Long-lived heavy neutral leptons at the LHC: probing N_RSMEFT operators.

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1. Motivation

Heavy neutral leptons (HNLs) are Standard Model (SM) singlet fermions that appear in many extensions of the SM addressing neutrino masses [1].

HNLs can be considered in isolation, as in the seesaw mechanism, where the HNLs couple to SM particles only via their mixing with active neutrinos, V_{lN}.

However, HNLs could also be part of an extended hidden sector, with new particles and interactions, associated to a very high energy scale. In this context, effective field theories (EFTs) come into play.

- SMEFT: the EFT of the SM, is a well-established framework in LHC searches.
- N_RSMEFT: extension of the latter including right-handed neutrinos, N_R. It has attracted significant interest in the last few years [2].

2. Theoretical framework: effective theory with N_R

If HNLs with masses below or around the electroweak scale exist in nature, the effects of new multi-TeV physics at much smaller energies can be systematically described in terms of an EFT built out of the SM fields and N_R, i.e. N_RSMEFT.

The full Lagrangian can be divided into a renormalizable part, including the fermion portal, and the terms describing non-renormalizable interactions $\mathcal{O}_i$. New physics effects are encoded in the Wilson coefficients c_i and are suppressed by Λ.

$$\mathcal{L} = \mathcal{L}_{\rm ren} + \sum_{d\geq 5} \frac{1}{\Lambda^{d-4}} \sum_i c_i^{(d)} \mathcal{O}_i^{(d)}\,, \tag{1}$$

$$\mathcal{L}_{\rm ren} = \mathcal{L}_{\rm SM} + \overline{N_R} i \partial\!\!\!/ N_R - \left[\frac{1}{2} \overline{N_R^c} M_N N_R + \overline{L} \tilde{H} Y_N N_R + \text{h.c.}\right]. \tag{2}$$

Effective interactions of $d \leq 6$ are the most interesting from a phenomenological point of view. In this work we concentrate on four-fermion ($d = 6$) operators including just one N_R. These **single-N_R operators can induce both production and decay of the HNLs** simultaneously, in contrast to operators with two N_R. Phenomenology of pair operators has recently been studied in [3].

For HNLs of $\mathcal{O}(10)$ GeV mass, single-N_R operators with a **new physics scale above $\sim$ 1 TeV can easily make the HNLs become long-lived**, leading to displaced vertices at the LHC.

Name	Structure (+ h.c.)	$n_N = 1$	$n_N = 3$
$\mathcal{O}_{duNe}$	$(\overline{d_R}\gamma^\mu u_R)(\overline{N_R}\gamma_\mu e_R)$	54	162
$\mathcal{O}_{LNQd}$	$(\overline{L}N_R)\epsilon(\overline{Q}d_R)$	54	162
$\mathcal{O}_{LdQN}$	$(\overline{L}d_R)\epsilon(\overline{Q}N_R)$	54	162
$\mathcal{O}_{QuNL}$	$(\overline{Q}u_R)(\overline{N_R}L)$	54	162

Table: Lepton-number-conserving four-fermion single-N_R operators and the number of independent real parameters they involve for $n_N = 1$ and $n_N = 3$ generations of N_R. We have a omitted a pure leptonic operator as it does not contribute to HNL production at the LHC.

3. Simulation details

Our signal topology contains a prompt lepton and a displaced vertex (DV) stemming from the N_R decay to leptons and quarks. Our analysis strategy builds up on an earlier work [4] and is inspired from ATLAS multi-track displaced searches [5].

- **Production**. We consider the collision process $pp \to Nl$ at the LHC ($\sqrt{s} = 14\,\text{TeV}$, $\mathcal{L}_{int} = 3\ \text{ab}^{-1}$). We generate LHE events with displaced information at the parton level with `MadGraph5`, which are read by `Pythia8` for showering and hadronization.
- **Decay reconstruction**. First, we select events with isolated prompt charged leptons. Secondly, we reconstruct the DV by selecting tracks with $p_T > 1\,\text{GeV}$ and demand the DV position to be inside the ATLAS inner tracker acceptance. Further cuts are applied to ensure we are in a region where the signal is free of backgrounds.

References

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[3] G. Cottin et al., *JHEP* **09** (2021) 039 [2105.13851]
[4] G. Cottin et al., *Phys. Rev. D* **98** (2018) 035012 [1806.05191]
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4. Numerical Results

We have estimated the experimental sensitivities (95% C.L. exclusion limits) of searches for long-lived HNLs at the ATLAS detector for two different theoretical scenarios. We assume a 3 + 1 scenario where the HNL mixes dominantly with only one active neutrino flavor at a time. We assume only one HNL is kinematically relevant. Plots shown are for a Dirac HNL.

- **Minimal scenario**. Only N_R are added to the particle content and renormalizable interactions are assumed. Production and decay of HNLs occur via mixing V_{lN}. We take HNL mass and V_{lN} as independent parameters (seesaw type-I is not assumed).

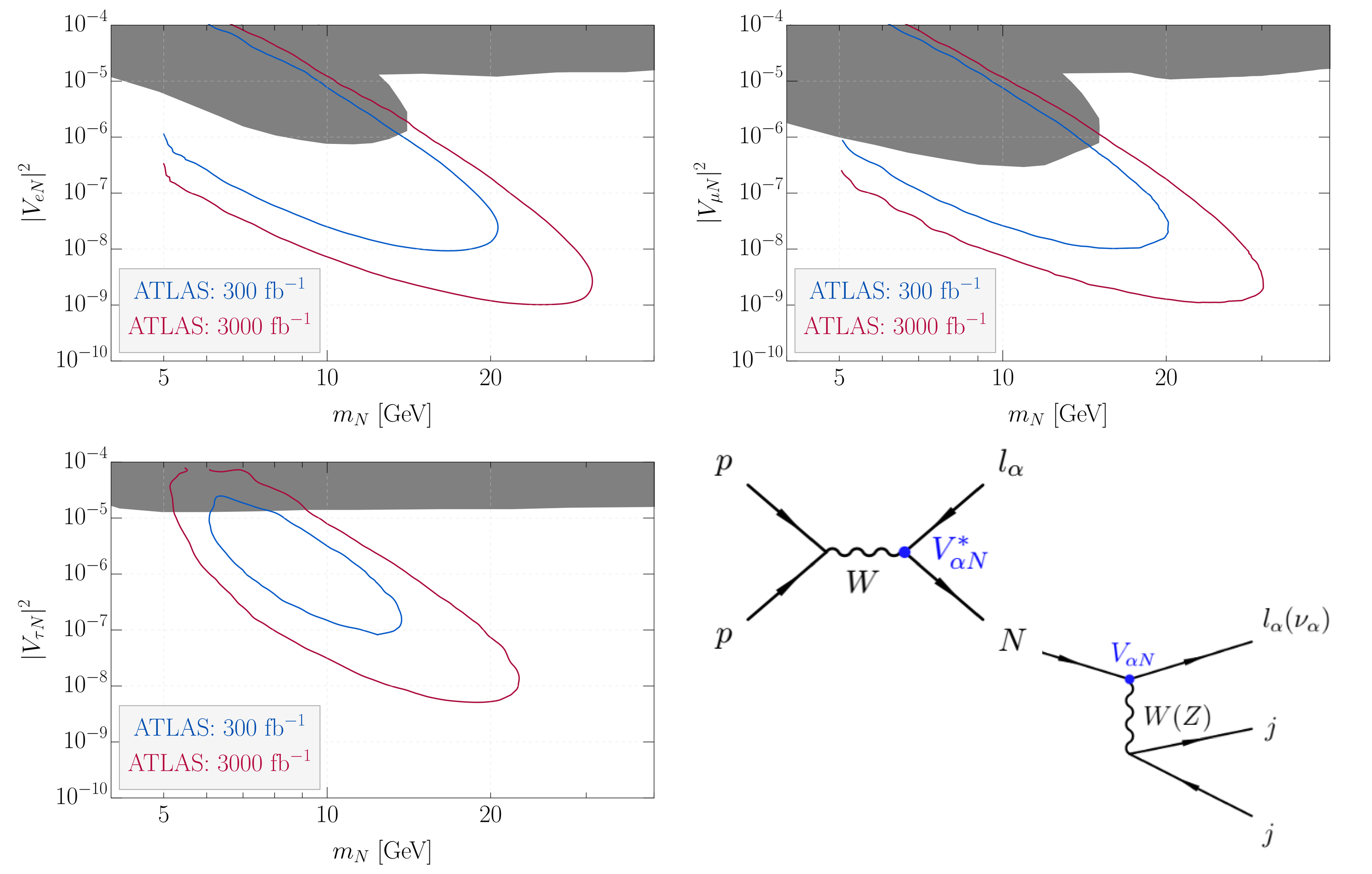

Figure: Minimal scenario sensitivity reach on $|V_{lN}|^2$ and m_N , for $l = e, \mu, \tau$. Dark region corresponds to current experimental limits (ATLAS, CMS, DELPHI, LHCb).

- **N_RSMEFT**: $\mathcal{O}_{duNe}$, $\mathcal{O}_{LNQd}$, $\mathcal{O}_{LdQN}$, $\mathcal{O}_{QuNL}$. We *switch on* one Wilson coefficient at a time (fixing $c_\mathcal{O} = 1$ for a given flavor index combination) and explore the parameter space in Λ and m_N.

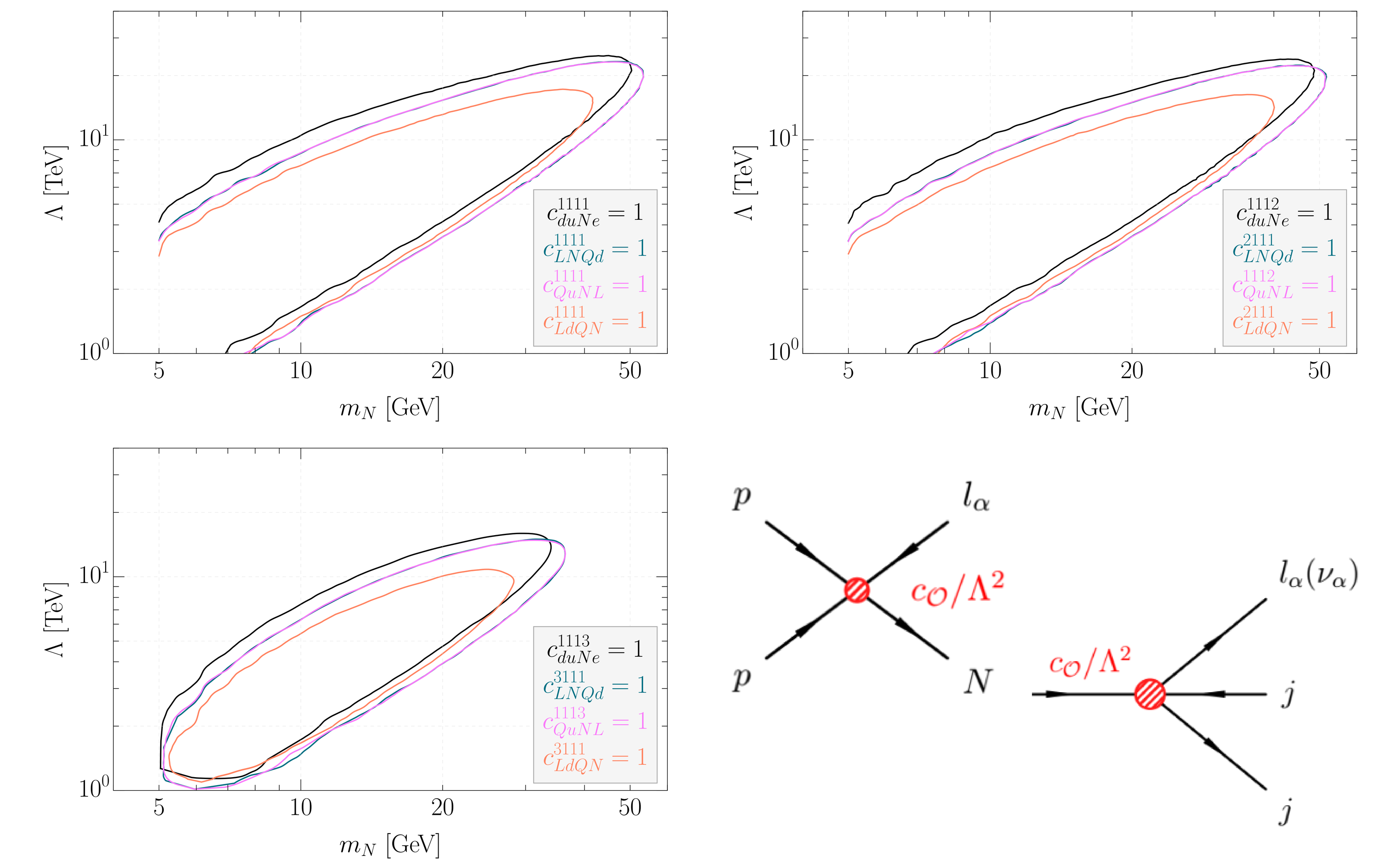

Figure: Exclusion limits on the new physics scale Λ as a function of m_N in the EFT scenario with operators including the first-generation quarks only, for 3 ab^{-1}. Top plots consider operators with electrons (left) and muons (right). Bottom plot (left) considers tau leptons.

5. Conclusions

- Electroweak scale HNL interact very weakly with SM sector (either through mixing or EFT operators) and if they exist, they are most probably long-lived.
- Our forecast limits for the minimal scenario can reach values as low as $|V_{eN}|^2, |V_{\mu N}|^2 \sim 10^{-9}$ for $m_N \sim 30\,\text{GeV}$ and 3 ab^{-1}. These values are naturally obtained in inverse seesaw models.
- A displaced-vertex search at ATLAS for HNLs can probe new physics scales up to about 20 TeV and, in some cases above, for HNL mass between 5 GeV and 50 GeV, depending on the quark and lepton flavors associated with the single-N_R operator under consideration.