

Search for leptoquarks and compositeness at CMS

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Leptoquarks are bosons whose discovery would be a sign of new physics. Fermion compositeness would give rise to excited states of quarks and leptons which would radiatively decay to standard-model fermions. This paper presents searches for leptoquarks and for fermion compositeness, focusing on the recent results obtained using data collected at Run-II of the LHC.

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1. Introduction

Leptoquarks and fermion compositeness are two manifestations of Beyond the Standard Model (BSM) physics. Leptoquarks (LQ) are predicted by a number of different BSM scenarios. A boson which couples to both quarks and leptons, a leptoquark would carry baryon number, lepton number, fractional electron charge, and could either be a scalar (spin 0) or vector (spin 1) particle. In this paper, we concentrate on the case of leptoquark pair production at the LHC, which proceeds primarily through gluon-gluon fusion, with a small contribution from quark-antiquark annihilation. Scalar pair-production of leptoquarks has negligible dependence on the LQ-quark-lepton coupling (λ) and thus leptoquark searches are considered λ -independent. Experimental results from searches for rare processes suggest that a particular leptoquark couples to only a single lepton/quark generation, without mixing between generations. Leptoquarks decay to a lepton and a quark of their generation with branching ratio β , giving rise to lepton-jet resonances. Here, we present results of searches for leptoquarks in all three generations.

Fermion compositeness is an idea which if true would help answer important open questions in the standard model, such as the mass hierarchy of quarks and leptons. One scenario proposed by Pati, Salam, and Strathdee, posits constituents called preons, bounded by a new strong interaction of scale Λ [1]. Quarks and leptons are then taken as bound states of preon pairs. In this case, it would be possible to observe excited states of fermions. Here we focus on excited fermions produced via a four-fermion contact interaction. This interaction is described by an effective Lagrangian

$$\mathcal{L}_{CI} = \frac{g^{*2}}{2\Lambda^2} j^\mu j_\mu \quad (1.1)$$

where g^{*2} is taken as 4π and j^μ is the fermion current. An excited fermion will decay to its same flavor standard model fermion (ground state), emitting a photon. The analysis presented here searches for the result of this decay, namely two same-flavor leptons (electrons or muons) and a photon in the final state.

The leptoquark searches and the search for compositeness were carried out using pp collision data at $\sqrt{s} = 13$ TeV collected with the CMS detector at the CERN LHC [2].

2. Leptoquark Searches

2.1 First and Second Generation Searches

As noted above, the leptoquark searches presented here are divided by generation. The final states of the two leptoquark decays are denoted as $\ell\ell jj$, where ℓ represents the lepton and j the jet arising from the quark. For the first and second generation analyses, the results presented here are for the $eejj$ and $\mu\mu jj$ channels only. The third generation analyses look for two different final state topologies: (1) both τ leptons decaying hadronically and (2) one τ decaying hadronically and the other to a lighter lepton.

The first (second) generation analysis looks for two isolated electrons (muons) with transverse momentum $p_T > 50$ GeV and two or more jets with $p_T > 50$ GeV. Both use pp collision data collected in 2015, amounting to 2.6 fb^{-1} (2.7 fb^{-1}) for the first (second) generation analysis [3, 4]. A single electron (first gen.) or single muon (second gen.) trigger is used. The discriminating

variables are the S_T , which is defined as the scalar p_T sum over the leading two jets and the two leptons and required to be greater 300 GeV; the minimum reconstructed lepton-jet invariant mass $M_{\ell j}^{\min}$; and the dilepton invariant mass $M_{\ell\ell}$. The $M_{\ell j}^{\min}$ is calculated using the lepton-jet pairing which minimizes the difference between the two $M_{\ell j}$ values. The major standard model backgrounds include Z/γ^* +jets and $t\bar{t}$ +jets, with smaller contributions from W +jets, single top quark production, QCD multijets, and γ +jets. The Z/γ^* +jets shapes are taken from Monte Carlo (MC) simulation, and are normalized in a control region around the Z boson peak. The $t\bar{t}$ +jets background is derived completely from a $e\mu jj$ data sideband in the second generation, while this sideband is used to normalize the MC shape for the first generation analysis. The QCD multijet background is derived using a data-driven method in the first generation analysis, which measures the probability for a jet to be misidentified as an electron, using data collected with single photon triggers.

The background prediction is validated using the loose preselection described above. Given the good agreement observed between data and background prediction at the preselection level, thresholds of the three discriminating variables are optimized by scanning over the full parameter space and maximizing the expected discovery significance. This process is applied to each leptoquark mass hypothesis, and the resulting thresholds as a function of leptoquark mass are smoothed to remove any fluctuations.

No evidence for leptoquarks is seen in the data. Upper limits are set on the scalar leptoquark production cross section σ . The 95% confidence level upper limits on $\sigma \times \beta^2$ along with the predicted next-to-leading order production cross sections are shown in Fig. 1. The intersection of

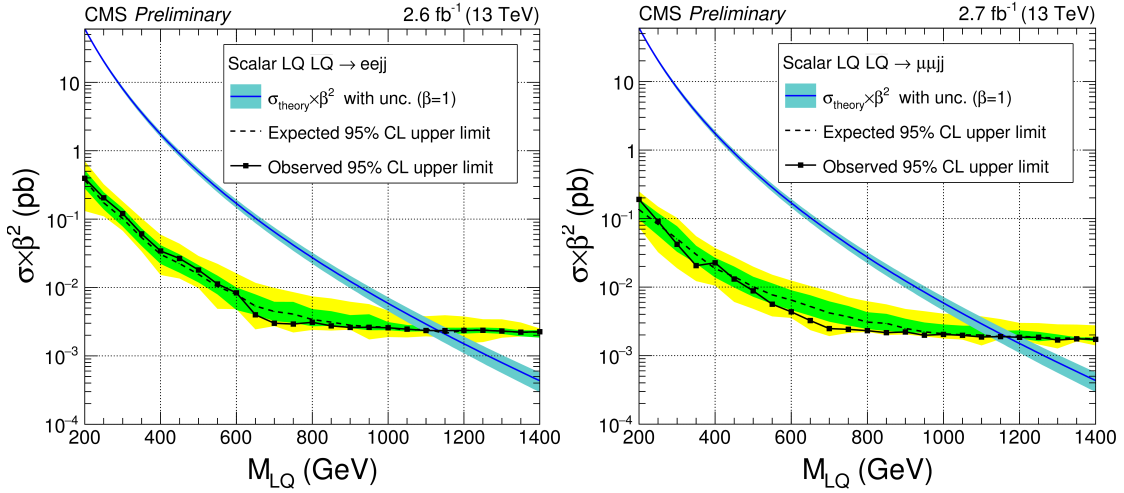


Figure 1: Upper limits at the 95% confidence level on the scalar leptoquark pair production cross section σ times β^2 for first generation (left) and second generation (right) leptoquarks. Observed (solid lines) and expected limits (dashed line; 1σ band in green; 2σ band in yellow) along with the theoretical prediction at next-to-leading order.

the theoretical prediction and the upper limits yields a lower limit on the leptoquark mass. For the first generation search, leptoquarks with masses less than 1130 (920) GeV are excluded for $\beta = 1.0$ ($\beta = 0.5$), while for the second generation search, masses less than 1165 (960) GeV are excluded

for $\beta = 1.0$ ($\beta = 0.5$). These improve on the 8 TeV limits set by CMS [5], as well as the ATLAS results using 3.2 fb^{-1} of pp collision data at $\sqrt{s} = 13 \text{ TeV}$ collected in 2015 [6].

2.2 Third Generation Searches

The third generation leptoquark searches are conducted as part of a search for heavy right-handed neutrinos and W bosons, in the scenario of the Left-Right Symmetric Standard Model [7]. In such models, heavy right-handed neutrinos (e.g., N_τ) arise as partners of the standard model neutrinos through a seesaw mechanism. We examine the case in which the W_R decays to N_τ and τ , while N_τ decays to τ and W_R , the latter decaying to two quarks. In the final state there are thus two τ leptons and two jets. The decays of pair-produced third-generation leptoquark to a pair of τ leptons and b quarks shares this final state. Here we focus on the leptoquark search.

There are two separate channels examined: two hadronically-decaying τ lepton candidates (τ_h) and at least two jets [9]; and one τ_h and one τ lepton which decays to an electron or a muon (τ_ℓ) along with at least two jets [8]. The jets are required to have $p_T > 50 \text{ GeV}$ and the τ_h candidates to have $p_T > 50$ to 70 GeV , depending on the analysis and channel. Spatial separation requirements are imposed: jets must be separated from the τ candidates and other leptons; the τ_ℓ and light lepton must be separated from each other in the $\tau_h \tau_\ell$ analysis; and the two τ_h must be separated from each other in the $\tau_h \tau_h$ analysis. In the context of the leptoquark search, the S_T is again examined, here defined as the scalar p_T sum of the two τ lepton candidates, the two highest- p_T jets in the events, and the missing transverse energy (MET).

In the case of the $\tau_h \tau_h$ analysis, a double τ lepton trigger is used. The invariant mass of the τ lepton pair is required to be over 100 GeV , and the missing transverse energy above 50 GeV . Here, QCD multijets are the dominant background; therefore, an ABCD method is used to estimate it from the data, using sidebands of MET and the amount of τ lepton isolation. Other backgrounds are derived from MC simulation. This analysis uses 2.1 fb^{-1} of pp collision data at $\sqrt{s} = 13 \text{ TeV}$ collected in 2015.

For the $\tau_\ell \tau_h$ analysis, the reconstructed mass of the τ_h -jet system is required to be above 250 GeV , and one jet must be identified as having arisen from a b -quark hadronization. The events are collected using triggers which require a single electron or a single muon with a p_T threshold of 45 GeV . The $t\bar{t}$ background is dominant here; it is taken from MC simulation, but validated using a sample of $e\mu$ events from the data; other backgrounds are taken from MC simulation. The data used here corresponds to 12.9 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$ collected in 2016.

Data and background agree well at final selections in the signal region. Upper limits on the third-generation leptoquark production cross section times branching ratio squared are set. The limits at 95% confidence level as a function of leptoquark candidate mass are shown in Fig. 2. Leptoquarks with masses less than 740 GeV are excluded by the $\tau_h \tau_h$ analysis; while the limit is at 900 GeV for the $\tau_\ell \tau_h$ analysis.

3. Compositeness and Excited Leptons

As described above, this analysis searches for two same-flavor leptons and a photon in the final state. The data used in this analysis was collected in 2015 and corresponds to 2.7 fb^{-1} with $\sqrt{s} = 13 \text{ TeV}$ [10]. To do this, events are collected with double electron and double muon triggers;

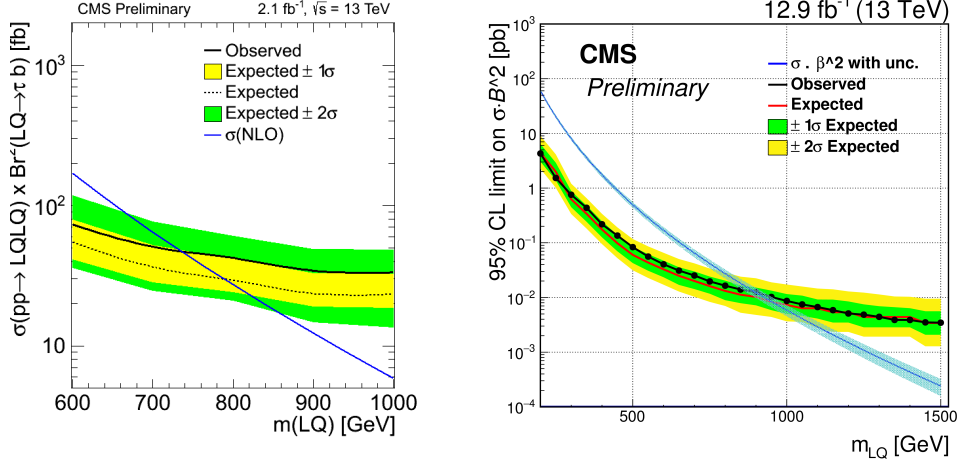


Figure 2: Upper limits at the 95% confidence level on the scalar third-generation leptoquark pair production cross section times branching ratio squared for the $\tau_h \tau_h$ channel (left) and the combination of the $e \tau_h$ and $\mu \tau_h$ analyses (right). Observed (solid lines) and expected limits (dashed line; 1σ band in green; 2σ band in yellow) along with the theoretical prediction at next-to-leading order.

the reconstructed electrons and muons must have $p_T > 35$ GeV to be above trigger turn-ons. Next, the event must contain a photon, and it must be spatially separated from the leptons. Drell-Yan background is suppressed by requiring a Z peak veto: dilepton invariant mass above 116 GeV. Other backgrounds (e.g., top pair production, diboson) are estimated using MC simulation, with the exception of QCD multijet events which are misidentified as a photon or electron; these are estimated using a data-driven technique. Then two $\ell\gamma$ invariant masses are calculated, which correspond to the possibilities of the lepton coming from the decay of the excited lepton or produced in association with the excited lepton. These are referred to as $M_{\ell\gamma}^{\min}$ and $M_{\ell\gamma}^{\max}$, sorted by mass. Plotting them against each other, the signal forms an “L” shape near the excited lepton mass, while the background tends to cluster at low values. This feature is used to create search windows in two dimensional regions of $M_{\ell\gamma}^{\min}$ and $M_{\ell\gamma}^{\max}$.

No significant excess of data over background is observed in the signal region. Limits are set on excited lepton production cross section times branching ratio and the compositeness scale. In the electron channel, excited lepton masses of less than 2.8 TeV are excluded, and a compositeness scale below 14 TeV is excluded; while in the muon channel, excited lepton masses of less than 3.0 TeV are excluded and the compositeness scale is constrained to be above 15 TeV.

4. Conclusions

The results presented above for both leptoquark and excited lepton searches improve upon previous limits set using LHC collision data. These analyses will be updated using the full amount of data collected in 2016, which should tighten constraints on the models examined above.

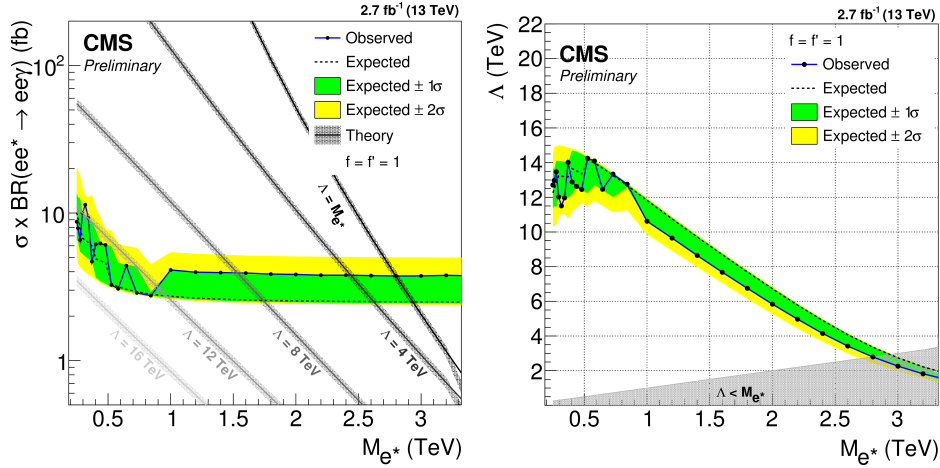


Figure 3: Limits on the excited lepton production cross section times branching fraction for the electron channel (left) and muon channel (right).

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