

New methods to probe Standard Model Extensions via Proton Decay and Neutrino Masses

Arnau Bas i Beneito

ABiB, J. Gargalionis, J. Herrero-García, M.A.Schmidt,
[arXiv 2503.20928 \[hep-ph\]](https://arxiv.org/abs/2503.20928) *JHEP* 10 (2025) 083

CPAN DAYS XVII 2025
València

November 20, 2025

SM physics

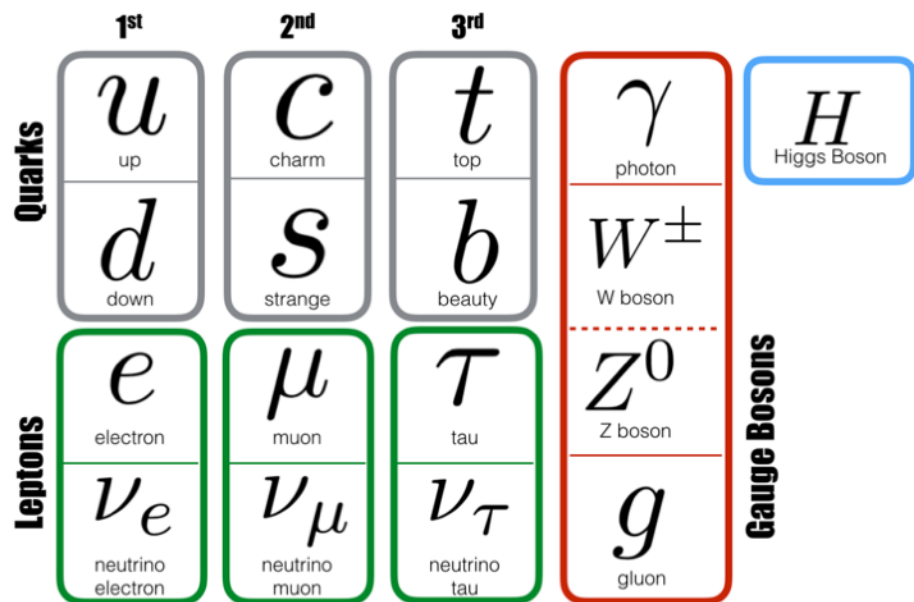
The SM of Particle Physics (SM) $\longrightarrow$ **Most accurate** theories of the interactions of particles

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

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

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

$\swarrow$ Chiral fermions $\swarrow$ Gauge bosons
 $\uparrow$ Higgs scalar



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

SM physics

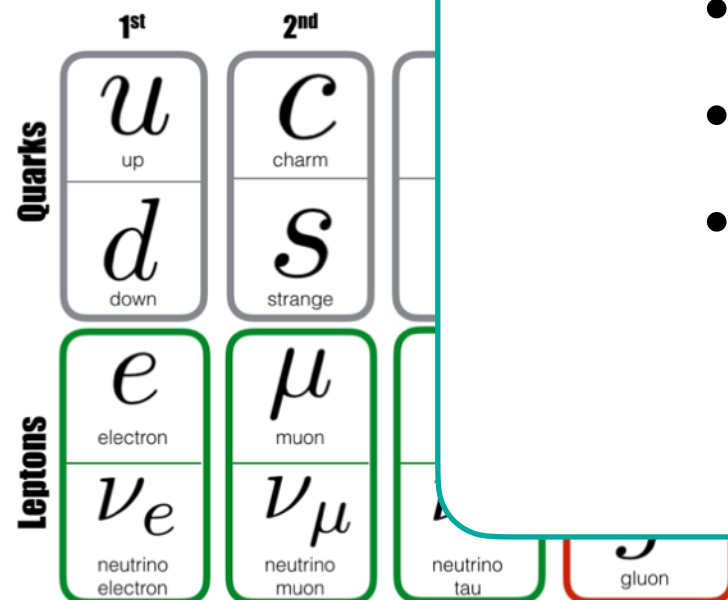
The SM of Particle Physics (SM) $\longrightarrow$ Most accurate theories of the interactions of particles

- **Ingredients:** Particles and interactions, symmetries (gauge symmetries)

What lies beyond the SM?

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

...



...

moment of

SM physics

The SM of Particle Physics (SM) $\longrightarrow$ Most accurate theories of the interactions of particles

• **Ingredients:** Particles and interactions
• Symmetries (gauge symmetries)

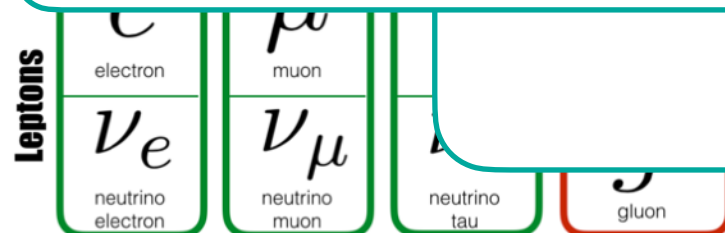
What lies beyond the SM?

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

Connected to **Lepton Number**

Connected to **Baryon Number**

[A. Sakharov 1967]



Lepton and Baryon Number

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

Kinetic terms preserve largest flavour symmetry $U(3)^5$

Yukawa
couplings

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

$$U(3)^5 \rightarrow U(1)_B \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$$

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

Quark sector

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



B (perturbatively) conserved



The proton (lightest baryon) is **stable**

Lepton sector

Observance of neutrino oscillations break Flavour Lepton Number to **Total Lepton Number**

$$U(1)_{L_i}^3 \rightarrow U(1)_L$$



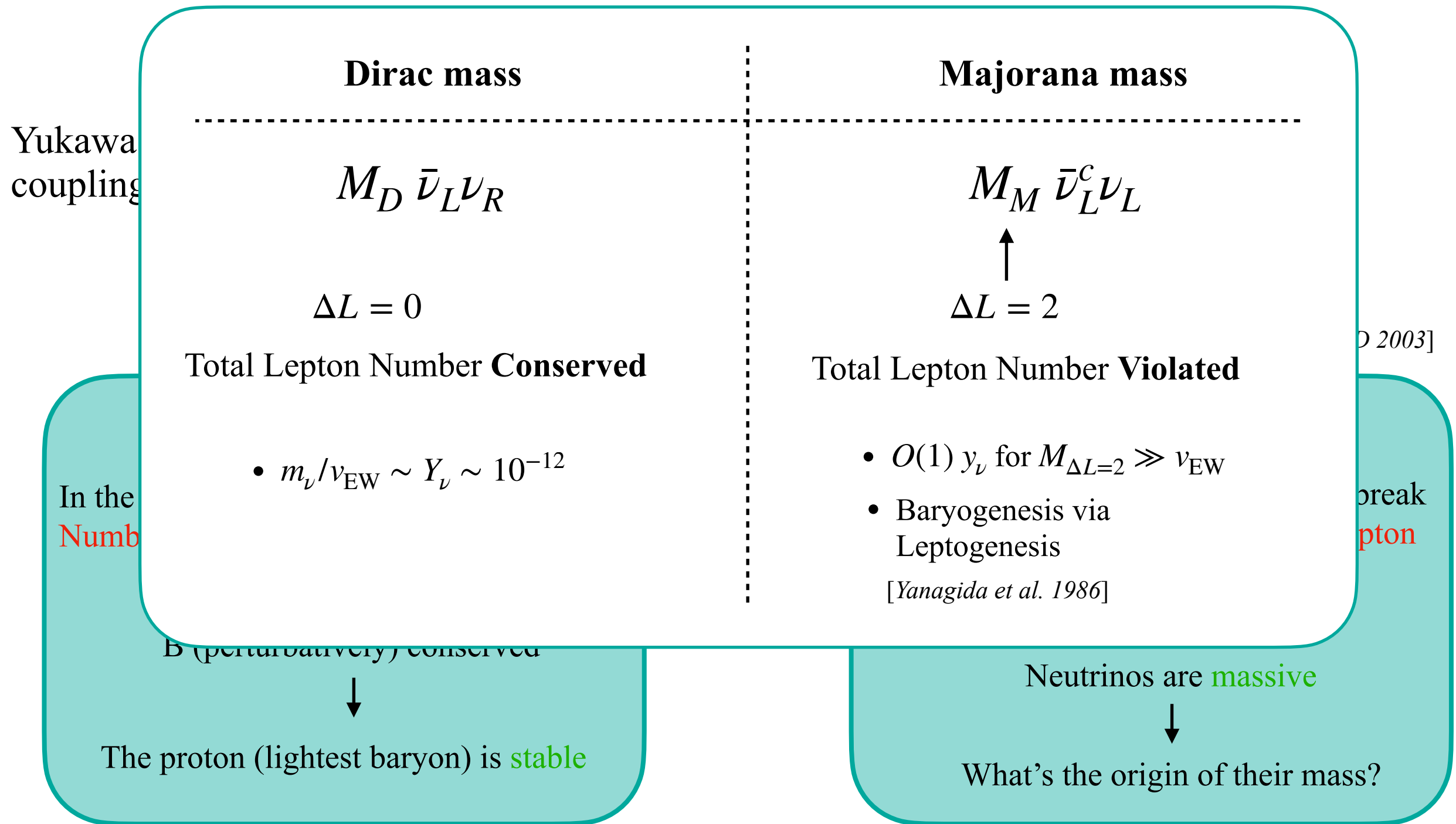
Neutrinos are **massive**



What's the origin of their mass?

Lepton and Baryon Number

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



Lepton and Baryon Number Violation

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



- No fundamental argument to have B and L conserved
- Explicit **BNV** and **LVN** in simple UV extensions: LQs, GUTs, Seesaw...
- **BNV** needed to account for Baryogenesis

...

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

Lepton and Baryon Number Violation

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



- No fundamental argument to have B and L conserved
- Explicit **BNV** and **LVN** in simple UV extensions: LQs, GUTs, Seesaw...
- **BNV** needed to account for Baryogenesis

...

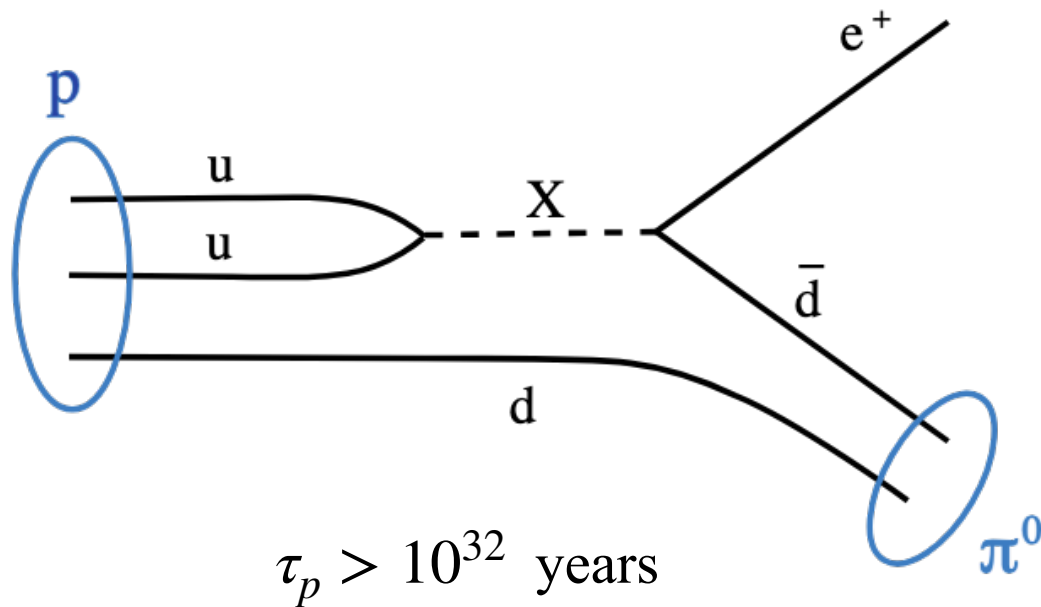
[Georgi et. al. 1973,
H. Fritzsch et al. 1975]

proton decay

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

← Low-energy processes →

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



[Super-Kamiokande 2020]

$$\nu_L \longrightarrow \times \longleftarrow \nu_L$$

$$\sum m_\nu \lesssim 10^{-11} \text{ GeV}$$

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

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)

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{1}{\Lambda^{d-4}} \mathcal{O}^{(d)} \quad \begin{array}{l} [\mathcal{O}^{(d)}] = d \\ \text{Invariant under } G_{SM} \end{array}$$

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

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

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)

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

Invariant under G_{SM}

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

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

$\Delta L = 2$

↓

↑

Number of
independent
Components:

$\Delta(B - L) = 0$

↓

↑

$\Delta(B - L) = 2$

↓

↑

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

SMEFT

The SM is

[S. Weinberg, F. Wilczek, B. Grzadka, W. Buchmüller, I. Brin, B. Henning, De Gouvea et al. 2014]

$$\begin{aligned} [\mathcal{O}_{\bar{l}dddH}]_{pqrs} &= (L_p^\dagger \bar{d}_q^\dagger)(\bar{d}_r^\dagger \bar{d}_s^\dagger)H, & [\mathcal{O}_{\bar{l}dq\tilde{H}}]_{pqrs} &= (L_p^\dagger \bar{d}_q^\dagger)(Q_r Q_s^i)\tilde{H}^j \epsilon_{ij}, \\ [\mathcal{O}_{\bar{e}qdd\tilde{H}}]_{pqrs} &= (\bar{e}_p Q_q^i)(\bar{d}_r^\dagger \bar{d}_s^\dagger)\tilde{H}^j \epsilon_{ij}, & [\mathcal{O}_{\bar{l}dud\tilde{H}}]_{pqrs} &= (L_p^\dagger \bar{d}_q^\dagger)(\bar{u}_r^\dagger \bar{d}_s^\dagger)\tilde{H}, \\ [\mathcal{O}_{\bar{l}qdDd}]_{pqrs} &= (L_p^\dagger \bar{\sigma}^\mu Q_q)(\bar{d}_r^\dagger i\overleftrightarrow{D}_\mu \bar{d}_s^\dagger), & [\mathcal{O}_{\bar{e}dddD}]_{pqrs} &= (\bar{e}_p \sigma^\mu \bar{d}_q^\dagger)(\bar{d}_r^\dagger i\overleftrightarrow{D}_\mu \bar{d}_s^\dagger). \end{aligned}$$

$\Delta a=4$

Invariant under G_{SM}

$$\begin{aligned} [\mathcal{O}_{qqql}]_{pqrs} &= (Q_p^i Q_q^j)(Q_r^l L_s^k) \epsilon_{ik} \epsilon_{jl}, & [\mathcal{O}_{qque}]_{pqrs} &= (Q_p^i Q_q^j)(\bar{u}_r^\dagger \bar{e}_s^\dagger) \epsilon_{ij}, \\ [\mathcal{O}_{duue}]_{pqrs} &= (\bar{d}_p^\dagger \bar{u}_q^\dagger)(\bar{u}_r^\dagger \bar{e}_s^\dagger), & [\mathcal{O}_{duql}]_{pqrs} &= (\bar{d}_p^\dagger \bar{u}_q^\dagger)(Q_r^i L_s^j) \epsilon_{ij}. \end{aligned}$$

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

Number of independent Components

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

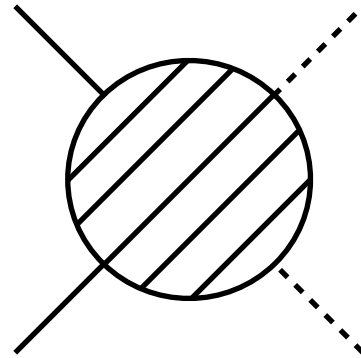
$N_f = 1$ (3)
) are BNV

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

Tree-level Proton decay and Neutrino masses

[S. Weinberg 1979]

$$\Delta L = 2$$



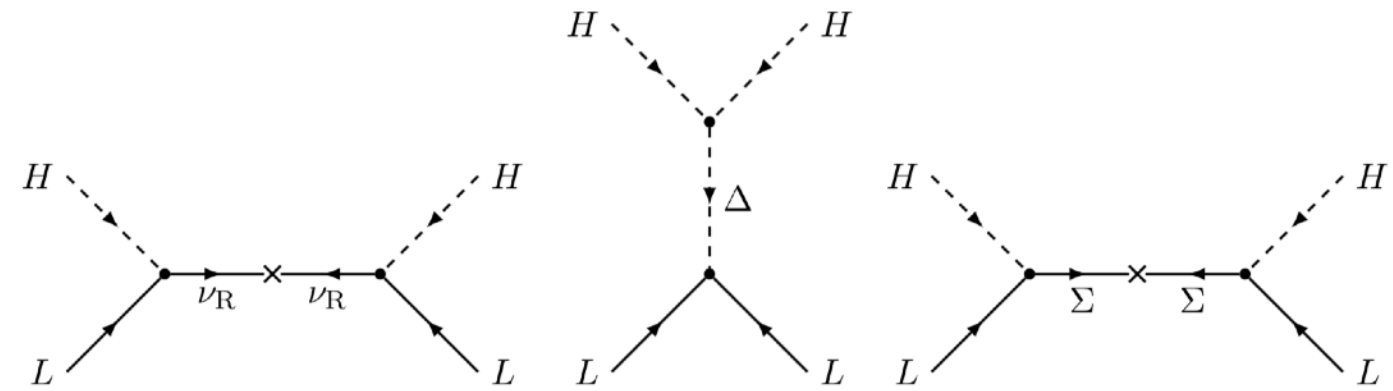
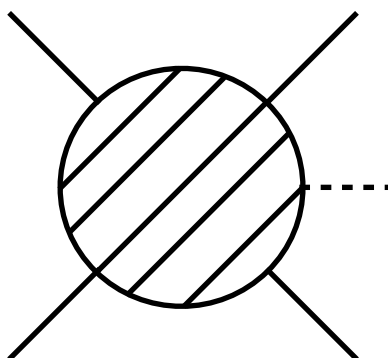
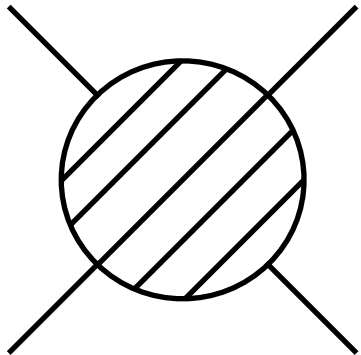
$$\Delta(B - L) = 0$$



Different
phenomenology

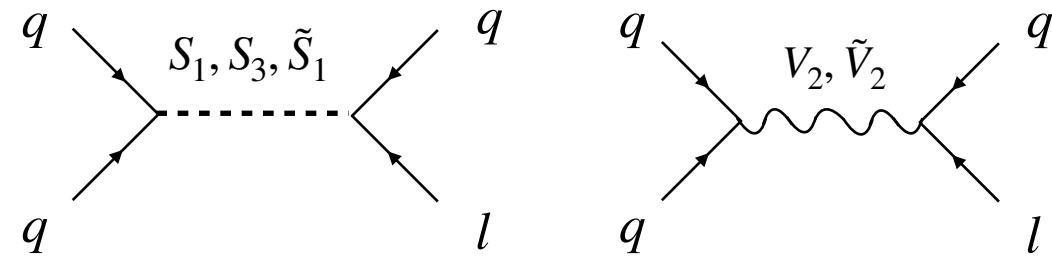


$$\Delta(B - L) = 2$$



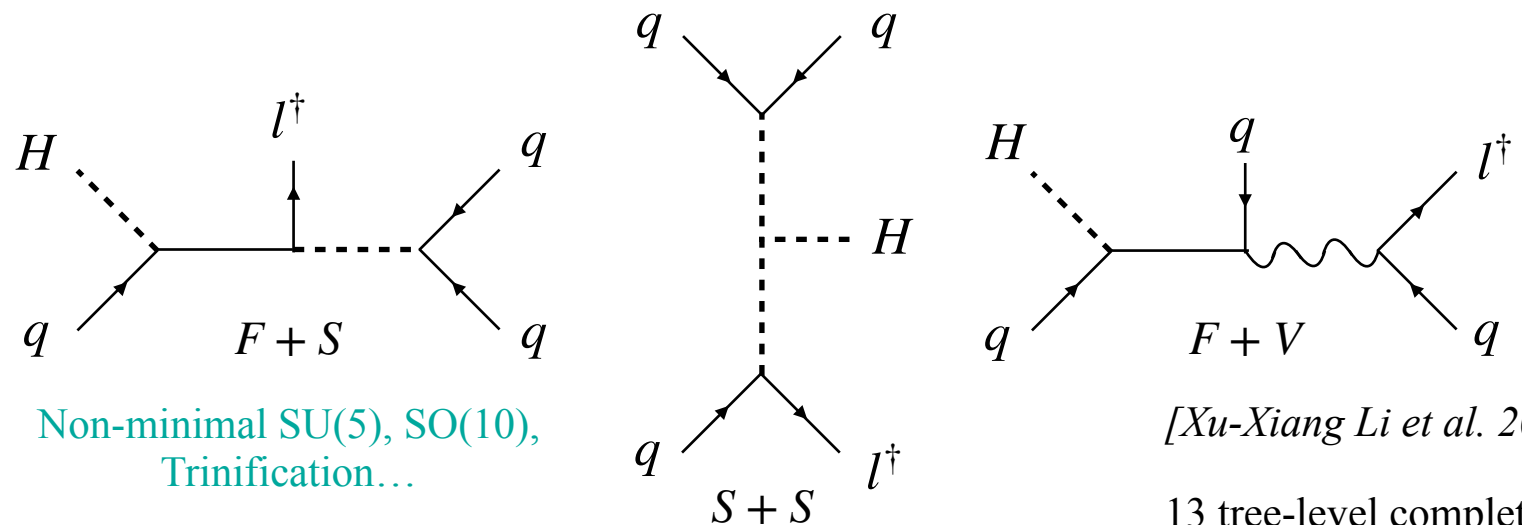
Seesaw mechanism

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



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

Minimal SU(5), SO(10), Trinification...



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

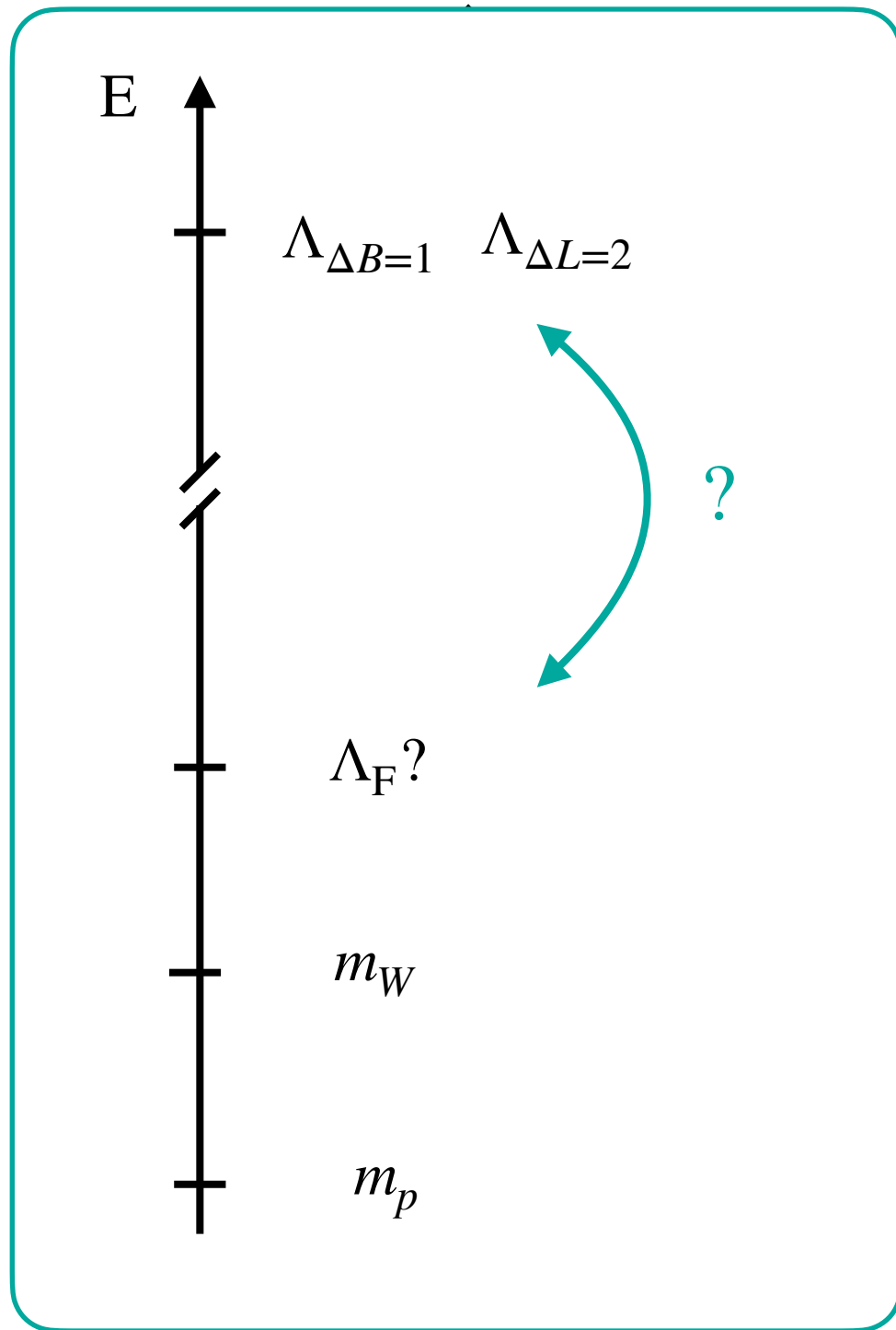
[Xu-Xiang Li et al. 2023]

13 tree-level completions

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

Tree-level Proton decay and Neutrino masses

[S. Weinberg 1979]



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



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

[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...]

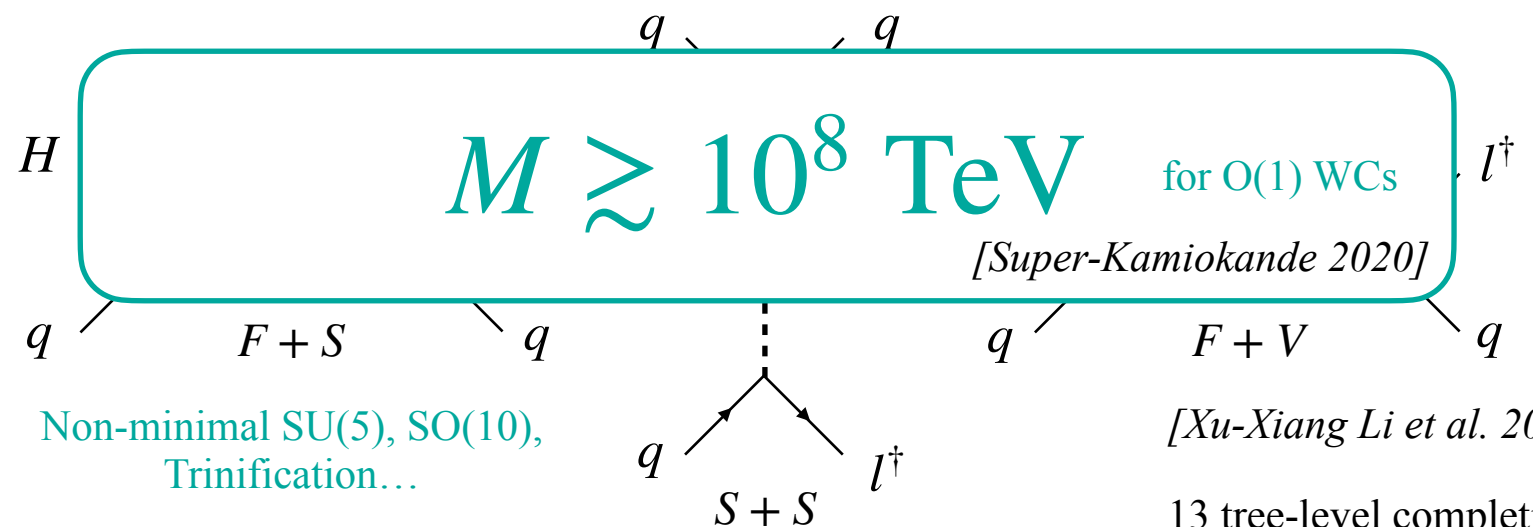
$$M \gtrsim 10^{12} \text{ TeV} \quad \text{for O(1) WCs}$$

[Super-Kamiokande 2020]

$q \quad l \quad q \quad l$

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

Minimal SU(5), SO(10), Trinification...



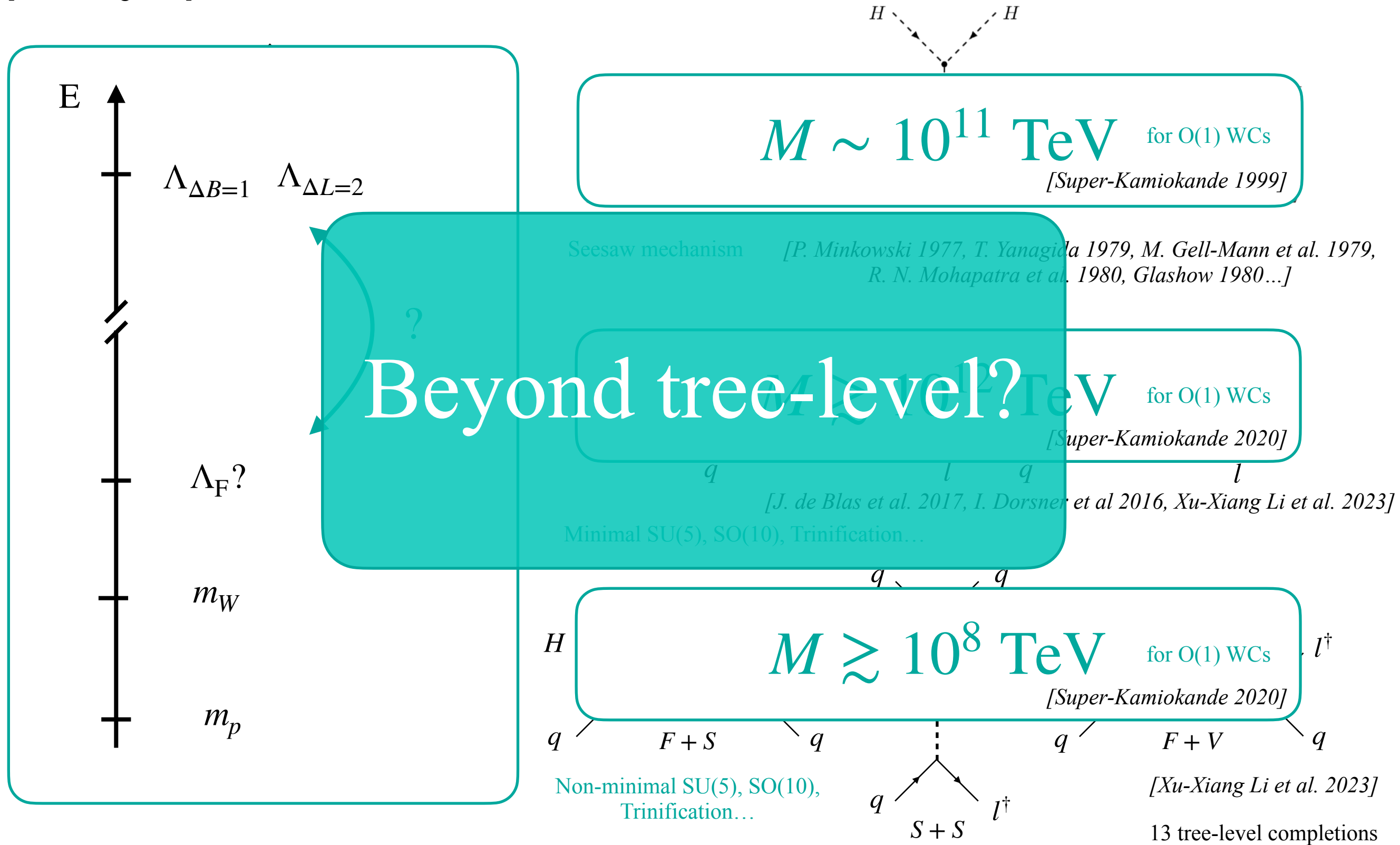
Non-minimal SU(5), SO(10), Trinification...

[Xu-Xiang Li et al. 2023]

13 tree-level completions

Tree-level Proton decay and Neutrino masses

[S. Weinberg 1979]

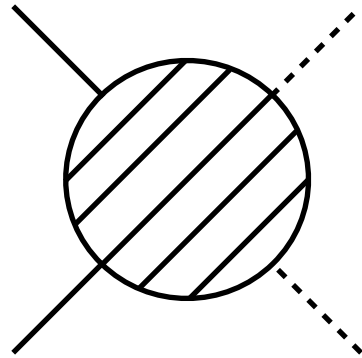


... and many more: $\Delta B = 2$, $\Delta(3B - L)$, $\Delta L = 4$...

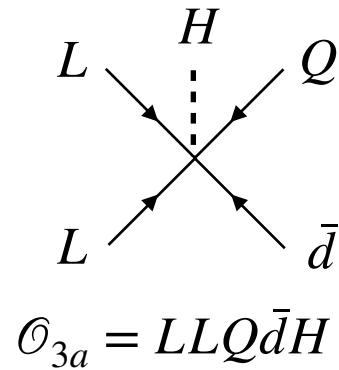
Loop-level Proton decay and Neutrino masses

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

$$\Delta L = 2$$



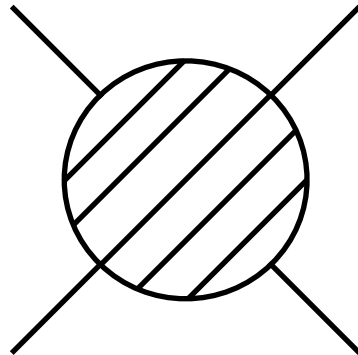
E.g.



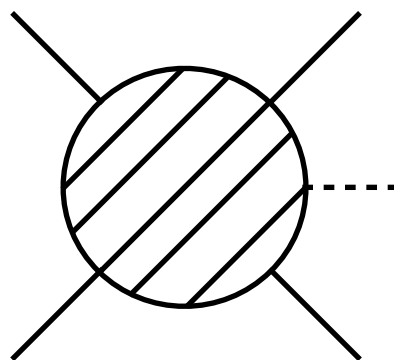
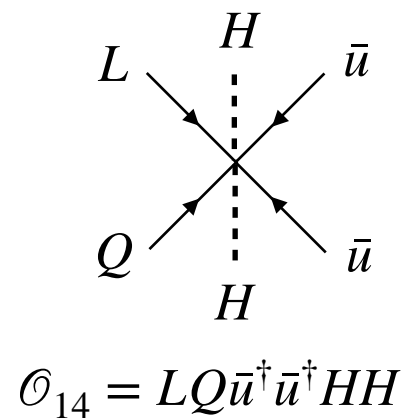
$$\Delta(B - L) = 0$$

Different
phenomenology

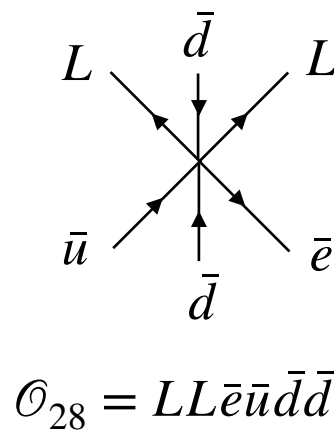
$$\Delta(B - L) = 2$$



E.g.



E.g.



Arising at even-d in the SMEFT

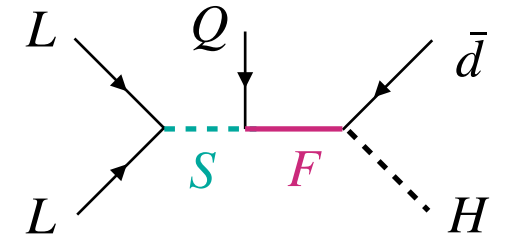
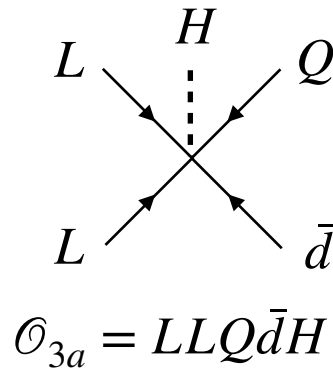
Arising at odd-d in the SMEFT [A. Kobach 2016]

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

$$\Delta L = 2$$

E.g.

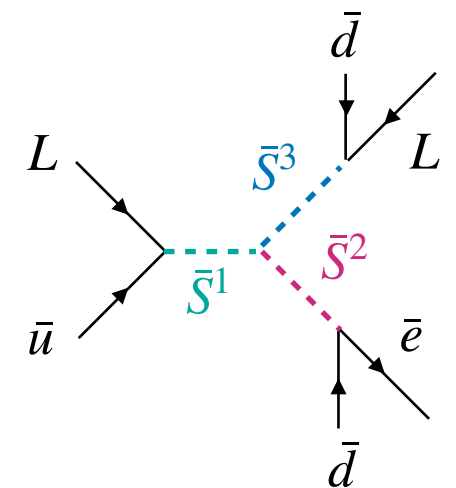
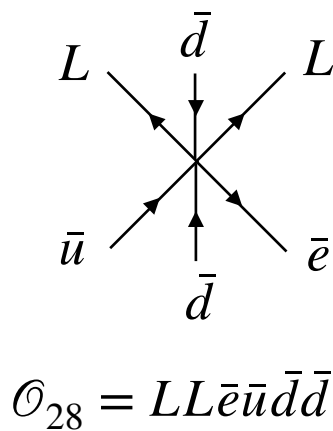
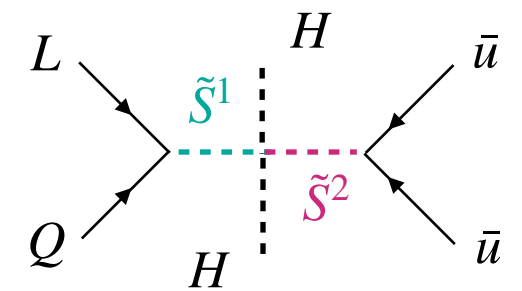
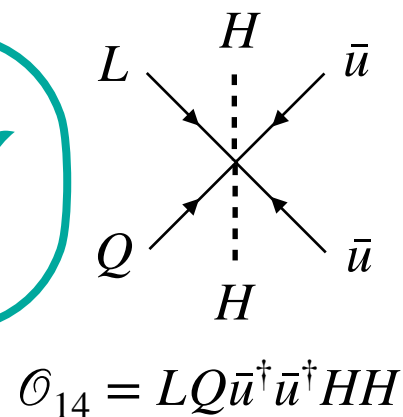


They admit a **finite number** of **tree-level completions** in the UV ✓

Different phenomenology

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

E.g.



Arising at even-d in the SMEFT

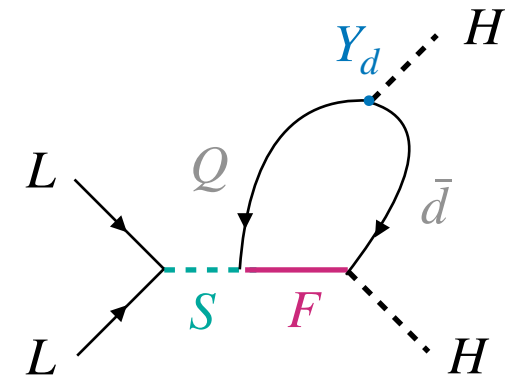
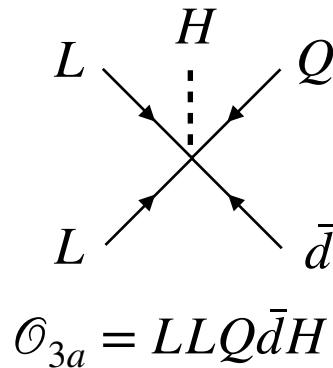
Arising at odd-d in the SMEFT [A. Kobach 2016]

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

$$\Delta L = 2$$

E.g.

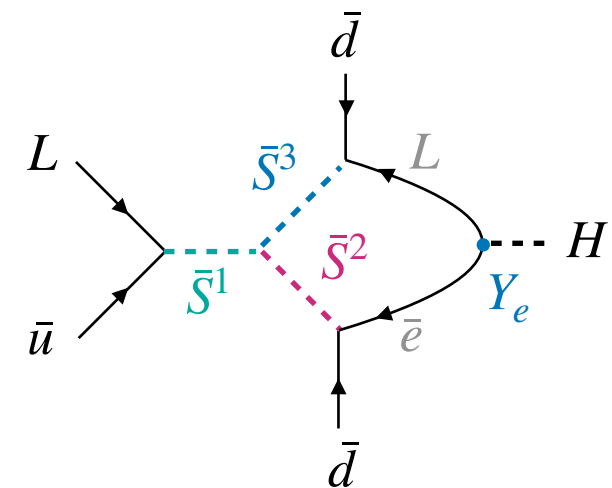
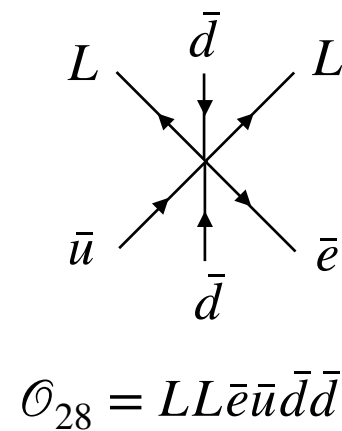
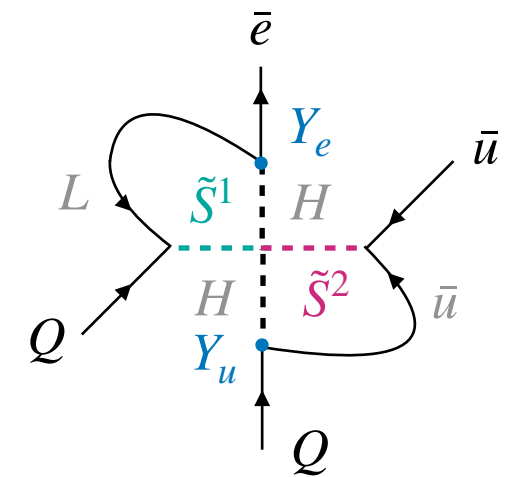
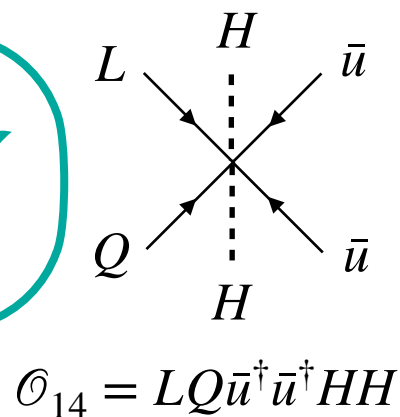


They admit a **finite number** of **tree-level completions** in the UV ✓

Different phenomenology

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

E.g.



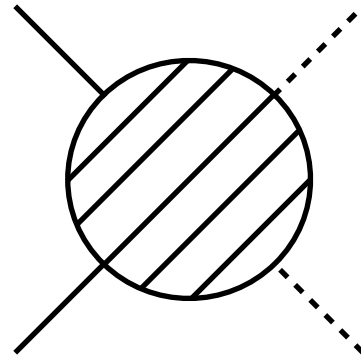
Arising at even-d in the SMEFT

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

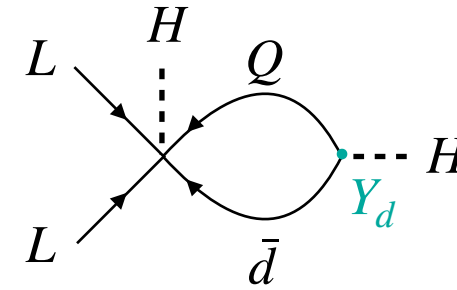
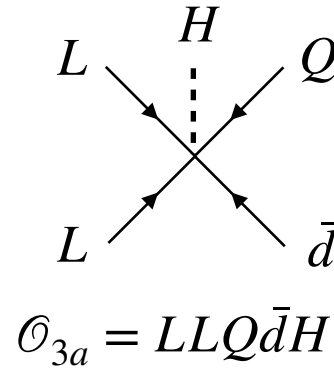
Loop-level Proton decay and Neutrino masses

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

$$\Delta L = 2$$



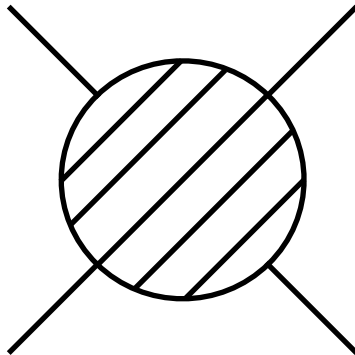
E.g.



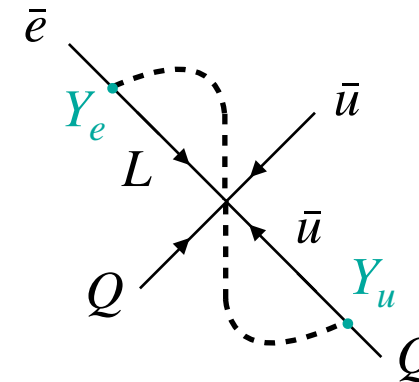
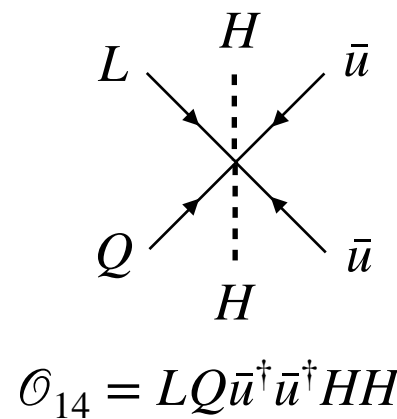
$$C_W \sim \frac{y_b}{16\pi^2} \frac{1}{\Lambda} c_{3a}$$

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

Different
phenomenology

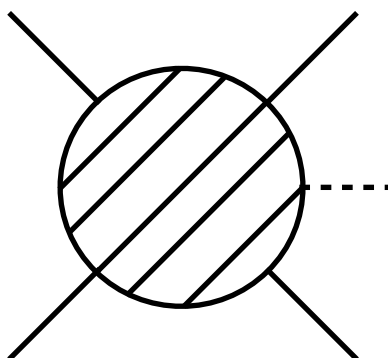


E.g.

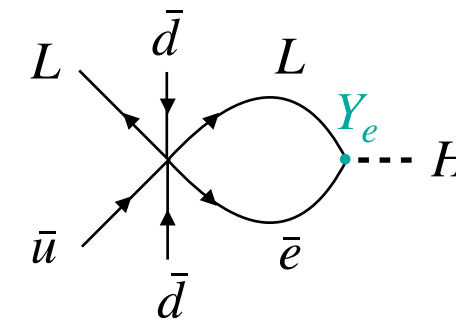
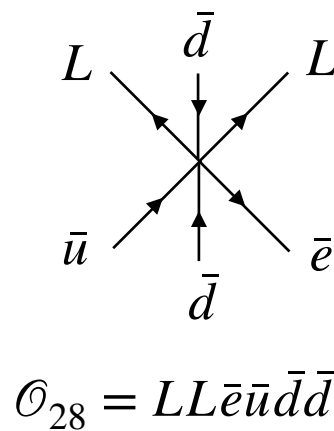


$$C_{qqe} \sim \frac{y_u y_e}{(16\pi^2)^2} \frac{1}{\Lambda^2} c_{14}$$

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



E.g.



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

Arising at even-d in the SMEFT

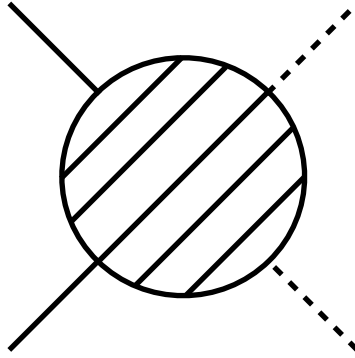
Arising at odd-d in the SMEFT [A. Kobach 2016]

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

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

$\Delta L = 2$

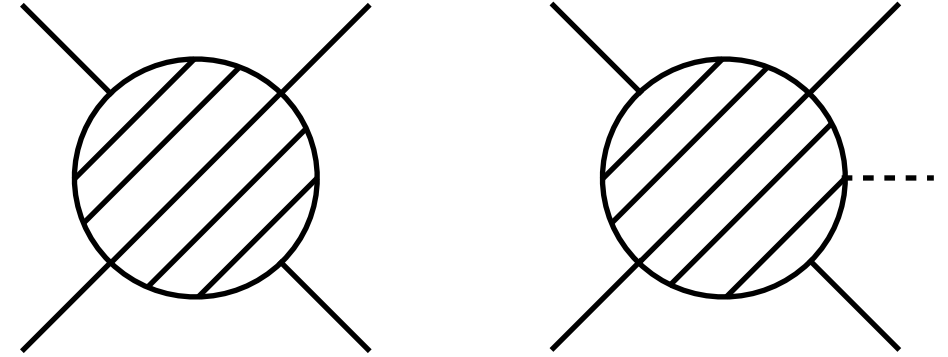


[J. Gargalionis et al. 2020]

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	$3 \cdot 10^{15}$	$p \rightarrow \pi^0 e^+$
2	$\bar{e}^\dagger Q Q \bar{u}^\dagger$	—	1111	$4 \cdot 10^{15}$	$p \rightarrow \pi^0 e^+$
3	$\bar{e}^\dagger \bar{u}^\dagger \bar{u}^\dagger \bar{d}^\dagger$	—	1111	$3 \cdot 10^{15}$	$p \rightarrow \pi^0 e^+$
4	$LQ \bar{u}^\dagger \bar{d}^\dagger$	—	1111	$3 \cdot 10^{15}$	$p \rightarrow \pi^0 e^+$
Dimension 7					
5	$L \bar{d} \bar{d} \bar{d} H^\dagger$	—	1112	$2 \cdot 10^{10}$	$n \rightarrow K^+ e^-$
6	$DLQ^\dagger \bar{d} \bar{d}$	—	1112	$6 \cdot 10^9$	$p \rightarrow K^+ \nu$
7	$D \bar{e}^\dagger \bar{d} \bar{d} \bar{d}$	—	1111	$3 \cdot 10^9$	$n \rightarrow \pi^+ e^-$
8	$LQ^\dagger Q^\dagger \bar{d} H$	—	1111	$6 \cdot 10^{10}$	$n \rightarrow \pi^0 \nu$
9	$\bar{e}^\dagger Q^\dagger \bar{d} \bar{d} H$	—	1112	$3 \cdot 10^{10}$	$n \rightarrow K^+ e^-$
10	$L \bar{u} \bar{d} \bar{d} H$	—	1111	$6 \cdot 10^{10}$	$n \rightarrow \pi^0 \nu$
Dimension 8					
11	$DLQQ \bar{d}^\dagger H$	$C_{qqql}^{pqrs} = \frac{1}{16\pi^2} V_{ru'}^*(y_d)^{u'} C_{11}^{spqu'}$	1113	$4 \cdot 10^{12}$	$p \rightarrow K^+ \nu$
12	$DL \bar{u}^\dagger \bar{d}^\dagger \bar{d}^\dagger H$	$C_{duql}^{pqrs} = \frac{1}{16\pi^2} V_{rt'}^*(y_d)^{t'} C_{12}^{sqtl'p}$	1131	$3 \cdot 10^{12}$	$p \rightarrow K^+ \nu$

Many possibilities!

50 $\Delta B = 1$ operators up to **dimension-9** in the SMEFT
(Both $\Delta(B - L) = 0, 2$ operators)

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

Proton decay and Neutrino masses

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

Neutrino masses

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

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

[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?

Neutrino masses

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

$$m_\nu \geq \sqrt{\Delta m_{\text{atm}}^2} \geq 0.05 \text{ eV} \implies \Lambda \leq \#^{\text{exp}}$$

[J. Herrero et al. 2019]

$$\uparrow \\ y \leq 1$$

Proton decay

No, only lower bounds on the combination $\Lambda^2 c$ from current limits from Super-K...

Using $c \leq 1$ does not help...

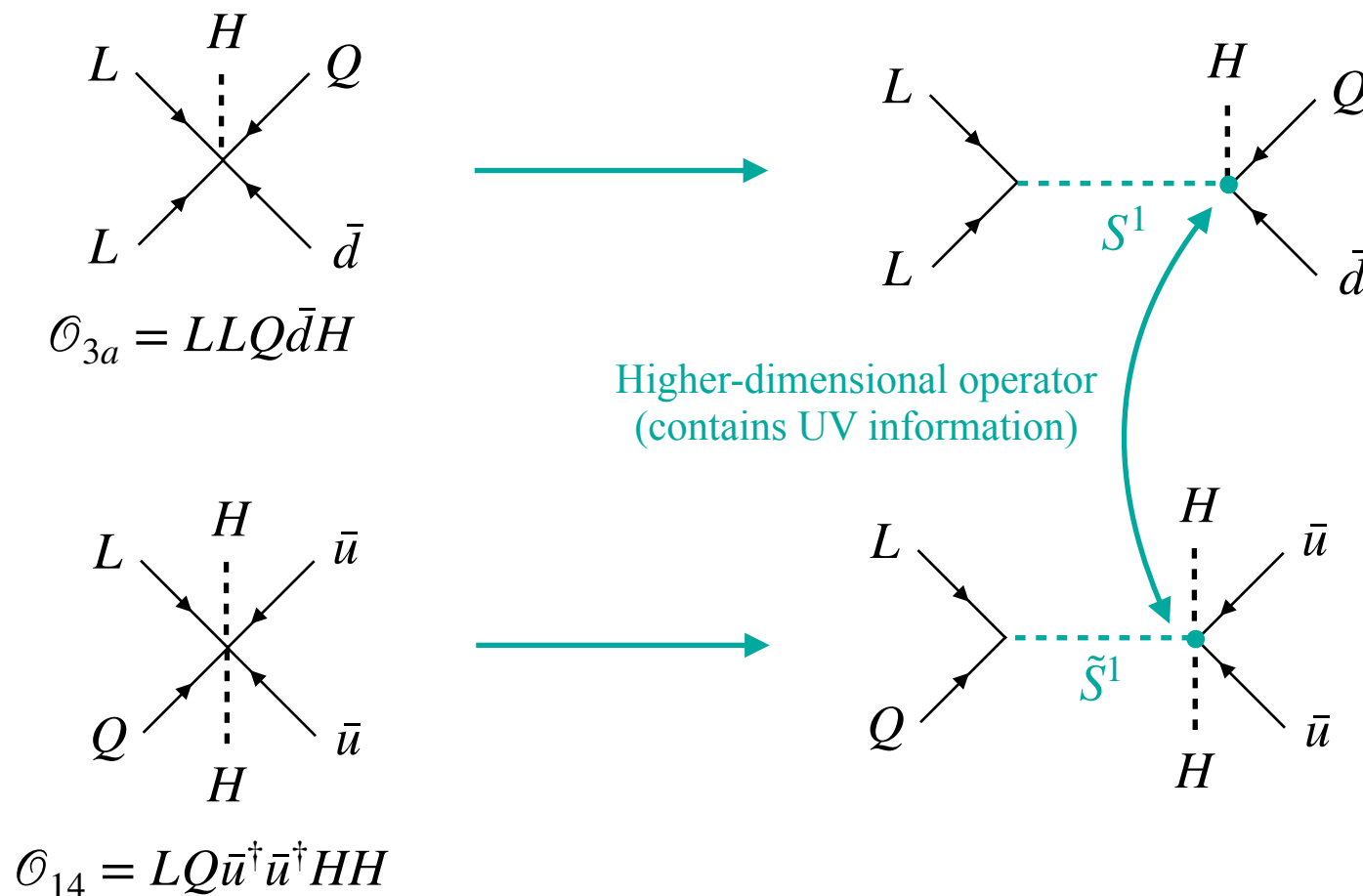
$$\tau_p > \tau_p^{\text{exp}} \implies \frac{c}{\Lambda^2}, \frac{c}{\Lambda^3} \leq \#^{\text{exp}}$$

[A. Bas i Beneito et al. 2023]

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

Neutrino masses

Proton decay



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

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**)

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**)

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

- 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

Theoretical framework

Granada dictionary

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
 $G_{\text{SM}} = (\text{SU}(3)_C, \text{SU}(2)_L, \text{U}(1)_Y)$

- These
 - We a
 - The a
- EFT.
- the l
- such

* Their elec

able

S

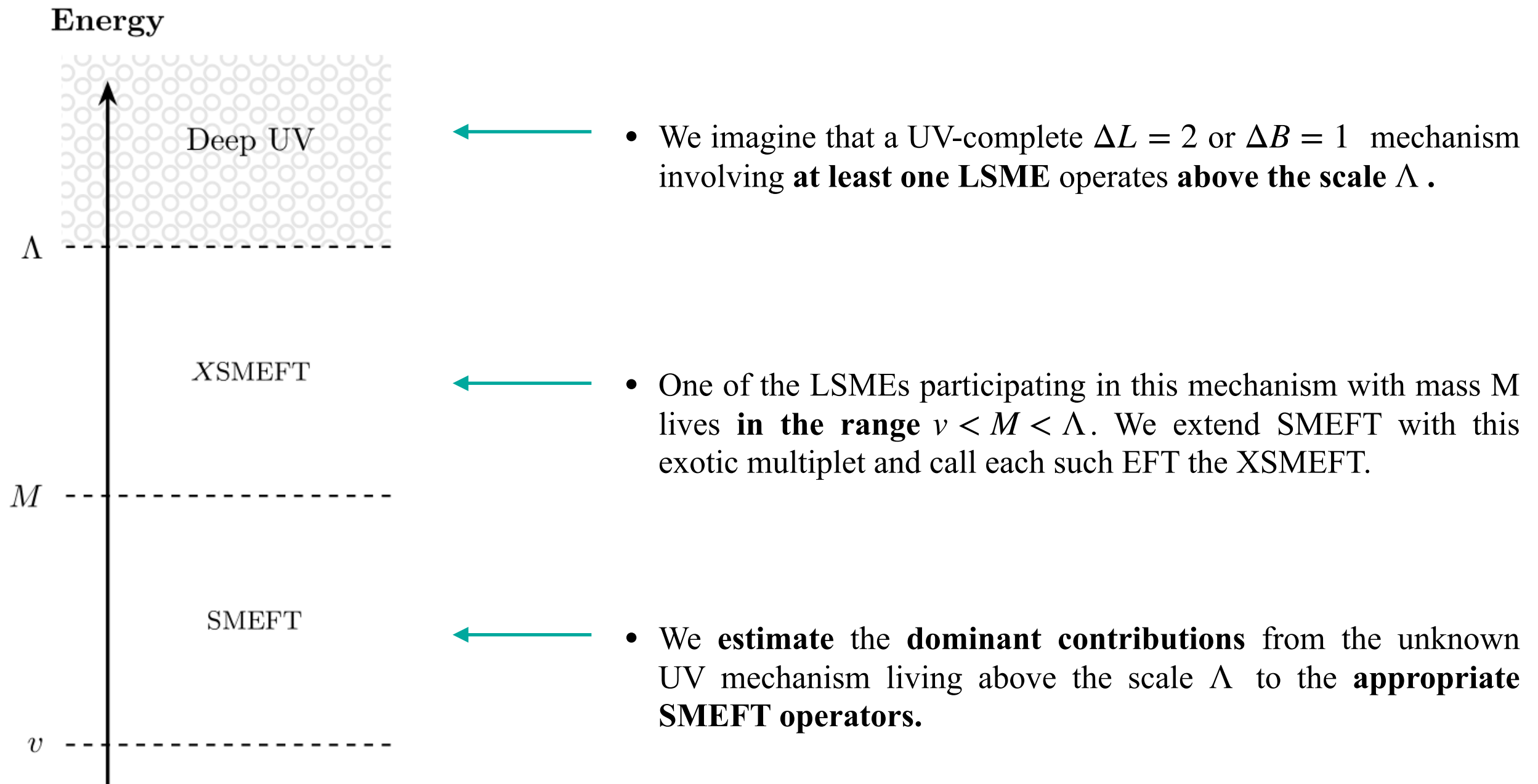
M)

)

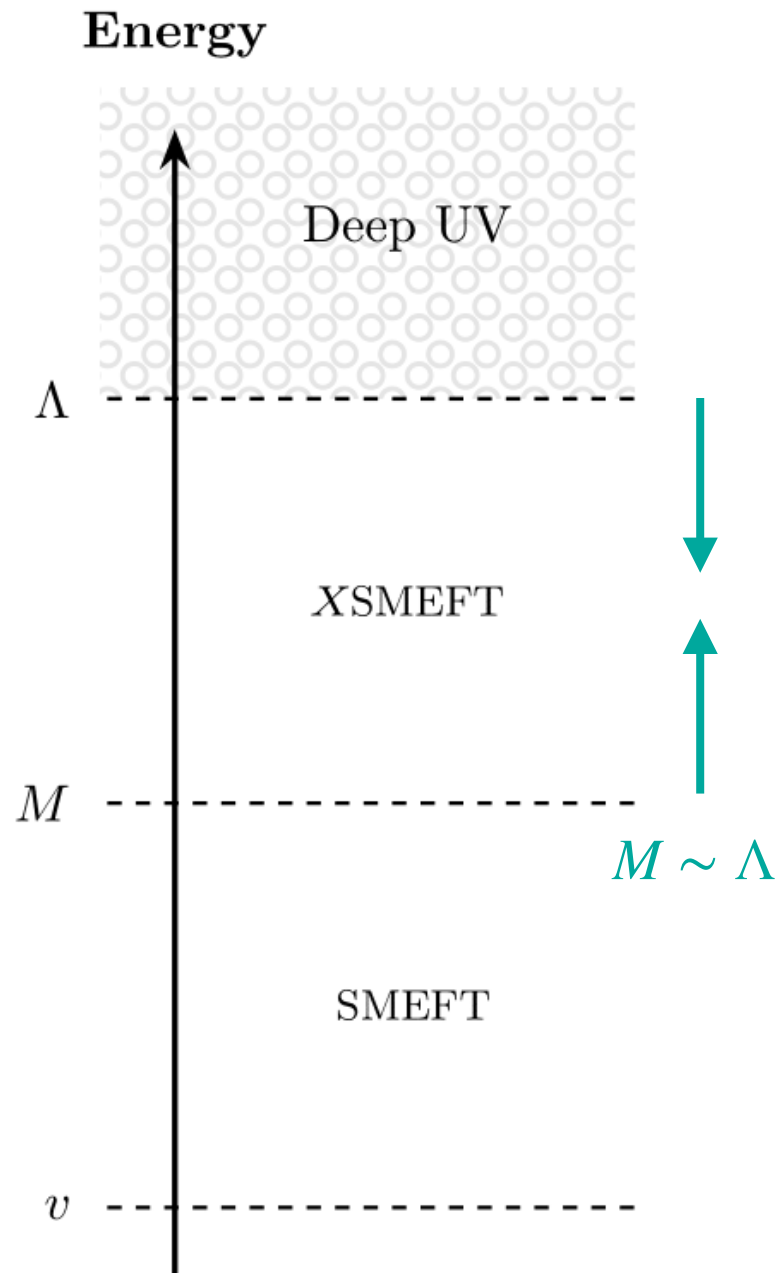
omena using

racterised by
that include

Theoretical framework



Theoretical framework



In this setup we can derive **upper bounds** on M if

- We impose the lower bound $m_\nu > \sqrt{\Delta m_{\text{atm}}^2} = 0.05 \text{ eV}$
- 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 $M \rightarrow \Lambda$ *

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 $M \sim \Lambda$

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

↓

Dimension-7 with a more suppressed contribution to Neutrino masses

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



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. $\omega_4 \sim (3,1, -4/3)_S \rightarrow$ Dimension-6 $y^{[pq]} \omega_4 (\bar{u}_{[p}^\dagger \bar{u}_{q]}^\dagger)$



No 2-body proton decay at tree-level

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. $\Theta_1 \sim (1,4,1/2)_S \rightarrow \text{dimension-5 } \Theta_{1ijk} \underbrace{L^i L^j}_{\Xi_1} \underbrace{H^k}_{\Sigma} \quad \times$

↓
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. $\mu \Xi H^\dagger H \rightarrow \langle \Xi^0 \rangle \sim \mu \frac{v^2}{M^2}$

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

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

Antisymmetry in flavour space

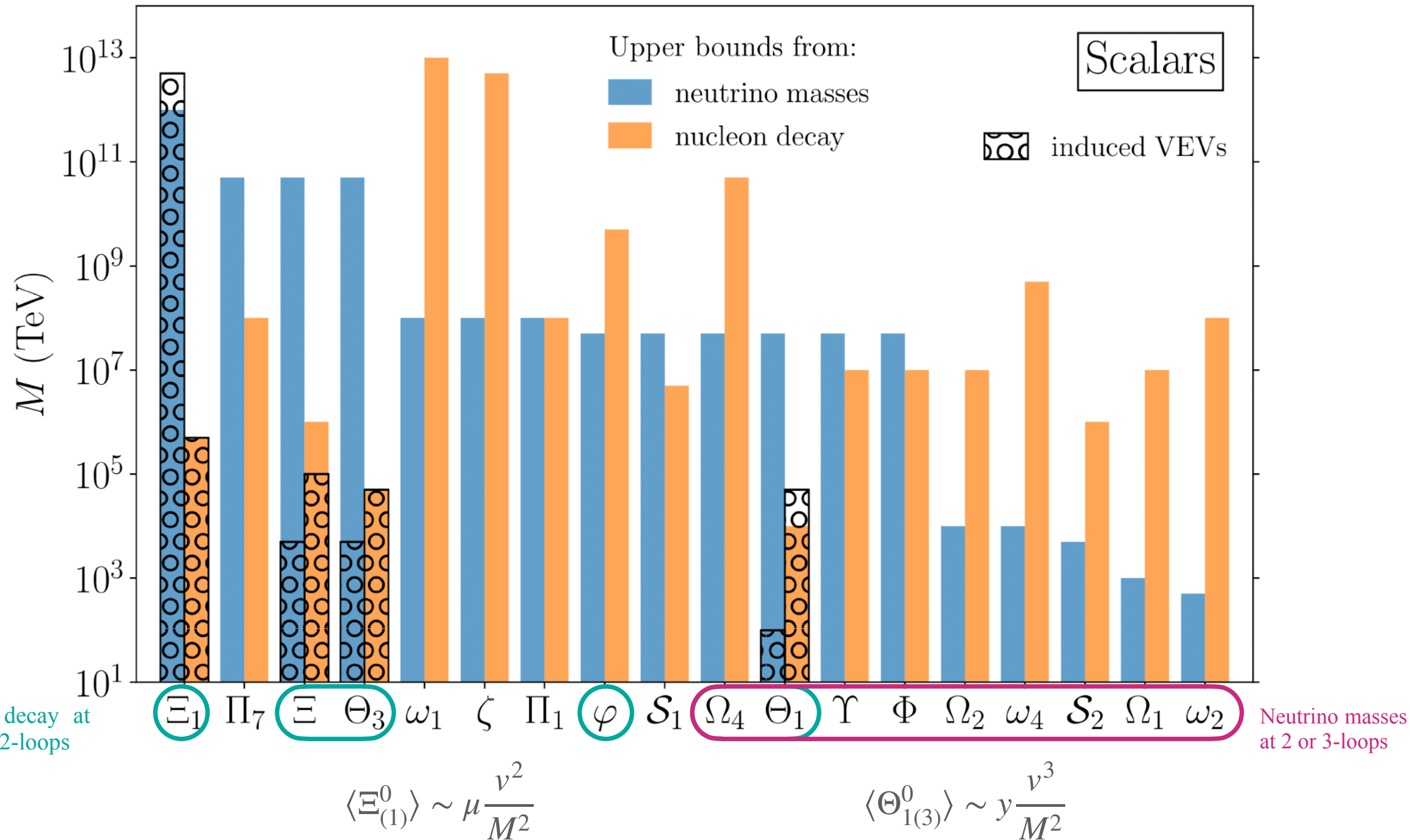
- Specific LSMEs have fixed flavour symmetries in the renormalisable operator, that impact the strongest constraints on the operator in two different ways:

- 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

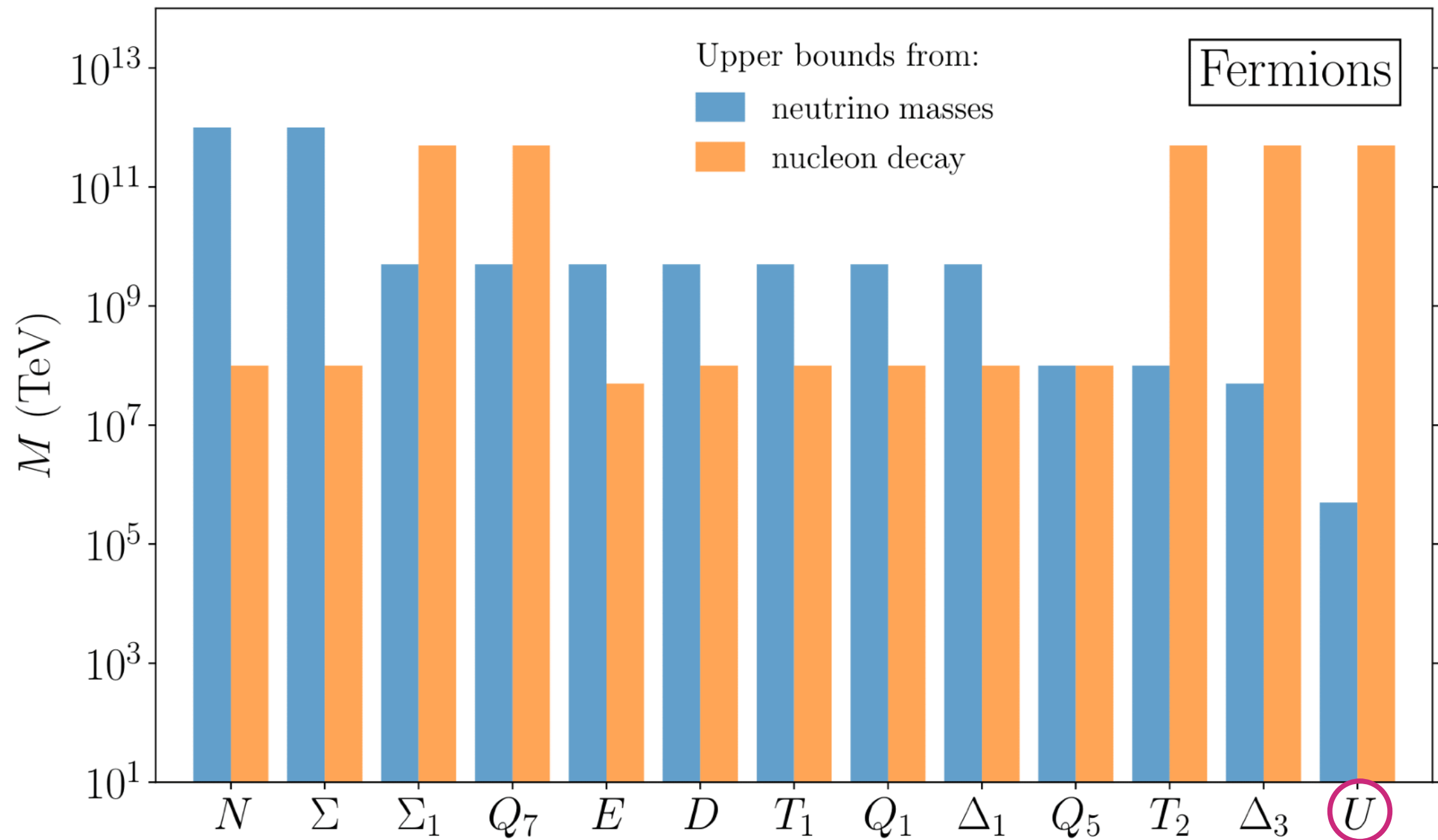
E.g. $\omega_4 \sim (3,1, -4/3)_S \rightarrow \text{Dimension-6 } y^{[pq]} \omega_4(\bar{u}_{[p}^\dagger \bar{u}_{q]}^\dagger)$

↑
No 2-body proton decay at tree-level

Upper bounds for scalars



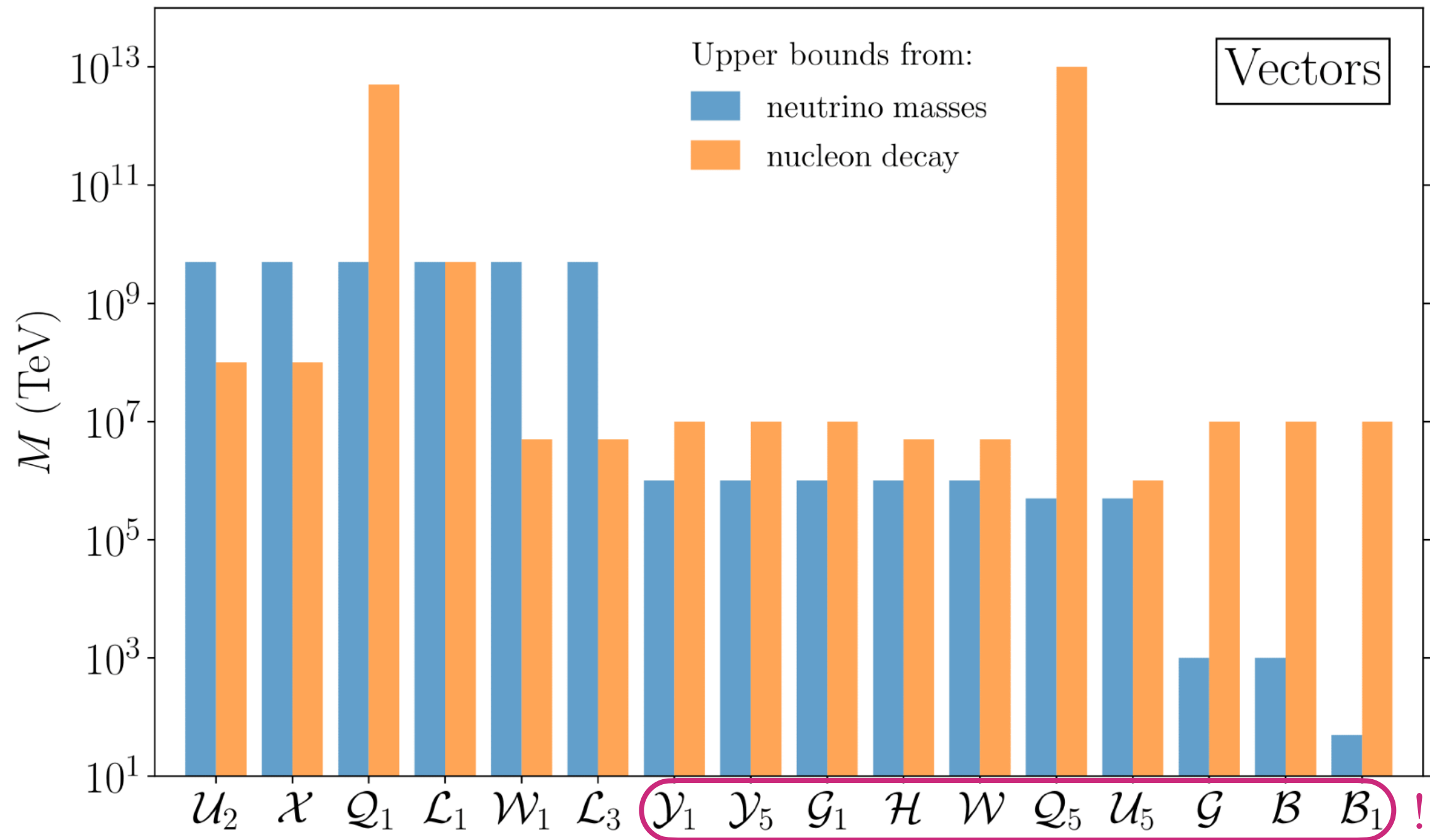
Upper bounds for fermions



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

Exception: Neutrino masses at 2-loops

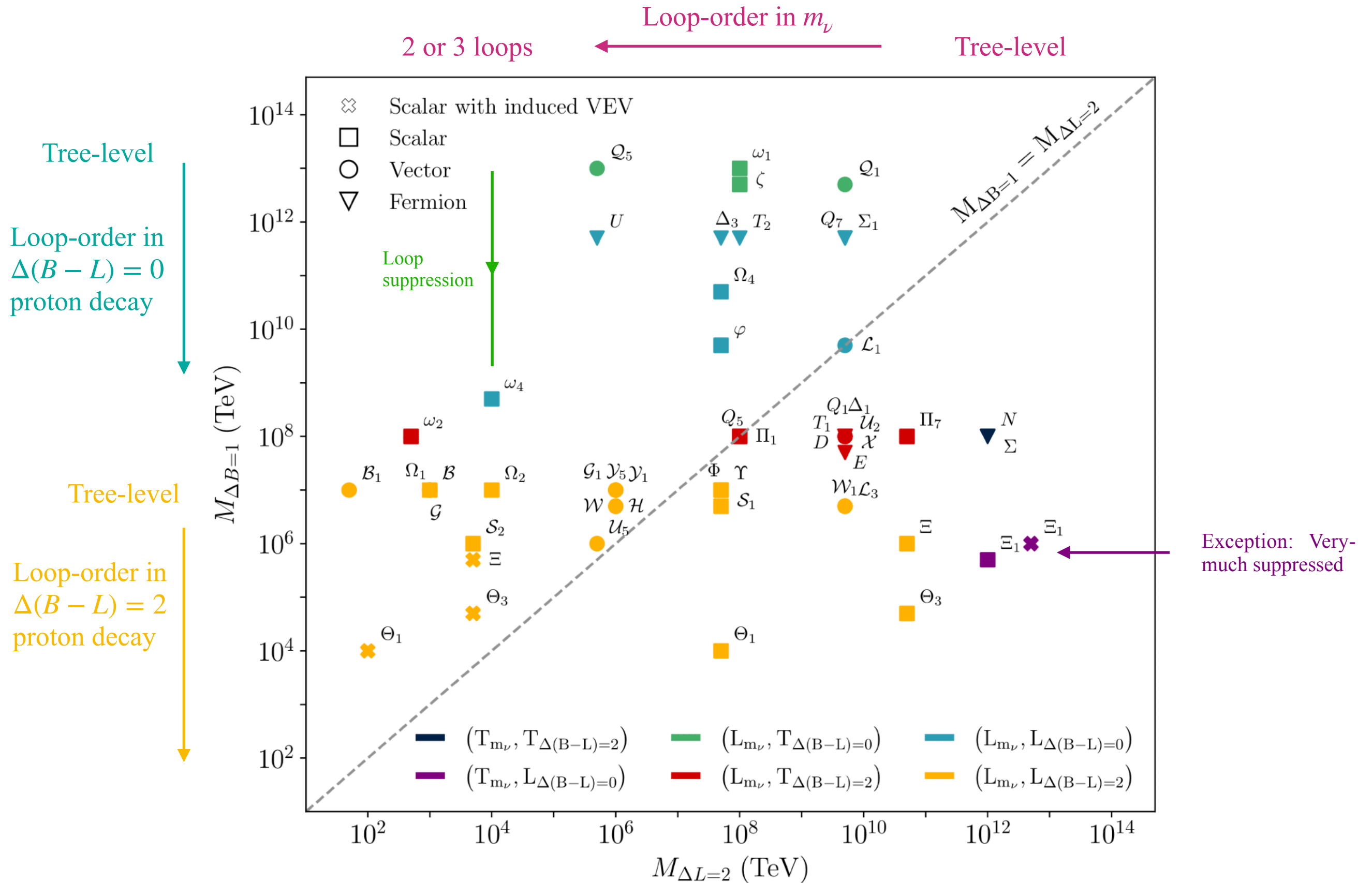
Upper bounds for vectors



Proton decay at most at 1-loop.

Neutrino masses at 2 or 3-loops

Neutrino masses and Proton decay



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.
- First steps to build **UV-complete models** with *low* $\Lambda_{\Delta B=1}$ and $\Lambda_{\Delta L=2}$

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.
- First steps to build **UV-complete models** with *low* $\Lambda_{\Delta B=1}$ and $\Lambda_{\Delta L=2}$

Gràcies!

Backup slides

Searches for Proton Decay

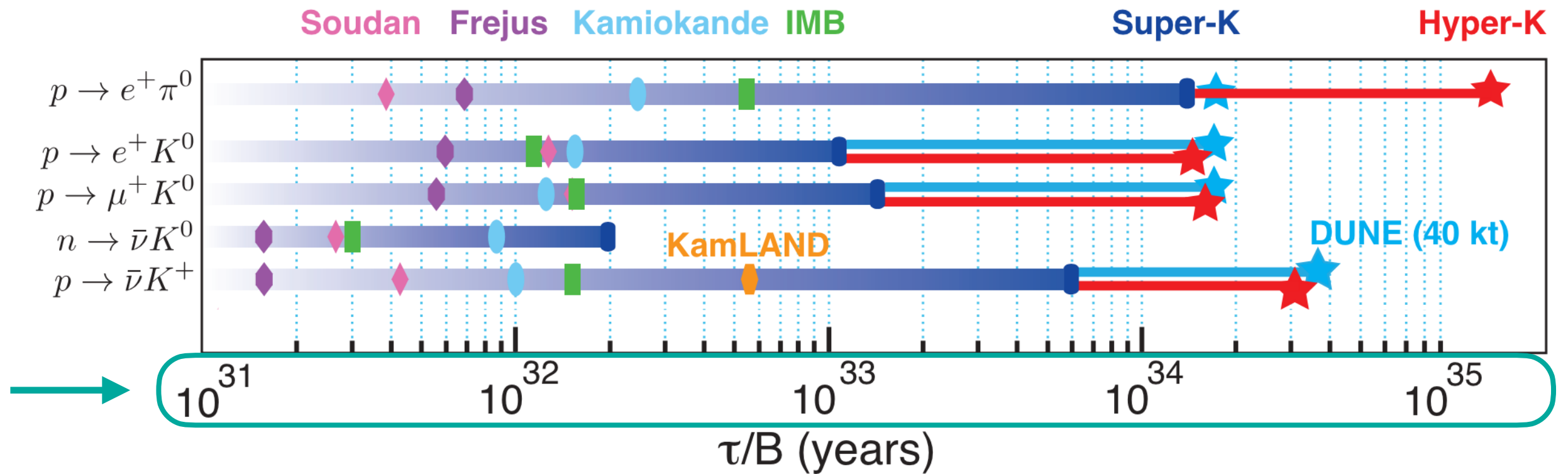
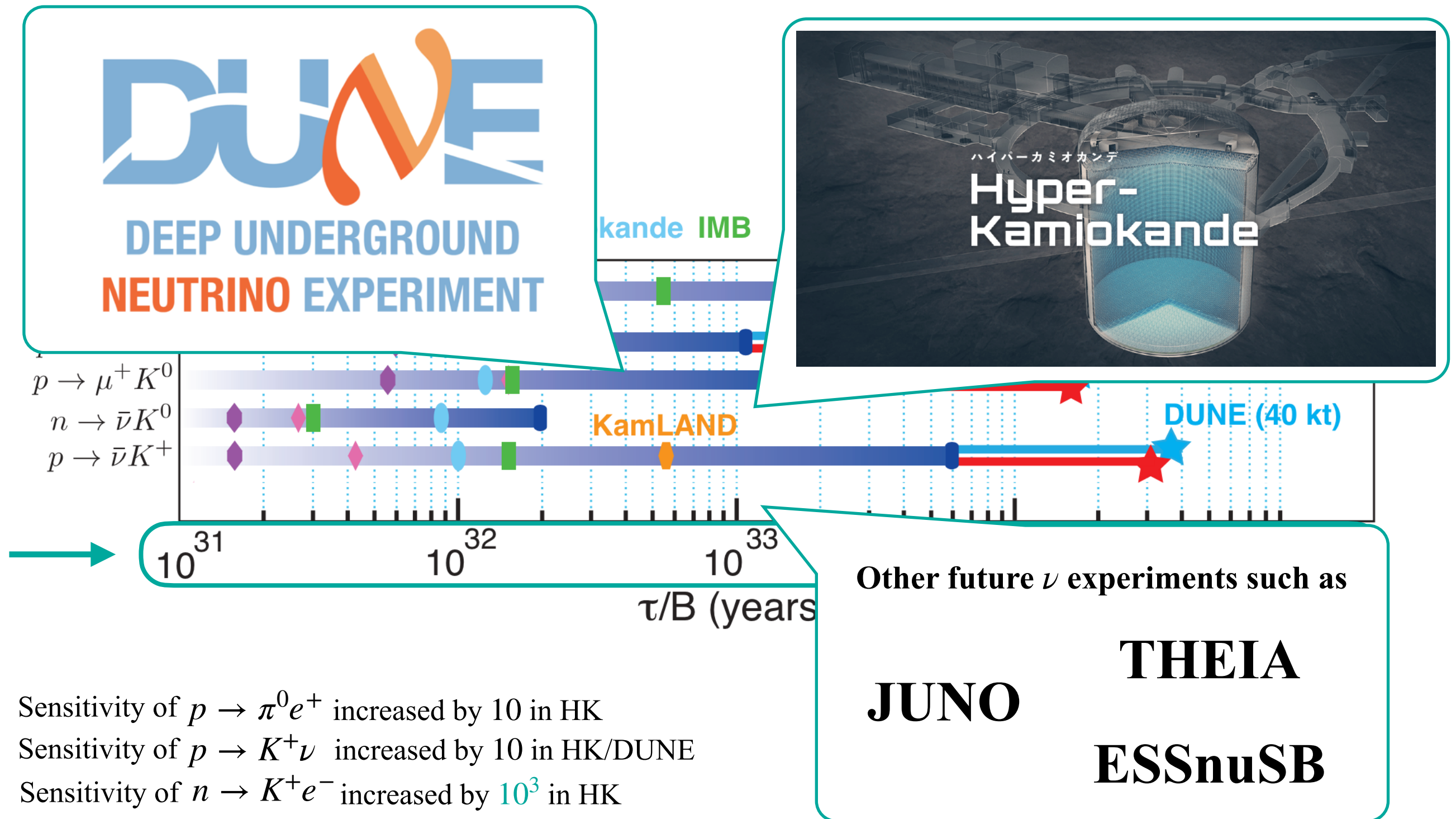


Image extracted from Hyper-K design report (edited)

Searches for Proton Decay



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) + U(1) _f	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]	$\sim 10^{34.9 \pm 1}$	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 <i>et al.</i> [33]	$10^{35} - 10^{37}$	no
SUSY ($d = 5$) SU(5) – option II	Alciati <i>et al.</i> [34]	$10^{36} - 10^{39}$	no

[Image extracted from T. Ohlsson 2023]

Running and matching estimates

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

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 be¹⁹

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

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

Matching $C_{5,\text{Match}} \sim \frac{1}{\Lambda} \left(\frac{M}{\Lambda} \right)^\delta ,$ (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:

Running dominates: $\Delta d \leq 1$

Model 1 ($\Delta d = 1$)

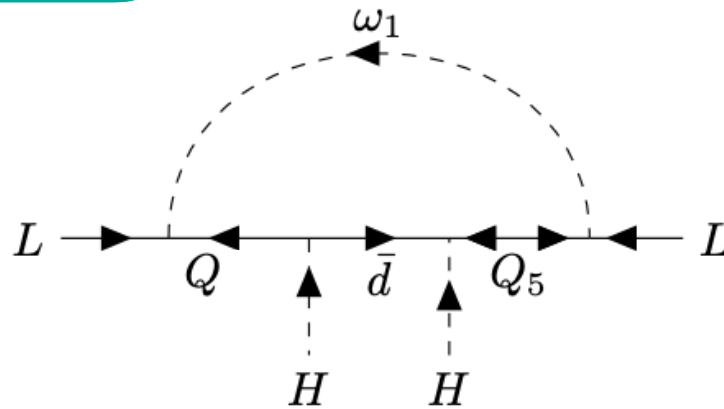


SM + ω_1 + Q_5 with $m_{Q_5} = M < m_{\omega_1} = \Lambda$

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

$$\propto \frac{y_b}{16\pi^2} \frac{M}{M^2 - \Lambda^2} \log\left(\frac{M}{\Lambda}\right),$$

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



Model 1 ($\Delta d = 0$)



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

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

$$\propto \frac{y_b}{16\pi^2} \frac{\Lambda}{M^2 - \Lambda^2} \log\left(\frac{M}{\Lambda}\right),$$

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

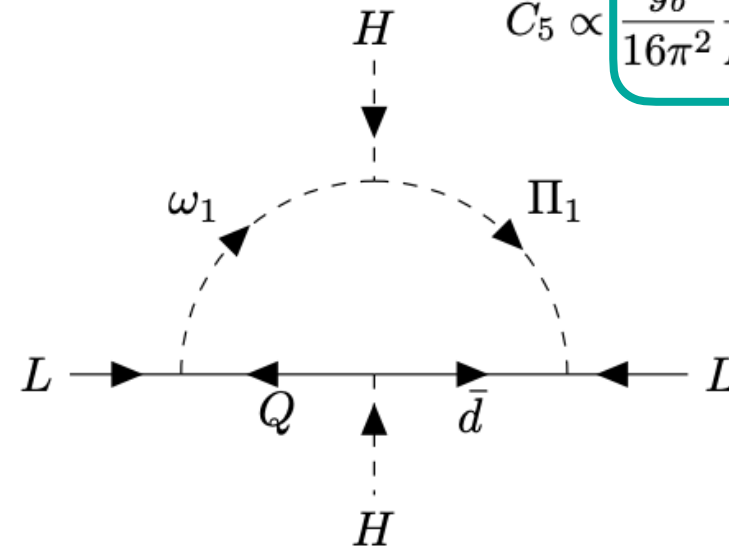


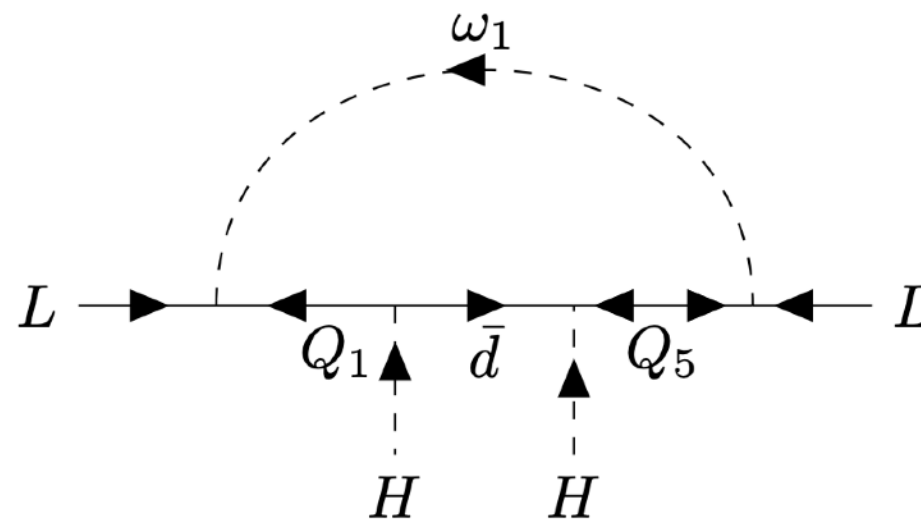
Figure 6. (Left) The neutrino mass diagram for the model presented in Ref. [42] for the choice of Q on the first internal fermion line. This is the example model presented in the $\Delta d = 1$ scenario of Sec. B.1. The choice of Q_1 is relevant for the $\Delta d > 1$ example model, presented in Sec. 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 + ω_1 + Q_1 + Π_1 with $m_{Q_1} = M < m_{\omega_1} = m_{\Pi_1} = \Lambda$

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



Illustrative example: S_2 for m_ν

Partially-resolved UV theory:

$$S_2 \sim (1, 1, 2)_s$$

Information of the full UV model

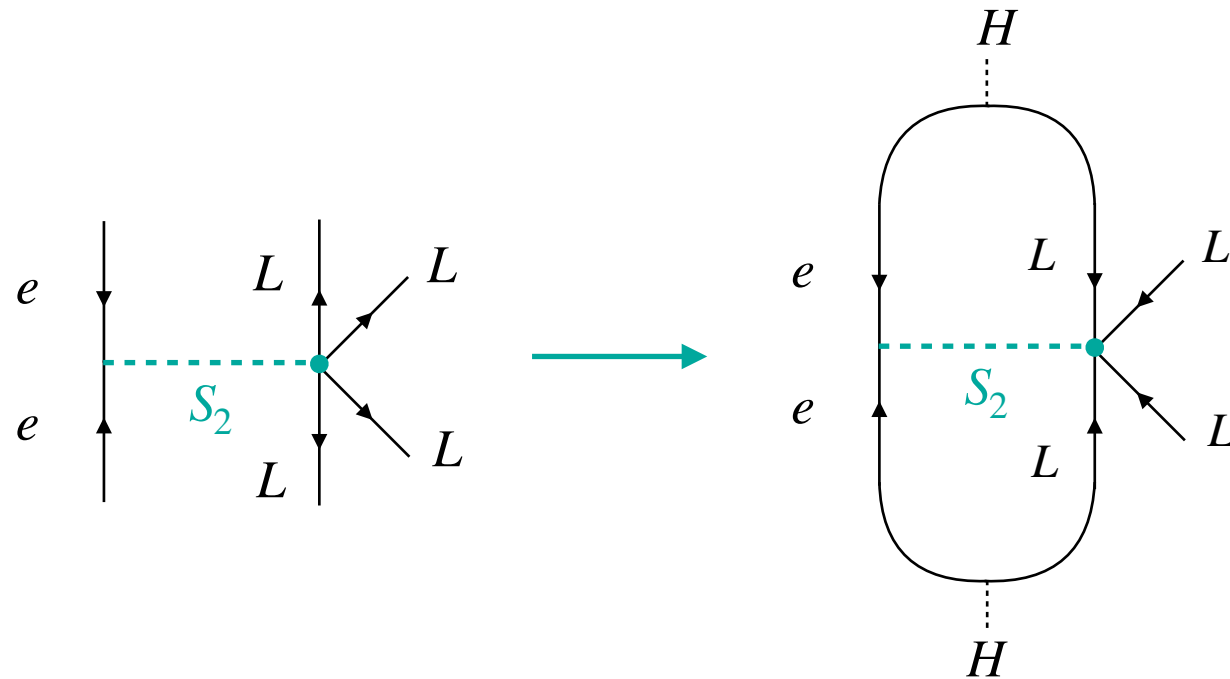
$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{S_2}^{\Delta L=2}$$



$$\mathcal{L}_{S_2}^{\Delta L=2} = y S_2 (\bar{e}^c e) + \frac{c}{\Lambda^3} S_2^\dagger (\bar{L}^c L) (\bar{L}^c L) + h.c.$$



d-6 SMEFT operators at tree-level



Two-loop generated m_ν

$$m_\nu \sim \frac{1}{(16\pi^2)^2} y c y_e^2 \frac{v^2}{\Lambda}$$

$$y, c \leq 1$$

$$M \rightarrow \Lambda$$

$$\sqrt{\Delta m_{\text{atm}}^2} < m_\nu \sim \frac{1}{(16\pi^2)^2} y c y_e^2 \frac{v^2}{\Lambda} \leq \frac{1}{(16\pi^2)^2} y_e^2 \frac{v^2}{\Lambda} \leq \frac{1}{(16\pi^2)^2} y_e^2 \frac{v^2}{M}$$

Illustrative example: S_2 for m_ν

Fully-resolved UV theory: **Zee-Babu model**

[A. Zee 1980, K. Babu 1980]

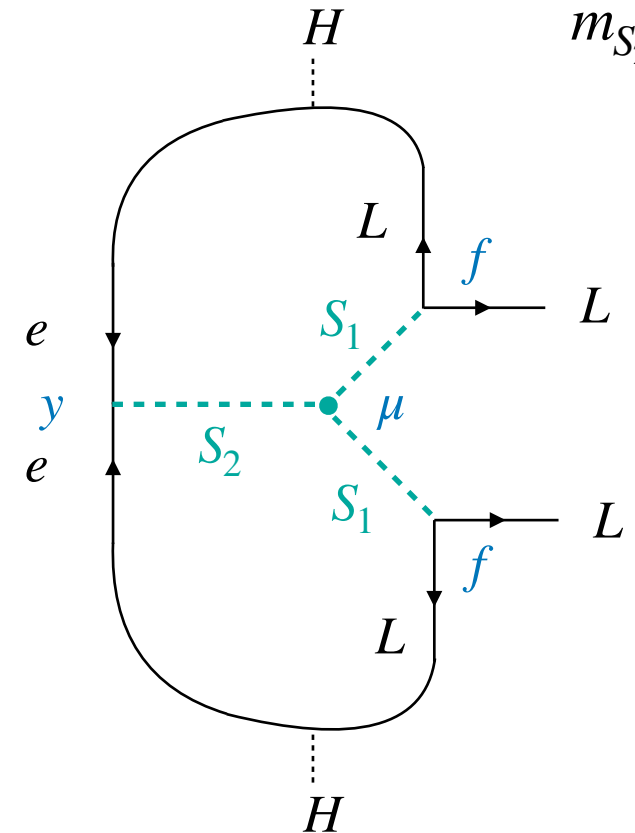
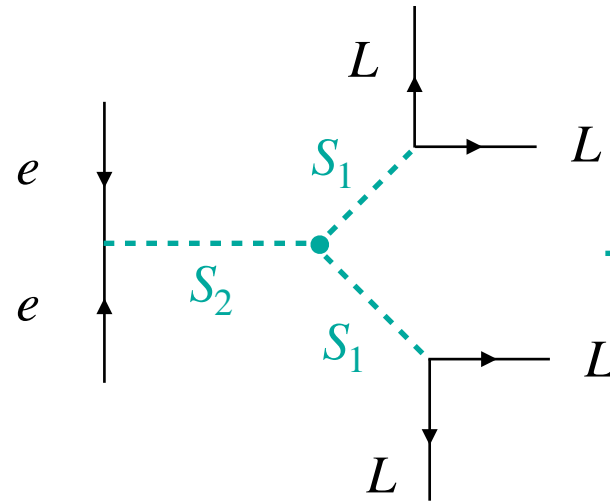
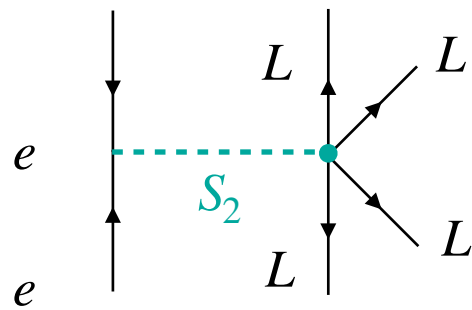
SM + S_1 and S_2

$$S_1 \sim (1, 1, 1)_s$$

$$S_2 \sim (1, 1, 2)_s$$

$$\mathcal{L} = \mathcal{L}_{SM} + y S_2 (\bar{e}^c e) + f S_1 (\bar{L}^c L) + \mu S_1^2 S_2 + h.c.$$

$$m_{S_2} \leq m_{S_1}$$



$$\mathcal{L}_\nu = -\frac{1}{2} \bar{\nu}_{Li}^c [m_\nu]_{ij} \nu_{Lj}$$

$$m_e \ll m_S$$

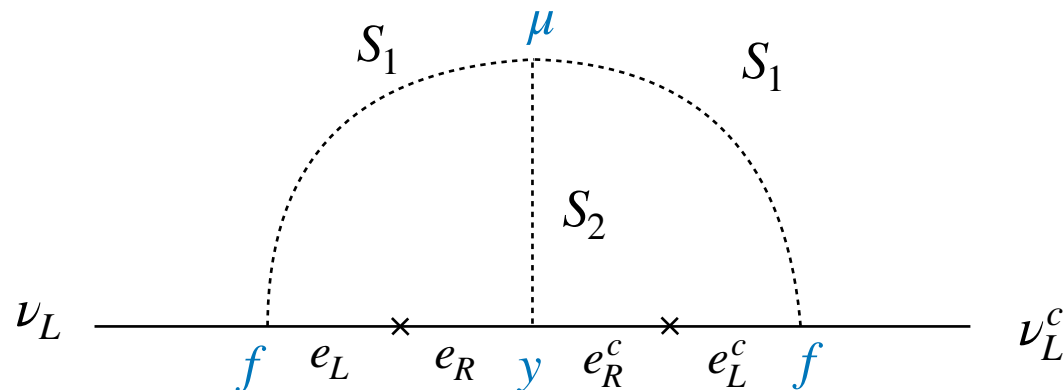


$$I_{ab} \sim \frac{1}{(16\pi^2)^2} \frac{1}{M^2}$$

$$M = \max[m_{S_1}, m_{S_2}] = m_{S_1}$$

Two-loop integral

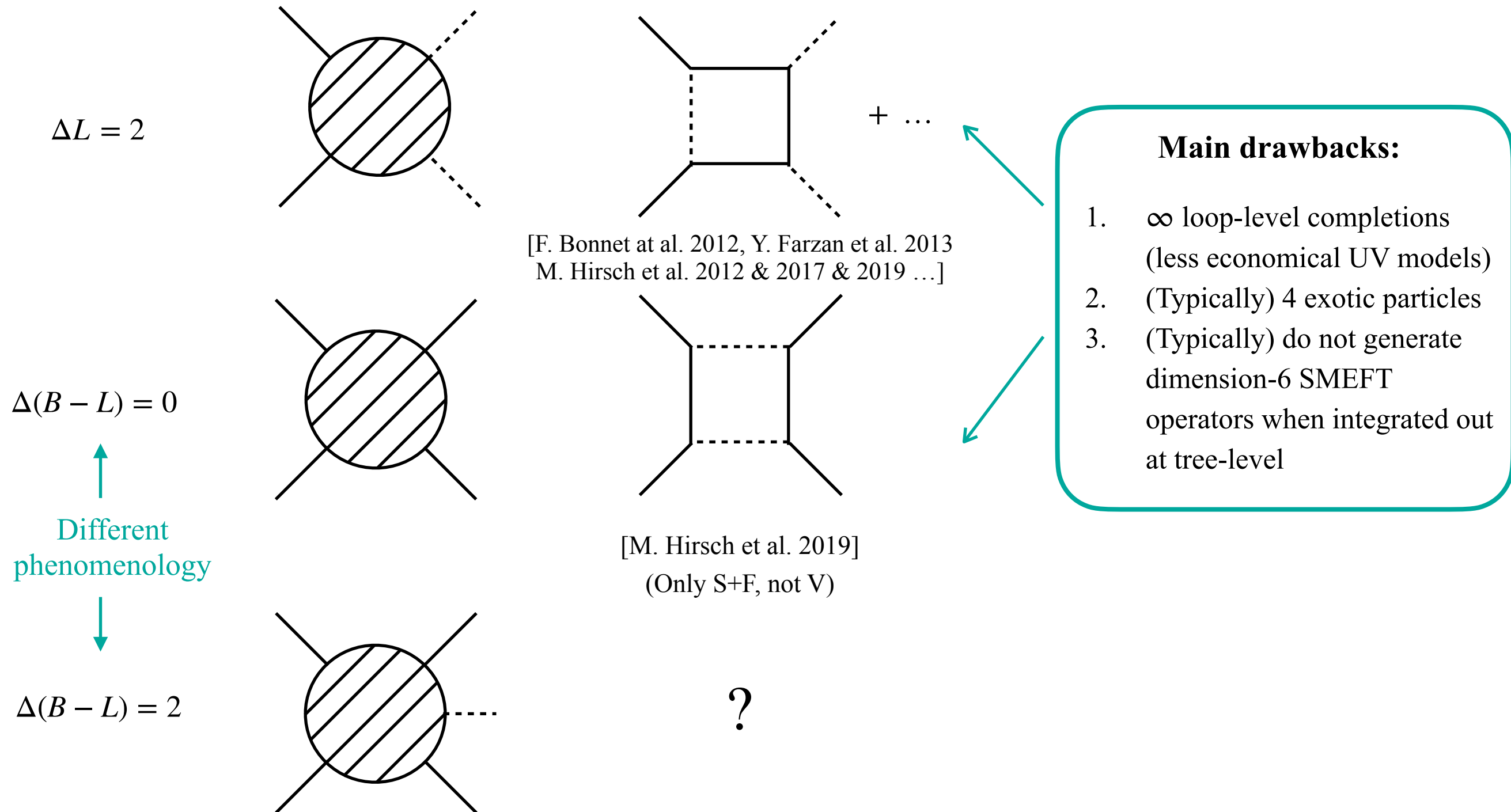
$$[m_\nu]_{ij} \sim \mu f_{ia} [m_e]_a y_{ab} I_{ab} m_b f_{jb}$$



$$m_\nu \sim \frac{1}{(16\pi^2)^2} m_e^2 \frac{\mu}{M_{S_1}^2} \equiv \frac{1}{(16\pi^2)^2} y_e^2 \frac{v^2}{\Lambda}$$

Loop-level Proton decay and Neutrino masses

Loop-level completions of operators giving rise to m_ν and **proton decay** 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	$(1, 3, 1)_S$	$\mu \Xi_1^\dagger H H + c_{\{pq\}} \Xi_1 (L_p L_q)$	$c_{\{pq\}} \left(\mu \frac{v^2}{M^2} \right)$	$5 \cdot 10^{12}$	$5 \cdot 10^{-15}$
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	$(1, 4, 3/2)_S$	$y \Theta_3^\dagger H H H + c_{\{pq\}} \Theta_3 (L_p L_q) H^\dagger$	$c_{\{pq\}} \frac{v}{\Lambda} \left(y \frac{v^3}{M^2} \right)$	$5 \cdot 10^3$	$5 \cdot 10^{-10}$
Θ_1	$(1, 4, 3/2)_S$	$y \Theta_1^\dagger H H^\dagger H + c_{pq} \Theta_1^{\{ijk\}} (L_p^l L_q^m) H^n H_l^\dagger H^o \epsilon_{im} \epsilon_{jn} \epsilon_{ko}$	$c_{pq} \frac{v^3}{\Lambda^3} \left(y \frac{v^3}{M^2} \right)$	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}	$\mathcal{L}_{\Delta B=1}$	$[L_{q_1 q_2 q_3}^{S,XY}]_{pqrs}$ [79, 92]	Upper Bound (TeV)	$\langle X^0 \rangle$ (TeV)
Ξ_1	$(1, 3, 1)_S$	$\mu \Xi_1^\dagger H H + c_{pq[rs]} \Xi_1 (Q_p L_q) (\bar{d}_r^\dagger \bar{d}_s^\dagger)$	$[L_{ddu}^{S,RL}]_{pqrs} = c_{rs[pq]} \frac{1}{\Lambda^3} \left(\mu \frac{v^2}{M^2} \right)$	$5 \cdot 10^5$	$6 \cdot 10^{-8}$
Ξ	$(1, 3, 0)_S$	$\mu \Xi H^\dagger H + c_{pq[rs]} \Xi_{ij} (L_{pk}^\dagger \bar{d}_q^\dagger) (Q_r^i Q_s^j) H_l^\dagger \epsilon^{kl}$	$[L_{udd}^{S,LR}]_{pqrs} = c_{rs[pq]} \frac{v}{\Lambda^4} \left(\mu \frac{v^2}{M^2} \right)$	10^5	$3 \cdot 10^{-7}$
Θ_3	$(1, 4, 3/2)_S$	$y \Theta_3 H^\dagger H^\dagger H^\dagger + c_{[pq]rs} \Theta_3^\dagger (Q_p Q_q) (L_r^\dagger \bar{u}_s^\dagger)$	$[L_{ddu}^{S,LR}]_{pqrs} = c_{[pq]rs} \frac{1}{\Lambda^3} \left(y \frac{v^3}{M^2} \right)$	$5 \cdot 10^4$	$2 \cdot 10^{-8}$
Θ_1	$(1, 4, 1/2)_S$	$y \Theta_1 H^\dagger H H^\dagger + c_{pq[rs]} \Theta_1^\dagger (L_p^\dagger \bar{d}_q^\dagger) (Q_r Q_s)$	$[L_{udd}^{S,LR}]_{pqrs} = c_{rs[pq]} \frac{1}{\Lambda^3} \left(y \frac{v^3}{M^2} \right)$	$5 \cdot 10^4$	$2 \cdot 10^{-8}$

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 $p \rightarrow K^+ \nu$ decay channel, from which the limit quoted in the sixth column is obtained.

Tables for scalars in $\Delta L = 2$

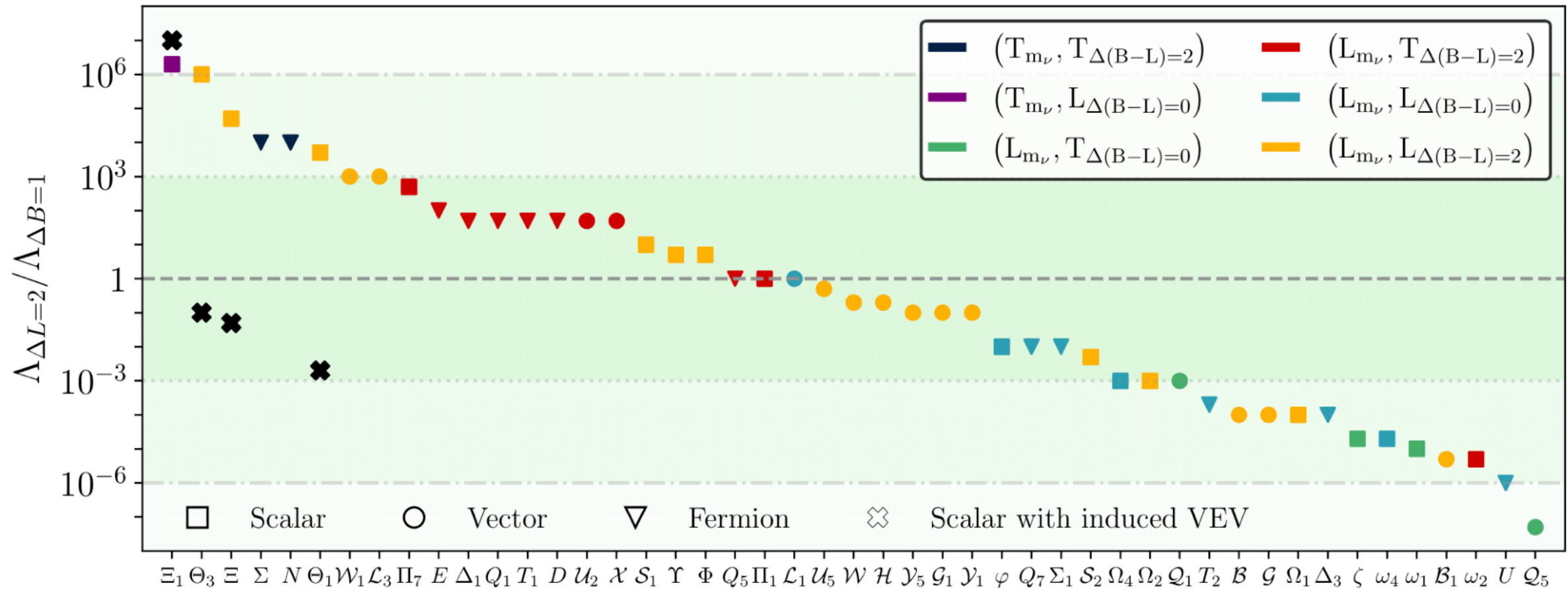
LSME	G_{SM}	$\mathcal{L}_{\Delta L=2}$	Δd	Op.	$[m_\nu]_{pq}$	Upper Bound (TeV)
Ξ_1	$(1, 3, 1)_S$	$y_{\{pq\}} \Xi_1(L_p L_q) + \mu \Xi_1^\dagger H H$	-2	$\mathcal{O}_1$	$y_{\{pq\}} \frac{\mu}{M} \frac{v^2}{M}$	10^{12}
Ξ	$(1, 3, 0)_S$	$\mu \Xi H^\dagger H + c_{\{pq\}} \Xi^{\{ij\}} (L_p^k L_q^l) H^m H^n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

Tables for scalars in $\Delta B = 1$

LSME	G_{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	$\mathcal{O}_2^{1111}$	$C_{qqe}^{pqrs} = y_{rs}c_{pq}\frac{1}{M^2}$	$p \rightarrow \pi^0 e^+$	10^{13}
ζ	$(3, 3, -1/3)_S$	$y_{pq}\zeta^\dagger(Q_pL_q) + c_{[rs]}\zeta(Q_rQ_s)$	-2	$\mathcal{O}_1^{1112}$	$C_{qqql}^{pqrs} = y_{rs}c_{[pq]}\frac{1}{M^2}$	$p \rightarrow K^+\nu$	$5 \cdot 10^{12}$
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	$\mathcal{O}_{\Omega_4}^{111313}$	$C_{qqe}^{pqrs} = y_{rw}c_{swpq}[y_u]_w\frac{1}{\Lambda^2}\epsilon^2$	$p \rightarrow \pi^0 e^+$	$5 \cdot 10^{10}$
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	$\mathcal{O}_\varphi^{131131}$	$C_{qqql}^{pqrs} = y_{ws}c_{sq[vw]}[y_d]_vV_{vp}^*\frac{1}{\Lambda^2}\epsilon^2$	$p \rightarrow K^+\nu$	$5 \cdot 10^9$
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	$\mathcal{O}_3^{1131}$	$C_{qqe}^{pqrs} = y_{sw}c_{[rq]}[y_u]_q[y_d]_wV_{wp}^*\frac{1}{M^2}L'$	$p \rightarrow \pi^0 e^+$	$5 \cdot 10^8$
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	$\mathcal{O}_8^{1112}$	$C_{ldqq\bar{H}}^{pqrs} = y_{pq}c_{rs}\frac{1}{M^2\Lambda}$	$p \rightarrow K^+\nu$	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	$\mathcal{O}_{10}^{1112}$	$C_{ldud\bar{H}}^{pqrs} = y_{pr}c_{[qs]}\frac{1}{M^2\Lambda}$	$p \rightarrow K^+\nu$	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	$\mathcal{O}_{10}^{1112}$	$C_{ldud\bar{H}}^{pqrs} = y_{[qs]}c_{pr}\frac{1}{M^2\Lambda}$	$p \rightarrow K^+\nu$	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	$\mathcal{O}_{40}^{113132}$	$C_{ldqq\bar{H}}^{pqrs} = y_{\{ws\}}c_{rwpq}[y_u]_w\frac{1}{\Lambda^3}L$	$p \rightarrow K^+\nu$	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	$\mathcal{O}_{40}^{111332}$	$C_{ldqq\bar{H}}^{pqrs} = y_{sw}c_{wrpq}[y_u]_w\frac{1}{\Lambda^3}L$	$p \rightarrow K^+\nu$	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	$\mathcal{O}_{50}^{131321}$	$C_{ldud\bar{H}}^{pqrs} = y_{qs}c_{wvpr}[y_u]_w\frac{1}{\Lambda^3}L$	$p \rightarrow K^+\nu$	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	$\mathcal{O}_{45}^{1131}$	$C_{ldqq\bar{H}}^{pqrs} = c_{pq[rs]}[y_u]_s[y_u]_s\frac{\mu}{\Lambda}\frac{1}{\Lambda^3}L^2$	$n \rightarrow K^+e^-$	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	$\mathcal{O}_{16}^{1132}$	$C_{qqql}^{pqrs} = c_{qs[vw]}[y_d]_v[y_d]_wV_{vp}^*V_{wr}^*\frac{\mu}{\Lambda}\frac{1}{\Lambda^2}L^2$	$p \rightarrow K^+\nu$	$5 \cdot 10^5$
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	$\mathcal{O}_{37}^{1123}$	$C_{ldqq\bar{H}}^{pqrs} = y c_{[rs]pw}[y_u]_w[y_d]_wV_{wq}\frac{1}{\Lambda^3}L^2$	$p \rightarrow K^+\nu$	$5 \cdot 10^4$
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	$\mathcal{O}_{45}^{1213}$	$C_{ldqq\bar{H}}^{pqrs} = y c_{pw[vr]}[y_d]_v[y_d]_wV_{ws}^*V_{vq}\frac{1}{\Lambda^3}L^2$	$p \rightarrow K^+\nu$	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	$\mathcal{O}_{40}^{113132}$	$C_{ldqq\bar{H}}^{pqrs} = y_{[wr]}c_{pqsw}[y_u]_w\frac{1}{\Lambda^3}L$	$p \rightarrow K^+\nu$	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	$\mathcal{O}_{28}^{133121}$	$C_{ldud\bar{H}}^{pqrs} = y_{[pw]}c_{wrqs}[y_e]_w\frac{1}{\Lambda^3}L$	$p \rightarrow K^+\nu$	$5 \cdot 10^6$
$\mathcal{S}_2$	$(1, 1, 2)_S$	$y_{\{pq\}}\mathcal{S}_2^\dagger(\bar{e}_p\bar{e}_q) + c_{rs[tu]}\mathcal{S}_2(\bar{e}_r^\dagger\bar{d}_s^\dagger)(\bar{d}_t^\dagger\bar{d}_u^\dagger)$	0	$\mathcal{O}_{25}^{133112}$	$C_{\bar{e}ddd}^{pqrs} = y_{\{pw\}}c_{wqrs}\frac{1}{\Lambda^3}L$	$n \rightarrow K^+e^-$	10^6

Alignment limit

- Degree of **fine-tuning** required for the dimensionless WCs associated with either $\Delta L = 2$ and $\Delta B = 1$ operators to **account for all observed phenomena** within the same UV framework.



$$\Lambda_{\Delta L=2} \gg \Lambda_{\Delta B=1} \implies c_{\Delta L=2} \ll c_{\Delta B=1}$$

$$\Lambda_{\Delta B=1} \gg \Lambda_{\Delta L=2} \implies c_{\Delta B=1} \ll c_{\Delta L=2}$$

Or through another (more-suppressed) mechanism

$M < \Lambda$ regime

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

$M < \Lambda$ regime

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

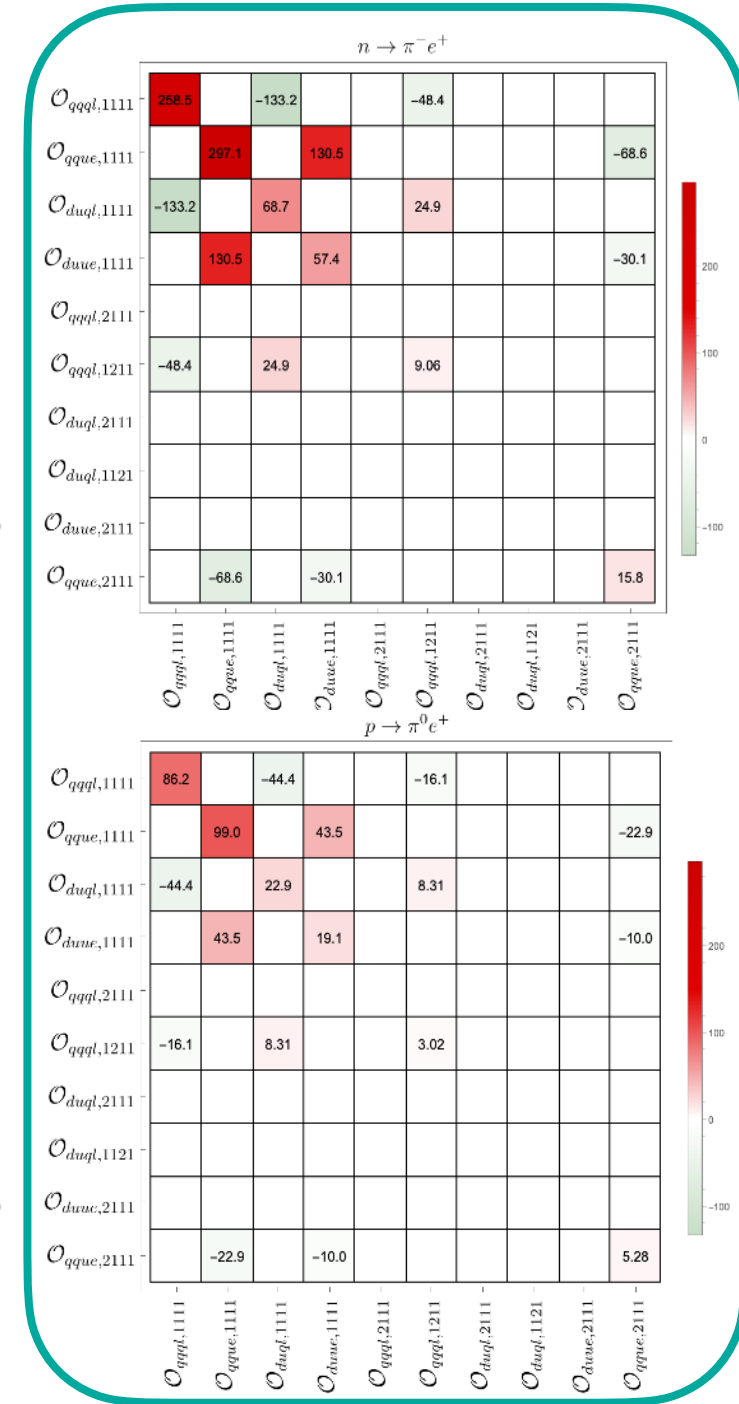
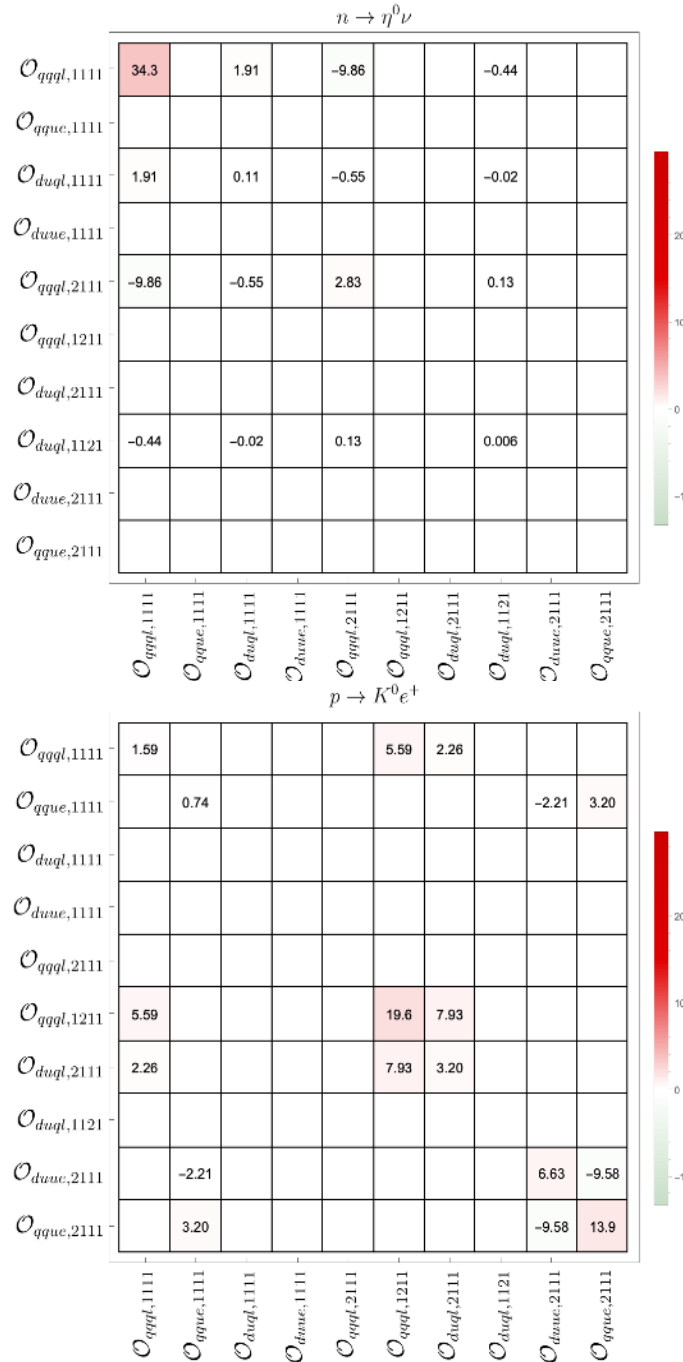
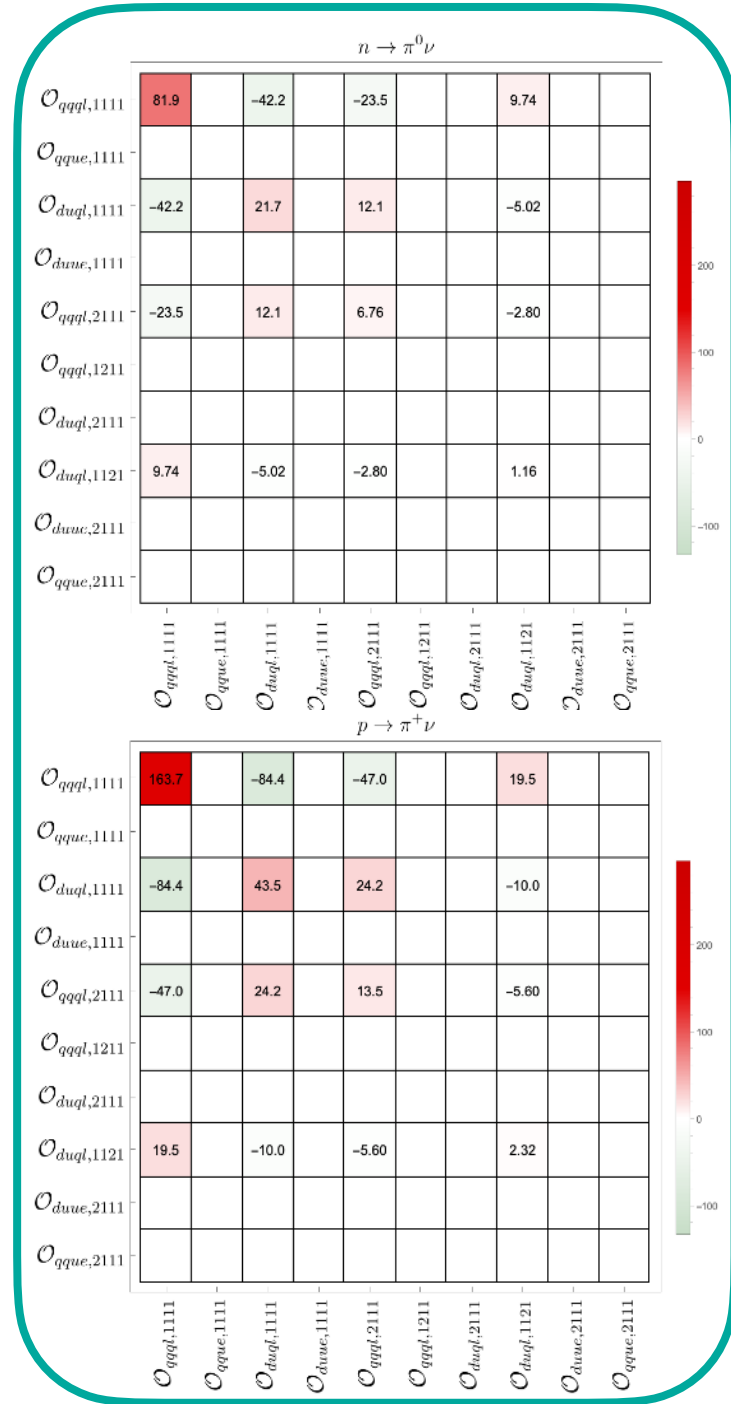
Phenomenological matrices for $\Delta(B - L) = 2$ proton decay

$$\Gamma_{(i)}^{\Delta(B-L)=0} \equiv 10^{-4} c_j^* \kappa_{(i)}^{jk} c_k \frac{m_p^5}{\Lambda^4} \quad \text{for} \quad i = p \rightarrow \pi^0 e^+, p \rightarrow K^+ \nu \dots \quad (9 \text{ matrices}) \quad [A. Bas i Beneito et al. 2023]$$

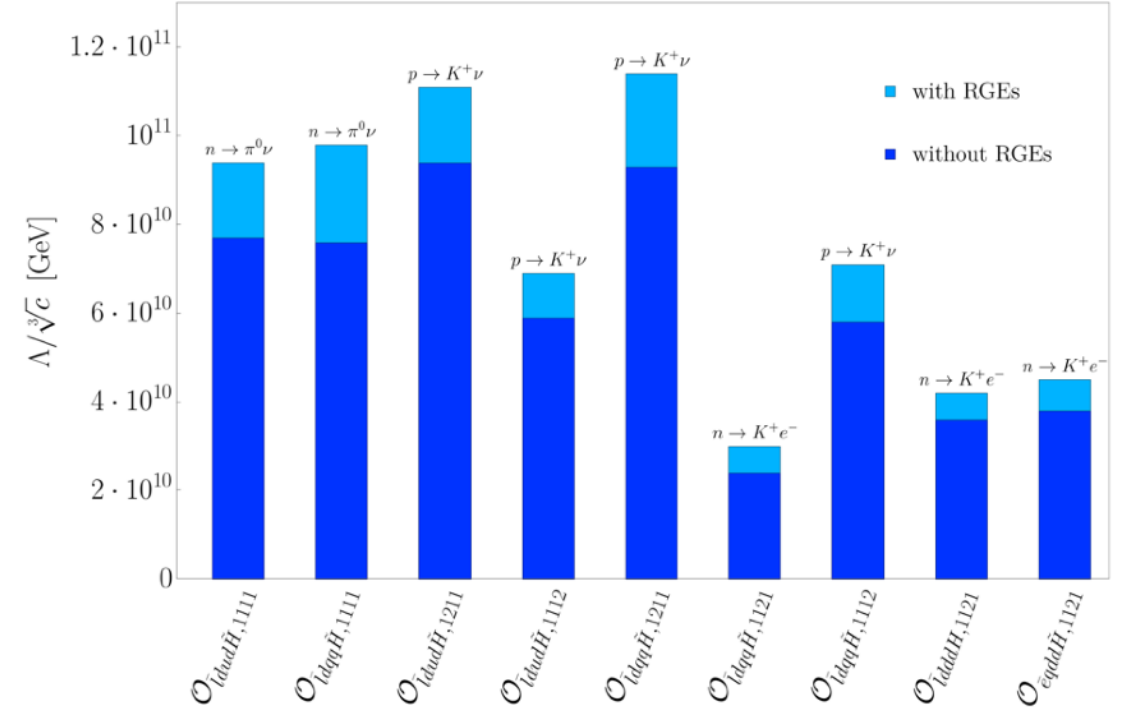
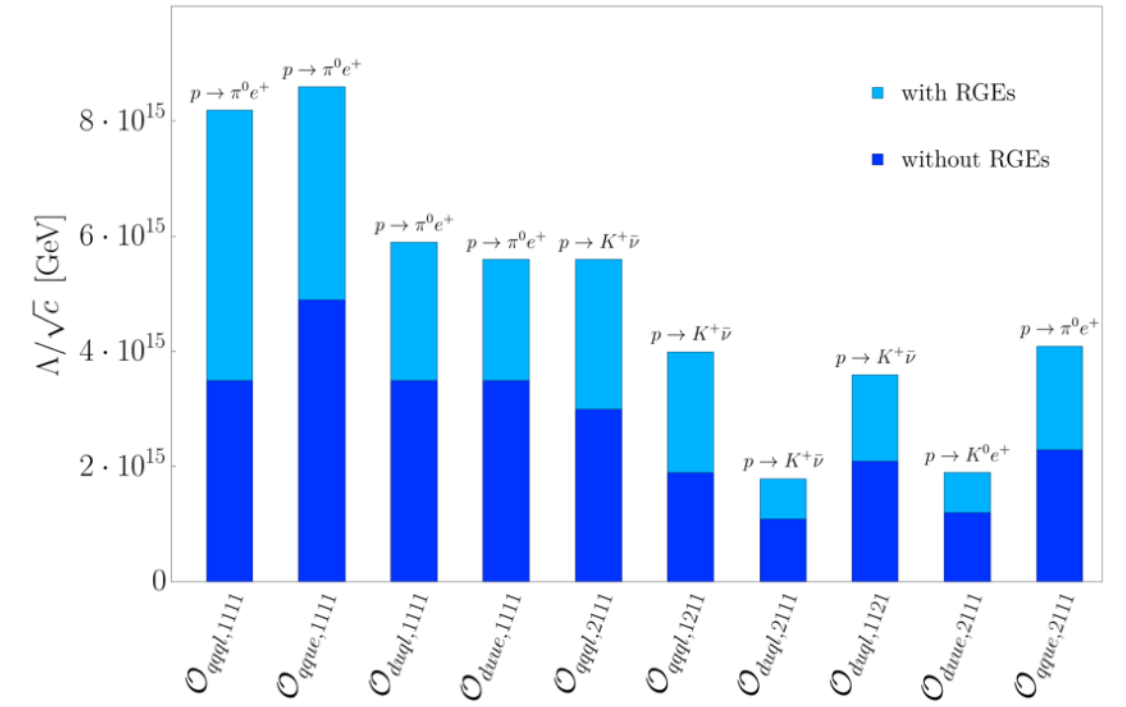
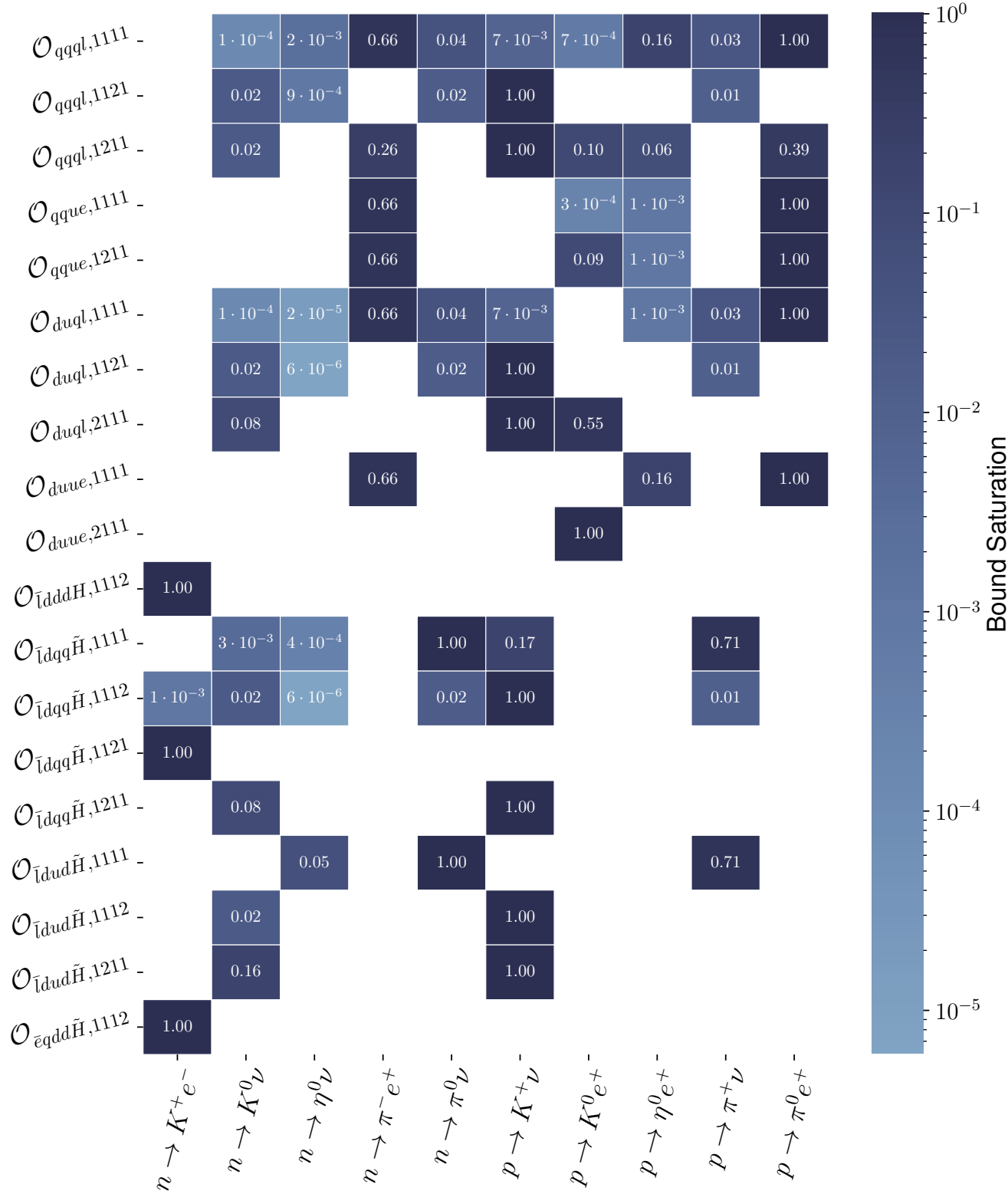
$$\Gamma_{(i)}^{|\Delta(B-L)|=2} \equiv c_j^* \kappa_{(i)}^{jk} c_k \frac{m_p^7}{\Lambda^6} \quad \text{for} \quad i = p \rightarrow K^+ \nu, n \rightarrow K^+ e^- \dots \quad (6 \text{ matrices})$$

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

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



Correlations & tree-level bounds on proton decay



[A. Bas i Beneito et al. 2023]

Matching onto B χ PT

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

$$\xi B \xi \rightarrow L \xi B \xi R^\dagger$$

$$\xi^\dagger B \xi^\dagger \rightarrow R \xi^\dagger B \xi^\dagger L^\dagger$$

$$\xi B \xi^\dagger \rightarrow L \xi B \xi^\dagger L^\dagger$$

$$\xi^\dagger B \xi \rightarrow R \xi^\dagger B \xi R^\dagger$$

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

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

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

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

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

BNV Nucleon decay channels

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

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