Searches for the pair production of scalar leptoquarks at CMS

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Abstract. Results are presented for searches for leptoquark (LQ) pair production using 1.8 - 5.0 fb$^{-1}$ of proton-proton collision data at $\sqrt{s} = 7$ TeV collected by the CMS detector at the LHC. First- and second-generation scalar leptoquarks are searched for in final states with either two leptons and two jets ($\ell\ell jj$) or one lepton, missing transverse energy ($E_T$, and two jets ($\ell\nu jj$). Third-generation leptoquarks are searched for in the final state with two b-tagged jets and large $E_T$ ($\nu\nu bb$). No significant excess beyond the standard model predictions is found and 95% confidence level (CL) upper limits are set on the scalar leptoquark pair production cross section in each channel. Limits are calculated for a range of leptoquark mass and for a variable branching fraction ($\beta$) of the leptoquark to a charge lepton and a quark. These limits are the most stringent to date.

1. Introduction
Leptoquarks (LQ) are hypothetical particles that carry both baryon number and lepton number and couple to both quarks and leptons. They are predicted by grand unified theories [1, 2], composite models [3], extended technicolor models [4, 5, 6], and superstring-inspired models [7]. LQs are color triplets with fractional electric charge and can be either scalar or vector. They couple to a lepton and a quark with a coupling strength $\lambda$, and decay to a charged lepton and a quark with an unknown branching fraction $\beta$. To satisfy constraints from bounds on flavor-changing neutral currents and from rare pion and kaon decays [3, 8], it is assumed that LQs couple to quarks and leptons of a single generation. LQs are classified as first-, second-, or third-generation, corresponding to the generation of leptons to which they couple. The dominant processes for LQ pair production at the LHC occur via gluon-gluon fusion and quark-antiquark annihilation, and have been calculated at next-to-leading order (NLO) [9].

Scalar leptoquark pair production is searched for with proton-proton collisions with a center-of-mass energy $\sqrt{s} = 7$ TeV, taken at the Large Hadron Collider (LHC) and recorded with the Compact Muon Solenoid (CMS) Detector, described in detail elsewhere [10]. The data samples used for first- and second-generation LQ searches correspond to an integrated luminosity of 5.0 fb$^{-1}$, and the third-generation search uses 1.8 fb$^{-1}$. First- and second-generation searches are performed in two final states. The $\ell\ell jj$ final state requires two high-$p_T$ jets and two high-$p_T$ muons or electrons. The $\ell\nu jj$ final state requires two high-$p_T$ jets, large $E_T$, and one high-$p_T$ muon or electron. Third-generation LQs are searched for in the $\nu\nu bb$ final state requiring large $E_T$ and two high-$p_T$ b-tagged jets.
2. Event Reconstruction and Object Identification
In the $eejj$ channel, events are required to pass double-electron or double-photon triggers with a $p_T$ threshold of 33 GeV. Triggers for the $evjj$ channel require an electron, $E_T$, and two jets, with transverse energy thresholds of 17 - 30 GeV, 15 - 20 GeV, and 25 - 30 GeV respectively. The $\mu j j$ and $\nu j j$ channels require a single-muon trigger with the muon having $|\eta| < 2.1$ and $p_T > 40$ GeV. The search in the $\nu \nu b b$ channel uses a set of triggers based on the razor variables [11, 12] described further in Section 3.

For $\ell\ell jj$ and $\ell\nu jj$ searches, electrons are selected [13] with $p_T > 40$ GeV and $|\eta| < 2.5(2.2)$ in the $eejj$($evjj$) channel, omitting the barrel-endcap transition region $1.44 < |\eta| < 1.57$. Electrons must have a cluster in the electromagnetic calorimeter (ECAL) that is spatially matched to a reconstructed track in the central tracking system, and a shower shape indicative of an electromagnetic shower. Electrons must also be isolated from additional energy deposits in the ECAL and from tracks not belonging to the electron itself. The electron track must have hits in all inner tracker layers. Muons are required to have $p_T > 40$ GeV and $|\eta| < 2.1$, and to be isolated such that the sum of the $p_T$ of all tracker tracks within a cone of $\Delta R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2} < 0.3$ around the muon track, excluding the muon track, is less than 0.1. The muon candidates must contain at least 10 hits in the silicon tracker and one hit in the pixel detector, and have a transverse impact parameter with respect to the primary vertex of less than 2 mm.

For the $\nu \nu b b$ analysis, electrons must have $p_T > 20$ GeV and $|\eta| < 2.5$, with pile-up corrected combined isolation less than 15% of the electron $p_T$. Additional requirements ensure the quality of the shower shape and track-cluster matching in the $\eta$ and $\phi$ directions. Muons are selected as for the $\ell\ell jj$ and $\ell\nu jj$ channels, but requiring $|\eta| < 2.4$ and using an isolation considering calorimetric energy deposits and tracker tracks, with a threshold of 15% of the muon $p_T$.

In the $\ell\ell jj$ and $\ell\nu jj$ searches, jets are reconstructed using a particle-flow algorithm [14], which identifies and measures stable particles by combining information from all CMS sub-detectors. Jets reconstruction uses the anti-$k_T$ [15] algorithm with $R = 0.5$. In the $\nu \nu b b$ search, jets are reconstructed from calorimeter energy deposits using the infrared-safe anti-$k_T$ algorithm with $R = 0.5$. In the $\ell\ell jj$ ($\ell\nu jj$) channel, jets are required to have $p_T > 30(40)$ GeV and be separated from leptons by $\Delta R > 0.3$. Jets energies are calibrated using the methods in [16]. All channels use $E_T$ reconstructed with particle-flow algorithm. The $\ell\nu jj$ analysis requires $E_T > 55$ GeV.

The $\nu \nu b b$ analysis also requires that jets are tagged as originating from b-quarks (b-tagged) with the Track-Counting High-Efficiency algorithm [17], which identifies jets with 2 good tracks and a three-dimensional impact-parameter significance greater than an optimized threshold. The efficiency of b-jet identification is estimated to be $0.76 \pm 0.01$.

3. Event Selection
3.1. Event selection in the $\ell\ell jj$ and $\ell\nu jj$ channels
For $\ell\ell jj$ and $\ell\nu jj$ searches, events are initially selected requiring the presence of the four leptoquark decay products in each channel. The $\ell\ell jj$ channel requires two electrons or muons and two jets. The $eejj$ ($\mu jj$) analysis requires a dilepton invariant mass ($M_{\ell\ell}$) of at least 60 (50) GeV. Additionally, the scalar sum of the transverse momenta of the decay products, $S_T^{\ell\ell} \equiv p_T(\ell_1) + p_T(\ell_2) + p_T(j_1) + p_T(j_2)$, must be at least 250 GeV.

The $\ell\nu jj$ channel requires two jets, exactly one lepton, and $E_T$. The leading jet and $E_T$ must be separated by $\Delta R > 0.5$, and the lepton and $E_T$ must be separated by $\Delta R > 0.8$. The transverse mass between the lepton and missing transverse energy ($M_T^{\ell}$) must be greater than 50 GeV, and $S_T^{\ell\nu} \equiv p_T(\ell) + E_T + p_T(j_1) + p_T(j_2)$ must be greater than 250 GeV.

A set final selection optimized thresholds is determined for each leptoquark mass by maximizing the expected signal significance $S/\sqrt{S+B}$. In the $\ell\ell jj$ channel, masses range from 250–900 GeV, and variables thresholds consist of $S_T^{\ell\ell} > 330–920$ GeV, $M_{\ell\ell} > 100–150$ GeV, and the smallest of the two lepton-jet invariant masses $M_{\ell j}^{min} > 60–520$ GeV. In the $\ell\nu jj$ channel,
masses range from 250–850 GeV, and variable thresholds consist of $S_T^F > 450–1000$ GeV, $E_T > 100–240$ GeV, and the lepton-jet invariant mass $M_{\ell j} > 150–540$ GeV. For the purpose of calculating lepton-jet invariant masses, leptons are matched to jets in the $\ell\ell jj$ ($\nu jj$) channel by choosing the lepton-jet pairing which minimizes the difference in lepton-jet invariant mass (lepton-jet transverse mass) between the pairs. The sets of optimized thresholds in each channel are detailed further in [18].

3.2. Event selection in the $\nu \nu bb$ channel

In the $\nu \nu bb$ search, events are selected using the razor variable method [11, 12]. Each event is split into two geometric regions, and all of the jets in each region are considered as a singular mega-jet. This defines the dijet topology used to calculate the razor variables, with megajet four-momenta $\vec{p}_1$ and $\vec{p}_2$. The razor mass ($M_R$) is defined as:

$$M_R \equiv \sqrt{(|\vec{p}_1| + |\vec{p}_2|)^2 - (p_1^z + p_2^z)^2},$$

and the razor transverse mass ($M_R^T$) is defined as:

$$M_R^T \equiv \sqrt{E_T(p_1^T + p_2^T) - E_T(p_1^T + p_2^T)}.$$

Together, $M_R$ and $M_R^T$ define the razor dimensionless ratio, $R \equiv M_R^T/M_R$.

Initial event selection requires a pair of b-tagged jets, large $E_T$, no isolated leptons, and at least two jets with $p_T > 60$ which may include the b-tagged jets. The razor Mass $M_R$ is required to be greater than 400 GeV, and $R^2$ thresholds are places at 0.25, 0.30, and 0.35 for LQ mass hypotheses greater than 200 GeV, 330 GeV, and 340 GeV respectively.

4. Background Modeling and Systematic Uncertainties

4.1. Backgrounds in the $\ell\ell jj$ and $\ell\nu jj$ channels

The $\ell\ell jj$ and $\ell\nu jj$ channel searches rely on MC simulation and data control samples for background estimation. The MC simulated samples used to estimate the contribution from SM background processes are $t\bar{t}$+jets events, generated with MADGRAPH [19, 20]; single-top events ($s$, $t$, and $tW$ channels), generated with POWHEG [21]; $Z/\gamma^*+jets$ events and $W+jets$ events, generated with SHERPA [22]; and diboson events, generated with PYTHIA [23].

In the $\ell\ell jj$ channel, the $Z/\gamma^*+jets$ contribution is estimated with MC. A rescaling factor is estimated in the Z-dominated region $80 < M_{\ell\ell} < 100$ GeV. The $t\bar{t}$ contribution is estimated entirely from data using a control sample of events with one electron, one muon, and at least two jets, weighted to account for the differences in degeneracy, reconstruction and identification efficiency, and trigger acceptance.

In the $\ell\nu jj$ channel, the $W+jets$ and $t\bar{t}$ contributions are estimated with MC. Rescaling factors are estimated in the region $50 < M_T^B < 110$ GeV. A W-dominated region with less than four jets is used for the W rescaling factor, whereas a $t\bar{t}$-dominated region of at least four jets is used for the $t\bar{t}$ rescaling.

Systematic uncertainties are considered for limit setting. They include integrated luminosity (2.2%); background normalization, based on the statistical uncertainties in the MC and data control samples; background shape, using MC samples with the factorization and renormalization scales and matrix element-parton shower matching threshold varied by a factor of two; number of pileup interactions (8%); momentum and energy scales, including jet energy (4%), muon momentum (1%), and electron energy (1-3%); momentum and energy resolutions, including jet energy (5-14%), muon momentum (4%), and electron energy (1-3%); parton distribution functions; lepton reconstruction, identification, and isolation efficiencies; and trigger acceptance.
4.2. Backgrounds in the ννbb channel

For the ννbb channel search, the shapes and scales of the final distributions of M_R and R^2 are determined for background processes to estimate final background contributions. The shape of M_R is well-described by two exponentials with different slope parameters(S_i) [11, 12], which relates to an R^2 threshold R_{cut} as S_i = A_i + B_i × R_{cut}. The final form of the M_R fit is given as:

\[ F(M_R) = e^{-(A_1+B_1×R_{min}^2)}M_R + f × e^{-(A_2+B_2×R_{min}^2)}M_R \]  

Events are considered in 3 disjoint samples to estimate [24] the R^2 and M_R shape and scale of the major backgrounds: heavy flavor multijets, t\bar{t}, and W/Z+b-jets. The hadronic sample contains no leptons. The muon and electron samples contain events with one muon or electron with p_T > 20 GeV, with leptons treated as neutrinos for the calculation of the razor variables. The muon and electron samples are depleted of LQ signal, but have the same kinematic properties of the background in the hadronic sample.

The lepton samples with at least two b-jets in heavy-flavor-enriched MADGRAPH MC determine the shape of the W+b-jets and Z+b-jets contributions. The shape of the t\bar{t} contribution is determined from the muon sample with at least two b-jets in real data. The contribution from heavy-flavor multijets is estimated with a muon sample in data, using a loosened muon isolation condition to enrich the sample with multijet events. Normalization of the background distributions is determined in a side-band of the signal-like hadronic sample requiring 0.2 < R^2 < 0.25 and only one b-jet.

Systematic uncertainties considered for limit setting include integrated luminosity (4.5%); trigger efficiencies (2-3%); parton distribution functions; b-tagging efficiency (10%); background shape, from variation within uncertainty on the fit parameters of equation 3; and jet energy scale and resolution, for W and Z backgrounds estimated from MC.

5. Results

In all channels, the observed number of events is in good agreement with the standard-model background expectation. Results are expressed as a 95% CL upper limit on the LQ cross-section using the CL_s modified frequentist approach [25, 26]. The results of the ℓℓjj and ℓνjj searches are in Figures 1 and 2. The results of the ννbb search is in 3. The ℓjj channel searches exclude first-generation (second-generation) LQs with masses below 830 (840) GeV, assuming \( \beta = 1 \). Combining the ℓjj and ℓνjj results, first-generation (second-generation) LQs with masses below 640 (650) GeV are excluded, assuming \( \beta = 1/2 \). The third-generation search excludes LQs with masses below 350 GeV, assuming \( \beta = 0 \). These are the most stringent limits to date.

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Figure 2. The limits on LQ Mass versus branching fraction \( \beta \), using the combination of the \( \ell\ell jj \) and \( \ell\nu jj \). (Left) The \( e\ell jj+e\nu jj \) channel limits. (Right) The \( \mu\ell jj+\mu\nu jj \) channel limits.
Figure 3. The limits in the $\nu\nu bb$ channel. (Left) The limit on LQ cross-section versus mass, assuming $\text{Br}(LQ \rightarrow b\nu_\tau) = 100\%$. (Right) The limit on $\text{Br}(LQ \rightarrow b\nu_\tau)$ versus LQ mass.

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