PROCEEDINGS OF SCIENCE

Searches for new physics in lepton+jet final states

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Results of searches for new particles in final states with leptons (charged or neutral) and jets are presented. These include leptoquarks, heavy neutrinos, and W bosons with right-handed couplings. Emphasis is given to recent results as obtained by the CMS collaboration at the LHC.

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1. Introduction

In high-energetic proton-proton collisions at the Large-Hadron-Collider (LHC) signatures with leptons and jets are expected in many scenarios beyond the Standard Model (SM) as they may arise from the decay of hypothetical heavy particles, as e.g. the decay of leptoquarks, new heavy bosons, or new heavy neutrinos. In this article an overview of searches for new physics in lepton plus jets final states is given. All searches presented in the following use data samples of proton-proton collisions at $\sqrt{s} = 13$ TeV collected with the CMS detector at the LHC [1] during the years 2015 and 2016.

Leptoquarks appear in many extentions of the SM, such as grand unification theories, technicolor, and compositeness models. They are color-triplet bosons, which carry lepton and baryon number, have fractional electric charge, and can be either scalar or vector. Leptoquarks decay into a lepton and a quark of their generation with branching ratio β. This article presents searches for pair production of scalar leptoquarks of all generations. Similar final states are expected in theories that include right-handed neutrinos. Such left-right symmetric extensions of the SM predict the existence of heavy charged gauge bosons (W_R).

Furthermore, heavy composite Majorana neutrinos could lead to the final state in question. In the composite-fermion model, quarks and leptons are expected to have an internal substructure. This substructure is supposed to manifest at high energy scale referred to as the compositeness scale Λ.

2. Searches for First and Second Generation Leptoquarks

The CMS collaboration has searched for the pair-production of leptoquarks of the first and second generation in the $eejj$ and $\mu\mu jj$ final states [2, 3]. Both analyses use proton-proton collision data collected in 2015, corresponding to an integrated luminosity of 2.6 fb^{-1}. A single lepton trigger is used and two isolated electrons (muons) with $p_{\mathrm{T}} > 50$ GeV and at least two jets with $p_{\mathrm{T}} > 50$ GeV are selected in the search for first (second) generation leptoquarks. The discriminating variables are S_{T} (defined as the scalar sum of the transverse momenta of the two leading leptons and jets in the events), the minimum invariant mass of the lepton-jet pair M_{lj}^{min} and the invariant mass of the leptons M_{ll}. Requirements applied to these variables are optimized for each leptoquark mass point. The main backgrounds in the analyses arise from Z/γ^{*}+jets and $t\bar{t}$ processes events. In both searches, the shape of the Z/γ^{*}+jets background is estimated in simulation and the normalization is derived from data in a control region around the Z-boson peak. The shape of the $t\bar{t}$ background in the first generation search is taken from simulation and the normalization is derived from a data sample that contains $e\mu$ events. In the second generation search the $t\bar{t}$ background is completely derived from a control region with $e\mu$ data events.

No significant deviation from the expected SM background is observed and upper cross section limits at 95% confidence level are set on the scalar leptoquark production as shown in Fig. 1. Production cross sections of 0.4 (0.2) pb for first (second) generation leptoquark masses of 200 GeV and about 0.001 pb for first and second generation leptoquark masses of 1400 GeV are excluded under the assumption of $\beta = 1.0$. Comparing these limits with the next-to-leading order cross

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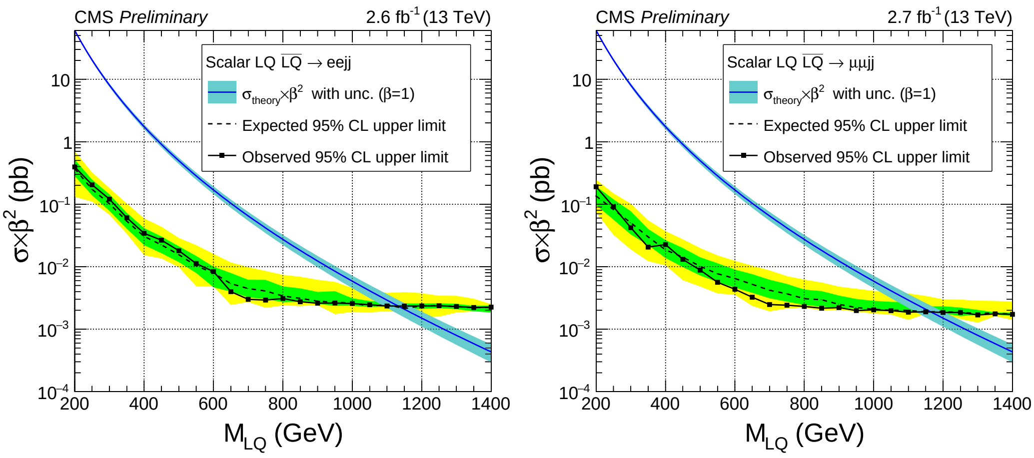

Figure 1: Upper limits at 95% confidence level on the cross section σ times branching fraction β^2 for first generation (left) and second generation (right) leptoquarks [2, 3]. The dashed line represents the expected limits and solid lines the observed limits. The green and yellow bands represent one and two standard deviation uncertainties in the expected limits. The theory curve corresponds to the next-to-leading order cross section with uncertainties from PDF and scale variations.

section, first (second) generation leptoquarks can be excluded up to masses of 1130 (1165) GeV. These results represent the most stringend limits on first and second generation leptoquarks to date.

3. Searches for Third Generation Leptoquarks

The CMS collaboration also searches for third generation leptoquarks. A search for third generation leptoquarks in a final state with top quarks and τ leptons has been performed at $\sqrt{s} = 8$ TeV [4]. The searches including third generation quarks and leptons presented in this article look for topologies with b quarks and with either both τ leptons decaying hadronically ($\tau_h\tau_h$) or one τ lepton decaying hadronically and the other to a lighter lepton ($\tau_h\tau_\ell$).

In both analyses, it is searched for leptoquarks and right handed gauge bosons, simultaneously. In case of the $\tau_h\tau_h$ analysis [5], a search has been performed with 2015 data, corresponding to an integrated luminosity of 2.1 fb^{-1}. A di-τ_h trigger is used and τ_h leptons must have $p_{\mathrm{T}} > 70$ GeV. The selected events contain two jets with $p_{\mathrm{T}} > 50$ GeV and must pass $\not{E}_{\mathrm{T}} > 50$ GeV. The invariant mass of the di-τ_h pair is required to be greater than 100 GeV. The dominant background from QCD multijet processes is estimated using a data-driven ABCD method in which control regions with inverted $\not{E}_{\mathrm{T}}$ and τ_h lepton isolation requirements are employed. Other backgrounds are derived from simulation. The final S_T distribution for the leptoquark analysis is shown in Fig. 2 (left). No excess above the SM expectation is observed. Exclusion limits on the production cross sections times branching ratios of leptoquarks and right handed gauge bosons W_R are set and the limits in the leptoquark analysis are shown in Fig. 2 (right). With this search, third generation leptoquarks can be excluded up to masses of 740 GeV, while W_R boson masses below 2.31 TeV are excluded.

In the $\tau_h\tau_\ell$ analysis [6], a single lepton trigger is used. Events were collected in 2016, corresponding to an integrated luminosity is 12.9 fb^{-1}. The τ_h leptons, electrons, and muons must fulfill

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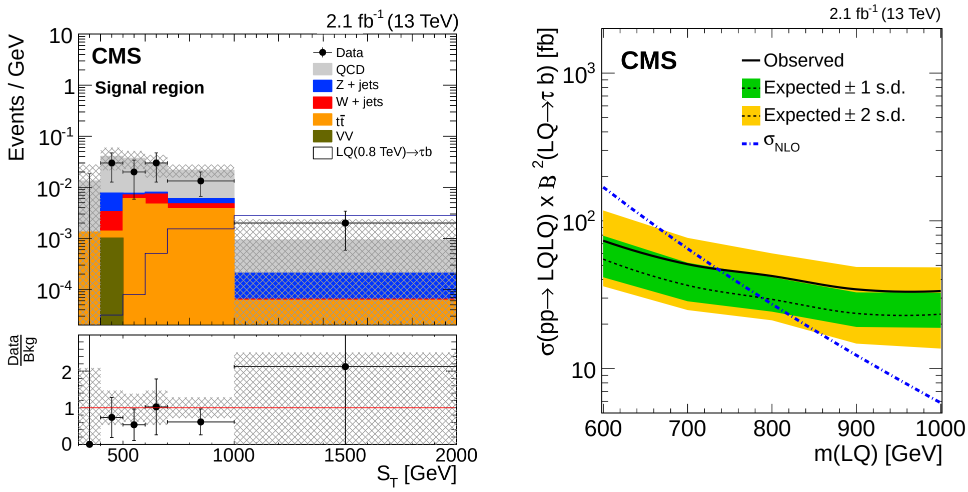

Figure 2: Measured S_T distribution (left) and upper limits at 95% confidence level on the product of cross section times branching ratio (right) for the leptoquark search in the $\tau_h\tau_h$ analysis [5].

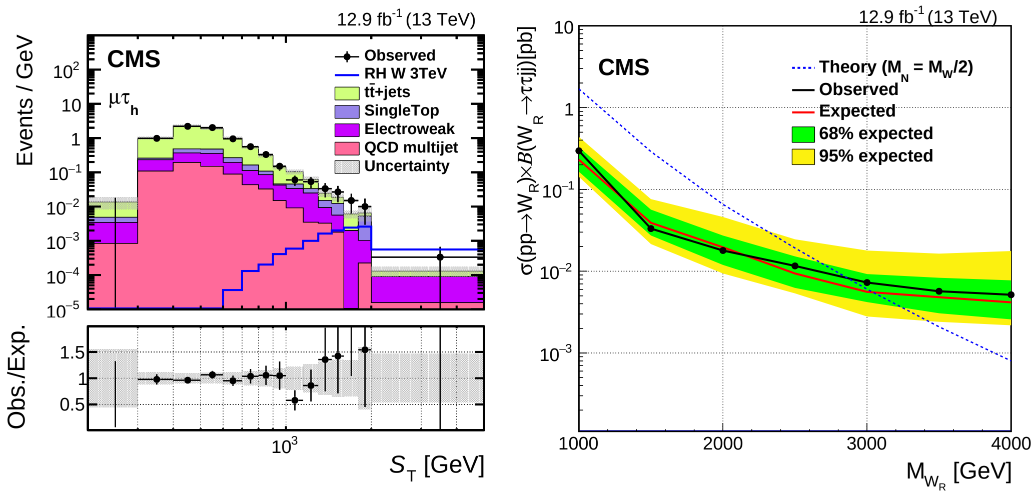

Figure 3: Measured S_T distribution (left) and upper limits at 95% confidence level on the product of cross section times branching ratio (right) for the W_R boson search in the $\tau_h\tau_\ell$ analysis [6].

$p_T > 50$ GeV. Two jets are required and at least one b-tagged jet must be identified. Requirements to the invariant mass of the τ_h-jet system and to the invariant mass of the $\tau_h\ell$ pair are applied. The dominant background arises from $t\bar{t}$ processes and is derived from simulation, after beeing verified in an $e\mu$ data control sample. W+jets events are estimated in simulation and the normalization derived in a control region. The QCD multijet background is determined in a data sample in which τ_h lepton candidates pass looser identification crtieria. Data and SM background are in a good agreement and upper limits are set on the production cross sections times branching ratios of leptoquarks and right handed gauge bosons W_R. The final S_T distribution for the W_R boson search in the $\tau_h\tau_\mu$ analysis is presented in Fig. 3 (left). The corresponding exclusion limits distribution is shown

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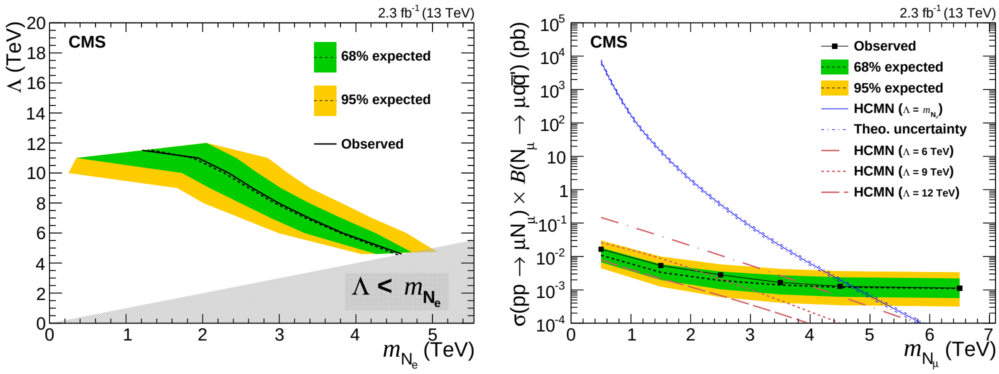

Figure 4: Upper limits at 95% confidence level on the production of heavy composite Majorana neutrinos in the electron channel (left) and muon channel (right) [7]. The green and yellow bands represent one and two standard deviation uncertainties in the expected limits. The grey shaded area in the left distribution represents the phase space, which is not allowed by the model. The solid blue curve in the right distribution corresponds to the theoretical cross section.

in Fig. 3 (right), where the $\tau_h\tau_e$ and $\tau_h\tau_\mu$ channels are combined. In this analysis, leptoquarks can be excluded up to masses of 850 GeV, while W_R boson masses below 2.9 TeV are excluded. These results represent the most stringend limits on third generation leptoquarks and W_R bosons with τ leptons in the final state to date.

4. Searches for Heavy Compositeness Majorana Neutrinos

The CMS collaboration searches for heavy compositeness Majorana neutrinos in a final state of two same-flavor leptons and two quarks [7]. The data used in this analysis was collected in 2015 and corresponds to an integrated luminosity of 2.3 fb^{-1}. Single-lepton triggers are used and reconstructed electrons (muons) must have 105(50) GeV. The invariant mass of the lepton pair is required to be greater than 300 GeV. A large radius jet with $p_T > 190$ GeV is selected.

The main background comes from $t\bar{t}$ processes, which is estimated together with single-top quark processes of the tW channel. An $e\mu$ data control sample is used to estimate these backgrounds. The Z/γ^*+jets background is estimated in simulation, but the normalization is derived in a data control region around the Z-boson peak. Other minor backgrounds are taken from simulation.

No significant deviation from the expected SM background is observed in data. Exclusion limits are set on the compositeness scale Λ and the heavy composite Majorana neutrino production cross section times branching ratio as shown in Fig. 4. Heavy compositeness Majorana neutrinos can be excluded up to masses of 4.6(4.7) TeV in the electron (muon) channel, while compositeness scales below 11.5(10.0) TeV are excluded. These results represent the first search for heavy composite Majorana neutrinos.

5. Conclusions

The most recent results of lepton plus jet final state searches at the CMS experiment are pre-

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sented in this article. In all searches, the data are found to be in a good agreement with the expected SM background. Upper limits at 95% are set to each generation of leptoquarks, to right handed gauge bosons W_R, and to heavy compositeness Majorana neutrinos.

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