expected and observed upper limits at 95% CL on the RPV SUSY  $\tilde{t}$  squark pair production cross section as a function of  $M_{\tilde{t}}$  for  $c\tau = 0$  cm. The expected limits represent the median values, while the inner green and outer yellow bands are the 68% and 95% confidence intervals, respectively.

are found to be in agreement with standard model background expectations and a lower limit at 95% confidence level is set on the scalar leptoquark mass at 1435 (1270) GeV for  $\beta = 1.0$  (0.5), where  $\beta$  is the branching fraction of the leptoquark decay to an electron and a quark. These results constitute the most stringent limits on the mass of first-generation scalar leptoquarks to date. The data are also interpreted in the context of an  $R$ -parity violating supersymmetric model with promptly decaying top squarks, which can decay into leptoquark-like final states. Top squarks are excluded for masses below 1100 GeV.

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## A Efficiencies and event yields

In Fig. 11 the product of signal acceptance and efficiency is shown after final optimized selections as a function of  $m_{LQ}$  for the  $eejj$  (left) and  $evjj$  (right) channels. Tables 2 and 3 list the number of events passing the final selection criteria in data and the various background components as a function of  $m_{LQ}$  for the  $eejj$  and  $evjj$  channels, respectively.

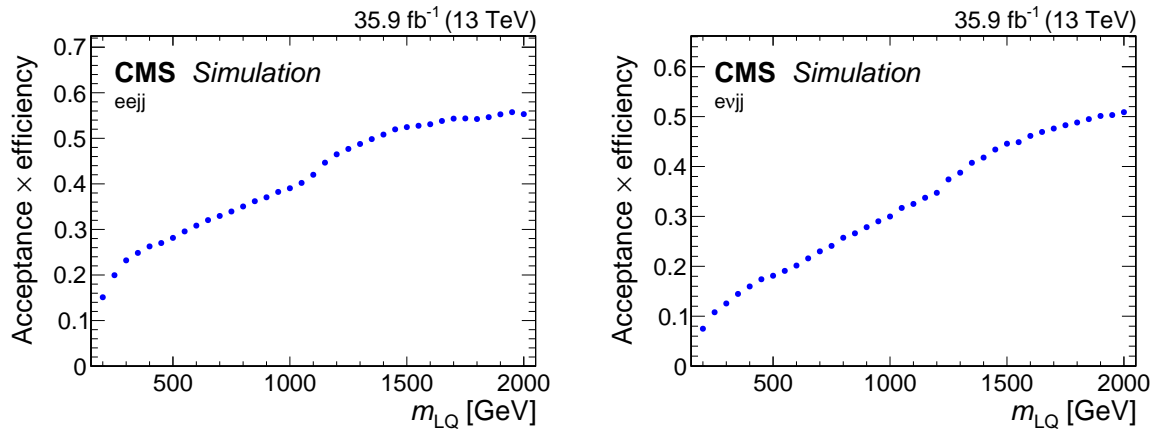


Figure 11: The product of signal acceptance and efficiency after final optimized selections, as a function of  $m_{LQ}$  for the  $eejj$  (left) and  $evjj$  (right) channels.

Table 2: Event yields after the optimized eejj selections. Uncertainties are statistical except for the total background, where both statistical and systematic uncertainties are shown. LQ masses are given in units of GeV.

LQ mass	Signal	$Z/\gamma^* + \text{jets}$	$t\bar{t}$	Multijet	$VV, W, \text{single } t, \gamma + \text{jets}$	Total background	Data
init. sel.	—	$41600 \pm 49$	$7100 \pm 68$	$26 \pm 0.1$	$2400 \pm 36$	$51100 \pm 91 \pm 2700$	50585
200	$311500 \pm 3300$	$1900 \pm 16$	$2300 \pm 39$	$15 \pm 0.1$	$630 \pm 18$	$4800 \pm 46 \pm 120$	4709
250	$137400 \pm 1200$	$910 \pm 11$	$1200 \pm 29$	$9.1 \pm 0.1$	$380 \pm 14$	$2500 \pm 34 \pm 69$	2426
300	$63160 \pm 510$	$470 \pm 4.2$	$630 \pm 22$	$4.8 \pm 0.0$	$220^{+10}_{-9.5}$	$1300^{+24}_{-24} \pm 24$	1278
350	$30150 \pm 230$	$250 \pm 2.7$	$310 \pm 15$	$2.5 \pm 0.0$	$140^{+9.5}_{-8.6}$	$700^{+18}_{-18} \pm 27$	652
400	$15440 \pm 110$	$140 \pm 1.8$	$150 \pm 11$	$1.0 \pm 0.0$	$89^{+7.2}_{-6.2}$	$380^{+13}_{-13} \pm 11$	376
450	$8260 \pm 60$	$85 \pm 1.5$	$79 \pm 7.7$	$0.6 \pm 0.0$	$49^{+2.3}_{-2.3}$	$210^{+8.2}_{-8.1} \pm 5.3$	209
500	$4700 \pm 33$	$54 \pm 1.1$	$36 \pm 5.5$	$0.3 \pm 0.0$	$30^{+2.0}_{-1.9}$	$120^{+6.0}_{-5.9} \pm 4.4$	128
550	$2830 \pm 19$	$33 \pm 0.8$	$15 \pm 4.0$	$0.2 \pm 0.0$	$22^{+1.8}_{-1.8}$	$70^{+4.5}_{-4.5} \pm 2.6$	84
600	$1750 \pm 12$	$21 \pm 0.6$	$9.6 \pm 3.3$	$0.1 \pm 0.0$	$16^{+1.6}_{-1.6}$	$47^{+3.7}_{-3.7} \pm 1.9$	58
650	$1110 \pm 7.2$	$15 \pm 0.6$	$7.7 \pm 2.9$	$0.1 \pm 0.0$	$11^{+1.4}_{-1.3}$	$34^{+3.2}_{-3.2} \pm 1.3$	37
700	$718 \pm 4.5$	$12 \pm 0.5$	$3.7 \pm 2.2$	$0.1 \pm 0.0$	$7.3^{+1.2}_{-1.2}$	$23^{+2.6}_{-2.6} \pm 1.0$	28
750	$470 \pm 2.9$	$7.8 \pm 0.3$	$2.0 \pm 1.9$	$0.0 \pm 0.0$	$5.5^{+1.1}_{-1.1}$	$15^{+2.2}_{-2.2} \pm 0.6$	17
800	$320 \pm 1.9$	$6.4 \pm 0.4$	$1.1^{+0.5}_{-0.4}$	$0.0 \pm 0.0$	$3.5^{+1.1}_{-0.9}$	$11^{+1.2}_{-1.1} \pm 0.6$	13
850	$220 \pm 1.3$	$4.9 \pm 0.3$	$1.5^{+0.7}_{-0.5}$	$0.0 \pm 0.0$	$2.8^{+1.0}_{-0.6}$	$9.2^{+1.3}_{-0.8} \pm 0.5$	10
900	$150 \pm 0.9$	$4.0 \pm 0.3$	$0.0^{+1.2}_{-0.0}$	$0.0 \pm 0.0$	$2.6^{+0.8}_{-0.5}$	$6.6^{+1.4}_{-0.6} \pm 0.4$	8
950	$110 \pm 0.6$	$3.6 \pm 0.5$	$0.0^{+0.9}_{-0.0}$	$0.0 \pm 0.0$	$2.1^{+0.7}_{-0.5}$	$5.7^{+1.3}_{-0.7} \pm 0.3$	5
1000	$77 \pm 0.4$	$2.2 \pm 0.1$	$0.0^{+0.7}_{-0.0}$	$0.0 \pm 0.0$	$1.9^{+1.0}_{-0.4}$	$4.1^{+1.0}_{-0.5} \pm 0.2$	5
1050	$55 \pm 0.3$	$1.8 \pm 0.1$	$0.0^{+0.3}_{-0.0}$	$0.0 \pm 0.0$	$1.4^{+0.6}_{-0.4}$	$3.2^{+0.7}_{-0.4} \pm 0.2$	4
1100	$41 \pm 0.2$	$1.8 \pm 0.1$	$0.0^{+0.3}_{-0.0}$	$0.0 \pm 0.0$	$1.4^{+0.6}_{-0.4}$	$3.2^{+0.7}_{-0.4} \pm 0.2$	4
1150	$31 \pm 0.2$	$1.8 \pm 0.1$	$0.0^{+0.3}_{-0.0}$	$0.0 \pm 0.0$	$1.4^{+0.6}_{-0.4}$	$3.2^{+0.7}_{-0.4} \pm 0.2$	4
1200	$23 \pm 0.1$	$1.8 \pm 0.1$	$0.0^{+0.3}_{-0.0}$	$0.0 \pm 0.0$	$1.4^{+0.6}_{-0.4}$	$3.2^{+0.7}_{-0.4} \pm 0.2$	4
1250	$17 \pm 0.1$	$1.8 \pm 0.1$	$0.0^{+0.3}_{-0.0}$	$0.0 \pm 0.0$	$1.4^{+0.6}_{-0.4}$	$3.2^{+0.7}_{-0.4} \pm 0.2$	4
1300	$13 \pm 0.1$	$1.8 \pm 0.1$	$0.0^{+0.3}_{-0.0}$	$0.0 \pm 0.0$	$1.4^{+0.6}_{-0.4}$	$3.2^{+0.7}_{-0.4} \pm 0.2$	4
1350	$9.8 \pm 0.0$	$1.8 \pm 0.1$	$0.0^{+0.3}_{-0.0}$	$0.0 \pm 0.0$	$1.4^{+0.6}_{-0.4}$	$3.2^{+0.7}_{-0.4} \pm 0.2$	4
1400	$7.4 \pm 0.0$	$1.8 \pm 0.1$	$0.0^{+0.3}_{-0.0}$	$0.0 \pm 0.0$	$1.4^{+0.6}_{-0.4}$	$3.2^{+0.7}_{-0.4} \pm 0.2$	4
1450	$5.6 \pm 0.0$	$1.8 \pm 0.1$	$0.0^{+0.3}_{-0.0}$	$0.0 \pm 0.0$	$1.4^{+0.6}_{-0.4}$	$3.2^{+0.7}_{-0.4} \pm 0.2$	4
1500	$4.2 \pm 0.0$	$1.8 \pm 0.1$	$0.0^{+0.3}_{-0.0}$	$0.0 \pm 0.0$	$1.4^{+0.6}_{-0.4}$	$3.2^{+0.7}_{-0.4} \pm 0.2$	4
1550	$3.2 \pm 0.0$	$1.8 \pm 0.1$	$0.0^{+0.3}_{-0.0}$	$0.0 \pm 0.0$	$1.4^{+0.6}_{-0.4}$	$3.2^{+0.7}_{-0.4} \pm 0.2$	4
1600	$2.4 \pm 0.0$	$1.8 \pm 0.1$	$0.0^{+0.3}_{-0.0}$	$0.0 \pm 0.0$	$1.4^{+0.6}_{-0.4}$	$3.2^{+0.7}_{-0.4} \pm 0.2$	4
1650	$1.8 \pm 0.0$	$1.8 \pm 0.1$	$0.0^{+0.3}_{-0.0}$	$0.0 \pm 0.0$	$1.4^{+0.6}_{-0.4}$	$3.2^{+0.7}_{-0.4} \pm 0.2$	4
1700	$1.4 \pm 0.0$	$1.8 \pm 0.1$	$0.0^{+0.3}_{-0.0}$	$0.0 \pm 0.0$	$1.4^{+0.6}_{-0.4}$	$3.2^{+0.7}_{-0.4} \pm 0.2$	4
1750	$1.1 \pm 0.0$	$1.8 \pm 0.1$	$0.0^{+0.3}_{-0.0}$	$0.0 \pm 0.0$	$1.4^{+0.6}_{-0.4}$	$3.2^{+0.7}_{-0.4} \pm 0.2$	4
1800	$0.8 \pm 0.0$	$1.8 \pm 0.1$	$0.0^{+0.3}_{-0.0}$	$0.0 \pm 0.0$	$1.4^{+0.6}_{-0.4}$	$3.2^{+0.7}_{-0.4} \pm 0.2$	4
1850	$0.6 \pm 0.0$	$1.8 \pm 0.1$	$0.0^{+0.3}_{-0.0}$	$0.0 \pm 0.0$	$1.4^{+0.6}_{-0.4}$	$3.2^{+0.7}_{-0.4} \pm 0.2$	4
1900	$0.5 \pm 0.0$	$1.8 \pm 0.1$	$0.0^{+0.3}_{-0.0}$	$0.0 \pm 0.0$	$1.4^{+0.6}_{-0.4}$	$3.2^{+0.7}_{-0.4} \pm 0.2$	4
1950	$0.4 \pm 0.0$	$1.8 \pm 0.1$	$0.0^{+0.3}_{-0.0}$	$0.0 \pm 0.0$	$1.4^{+0.6}_{-0.4}$	$3.2^{+0.7}_{-0.4} \pm 0.2$	4
2000	$0.3 \pm 0.0$	$1.8 \pm 0.1$	$0.0^{+0.3}_{-0.0}$	$0.0 \pm 0.0$	$1.4^{+0.6}_{-0.4}$	$3.2^{+0.7}_{-0.4} \pm 0.2$	4

Table 3: Event yields after the optimized  $e\nu jj$  selections. Uncertainties are statistical except for the total background, where both statistical and systematic uncertainties are shown. LQ masses are given in units of GeV.

LQ mass	Signal	W+jets	$t\bar{t}$	Multijet	VV, Z, single t, $\gamma$ +jets	Total background	Data
init. sel.	—	$47900 \pm 160$	$66900 \pm 110$	$2800 \pm 15$	$11300 \pm 72$	$128900 \pm 210 \pm 8800$	125076
200	$130800 \pm 1600$	$40100 \pm 150$	$52800 \pm 94$	$2100 \pm 11$	$9600 \pm 57$	$104500 \pm 190 \pm 7300$	101618
250	$44200 \pm 520$	$1800 \pm 25$	$3800 \pm 25$	$300 \pm 2.3$	$1300 \pm 38$	$7100 \pm 52 \pm 430$	7151
300	$19800 \pm 220$	$800 \pm 15$	$1400 \pm 16$	$120 \pm 1.4$	$660 \pm 37$	$3000 \pm 43 \pm 170$	3164
350	$9800 \pm 100$	$410 \pm 13$	$610 \pm 10$	$62 \pm 1.0$	$330 \pm 11$	$1400 \pm 20 \pm 88$	1539
400	$5100 \pm 51$	$230 \pm 8.9$	$300 \pm 7.2$	$37 \pm 0.8$	$200 \pm 10$	$760 \pm 15 \pm 74$	847
450	$2900 \pm 27$	$150 \pm 6.0$	$160 \pm 5.2$	$28 \pm 0.8$	$120 \pm 9.6$	$460 \pm 12 \pm 31$	496
500	$1700 \pm 15$	$90 \pm 4.1$	$88 \pm 3.9$	$21 \pm 0.8$	$75^{+3.9}_{-3.3}$	$270^{+6.9}_{-6.6} \pm 21$	298
550	$990 \pm 8.8$	$59 \pm 5.2$	$49 \pm 2.9$	$9.1 \pm 0.4$	$53^{+3.5}_{-2.9}$	$170^{+6.9}_{-6.6} \pm 13$	195
600	$620 \pm 5.3$	$45 \pm 5.1$	$32 \pm 2.3$	$6.1 \pm 0.4$	$36^{+2.8}_{-2.2}$	$120^{+6.3}_{-6.0} \pm 12$	132
650	$400 \pm 3.3$	$34 \pm 5.0$	$20 \pm 1.8$	$5.0 \pm 0.4$	$26^{+2.5}_{-1.9}$	$84^{+5.9}_{-5.7} \pm 8.1$	94
700	$270 \pm 2.1$	$22 \pm 1.2$	$12 \pm 1.5$	$4.2 \pm 0.5$	$18^{+2.1}_{-1.5}$	$56^{+2.9}_{-2.5} \pm 6.1$	71
750	$180 \pm 1.4$	$15 \pm 0.9$	$10 \pm 1.3$	$3.7 \pm 0.5$	$13^{+2.1}_{-1.3}$	$42^{+2.7}_{-2.1} \pm 4.9$	49
800	$130 \pm 0.9$	$13 \pm 1.0$	$6.3 \pm 1.0$	$3.4 \pm 0.6$	$9.8^{+2.0}_{-1.1}$	$32^{+2.5}_{-1.9} \pm 4.6$	38
850	$86 \pm 0.6$	$13 \pm 1.1$	$5.2 \pm 0.9$	$3.2 \pm 0.7$	$7.0^{+2.0}_{-1.2}$	$28^{+2.6}_{-2.0} \pm 4.8$	28
900	$61 \pm 0.4$	$11 \pm 1.2$	$3.8 \pm 0.8$	$3.0 \pm 0.7$	$6.3^{+2.0}_{-1.1}$	$24^{+2.6}_{-2.0} \pm 4.1$	21
950	$44 \pm 0.3$	$8.4 \pm 1.0$	$3.0 \pm 0.7$	$0.7 \pm 0.1$	$5.7^{+2.0}_{-1.1}$	$18^{+2.3}_{-1.6} \pm 3.3$	20
1000	$31 \pm 0.2$	$7.9 \pm 0.9$	$2.2 \pm 0.6$	$0.6 \pm 0.1$	$4.8^{+2.0}_{-1.1}$	$16^{+2.3}_{-1.5} \pm 2.8$	15
1050	$23 \pm 0.2$	$7.1 \pm 0.9$	$1.4^{+0.7}_{-0.5}$	$0.5 \pm 0.1$	$4.4^{+2.0}_{-1.1}$	$13^{+2.3}_{-1.4} \pm 2.5$	14
1100	$17 \pm 0.1$	$5.9 \pm 0.8$	$1.2^{+0.6}_{-0.4}$	$0.5 \pm 0.1$	$4.0^{+2.0}_{-1.0}$	$12^{+2.3}_{-1.4} \pm 2.1$	12
1150	$12 \pm 0.1$	$5.4 \pm 0.9$	$0.9^{+0.6}_{-0.4}$	$0.4 \pm 0.1$	$3.3^{+2.0}_{-1.4}$	$10^{+2.3}_{-1.4} \pm 1.7$	12
1200	$9.1 \pm 0.1$	$5.2 \pm 1.1$	$0.7^{+0.6}_{-0.4}$	$0.4 \pm 0.1$	$3.2^{+2.0}_{-1.0}$	$9.5^{+2.3}_{-1.5} \pm 1.6$	10
1250	$7.1 \pm 0.0$	$5.0 \pm 1.1$	$0.7^{+0.6}_{-0.4}$	$0.4 \pm 0.1$	$3.0^{+2.0}_{-1.0}$	$9.1^{+2.3}_{-1.5} \pm 1.5$	9
1300	$5.4 \pm 0.0$	$5.0 \pm 1.1$	$0.7^{+0.6}_{-0.4}$	$0.4 \pm 0.1$	$3.0^{+2.0}_{-1.0}$	$9.1^{+2.3}_{-1.5} \pm 1.5$	9
1350	$4.1 \pm 0.0$	$5.0 \pm 1.1$	$0.7^{+0.6}_{-0.4}$	$0.4 \pm 0.1$	$3.0^{+2.0}_{-1.0}$	$9.1^{+2.3}_{-1.5} \pm 1.5$	9
1400	$3.1 \pm 0.0$	$5.0 \pm 1.1$	$0.7^{+0.6}_{-0.4}$	$0.4 \pm 0.1$	$3.0^{+2.0}_{-1.0}$	$9.1^{+2.3}_{-1.5} \pm 1.5$	9
1450	$2.4 \pm 0.0$	$5.0 \pm 1.1$	$0.7^{+0.6}_{-0.4}$	$0.4 \pm 0.1$	$3.0^{+2.0}_{-1.0}$	$9.1^{+2.3}_{-1.5} \pm 1.5$	9
1500	$1.9 \pm 0.0$	$5.0 \pm 1.1$	$0.7^{+0.6}_{-0.4}$	$0.4 \pm 0.1$	$3.0^{+2.0}_{-1.0}$	$9.1^{+2.3}_{-1.5} \pm 1.5$	9
1550	$1.4 \pm 0.0$	$5.0 \pm 1.1$	$0.7^{+0.6}_{-0.4}$	$0.4 \pm 0.1$	$3.0^{+2.0}_{-1.0}$	$9.1^{+2.3}_{-1.5} \pm 1.5$	9
1600	$1.1 \pm 0.0$	$5.0 \pm 1.1$	$0.7^{+0.6}_{-0.4}$	$0.4 \pm 0.1$	$3.0^{+2.0}_{-1.0}$	$9.1^{+2.3}_{-1.5} \pm 1.5$	9
1650	$0.8 \pm 0.0$	$5.0 \pm 1.1$	$0.7^{+0.6}_{-0.4}$	$0.4 \pm 0.1$	$3.0^{+2.0}_{-1.0}$	$9.1^{+2.3}_{-1.5} \pm 1.5$	9
1700	$0.6 \pm 0.0$	$5.0 \pm 1.1$	$0.7^{+0.6}_{-0.4}$	$0.4 \pm 0.1$	$3.0^{+2.0}_{-1.0}$	$9.1^{+2.3}_{-1.5} \pm 1.5$	9
1750	$0.5 \pm 0.0$	$5.0 \pm 1.1$	$0.7^{+0.6}_{-0.4}$	$0.4 \pm 0.1$	$3.0^{+2.0}_{-1.0}$	$9.1^{+2.3}_{-1.5} \pm 1.5$	9
1800	$0.4 \pm 0.0$	$5.0 \pm 1.1$	$0.7^{+0.6}_{-0.4}$	$0.4 \pm 0.1$	$3.0^{+2.0}_{-1.0}$	$9.1^{+2.3}_{-1.5} \pm 1.5$	9
1850	$0.3 \pm 0.0$	$5.0 \pm 1.1$	$0.7^{+0.6}_{-0.4}$	$0.4 \pm 0.1$	$3.0^{+2.0}_{-1.0}$	$9.1^{+2.3}_{-1.5} \pm 1.5$	9
1900	$0.2 \pm 0.0$	$5.0 \pm 1.1$	$0.7^{+0.6}_{-0.4}$	$0.4 \pm 0.1$	$3.0^{+2.0}_{-1.0}$	$9.1^{+2.3}_{-1.5} \pm 1.5$	9
1950	$0.2 \pm 0.0$	$5.0 \pm 1.1$	$0.7^{+0.6}_{-0.4}$	$0.4 \pm 0.1$	$3.0^{+2.0}_{-1.0}$	$9.1^{+2.3}_{-1.5} \pm 1.5$	9
2000	$0.1 \pm 0.0$	$5.0 \pm 1.1$	$0.7^{+0.6}_{-0.4}$	$0.4 \pm 0.1$	$3.0^{+2.0}_{-1.0}$	$9.1^{+2.3}_{-1.5} \pm 1.5$	9



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