PROCEEDINGS OF SCIENCE

Heavy Neutral Lepton searches at ATLAS

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A summary of searches for heavy neutral leptons (HNLs) at the ATLAS experiment at the Large Hadron Collider is presented. This includes partial and full Run 2 rare W decay searches through lepton number violation and displaced vertices alongside WW scattering events. The searches for HNLs consider lepton number violating decays of the W bosons. Additionally, the contributions of HNLs in WW scattering are taken into account. This includes the first experimental test for a mixed-flavour Weinberg operator, denoted as $C^{(5)}_{e\mu}$. Furthermore, mixed-flavour HNL masses are explored at the TeV scale. No significant excesses are seen, and 95% CL limits are set in first- and second-generation mixing matrix elements for HNL masses between 2 GeV and 20 TeV.

ATL-PHYS-PROC-2024-093
22 October 2024

12th Large Hadron Collider Physics Conference
3-7 June 2024
Northeastern University, Boston, USA

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1. Introduction

The neutrino sector is one of the least experimentally probed parts of the Standard Model. As a result, it is not known for certain if neutrinos are Dirac or Majorana particles. By adding a right-handed Majorana neutrino term to the Standard Model, we can construct models that explain baryogenisis and leptogenisis in the early universe through seesaw mechanisms. This paper focuses on the Type-I seesaw mechanism [1]. At higher mass scales (Grand unification theory energy scales), this can be used to explain the suppression of the masses of neutrinos compared to other particles. These are known as Heavy Neutral Leptons (HNLs), denoted as N, and are typically embedded into larger models.

The ATLAS experiment at the Large Hadron Collider (LHC) considers three types of neutrino models in the search for HNLs [2]:

1. The simplest model is Single lepton Flavour HNLs (1SFH). This is a Type-I seesaw with one lepton flavour typically known as the νMSM [3]. This is parameterised by a HNL mass (m_{N}) and a mixing angle corresponding to coupling the HNL to W/Z boson decays (PNMS-style matrices denoted V or U).

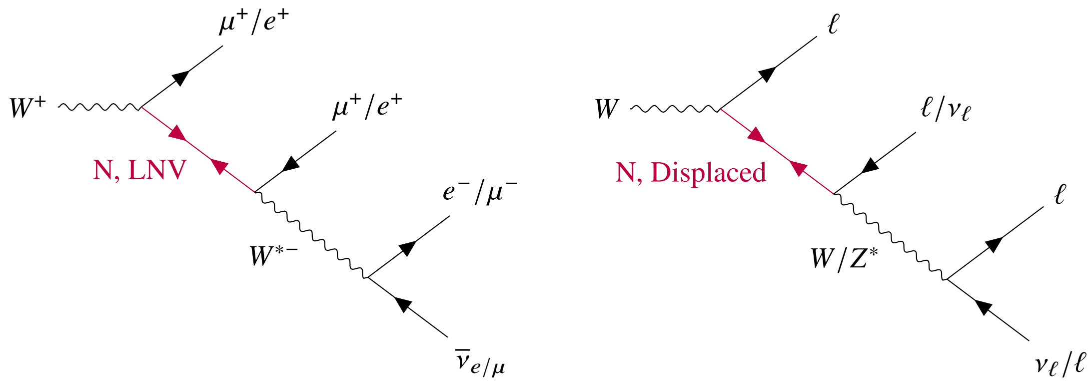
2. An extended phenomenology Type-I seesaw model using two-mass degenerate state is known as Quasi-Dirac HNLs (2QDH) [4]. The results are presented identically to 1SFH except the mixing between HNLs and Standard Model lepton flavours is split between flavours according to neutrino fit data (denoted x_e, x_μ, x_τ). This can lead to the suppression of the lepton number violating modes of HNLs.

3. The Weinberg operator, a dimension-5 operator, generates a Majorana neutrino contact interaction through the Standard Model Higgs doublet. This is a Standard Model style effective field theory operator if neutrinos are taken to be Majorana and hence has a corresponding Wilson coefficient and energy scale. This operator is typically investigated through searches for neutrino-less double beta decay [5] and can be linked to an effective neutrino mass denoted $m_{\ell\ell'} = C_5^{\ell\ell'} v^2/\Lambda$, where v is the Standard Model Higgs vacuum expectation and $C_5^{\ell\ell'}/\Lambda$ is the wilson coefficient divided by the energy scale .

2. Prompt and displaced s-channel analyses

The ATLAS Run 2 dataset has been used by the collaboration to perform two competitively sensitive searches for HNLs from on-shell W boson decays [6, 9]. This segment of parameter space ($m_{\mathrm{N}} \lesssim m_W$) is of phenomenological interest due to the presence of a regime in which, if $m_{\mathrm{N}} \sim 5$ GeV, the HNL's lifetime becomes long enough to facilitate the formation of a displaced vertex from the HNL decay into a lepton pair. The HNL's lifetime is characterised by $\tau_{\mathrm{N}} \approx \left(4.3 \times 10^{-12}\ \mathrm{s}\right) |U|^{-2} \left(m_{\mathrm{N}}/1\mathrm{GeV}\right)^{-5}$ where $|U|^2 \equiv \sum_{e,\mu,\tau} |U_\alpha|^2$ [8]. Hence for completeness, a prompt and displaced analysis was designed.

The first search targets a signature with high enough HNL masses that the $\mathrm{N} \to \ell\ell\nu$ decay occurs promptly so a displaced vertex can't be exploited. Instead, to reject background, the analysis focuses on lepton number violation (LNV) illustrated in Figure 1a. This is selected because the



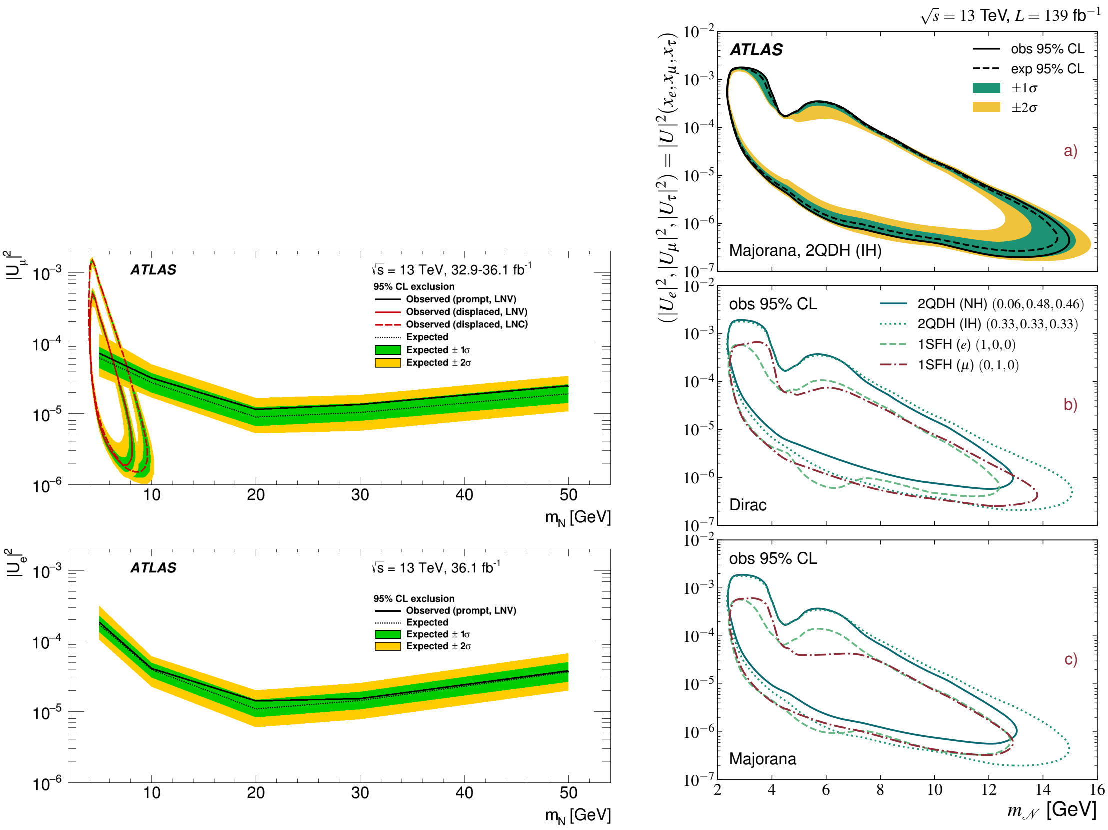
(a) **(b)**

Figure 1: The two signal topologies for ATLAS W decay searches. (a) Prompt lepton number violating (LNV) signature using 1SFH. (b) Displaced signature using 1SFH or 2QDH. The key difference between these is the reliance on a same-sign same-flavour pair for the prompt signature and the displaced lepton pair from the long-lived N for the HNL decay.

Standard Model backgrounds are negligible compared to the lepton number conserving current. This partial Run 2 analysis selects exactly $\mu^\pm\mu^\pm e^\mp$ and $e^\pm e^\pm \mu^\mp$ signature final states with a di-muon or single electron trigger.

In the signal region, specific criteria are applied to reduce Standard Model contamination. A requirement is set on the leptons momenta $p_{\mathrm{T},e(\mu),1} > 27(23)$ GeV and $p_{\mathrm{T},e(\mu),2} > 10(14)$ GeV . The tri-lepton mass ($m_{\ell\ell\ell}$), must fall between 40 and 90 GeV. These are both to match the signal topology from a W boson decay with a unreconstructable neutrino and prompt on-shell HNL. The event must not contain a b-jet. A requirement of 60 GeV is imposed on $E_{\mathrm{T}}^{\mathrm{miss}}$. The event also must not contain a tagged b-jet to reject tops. Finally, for the $e^\pm e^\pm \mu^\mp$ channel, there is a $m_{ee} < 78$ GeV requirement to reduce background from Z+jets with charge misidentification. The primary background is then from rare multijet and W + jets events with b- and c-hadron decays, which are estimated using data-driven methods. No excesses are seen and competitive limits are set for HNL masses between 10 and 50 GeV (Figure 2a).

The second search targets a signature with lower HNL masses, where the $\mathrm{N} \rightarrow \ell\ell\nu$ decay is no longer prompt (Figure 1b). The single isolated lepton (e/μ) from the on-shell W boson decay is used to fire the trigger. This is then combined with dedicated algorithms to search for the displaced lepton pair in the tracker. For the signal region, the displaced vertex must be reconstructed in a radius between 4 mm and 300 mm and the same trilepton mass cut is applied as the prompt analysis. Using the flight direction of the HNL and the kinematics of three visible leptons, the four-momentum of the HNL is approximated and used to estimate the m_{N} for the event. A purely data-driven estimate is used and validated once dilepton mass cuts reject displaced heavy flavour decays. No excesses are seen, and limits for SFH and 2QDH for HNL masses between 2 and 10 GeV (Figure 2b).



(a) **(b)**

Figure 2: 95% CL Limits of squared mixing matrix elements against m_{N} from the ATLAS analyses targeting HNLs from W decays. (a) Prompt analysis limits (with the partial Run 2 displaced result overlaid for the μ mixing channel) [6]. (b) Full Run 2 displaced analysis limits [9].

3. HNLs in same-sign WW scattering

The ATLAS Run 2 collision dataset allows for a previously untested part of parameter space ($m_{\mathrm{N}} \gtrsim 1$ TeV) by utilising the relatively abundant collection of Vector Boson Scattering (VBS) events. Diagrams for HNLs or the Weinberg operator can be constructed that share identical topologies with neutrinoless double beta decay, as illustrated in Figure 3a and Figure 3b. The $\sqrt{s} = 13$ TeV centre of mass energies of the LHC facilitates the detection of final state flavours and mixings that are not observable through rare nuclear decays, specifically in the $e\mu$ and $\mu\mu$ channels. The analysis targets lepton number violating (LNV) events in the ee, $e\mu$, and $\mu\mu$ configurations.

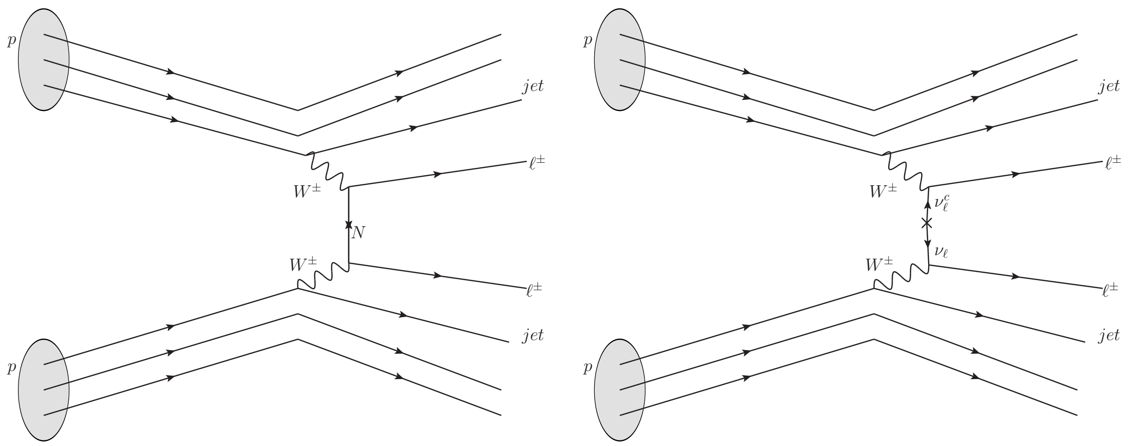
This analysis focuses on identifying an excess of LNV events with high transverse momentum leptons with no missing transverse energy, which may indicate the presence of heavy neutral leptons (HNLs). Additionally, the analysis considers the presence of back-to-back jets through high invariant mass (m_{jj}) and rapidity separation (Δy_{jj}). This is driven by the lack of colour connectedness.

3.1 Background Estimation

The backgrounds for these analyses can be split into two categories. Firstly, there are prompt Standard Model lepton backgrounds with well-described Monte Carlo generators from ATLAS Standard Model VBS searches (WW,WZ). Non-prompt backgrounds use data-enriched regions to describe phenomena that are less well-modeled in simulation. The leading background is the Standard Model process same-sign WW (ssWW) scattering, which has an identical visible outgoing topology. However, these are different kinematic distributions due to the final state neutrinos missing from the HNL topology. The other main prompt background is WZ scattering, where one lepton is lost to make it coincidentally look like the signal process. These process normalisations are allowed to float in the profile-likelihood fit. There are also sub-leading contributions from $t\bar{t}$ and tri-boson processes.

The first category, referred to as non-prompt leptons, primarily arises from B meson decays. To enhance the rejection of non-prompt objects, tracking and isolation criteria are utilised, focusing on a subset of events that fail certain identification cuts, specifically comparing identified versus anti-identified leptons. p_{T} and η-dependent transfer factors are calculated using a di-jet enriched dataset containing electrons and muons. These transfer factors are defined by creating a ID and anti-ID lepton collection where anti-ID leptons fail the isolation or identification criterion. Prompt standard model contaminations are corrected through Monte Carlo simulations. These transfer factors are subsequently applied to regions adjacent to the signal regions (SRs) and control regions (CRs).

The second category involves 'charge-flip' leptons, which predominantly originate from electron bremsstrahlung processes. For this background, a region enriched in $Z \to ee$ events is designed to derive a misidentification probability. The misidentification probability is applied to a region orthogonal to the signal region, defined by the same criteria other than inverting the same-sign requirement. Additionally, other potential backgrounds, such as double-parton scattering, coincidental W productions, and charge-flip muons, were considered but determined to be negligible in the context of the analysis.



(a) **(b)**

Figure 3: Diagrams of the WW signal processes mediated through (a) a HNL and (b) a Weinberg operator contact interaction.

Channel	Variable	SR	$W^{\pm}W^{\pm}$ CR	WZ CR
$ee/e\mu$	N_ℓ	=2		=3
	$\lvert\Delta y_{jj}\rvert$	> 2		
	m_{jj}	> 500 GeV		
	$m_{\ell\ell\ell}$	–	–	> 106 GeV
ee	$\lvert m_{\ell\ell} - m_Z\rvert$	> 15 GeV		–
	$\lvert\eta_\ell\rvert$	<2		
	$m_{\ell\ell}$	> 20 GeV		
	$p_T^{\ell_1}$	–	< 250	–
	$p_T^{j_1}$	> 30 GeV	> 45 GeV	> 30 GeV
	$p_T^{j_2}$	> 25 GeV	> 30 GeV	> 25 GeV
	$\mathcal{S}$	< 4.5	> 4.5	–
$e\mu$	$p_T^{j_1}$	> 30 GeV	> 45 GeV	> 45 GeV
	$p_T^{j_2}$	> 25 GeV	> 30 GeV	> 30 GeV
	$\lvert\Delta\phi_{e\mu}\rvert$	> 2.0	< 2.0	–

(a) $ee/\mu e$, a 0 b-jet requirement is applied throughout

Observable	SR	ssWW-CR	WZ-CR
Same-sign muons	= 2 (signal μ)		
Number of b-jets	= 0		
m_{jj}	> 300 GeV		
$\lvert\Delta y_{jj}\rvert$	> 4		
Third lepton (OS)	= 0 (baseline)	= 0 (baseline)	= 1 (signal μ)
E_T^{miss} signif. $\mathcal{S}$	< 4.5	> 5.8	< 4.5
$m_{\ell\ell\ell}$	—	—	> 100 GeV
$p_T^{\mu_2}$	—	< 120 GeV	—

(b) $\mu\mu$

Table 1: The SR and CR event selections for (a) ee with $e\mu$ [7] and (b) $\mu\mu$ [10].

3.2 Region Designs

A full description of the Signal and Control Region (SR and CR) requirements is shown in Table 1[7, 10]. Events with exactly two same-charge leptons are selected ($ee, e\mu, \mu\mu$). For the two highest p_T jets in the event it is required that m_{jj} and Δy_{jj} is large enough to be consistent with a VBS scattering style event. Finally, to distinguish ssWW and signal, a requirement on E_T^{miss} significance ($\mathcal{S}$) or lepton angular separation ($|\Delta\phi_{e\mu}|$) is made and binned in sub-leading lepton p_T for the signal hypothesis discrimination. For the ssWW control region, the $S/|\Delta\phi_{e\mu}|$ requirement is inverted with additional minor selections to reduce signal contamination. Similarly, to select for WZ events, the two lepton requirement is changed to three.

A simultaneous fit of the target signal process, ssWW and WZ normalisation, is used for statistical tests and to extract $|V|^2$ limits as function of m_N.

4. Results and Combinations

No significant excesses are seen in any of the channels' regions. Limits are set on mixing to HNLs as a function of m_N (Figure 4). For the Weinberg operator, expected (observed) limits of $m_{ee} > 24(24)$ GeV, $m_{e\mu} > 13(15)$ GeV and $m_{\mu\mu} > 16.7(13.1)$ GeV are set.

To form a statistical combination of channels for HNLs, the $|V_e|^2$ and $|V_\mu|^2$ parameters are floated alongside each background normalisation separately. The common experimental systematics are correlated together. This leads to the limit contours shown in Figure 4b. If it is assumed $|V_e| = |V_\mu|$, the expected (observed) limit is improved by about 32% (24%) compared to the $\mu\mu$ limits. This is visualised in Section 4. As the Weinberg signal strengths are uncorrelated, a combination is not necessary. This provides the upper end of ATLAS's mass sensitivity for HNLs. The full ATLAS search space is shown for the ee and $\mu\mu$ in Figures 4c and 4d which overlays the three analysis' 95% CL limits as function of m_N and $|V|^2$. The VBS search has much weaker limits due to the reduced cross section. The upper bound on m_N contours is driven by unitary limits on V and the lower bound is limited by detectable lifetimes of the displaced analysis.

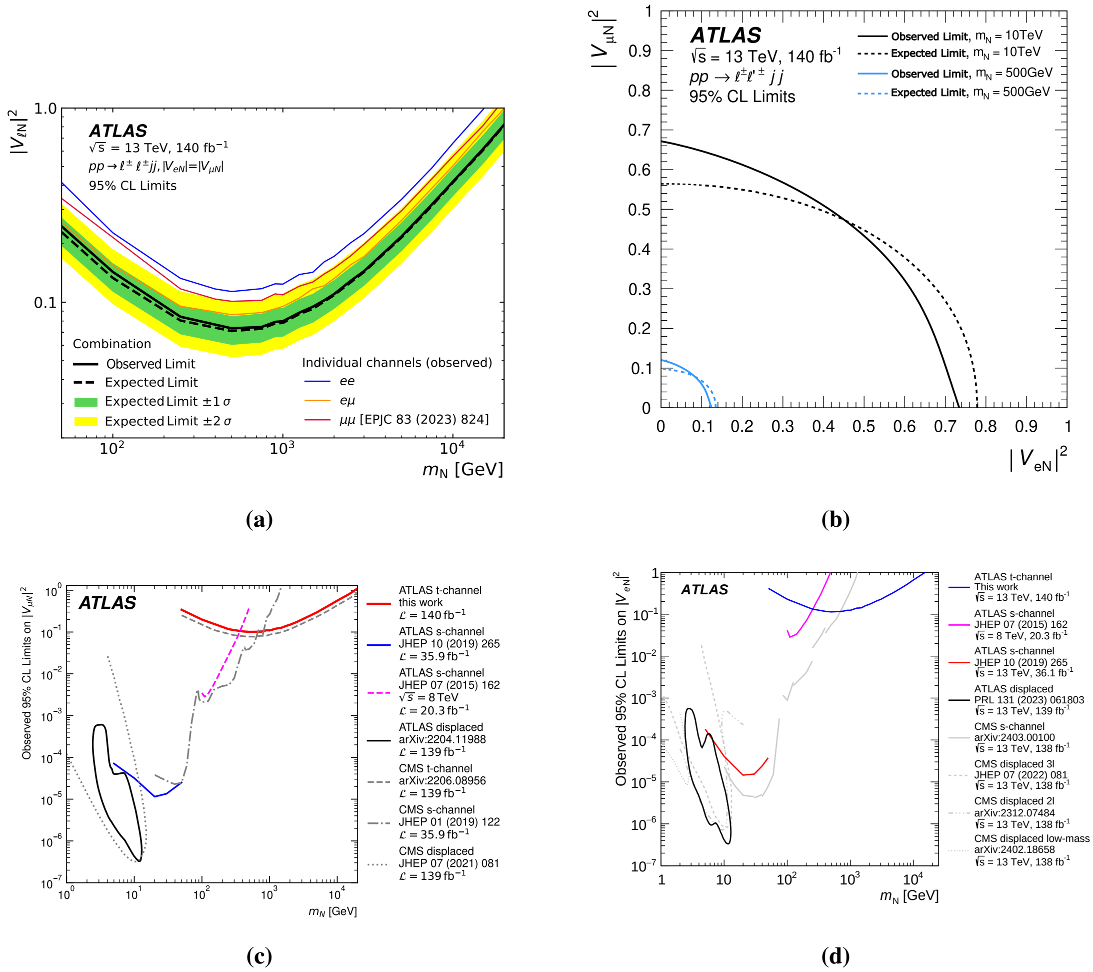


Figure 4: (a) The observed 95% $\mathrm{CL_s}$ limits of HNL mixing vs m_{N} for each of the three channels alongside the statistical combination assuming $|V_e| = |V_\mu|$ [7]. (b) The observed and expected 95% $\mathrm{CL_s}$ contours for m_{N}=500 GeV and 1 TeV [7]. (c) and (d) show ATLAS's whole analysis paradigm overlaid in one plot alongside CMS searches [7, 10].

5. Conclusions

The ATLAS experiment at the LHC has a program of searches for HNLs with masses between 2 GeV and 20 TeV, encompassing signatures of prompt and displaced HNL decays as well as WW scattering. Recently, ATLAS has produced results for μe and ee WW scattering with a statistical combination of channels. These provide the first constraints for $|V_\mu V_e^*|^2$ and $C_{e\mu}^{(5)}$ up to the TeV scale.

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