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HNLs at CMS

Leonardo Lunerti for the CMS Collaboration

Abstract

The discovery of neutrino oscillations suggests non-zero masses for active neutrinos, which may result from the presence of massive sterile neutrinos, or heavy neutral leptons (HNLs). The most recent searches for HNLs at the CMS experiment are presented. Searches using proton-proton collisions at $\sqrt{s} = 13$ TeV recorded in the 2016-2018 data-taking period exploited various production and decay channels, focusing both on short- and long-lived HNLs for masses ranging from few GeV to the TeV scale. So far, observations are consistent with SM background predictions. The results are interpreted as upper limits on active-sterile mixing parameters, for various mixing scenarios, and under both Majorana and Dirac assumptions.

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HNLs at CMS

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The discovery of neutrino oscillations implies non-zero masses for active neutrinos, which may result from the presence of massive sterile neutrinos, or heavy neutral leptons (HNLs). The most recent searches for HNLs at the CMS experiment are presented. Searches using proton-proton collisions at $\sqrt{s}$ = 13 TeV recorded in the 2016-2018 data-taking period exploited various production and decay channels, focusing both on short- and long-lived HNLs for masses ranging from few GeV to the TeV scale. So far, observations are consistent with SM background predictions. The results are interpreted as upper limits on active-sterile mixing parameters, for various mixing scenarios, and under both Majorana and Dirac assumptions.

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1. Introduction

The standard model (SM) predicts neutrinos to be massless, but the discovery of neutrino oscillations indicates that at least two active neutrinos have non-zero mass. Beyond SM theories predict massive sterile right-handed neutrinos, or heavy neutral leptons (HNL), denoted N, leading to a mass term for left-handed neutrinos. The HNL interactions with the SM arise only through active-sterile mixing, governed by the matrix V. An HNL search can focus on a single HNL with mass m_N and mixing amplitudes $V_{\ell N}$, $\ell = e, \mu, \tau$. The mass and the mixing matrix parameters determine the HNL lifetime $\tau_N \sim 1/m_N^5|V|^2$. The most recent results on HNL searches at the CMS [1] experiment are presented. All results besides Sec. 6 make use of the full Run 2 data set, corresponding to 138fb^1 integrated luminosity. A complete review of HNL searches at CMS is in Ref. [2].

2. Search for long-lived heavy neutral leptons in proton-proton collision events with a lepton and a jet from a secondary vertex at $\sqrt{s} = 13$ TeV

The HNL search in Ref. [3] targets HNL production, in association with a lepton ℓ_1 which must match the triggering muon, from W boson decay. The HNL decays into a lepton ℓ_2 and a pair of quarks. The search is optimized for long-lived HNLs and for $1 < m_N < 20$ GeV. The two quarks merged in a single jet also contains ℓ_2. Electrons and muons are considered for ℓ_1 and ℓ_2. The HNL can be a Dirac or Majorana particle, i.e. ℓ_1 and ℓ_2 can have opposite- or same-sign electric charge. Events are categorized based on the lepton flavor.

The lepton selection criteria are based on the track quality, the impact parameter of the track with respect to the primary vertex (PV), and the isolation. The lepton selection criteria are described in Ref. [3]. The event selection requires: a prompt lepton geometrically matched to the trigger selection; one non-prompt lepton geometrically matched with one jet; the non-prompt lepton to be part of the reconstructed SV. A particle flow network (PFN) algorithm is trained to differentiate between secondary vertices (SVs) from HNL signal and those from SM background events.

The background yield is estimated using the ABCD method. A target region A defined by requiring $50 < m(\ell_1, \mathrm{SV}) < 85$ GeV and that the PFN score exceed a value x optimized per category. Regions B, C and D are defined by inverting one or both requirements on $m(\ell_1, \mathrm{SV})$ and PFN score. Observed data is compatible with the predicted background. Results are interpreted as exclusion limits at 95% CL on $|V_{eN}|^2$, $|V_{\mu N}|^2$ and $|V_{eN}V_{\mu N}|^2/(|V_{eN}|^2 + |V_{\mu N}|^2)$ as a function of m_N and for Majorana and Dirac HNLs. The limits for the exclusive coupling to ν_μ is shown in Fig. 1. A complete overview of the results is in Ref. [3]. These results exceed previous experimental constraints in the mass range 11–16 GeV for HNLs coupling to electrons or muons and provide the most stringent limits to date.

3. Search for long-lived heavy neutral leptons with lepton flavour conserving or violating decays to a jet and a charged lepton

The HNL search in [4] exploits the same HNL production and decay channel of Sec. 2. A deep neural network (DNN) is used for the displaced jet identification. The DNN does not rely on the displaced vertices reconstruction, achieving good sensitivity for long- and short-lived HNLs.

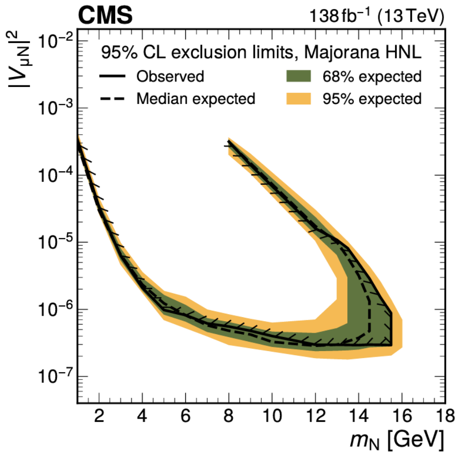

Figure 1: Limit on $|V_{\mu N}|^2$ as a function of m_N (Ref. [3])

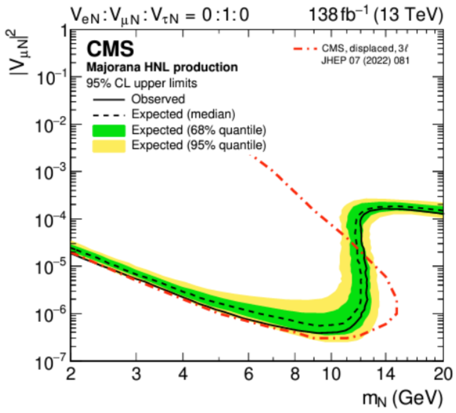

Figure 2: Limit on $|V_{\mu N}|^2$ as a function of m_N (Ref. [4])

Events must contain a lepton ℓ_1 originating from the PV. The semileptonic HNL decay results in a lepton ℓ_2 and a jet ($j*$). Leptons can be electrons or muons: only hadronic τ decay events are excluded. The ℓ_1 lepton is geometrically matched to the triggering lepton and it must pass more stringent identification criteria than ℓ_2.

Lepton identification criteria applied to ℓ_1 and ℓ_2 depend on whether $\ell = e$ or μ and are described in Ref. [4]. These selection criteria include requirements on the p_T and η of the lepton, electron or muon identification, and the impact parameter with respect to the PV. Only jets with $|\eta| < 2.4$, $p_T > 20\,\text{GeV}$ and having a $\Delta R > 0.4$ with respect to ℓ_1 are considered. Given the HNL boost, ℓ_2 and the jet must fall within a $\Delta R = 1.3$ cone. Events in the signal region (SR) are categorized based on the flavor of the leptons, their relative electric charge, and the *boosted* or *resolved* topology, i.e. if $j*$ and ℓ_2 are overlapped ($\Delta R < 0.4$). Finally events are split into three subcategories depending on the significance of the transverse displacement of ℓ_2.

The background yield is determined from data using an ABCD method. A signal-enriched region D is defined based on the $\ell_1\ell_2 j*$ invariant mass being between 70 and 90 GeV and on the DNN score. The background-enriched regions A, B and C, are defined by inverting one or both these requirements. The observed events are in agreement with the estimated background. Results are interpreted as limits on the active-sterile neutrino mixing matrix parameters as a function of m_N. Different active-sterile neutrino mixing scenarios have been explored: exclusive mixing with a single lepton flavor and non-trivial mixing with more than one lepton flavor. Both scenarios where N is a Dirac- or a Majorana-like particle have been considered. In Fig. 2 only the limit in the exclusive ν_μ-coupling scenario for a Majorana-like HNL is displayed, which shows the most stringent limit achieved by the analysis. The complete set of results is available in Ref. [4]. This analysis is the frst HNL search at the LHC targeting long-lived and hadronically decaying HNLs in the 2–20 GeV mass range, with inclusive coupling to all three lepton generations.

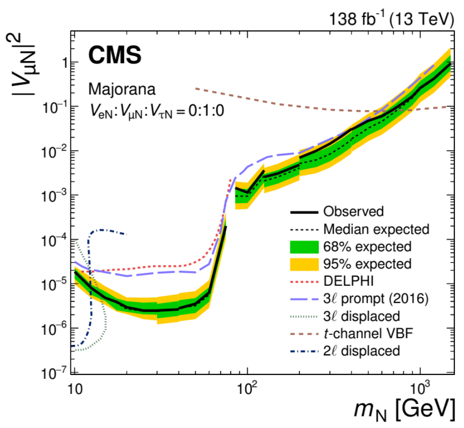

Figure 3: Limit on $|V_{\mu N}|^2$ as a function of m_N (Ref. [5])

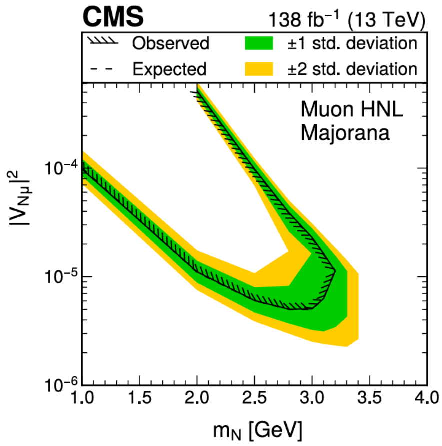

Figure 4: Limit on $|V_{\mu N}|^2$ as a function of m_N (Ref. [6])

4. Search for heavy neutral leptons in final states with electrons, muons, and hadronically decaying tau leptons in proton-proton collisions at $\sqrt{s}$ = 13 TeV

In Ref. [5], the search for HNL exploits its production from the leptonic decay of a prompt W boson. Fully leptonic HNL decays resulting in two leptons and a neutrino are considered. Events with three charged leptons are selected: electrons, muons and hadronically decaying tau leptons (τ_h). The analysis is sensitive to short-lived HNLs and $m_N > 10$ GeV.

Electrons and muons are required to have $p_T > 10$ GeV, to be compatible with the PV and to be isolated from other particles in the event. Prompt and non-prompt leptons are distinguished by applying two sets of identification (ID) criteria defined in Ref. [7]. The "tight" ("loose") IDs are applied to select prompt (non-prompt) electrons and muons. Hadronic tau lepton decays are identified using the DeepTau algorithm [8]. Different working points of the DeepTau define "loose" and a "tight" IDs for τ_h. A complete description of the lepton selection criteria can be found in Ref. [5].

Events are categorized according to the leptons flavor. Only events with at most one lepton failing the tight ID, but passing the loose ID, are selected. Events with more than one τ_h are discarded due to larger background contamination. Two orthogonal event selections are optimized based on whether the prompt lepton p_T is above ("high mass") or below ("low mass") 55 GeV. The SR definition is based first on whether there is an oppositely-charged same-flavor lepton pair. In the low mass region, SRs are defined in bins of the prompt lepton p_T and the smallest invariant mass of any opposite-sign lepton pair ($m(\ell^+\ell^-)$). In the high-mass region, the SRs are defined in bins of $m(\ell^+\ell^-)$, the three lepton invariant mass ($m(3\ell)$), and the transverse mass m_T calculated with the missing transverse momentum of the event and the lepton not used for $m(\ell^+\ell^-)$. The SRs are defined in Ref. [5].

Background yields are estimated by combining methods based on control regions in data and simulated event samples. Sub-dominant contributions come from associated top quark production and triboson production. Nonprompt-lepton background contributions mainly come from $t\bar{t}$ and Z + jets production with an additional non-prompt lepton.

Observed events are compatible with the background predictions. Limits at 95% CL are derived on the active-sterile neutrino mixing matrix as a function of m_N in the $10\,\text{GeV} < m_N < 10.5\,\text{TeV}$ range. Limits are derived assuming that the HNL can couple exclusively with ν_e, $\nu_m u$ or ν_τ. The HNL is considered to be either a Majorana or a Dirac particle. In Fig. 3 the limit on the exclusive coupling with ν_μ is shown. The limits for the other scenarios are reported in Ref. [5] and exceed previous experimental constraints over large parts of the mass range.

5. Search for long-lived heavy neutral leptons decaying in the CMS muon detectors in proton-proton collisions at $\sqrt{s} = 13$ TeV

The HNL search in [6] exploits the HNL production from prompt leptonic W boson decays. The lepton associated to the HNL production is used to trigger the event. A decay topology where HNL decays in the muon system shielding material creating hadronic and electromagnetic showers eventually detected by muon chambers is targeted. This allows to probe $m_N < 4\,\text{GeV}$ and $O(\text{m})$ proper decay lengths.

The hits clustered in the muon chambers are referred to as muon detector shower (MDS) objects. Jet punch-through and muon bremsstrahlung can produce MDS object. These backgrounds are suppressed by requiring the MDS object not to overlap with a reconstructed jet or muon. To further suppress the jet punch-through background, events with signals in the muon stations closest to the interaction region, and compatible with the MDS direction, are vetoed. The remaining dominant background consists of clusters from pileup, including interactions not in the same bunch crossing as the PV. To suppress this background, the cluster time is reconstructed and used as a discriminant. Then, only events containing clusters with at least 50 hits are selected. The presence of an MDS cluster that passes the associated vetoes and identification criteria suppresses the SM background by a factor $> 10^7$, while maintaining 25%–35% signal efficiency.

The remaining background events are *muon-induced*, i.e. $Z \to \mu\mu$ events where one muons undergoes bremsstrahlung in the muon detector producing a MDS cluster, or non-muon-induced, where the MDS cluster is produced by low momentum hadrons from pileup or an underlying event. For the non-muon-induced background, an ABCD method is used. The SR D is defined by requiring an azimuthal angle between the prompt lepton and the cluster centroid of 2.8 and the number of hits in the cluster to be above 150, or 200 depending on the muon chamber type. The A, B and C regions are defined by inverting one or both of the former requirements. For $Z \to \mu\mu$, background estimation is derived from dedicated control regions in data and extrapolated in the SR via appropriate transfer factors.

The observed event yield is compatible with the predicted background. Results are interpreted as upper limits at 95% CL on the active-sterile neutrino mixing parameter as a function of m_N for the Majorana and Dirac HNL interpretations. The limits have been computed both for the exclusive coupling scenario with either one of the three lepton flavors, and for the scenario where the HNL have a non-trivial mixing with all lepton flavors. Figure 4 shows the obtained limit for the exclusive coupling scenario with ν_μ, where the HNL is a Majorana particle. The full set of limits is available in Ref. [6]. The most stringent limits in the 2.1-3.0 (1.9-3.3) GeV HNL mass range in the e (μ) channel are set.

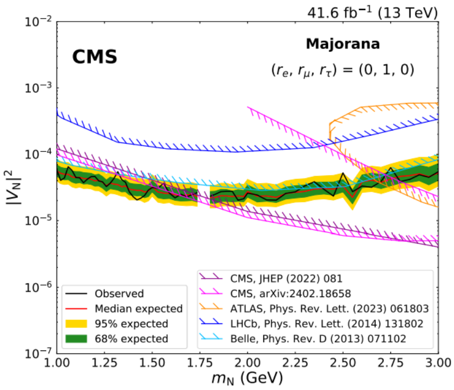

Figure 5: Limit on $|V_{\mu N}|^2$ as a function of m_N (Ref. [9])

6. Search for long-lived heavy neutrinos in the decays of B mesons produced in proton-proton collisions at $\sqrt{s}$ = 13 TeV

The search in Ref. [9] targets HNLs produced in semileptonic B mesons decays. The HNL subsequently decays into a lepton $\ell^{\pm}$ and a pion $\pi^{\mp}$. The event sample used in this analysis was recorded in 2018 using single non-prompt muon triggers with low muon p_T thresholds, the so-called "B-Parking" data-taking [10], and corresponds to a total integrated luminosity of 41.6fb^{-}1. At least one of the leptons must be a muon triggering the event. The search is performed as a bump hunt over the $\ell^{\pm}\pi^{\mp}$ invariant mass spectrum.

A baseline selection designed to ensure that the two leptons and the charged pion are well reconstructed, and the tracks associated with the $\ell^{\pm}\pi^{\mp}$ system are consistent with a common, displaced decay vertex is applied. Events are categorized based on the significance of the transverse decay length of the $\ell^{\pm}\pi^{\mp}$ system, the relative charge of the final state leptons, the total invariant mass of the lepton ℓ_B from the B decay and the $\ell^{\pm}\pi^{\mp}$ system, and the presence of an electron. The selection is further optimized by applying a multivariate-classifier-based selection. A parametric neural network (pNN) [11] has been implemented to properly incorporate a functional dependence on m_N. The pNN is trained using input variables that provide a good signal-background discrimination: transverse momenta, invariant masses, track separation, displaced vertex properties, displacement-related quantities, track-related information, and lepton isolation. Ref. [9] contains a detailed description of the pNN.

The signal yield for each HNL mass hypothesis is extracted from a simultaneous parametric fit to the $\ell^{\pm}\pi^{\mp}$ invariant mass in data. The fits to the data are performed in a series of sliding $\ell^{\pm}\pi^{\mp}$ mass windows centered around a set of closely spaced trial mass values. For each mass hypothesis the background prediction is studied prior to the final fit in the sidebands.

No excesses over the predicted background yield is observed. Results are interpreted as upper limits at 95% CL on the active-sterile neutrino mixing parameters. Limits are computed either in the exclusive coupling scenario with muon neutrino and in the scenario where the HNL has a non-trivial coupling with each of the three lepton flavor. As shown in Fig. 5, for the exclusive coupling scenario with ν_μ, this search provides the most stringent exclusion limits for masses between 1 and 1.7 GeV from a collider experiment to date.

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