Neutrino Masses and Nucleon Decay as Probes of Standard Model Linear Extensions

Arnau Bas i Beneito

ABiB, J. Gargalionis, J. Herrero-García, M.A.Schmidt, arXiv 2503.20928 [hep-ph]

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May 27, 2025

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CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

AGENCIA ESTATAL DE INVESTIGACIÓN

The SM of Particle Physics (SM) ⟶ Most accurate theories of the interactions of particles

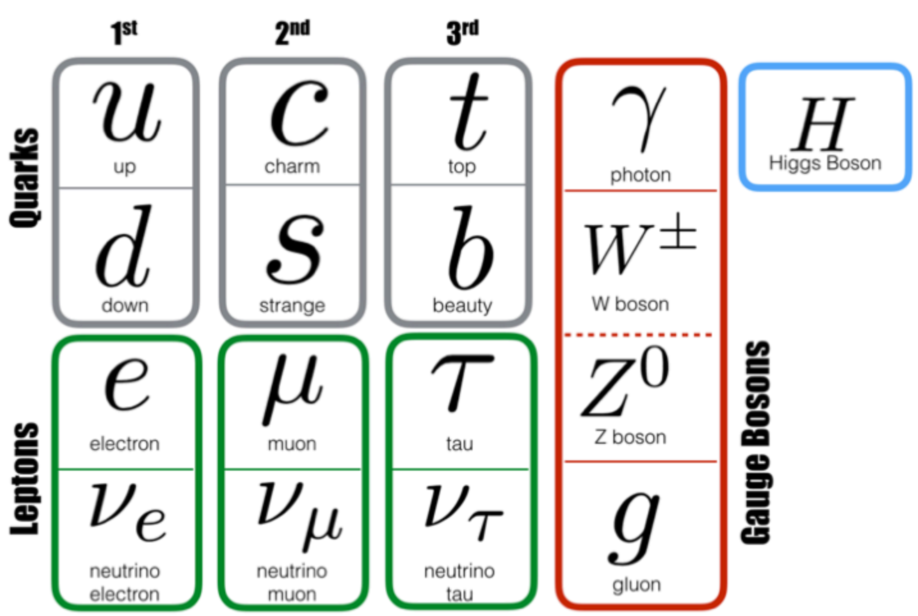
· **Ingredients:** Particle content and local symmetries (gauge group)

· **Recipe:** interactions between the particles allowed by our gauge (and Lorentz) group

Chiral fermions Gauge bosons

$$\mathscr{L}_{SM} = \mathscr{L}^{\text{kin}}(\psi, \phi, A) + \mathscr{L}^{\text{int}}(\psi, \phi, A)$$

Higgs scalar



[Extracted from N. Serra's UZH group webpage]

- Anomalous magnetic dipole moment of the electron $(g-2)$
- EWPTs, m_W and m_Z
- Existence of a (light) scalar

…

The SM of Particle Physics (SM) ⟶ Most accurate theories of the interactions of particles

· **Ingredients:** P … **B** … the particles
local symmetri … tz) group

What lies beyond the SM?

- Neutrino masses
- Matter over anti-matter antisymmetry
- Dark Matter
- Strong CP puzzle
- Flavour puzzle
- Dark Energy

…

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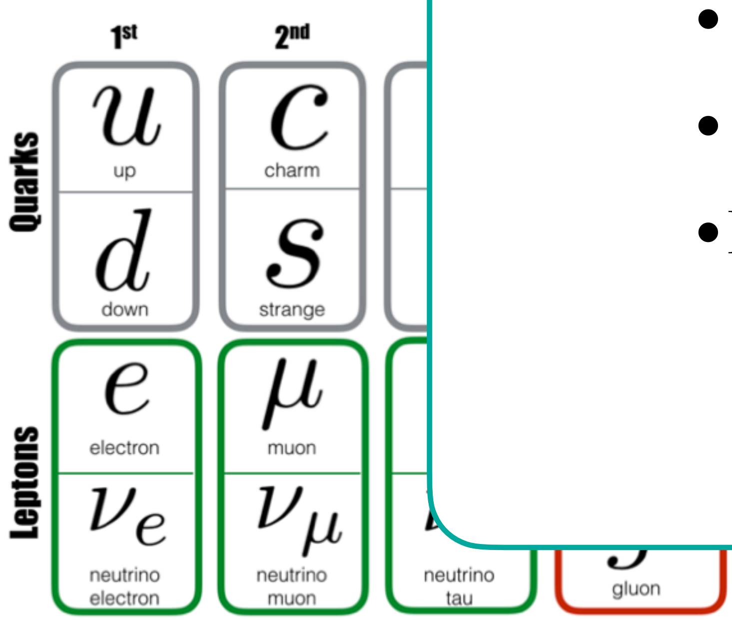
- 2)



…

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SM physics

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What lies beyond the SM?

- Neutrino masses
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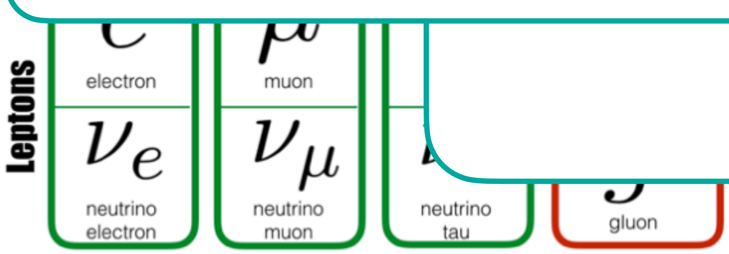
- ...uzzle
- ...gy

. . .

Connected to **Lepton Number**

Connected to **Baryon Number**



. . .

[Extracted from N. Serra's UZH group webpage]

Lepton and Baryon Number Violation

$$\mathcal{L}_{\text{SM}} \supset \bar{L} i \not{D} L + \bar{e}_R i \not{D} e_R + \bar{Q} i \not{D} Q + \bar{u}_R i \not{D} u_R + \bar{d}_R i \not{D} d_R$$

Kinetic terms preserve largest flavour symmetry $\text{U}(3)^5$

Yukawa couplings → $[Y_e]_{pq} \bar{L}^p e_R^q H$ $\quad [Y_d]_{pq} \bar{Q}^p d_R^q H$ $\quad [Y_u]_{pq} \bar{Q}^p u_R^q i\sigma_2 H^*$

$$\text{U}(3)^5 \rightarrow \text{U}(1)_{\text{B}} \times \text{U}(1)_{\text{L}_e} \times \text{U}(1)_{\text{L}_\mu} \times \text{U}(1)_{\text{L}_\tau}$$

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[*Super-Kamiokande 1999, SNO 2002, KamLAND 2003*]

Quark sector

In the SM Lagrangian there are no Baryon Number Violating (BNV) interactions

$\downarrow$

B (perturbatively) conserved

$\downarrow$

The proton (lightest baryon) is stable

Lepton sector

Observance of neutrino oscillations break Flavour Lepton Number to Total Lepton Number $U(1)^3_{L_i} \rightarrow U(1)_L$

$\downarrow$

Neutrinos are massive

$\downarrow$

What's the origin of their mass?

Lepton and Baryon Number Violation

Solar and atmospheric neutrinos

$$\sqrt{\Delta m^2_{\rm atm}} > 0.05 \text{ eV}$$

$\not{D} e_R + \bar{Q} i \not{D} Q + \bar{u}_R$

serve largest flavour

Cosmological bound & Tritium $\beta-$decay

$$\sum m_\nu < \#$$

Dirac mass	**Majorana mass**
$M_D\, \bar{\nu}_L \nu_R$	$M_M\, \bar{\nu}^c_L \nu_L$
$\uparrow$	$\uparrow$
$\Delta L = 0$	$\Delta L = 2$
Total Lepton Number **Conserved**	Total Lepton Number **Violated**

D 2003]

In the

Numb

s break

Lepton

B (perturbatively) conserved

e

The

Future ν experiments such as:

DUNE, Hyper-Kamiokande, JUNO, KATRIN, LEGEND, IceCube…

mass?

Lepton and Baryon Number Violation

B and L are **accidental symmetries** of the SM and seems **artificial** to forbid them in UV models

↓

- No fundamental argument to have B and L conserved
- Explicit **BNV** and **LNV** in simple UV extensions: LQs, GUTs, Seesaw…

[*Georgi et. al. 1973, H. Fritzsch et al. 1975***]**

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[*Georgi et. al. 1973, H. Fritzsch et al. 1975*]

[A. Sakharov 1967]

Sakharov Conditions

1. C and CP violation
2. Out of Thermal equilibrium
3. **Baryon Number Violation**

B and L are **accidental symmetries** of the SM and seems **artificial** to forbid them in UV models

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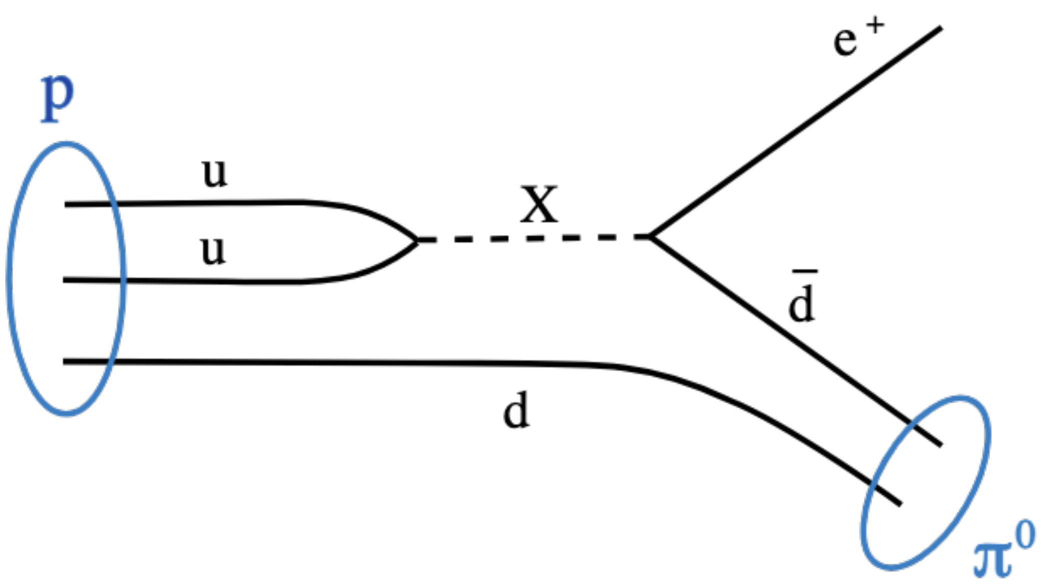
- Explicit **BNV** and **LNV** in simple UV extensions: LQs, GUTs, Seesaw…

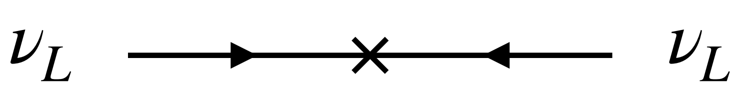
[*Georgi et. al. 1973, H. Fritzsch et al. 1975*]

proton decay
($\Delta B = \pm \Delta L = 1$ processes)

Low-energy processes

(Majorana) m_ν
($\Delta L = 2$ processes)





(See also $0\nu\beta\beta-$decay)

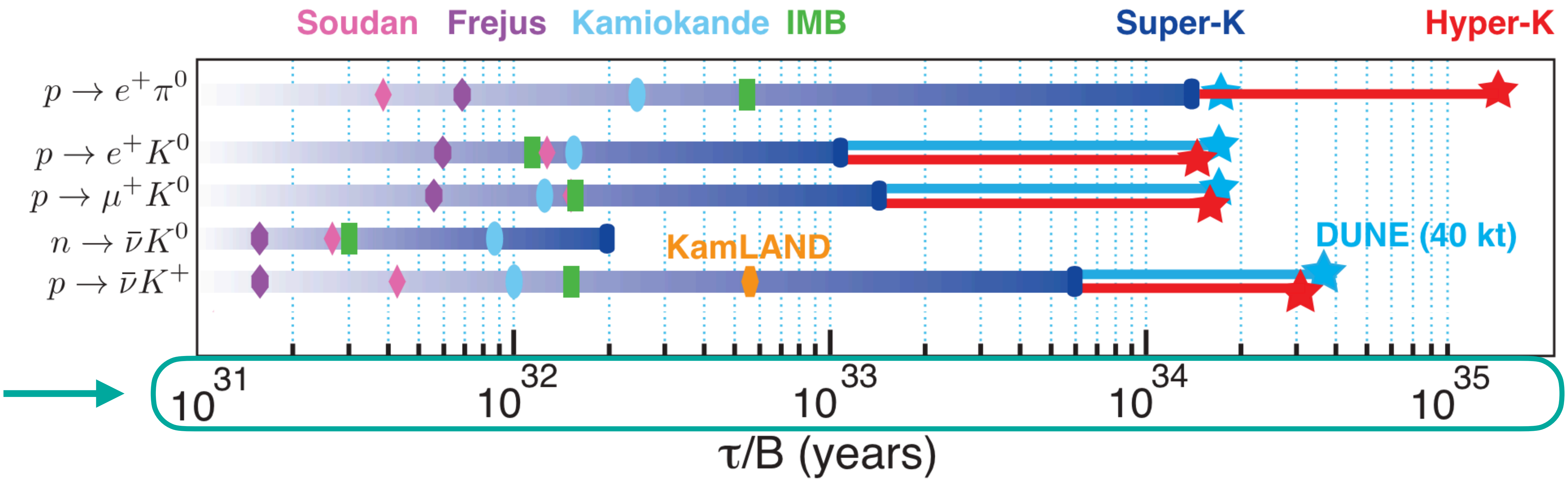
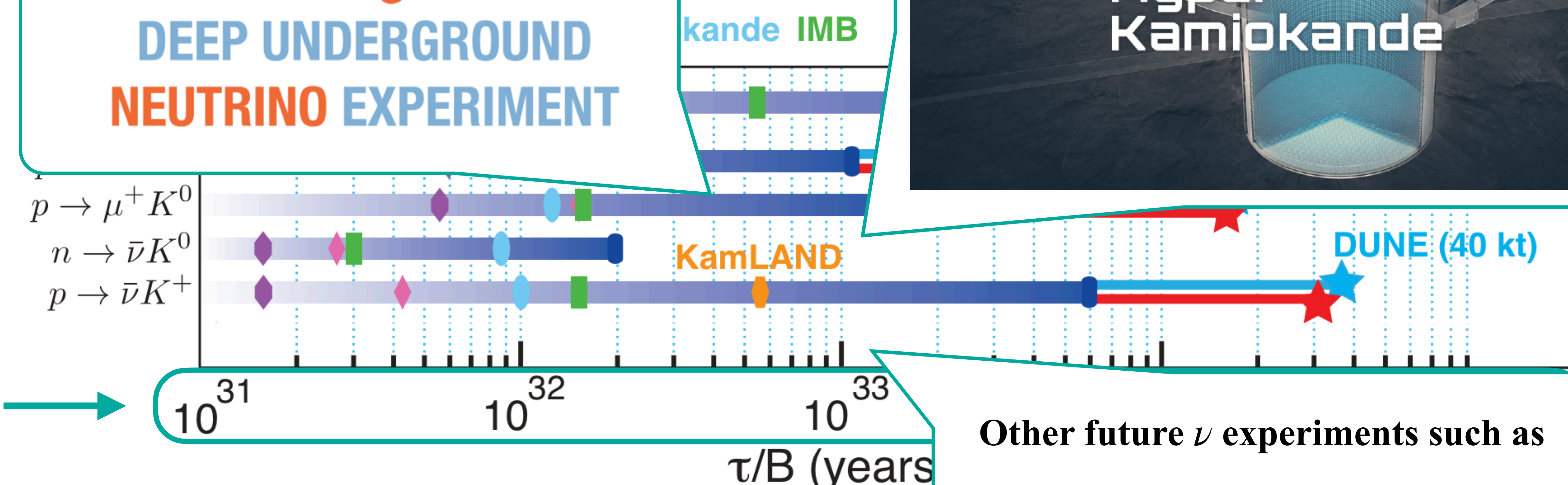


Image extracted from Hyper-K design report (edited)

Searches for Proton Decay

DEEP UNDERGROUND NEUTRINO EXPERIMENT



Other future ν experiments such as

JUNO

THEIA

ESSnuSB

Sensitivity of $p \to \pi^0 e^+$ increased by 10 in HK

Sensitivity of $p \to K^+ \nu$ increased by 10 in HK/DUNE

Sensitivity of $n \to K^+ e^-$ increased by 10^3 in HK

…

BNV nucleon decay could be the next big discovery!

The SM is an **effective theory** → **New Physics** parametrised by **higher-dimensional operators**

[S. Weinberg 1979 ,
F. Wilczek et al 1979,
B. Grzadkowski et al. 2010,
W. Buchmuller et al. 1986,
I. Brivio et al. 2019,
B. Henning et al. 2016,
De Gouvea et al. 2014]

SM Effective Field Theory (SMEFT)

$$\mathscr{L} = \mathscr{L}_{SM} + \sum \frac{1}{\Lambda^{d-4}} \mathscr{O}^{(d)}$$

$$\left[\mathscr{O}^{(d)}\right] = d$$

Invariant under G_{SM}

Bounds on SMEFT WCs serve as a **bridge** to specific UV models

$$\mathscr{L} = \mathscr{L}_{SM} + \frac{c^{d=5}}{\Lambda} \mathscr{O}_W + \frac{c^{d=6}}{\Lambda^2} \mathscr{O}^{d=6} + \frac{c^{d=7}}{\Lambda^3} \mathscr{O}^{d=7} + \dots$$

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Bounds on SMEFT WCs serve as a **bridge** to specific UV models

$\Delta L = 2$ $\quad$ $\Delta(B-L) = 0$ $\quad$ $\Delta(B-L) = 2$

$$\mathscr{L} = \mathscr{L}_{SM} + \boxed{\frac{c^{d=5}}{\Lambda} \mathscr{O}_W} + \boxed{\frac{c^{d=6}}{\Lambda^2} \mathscr{O}^{d=6}} + \boxed{\frac{c^{d=7}}{\Lambda^3} \mathscr{O}^{d=7}} + \ldots$$

Number of independent Components:

1 (6) for $N_f = 1$ (3)

63 (2772) for $N_f = 1$ (3)
Of which 4 (273) are BNV

18 (771) for $N_f = 1$ (3)
Of which 6 (297) are BNV

The SM is

[S. W
F. Wil
B. Grzadl
W. Buch
I. Bri
B. Henn
De Gouvea et al. 2014]

$$[\mathcal{O}_{\bar{l}dddH}]_{pqrs} = (L_p^\dagger \bar{d}_q^\dagger)(\bar{d}_r^\dagger \bar{d}_s^\dagger)H\,, \qquad \left[\mathcal{O}_{\bar{l}dqq\tilde{H}}\right]_{pqrs} = (L_p^\dagger \bar{d}_q^\dagger)(Q_r Q_s^i)\tilde{H}^j \epsilon_{ij}\,,$$

$$\left[\mathcal{O}_{\bar{e}qdd\tilde{H}}\right]_{pqrs} = (\bar{e}_p Q_q^i)(\bar{d}_r^\dagger \bar{d}_s^\dagger)\tilde{H}^j \epsilon_{ij}\,, \qquad [\mathcal{O}_{\bar{l}dud\tilde{H}}]_{pqrs} = (L_p^\dagger \bar{d}_q^\dagger)(\bar{u}_r^\dagger \bar{d}_s^\dagger)\tilde{H}\,,$$

$$[\mathcal{O}_{\bar{l}qdDd}]_{pqrs} = (L_p^\dagger \bar{\sigma}^\mu Q_q)(\bar{d}_r^\dagger i\overleftrightarrow{D}_\mu \bar{d}_s^\dagger)\,, \qquad [\mathcal{O}_{\bar{e}dddD}]_{pqrs} = (\bar{e}_p \sigma^\mu \bar{d}_q^\dagger)(\bar{d}_r^\dagger i\overleftrightarrow{D}_\mu \bar{d}_s^\dagger)\,.$$

SM $\quad \Lambda^{d-4}$

Invariant under $G_{\rm SM}$

$$[\mathcal{O}_{qqql}]_{pqrs} = (Q_p^i Q_q^j)(Q_r^l L_s^k)\epsilon_{ik}\epsilon_{jl}\,, \qquad [\mathcal{O}_{qque}]_{pqrs} = (Q_p^i Q_q^j)(\bar{u}_r^\dagger \bar{e}_s^\dagger)\epsilon_{ij}\,,$$

$$[\mathcal{O}_{duue}]_{pqrs} = (\bar{d}_p^\dagger \bar{u}_q^\dagger)(\bar{u}_r^\dagger \bar{e}_s^\dagger)\,, \qquad [\mathcal{O}_{duql}]_{pqrs} = (\bar{d}_p^\dagger \bar{u}_q^\dagger)(Q_r^i L_s^j)\epsilon_{ij}\,.$$

$$\mathscr{L} = \mathscr{L}_{SM} + \boxed{\frac{c^{d=5}}{\Lambda}\mathcal{O}_W} + \boxed{\frac{c^{d=6}}{\Lambda^2}\mathcal{O}^{d=6}} + \boxed{\frac{c^{d=7}}{\Lambda^3}\mathcal{O}^{d=7}} + \ldots$$

Number of independent Components

$$[\mathcal{O}_5]_{pq} = (L_p^i L_q^j)H^k H^l \epsilon_{ik}\epsilon_{jl}$$

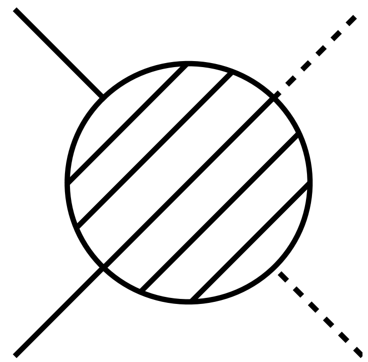
$_f = 1$ (3)
) are BNV

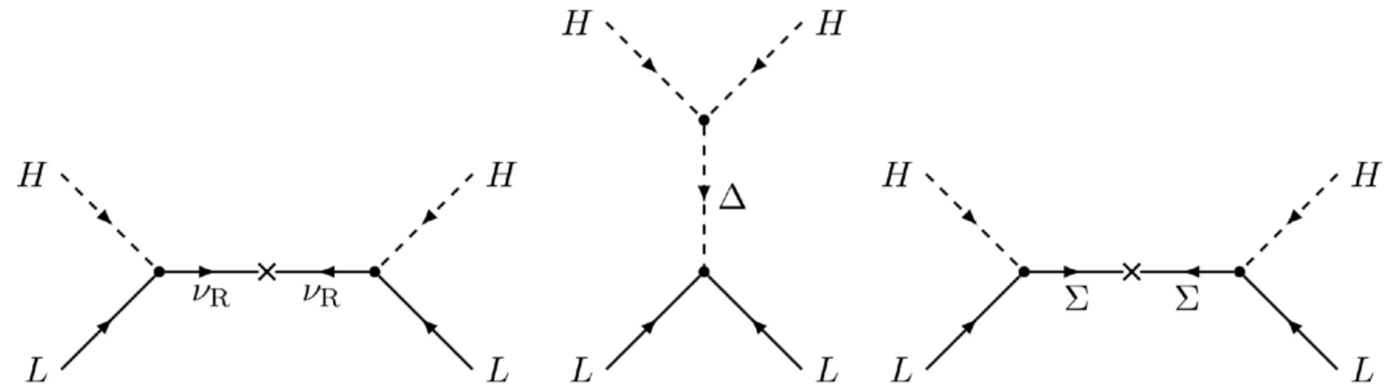
18 (771) for $N_f = 1$ (3)
Of which 6 (297) are BNV

Tree-level Proton decay and Neutrino masses

[S. Weinberg 1979]

$\Delta L = 2$

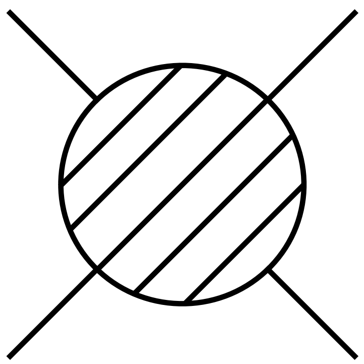


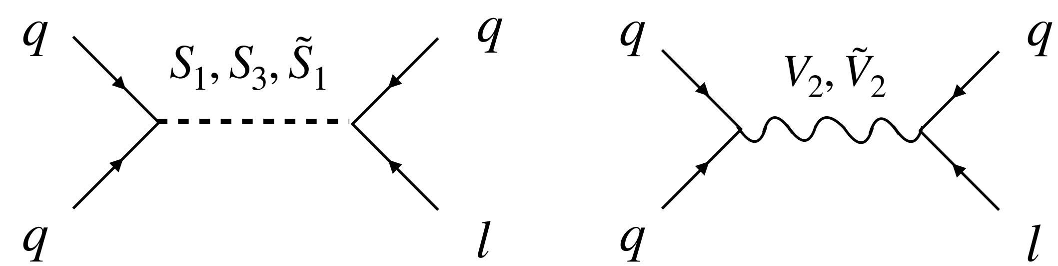


Seesaw mechanism

[P. Minkowski 1977, T. Yanagida 1979, M. Gell-Mann et al. 1979, R. N. Mohapatra et al. 1980, Glashow 1980…]

$\Delta(B-L) = 0$



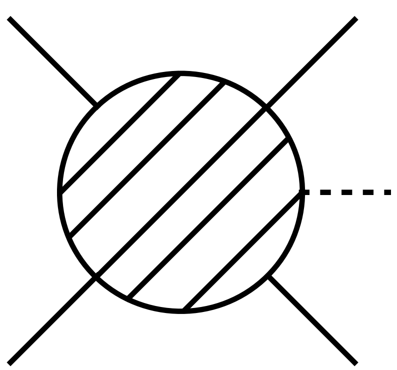


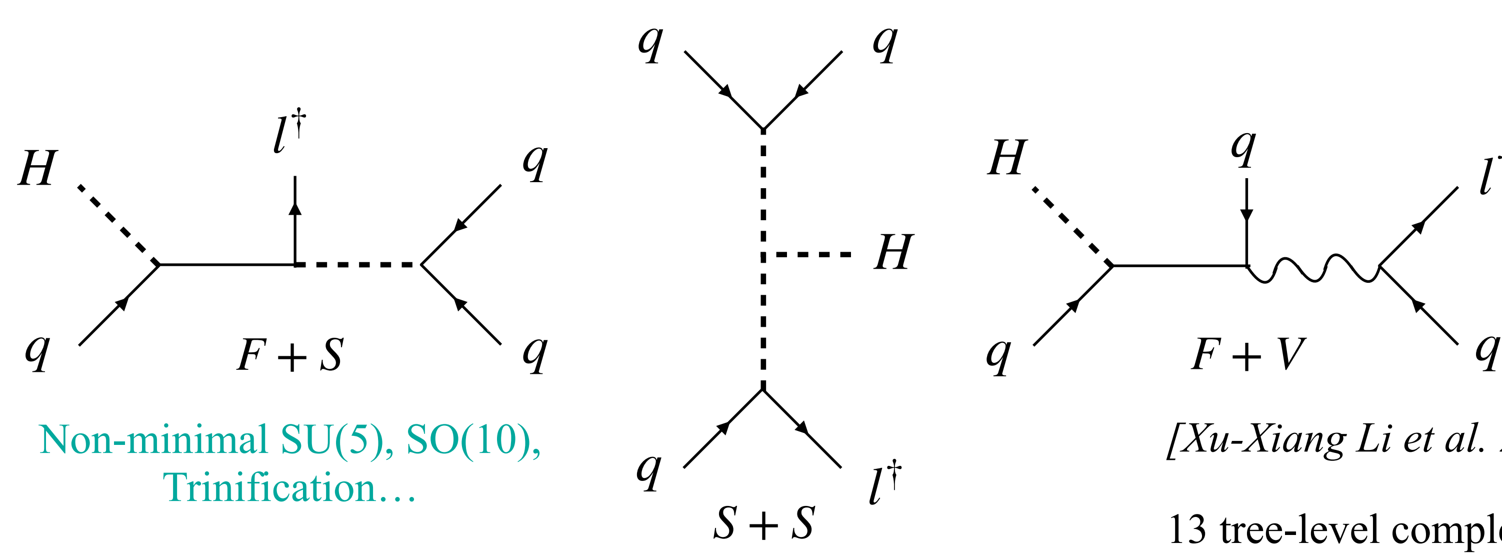
[J. de Blas et al. 2017, I. Dorsner et al 2016, Xu-Xiang Li et al. 2023]

Minimal SU(5), SO(10), Trinification…

Different phenomenology

$\Delta(B-L) = 2$





Non-minimal SU(5), SO(10), Trinification…

[Xu-Xiang Li et al. 2023]

13 tree-level completions

… and many more: $\Delta B = 2$, $\Delta(3B-L)$, $\Delta L = 4$ …

Tree-level Proton decay and Neutrino masses

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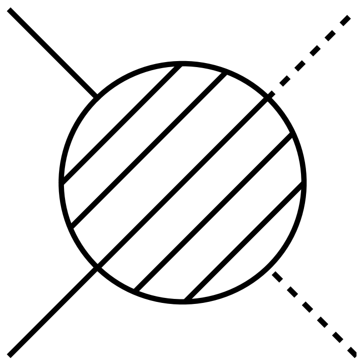

H H

$$M \sim 10^{11}\ \text{TeV}$$ for O(1) WCs

[Super-Kamiokande 1999]

Seesaw mechanism *[P. Minkowski 1977, T. Yanagida 1979, M. Gell-Mann et al. 1979, R. N. Mohapatra et al. 1980, Glashow 1980…]*

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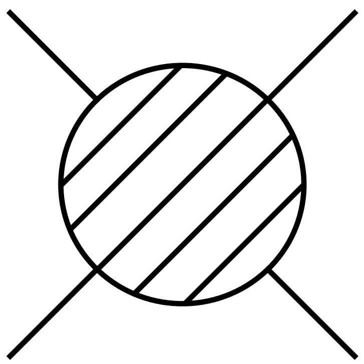

$$M \gtrsim 10^{12}\ \text{TeV}$$ for O(1) WCs

[Super-Kamiokande 2020]

q l q l

[J. de Blas et al. 2017, I. Dorsner et al 2016, Xu-Xiang Li et al. 2023]

Minimal SU(5), SO(10), Trinification…

Different phenomenology

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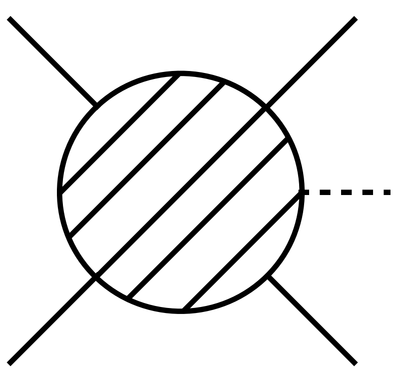

q q

H

$$M \gtrsim 10^{8}\ \text{TeV}$$ for O(1) WCs

$l^\dagger$

[Super-Kamiokande 2020]

q $F+S$ q q $F+V$ q

Non-minimal SU(5), SO(10), Trinification…

q $S+S$ $l^\dagger$

[Xu-Xiang Li et al. 2023]

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… and many more: $\Delta B = 2$, $\Delta(3B-L)$, $\Delta L = 4$ …

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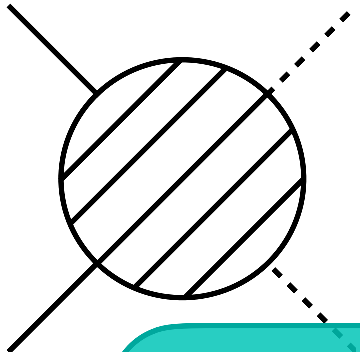


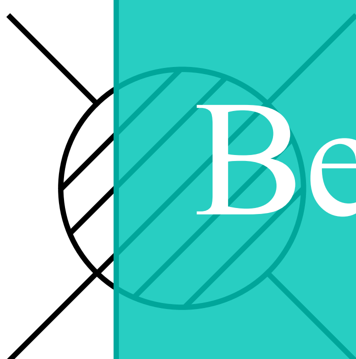
$M \sim 10^{11}$ TeV for O(1) WCs

[Super-Kamiokande 1999]

Seesaw mechanism *[P. Minkowski 1977, T. Yanagida 1979, M. Gell-Mann et al. 1979, R. N. Mohapatra et al. 1980, Glashow 1980…]*

Beyond tree-level?

$\Delta(B-L) = 0$



$M \gtrsim 10^{12}$ TeV for O(1) WCs

[Super-Kamiokande 2020]

q l q l

[J. de Blas et al. 2017, I. Dorsner et al 2016, Xu-Xiang Li et al. 2023]

Minimal SU(5), SO(10), Trinification…

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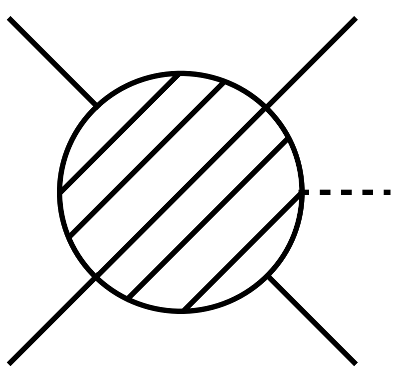

q q

H $l^\dagger$

$M \gtrsim 10^8$ TeV for O(1) WCs

[Super-Kamiokande 2020]

q $F+S$ q q $F+V$ q

Non-minimal SU(5), SO(10), Trinification…

q $l^\dagger$ $S+S$

[Xu-Xiang Li et al. 2023]

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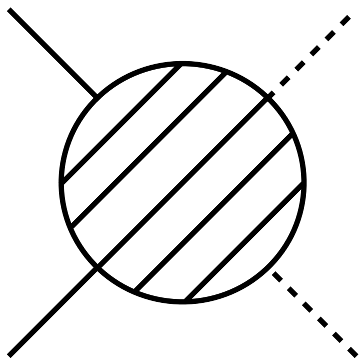
… and many more: $\Delta B = 2$, $\Delta(3B-L)$, $\Delta L = 4$ …

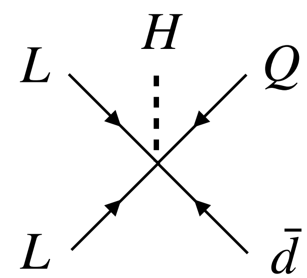
Loop-level Proton decay and Neutrino masses

Tree-level completions of **high-dimensional $\Delta L = 2$ and $\Delta B = 1$ operators** that lead to m_ν and **proton decay at loop level**

$\Delta L = 2$



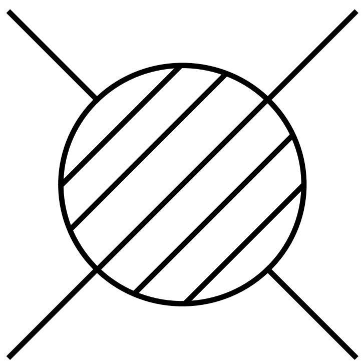
E.g.



$\mathcal{O}_{3a} = LLQ\bar{d}H$

$\Delta(B - L) = 0$

Different phenomenology



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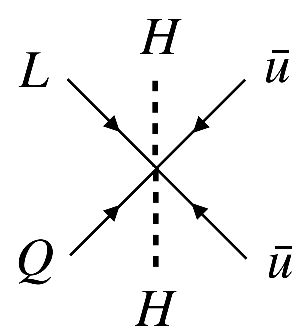
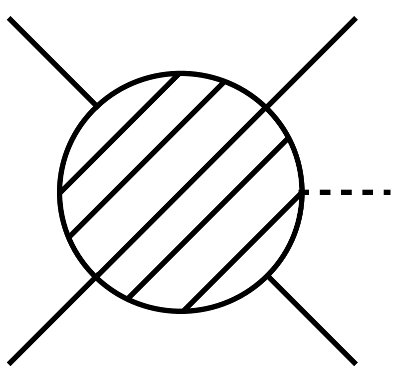


$\mathcal{O}_{14} = LQ\bar{u}^\dagger\bar{u}^\dagger HH$

$\Delta(B - L) = 2$



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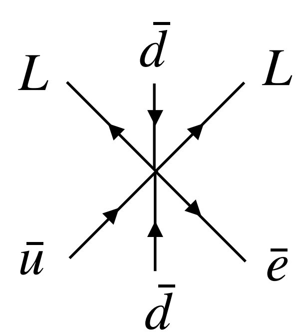

$\mathcal{O}_{28} = LL\bar{e}\bar{u}\bar{d}\bar{d}$

Arising at even-d in the SMEFT

Arising at even-d in the SMEFT [A. Kobach 2016]

Loop-level Proton decay and Neutrino masses

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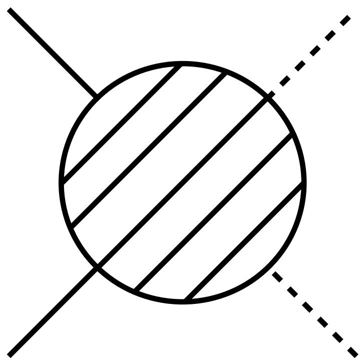
$\Delta L = 2$



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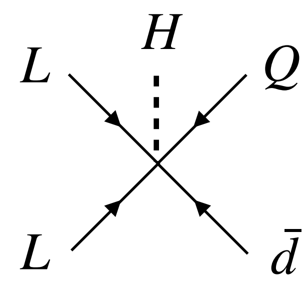
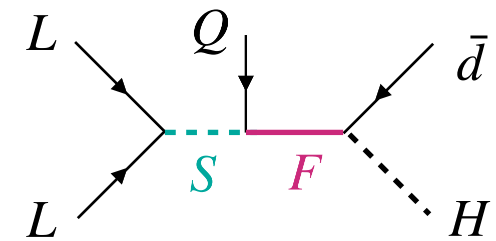
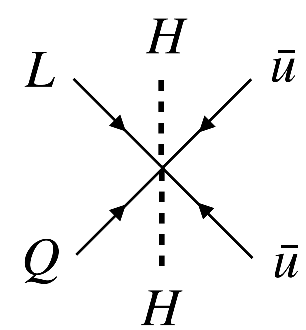


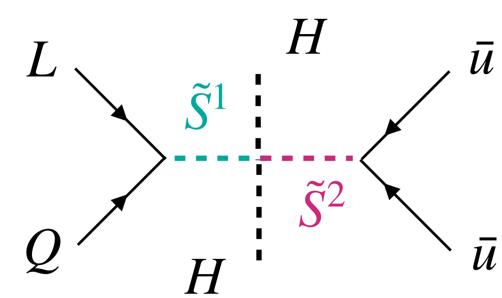
$\mathcal{O}_{3a} = LLQ\bar{d}H$



They admit a **finite number** of **tree-level completions** in the UV ✓

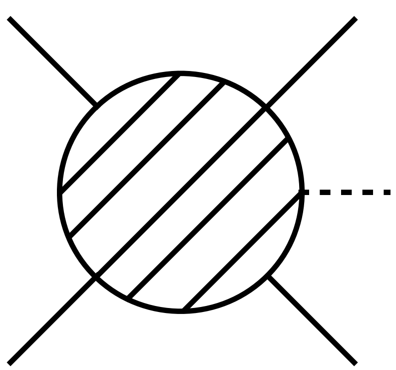


$\mathcal{O}_{14} = LQ\bar{u}^\dagger\bar{u}^\dagger HH$

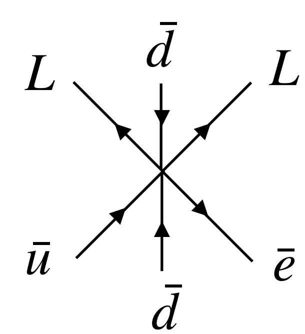


Different phenomenology

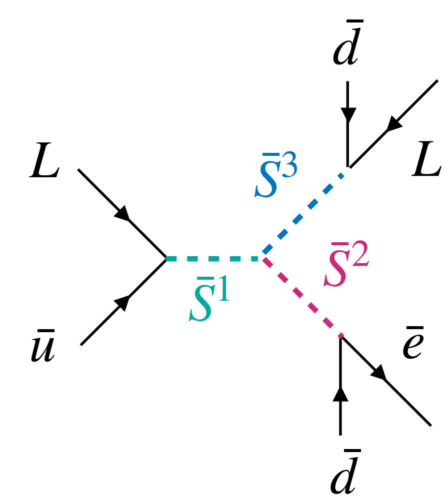
$\Delta(B-L) = 2$



E.g.



$\mathcal{O}_{28} = LL\bar{e}\bar{u}\bar{d}\bar{d}$

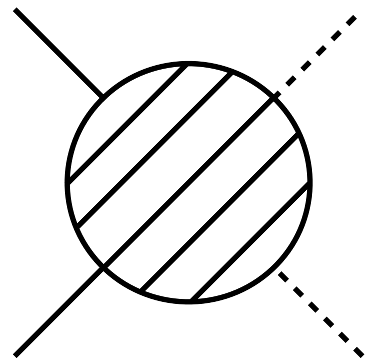


Arising at even-d in the SMEFT

Arising at even-d in the SMEFT [A. Kobach 2016]

Tree-level completions of **high-dimensional $\Delta L = 2$ and $\Delta B = 1$ operators** that lead to m_ν and **proton decay at loop level**

$\Delta L = 2$



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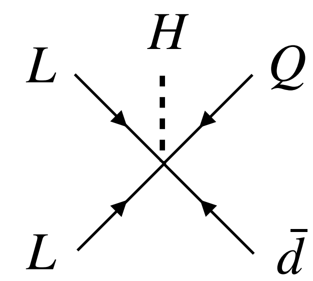
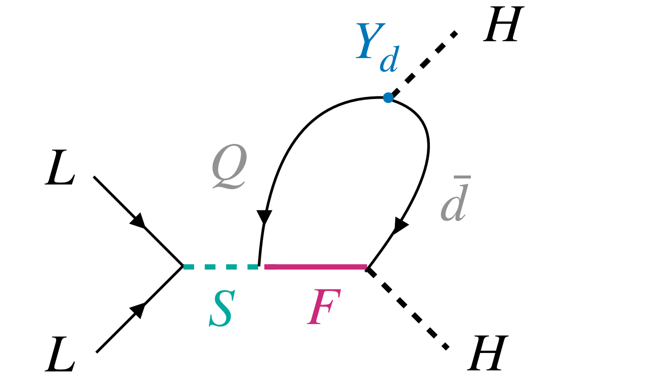
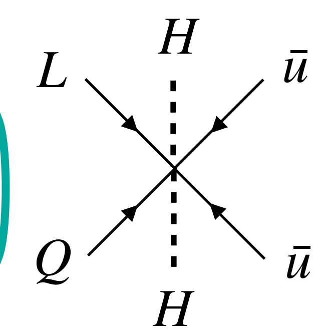


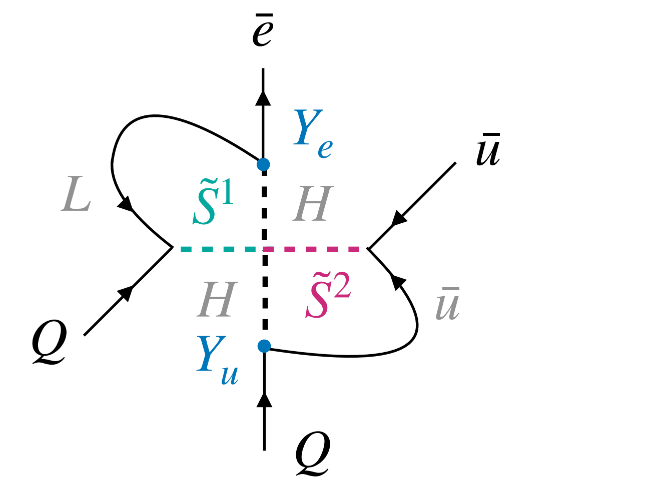
$\mathcal{O}_{3a} = LLQ\bar{d}H$



They admit a **finite number** of **tree-level completions** in the UV ✓



$\mathcal{O}_{14} = LQ\bar{u}^\dagger\bar{u}^\dagger HH$



Different phenomenology

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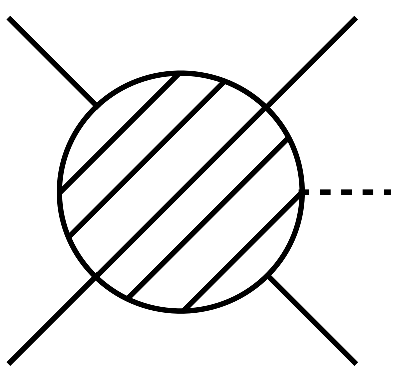

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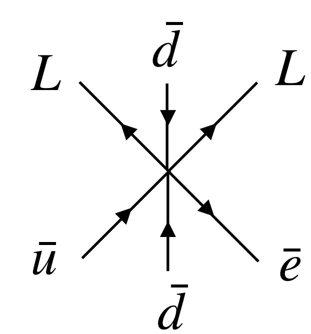
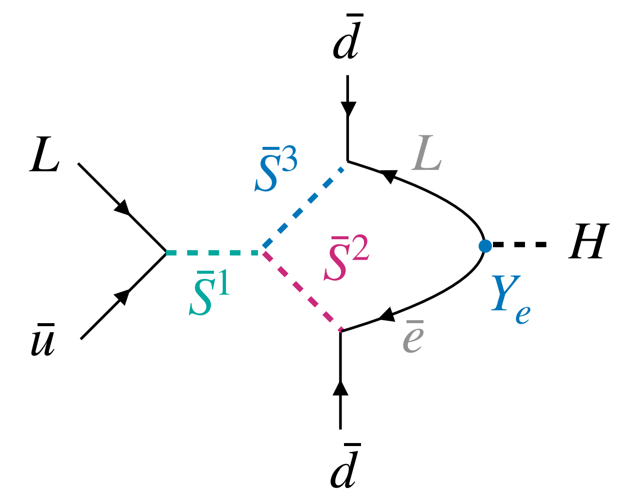


$\mathcal{O}_{28} = LL\bar{e}\bar{u}\bar{d}\bar{d}$



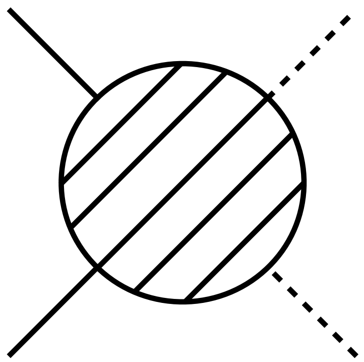
Arising at even-d in the SMEFT

Arising at even-d in the SMEFT [A. Kobach 2016]

Loop-level Proton decay and Neutrino masses

Tree-level completions of **high-dimensional $\Delta L = 2$ and $\Delta B = 1$ operators** that lead to m_ν and **proton decay at loop level**

$\Delta L = 2$



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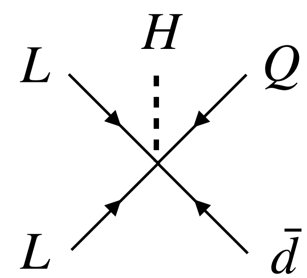
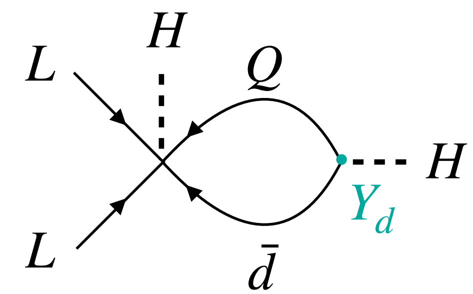


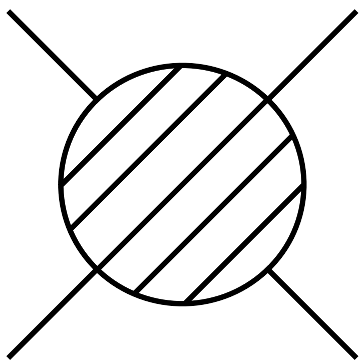
$\mathcal{O}_{3a} = LLQ\bar{d}H$



$$C_W \sim \frac{y_b}{16\pi^2}\frac{1}{\Lambda}c_{3a}$$

$\Delta(B-L) = 0$

Different phenomenology



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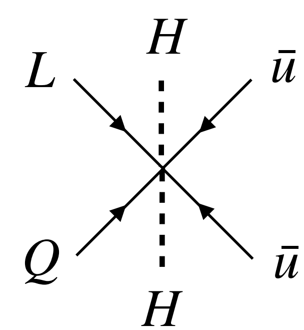

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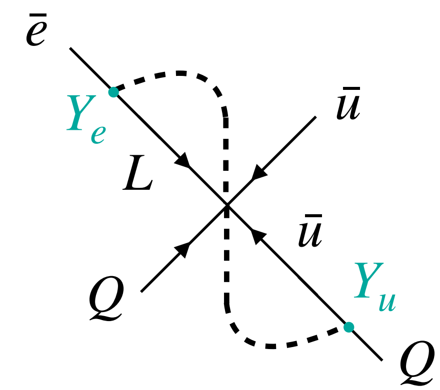
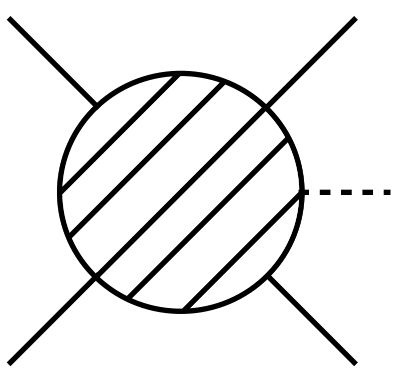


$$C_{qque} \sim \frac{y_u y_e}{(16\pi^2)^2}\frac{1}{\Lambda^2}c_{14}$$

$\Delta(B-L) = 2$



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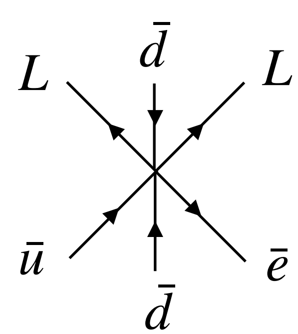

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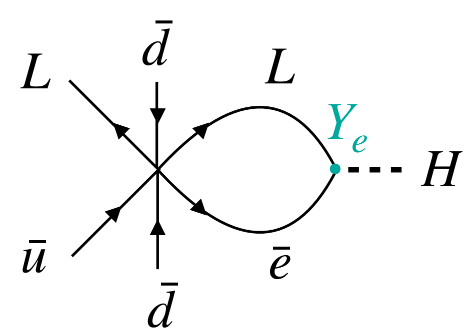


$$C_{\bar{l}dud\tilde{H}} \sim \frac{y_e}{16\pi^2}\frac{1}{\Lambda^3}c_{28}$$

Loop-level estimates
(Without specifying the full UV completion)

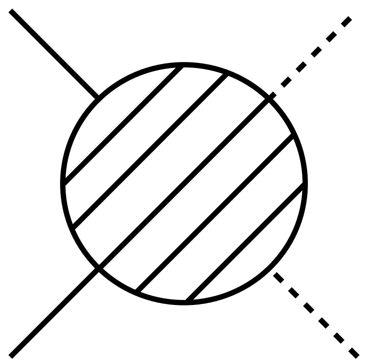
Arising at even-d in the SMEFT

Arising at even-d in the SMEFT [A. Kobach 2016]

Loop-level Proton decay and Neutrino masses

Tree-level completions of **high-dimensional $\Delta L = 2$ and $\Delta B = 1$ operators** that lead to m_ν and **proton decay at loop level**

$\Delta L = 2$

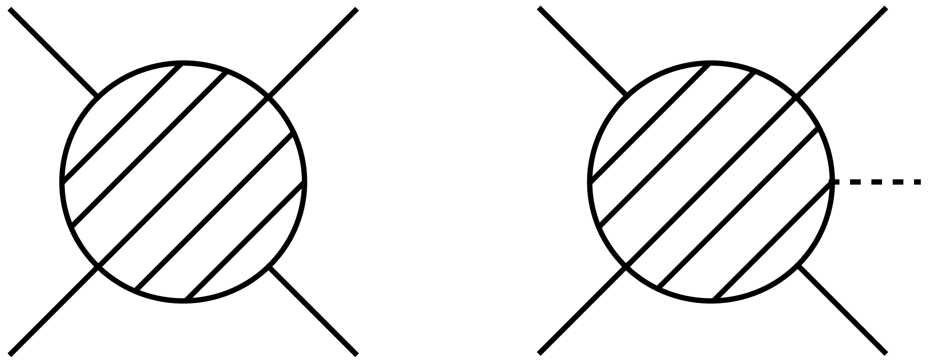


[J. Gargalionis et al. 2020]

Labels	Operator	Models	Filtered	Loops	Λ [TeV]
1	$L^i L^j H^k H^l \cdot \epsilon_{ik}\epsilon_{jl}$	3	3	0	$6 \cdot 10^{11}$
2	$L^i L^j L^k \bar{e} H^l \cdot \epsilon_{ik}\epsilon_{jl}$	8	2	1	$4 \cdot 10^{7}$
3a	$L^i L^j Q^k \bar{d} H^l \cdot \epsilon_{ij}\epsilon_{kl}$	9	2	2	$2 \cdot 10^{5}$
3b	$L^i L^j Q^k \bar{d} H^l \cdot \epsilon_{ik}\epsilon_{jl}$	14	5	1	$9 \cdot 10^{7}$
4a	$L^i L^j \tilde{Q}^k \bar{u}^\dagger H^l \cdot \epsilon_{ik}\epsilon_{jl}$	5	0	1	$4 \cdot 10^{9}$
4b	$L^i L^j \tilde{Q}^k \bar{u}^\dagger H^l \cdot \epsilon_{ij}\epsilon_{kl}$	4	2	2	$10 \cdot 10^{6}$
5a	$L^i L^j Q^k \bar{d} H^l H^m \tilde{H}^n \cdot \epsilon_{il}\epsilon_{jn}\epsilon_{km}$	790	36	2	$6 \cdot 10^{5}$
5b	$\mathcal{O}_1 \cdot Q^i \bar{d} \tilde{H}^j \cdot \epsilon_{ij}$	492	14	1,2	$6 \cdot 10^{5}$
5c	$\mathcal{O}_{3a} \cdot H^i \tilde{H}^j \cdot \epsilon_{ij}$	509	0	2,3	$1 \cdot 10^{3}$
5d	$\mathcal{O}_{3b} \cdot H^i \tilde{H}^j \cdot \epsilon_{ij}$	799	16	1,2	$6 \cdot 10^{5}$
6a	$L^i L^j \tilde{Q}^k \bar{u}^\dagger H^l H^m \tilde{H}^n \cdot \epsilon_{il}\epsilon_{jn}\epsilon_{km}$	289	14	2	$2 \cdot 10^{7}$
6b	$\mathcal{O}_1 \cdot \tilde{Q}^i \bar{u}^\dagger \tilde{H}^j \cdot \epsilon_{ij}$	177	0	1,2	$2 \cdot 10^{7}$
6c	$\mathcal{O}_{4a} \cdot H^i \tilde{H}^j \cdot \epsilon_{ij}$	262	0	1,2	$2 \cdot 10^{7}$
6d	$\mathcal{O}_{4b} \cdot H^i \tilde{H}^j \cdot \epsilon_{ij}$	208	0	2,3	$6 \cdot 10^{4}$
7	$L^i \bar{e}^\dagger Q^j \tilde{Q}^k H^l H^m H^n \cdot \epsilon_{il}\epsilon_{jm}\epsilon_{kn}$	240	15	2	$2 \cdot 10^{5}$

114 $\Delta L = 2$ operators up to **dimension-11** in the SMEFT

$\Delta(B-L) = 0, 2$



[J. Gargalionis et al. 2024]

#	Operator	Matching estimate	Flavour	Λ [GeV]	Process
Dimension 6					
1	$LQQQ$	—	1111	$3 \cdot 10^{15}$	$p \to \pi^0 e^+$
2	$\bar{e}^\dagger QQ\bar{u}^\dagger$	—	1111	$4 \cdot 10^{15}$	$p \to \pi^0 e^+$
3	$\bar{e}^\dagger \bar{u}^\dagger \bar{u}^\dagger \bar{d}^\dagger$	—	1111	$3 \cdot 10^{15}$	$p \to \pi^0 e^+$
4	$LQ\bar{u}^\dagger \bar{d}^\dagger$	—	1111	$3 \cdot 10^{15}$	$p \to \pi^0 e^+$
Dimension 7					
5	$L\bar{d}\bar{d}\bar{d}H^\dagger$	—	1112	$2 \cdot 10^{10}$	$n \to K^+ e^-$
6	$DLQ^\dagger \bar{d}\bar{d}$	—	1112	$6 \cdot 10^{9}$	$p \to K^+ \nu$
7	$D\bar{e}^\dagger \bar{d}\bar{d}\bar{d}$	—	1111	$3 \cdot 10^{9}$	$n \to \pi^+ e^-$
8	$LQ^\dagger Q^\dagger \bar{d}H$	—	1111	$6 \cdot 10^{10}$	$n \to \pi^0 \nu$
9	$\bar{e}^\dagger Q^\dagger \bar{d}\bar{d}H$	—	1112	$3 \cdot 10^{10}$	$n \to K^+ e^-$
10	$L\bar{u}\bar{d}\bar{d}H$	—	1111	$6 \cdot 10^{10}$	$n \to \pi^0 \nu$
Dimension 8					
11	$DLQQ\bar{d}^\dagger H$	$C^{pqrs}_{qqql} = \frac{1}{16\pi^2} V^*_{ru'} (y_d)^{u'} C^{spqu'}_{11}$	1113	$4 \cdot 10^{12}$	$p \to K^+ \nu$
12	$DL\bar{u}^\dagger \bar{d}^\dagger \bar{d}^\dagger H$	$C^{pqrs}_{duql} = \frac{1}{16\pi^2} V^*_{rt'} (y_d)^{t'} C^{sqt'p}_{12}$	1131	$3 \cdot 10^{12}$	$p \to K^+ \nu$

Many possibilities!

50 $\Delta L = 2$ operators up to **dimension-9** in the SMEFT
(Both $\Delta(B-L) = 0, 2$ operators)

Proton decay and Neutrino masses

Can we say **anything** about the **mass of the mediator(s)** in these BSM processes?

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Neutrino masses

Yes, if we demand that the **atmospheric lower bound** on Δm^2_{atm} be reproduced.

$$m_\nu \geq \sqrt{\Delta m^2_{\text{atm}}} \geq 0.05 \text{ eV} \implies \Lambda \underset{\substack{\uparrow \\ y \leq 1}}{\leq} \#^{\text{exp}}$$

[J. Herrero et al. 2019]

Proton decay

No, only lower bounds on the the combination $\Lambda/\sqrt{c}$ from current limits from Super-K…

Using $c \leq 1$ does not help…

$$\tau_p > \tau_p^{\text{exp}} \implies \frac{c}{\Lambda^2}, \frac{c}{\Lambda^3} \leq \#^{\text{exp}}$$

[A. Bas i Beneito et al. 2023]

If we saw proton decay, how could we establish what the **underlying mechanism** is?

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[J. Herrero et al. 2019]

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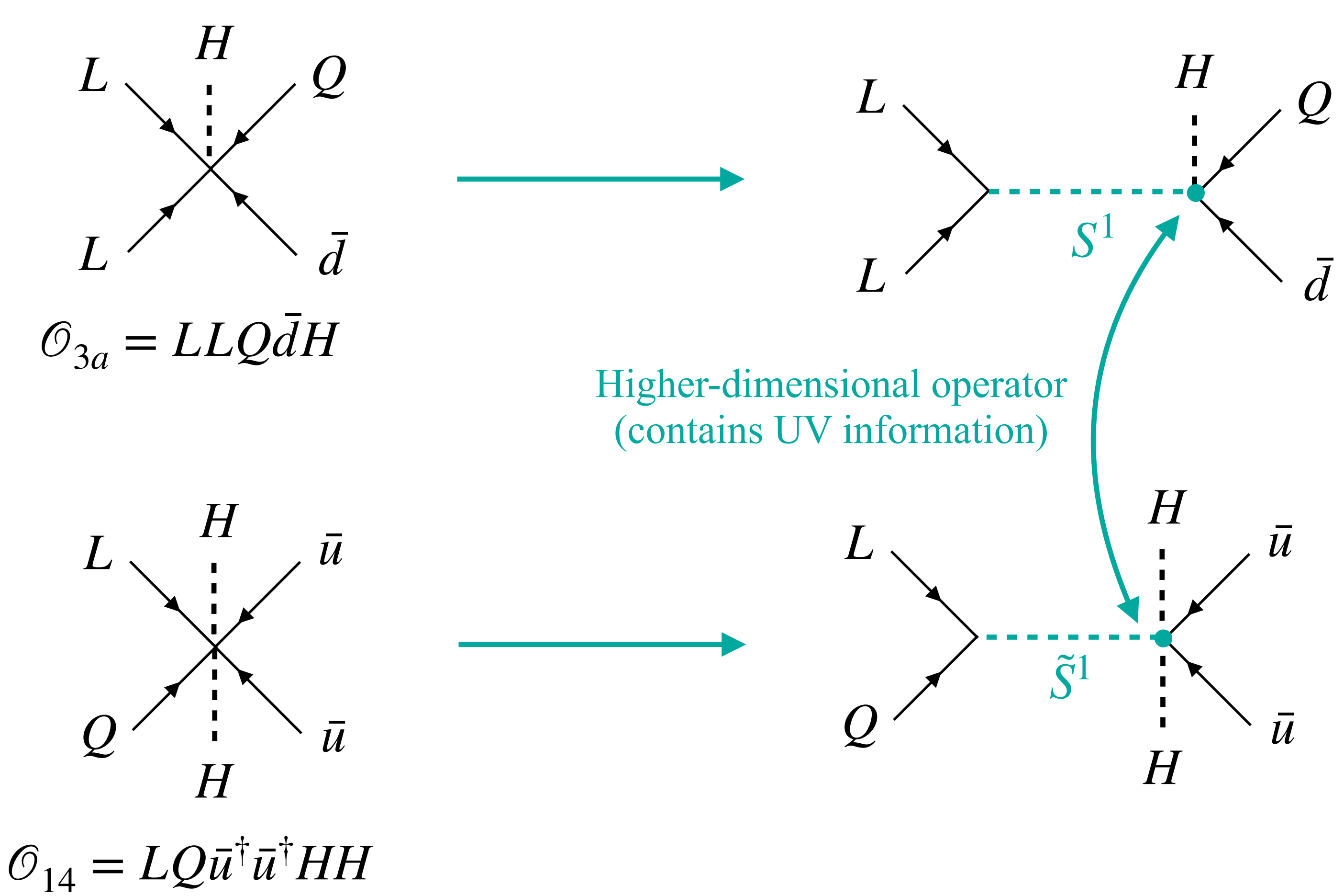
Neutrino masses **Proton decay**



Assuming this particle to be the **lightest BSM particle**, can we say something about its **mass**?

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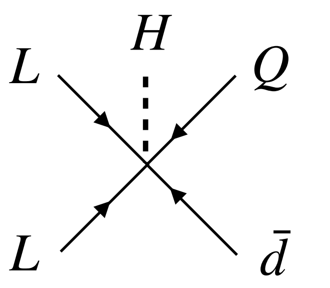
Neutrino masses

Proton decay



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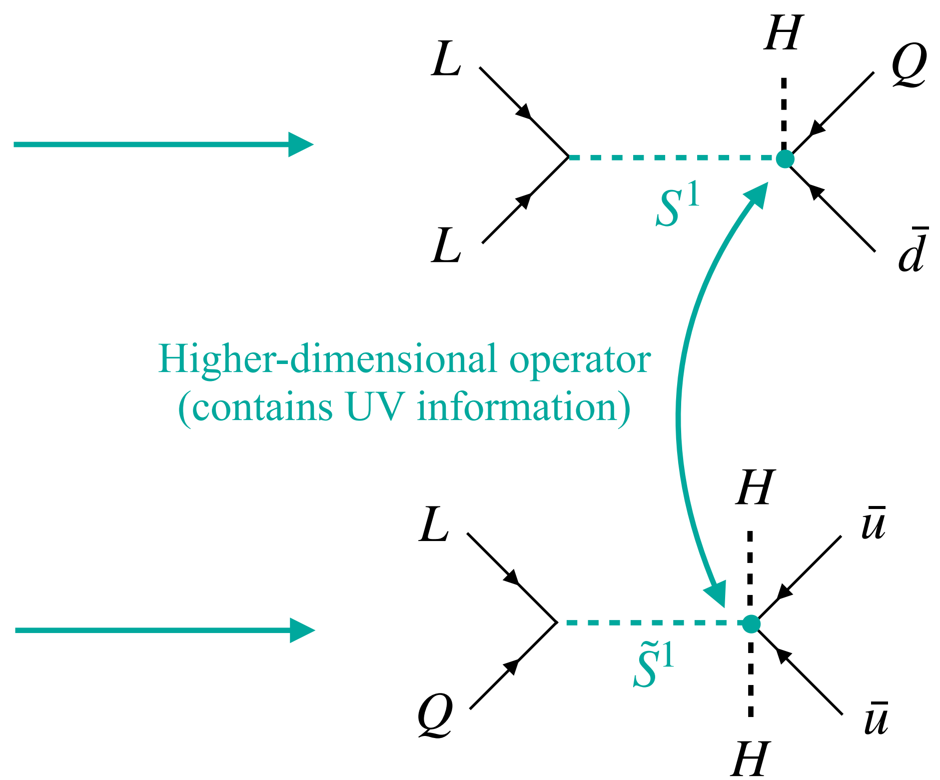
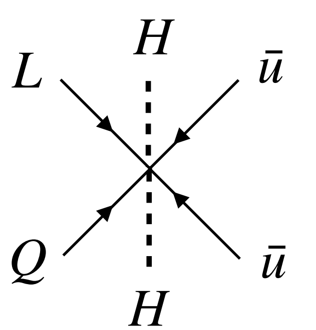




$\mathcal{O}_{14} = LQ\bar{u}^\dagger\bar{u}^\dagger HH$

Assuming this particle to be the **lightest BSM particle**, can we say something about its **mass**?

YES! ✓
(Under a few assumptions)

Theoretical framework

Tree-level completions of **higher-dimensional** $\Delta L = 2$ and $\Delta(B-L) = 0, 2$ operators

We choose to study the set of **48 exotic multiplets** that **couple linearly** to the SM at the **renormalisable level**, what we call Linear SM Extensions **(LSMEs)**

Tree-level completions of **higher-dimensional** $\Delta L = 2$ and $\Delta(B-L) = 0, 2$ operators

↓

We choose to study the set of **48 exotic multiplets** that **couple linearly** to the SM at the **renormalisable level**, what we call Linear SM Extensions **(LSMEs)**

19 SCALARS	**13 FERMIONS**	**16 VECTORS**
$X\,(\psi_{\text{SM}}\,\psi_{\text{SM}})$	$(X\,\psi_{\text{SM}})\,H$	$X^{\mu}(\psi^{\dagger}_{\text{SM}}\,\sigma_{\mu}\,\psi_{\text{SM}})$
$X \cdot f(H, H^{\dagger})$ *		$X^{\mu}\,D_{\mu}H\,(H)$

- These multiplets generate **dimension-5** and **dimension-6 operators in the SMEFT at tree level**.
- We aim to **constrain each LSME** by analysing their **contributions to** $\Delta L = 2$ **and** $\Delta B = 1$ phenomena using EFT.
- The analysis applies to the **simplest** and **most minimal UV models** in which the LSME appears, characterised by the **lowest-dimensional operator** we can write. To achieve this, we write down **effective operators** that include such exotic multiplets.

* Their electrically neutral component may acquire a VEV

Granada dictionary

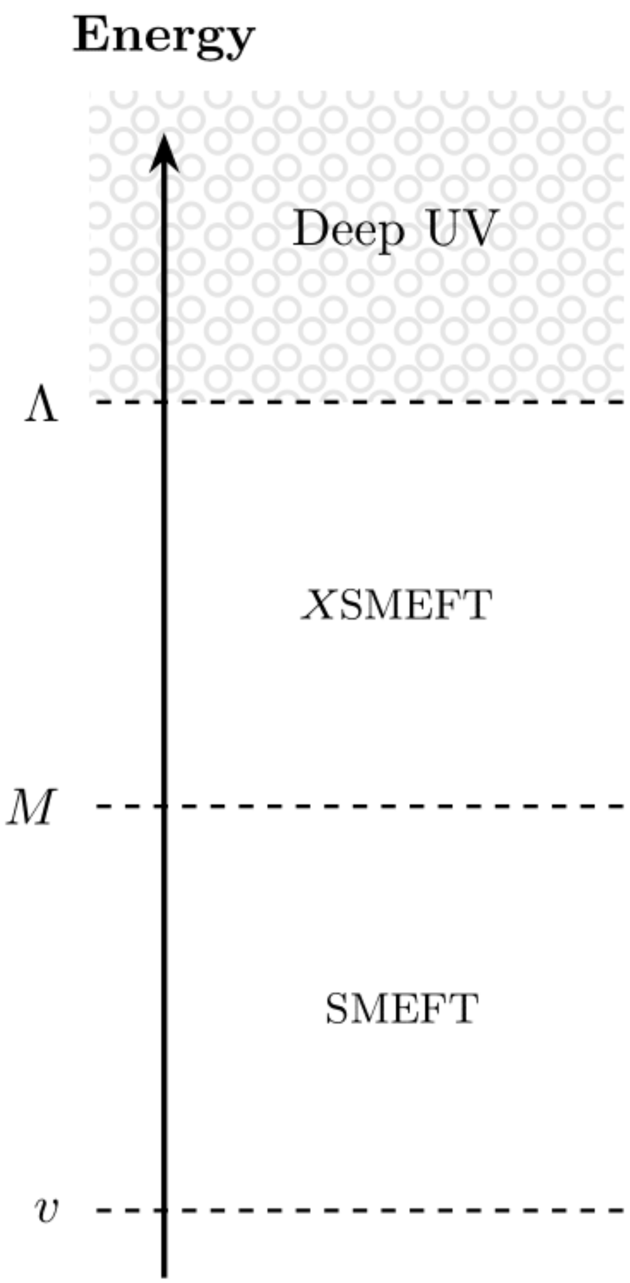
[J. de Blas et al. 2017]

Dimension-6 proton decay

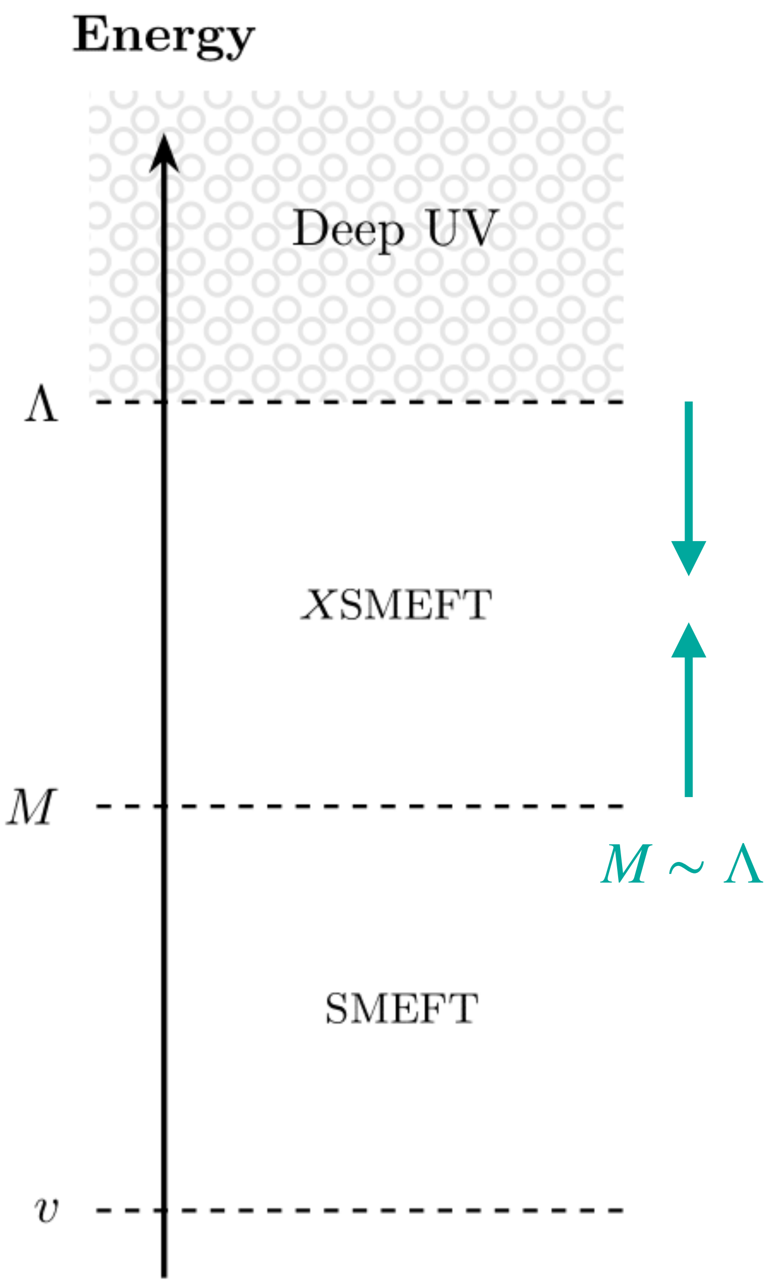
Seesaw mediators

Scalars	Vectors	Fermions
$\Xi_1 \sim (1,3,1)_S$	$\mathcal{U}_2 \sim (3,1,2/3)_V$	$N \sim (1,1,0)_F$
$\mathcal{S} \sim (1,1,0)_S$	$\mathcal{X} \sim (3,3,2/3)_V$	$\Sigma \sim (1,3,0)_F$
$\varphi \sim (1,2,1/2)_S$	$\mathcal{Q}_1 \sim (3,2,1/6)_V$	$\Sigma_1 \sim (1,3,-1)_F$
$\Xi \sim (1,3,0)_S$	$\mathcal{L}_1 \sim (1,2,1/2)_V$	$Q_7 \sim (3,2,7/6)_F$
$\Theta_1 \sim (1,4,1/2)_S$	$\mathcal{Y}_1 \sim (\bar{6},2,1/6)_V$	$T_1 \sim (3,3,-1/3)_F$
$\Theta_3 \sim (1,4,3/2)_S$	$\mathcal{Y}_5 \sim (\bar{6},2,-5/6)_V$	$Q_1 \sim (3,2,1/6)_F$
$\omega_1 \sim (3,1,-1/3)_S$	$\mathcal{G}_1 \sim (8,1,1)_V$	$Q_5 \sim (3,2,-5/6)_F$
$\zeta \sim (3,3,-1/3)_S$	$\mathcal{H} \sim (8,3,0)_V$	$T_2 \sim (3,3,2/3)_F$
$\Pi_1 \sim (3,2,1/6)_S$	$\mathcal{B} \sim (1,1,0)_V$	$\Delta_1 \sim (1,2,-1/2)_F$
$\mathcal{S}_1 \sim (1,1,1)_S$	$\mathcal{W} \sim (1,3,0)_V$	$\Delta_3 \sim (1,2,-3/2)_F$
$\Omega_4 \sim (6,1,4/3)_S$	$\mathcal{G} \sim (8,1,0)_V$	$E \sim (1,1,-1)_F$
$\Upsilon \sim (6,3,1/3)_S$	$\mathcal{Q}_5 \sim (3,2,-5/6)_V$	$D \sim (3,1,-1/3)_F$
$\Phi \sim (8,2,1/2)_S$	$\mathcal{U}_5 \sim (3,1,5/3)_V$	$U \sim (3,1,2/3)_F$
$\Omega_2 \sim (6,1,-2/3)_S$	$\mathcal{B}_1 \sim (1,1,1)_V$	
$\omega_4 \sim (3,1,-4/3)_S$	$\mathcal{W}_1 \sim (1,3,1)_V$	
$\Pi_7 \sim (3,2,7/6)_S$	$\mathcal{L}_3 \sim (1,2,-3/2)_V$	
$\mathcal{S}_2 \sim (1,1,2)_S$		
$\omega_2 \sim (3,1,2/3)_S$		
$\Omega_1 \sim (6,1,1/3)_S$		

Quantum numbers under
$G_{SM} = (SU(3)_C, SU(2)_L, U(1)_Y)$



- We imagine that a UV-complete $\Delta L = 2$ or $\Delta B = 1$ mechanism involving **at least one LSME** operates **above the scale** Λ **.**
- One of the LSMEs participating in this mechanism with mass M lives **in the range** $v < M < \Lambda$. We extend SMEFT with this exotic multiplet and call each such EFT the XSMEFT.
- We **estimate** the **dominant contributions** from the unknown UV mechanism living above the scale Λ to the **appropriate SMEFT operators.**



In this setup we can derive **upper bounds** on M <u>if</u>

- We impose the lower bound $m_\nu > \sqrt{\Delta m^2_{\text{atm}}} = 0.05\,\text{eV}$
- We assume a **positive signal** in Hyper-K: $\tau_p \simeq 10^{35}$ years
- We select **third-family Yukawa couplings** to estimate the **largest contribution** to $\Delta L = 2$ and $\Delta B = 1$ processes.
- We set dimensionless WCs $y, c \leq 1$
- We saturate the EFT condition $M \to \Lambda$ *

Very conservative assumptions!

* All expressions will depend on the two energy scales of our set-up: M and Λ. However, to remain as conservative as possible, we saturate the limit $M \sim \Lambda$

Derivation of the limits

Genuineness procedure

- Verification that the **lowest-dimensional XSMEFT** operators **dominantly contribute** to neutrino masses or nucleon decay.
- The UV completions of the XSMEFT operators **do not include** a subset of particles that gives rise to the same phenomenon more dominantly.

E.g. $\Theta_1 \sim (1,4,1/2)_S \longrightarrow$ dimension-5 $\Theta_{1ijk} L^i L^j H^k$

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$\downarrow$

Dimension-7 with a more suppressed contribution to Neutrino masses

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$\downarrow$

Dimension-7 with a more suppressed contribution to Neutrino masses

Antisymmetry in flavour space

- Specific LSMEs have fixed flavour symmetries in the renormalisable operator, that impact the strongest constraints on the operator in two different ways:

1) For neutrino masses: we cannot choose third family-Yukawa to get the would-be most dominant estimate
2) For proton decay: we may not generate proton decay at tree-level

E.g. $\omega_4 \sim (3,1,-4/3)_S \longrightarrow$ Dimension-6 $y^{[pq]}\omega_4(\bar{u}^\dagger_{[p}\bar{u}^\dagger_{q]})$

$\uparrow$

No 2-body proton decay at tree-level

Derivation of the limits

Genuineness procedure

- Verification that the **lowest-dimensional XSMEFT** operators **dominantly contribute** to neutrino masses or nucleon decay.
- The UV completions of the XSMEFT operators **do not include** a subset of particles that gives rise to the same phenomenon more dominantly.

E.g. $\Theta_1 \sim (1,4,1/2)_S \longrightarrow$ dimension-5 $\Theta_{1ijk}\underbrace{L^i}_{\Xi_1}\underbrace{L^j H^k}_{\Sigma}$ ✗

$\downarrow$

Dimension-7 with a more suppressed contribution to Neutrino masses

Scalars with neutral components

- We also consider the possibility that the electrically neutral component of certain scalar multiplets **acquires a VEV**, **induced** by **EWSB**. Specifically those triplets and quadruplets under $SU(2)_L$:

E.g. $\mu \Xi H^\dagger H \longrightarrow \langle \Xi^0 \rangle \sim \mu \dfrac{v^2}{M^2}$

E.g. $y\Theta_1 H^\dagger H H^\dagger \longrightarrow \langle \Xi^0 \rangle \sim y \dfrac{v^3}{M^2}$

From EWPTs
$\langle X^0 \rangle \lesssim 1$ GeV

Antisymmetry in flavour space

- Specific LSMEs have fixed flavour symmetries in the renormalisable operator, that impact the strongest constraints on the operator in two different ways:

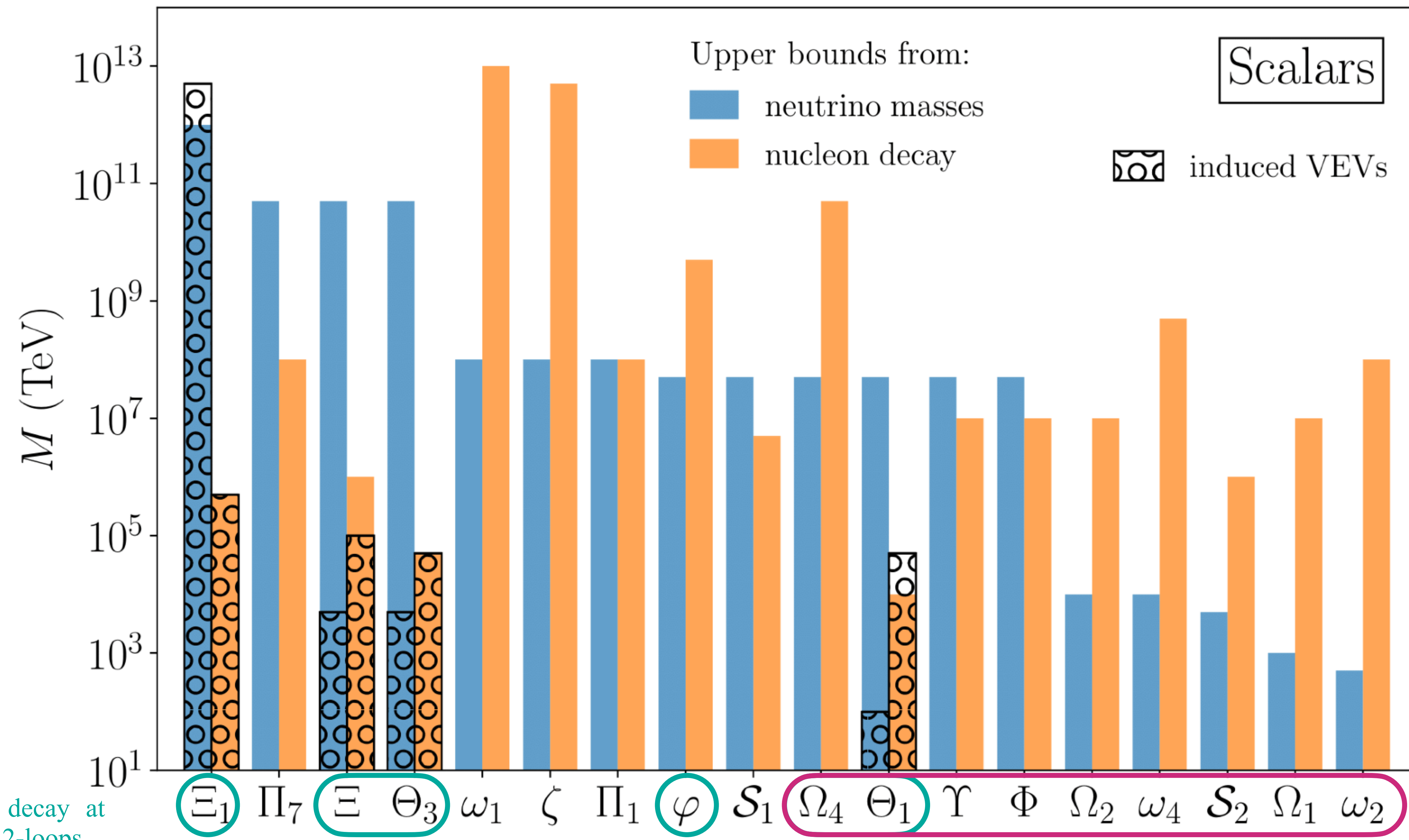
1) For neutrino masses: we cannot choose third family-Yukawa to get the would-be most dominant estimate
2) For proton decay: we may not generate proton decay at tree-level

E.g. $\omega_4 \sim (3,1,-4/3)_S \longrightarrow$ Dimension-6 $y^{[pq]}\omega_4(\bar{u}^\dagger_{[p}\bar{u}^\dagger_{q]})$

$\uparrow$

No 2-body proton decay at tree-level

Upper bounds for scalars

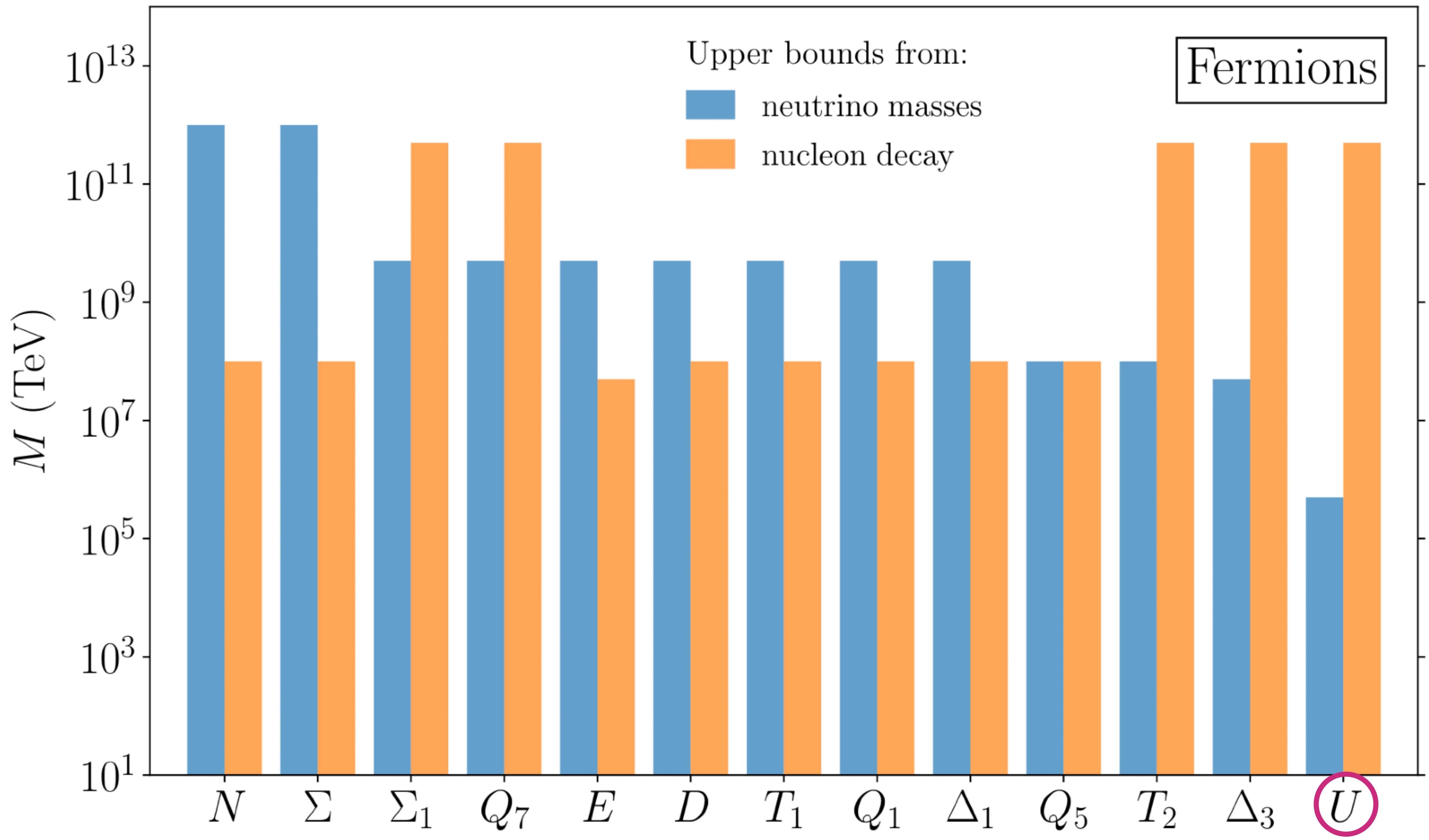


Proton decay at least at 2-loops

Neutrino masses at 2 or 3-loops

$$\langle \Xi^0_{(1)} \rangle \sim \mu \frac{v^2}{M^2} \qquad \langle \Theta^0_{1(3)} \rangle \sim y \frac{v^3}{M^2}$$

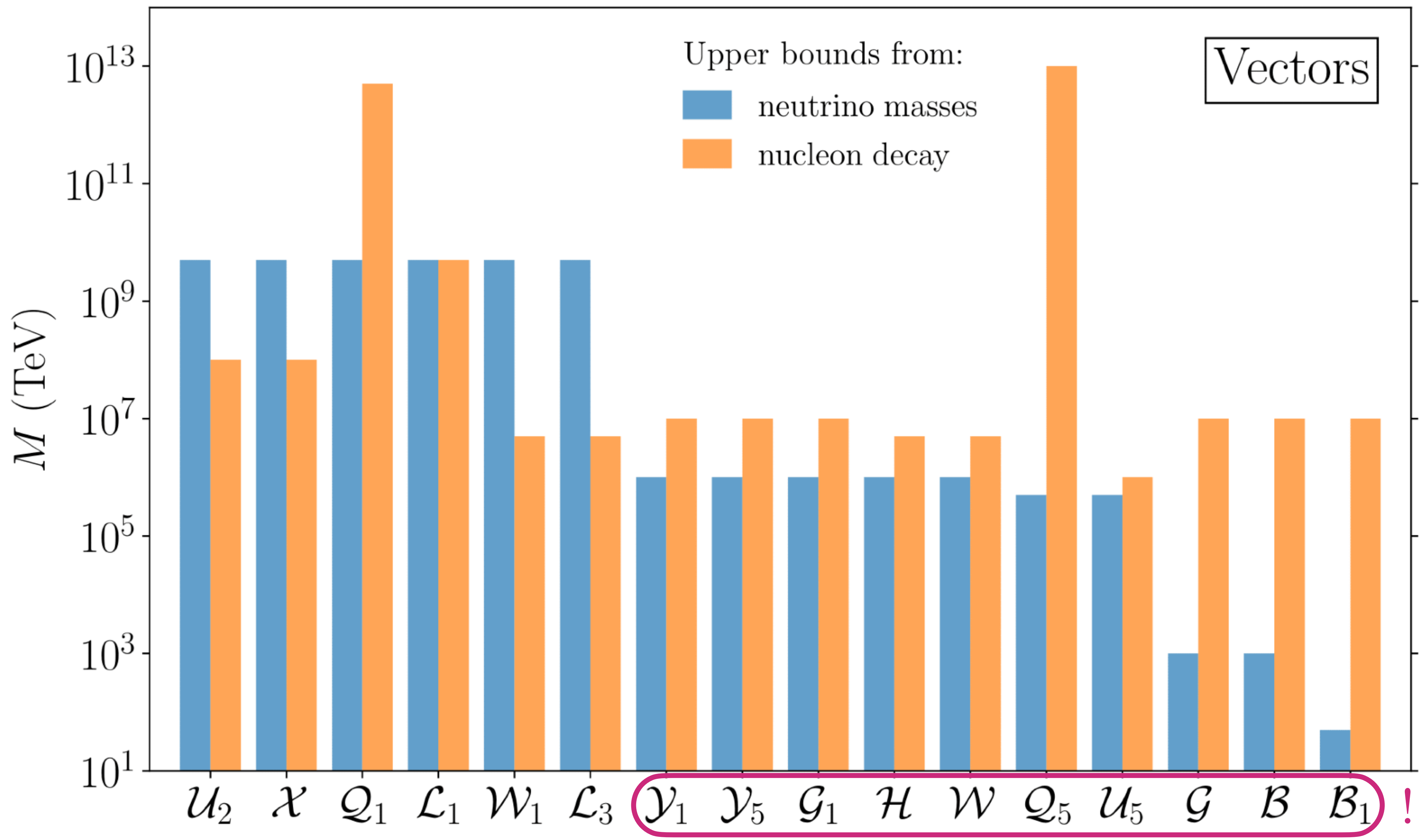
Upper bounds for fermions



Both Neutrino masses and Proton decay at tree-level or at most 1-loop.

Exception: Neutrino masses at 2-loops

Upper bounds for vectors



Proton decay at most at 1-loop.

Neutrino masses at 2 or 3-loops

Neutrino masses and Proton decay

Loop-order in m_ν

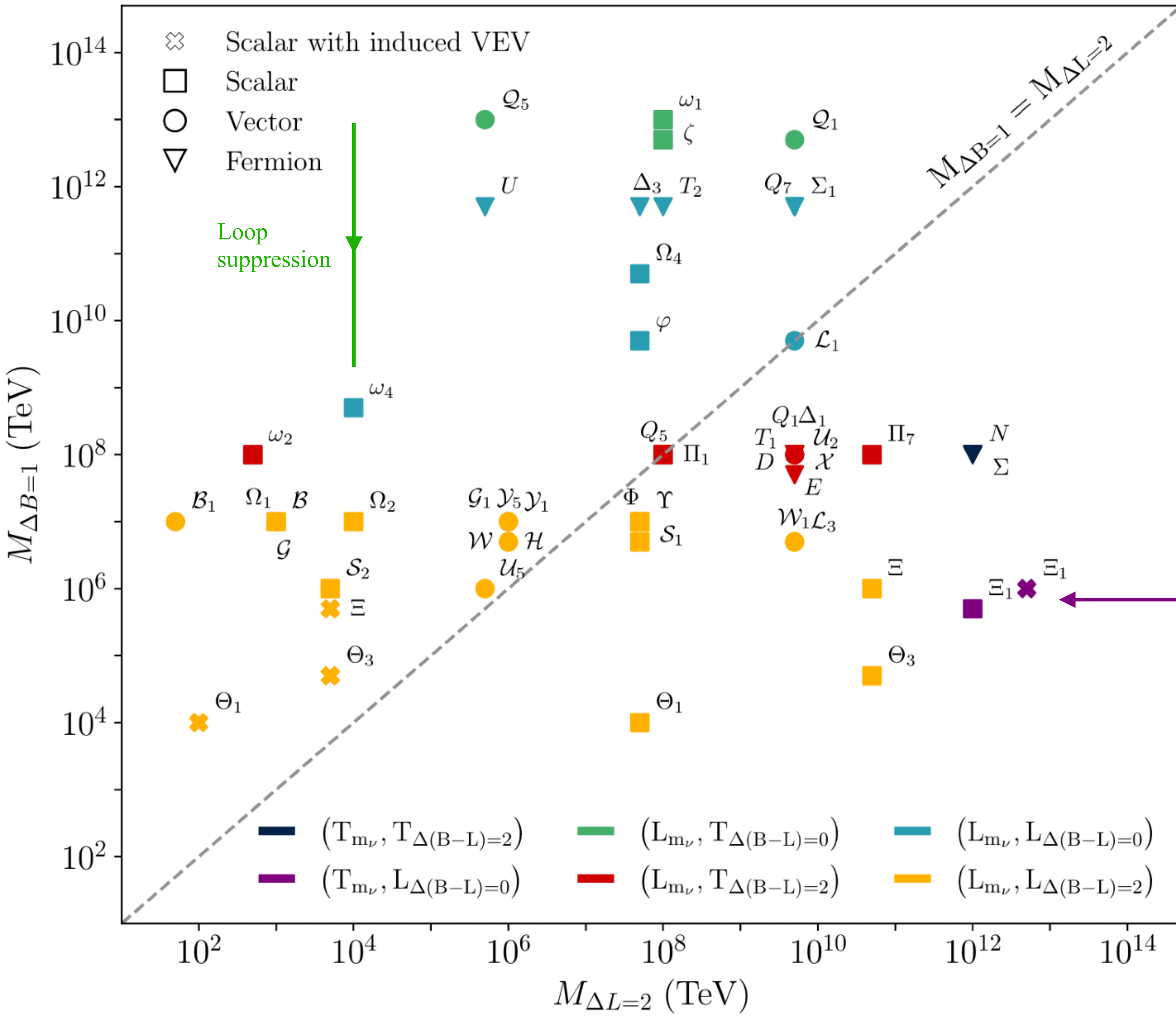
2 or 3 loops ← Tree-level

Tree-level

Loop-order in $\Delta(B-L)=0$ proton decay

Tree-level

Loop-order in $\Delta(B-L)=2$ proton decay



Exception: Very-much suppressed

Neutrino masses and Proton decay

Loop-order in m_ν

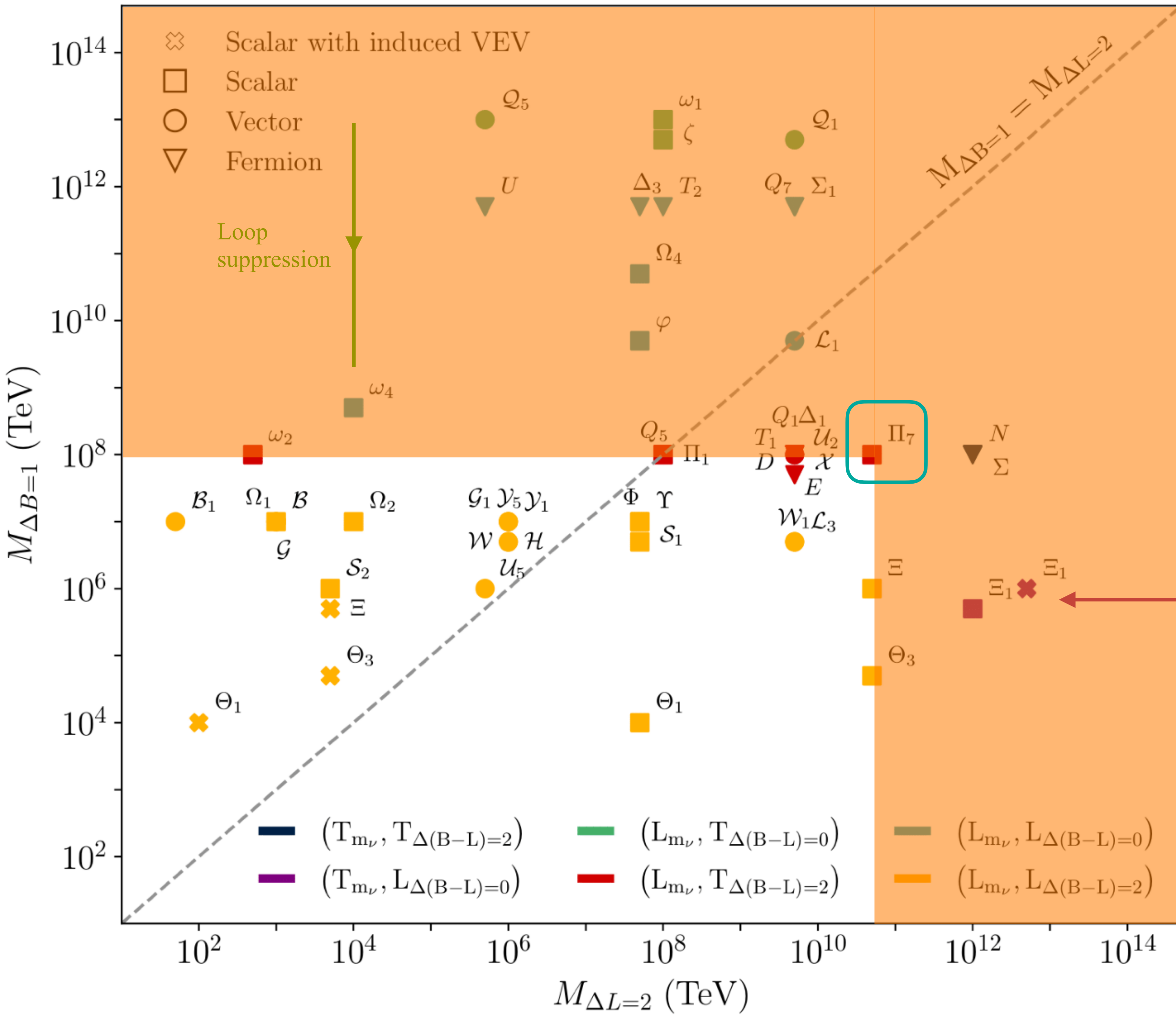
2 or 3 loops ← Tree-level

Tree-level

Loop-order in $\Delta(B-L)=0$ proton decay

Tree-level

Loop-order in $\Delta(B-L)=2$ proton decay



Exception: Very-much suppressed

Conclusions

- **Conservative upper bounds** on the mass of the **lightest mediator** of Majorana neutrino masses and proton decay, both $B-L$ conserving and violating.
- **Framework** to **organise the space of UV models** generating $\Delta L = 2$ and $\Delta B = 1$ phenomena.
- **Tool for model builders** interested in explaining (radiative) Majorana neutrino masses and proton decay.
- **Classification** of heavy multiplets that **could be probed** and searched for in **complementary searches**

Thank you!

Backup slides

Model class	References	Lifetime [years]	Ruled out?
Minimal SU(5)	Georgi & Glashow [21]	$10^{30} - 10^{31}$	yes
Minimal SUSY SU(5)	Dimopoulos & Georgi [22]; Sakai & Yanagida [23]	$10^{28} - 10^{34}$	yes
SUGRA SU(5)	Nath, Chamseddine & Arnowitt [24]	$10^{32} - 10^{34}$	yes
SUSY (MSSM/ESSM) SO(10)/$G(224)$	Babu, Pati & Wilczek [25]	$2 \cdot 10^{34}$	yes
SUSY (MSSM/ESSM, $d = 5$) SO(10)	Lucas & Raby [26]; Pati [27]	$10^{32} - 10^{35}$	partially
SUSY SO(10) + $\mathrm{U}(1)_{\mathrm{fl}}$	Shafi & Tavartkiladze [28]	$10^{32} - 10^{35}$	partially
SUSY ($d = 5$) SU(5) – option I	Hebecker & March-Russell [29]	$10^{34} - 10^{35}$	partially
SUSY (MSSM, $d = 6$) SU(5) or SO(10)	Pati [27]	$\sim 10^{34.9\pm1}$	partially
Minimal non-SUSY SU(5)	Doršner & Fileviez-Pérez [30]	$10^{31} - 10^{38}$	partially
Minimal non-SUSY SO(10)		—	no
SUSY (CMSSM) flipped SU(5)	Ellis, Nanopoulos & Walker [31]	$10^{35} - 10^{36}$	no
GUT-like models from string theory	Klebanov & Witten [32]	$\sim 10^{36}$	no
Split SUSY SU(5)	Arkani-Hamed *et al.* [33]	$10^{35} - 10^{37}$	no
SUSY ($d = 5$) SU(5) – option II	Alciati *et al.* [34]	$10^{36} - 10^{39}$	no

[Image extracted from T. Ohlsson 2023]

$$\Delta d \equiv d_{XSMEFT} - d_{SMEFT}$$

We distinguish two ways in which the Weinberg operator or the $d \leq 7$ baryon-number-violating operators may arise at the low scale:

$\Delta d \leq 1$ 1. Renormalisation group mixing of low-dimensional lepton- and baryon-number-violating operators in the XSMEFT featuring the exotic field X into the appropriate SMEFT operators between the scales Λ and M;

$\Delta d > 1$ 2. Loop-level matching at the scale Λ onto the relevant SMEFT operators.

First, we highlight that the running contributions to the dimension-5 Weinberg operator defined in Eq. (2.1) C_5 are fixed by dimensional analysis to be[19]

Running
$$\boxed{C_{5,\text{EFT}} \sim \frac{1}{\Lambda}\left(\frac{M}{\Lambda}\right)^{d-5} .} \tag{A.1}$$

The matching contributions that might compete with this can also have a similar form, which we write schematically as

Matching
$$\boxed{C_{5,\text{Match}} \sim \frac{1}{\Lambda}\left(\frac{M}{\Lambda}\right)^{\delta} ,} \tag{A.2}$$

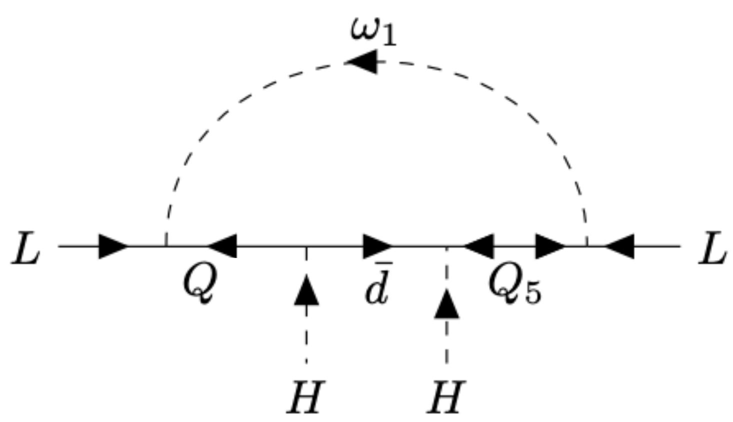
where $\delta = 1$ if we can conclude that the neutrino mass must contain a massive parameter in the numerator, and otherwise $\delta = 0$. We distinguish two possible cases where the matching contribution to the Weinberg operator might take this form in our framework:

Model 1 ($\Delta d = 1$)

SM + ω_1 + Q_5 with $m_{Q_5} = M < m_{\omega_1} = \Lambda$

$$C_5 \propto y_b M \int \frac{d^4q}{(2\pi)^4} \frac{1}{q^2} \frac{1}{q^2 - \Lambda^2} \frac{1}{q^2 - M^2}$$
$$\propto \frac{y_b}{16\pi^2} \frac{M}{M^2 - \Lambda^2} \log\left(\frac{M}{\Lambda}\right) ,$$

$$C_5 \propto \frac{y_b}{16\pi^2} \frac{M}{\Lambda^2} \log\left(\frac{M}{\Lambda}\right) + \mathcal{O}(M^3/\Lambda^3) ,$$



Model 1 ($\Delta d = 0$)

SM + ω_1 + Π_1 with $m_{\omega_1} = M < m_{\Pi_1} = \Lambda$

$$C_5 \propto i y_b \Lambda \int \frac{d^4q}{(2\pi)^4} \frac{1}{q^2} \frac{1}{q^2 - \Lambda^2} \frac{1}{q^2 - M^2}$$
$$\propto \frac{y_b}{16\pi^2} \frac{\Lambda}{M^2 - \Lambda^2} \log\left(\frac{M}{\Lambda}\right) ,$$

$$C_5 \propto \frac{y_b}{16\pi^2} \frac{1}{\Lambda} \log\left(\frac{M}{\Lambda}\right) + \mathcal{O}(M^2/\Lambda^2) ,$$

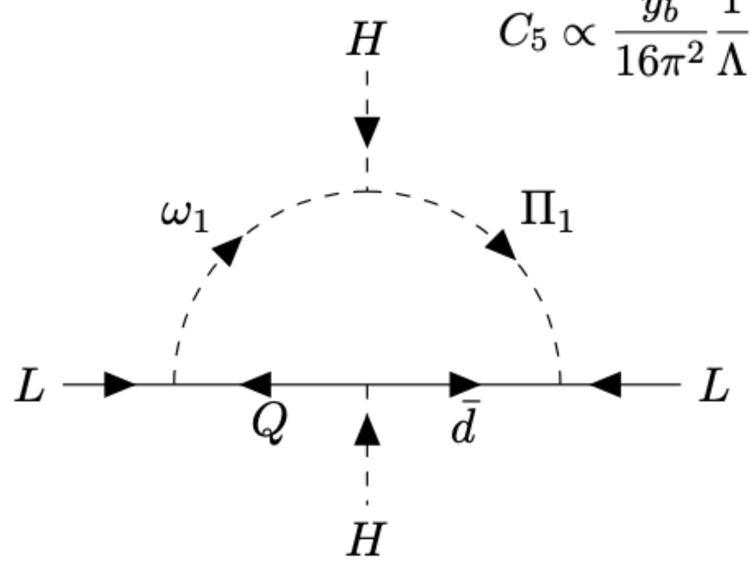
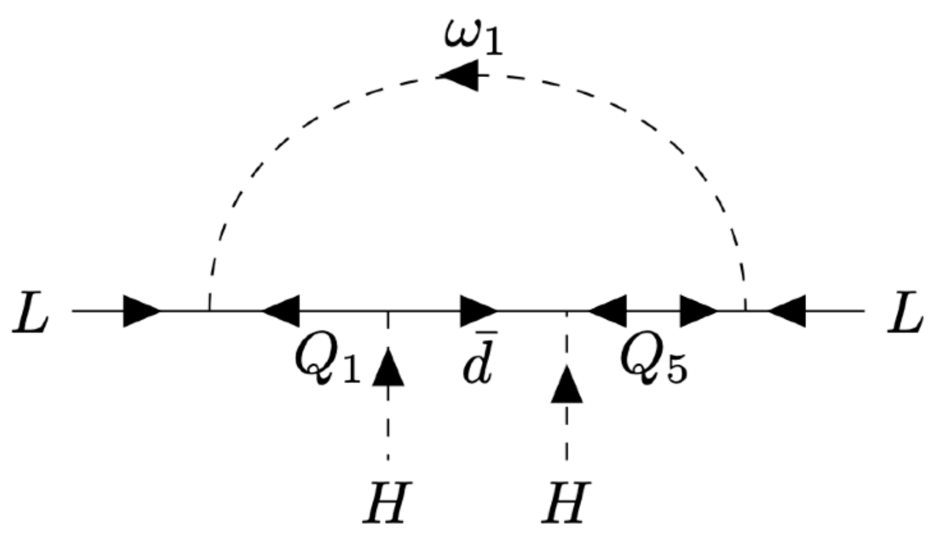


Figure 6. (Left) The neutrino mass diagram for the model presented in Ref. [42] for the choice of Q on the first internal fermion line. This is the example model presented in the $\Delta d = 1$ scenario of Sec. B.1. The choice of Q_1 is relevant for the $\Delta d > 1$ example model, presented in Sec. B.3. (Right) The neutrino-mass diagram for the leptoquark model of neutrino masses, as presented in Sec. B.2.

Matching dominates: $\Delta d > 1$

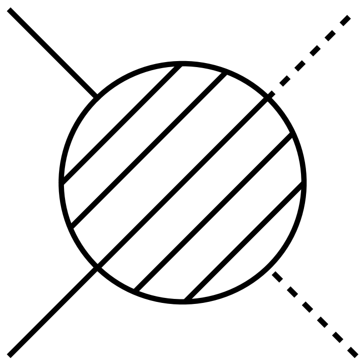
SM + $\omega_1 + Q_1 + \Pi_1$ with $m_{Q_1} = M < m_{\omega_1} = m_{\Pi_1} = \Lambda$

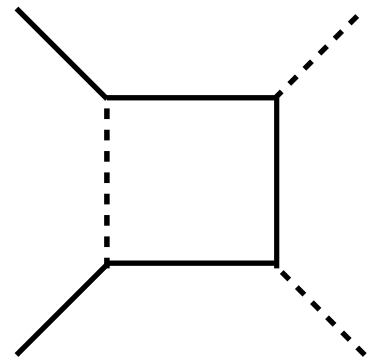
$$
\begin{aligned}
I &\propto \Lambda \int \frac{d^4 q}{(2\pi)^4} \frac{\bar{\sigma} \cdot q}{q^2 - M^2} \frac{\sigma \cdot q}{q^2} \left(\frac{1}{q^2 - \Lambda^2} \right)^2 \\
&\propto \frac{\Lambda}{16\pi^2} \left[\frac{1}{M^2 - \Lambda^2} - \frac{M^2}{(M^2 - \Lambda^2)^2} \log \frac{M^2}{\Lambda^2} \right] \\
&\propto \frac{1}{16\pi^2 \Lambda} + \mathcal{O}(M^2/\Lambda^2) \,,
\end{aligned}
$$



Loop-level completions of operators giving rise to m_ν and **proton decay** at **tree level**

$\Delta L = 2$

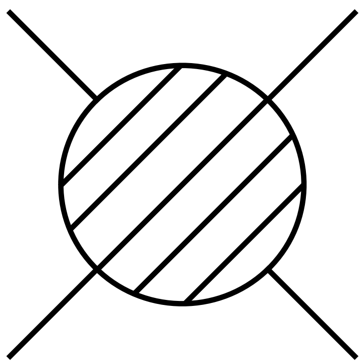


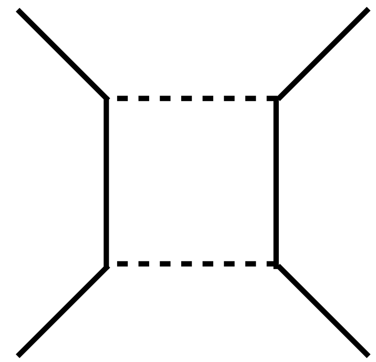


$+ \ \dots$

[F. Bonnet at al. 2012, Y. Farzan et al. 2013
M. Hirsch et al. 2012 & 2017 & 2019 …]

$\Delta(B-L) = 0$

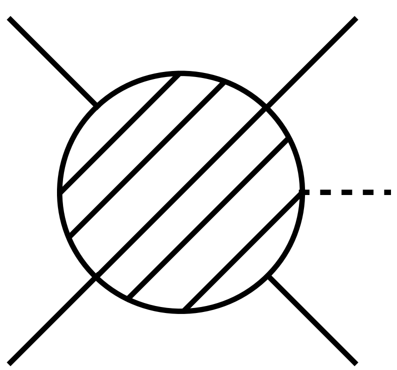




[M. Hirsch et al. 2019]
(Only S+F, not V)

Different phenomenology

$\Delta(B-L) = 2$



?

Main drawbacks:

1. ∞ loop-level completions (less economical UV models)
2. (Typically) 4 exotic particles
3. (Typically) do not generate dimension-6 SMEFT operators when integrated out at tree-level

Induced VEVs

LSME	G_{SM}	$\mathcal{L}_{\Delta L=2}$	$[m_\nu]_{pq}$	Upper Bound (TeV)	$\langle X^0 \rangle$ (TeV)
Ξ_1	$(1,3,1)_S$	$\mu \Xi_1^\dagger HH + c_{\{pq\}}\, \Xi_1(L_pL_q)$	$c_{\{pq\}} \left(\mu\, \frac{v^2}{M^2}\right)$	$5 \cdot 10^{12}$	$5 \cdot 10^{-15}$
Ξ	$(1,3,0)_S$	$\mu \Xi H^\dagger H + c_{\{pq\}} \Xi^{\{ij\}} (L_p^k L_q^l) H^m H^n \epsilon_{km}\epsilon_{il}\epsilon_{jn}$	$c_{\{pq\}}\, \frac{v^2}{\Lambda^2} \left(\mu\, \frac{v^2}{M^2}\right)$	$5 \cdot 10^{3}$	$6 \cdot 10^{-6}$
Θ_3	$(1,4,3/2)_S$	$y\Theta_3^\dagger HHH + c_{\{pq\}} \Theta_3 (L_pL_q) H^\dagger$	$c_{\{pq\}}\, \frac{v}{\Lambda} \left(y\, \frac{v^3}{M^2}\right)$	$5 \cdot 10^{3}$	$5 \cdot 10^{-10}$
Θ_1	$(1,4,3/2)_S$	$y\Theta_1^\dagger HH^\dagger H + c_{pq} \Theta_1^{\{ijk\}} (L_p^l L_q^m) H^n H_l^\dagger H^o \epsilon_{im}\epsilon_{jn}\epsilon_{ko}$	$c_{pq}\, \frac{v^3}{\Lambda^3} \left(y\, \frac{v^3}{M^2}\right)$	10^{2}	$5 \cdot 10^{-7}$

Table 5. Same as Tab. 2 for the generation of Majorana neutrino masses by the four scalar LSMEs that have a neutral component and may develop a VEV, as explained in Sec. 2.4. In the sixth column we quote the upper bound on Λ in the limit $\mu \sim M \sim \Lambda$, and in the last column, we display the value of the VEV induced by the SM Higgs doublet.

LSME	G_{SM}	$\mathcal{L}_{\Delta B=1}$	$[L^{S,XY}_{q_1q_2q_3}]_{pqrs}$ [79, 92]	Upper Bound (TeV)	$\langle X^0 \rangle$ (TeV)
Ξ_1	$(1,3,1)_S$	$\mu\, \Xi_1^\dagger HH + c_{pq[rs]} \Xi_1 (Q_pL_q)(\bar{d}_r^\dagger \bar{d}_s^\dagger)$	$[L^{S,RL}_{ddu}]_{pqrs} = c_{rs[pq]}\, \frac{1}{\Lambda^3} \left(\mu\, \frac{v^2}{M^2}\right)$	$5 \cdot 10^{5}$	$6 \cdot 10^{-8}$
Ξ	$(1,3,0)_S$	$\mu\, \Xi H^\dagger H + c_{pq[rs]} \Xi_{ij} (L_{pk}^\dagger \bar{d}_q^\dagger)(Q_r^i Q_s^j) H_l^\dagger \epsilon^{kl}$	$[L^{S,LR}_{udd}]_{pqrs} = c_{rs[pq]}\, \frac{v}{\Lambda^4} \left(\mu\, \frac{v^2}{M^2}\right)$	10^{5}	$3 \cdot 10^{-7}$
Θ_3	$(1,4,3/2)_S$	$y\Theta_3 H^\dagger H^\dagger H^\dagger + c_{[pq]rs}\, \Theta_3^\dagger (Q_pQ_q)(L_r^\dagger \bar{u}_s^\dagger)$	$[L^{S,LR}_{ddu}]_{pqrs} = c_{[pq]rs}\, \frac{1}{\Lambda^3} \left(y\, \frac{v^3}{M^2}\right)$	$5 \cdot 10^{4}$	$2 \cdot 10^{-8}$
Θ_1	$(1,4,1/2)_S$	$y\Theta_1 H^\dagger H H^\dagger + c_{pq[rs]}\, \Theta_1^\dagger (L_p^\dagger \bar{d}_q^\dagger)(Q_rQ_s)$	$[L^{S,LR}_{udd}]_{pqrs} = c_{rs[pq]}\, \frac{1}{\Lambda^3} \left(y\, \frac{v^3}{M^2}\right)$	$5 \cdot 10^{4}$	$2 \cdot 10^{-8}$

Table 6. Same as Tab. 2 for the generation of nucleon decays by the four scalar LSMEs that have a neutral component and may develop a VEV, as explained in Sec. 2.4. All the $\Delta B = 1$ LEFT WCs lead to the $p \to K^+\nu$ decay channel, from which the limit quoted in the sixth column is obtained.

Tables for scalars in $\Delta L = 2$

LSME	$G_{\rm SM}$	$\mathcal{L}_{\Delta L=2}$	Δd	Op.	$[m_\nu]_{pq}$	Upper Bound (TeV)
Ξ_1	$(1,3,1)_S$	$y_{\{pq\}}\,\Xi_1(L_pL_q) + \mu\Xi_1^\dagger HH$	-2	$\mathcal{O}_1$	$y_{\{pq\}}\frac{\mu}{M}\frac{v^2}{M}$	10^{12}
Ξ	$(1,3,0)_S$	$\mu\Xi H^\dagger H + c_{\{pq\}}\Xi^{\{ij\}}(L_p^kL_q^l)H^mH^n\epsilon_{km}\epsilon_{il}\epsilon_{jn}$	1	$\mathcal{O}_1'$	$c_{\{pq\}}\left(L+\frac{v^2}{\Lambda^2}\right)\frac{\mu}{\Lambda}\frac{v^2}{\Lambda}$	$5\cdot10^9$
Θ_3	$(1,4,3/2)_S$	$y\Theta_3^\dagger HHH + c_{\{pq\}}\Theta_3(L_pL_q)H^\dagger$	0	$\mathcal{O}_1'$	$y\,c_{\{pq\}}\left(L+\frac{v^2}{\Lambda^2}\right)\frac{v^2}{\Lambda}$	$5\cdot10^9$
Π_7	$(3,2,7/6)_S$	$y_{pr}\Pi_7(\bar{u}_rL_p) + c_{qs}\Pi_{7i}^\dagger L_q^j\bar{u}_s^\dagger(DH)^iH^l\epsilon_{jl}$	2	$\mathcal{O}_{D12a}$	$y_{pr}c_{qr}\frac{v^2}{\Lambda}\,\epsilon$	$5\cdot10^9$
ω_1	$(3,1,-1/3)_S$	$y_{pr}\omega_1^\dagger(L_pQ_r) + c_{qs}\omega_1(L_q\bar{d}_s)H$	0	$\mathcal{O}_{3b}$	$y_{pr}c_{qr}[y_d]_r\frac{v^2}{\Lambda}\,L$	10^8
ζ	$(3,3,-1/3)_S$	$y_{pr}\zeta^\dagger(L_pQ_r) + c_{qs}\zeta(L_q\bar{d}_s)H$	0	$\mathcal{O}_{3b}$	$y_{pr}c_{qr}[y_d]_r\frac{v^2}{\Lambda}\,L$	10^8
Π_1	$(3,2,1/6)_S$	$y_{pr}\Pi_1(L_p\bar{d}_r) + c_{qs}\Pi_{1i}^\dagger(L_q^jQ_s^i)H^l\epsilon_{jl}$	0	$\mathcal{O}_{3b}$	$y_{pr}c_{qr}[y_d]_r\frac{v^2}{\Lambda}\,L$	10^8
φ	$(1,2,1/2)_S$	$y_{rp}\varphi^\dagger(\bar{e}_rL_p) + c_{[qs]}\varphi^iH^j(L_q^kL_s^l)\epsilon_{ij}\epsilon_{kl}$	0	$\mathcal{O}_2$	$y_{sq}c_{[sp]}[y_e]_s\frac{v^2}{\Lambda}\,L$	$5\cdot10^7$
Θ_1	$(1,4,1/2)_S$	$y\Theta_1^\dagger HH^\dagger H + c_{pq}\Theta_1^{\{ijk\}}(L_p^lL_q^m)H^nH_l^\dagger H^o\epsilon_{im}\epsilon_{jn}\epsilon_{ko}$	2	$\mathcal{O}_1''$	$y\,c_{pq}\left[\epsilon^2+\left(\frac{v^2}{\Lambda^2}\right)^2\right]\frac{v^2}{\Lambda}$	$5\cdot10^7$
$\mathcal{S}_1$	$(1,1,1)_S$	$y_{[pr]}\mathcal{S}_1(L_pL_r) + c_{qs}\mathcal{S}_1^\dagger(L_q\bar{e}_s)H$	0	$\mathcal{O}_2$	$y_{[pr]}c_{qr}[y_e]_r\frac{v^2}{\Lambda}\,L$	$5\cdot10^7$
Ω_4	$(6,1,4/3)_S$	$y_{\{rs\}}\Omega_4^\dagger(\bar{u}_r^\dagger\bar{u}_s^\dagger) + c_{pqtu}\Omega_4(L_pL_q)^{\{ij\}}(Q_t^\dagger Q_u^\dagger)_{ij}$	2	$\mathcal{O}_{12a}$	$y_{\{rs\}}c_{pqrs}[y_u]_r[y_u]_s\frac{v^2}{\Lambda}\,\epsilon^2$	$5\cdot10^7$
Υ	$(6,3,1/3)_S$	$y_{\{rs\}}\Upsilon(Q_r^\dagger Q_s^\dagger) + c_{\{pq\}\{tu\}}\Upsilon^\dagger(L_pL_q)(\bar{u}_t^\dagger\bar{u}_u^\dagger)$	2	$\mathcal{O}_{12a}$	$y_{sr}c_{\{pq\}\{rs\}}[y_u]_r[y_u]_s\frac{v^2}{\Lambda}\,\epsilon^2$	$5\cdot10^7$
Φ	$(8,2,1/2)_S$	$y_{rs}\Phi^\dagger(Q_r^\dagger\bar{u}_s^\dagger) + c_{pqtu}\Phi^i(L_p^jL_q^k)(Q_{tk}^\dagger\bar{u}_u^\dagger)\epsilon_{ij}$	2	$\mathcal{O}_{12a}$	$y_{sr}c_{pqrs}[y_u]_r[y_u]_s\frac{v^2}{\Lambda}\,\epsilon^2$	$5\cdot10^7$
Ω_2	$(6,1,-2/3)_S$	$y_{\{rs\}}\Omega_2(\bar{d}_r\bar{d}_s) + c_{pqtu}\Omega_2^\dagger(L_p^iQ_t^k)(L_q^jQ_u^l)\epsilon_{ik}\epsilon_{jl}$	2	$\mathcal{O}_{11b}$	$y_{\{rs\}}c_{pqrs}[y_d]_r[y_d]_s\frac{v^2}{\Lambda}\,\epsilon^2$	10^4
ω_4	$(3,1,4/3)_S$	$y_{rs}\omega_4(\bar{e}_r\bar{d}_s) + c_{pqrs}\omega_4^\dagger(L_p^iL_q^j)(L_r^kQ_s^l)\epsilon_{ik}\epsilon_{jl}$	2	$\mathcal{O}_{10}$	$y_{rs}c_{\{pqr\}s}[y_e]_r[y_d]_s\frac{v^2}{\Lambda}\,\epsilon^2$	10^4
$\mathcal{S}_2$	$(1,1,2)_S$	$y_{\{rs\}}\mathcal{S}_2^\dagger(\bar{e}_r\bar{e}_s) + c_{[pq][tu]}\mathcal{S}_2(L_p^iL_t^j)(L_q^kL_u^l)\epsilon_{ij}\epsilon_{kl}$	2	$\mathcal{O}_9$	$y_{\{rs\}}c_{pqrs}[y_e]_r[y_e]_s\frac{v^2}{\Lambda}\,\epsilon^2$	$5\cdot10^5$
Ω_1	$(6,1,1/3)_S$	$y_{rs}\Omega_1^\dagger(\bar{u}_r^\dagger\bar{d}_s^\dagger) + c_{pqtu}\Omega_1(L_p\bar{d}_t)(L_q\bar{d}_u)$	2	$\mathcal{O}_{17}$	$y_{ru}c_{pqtu}[y_d]_r[y_u]_rg^2\frac{v^2}{\Lambda}\,\epsilon^3$	10^3
ω_2	$(3,1,2/3)_S$	$y_{[rs]}\omega_2^\dagger(\bar{d}_r\bar{d}_s) + c_{pqtu}\omega_2(L_p^iQ_t^j)(L_q^kQ_u^l)\epsilon_{ij}\epsilon_{kl}$	2	$\mathcal{O}_{11b}$	$y_{[rs]}c_{pqrs}[y_d]_r[y_d]_s\frac{v^2}{\Lambda}\,\epsilon^2$	$5\cdot10^2$

Tables for scalars in $\Delta B = 1$

LSME	$G_{\rm SM}$	$\mathcal{L}_{\Delta B=1}$	Δd	Op.	Matching	Process	Upper Bound (TeV)
ω_1	$(3,1,-1/3)_S$	$y_{pq}\omega_1^\dagger(\bar{u}_p^\dagger\bar{e}_q^\dagger) + c_{\{rs\}}\,\omega_1(Q_rQ_s)$	-2	$\mathcal{O}_2^{1111}$	$C_{qque}^{pqrs} = y_{rs}c_{pq}\frac{1}{M^2}$	$p\to\pi^0e^+$	10^{13}
ζ	$(3,3,-1/3)_S$	$y_{pq}\,\zeta^\dagger(Q_pL_q) + c_{[rs]}\,\zeta(Q_rQ_s)$	-2	$\mathcal{O}_1^{1112}$	$C_{qqql}^{pqrs} = y_{rs}c_{[pq]}\frac{1}{M^2}$	$p\to K^+\nu$	$5\cdot10^{12}$
Ω_4	$(6,1,4/3)_S$	$y_{\{pq\}}\,\Omega_4^\dagger(\bar{u}_p^\dagger\bar{u}_q^\dagger) + c_{rstu}\Omega_4(\bar{e}^\dagger Q^\dagger)(QQ)H^\dagger$	2	$\mathcal{O}_{\Omega_4}^{111313}$	$C_{qque}^{pqrs} = y_{rw}c_{swpq}[y_u]_w\frac{1}{\Lambda^2}\,\epsilon^2$	$p\to\pi^0e^+$	$5\cdot10^{10}$
φ	$(1,2,1/2)_S$	$y_{pq}\varphi^\dagger Q_p\bar{d}_q + c_{rs[tu]}\varphi^i(L_r^jQ_s^k)(\bar{d}_t^\dagger\bar{d}_u^\dagger)H^l\epsilon_{il}\epsilon_{jk}$	2	$\mathcal{O}_\varphi^{131131}$	$C_{qqql}^{pqrs} = y_{ws}c_{sq[vw]}[y_d]_vV_{vp}^*\frac{1}{\Lambda^2}\,\epsilon^2$	$p\to K^+\nu$	$5\cdot10^9$
ω_4	$(3,1,-4/3)_S$	$y_{pq}\omega_4^\dagger(\bar{e}_p^\dagger\bar{d}_q^\dagger) + c_{[rs]}\,\omega_4(\bar{u}_r^\dagger\bar{u}_s^\dagger)$	-2	$\mathcal{O}_3^{1131}$	$C_{qque}^{pqrs} = y_{sw}c_{[rq]}[y_u]_q[y_d]_wV_{wp}^*\frac{1}{M^2}\,L'$	$p\to\pi^0e^+$	$5\cdot10^8$
Π_1	$(3,2,1/6)_S$	$y_{pq}\Pi_1^\dagger(L_p^\dagger\bar{d}_q^\dagger) + c_{rs}\Pi_1(Q_rQ_s)H^\dagger$	-2	$\mathcal{O}_8^{1112}$	$C_{\bar{l}dqq\tilde{H}}^{pqrs} = y_{pq}c_{rs}\frac{1}{M^2\Lambda}$	$p\to K^+\nu$	10^8
Π_7	$(3,2,7/6)_S$	$y_{pq}\Pi_7^\dagger(L_p^\dagger\bar{u}_q^\dagger) + c_{[rs]}\,\Pi_7H^\dagger(\bar{d}_r^\dagger\bar{d}_s^\dagger)$	-2	$\mathcal{O}_{10}^{1112}$	$C_{\bar{l}dud\tilde{H}}^{pqrs} = y_{pr}c_{[qs]}\frac{1}{M^2\Lambda}$	$p\to K^+\nu$	10^8
ω_2	$(3,1,2/3)_S$	$y_{[pq]}\,\omega_2(\bar{d}_p^\dagger\bar{d}_q^\dagger) + c_{rs}\omega_2^\dagger(L_r^\dagger\bar{u}_s^\dagger)H^\dagger$	-2	$\mathcal{O}_{10}^{1112}$	$C_{\bar{l}dud\tilde{H}}^{pqrs} = y_{[qs]}c_{pr}\frac{1}{M^2\Lambda}$	$p\to K^+\nu$	10^8
Υ	$(6,3,1/6)_S$	$y_{\{pq\}}\,\Upsilon^\dagger(Q_pQ_q) + c_{rstu}\Upsilon(Q_r\bar{u}_s)(L_t^\dagger\bar{d}_u^\dagger)$	0	$\mathcal{O}_{40}^{113132}$	$C_{\bar{l}dqq\tilde{H}}^{pqrs} = y_{\{ws\}}c_{rwpq}[y_u]_w\frac{1}{\Lambda^3}\,L$	$p\to K^+\nu$	10^7
Φ	$(8,2,1/2)_S$	$y_{pq}\Phi(Q_p\bar{u}_q) + c_{rstu}\Phi^\dagger(Q_rQ_s)(L_t^\dagger\bar{d}_u^\dagger)$	0	$\mathcal{O}_{40}^{111332}$	$C_{\bar{l}dqq\tilde{H}}^{pqrs} = y_{sw}c_{wrpq}[y_u]_w\frac{1}{\Lambda^3}\,L$	$p\to K^+\nu$	10^7
Ω_2	$(6,1,-2/3)_S$	$y_{\{pq\}}\,\Omega_2^\dagger(\bar{d}_p^\dagger\bar{d}_q^\dagger) + c_{rstu}\Omega_2(Q_r\bar{u}_s)(L_t^\dagger\bar{u}_u^\dagger)$	0	$\mathcal{O}_{50}^{131321}$	$C_{\bar{l}dud\tilde{H}}^{pqrs} = y_{qs}c_{wwpr}[y_u]_w\frac{1}{\Lambda^3}\,L$	$p\to K^+\nu$	10^7
Ξ	$(1,3,0)_S$	$\mu\,\Xi H^\dagger H + c_{pq[rs]}\Xi_{ij}(L_{pk}^\dagger\bar{d}_q^\dagger)(Q_r^iQ_s^j)H_l^\dagger\epsilon^{kl}$	1	$\mathcal{O}_{45}^{1131}$	$C_{\bar{l}dqq\tilde{H}}^{pqrs} = c_{pq[rs]}[y_u]_s[y_u]_s\frac{\mu}{\Lambda}\frac{1}{\Lambda^3}\,L^2$	$n\to K^+e^-$	10^6
Ξ_1	$(1,3,1)_S$	$\mu\,\Xi_1^\dagger HH + c_{rs[tu]}\Xi_1(Q_rL_s)(\bar{d}_t^\dagger\bar{d}_u^\dagger)$	1	$\mathcal{O}_{16}^{1132}$	$C_{qqql}^{pqrs} = c_{qs[vw]}[y_d]_v[y_d]_wV_{vp}^*V_{wr}^*\frac{\mu}{\Lambda}\frac{1}{\Lambda^2}\,L^2$	$p\to K^+\nu$	$5\cdot10^5$
Θ_3	$(1,4,3/2)_S$	$y\Theta_3H^\dagger H^\dagger H^\dagger + c_{[pq]rs}\,\Theta_3^\dagger(Q_pQ_q)(L_r^\dagger\bar{u}_s^\dagger)$	0	$\mathcal{O}_{37}^{1123}$	$C_{\bar{l}dqq\tilde{H}}^{pqrs} = y\,c_{[rs]pw}[y_u]_w[y_d]_wV_{wq}\frac{1}{\Lambda^3}\,L^2$	$p\to K^+\nu$	$5\cdot10^4$
Θ_1	$(1,4,1/2)_S$	$y\Theta_1H^\dagger HH^\dagger + c_{pq[rs]}\,\Theta_1^\dagger(L_p^\dagger\bar{d}_q^\dagger)(Q_rQ_s)$	0	$\mathcal{O}_{45}^{1213}$	$C_{\bar{l}dqq\tilde{H}}^{pqrs} = y\,c_{pw[vr]}[y_d]_v[y_d]_wV_{ws}^*V_{vq}\frac{1}{\Lambda^3}\,L^2$	$p\to K^+\nu$	10^4
Ω_1	$(6,1,1/3)_S$	$y_{[pq]}\,\Omega_1^\dagger(Q_pQ_q) + c_{rstu}\Omega_1(L_r^\dagger\bar{d}_s^\dagger)(Q_t\bar{u}_u)$	0	$\mathcal{O}_{40}^{113132}$	$C_{\bar{l}dqq\tilde{H}}^{pqrs} = y_{[wr]}c_{pqsw}[y_u]_w\frac{1}{\Lambda^3}\,L$	$p\to K^+\nu$	10^7
$\mathcal{S}_1$	$(1,1,1)_S$	$y_{[pq]}\,\mathcal{S}_1^\dagger(L_p^\dagger L_q^\dagger) + c_{rstu}\mathcal{S}_1\bar{e}_p^\dagger\bar{u}_q^\dagger\bar{d}_r^\dagger\bar{d}_s^\dagger$	0	$\mathcal{O}_{28}^{133121}$	$C_{\bar{l}dud\tilde{H}}^{pqrs} = y_{[pw]}c_{wrqs}[y_e]_w\frac{1}{\Lambda^3}\,L$	$p\to K^+\nu$	$5\cdot10^6$
$\mathcal{S}_2$	$(1,1,2)_S$	$y_{\{pq\}}\,\mathcal{S}_2^\dagger(\bar{e}_p\bar{e}_q) + c_{rs[tu]}\,\mathcal{S}_2(\bar{e}_r^\dagger\bar{d}_s^\dagger)(\bar{d}_t^\dagger\bar{d}_u^\dagger)$	0	$\mathcal{O}_{25}^{133112}$	$C_{\bar{e}dddD}^{pqrs} = y_{\{pw\}}c_{wqrs}\frac{1}{\Lambda^3}\,L$	$n\to K^+e^-$	10^6

$M < \Lambda$ regime

	m_ν	Γ_p
$(T_{m_\nu}, L_{\Delta(B-L)=0})$	$\frac{\mu}{M}\frac{1}{M}$	$\frac{\mu}{\Lambda}\frac{1}{\Lambda^2}\left(\log\frac{\Lambda}{M}\right)^2$
$(T_{m_\nu}, T_{\Delta(B-L)=2})$	$\frac{1}{M}$	$\frac{1}{\Lambda^2 M}$
$(L_{m_\nu}, T_{\Delta(B-L)=0})$	$\frac{1}{\Lambda}\log\frac{\Lambda}{M}$ | $\frac{M}{\Lambda}\frac{1}{\Lambda}\log\frac{\Lambda}{M}$	$\frac{1}{M^2}$
$(L_{m_\nu}, T_{\Delta(B-L)=2})$	$\frac{1}{\Lambda}\log\frac{\Lambda}{M}$ | $\frac{M}{\Lambda}\frac{1}{\Lambda}\log\frac{\Lambda}{M}$	$\frac{1}{\Lambda^2 M}$
$(L_{m_\nu}, L_{\Delta(B-L)=0})$	$\frac{1}{\Lambda}\log\frac{\Lambda}{M}$ | $\frac{M}{\Lambda}\frac{1}{\Lambda}\log\frac{\Lambda}{M}$	$\frac{1}{\Lambda^2}\log\frac{\Lambda}{M}$ | $\frac{M}{\Lambda}\frac{1}{\Lambda^2}\log\frac{\Lambda}{M}$
$(L_{m_\nu}, L_{\Delta(B-L)=2})$	$\frac{1}{\Lambda}\log\frac{\Lambda}{M}$ | $\frac{M}{\Lambda}\frac{1}{\Lambda}\log\frac{\Lambda}{M}$	$\frac{1}{\Lambda^3}\log\frac{\Lambda}{M}$

$M < \Lambda$ regime

$\alpha = M/\Lambda \leq 1$	m_ν	Γ_p
$(T_{m_\nu}, L_{\Delta(B-L)=0})$	$\frac{\mu}{M}\frac{1}{M}$ ✓	$\alpha^3 \left[\log\left(\frac{1}{\alpha}\right)\right]^2 \frac{\mu}{M}\frac{1}{M^2}$ ✓
$(T_{m_\nu}, T_{\Delta(B-L)=2})$	$\frac{1}{M}$ ✓	$\frac{1}{(M/\alpha)^2 M} = \frac{\alpha^2}{M^3}$ ✓
$(L_{m_\nu}, T_{\Delta(B-L)=0})$	$\alpha \log\left(\frac{1}{\alpha}\right)\frac{1}{M}$ $\alpha^2 \log\left(\frac{1}{\alpha}\right)\frac{1}{M}$ ✓	$\frac{1}{M^2}$ ✓
$(L_{m_\nu}, T_{\Delta(B-L)=2})$	$\alpha \log\left(\frac{1}{\alpha}\right)\frac{1}{M}$ $\alpha^2 \log\left(\frac{1}{\alpha}\right)\frac{1}{M}$ ✓	$\frac{1}{(M/\alpha)^2 M} = \frac{\alpha^2}{M^3}$ ✓
$(L_{m_\nu}, L_{\Delta(B-L)=0})$	$\alpha \log\left(\frac{1}{\alpha}\right)\frac{1}{M}$ $\alpha^2 \log\left(\frac{1}{\alpha}\right)\frac{1}{M}$ ✓	$\alpha^2 \log\left(\frac{1}{\alpha}\right)\frac{1}{M^2}$ $\alpha^3 \log\left(\frac{1}{\alpha}\right)\frac{1}{M^2}$ ✓
$(L_{m_\nu}, L_{\Delta(B-L)=2})$	$\alpha \log\left(\frac{1}{\alpha}\right)\frac{1}{M}$ $\alpha^2 \log\left(\frac{1}{\alpha}\right)\frac{1}{M}$ ✓	$\alpha^3 \log\left(\frac{1}{\alpha}\right)\frac{1}{M^3}$ ✓

Phenomenological matrices for $\Delta(B-L)=2$ proton decay

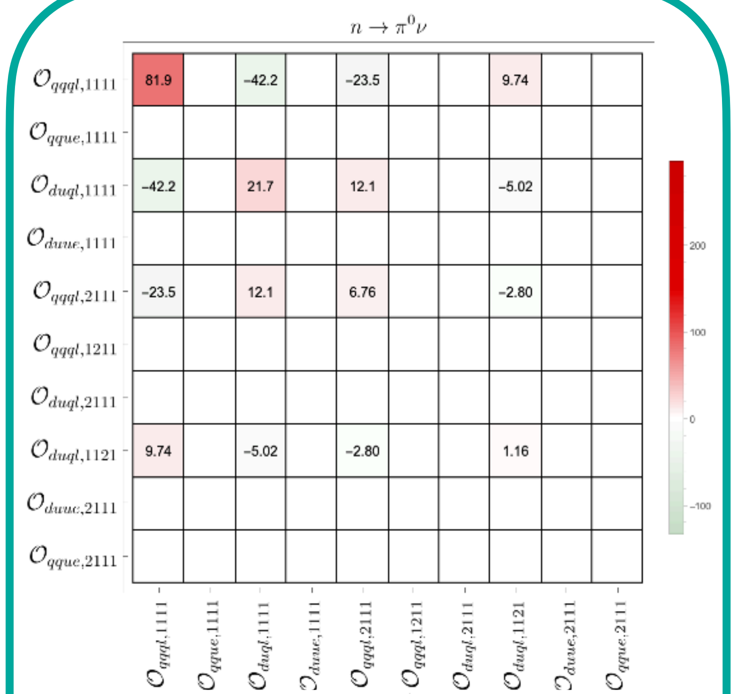
[A. Bas i Beneito et al. 2023]

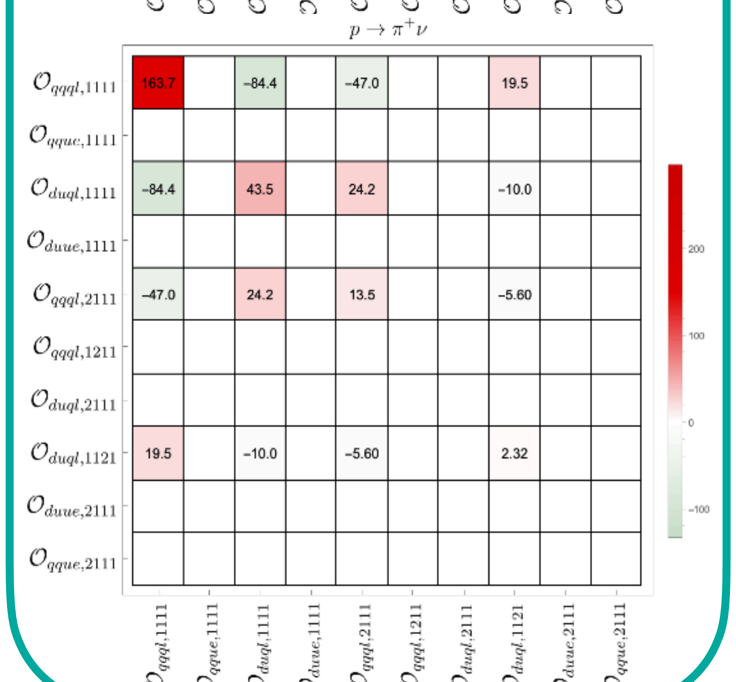
$$\Gamma^{\Delta(B-L)=0}_{(i)} \equiv 10^{-4}\, c_j^*\, \boldsymbol{\kappa}^{jk}_{(i)}\, c_k \frac{m_p^5}{\Lambda^4} \quad \text{for} \quad i = p\to\pi^0 e^+, p\to K^+\nu\ldots \quad \text{(9 matrices)}$$

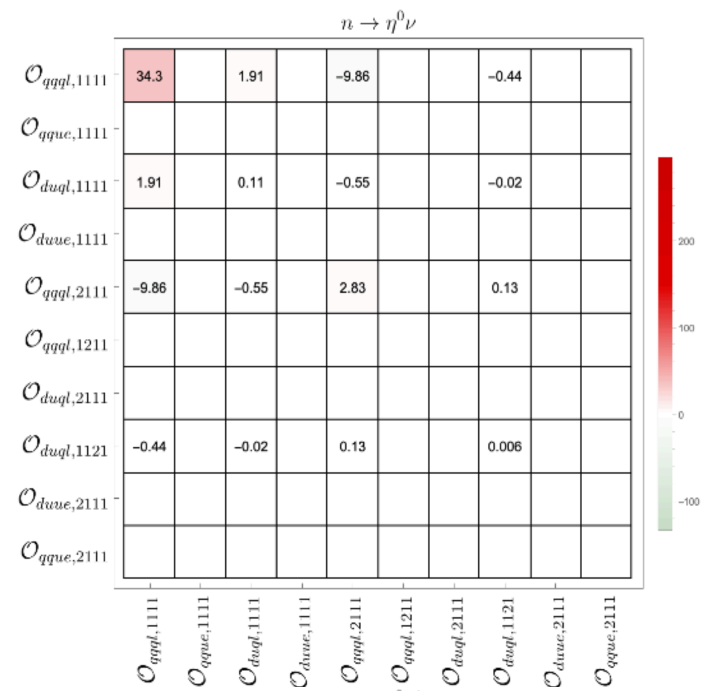
$$\Gamma^{|\Delta(B-L)|=2}_{(i)} \equiv c_j^*\, \boldsymbol{\kappa}^{jk}_{(i)}\, c_k \frac{m_p^7}{\Lambda^6} \quad \text{for} \quad i = p\to K^+\nu, n\to K^+e^-\ldots \quad \text{(6 matrices)}$$

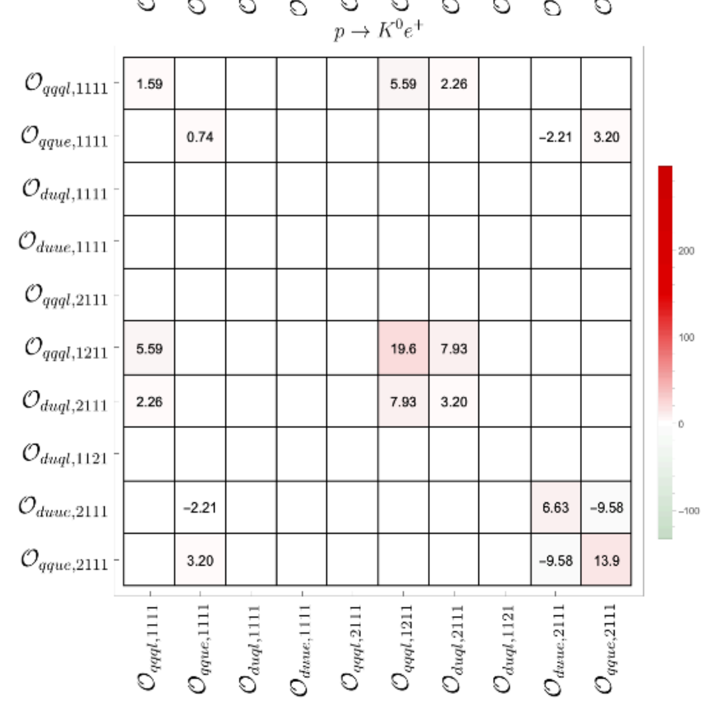
$\Gamma(p\to\pi^+\nu) = 2\,\Gamma(n\to\pi^0\nu)$

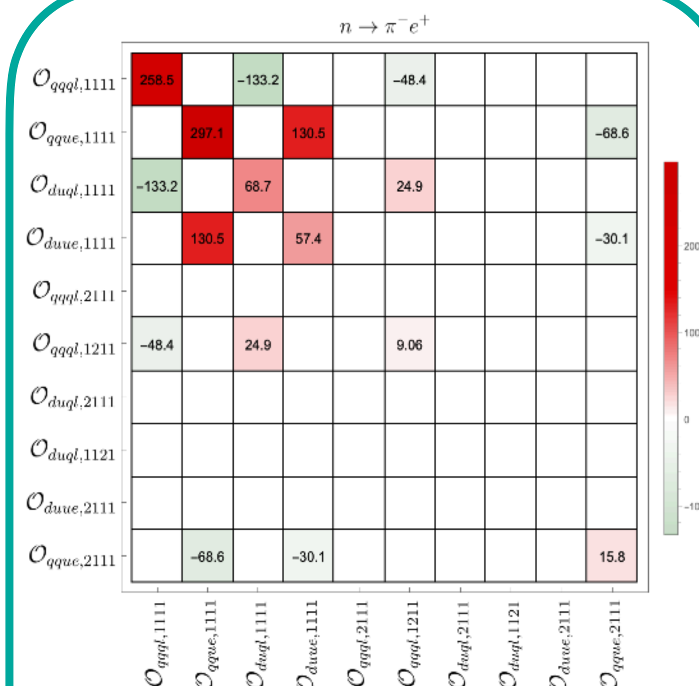
$\Gamma(n\to\pi^-e^+) = 3\,\Gamma(p\to\pi^0 e^+)$

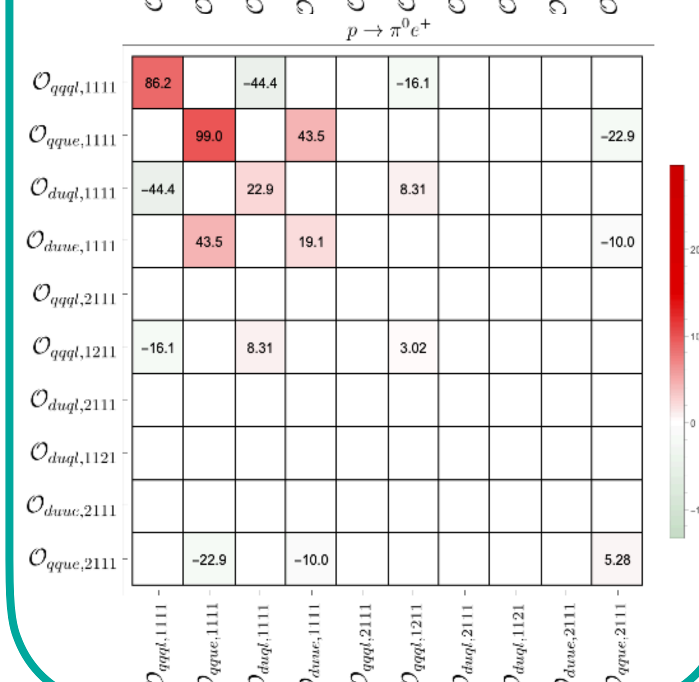




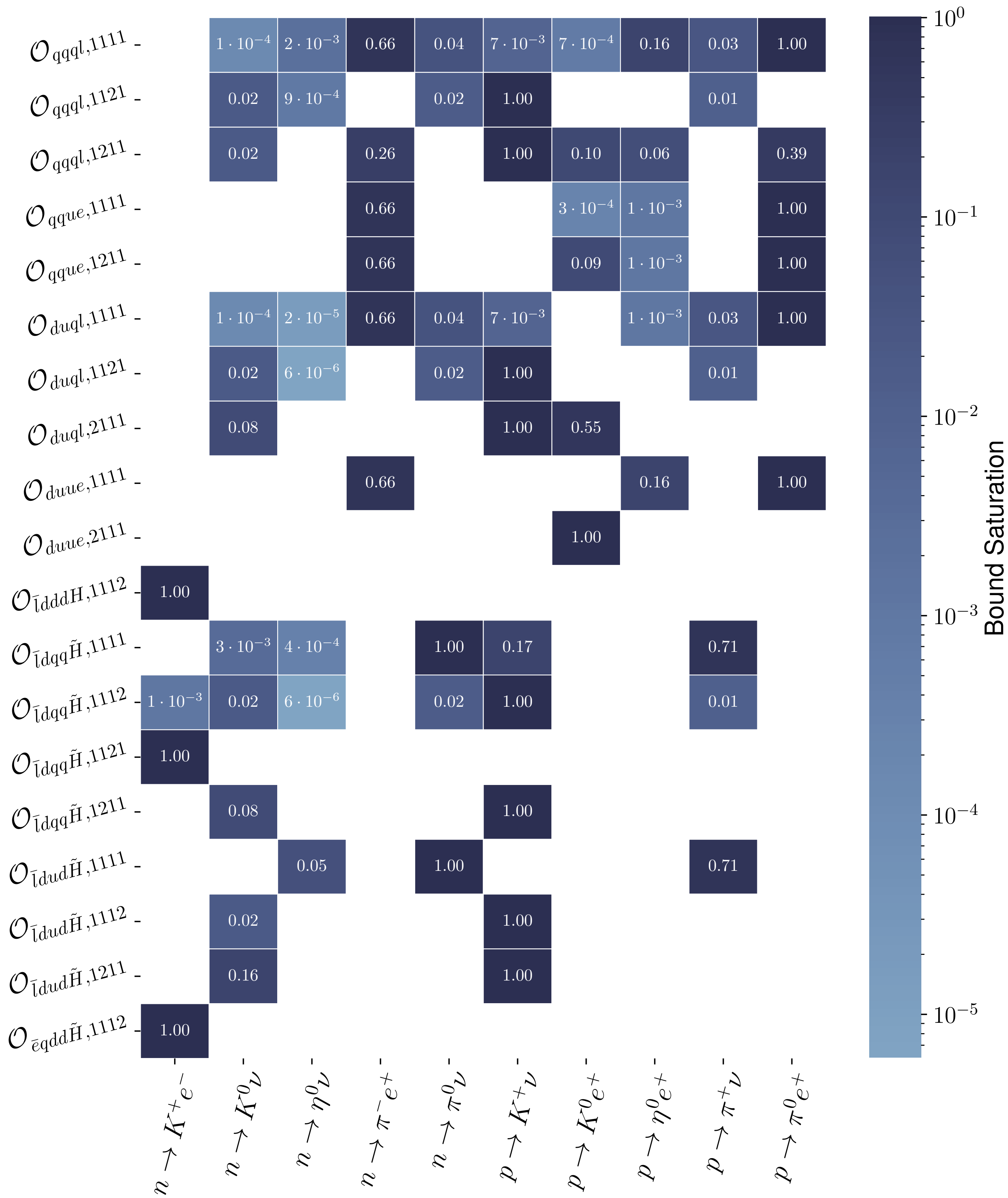


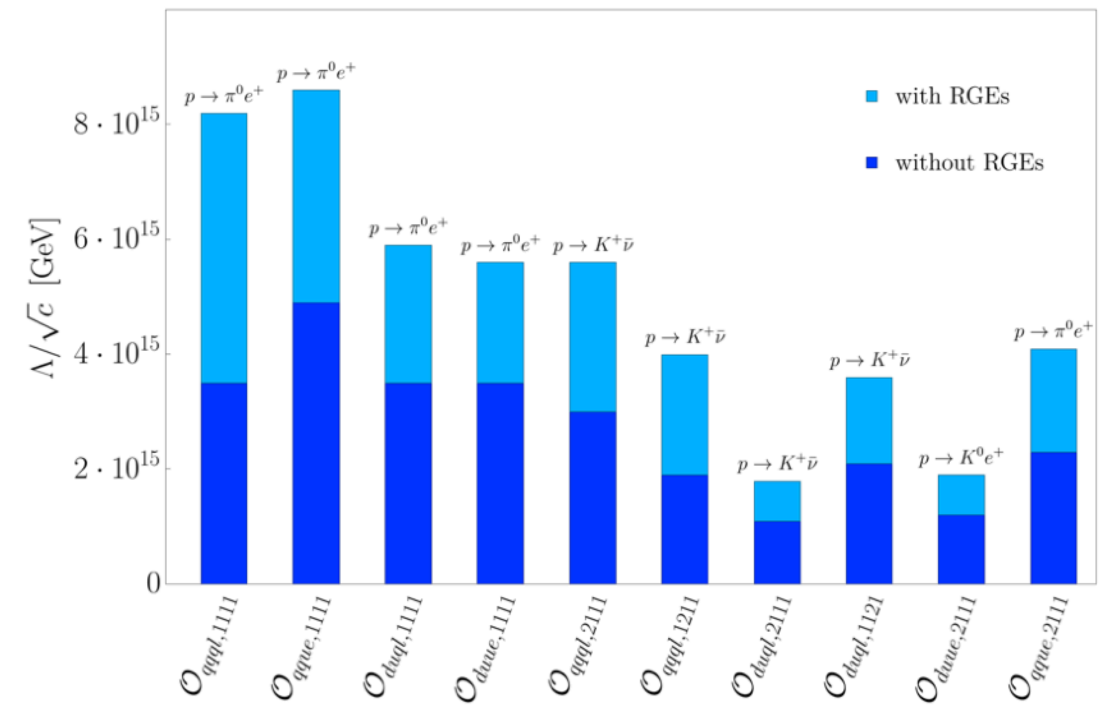


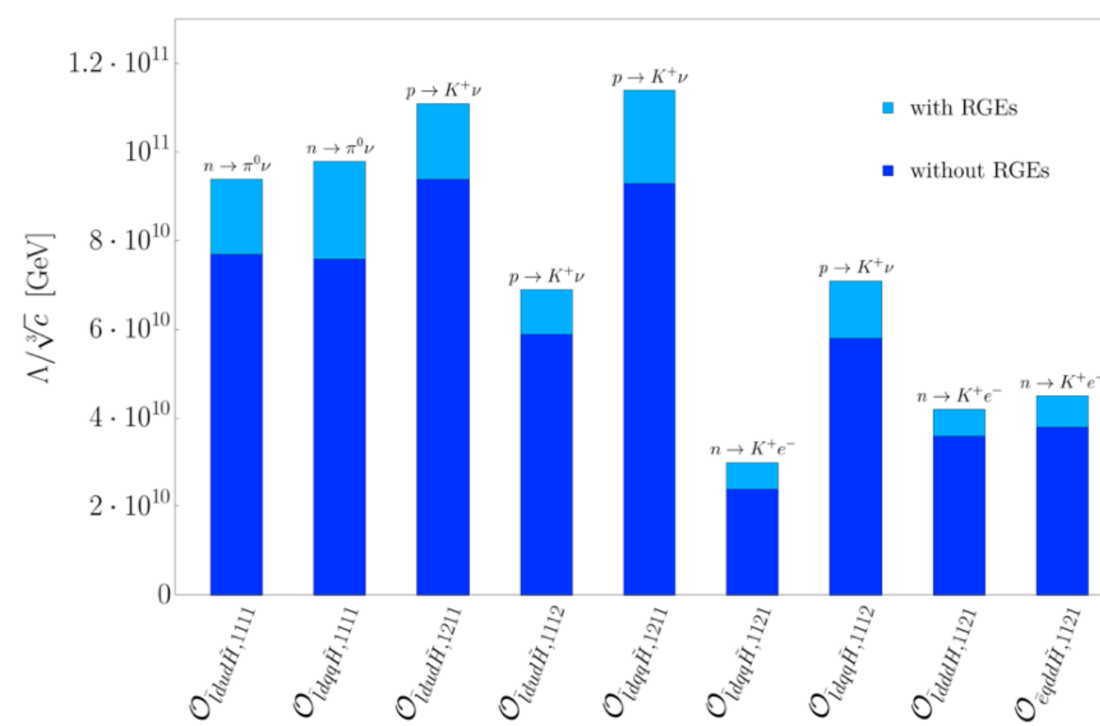




Correlations & tree-level bounds on proton decay







[A. Bas i Beneito et al. 2023]

Matching onto BχPT

$$\begin{aligned}
\mathcal{L}_0 \supset & \left(\frac{D-F}{f_\pi}\,\overline{\Sigma^+}\gamma^\mu\gamma_5 p - \frac{D+3F}{\sqrt{6}f_\pi}\,\overline{\Lambda^0}\gamma^\mu\gamma_5 n - \frac{D-F}{\sqrt{2}f_\pi}\,\overline{\Sigma^0}\gamma^\mu\gamma_5 n\right)\partial_\mu \bar{K}^0 \\
& + \left(\frac{D-F}{\sqrt{2}f_\pi}\,\overline{\Sigma^0}\gamma^\mu\gamma_5 p - \frac{D+3F}{\sqrt{6}f_\pi}\,\overline{\Lambda^0}\gamma^\mu\gamma_5 p + \frac{D-F}{f_\pi}\,\overline{\Sigma^-}\gamma^\mu\gamma_5 n\right)\partial_\mu K^- \\
& + \frac{3F-D}{2\sqrt{6}f_\pi}\left(\overline{p}\gamma^\mu\gamma_5 p + \overline{n}\gamma^\mu\gamma_5 n\right)\partial_\mu\eta \\
& + \frac{D+F}{f_\pi}\,\overline{p}\gamma^\mu\gamma_5 n\,\partial_\mu\pi^+ \\
& + \frac{D+F}{2\sqrt{2}f_\pi}\left(\overline{p}\gamma^\mu\gamma_5 p - \overline{n}\gamma^\mu\gamma_5 n\right)\partial_\mu\pi^0 + \text{h.c.}\,.
\end{aligned}$$

$$\xi B\xi \to L\xi B\xi R^\dagger \qquad \xi^\dagger B\xi^\dagger \to R\xi^\dagger B\xi^\dagger L^\dagger$$

$$\xi B\xi^\dagger \to L\xi B\xi^\dagger L^\dagger \qquad \xi^\dagger B\xi \to R\xi^\dagger B\xi R^\dagger$$

$$\xi B\xi \sim (\mathbf{3},\bar{\mathbf{3}}),\quad \xi^\dagger B\xi^\dagger \sim (\bar{\mathbf{3}},\ \mathbf{3}),\quad \xi B\xi^\dagger \sim (\mathbf{8},\mathbf{1}),\quad \xi^\dagger B\xi \sim (\mathbf{1},\mathbf{8})$$

$$\alpha\cdot\nu\ \mathrm{tr}(\xi B\xi^\dagger P_{32}) = -\,(du)(d\nu) = [\mathcal{O}_{udd}]^{S,LL}_{1111}$$

$$\langle 0|\epsilon^{abc}(\bar{u}^\dagger_a\bar{d}^\dagger_b)u_c|p^{(s)}\rangle = \alpha P_L u_p^{(s)}$$

$$\langle 0|\epsilon^{abc}(u_a d_b)u_c|p^{(s)}\rangle = \beta P_L u_p^{(s)}$$

Name	LEFT	Flavour/BχPT
$[\mathcal{O}^{S,LL}_{udd}]_{rstu}$	$(u_r d_s)(d_t\nu_u)$	$(\mathbf{8},\mathbf{1})$
$[\mathcal{O}^{S,LL}_{udd}]_{111r}$	$(ud)(d\nu_r)$	$-\beta\overline{\nu^c_{Lr}}\mathrm{tr}(\xi B\xi^\dagger P_{32}) \supset -\beta\overline{\nu^c_{Lr}}n - \frac{i\beta}{f_\pi}\overline{\nu^c_{Lr}}\left(\sqrt{\frac{3}{2}}n\eta - \frac{1}{\sqrt{2}}n\pi^0 + p\pi^-\right)$
$[\mathcal{O}^{S,LL}_{udd}]_{121r}$	$(us)(d\nu_r)$	$-\beta\overline{\nu^c_{Lr}}\mathrm{tr}(\xi B\xi^\dagger\tilde{P}_{22}) \supset -\beta\overline{\nu^c_{Lr}}\left(-\frac{\Lambda^0}{\sqrt{6}} + \frac{\Sigma^0}{\sqrt{2}}\right) - \frac{i\beta}{f_\pi}\overline{\nu^c_{Lr}}n\bar{K}^0$
$[\mathcal{O}^{S,LL}_{udd}]_{112r}$	$(ud)(s\nu_r)$	$-\beta\overline{\nu^c_{Lr}}\mathrm{tr}(\xi B\xi^\dagger P_{33}) \supset \beta\sqrt{\frac{2}{3}}\overline{\nu^c_{Lr}}\Lambda^0 - \frac{i\beta}{f_\pi}\overline{\nu^c_{Lr}}\left(n\bar{K}^0 + pK^-\right)$
$[\mathcal{O}^{S,LL}_{duu}]_{rstu}$	$(d_r u_s)(u_t e_u)$	$(\mathbf{8},\mathbf{1})$
$[\mathcal{O}^{S,LL}_{duu}]_{111r}$	$(du)(ue_r)$	$-\beta\overline{e^c_{Lr}}\mathrm{tr}(\xi B\xi^\dagger\tilde{P}_{31}) \supset \beta\overline{e^c_{Lr}}p + \frac{i\beta}{f_\pi}\overline{e^c_{Lr}}\left(\sqrt{\frac{3}{2}}p\eta + \frac{1}{\sqrt{2}}p\pi^0 + n\pi^+\right)$
$[\mathcal{O}^{S,LL}_{duu}]_{211r}$	$(su)(ue_r)$	$-\beta\overline{e^c_{Lr}}\mathrm{tr}(\xi B\xi^\dagger P_{21}) \supset -\beta\overline{e^c_{Lr}}\Sigma^+ + \frac{i\beta}{f_\pi}\overline{e^c_{Lr}}p\bar{K}^0$
$[\mathcal{O}^{S,LR}_{uud}]_{[rs]tu}$	$(u_r u_s)(\bar{d}^\dagger_t\bar{e}^\dagger_u)$	—
$[\mathcal{O}^{S,LR}_{duu}]_{rstu}$	$(d_r u_s)(\bar{u}^\dagger_t\bar{e}^\dagger_u)$	$(\bar{\mathbf{3}},\mathbf{3})$
$[\mathcal{O}^{S,LR}_{duu}]_{111r}$	$(du)(\bar{u}^\dagger\bar{e}^\dagger_r)$	$\alpha\overline{e^c_{Rr}}\mathrm{tr}(\xi^\dagger B\xi^\dagger\tilde{P}_{31}) \supset -\alpha\overline{e^c_{Rr}}p + \frac{i\alpha}{f_\pi}\overline{e^c_{Rr}}\left(-\frac{1}{\sqrt{6}}p\eta + \frac{1}{\sqrt{2}}p\pi^0 + n\pi^+\right)$
$[\mathcal{O}^{S,LR}_{duu}]_{211r}$	$(su)(\bar{u}^\dagger\bar{e}^\dagger_r)$	$\alpha\overline{e^c_{Rr}}\mathrm{tr}(\xi^\dagger B\xi^\dagger P_{21}) \supset \alpha\overline{e^c_{Rr}}\Sigma^+ - \frac{i\alpha}{f_\pi}\overline{e^c_{Rr}}p\bar{K}^0$
$[\mathcal{O}^{S,RL}_{uud}]_{[rs]tu}$	$(\bar{u}^\dagger_r\bar{u}^\dagger_s)(d_t e_u)$	—
$[\mathcal{O}^{S,RL}_{duu}]_{rstu}$	$(\bar{d}^\dagger_r\bar{u}^\dagger_s)(u_t e_u)$	$(\mathbf{3},\bar{\mathbf{3}})$
$[\mathcal{O}^{S,RL}_{duu}]_{111r}$	$(\bar{d}^\dagger\bar{u}^\dagger)(ue_r)$	$-\alpha\overline{e^c_{Lr}}\mathrm{tr}(\xi B\xi\tilde{P}_{31}) \supset \alpha\overline{e^c_{Lr}}p + \frac{i\alpha}{f_\pi}\overline{e^c_{Lr}}\left(-\frac{1}{\sqrt{6}}p\eta + \frac{1}{\sqrt{2}}p\pi^0 + n\pi^+\right)$
$[\mathcal{O}^{S,RL}_{duu}]_{211r}$	$(\bar{s}^\dagger\bar{u}^\dagger)(ue_r)$	$-\alpha\overline{e^c_{Lr}}\mathrm{tr}(\xi B\xi P_{21}) \supset -\alpha\overline{e^c_{Lr}}\Sigma^+ - \frac{i\alpha}{f_\pi}\overline{e^c_{Lr}}p\bar{K}^0$
$[\mathcal{O}^{S,RL}_{dud}]_{rstu}$	$(\bar{d}^\dagger_r\bar{u}^\dagger_s)(d_t\nu_u)$	$(\mathbf{3},\bar{\mathbf{3}})$
$[\mathcal{O}^{S,RL}_{dud}]_{111r}$	$(\bar{d}^\dagger\bar{u}^\dagger)(d\nu_r)$	$\alpha\overline{\nu^c_{Lr}}\mathrm{tr}(\xi B\xi\tilde{P}_{32}) \supset -\alpha\overline{\nu^c_{Lr}}n + \frac{i\alpha}{f_\pi}\overline{\nu^c_{Lr}}\left(\frac{1}{\sqrt{6}}n\eta + \frac{1}{\sqrt{2}}n\pi^0 - p\pi^-\right)$
$[\mathcal{O}^{S,RL}_{dud}]_{211r}$	$(\bar{s}^\dagger\bar{u}^\dagger)(d\nu_r)$	$\alpha\overline{\nu^c_{Lr}}\mathrm{tr}(\xi B\xi P_{22}) \supset \alpha\overline{\nu^c_{Lr}}\left(\frac{\Lambda^0}{\sqrt{6}} - \frac{\Sigma^0}{\sqrt{2}}\right) + \frac{i\alpha}{f_\pi}\overline{\nu^c_{Lr}}n\bar{K}^0$
$[\mathcal{O}^{S,RL}_{dud}]_{112r}$	$(\bar{d}^\dagger\bar{u}^\dagger)(s\nu_r)$	$\alpha\overline{\nu^c_{Lr}}\mathrm{tr}(\xi B\xi\tilde{P}_{33}) \supset \alpha\overline{\nu^c_{Lr}}\sqrt{\frac{2}{3}}\Lambda^0 - \frac{i\alpha}{f_\pi}\overline{\nu^c_{Lr}}\left(n\bar{K}^0 + pK^-\right)$
$[\mathcal{O}^{S,RL}_{dud}]_{212r}$	$(\bar{s}^\dagger\bar{u}^\dagger)(s\nu_r)$	$\alpha\overline{\nu^c_{Lr}}\mathrm{tr}(\xi B\xi P_{23}) \supset \alpha\overline{\nu^c_{Lr}}\Xi^0$
$[\mathcal{O}^{S,RL}_{ddu}]_{[rs]tu}$	$(\bar{d}^\dagger_r\bar{d}^\dagger_s)(u_t\nu_u)$	$(\mathbf{3},\bar{\mathbf{3}})$
$[\mathcal{O}^{S,RL}_{ddu}]_{[12]1r}$	$(\bar{d}^\dagger\bar{s}^\dagger)(u\nu_r)$	$-\alpha\overline{\nu^c_{Lr}}\mathrm{tr}(\xi B\xi P_{11}) \supset \alpha\overline{\nu^c_{Lr}}\left(\frac{\Lambda^0}{\sqrt{6}} + \frac{\Sigma^0}{\sqrt{2}}\right) - \frac{i\alpha}{f_\pi}\overline{\nu^c_{Lr}}pK^-$
$[\mathcal{O}^{S,RR}_{duu}]_{rstu}$	$(\bar{d}^\dagger_r\bar{u}^\dagger_s)(\bar{u}^\dagger_t\bar{e}^\dagger_u)$	$(\mathbf{1},\mathbf{8})$
$[\mathcal{O}^{S,RR}_{duu}]_{111r}$	$(\bar{d}^\dagger\bar{u}^\dagger)(\bar{u}^\dagger\bar{e}^\dagger_r)$	$\beta\overline{e^c_{Rr}}\mathrm{tr}(\xi^\dagger B\xi\tilde{P}_{31}) \supset -\beta\overline{e^c_{Rr}}p + \frac{i\beta}{f_\pi}\overline{e^c_{Rr}}\left(\sqrt{\frac{3}{2}}p\eta + \frac{1}{\sqrt{2}}p\pi^0 + n\pi^+\right)$
$[\mathcal{O}^{S,RR}_{duu}]_{211r}$	$(\bar{s}^\dagger\bar{u}^\dagger)(\bar{u}^\dagger\bar{e}^\dagger_r)$	$\beta\overline{e^c_{Rr}}\mathrm{tr}(\xi^\dagger B\xi P_{21}) \supset \beta\overline{e^c_{Rr}}\Sigma^+ + \frac{i\beta}{f_\pi}\overline{e^c_{Rr}}p\bar{K}^0$

BNV Nucleon decay channels

$$\Gamma(N \to M\ell_\alpha) \quad \Delta(B-L)=0 \quad \left\{ \begin{array}{l} n \to \eta^0 \nu \\ n \to \pi^0 \nu \\ p \to \pi^+ \nu \\ n \to \pi^- e^+ \\ p \to \eta^0 e^+ \\ p \to \pi^0 e^+ \\ p \to K^0 e^+ \\ n \to K^0 \nu \\ p \to K^+ \nu \end{array} \right.$$

$$\Gamma(N \to M\ell_\alpha) \quad |\Delta(B-L)|=2 \quad \left\{ \begin{array}{l} n \to \eta^0 \nu \\ n \to \pi^0 \nu \\ p \to \pi^+ \nu \\ n \to K^0 \nu \\ p \to K^+ \nu \\ n \to K^+ e^- \end{array} \right.$$

- **All 2-body PS decays except for** $p \to \bar{K}^0 e^+$ $\quad n \to \bar{K}^0 \nu$ $\quad n \to K^- e^+$ $\quad n \to \pi^+ e^-$
- **No BχPT formalism developed for PD into vector mesons, e.g.** $p \to \rho^0 e^+$ **and** $p \to \omega^0 e^+$