Heavy neutral leptons and EFT

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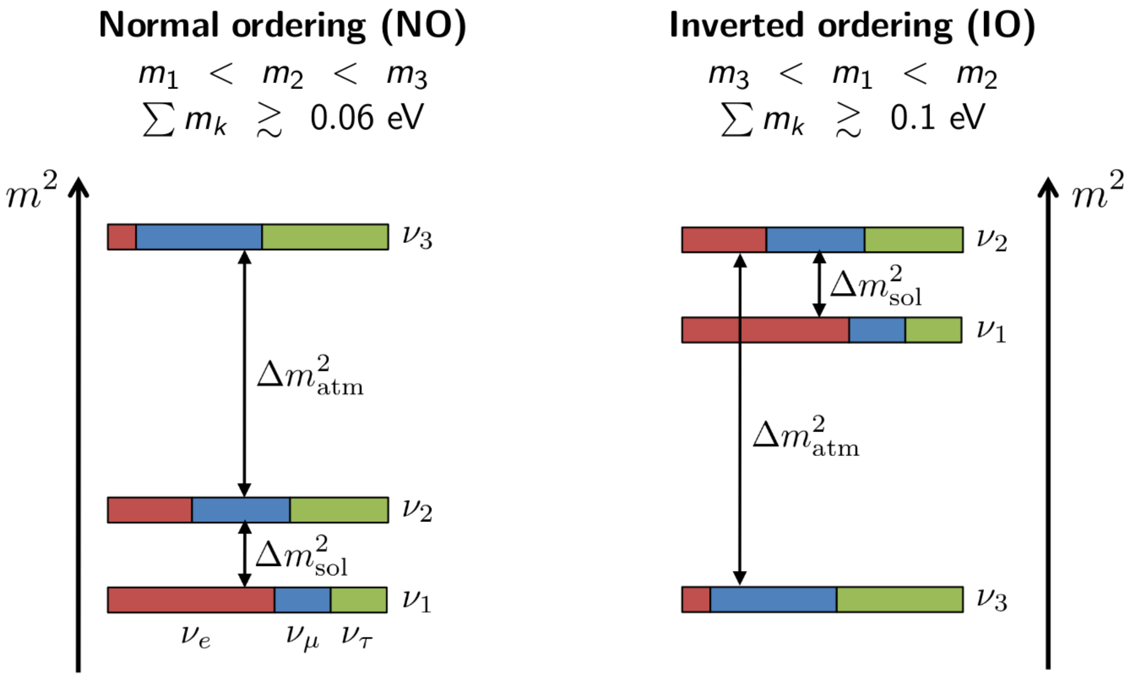
http://www.astroparticles.es/

Contents

$\mathcal{I}.$

Introduction

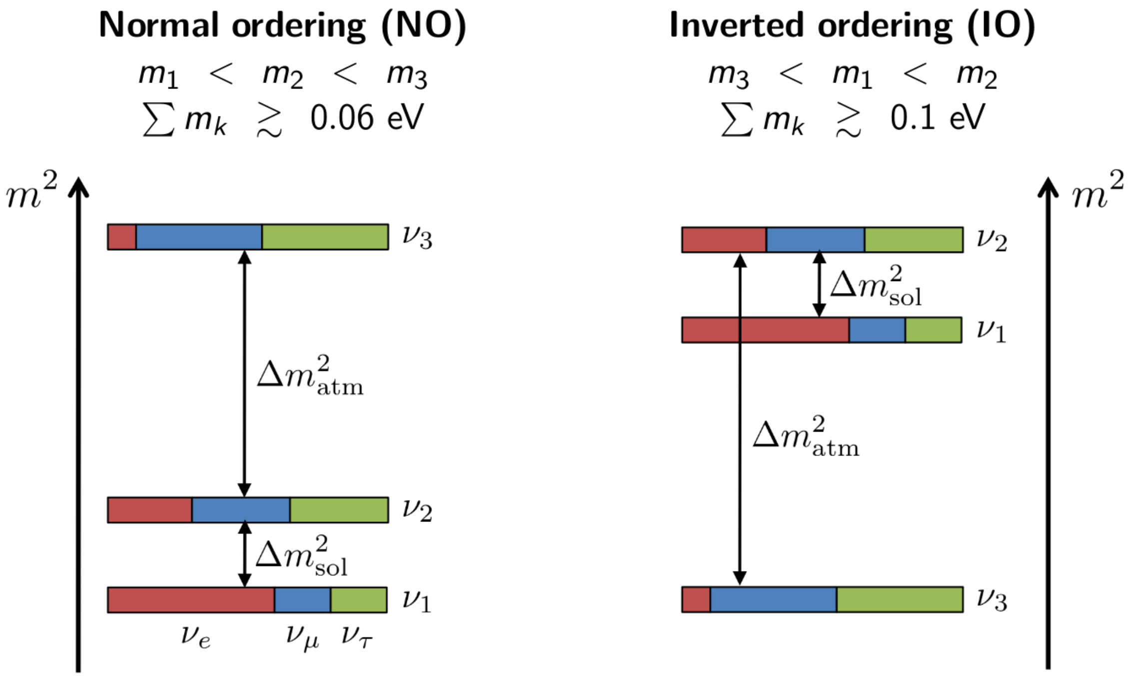
Neutrino oscillations



More than
20 years after
Super-K, 1998

2 Δm^2 and
all 3 θ_{ij}
measured with
high precision,
but ...

Neutrino oscillations



More than
20 years after
Super-K, 1998

2 Δm^2 and
all 3 θ_{ij}
measured with
high precision,
but ...

BUT, still unknown:

Absolute mass scale?	Upper limit: ~ 1 eV (KATRIN), $\sim (0.1 - 0.2)$ eV ($0\nu\beta\beta$)
Which hierarchy?	$\sim 2\ \sigma$ preference for NO
CP phase?	Indication for $\delta \sim (3/2)\pi$? - But tension T2K/NOνA
Majorana OR Dirac?	Unknown

Theoretical expectations

Majorana Neutrino mass

Many possibilities exist!
See talk by K. Babu

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

Weinberg, 1979

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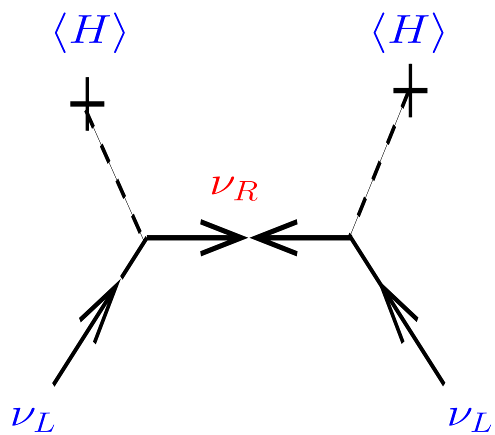
Smallness of neutrino mass
can be "explained" by:

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



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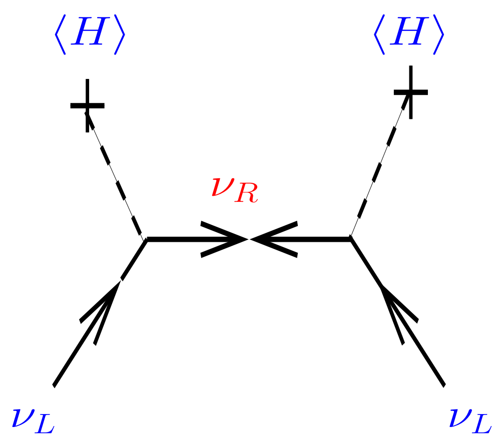

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OR:

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

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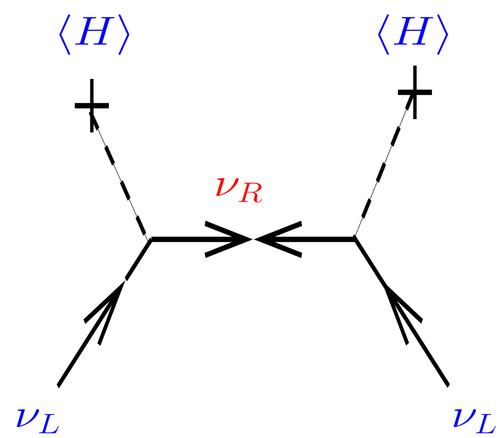

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"Heavy neutral lepton"
A "nearly" singlet fermion

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

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

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

$\Rightarrow$ Supposedly $V_{\alpha N_j} \ll 1$

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

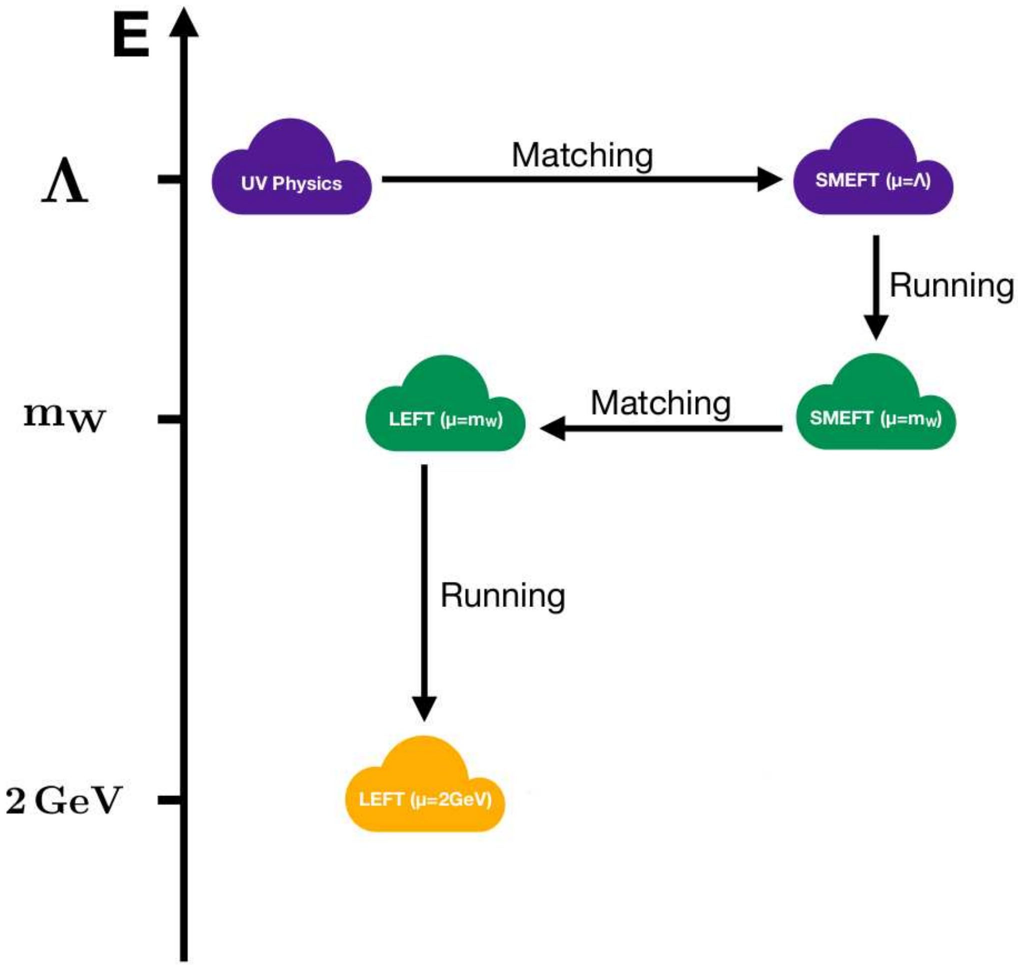
⇒ Supposedly $V_{\alpha N_j} \ll 1$

Note:

⇒ this makes no reference to any model
⇒ gives no explanation for mass of N
⇒ Does not specify N to be Majorana/Dirac

Effective field theory

See talk by C. Burgess



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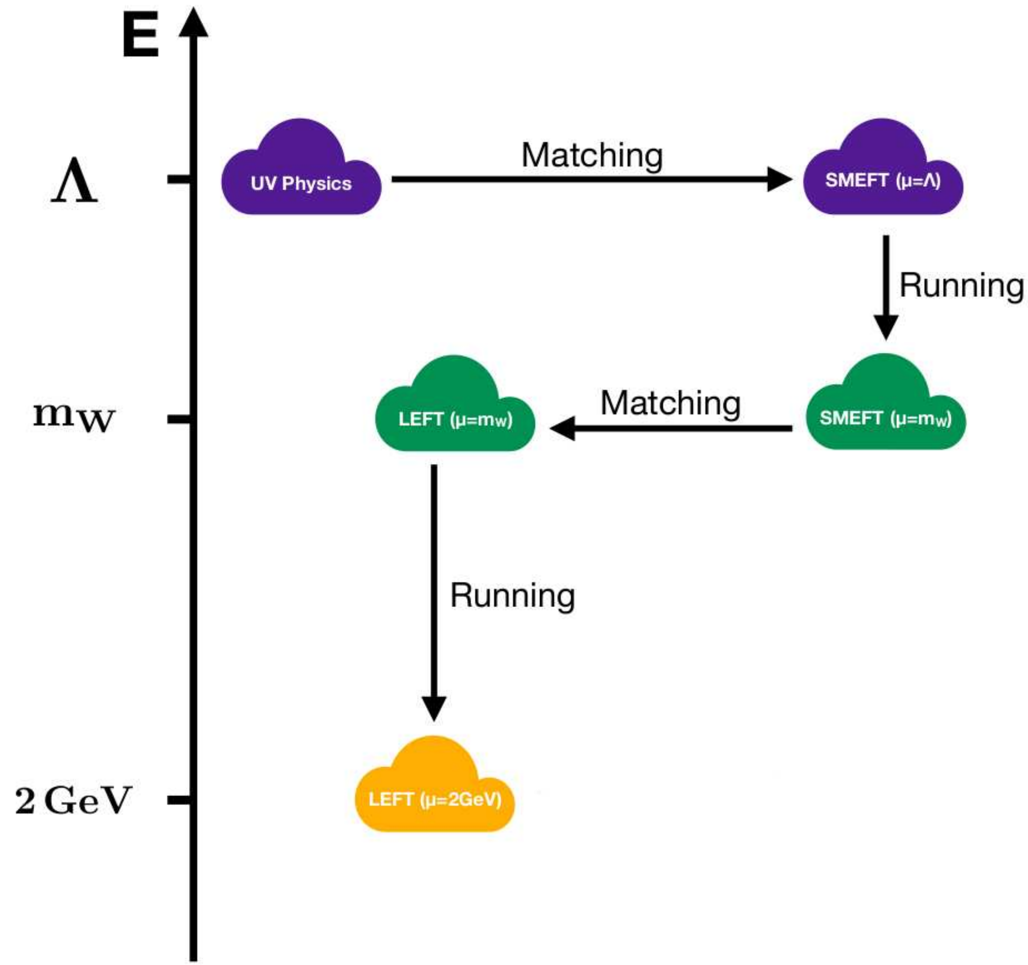

SMEFT:

Standard model symmetries

and standard model fields:

$$L_i\,,\,e_{R_i}\,,\,Q_i\,,\,u_{R_i}\,,\,d_{R_i}$$

$$+\;H\,,\,B_{\mu\nu}\,,\,W_{\mu\nu}\,,\,G_{\mu\nu}$$

Effective field theory

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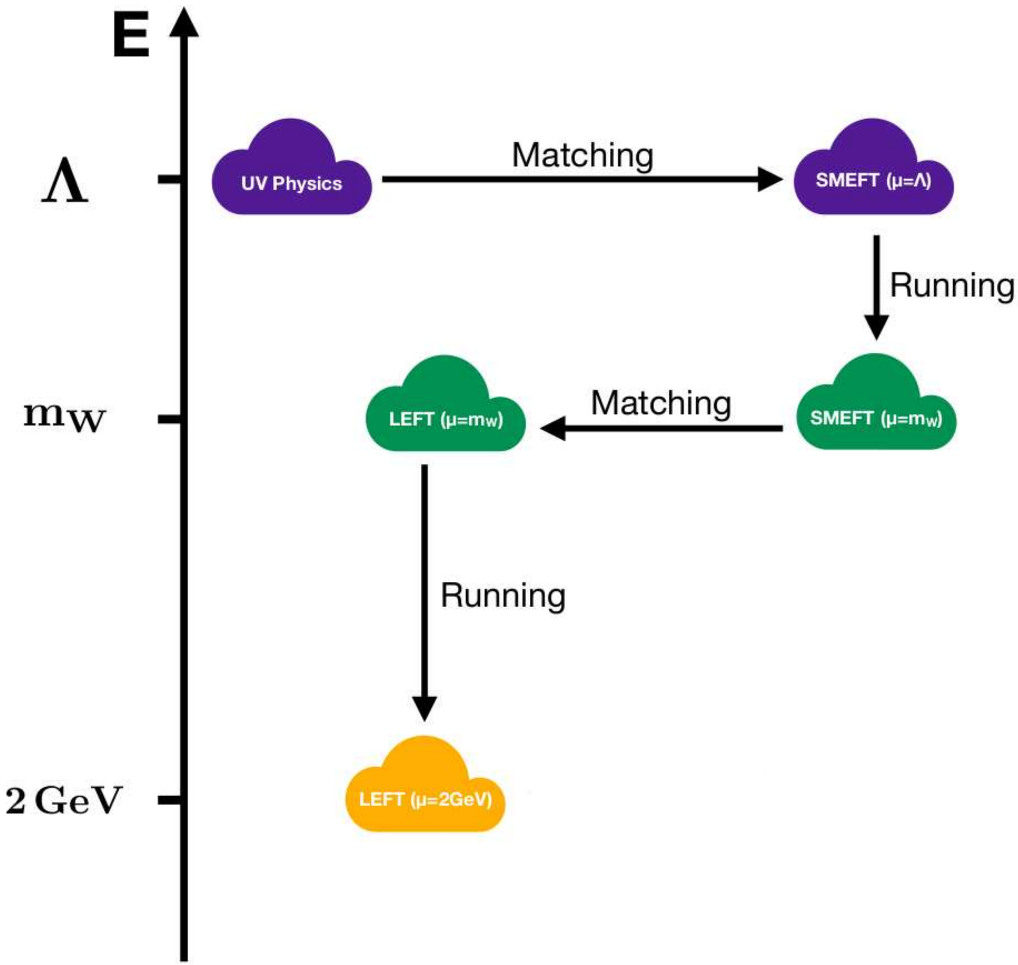

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Below m_W:

LEFT

Integrate out $H\,,\, W_{\mu\nu}\,,\,\cdots$

Effective field theory

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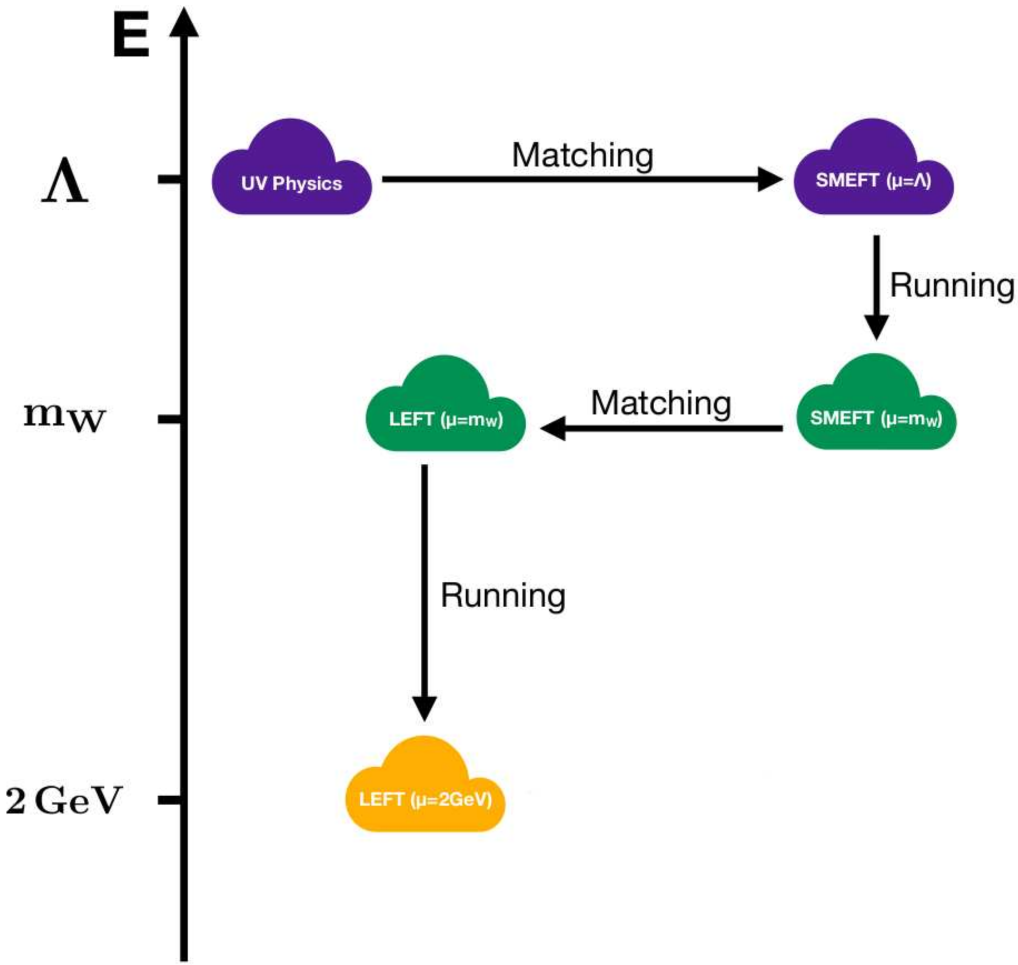

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Below m_W:

LEFT

Integrate out $H\,,\,W_{\mu\nu}\,,\,\cdots$

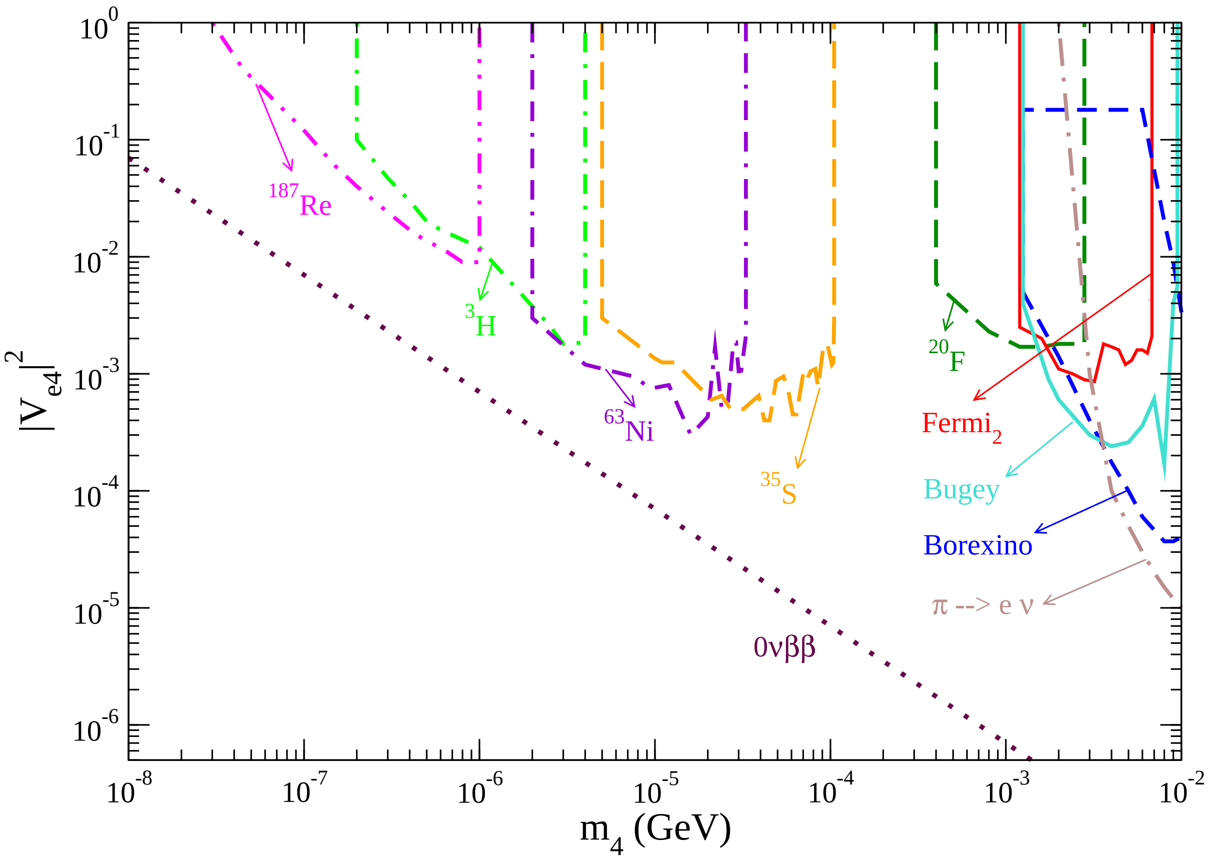
Add fermionic singlets:

N_RSMEFT + N_RLEFT

$\mathcal{II}.$

Minimal HNLs

Bounds on HNLs

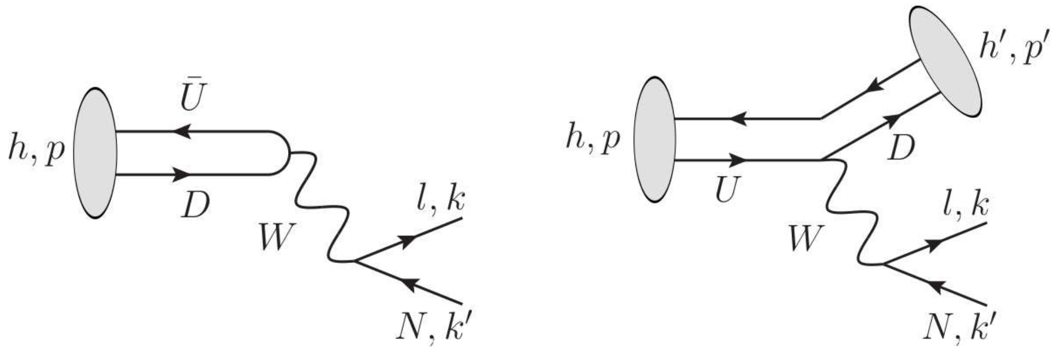


Atre et al, JHEP05 (2009) 030

⇒ Mostly "kink" searches

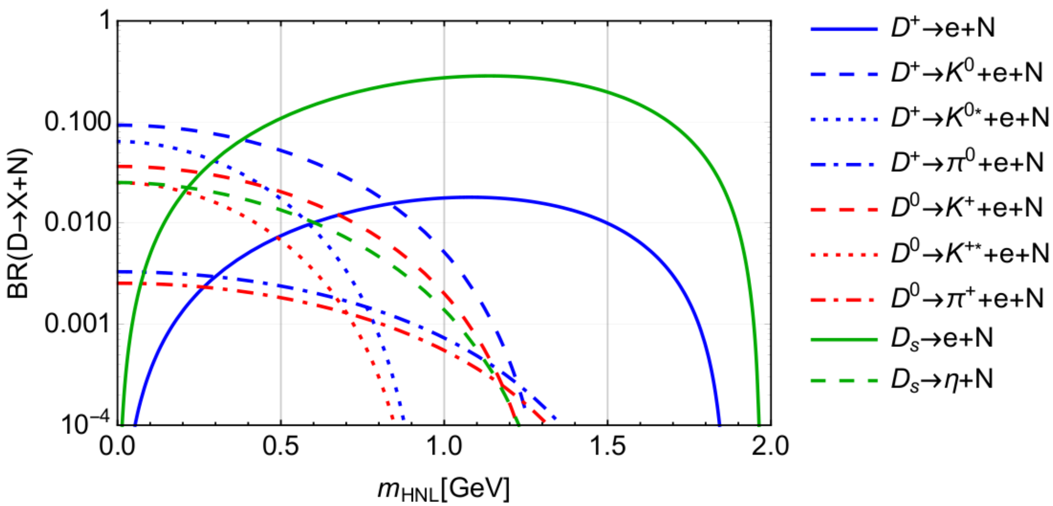
⇒ $0\nu\beta\beta$ applies only for Majorana HNL

HNL production



Bondarenko et al, JHEP11 (2018) 032

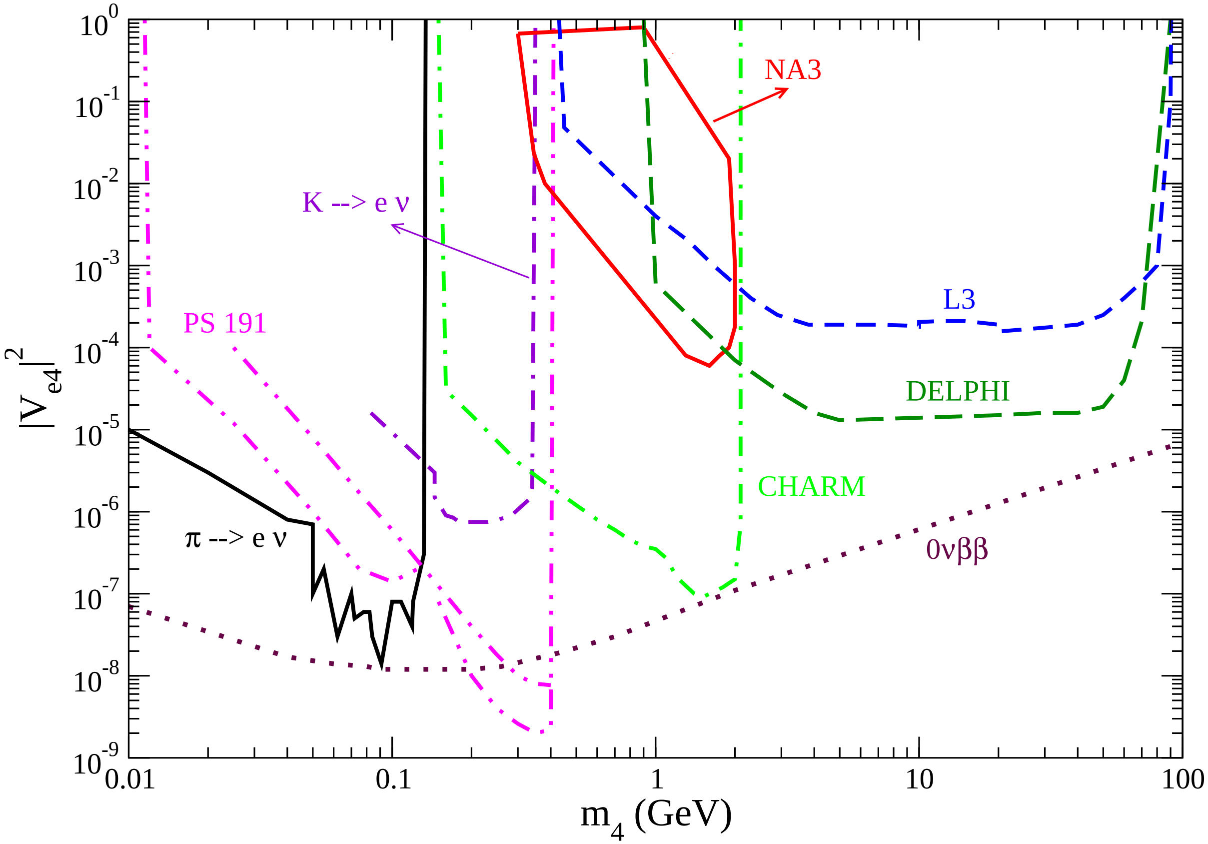
Example:



⇒ Branching ratio for $V_{\alpha N_j} = 1$

⇒ For $m_{HNL} \simeq [0.1, 5]$ GeV HNL from meson decays

Bounds on HNLs



Atre et al, JHEP05 (2009) 030

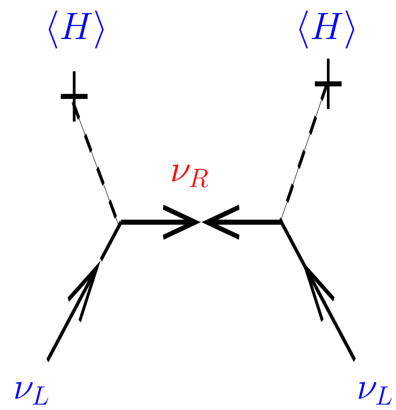
$\Rightarrow$ $0\nu\beta\beta$ applies only for Majorana HNL

$\Rightarrow$ LEP (DELPHI, L3) searched for $Z^0 \rightarrow \nu N$

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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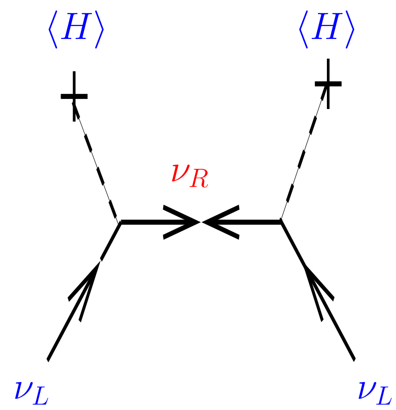

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For $m_D \ll M_M$, eigenvalue and heavy-light mixing given by:

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

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

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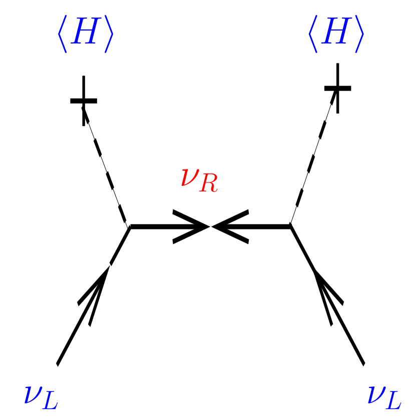

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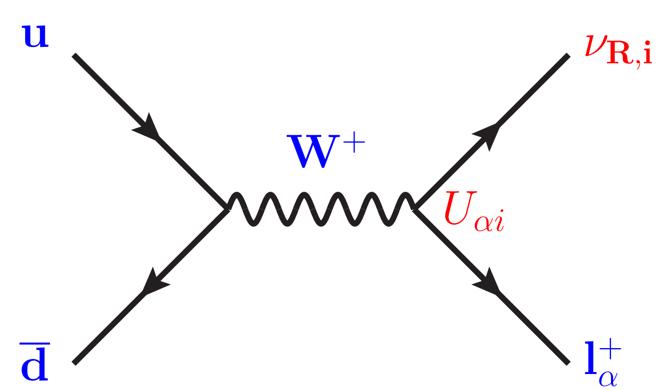

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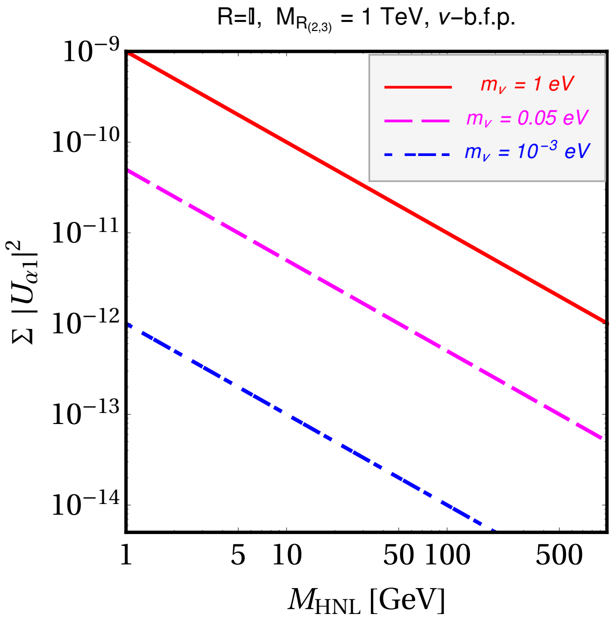
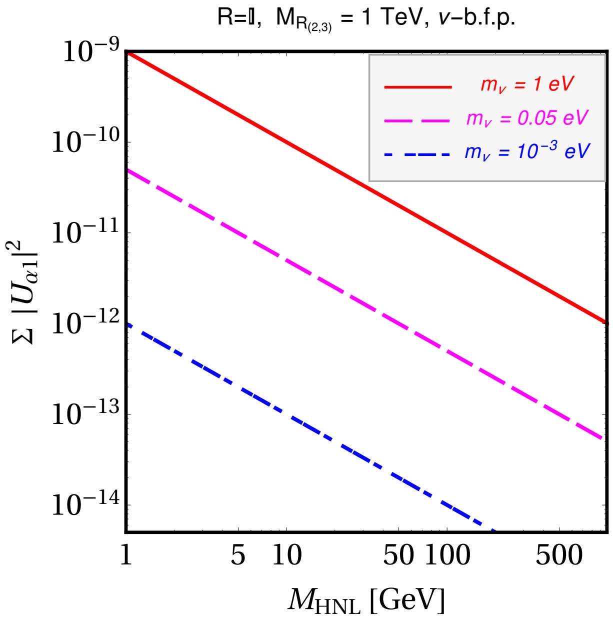
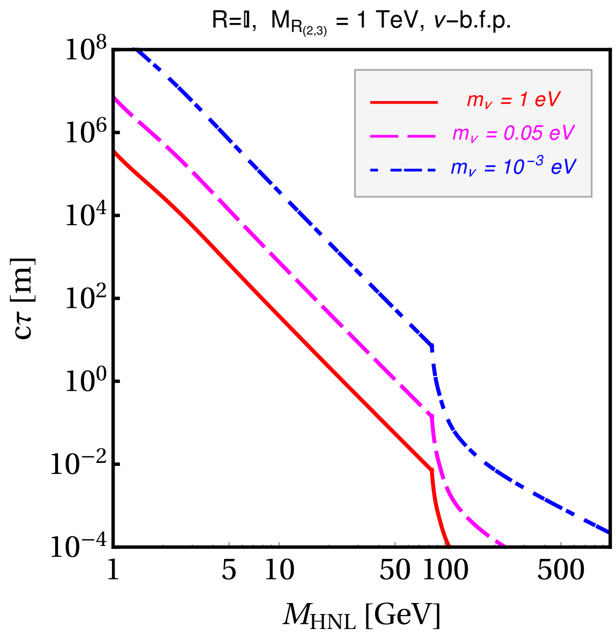
Decay length seesaw-I



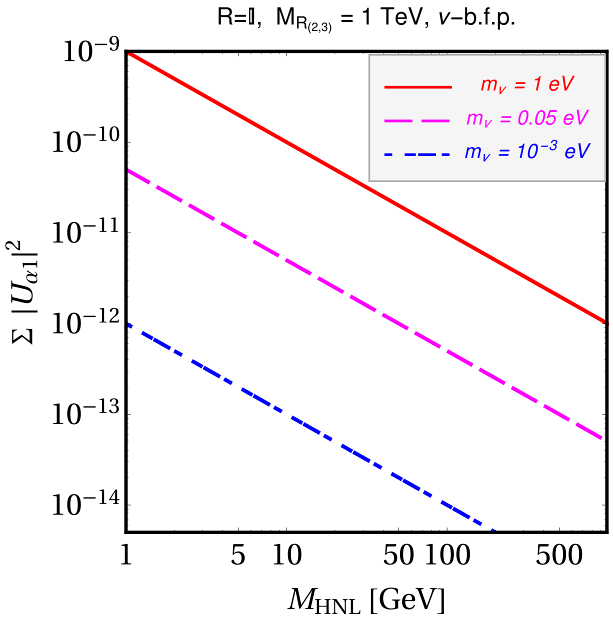
Decay length seesaw-I



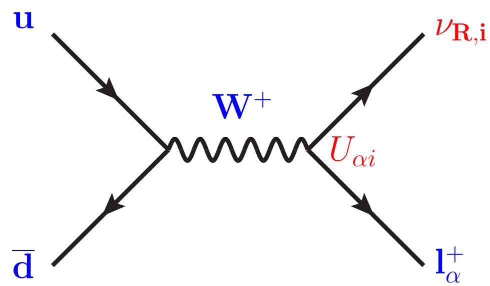


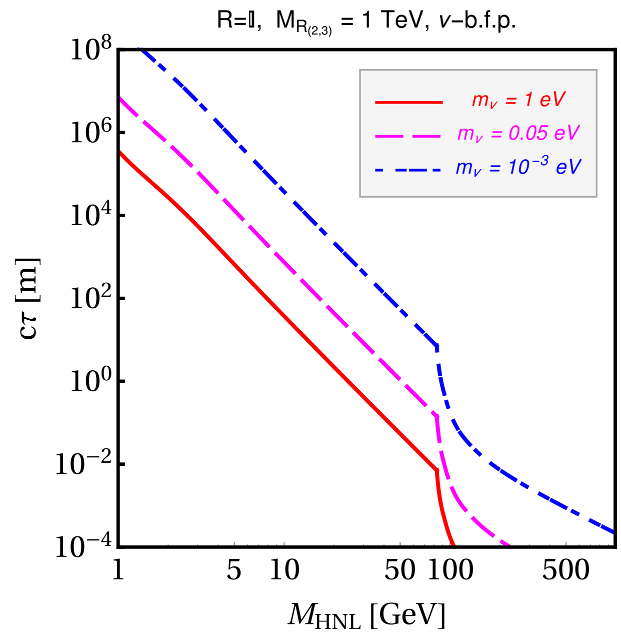
Neutrino decay width calculation from:
Atre et al.
JHEP 0905 (2009) 030
and
Bondarenko et al.
1805.08567

Decay length seesaw-I



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





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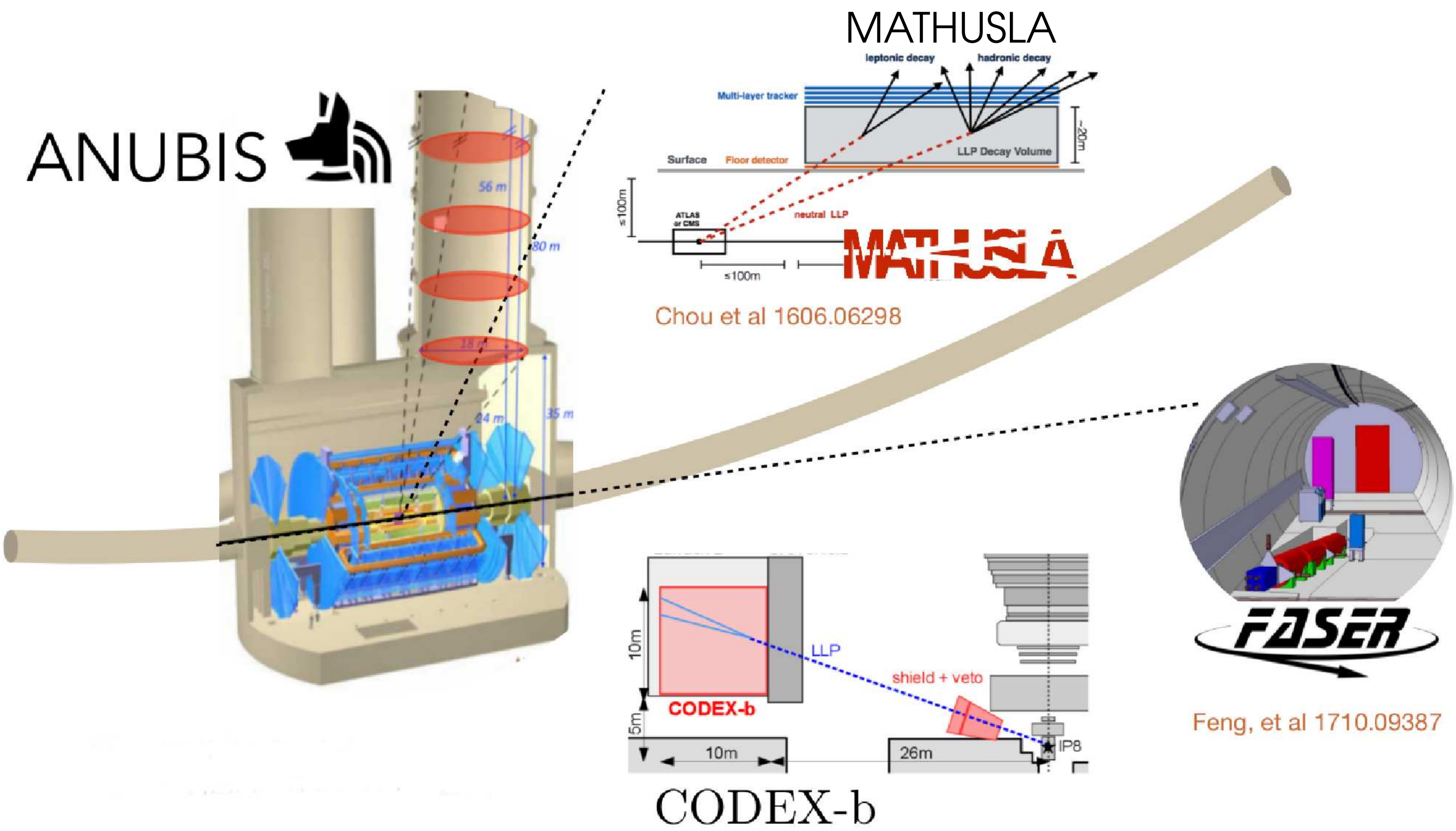
Where to look for LLPs?



Chou et al 1606.06298

Feng, et al 1710.09387

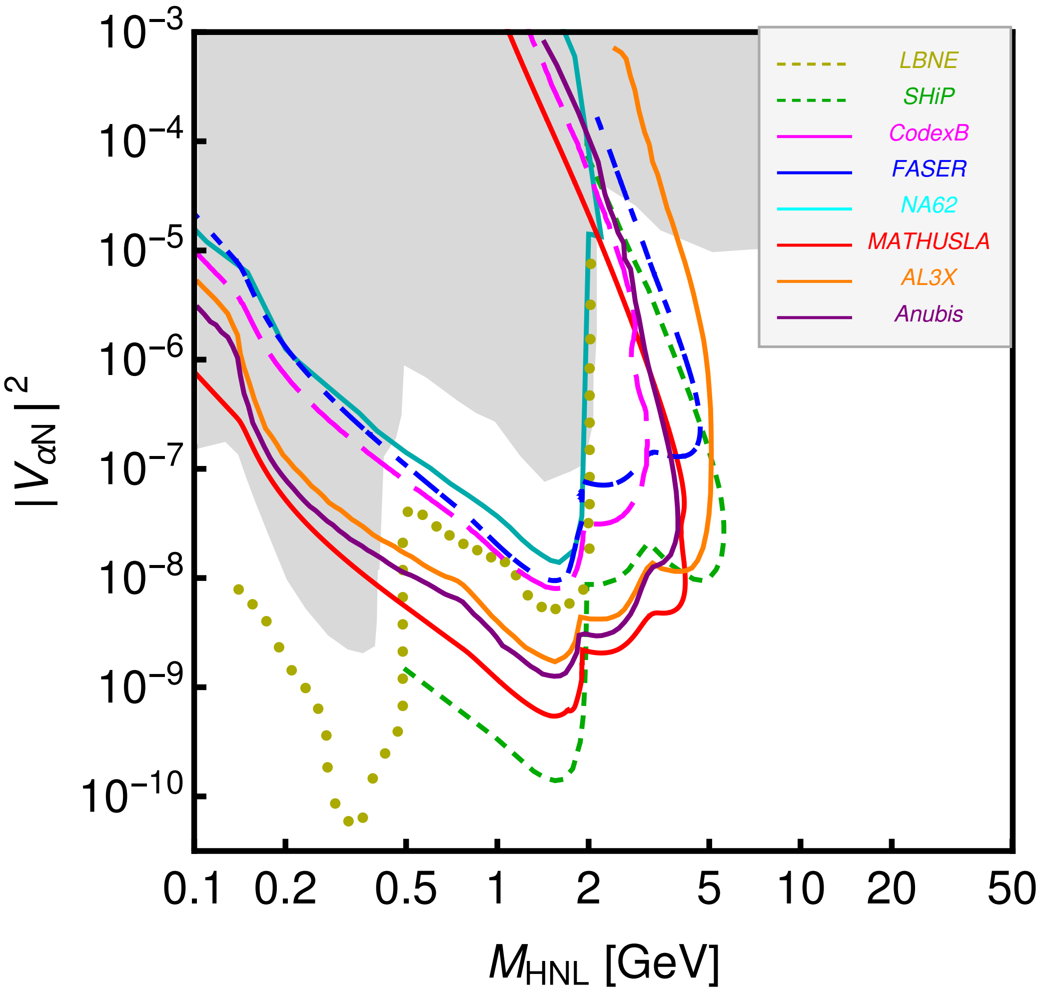
Gligorov et al 1708.09395

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

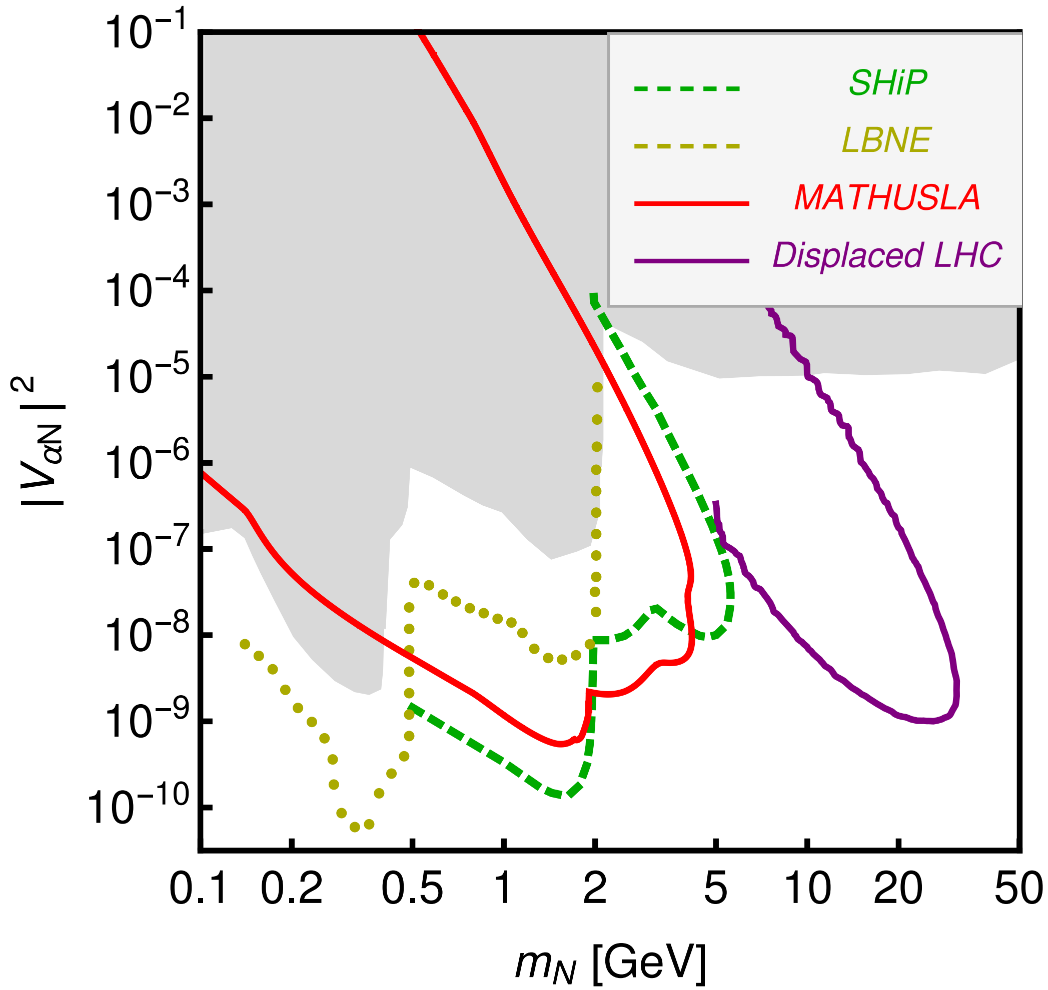
NA62; 1801.04207

MATHUSLA; 1806.07396

AL3X; 1810.03636

ANUBIS; 1909.13022

Forecast searches



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

Cottin et al.; PRD98 (2018) 035012

Complementary to far detectors!

$\mathcal{III}.$

N_RSMEFT

Effective field theory

Basic idea of EFT:

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

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

$\Rightarrow$ "Integrating out" the heavy resonances "generates" a tower of operators

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

$\Rightarrow$ Λ is the energy scale of new physics

$\Rightarrow$ C_k the Wilson coefficient, free parameters in SMEFT

$\Rightarrow$ 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!)

$d = 5$ 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

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
$\mathcal{O}_{uN}$	$\left(\overline{u_R}\gamma^\mu u_R\right)\left(\overline{N_R}\gamma_\mu N_R\right)$	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
$\mathcal{O}_{NN}$	$\left(\overline{N_R}\gamma_\mu N_R\right)\left(\overline{N_R}\gamma_\mu N_R\right)$	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
$\mathcal{O}_{LNQd}$	$\left(\overline{L}N_R\right)\epsilon\left(\overline{Q}d_R\right)$ +h.c.	54	162
$\mathcal{O}_{LdQN}$	$\left(\overline{L}d_R\right)\epsilon\left(\overline{Q}N_R\right)$ +h.c.	54	162
$\mathcal{O}_{LNLe}$	$\left(\overline{L}N_R\right)\epsilon\left(\overline{L}e_R\right)$ +h.c.	54	162
$\mathcal{O}_{QuNL}$	$\left(\overline{Q}u_R\right)\left(\overline{N_R}L\right)$ +h.c.	54	162

single N_R operators

$d = 6$ operators in N_RSMEFT

Name	$\Psi^2 D H^2$	$n_N = 1$	$n_N = 3$
$\mathcal{O}_{NHD_\mu}$	$(\overline{N_R}\gamma^\mu N_R)\,(H^\dagger i D_\mu H)$	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	$\Psi^2 H X$	$n_N = 1$	$n_N = 3$
$\mathcal{O}_{LNHB}$	$(\overline{L}\sigma^{\mu\nu} N_R)\,\tilde{H} B_{\mu\nu}$ + 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

N_RLEFT

For completeness, operators in N_RLEFT up to d=6:

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

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JHEP 05 (2020) 139

One-loop matching
N_RSMEFT $\leftrightarrow$ N_RLEFT

N_RLEFT

For completeness, operators in N_RLEFT up to d=6:

Dipole	$\mathcal{O}_{N\gamma} = \overline{\nu_L}\sigma^{\mu\nu} N A_{\mu\nu}$	
RRRR	$\mathcal{O}_{NN}^{V,RR} = (\overline{N}\gamma_\mu N)(\overline{N}\gamma^\mu N)$	
	$\mathcal{O}_{eN}^{V,RR} = (\overline{e_R}\gamma_\mu e_R)(\overline{N}\gamma^\mu N)$	$\mathcal{O}_{uN}^{V,RR} = (\overline{u_R}\gamma_\mu u_R)(\overline{N}\gamma^\mu N)$
	$\mathcal{O}_{dN}^{V,RR} = (\overline{d_R}\gamma_\mu d_R)(\overline{N}\gamma^\mu N)$	$\mathcal{O}_{udeN}^{V,RR} = (\overline{u_R}\gamma_\mu d_R)(\overline{e_R}\gamma^\mu N)$
LLRR	$\mathcal{O}_{\nu N}^{V,LR} = (\overline{\nu_L}\gamma_\mu \nu_L)(\overline{N}\gamma^\mu N)$	$\mathcal{O}_{eN}^{V,LR} = (\overline{e_L}\gamma_\mu e_L)(\overline{N}\gamma^\mu N)$
	$\mathcal{O}_{uN}^{V,LR} = (\overline{u_L}\gamma_\mu u_L)(\overline{N}\gamma^\mu N)$	$\mathcal{O}_{dN}^{V,LR} = (\overline{d_L}\gamma_\mu d_L)(\overline{N}\gamma^\mu N)$
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LRLR	$\mathcal{O}_{NN}^{S,RR} = (\overline{\nu_L} N)(\overline{\nu_L} N)$	
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	$\mathcal{O}_{uN}^{S,RR} = (\overline{u_L} u_R)(\overline{\nu_L} N)$	$\mathcal{O}_{uN}^{T,RR} = (\overline{u_L}\sigma_{\mu\nu} u_R)(\overline{\nu_L}\sigma^{\mu\nu} N)$
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M. Chala & A. Titov
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One-loop matching
N_RSMEFT $\leftrightarrow$ N_RLEFT

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

Limits on N_RSMEFT?

At $d = 5$ there are two new operators:

$$\mathcal{O}_{NH} \propto (H^\dagger H)(\overline{N_R^c} N_R)$$

$$\mathcal{O}_{NB} \propto (\overline{N_R^c} \sigma^{\mu\nu} N_R) B_{\mu\nu}$$

A. Aparici et. al,
PRD 80 (2009) 013010

see also
L. Duarte et al.,
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$\Rightarrow \mathcal{O}_{NH}$, after EWSB contribution to:

$$M_R \overline{N^c_R} N_R \rightarrow (M_R + \frac{cv^2}{\Lambda}) \overline{N^c_R} N_R$$

$\Rightarrow \mathcal{O}_{NH}$, invisible Higgs decay, rough estimate:

Experimental limits
CMS
& ATLAS

$$\Lambda \gtrsim 20\sqrt{c}\ \text{TeV} \qquad (\text{for } m_N \rightarrow 0)$$

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$\Rightarrow \mathcal{O}_{NB}$ N_R; magnetic moments

$\Rightarrow \mathcal{O}_{NB}$ N_R: $N_{R_j} \rightarrow N_{R_i} + \gamma$ decays , very stringent limit from RG cooling:

$$\Lambda \geq 4 \times 10^6 \text{ TeV for } m_N \leq 10 \text{ keV}$$

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$\Rightarrow$ If both $\mathcal{O}_{NH}$ and $\mathcal{O}_{NB}$
new contibution to $h \rightarrow \gamma\gamma$

Butterworth et. al,
PRD 100 (2019) 115019

Limits on N_RSMEFT?

Similarly $d = 6$ operators involving Higgses:

Butterworth et. al,
PRD 100 (2019) 115019
L. Duarte et al.,
PRD 92 (2015) 093002

$\mathcal{O}_{NHD_\mu}$: $(\overline{N_R}\gamma^\mu N_R)\,(H^\dagger iD_\mu H)$
$\mathcal{O}_{NeHD_\mu}$: $(\overline{N_R}\gamma^\mu e_R)\,(\tilde{H}^\dagger iD_\mu H)$
$\mathcal{O}_{LNHB}$: $(\overline{L}\sigma^{\mu\nu}N_R)\,\tilde{H}B_{\mu\nu}$
$\mathcal{O}_{LNHW}$: $(\overline{L}\sigma^{\mu\nu}N_R)\,\tilde{H}(\vec{\sigma}W_{\mu\nu})$

$\Rightarrow$ $\mathcal{O}_{NHD_\mu}$: Invisible Z^0 decay, $Z^0 \to N\bar{N}$
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V. Cirigliano et al. JHEP 08 (2021) 103

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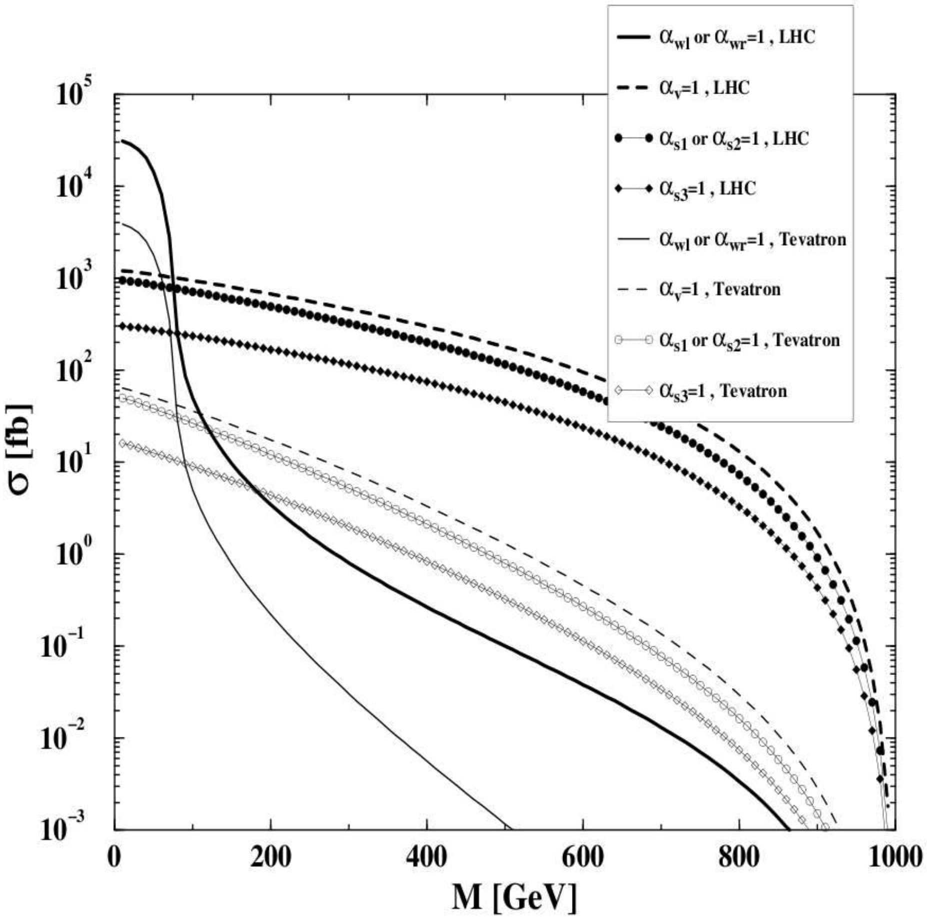
V. Cirigliano et al. JHEP 08 (2021) 103

$\mathcal{O}_{LNH}$: $(\overline{L}N_R)\,\tilde{H}(H^\dagger H)$

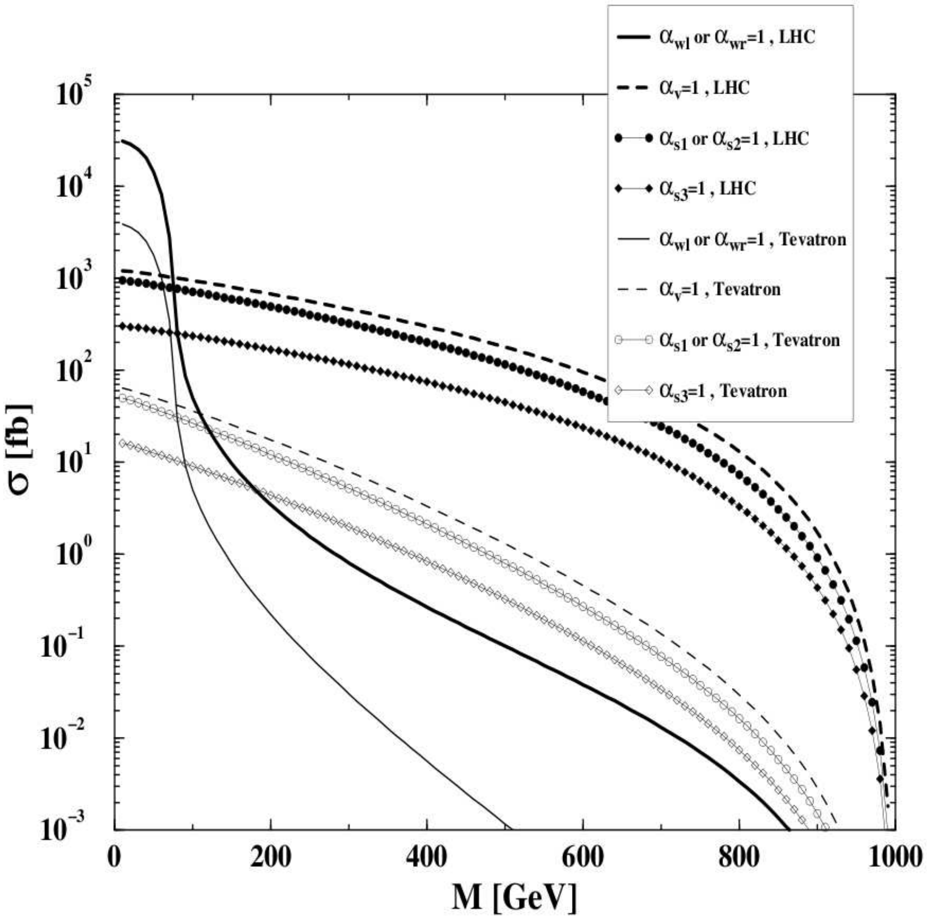
$\Rightarrow$ Higher order contribution to Yukawa, Y_ν
$\Rightarrow$ Again, invisible Higgs decay

4F operators in N_RSMEFT



F. del Águila et al., PLB 670 (2009) 399

4F operators in N_RSMEFT



F. del Águila et al., PLB 670 (2009) 399

Considered stable N_R

proposed to measure differential distributions $p\overline{p}/(pp) \to l + \not{E}$

rather weak limits, despite large X-sections

Example: $\mathcal{O}_{duNe}$: $pp \to Ne$

$\not{B}$ in N_RSMEFT

Proton decay as test?

Hirsch, Helo & Ota
JHEP06 (2018) 047

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)		$1.2 \cdot 10^{35}$	$> 3 \cdot 10^{34}$
$\mathcal{O}_{(du)(QL)}$	✓	✓	✓
$\mathcal{O}_{(QQ)(ue)}$	—	✓	—
$\mathcal{O}_{(QQ)(QL)}$	✓	✓	✓
$\mathcal{O}_{(Q\vec{\tau}Q)(Q\vec{\tau}L)}$	—	—	✓
$\mathcal{O}_{(du)(ue)}$	—	✓	—
$\mathcal{O}_{QQdN}$	✓	—	✓
$\mathcal{O}_{uddN}$	✓	—	✓

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

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

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$\mathcal{O}_{uddN}$	✓	—	✓

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

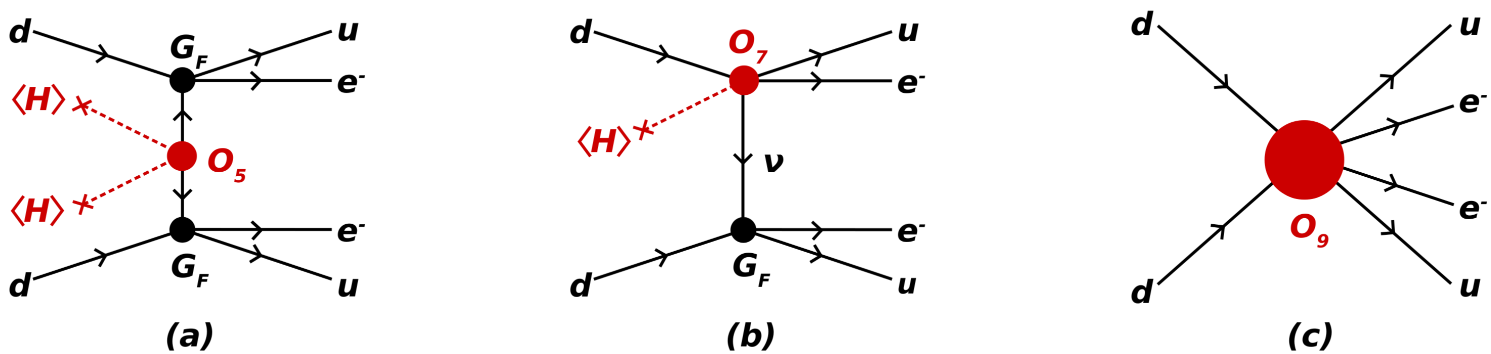
Finally, four LNV operator:
$\mathcal{O}_{NNNN} = (\overline{N_R^C} N_R)(\overline{N_R^C} N_R)$??

No paper?

$0\nu\beta\beta$ decay

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

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



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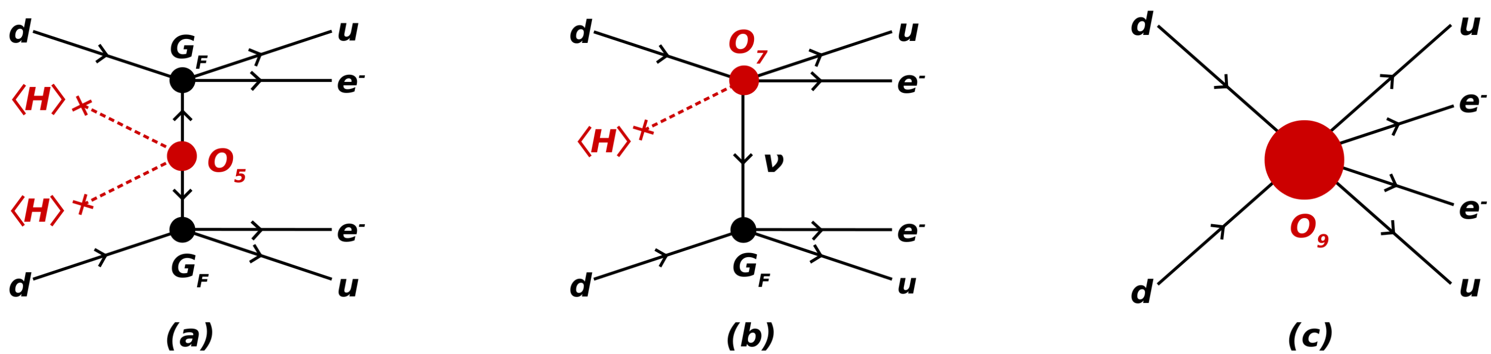

$\Rightarrow$ In N_RLEFT long range contribution $d = 6$ operator,
but in N_RSMEFT due to $d = 7$ operator(s)

Helo, Hirsch & Ota
JHEP06 (2016) 006

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

+

$\Rightarrow$ Recently reanalized in W. Dekens et al., JHEP 08 (2021) 128

$\mathcal{IV}.$

Future prospects: LLPs

$d = 6$ 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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pair N_R operators

Lightest N_R can not decay via N_R pair operators!

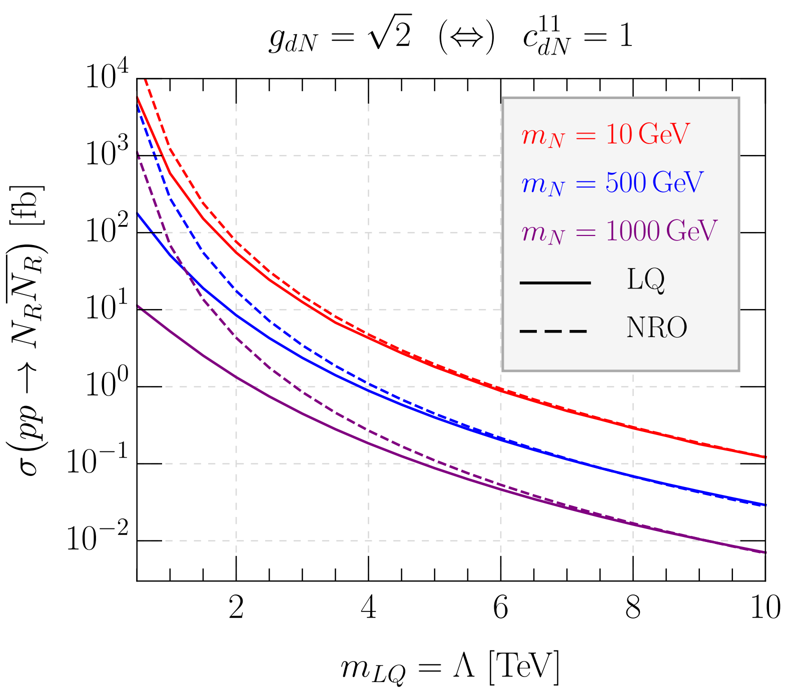
$\Rightarrow$ N_R decay via mixing

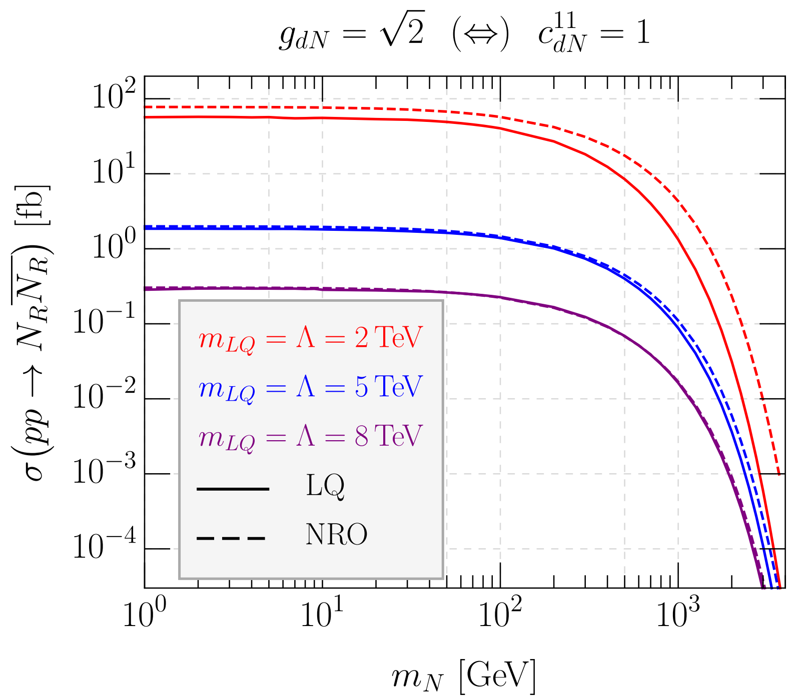
single N_R operators

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

Cross sections

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





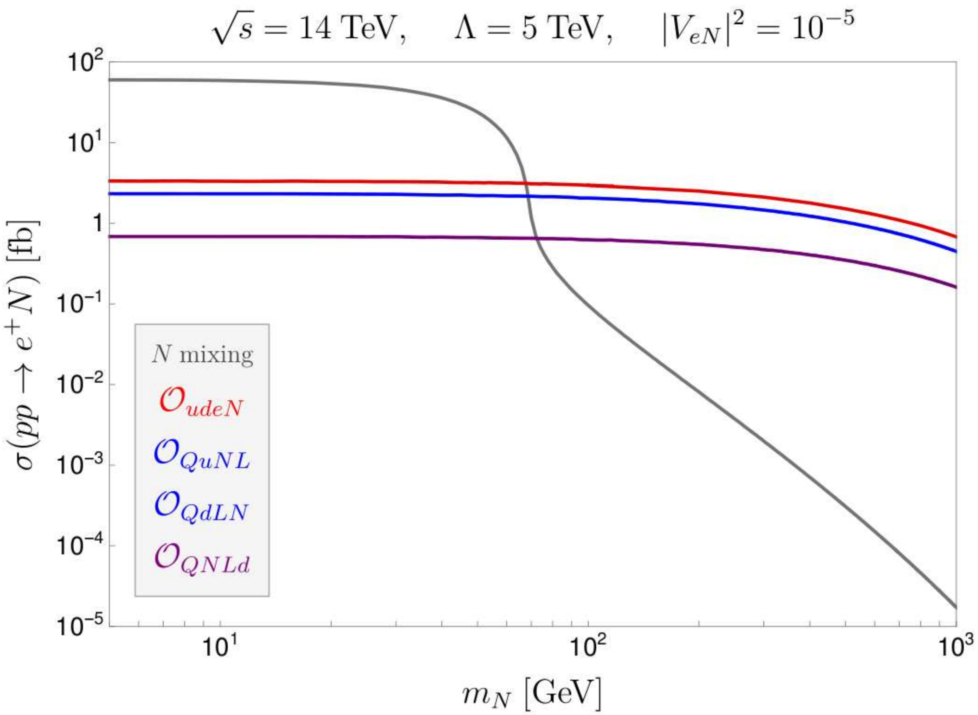
⇒ Total $\sigma(pp \to N_R\overline{N_R}) \propto \Lambda^{-4}$

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

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

Cross sections

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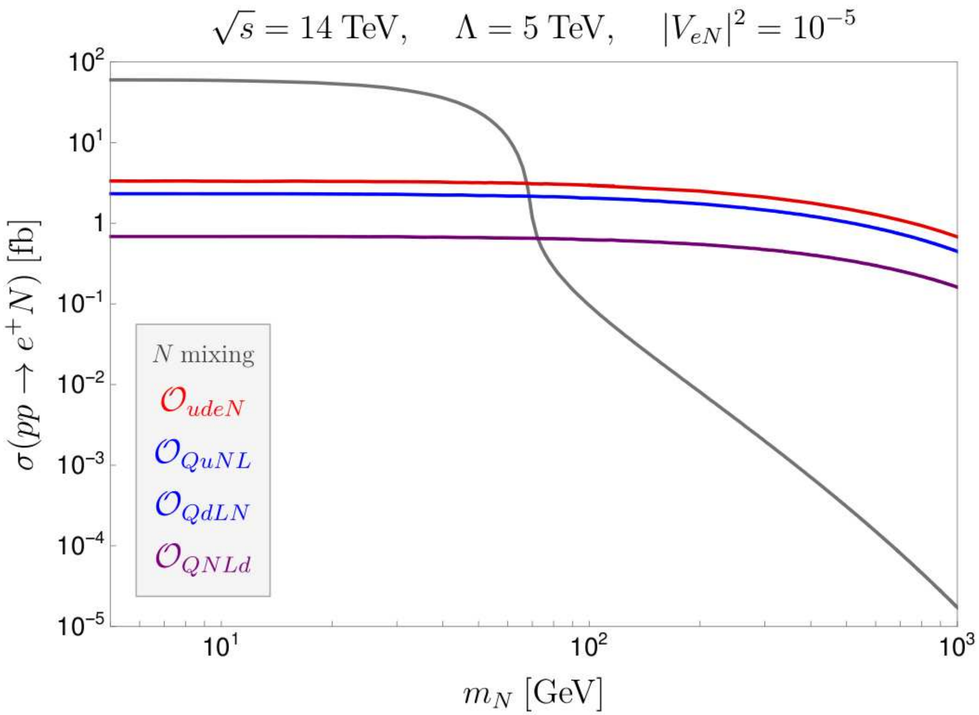


Recall:

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

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

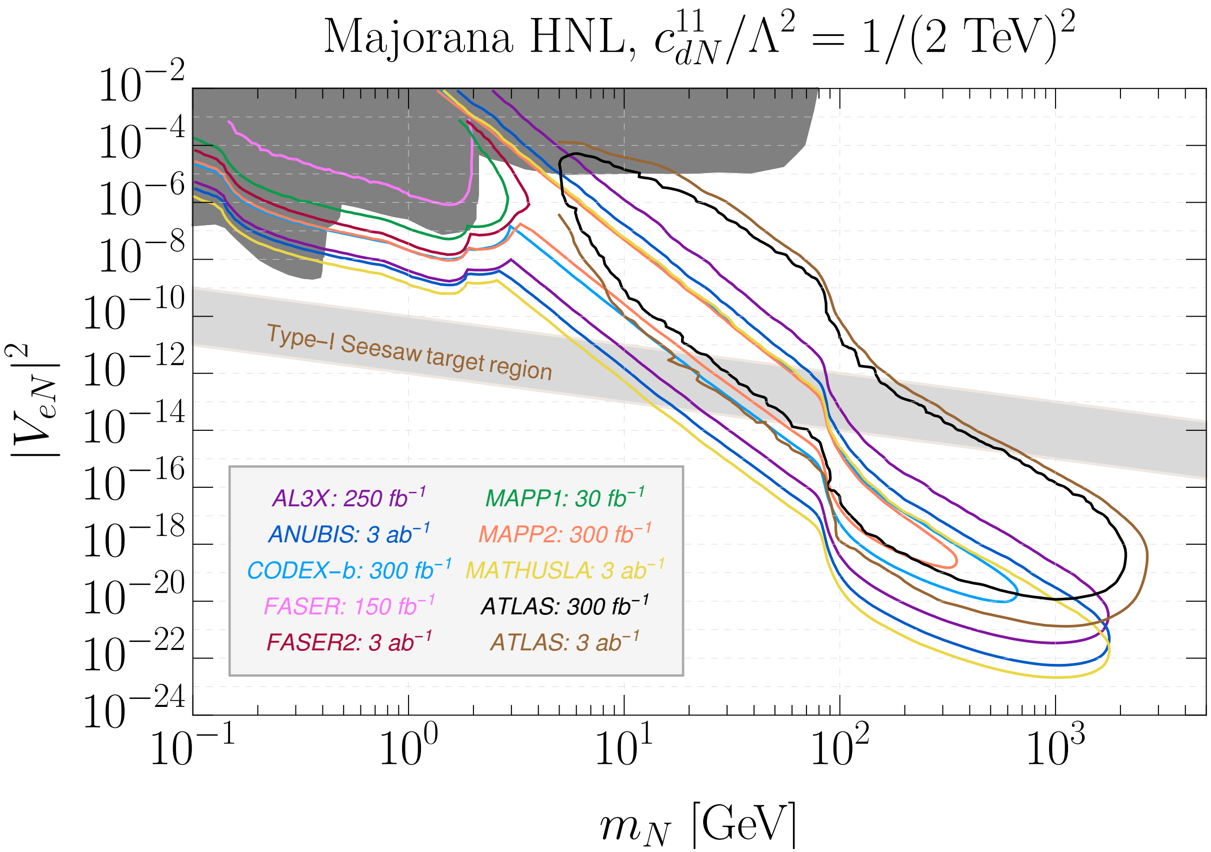
$\Rightarrow$ Total $\sigma(pp \to N_R \overline{N_R}) \propto \Lambda^{-4}$

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



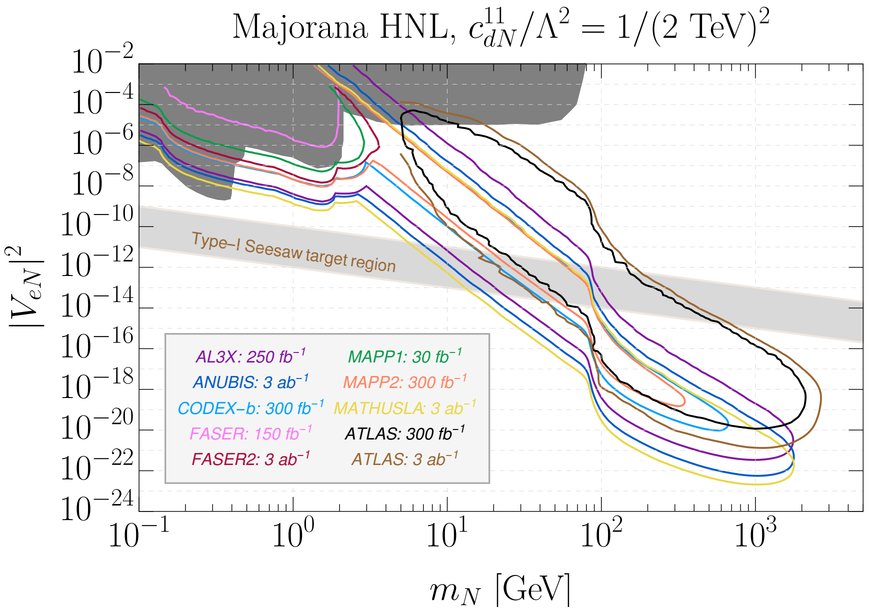
Note the axis!

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

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

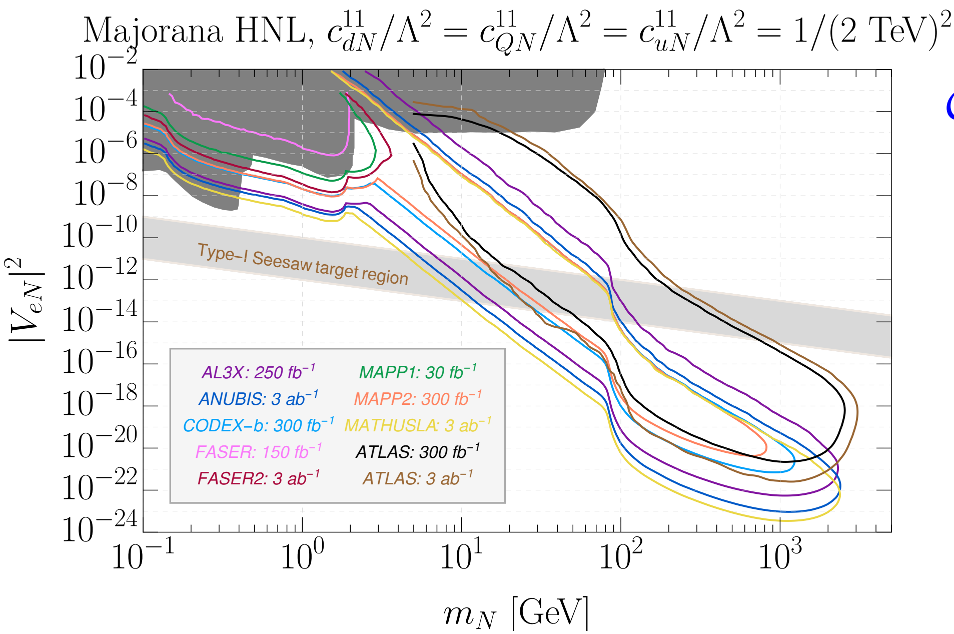
$\Rightarrow$ m_N up to TeV could be probed!

Forecast searches



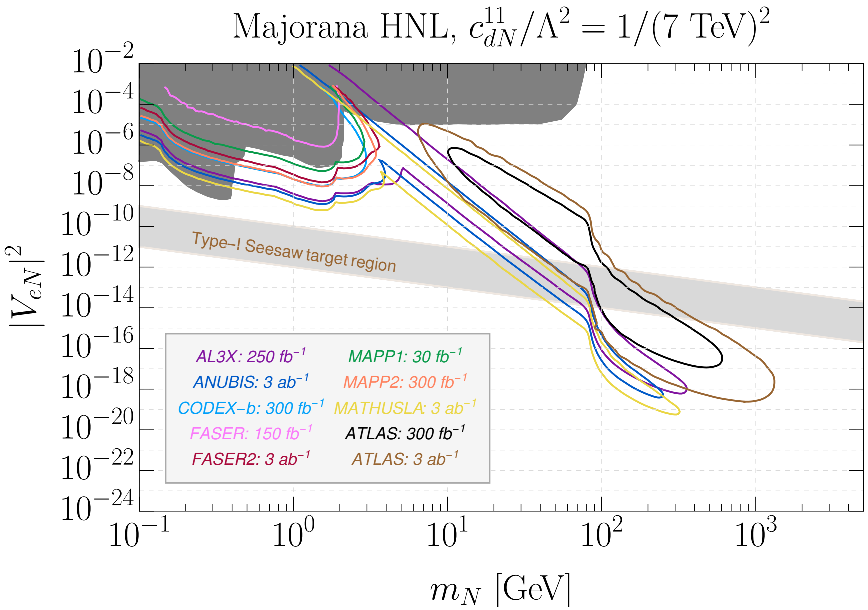
Only $\mathcal{O}_{dN}$

$\Lambda = 2$ TeV



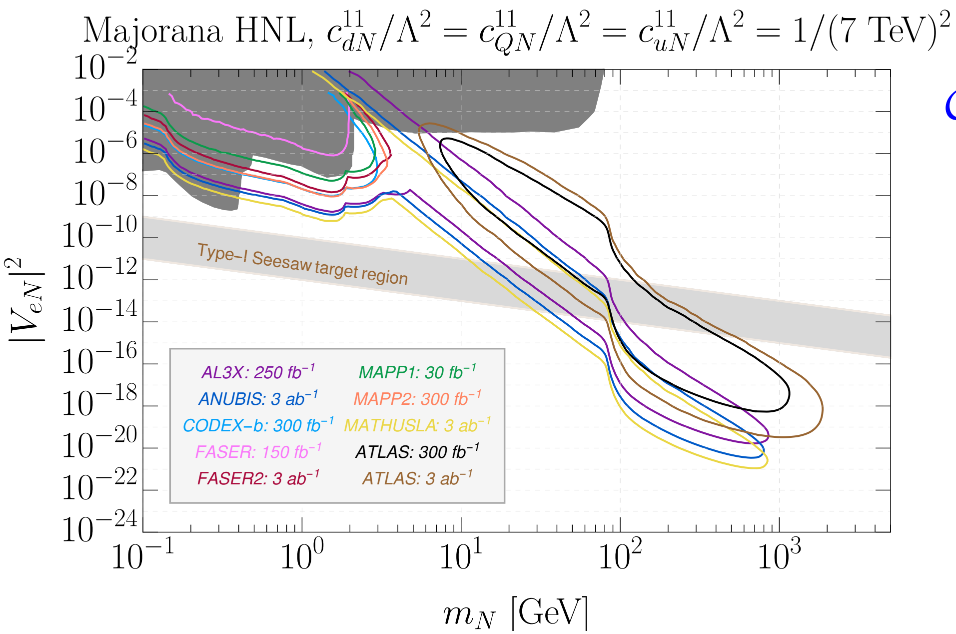
$\mathcal{O}_{dN} + \mathcal{O}_{uN} + \mathcal{O}_{QN}$

Forecast searches



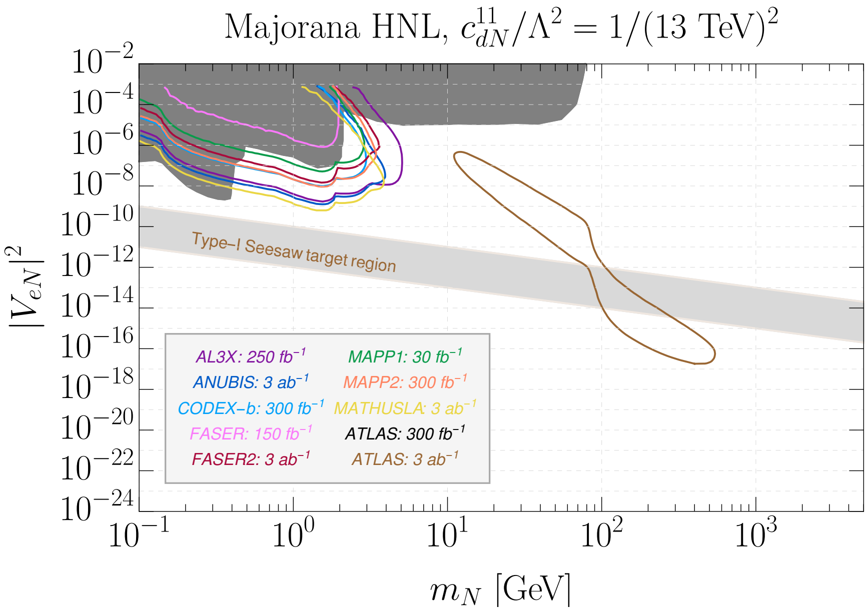
Only $\mathcal{O}_{dN}$

$\Lambda = 7$ TeV



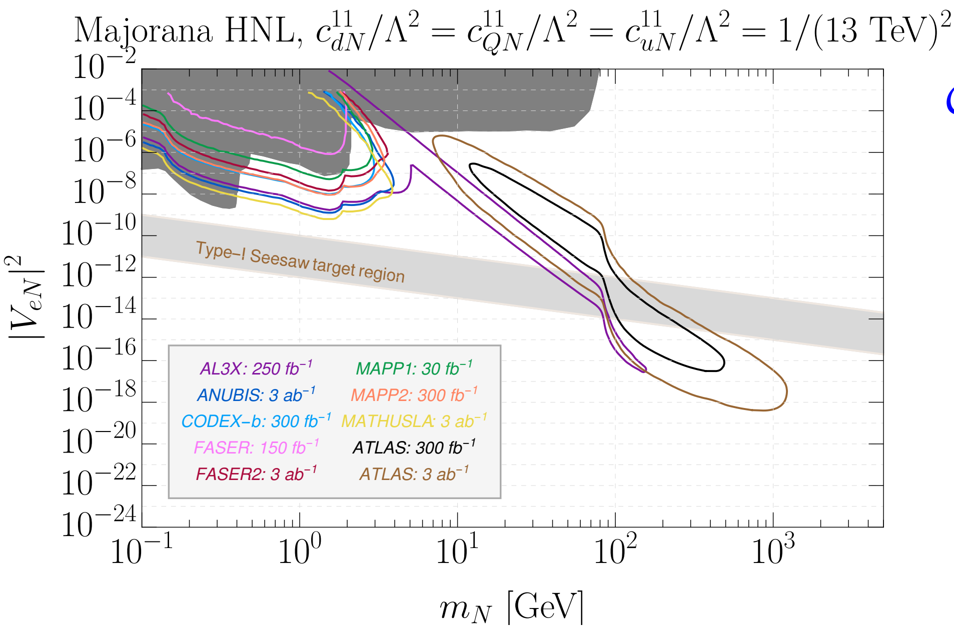
$\mathcal{O}_{dN} + \mathcal{O}_{uN} + \mathcal{O}_{QN}$

Forecast searches



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

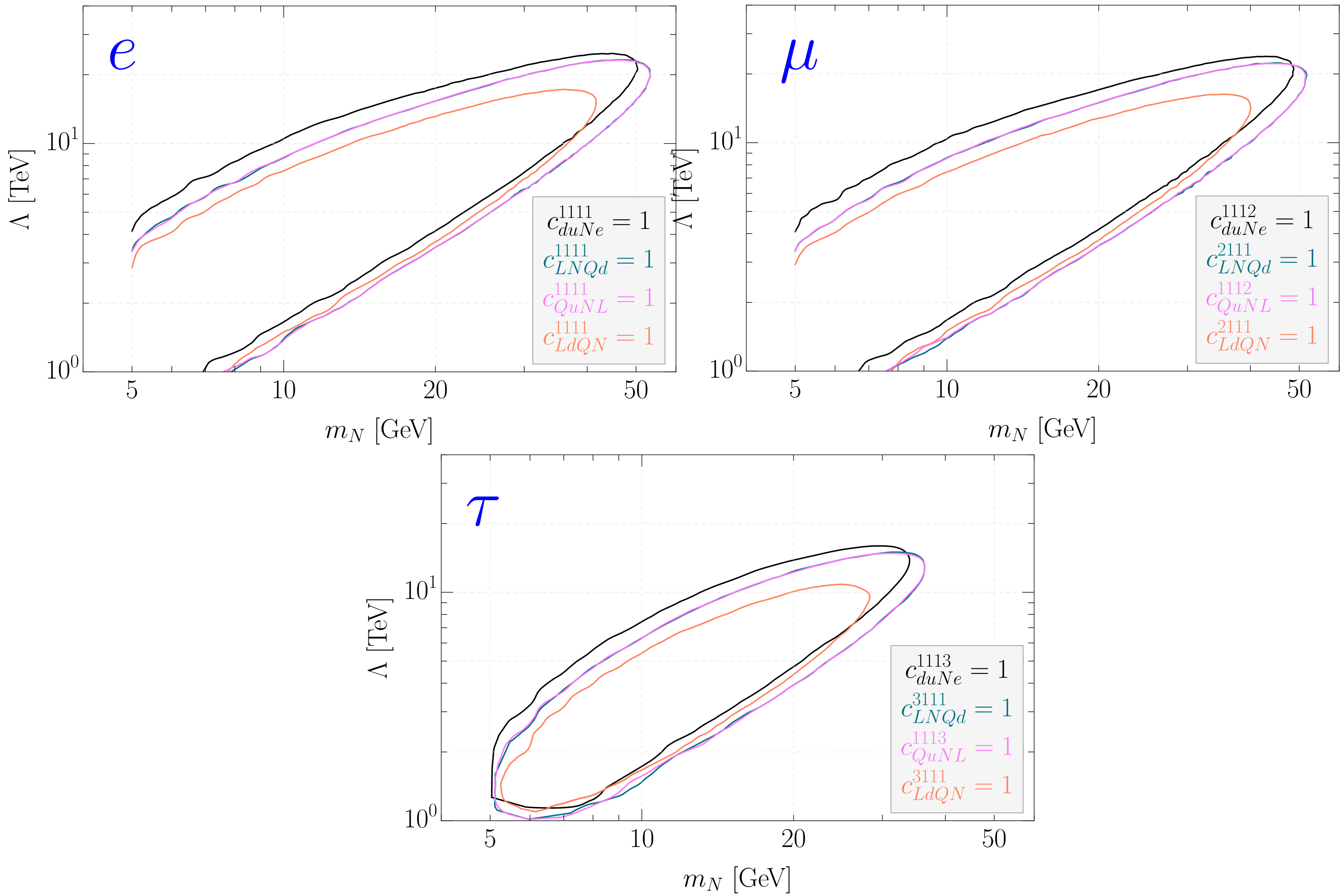
$\Lambda = 13$ TeV



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

Forecast searches

Sensitivity reach (ATLAS) for single N_R operators:



$\Rightarrow$ Λ up to (25-27) TeV could be probed!

$\Rightarrow$ m_N reach up to ~ 55 GeV

Conclusions

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

⇒ 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!

⇒ Other SMEFTs? SN_RSMEFT?

Belanger et al,
PRD104 (2021) 055047

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

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$\Rightarrow$ Many BSM models contain new particles

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

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

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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

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:

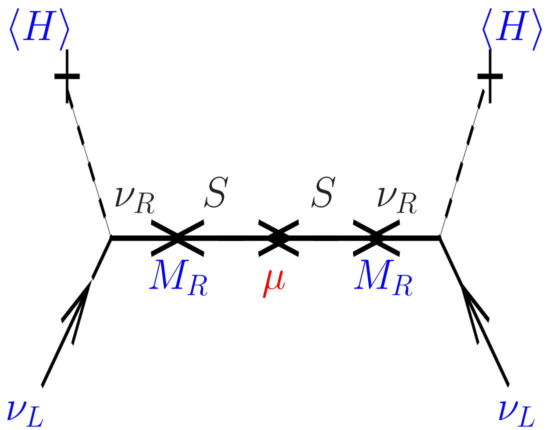
$$\begin{aligned} \hat{m}_\nu = V_L m_\nu V_L^T &= V_L m_D^T.(M_R^T)^{-1}.\mu.(M_R)^{-1}.m_D V_L^T \\ M_\pm &= \left(\hat{M}_R + \left\{m_D.m_D^T, \hat{M}_R^{-1}\right\}\right) \pm \frac{1}{2}\mu_V \end{aligned}$$

$\Rightarrow$ - 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!

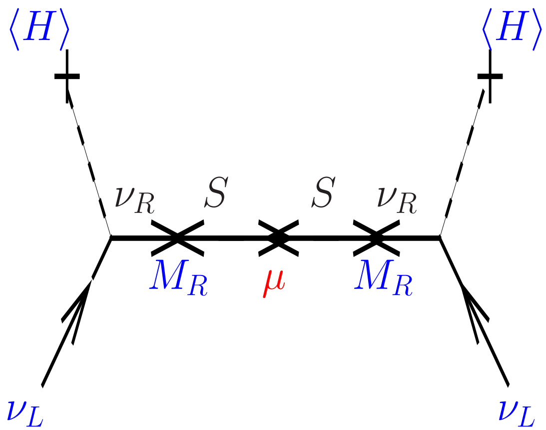
$c\tau$: Inverse seesaw



$$m_\nu \simeq \left(\frac{m_D}{M_R}\right)^2 \mu$$

$$U_{\alpha i} \propto \frac{m_D}{M_R} \propto \sqrt{\frac{m_\nu}{\mu}}$$

$c\tau$: Inverse seesaw



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