Heavy Neutral Leptons as long-lived particles

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http://www.astroparticles.es/

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$\mathcal{I}$.

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Theoretical expectations

Majorana Neutrino mass

Many possibilities exist!

$$m_\nu \simeq \frac{(Y v)^2}{\Lambda}$$

Weinberg, 1979

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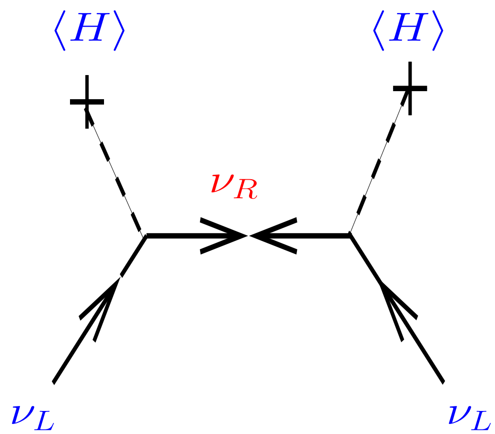
Smallness of neutrino mass
can be "explained" by:

$\Rightarrow$ High scale: Large $\Lambda \sim 10^{(14-15)}$ GeV
"classical" seesaw: $Y \sim 1$



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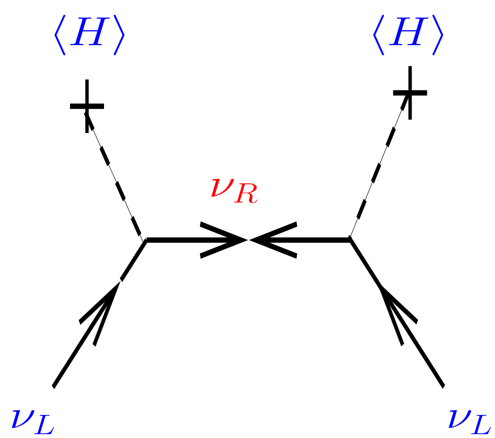
OR:

$\Rightarrow$ $\Lambda \sim 100$ GeV and $Y \sim 10^{-6}$
"electro-weak scale" seesaw



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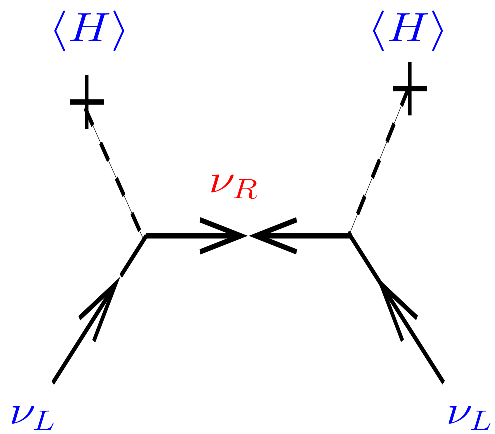

OR:

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"Heavy neutral lepton"
A "nearly" singlet fermion

N_R or HNL?

From the experimental point of view a HNL is simply a heavy fermion singlet with suppressed charged (CC) and neutral current (NC) interactions are

$$\mathcal{L} \quad = \quad \frac{g}{\sqrt{2}} V_{\alpha N_j} \, \bar{l}_\alpha \gamma^\mu P_L N_j W^-_{L\mu} + \frac{g}{2\cos\theta_W} \sum_{\alpha,i,j} V^L_{\alpha i} V^*_{\alpha N_j} \overline{N_j} \gamma^\mu P_L \nu_i Z_\mu ,$$

⇒ This $\mathcal{L}$ (+mass): "Minimal HNL"

⇒ From phenomenology $V_{\alpha N_j} \ll 1$

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Note:

⇒ This makes no reference to any model
⇒ Gives no explanation for mass of N
⇒ Does not specify N to be Majorana/Dirac
⇒ Does not give relation to m_ν

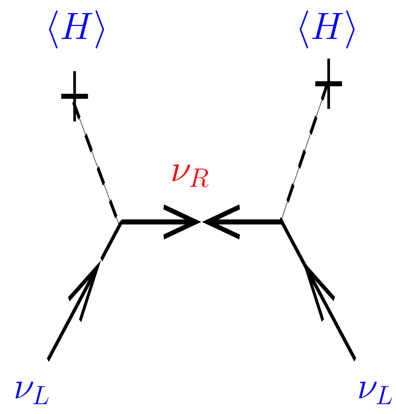
$\mathcal{II}$.

Minimal HNLs

Seesaw type-I - again

In one generation notation, in the basis (ν_L, ν_R^c):

$$M = \begin{pmatrix} 0 & m_D \\ m_D & M_M \end{pmatrix}$$



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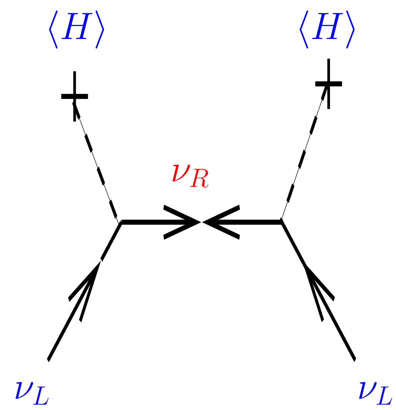

For $m_D \ll M_M$, eigenvalue and heavy-light mixing given by:

$$m_\nu \simeq -\frac{(m_D)^2}{M_M} = -\frac{(Y_\nu v)^2}{M_M}$$

$$(U)_{HL} \propto \frac{(Y_\nu v)}{M_M} \propto \sqrt{\frac{m_\nu}{M_M}}$$

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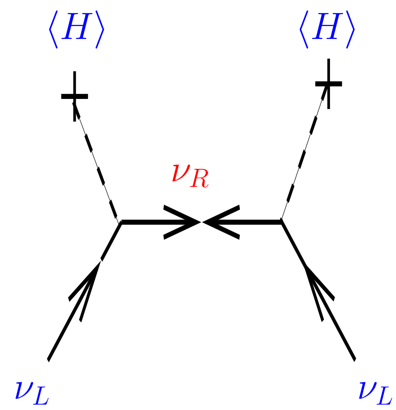

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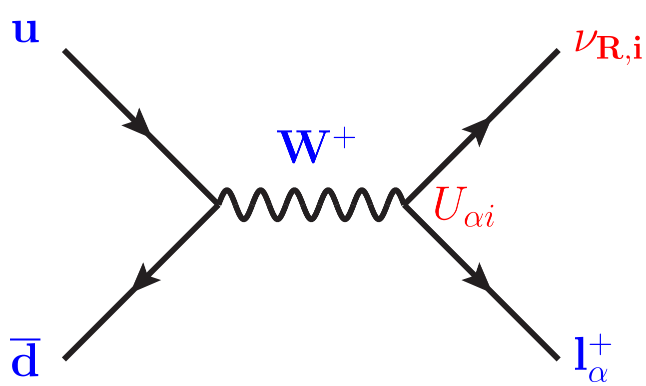
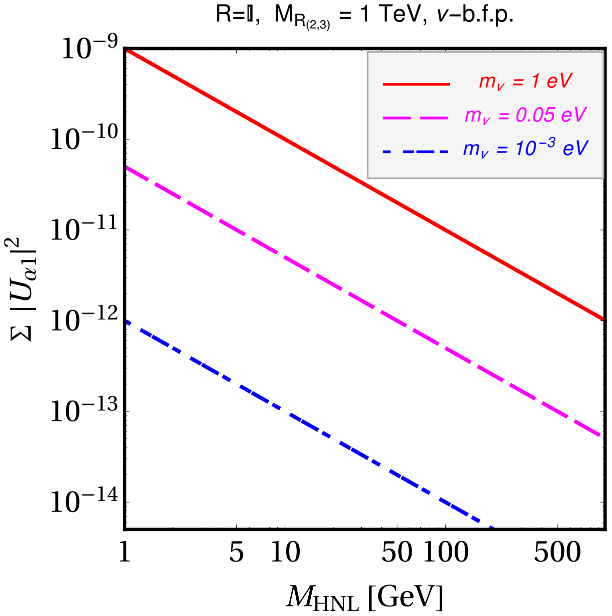


Decay length seesaw-I



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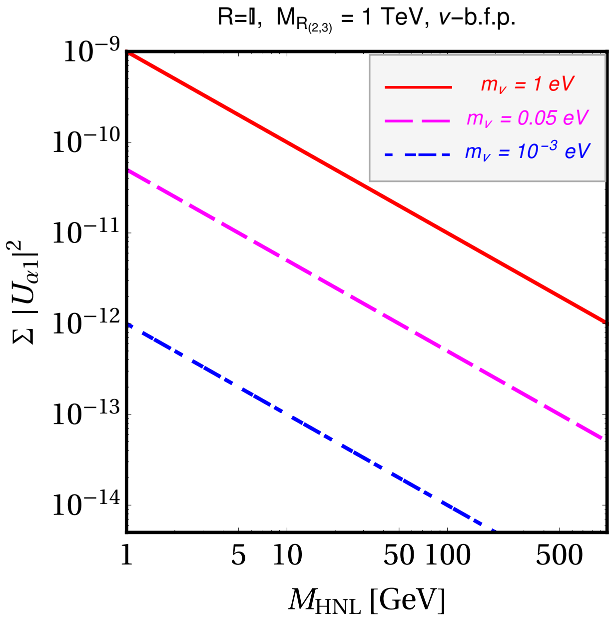

Neutrino decay width calculation from:

Atre et al.

JHEP 0905 (2009) 030 (arXiv:0901.3589)

and

Bondarenko et al.

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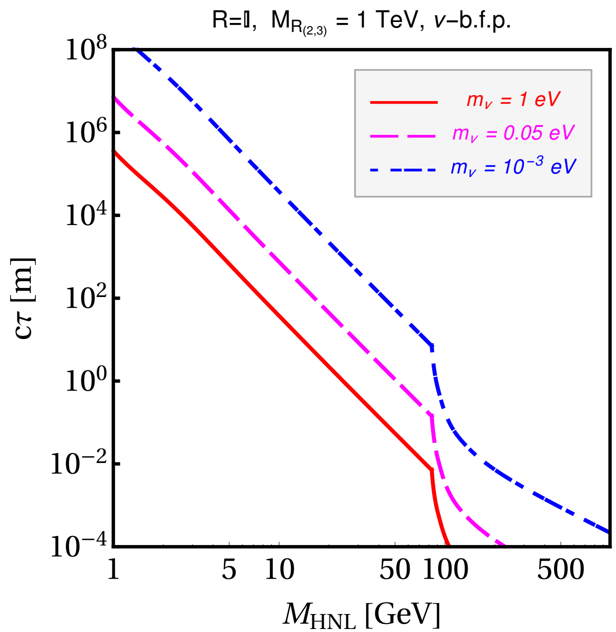

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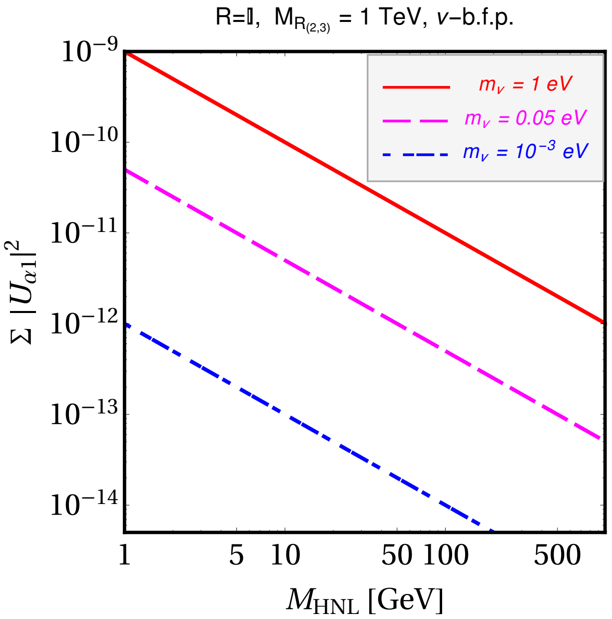
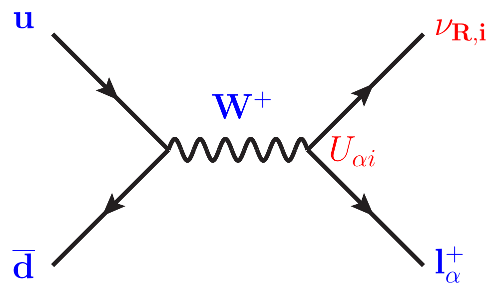


Note: Small mixing implies
small production
x-section @ LHC!



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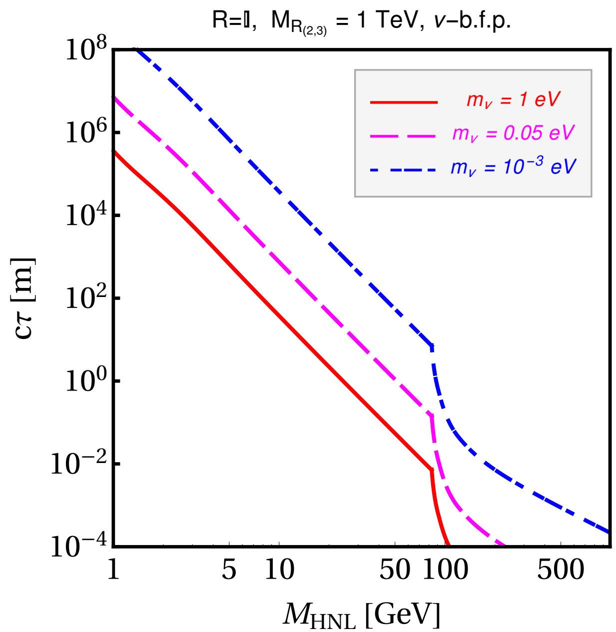


Inverse seesaw

Inverse seesaw, basis (ν_L, ν_R^c, S_R^c):

Mohapatra & Valle, 1986

$$M_\nu = \begin{pmatrix} 0 & m_D^T & 0 \\ m_D & 0 & M_R \\ 0 & M_R^T & \mu \end{pmatrix}$$

“Inverse” seesaw, because:

$$\hat{m}_\nu = V_L m_\nu V_L^T = V_L m_D^T.(M_R^T)^{-1}.\mu.(M_R)^{-1}.m_D V_L^T$$

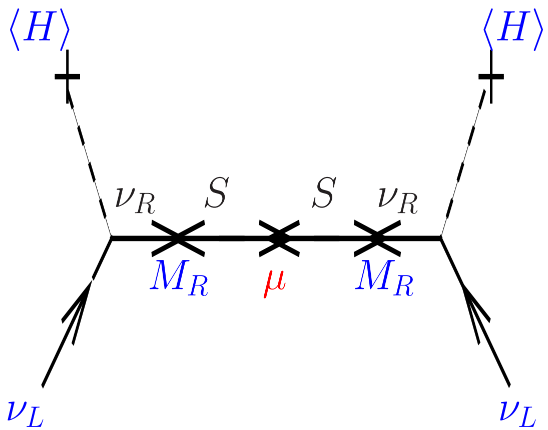
$$M_\pm = \left(\hat{M}_R + \left\{m_D.m_D^T, \hat{M}_R^{-1}\right\}\right) \pm \frac{1}{2}\mu_V$$

$\Rightarrow$ - 3 light eigenvalues: $\hat{m}_\nu$

$\Rightarrow$ - (3+3) heavy (nearly diagonal) eigenvalues : $\hat{M}_\pm = \hat{M}_R \pm \frac{1}{2}\mu_V$ Quasi-Dirac!

Smallness of m_ν due to nearly conserved L!

$c\tau$: Inverse seesaw



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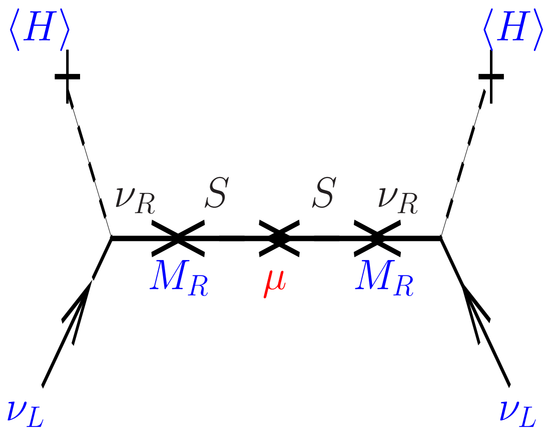

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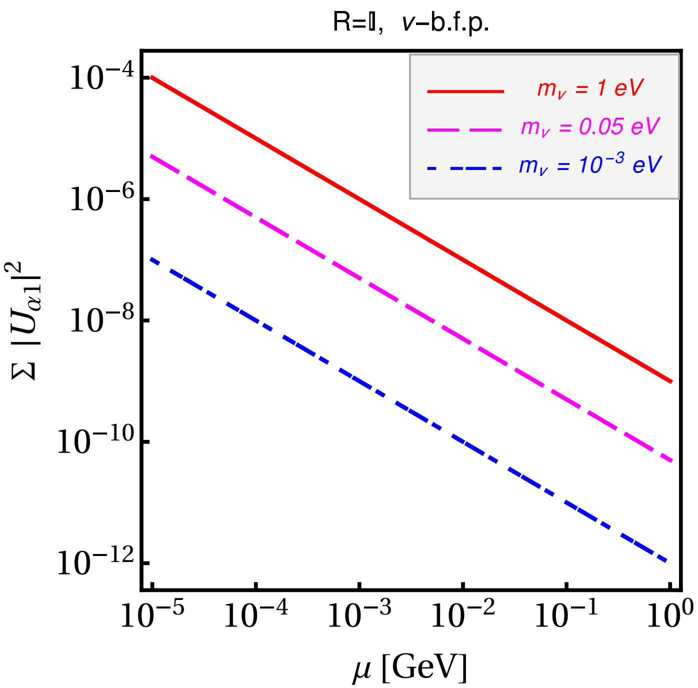
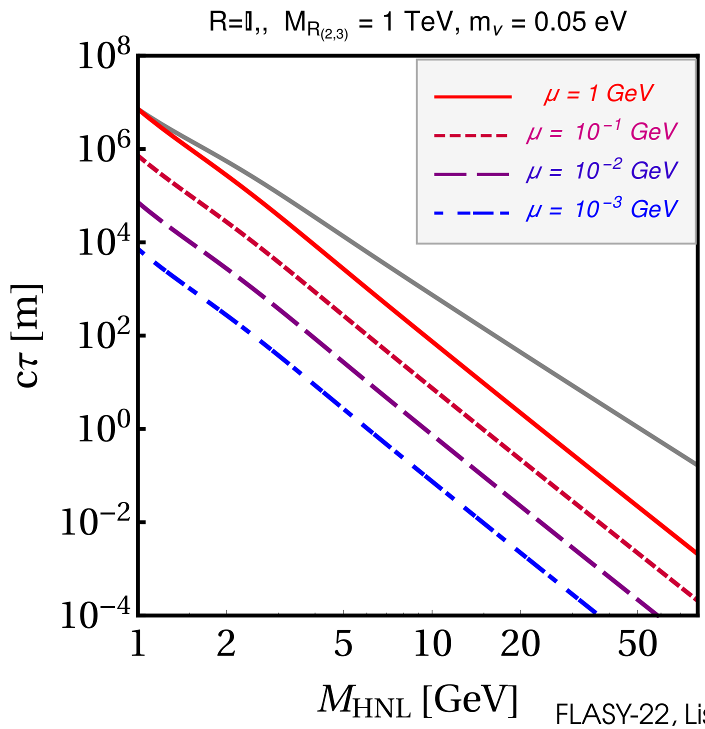
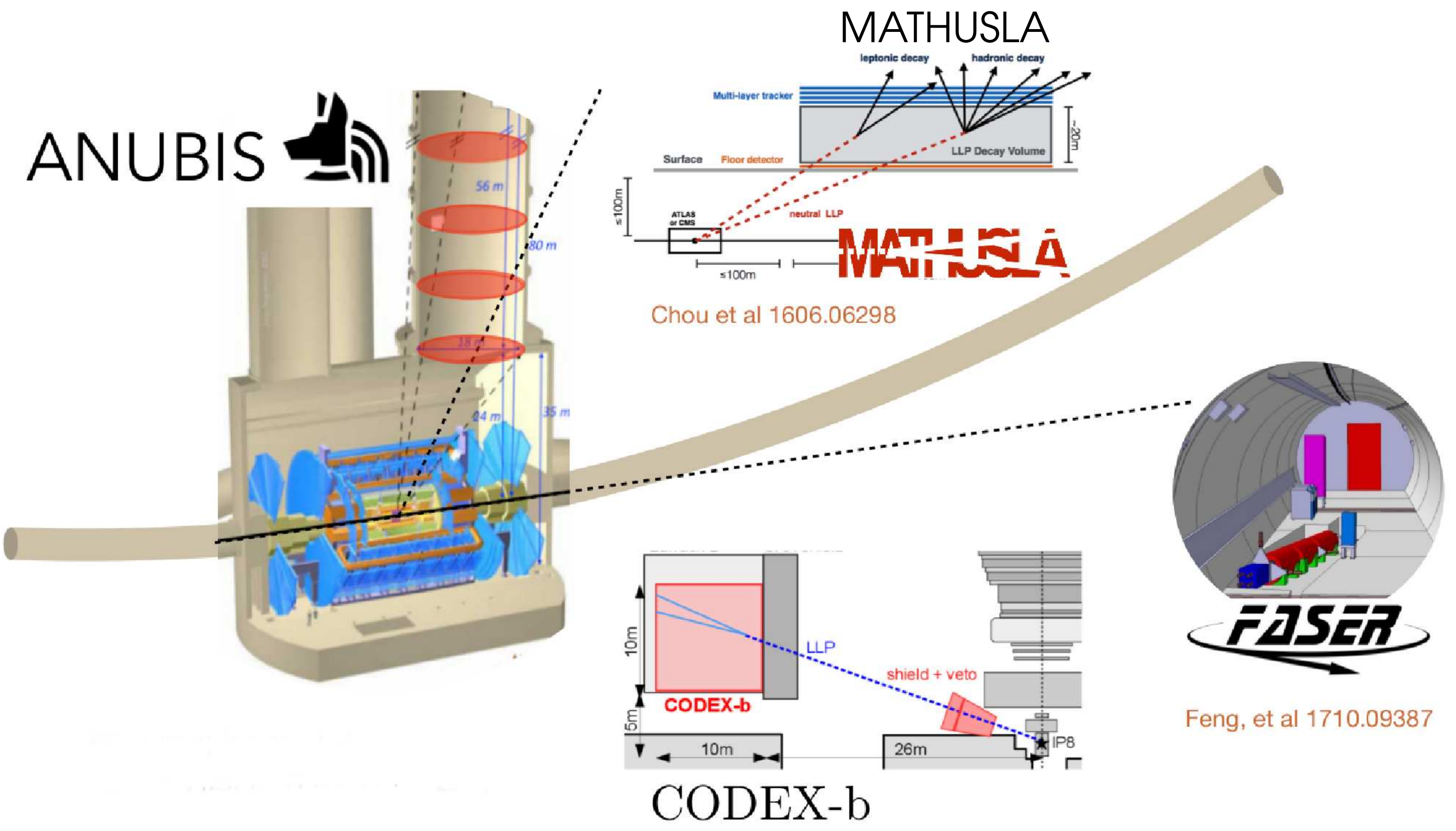




Where to look for LLPs?



Chou et al 1606.06298

Feng, et al 1710.09387

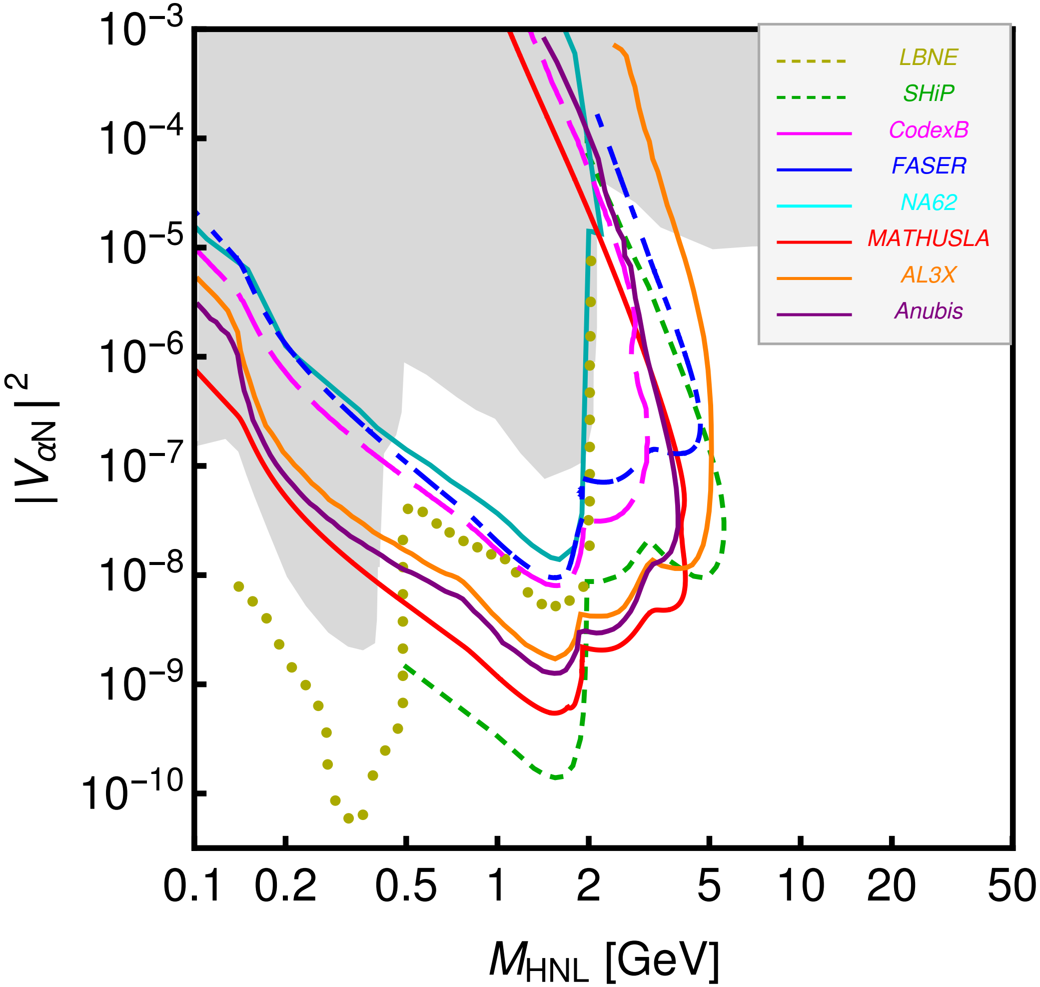
Gligorov et al 1708.09395

Bauer, OB, Lee, Ohm 1909.13022

Many proposals in the past few years. In addition:

+ Dune (ND), AL3X, SHiP, NA62, $\cdots$

Forecast searches



Plot from:
Helo et al.; 1803.02212
and
Hirsch & Wang 2001.04750

LBNE; 1307.7335

SHiP; 1504.04855, 1810.03636

CodexB; 1708.09395

FASER; 1708.09389

NA62; 1801.04207

MATHUSLA; 1806.07396

AL3X; 1810.03636

ANUBIS; 1909.13022

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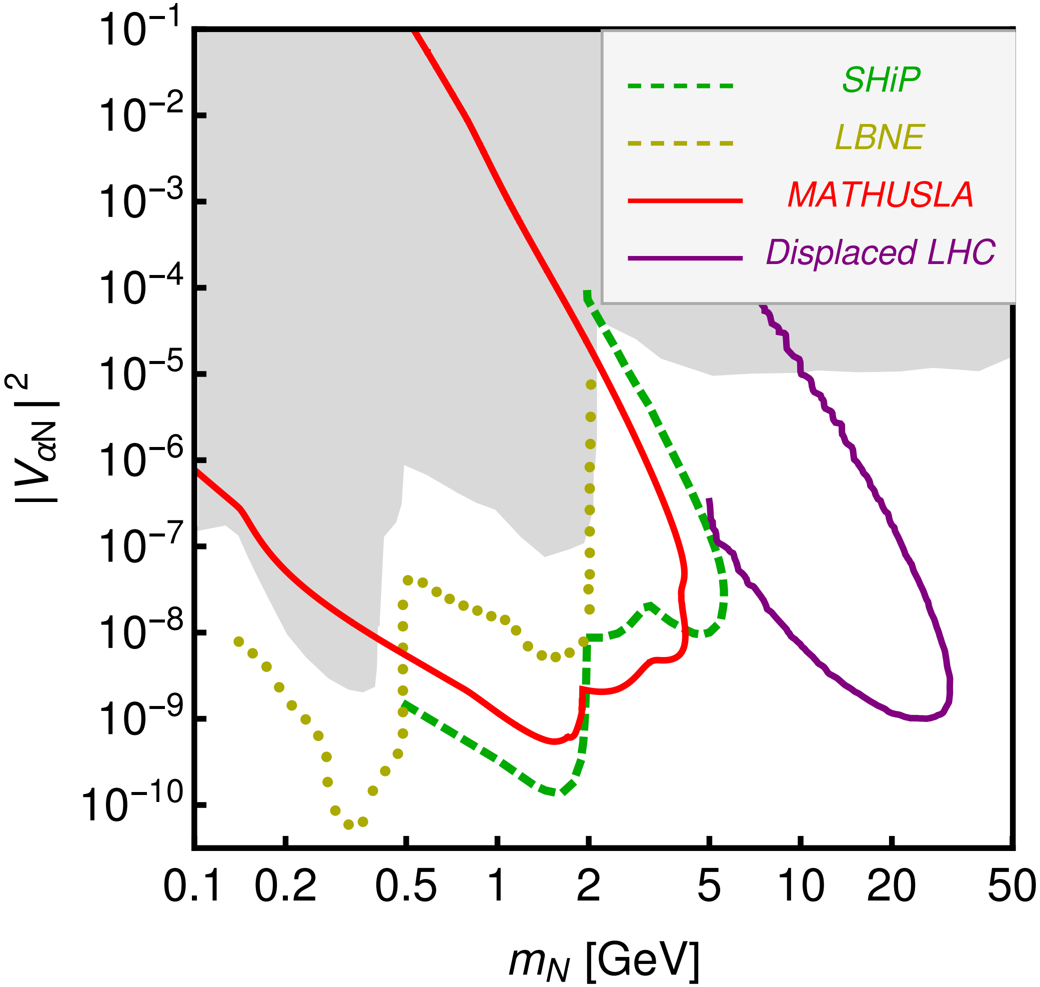

LHC displaced vertex search forecast for $\mathcal{L} = 3$/ab:

Cottin et al.; PRD98 (2018) 035012

Complementary to far detectors!

$\mathcal{III}$.

N_RSMEFT and LLPs

G. Cottin et al., JHEP09 (2021) 039 (arXiv:2105.13851)

R. Beltrán et al., JHEP01 (2022) 044 (arXiv:2110.15096)

Effective field theory

Basic idea of EFT:

New physics exists, but the mass scale involved is $\sqrt{s} \ll \Lambda$:

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_k \frac{C_k}{\Lambda^{d-4}} \mathcal{O}_k$$

⇒ "Integrating out" the heavy resonances "generates" a tower of operators

⇒ d is the dimension of $\mathcal{O}_k$

⇒ Λ is the energy scale of new physics

⇒ C_k the Wilson coefficient, free parameters in SMEFT

⇒ Since suppressed by higher powers of Λ larger d operators become quickly irrelevant phenomenologically

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$\Rightarrow$ At $d = 5$ in SMEFT only one operator: Weinberg operator with 6 complex parameters for 3 generations of leptons

$\Rightarrow$ At $d = 6$ SMEFT has already more than $\mathcal{O}(50)$ operators, with 2499 independent parameters (3 generations)

N_RSMEFT

Huge progress in construction of operator basis in recent years:

d=5: A. Aparici et al., PRD 80 (2009) 013010
d=6: F. del Águila et al., PLB 670 (2009) 399

d=7: Liao and Ma, PRD 96, 015012 (2017)

Up to d=9: Li et al, JHEP11(2021)003

Table: Number of parameters as function of d,
counting only new operators with at least one N_R

d	$n_N = 1$	$n_N = 3$
5	2	18
6	29	1614
7	80	4206
8	323	20400
9	1358	243944

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Want to check yourself?

R.M. Fonseca,
Comput.Phys.
Commun. 267
(2021) 108085

(Mathematica package!)

$d = 6$ operators in N_RSMEFT

List of $d = 6$ 4-fermion operators with one, two or 4 N_R:

Name	Structure	$n_N = 1$	$n_N = 3$
$\mathcal{O}_{dN}$	$\left(\overline{d_R}\gamma^\mu d_R\right)\left(\overline{N_R}\gamma_\mu N_R\right)$	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
$\mathcal{O}_{LN}$	$(\overline{L}\gamma^\mu L)\,(\overline{N_R}\gamma_\mu N_R)$	9	81
$\mathcal{O}_{NN}$	$(\overline{N_R}\gamma_\mu N_R)\,(\overline{N_R}\gamma_\mu N_R)$	1	36

pair N_R operators

four N_R operator

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

single N_R ops

N_RLEFT

Operators in N_RLEFT up to d=6:

Dipole	$\mathcal{O}_{N\gamma} = \overline{\nu_L}\sigma^{\mu\nu} N A_{\mu\nu}$	
RRRR	$\mathcal{O}_{NN}^{V,RR} = (\overline{N}\gamma_\mu N)(\overline{N}\gamma^\mu N)$	
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LLRR	$\mathcal{O}_{\nu N}^{V,LR} = (\overline{\nu_L}\gamma_\mu \nu_L)(\overline{N}\gamma^\mu N)$	$\mathcal{O}_{eN}^{V,LR} = (\overline{e_L}\gamma_\mu e_L)(\overline{N}\gamma^\mu N)$
	$\mathcal{O}_{uN}^{V,LR} = (\overline{u_L}\gamma_\mu u_L)(\overline{N}\gamma^\mu N)$	$\mathcal{O}_{dN}^{V,LR} = (\overline{d_L}\gamma_\mu d_L)(\overline{N}\gamma^\mu N)$
	$\mathcal{O}_{udeN}^{V,LR} = (\overline{u_L}\gamma_\mu d_L)(\overline{e_R}\gamma^\mu N)$	
LRLR	$\mathcal{O}_{NN}^{S,RR} = (\overline{\nu_L} N)(\overline{\nu_L} N)$	
	$\mathcal{O}_{eN}^{S,RR} = (\overline{e_L} e_R)(\overline{\nu_L} N)$	$\mathcal{O}_{eN}^{T,RR} = (\overline{e_L}\sigma_{\mu\nu} e_R)(\overline{\nu_L}\sigma^{\mu\nu} N)$
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M. Chala & A. Titov
JHEP 05 (2020) 139

Tree-level matching of
N_RSMEFT $\leftrightarrow$ N_RLEFT

N_RLEFT

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Recall:
For $E \simeq M$(mesons)
need to use N_RLEFT

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RRRR	$\mathcal{O}_{NN}^{V,RR} = (\overline{N}\gamma_\mu N)(\overline{N}\gamma^\mu N)$
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	$\mathcal{O}_{dN}^{V,RR} = (\overline{d_R}\gamma_\mu d_R)(\overline{N}\gamma^\mu N)$ $\mathcal{O}_{udeN}^{V,RR} = (\overline{u_R}\gamma_\mu d_R)(\overline{e_R}\gamma^\mu N)$
LLRR	$\mathcal{O}_{\nu N}^{V,LR} = (\overline{\nu_L}\gamma_\mu \nu_L)(\overline{N}\gamma^\mu N)$ $\mathcal{O}_{eN}^{V,LR} = (\overline{e_L}\gamma_\mu e_L)(\overline{N}\gamma^\mu N)$
	$\mathcal{O}_{uN}^{V,LR} = (\overline{u_L}\gamma_\mu u_L)(\overline{N}\gamma^\mu N)$ $\mathcal{O}_{dN}^{V,LR} = (\overline{d_L}\gamma_\mu d_L)(\overline{N}\gamma^\mu N)$
	$\mathcal{O}_{udeN}^{V,LR} = (\overline{u_L}\gamma_\mu d_L)(\overline{e_R}\gamma^\mu N)$
LRLR	$\mathcal{O}_{NN}^{S,RR} = (\overline{\nu_L}N)(\overline{\nu_L}N)$
	$\mathcal{O}_{eN}^{S,RR} = (\overline{e_L}e_R)(\overline{\nu_L}N)$ $\mathcal{O}_{eN}^{T,RR} = (\overline{e_L}\sigma_{\mu\nu}e_R)(\overline{\nu_L}\sigma^{\mu\nu}N)$
	$\mathcal{O}_{uN}^{S,RR} = (\overline{u_L}u_R)(\overline{\nu_L}N)$ $\mathcal{O}_{uN}^{T,RR} = (\overline{u_L}\sigma_{\mu\nu}u_R)(\overline{\nu_L}\sigma^{\mu\nu}N)$
	$\mathcal{O}_{dN}^{S,RR} = (\overline{d_L}d_R)(\overline{\nu_L}N)$ $\mathcal{O}_{dN}^{T,RR} = (\overline{d_L}\sigma_{\mu\nu}d_R)(\overline{\nu_L}\sigma^{\mu\nu}N)$
	$\mathcal{O}_{udeN}^{S,RR} = (\overline{u_L}d_R)(\overline{e_L}N)$ $\mathcal{O}_{udeN}^{T,RR} = (\overline{u_L}\sigma_{\mu\nu}d_R)(\overline{e_L}\sigma^{\mu\nu}N)$
RLLR	$\mathcal{O}_{eN}^{S,LR} = (\overline{e_R}e_L)(\overline{\nu_L}N)$ $\mathcal{O}_{uN}^{S,LR} = (\overline{u_R}u_L)(\overline{\nu_L}N)$
	$\mathcal{O}_{dN}^{S,LR} = (\overline{d_R}d_L)(\overline{\nu_L}N)$ $\mathcal{O}_{udeN}^{S,LR} = (\overline{u_R}d_L)(\overline{e_L}N)$

M. Chala & A. Titov
JHEP 05 (2020) 139

Tree-level matching of
N_RSMEFT $\leftrightarrow$ N_RLEFT

Recall:
For $E \simeq M$(mesons)
need to use N_RLEFT

See talk by:
R. Beltrán

$d = 6$ operators in N_RSMEFT

List of $d = 6$ 4-fermion operators with one or two N_R:

pair N_R operators

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

single N_R operators

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

$d = 6$ operators in N_RSMEFT

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$\mathcal{O}_{LN}$	$\left(\overline{L}\gamma^\mu L\right)\left(\overline{N_R}\gamma_\mu N_R\right)$	9	81

pair N_R operators

Lightest N_R can not decay via N_R pair operators!

$\Rightarrow$ N_R decay via mixing

Name	Structure (+ h.c.)	$n_N = 1$	$n_N = 3$
$\mathcal{O}_{duNe}$	$\left(\overline{d_R}\gamma^\mu u_R\right)\left(\overline{N_R}\gamma_\mu e_R\right)$	54	162
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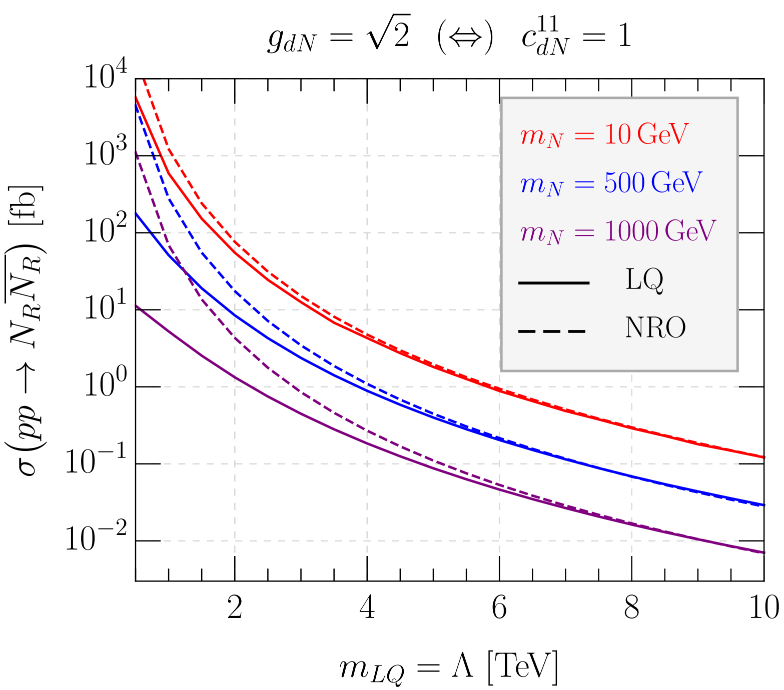
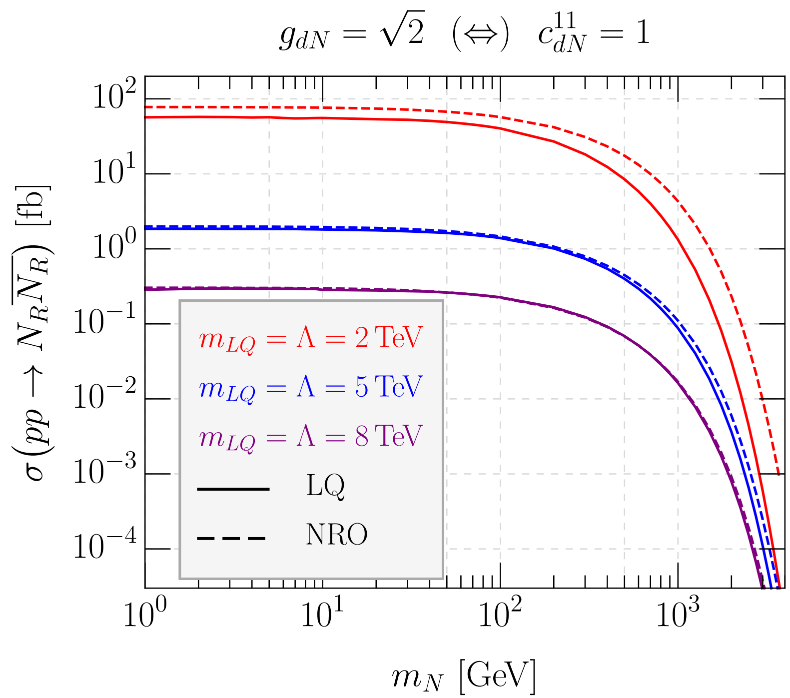
single N_R operators

$\Rightarrow$ N_R decay via operator (easily) dominates!

Cross sections

Example cross sections for pair N_R operator $\mathcal{O}_{dN}$:





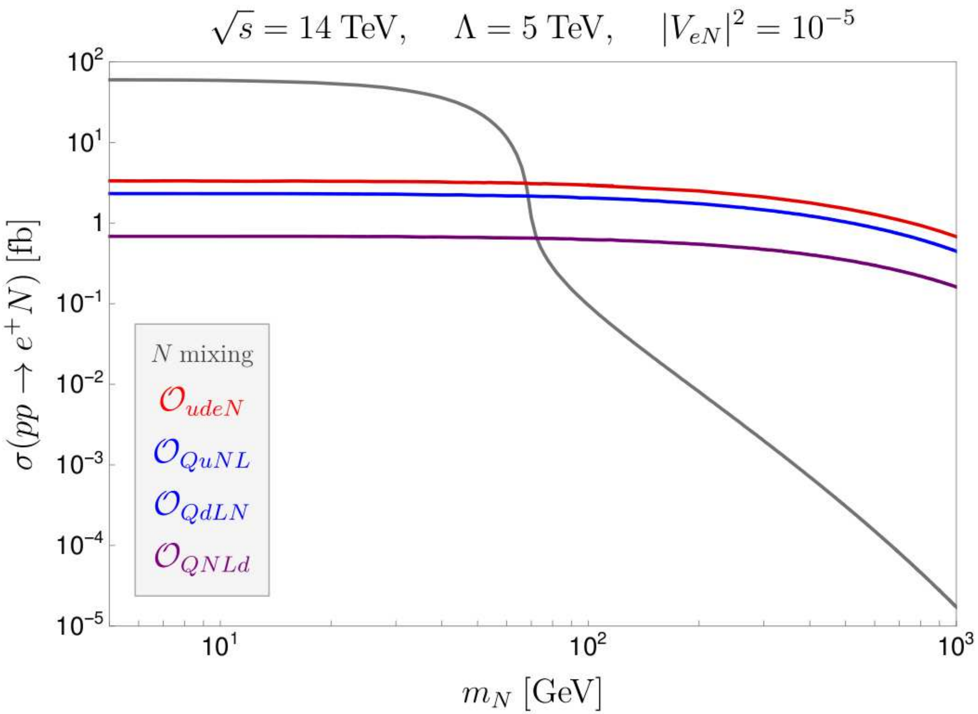
$\Rightarrow$ Total $\sigma(pp \to N_R\overline{N_R}) \propto \Lambda^{-4}$

$\Rightarrow$ m_N dependence determined only by kinematics, i.e. sizeable x-sections up to $m_N \sim 1$ TeV (and above)

$\Rightarrow$ “LQ” - full calculation with leptoquark model, “NRO” calculation in EFT limit

Cross sections

Example cross sections for single N_R operators:



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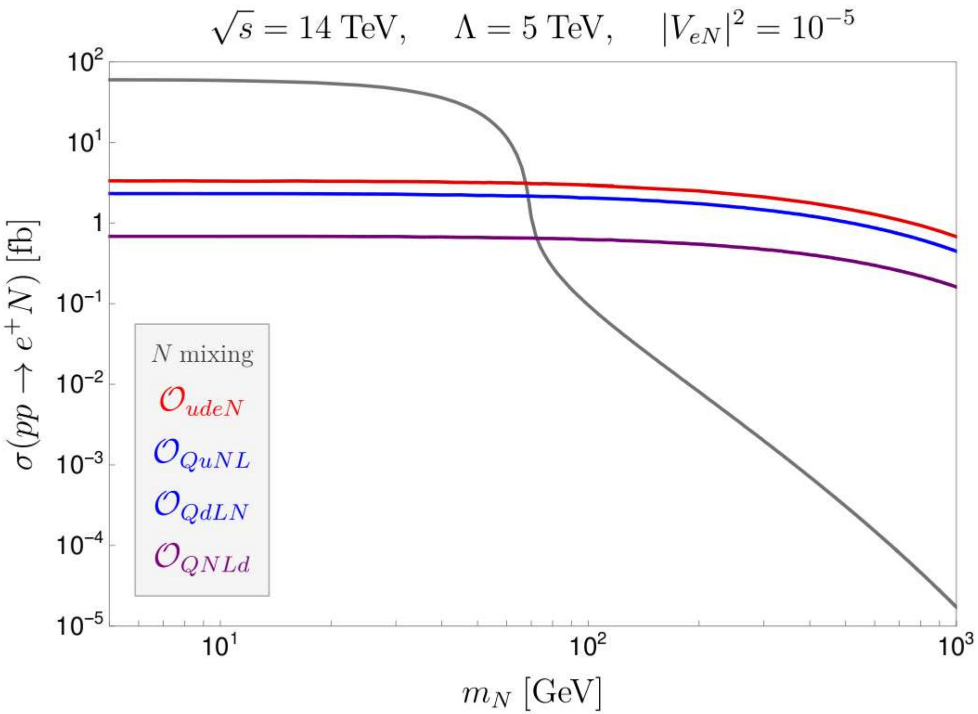
⇒ "N mixing" - cross section via charged current

Cross sections

Example cross sections for single N_R operators:



Recall:

$\sigma^{\mathrm{Mix}} \propto |V_{eN}|^2$

$\sigma^{\mathrm{Mix}}_{(|V_{eN}|^2=10^{-7})} < \sigma^{\mathcal{O}}_{(\Lambda=5\ \mathrm{TeV})}$

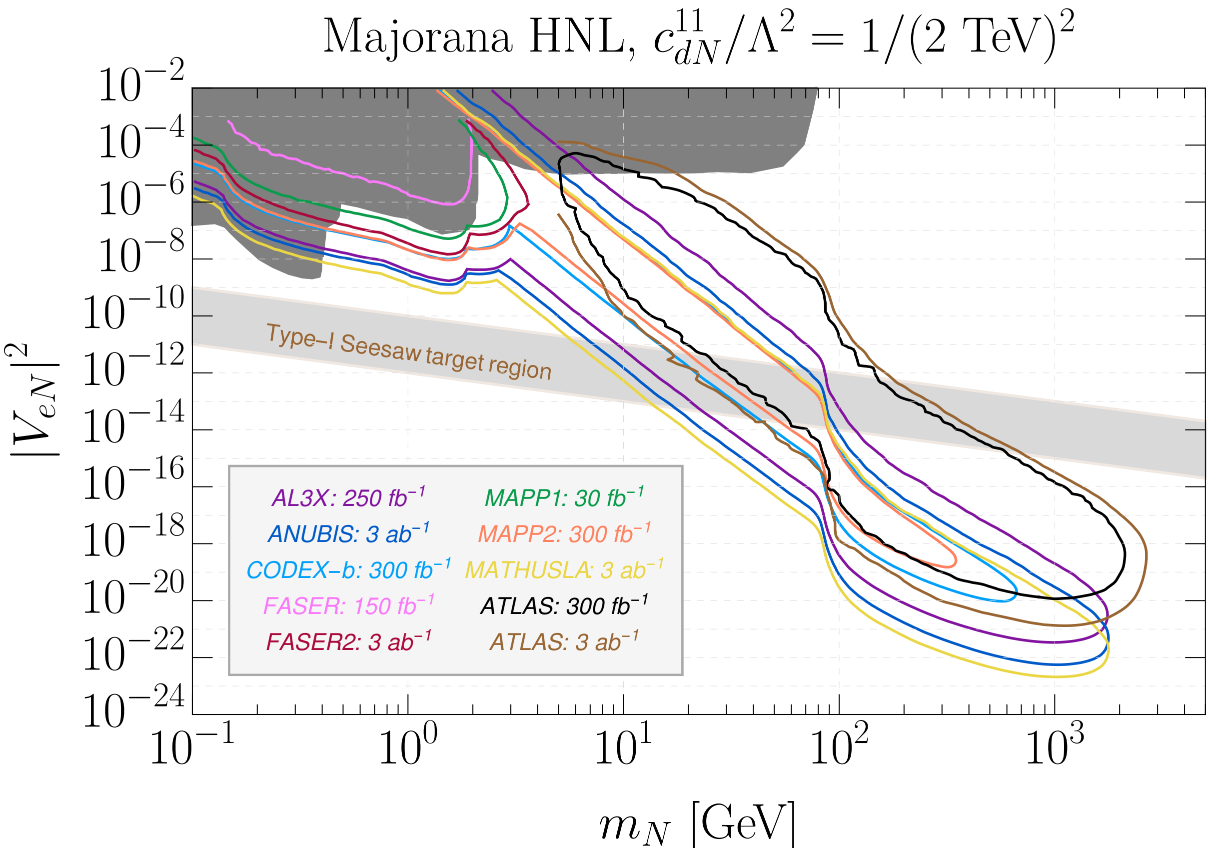
$\Rightarrow$ Total $\sigma(pp \to N_R \overline{N_R}) \propto \Lambda^{-4}$

$\Rightarrow$ m_N dependence determined only by kinematics, i.e. sizeable x-sections up to $m_N \sim 1$ TeV (and above)

$\Rightarrow$ "N mixing" - cross section via charged current

Forecast searches

Example reach for operator $\mathcal{O}_{dN}$



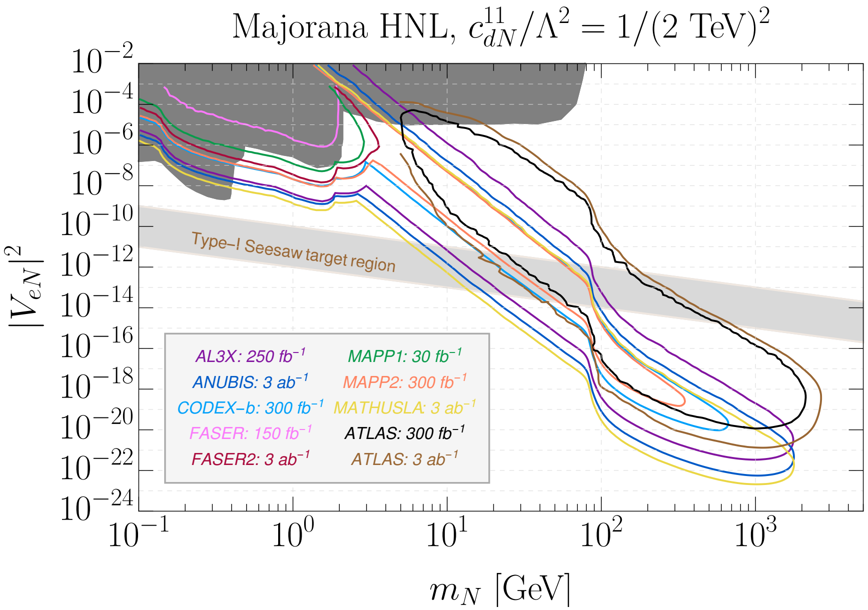
Note the axis!

$\Rightarrow$ Assumption: only N_R pair operators, decay via mixing

$\Rightarrow$ Mixing as small as (and smaller!) than naive seesaw expectation can be probed!

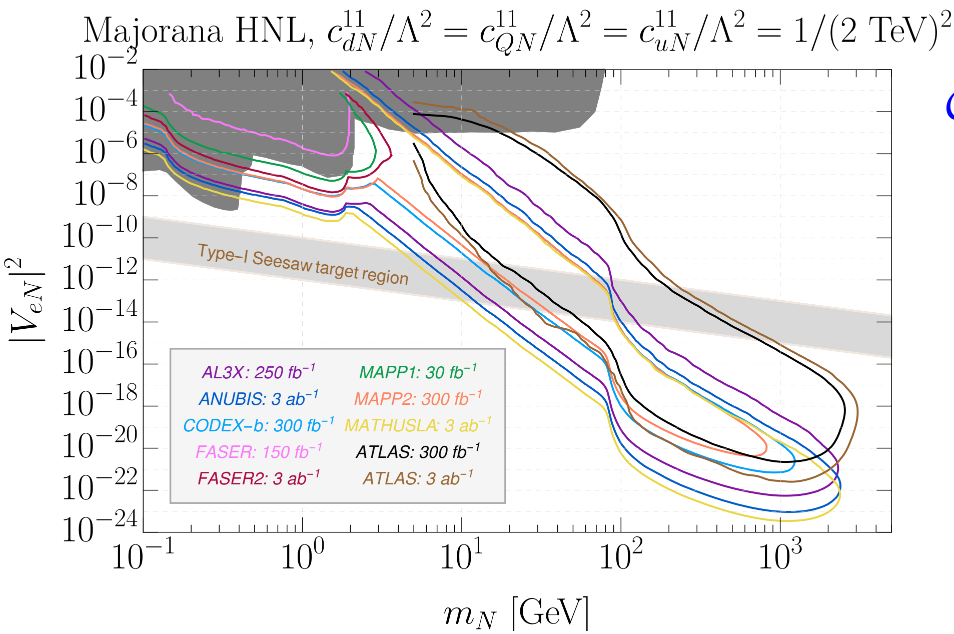
$\Rightarrow$ m_N up to TeV could be probed!

Forecast searches



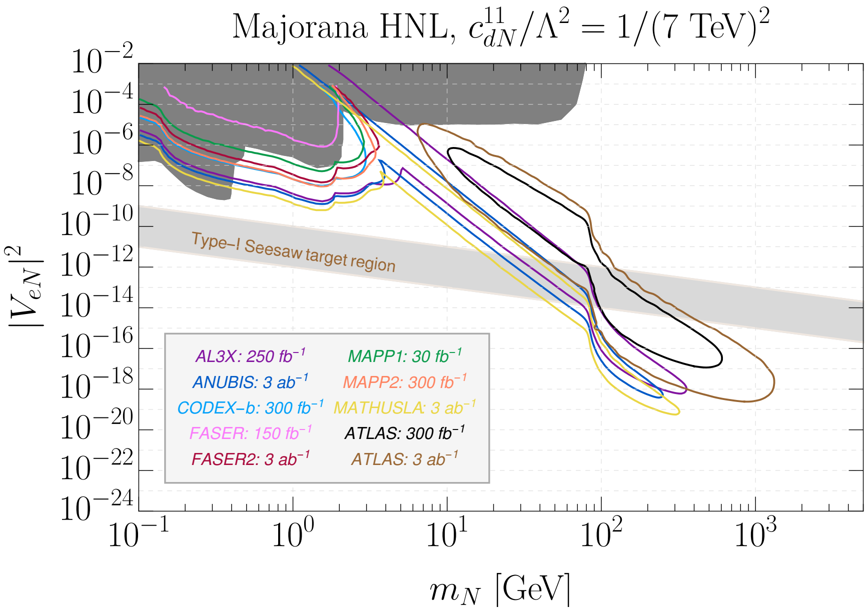
Only $\mathcal{O}_{dN}$

$\Lambda = 2$ TeV



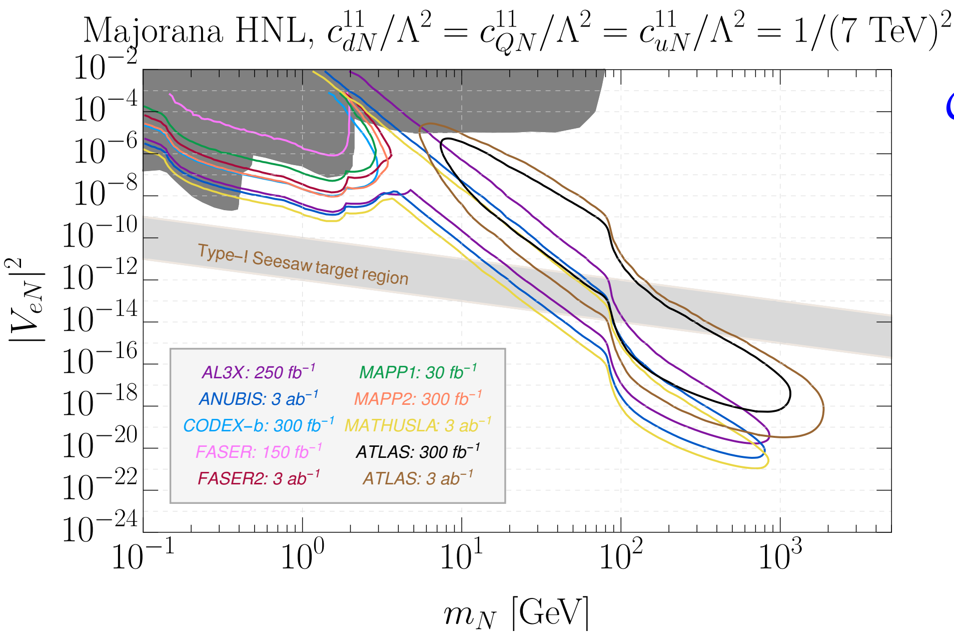
$\mathcal{O}_{dN} + \mathcal{O}_{uN} + \mathcal{O}_{QN}$

Forecast searches



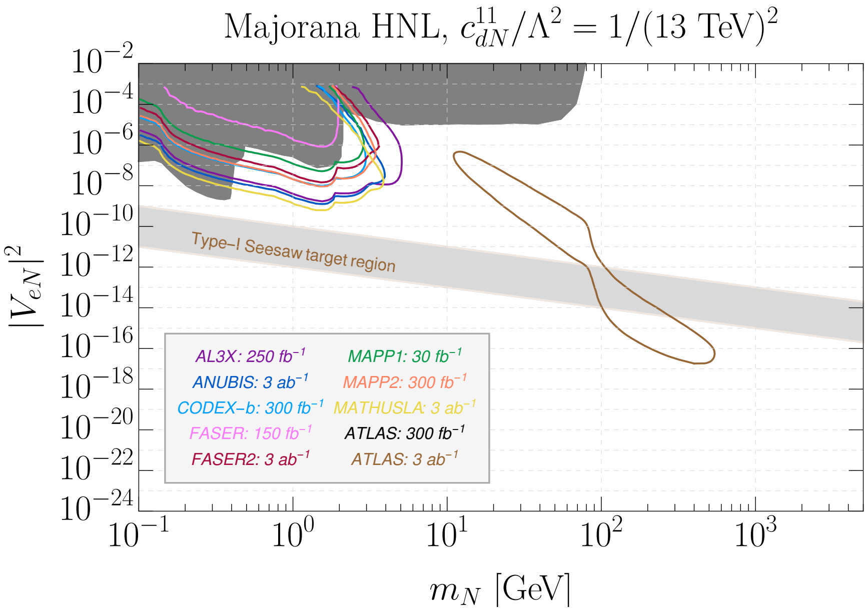
Only $\mathcal{O}_{dN}$

$\Lambda = 7$ TeV



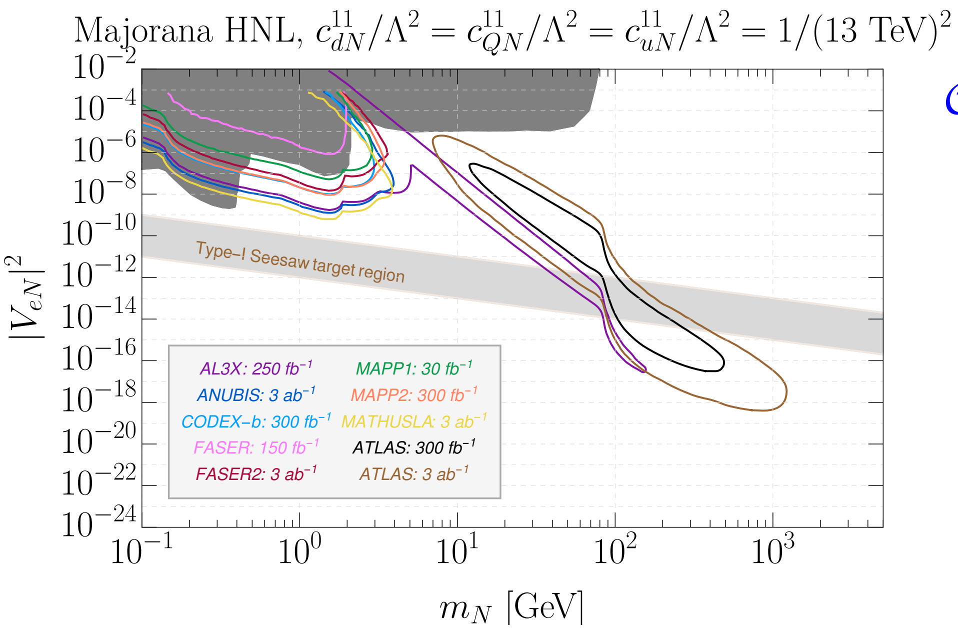
$\mathcal{O}_{dN} + \mathcal{O}_{uN} + \mathcal{O}_{QN}$

Forecast searches



Only $\mathcal{O}_{dN}$

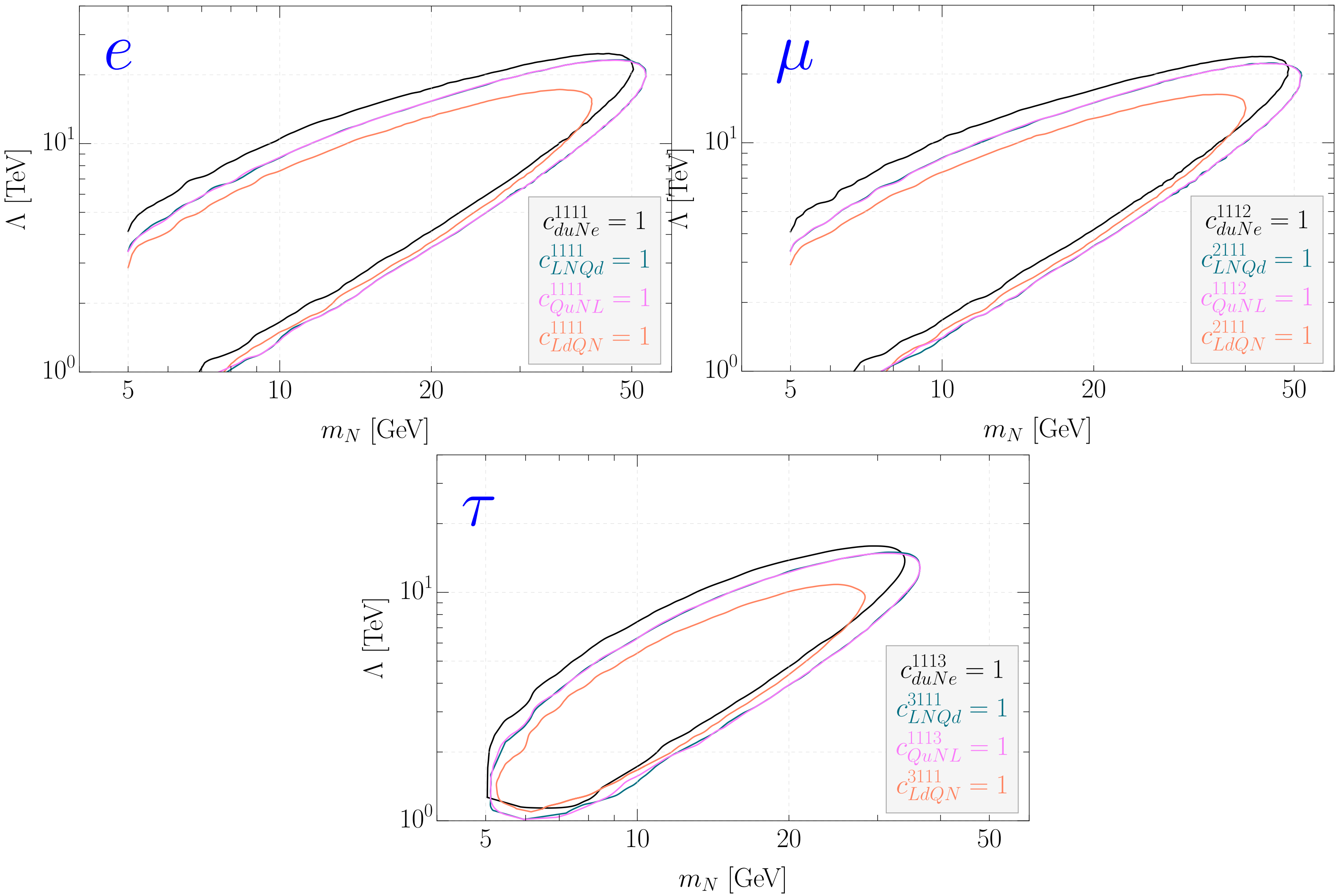
$\Lambda = 13$ TeV



$\mathcal{O}_{dN} + \mathcal{O}_{uN} + \mathcal{O}_{QN}$

Forecast searches

Sensitivity reach (ATLAS) for single N_R operators:



⇒ Λ up to (25-27) TeV could be probed!

⇒ m_N reach up to ~ 55 GeV

Conclusions

⇒ No definite sign of new physics at the LHC (so far!)

⇒ Many new experimental proposals for LLP searches

⇒ HNLs from neutrino mass models automatically long-lived

⇒ Effective field theory has become very popular: SMEFT

⇒ N_RSMEFT includes fermionic singlets

⇒ If N_RSMEFT operators exist with $\Lambda < (10 - 20)$ TeV very promising!

Backup

Beyond minimal seesaw

Lagrangian of the minimal seesaw model:

$$\mathcal{L}^{\mathrm{Type-I}} = \mathcal{L}^{SM} + Y_\nu \overline{L}\tilde{H}N_R + M_M \overline{N_R^c} N_R + \mathrm{h.c.}$$

$\Rightarrow$ N_R interacts with SM particles only via mixing

Beyond minimal seesaw

Lagrangian of the minimal seesaw model:

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$\Rightarrow$ N_R interacts with SM particles only via mixing

$\Rightarrow$ Many BSM models contain new particles

A (particularly) simple example: Type-I seesaw + Leptoquark

$$\mathcal{L}^{\mathrm{BSM}} = \mathcal{L}^{\mathrm{Type-I}} + g \overline{u_R} N_R^c S_{\mathrm{LQ}} + \mathrm{h.c.} + m_{\mathrm{LQ}}^2 |S_{\mathrm{LQ}}|^2$$

Beyond minimal seesaw

Lagrangian of the minimal seesaw model:

$$\mathcal{L}^{\rm Type-I} = \mathcal{L}^{SM} + Y_\nu \overline{L} \tilde{H} N_R + M_M \overline{N_R^c} N_R + \text{h.c.}$$

$\Rightarrow$ N_R interacts with SM particles only via mixing

$\Rightarrow$ Many BSM models contain new particles

A (particularly) simple example: Type-I seesaw + Leptoquark

$$\mathcal{L}^{\rm BSM} = \mathcal{L}^{\rm Type-I} + g \overline{u_R} N_R^c S_{\rm LQ} + \text{h.c.} + m_{\rm LQ}^2 |S_{\rm LQ}|^2$$

If $S_{\rm LQ}$ is too heavy to be produced at the LHC, "integrate out" $S_{\rm LQ}$:

$$\begin{aligned} \mathcal{L}^{\rm BSM} &= \mathcal{L}^{\rm Type-I} + \frac{g^2}{m_{LQ}^2} (\overline{u_R} N_R^c)(\overline{N_R^c} u_R) + \cdots \\ &= \mathcal{L}^{\rm Type-I} + \frac{C}{\Lambda^2} (\overline{u_R} \gamma^\mu u_R)(\overline{N_R} \gamma_\mu N_R) + \cdots \end{aligned}$$

Fierz transformation

$\Rightarrow$ $\mathcal{O}_{uN}$, a $d = 6$ four-fermion operator is generated

$d = 5$ operators in N_RSMEFT

Recall, at $d = 5$ in SMEFT only one operator: Weinberg operator with 6 complex parameters for 3 generations of leptons:

$$\mathcal{O}_W = \frac{c_{\alpha\beta}}{\Lambda}(\overline{L^c_\alpha} H)(H L_\beta)$$

$\Rightarrow$ After EWSB: Majorana neutrino mass!

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Adding $n = 3$ neutral singlets, N_R allows to add two more operators with 12 and 6 parameters:

$$\mathcal{O}_{NH} \propto (H^\dagger H)(\overline{N^c_R} N_R) + \text{h.c.}$$

$$\mathcal{O}_{NB} \propto (\overline{N^c_R} \sigma^{\mu\nu} N_R) B_{\mu\nu} + \text{h.c.}$$

$\Rightarrow$ $\mathcal{O}_W$, $\mathcal{O}_{NH}$ and $\mathcal{O}_{NB}$ violate lepton number by $\Delta L = 2$

$d = 6$ operators in N_RSMEFT

Name	$\Psi^2 DH^2$	$n_N = 1$	$n_N = 3$
$\mathcal{O}_{NHD_\mu}$	$(\overline{N_R}\gamma^\mu N_R)\,(H^\dagger i D_\mu H)$	1	18
$\mathcal{O}_{NeHD_\mu}$	$(\overline{N_R}\gamma^\mu e_R)\,(\tilde{H}^\dagger i D_\mu H)$ + h.c.	2	18

Name	$\Psi^2 HX$	$n_N = 1$	$n_N = 3$
$\mathcal{O}_{LNHB}$	$(\overline{L}\sigma^{\mu\nu} N_R)\,\tilde{H} B_{\mu\nu}$ + h.c.	2	18
$\mathcal{O}_{LNHW}$	$(\overline{L}\sigma^{\mu\nu} N_R)\,\tilde{H}(\vec{\sigma} W_{\mu\nu})$ +h.c.	2	18

Name	$\Psi^2 H^3$	$n_N = 1$	$n_N = 3$
$\mathcal{O}_{LNH}$	$(\overline{L} N_R)\,\tilde{H}(H^\dagger H)$ +h.c.	2	18

Operators involving Higgses

Name	$\Delta B = \Delta L = 1$	$n_N = 1$	$n_N = 3$
$\mathcal{O}_{QQdN}$	$\epsilon_{ij}\epsilon_{pqr}(Q_i^p C Q_j^q)(d_R^r C N_R)$ + h.c.	2	108
$\mathcal{O}_{uddN}$	$\epsilon_{pqr}(u_R^p C d_R^q)(d_R^r C N_R)$ + h.c.	2	162

Name	$\Delta L = 4$	$n_N = 1$	$n_N = 3$
$\mathcal{O}_{NNNN}$	$(\overline{N_R^C} N_R)(\overline{N_R^C} N_R)$ + h.c.	0	12

Operators violating B or L

$\not{B}$ in N_RSMEFT

Proton decay as test?

Modes (p)	$\pi^+ + \not{E}$	$\pi^0 e^+$	$K^+ + \not{E}$
Current (yrs)	$3.9 \cdot 10^{32}$	$1.6 \cdot 10^{34}$	$5.9 \cdot 10^{33}$
Future (yrs)		$1.2 \cdot 10^{35}$	$> 3 \cdot 10^{34}$
$\mathcal{O}_{(du)(QL)}$	✓	✓	✓
$\mathcal{O}_{(QQ)(ue)}$	—	✓	—
$\mathcal{O}_{(QQ)(QL)}$	✓	✓	✓
$\mathcal{O}_{(Q\vec{\tau}Q)(Q\vec{\tau}L)}$	—	—	✓
$\mathcal{O}_{(du)(ue)}$	—	✓	—
$\mathcal{O}_{QQdN}$	✓	—	✓
$\mathcal{O}_{uddN}$	✓	—	✓

Hirsch, Helo & Ota
JHEP06 (2018) 047

$\not{B}$ in N_RSMEFT

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$\mathcal{O}_{(du)(ue)}$	—	✓	—
$\mathcal{O}_{QQdN}$	✓	—	✓
$\mathcal{O}_{uddN}$	✓	—	✓

Hirsch, Helo & Ota
JHEP06 (2018) 047

Only $\mathcal{O}_{QQdN}$ & $\mathcal{O}_{uddN}$ show pattern $(\checkmark, -, \checkmark)$

Very strong limits (for $m_N \ll 1$ GeV)
$\Lambda \gtrsim 10^{(14-15)}$ GeV

$\not{B}$ in N_RSMEFT

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$\mathcal{O}_{(du)(ue)}$	—	✓	—
$\mathcal{O}_{QQdN}$	✓	—	✓
$\mathcal{O}_{uddN}$	✓	—	✓

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JHEP06 (2018) 047

Only $\mathcal{O}_{QQdN}$ & $\mathcal{O}_{uddN}$ show pattern $(\checkmark, -, \checkmark)$

Very strong limits (for $m_N \ll 1$ GeV)
$\Lambda \gtrsim 10^{(14-15)}$ GeV

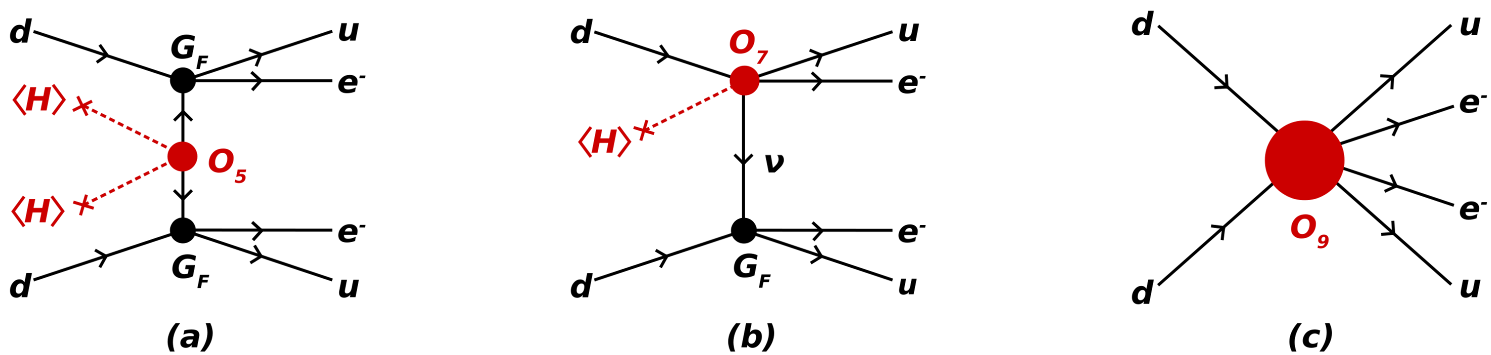
Finally, four LNV operator:
$\mathcal{O}_{NNNN} = (\overline{N_R^C} N_R)(\overline{N_R^C} N_R)$??

No paper?

$0\nu\beta\beta$ decay

Päs et al.
PLBB453 (1999) 194
PLB498 (2001) 35

Amplitude for $(Z, A) \rightarrow (Z \pm 2, A) + e^{\mp}e^{\mp}$ can be divided into:



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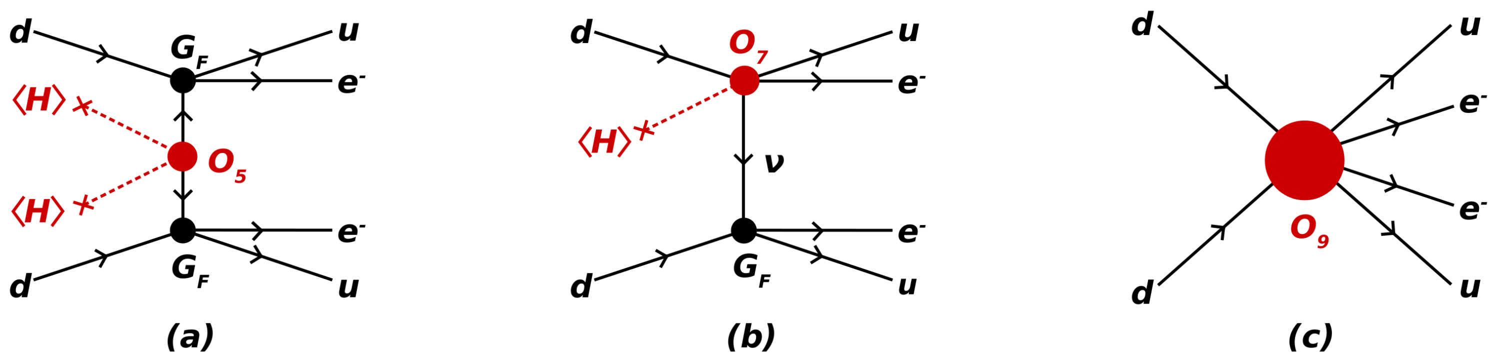

$\Rightarrow$ In N_RLEFT long range contribution $d = 6$ operator, but in N_RSMEFT due to $d = 7$ operator(s)

Helo, Hirsch & Ota
JHEP06 (2016) 006

$\Lambda \gtrsim g_{eff}(17 - 180)$ TeV (depending on operator)

+