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Searches for heavy neutral leptons at the LHC

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Abstract

Heavy neutral leptons (HNLs) are introduced in extensions of the standard model (SM) of particle physics to explain the nonzero neutrino masses via the seesaw mechanism. They can also be a dark matter candidate, or provide a mechanism for the generation of the matter-antimatter asymmetry in the universe. At the CERN Large Hadron Collider (LHC), HNLs could be produced in proton-proton collisions through various processes. The ATLAS and CMS experiments have performed HNL searches covering a wide mass range from a few GeV to several TeV. Here, a selection of recent results is presented that are based on the full pp collisions data set at 13 TeV recorded during Run 2 of the LHC (2015-2018).

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Searches for heavy neutral leptons at the LHC

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1 Introduction

Heavy neutral leptons (HNLs) are introduced in extensions of the standard model (SM) of particle physics to explain the nonzero neutrino masses via the seesaw mechanism. They can also be a dark matter candidate, or provide a mechanism for the generation of the matter-antimatter asymmetry in the universe. At the CERN Large Hadron Collider (LHC), HNLs could be produced in proton-proton (pp) collisions through various processes. The ATLAS [1] and CMS [2] experiments have performed HNL searches covering a wide mass range from a few GeV to several TeV, making use of the excellent reconstruction of charged leptons, jets, and missing momentum with their detectors.

Here, a selection of recent ATLAS and CMS results is presented that are based on the full pp collision data set at $\sqrt{s} = 13\,\text{TeV}$ recorded during Run 2 of the LHC (2015–2018), corresponding to an integrated luminosity of about $140\,\text{fb}^{-1}$. The searches cover a wide range of HNL phenomenologies: HNL production in type-I seesaw models through the Drell–Yan (DY) or a t-channel vector boson fusion (VBF) process [3–5]; pair production of heavy neutral and charged leptons in type-III seesaw models [6]; and HNL pair production in decays of a new heavy Z' boson [7].

2 Searches for long-lived HNLs in DY production

In a type-I seesaw model, HNLs of Majorana or Dirac nature can be produced in the DY process via their mixing with SM neutrinos, as illustrated in Fig. 1 (upper left). The HNL decay can proceed to two charged leptons and a SM neutrino (resulting in a trilepton final state), or to a charged lepton and two quarks (dilepton final state). Searches for this production mode in both final states have been performed by the ATLAS, CMS, and LHCb experiments, covering HNL masses between $1\,\text{GeV}$ and $1.6\,\text{TeV}$ [8–11]. For HNL masses below $20\,\text{GeV}$, the HNL lifetime becomes so large that the displacement of the HNL decay vertex can be resolved by the experiments, such that dedicated searches for long-lived decays become possible.

In Ref. [3], the CMS Collaboration presents a search for HNL production through the DY process in the trilepton final state with a secondary dilepton vertex. Events are categorized by the invariant mass of the secondary dilepton system and the transverse displacement of the secondary vertex. Background contributions arise from nonprompt leptons selected for the secondary dilepton vertex, and are estimated with a "loose-not-tight ratio" method from data. Exclusion limits are derived from a template fit, considering exclusive HNL couplings to either electrons or muons, with one example shown in Fig. 1 (lower left).

In Ref. [4], the ATLAS Collaboration presents a search for the same HNL process, using events with a displaced dilepton vertex. The HNL mass is reconstructed from

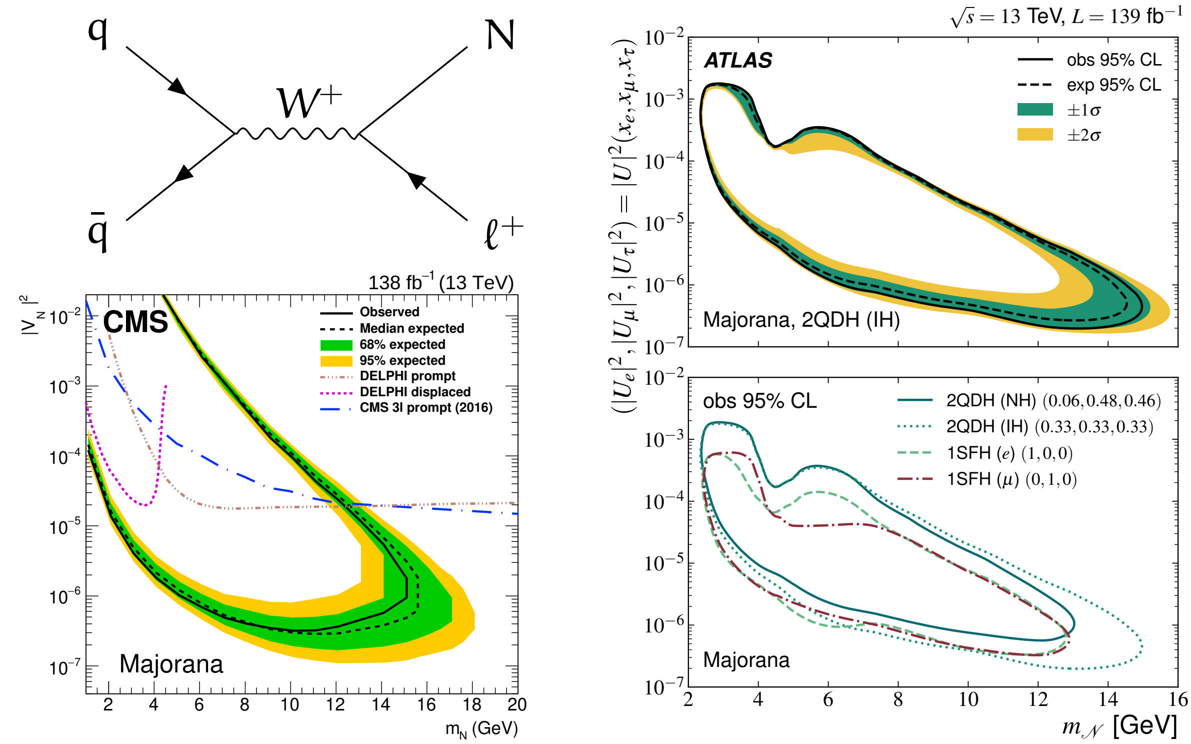

Figure 1: (Upper left) Example Feynman diagram for HNL production via the DY process in type-I seesaw models. (Lower left) Exclusion limits on the mixing parameter $|V_{N\mu}|^2$ between HNL and muon in type-I seesaw models as a function of the HNL mass m_N from Ref. [3]. (Right) Exclusion limits on the mixing parameter $|U|^2$ in type-I seesaw models with different mixing assumptions as a function of the HNL mass $m_{\mathcal{N}}$ from Ref. [4].

the selected leptons using a W boson mass constraint and imposing the vector from the primary to the displaced vertex as the HNL flight direction, and is used to categorize the events. Background contributions arise from random track crossings, and are estimated with an "event shuffling" method from data. Exclusion limits are derived from a template fit, considering exclusive HNL couplings to either electrons or muons, as well as mixed-coupling scenarios with two quasi-degenerate HNLs. Examples are shown in Fig. 1 (right).

The exclusion limits of the long-lived searches significantly improve over the results from the prompt searches in the mass range 1–15 GeV. Differences between the results from the two experiments arise from different p_T thresholds in the single-lepton triggers, different strategies for the selection of a secondary or displaced vertex, and different requirements for the removal of background contributions from low-mass resonances.

3 Search for HNLs in t-channel VBF production

The production of HNLs in type-I seesaw models is also possible via VBF processes, relevant typically only at large HNL masses. In Ref. [5], the CMS Collaboration presents a search for HNL production in a t-channel VBF process, as illustrated in Fig. 2 (left), characterized by the presence of two jets with large rapidity separation, using events with two same-sign muons. An HNL of Majorana nature with exclusive couplings to muons is considered.

The selected events are categorized by the azimuthal angle between the two muons.

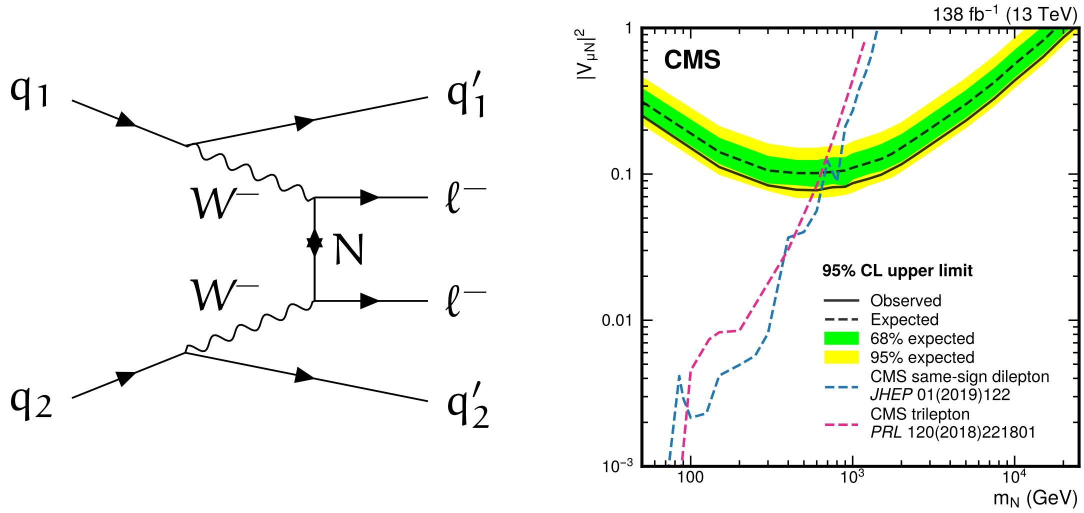

Figure 2: (Left) Example Feynman diagram for HNL production in a t-channel VBF process in type-I seesaw models. (Right) Exclusion limits on the mixing parameter $|V_{\mu\mathrm{N}}|^2$ between HNL and muon in type-I seesaw models as a function of the HNL mass m_N from Ref. [5].

Background contributions with nonprompt muons are estimated from data, while contributions from diboson and associated top quark plus boson production are estimated from simulation. Exclusion limits are derived from template fits to the distribution of the ratio of the scalar p_T sum of all selected jets to the leading muon p_T. The limits are shown in Fig. 2 (right). The search in the t-channel VBF production process provides better sensitivity than previous searches in the DY production process [8, 9] for HNL masses above 650 GeV.

4 Search for heavy leptons in type-III seesaw models

In a type-III seesaw model, the SM is extended with an additional fermionic $\mathrm{SU}(2)_L$ triplet, resulting in new heavy neutral and charged leptons. These can be pair produced via s-channel production of virtual electroweak gauge bosons, and decay each to a boson

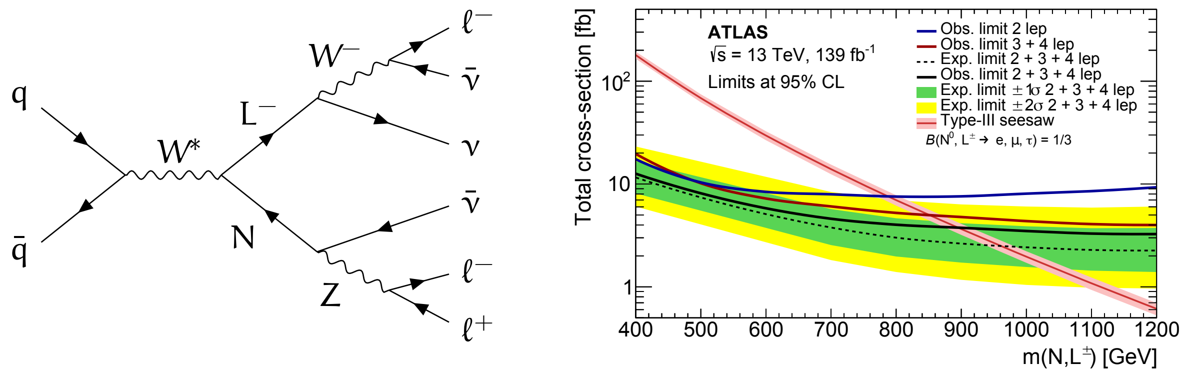

Figure 3: (Left) Example Feynman diagram for HNL and heavy charged lepton pair production in type-III seesaw models. (Right) Exclusion limits on the production cross section as a function of the degenerate HNL and heavy charged lepton mass $m(\mathrm{N}, \mathrm{L}^{\pm})$ for events with different number of leptons and their combination from Ref. [6].

(H, Z, or W) and a charged lepton or neutrino. An example is illustrated in Fig. 3 (left).

In Ref. [6], the ATLAS Collaboration presents a search for pair production of heavy neutral and charged leptons, in a mass-degenerate scenario with "democratic" mixing parameters, using final states with three or four charged leptons. The selected events are categorized by the presence of Z boson candidate (an opposite-sign same-flavour lepton pair with invariant mass close to the Z boson mass) and the number of jets, targeting different possible final state combinations of the bosons in the decay. Background contributions with nonprompt leptons and charge-misidentified electrons are estimated from data, while diboson and $t\bar{t}$+boson contributions are estimated from simulation.

Exclusion limits are derived from template fits to the distribution of the transverse mass of the three-lepton system (the scalar p_T sum of all reconstructed charged leptons and jets and of the missing transverse momentum) for three-lepton (four-lepton) events. The results are also combined with a similar search using dilepton events from Ref. [12]. The individual and combined limits are shown in Fig. 3 (right). Heavy neutral and charged leptons in type-III seesaw models are excluded up to 910 GeV.

5 Search for HNL pair production in Z′ decays

In a left-right symmetry model (LRSM), the SM is extended with three additional gauge bosons ($W_R^{\pm}$ and Z′) and three right-handed neutrinos to establish a symmetry between left and right SU(2) groups. The unique LRSM signature yields events with both extra gauge bosons and right-handed neutrinos.

In Ref. [7], the CMS Collaboration presents a search for HNL pair production in Z′ decays, illustrated in Fig. 4 (left), targeting scenarios with a large mass gap between the HNL and the Z′ such that the HNLs and their decay products are highly boosted. The HNL decays via a virtual $W_R^{\pm}$ to a charged lepton and two quarks are selected either with a boosted (non-isolated charged lepton and a large-radius jet) or a resolved (isolated charged lepton and two small-radius jets) topology. Events are categorized by the lepton flavour and the number of large-radius jets, and the Z′ is reconstructed from the selected HNL decay products. Background contributions arise dominantly from $t\bar{t}$ and $\ell^+\ell^-$ production,

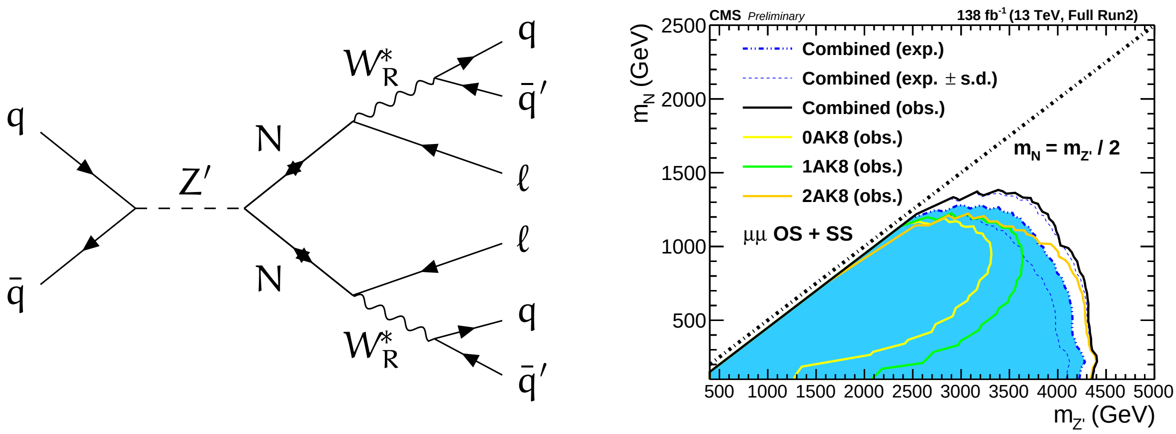

Figure 4: (Left) Example Feynman diagram for HNL pair production in Z′ decays. (Right) Exclusion limits derived from dimuon events on LRSM models as a function of HNL mass m_N and Z′ mass $m_{Z'}$ for events with different number of large-radius jets ("AK8") and their combination from Ref. [7].

and are estimated from simulation.

Exclusion limits are derived from template fits to the reconstructed Z' mass distribution, and one example is shown in Fig. 4 (right). For the lowest considered HNL mass of 100 GeV, the LRSM model is excluded for a Z' mass of up to 2.8 (4.35) TeV in the electron (muon) channel. The largest excluded values of the HNL mass are 1.2 (1.4) TeV at a Z' mass of about 3.0 (3.4) TeV in the electron (muon) channel.

6 Outlook

While the ATLAS and CMS collaborations have presented many results on HNL searches with the full Run 2 data set, further analysis efforts are ongoing to extend results that were so far only performed on a partial data set, to include new models and final states, and to use new and improved analysis techniques. Additionally, the LHC has resumed data taking in 2022 at an increased energy $\sqrt{s} = 13.6$ TeV, providing interesting prospects, especially for HNL models with very high masses.

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