Search for leptoquarks and heavy neutrino

James Francis Hirschauer for the CMS Collaboration

Abstract

Many theories of new physics predict the existence of new particles decaying to leptons and hadronic jets, including leptoquarks of grand unified theories, heavy neutrinos and right-handed $W_R$ bosons of left-right symmetric extensions of the standard model, heavy Majorana neutrinos of see-saw mechanism, and scalar quarks in supersymmetric theories that violate $R$-parity. The results of searches for these particles, in final states including jets, electrons, muons, and tau leptons, are reported. The studies are based on samples of proton-proton collisions at $\sqrt{s} = 7$ TeV (corresponding to 5.0 and 4.8 of integrated luminosity) and $\sqrt{s} = 8$ TeV (corresponding to 3.6 of integrated luminosity) collected with the CMS detector at the CERN Large Hadron Collider. Based on good agreement between the data and the standard model expectations, the data are used to determine limits on new particle production at the 95% confidence level.

Presented at ICHEP 2012: International Conference on High Energy Physics
Search for physics beyond the standard model in events with leptons and jets at CMS

James F. Hirschauer∗
On behalf of the CMS Collaboration
Fermi National Accelerator Laboratory
E-mail: james.francis.hirschauer@cern.ch

Many theories of new physics predict the existence of new particles decaying to leptons and hadronic jets, including leptoquarks of grand unified theories, heavy neutrinos and right-handed $W_R$ bosons of left-right symmetric extensions of the standard model, heavy Majorana neutrinos of see-saw mechanism, and scalar quarks in supersymmetric theories that violate $R$-parity. The results of searches for these particles, in final states including jets, electrons, muons, and tau leptons, are reported. The studies are based on samples of proton-proton collisions at $\sqrt{s} = 7$ TeV (corresponding to 5.0 fb$^{-1}$ and 4.8 fb$^{-1}$ of integrated luminosity) and $\sqrt{s} = 8$ TeV (corresponding to 3.6 fb$^{-1}$ of integrated luminosity) collected with the CMS detector at the CERN Large Hadron Collider. Based on good agreement between the data and the standard model expectations, the data are used to determine limits on new particle production at the 95% confidence level.
1. Introduction

We describe searches for several new particles: first (LQ1) and second generation scalar leptoquarks (LQ2) [1], third generation scalar (LQ3) and vector leptoquarks (VLQ) [2], the scalar partner of the top quark (stop) from supersymmetry (SUSY) models with \(R\)-parity violation [2], heavy neutrinos (either Dirac or Majorana) and right-handed \(W_R\) bosons of left-right symmetric extensions (LRSM) of the standard model (SM) [3], and heavy Majorana neutrinos [4]. The searches are performed in events with two quarks and two leptons of the same flavor; the leptons are either both charged or one charged and one neutral. Since the quarks manifest as hadronic jets (\(j\)) and the neutral leptons as missing transverse energy (\(E_T^{\text{miss}}\)), we search in final states of \(e\)\(e\)\(jj\), \(\mu\)\(\mu\)\(jj\), \(\tau\)\(\tau\)\(jj\), \(e\)\(j\)\(j\)\(+E_T^{\text{miss}}\), and \(\mu\)\(j\)\(j\)\(+E_T^{\text{miss}}\). In final states with \(\tau\), we require that the jets are identified as originating from \(b\)-quark hadronization (\(b\)-tagged jets, or \(b\) jets). In searches for Majorana neutrinos, we require that the charged leptons have the same sign, as expected from the theory. The studies are based on samples of \(pp\) collisions at \(\sqrt{s}=7\) TeV (corresponding to 5.0 \(fb^{-1}\) and 4.8 \(fb^{-1}\) of integrated luminosity) and \(\sqrt{s}=8\) TeV (corresponding to 3.6 \(fb^{-1}\) of integrated luminosity) recorded with the CMS detector [5] at the CERN Large Hadron Collider (LHC).

These proceedings are intended as a brief reference for readers seeking to qualitatively understand the motivations, experimental methods, and tested theories of the studies described herein. We refer the reader to the individual papers for many of the details of each analysis, including relevant references.

Electron candidates are reconstructed from energy clusters in the electromagnetic calorimeter (ECAL) that have a shower shape consistent with that of an electron, are matched to hits in the central tracker, and are isolated from other energy deposits in the calorimeter and reconstructed tracks. Muons are reconstructed from pairs of matched tracks from the muon and tracking systems that are also required to be isolated. Jets and \(E_T^{\text{miss}}\) are reconstructed with a particle-flow algorithm, which identifies and measures stable particles by combining information from all CMS sub-detectors. These electron, muon, and jet candidates have transverse momentum \(p_T\) exceeding 30-40 GeV, pseudorapidity \(\eta\) less than 2.1-2.5, and spatial separation \(\sqrt{(\Delta \phi)^2 + (\Delta \eta)^2}\) greater than 0.5-0.8, depending on the analysis.

In all studies, the data are observed to agree with the SM expectation, which is estimated from both Monte Carlo (MC) simulations and data control samples. Based on this agreement, limits are computed at the 95% confidence level (CL) with the modified frequentist CL\(_s\) method based on profile likelihood ratio test statistics constructed from the Poisson probability for the observed number of events given the expectations for background and signal. In some cases, correlated and uncorrelated observations from separate datasets or event categories are statistically combined via the likelihood.

2. Searches for Leptoquarks and Scalar Tops

As part of the explanation of the underlying relationship between quarks and leptons, many extensions of the SM, including grand unified theories, composite models, and superstring-inspired models, predict the existence of particles that couple to both quarks and leptons. These leptoquarks (LQ) have spin zero or one and decay to a charged lepton and a quark with an unknown branching
fraction $\beta$ or to a neutrino and a quark with branching fraction $1 - \beta$. To satisfy constraints from bounds on flavor-changing neutral currents and from rare pion and kaon decays, LQ are assumed to couple only to quarks and leptons of a single SM generation. Depending on the generation to which they couple, LQ are classified as first-, second-, or third-generation. At the LHC, LQ would be produced in pairs via gluon-gluon fusion and quark-antiquark annihilation.

2.1 Search for first and second generation leptoquarks

We search for LQ1 (LQ2) in the $eejj$ and $e\nu jj$ ($\mu\mu jj$ and $\mu\nu jj$) final states in a sample of pp collisions at $\sqrt{s} = 7$ TeV corresponding to 5.0 fb$^{-1}$ of integrated luminosity. For the $eejj$ analysis, events are required to pass a double-electron trigger or a double-photon trigger with a 33 GeV $p_T$ threshold. For the $e\nu jj$ analysis, events pass either a single-electron trigger or a trigger requiring an electron with $p_T > 17-30$ GeV, $E_T^{\text{miss}} > 15-20$ GeV, and two jets with $p_T > 25-30$ GeV; the thresholds vary according to the instantaneous luminosity to keep trigger rates approximately constant. For the LQ2 analyses, events are required to pass a single-muon trigger with a $p_T$ threshold of 40 GeV.

After the basic selection described above, the sensitivities of the $\ell\ell jj$ searches are optimized with thresholds on the dilepton invariant mass ($M_{\ell\ell}$), the scalar sum of lepton and jet $p_T$ ($S_T$), and the smaller of the lepton-jet invariant masses from the pairing that minimizes the LQ-$\ell\ell$ invariant mass difference ($M_{\ell\ell}^{\text{min}}$). In the $\ell\nu jj$ search, we require that the lepton-$E_T^{\text{miss}}$ transverse mass $M_T$ exceed 120 GeV, and the sensitivity is then optimized with requirements on $E_T^{\text{miss}}$, $S_T$, and $M_{\ell\ell}$, which is defined as the lepton-jet invariant mass from the pairing that minimizes the LQ-$\ell\ell$ transverse mass difference. Depending on LQ mass hypothesis and final state, the thresholds are 100-150 GeV for $M_{\ell\ell}$, 330-1000 GeV for $S_T$, 60-520 GeV for $M_{\ell\ell}^{\text{min}}$, 100-240 GeV for $E_T^{\text{miss}}$, and 150-540 GeV for $M_{\ell\ell}$.

The main SM backgrounds in the $\ell\ell jj$ channel are $Z/\gamma^*+jets$ and $t\bar{t}$ events. We obtain the $Z/\gamma^*+jets$ background prediction from MC that has been normalized with data for which $M_{\ell\ell}$ is consistent with that of a Z boson. The $t\bar{t}$ contribution is estimated from an $e\mu$ data sample with appropriate corrections for differences in electron and muon efficiency and assuming ee and $\mu\mu$ rates are half the $e\mu$ rate. The main SM backgrounds in the $\ell\nu jj$ channels are $W+jets$ and $t\bar{t}$, which are estimated from MC that has been normalized using data with low $M_T$.

The dominant sources of systematic uncertainty on the expected signal are the jet energy scale (2-3%), muon reconstruction efficiency (2%), and the integrated luminosity (2.2%). The dominant uncertainty on the background expectation comes from the extrapolation from $Z/\gamma^*+jets$ and $W+jets$ control samples (11%).

In Fig. 1, we show the 95% exclusion regions as functions of $\beta$ and LQ1 mass and LQ2 mass from the statistical combinations of $\ell\ell jj$ and $\ell\nu jj$ channels. The limits on LQ masses are shown in Table 1.

2.2 Search for third generation leptoquarks and scalar quarks

We search for LQ3, VLQ, and stops decaying into a $\tau$ and b quark in a sample of pp collisions at $\sqrt{s} = 7$ TeV corresponding to 4.8 fb$^{-1}$ of integrated luminosity. There are versions of supersymmetry (SUSY) in which the large mixing angle between the left-chiral ($\tilde{t}_L$) and right-chiral ($\tilde{t}_R$)
Figure 1: Left (Right) frame: the expected and observed exclusion limits at 95% CL on the LQ1 (LQ2) hypothesis in the $\beta$ versus mass plane using the central value of signal cross section for the individual eejj and evjj ($\mu \mu jj$ and $\nu \nu jj$) channels and their combination. The dark green and light yellow expected limit uncertainty bands represent the 68% and 95% confidence intervals. Solid lines represent the observed limits in each channel, and dashed lines represent the expected limits. The shaded region is excluded by the current ATLAS limits $[6, 7]$. 

stops produces two mass eigenstates, $\tilde{t}_1$ and $\tilde{t}_2$, with a large mass splitting and $M_{\tilde{t}_1}$ substantially smaller than the masses of the other scalar SUSY particles. Additionally, in R-parity-violating (RPV) SUSY models, trilinear RPV operators allow the lepton-number-violating decay $\tilde{t}_L \rightarrow \tau b$ with a coupling $\lambda'_{333}$. Assuming $\lambda'_{333}$ and $\tilde{t}_L \rightarrow \tau b$ branching fraction ($B_{\tilde{t}_L}$) to be unity, stop and LQ3 production and decay are identical, and the search results are applicable to both particles. In addition to this simple interpretation, we also consider an MSSM-based benchmark scenario in which $B_{\tilde{t}_L}$ decreases with increasing stop mass as $R$-parity-conserving decays become kinematically accessible; the MSSM parameters used in this scenario are in Ref. $[2]$. We consider a range of $\lambda'_{333}$ from 1 to $O(10^{-7})$, below which the decay length exceeds 0.5 mm making this analysis insensitive because of vertex requirements.

In addition to requiring b-tagged jets, we require that one $\tau$ in each event decays leptonically and the other hadronically ($\tau_h$), yielding final states of $\tau_h \mu bb$ and $\tau_h \nu e bb$. Events are required to pass $\tau_h$+electron or $\tau_h$+muon triggers with lepton $p_T$ thresholds of 15-20 GeV and 12-20 GeV, respectively, depending on the data-taking period. After basic selection, we require that the $\tau_h$+b invariant mass $M_{\tau_h b}$ exceed 170 GeV; $M_{\tau_h b}$ is defined with the particle pairing that minimizes the LQ - $\overline{LQ}$ invariant mass difference. After the final selection, the observed and expected event counts are examined as functions of the $\tau_h\ell bb$ $S_T$. The primary SM backgrounds are $t\bar{t}$, Z+jets, and W+jets events. The $t\bar{t}$ background is estimated from simulation that has been normalized with the low-$M_{\tau_h b}$ data sample. The Z+jets and W+jets backgrounds, in which one jet is misidentified as $\tau_h$, are estimated from the data. The dominant sources of systematic uncertainty on the expected signal are the jet energy scale (2-4%) and the integrated luminosity (2.2%). The dominant uncertainty on the background expectation comes from the normalization of the $t\bar{t}$ MC (13-17%) and the estimation of Z+jets and W+jets backgrounds (40%).
In Fig. 2, we show 95% CL limits on the effective cross section as a function of particle mass, and the 95% CL exclusion region as a function of $\lambda'_{333}$ and stop mass for two values of the heavy SU(2) gaugino mass $M_2$. By comparing predicted cross sections to the limit, we obtain limits on particle mass, which are shown in Table 1.

![Figure 2](image)

**Figure 2:** Left: the expected and observed upper limit at 95% CL on the product of cross section and $\tau_b$ branching fraction as a function of mass. The $\pm 1\sigma$ and $\pm 2\sigma$ uncertainties on the expected limit are also shown as green (inner) and yellow (outer) bands about the expected limit. The blue (solid) curve, magenta (dashed) curve, and red (dotted) curves and the matching shaded bands represent the theoretical LQ$^3$, $\tilde{t}_1$, and VLQ pair production cross sections with theoretical uncertainty. Right: limits at 95% CL on the RPV coupling $\lambda'_{333}$ as a function of $\tilde{t}_1$ for $M_2 = 250$ GeV and $M_2 = 1$ TeV.

### 3. Search for the heavy neutrinos and $W_R$ bosons in a left-right symmetric model

We search for production of heavy neutrinos ($N_e, N_\mu$) and $W_R$ bosons of the LRSM in samples of pp collisions at $\sqrt{s} = 7$ and $\sqrt{s} = 8$ TeV corresponding to 5.0 fb$^{-1}$ and 3.6 fb$^{-1}$ of integrated luminosity, respectively. The LRSM was initially proposed to explain parity violation in electroweak interactions as the result of a spontaneously broken left-right symmetry; additionally, the large mass of $N_\ell$ can explain the very small masses of SM neutrinos through the see-saw mechanism. The LRSM produces $\ell\ell jj$ ($\ell = e, \mu$) final states through the process $pp \rightarrow W_R \rightarrow \ell N_\ell$, with $N_\ell \rightarrow \ell W_R^\pm$, followed by $W_R^\pm \rightarrow jj$. We assume that left and right gauge couplings are the same and that $W_R - W_L$ and $N_\ell - N_\ell'$ mixing is small.

Events are collected with double electron and single muon triggers. After basic selection, we require that the leading lepton have $p_T > 60$ GeV and $M_{\ell\ell} > 200$ GeV, and we examine the four-object mass distribution with $M_{\ell\ell jj} > 600$ for evidence of $W_R$ production. The primary backgrounds are $t\bar{t}$ and Z+jets, which are estimated as in the LQ searches. The dominant sources of systematic uncertainty on the expected signal are the lepton reconstruction efficiency (6-10%); the dominant uncertainty on the background expectation comes from shape uncertainties in $t\bar{t}$ and Z+jets MC (16-53%).
In Fig. 3, we show 3.6 fb$^{-1}$ of 8 TeV ee$jj$ data compared to the background expectation and the 95% exclusion region as functions $M_{W_R}$ and $M_{N_\mu}$ from the statistical combination of the results from the 7 TeV and 8 TeV $\mu\mu jj$ datasets. The limits on $M_{W_R}$ assuming $M_{N_\ell} = \frac{1}{2} M_{W_R}$ are shown in Table 1.

![Figure 3: Left: Comparison of observed and expected $M_{\ell\ell jj}$ distributions in ee$jj$ events passing all selection criteria except the $M_{ee}$ requirement. Right: The 95% CL exclusion region as functions of $M_{W_R}$ and $M_{N_\mu}$ from the combined 7 TeV and 8 TeV $\mu\mu jj$ datasets.](image)

4. Search for the heavy Majorana neutrinos

We search for heavy Majorana neutrinos ($N_{\ell}^{\text{Maj}}$, $\ell = e, \mu$) that couple to W bosons and leptons of the SM via the parameter $V_{\ell N}$ in a sample of pp collisions at $\sqrt{s} = 7$ TeV corresponding to 5.0 fb$^{-1}$ of integrated luminosity. Production and decay of $N_{\ell}^{\text{Maj}}$ is identical to that of $N_{\ell}$ except the $W_R$ boson is assumed to be a SM $W$ boson. The salient feature of the model is that the Majorana nature of $N_{\ell}^{\text{Maj}}$ results in lepton-number violation by two units and final states with leptons of the same charge and flavor ($\ell^\pm \ell^\pm jj$). This analysis focuses on smaller heavy neutrino mass than the LRSM search described above.

Events are collected with double lepton triggers with $p_T > 7-17$ GeV. After basic selection and a $E_T^{\text{miss}} < 50$ GeV requirement, few events remain because of the same charge requirement. The primary backgrounds are QCD events with two misidentified isolated leptons and $W$+jets or $t\bar{t}$ events with one misidentified isolated lepton. These contributions are simultaneously estimated with data control samples. The dominant source of systematic uncertainty on the expected signal is the jet energy scale (3.3%); the dominant uncertainty on the background expectation comes from estimating the misidentification rate (35%).

In Fig. 4, we show the ee$jj$ data compared to the background expectation and the 95% exclusion region as functions of $M_{N_\mu}$ and $|V_{\mu N}|^2$ in the $\mu\mu jj$ channel. The limits on $M_{N_\mu}$ for $|V_{\mu N}|^2 = 0.5$ are shown in Table 1. For $M_{N_\mu} = 90$ GeV the limits are $|V_{\mu N}|^2 < 0.07$ and $|V_{eN}|^2 < 0.22$. At $M_{N_\mu} = 210$ GeV the limits are $|V_{\mu N}|^2 < 0.43$, while for $|V_{eN}|^2$ the limit reaches 1.0 at a mass of 203 GeV. These are the first direct upper limits on $|V_{\ell N}|^2$ for $M_{N_\ell} > 90$ GeV.
Leptoquarks and Heavy Neutrinos

James F. Hirschauer

5. Summary

We describe searches for first, second, and third generation scalar leptoquarks, third generation vector leptoquarks, light stops in RPV SUSY, heavy neutrinos and $W_R$ of the LRSM, and heavy Majorana neutrinos. The searches are performed in final states of $eejj$, $\mu\mu jj$, $ej + E_{T}^{miss}$, $\mu jj + E_{T}^{miss}$, $\tau_{\ell} j bb$, and $\tau_{\ell} j \mu bb$. The studies are based on samples of pp collisions at $\sqrt{s} = 7$ TeV (corresponding to 5.0 fb$^{-1}$ and 4.8 fb$^{-1}$ of integrated luminosity) and $\sqrt{s} = 8$ TeV (corresponding to 3.6 fb$^{-1}$ of integrated luminosity) recorded with the CMS detector in 2011 and 2012. The limits on masses of these particles, which are shown in Table 1, extend the previous limits as described in Refs. [1, 2, 3, 4].

Table 1: Summary of lower mass limits on LQ1, LQ2, LQ3, and VLQ for values $\beta$; on stop from a simplified model with $B_{\tilde{t}_1} = 1$ and from the benchmark MSSM scenario for values of $M_2$ and $\lambda'_{333}$; and on $W_R$ and the mass of a heavy Majorana neutrino for electron and muon final states. All entries have units of GeV.

| Leptoquarks | $\beta = 0.5$ | $\beta = 1.0$ |
|-------------|--------------|--------------|
| LQ1         | 640          | 830          |
| LQ2         | 650          | 840          |
| LQ3         | -            | 525          |
| VLQ3        | -            | 760          |
| Stops       |              |              |
| $\tilde{t}_1$, $B_{\tilde{t}_1} = 1$ | 525          | -            |
| $\tilde{t}_1$, $M_2 = 250$ GeV | 450          | 240          |
| $\tilde{t}_1$, $M_2 = 1000$ GeV | -            | 340          |
| Heavy Neutrinos | $eejj$ | $\mu\mu jj$ |
| $W_R$, $M_{N_l} = \frac{1}{2}M_{W_R}$ | 2500         | 2800         |
| $N_{l_{Maj}}$, $|V_{\mu N}|^2 = 0.5$ | 160          | 210          |
References

[1] CMS Collaboration, arXiv:1207.5406 (2012); Accepted by Phys. Rev. D.

[2] CMS Collaboration, arXiv:1210.5627 (2012); Submitted to Phys. Rev. Lett.

[3] CMS Collaboration, CMS-PAS-EXO-12-017 (2012).

[4] CMS Collaboration, Phys. Lett. B717 (2012) 109.

[5] CMS Collaboration, JINST 3 (2008) S08004.

[6] ATLAS Collaboration, Phys. Lett. B709 (2012) 158.

[7] ATLAS Collaboration, arXiv:1112.4828 (2012); Submitted to Eur. Phys. J. C.