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Long-lived HNLs in N_RSMEFT

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Based on 2110.15096 and 2105.13851(JHEP 09 (2021) 039)

Searching for Long-Lived Particles at the LHC and beyond: Tenth Workshop of the LLP Community

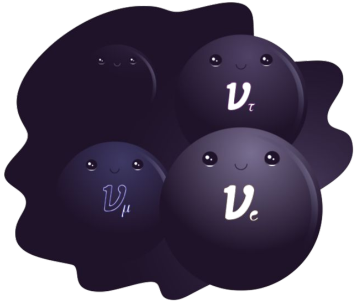
November 2021

Heavy Neutral Leptons
Right-handed singlet fermions or sterile neutrinos can be LLP

HNL LLP Motivation

An answer for neutrino mass generation mechanism

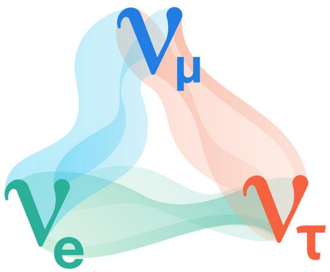
See review in A. Atre, T. Han, S. Pascoli, B. Zhang, JHEP 05 (2009) 030, arXiv:0901.3589



@symmetrymagazine

Known

- Neutrino oscillations therefore neutrinos in the SM have mass



See P. F. de Salas et al., JHEP 02 (2021) 071, arXiv:2006.11237

Unknown

- Neutrino Mass Mechanism involving HNL (i.e seesaw mechanism, inverse seesaw, ...)
- Specific BSM Model of neutrino mass generation (i.e new interactions of HNL beyond Yukawa ones?)
- HNL nature (Dirac or Majorana)
- HNL mass scale

Seesaw
P. Minkowski, Phys. Lett. 67B (1977)
R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. 44 (1980)
J. Schechter and J. W. F. Valle, Phys. Rev. D22, 2227 (1980)
Inverse seesaw
R. Mohapatra and J. Valle, Phys. Rev. D34 (1986) 1642

Minimal Type I seesaw

See reviews for HNL phenomenology
M. Drewes, Int.J.Mod.Phys.E 22 (2013) 1330019, arXiv:1303.6912
F. Deppisch, P. S. Bhupal Dev, Apostolos Pilaftsis, New J.Phys. 17 (2015) 7, 075019, arXiv:1502.06541
Y. Cai, T. Han, Tong Li, R. Ruiz, Front.in Phys. 6 (2018) 40, arXiv: :1711.02180

- Predicts HNLs
- HNLs mix with SM neutrinos
- Can be realised in many BSM models

$$\mathcal{L}_{SM+N_R} = \mathcal{L}_{SM} + \bar{N}_{Ri}\, \partial\!\!\!/\, N_R - \left[\frac{1}{2}\bar{N}_R^c M_N N_R + \bar{L}\tilde{H} Y_N N_R + h.c.\right]$$

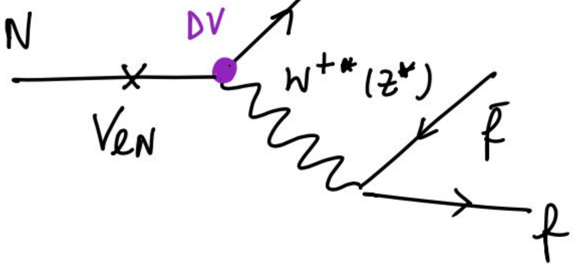
$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix}$$

$$V_{\ell N} = m_D M_N^{-1} \Rightarrow V_{\ell N}^2 \sim m_\nu / M_N$$

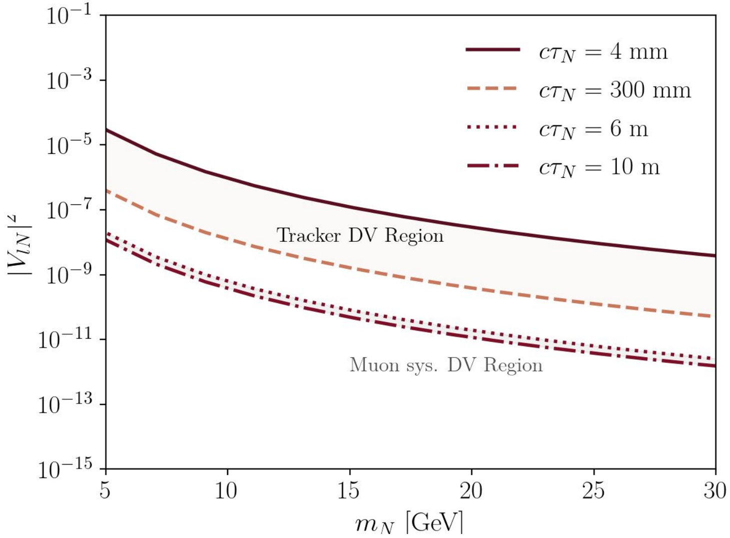
$$\Gamma \sim G_F^2 |V_{\ell N}|^2 m_N^5$$

Small mixings and ~ GeV scale HNL $\Rightarrow$ LLP!

$m_N < m_W$



Adapted from G. Cottin, J.C. Helo and M. Hirsch, PRD 98 (2018)



Pheno approach: consider HNL mass and mixing as independent parameters

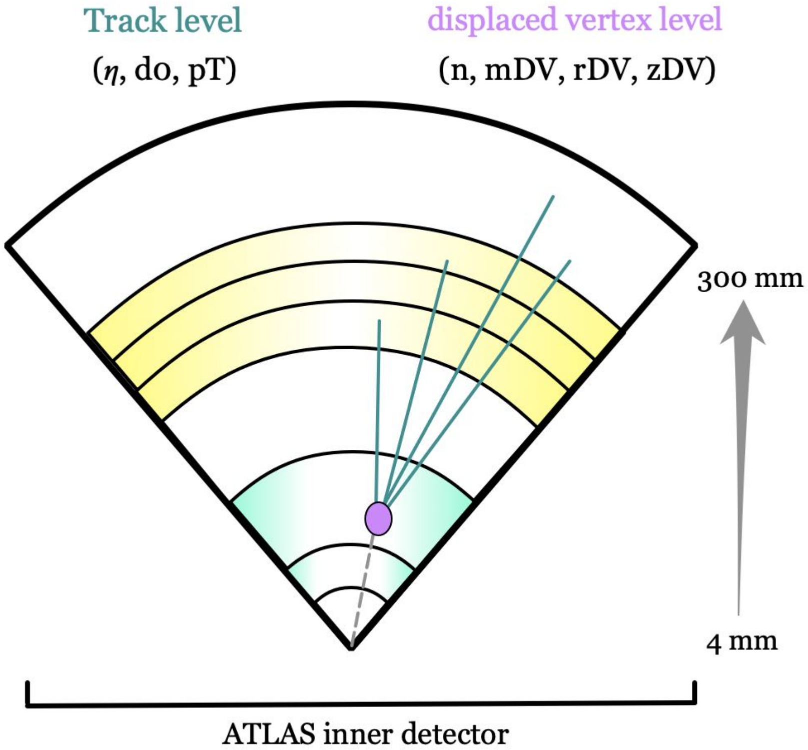
Phenomenology with displaced vertices at LHC

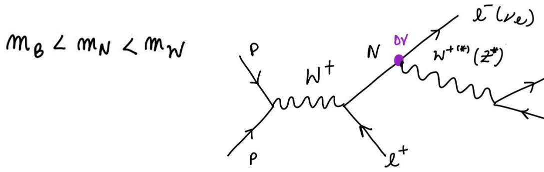
“HNL optimized” multitrack DV search strategy

First proposed in G. Cottin, J.C. Helo and M. Hirsch, PRD 98 (2018)

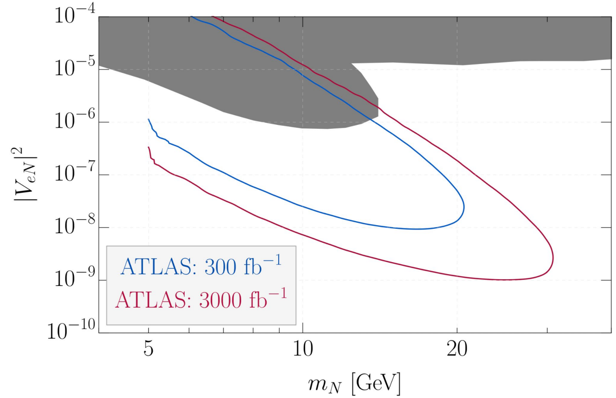
Builds up on ATLAS experimental searches in 1710.04901, 1504.05162

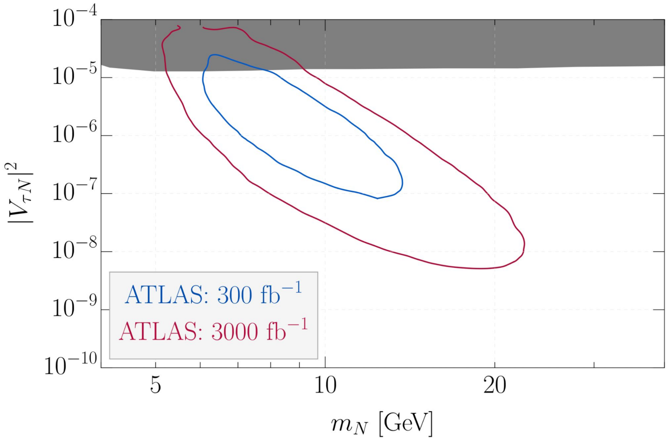
Updated in R. Beltrán, G. Cottin, J.C. Helo, M. Hirsch, A. Titov, Z.S. Wang, 2110.15096





2110.15096 (with CMS PAS EXO-20-009 DV constrain included for *e*)





N_RSMEFT

Offers a systematic way to study non-minimal HNL models, with NRO which are suppressed by a new physics scale Λ

$$\mathcal{L}_{N_R SMEFT} = \mathcal{L}_{SM+N_R} + \sum_{d\geq 5} \frac{1}{\Lambda^{d-4}} \sum_i c_i^{(d)} \mathcal{O}_i^{(d)}$$

d=6 four-fermion operators with *a single* HNL

R. Beltrán, G. Cottin, J.C. Helo, M. Hirsch, A. Titov, Z.S. Wang, 2110.15096

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
$\mathcal{O}_{LNLe}$	$(\overline{L}N_R)\epsilon(\overline{L}e_R)$	54	162
$\mathcal{O}_{QuNL}$	$(\overline{Q}u_R)(\overline{N_R}L)$	54	162

d=6 four-fermion operators with *pairs* of HNL

G. Cottin, J. C. Helo, M. Hirsch, A. Titov, Z. S. Wang, 2105.13851, (JHEP 09 (2021) 039)

Name	Structure	$n_N = 1$	$n_N = 3$
$\mathcal{O}_{dN}$	$(\overline{d_R}\gamma^\mu d_R)(\overline{N_R}\gamma_\mu N_R)$	9	81
$\mathcal{O}_{uN}$	$(\overline{u_R}\gamma^\mu u_R)(\overline{N_R}\gamma_\mu N_R)$	9	81
$\mathcal{O}_{QN}$	$(\overline{Q}\gamma^\mu Q)(\overline{N_R}\gamma_\mu N_R)$	9	81
$\mathcal{O}_{eN}$	$(\overline{e_R}\gamma^\mu e_R)(\overline{N_R}\gamma_\mu N_R)$	9	81
$\mathcal{O}_{NN}$	$(\overline{N_R}\gamma_\mu N_R)(\overline{N_R}\gamma_\mu N_R)$	1	36
$\mathcal{O}_{LN}$	$(\overline{L}\gamma^\mu L)(\overline{N_R}\gamma_\mu N_R)$	9	81

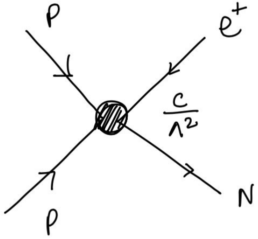
First developed in
F. del Aguila, S. Bar-Shalom, A. Soni, J. Wudka, 0806.0876 (Phys.Lett.B670, 2008)
A. Aparici, K. Kim, A. Santamaria, J. Wudka, 0904.3244 (Phys.Rev.D80 ,2009)
Basis for d<=9 in
H.-L. Li, Z. Ren, M.-L. Xiao, J.-H. Yu, Y.-H. Zheng, 2105.09329

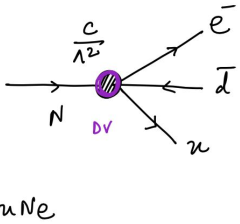
Additional HNLs in EFT with LLPs at the LHC studies
d=5 in A. Caputo, P. Hernandez, J. Lopez-Pavon, J. Salvado, JHEP 06 (2017)
d=6, diff. mass regime in Jordy de Vries, H. K. Dreiner, J. Y. Günther, Z. S. Wang, G. Zhou, JHEP 03 (2021)

N_RSMEFT

d=6 four-fermion operators with *a single* HNL (2110.15096)

- Production and decay dominated by the operator
- Operators with Λ above ~ 1 TeV make the HNL long-lived





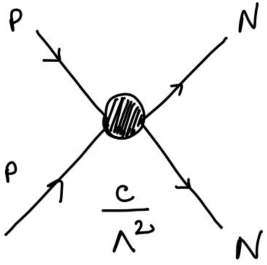
DV strategy in the inner trackers of LHC main detectors

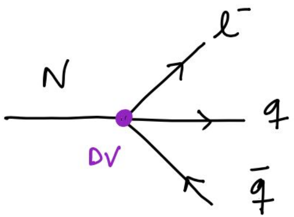
- Reconstruction of a prompt isolated lepton (*e*, ***μ***, ***τ***)
- HNL decays via the operator leading to two jets and one neutral or charged lepton
- At least one high-mass and displaced track multiplicity DV in inner tracker (to suppress hadronic bkgs.)

$$\Gamma(N_R \to \ell q q') = \frac{c_O^2}{f_O} \frac{m_N^5}{512\pi^3 \Lambda^4}$$

d=6 four-fermion operators with *pairs* of HNL (2105.13851)

- Production dominated by the operator
- HNLs decay only via their mixing with the active neutrinos





DV strategy in the inner trackers of LHC main detectors.
Probability of displaced decay in fiducial volume in far detectors

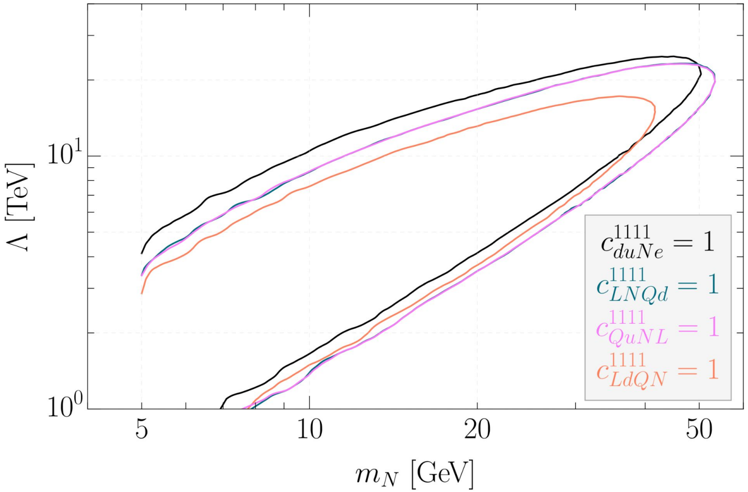
- HNL decays via mixing leptonically and/or semileptonically. We consider *N->ejj*
- Non-isolated electrons with high pT truth-matched to lepton index from DV. At least one high-mass and displaced track multiplicity DV in inner tracker
- For far detectors, the decay probability of each simulated HNL in the fiducial volume is computed

$$\Gamma \sim G_F^2 \, m_N^5 \, |V_{eN}|^2$$

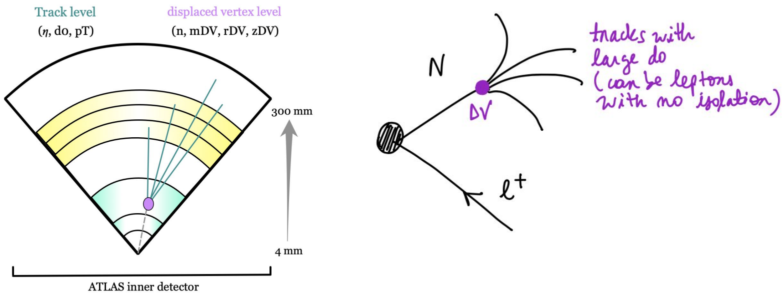
N_RSMEFT sensitivity with displaced vertices

d=6 four-fermion operators with *a single* HNL

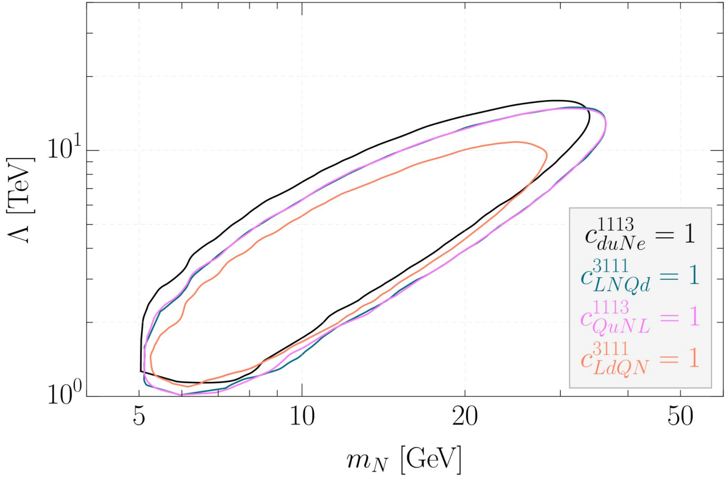
R. Beltrán, G. Cottin, J.C. Helo, M. Hirsch, A. Titov, Z.S. Wang, 2110.15096



New physics scales in excess of ~20 TeV could be probed at the LHC with 3ab-1 for HNL masses ~50 GeV for operators with electrons and muons

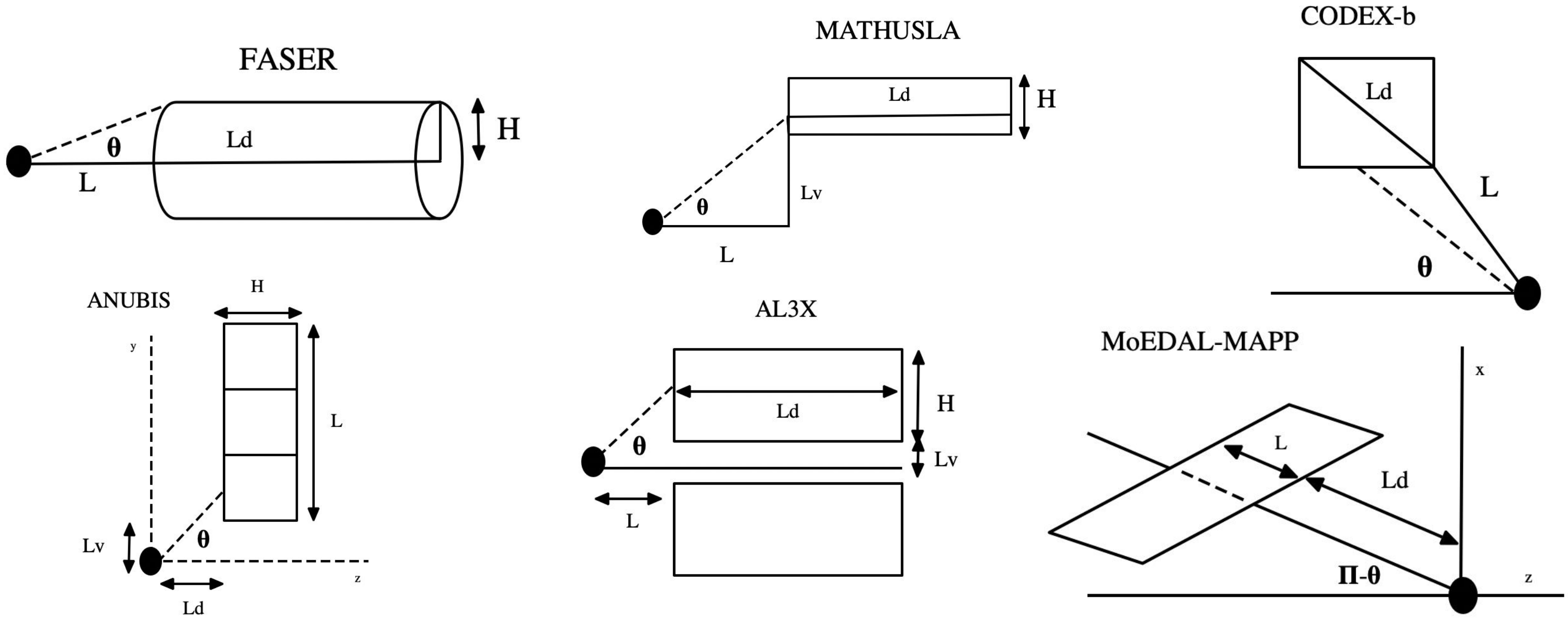


New physics scales ~10 TeV could be probed for operators with taus



Phenomenology with displaced vertices at far detectors

Decay probability of each simulated HNL takes into account the far detector geometry (L, Ld, Lv, H, θ) and their kinematics



Details of probability of decay formulas in fiducial volumes
See Jordy de Vries, H. K. Dreiner, J. Y. Günther, Z. S. Wang, G. Zhou, 2010.07305 (JHEP 03 (2021))
For FASER, MATHUSLA and CODEX-b see D. Dercks, J. de Vries, H. K. Dreiner, Z. S. Wang, 1810.03617 (Phys. Rev. D 99, 055039 (2019)) *and earlier in* J.C. Helo, M. Hirsch, Z. S. Wang, 1803.02212 (JHEP 07 (2018))
For ANUBIS see M. Hirsch, Z. S. Wang, 2001.04750 (Phys. Rev. D 101, 055034 (2020))
For AL3X see D. Dercks, H.K. Dreiner, M. Hirsch, Z. S. Wang,1811.01995 (Phys.Rev. D 99, 055020 (2019))
For MAPP see H. K. Dreiner, J. Y. Günther, Z. S. Wang, 2008.07539 (Phys. Rev. D 103, 075013 (2021))

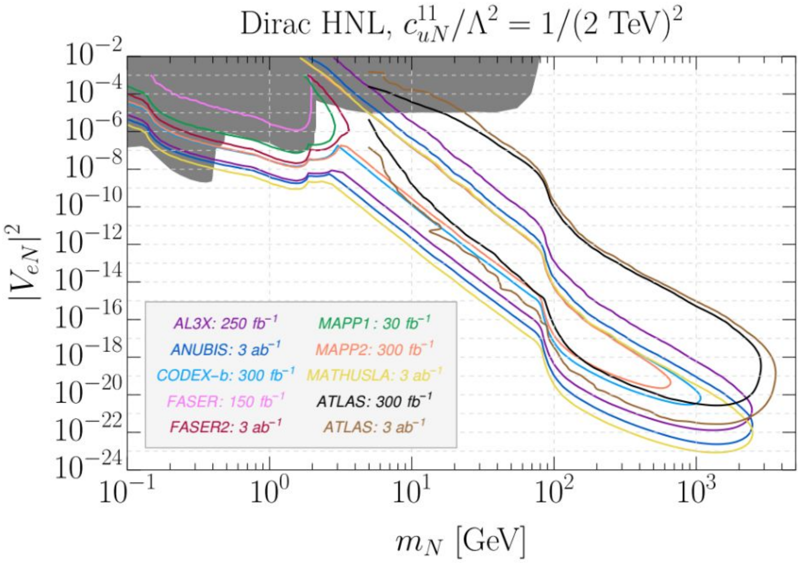
N_RSMEFT sensitivity with displaced vertices

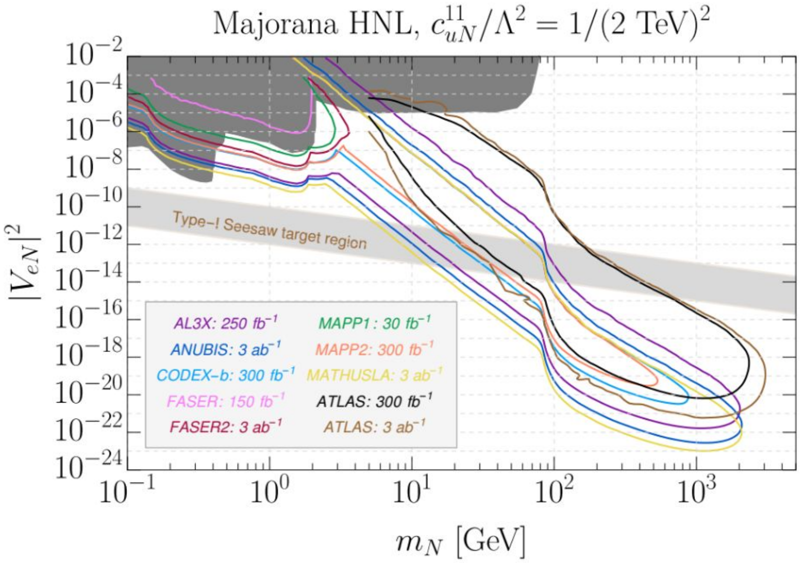
d=6 four-fermion operators with *pairs* of HNL

G. Cottin, J. C. Helo, M. Hirsch, A. Titov, Z. S. Wang, 2105.13851, (JHEP 09 (2021) 039)

$$\mathcal{L}_6 \supset \frac{1}{\Lambda^2}\left(c_{dN}\,\mathcal{O}_{dN} + c_{uN}\,\mathcal{O}_{uN} + c_{QN}\,\mathcal{O}_{QN} \right)$$

$$\mathcal{O}_{dN} \quad (\bar{d}_R \gamma^\mu d_R)(\bar{N}_R \gamma_\mu N_R)$$
$$\mathcal{O}_{uN} \quad (\bar{u}_R \gamma^\mu u_R)(\bar{N}_R \gamma_\mu N_R)$$
$$\mathcal{O}_{QN} \quad (\bar{Q} \gamma^\mu Q)(\bar{N}_R \gamma_\mu N_R)$$



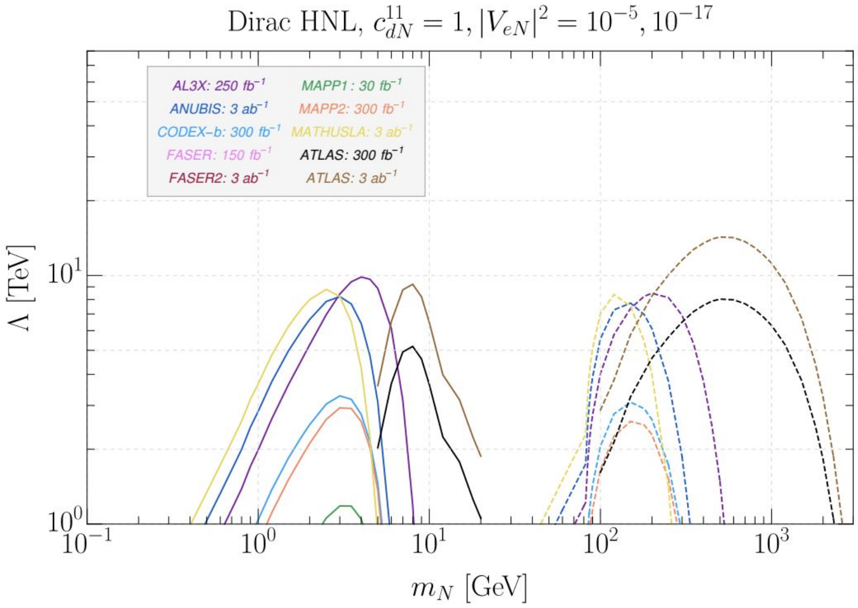


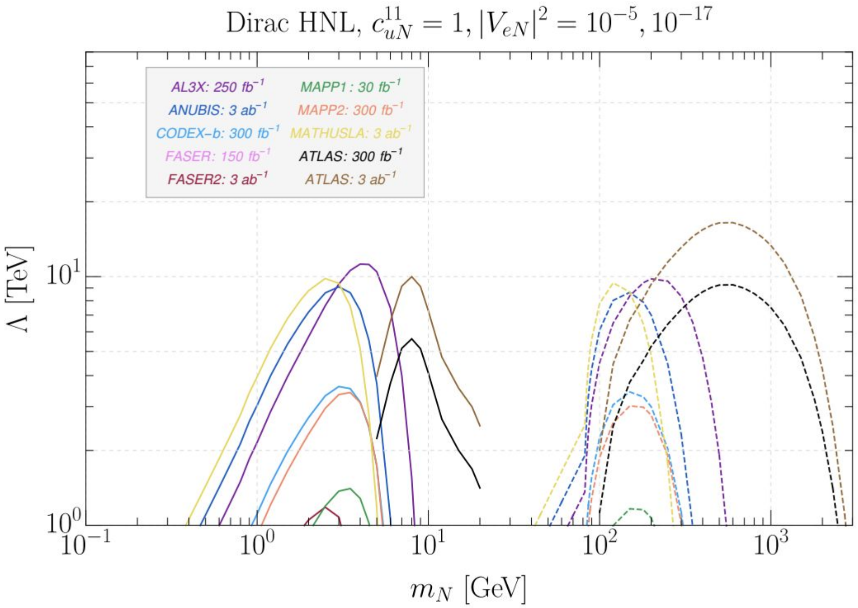
N_RSMEFT sensitivity with displaced vertices

O_{dN} $(\bar{d}_R \gamma^\mu d_R)(\bar{N}_R \gamma_\mu N_R)$
O_{uN} $(\bar{u}_R \gamma^\mu u_R)(\bar{N}_R \gamma_\mu N_R)$
O_{QN} $(\bar{Q} \gamma^\mu Q)(\bar{N}_R \gamma_\mu N_R)$

d=6 four-fermion operators with *pairs* of HNL

G. Cottin, J. C. Helo, M. Hirsch, A. Titov, Z. S. Wang, 2105.13851, (JHEP 09 (2021) 039)





Summary

- HNLs are predicted in (seesaw) mechanisms able to explain the origin of small neutrino masses in the SM, and they can be automatically long-lived particles with masses around or below the electroweak scale

- HNL production in non-minimal models beyond Type I seesaw can be studied systematically within N_RSMEFT. *d=6* four fermion operators can lead to enhanced cross-sections (which are not suppressed by the small mixing of the HNLs with the SM neutrinos) leading to a larger sensitivity reach at the HL-LHC

- The main detectors as ATLAS can extend existing limits for (or provide discovery of) HNLs using displaced searches. For four-fermion operators with a single HNL, new physics scales ~20 TeV could be probed. Dedicated (far) detectors can cover complementary regions in HNL mass and mixing space for operators with pairs of HNLs

Displaced searches can provide a clear collider test of many models for neutrino mass generation

Source image @https://twiki.cern.ch/twiki/pub/AtlasPublic/EventDisplayRun2Physics/selectron_simulation_me_500GeV.png