Search for Heavy Neutrinos in di-lepton and di-jet events

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Abstract

The di-lepton and di-jet final state is sensitive to many theoretical models beyond the Standard Model, including scalar and vector leptoquarks of the three generations and heavy Majorana neutrinos, arising from the seesaw mechanism, also in the context of a LR-symmetry extension or in a compositeness scenario. The most recent CMS results have shown a significant excess in the di-electron and di-jet channel, in two independent analyses: one is a search for heavy neutrinos, deriving from the LR-symmetry extension and the other looks for a pair-production of first generation scalar leptoquarks, both performed at 8 TeV. No excess has been observed in the di-muon and di-jet channel; while the di-tau and di-jet signature has not yet been explored for the heavy neutrinos specific search, but only for the leptoquarks, with a b jet jet tagging. A benchmark process with a same flavour di-lepton plus di-jet signature, in the frame of composite neutrinos and contact interactions, is taken into consideration to clarify the nature of the excess and to extend the mass limit for the heavy neutrinos, exploiting the run 2 of CMS.

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Search for Heavy Neutrinos in dilepton plus dijet events with the CMS detector

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**Summary.** — The dilepton plus dijet final state is sensitive to many theoretical models beyond the Standard Model, including scalar LeptoQuarks of the three generations and Heavy Majorana Neutrinos, arising from the seesaw mechanism, in the context of a LR-symmetry extension or in a compositeness scenario.

Recent CMS measurements, looking for first generation LeptoQuark and Heavy Neutrinos, in the final state with two electrons and two jets, have shown a significant excess in analyses performed at the center of mass energy of 8 TeV with 19.7 \( fb^{-1} \). No excess has been observed in the dimuon plus dijet channel; while the ditau plus dijet signature has not yet been explored for the Heavy Neutrinos specific search, but only for searches motivated by LeptoQuarks models, in the final state where the tau pair is produced with two b or two t quarks.

Considering composite neutrinos and contact interactions, a benchmark process with a same flavour dilepton plus dijet signature, is taken into consideration to provide a possible explanation of the excess and to extend the limits on the parameters of the Heavy Neutrinos search, in view of the Run 2 at CERN.

1. **Run 2 perspectives**

The recent discovery of the Higgs boson at the LHC (Large Hadron Collider) was announced together by the CMS [12] and ATLAS collaborations in 2012 and has opened a new exciting era for the High Energy Physics. Albeit the impressive efforts put in by these experiments, the hunt for new particles has been unsuccessful so far and the robustness of the Standard Model (SM) has been confirmed.

The incoming Run 2 of the LHC machine will increase the luminosity and reach the energy of 13 TeV in the centre of mass of the colliding protons, marking a new energy record for the hadron colliders. This new experimental conditions will provide a greater statistics and cross section for the discovery of new particles or for the extensions of the exclusion limits in their search. The main aims of the Run 2 will be the detailed characterization of the Higgs boson and the continuance of the search for new physics.
2. – Theoretical motivations

In this paragraph two theoretical extensions of the SM, sensitive to the dilepton plus dijet final state, are briefly presented. One is related to the LeptoQuark model and the other to the production of Heavy Neutrinos that may be foreseen in quite different scenarios.

Several models beyond the SM, like Grand Unification, compositness, superstrings and technicolor include LeptoQuarks (LQ) of the three generations. These new particles are scalar or vector bosons which carry non-zero leptonic and baryonic number, color charge and fractional electric charge. Experimental limits suggest that their research should be mainly focused on LQ pair production, via gluon fusion or quark annihilation and on the dominant decay process in a lepton and a quark of the same generation of the LQ (Fig.1). Their decay BR (Branching Ratio) is model dependent and the free parameters are the LQ mass ($M_{LQ}$) and the BR decay in a charge lepton plus a quark, usually denoted as $\beta$ [5], [6], [7].

The SM assumes that the neutrinos of the three generations are massless, however the observation of neutrino oscillations implies a non-zero mass and definitely points to new physics models. One way to confer mass to neutrinos is provided by the Left-Right Symmetry extension (LRSM), in which the SM group $SU_L(2)$ has a right-handed counterpart and the symmetry group is $SU_C(3) \otimes SU_L(2) \otimes SU_R(2) \otimes U(1)$, originally introduced to explain the reason of parity non-conservation in weak interactions. The new $SU_R(2)$ group, similar to the $SU_L(2)$, predicts the existence of three new gauge bosons, $W^{\pm}_R$ and $Z'$, and three Heavy right-handed Neutrino states $N_\ell$ ($\ell = e, \mu, \tau$), partners of the light neutrinos states $\nu_\ell$, and can explain the neutrinos’ mass hierarchy in the context of the see-saw mechanism. A reference process allowed by this model is the production of a $W_R$ that decays in a Heavy Neutrino (HN) and a lepton of the same generation ($qq \rightarrow \ell + N_\ell \rightarrow \ell + (\ell qq')$) and gives two jets and two same flavour leptons in the final state (Fig.1) [8].

Heavy Majorana Neutrinos can also arise in the scenario of composite quark and leptons, where the heavy excited states ($q^*, \ell^*, \nu^*$) can couple with the SM known fermions, through gauge and contact interactions. These are the residual result of the forces among the elementary constituents [1], [2], [3], [4]. The benchmark examined process in this context is the Heavy Neutrino production and its decay in two quarks.

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**Fig. 1.** Feynman diagrams for the LeptoQuark pair production via gluon fusion or via quark annihilation (above) and for the Heavy Neutrino production in the model of a Left-Right symmetric model (below) [5],[6],[7],[8].
and a lepton \((qq \rightarrow \ell + N_{\ell} \rightarrow \ell + (\ell qq'))\), both gauge and contact interaction are included at the vertices (Fig. 2).

![Feynman diagram for the Heavy Neutrino resonant production in a compositness scenario with both contact and gauge interaction included at vertices (grey blobs in Fig.2).](image)

Fig. 2. – Feynman diagram for the Heavy Neutrino resonant production in a compositness scenario with both contact and gauge interaction included at vertices (grey blobs in Fig.2).

**3. – Experimental results for Run 1**

Recent CMS measurements looking for first generation LeptoQuark and Heavy Neutrinos in the final state with two electrons and two jets have shown a significant excess in analyses performed at the center of mass energy of 8 TeV with 19.7 fb\(^{-1}\): the first one looking for scalar LeptoQuarks of the first generation and the second one searching for Heavy Neutrinos within the LR-symmetry extension.

Concerning the LQ scenario, with the LQ produced in pairs, it has been possible to exclude, at the 95% of confidence level, for the first generation \((LQ_1) M_{LQ1} < 950(845) \text{ GeV}\) with \(\beta = 1(0.5)\), for the second generation \((LQ_2) M_{LQ2} < 1070(785) \text{ GeV}\) with \(\beta = 1(0.5)\) and for the third one \((LQ_3) M_{LQ3} < 740 \text{ GeV}\) \([5],[6],[7]\).

An excess of 2.4(2.8)\(\sigma\) with respect to the predicted contribution from SM background has been observed at around 650 GeV in the \(eejj(\ell\nu jj)\) final state. This excess cannot be explained within the \(LQ_1\) model considered in \([5]\) (Fig.3).

In the context of the LR-symmetry extension the \(\mu\nu jj\) and \(eejj\) channels have been investigated and the exclusion of \(W_R\) masses until 3 TeV has been established at 95% of confidence level.

A broad excess around \(M_N = 2.2 \text{ TeV}\) has been measured with respect to the cross section of the SM background, corresponding to 2.8 \(\sigma\). This is not explained considering the LR model parametrization in \([8]\) (Fig.3).

Several theoretical attempts have been made to justify this excess in the electronic channel: LR-symmetry with \(g_L \neq g_R\), \(W_R\) and \(Z'\) gauge boson production and decay \([9]\), in R-parity violating processes via the resonant production of a slepton \([10]\) and connecting leptoquarks to dark matter \([11]\).

In addition to the extensions of the SM that has been considered, in order to clarify the nature of these deviations of the data from the SM expectations, we have studied a model in which the Heavy Majorana Neutrino arises, assuming compositeness of fermions. This model is briefly described in the next section.

**4. – Heavy composite Majorana Neutrinos**

The multiplicity of the SM fermions has suggested to consider the possibility of their further compositness in terms of more fundamental constituents, the "preons"; the known
fermions have a substructure that becomes evident only at a certain high energy scale, named $\Lambda$. This hypothesis has the following direct consequences:

- heavier excited states of the SM fermions, such as the Heavy Neutrinos (HN), can be predicted;
- composite fermions can interact via contact interactions, a residual interaction of the force among their elementary constituents.

The SM fermions are expected to interact with the heavier excited states, such as the Heavy Neutrinos of the three generation ($N_e, N_\mu, N_\tau$), by means of both contact and gauge couplings.

We have conducted a study with the CalcHEP generator which shows that the production cross section of the Heavy Neutrino is dominated by the contact interactions, greater then the gauge ones of 2-3 orders of size, depending on the Heavy Neutrino’s mass hypothesis. The decay channel with the highest BR is $N \rightarrow q\bar{q}'$, that instead is characterised by a similar contribution from contact and gauge interactions. Although the dilepton plus dijet final state can occur via a virtual (t-channel) or a resonant neutrino (s-channel), the production of a virtual neutrino is negligible and thus the final cross section is calculated considering only the s-channel.

The possibility to don’t ask for any charge requirement for the final state leptons could be advantageous, because it makes sensitive to both the following hypotheses:

- same sign leptons, obtainable via a Majorana neutrinos and a leptonic number violation $\Delta L = \pm 2$;
- opposite sign leptons, possible via both Majorana or Dirac neutrinos, with the L number conservation.
A kinematical study at generator level has been performed at √s = 13 TeV with the tool CalcHEP and has suggested that a cut on the transverse momentum p_T at high values for the leading (e.g. 200 GeV) and for the second leading lepton (e.g. 100 GeV) for a Neutrino's mass of 1 TeV can help to significantly reduce the relevant backgrounds, TTbar is considered the main one. In addition, this starting study has put in evidence the necessity to face with the jet merging, for the jets above 200 GeV, because of the high boost rate of N.

A first significance estimate has been obtained by the Delphes simulator, able to simulate the acceptance and response of the CMS detector, including only the TTbar and WW backgrounds and cutting preliminarly on p_T. The results of the simulation show an extension of the potential exclusion or discovery limit for the Heavy Neutrinos in the bi-dimensional parameter plane (M_N, Λ) where M_L is the HN mass and Λ is the energy scale. Collecting an integrated luminosity of 3000 fb^{-1} the range (M_N, Λ) = (1-4 TeV, 10-16 TeV) can be covered, according to the simulation (Fig.4).

![Significance curves for S=3 and S=5 at three different stages of luminosity.](image)

Fig. 4. - Plots of significance of the Heavy Neutrino process in the parameter space (m* = neutrino’s mass, Λ = energy scale) including TTbar and WWW backgrounds, with p_T preliminary cuts and using the Delphes simulator. On the left: significance curve for S=3 (light blue) and S=5 (blue) at 3’000 fb^{-1}. On the right: significance curves for S=5 at three different stages of luminosity.

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