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CMS Physics Analysis Summary

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Constraints on models of scalar and vector leptoquarks decaying to a quark and a neutrino at $\sqrt{s} = 13$ TeV

The CMS Collaboration

Abstract

Many searches for Supersymmetry at the CERN LHC are sensitive to other scenarios of physics beyond the standard model. In this note, the results of a previous search for squarks and gluinos are re-interpreted to constrain models of leptoquark production. Pair production is considered, and both leptoquarks are assumed to decay to a quark and a neutrino. The search selects jets in association with a transverse momentum imbalance, using the M_{T2} variable. The analysis uses proton-proton collision data at $\sqrt{s} = 13$ TeV, recorded with the CMS detector at the LHC in 2016 and corresponding to an integrated luminosity of 35.9 fb^{-1}. Compared to previous CMS results, both scalar and vector leptoquarks are considered, as well as higher leptoquark mass values, and for the first time, leptoquark decays to a light quark (any single one of u, d, s, or c) and a neutrino are considered. Assuming scalar (vector) leptoquarks decaying with unity branching fraction to a light quark and neutrino, masses below 980 (1790) GeV are excluded by the observed data. For leptoquarks decaying to a bottom quark and a neutrino, masses below 1100 (1810) GeV are excluded, while assuming decays to a top quark and a neutrino, masses below 1020 (1780) GeV are excluded. Vector leptoquarks decaying with a 50% branching fraction to a top quark and a neutrino, and 50% to a bottom quark and tau lepton, have been proposed as an explanation of anomalous flavor physics results. In such a model, we exclude leptoquarks with masses below 1530 GeV, placing the most stringent constraint to date.

1 Introduction

Leptoquarks (LQ) are hypothetical new particles with couplings to both quarks and leptons [1]. The spin of an LQ state is either 0 (scalar LQ, denoted LQ_S) or 1 (vector LQ, denoted LQ_V). They appear in theories beyond the standard model (SM) such as grand unified theories [2–4], technicolor models [5, 6], compositeness scenarios [7, 8], and R-parity [9] violating Supersymmetry (SUSY) [10–18]. Leptoquarks have been postulated as a potential explanation [19–24] for a collection of anomalies observed in flavor physics by the BaBar [25, 26], Belle [27–30], and LHCb [31–35] Collaborations.

Direct searches for leptoquark production have been performed at the CERN LHC by the ATLAS [36–38] and CMS [39–44] Collaborations covering several final states. This note focuses on the decay of leptoquarks to a quark and a neutrino, which have been searched for by the ATLAS [37] and CMS [43, 44] Collaborations. The pair production and decay of LQ_S results in the same final states as those considered in searches for squark pair production in R-parity conserving SUSY, assuming that the squark decays directly to a quark and a massless neutralino [45]. Searches for squark pair production have been reported by the ATLAS [46–50] and CMS [51–57] Collaborations. The results from the CMS search for jets in association with a transverse momentum imbalance (p_T^{miss}) using the M_{T2} variable [58], reported in Ref. [51], have recently been reinterpreted as part of a review of LQ searches to place the strongest limits on the pair production of leptoquarks decaying to a quark and a neutrino [45]. However, for LQ_V, the pair production cross sections are large enough that the mass range of interest was not covered by the simulated samples used in [51].

In this note, we present an extended interpretation of the search from Ref. [51] considering higher mass values for the signal samples. Exploiting the similarity in final states between squark and LQ pair production, we verify that our analysis acceptance is consistent for squark, LQ_S, and LQ_V production. We thus proceed to use simulated squark samples to place limits on both LQ_S and LQ_V production. At high LQ mass values, using the extended signal samples and full analysis results allows us to improve the upper limits on LQ pair production cross sections by as much as a factor of 2.8 over the extrapolation assumed in Ref. [45].

2 Analysis overview

The CMS search for jets and p_T^{miss} exploiting the M_{T2} variable is used for these results. The analysis itself is unchanged from Ref. [51], where a full description can be found, and is briefly summarized here. The search uses proton-proton collision data at $\sqrt{s} = 13\,\text{TeV}$, recorded with the CMS detector in 2016 and corresponding to an integrated luminosity of $35.9\,\text{fb}^{-1}$. A description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [59].

Events are selected in the CMS trigger requiring either large p_T^{miss} or large hadronic activity H_T, defined as the scalar sum of jet transverse momentum p_T. Jets are clustered using the anti-k_T clustering algorithm [60] with a distance parameter of 0.4, as implemented in the FASTJET package [61]. They are required to satisfy $p_T > 30\,\text{GeV}$ and pseudorapidity $|\eta| < 2.4$ to be counted and used in the H_T calculation. The trigger selections have efficiency greater than 98% for events with offline reconstructed values of $p_T^{miss} > 250\,\text{GeV}$ or $H_T > 1000\,\text{GeV}$. The baseline analysis selection requires events to have at least one jet and pass either $p_T^{miss} > 30\,\text{GeV}$ if they have $H_T > 1000\,\text{GeV}$, or $p_T^{miss} > 250\,\text{GeV}$ if they have $250 < H_T < 1000\,\text{GeV}$. For events with at least two jets, the variable M_{T2} is computed from the jets and the p_T^{miss}, after the jets are reclustered into two "pseudojets." The baseline selection for events with at least two jets requires $M_{T2} > 200\,\text{GeV}$, which is raised to $M_{T2} > 400\,\text{GeV}$ for events with $H_T > 1500\,\text{GeV}$ to reject background. Additional baseline requirements are imposed, including that $\vec{p}_T^{\text{miss}}$ is not aligned in ϕ with any of the four leading jets in p_T, that the vector sum of jets $\vec{H}_T^{\text{miss}}$ is consistent with $\vec{p}_T^{\text{miss}}$, and that no loosely identified charged leptons or isolated tracks are found in the event.

Events passing the baseline selection are categorized according to four variables: H_T, M_{T2}, the number of jets N_j, and the number of b-tagged jets N_b. Jets are identified as b-tagged using the combined secondary vertex (CSVv2) algorithm [62], and b-tagged jets must pass a looser requirement of $p_T > 20\,\text{GeV}$ to be counted. Events with exactly one jet are categorized according to the jet p_T and the presence or absence of a b tag. In total, the analysis contains 213 search bins.

The SM backgrounds to the search comprise three categories: Z+jets production with the decay $Z \to \nu\bar{\nu}$, W+jets or $t\bar{t}$+jets production with the decay $W \to \ell\nu$ where the charged lepton is outside acceptance or not identified ("lost lepton"), and quantum chromodynamics (QCD) multijet production where p_T^{miss} arises from jet mismeasurement. Each of these backgrounds is predicted primarily from data control regions: Z+jets from $Z \to \ell^+\ell^-$ events, W+jets and $t\bar{t}$+jets from events containing an electron or muon, and QCD multijets from events with a jet aligned in ϕ with p_T^{miss}.

The most sensitive analysis bins depend on the LQ mass and decay products. Fig. 1 shows the M_{T2} distribution for data, the background predictions, and a hypothetical LQ_V signal in the two most sensitive search categories for an LQ of mass 1500 GeV decaying with unity branching fraction to a top quark and a neutrino. Both categories require $H_T > 1500\,\text{GeV}$ and 4–6 jets. The category shown in the left plot requires exactly one b-tagged jet, while in the right, two are required. No significant deviations from the SM prediction are observed, taking into account all of the analysis bins. Simultaneous likelihood fits of all bins are performed, and the results are interpreted as limits on the production cross sections of hypothetical scenarios of leptoquark pair production.

3 Simulated samples

Monte Carlo (MC) simulated samples are used in the estimation of background from some SM processes, to assess systematic uncertainties in prediction methods that rely on data, and to calculate the selection efficiency for signal models. The details of the MC samples used for SM processes are given in Ref. [51].

Signal samples are generated with the MADGRAPH5_aMC@NLO v2.3.3 generator [63] at leading order (LO) precision in perturbative QCD, including up to two additional partons in the matrix element calculations. The NNPDF3.0 LO [64] parton distribution functions (PDFs) are used in the event generation. Parton showering and fragmentation are performed using the PYTHIA v8.212 [65] generator and the CUETP8M1 tune [66]. A double counting of the partons generated with MADGRAPH5_aMC@NLO and those with PYTHIA is removed using the MLM [67] matching scheme.

To improve on the modeling of the multiplicity of additional jets from initial state radiation (ISR), we weight the signal MC events based on the number of ISR jets (N_j^{ISR}). The weighting factors are obtained from a control region enriched in $t\bar{t}$, obtained by selecting events with two leptons and exactly two b-tagged jets. The factors are chosen to make the jet multiplicity agree with data, and they vary between 0.92 for $N_j^{\text{ISR}} = 1$ and 0.51 for $N_j^{\text{ISR}} \geq 6$. We take one half

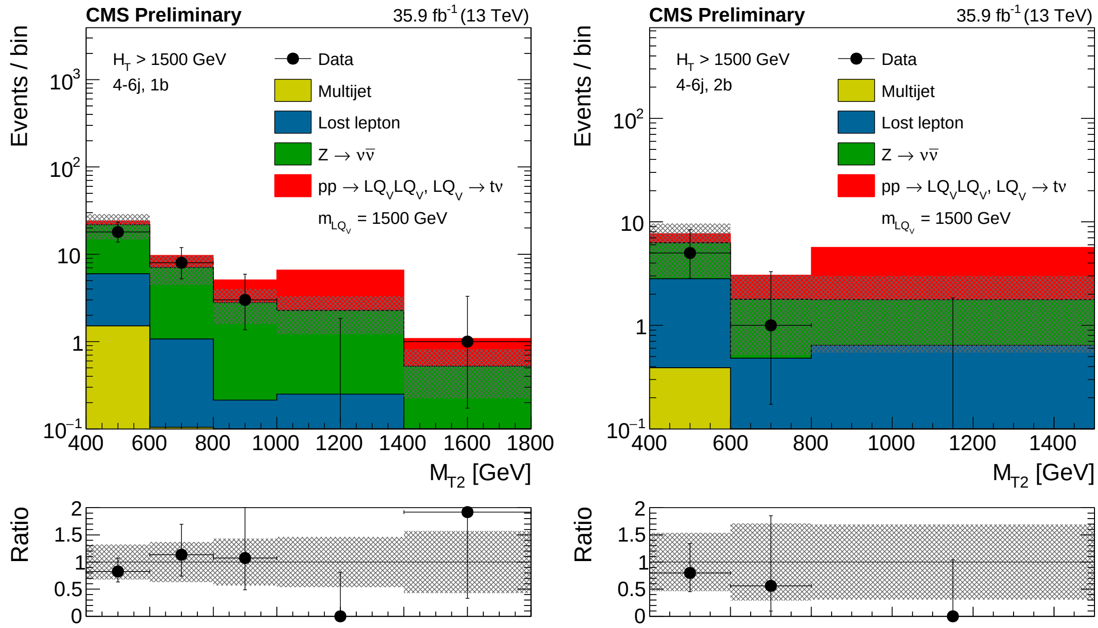

Figure 1: Distributions of M_{T2} showing data, the background predictions, and a hypothetical LQ_V signal with LQ mass of 1500 GeV decaying with unity branching fraction to tν. The rightmost bin in each plot also includes events with larger values of M_{T2}. The hatched band shows the uncertainty in the background prediction including both statistical and systematic sources. The lower pane of each plot shows the ratio of observed data over predicted background. The categories require $H_T > 1500$ GeV, 4–6 jets, and (left) exactly one b-tagged jet or (right) exactly two b-tagged jets.

of the deviation from unity as the systematic uncertainty in these reweighting factors, to cover for differences between $t\bar{t}$ and signal production.

Additional simultaneous proton-proton interactions (pileup) are generated with PYTHIA and superimposed on the hard collisions. The response of the CMS detector for new physics signals is performed using the CMS fast simulation package [68]. All simulated events are processed with the same chain of reconstruction programs as used for collision data. Corrections are applied to simulated samples to account for differences between the trigger, b tagging, lepton and photon selection efficiencies, and the modeling of p_T^{miss} measured in data and the fast simulation.

The generated signal samples used for this interpretation consist of simplified models [69–73] of squark pair production, with the squark decaying to a quark of the same flavor and a neutralino with mass 1 GeV. Three samples are generated with different squark flavors: "light" squarks with an equal fraction of each of ($\tilde{u}$,$\tilde{d}$,$\tilde{s}$,$\tilde{c}$), bottom squarks, and top squarks. Compared to Ref. [51], higher squark masses are considered, up to 2300 GeV.

Samples of pair production of LQ_S and LQ_V are also generated for a limited number of LQ mass values, to verify that the acceptance of the analysis at generator level is consistent with the squark samples used. Scalar LQ samples are generated with the PYTHIA v8.2052 [65] generator, using the NNPDF2.3 LO [74] PDFs. Vector LQ samples are generated with the MadGraph5_aMC@NLO v2.3.3 generator [63] at LO precision in perturbative QCD, including up to two additional partons in the matrix element calculations and using the MLM matching scheme. The NNPDF3.1 LO [75] PDFs are used in the vector LQ event generation. The kinematics of the generated squark samples have been compared to those in LQ_S and LQ_V pair production samples. The acceptance of the analysis, both the baseline selection and the kinematic requirements for the most sensitive signal bins, was found to be consistent within statistical uncertainties of $\sim$10% for the squark, LQ_S, and LQ_V samples. As such, no additional systematic uncertainty in acceptance is assigned for using the squark samples to set limits on LQ pair production.

The cross sections for LQ_S pair production are computed to next-to-leading-order (NLO) precision in perturbative QCD following Ref. [24] and using the NNPDF2.3 NLO PDF set. The cross sections for LQ_V pair production are computed to LO precision, also following Ref. [24] and using the NNPDF2.3 LO PDF set. The vector LQ model has additional free parameters beyond the LQ mass. In particular, we use the model of Ref. [24] developed to explain anomalous results in flavor physics. We assume $\kappa = 1$, and we further assume $g_{t_L} = g_{b_L} = 0.1$, though these latter parameters do not affect the pair production cross section or the acceptance. The uncertainties in cross section calculations arise from PDF variations and from renormalization and factorization scale variations. For PDF uncertainties, the NNPDF2.3 PDF set variations are used. For scale uncertainties, renormalization and factorization scales are varied up and down by a factor of two with respect to the nominal value.

4 Interpretation

The search results of Ref. [51] are interpreted to place cross section limits on LQ pair production as a function of the LQ mass. The following sources of uncertainty in the signal acceptance and efficiency are evaluated and taken to be fully correlated across all analysis bins: determination of the integrated luminosity, trigger efficiency, lepton identification and isolation efficiency, lepton efficiency modeling in fast simulation, b tagging efficiency, jet energy scale, modeling of p_T^{miss} in fast simulation, modeling of ISR, simulation of pileup, and variations of the generator factorization and renormalization scales. The uncertainty in the signal acceptance from PDF variations is not considered as it is found to be highly redundant with the uncertainty assigned in the modeling of ISR. The statistical uncertainty of the simulated signal samples is taken as being uncorrelated in every bin. The total uncertainty in signal acceptance is typically around 5–25% in the most sensitive analysis bins.

Exclusion limits at the 95% confidence level (CL) on the cross section of LQ pair production are shown in Fig. 2. In each case, we assume that there is only one LQ state within mass reach of the LHC, with any other potential LQ states having masses too large to be produced. We assume that the LQ decays with unity branching fraction to a neutrino and a single type of quark, as specified below. In the simulated samples used to determine signal acceptance, and for the cross sections displayed, we consider only LQ pair production and not single LQ production.

We first consider LQ decays to a neutrino and a light quark, which can be any single one of u, d, s, or c. The observed (expected) limit on the LQ mass is 980 (940) GeV for LQ_S and 1790 (1830) for LQ_V, corresponding to an LQ pair production cross section of 0.0059 (0.0080) pb for LQ_S and 0.0011 (0.0009) pb for LQ_V. As the analysis includes categorization in the number of b-tagged jets, we check whether the cross section limit obtained for an LQ decaying to a neutrino and a c quark differs significantly from an LQ decaying to a neutrino and one of the u, d, or s quarks. The cross section limit differs by at most 10%, resulting in a negligible impact on the mass limit, and we therefore do not produce separate limit results for these cases. For LQ decays to a bottom quark and a neutrino, the limit is 1100 (1070) GeV for LQ_S and 1810 (1800) GeV for LQ_V, corresponding to an LQ pair production cross section of 0.0024 (0.0030) pb and 0.0010 (0.0011) pb, while for LQ decays to a top quark and a neutrino, the limit is 1020 (980) GeV for LQ_S and 1780 (1740) GeV for LQ_V, corresponding to an LQ pair production cross section of 0.0043 (0.0059) pb and 0.0012 (0.0015) pb.

The model proposed in Refs. [23, 24] as a coherent explanation of the flavor physics anomalies predicts an LQ_V with 50% branching fraction to each of the tν and bτ final states. As our analysis removes events with charged leptons, including hadronically decaying τ leptons, we only consider the 25% of events where both leptoquarks decay to tν to place constraints on this model. We show the theoretical prediction for this branching fraction as a separate curve in Fig. 2(lower), and we find an observed (expected) limit on the LQ_V mass of 1530 (1460) GeV, corresponding to a value of 0.0013 (0.0021) pb for the product of the LQ pair production cross section and the square of the branching fraction.

5 Summary

The CMS search for jets and missing transverse momentum using the M_{T2} variable has been reinterpreted to place limits on leptoquark (LQ) pair production, where the LQ decays with unity branching fraction to a quark and a neutrino. The search uses proton-proton collision data at $\sqrt{s} = 13$ TeV, recorded with the CMS detector in 2016 and corresponding to an integrated luminosity of 35.9 fb^{-1}. Compared to previous CMS results, both scalar and vector leptoquarks are considered, as well as higher leptoquark mass values, and for the first time, leptoquark decays to a light quark (any single one of u, d, s, or c) and a neutrino are considered. Assuming that there is only one LQ state within mass reach of the LHC, for scalar (vector) leptoquarks decaying to a light quark and a neutrino, masses below 980 (1790) GeV have been excluded by the observed data, corresponding to a pair production cross section of 0.0059 (0.0011) pb. For leptoquarks decaying to a bottom quark and a neutrino, masses below 1100 (1810) GeV have been excluded, corresponding to a cross section of 0.0024 (0.0010) pb, while assuming decays to a top quark and a neutrino, masses below 1020 (1780) GeV have been excluded, corresponding to a cross section of 0.0043 (0.0012) pb. In the model of Refs. [23, 24], a vector leptoquark with 50% branching fraction to a top quark and a neutrino is predicted. We exclude masses below 1530 GeV for such a state with our observed data, providing the strongest constraint to date in this model. At high LQ mass values, these results improve the upper limits on LQ pair production cross sections by as much as a factor of 2.8 over the extrapolation assumed in Ref. [45].

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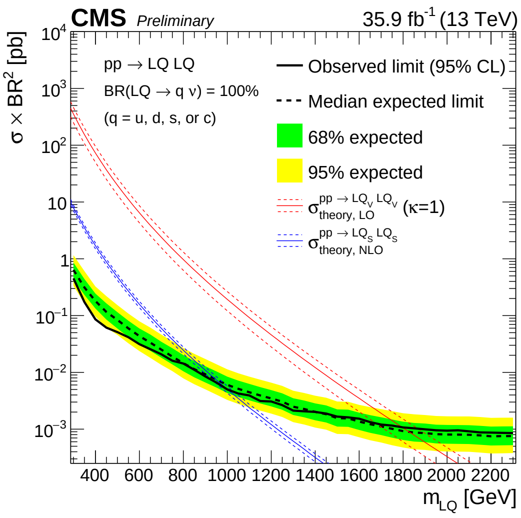

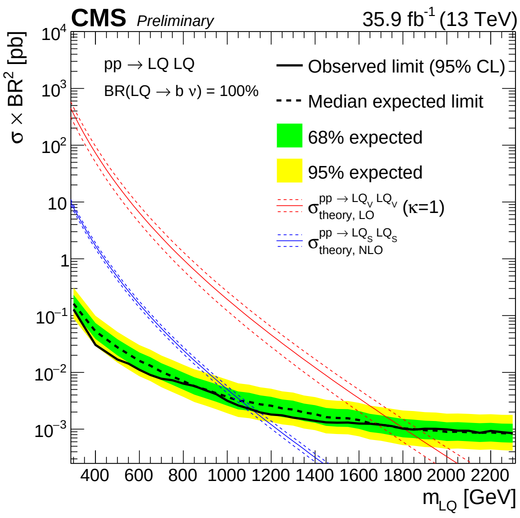

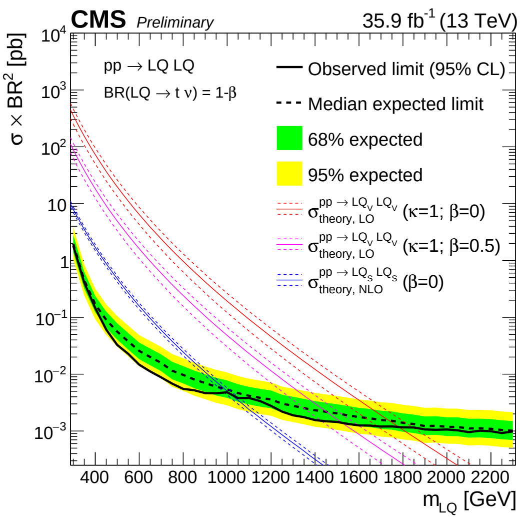

Figure 2: The 95% CL upper limits on the production cross sections as a function of LQ mass for LQ pair production decaying with unity branching fraction to a neutrino and: (upper left) a light quark (one of u, d, s, or c), (upper right) a bottom quark, and (lower) a top quark. The solid black line represents the observed exclusion. The dashed black line represents the median expected exclusion. The inner (green) band and the outer (yellow) band indicate the regions containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis. The blue lines show the theoretical cross section for scalar LQ pair production with its uncertainty, and the red lines show the same for vector LQ pair production. (lower) Also shown in magenta is the product of the theoretical cross section and the square of the branching fraction, for vector LQ pair production assuming a 50% branching fraction to a top quark and a neutrino.

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