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Long-lived Particles and Heavy Neutral Leptons: Theory/Pheno Perspective

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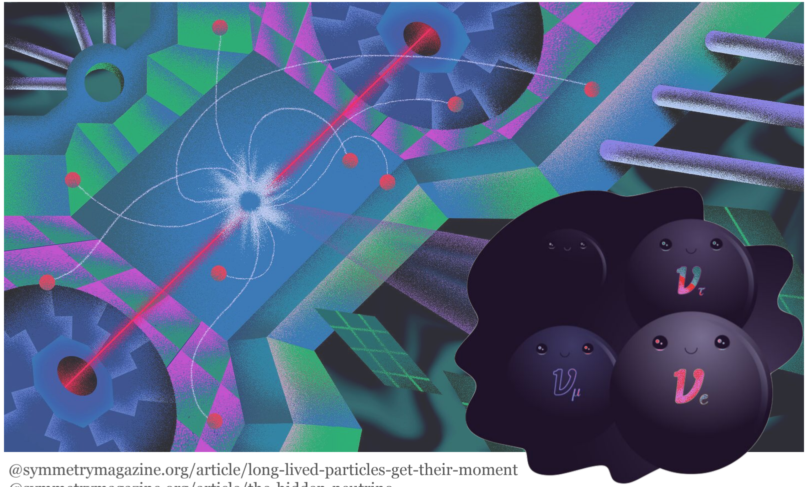
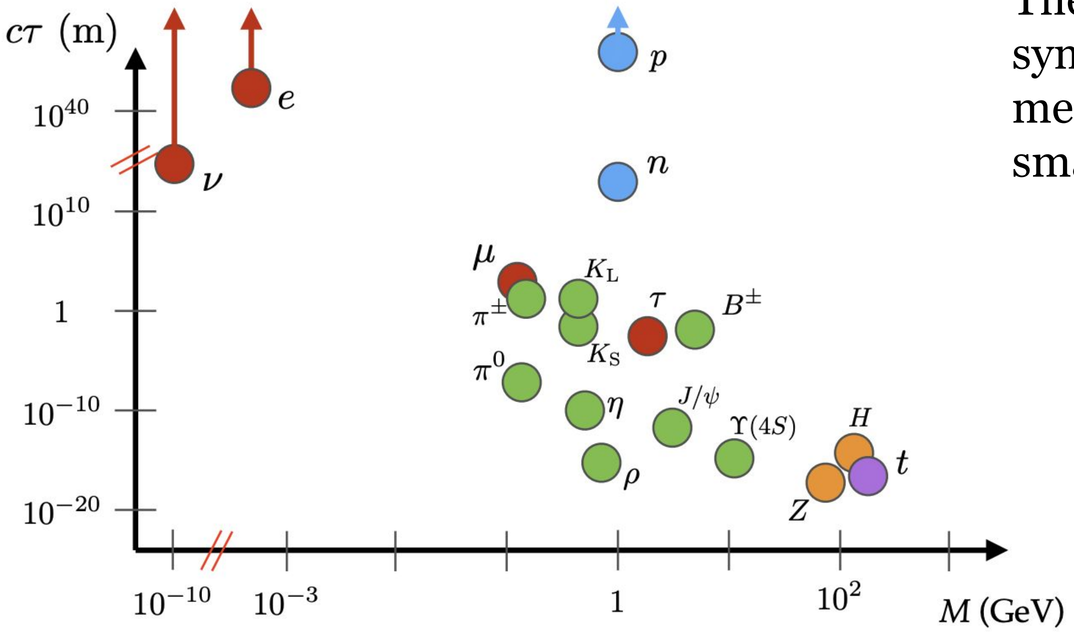


@symmetrymagazine.org/article/long-lived-particles-get-their-moment
@symmetrymagazine.org/article/the-hidden-neutrino

Long-Lived Particles can travel macroscopic distances before decaying

LLP in the SM



Their presence comes from conserved symmetries, feebly couplings, heavy mediators/hierarchy of mass scales, small phase space.

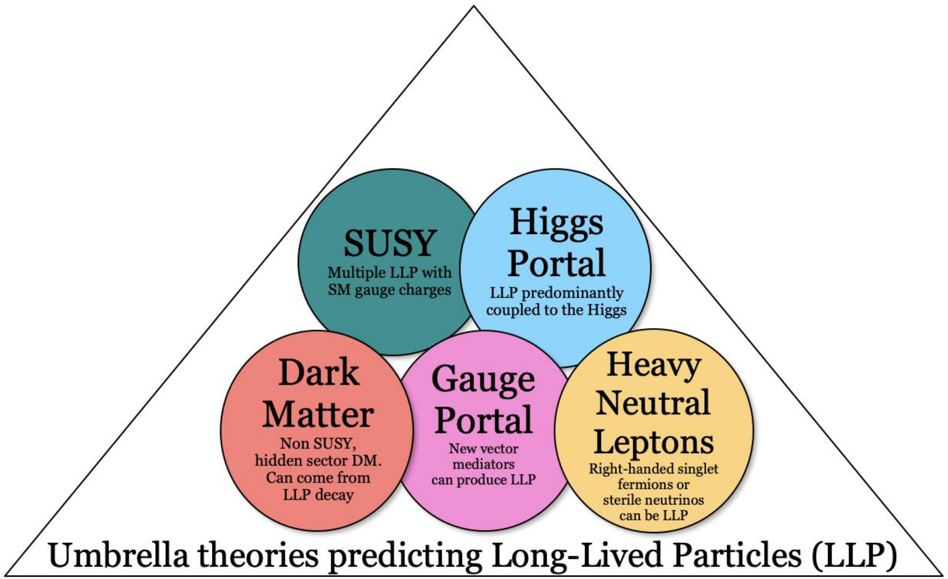
$$\Gamma \sim \lambda^2 \left(\frac{\Delta m}{\Lambda}\right)^n \Delta m$$

$$c\tau = \Gamma^{-1}$$

Image by B.Shuve.
Long-lived Particle Community White Paper, J. Alimena et al, arXiv:1903.04497

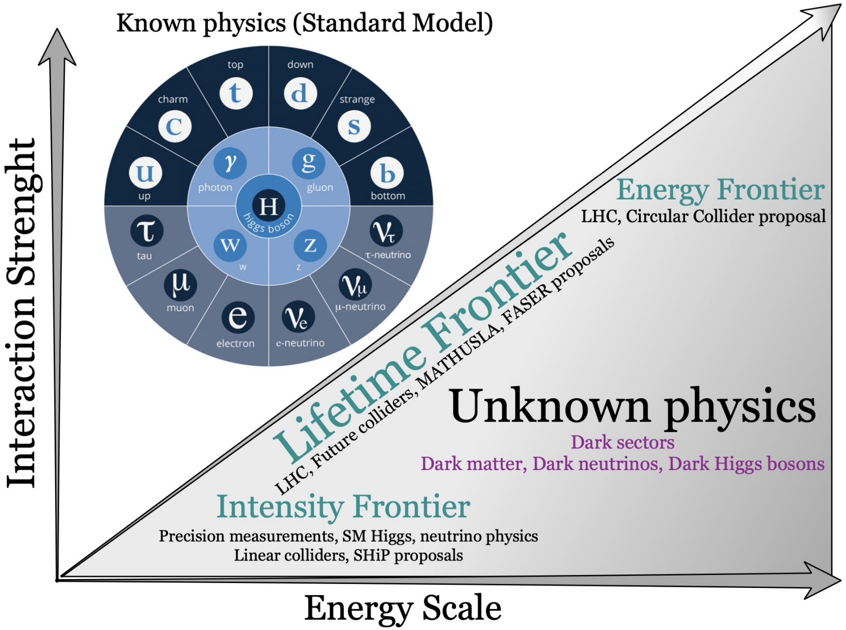
Long-Lived Particles are predicted in many beyond the Standard Model theories

LLP in BSM can arise from many well motivated classes of theories



Long-lived Particle Community White Paper, J. Alimena et al, arXiv:1903.04497
See also MATHUSLA physics case motivating models, D. Curtin et al, arXiv:1806.07396

Why? We need BSM to explain matter/antimatter asymmetry, dark matter and neutrino masses.
Need to invest in a dedicated long-lived particle (LLP) program at colliders/experiments !



SM image @ CERN, ATLAS web

HNL LLP Motivation

An answer for neutrino mass generation mechanism

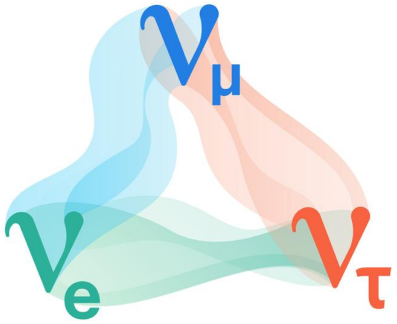
See review in A. Atre, T. Han, S. Pascoli, B. Zhang, JHEP 05 (2009) 030, arXiv:0901.3589

Could also explain Dark Matter and Baryon Asymmetry

T.Asaka, M.Shaposhnikov, PL B620 (2005), hep-ph/0505013
See reviews in A. Boyarsky, et al., Prog. in Part. and Nucl. Phys. 104 (2019), arXiv:1807.07938,
A. Boyarsky, O. Ruchayskiy, M. Shaposhnikov, Ann.Rev.Nucl.Part.Sci. 59 (2009), arXiv: 0901.0011

Known

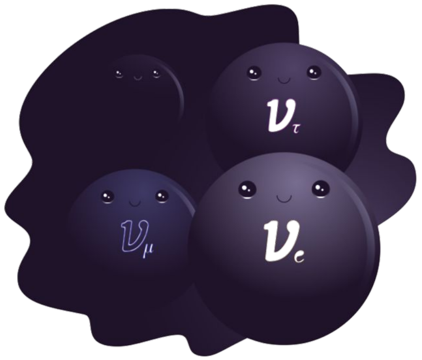
- Neutrino oscillations therefore neutrinos in the SM have mass



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



Images by @symmetrymagazine

Seesaw Mechanism(s)

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

@symmetrymagazine

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

Is not the only possibility … i.e Inverse Seesaw

$$\mathcal{L}_{\nu mass} = \frac{1}{2}\left(\overline{\nu_L^c}\ \overline{N_R}\right)\mathcal{M}_\nu\begin{pmatrix}\nu_L \\ N_R^c\end{pmatrix} + h.c$$

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix}$$

$M_N \gg m_D$

$$m_\nu \approx -m_D \cdot M_N^{-1} \cdot m_D^T$$

$$m_N \approx M_N$$

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

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$$(\nu_L, N_R^c, S_L)$$

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D^T & \epsilon^T \\ m_D & M & M_N \\ \epsilon & M_N^T & \mu \end{pmatrix}$$

$\mu \ll M_N$ Inverse seesaw $\longrightarrow V_N^2 \sim m_\nu / \mu$

Pheno approach: consider HNL mass and mixing as independent parameters

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

HNL LLP Motivation

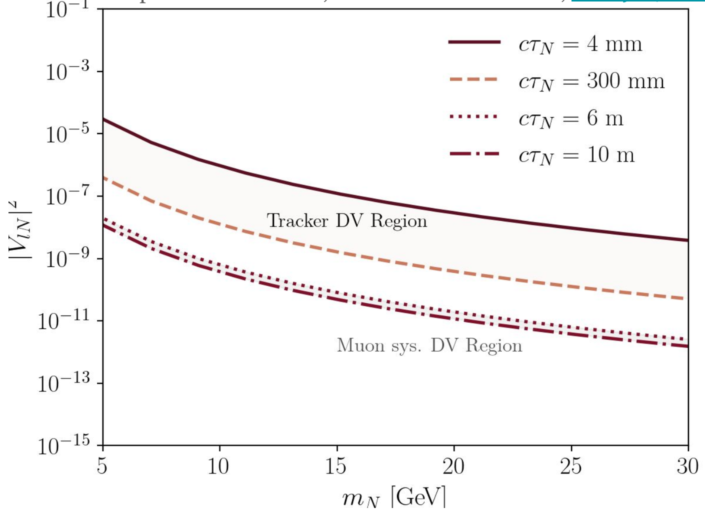
Rich collider phenomenology across different masses

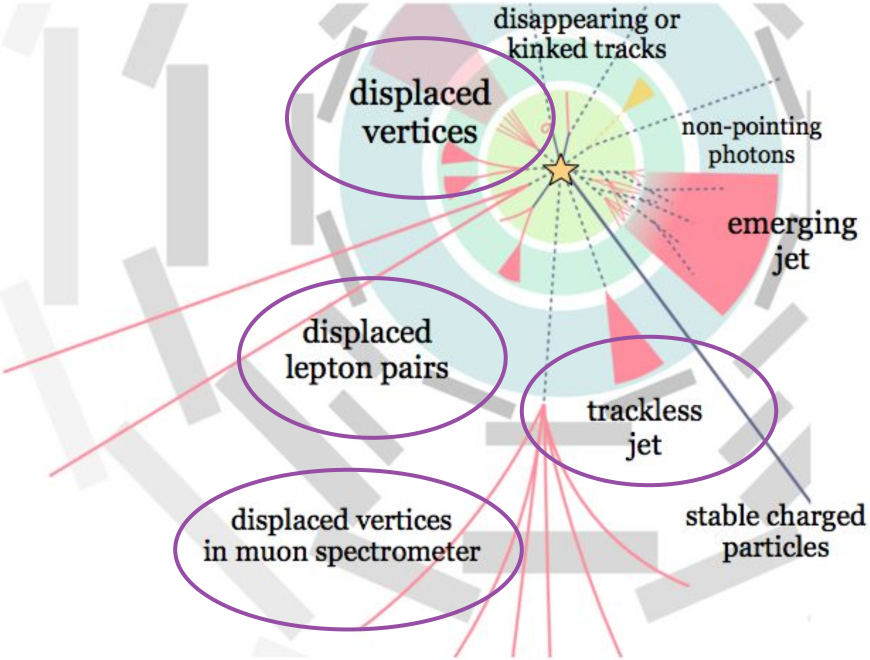
See reviews
M. Drewes, Int.J.Mod.Phys.E 22 (2013) 1330019, arXiv:1303.6912
F. Deppisch, P. S. Bhupal Dev, Apostolos Pilaftsis, New J.Phys. 17 (2015) 7, 075019, arXiv:1502.06541
Y. Cai, T. Han, Tong Li, R. Ruiz, Front.in Phys. 6 (2018) 40, arXiv: :1711.02180

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

Small mixings and ~ GeV scale HNL ⇒ LLP!

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





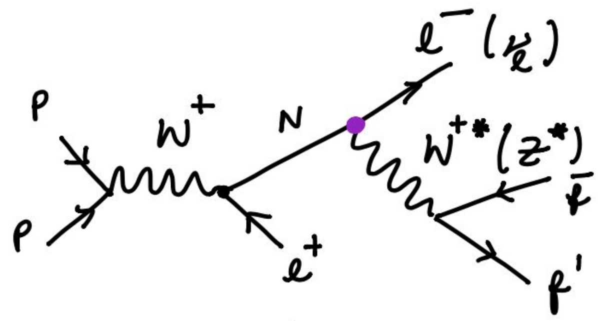
HNL discovery potential with a variety of LLP signatures!

Adapted from Heather Russel
J. Alimena et al, arXiv:1903.04497

HNL LLP Phenomenology in Minimal Type I seesaw

HNL mixes with SM neutrino. Large lifetime due to off-shell decay

$m_N < m_W$



"HNL optimized" displaced strategies/proposals that build up on experimental LLP-LHC searches not really designed for HNLs (apologies if I missed your work!)

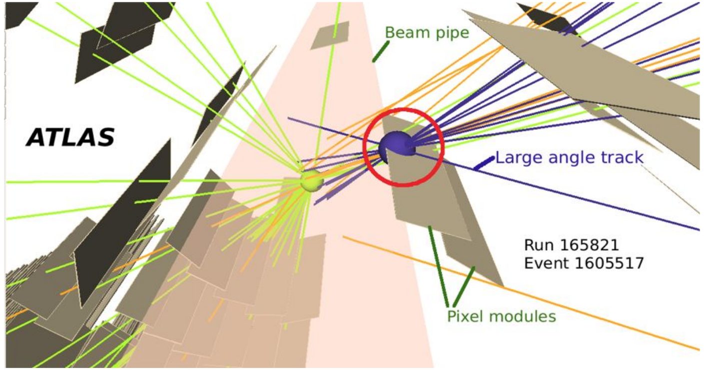
Displaced vertex searches

- HNL decays leptonically and/or semileptonically
- prompt lepton trigger from W decay

Inner Trackers (IT)

- high-mass and displaced track multiplicity DVs in inner tracker to suppress hadronic bkgs.

J. C. Helo, M. Hirsch, S. Kovalenko, PRD 89 (2014), G. Cottin, J.C. Helo and M. Hirsch, PRD 98 (2018), Iryna Boiarska et al., arXiv:1902.04535, A. Abada, et al., JHEP 93 (2019), M. Drewes, J. Hajer, JHEP 70 (2020)



ATLAS Event Display arXiv:1109.2242

Muon Systems (MS)

- can access larger displacements (i.e lower HNL masses)
- purely muonic vertices give better sensitivity at low HNL masses (not necessarily limited by invariant mass cut of DV)

K. Bondarenko et al., Phys. Rev. D 100 (2019)
M. Drewes, J. Hajer, JHEP 70 (2020)

HNL LLP Phenomenology in Minimal Type I seesaw

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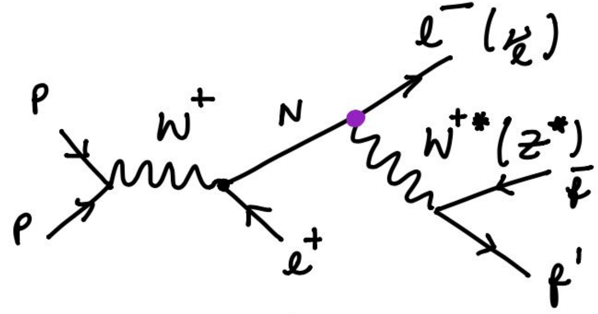


"HNL optimized" displaced strategies/proposals that build up on experimental LLP-LHC searches not really* designed for HNLs (apologies if I missed your work!)

Displaced lepton searches

- HNL decays leptonically
- prompt lepton trigger
- At least one displaced track from HNL is a non-isolated lepton
- Can do explicit vertex reconstruction of displaced di-muon/di-electron/emu vertices in ID or MS
- No explicit vertex requirement leads to additional sources of SM bkgs.

J. Liu, Z. Liu, Lian-Tao Wang, Xiao-Ping Wang, JHEP 07(2019)
M. Drewes, J. Hajer, JHEP 70 (2020)
* ATLAS JHEP 10 (2019) (first) dedicated HNL displaced search at the LHC

Displaced lepton-jets

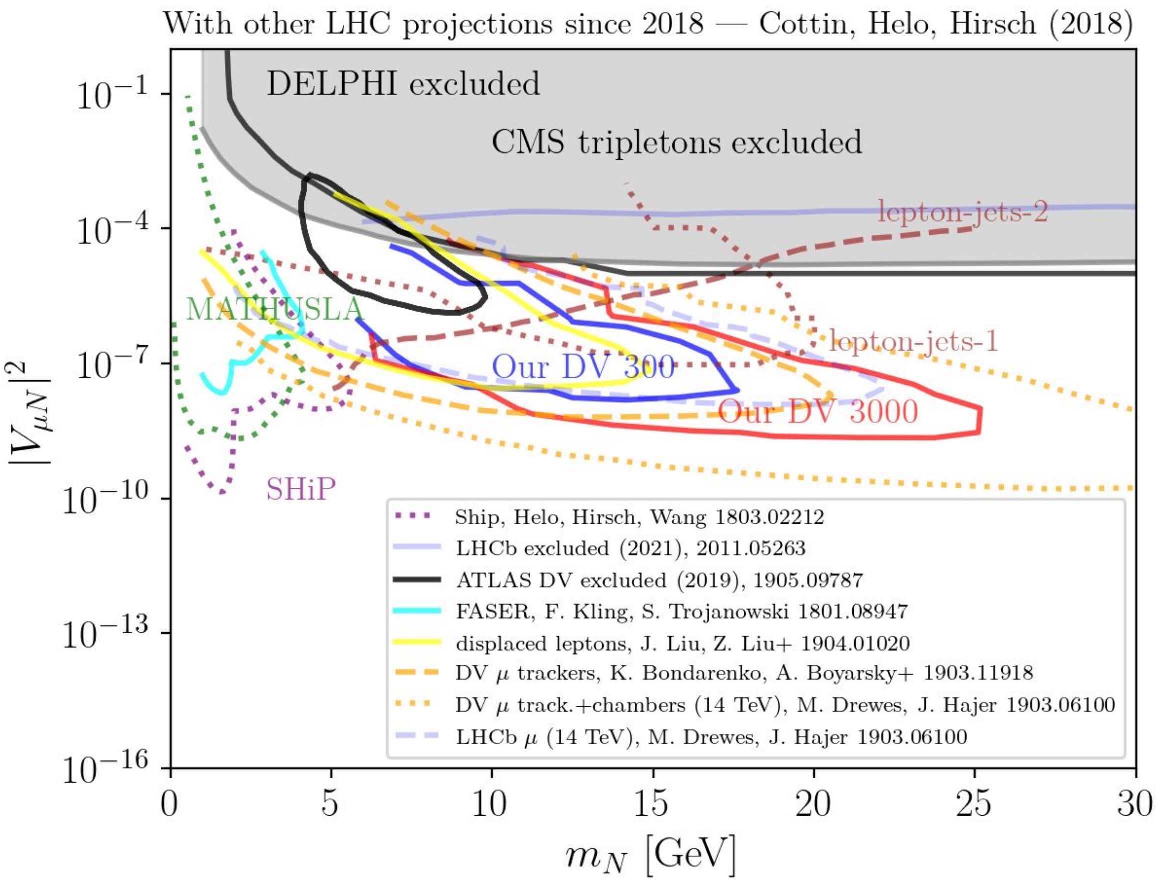
- Prompt lepton trigger from W decay
- Reconstruct boosted HNL decay as a single displaced *lj* object
  (with more than one leptonic displaced track concentrated within a cone)

E. Izaguirre and B. Shuve, Phys. Rev. D91 (2015)
S. Dube, D. Gadkari, and A. M. Thalapillil, Phys. Rev. D96 (2017)

HNL landscape with LLP strategies *- apologies if your work is not in this plot!*

electron mixing qualitatively similar, tau sector is far less constrained experimentally!

e.g.. see G. Cottin, J.C. Helo and M. Hirsch, PRD 98 (2018)



HNL landscape with LLP strategies *- apologies if your work is not in this plot!*

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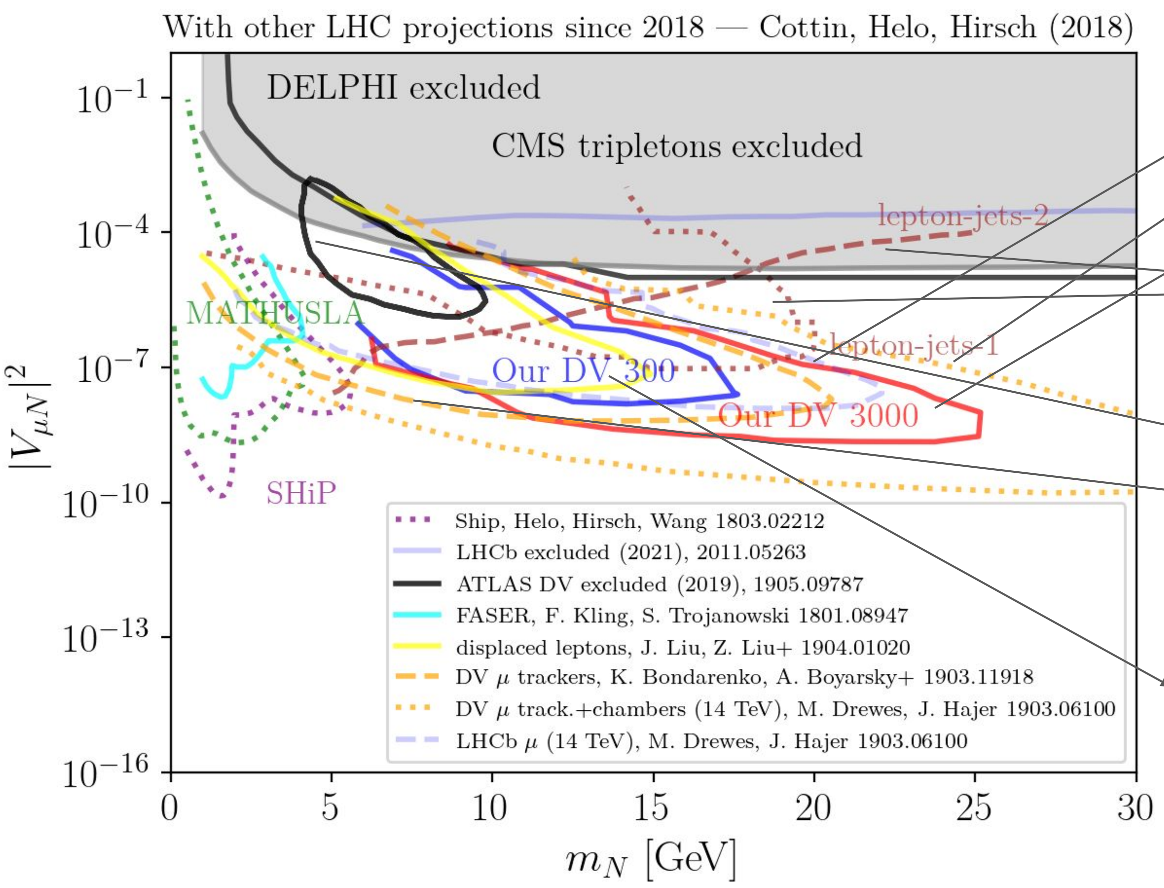
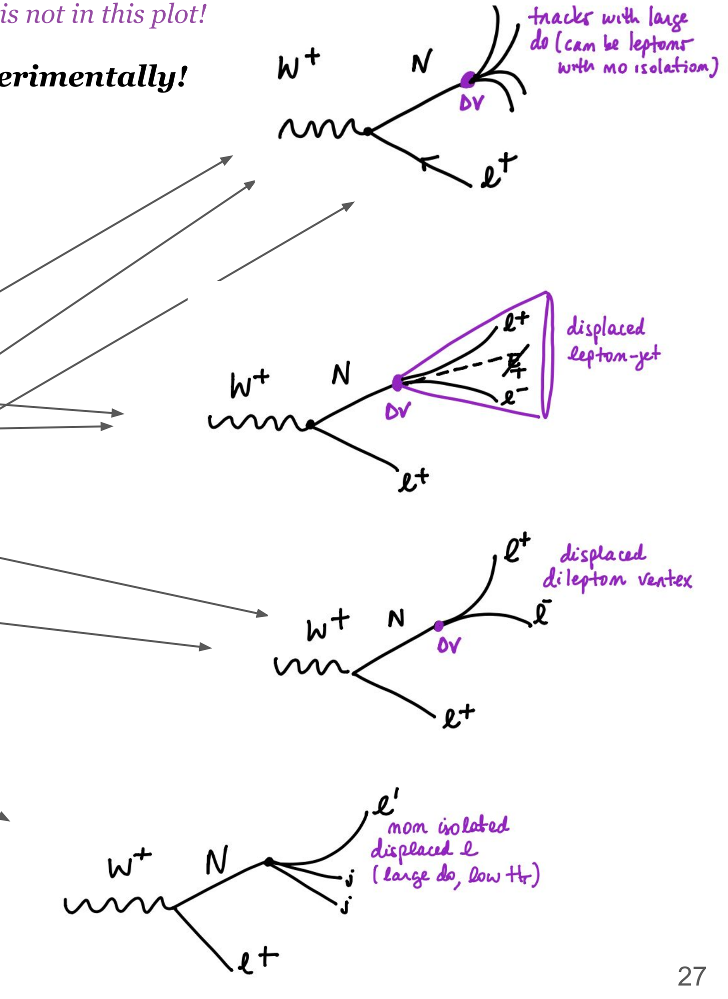
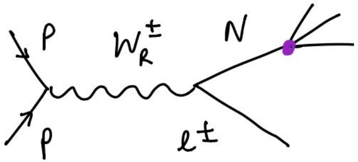




Beyond Minimal Type I seesaw

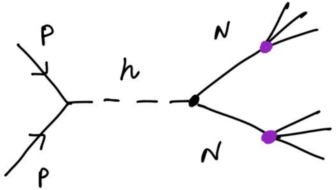
Similar LLP HNL displaced search strategies have been proposed that can be sensitive to non-minimal HNL models with additional production modes via e.g. new gauge bosons (Z', WR), higgs(es).

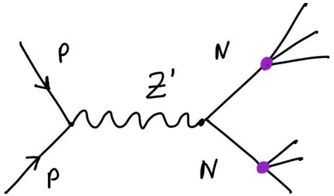
Can have 1DV or 2 DVs with no additional prompt objects (highlighting a critical need for dedicated displaced triggers)



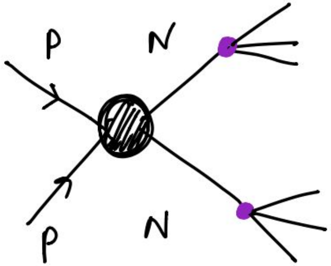
For Left-Right, see e.g.
G. Cottin, J.C. Helo, M. Hirsch, D. Silva, PRD 99 (2019), G. Cottin, J.C. Helo, M. Hirsch, PRD 97 (2018), M. Nemevšek, F. Nesti, G. Popara, PRD 97, (2018)

For B-L, see e.g.
C.-W. Chiang, G. Cottin et. al, JHEP 12 (2019), F. Deppisch et al., PRD 100 (2019), F. Deppisch et al., JHEP 08 (2018) , B. Batell et al., JHEP08(2016)





A systematic way to study such non-minimal HNLs is to apply effective field theory (EFT), with NRO which are suppressed by a new physics scale Λ



For HNLs in EFT with LLPs at the LHC, see e.g.
G. Cottin, J. C. Helo, M. Hirsch, A. Titov, Z. S. Wang, arXiv:2105.13851
Jordy de Vries, H. K. Dreiner, J. Y. Günther, Z. S. Wang, G. Zhou, JHEP 03 (2021)
A. Caputo, P. Hernandez, J. Lopez-Pavon, J. Salvado, JHEP 06 (2017)

Beyond Minimal Type I seesaw

An example for d = 6 for the "NRSMEFT", the EFT of the SM extended with HNLs

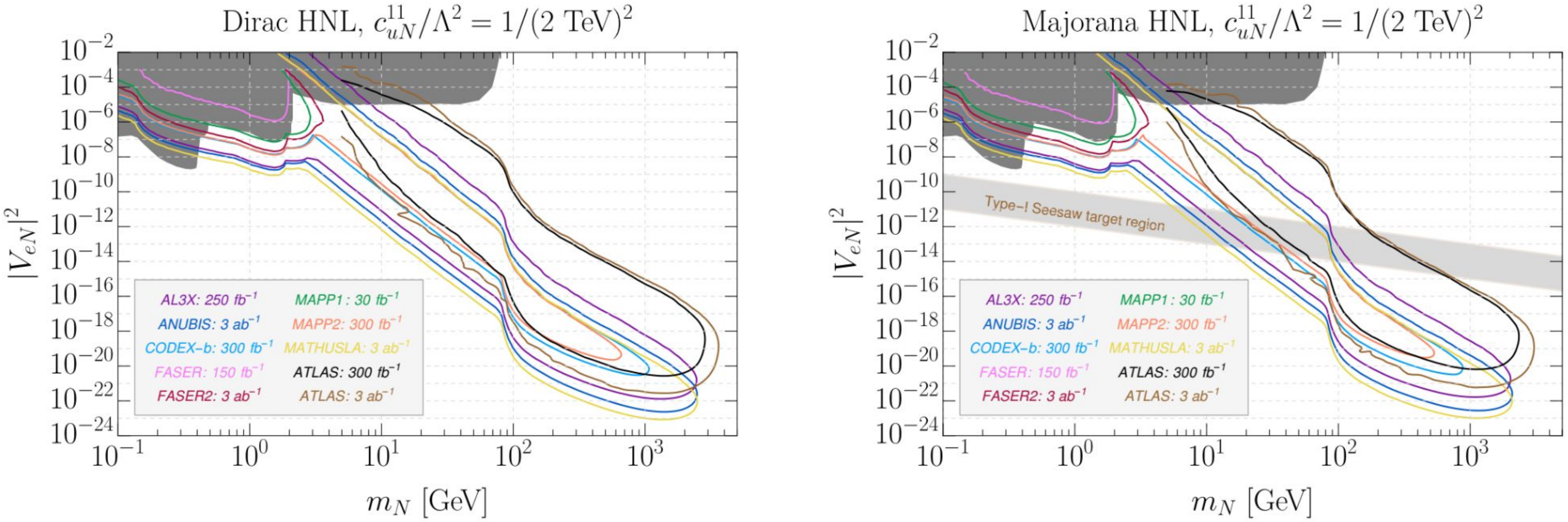
G. Cottin, J. C. Helo, M. Hirsch, A. Titov, Z. S. Wang, arXiv:2105.13851

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

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

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

$$\mathcal{O}_{QN} \quad (\bar{Q} \gamma^\mu Q)(\bar{N}_R \gamma_\mu N_R)$$



Much larger sensitivities can be achieved with LHC-LLP searches as compared to the Minimal Type I seesaw !

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 below the electroweak scale

- In the high-luminosity phase of the LHC, both LHCb and the main detectors ATLAS and CMS can extend existing limits for (or provide discovery of) HNLs using displaced searches. Dedicated detectors can cover complementary regions in HNL mass and mixing space

- Dedicated searches and displaced triggers (able to identify directly the HNL signature) are critical to enhance sensitivity. Experimental searches with different HNL decay signatures i.e. $N \rightarrow e\,jj$, $N \rightarrow \tau\,jj$, are desirable to complement existing analyses (existing pheno proposals to test other mixing parameters)

- HNL production in non-minimal models beyond Type I seesaw 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

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