PROCEEDINGS OF SCIENCE

Heavy Neutrino Searches at LHC

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A wide variety of searches for Heavy neutral leptons (HNLs) is carried out at the Large Hadron Collider, featuring a variety of signatures and theoretical models. In this note, several recent searches carried out by the CMS and ATLAS experiments for a HNL mass range from 1 GeV to several TeVs are reviewed.

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1. Introduction

Different well-motivated beyond the standard (BSM) theories extend the neutrino sector postulating the existence of additional neutral fermions. Such states are referred to as heavy neutral leptons (HNLs) when they cannot be produced in oscillations due to their large mass. Different phenomena, as the baryon asymmetry in the universe, the nature of dark matter, or the g_μ-2 anomaly [1], could be explained by models with HNLs. Some recent representative ATLAS [2] and CMS [3] searches for HNLs with masses from O(GeV) to several TeVs, making use of the full dataset available from the LHC Run 2, are reviewed in the next sections. These searches exploit a variety of signatures and models and consider a Seesaw mechanism to introduce Majorana or Dirac HNLs.

2. Right-handed W and N searches in events with charged leptons and jets

In left-right symmetric models (LRSM), right-handed partners to the W and Z standard model (SM) vector bosons, as well as right-handed heavy neutrinos, can be introduced depending on the type of model, to explain the broken parity symmetry of the weak interaction in the SM. A search for heavy right-handed gauge bosons W_R, and right-handed neutrinos, N_R, has been carried out for an integrated luminosity of 139 fb^{-1} using data collected by ATLAS during the Run 2 of the LHC [4]. This search selects events with energetic electrons or muons, and jets. The results are interpreted assuming a Majorana or Dirac N_R, concretely a Keung-Senjanović process is considered [5]. The corresponding leading order Feynman of interest for this search are shown in Figure 1.

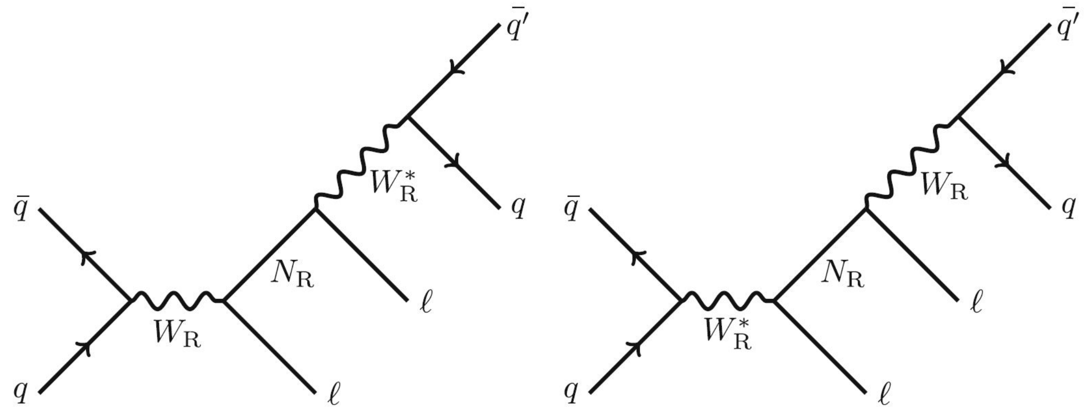

Figure 1: Leading-order Feynman diagrams for the Keung–Senjanovic process for m(W_R) > m(N_R) (left) and m(N_R) > m(W_R) (right).

Although in principle it is possible to have flavour mixing in LRSM models, this analysis targets final states with same flavour electrons or muons. Events with same-sign charged leptons are expected 50% of the times for a Majorana N_R, and therefore both same- or opposite-sign events are considered. The search focuses on W_R hadronic decays, due to the larger branching fraction; and is carried out separately for "resolved" topologies, with well-separated final state particles; and for "boosted" events, with partially overlapping leptonic or hadronic objects reconstructed as a large-radius jet. Both approaches are complementary, as the best sensitivity depends on the mass hierarchy of the new particles. This is illustrated in Figure 2, where 95% confidence level (CL) exclusion limits on W_R and N_R are shown for the individual searches for the Majorana case. A range up to $m(W_R)$ = 6.4 TeV is excluded both for Majorana and Dirac heavy neutrino for $m(N_R)$ < 1 TeV. The best exclusion of N_R takes place around 3.5 TeV for both electron and muon channels for a mass of W_R around 4.8 (5.1) TeV for the Majorana (Dirac) case. A similar Run 2 search, interpreting the results considering a Majorana N_R, and placing limits on W_R up to 4.7 (5.0) TeV for the electron (muon) channel has been carried out at CMS [6], and is also shown in the figure.

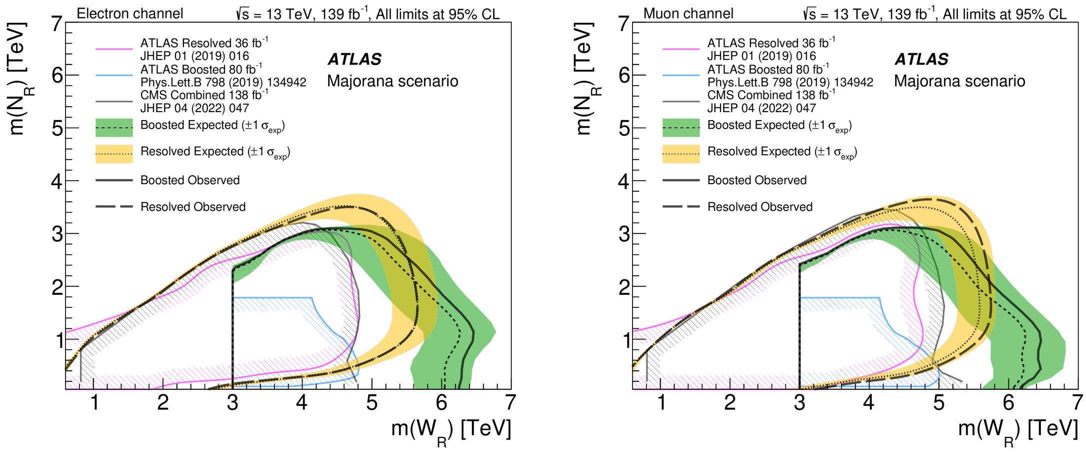

Figure 2: 95% CL exclusion limits on the $m(W_R)$ vs $m(N_R)$ phase space for the electron (left) and muon (right) channels for a Majorana N_R. Figures are taken from Ref. [4].

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3. Majorana neutrinos in same-sign WW scattering

An ATLAS search for same-sign WW scattering mediated by a Majorana neutrino N has been carried out using 140 fb^{-1} of integrated luminosity [7]. The characteristic signature of this process consists on the presence of two same-sign muons and two jets well separated in rapidity. This process and the SM same-sign WW scattering production, which constitutes the main background of this search, are shown in Figure 3. The SM WW scattering and the WZ production, another relevant background, are constrained in data using control regions depleted on signal events. The transverse momentum of the subleading muon, $p_T^{\mu 2}$, is found to provide the best discrimination between signal and background amongst different kinematical variables, and is therefore used to search for the heavy Majorana neutrino production using a profile combined likelihood fit in the signal and control regions. No significant excess is observed and 95% CL limits are placed on the squared muon-neutrino-heavy-neutrino mass-mixing matrix element $|V_{\mu N}|^2$ as a function of m_N. The post-fit distribution of $p_T^{\mu 2}$ in the signal region, and the upper exclusion limits are shown in Figure 4.

A similar CMS search for HNL in same-sign WW scattering has also been carried out using data from the LHC Run 2 [8]. Both of them extend the reach of LHC towards a higher m_N range. For lower values of m_N, production through s-channel processes present better sensitivity, as illustrated in Figure 5 for the muon coupling. For the lowest values of the heavy neutrino mass within the LHC range, the HNL becomes relatively long-lived, and specific searches designed to reconstruct

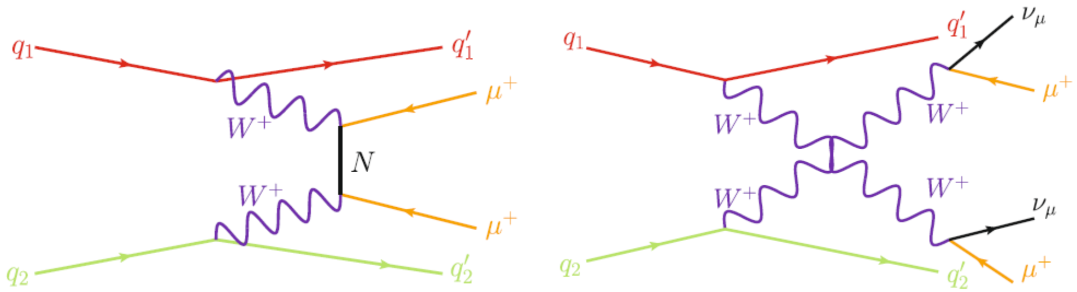

Figure 3: Diagrammatic representation of the same-sign WW scattering mediated by a Majorana neutrino signal (left) and electroweak same-sign WW scattering (right).

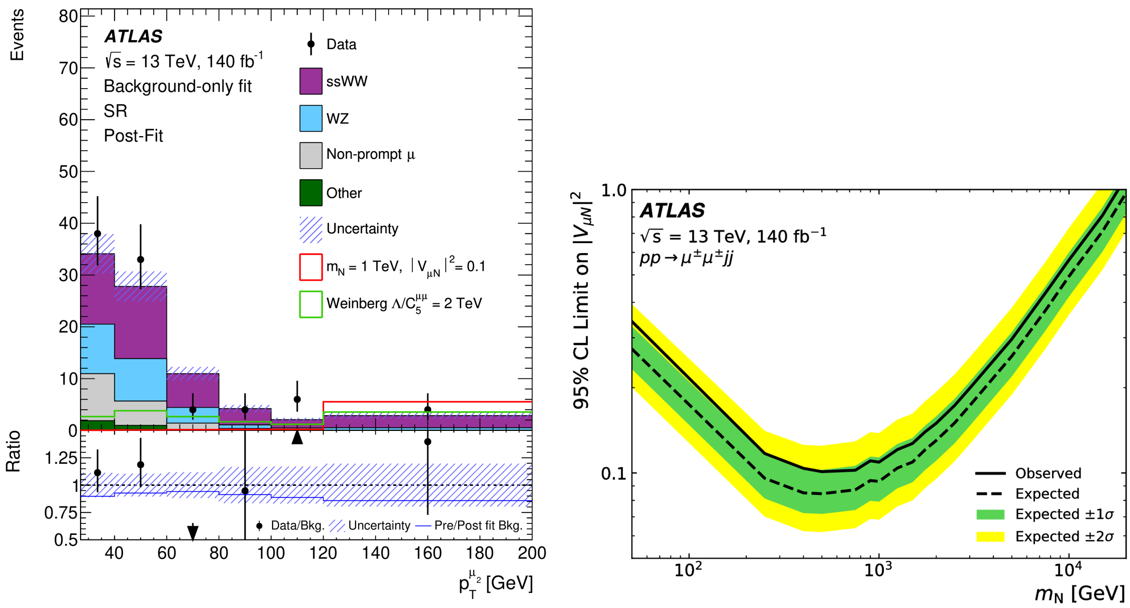

Figure 4: Post-fit data and prediction comparison of the $p_T^{\mu 2}$ distribution (left) and 95% confidence-level upper limits on $|V_{\mu N}|^2$ as a function of m_N. Figures are taken from Ref. [7].

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objects displaced form the interaction point are required. Examples of this kind of searches are shown in the next sections.

4. HNLs with displaced e/μ/τ+jet

A search for long-lived HNLs using events comprising two electrons or muons and jets has been carried at CMS with an integrated luminosity of 138 fb $^{-1}$ [9]. The search considers HNL production through an on-shell W boson decay, and a subsequent three-body decay involving a virtual W boson giving rise to hadronic activity, as illustrated in Figure 6. Two charged leptons are also present in the final state. One of the leptons, ℓ_2, is displaced with respect to the primary vertex for a long-lived HNL, while the other one, ℓ_1, is used to trigger the event. The search considers

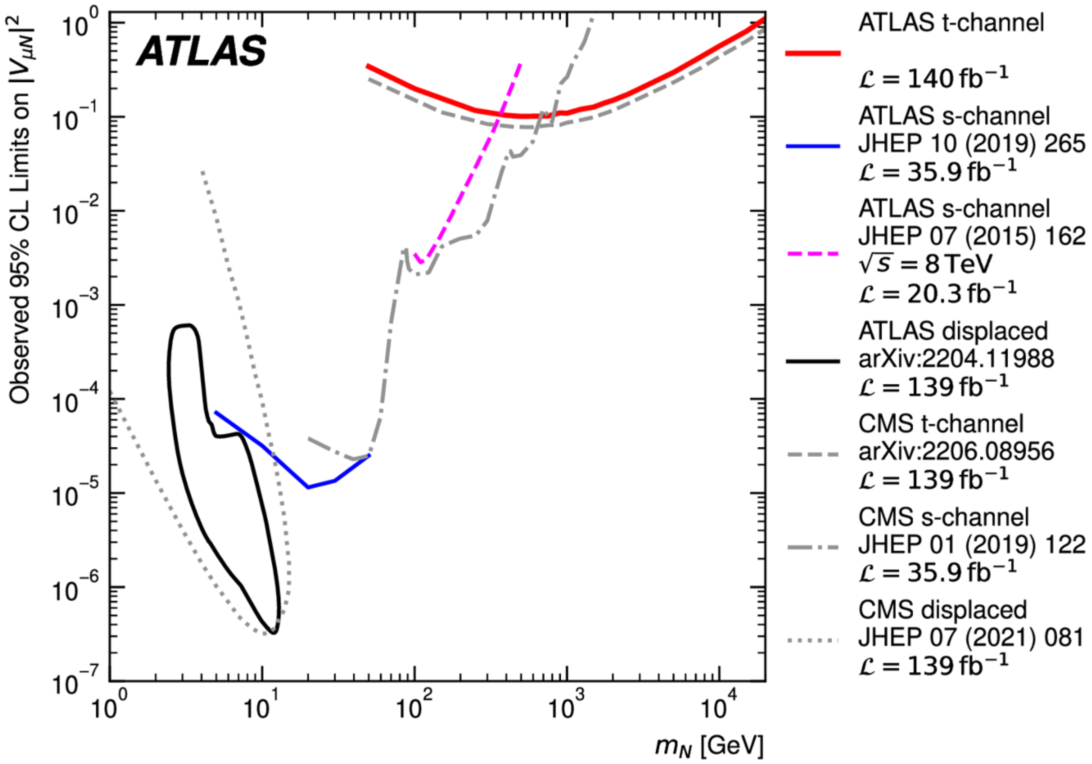

Figure 5: Summary of the 95% $|V_{\mu N}|$ exclusion limits for a variety of ATLAS and CMS searches. The red line shows the exclusion limits for the search described in Section 3. The reference for the CMS t-channel publication is given in Ref. [8]. The figure is taken from the auxiliary material corresponding to Ref. [7].

any flavour combination of electrons and muons, and is also sensitive to taus via its lepton decay (hadronic tau decays are not considered).

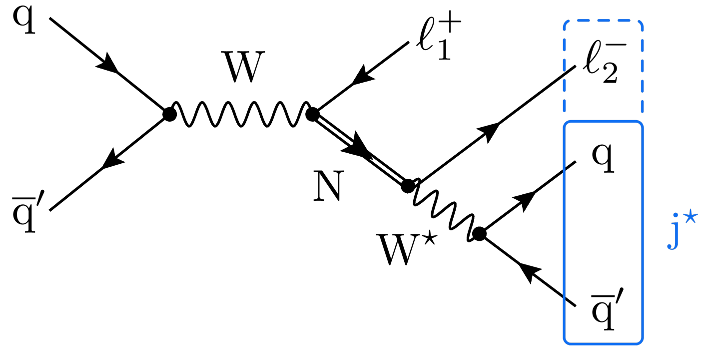

Figure 6: Tree-level Feynman diagram for Dirac HNL production and decay products targeted by the search presented in Section 4. Dirac anti-HNL and Majorana HNL diagrams are also considered. The objects shown in boxes can be collimated and reconstructed within a single jet j*.

Both Dirac and Majorana HNLs are considered and arbitrary couplings to the three lepton generations are probed. The search is carried out for the range $2 < m_N < 20$ GeV, allowing to explore HNL proper decay lengths up to $c\tau_0 = 10^4$mm. A key feature of the search is a deep neural network designed to identify jets from an HNL decay exploiting features of the jet and its constituent particles. Up to 48 event categories are defined based on the flavour, sign of the leptons, whether ℓ_2 overlaps with the hadronic activity from the HNL decay (boosted or resolved event), and the significance of the displacement of ℓ_2. This allows to be simultaneously sensitive to different masses of a Majorana or Dirac HNL for various coupling scenarios. Upper limits are set on the HNL production cross section as a function of the three coupling strengths. The most stringent limits are found for the pure muon coupling scenario, excluding $|V_{\mu N}|^2 > 5\ (4) \times 10^{-7}$ for Dirac (Majorana) HNLs for m_N = 10 GeV at 95% CL, as shown in the left panel of Figure 7 for the Dirac case. The right panel of the figure shows the excluded proper lifetimes for m_N = 4.5 GeV, as a function of the coupling strengths to the three lepton generations.

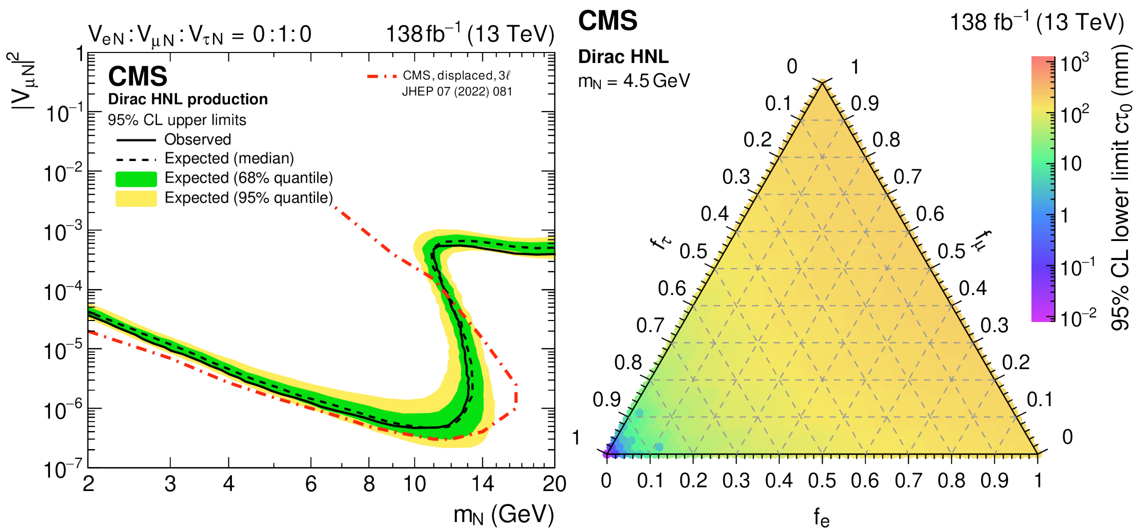

Figure 7: Upper 95% CL limits on $|V_{\ell N}|^2$ for the pure muon coupling scenario (left), and lower limits on the proper decay length of an HNL with a mass of 4.5 GeV as function of the relative coupling strengths to the three lepton generations (right). Dirac HNLs are considered. Figures are taken from Ref. [9].

5. HNL decays on muon detectors

CMS has performed a search for HNLs decaying in the muon detectors [10]. The distance of several meters between the CMS muon system and the interaction point constitutes an excellent handle to investigate the HNL decay-length range of 0.1 - 10 m, allowing to extend the sensitivity to $V_{\ell N}$ in the mass range $1 < m_N < 3$ GeV. As in Section 4, HNLs produced by an on-sell W boson decay are considered, but a wider variety of diagrams can contribute to the targeted signal, as shown in the left panel of Figure 8. The signature is characterized by a high multiplicity cluster of muon detector hits, referred to as a muon shower (MDS). Electrons or hadronic products from HNL decays, which can originate from an intermediate tau lepton decay, can produce an MDS as a consequence of the particle shower created by their interaction with the shielding materials in the muon detectors. Prompt leptons (electrons or muons) are also expected and are used for triggering. Both drift-tube (DTs) detectors in the barrel region, and cathode strip chambers (CSCs), covering the forward region, are used for MDS reconstruction. The background can arise from $Z \to \mu\mu$ events for signals triggered by prompt muons. A non-muon induced background originates from

SM processes, dominated by W production, accompanied by low momentum hadrons from pileup or the underlying event producing a MDS object. This component of the background is present for events triggered both by electrons or muons. The right panel of Figure 8 presents the expected background and signals yields for m_N = 2 GeV and $c\tau_0$ = 1m, for the different event categories employed in the search, which depend on the flavour of the prompt lepton and on the detector in which the MDS is reconstructed.

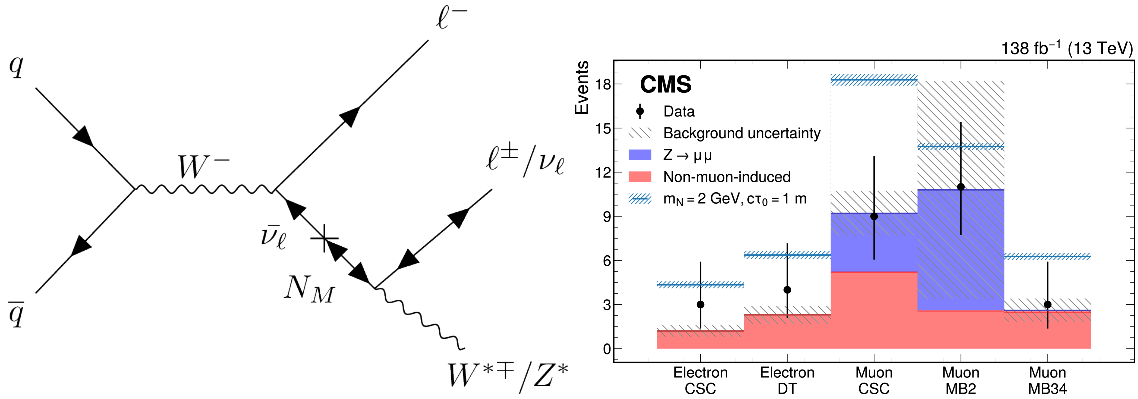

Figure 8: Feynman diagram for the production of a Majorana HNL (left) and expected and observed number of events in the signal region. MB2 and MB34 (MB3 and MB4) refer to different "stations" of the drift tube detectors. Figures are taken from Ref. [10].

No significant excess over the SM background is observed and 95% CL limits are set on the HNL production cross section as a function of the 3 coupling strengths. The search sets the most stringent limits to date for the electron (muon) channel in the HNL mass range of 2.1 - 3.0 (1.9 - 3.3) GeV, reaching 95% CL exclusion limits on $|V_{\ell N}|^2$ as low as 8.6 (4.6) $\times$ 10^{-6}. The limits are shown in Figure 9 for the pure electron or muon coupling for a Majorana HNL as a function of m_N.

6. Summary

In this note, recent ATLAS and CMS searches for HNLs at $\sqrt{s}$ = 13 TeV have been reviewed. Different models based on a Seesaw mechanism, predicting a Majorana or Dirac HNL, are considered. An HNL mass range from 1 GeV to several TeV is covered, exploiting various production modes, such as WW scattering or through a SM or right-handed W boson decay; and decay signatures, including those featuring displaced objects from the interaction point for lower HNL masses.

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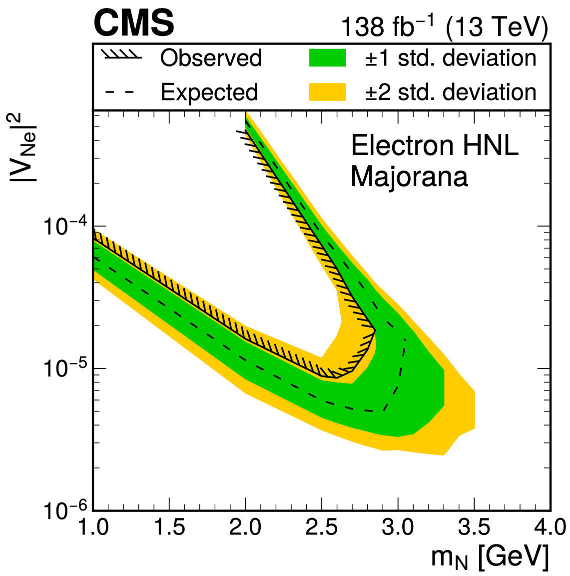

Figure 9: Upper 95% CL limits on $|V_{\ell N}|^2$ for the pure electron (left) or muon (right) coupling as a function of m_N. Figures are taken from Ref. [10].

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