Long-lived particles and meson decays in N_RLEFT

Rebeca Beltrán
IFIC (CSIC/University of Valencia)

In collaboration with
G. Cottin, J.C. Helo, M. Hirsch, A. Titov & Z.S. Wang

Outline

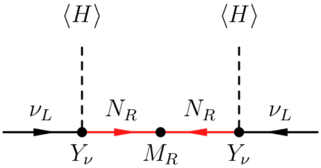
1. Motivation
2. HNLs and EFTs: N_RLEFT
3. Searching for HNLs at the LHC
4. Conclusions

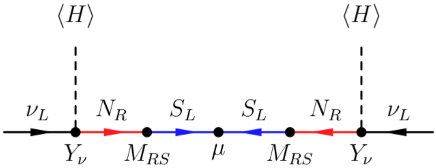
Outline

1. Motivation
2. HNLs and EFTs: N_RLEFT
3. Searching for HNLs at the LHC
4. Conclusions

Motivation for HNLs: neutrino masses

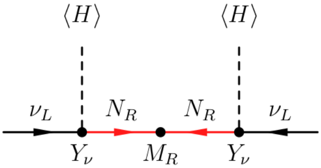
- Neutrino mass models predict the existence of heavy neutral leptons (HNLs): fermionic singlets under SM gauge group.

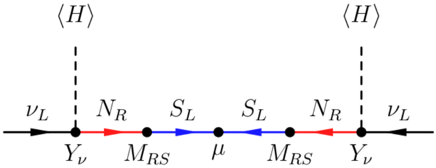




Motivation for HNLs: neutrino masses

➡ Neutrino mass models predict the existence of heavy neutral leptons (HNLs): fermionic singlets under SM gauge group.



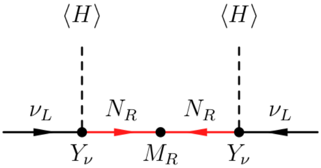


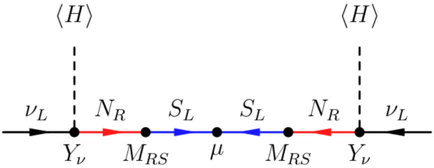
Type-I seesaw

- Adds three singlets: N_R
- $m_\nu \propto -(Y_\nu v)^T M_R^{-1} (Y_\nu v)$
- New physics scale easily out of range of experiments

Motivation for HNLs: neutrino masses

➨ Neutrino mass models predict the existence of heavy neutral leptons (HNLs): fermionic singlets under SM gauge group.





Type-I seesaw

- Adds three singlets: N_R
- $m_\nu \propto -(Y_\nu v)^T M_R^{-1} (Y_\nu v)$
- New physics scale easily out of range of experiments

Inverse seesaw

- Adds six singlets: N_R, S_L
- $m_\nu \propto (Y_\nu v)^T\, M_{RS}^{T\,-1} \mu\, M_{RS}^{-1}\, (Y_\nu v)$
- Scale of new physics can be $\mathcal{O}(\mathrm{TeV})$

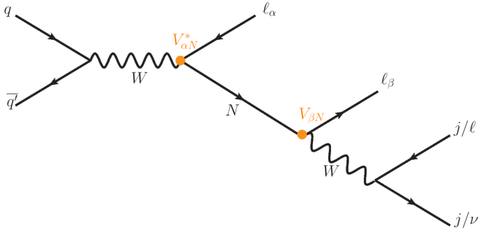
Motivation for HNLs: minimal scenario

➡ In seesaw mechanisms the HNLs interact with SM fields via active-heavy neutrino mixing.

$$-\mathcal{L}_{\rm CC+NC} = \frac{g}{\sqrt{2}} V_{\alpha N} \left(\bar{l}_\alpha \gamma^\mu P_L N\right) W_\mu + \frac{g}{2\cos\theta_W} U_{\alpha i} V^*_{\alpha N} \left(\bar{N}\gamma^\mu P_L \nu_i\right) Z_\mu + \text{h.c.}$$

Naive estimation for one generation:

$$V_{\text{type-I}} \propto \sqrt{\frac{m_\nu}{M_R}},\; V_{\text{ISS}} \propto \sqrt{\frac{m_\nu}{\mu}}$$



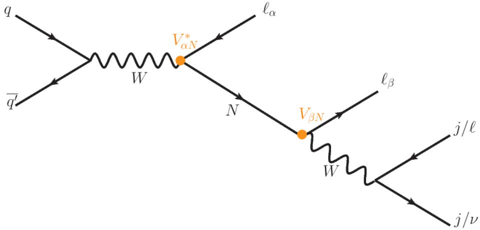
Motivation for HNLs: minimal scenario

➡ In seesaw mechanisms the HNLs interact with SM fields via active-heavy neutrino mixing.

$$-\mathcal{L}_{\rm CC+NC} = \frac{g}{\sqrt{2}} V_{\alpha N}\,(\bar{l}_\alpha \gamma^\mu P_L N)\, W_\mu + \frac{g}{2\cos\theta_W} U_{\alpha i} V^*_{\alpha N} (\bar{N}\gamma^\mu P_L \nu_i)\, Z_\mu + \text{h.c.}$$

Naive estimation for one generation:

$$V_{\text{type-I}} \propto \sqrt{\frac{m_\nu}{M_R}},\; V_{\text{ISS}} \propto \sqrt{\frac{m_\nu}{\mu}}$$



➡ Very small mixings imply:

Large decay lengths: **long-lived** candidate.

Low production rates. Detection $\propto |V|^4$.

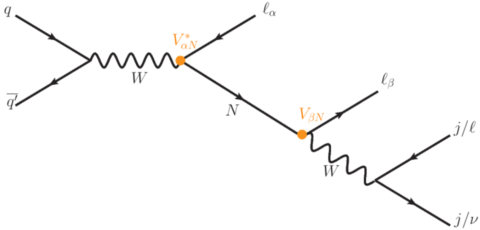
Motivation for HNLs: minimal scenario

➡ In seesaw mechanisms the HNLs interact with SM fields via active-heavy neutrino mixing.

$$-\mathcal{L}_{\rm CC+NC} = \frac{g}{\sqrt{2}} V_{\alpha N} \left(\bar{l}_\alpha \gamma^\mu P_L N\right) W_\mu + \frac{g}{2\cos\theta_W} U_{\alpha i} V^*_{\alpha N} \left(\bar{N}\gamma^\mu P_L \nu_i\right) Z_\mu + \text{h.c.}$$

Naive estimation for one generation:

$$V_{\text{type-I}} \propto \sqrt{\frac{m_\nu}{M_R}},\ V_{\text{ISS}} \propto \sqrt{\frac{m_\nu}{\mu}}$$



➡ Very small mixings imply:

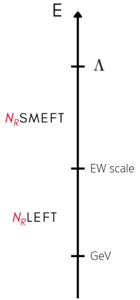
Large decay lengths: **long-lived** candidate.

Low production rates. Detection $\propto |V|^4$.

¿New interactions?

➡ Most general description of BSM physics at low energies: SMEFT.
Buchmuller & Wyler (1968), Grzadkowski *et al.* (2010)

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_{d>4} \frac{1}{\Lambda^{d-4}} \sum_i \alpha_i^{(d)} \mathcal{O}_i^{(d)}$$



Λ : new physics energy scale

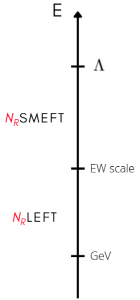
$\alpha_i^{(d)}$: dimensionless coefficients

$\mathcal{O}_i^{(d)}$: gauge and Lorentz invariant operators

Effective field theories

- Most general description of BSM physics at low energies: SMEFT.
  Buchmuller & Wyler (1968), Grzadkowski *et al.* (2010)

$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\textsf{SM}+N} + \sum_{d>4} \frac{1}{\Lambda^{d-4}} \sum_i \alpha_i^{(d)} \mathcal{O}_i^{(d)}$$



Λ : new physics energy scale

$\alpha_i^{(d)}$: dimensionless coefficients

$\mathcal{O}_i^{(d)}$: gauge and Lorentz invariant operators

- If HNL mass is around (or below) the electroweak scale: N_RSMEFT.
  del Aguila *et al.* (2009), Aparici *et al.* (2009), Liao *et al.* (2016)

Effective field theories

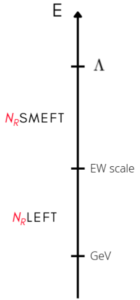
- Most general description of BSM physics at low energies: SMEFT.
  Buchmuller & Wyler (1968), Grzadkowski *et al.* (2010)

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}'_{\text{SM}+N} + \sum_{d>4} \frac{1}{\Lambda^{d-4}} \sum_i \alpha_i^{(d)} \mathcal{O}_i^{(d)}$$

Λ : new physics energy scale

$\alpha_i^{(d)}$: dimensionless coefficients

$\mathcal{O}_i^{(d)}$: gauge and Lorentz invariant operators



- If HNL mass is around (or below) the electroweak scale: N_RSMEFT.
  del Aguila *et al.* (2009), Aparici *et al.* (2009), Liao *et al.* (2016)
- If $E \simeq \mathcal{O}(\text{GeV})$, as in meson decays: N_RLEFT.
  Li *et al.* (2020), Chala & Titov (2020)

N_RLEFT operators

- $d=6$ four-fermion operators containing two quark fields and
  - two HNLs.
  - HNL and ν.
  - HNL and ℓ: de Vries *et al.* (2021)

	Name	Structure	$n_N=1$	$n_N=3$
LNC	$\mathcal{O}_{dN}^{V,RR}$	$(\overline{d_R}\gamma_\mu d_R)\,(\overline{N_R}\gamma^\mu N_R)$	9	81
LNC	$\mathcal{O}_{uN}^{V,RR}$	$(\overline{u_R}\gamma_\mu u_R)\,(\overline{N_R}\gamma^\mu N_R)$	4	36
LNC	$\mathcal{O}_{dN}^{V,LR}$	$(\overline{d_L}\gamma_\mu d_L)\,(\overline{N_R}\gamma^\mu N_R)$	9	81
LNC	$\mathcal{O}_{uN}^{V,LR}$	$(\overline{u_L}\gamma_\mu u_L)\,(\overline{N_R}\gamma^\mu N_R)$	4	36
LNV	$\mathcal{O}_{dN}^{S,RR}$	$(\overline{d_L}d_R)\,(\overline{N_R^c}N_R)$	18	108
LNV	$\mathcal{O}_{dN}^{T,RR}$	$(\overline{d_L}\sigma_{\mu\nu}d_R)\,(\overline{N_R^c}\sigma^{\mu\nu}N_R)$	0	54
LNV	$\mathcal{O}_{uN}^{S,RR}$	$(\overline{u_L}u_R)\,(\overline{N_R^c}N_R)$	8	48
LNV	$\mathcal{O}_{uN}^{T,RR}$	$(\overline{u_L}\sigma_{\mu\nu}u_R)\,(\overline{N_R^c}\sigma^{\mu\nu}N_R)$	0	24
LNV	$\mathcal{O}_{dN}^{S,LR}$	$(\overline{d_R}d_L)\,(\overline{N_R^c}N_R)$	18	108
LNV	$\mathcal{O}_{uN}^{S,LR}$	$(\overline{u_R}u_L)\,(\overline{N_R^c}N_R)$	8	48

Pair-N_R operators. Work in progress

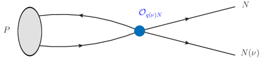
	Name	Structure	$n_N=1$	$n_N=3$
LNC	$\mathcal{O}_{d\nu N}^{S,RR}$	$(\overline{d_L}d_R)\,(\overline{\nu_L}N_R)$	54	162
LNC	$\mathcal{O}_{d\nu N}^{T,RR}$	$(\overline{d_L}\sigma_{\mu\nu}d_R)\,(\overline{\nu_L}\sigma^{\mu\nu}N_R)$	54	162
LNC	$\mathcal{O}_{u\nu N}^{S,RR}$	$(\overline{u_L}u_R)\,(\overline{\nu_L}N_R)$	24	72
LNC	$\mathcal{O}_{u\nu N}^{T,RR}$	$(\overline{u_L}\sigma_{\mu\nu}u_R)\,(\overline{\nu_L}\sigma^{\mu\nu}N_R)$	24	72
LNC	$\mathcal{O}_{d\nu N}^{S,LR}$	$(\overline{d_R}d_L)\,(\overline{\nu_L}N_R)$	54	162
LNC	$\mathcal{O}_{u\nu N}^{S,LR}$	$(\overline{u_R}u_L)\,(\overline{\nu_L}N_R)$	24	72
LNV	$\mathcal{O}_{d\nu N}^{V,RR}$	$(\overline{d_R}\gamma_\mu d_R)\,(\overline{\nu_L^c}\gamma^\mu N_R)$	54	162
LNV	$\mathcal{O}_{u\nu N}^{V,RR}$	$(\overline{u_R}\gamma_\mu u_R)\,(\overline{\nu_L^c}\gamma^\mu N_R)$	24	72
LNV	$\mathcal{O}_{d\nu N}^{V,LR}$	$(\overline{d_L}\gamma_\mu d_L)\,(\overline{\nu_L^c}\gamma^\mu N_R)$	54	162
LNV	$\mathcal{O}_{u\nu N}^{V,LR}$	$(\overline{u_L}\gamma_\mu u_L)\,(\overline{\nu_L^c}\gamma^\mu N_R)$	24	72

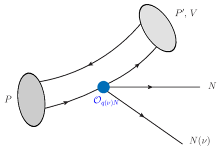
Neutral single-N_R operators. To be done

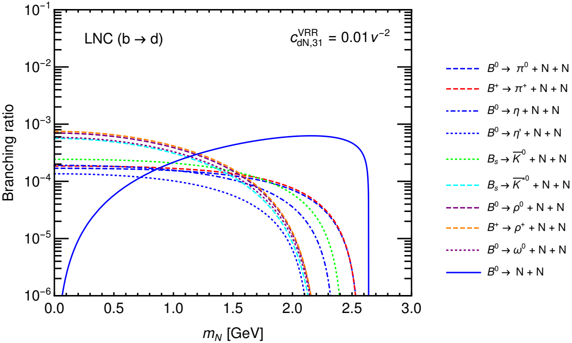
Searching for HNLs @ LHC: production

- **HNL production** occurs via meson decays for $m_N < 5\,\text{GeV}$.
- N_RLEFT operators trigger B/D meson decays into neutral leptons (+hadron), depending on the quark flavor composition.

$$O^{V,RR}_{dN,\,31}: \quad \left(\overline{b_R}\gamma_\mu d_R\right)\left(\overline{N_R}\gamma^\mu N_R\right)$$

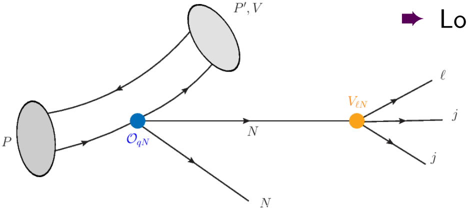






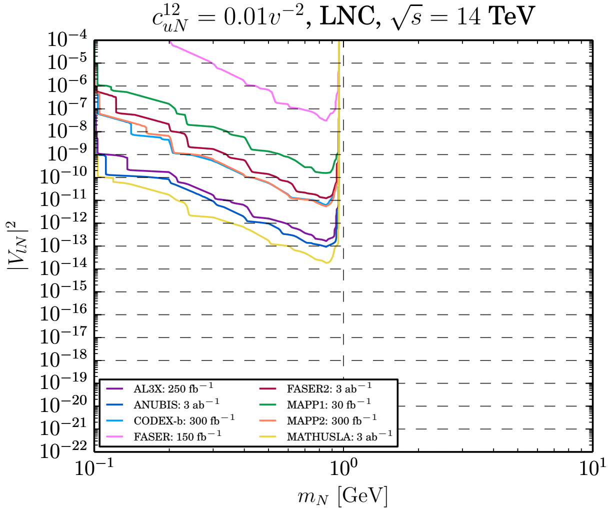
Searching for HNLs @ LHC: decay

- Pair-N_R operators cannot make the **HNL decay**. Active-heavy neutrino mixing controls the decay. HNL decay width: Bondarenko *et al.* (2018)
- Single-N_R operators can compete with the mixing if more than one coefficient is *switched on*. de Vries *et al.* (2021)



- Long-lived HNLs reach the **far detectors:**
  - MATHUSLA
  - CODEX-b
  - ANUBIS
  - FASER
  - AL3X
  - MAPP

Searching for HNLs @ LHC: preliminary results



$c_{uN}^{12} \equiv c_{uN,12}^{V,RR}$

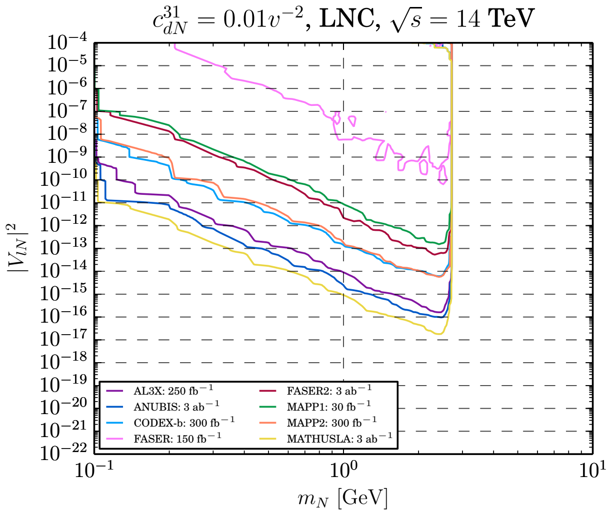
Production via $\mathcal{O}_{uN}^{V,RR}$

$(\overline{u_R}\gamma_\mu c_R)\left(\overline{N_R}\gamma^\mu N_R\right)$

D meson decays

Preliminary sensitivity projections.

Searching for HNLs @ LHC: preliminary results



$c_{dN}^{31} \equiv c_{dN,31}^{V,RR}$

Production via $\mathcal{O}_{dN}^{V,RR}$

$(\overline{b_R}\gamma_\mu d_R)\,(\overline{N_R}\gamma^\mu N_R)$

B meson decays

Preliminary sensitivity projections.

Conclusions

- Heavy neutral leptons (HNLs) are being searched for at the LHC. Different search strategies are trying to cover all possible regions of parameter space.
- HNLs with $m_N < 5\,\text{GeV}$ can be produced in meson decays at LHC through higher-dimensional operators (N_RLEFT).
- Far detectors could probe:

  $\Rightarrow$ Squared mixing values: $|V_{eN}|^2 \gtrsim \mathcal{O}(10^{-16})$

  $\Rightarrow$ New physics scales: $\Lambda \leq \mathcal{O}(100)\,\text{TeV}$

Long-lived particles and meson decays in N_RLEFT

Rebeca Beltrán
IFIC (CSIC/University of Valencia)

In collaboration with
G. Cottin, J.C. Helo, M. Hirsch, A. Titov & Z.S. Wang

Backup. Matching onto N_RSMEFT

- We assume N_RLEFT originates from N_RSMEFT and we perform matching at the EW scale. Chala & Titov (2020)
- N_RSMEFT operators relevant for the tree-level matching:

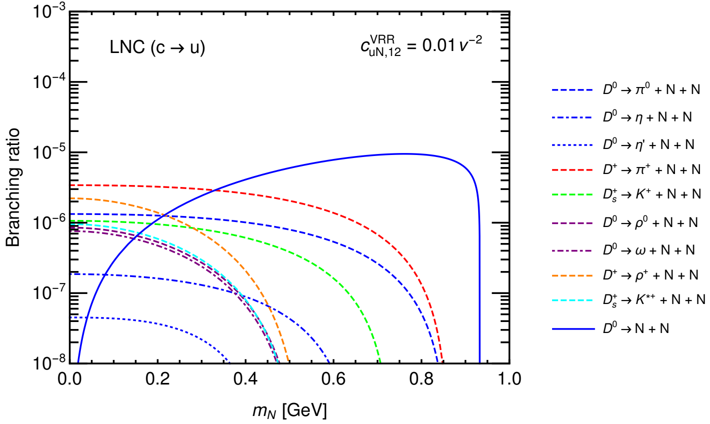
	Name	Structure	$n_N = 1$	$n_N = 3$
$d=6$ (LNC)	$\mathcal{O}_{dN}$	$(\overline{d_R}\gamma_\mu d_R)\,(\overline{N_R}\gamma^\mu N_R)$	9	81
	$\mathcal{O}_{uN}$	$(\overline{u_R}\gamma_\mu u_R)\,(\overline{N_R}\gamma^\mu N_R)$	9	81
	$\mathcal{O}_{QN}$	$(\overline{Q}\gamma_\mu Q)\,(\overline{N_R}\gamma^\mu N_R)$	9	81
	$\mathcal{O}_{HN}$	$\left(H^\dagger i\overleftrightarrow{D}_\mu H\right)(\overline{N_R}\gamma^\mu N_R)$	1	9
$d=7$ (LNV)	$\mathcal{O}_{QNdH}$	$(\overline{Q}N_R)\,(\overline{N_R^c}d_R)\,H$	18	162
	$\mathcal{O}_{dQNH}$	$H^\dagger\,(\overline{d_R}Q)\,(\overline{N_R^c}N_R)$	18	108
	$\mathcal{O}_{QNuH}$	$(\overline{Q}N_R)\,(\overline{N_R^c}u_R)\,\widetilde{H}$	18	162
	$\mathcal{O}_{uQNH}$	$\widetilde{H}^\dagger\,(\overline{u_R}Q)\,(\overline{N_R^c}N_R)$	18	108

- We identify $\Lambda_{\text{LEFT}} = v$. Bounds on the Wilson coefficients can be then translated into Λ_{SMEFT} bounds. Example:

$$\frac{\alpha_{dN}^{V,RR}}{v^2} = \frac{\alpha_{dN}}{\Lambda^2} \quad \xrightarrow{\alpha_{dN}=1} \quad \Lambda \propto v\sqrt{\frac{1}{\alpha_{dN}^{V,RR}}} \approx \frac{1}{4}\sqrt{\frac{1}{\alpha_{dN}^{V,RR}}}\,\text{TeV}$$

Backup. Meson branching ratios: LNC operator

- **HNL production** from pair-N_R lepton-number conserving (LNC) operators.



Backup. Meson branching ratios: LNV operator

➡ **HNL production** from pair-N_R lepton-number violating (LNV) operators.