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Search for heavy neutral leptons, right-handed neutrinos and long-lived particles with the CMS detector

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Abstract

A selection of recent CMS results on heavy neutral leptons, right-handed neutrinos and long-lived particles is reported. The search for heavy neutral leptons in the trilepton channel and in the same-sign dilepton channel, the search of a W_R decaying into two leptons and two jets through a right-handed neutrino, and the searches on stopped long-lived particles and disappearing tracks are presented.

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Search for heavy neutral leptons, right-handed neutrinos and long-lived particles with the CMS detector

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A selection of recent CMS results on heavy neutral leptons, right-handed neutrinos and long-lived particles is reported. The search for heavy neutral leptons in the trilepton channel and in the same-sign dilepton channel, the search of a W_R decaying into two leptons and two jets through a right-handed neutrino, and the searches on stopped long-lived particles and disappearing tracks are presented.

1 Introduction

Phenomena like the dark matter or the baryon asymmetry of the universe (BAU), not explained by the standard model (SM), and the fact that the neutrinos should have a mass, even if very small, due to the observation of neutrino oscillations, suggest the existence of physics beyond the SM. In particular, the introduction of right-handed (RH) neutrinos, missing in the SM, could give a solution to these unresolved problems. They are introduced with beyond SM models like the neutrino Minimal Standard Model (νMSM), which introduces three sterile heavy neutrinos that interact only with the light active SM neutrinos through their mixing. This model could explain the origin of the SM neutrino masses through the seesaw mechanism, provide a dark matter candidate with the first heavy neutrino, N_1 ($m_{N_1} \sim 1$ keV), and explain the matter-antimatter asymmetry of the universe with the other two neutrinos, N_2 and N_3 ($1 < m_{N_2,N_3} < 100$ GeV), massive enough to be searched for at the LHC. Another interesting model used to introduce the RH neutrinos is the left-right (LR) symmetric model, which introduces an $SU(2)_R$ group, considering $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)$, with three additional gauge bosons, $W_R^{+,-}$ and Z', and three heavy RH neutrinos interacting with them. This model could provide an explanation for the parity violation in weak interactions and for the origin of the SM neutrino masses via the seesaw mechanism.

2 Heavy Neutral Leptons

Heavy neutrinos can be produced through the decay of a W boson into a lepton and a heavy neutrino, which is the one considered in the analyses reported here because of the low background, or through the decay of a Z or Higgs boson into a light neutrino and a heavy neutrino. Their decay can then be into a W boson and a lepton, with the W boson decaying into a pair of quarks or into a lepton and a light neutrino, which is experimentally the more accessible, or into a Z or Higgs boson and a light neutrino. Their lifetime can vary from very small values, giving *prompt decays* that are the ones explored so far in CMS [1], to macroscopic distances from the production vertex, giving *displaced decays* that are possible for lower couplings at low masses. In Fig. 1

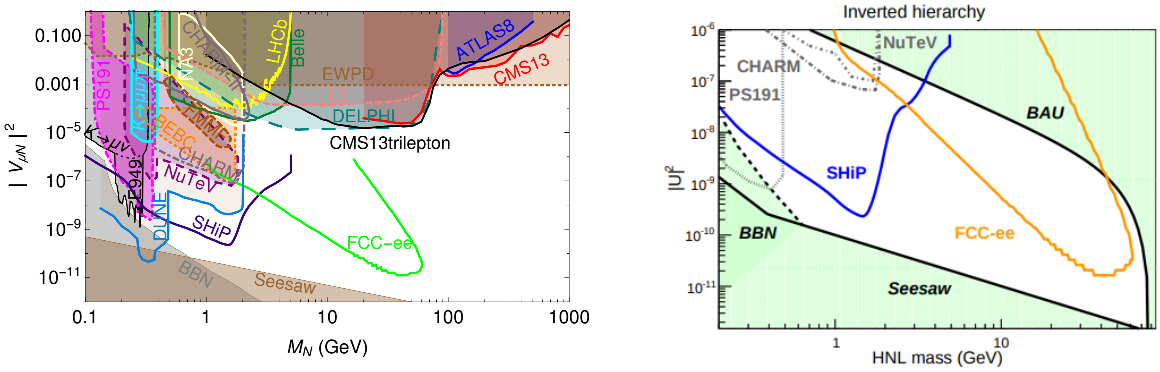

Figure 1 – Left: Constraints (filled area) and projections (contours) on the mixing angle between a HNL and a muon as a function of the HNL mass for different experiments. Right: Constraints on the mixing angle between a HNL and a muon as a function of the HNL mass given by future experiments projections and theoretical models. [2]

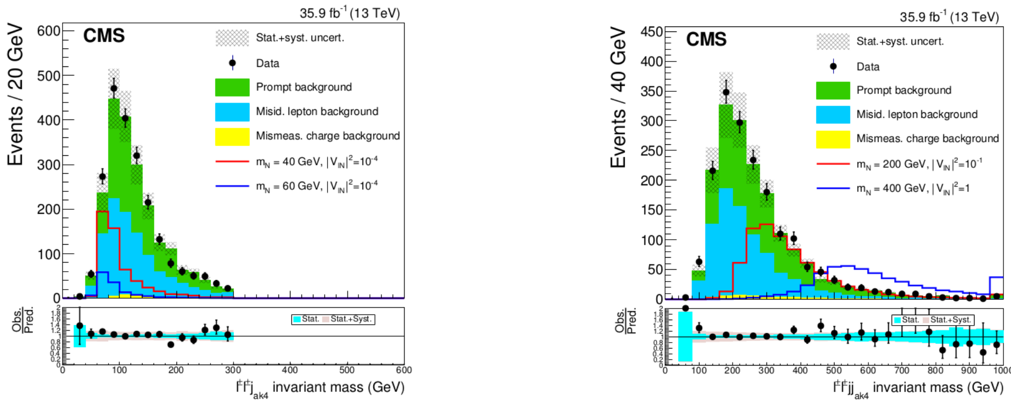

Figure 2 – Dilepton-dijet invariant mass distributions for the low-mass (left) and the high-mass (right) signal region for data, background samples, and two signal hyphotheses in the SS dilepton channel. [6]

(left), the existing constraints from different experiments and projections for future experiments on the mixing angle between a heavy neutral lepton (HNL) and a muon as a function of the HNL mass are represented. The right top region of the plot, corresponding to the prompt decay region with HNL masses from the order of GeV to the order of TeV, is the focus of the analyses reported here, while the left region corresponds to the displaced decays that began to be studied. From this plot it is evident that the LHC just started to probe the region not excluded by the EW precision data. The available parameter space is limited theoretically by observations of BAU, big bang nucleosynthesis and seesaw model, as shown in Fig. 1 (right), but the remaining allowed parameter space can be explored with direct searches at future experiments: fixed target experiment like SHiP [3] can improve the sensitivity to HNL with masses below 2 GeV by several orders of magnitude, while electron-positron circular collider like FCC-ee [4] can improve the sensitivity to the RH neutrinos with masses above 2 GeV.
The HNL analyses reported in Sections 2.1 and 2.2 use the 2016 data at 13 TeV with a luminosity of 35.9 fb^{-1}.

2.1 Sterile neutrinos

The HNL analysis of sterile neutrinos in the trilepton channel [5] considers the decay of a W boson into three leptons and a light neutrino. The main backgrounds, estimated through a data-driven method, are the non-prompt leptons coming from DY+jets and $t\bar{t}$, the prompt trileptons coming from $WZ \to 3l\nu$ and $ZZ \to 4l$, and conversions $X\gamma$ (i.e. $Z\gamma^*$ with γ^* going into two leptons). Upper limits at 95% confidence level (CL) are set on mixing parameters between HNL and

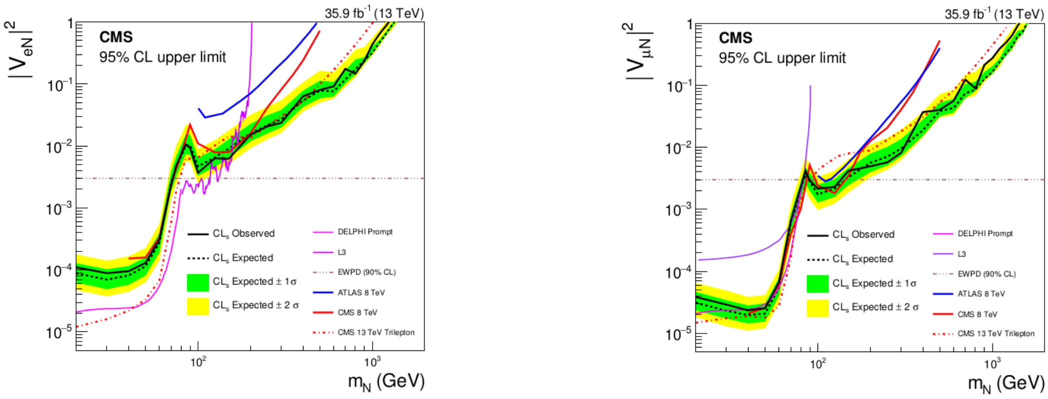

Figure 3 – Observed and expected upper limits at 95% CL on mixing paramter between HNL and electron (left) or muon (right) as a function of the HNL mass in the SS dilepton channel. The trilepton channel results are shown by the red dashed line. [6]

electrons or muons and vary between 1.5×10^{-5} and 1.8 for HNL masses between 1 GeV and 1.2 TeV, as shown in Fig. 3 by the red dashed line.

The same-sign (SS) dilepton search of HNL [6] considers the decay of a W boson into two SS leptons and a pair of jets. The main backgrounds are the prompt leptons coming from WZ and ZZ decays, estimated from simulation, the misidentified leptons coming from DY+jets, $t\bar{t}$, and W+jets, estimated through a data-driven method, and the mismeasured charge events from DY, estimated from simulation. The strategy used in this analysis is to search for an excess of events in the dilepton-dijet invariant mass distribution, considering two different regions: the *low-mass region* for $m_N < m_W$ and the *high-mass region* for $m_N > m_W$, shown in Fig. 2. No significant excess is observed in these distributions. Upper limits at 95% CL are set on the mixing parameters between HNL and electrons or muons, varying between 2.3×10^{-5} and 1 for HNL masses between 20 GeV and 1600 GeV, as shown in Fig. 3. Comparing these results with the ones of the trilepton channel analysis (represented in Fig. 3 by the red dashed line), it can be noted that the trilepton channel has more stringent limits for low masses of HNL, while the SS dilepton channel has higher sensitivity at high masses, giving the most restrictive direct limits for $m_N > 100$ GeV and the first limits for $m_N > 1.2$ TeV.

2.2 Right-handed neutrinos

The search for RH neutrinos [7] looks for a W_R boson decaying into two leptons and two jets following the LR symmetric model without flavour changing. The final states are divided in two different regions: the *electron channel* with two electrons and two jets, and the *muon channel* with two muons and two jets. To select the events, two leptons at high-p_T and two jets at high-p_T with $|\eta| < 2.4$ are required. A $\Delta R > 0.4$ requirement is used to ensure the separation between the final state candidates. For the signal region, a dilepton invariant mass > 200 GeV and a dilepton-dijet invariant mass (m_{lljj}) > 600 GeV are also required. The main backgrounds are the $t\bar{t}$, estimated through a data-driven method from a control region with one electron and one muon, and the DY+jets, estimated from simulation and normalized to data in the Z peak region. Other additional backgrounds are W+jets, diboson, and single top quark production, estimated from simulation. The limit extraction used in different regions of m_{lljj} looks for an excess in the dilepton-dijet invariant mass distribution, shown in Fig. 4 [a] (top). No significant excess is observed in these distributions. Upper limits at 95% CL are set on W_R mass assuming $m_{N_R} = \frac{1}{2} m_{W_R}$ and are also estimated in the 2D plane (m_{N_R}, m_{W_R}), as shown in Fig. 4 (bottom). From these results, a W_R boson is excluded up to a mass of 4.4 TeV in both channels, improving the last CMS public results of 2015 of ~ 1 TeV.

[a] Only the results for the electron channel are shown here. The muon channel has similar results.

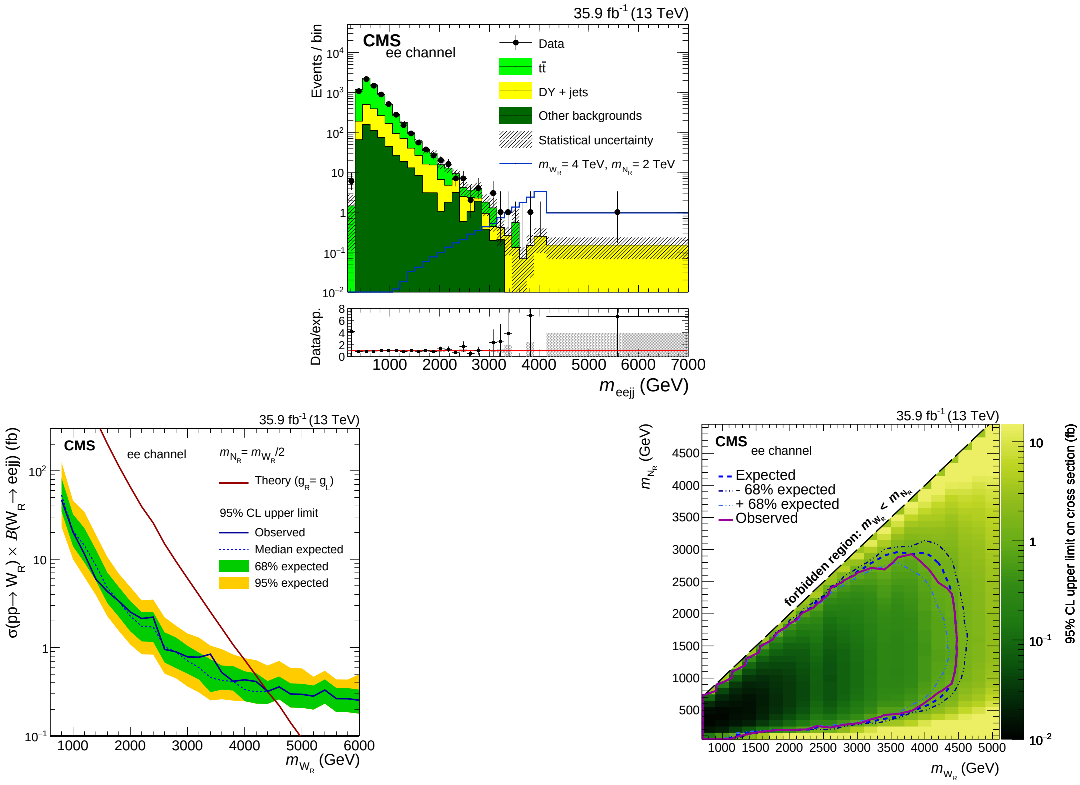

Figure 4 – Top: dilepton-dijet invariant mass distributions for data, background samples and one signal hyphothesis in the electron channel. Bottom left: Observed and expected upper limits at 95% CL on cross section as a function of W_R mass in the electron channel. Bottom right: Observed and expected 2D limits on W_R cross section for different W_R and N_R mass hypotheses in the electron channel. [7]

3 Long-lived particles

The long-lived particles (LLPs) are resonances that live long enough to escape the detector or, if they loose all their kinematic energy via ionization or strong interactions, to decay in it with a displaced vertex outside the tracker. The LLPs are predicted by many models, such as small couplings, decay through heavy particle, and small mass splitting. Their signatures are then very different and unusual, such as stopped particles and disappearing tracks (which are presented in Sections 3.1 and 3.2), displaced leptons/jets and heavy-stable-charged-particles. They are visible in different parts of the detector, requiring dedicated searches and often specialized triggers.

3.1 Stopped particles

The analysis on the stopped long-lived particles [8] looks for two heavy exotic LLPs with a lifetime between 100 ns and 10^6 s coming to rest in the detector. Two different decays are considered: an *hadron decay* which can be detected in the hadronic calorimeter with two out-of-time (OOT) jets with large energy deposits, and a *muon decay* which can be detected in the muon system with two OOT muons with displaced tracks. This last decay has been studied for the first time at the LHC. The two signatures need to be at least two bunch-crossings (50 ns) away from any proton bunch since the decay happens when there are no colliding beams. For this analysis, 2015 and 2016 data at 13 TeV are used, with a luminosity of 38.6 (39.0) fb^{-1} for the hadron (muon) decay, corresponding to a search interval of 721 (744) hours. For the hadron decay, the signal models are the two- or three-body decay of the gluino (*"split SUSY"*) and the decay of the top squark in a neutralino, while for the muon decay are the three-body decay of the gluino in a neutralino following a different model (*"T3lh"* SUSY model) and the decay of the multiply charged massive particles (MCHAMPs), with a charge two times the charge of the electron, into

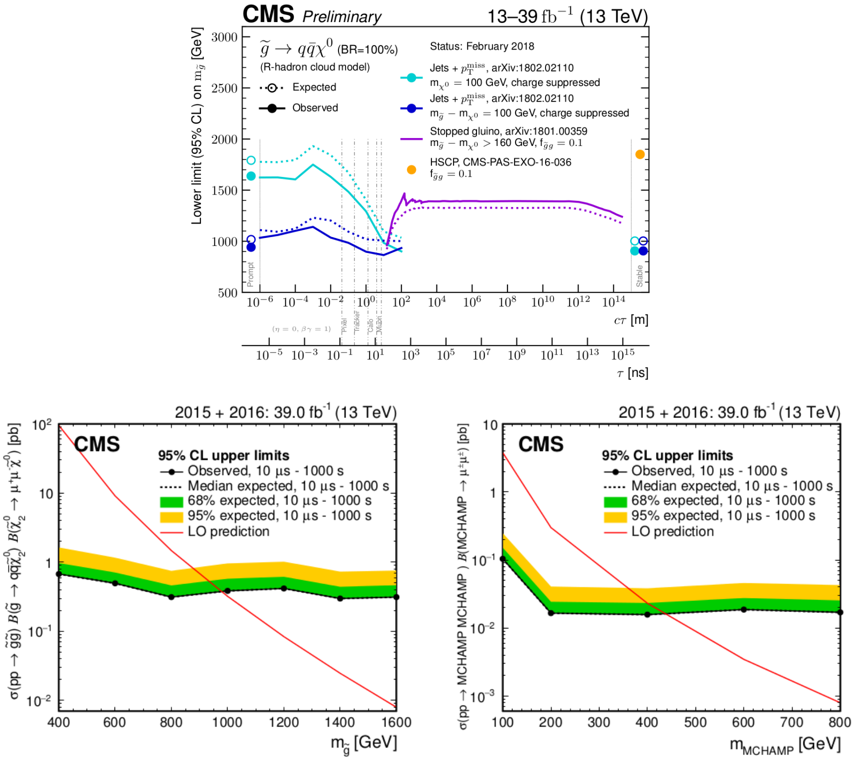

Figure 5 – Top: Observed and expected lower limits at 95% CL on gluino mass as a function of lifetime in the hadron decay. Bottom left: Observed and expected upper limits at 95% CL on cross section as a function of mass for gluinos in the muon decay. Bottom right: Observed and expected upper limits at 95% CL on cross section as a function of mass for MCHAMPs in the muon decay. [8]

two back-to-back same-sign muons. The main backgrounds for both the decays are cosmic rays, beam halo particles and detector noise, estimated from control samples in data. The observed data (4 in 2015 and 13 in 2016) do not show any excess over the background. Combining the results from 2015 and 2016 data, for lifetimes between 10 μs and 1000 s, gluinos with masses below 1385 (1393) GeV for the two-(three-)body decay and top squarks with mass below 744 GeV are excluded in the hadron decay, while gluinos with masses between 400 and 980 GeV and MCHAMPs with masses between 100 and 440 GeV are excluded in the muon decay, as shown in Fig. 5.

3.2 Disappearing tracks

The search for disappearing tracks [9] looks for LLPs decaying in the inner tracking system with very weakly interacting decay products using the 2015 and 2016 data at 13 TeV with a luminosity of 38.4 fb^{-1}. The anomaly-mediated SUSY breaking model considering the decay of a chargino into a pion and a neutralino (which is a stable lightest-supersymmetric-particle) is used as signal model. Due to the small mass splitting between chargino and neutralino, the chargino can be considered long-lived with a lifetime of $\sim$ 1 ns while the pion with a $p_T \sim 100$ MeV is too soft to be reconstructed. A disappearing track is then produced by a chargino pair with an initial-state-radiation jet. There are no hits in the outer silicon tracker, little associated energy in the calorimeter and no hits in the muon chambers. The main backgrounds, estimated with a data-driven method, are spurious tracks and charged leptons coming from the decays of $W \to l\nu$ and $Z \to ll$. The 7 observed events are compatible with the expected background. Upper limits at 95% CL on chargino mass as a function of chargino lifetime and on cross section as a function of chargino mass are set, as shown in Fig. 6. For $\tau = 3$ ns, the charginos are excluded up to 715 GeV, improving the previous CMS Run 1 results of $\sim$ 200 GeV.

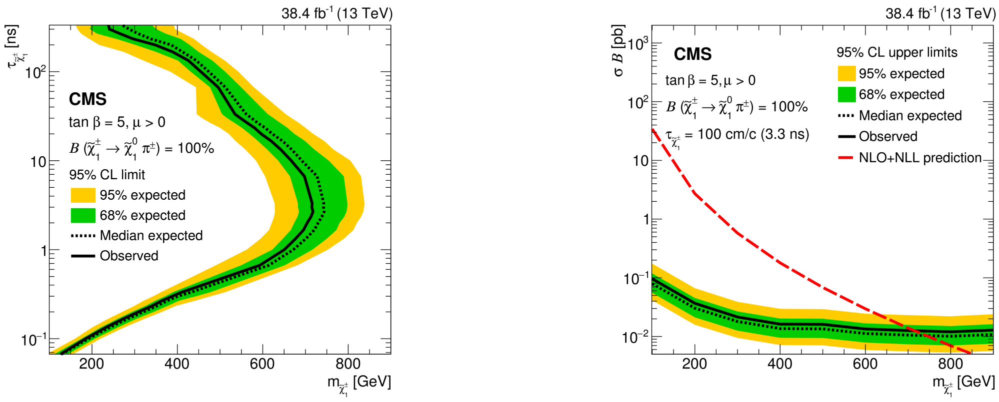

Figure 6 – Left: Observed and expected 95% CL upper limits on chargino mass as a function of chargino lifetime. Right: Observed and expected 95% CL upper limits on cross section as a function of chargino mass. [9]

4 Conclusions

The CMS experiment covers a wide program of HNL, RH neutrinos and LLP searches and has performed the first search at LHC on stopped particles decaying to higly delayed and displaced muons. A lot of stringent limits on different benchmark models are set but so far no significant excess has been observed above the SM predictions. Anyway, LHC is still a developing area of research with new techniques, new specific triggers, and more data to collect, and a lot of channels, like other production modes and displaced decays which will increase the sensitivity to HNL with low mass and low couplings, have still to be explored. Future searches at LHC will then allow to significantly extend the parameter space probed so far and the synergy between experiments like SHiP and FCC-ee will allow the exploration of a large parameter space for sterile neutrinos, providing great prospects for RH neutrino searches also at future experiments.

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