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Displaced vertex search for heavy neutral leptons with the ATLAS detector

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Summary. — The results of a search for long-lived heavy neutral leptons (HNLs) in proton-proton collisions at the Large Hadron Collider are presented. The Standard Model (SM) of particle physics is an extremely successful theory and its major predictions have been precisely confirmed. However, the existence of neutrinos, with small nonzero masses, provides evidence that the SM is incomplete. Introducing HNLs into the SM is a natural way to generate the light neutrino masses through a seesaw mechanism. This search uses 139 fb^{-1} of ATLAS experimental data collected between 2015 and 2018 at a centre-of-mass energy of 13 TeV. A non-standard technique is used to search for a displaced vertex from particle trajectories produced in the HNL decay to leptons. The dominant background from uncorrelated leptons crossing in the ATLAS detector is estimated using an object shuffling method. The reconstructed HNL mass is used to discriminate between signal and background. No excess of events is observed and constraints on the strength of the interactions between HNLs and neutrinos are imposed in various scenarios.

1. – Introduction

The Standard Model of particle physics (SM) is an extremely successful theory, and its major predictions have been precisely confirmed. However, not all observed phenomena are described in this theory. For instance, the SM predicts that neutrinos are massless, which contradicts the observations of neutrino flavour oscillations [1, 2]. Introducing right-handed neutrino states, called heavy neutral leptons (HNLs), provides a natural way to generate light neutrino masses through a Type-I seesaw mechanism. HNL theories can also provide an explanation for the baryon asymmetry of the universe via charge-parity violating oscillations that would have occurred during neutrino production in the early universe. Furthermore, models with three HNLs can incorporate a dark matter candidate.

2. – HNL signal model

HNLs experience "weak-like" interactions controlled by dimensionless mixing coefficients U_α, where $\alpha = \{e, \mu, \tau\}$ is the flavour of the left-handed neutrino state. This mixing is small, such that $|U_\alpha| \ll 1$. At the Large Hadron Collider (LHC), searches for HNLs study W boson decays where the new physics could be produced via $W \to \mathcal{N}\ell_\alpha$, where ℓ is a charged lepton with flavour α and $\mathcal{N}$ is the HNL state. The HNL decays weakly into fully-leptonic or semi-leptonic final states. The search in question considers the HNL production with $\alpha = \{e, \mu\}$ flavoured leptons and the HNL decay into two oppositely charged leptons and a neutrino: $\mathcal{N} \to \ell_\beta \ell_\gamma \nu_\gamma$ via an intermediate W^* boson, or $\mathcal{N} \to \nu_\beta \ell_\gamma \ell_\gamma$ via a Z^* boson, where $\beta, \gamma = e$ or μ. Other experimentally relevant observables include the mass of the HNL, $m_\mathcal{N}$, which dictates the kinematics of the process. The HNL lifetime is related to the mixing coefficient and HNL mass such that $\tau_\mathcal{N} \approx (4.3\times10^{-12}\ \mathrm{s})|U|^{-2}(m_\mathcal{N}/1\ \mathrm{GeV})^{-5}$ [3] where $|U|^2 \equiv \sum_\alpha |U_\alpha|^2$. This search targets HNL models that produce decays on the order of a few millimeters and thus, focuses on the mass range with $m_\mathcal{N} < 20$ GeV where the HNL is long-lived.

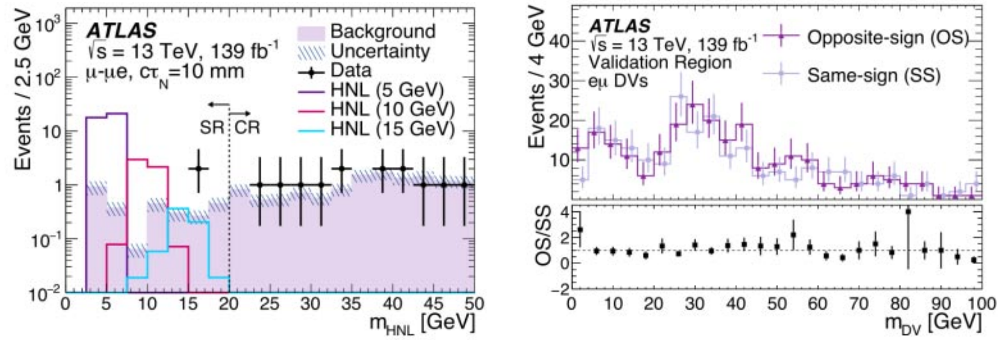
This search presents results assuming different mixing scenarios. The first is a simple model with one HNL that only has mixing with a single neutrino flavour (1SFH). While this model has been used previous experimental searches, it does not account for the small neutrino masses nor does it account for two neutrino mass splittings [4-6]. Thus, a second model is considered with two quasi-degenerate HNLs (2QDH) each with a small mass splitting and non-zero U_α for all three neutrino flavours. Two mixing benchmarks consistent with the observations of neutrino flavor oscillations assuming inverted (IH) and normal (NH) neutrino mass hierarchy are used [6, 7].

3. – Search overview

This search analyzes 139 fb^{-1} of proton-proton collision data collected using the ATLAS detector [8] at the LHC between 2015 and 2018. The particular features of the HNL signal include a "prompt" lepton, which originates from the proton interaction point (IP), and a displaced vertex (DV) at a position that is significantly displaced with respect to the IP. This DV is formed in the leptonic decay of the HNL and consists of exactly two leptons with opposite charge. Six search channels are denoted by "ℓ_α–$\ell_\beta\ell_\gamma$", according to the flavour of the prompt lepton (ℓ_α) and the two displaced leptons ($\ell_\beta\ell_\gamma$). The analysis' sensitivity to each channel depends on the value of U_α in each mixing scenario. In the 1SFH models, the $\mu-\mu\mu$, $\mu-\mu e$and $\mu-ee$channels provide sensitivity to $|U_\mu|^2$and the $e-ee$, $e-e\mu$and $e-\mu\mu$channels provide sensitivity to $|U_e|^2$. In the 2QDH models, all six channels are combined to provide sensitivity to $|U_\mu|^2$, $|U_e|^2$and $|U_\tau|^2$. More details about this search can be found in ref. [9].

4. – Event reconstruction

The event reconstruction relies heavily on the formation of charged particle trajectories (tracks). Standard tracks are reconstructed using information from silicon detectors and are constrained to originate from the primary vertex (PV) where the proton collision occurred. To maintain sensitivity to displaced tracks that do not originate from the PV, selected data events are processed with a large-radius tracking (LRT) algorithm [10]. Muons (electrons) are reconstructed from both standard and large-radius tracks matched to muon-spectrometer tracks (electromagnetic energy clusters) using momentum and direction information. DV reconstruction is performed by selecting a subset tracks, finding pairs of compatible tracks to form "seed" DVs, subsequently adding additional tracks



(a) (b)

Fig. 1. – (a) The m_{HNL} distribution in the signal (SR) and control (CR) regions for the observed data, the shuffled-event-model background normalized by the fit described in the text with its uncertainty, and simulated signal for three different mass hypotheses. (b) The m_{DV}distributions for the OS and SS $e\mu$ DVs in the validation region. Figures from [9].

and merging nearby DVs. This search uses an optimized version of the DV reconstruction algorithm described in ref. [11]. The version initially selects only tracks matched to muons or electrons. This lepton-only requirement significantly reduces the number of track combinations, which means other cuts may be loosed without significantly affecting the computation time. For example, the transverse impact parameter (d_0) is loosened such that at least one lepton in the seed DV satisfies $|d_0| > 1$ mm. Once lepton-only DVs are formed, compatible hadron tracks are added to the vertex. This is included to remove SM backgrounds from two-lepton DVs that are surrounded by detector activity.

5. – Event selection

Events in the signal region (SR) are selected with single muon and electron triggers with a minimum transverse momentum (p_{T}) of 27 GeV. A filter algorithm, used to select events to be processed with LRT, requires that the prompt lepton is isolated from detector activity and there is a least one other lepton with $p_{\mathrm{T}} > 5$ GeV. SR events must also contain a two-lepton DV with opposite-sign (OS) electric charge. The radial position of the DV (r_{DV}) must satisfy 4 mm $< r_{\mathrm{DV}} <$ 300 mm. The invariant mass of the DV and the prompt lepton ($m_{\mathrm{DV}+\ell}$) must have 40 GeV $< m_{\mathrm{DV}+\ell} <$ 90 GeV. In signal, $m_{\mathrm{DV}+\ell}$ is generally smaller than the W mass because of the missing the neutrino momentum. The reconstructed mass of the HNL (m_{HNL}) is obtained using energy-momentum conservation. The kinematics of the charged leptons, the W mass, a massless approximation for the charged leptons and the flight direction of the HNL, given by the vector connecting the PV and DV, are used to fully constrain the neutrino momentum in the $\mathcal{N} \to \ell\ell\nu$ decay. The m_{HNL} distributions for signal events, shown in fig. 1(a), peak at the generated values of $m_{\mathcal{N}}$. SR events are required to have $m_{\mathrm{HNL}} < 20$ GeV.

6. – Backgrounds

Five background sources are identified that produce two-lepton OS DVs. They include DVs from random lepton crossings, interactions with the detector material, comic-ray muons, leptonic Z boson decays, and metastable SM particle decays.

A data-driven method is used to estimate the background from random lepton crossings and additional SR selections are designed to suppress the background from the other four sources. Detector material interactions mainly produce ee DVs, which are vetoed using a three-dimensional map of the detector. Cosmic-ray muons can be reconstructed as back-to-back tracks and thus, requiring the two displaced tracks satisfy $\sqrt{(\Sigma\eta)^2 + (\pi - \Delta\phi)^2} > 0.05$ rejects this background [12]. $Z \to \ell\ell$ decays can produce a two-lepton DV if one lepton is identified as the prompt lepton, while the other lepton forms a DV with a third lepton. A symmetric mass veto around the Z mass rejects this background for events where the prompt and one displaced lepton have the same-flavour and opposite charges (*i.e.* $m(\ell_\alpha^\pm \ell_\beta^\mp) < 80$ GeV or $m(\ell_\alpha^\pm \ell_\beta^\mp) > 100$ GeV for $\alpha = \beta$). Imposing a lower limit on the DV invariant mass (m_{DV}) is an effective way to remove decays from SM metastable particles, such as J/ψ and other heavy-flavor decays. However, m_{DV} selections also reduce the sensitivity to HNLs with small masses. For ee and $e\mu$ vertices, the correlation between m_{DV} and r_{DV} in SM decays is exploited to suppress decays from metastable particles. The imposed selections are: $m_{\mathrm{DV}} > 5.5$ GeV for $r_{\mathrm{DV}} < (225/7)$ mm; $m_{\mathrm{DV}} > 2$ GeV for $r_{\mathrm{DV}} > (750/7)$ mm; and $m_{\mathrm{DV}} > 7$ GeV $\times(1 - r_{\mathrm{DV}}/(150\ \mathrm{mm}))$ between these r_{DV}regions. For $\mu\mu$ decays, which have a larger reconstruction efficiency, an $m_{\mathrm{DV}} > 5.5$ GeV selection is required.

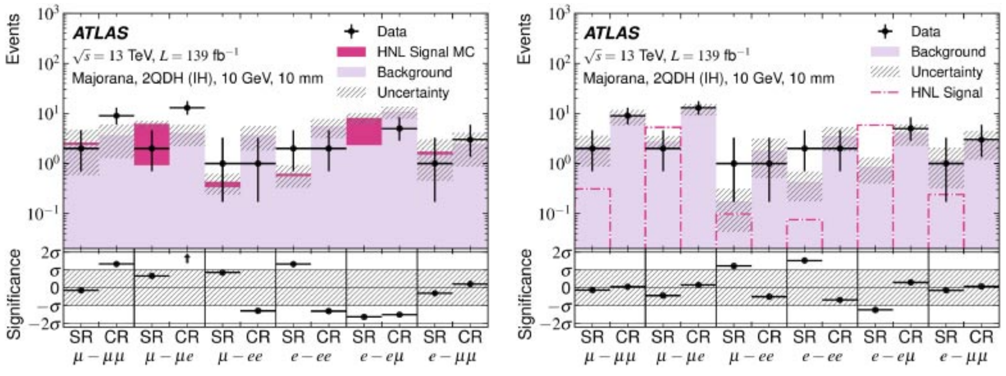
The assumption that previously listed background rejection selections are sufficient to suppress the background from all sources except random lepton crossings is tested in the validation region (VR). This region is comprised of data events that contain two-lepton DVs, but have no prompt lepton. The random crossing probability is independent of lepton charge and therefore, if random lepton crossings dominate, the distribution of DVs with same-sign (SS) electric charge and OS should be similar. This validation is shown in fig. 1(b) for $e\mu$ DVs in the VR. With the background rejection selections applied, good agreement between OS and SS DV distributions is observed, which confirms that random crossings dominate the background.

7. – Background estimate

A data-driven object shuffling method is used to estimate the background from random lepton crossings. Prompt leptons from events with SS DVs in the SR are shuffled with each OS DV selected in the VR. For each shuffled event, the m_{HNL} is computed, which can fall either in the SR with $m_{\mathrm{HNL}} < 20$ GeV or in the control region (CR) that has 20 GeV $< m_{\mathrm{HNL}} < 50$ GeV. This provides a high-statistics way to estimate the ratio between the expected number of background events in the SR and CR. The largest uncertainty in this estimation method comes from the assumption that nonrandom backgrounds are negligible. This uncertainty is estimated to vary between 5% for the $e{-}e\mu$channel and 79% for the $\mu{-}\mu\mu$channel. These systematics have little impact on the final results as the regions for each channel are statistical limited.

8. – Results

The signal and background yields are determined using a global fit. The inputs to the fit include: estimates for the signal yields, the observed data events, nuisance parameters for the uncertainties and the background ratios in the SR and CR estimated using the previously described method. One signal strength is shared across all channels that contribute in each mixing scenario and each channel has an independent normalization factor for the background estimate. The largest uncertainties come from the background estimate (5-79%) and the reconstruction of displaced tracks and vertices (up to 28%).

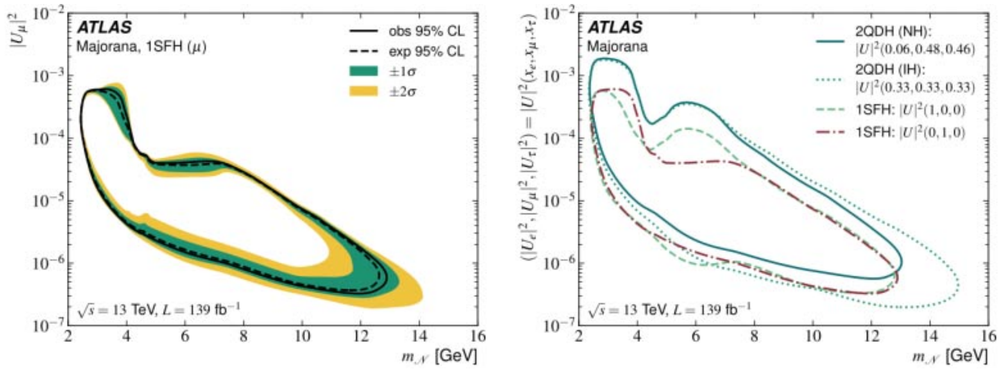


(a) (b)

Fig. 2. – Summary plots for the 2QDH (IH) (two quasi degenerate HNLs, inverted neutrino mass hierarchy mixing, $x_e = x_\mu = x_\tau = 0.33$ model, where $x_\alpha = |U_\alpha|^2/|U|^2$). Shown is the pre-fit plot (a) with background and HNL signal MC stacked, and the post-fit plot (b) in which the pre-fit signal contribution is overlaid as a dashed line (post-fit signal contribution is zero). Figures from [9].

The inputs to the model, prior to the global fit, are shown in fig. 2(a) for the 2QDH model with IH mixing. In fig. 2(b), the the observed yields are shown after the fit and are found to be consistent with the estimated backgrounds. No significant excesses are found in any of the six channels in any of the mixing scenarios.

Since no evidence of new physics was observed, limits on $|U|^2$ as a function of $m_\mathcal{N}$ are set for each mixing scenario. The excluded region at 95% confidence level is shown in fig. 3 for the various mixing scenarios. fig. 3(a) shows the expected and observed limits for the 1SFH muon-only mixing scenario. The observed limits are within one standard



(a) (b)

Fig. 3. – (a) The observed and expected 95% CL limits on $|U|^2$ *vs.* $m_\mathcal{N}$ for 1SFH model with muon-only mixing. The green and yellow bands show the one and two standard deviation (σ) spreads for the expected limits. (b) The observed limits in the 2QDH scenario with inverted (IH) and normal (NH) mass hierarchy, and in 1SFH scenarios where the HNL mixes with only ν_μ or ν_e. Each mixing scenario is labelled as $|U^2|(x_e, x_\mu, x_\tau)$, where x_α is the ratio of $|U_\alpha|^2$ to the total mixing $|U|^2$. Figures from [9].

deviation of the expected limits for all models. This result for the muon-only mixing scenario is improved with respect to the 36 fb^{-1} ATLAS result [13] in both the low- and high-mass regions. Moreover, the result excludes values of $|U|^2$ that are approximately three times smaller than the previous limits. fig. 3(b) compares the excluded parameter space for the various mixing scenarios. These results include the first electron-only mixing limits and limits on the realistic model with two quasi-Dirac HNLs assuming either IH or NH mixing. The strongest limits are observed for the IH mixing model where there is equal mixing with all three neutrino flavours.

9. – Conclusion

A search for displaced heavy neutral leptons was performed using 139 fb^{-1} of proton collision data using the ATLAS experiment. No evidence for new physics is observed. Brand new limits for electron-only and multi-flavour mixing scenarios were presented. Improved limits, with respect to the 36 fb^{-1} ATLAS result [13], in muon-only mixing scenarios were also presented.

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