N_RSMEFT and long-lived HNLs

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http://www.astroparticles.es/

Contents

$\mathcal{I}.$

Introduction

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"

⇒ Experimentally we know: $V_{\alpha N_j} \ll 1$ (for $m_N \leq 1$ TeV)

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Note:

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

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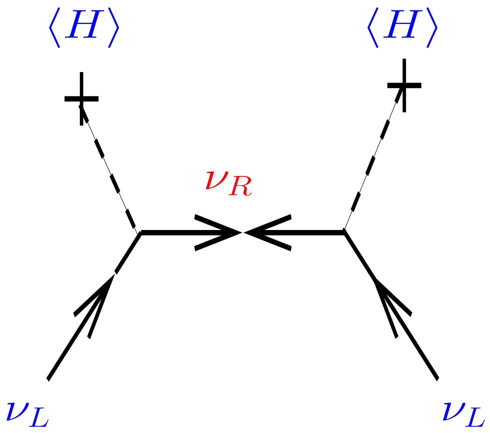
⇒ Experimentally we know: $V_{\alpha N_j} \ll 1$ (for $m_N \leq 1$ TeV)

Note:

⇒ this makes no reference to any (neutrino mass) model
⇒ gives no explanation for mass of N
⇒ Does not specify N to be Majorana/Dirac
⇒ gives no explanation for neutrino oscillations!
⇒ Need to specify a specific seesaw variant to make contact to light neutrino masses!

Which seesaw?

Classical type-I seesaw:



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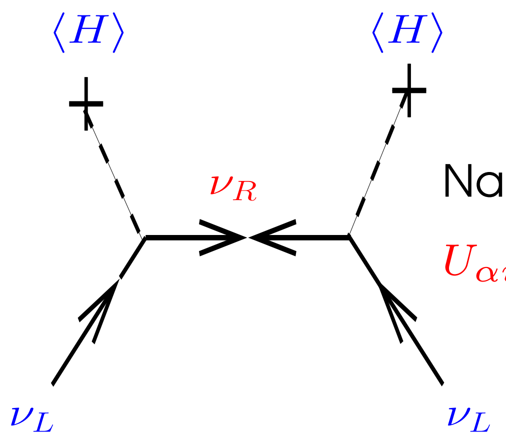

Naive seesaw estimate:

$$U_{\alpha i} \propto \frac{(Y_\nu v)}{M_M} \propto \sqrt{\frac{m_{\nu_\alpha}}{M_{M_i}}}$$

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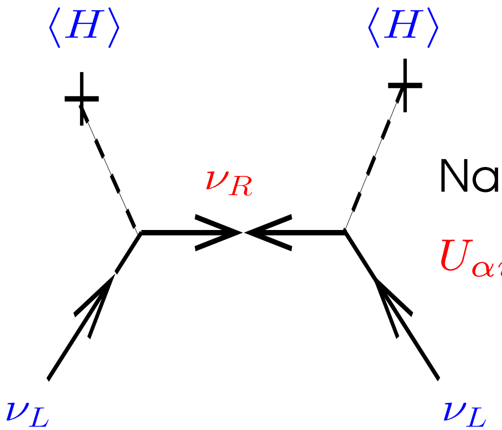

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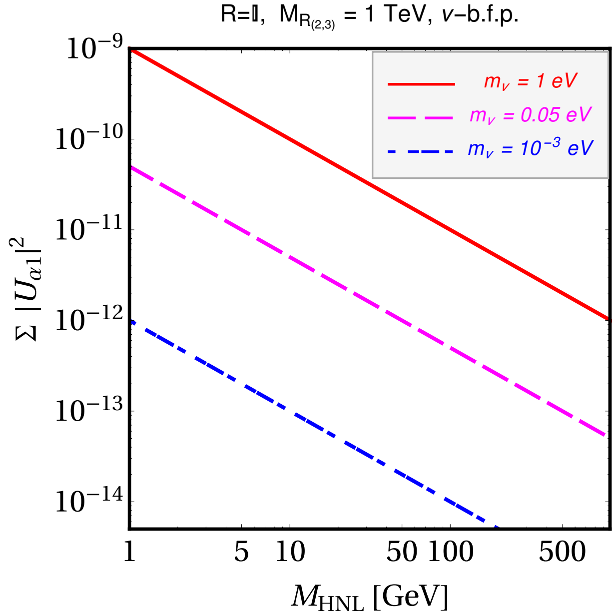

⇒ Larger mixing possible for the price of fine-tuning parameters

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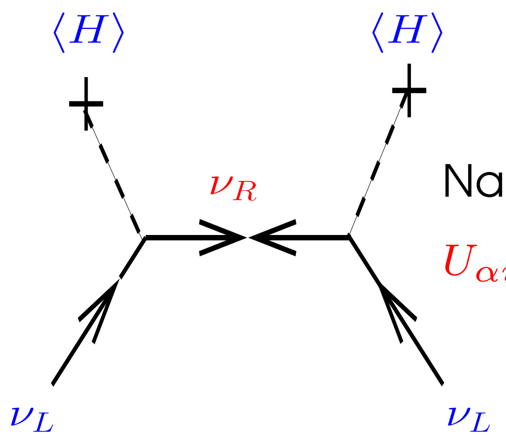

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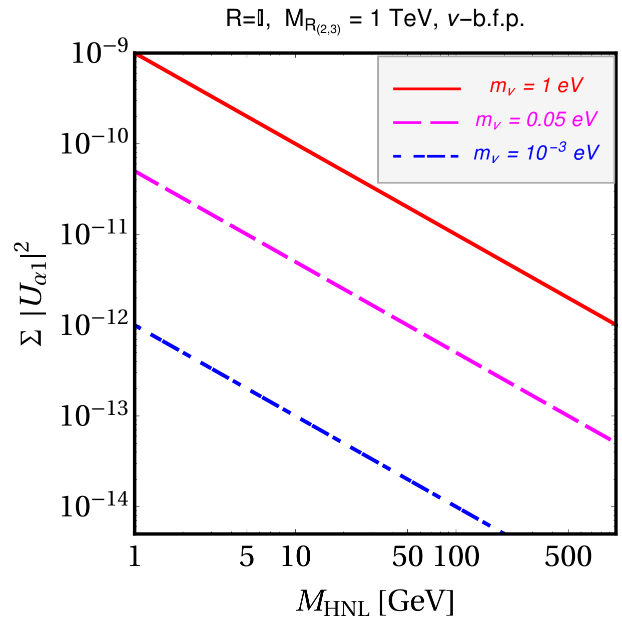
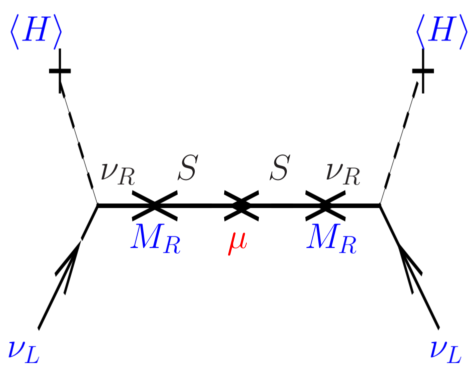
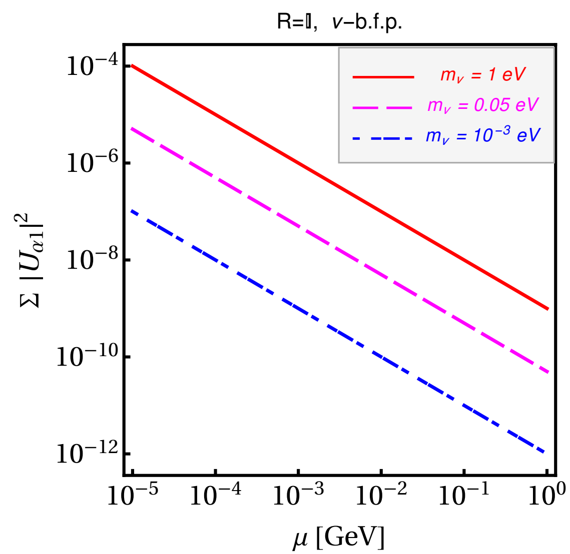


⇒ Larger mixing possible for the price of fine-tuning parameters

Inverse seesaw type-I:



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



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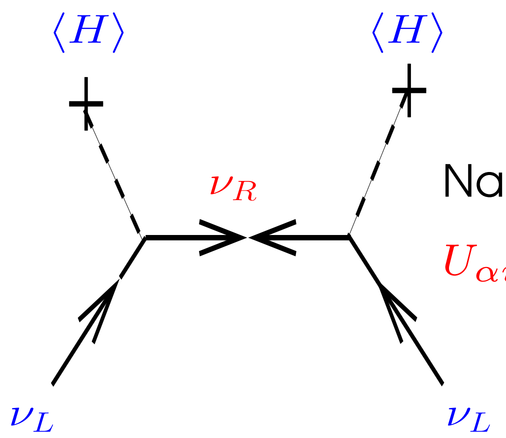

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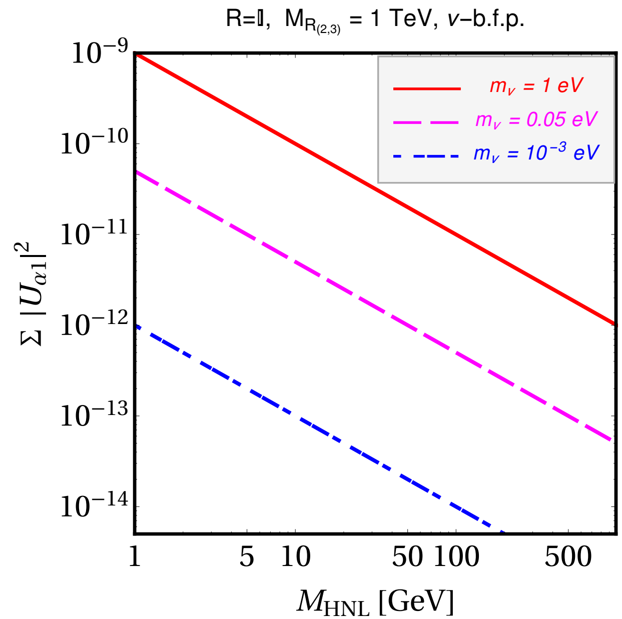

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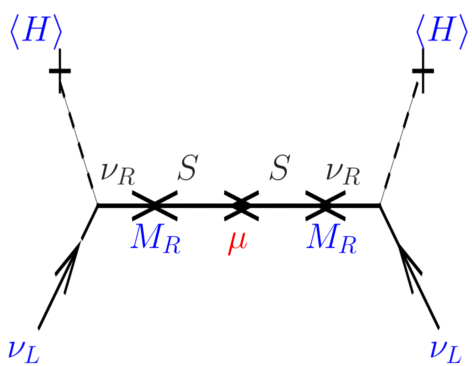

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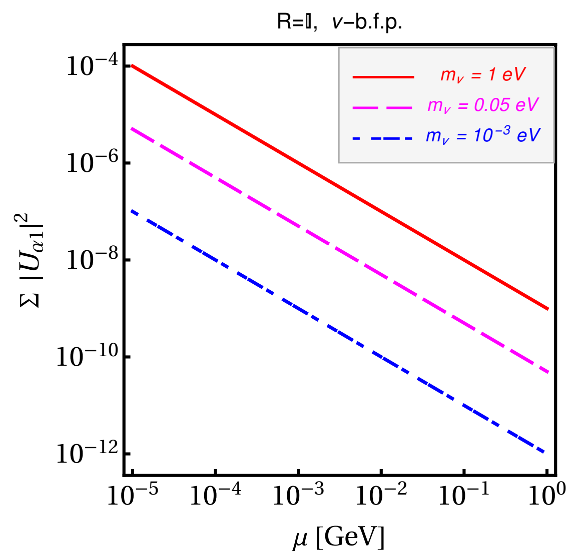
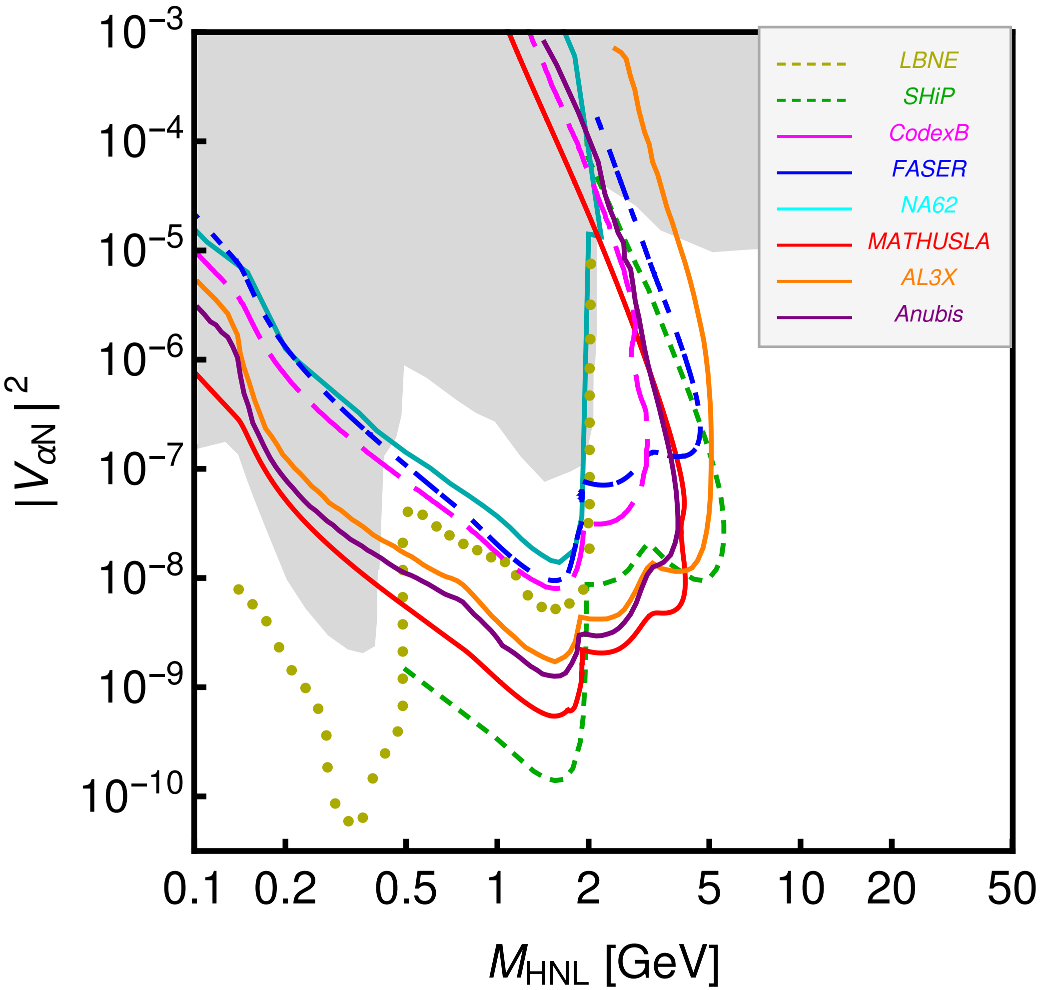


⇒ Larger mixing expected
for the price of one small parameter

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

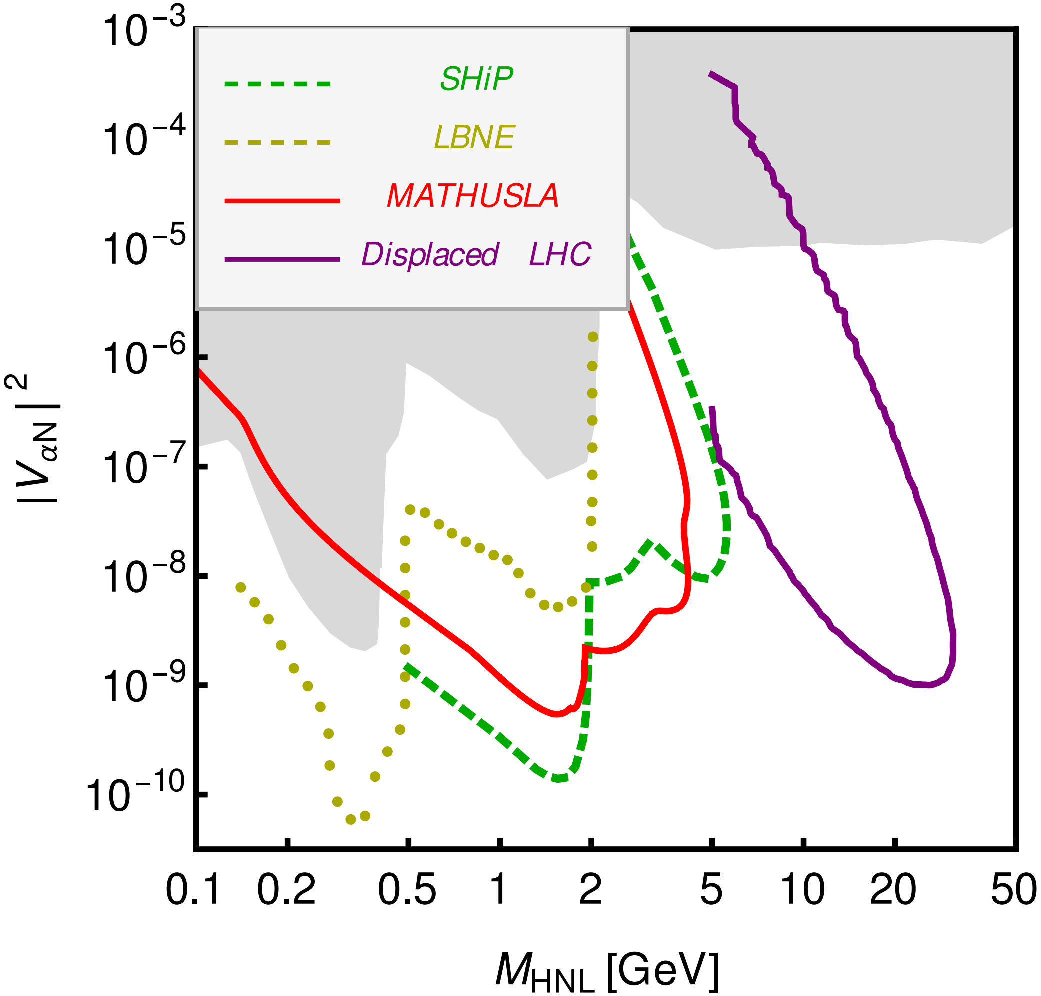
NA62; 1801.04207

MATHUSLA; 1806.07396

AL3X; 1810.03636

ANUBIS; 1909.13022

Forecast searches



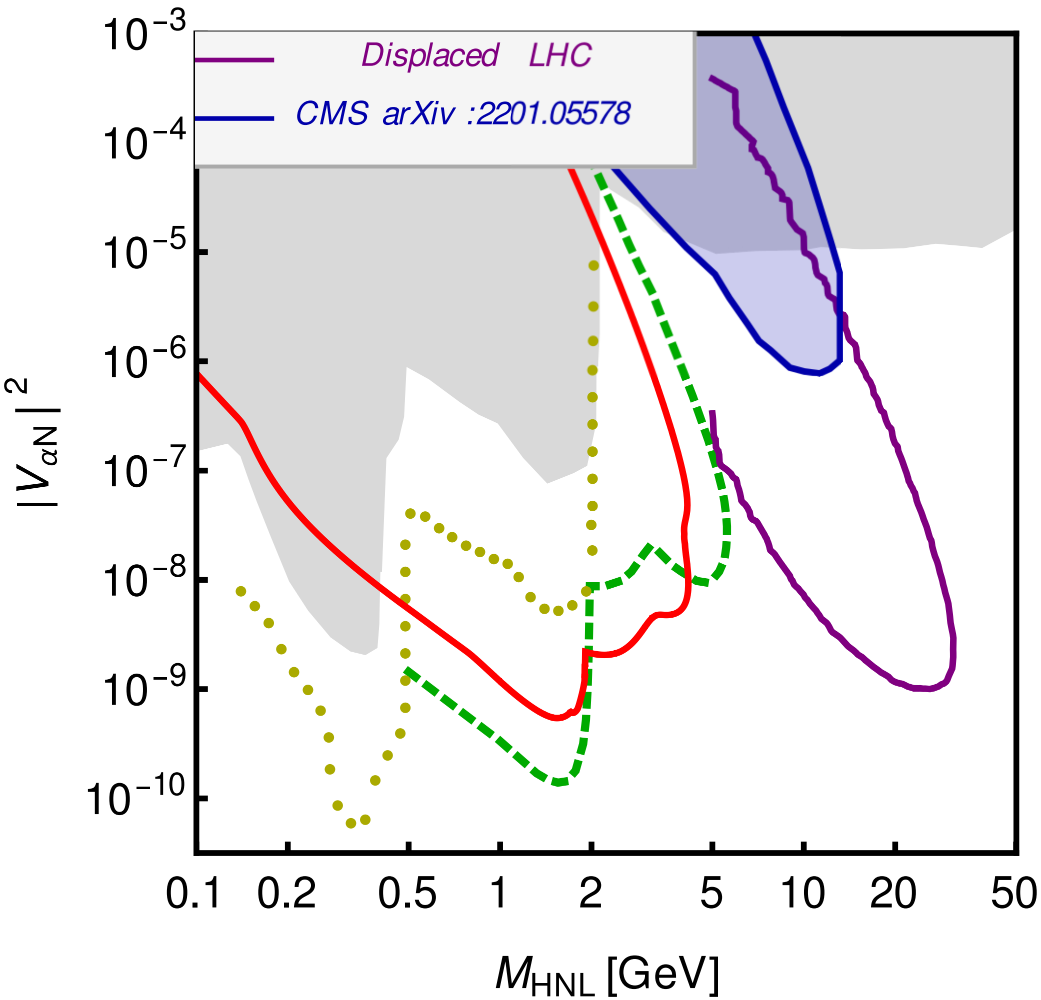
LHC displaced vertex search forecast for $\mathcal{L} = 3$/ab:

Cottin et al.; PRD98 (2018) 035012

updated in R. Beltrán et al.; JHEP01 (2022) 044

Complementary to far detectors!

Forecast searches



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Cottin et al.; PRD98 (2018) 035012

Experimental search result: **CMS JHEP 07 (2022) 081** based on: $\mathcal{L} = 138$/**fb**

$\mathcal{II}.$

N_RSMEFT

(and tree-level UV completions)

R. Beltrán, R. Cepedello, M. Hirsch,

JHEP08 (2023) 166

Effective field theory

Basic idea of EFT:

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

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

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

⇒ At $d = 6$ already more than $\mathcal{O}(50)$ operators, with 2499 (3045) independent parameters

N_RSMEFT

Huge progress in construction of operator basis in recent years:

SMEFT is known up to $d = 12$! Harlander et al., PRD108 (2023) 055020

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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?

`Sym2Int`
R.M. Fonseca, Comput.Phys. Commun. 267 (2021) 108085

and:

`AutoEFT`
Harlander et al. arXiv:2309.15783

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$\Leftarrow$ Most relevant for LLPs @ LHC: $d = 6$ and - maybe! - $d = 7$

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N_RSMEFT at $d = 6$

$d = 6$ operators that can be opened at tree-level:

$\psi^2 H^3$ (+h.c.)	
$\mathcal{O}_{LNH^3}$	$(\overline{L} N_R)\tilde{H}(H^\dagger H)$
$\psi^2 H^2 D$ (+h.c.)	
$\mathcal{O}_{NH^2D}$	$(\overline{N_R}\gamma^\mu N_R)(H^\dagger i\overleftrightarrow{D}_\mu H)$
$\mathcal{O}_{NeH^2D}$	$(\overline{N_R}\gamma^\mu e_R)(\tilde{H}^\dagger i D_\mu H)$
$(\overline{L}R)(\overline{R}L)$ (+h.c.)	
$\mathcal{O}_{QuNL}$	$(\overline{Q} u_R)(\overline{N_R} L)$

$(\overline{R}R)(\overline{R}R)$	
$\mathcal{O}_{NN}$	$(\overline{N_R}\gamma^\mu N_R)(\overline{N_R}\gamma_\mu N_R)$
$\mathcal{O}_{eN}$	$(\overline{e}_R\gamma^\mu e_R)(\overline{N_R}\gamma_\mu N_R)$
$\mathcal{O}_{uN}$	$(\overline{u}_R\gamma^\mu u_R)(\overline{N_R}\gamma_\mu N_R)$
$\mathcal{O}_{dN}$	$(\overline{d}_R\gamma^\mu d_R)(\overline{N_R}\gamma_\mu N_R)$
$\mathcal{O}_{duNe}$	$(\overline{d}_R\gamma^\mu u_R)(\overline{N_R}\gamma_\mu e_R)$
$\mathcal{O}_{NNNN}$	$(\overline{N_R^c} N_R)(\overline{N_R^c} N_R)$

$(\overline{L}L)(\overline{R}R)$	
$\mathcal{O}_{LN}$	$(\overline{L}\gamma^\mu L)(\overline{N_R}\gamma_\mu N_R)$
$\mathcal{O}_{QN}$	$(\overline{Q}\gamma^\mu Q)(\overline{N_R}\gamma_\mu N_R)$
$(\overline{L}R)(\overline{L}R)$ (+h.c.)	
$\mathcal{O}_{LNLe}$	$(\overline{L} N_R)\epsilon(\overline{L} e_R)$
$\mathcal{O}_{LNQd}$	$(\overline{L} N_R)\epsilon(\overline{Q} d_R)$
$\mathcal{O}_{LdQN}$	$(\overline{L} d_R)\epsilon(\overline{Q} N_R)$

N_RSMEFT at $d = 6$

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$\not{B}$: ψ^4 (+h.c.)	
$\mathcal{O}_{QQdN}$	$(QQ)(d_R N_R)$
$\mathcal{O}_{uddN}$	$(u_R d_R)(d_R N_R)$

Tree-level, but
baryon number violating
proton decay!

Hirsch, Helo & Ota
JHEP06 (2018) 047

N_RSMEFT at $d = 6$

$d = 6$ operators that can be opened at tree-level:

ψ^2H^3 (+h.c.)		$(\overline{R}R)(\overline{R}R)$		$(\overline{L}L)(\overline{R}R)$	
$\mathcal{O}_{LNH^3}$	$(\overline{L}N_R)\tilde{H}(H^\dagger H)$	$\mathcal{O}_{NN}$	$(\overline{N_R}\gamma^\mu N_R)(\overline{N_R}\gamma_\mu N_R)$	$\mathcal{O}_{LN}$	$(\overline{L}\gamma^\mu L)(\overline{N_R}\gamma_\mu N_R)$
ψ^2H^2D (+h.c.)		$\mathcal{O}_{eN}$	$(\overline{e}_R\gamma^\mu e_R)(\overline{N_R}\gamma_\mu N_R)$	$\mathcal{O}_{QN}$	$(\overline{Q}\gamma^\mu Q)(\overline{N_R}\gamma_\mu N_R)$
$\mathcal{O}_{NH^2D}$	$(\overline{N_R}\gamma^\mu N_R)(H^\dagger i\overleftrightarrow{D}_\mu H)$	$\mathcal{O}_{uN}$	$(\overline{u}_R\gamma^\mu u_R)(\overline{N_R}\gamma_\mu N_R)$	$(\overline{L}R)(\overline{L}R)$ (+h.c.)	
$\mathcal{O}_{NeH^2D}$	$(\overline{N_R}\gamma^\mu e_R)(\tilde{H}^\dagger iD_\mu H)$	$\mathcal{O}_{dN}$	$(\overline{d}_R\gamma^\mu d_R)(\overline{N_R}\gamma_\mu N_R)$	$\mathcal{O}_{LNLe}$	$(\overline{L}N_R)\epsilon(\overline{L}e_R)$
$(\overline{L}R)(\overline{R}L)$ (+h.c.)		$\mathcal{O}_{duNe}$	$(\overline{d}_R\gamma^\mu u_R)(\overline{N_R}\gamma_\mu e_R)$	$\mathcal{O}_{LNQd}$	$(\overline{L}N_R)\epsilon(\overline{Q}d_R)$
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Tree-level, but
baryon number violating — Hirsch, Helo & Ota
proton decay! — JHEP06 (2018) 047

ψ^2HX (+h.c.)	
$\mathcal{O}_{NB}$	$\overline{L}\sigma_{\mu\nu}N_R\tilde{H}B^{\mu\nu}$
$\mathcal{O}_{NW}$	$\overline{L}\sigma_{\mu\nu}N_R\tilde{H}W^{\mu\nu}$

Loop generated operators
Neutrino magnetic moments — Aparici et al.
$N_R \to \gamma + \nu$ — PRD 80 (2009) 013010

N_RSMEFT at $d = 7$

$d = 7$ operators that can be opened at tree-level:

$\psi^2 H^3 D$		$\psi^4 H$		$\psi^4 H$	
$\mathcal{O}_{NLH^3D}$	$\epsilon_{ij}(\overline{N_R^c}\gamma_\mu L^i)(iD^\mu H^j)(H^\dagger H)$	$\mathcal{O}_{LNLH}$	$\epsilon_{ij}(\overline{L}\gamma_\mu L)(\overline{N_R^c}\gamma^\mu L^i)H^j$	$\mathcal{O}_{LNeH}$	$(\overline{L}N_R)(\overline{N_R^c}e_R)H$
	$\epsilon_{ij}(\overline{N_R^c}\gamma_\mu L^i)H^j(H^\dagger i\overleftrightarrow{D}^\mu H)$	$\mathcal{O}_{QNLH}$	$\epsilon_{ij}(\overline{Q}\gamma_\mu Q)(\overline{N_R^c}\gamma^\mu L^i)H^j$	$\mathcal{O}_{eLNH}$	$H^\dagger(\overline{e_R}L)(\overline{N_R^c}N_R)$
$\psi^2 H^2 D^2$			$\epsilon_{ij}(\overline{Q}\gamma_\mu Q^i)(\overline{N_R^c}\gamma^\mu L^j)H$	$\mathcal{O}_{QNdH}$	$(\overline{Q}N_R)(\overline{N_R^c}d_R)H$
$\mathcal{O}_{NeH^2D^2}$	$\epsilon_{ij}(\overline{N_R^c}\overleftrightarrow{D}_\mu e_R)(H^i D^\mu H^j)$	$\mathcal{O}_{eNLH}$	$\epsilon_{ij}(\overline{e_R}\gamma_\mu e_R)(\overline{N_R^c}\gamma^\mu L^i)H^j$	$\mathcal{O}_{dQNH}$	$H^\dagger(\overline{d_R}Q)(\overline{N_R^c}N_R)$
$\mathcal{O}_{NH^2D^2}$	$(\overline{N_R^c}\overleftrightarrow{\partial}_\mu N_R)(H^\dagger\overleftrightarrow{D}^\mu H)$	$\mathcal{O}_{dNLH}$	$\epsilon_{ij}(\overline{d_R}\gamma_\mu d_R)(\overline{N_R^c}\gamma^\mu L^i)H^j$	$\mathcal{O}_{QNuH}$	$(\overline{Q}N_R)(\overline{N_R^c}u_R)\tilde{H}$
	$(\overline{N_R^c}N_R)(D_\mu H)^\dagger D^\mu H$	$\mathcal{O}_{uNLH}$	$\epsilon_{ij}(\overline{u_R}\gamma_\mu u_R)(\overline{N_R^c}\gamma^\mu L^i)H^j$	$\mathcal{O}_{uQNH}$	$\tilde{H}^\dagger(\overline{u_R}Q)(\overline{N_R^c}N_R)$
$\psi^2 H^2 X$		$\mathcal{O}_{duNLH}$	$\epsilon_{ij}(\overline{d_R}\gamma_\mu u_R)(\overline{N_R^c}\gamma^\mu L^i)\tilde{H}^j$	$\mathcal{O}_{LNNH}$	$(\overline{L}N_R)(\overline{N_R^c}N_R)\tilde{H}$
$\mathcal{O}_{NeH^2W}$	$(\epsilon\tau^I)_{ij}(\overline{N_R^c}\sigma^{\mu\nu}e_R)(H^i H^j)W^I_{\mu\nu}$	$\mathcal{O}_{dQNeH}$	$\epsilon_{ij}(\overline{d_R}Q^i)(\overline{N_R^c}e_R)H^j$	$\mathcal{O}_{NLNH}$	$\tilde{H}^\dagger(\overline{N_R}L)(\overline{N_R^c}N_R)$
$\mathcal{O}_{NH^2B}$	$(\overline{N_R^c}\sigma^{\mu\nu}N_R)(H^\dagger H)B_{\mu\nu}$	$\mathcal{O}_{QuNeH}$	$(\overline{Q}u_R)(\overline{N_R^c}e_R)H$	$\psi^2 H^4$	
$\mathcal{O}_{NH^2W}$	$(\overline{N_R^c}\sigma^{\mu\nu}N_R)(H^\dagger\tau^I H)W^I_{\mu\nu}$		$(\overline{Q}\sigma_{\mu\nu}u_R)(\overline{N_R^c}\sigma^{\mu\nu}e_R)H$	$\mathcal{O}_{NH^4}$	$(\overline{N_R^c}N_R)(H^\dagger H)^2$

N_RSMEFT at $d = 7$

$d = 7$ operators that can be opened at tree-level:

$\psi^2 H^3 D$	
$\mathcal{O}_{NLH^3D}$	$\epsilon_{ij}(\overline{N_R^c}\gamma_\mu L^i)(iD^\mu H^j)(H^\dagger H)$
	$\epsilon_{ij}(\overline{N_R^c}\gamma_\mu L^i)H^j(H^\dagger i\overleftrightarrow{D}^\mu H)$
$\psi^2 H^2 D^2$	
$\mathcal{O}_{NeH^2D^2}$	$\epsilon_{ij}(\overline{N_R^c}\overleftrightarrow{D}_\mu e_R)(H^i D^\mu H^j)$
$\mathcal{O}_{NH^2D^2}$	$(\overline{N_R^c}\overleftrightarrow{\partial}_\mu N_R)(H^\dagger \overleftrightarrow{D}^\mu H)$
	$(\overline{N_R^c}N_R)(D_\mu H)^\dagger D^\mu H$
$\psi^2 H^2 X$	
$\mathcal{O}_{NeH^2W}$	$(\epsilon\tau^I)_{ij}(\overline{N_R^c}\sigma^{\mu\nu}e_R)(H^i H^j)W^I_{\mu\nu}$
$\mathcal{O}_{NH^2B}$	$(\overline{N_R^c}\sigma^{\mu\nu}N_R)(H^\dagger H)B_{\mu\nu}$
$\mathcal{O}_{NH^2W}$	$(\overline{N_R^c}\sigma^{\mu\nu}N_R)(H^\dagger\tau^I H)W^I_{\mu\nu}$

$\psi^4 H$	
$\mathcal{O}_{LNLH}$	$\epsilon_{ij}(\overline{L}\gamma_\mu L)(\overline{N_R^c}\gamma^\mu L^i)H^j$
$\mathcal{O}_{QNLH}$	$\epsilon_{ij}(\overline{Q}\gamma_\mu Q)(\overline{N_R^c}\gamma^\mu L^i)H^j$
	$\epsilon_{ij}(\overline{Q}\gamma_\mu Q^i)(\overline{N_R^c}\gamma^\mu L^j)H$
$\mathcal{O}_{eNLH}$	$\epsilon_{ij}(\overline{e_R}\gamma_\mu e_R)(\overline{N_R^c}\gamma^\mu L^i)H^j$
$\mathcal{O}_{dNLH}$	$\epsilon_{ij}(\overline{d_R}\gamma_\mu d_R)(\overline{N_R^c}\gamma^\mu L^i)H^j$
$\mathcal{O}_{uNLH}$	$\epsilon_{ij}(\overline{u_R}\gamma_\mu u_R)(\overline{N_R^c}\gamma^\mu L^i)H^j$
$\mathcal{O}_{duNLH}$	$\epsilon_{ij}(\overline{d_R}\gamma_\mu u_R)(\overline{N_R^c}\gamma^\mu L^i)\tilde{H}^j$
$\mathcal{O}_{dQNeH}$	$\epsilon_{ij}(\overline{d_R}Q^i)(\overline{N_R^c}e_R)H^j$
$\mathcal{O}_{QuNeH}$	$(\overline{Q}u_R)(\overline{N_R^c}e_R)H$
	$(\overline{Q}\sigma_{\mu\nu}u_R)(\overline{N_R^c}\sigma^{\mu\nu}e_R)H$

$\psi^4 H$	
$\mathcal{O}_{LNeH}$	$(\overline{L}N_R)(\overline{N_R^c}e_R)H$
$\mathcal{O}_{eLNH}$	$H^\dagger(\overline{e_R}L)(\overline{N_R^c}N_R)$
$\mathcal{O}_{QNdH}$	$(\overline{Q}N_R)(\overline{N_R^c}d_R)H$
$\mathcal{O}_{dQNH}$	$H^\dagger(\overline{d_R}Q)(\overline{N_R^c}N_R)$
$\mathcal{O}_{QNuH}$	$(\overline{Q}N_R)(\overline{N_R^c}u_R)\tilde{H}$
$\mathcal{O}_{uQNH}$	$\tilde{H}^\dagger(\overline{u_R}Q)(\overline{N_R^c}N_R)$
$\mathcal{O}_{LNNH}$	$(\overline{L}N_R)(\overline{N_R^c}N_R)\tilde{H}$
$\mathcal{O}_{NLNH}$	$\tilde{H}^\dagger(\overline{N_R}L)(\overline{N_R^c}N_R)$
$\psi^2 H^4$	
$\mathcal{O}_{NH^4}$	$(\overline{N_R^c}N_R)(H^\dagger H)^2$

Are these operators violating lepton number?

N_RSMEFT at $d = 7$

$d = 7$ operators that can be opened at tree-level:

$\psi^2 H^3 D$	
$\mathcal{O}_{NLH^3D}$	$\epsilon_{ij}(\overline{N_R^c}\gamma_\mu L^i)(iD^\mu H^j)(H^\dagger H)$
	$\epsilon_{ij}(\overline{N_R^c}\gamma_\mu L^i)H^j(H^\dagger i\overleftrightarrow{D}^\mu H)$
$\psi^2 H^2 D^2$	
$\mathcal{O}_{NeH^2D^2}$	$\epsilon_{ij}(\overline{N_R^c}\overleftrightarrow{D}_\mu e_R)(H^i D^\mu H^j)$
$\mathcal{O}_{NH^2D^2}$	$(\overline{N_R^c}\overleftrightarrow{\partial}_\mu N_R)(H^\dagger \overleftrightarrow{D}^\mu H)$
	$(\overline{N_R^c}N_R)(D_\mu H)^\dagger D^\mu H$
$\psi^2 H^2 X$	
$\mathcal{O}_{NeH^2W}$	$(\epsilon\tau^I)_{ij}(\overline{N_R^c}\sigma^{\mu\nu}e_R)(H^i H^j)W^I_{\mu\nu}$
$\mathcal{O}_{NH^2B}$	$(\overline{N_R^c}\sigma^{\mu\nu}N_R)(H^\dagger H)B_{\mu\nu}$
$\mathcal{O}_{NH^2W}$	$(\overline{N_R^c}\sigma^{\mu\nu}N_R)(H^\dagger\tau^I H)W^I_{\mu\nu}$

$\psi^4 H$	
$\mathcal{O}_{LNLH}$	$\epsilon_{ij}(\overline{L}\gamma_\mu L)(\overline{N_R^c}\gamma^\mu L^i)H^j$
$\mathcal{O}_{QNLH}$	$\epsilon_{ij}(\overline{Q}\gamma_\mu Q)(\overline{N_R^c}\gamma^\mu L^i)H^j$
	$\epsilon_{ij}(\overline{Q}\gamma_\mu Q^i)(\overline{N_R^c}\gamma^\mu L^j)H$
$\mathcal{O}_{eNLH}$	$\epsilon_{ij}(\overline{e_R}\gamma_\mu e_R)(\overline{N_R^c}\gamma^\mu L^i)H^j$
$\mathcal{O}_{dNLH}$	$\epsilon_{ij}(\overline{d_R}\gamma_\mu d_R)(\overline{N_R^c}\gamma^\mu L^i)H^j$
$\mathcal{O}_{uNLH}$	$\epsilon_{ij}(\overline{u_R}\gamma_\mu u_R)(\overline{N_R^c}\gamma^\mu L^i)H^j$
$\mathcal{O}_{duNLH}$	$\epsilon_{ij}(\overline{d_R}\gamma_\mu u_R)(\overline{N_R^c}\gamma^\mu L^i)\tilde{H}^j$
$\mathcal{O}_{dQNeH}$	$\epsilon_{ij}(\overline{d_R}Q^i)(\overline{N_R^c}e_R)H^j$
$\mathcal{O}_{QuNeH}$	$(\overline{Q}u_R)(\overline{N_R^c}e_R)H$
	$(\overline{Q}\sigma_{\mu\nu}u_R)(\overline{N_R^c}\sigma^{\mu\nu}e_R)H$

$\psi^4 H$	
$\mathcal{O}_{LNeH}$	$(\overline{L}N_R)(\overline{N_R^c}e_R)H$
$\mathcal{O}_{eLNH}$	$H^\dagger(\overline{e_R}L)(\overline{N_R^c}N_R)$
$\mathcal{O}_{QNdH}$	$(\overline{Q}N_R)(\overline{N_R^c}d_R)H$
$\mathcal{O}_{dQNH}$	$H^\dagger(\overline{d_R}Q)(\overline{N_R^c}N_R)$
$\mathcal{O}_{QNuH}$	$(\overline{Q}N_R)(\overline{N_R^c}u_R)\tilde{H}$
$\mathcal{O}_{uQNH}$	$\tilde{H}^\dagger(\overline{u_R}Q)(\overline{N_R^c}N_R)$
$\mathcal{O}_{LNNH}$	$(\overline{L}N_R)(\overline{N_R^c}N_R)\tilde{H}$
$\mathcal{O}_{NLNH}$	$\tilde{H}^\dagger(\overline{N_R}L)(\overline{N_R^c}N_R)$
$\psi^2 H^4$	
$\mathcal{O}_{NH^4}$	$(\overline{N_R^c}N_R)(H^\dagger H)^2$

Are these operators violating lepton number?

If $L(N_R) = 1$: yes! But ...

N_RSMEFT at $d = 7$

$d = 7$ operators that can be opened at tree-level:

$\psi^2 H^3 D$	
$\mathcal{O}_{NLH^3D}$	$\epsilon_{ij}(\overline{N_R^c}\gamma_\mu L^i)(iD^\mu H^j)(H^\dagger H)$
	$\epsilon_{ij}(\overline{N_R^c}\gamma_\mu L^i)H^j(H^\dagger i\overleftrightarrow{D}^\mu H)$
$\psi^2 H^2 D^2$	
$\mathcal{O}_{NeH^2D^2}$	$\epsilon_{ij}(\overline{N_R^c}\overleftrightarrow{D}_\mu e_R)(H^i D^\mu H^j)$
$\mathcal{O}_{NH^2D^2}$	$(\overline{N_R^c}\overleftrightarrow{\partial}_\mu N_R)(H^\dagger \overleftrightarrow{D}^\mu H)$
	$(\overline{N_R^c}N_R)(D_\mu H)^\dagger D^\mu H$
$\psi^2 H^2 X$	
$\mathcal{O}_{NeH^2W}$	$(\epsilon\tau^I)_{ij}(\overline{N_R^c}\sigma^{\mu\nu}e_R)(H^i H^j)W^I_{\mu\nu}$
$\mathcal{O}_{NH^2B}$	$(\overline{N_R^c}\sigma^{\mu\nu}N_R)(H^\dagger H)B_{\mu\nu}$
$\mathcal{O}_{NH^2W}$	$(\overline{N_R^c}\sigma^{\mu\nu}N_R)(H^\dagger\tau^I H)W^I_{\mu\nu}$

$\psi^4 H$	
$\mathcal{O}_{LNLH}$	$\epsilon_{ij}(\overline{L}\gamma_\mu L)(\overline{N_R^c}\gamma^\mu L^i)H^j$
$\mathcal{O}_{QNLH}$	$\epsilon_{ij}(\overline{Q}\gamma_\mu Q)(\overline{N_R^c}\gamma^\mu L^i)H^j$
	$\epsilon_{ij}(\overline{Q}\gamma_\mu Q^i)(\overline{N_R^c}\gamma^\mu L^j)H$
$\mathcal{O}_{eNLH}$	$\epsilon_{ij}(\overline{e_R}\gamma_\mu e_R)(\overline{N_R^c}\gamma^\mu L^i)H^j$
$\mathcal{O}_{dNLH}$	$\epsilon_{ij}(\overline{d_R}\gamma_\mu d_R)(\overline{N_R^c}\gamma^\mu L^i)H^j$
$\mathcal{O}_{uNLH}$	$\epsilon_{ij}(\overline{u_R}\gamma_\mu u_R)(\overline{N_R^c}\gamma^\mu L^i)H^j$
$\mathcal{O}_{duNLH}$	$\epsilon_{ij}(\overline{d_R}\gamma_\mu u_R)(\overline{N_R^c}\gamma^\mu L^i)\tilde{H}^j$
$\mathcal{O}_{dQNeH}$	$\epsilon_{ij}(\overline{d_R}Q^i)(\overline{N_R^c}e_R)H^j$
$\mathcal{O}_{QuNeH}$	$(\overline{Q}u_R)(\overline{N_R^c}e_R)H$
	$(\overline{Q}\sigma_{\mu\nu}u_R)(\overline{N_R^c}\sigma^{\mu\nu}e_R)H$

$\psi^4 H$	
$\mathcal{O}_{LNeH}$	$(\overline{L}N_R)(\overline{N_R^c}e_R)H$
$\mathcal{O}_{eLNH}$	$H^\dagger(\overline{e_R}L)(\overline{N_R^c}N_R)$
$\mathcal{O}_{QNdH}$	$(\overline{Q}N_R)(\overline{N_R^c}d_R)H$
$\mathcal{O}_{dQNH}$	$H^\dagger(\overline{d_R}Q)(\overline{N_R^c}N_R)$
$\mathcal{O}_{QNuH}$	$(\overline{Q}N_R)(\overline{N_R^c}u_R)\tilde{H}$
$\mathcal{O}_{uQNH}$	$\tilde{H}^\dagger(\overline{u_R}Q)(\overline{N_R^c}N_R)$
$\mathcal{O}_{LNNH}$	$(\overline{L}N_R)(\overline{N_R^c}N_R)\tilde{H}$
$\mathcal{O}_{NLNH}$	$\tilde{H}^\dagger(\overline{N_R}L)(\overline{N_R^c}N_R)$
$\psi^2 H^4$	
$\mathcal{O}_{NH^4}$	$(\overline{N_R^c}N_R)(H^\dagger H)^2$

Are these operators violating lepton number?

If $L(N_R) = 1$: yes! But ...

(i) Single N_R operators conserve L if $L(N_R) = -1$

(ii) Pair N_R operators conserve L if $L(N_R) = 0$

One operator alone not sufficient to define LNV!

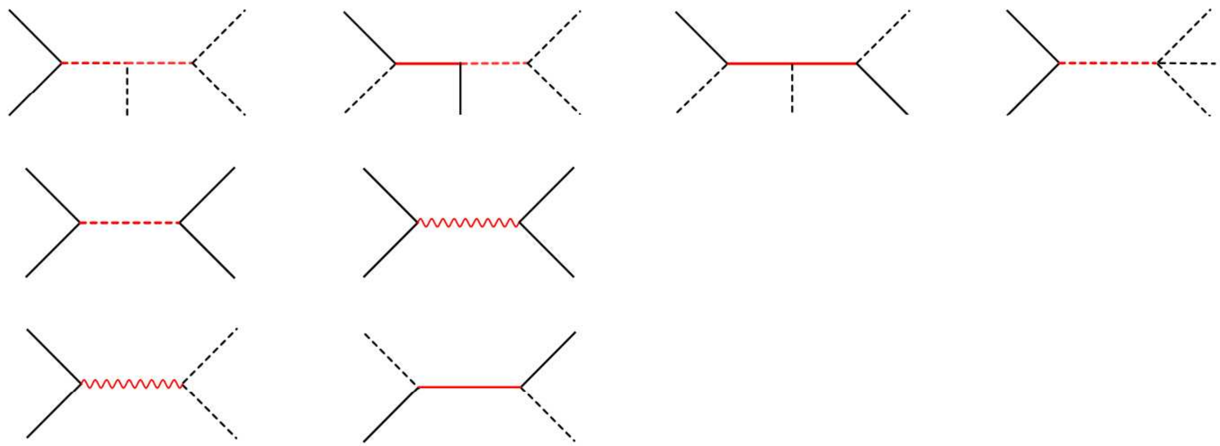
Decompositions for N_RSMEFT

Tree-level diagrams for $d = 6$ operators:

$\psi^2 H^3$:

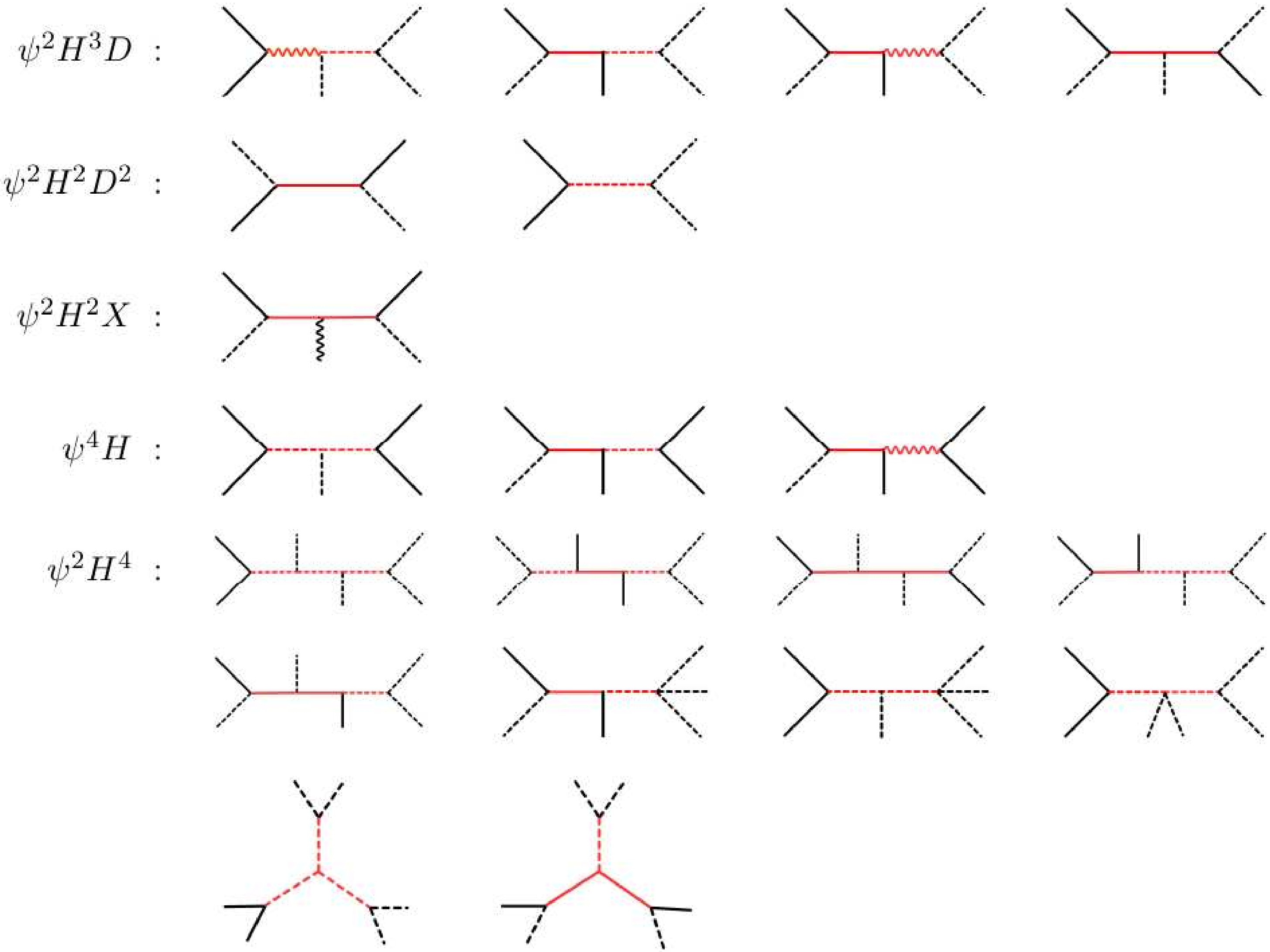
ψ^4 :

$\psi^2 H^2 D$:



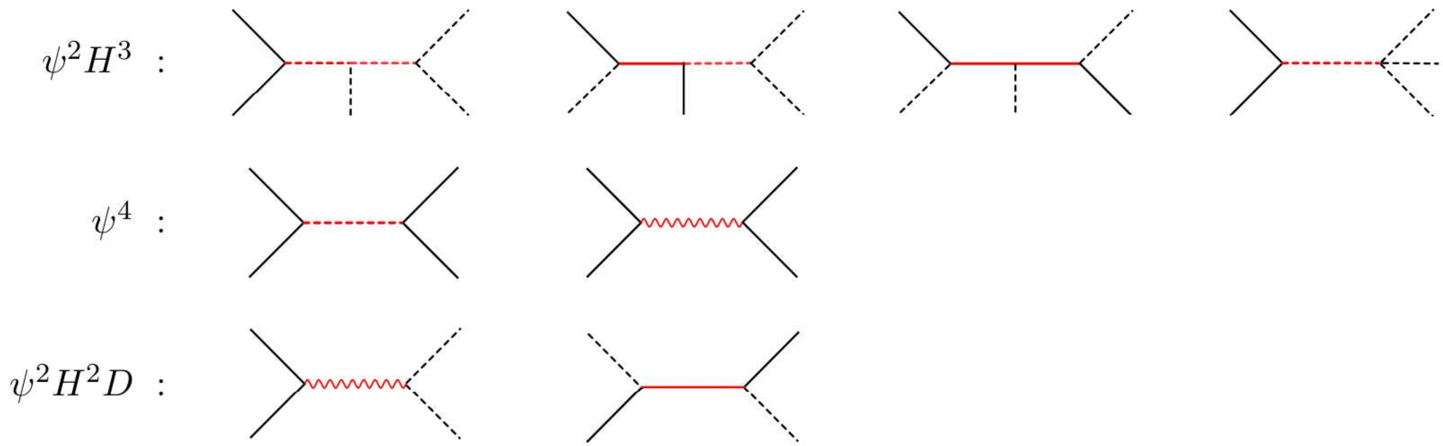
Decompositions for N_RSMEFT

Tree-level diagrams for $d = 7$ operators:



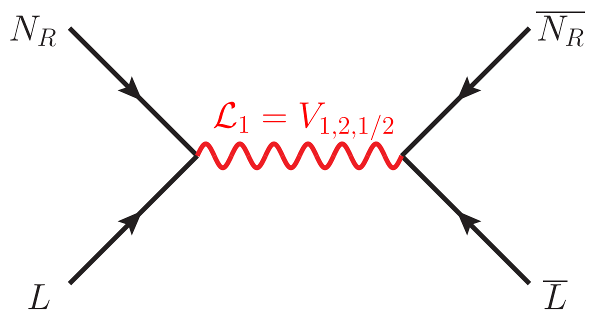
Decompositions for N_RSMEFT

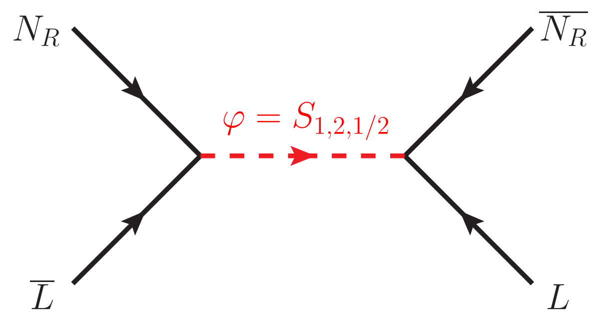
Tree-level diagrams for $d = 6$ operators:



Example (ψ^4): Vector: Scalar:

$\mathcal{O}_{\mathbf{LN}}$:





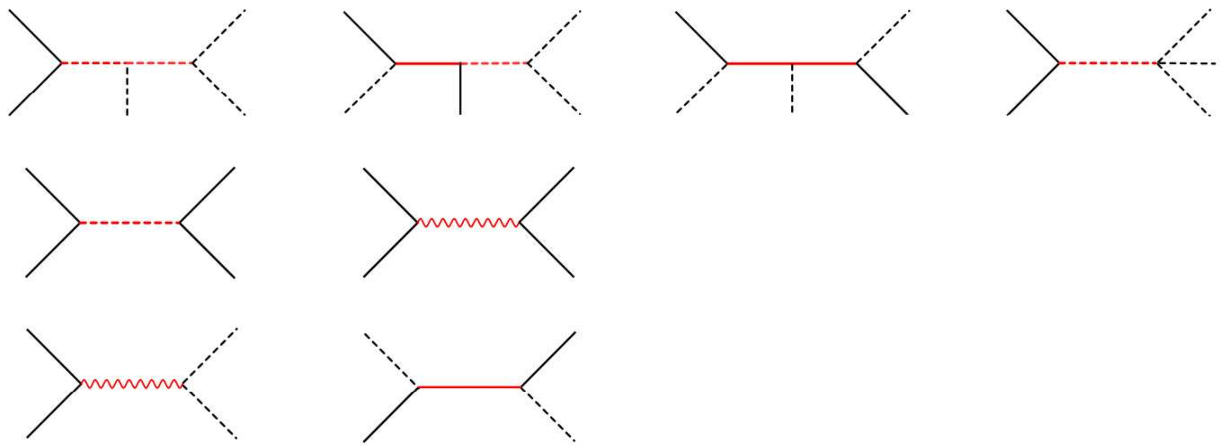
Decompositions for N_RSMEFT

Tree-level diagrams for $d = 6$ operators:

$\psi^2 H^3$:

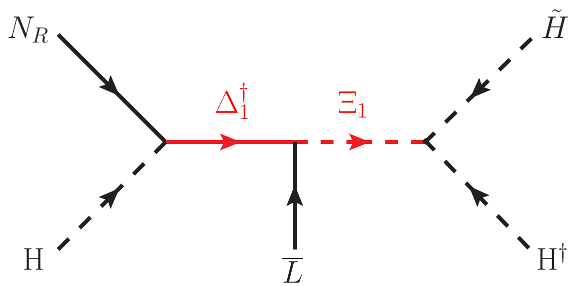
ψ^4 :

$\psi^2 H^2 D$:



One more example ($\psi^2 H^3$):

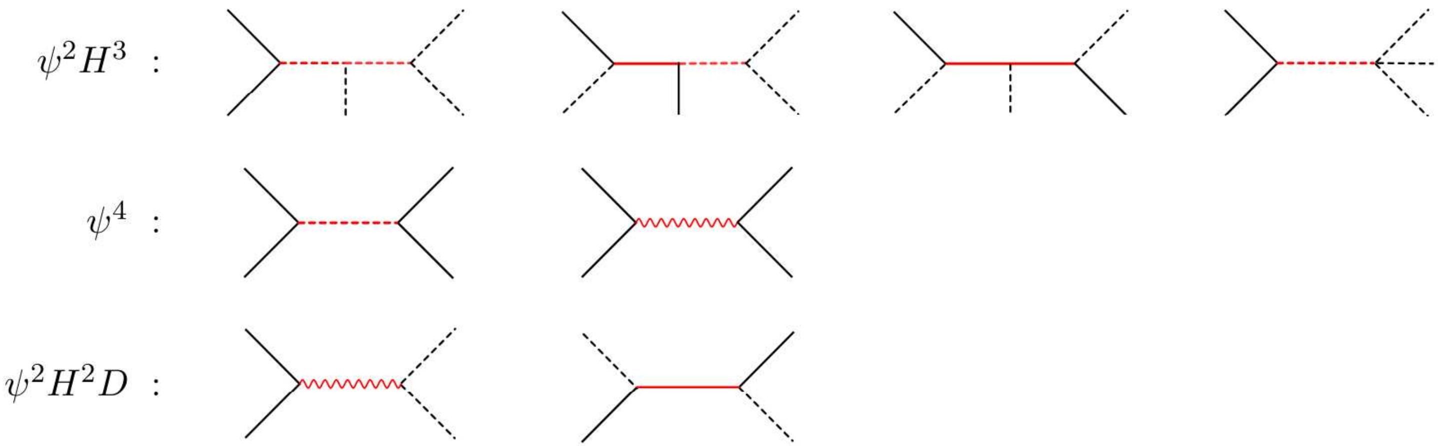
$\mathcal{O}_{\mathbf{LNH^3}}$:



Fermion-scalar

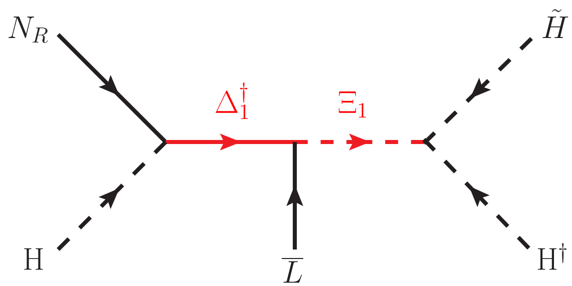
Decompositions for N_RSMEFT

Tree-level diagrams for $d = 6$ operators:



One more example ($\psi^2 H^3$):

$\mathcal{O}_{\mathbf{LNH^3}}$:

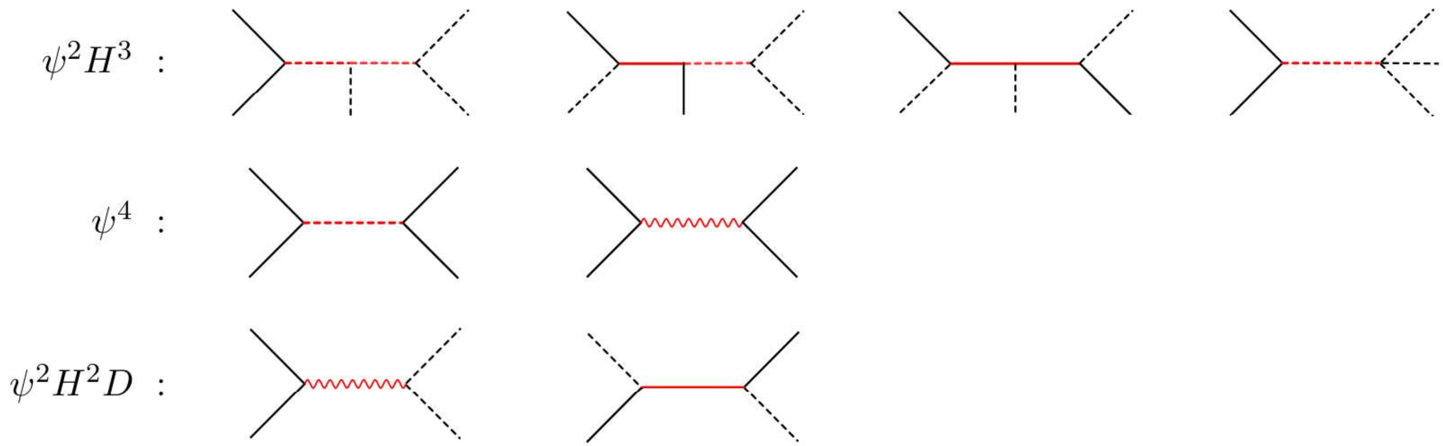


Fermion-scalar

$\Rightarrow$ Repeat for all operators and diagrams $\longrightarrow\!\longrightarrow\!\longrightarrow$ "dictionary"

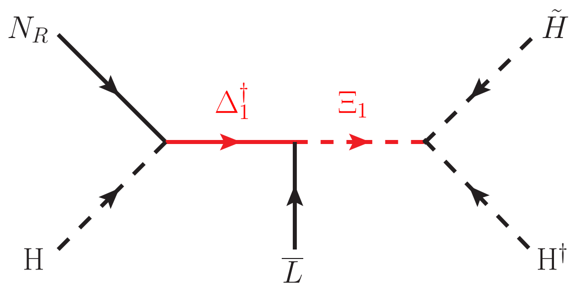
Decompositions for N_RSMEFT

Tree-level diagrams for $d = 6$ operators:



One more example ($\psi^2 H^3$):

$\mathcal{O}_{\mathbf{LNH^3}}$:



Fermion-scalar

⇒ Repeat for all operators and diagrams →→→ "dictionary"

⇒ `Mathematica` code `ModGen` Cepdello et al., JHEP09 (2022) 229

Fields in N_RSMEFT at $d = 6/7$

Scalars

Name	$\mathcal{S}$	$\mathcal{S}_1$	φ	Ξ	Ξ_1
Irrep	$(1,1,0)$	$(1,1,1)$	$(1,2,\frac{1}{2})$	$(1,3,0)$	$(1,3,1)$
$d=6$	$\circ$	$\circ$	$\circ$	$\circ$	$\circ$

Name	ω_1	ω_2	Π_1	Π_7	ζ
Irrep	$(3,1,-\frac{1}{3})$	$(3,1,\frac{2}{3})$	$(3,2,\frac{1}{6})$	$(3,2,\frac{7}{6})$	$(3,3,-\frac{1}{3})$
$d=6$	$\circ$	$\circ$	$\circ$		

Fermions

Name	N	E	Δ_1	Δ_3	Σ	Σ_1
Irrep	$(1,1,0)$	$(1,1,-1)$	$(1,2,-\frac{1}{2})$	$(1,2,-\frac{3}{2})$	$(1,3,0)$	$(1,3,-1)$
$d=6$	$\circ$		$\circ$		$\circ$	$\circ$

Name	U	D	Q_1	Q_5	Q_7	T_1	T_2
Irrep	$(3,1,\frac{2}{3})$	$(3,1,-\frac{1}{3})$	$(3,2,\frac{1}{6})$	$(3,2,-\frac{5}{6})$	$(3,2,\frac{7}{6})$	$(3,3,-\frac{1}{3})$	$(3,3,\frac{2}{3})$
$d=6$							

Vectors

Name	$\mathcal{B}$	$\mathcal{B}_1$	$\mathcal{W}$	$\mathcal{W}_1$	$\mathcal{L}_1$	$\mathcal{L}_3$
Irrep	$(1,1,0)$	$(1,1,1)$	$(1,3,0)$	$(1,3,1)$	$(1,2,\frac{1}{2})$	$(1,2,-\frac{3}{2})$
$d=6$	$\circ$	$\circ$			$\circ$	

Name	$\mathcal{U}_1$	$\mathcal{U}_2$	$\mathcal{Q}_1$	$\mathcal{Q}_5$	$\mathcal{X}$
Irrep	$(3,1,-\frac{1}{3})$	$(3,1,\frac{2}{3})$	$(3,2,\frac{1}{6})$	$(3,2,-\frac{5}{6})$	$(3,3,\frac{2}{3})$
$d=6$	$\circ$	$\circ$	$\circ$		

Notation follows closely:

de Blas et al.
JHEP 03 (2018) 109

"Granada dictionary"

$\rightarrow$ tree-level $d = 6$ SMEFT

Models and operators: $d = 6$

Models	Operators
$\mathcal{S}$	$\mathcal{O}_{NN}$, $\mathcal{O}_{NNNN}$
$\mathcal{S}_1$	$\mathcal{O}_{LNLe}$, $\mathcal{O}_{eN}$
φ	$\mathcal{O}_{QuNL}$, $\mathcal{O}_{LNLe}$, $\mathcal{O}_{LNQd}$, $\mathcal{O}_{LN}$, $\mathcal{O}_{LNH^3}$
ω_1	$\mathcal{O}_{LNQd}$, $\mathcal{O}_{dN}$, $\mathcal{O}_{duNe}$
ω_2	$\mathcal{O}_{uN}$
Π_1	$\mathcal{O}_{LNQd}$, $\mathcal{O}_{QN}$
Δ_1	$\mathcal{O}_{NH^2D}$, $\mathcal{O}_{NeH^2D}$
$\mathcal{B}$	$\mathcal{O}_{NH^2D}$, $\mathcal{O}_{NN}$, $\mathcal{O}_{eN}$, $\mathcal{O}_{uN}$, $\mathcal{O}_{dN}$, $\mathcal{O}_{LN}$, $\mathcal{O}_{QN}$
$\mathcal{B}_1$	$\mathcal{O}_{NeH^2D}$, $\mathcal{O}_{eN}$, $\mathcal{O}_{duNe}$
$\mathcal{L}_1$	$\mathcal{O}_{LN}$
$\mathcal{U}_1$	$\mathcal{O}_{dN}$
$\mathcal{U}_2$	$\mathcal{O}_{QuNL}$, $\mathcal{O}_{uN}$, $\mathcal{O}_{duNe}$
$\mathcal{Q}_1$	$\mathcal{O}_{QuNL}$, $\mathcal{O}_{QN}$

Table:

One particle models and operators

Models and operators: $d = 6$

Models	Operators
$\mathcal{S}$	$\mathcal{O}_{NN}$, $\mathcal{O}_{NNNN}$
$\mathcal{S}_1$	$\mathcal{O}_{LNLe}$, $\mathcal{O}_{eN}$
φ	$\mathcal{O}_{QuNL}$, $\mathcal{O}_{LNLe}$, $\mathcal{O}_{LNQd}$, $\mathcal{O}_{LN}$, $\mathcal{O}_{LNH^3}$
ω_1	$\mathcal{O}_{LNQd}$, $\mathcal{O}_{dN}$, $\mathcal{O}_{duNe}$
ω_2	$\mathcal{O}_{uN}$
Π_1	$\mathcal{O}_{LNQd}$, $\mathcal{O}_{QN}$
Δ_1	$\mathcal{O}_{NH^2D}$, $\mathcal{O}_{NeH^2D}$
$\mathcal{B}$	$\mathcal{O}_{NH^2D}$, $\mathcal{O}_{NN}$, $\mathcal{O}_{eN}$, $\mathcal{O}_{uN}$, $\mathcal{O}_{dN}$, $\mathcal{O}_{LN}$, $\mathcal{O}_{QN}$
$\mathcal{B}_1$	$\mathcal{O}_{NeH^2D}$, $\mathcal{O}_{eN}$, $\mathcal{O}_{duNe}$
$\mathcal{L}_1$	$\mathcal{O}_{LN}$
$\mathcal{U}_1$	$\mathcal{O}_{dN}$
$\mathcal{U}_2$	$\mathcal{O}_{QuNL}$, $\mathcal{O}_{uN}$, $\mathcal{O}_{duNe}$
$\mathcal{Q}_1$	$\mathcal{O}_{QuNL}$, $\mathcal{O}_{QN}$

Table:

One particle models and operators

$\psi^2 H^3$	Two-particle models
$\mathcal{O}_{LNH^3}$	$SS:$ $(\mathcal{S},\varphi)$, (Ξ_1,φ), (Ξ,φ) $FF:$ $(\Delta_1,\mathcal{N})$, (Δ_1,Σ_1), (Δ_1,Σ) $FS:$ $(\mathcal{N},\mathcal{S})$, $(\Delta_1,\mathcal{S})$, (Δ_1,Ξ_1), (Σ_1,Ξ_1), (Δ_1,Ξ), (Σ,Ξ)

Two particle models and operator $\mathcal{O}_{LNH^3}$

Models and operators: $d = 6$

Models	Operators
$\mathcal{S}$	$\mathcal{O}_{NN}$, $\mathcal{O}_{NNNN}$
$\mathcal{S}_1$	$\mathcal{O}_{LNLe}$, $\mathcal{O}_{eN}$
φ	$\mathcal{O}_{QuNL}$, $\mathcal{O}_{LNLe}$, $\mathcal{O}_{LNQd}$, $\mathcal{O}_{LN}$, $\mathcal{O}_{LNH^3}$
ω_1	$\mathcal{O}_{LNQd}$, $\mathcal{O}_{dN}$, $\mathcal{O}_{duNe}$
ω_2	$\mathcal{O}_{uN}$
Π_1	$\mathcal{O}_{LNQd}$, $\mathcal{O}_{QN}$
Δ_1	$\mathcal{O}_{NH^2D}$, $\mathcal{O}_{NeH^2D}$
$\mathcal{B}$	$\mathcal{O}_{NH^2D}$, $\mathcal{O}_{NN}$, $\mathcal{O}_{eN}$, $\mathcal{O}_{uN}$, $\mathcal{O}_{dN}$, $\mathcal{O}_{LN}$, $\mathcal{O}_{QN}$
$\mathcal{B}_1$	$\mathcal{O}_{NeH^2D}$, $\mathcal{O}_{eN}$, $\mathcal{O}_{duNe}$
$\mathcal{L}_1$	$\mathcal{O}_{LN}$
$\mathcal{U}_1$	$\mathcal{O}_{dN}$
$\mathcal{U}_2$	$\mathcal{O}_{QuNL}$, $\mathcal{O}_{uN}$, $\mathcal{O}_{duNe}$
$\mathcal{Q}_1$	$\mathcal{O}_{QuNL}$, $\mathcal{O}_{QN}$

Table:

One particle models and operators

$\psi^2 H^3$	Two-particle models
$\mathcal{O}_{LNH^3}$	$SS:$ $(\mathcal{S},\varphi)$, (Ξ_1,φ), (Ξ,φ)
	$FF:$ $(\Delta_1,\mathcal{N})$, (Δ_1,Σ_1), (Δ_1,Σ)
	$FS:$ $(\mathcal{N},\mathcal{S})$, $(\Delta_1,\mathcal{S})$, (Δ_1,Ξ_1), (Σ_1,Ξ_1), (Δ_1,Ξ), (Σ,Ξ)

Two particle models and operator $\mathcal{O}_{LNH^3}$

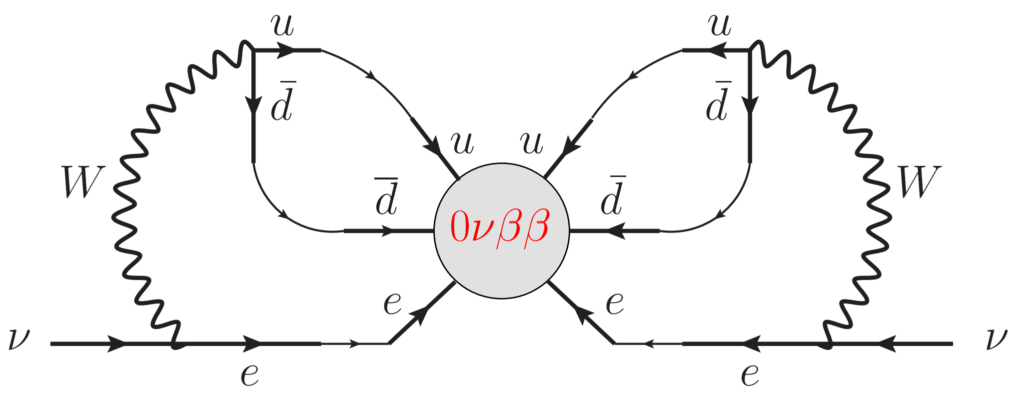
$\Rightarrow$ Repeat for $d = 7$: see JHEP08 (2023) 166

$\mathcal{III}.$

LNV and N_RSMEFT

Lepton number violation

The "black box" theorem for $0\nu\beta\beta$ decay:



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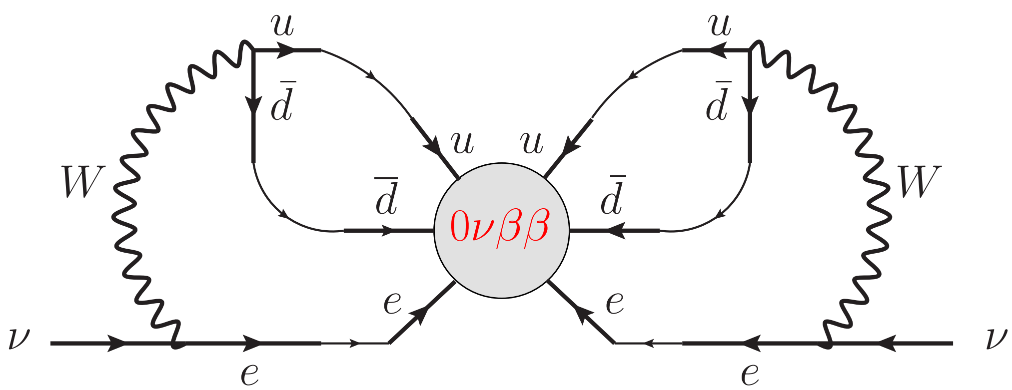

Any mechanism generating $0\nu\beta\beta$ decay will also generate a Majorana mass term for (at least) one neutrino

Schechter & Valle, 1982

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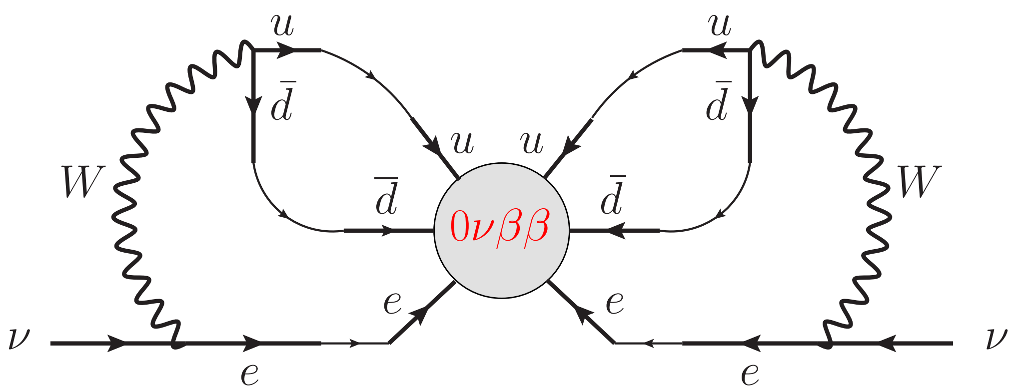

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In SMEFT: $0\nu\beta\beta$ decay is a d=9 operator

Simplest example: $\mathcal{O}_{u^2d^2e^2} = \frac{1}{\Lambda^5}(u_R u_R)(d^c_R d^c_R)(e_R e_R)$

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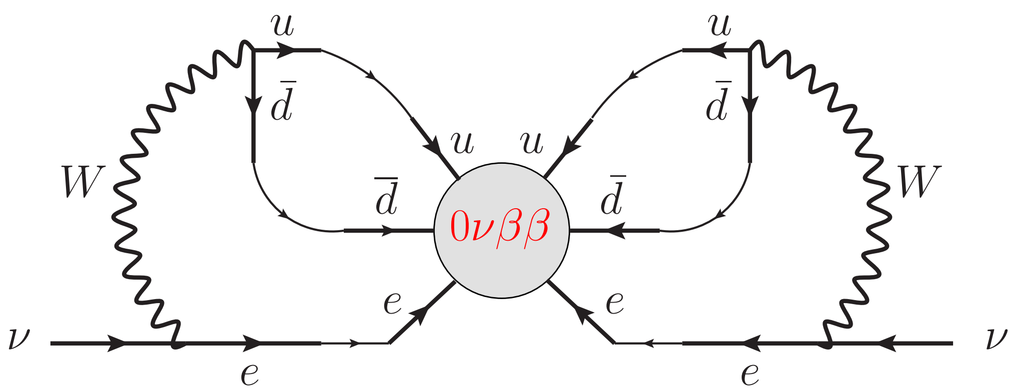

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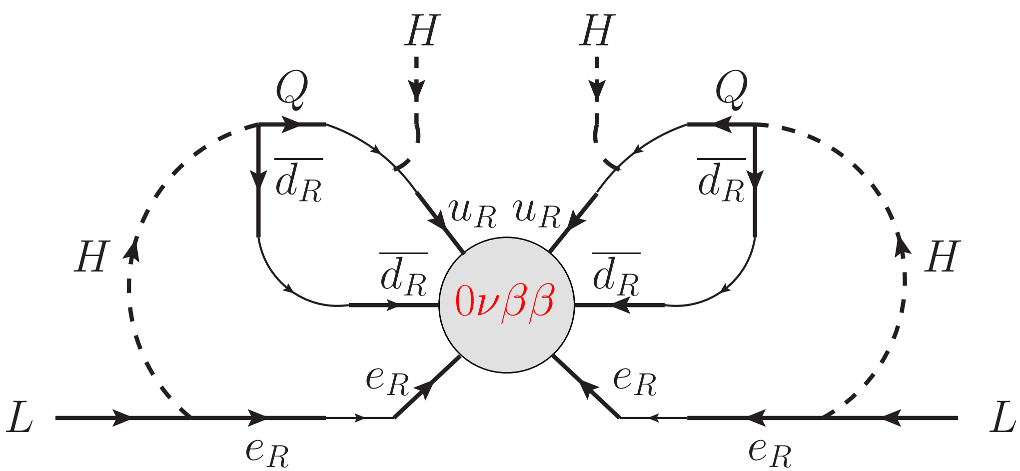

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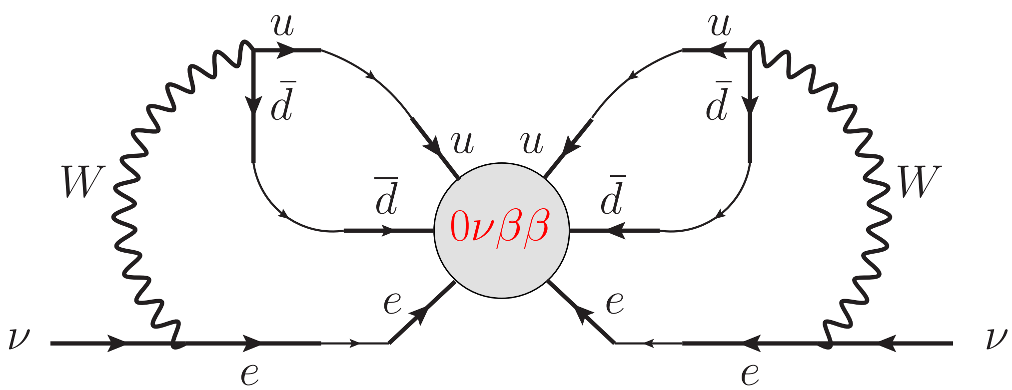

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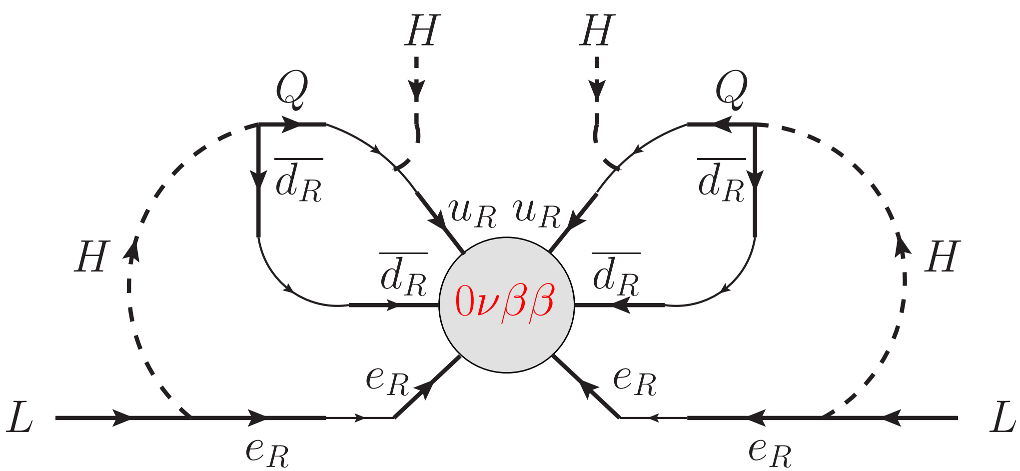


Disclaimer:

4-loop diagram!

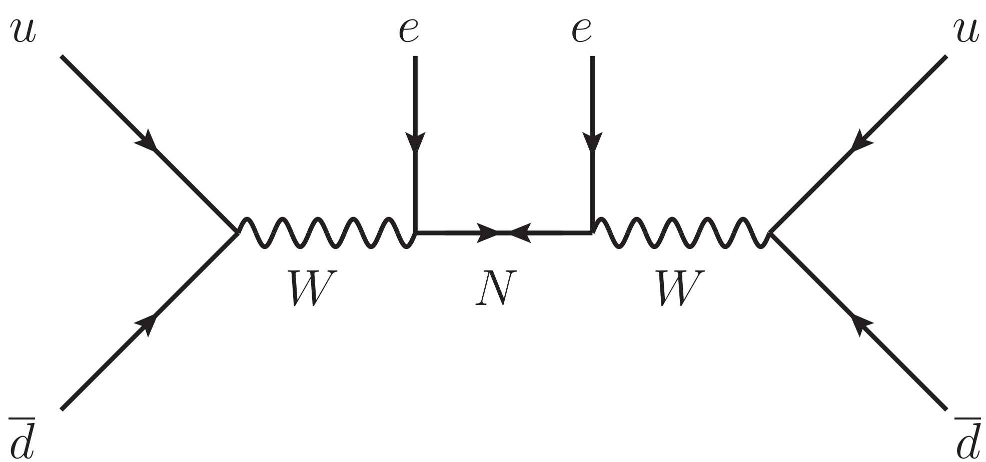
Not the main contribution to m_ν

Decomposition of $0\nu\beta\beta$ decay $d = 9$ operators in:

Bonnet et al., JHEP 03 (2013) 055

$0\nu\beta\beta$ @ LHC

Consider this simple example diagram with N_R:



$$pp \to W^+ \to e^+ N \to e^+ (W^-)^* \to jj$$

$0\nu\beta\beta$ @ *LHC*

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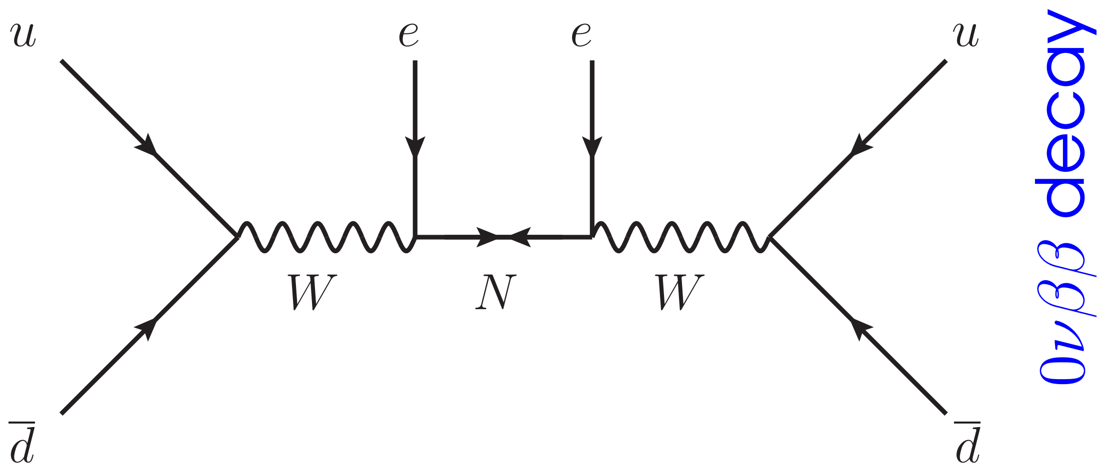

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Sterile neutrino decaying to like-sign lepton "equivalent" to $0\nu\beta\beta$ decay

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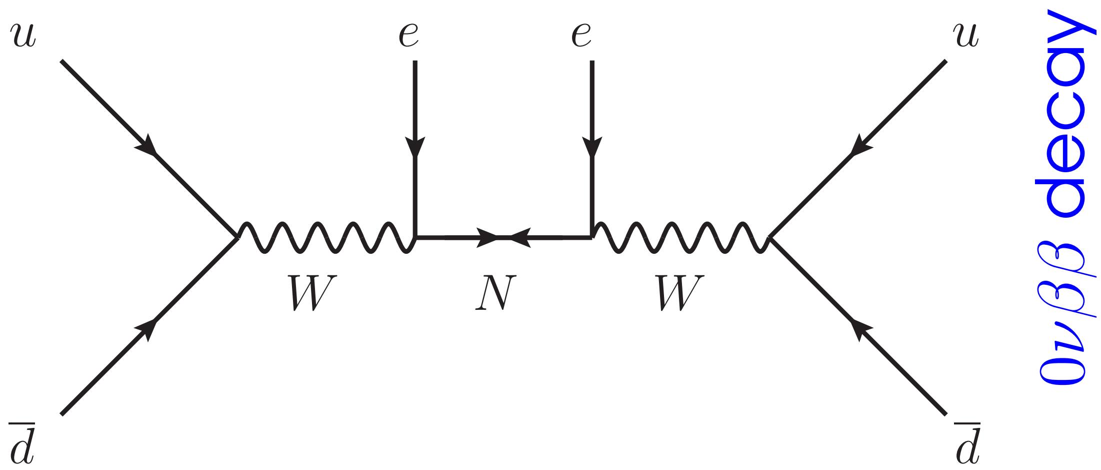

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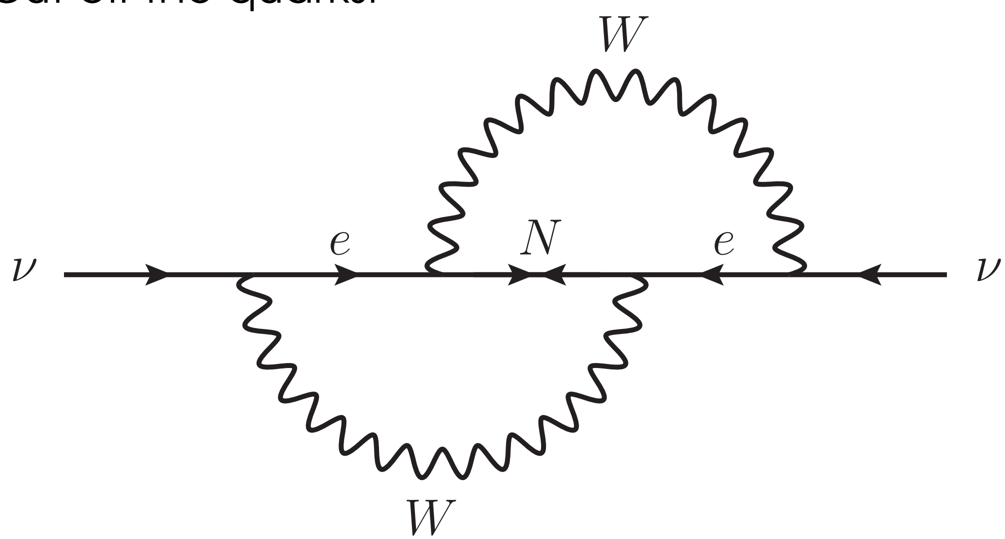

2-loop diagram for m_ν in mass eigenstate basis

$0\nu\beta\beta$ @ *LHC*

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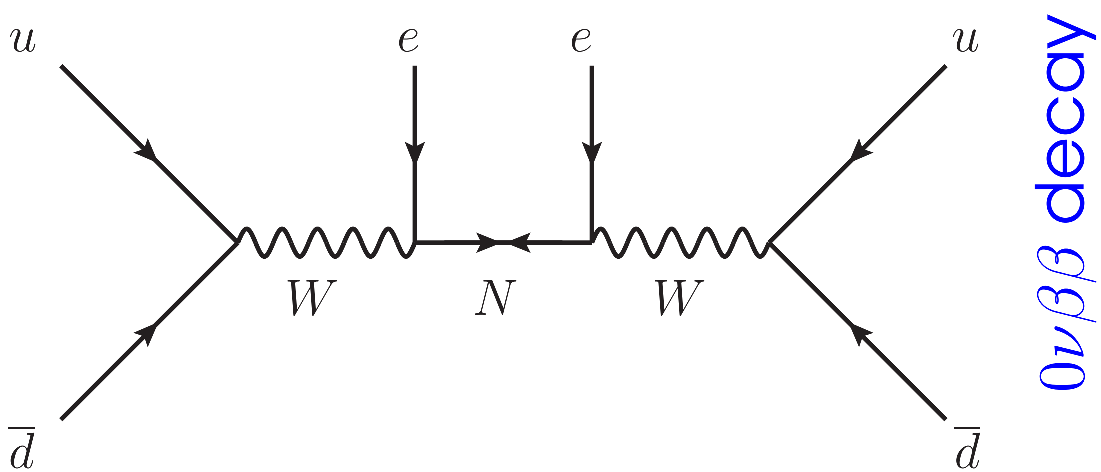

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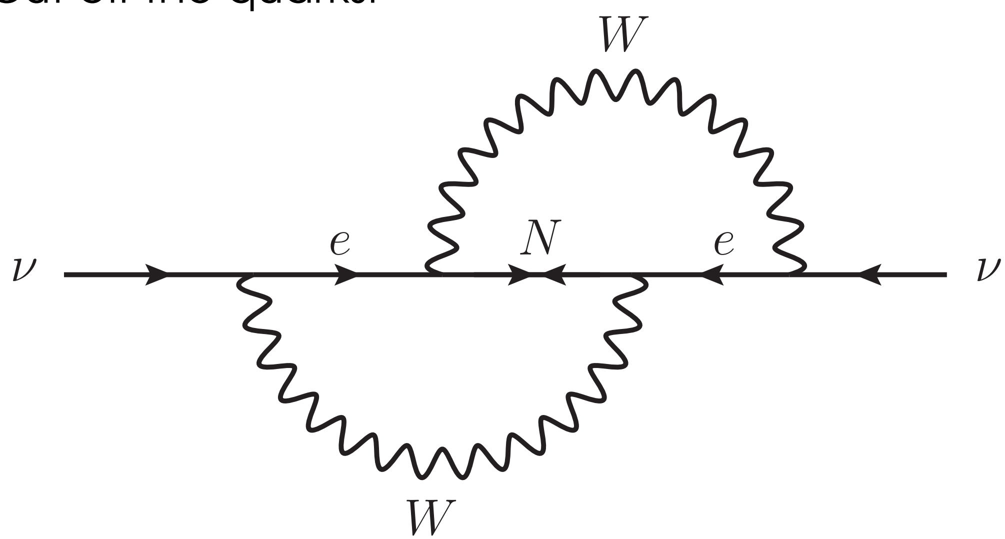

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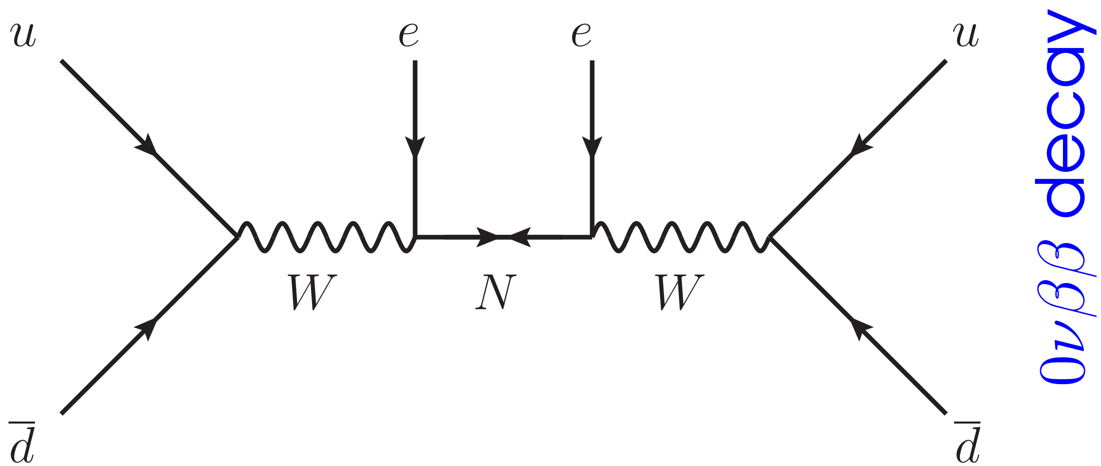

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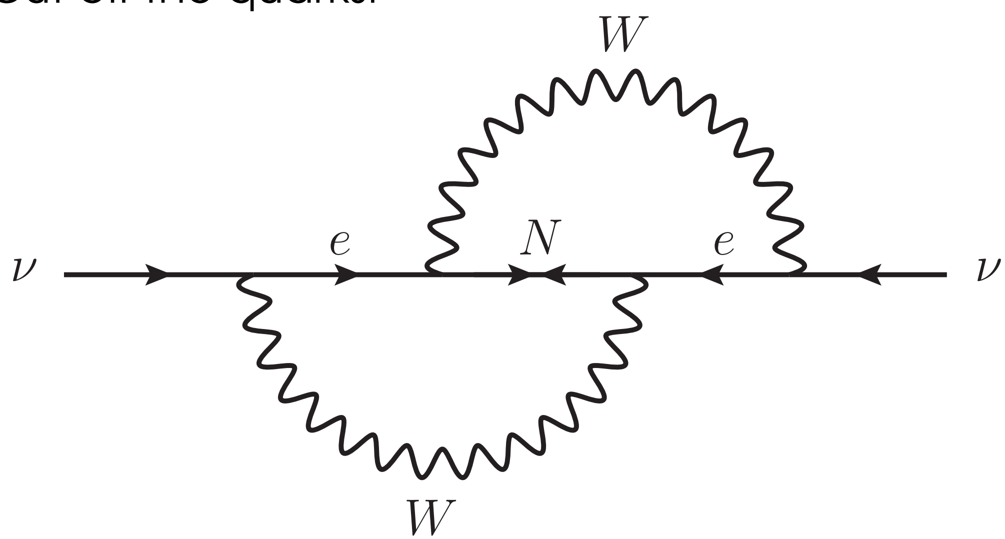

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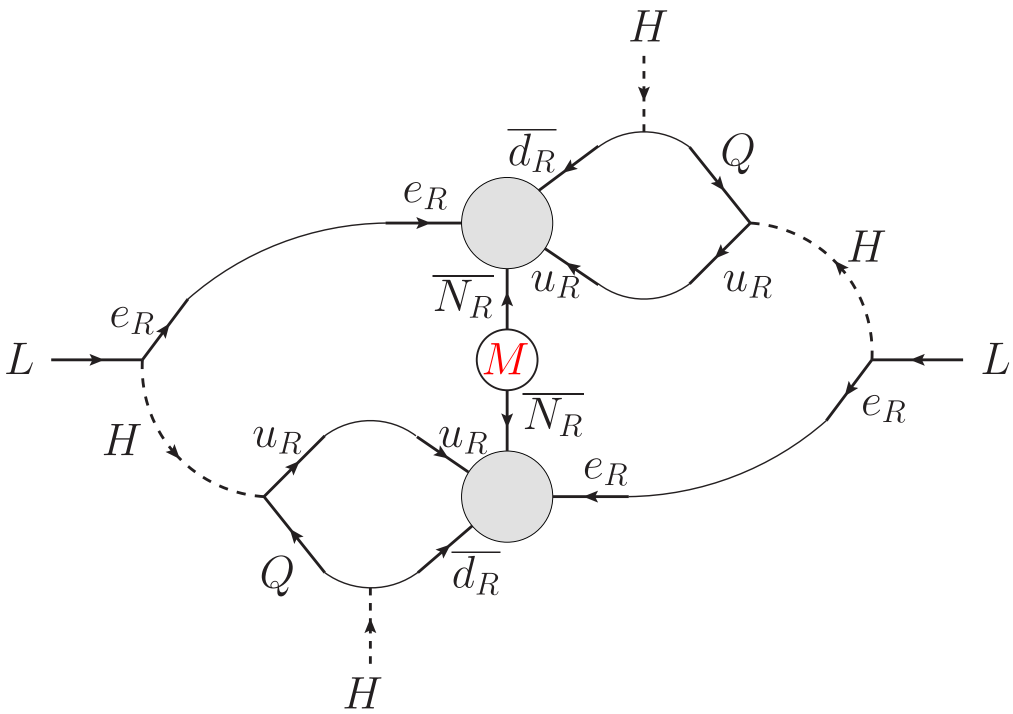
Again:
Not the dominant contribution to m_ν!
Tree-level seesaw!

m_ν @ LHC

Diagram using $d = 6$ N_RSMEFT operator(s):



Example: $\mathcal{O}_{duNe}$

LNV via M_M

m_ν @ LHC

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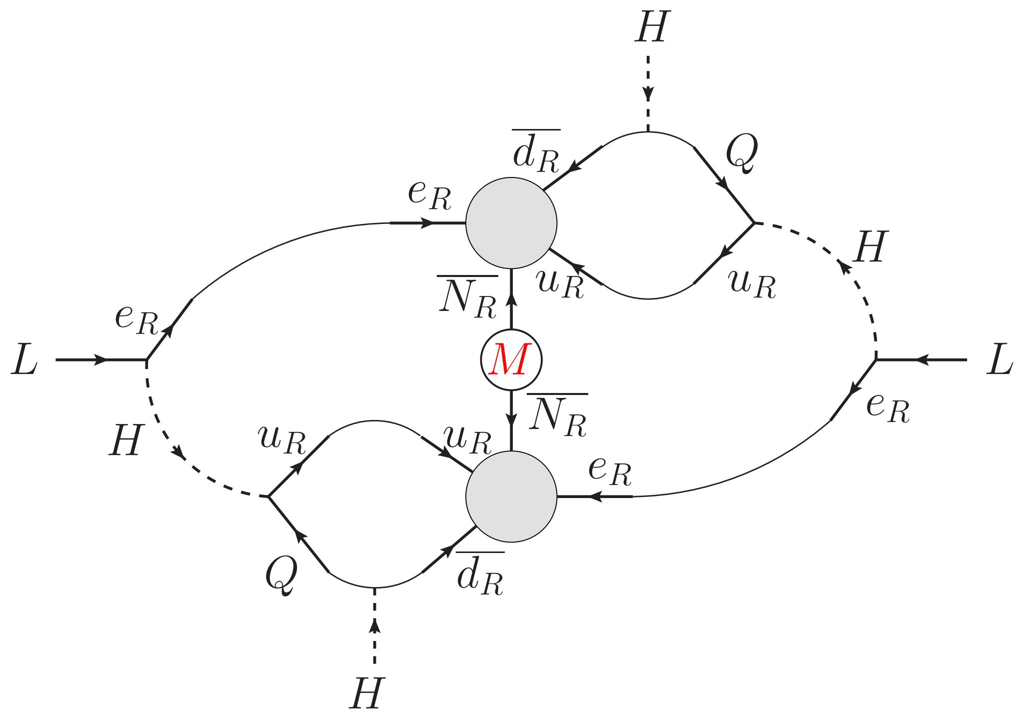

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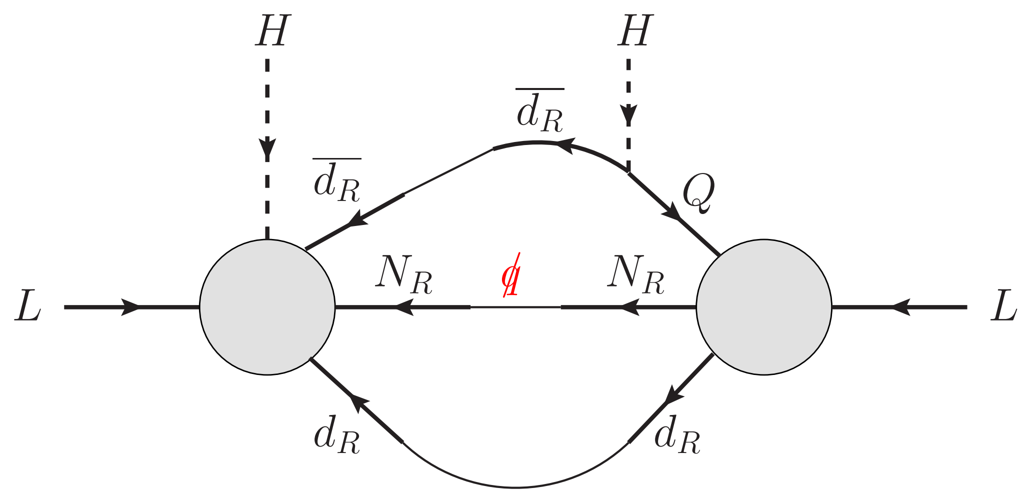

Example: LNV via $\mathcal{O}_{dLNH}$ + $\mathcal{O}_{QdNL}$

m_ν @ LHC

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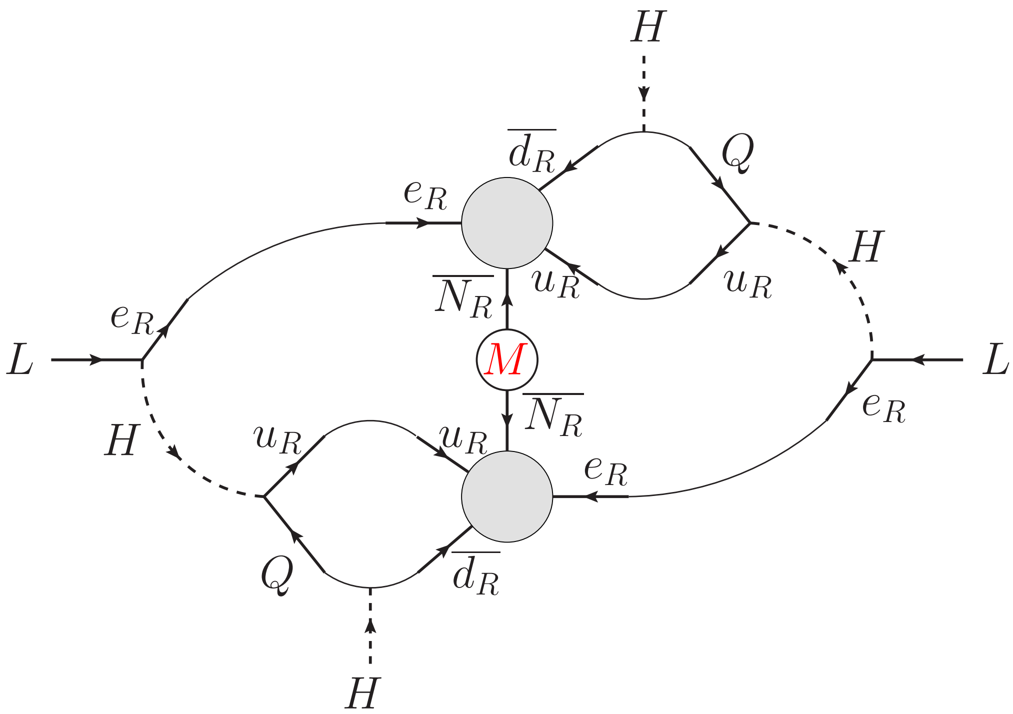

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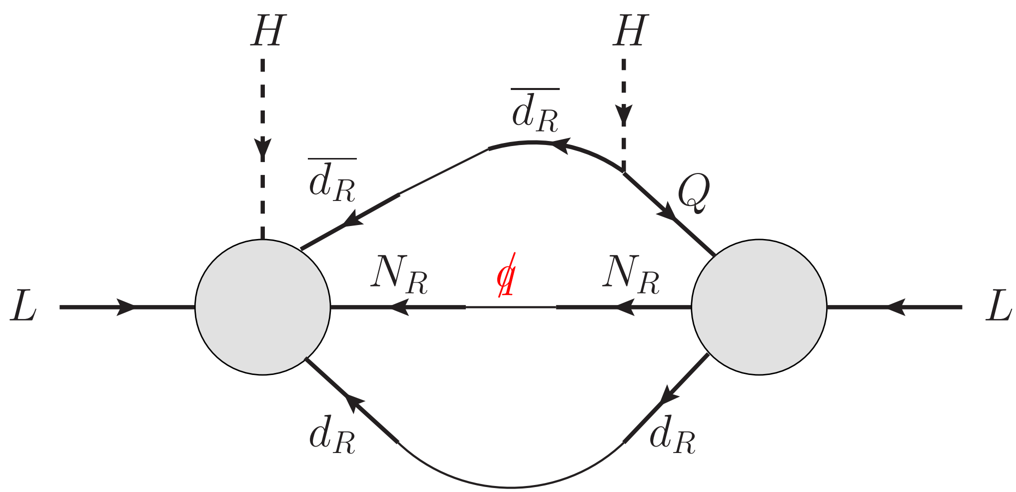
LNV via M_M

Disclaimer:
Loops (practically) never
the main contribution to m_ν



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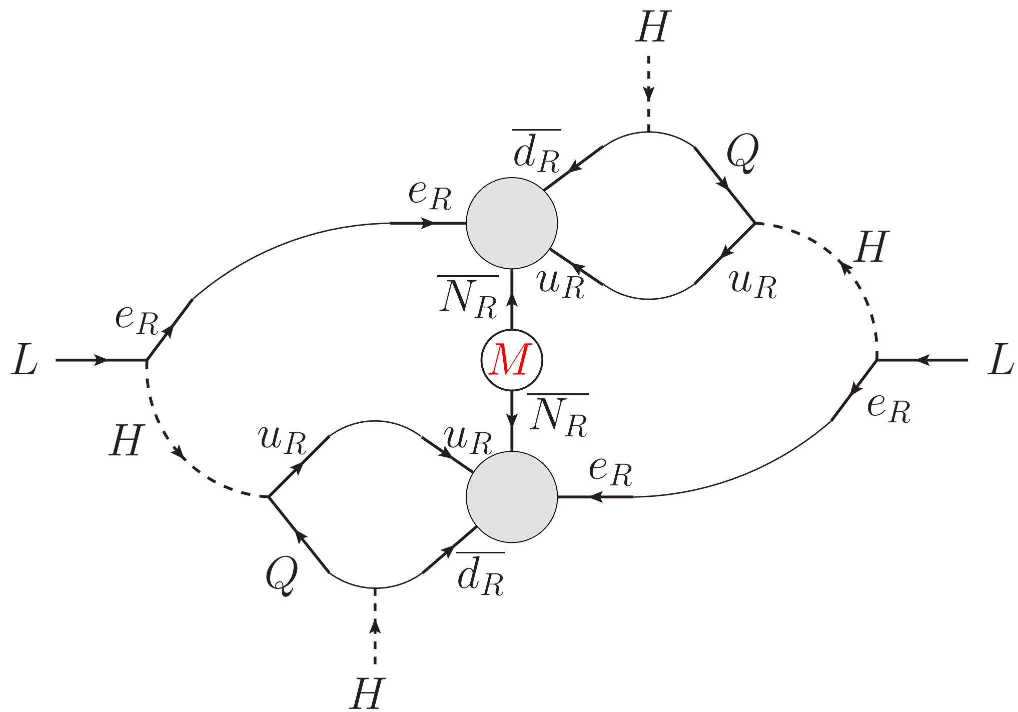

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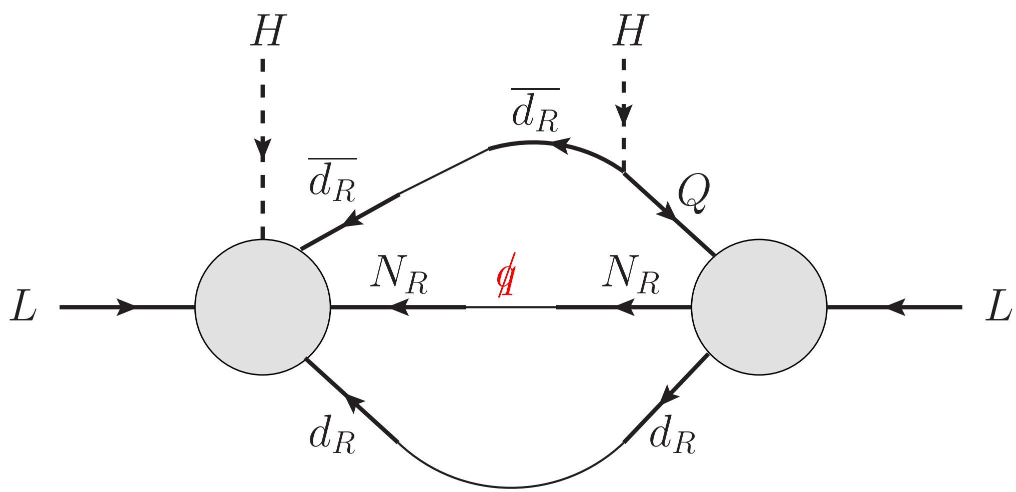


Disclaimer:

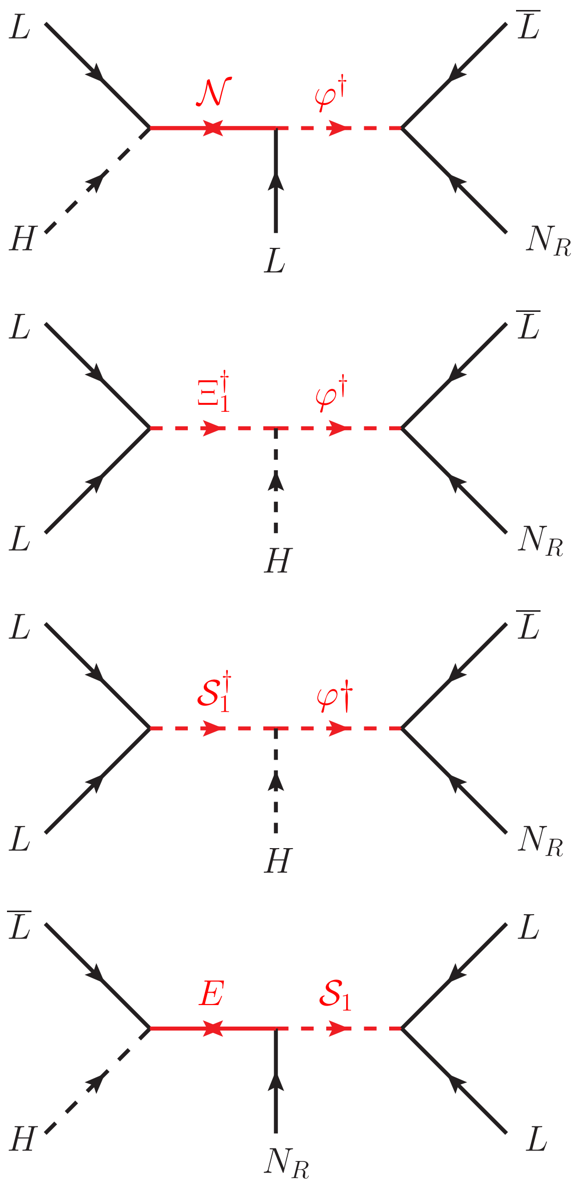
Loops (practically) never the main contribution to m_ν

Need UV model to calculate m_ν!

Example: LNV via $\mathcal{O}_{dLNH}$ + $\mathcal{O}_{QdNL}$

m_ν and $d = 7$ N_RSMEFT

Example operator: $\mathcal{O}_{LNLH}$, four decompositions:



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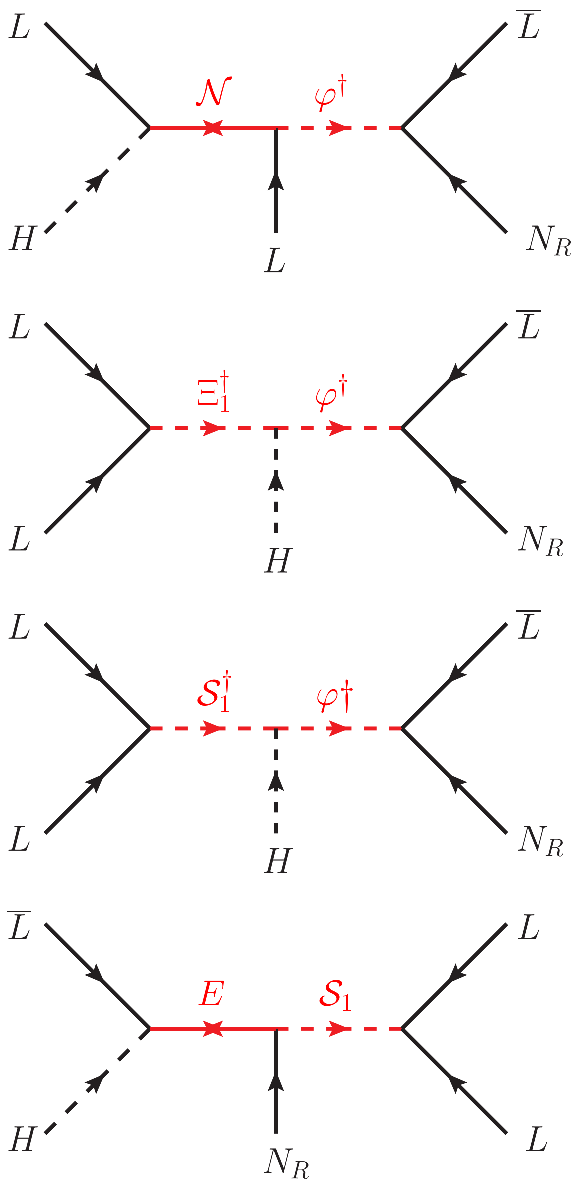

$\Rightarrow$ Majorana $\mathcal{N}$!

seesaw type-I

strong constraint on c_{LNLH} from m_ν

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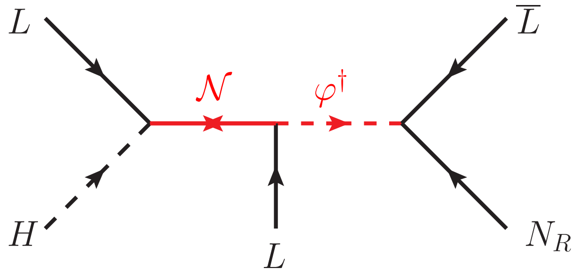

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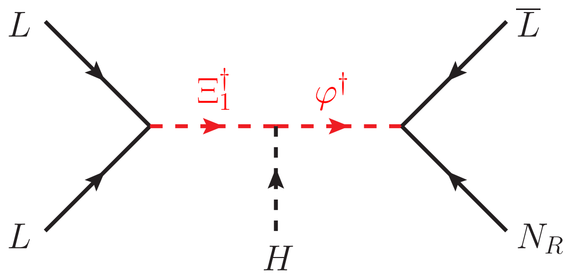
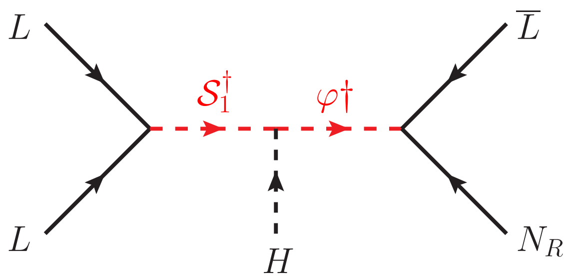
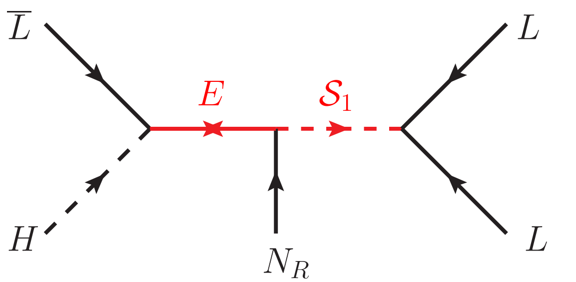


$\Rightarrow \Xi_1 = \Delta = S_{1,3,1}$!

seesaw type-II

strong constraint on c_{LNLH} from m_ν





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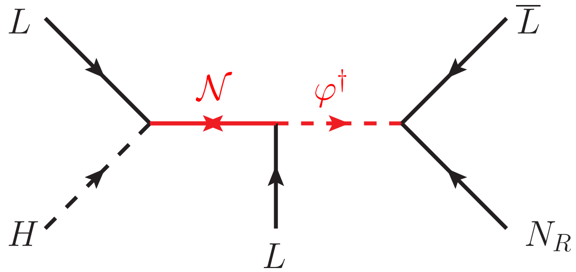

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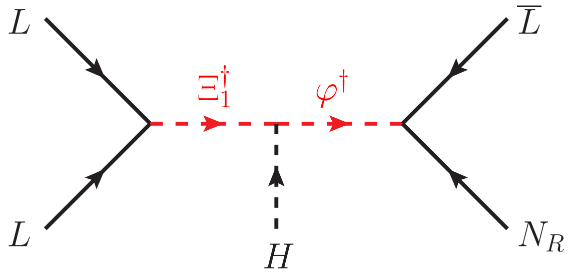

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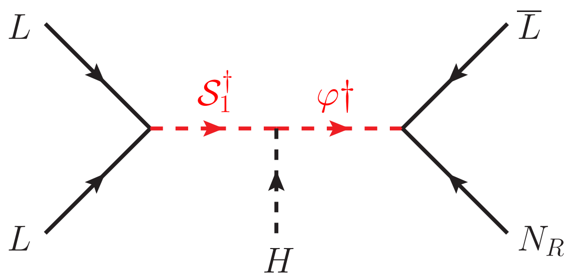
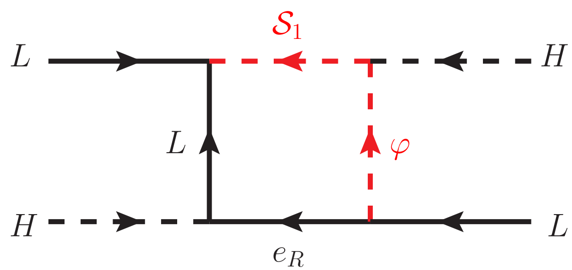
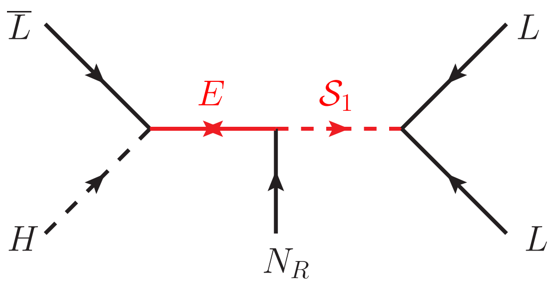




1-loop neutrino mass

One of: c_{LNLH} c_{eNLH} or c_{LNeH} small



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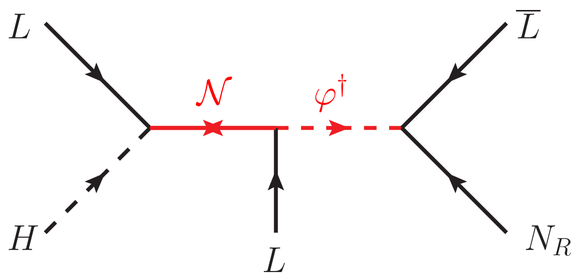

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seesaw type-I
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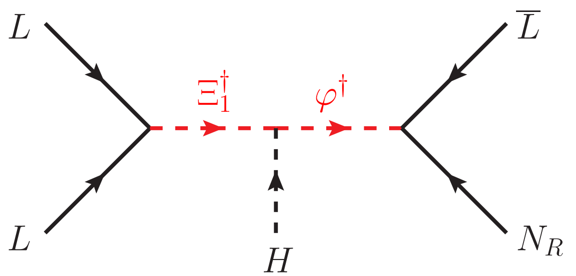

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seesaw type-II
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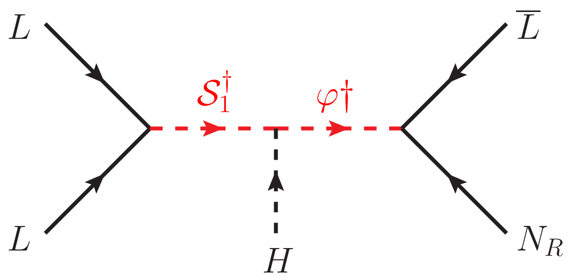

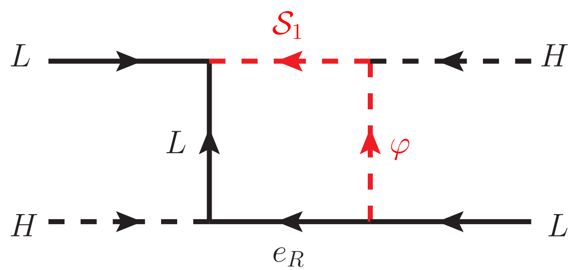

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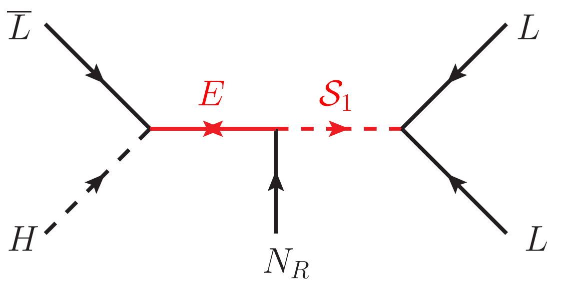
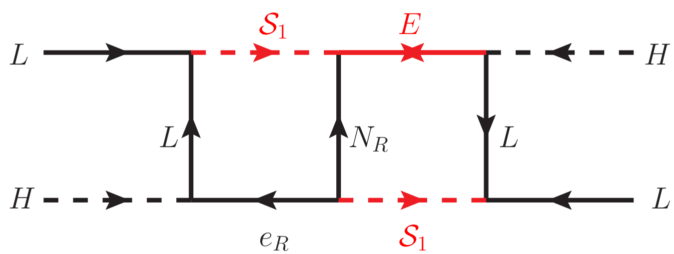


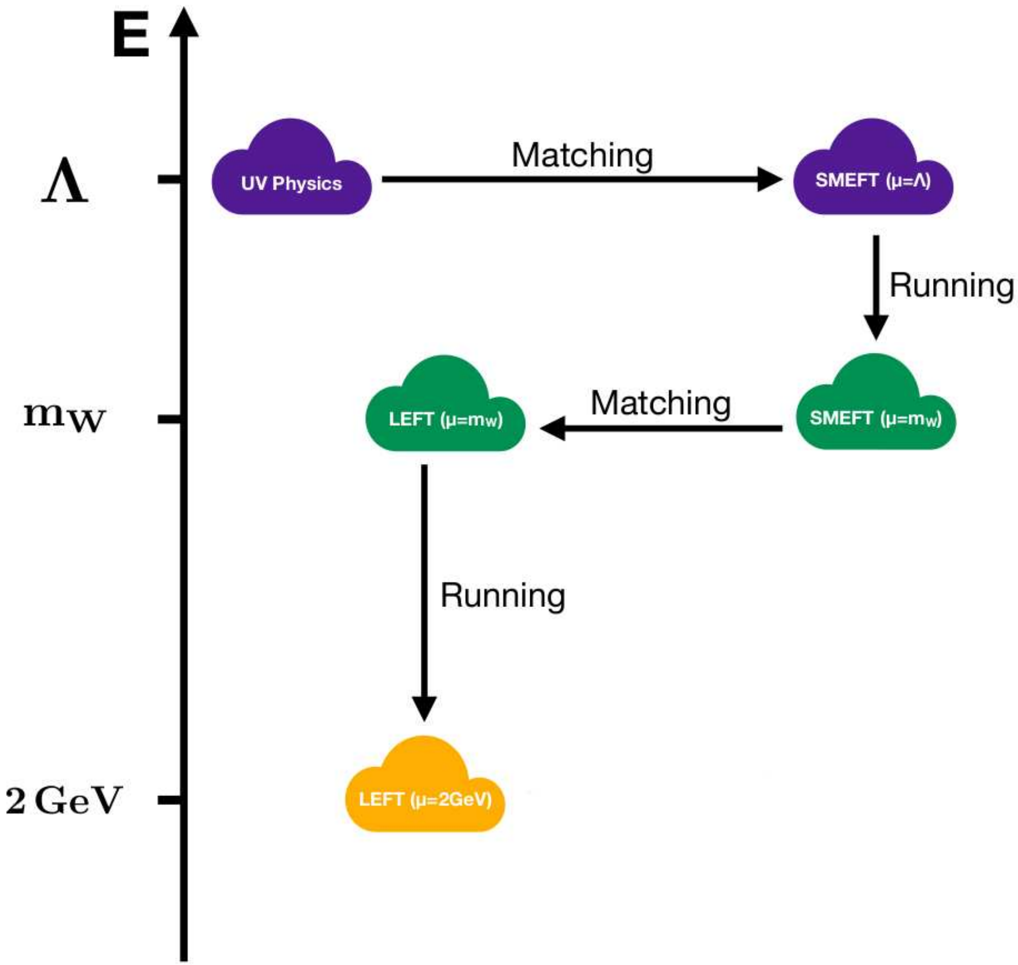


2-loop m_ν
Either c_{LNLH} or c_{LNeH} small

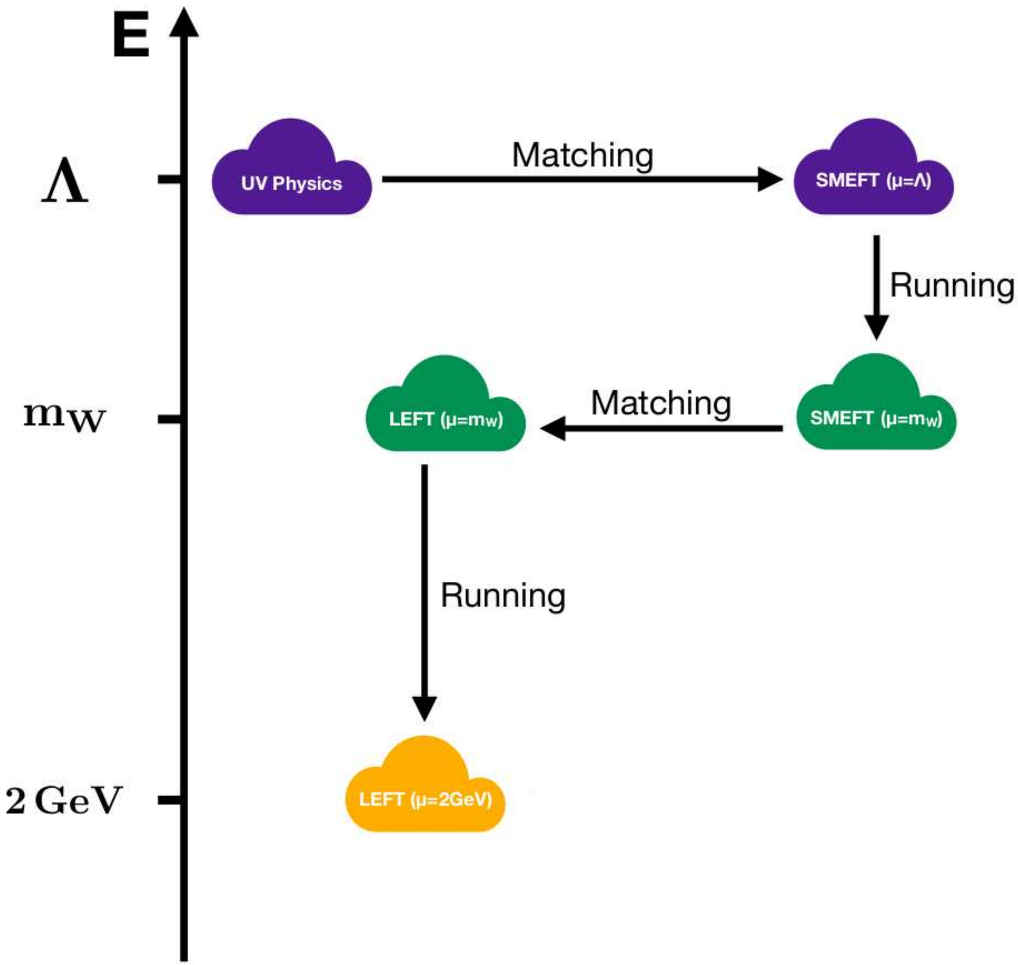
$\mathcal{IV}.$

Phenomenology

Which EFT?


E
Λ
mW
2 GeV
UV Physics
Matching
SMEFT (μ=Λ)
Running
SMEFT (μ=mW)
Matching
LEFT (μ=mW)
Running
LEFT (μ=2GeV)

Which EFT?

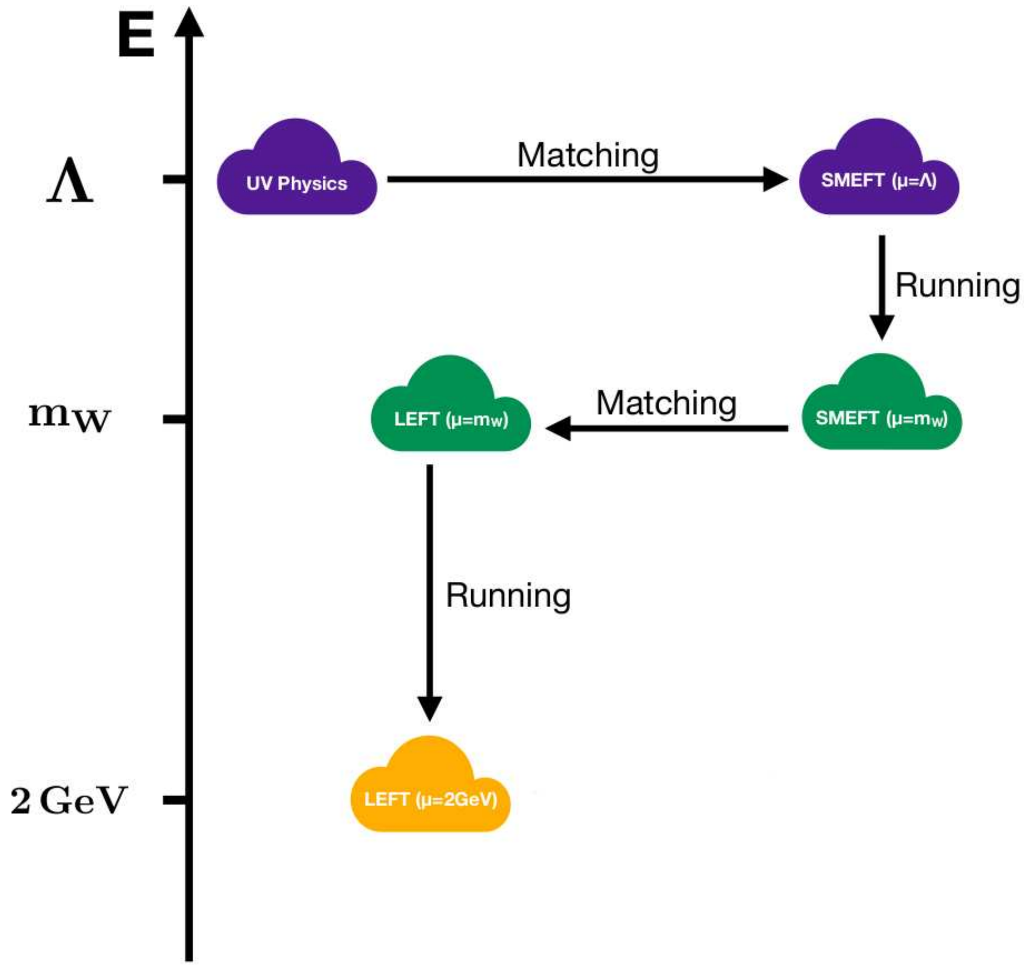


SMEFT / N_RSMEFT:

Standard model symmetries

and SM field content $+N_R$

Which EFT?



SMEFT / N_RSMEFT:

Standard model symmetries

and SM field content $+N_R$

Below m_t/m_W:

LEFT / N_RLEFT

Integrate out t, H, $\cdots$

$d = 6$ operators in N_RSMEFT

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

pair N_R operators

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

single N_R operators

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

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$\mathcal{O}_{QN}$	$\left(\overline{Q}\gamma^\mu Q\right)\left(\overline{N_R}\gamma_\mu N_R\right)$	9	81
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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.)	$n_N = 1$	$n_N = 3$
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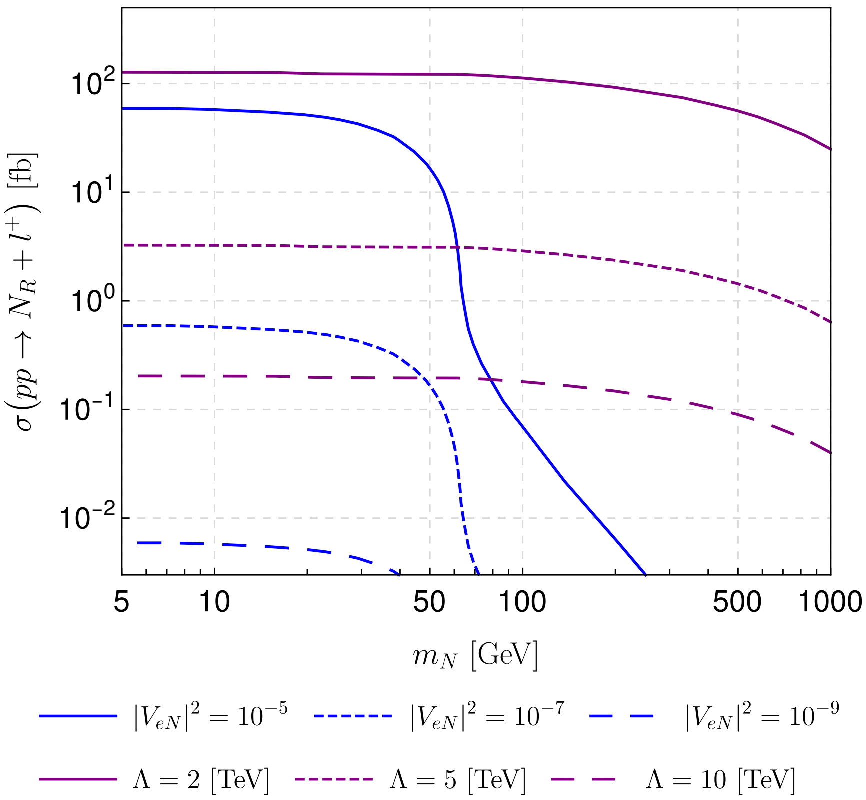
single N_R operators

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

Cross sections

Example cross sections for production via mixing and single N_R operator, example $\mathcal{O}_{duNe}$:

Beltrán et al., 2021



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

N_RSMEFT: $\sigma^{\mathcal{O}} \propto (1/\Lambda)^4$

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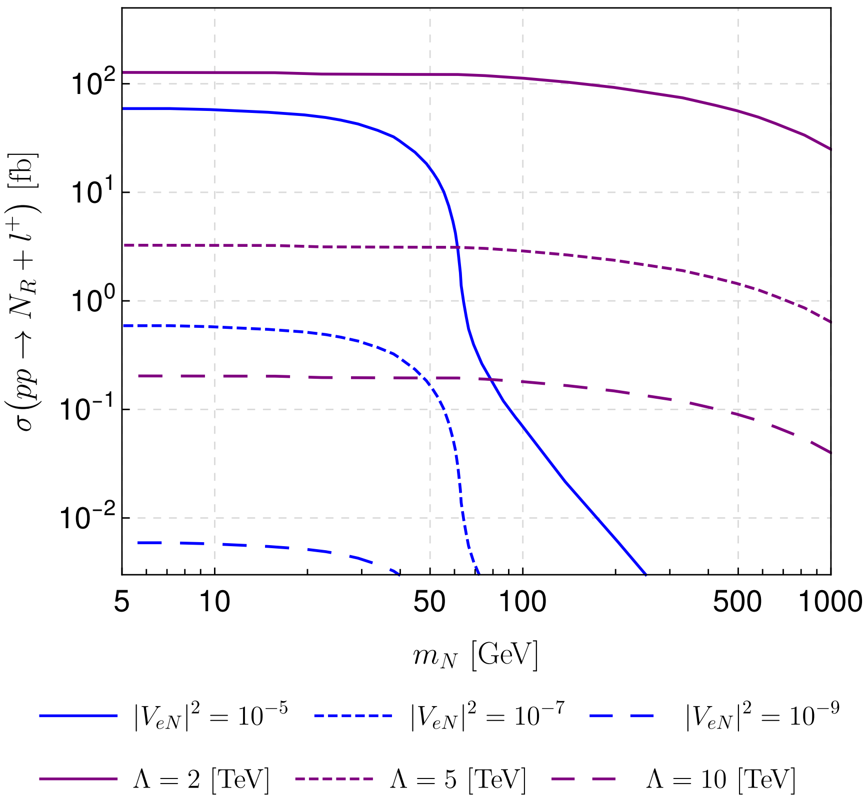


Minimal HNL: $\sigma^{\rm Mix} \propto |V_{eN}|^2$

N_RSMEFT: $\sigma^{\mathcal{O}} \propto (1/\Lambda)^4$

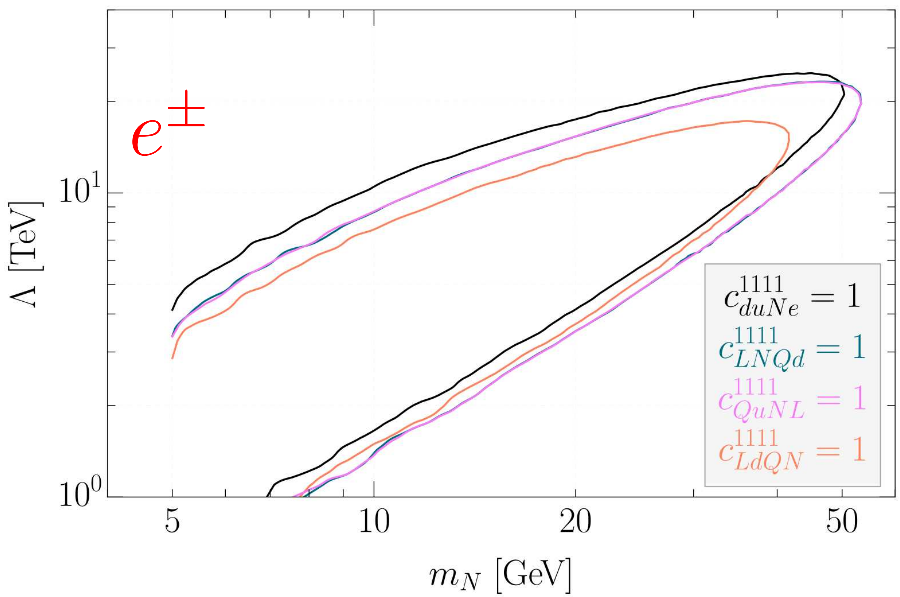
Below roughly $m_N \sim 30$ GeV

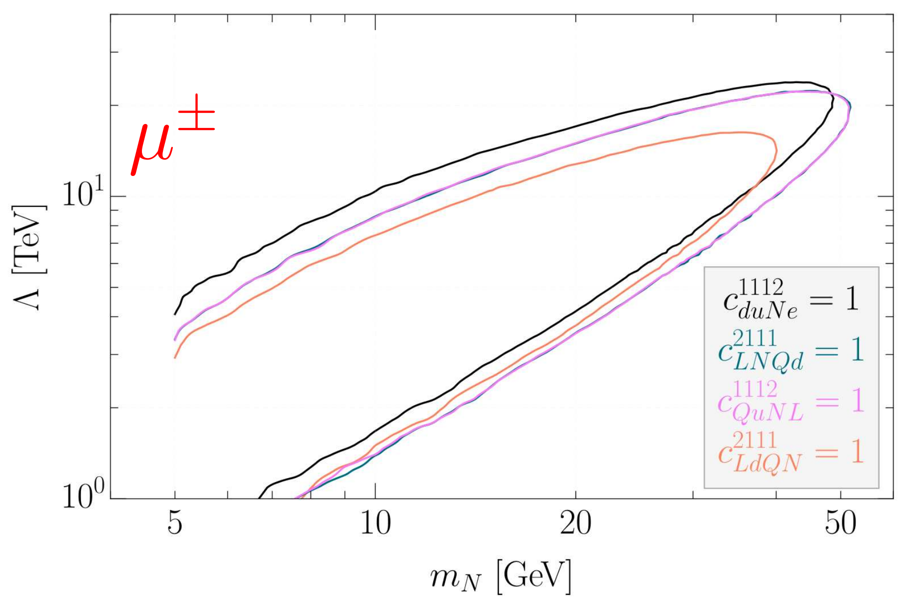
$\Lambda = 25$ TeV $\Leftrightarrow |V_{eN}|^2 \simeq 10^{-9}$

But ...

Cross section from mixing drops exponentially for $m_N > m_W$

Forecast: Single-N_R





Beltrán et al., 2021

Production cross section:

$$\sigma(pp \to N + l^{\pm}) \propto \frac{1}{\Lambda^4}$$

Decay length:

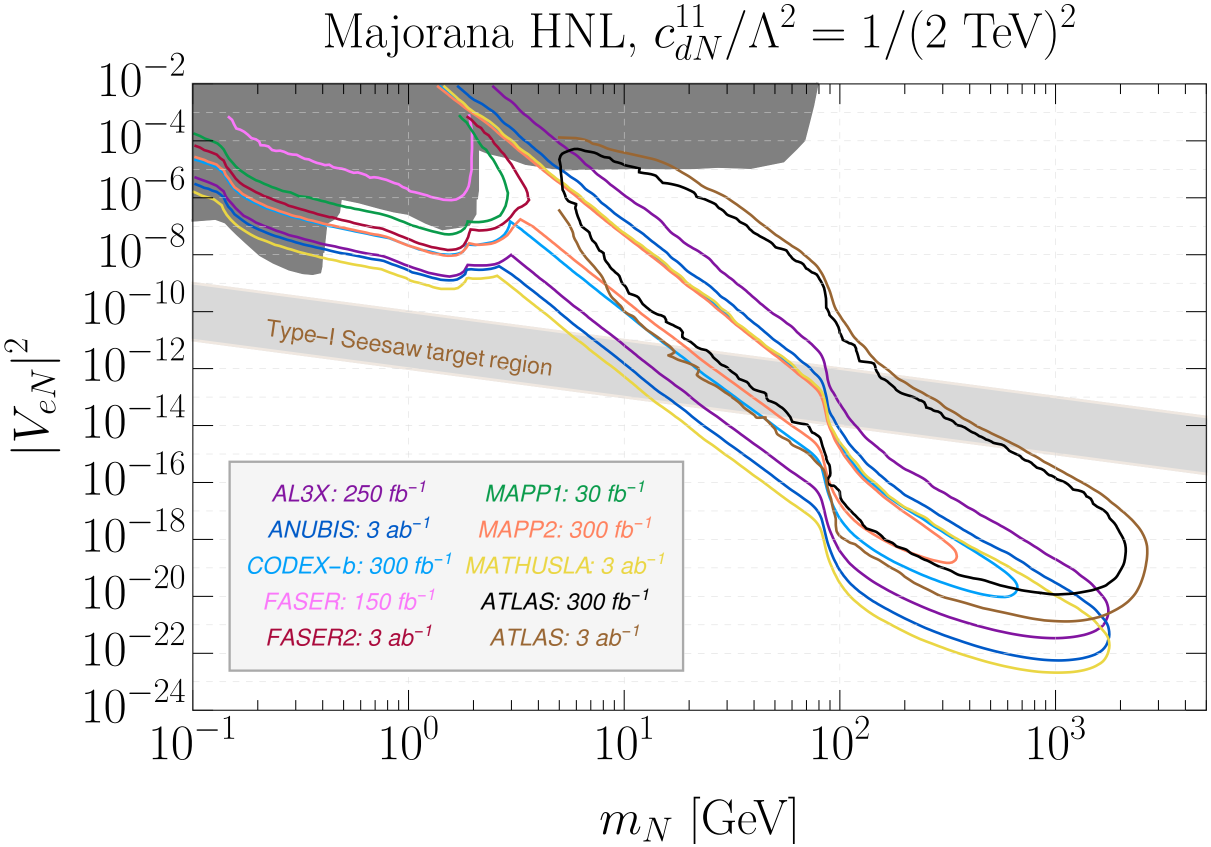
$$c\tau \propto \frac{\Lambda^4}{m_N^5}$$

No displaced vertex for $m_N \gtrsim 50$ GeV

Forecast: Pair-N_R operators

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

Cottin et al., 2021

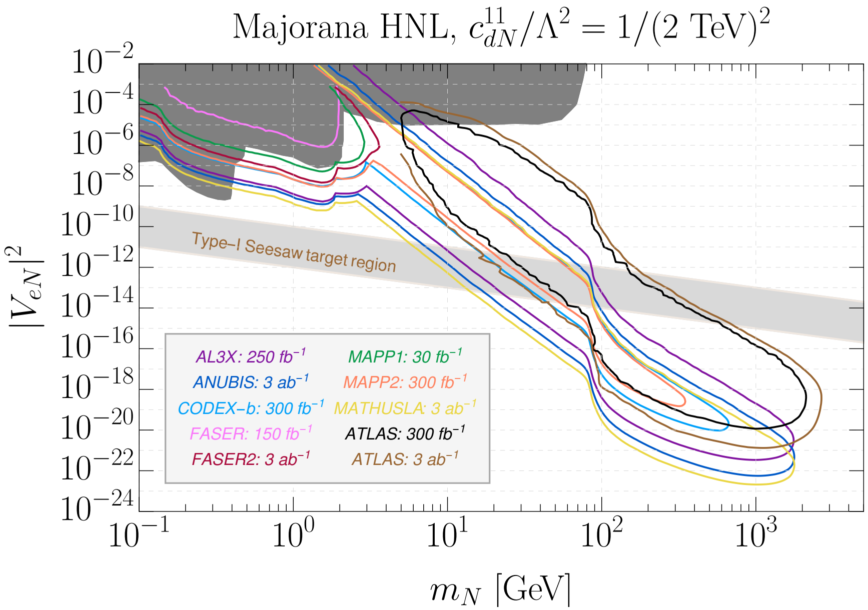


$\Rightarrow$ Assumption: only N_R pair operators, decay via mixing

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

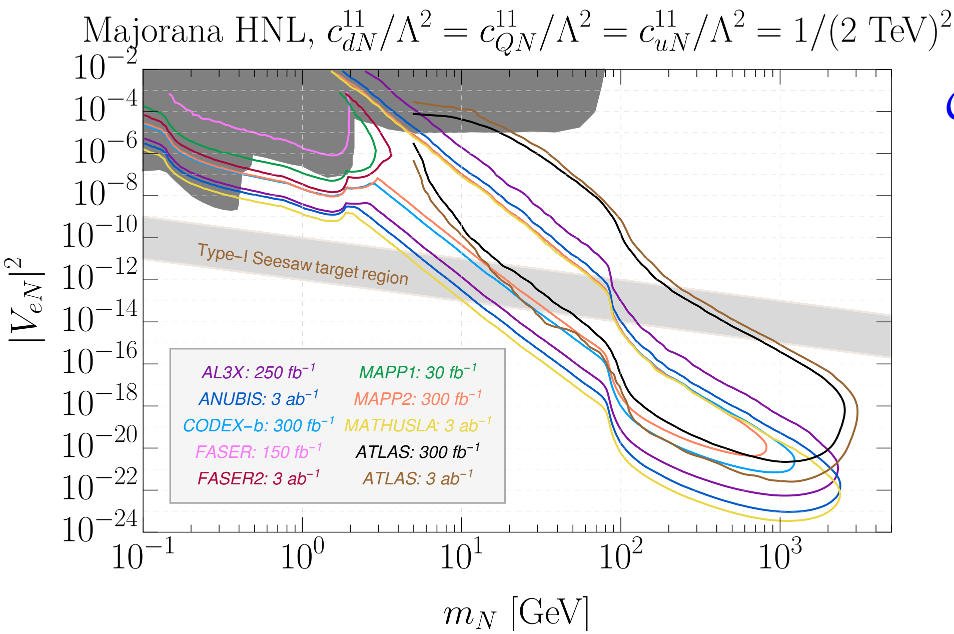
$\Rightarrow$ m_N up to TeV could be probed!

Forecast searches



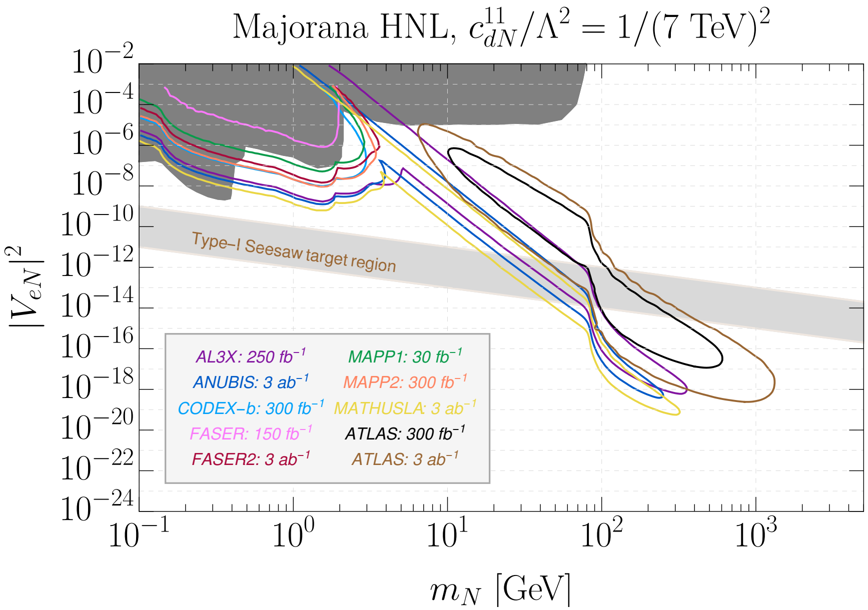
Only $\mathcal{O}_{dN}$

$\Lambda = 2$ TeV



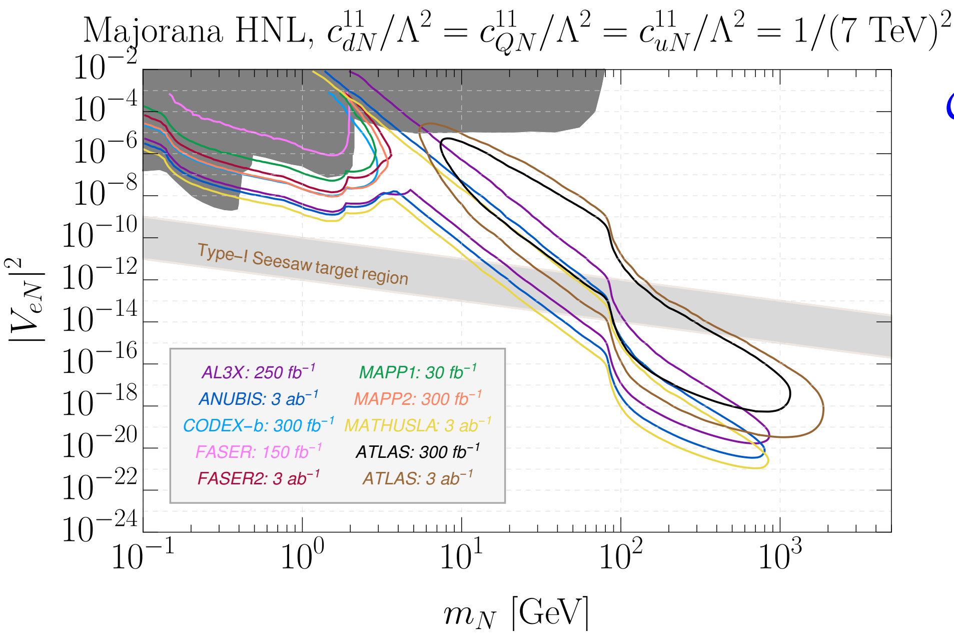
$\mathcal{O}_{dN} + \mathcal{O}_{uN} + \mathcal{O}_{QN}$

Forecast searches



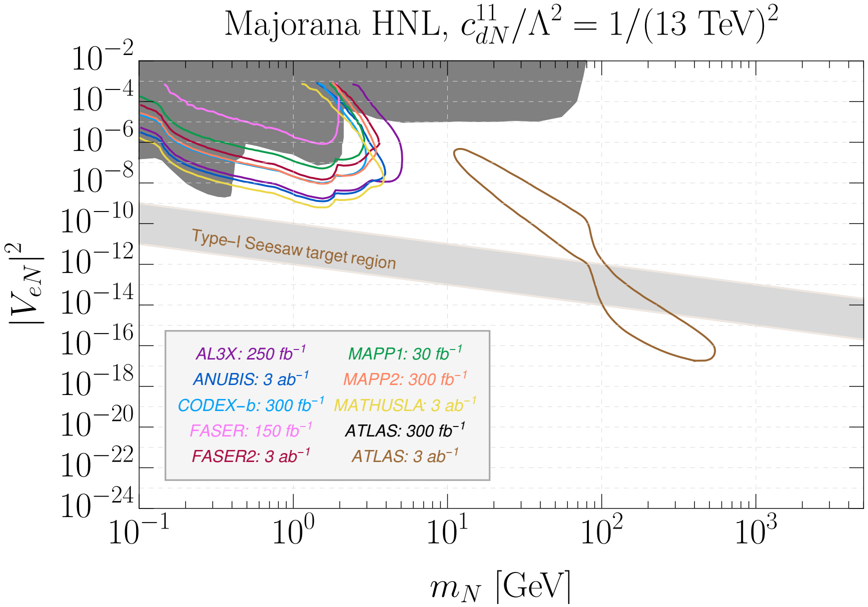
Only $\mathcal{O}_{dN}$

$\Lambda = 7$ TeV



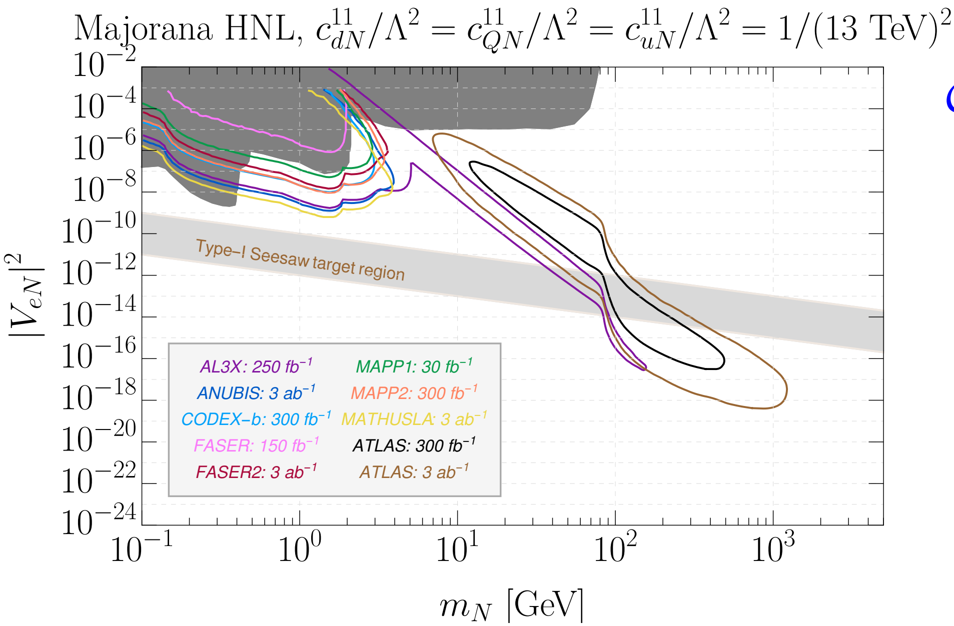
$\mathcal{O}_{dN} + \mathcal{O}_{uN} + \mathcal{O}_{QN}$

Forecast searches



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

$\Lambda = 13$ TeV



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

4F operators in N_RLEFT

$d = 6$ operators with pairs of N_R:

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

$\Rightarrow$ For single N_R operators, see:
R. Beltrán et al., 2210.02461 and De Vries et al., 2010.07305

Mesons at LHC

Meson production at LHC for $\mathcal{L} = 3/$ab:

D^0	$D^\pm$	$D_s^\pm$	B^0	$B^\pm$	B_s^0
4.12×10^{16}	2.16×10^{16}	7.02×10^{15}	1.58×10^{15}	1.58×10^{15}	2.73×10^{14}

Mesons at LHC

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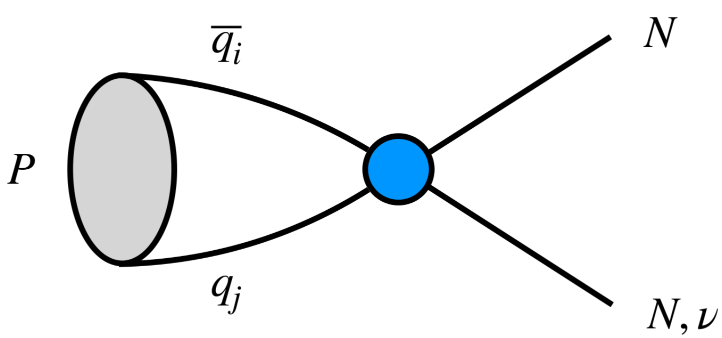
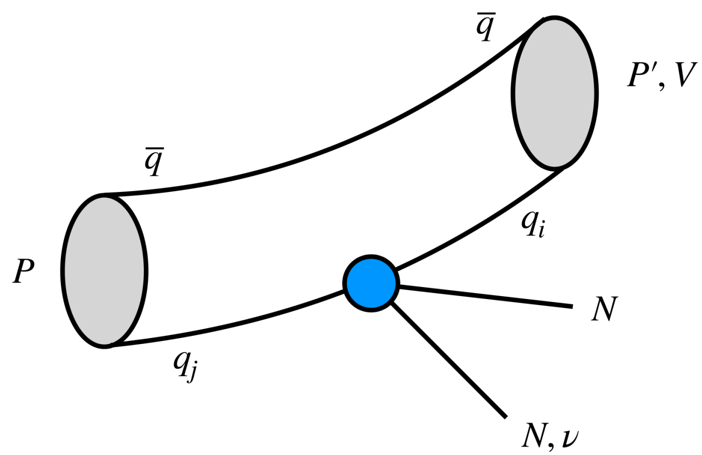
4.12×10^{16}	2.16×10^{16}	7.02×10^{15}	1.58×10^{15}	1.58×10^{15}	2.73×10^{14}

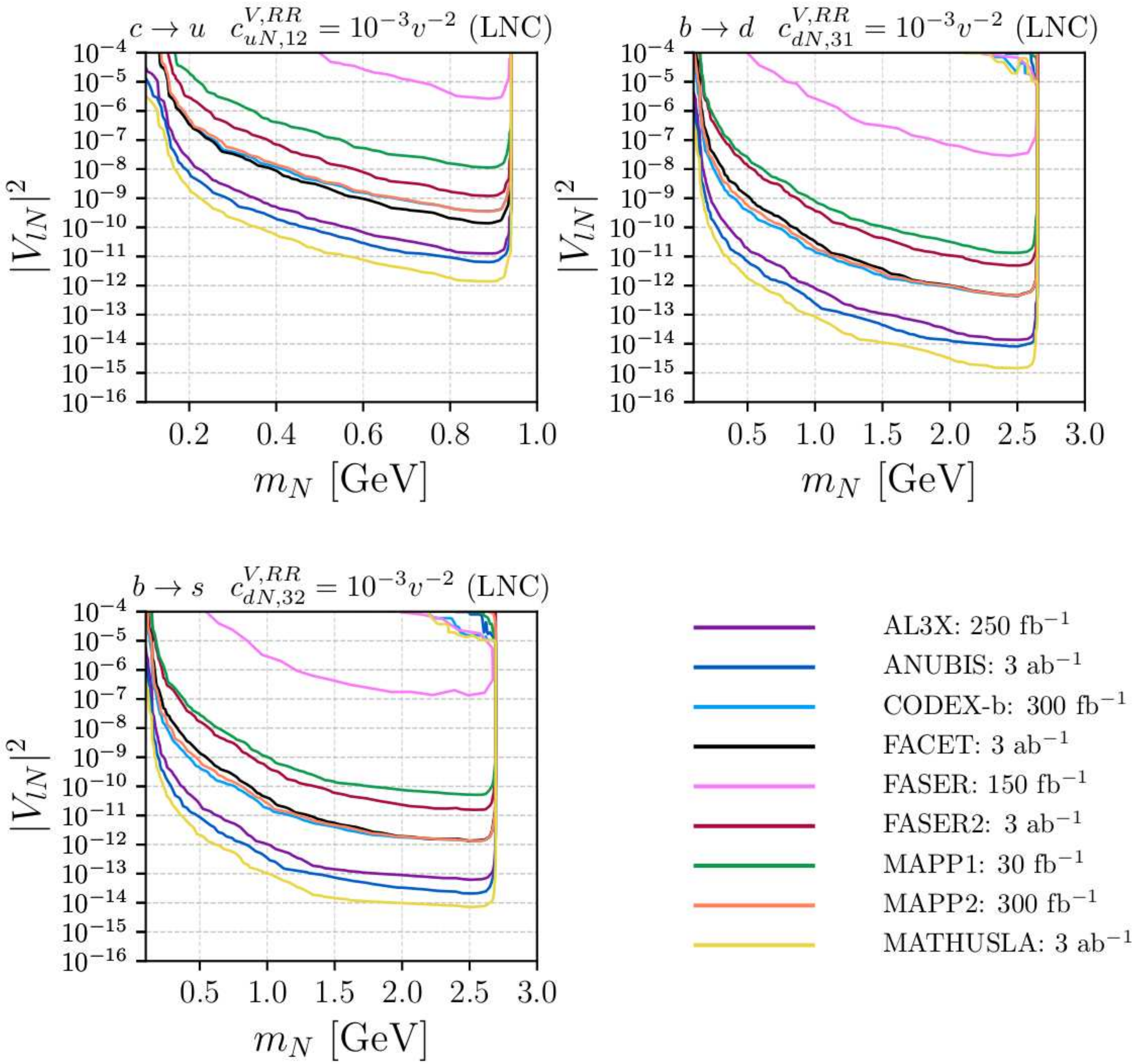
Meson decay via N_RLEFT operators:





For example: $B^0 \to NN$ $\qquad$ $B^+ \to \pi^+ NN$

Projected sensitivities

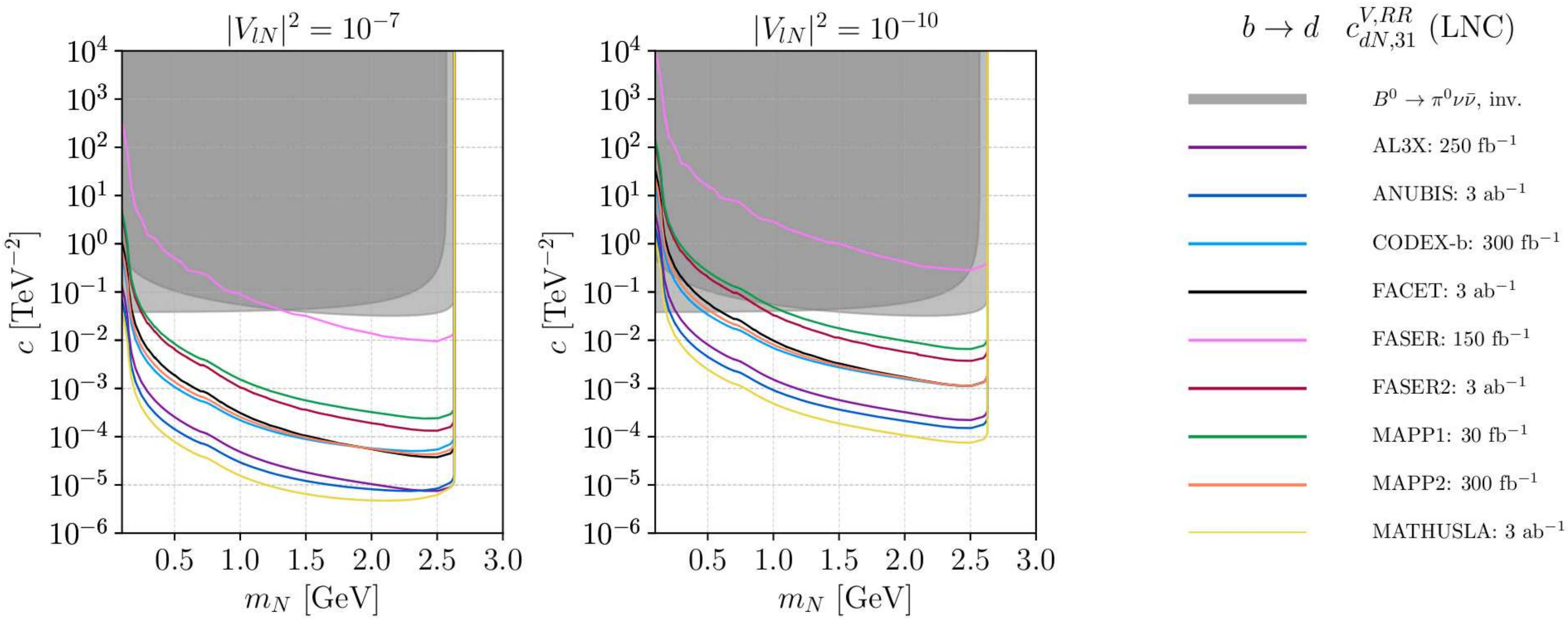


3-dimensional
parameter space
fix, as example:
$c = 10^{-3}/v^2$

Projected sensitivities

Beltran et al, 2022

Example LNC operator:



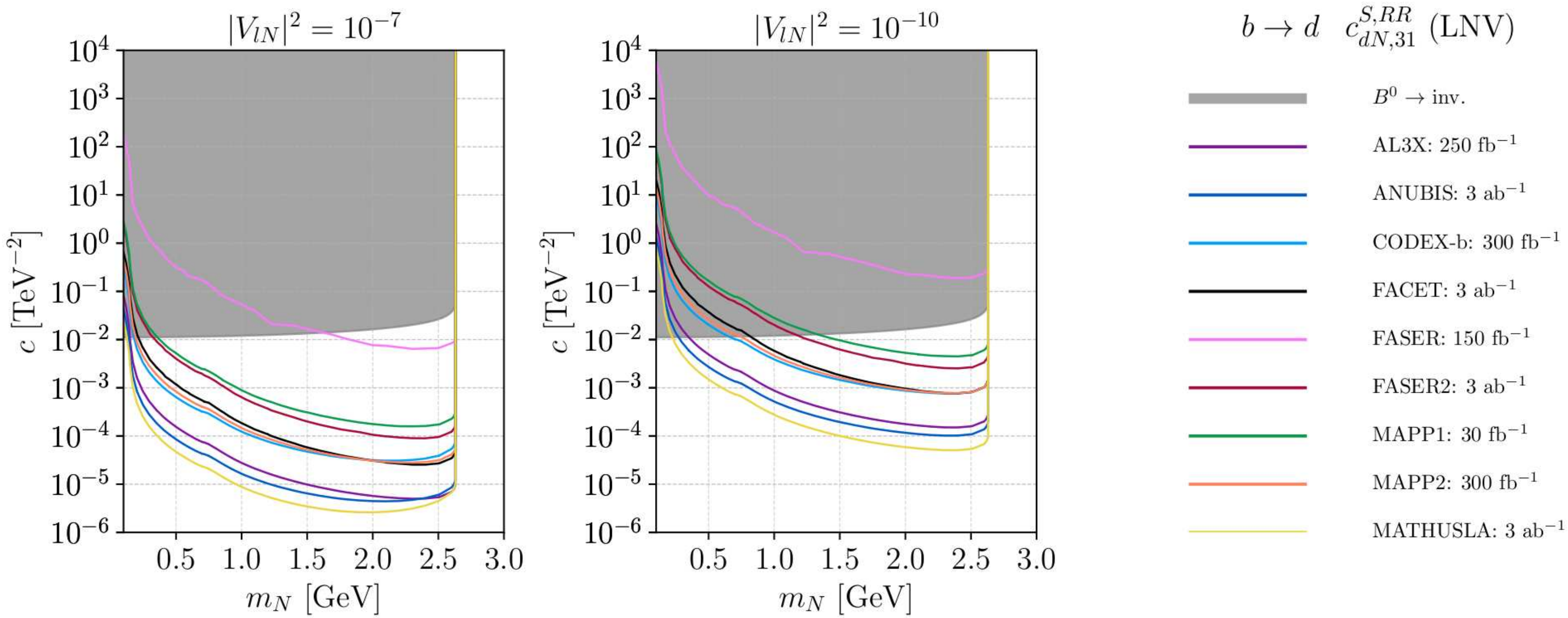
$\Rightarrow$ Rough estimate, LNC scales as $1/\Lambda^2$:

$$c \sim 10^{-4}(10^{-5}) \qquad \rightarrow \qquad \Lambda \sim 100(300)\ \text{TeV}$$

Projected sensitivities

Beltran et al, 2022

Example LNV operator:



$\Rightarrow$ Rough estimate, LNV scales as $1/\Lambda^3$:

$$c \sim 10^{-4}(10^{-5}) \qquad \to \qquad \Lambda \sim 10(21) \text{ TeV}$$

Conclusions

⇒ Renewed interest in long-lived particles (dark matter & neutrinos)

⇒ Many new proposals to look for LLPs at LHC: ATLAS/CMS (!!), MATHUSLA, FASER, CODEX-b, ANUBIS $\cdots$

⇒ If EW scale N_R exists, it should be long-lived

⇒ Large discovery potential or improvement of existing limits by several orders of magnitude

⇒ N_RSMEFT (N_RLEFT) operators can be probed up to $\Lambda < (10 - 20)$ TeV ($\Lambda < (100 - 300)$ TeV)

⇒ For pair-N_R operators, can probe tiny mixing angles!