

CHARLES
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Cartography of lepton-number violation in the SMEFT: Implications for $0\nu\beta\beta$ and radiative neutrino masses

based on
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Lepton number violation (LNV)

- Lepton number $L = n_l - n_{\bar{l}}$ is conserved in the SM
- an observation of LNV processes would be evidence for BSM physics
- processes with $\Delta L = 2$ could e.g. be observed in $0\nu\beta\beta$, cLFV processes, neutrino masses
- how can we describe them in the SMEFT picture? At which operator dimension and loop order?

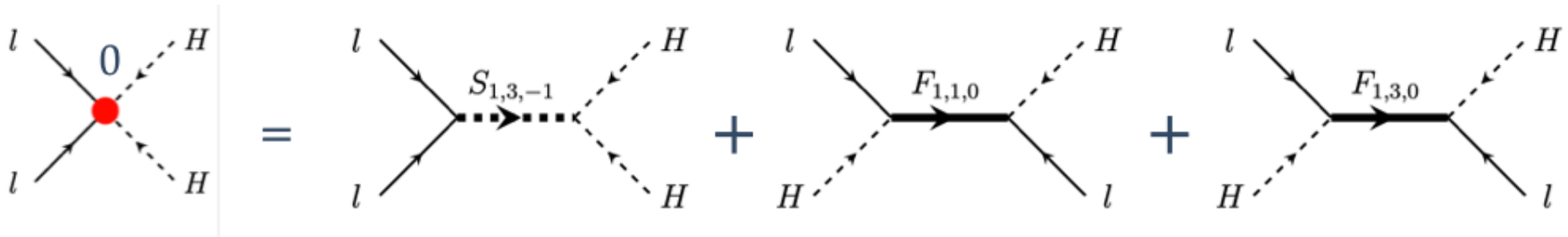
Lepton number violation in the SMEFT

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + c_5\mathcal{O}_5 + \sum_i c_{6i}\mathcal{O}_{6i} + \sum_i c_{7i}\mathcal{O}_{7i} + \sum_i c_{8i}\mathcal{O}_{8i} + \sum_i c_{9i}\mathcal{O}_{9i} + \dots$$

lepton number violation, neutrino masses, $0\nu\beta\beta$ decay, …

- $\Delta L = 2$ operators appear at odd dimensions in the SMEFT.
- What is the relative importance and the interplay of these operators in neutrino masses, $0\nu\beta\beta$ and cLFV?
- Can we make general statements or does this depend on the UV model?

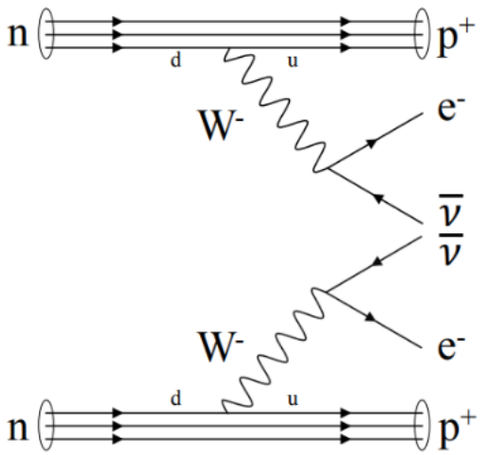
LNV could explain tiny neutrino masses trough the Weinberg operator $\mathcal{O}^{(5)}_{LH}$
which could be realised at tree level via seesaw models



Neutrinoless double beta decay ($0\nu\beta\beta$)

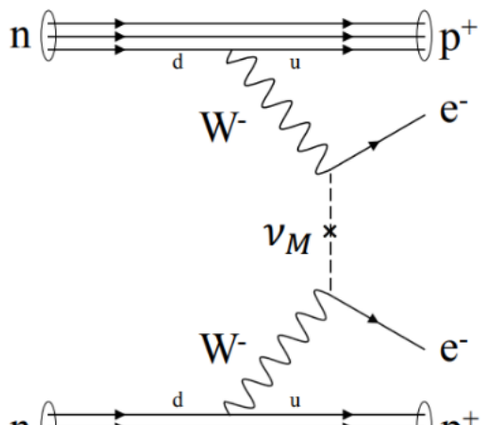
$2\nu\beta\beta$:

$nn \to ppee\bar{\nu}\bar{\nu}$



$0\nu\beta\beta$:

$nn \to ppee$

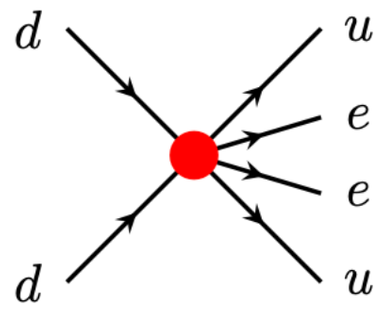


standard mechanism for $0\nu\beta\beta$

Exchange of a light Majorana neutrino, proportional to the (dim-5) mass term

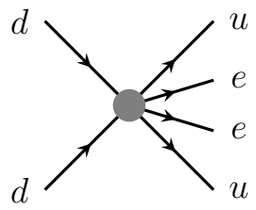
In SMEFT, contact operators with $\Delta L = 2$ can generate $0\nu\beta\beta$ at tree-level, e.g. $\mathcal{O}^{(9)}_{ddueue}$

$\mathcal{O}^{(9)}_{ddueue}$

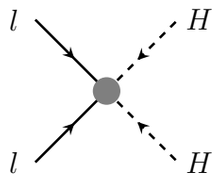


Operator basis for $0\nu\beta\beta$

[O. Scholer, J. de Vries, L. Gráf, '23]



$\mathcal{O}^{(9)}_{ddueue}$



Weinberg operator

Dim 5

Ψ^2H^2	$\mathcal{O}^{(5)}_{LH}$	LH(5)	$\epsilon_{ij}\epsilon_{kl}\left[\overline{L_i^C}L_k\right]\left[H_jH_n\right]$

Dim 7

Ψ^2H^4	$\mathcal{O}^{(7)}_{LH}$	LH(7)	$\epsilon_{ij}\epsilon_{kl}\left[\overline{L_i^C}L_k\right]\left[H_jH_n\right]\left[H^\dagger H\right]$
Ψ^2H^3D	$\mathcal{O}^{(7)}_{LHDe}$	LHDe(7)	$\epsilon_{ij}\epsilon_{kl}\left[\overline{L_i^C}\gamma^\mu e\right]\left[H_jH_k\right]\left[D_\mu H\right]_l$
$\Psi^2H^2D^2$	$\mathcal{O}^{(7)}_{LHD1}$	LHD1(7)	$\epsilon_{ij}\epsilon_{kl}\left[\overline{L_i^C}\left(D_\mu L\right)_j\right]\left[H_k\left(D_\mu H\right)_l\right]$
	$\mathcal{O}^{(7)}_{LHD2}$	LHD2(7)	$\epsilon_{ik}\epsilon_{jl}\left[\overline{L_i^C}\left(D_\mu L\right)_j\right]\left[H_k\left(D_\mu H\right)_l\right]$
Ψ^2H^2W	$\mathcal{O}^{(7)}_{LHW}$	LHW(7)	$\epsilon_{ij}\epsilon_{km}\tau^I_{ml}g_2\left[\overline{L_i^C}\sigma^{\mu\nu}L_k\right]\left[H_jH_l\right]W^I_{\mu\nu}$
Ψ^4D	$\mathcal{O}^{(7)}_{LLduD1}$	LLduD1(7)	$\epsilon_{ij}\left[\bar{d}\gamma^\mu u\right]\left[\overline{L_i^C}\left(D_\mu L\right)_j\right]$
Ψ^4H	$\mathcal{O}^{(7)}_{LLQdH1}$	LLQdH1(7)	$\epsilon_{ik}\epsilon_{jl}\left[\bar{d}L_i\right]\left[\overline{Q^C}_jL_k\right]H_l$
	$\mathcal{O}^{(7)}_{LLQdH2}$	LLQdH2(7)	$\epsilon_{ij}\epsilon_{kl}\left[\bar{d}L_i\right]\left[\overline{Q^C}_jL_k\right]H_l$
	$\mathcal{O}^{(7)}_{LLQuH}$	LLQuH(7)	$\epsilon_{ij}\left[\bar{Q}_ku\right]\left[\overline{L^C}_kL_i\right]H_j$
	$\mathcal{O}^{(7)}_{LeudH}$	LeudH(7)	$\epsilon_{ij}\left[\overline{L^C}_i\gamma^\mu e\right]\left[\bar{d}\gamma_\mu u\right]H_j$

Dim 9

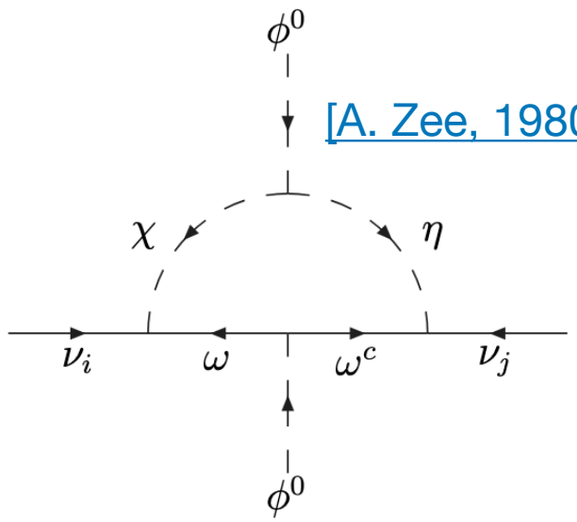
	$\mathcal{O}^{(9)}_{ddueue}$	ddueue(9)	$\left[\bar{d}^\alpha d^{C\beta}\right]\left[\overline{u^{C\alpha}}e\right]\left[\overline{u^{C\beta}}e\right]$
Ψ^6	$\mathcal{O}^{(9)}_{dQdueL1}$	dQdueL1(9)	$\epsilon_{ij}\left[\bar{d}Q_i\right]\left[\bar{d}\gamma^\mu u\right]\left[\overline{e^C}\gamma_\mu L_j\right]$
	$\mathcal{O}^{(9)}_{dQdueL2}$	dQdueL2(9)	$\epsilon_{ij}\left[\bar{d}^\alpha Q_i^\beta\right]\left[\bar{d}^\beta\gamma^\mu u^\alpha\right]\left[\overline{e^C}\gamma_\mu L_j\right]$
	$\mathcal{O}^{(9)}_{QdueL1}$	QdueL1(9)	$\left[\bar{Q}u\right]\left[\bar{d}\gamma^\mu u\right]\left[\overline{e^C}\gamma_\mu L_j\right]$
	$\mathcal{O}^{(9)}_{QdueL2}$	QdueL2(9)	$\left[\bar{Q}^\alpha u^\beta\right]\left[\bar{d}^\beta\gamma^\mu u^\alpha\right]\left[\overline{e^C}\gamma_\mu L_j\right]$
	$\mathcal{O}^{(9)}_{dQdQLL1}$	dQdQLL1(9)	$\epsilon_{ik}\epsilon_{jl}\left[\bar{d}Q_i\right]\left[\bar{d}\gamma^\mu Q_j\right]\left[\overline{L_k^C}\gamma_\mu L_l\right]$
	$\mathcal{O}^{(9)}_{dQdQLL2}$	dQdQLL2(9)	$\epsilon_{ik}\epsilon_{jl}\left[\bar{d}^\alpha Q_i^\beta\right]\left[\bar{d}^\beta\gamma^\mu Q_j^\alpha\right]\left[\overline{L_k^C}\gamma_\mu L_l\right]$
	$\mathcal{O}^{(9)}_{dQQuLL1}$	dQQuLL1(9)	$\epsilon_{ij}\left[\bar{d}Q_i\right]\left[\bar{Q}u\right]\left[\overline{L^C}L_j\right]$
	$\mathcal{O}^{(9)}_{dQQuLL2}$	dQQuLL2(9)	$\epsilon_{ij}\left[\bar{d}^\alpha Q_i^\beta\right]\left[\bar{Q}^\beta u^\alpha\right]\left[\overline{L^C}L_j\right]$
	$\mathcal{O}^{(9)}_{QuQuLL1}$	QuQuLL1(9)	$\left[\bar{Q}_iu\right]\left[\bar{Q}_ju\right]\left[\overline{L_i^C}L_j\right]$
	$\mathcal{O}^{(9)}_{QuQuLL2}$	QuQuLL2(9)	$\left[\bar{Q}_i^\alpha u^\beta\right]\left[\bar{Q}_j^\beta u^\alpha\right]\left[\overline{L_i^C}L_j\right]$
Ψ^2H^4W	$\mathcal{O}^{(9)}_{LLH^4W1}$	LLH4W1(9)	$\epsilon_{ij}\epsilon_{km}\tau^I_{ml}g_2\left[\overline{L_i^C}\sigma^{\mu\nu}L_k\right]\left[H_jH_l\right]W^I_{\mu\nu}\left[H^\dagger H\right]$
$D^2\Psi^2H^4$	$\mathcal{O}^{(9)}_{eeH^4D^2}$	eeH4D2(9)	$\epsilon_{ij}\epsilon_{kl}\left[\overline{e^C}e\right]\left[H_i\left(D_\mu H\right)_j\right]\left[H_k\left(D^\mu H\right)_l\right]$
	$\mathcal{O}^{(9)}_{LLH^4D^23}$	LLH4D23(9)	$\epsilon_{ik}\epsilon_{jl}\left[\left(D_\mu L^C\right)_i\left(D^\mu L\right)_j\right]\left[H_kH_l\right]\left[H^\dagger H\right]$
	$\mathcal{O}^{(9)}_{LLH^4D^24}$	LLH4D24(9)	$\epsilon_{ik}\epsilon_{jl}\left[\overline{L^C}_i\left(D^\mu L\right)_j\right]\left[\left(D_\mu H\right)_kH_l\right]\left[H^\dagger H\right]$
$D\Psi^4H^2$	$\mathcal{O}^{(9)}_{deueH^2D}$	deueH2D(9)	$\epsilon_{ij}\left[\bar{d}\gamma^\mu e\right]\left[\overline{u^C}e\right]\left[H_i\left(iD_\mu H\right)_j\right]$
	$\mathcal{O}^{(9)}_{dQLeH^2D2}$	dQLeH2D2(9)	$\epsilon_{ik}\epsilon_{jl}\left[\bar{d}Q_i\right]\left[\overline{L_j^C}\gamma^\mu e\right]\left[H_k\left(iD_\mu H\right)_l\right]$
	$\mathcal{O}^{(9)}_{dLQeH^2D1}$	dLQeH2D1(9)	$\epsilon_{ik}\epsilon_{jl}\left[\bar{d}L_i\right]\left[\overline{Q_j^C}\gamma^\mu e\right]\left[\left(iD_\mu H\right)_kH_l\right]$
	$\mathcal{O}^{(9)}_{dLuLH^2D2}$	dLuLH2D2(9)	$\epsilon_{ik}\epsilon_{jl}\left[\bar{d}L_i\right]\left[\overline{u^C}\gamma_\mu L_j\right]\left[\tilde{H}_k\left(iD^\mu H\right)_l\right]$
	$\mathcal{O}^{(9)}_{duLLH^2D}$	duLLH2D(9)	$\epsilon_{ik}\epsilon_{jl}\left[\bar{d}\gamma_\mu u\right]\left[\overline{L^C}_i\left(iD^\mu L\right)_j\right]\left[\tilde{H}_kH_l\right]$
	$\mathcal{O}^{(9)}_{deQLH^2D}$	deQLH2D(9)	$\epsilon_{ik}\epsilon_{jl}\left[\bar{d}\gamma^\mu e\right]\left[\overline{Q_i^C}\left(iD_\mu L\right)_j\right]\left[H_kH_l\right]$
	$\mathcal{O}^{(9)}_{QueLH^2D2}$	QueLH2D2(9)	$\epsilon_{jk}\left[\bar{Q}_iu\right]\left[\overline{u^C}\gamma^\mu L_j\right]\left[H_i\left(iD_\mu H\right)_k\right]$
	$\mathcal{O}^{(9)}_{QeuLH^2D2}$	QeuLH2D2(9)	$\delta_{ik}\epsilon_{jl}\left[\bar{Q}_ie\right]\left[\overline{u^C}\gamma^\mu L_j\right]\left[H_k\left(iD_\mu H\right)_l\right]$
	$\mathcal{O}^{(9)}_{QLQLH^2D2}$	QLQLH2D2(9)	$\epsilon_{ik}\epsilon_{jl}\left[\bar{Q}\gamma^\mu L\right]\left[\overline{Q_i^C}\gamma^\mu L_j\right]\left[H_k\left(iD_\mu H\right)_l\right]$
	$\mathcal{O}^{(9)}_{QLQLH^2D5}$	QLQLH2D5(9)	$\epsilon_{ik}\epsilon_{jl}\left[\bar{Q}\gamma^\mu L_i\right]\left[\overline{Q_j^C}\gamma^\mu L\right]\left[\left(iD_\mu H\right)_kH_l\right]$
	$\mathcal{O}^{(9)}_{QQLLH^2D2}$	QQLLH2D2(9)	$\epsilon_{ik}\epsilon_{jl}\left[\bar{Q}\gamma^\mu Q_i\right]\left[\overline{L^C}\left(iD_\mu L\right)_j\right]\left[H_kH_l\right]$

$0\nu\beta\beta$ singles out the couplings to first generation leptons and quarks!

Radiative neutrino masses

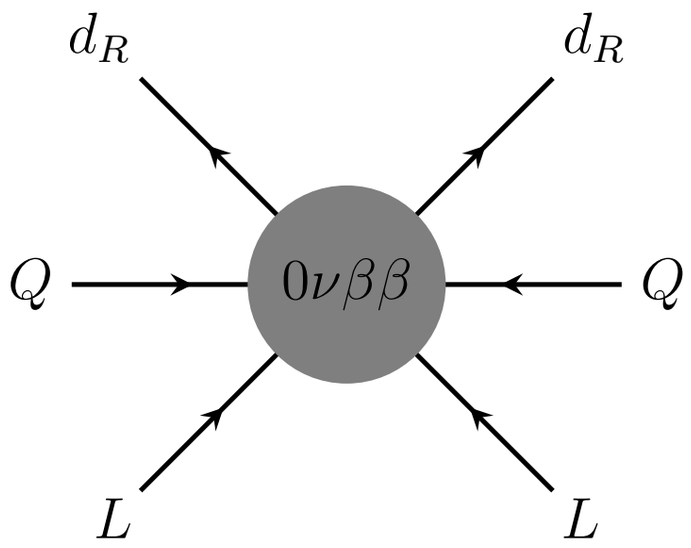
- Weinberg operator and neutrino masses do not have to be realised at tree-level, could be via loop effects
- ***Blackbox theorem***: A model that generates $0\nu\beta\beta$ at tree level will give a Majorana neutrino mass for at least one SM neutrino at maximally 4-loop

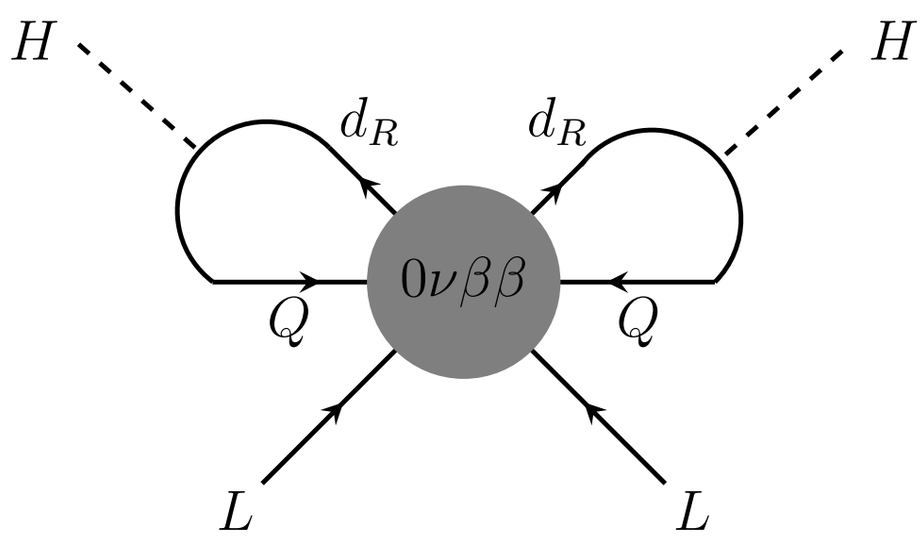
[Schechter, Valle 1981]



[A. Zee, 1980]

Models for 6-fermion operators with **two lepton doublets** will give neutrino masses at **maximally 2-loop**





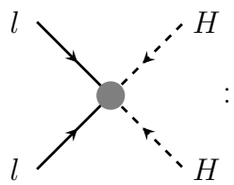
Tree-level dim-9 vs. higher loop Weinberg?

- The loop suppression of dim-5 Weinberg operator will compete with the scale suppression of the higher orders.
  Which contribution will dominate $0\nu\beta\beta$??

$$\mathcal{L}_{SMEFT} \sim \frac{1}{16\pi^2\Lambda}\mathcal{O}^{(5)}_{LH} + \frac{1}{\Lambda^3}\mathcal{O}^{(7)} + \frac{1}{\Lambda^5}\mathcal{O}^{(9)} + \dots$$

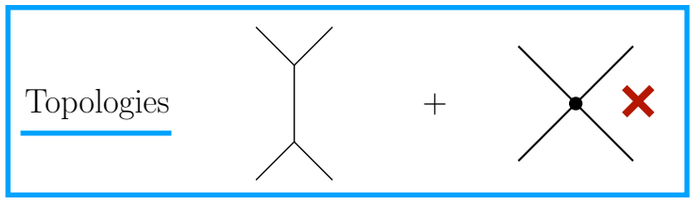
- For a specific model, this estimate will depend on the couplings, mass ratios, flavour assumptions …
- We are interested in models that can simultaneously give (dim-9 induced) observable $0\nu\beta\beta$, correct neutrino masses and evades constraints from charged lepton flavour violating (cLFV) probes
- Scan over all models that open $\Delta L = 2$ dim-9 operators at tree level, using a diagrammatic approach, exclude models that generate dim-7 and dim-5 at tree-level
- Focus on minimal models with 2 BSM particles and no vectors

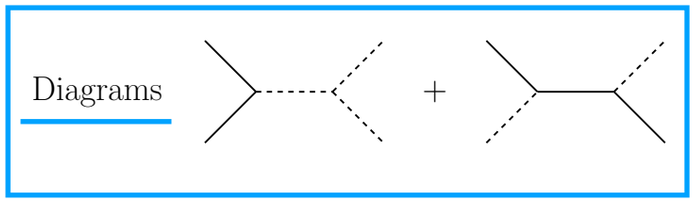
Diagrammatic approach - From operators to models



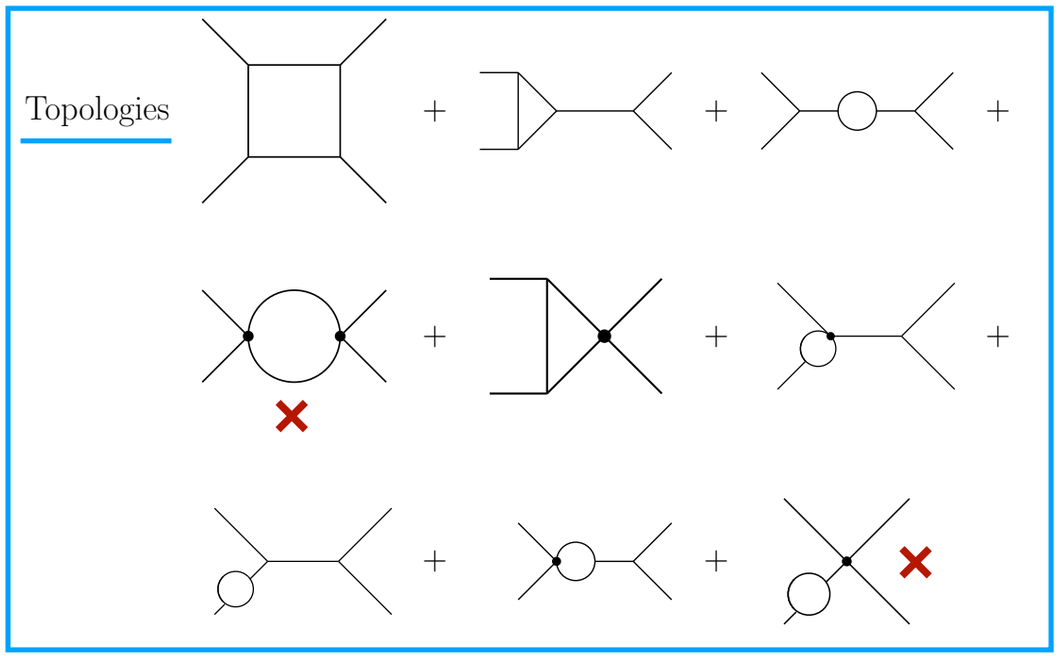
Weinberg operators

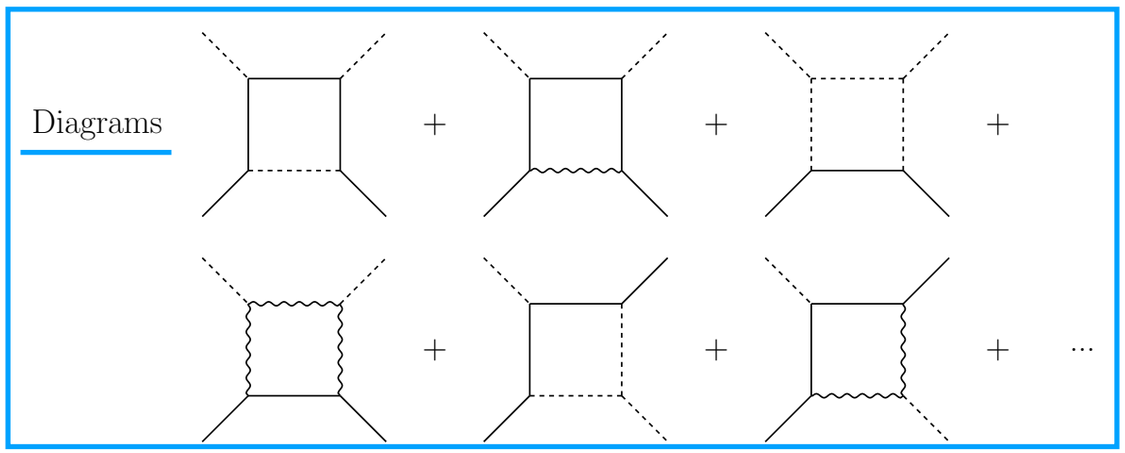
(i) Tree level:





(ii) 1-loop:





[Cepedello, Fonseca, Hirsch '19]
[Cepedello, FE, Hirsch, Sanz '22]
[Cepedello, FE, Hirsch, Sanz '23]
[Cepedello, FE, Hirsch, Sanz '24]

✗ non-renormalisable vertex

1.) For any given operator, one can first find all ***topologies with n external legs and k loops***

→ ***Topologies***

2.) Insert ***fermions, scalars and vectors*** *in all possible ways allowed by Lorentz invariance. Keep only renormalisable interactions*

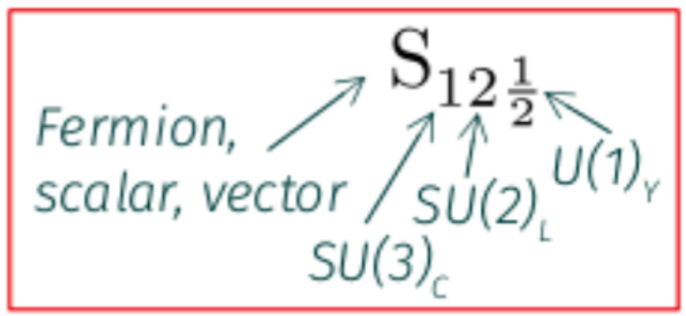
→ ***Diagrams***

Diagrammatic approach - From operators to models

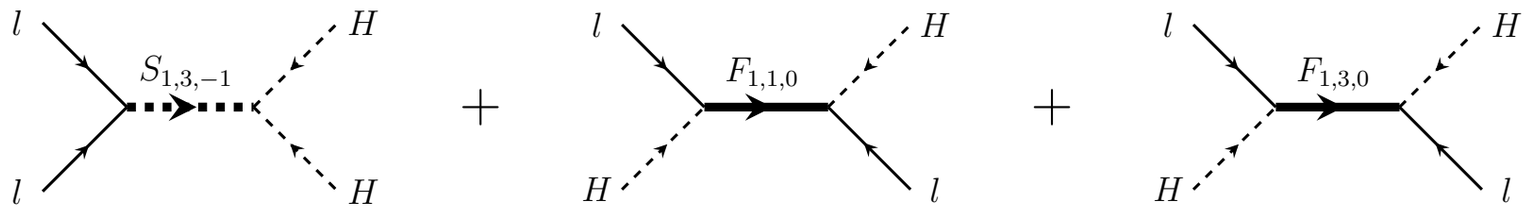
*3.) Insert **all possible representations** for fermions, scalars and vectors (i.e. specific particles)*

→ ***Model diagrams***

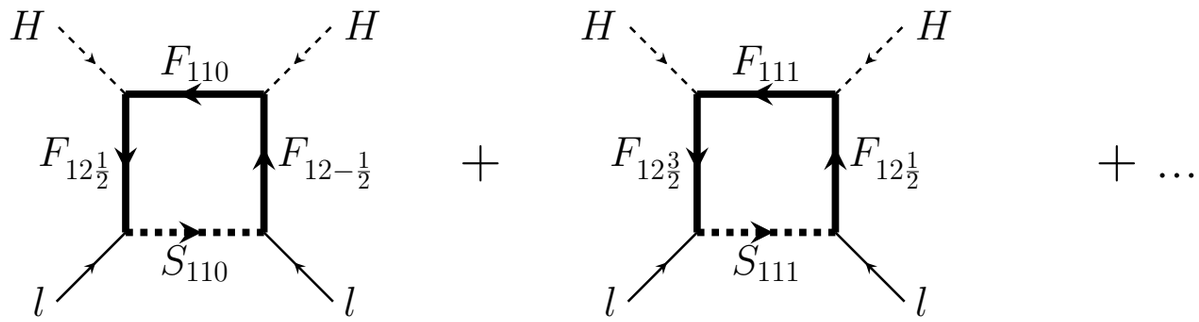
Notation:



Model diagrams: (i) Tree level:



(ii) 1-loop level:



1L Weinberg: dim-5 contributions to $0\nu\beta\beta$ will dominate

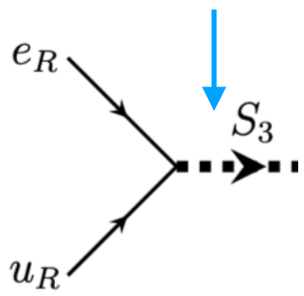
Minimal models

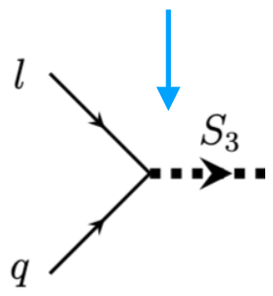
#	Model	dim-9 tree level	dim-7 1L	dim-5	type
M1	$(S_{8,2,\frac{1}{2}}, F_{8,1,0})$	$\mathcal{O}^{(9)}_{dQdQLL}$, $\mathcal{O}^{(9)}_{dQQuLL}$, $\mathcal{O}^{(9)}_{QuQuLL}$	$\mathcal{O}^{(7)}_{LH}$, $\mathcal{O}^{(7)}_{LHD}$, $\mathcal{O}^{(7)}_{LLduD}$, $\mathcal{O}^{(7)}_{LLQdH}$, $\mathcal{O}^{(7)}_{LLQuH}$	1L	T3
M2	$(S_{8,2,\frac{1}{2}}, F_{8,3,0})$	$\mathcal{O}^{(9)}_{dQdQLL}$, $\mathcal{O}^{(9)}_{dQQuLL}$, $\mathcal{O}^{(9)}_{QuQuLL}$	$\mathcal{O}^{(7)}_{LH}$, $\mathcal{O}^{(7)}_{LHD}$, $\mathcal{O}^{(7)}_{LLduD}$, $\mathcal{O}^{(7)}_{LLQdH}$, $\mathcal{O}^{(7)}_{LLQuH}$	1L	T3
M3	$(S_{1,1,1}, S_{1,3,0})$	$\mathcal{O}^{(9)}_{LLH^4(D/W)^2}$	$\mathcal{O}^{(7)}_{LHD}$	2L, anti	CLBZ-10
M4	$(S_{1,1,1}, S_{8,2,\frac{1}{2}})$	$\mathcal{O}^{(9)}_{dQdQLL}$, $\mathcal{O}^{(9)}_{dQQuLL}$, $\mathcal{O}^{(9)}_{QuQuLL}$	$\mathcal{O}^{(7)}_{LLduD}$, $\mathcal{O}^{(7)}_{LLQdH}$, $\mathcal{O}^{(7)}_{LLQuH}$	2L, anti	NG
M5	$(S_{3,1,-\frac{1}{3}}, S_{3,1,\frac{2}{3}})$	$\mathcal{O}^{(9)}_{ddueue}$, $\mathcal{O}^{(9)}_{dQdueL}$, $\mathcal{O}^{(9)}_{dQdQLL}$	$\mathcal{O}^{(7)}_{LLQdH}$, $\mathcal{O}^{(7)}_{LeudH}$	2L, anti	CLBZ-1
M6	$(S_{3,1,-\frac{1}{3}}, S_{6,1,-\frac{2}{3}})$	$\mathcal{O}^{(9)}_{ddueue}$, $\mathcal{O}^{(9)}_{dQdueL}$, $\mathcal{O}^{(9)}_{dQdQLL}$	$\mathcal{O}^{(7)}_{LLQdH}$, $\mathcal{O}^{(7)}_{LeudH}$	2L, sym	CLBZ-1
M7	$(S_{3,3,-\frac{1}{3}}, S_{3,1,\frac{2}{3}})$	$\mathcal{O}^{(9)}_{dQdQLL}$	$\mathcal{O}^{(7)}_{LLQdH}$, $\mathcal{O}^{(7)}_{LeudH}$	2L, anti	CLBZ-1
M8	$(S_{3,3,-\frac{1}{3}}, S_{6,1,-\frac{2}{3}})$	$\mathcal{O}^{(9)}_{dQdQLL}$	$\mathcal{O}^{(7)}_{LLQdH}$, $\mathcal{O}^{(7)}_{LeudH}$	2L, sym	CLBZ-1
M9	$(S_{3,2,\frac{1}{6}}, S_{6,1,\frac{1}{3}})$	$\mathcal{O}^{(9)}_{dQdQLL}$	$\mathcal{O}^{(7)}_{LLduD}$, $\mathcal{O}^{(7)}_{LLQdH}$, $\mathcal{O}^{(7)}_{LeudH}$	2L, anti	CLBZ-1
M10	$(S_{3,2,\frac{1}{6}}, S_{6,3,\frac{1}{3}})$	$\mathcal{O}^{(9)}_{dQdQLL}$	$\mathcal{O}^{(7)}_{LLQdH}$, $\mathcal{O}^{(7)}_{LeudH}$	2L, anti	CLBZ-1
M11	$(S_{3,1,-\frac{1}{3}}, F_{8,1,0})$	$\mathcal{O}^{(9)}_{ddueue}$, $\mathcal{O}^{(9)}_{dQdueL}$, $\mathcal{O}^{(9)}_{dQdQLL}$	$\mathcal{O}^{(7)}_{LLQdH}$, $\mathcal{O}^{(7)}_{LeudH}$	2L, sym	PTBM-1
M12	$(S_{3,3,-\frac{1}{3}}, F_{8,3,0})$	$\mathcal{O}^{(9)}_{dQdQLL}$	$\mathcal{O}^{(7)}_{LLQdH}$	2L, sym	PTBM-1
M13	$(S_{3,2,\frac{1}{6}}, F_{8,1,0})$	$\mathcal{O}^{(9)}_{dQdQLL}$	$\mathcal{O}^{(7)}_{LLQdH}$	2L, sym	PTBM-1
M14	$(S_{3,2,\frac{1}{6}}, F_{8,3,0})$	$\mathcal{O}^{(9)}_{dQdQLL}$	$\mathcal{O}^{(7)}_{LLQdH}$	2L, sym	PTBM-1

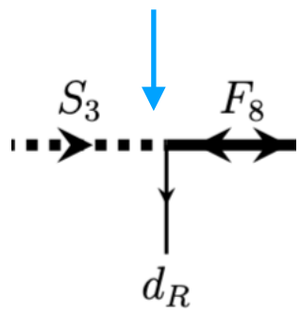
2L Weinberg example model: $(S_{3,1,-\frac{1}{3}}, F_{8,1,0})$

The model: a scalar leptoquark $S_3 = S_{3,1,-\frac{1}{3}}$ and a fermionic colour octet $F_8 = F_{8,1,0}$

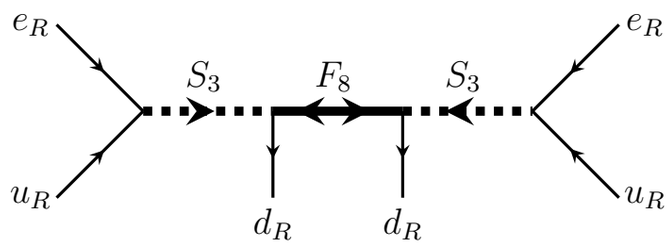
$$\mathcal{L}_{Int}^{UV} = y_{Sue}^{pr} S_3^a \left(\overline{u_a^p} \cdot e^{r,C}\right) + y_{SLQ}^{pr} \epsilon^{ij} S_3^a \left(\overline{q_{ai}^p} \cdot l_j^{r,C}\right) + y_{SdF}^{p} T_b^{Aa} S_3^b \left(\bar{d}_a^p \cdot P_L \cdot F_8^A\right) + \text{h.c.}$$

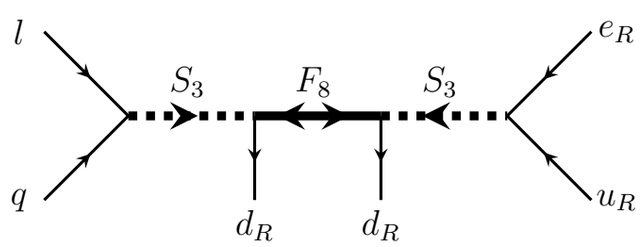


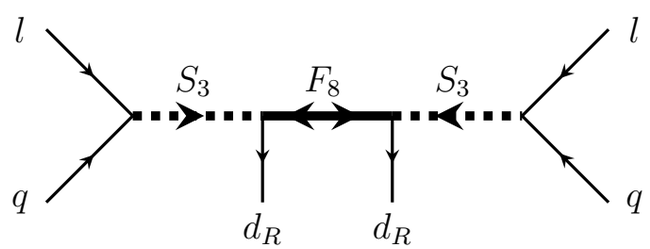




Dimension-9 operators:







$$c_{ddueue}^{(9),uvsptr} = \frac{1}{2\sqrt{2}} \frac{1}{\Lambda^5} y_{SdF}^{u} y_{SdF}^{v} \overline{y_{Sue}}^{sp} \overline{y_{Sue}}^{tr}$$

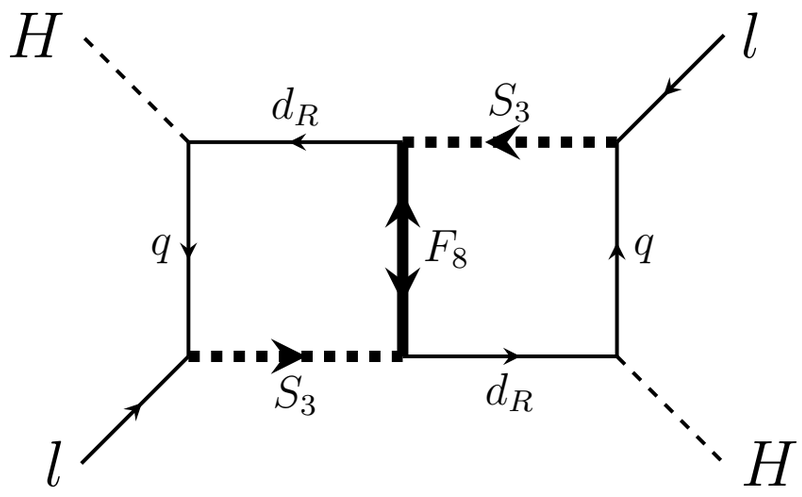
$$c_{dQdueL1}^{(9),uvsptr} = \frac{1}{2\sqrt{2}} \frac{1}{\Lambda^5} y_{SdF}^{u} y_{SdF}^{v} \overline{y_{SLQ}}^{sr} \overline{y_{Sue}}^{tp}$$

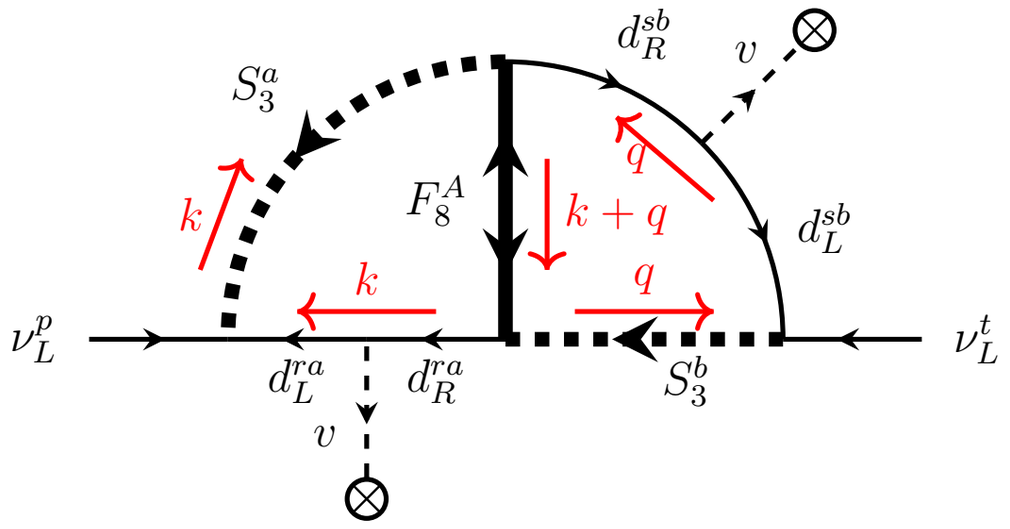
$$c_{dQdueL2}^{(9),usvtpr} = \frac{1}{2\sqrt{2}} \frac{1}{\Lambda^5} y_{SdF}^{u} y_{SdF}^{v} \overline{y_{SLQ}}^{sr} \overline{y_{Sue}}^{tp}$$

$$c_{dQdQLL1}^{(9),usvtpr} = \frac{1}{4\sqrt{2}} \frac{1}{\Lambda^5} y_{SdF}^{u} y_{SdF}^{v} \overline{y_{SLQ}}^{sp} \overline{y_{SLQ}}^{tr}$$

$$c_{dQdQLL2}^{(9),usvtpr} = \frac{1}{4\sqrt{2}} \frac{1}{\Lambda^5} y_{SdF}^{u} y_{SdF}^{v} \overline{y_{SLQ}}^{sp} \overline{y_{SLQ}}^{tr}$$

$(S_{3,1,-\frac{1}{3}}, F_{8,1,0})$ - 2-loop Weinberg





Neutrino mass matrix:

$$iM_{\nu\nu}^{pt} = -6\sqrt{2}i\, m_{d^r}\, m_{d^s}\, m_{F_8} \left(y_{SLQ}^*\right)^{pr} \left(y_{SLQ}^*\right)^{ts} y_{SdF}^r y_{SdF}^s \mathcal{I}_{d^r d^s, S_3 S_3, F_8}$$

Master integral:

$$\mathcal{I}_{ab,\alpha\beta,X} = \int \frac{d^4k}{(2\pi)^4} \int \frac{d^4q}{(2\pi)^4} \frac{1}{(k^2 - m_a^2)\left(q^2 - m_b^2\right)\left(k^2 - m_\alpha^2\right)\left(q^2 - m_\beta^2\right)\left((k+q)^2 - m_X\right)^2}$$

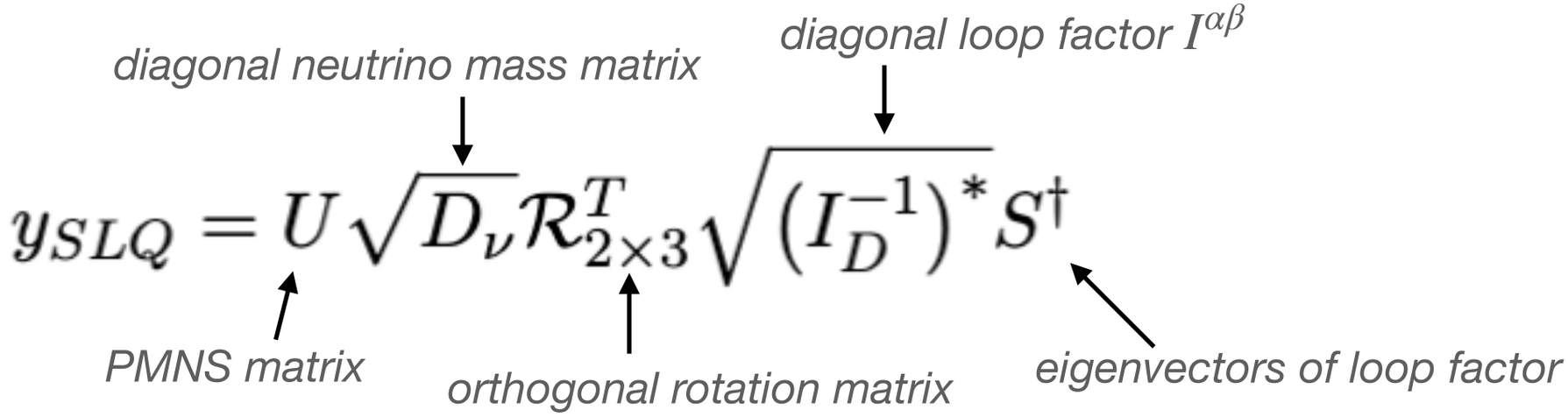
Two d-type SM quarks in the loops, dominated by b-quarks, unless there are additional flavour assumption on y_{SLQ}

Fit to neutrino masses

- 2 generations of the leptoquark $S_{3,1,-\frac{1}{3}}$ needed to reproduce the observed mass differences and mixing angles in the neutrino sector and to keep all Yukawa couplings perturbative

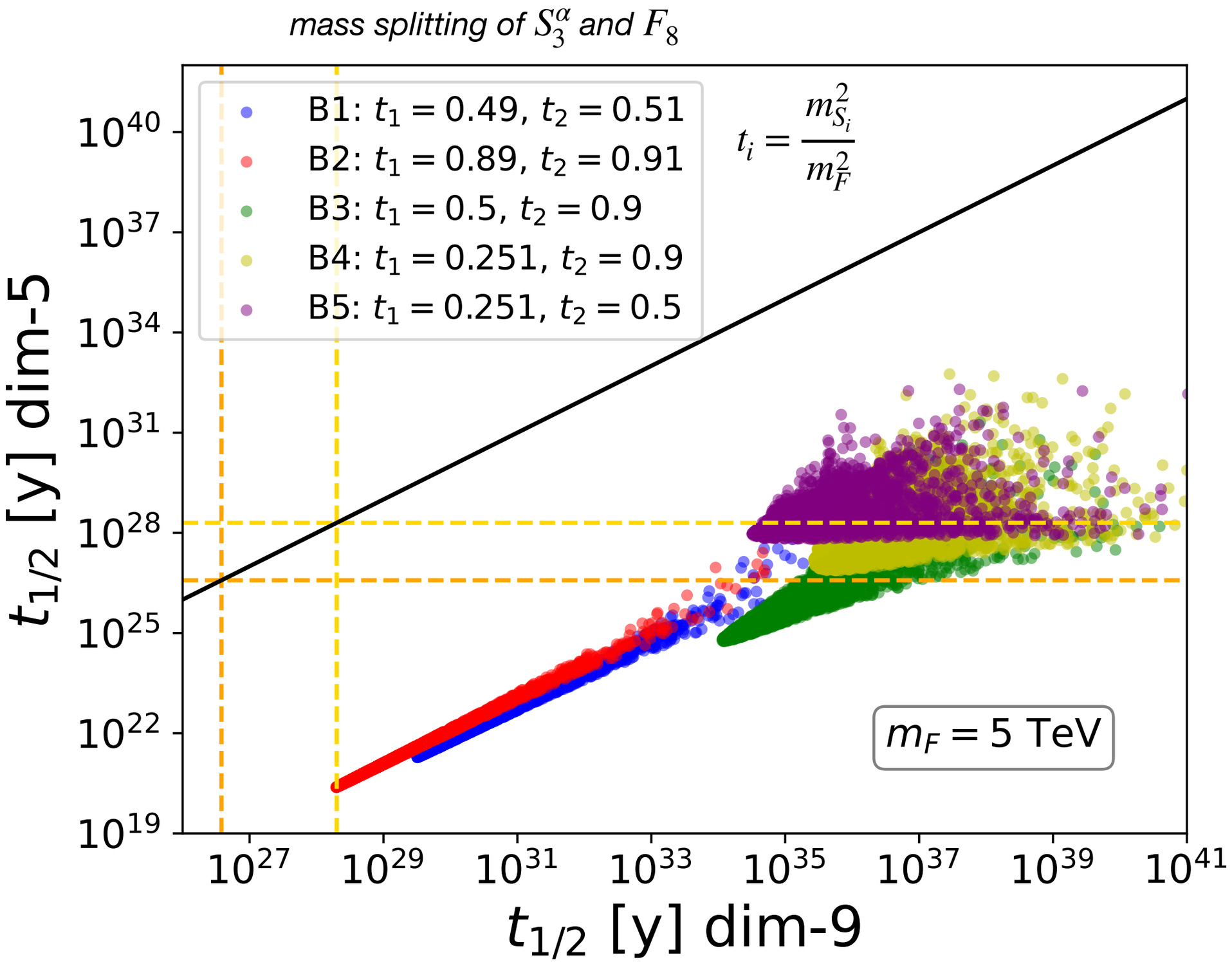
  [Angel, Cai, Rodd, Schmidt, Volkas '13]

- 3rd generation SM quarks dominate in the loop ⇒ Yukawa couplings $y_{SLQ}^{p3\alpha}$ are 3x2 matrices
- Sample Yukawa couplings $y_{SLQ}^{p3\alpha}$ from a modified Casas-Ibarra parametrisation



Only $y_{SLQ}^{p3\alpha}$ is constrained, need a **flavour assumption for $y_{SLQ}^{11\alpha}$**, the coupling that enters $0\nu\beta\beta$

$0\nu\beta\beta$ half-life for *quark flavour universal* y_{SLQ}

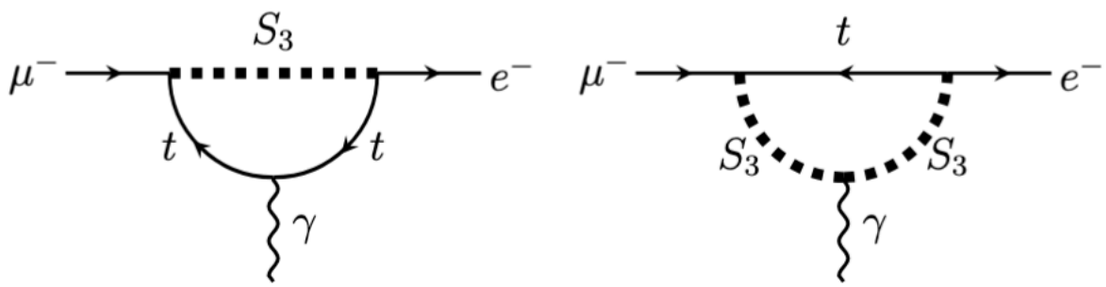


Smaller half-life = larger impact!

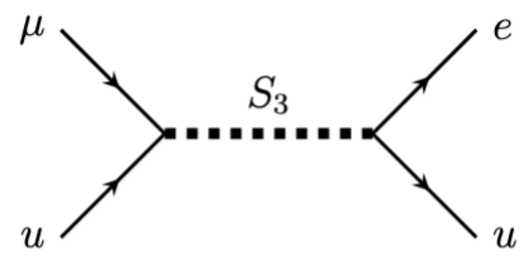
Dim-5 dominates over dim-9
Dim-9 prediction above future sensitivity

Charged Lepton Flavour Violation

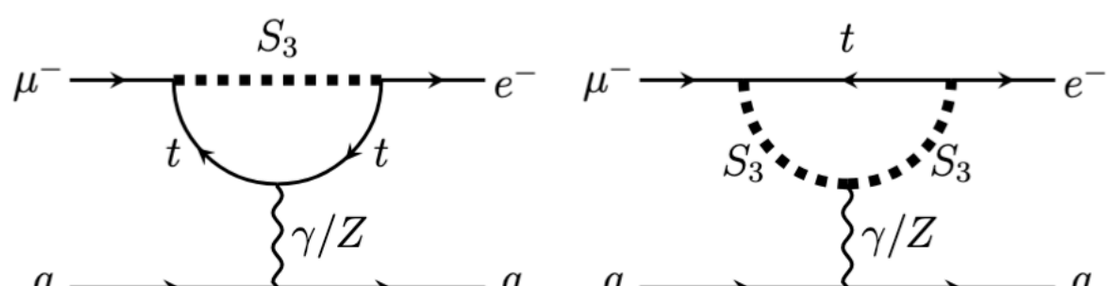
Most stringent constraints from $\mu \to e\gamma$
and $\mu \to e$ conversion in nuclei



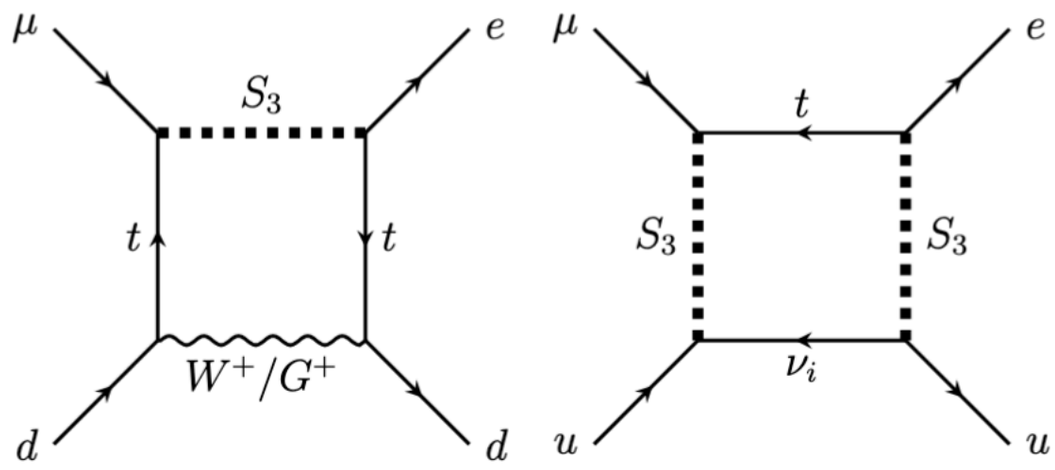
(a) Diagrams for $\mu \to e\gamma$



(b) Tree-level diagram for μ to e conversion

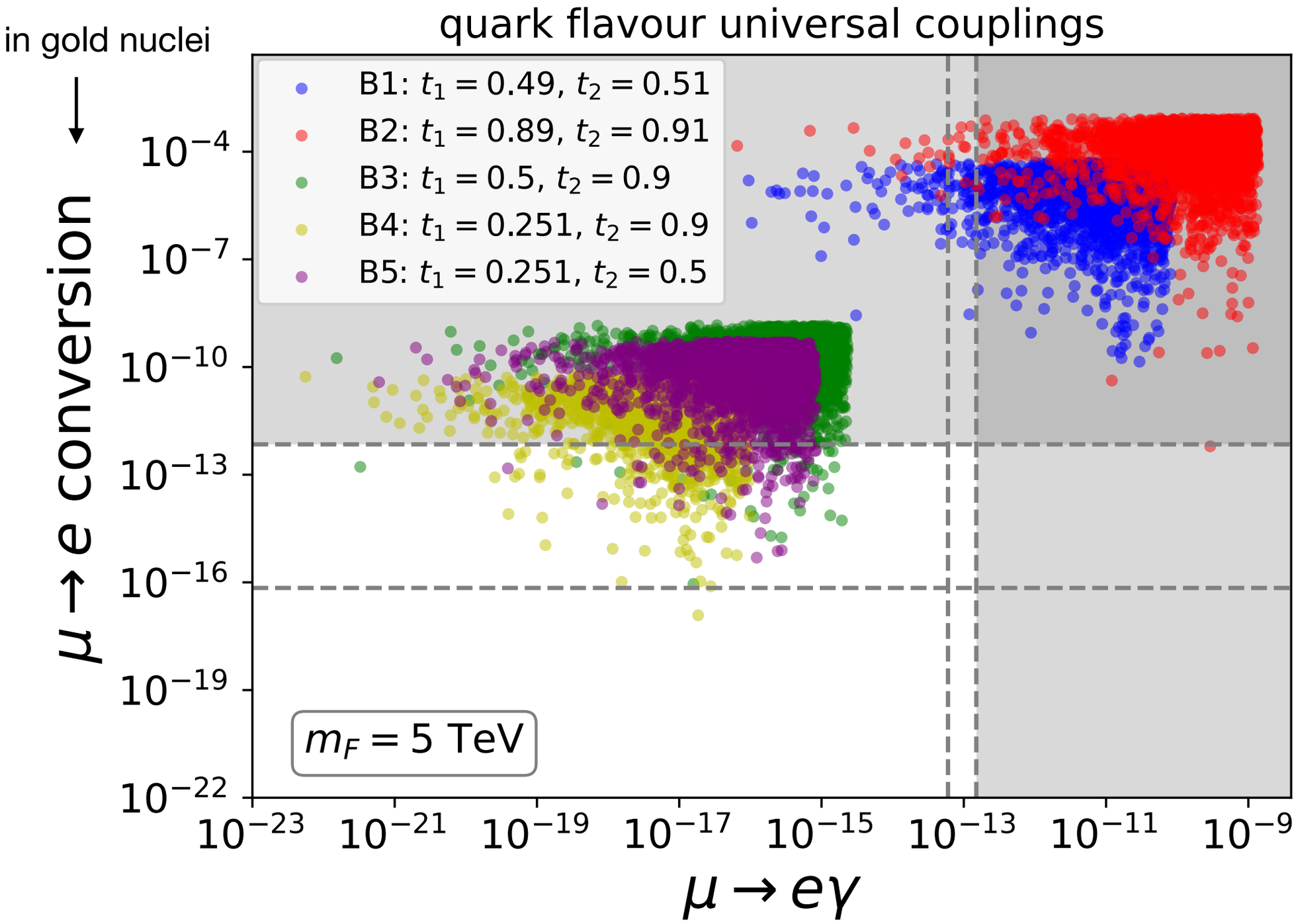


(c) Penguin diagrams for μ to e conversion



(d) Box diagrams for μ to e conversion.

cLFV constraints



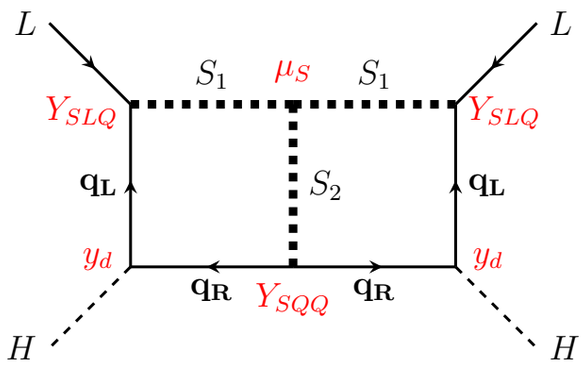
Most benchmark points are excluded by $\mu \to e$ conversion and/or $\mu \to e\gamma$

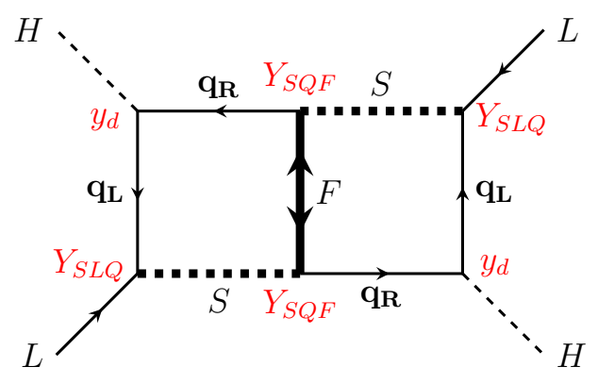
Quark-flavour universal y_{SLQ}?

For quark flavour universal couplings y_{SLQ} in this model, it is impossible to simultaneously

- have visible dim-9 contribution to $0\nu\beta\beta$
  → requires large first generation couplings y_{SLQ}^{11}
- explain neutrino masses
  → mass differences and mixing angles force $y_{SLQ}^{1i} \sim y_{SLQ}^{2i} \sim y_{SLQ}^{3i}$
- satisfy cLFV constraints
  → $\mu \to e\gamma$ and $\mu \to e$ put stringent bounds on the product $(y_{SLQ}^{13})^* y_{SLQ}^{23}$

Model-independent statement: All 12 minimal models with 2L Weinberg operators generate neutrino masses via double-box diagrams, they differ only by prefactors of order 1-10.





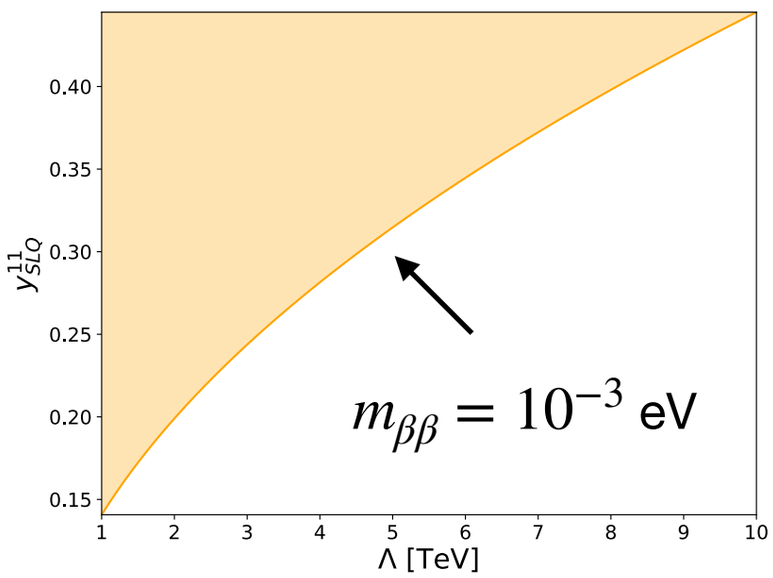
Flavour non-universal Yukawa couplings

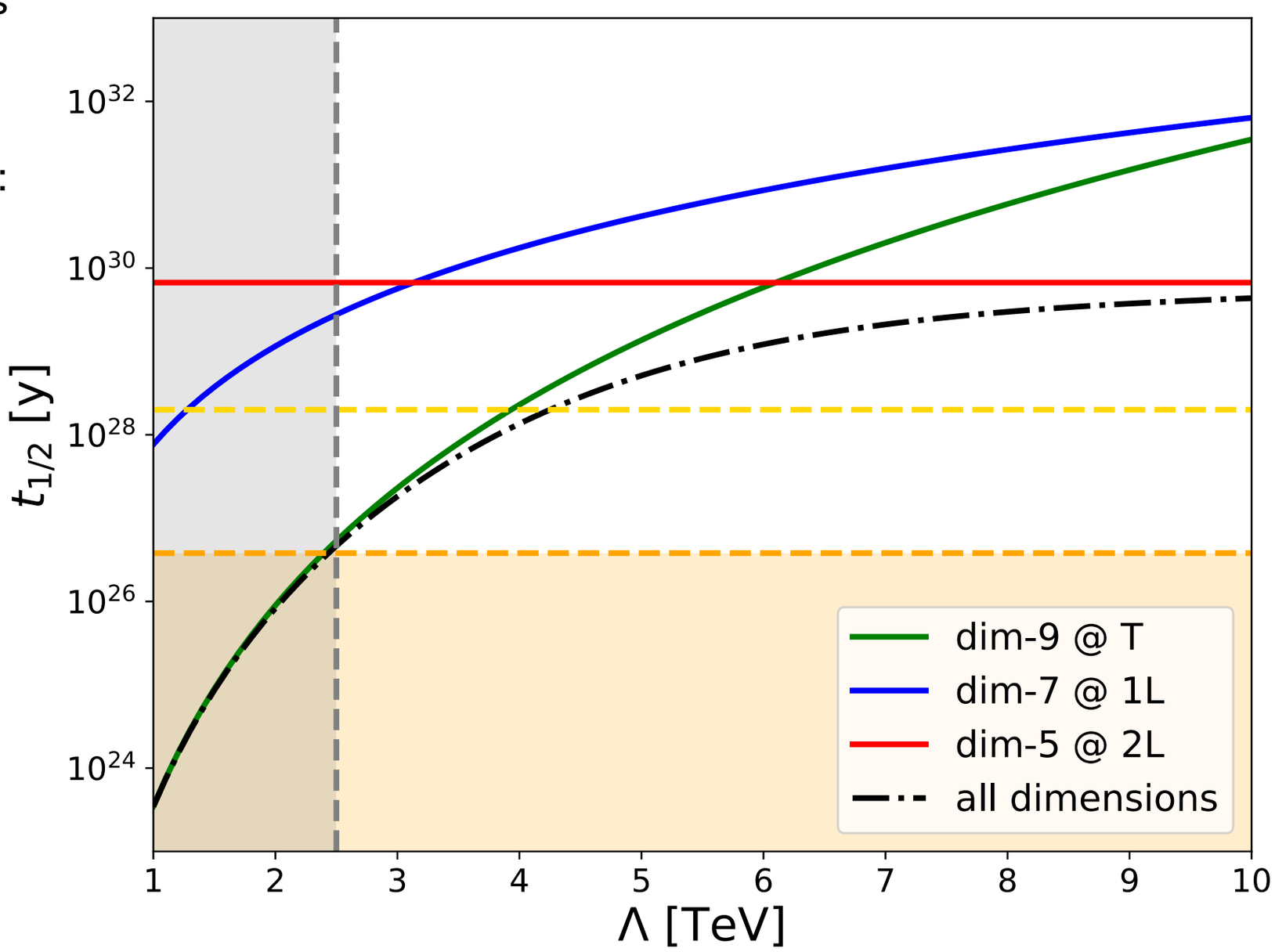
Fix $y_{SLQ}^{p3\alpha}$ to explain the neutrino masses

→ satisfies cLFV bounds

Choose $y_{SLQ}^{11\alpha}$ such that $m_{\beta\beta} = 10^{-3}$ eV:

- Dim-5 contribution to $0\nu\beta\beta$ as function of Λ is constant
- Dim-9 can dominate and be detectable at nEXO for $\Lambda \sim 2.5 - 4$ TeV





Conclusions and Outlook

- Odd-dimensional SMEFT operators can mediate LNV and be tested e.g. by $0\nu\beta\beta$
- We identified classes of models that generate dim-9 operators at tree-level with loop-suppressed dim-5 and dim-7 operators; 14 2-particle models without vectors found.
- I presented the matching and the neutrino mass fit for a 2L-Weinberg model with a scalar leptoquark $S_{3,1,-\frac{1}{3}}$ and a vector-like fermion $F_{8,1,0}$.
- The flavour assumptions of the model are crucial:
  - for quark-flavour universal couplings we can not simultaneously have a dominant tree-level dim-9 operators contribution to $0\nu\beta\beta$, reproduce the neutrino masses and obey cLFV bounds
  - For different flavour assumptions, dim-9 operators could dominate.
- Models with 3L-Weinberg operator could be a sweet spot and give a large parameter space in which dim-9 operators dominate $0\nu\beta\beta$ [WIP]!

Dakujem!



Back up

Standard Model Effective Field Theory

- Effective field theories provide an accurate description if the scales are separated $E \ll \Lambda$
- parametrise the effects of heavy new physics in terms of interactions among the light particles
- "Integrate out" heavy particles with mass $M \sim \Lambda$, keep light modes $m \ll \Lambda$
- replace non-local heavy particle exchanges by a series of local interactions among the light particles
- higher-dimensional ("irrelevant") operators are suppressed by powers of Λ

$$\mathcal{L}_{EFT} = \sum_i c_i \mathcal{O}_i \quad \text{with} \quad c_i \propto \frac{1}{\Lambda^{d_i-4}}$$

Starting with the SM particles and symmetries at the EW scale: SMEFT

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + c_5\mathcal{O}_5 + \sum_i c_{6i}\mathcal{O}_{6i} + \sum_i c_{7i}\mathcal{O}_{7i} + \sum_i c_{8i}\mathcal{O}_{8i} + \sum_i c_{9i}\mathcal{O}_{9i} + \dots$$

lepton number violation, neutrino masses, $0\nu\beta\beta$ decay, …

$\Delta L = 2$ operators appear only at odd dimension!

Model-independent approach to search for new physics!

Effect of SMEFT operators on $0\nu\beta\beta$

- $0\nu\beta\beta$ can be observed in many isotopes, we focus on the half-life in ^{136}Xe
- the subamplitudes as function of the Wilson coefficients have been calculated

  [V. Cirigliano, W. Dekens, J. de Vries, M.L. Graessera and E. Mereghettia '18]

  and implemented in vDoBe [O. Scholer, J. de Vries, L. Gráf: JHEP 08 (2023) 043]

coupling ~1.27

atomic phase space factors

$$T_{1/2}^{-1} = g_A^4 \sum_k G_{0k} |\mathcal{A}_k(\{C_i\})|^2$$

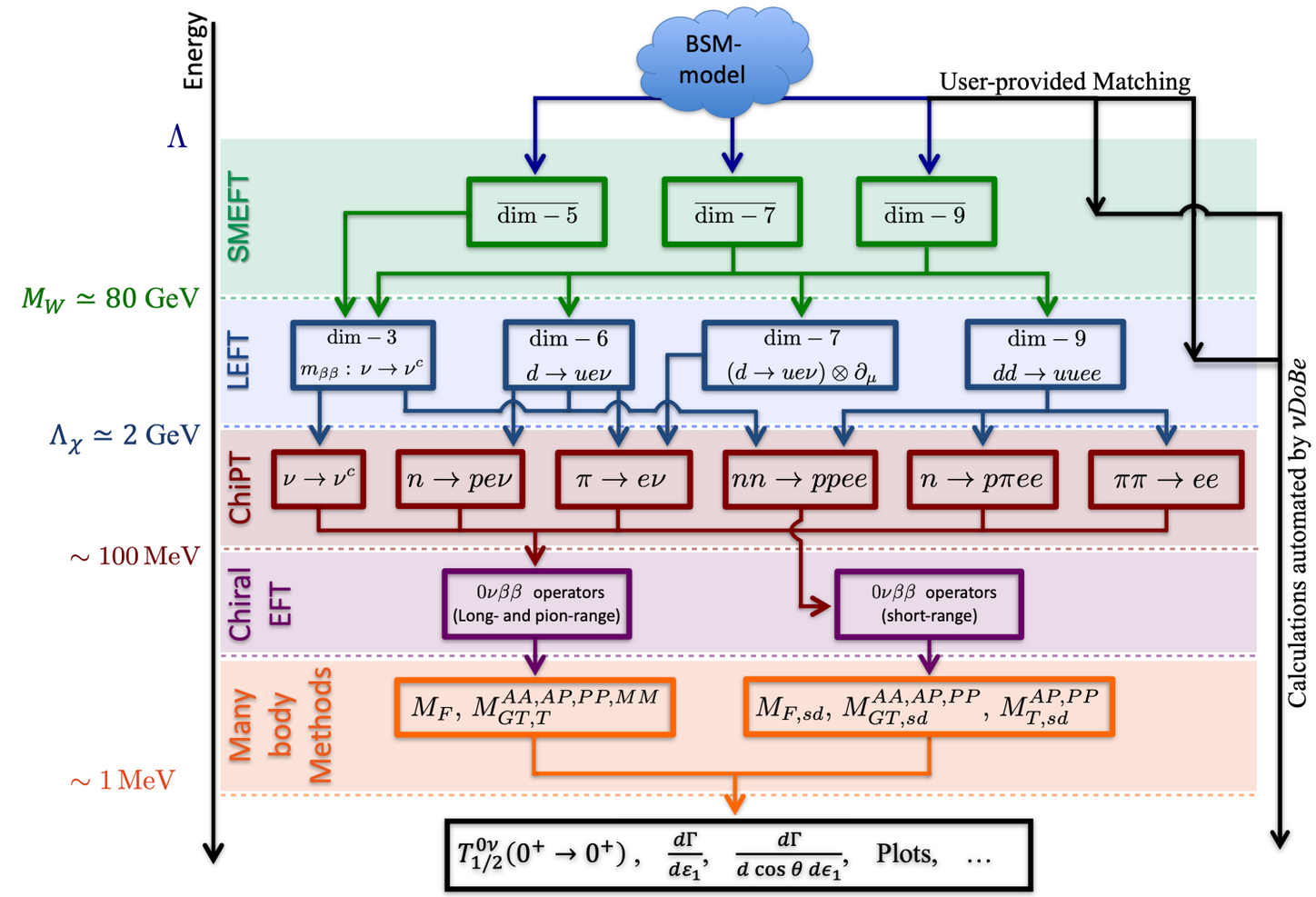
subamplitudes, depend on

- nuclear matrix elements (NME)
- phase space factors
- low-energy constants
- **Wilson coefficients**

vDoBe: A Python Tool for 0νββ

- user inputs:
  - scale + selection of operators
  - isotope(s), type of NMEs
- data inputs:
  - nuclear matrix elements
  - phase-space factors
  - low-energy constants
- outputs:
  - half-life formula for the given case
  - limits on selected couplings
  - $m_{\beta\beta}$ vs. m_ν plots, etc.
  - chosen contour plots showing correlations of different parameters, ...

O. Scholer, J. de Vries, L. Gráf: JHEP 08 (2023) 043



download: https://github.com/OScholer/nudobe
online tool: https://nudobe.streamlit.app

Dependence of the amplitudes for $0\nu\beta\beta$ on the WCs C_i

[V. Cirigliano, W. Dekens, J. de Vries, M.L. Graessera and E. Mereghettia '18]

$0\nu\beta\beta$ potential from dim-9 operators:

$$V(\mathbf{q}^2) = V_3(\mathbf{q}^2) + V_6(\mathbf{q}^2) + V_7(\mathbf{q}^2) + V_9(\mathbf{q}^2)$$

Amplitude for $0\nu\beta\beta$:

$$\boxed{\mathcal{A} = \langle 0^+ | \sum_{m,n} \int \frac{d^3\mathbf{q}}{(2\pi)^3} e^{i\mathbf{q}\cdot\mathbf{r}} V(\mathbf{q}^2) | 0^+ \rangle}$$

Decompose amplitude into sub-amplitudes

$$\mathcal{A} = \frac{g_A^2 G_F^2 m_e}{\pi R_A} \Big[\mathcal{A}_\nu \, \bar{u}(k_1) P_R C \bar{u}^T(k_2) + \mathcal{A}_R \, \bar{u}(k_1) P_L C \bar{u}^T(k_2) \\ + \mathcal{A}_E \, \bar{u}(k_1) \gamma_0 C \bar{u}^T(k_2) \, \frac{E_1 - E_2}{m_e} + \mathcal{A}_{m_e} \, \bar{u}(k_1) C \bar{u}^T(k_2) + \mathcal{A}_M \, \bar{u}(k_1) \gamma_0 \gamma_5 C \bar{u}^T(k_2) \Big]$$

$$V_9(\mathbf{q}^2) = -(\tau^{(1)+}\tau^{(2)+}) \, g_A^2 \, \frac{4G_F^2}{v} \, \bar{u}(k_1) P_R C \bar{u}^T(k_2) \\ \times \Bigg[-\Big(\boldsymbol{\sigma}^{(1)} \cdot \boldsymbol{\sigma}^{(2)} - S^{(12)} \Big) \left(\frac{C^{(9)}_{\pi\pi\,\mathrm{L}}}{6} \frac{\mathbf{q}^2}{(\mathbf{q}^2 + m_\pi^2)^2} - \frac{C^{(9)}_{\pi N\,\mathrm{L}}}{3} \frac{\mathbf{q}^2}{\mathbf{q}^2 + m_\pi^2} \right) \\ + \frac{2}{g_A^2} C^{(9)}_{NN\,\mathrm{L}} \Bigg] - (\tau^{(1)+}\tau^{(2)+}) \, g_A^2 \, \frac{4G_F^2}{v} \, \bar{u}(k_1) \gamma_0 \gamma_5 C \bar{u}^T(k_2) \\ \times \Bigg[\frac{g_V^{\pi N} C_V^{(9)} + \tilde{g}_V^{\pi N} \tilde{C}_V^{(9)}}{3} \Big(\boldsymbol{\sigma}^{(1)} \cdot \boldsymbol{\sigma}^{(2)} - S^{(12)} \Big) \frac{\mathbf{q}^2}{\mathbf{q}^2 + m_\pi^2} \\ + \frac{2}{g_A^2} \left(g_6^{NN} C_V^{(9)} + g_7^{NN} \tilde{C}_V^{(9)} \right) \Bigg] + (L \leftrightarrow R) \, .$$

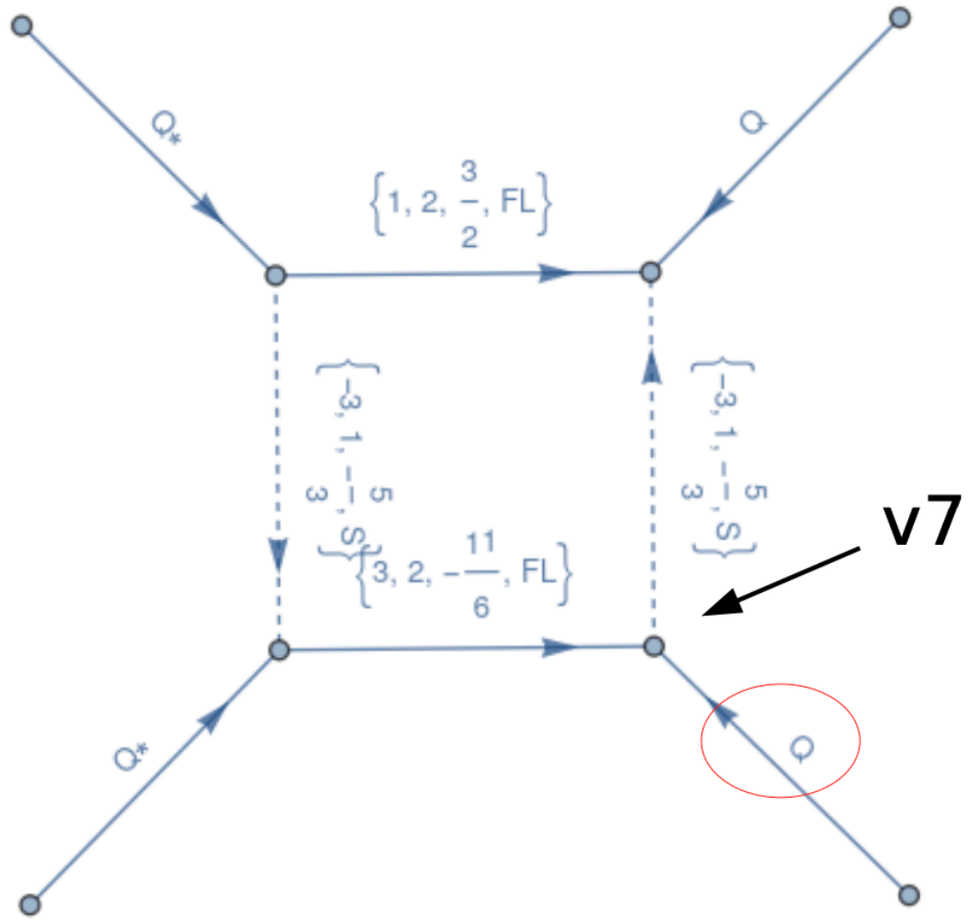
with e.g.

$$\mathcal{M}_\nu^{(3)} = -V_{ud}^2 \left(-\frac{1}{g_A^2} M_F + \mathcal{M}_{GT} + \mathcal{M}_T + 2 \frac{m_\pi^2 \, g_\nu^{NN}}{g_A^2} M_{F,\,sd} \right) , \\ \mathcal{M}_\nu^{(6)} = V_{ud} \left(\frac{B}{m_N} (C^{(6)}_{\mathrm{SL}} - C^{(6)}_{\mathrm{SR}}) + \frac{m_\pi^2}{m_N v} \left(C^{(7)}_{\mathrm{VL}} - C^{(7)}_{\mathrm{VR}} \right) \right) \mathcal{M}_{PS} + V_{ud} C^{(6)}_{\mathrm{T}} \mathcal{M}_{T6} \, , \\ \mathcal{M}_\nu^{(9)} = -\frac{1}{2m_N^2} C^{(9)}_{\pi\pi\,\mathrm{L}} \left(\frac{1}{2} M^{AP}_{GT,sd} + M^{PP}_{GT,sd} + \frac{1}{2} M^{AP}_{T,sd} + M^{PP}_{T,sd} \right) \\ + \frac{m_\pi^2}{2m_N^2} C^{(9)}_{\pi N\,\mathrm{L}} \left(M^{AP}_{GT,sd} + M^{AP}_{T,sd} \right) - \frac{2}{g_A^2} \frac{m_\pi^2}{m_N^2} C^{(9)}_{NN\,\mathrm{L}} \, M_{F,\,sd} \, ,$$

Bottom-up EFT:
Classifying UV completions to SMEFT operators

Generalised adjacency matrices

All the process can be ***automated*** **via "generalised" adjacency matrices***:*
the entries are the quantum numbers of the particles in the diagram with every column and row invariant under the symmetries

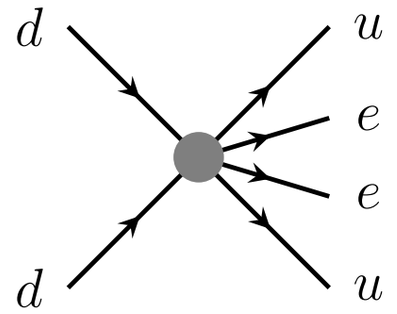


vertex 7

vertex 2

0	0	0	0	0	0	0	$\{3, 2, \frac{1}{6}, FL, 1\}$
0	0	0	0	0	0	$\{3, 2, \frac{1}{6}, FL, 1\}$	0
0	0	0	0	0	$\{-3, 2, -\frac{1}{6}, FR, 1\}$	0	0
0	0	0	0	$\{-3, 2, -\frac{1}{6}, FR, 1\}$	0	0	0
0	0	0	$\{3, 2, \frac{1}{6}, FL, 1\}$	0	$\{-3, 1, -\frac{5}{3}, S, 0\}$	0	$\{1, 2, \frac{3}{2}, FL, 0\}$
0	0	$\{3, 2, \frac{1}{6}, FL, 1\}$	0	$\{3, 1, \frac{5}{3}, S, 0\}$	0	$\{3, 2, -\frac{11}{6}, FL, 0\}$	0
0	$\{-3, 2, -\frac{1}{6}, FR, 1\}$	0	0	0	$\{-3, 2, \frac{11}{6}, FR, 0\}$	0	$\{-3, 1, -\frac{5}{3}, S, 0\}$
$\{-3, 2, -\frac{1}{6}, FR, 1\}$	0	0	0	$\{1, 2, -\frac{3}{2}, FR, 0\}$	0	$\{3, 1, \frac{5}{3}, S, 0\}$	0

6-fermion dim-9 operators



Ψ^6	$\mathcal{O}^{(9)}_{ddueue}$	ddueue(9)	$\left[\overline{d^\alpha} d^{C\beta}\right]\left[\overline{u^{C\alpha}} e\right]\left[\overline{u^{C\beta}} e\right]$
	$\mathcal{O}^{(9)}_{dQdueL1}$	dQdueL1(9)	$\epsilon_{ij}\left[\overline{d} Q_i\right]\left[\overline{d}\gamma^\mu u\right]\left[\overline{e^C}\gamma_\mu L_j\right]$
	$\mathcal{O}^{(9)}_{dQdueL2}$	dQdueL2(9)	$\epsilon_{ij}\left[\overline{d^\alpha} Q_i^\beta\right]\left[\overline{d^\beta}\gamma^\mu u^\alpha\right]\left[\overline{e^C}\gamma_\mu L_j\right]$
	$\mathcal{O}^{(9)}_{QudueL1}$	QudueL1(9)	$\left[\overline{Q} u\right]\left[\overline{d}\gamma^\mu u\right]\left[\overline{e^C}\gamma_\mu L_j\right]$
	$\mathcal{O}^{(9)}_{QudueL2}$	QudueL2(9)	$\left[\overline{Q^\alpha} u^\beta\right]\left[\overline{d^\beta}\gamma^\mu u^\alpha\right]\left[\overline{e^C}\gamma_\mu L_j\right]$
	$\mathcal{O}^{(9)}_{dQdQLL1}$	dQdQLL1(9)	$\epsilon_{ik}\epsilon_{jl}\left[\overline{d} Q_i\right]\left[\overline{d}\gamma^\mu Q_j\right]\left[\overline{L_k^C}\gamma_\mu L_l\right]$
	$\mathcal{O}^{(9)}_{dQdQLL2}$	dQdQLL2(9)	$\epsilon_{ik}\epsilon_{jl}\left[\overline{d^\alpha} Q_i^\beta\right]\left[\overline{d^\beta}\gamma^\mu Q_j^\alpha\right]\left[\overline{L_k^C}\gamma_\mu L_l\right]$
	$\mathcal{O}^{(9)}_{dQQuLL1}$	dQQuLL1(9)	$\epsilon_{ij}\left[\overline{d} Q_i\right]\left[\overline{Q} u\right]\left[\overline{L^C} L_j\right]$
	$\mathcal{O}^{(9)}_{dQQuLL2}$	dQQuLL2(9)	$\epsilon_{ij}\left[\overline{d^\alpha} Q_i^\beta\right]\left[\overline{Q^\beta} u^\alpha\right]\left[\overline{L^C} L_j\right]$
	$\mathcal{O}^{(9)}_{QuQuLL1}$	QuQuLL1(9)	$\left[\overline{Q_i} u\right]\left[\overline{Q_j} u\right]\left[\overline{L_i^C} L_j\right]$
	$\mathcal{O}^{(9)}_{QuQuLL2}$	QuQuLL2(9)	$\left[\overline{Q_i^\alpha} u^\beta\right]\left[\overline{Q_j^\beta} u^\alpha\right]\left[\overline{L_i^C} L_j\right]$

Minimal models

#	Model	dim-9 tree level	dim-7 1L	dim-5	type
M1	$(S_{8,2,\frac{1}{2}}, F_{8,1,0})$	$\mathcal{O}^{(9)}_{dQdQLL}$, $\mathcal{O}^{(9)}_{dQQuLL}$, $\mathcal{O}^{(9)}_{QuQuLL}$	$\mathcal{O}^{(7)}_{LH}$, $\mathcal{O}^{(7)}_{LHD}$, $\mathcal{O}^{(7)}_{LLduD}$, $\mathcal{O}^{(7)}_{LLQdH}$, $\mathcal{O}^{(7)}_{LLQuH}$	1L	T3
M2	$(S_{8,2,\frac{1}{2}}, F_{8,3,0})$	$\mathcal{O}^{(9)}_{dQdQLL}$, $\mathcal{O}^{(9)}_{dQQuLL}$, $\mathcal{O}^{(9)}_{QuQuLL}$	$\mathcal{O}^{(7)}_{LH}$, $\mathcal{O}^{(7)}_{LHD}$, $\mathcal{O}^{(7)}_{LLduD}$, $\mathcal{O}^{(7)}_{LLQdH}$, $\mathcal{O}^{(7)}_{LLQuH}$	1L	T3
M3	$(S_{1,1,1}, S_{1,3,0})$	$\mathcal{O}^{(9)}_{LLH^4(D/W)^2}$	$\mathcal{O}^{(7)}_{LHD}$	2L, anti	CLBZ-10
M4	$(S_{1,1,1}, S_{8,2,\frac{1}{2}})$	$\mathcal{O}^{(9)}_{dQdQLL}$, $\mathcal{O}^{(9)}_{dQQuLL}$, $\mathcal{O}^{(9)}_{QuQuLL}$	$\mathcal{O}^{(7)}_{LLduD}$, $\mathcal{O}^{(7)}_{LLQdH}$, $\mathcal{O}^{(7)}_{LLQuH}$	2L, anti	NG
M5	$(S_{3,1,-\frac{1}{3}}, S_{3,1,\frac{2}{3}})$	$\mathcal{O}^{(9)}_{ddueue}$, $\mathcal{O}^{(9)}_{dQdueL}$, $\mathcal{O}^{(9)}_{dQdQLL}$	$\mathcal{O}^{(7)}_{LLQdH}$, $\mathcal{O}^{(7)}_{LeudH}$	2L, anti	CLBZ-1
M6	$(S_{3,1,-\frac{1}{3}}, S_{6,1,-\frac{2}{3}})$	$\mathcal{O}^{(9)}_{ddueue}$, $\mathcal{O}^{(9)}_{dQdueL}$, $\mathcal{O}^{(9)}_{dQdQLL}$	$\mathcal{O}^{(7)}_{LLQdH}$, $\mathcal{O}^{(7)}_{LeudH}$	2L, sym	CLBZ-1
M7	$(S_{3,3,-\frac{1}{3}}, S_{3,1,\frac{2}{3}})$	$\mathcal{O}^{(9)}_{dQdQLL}$	$\mathcal{O}^{(7)}_{LLQdH}$, $\mathcal{O}^{(7)}_{LeudH}$	2L, anti	CLBZ-1
M8	$(S_{3,3,-\frac{1}{3}}, S_{6,1,-\frac{2}{3}})$	$\mathcal{O}^{(9)}_{dQdQLL}$	$\mathcal{O}^{(7)}_{LLQdH}$, $\mathcal{O}^{(7)}_{LeudH}$	2L, sym	CLBZ-1
M9	$(S_{3,2,\frac{1}{6}}, S_{6,1,\frac{1}{3}})$	$\mathcal{O}^{(9)}_{dQdQLL}$	$\mathcal{O}^{(7)}_{LLduD}$, $\mathcal{O}^{(7)}_{LLQdH}$, $\mathcal{O}^{(7)}_{LeudH}$	2L, anti	CLBZ-1
M10	$(S_{3,2,\frac{1}{6}}, S_{6,3,\frac{1}{3}})$	$\mathcal{O}^{(9)}_{dQdQLL}$	$\mathcal{O}^{(7)}_{LLQdH}$, $\mathcal{O}^{(7)}_{LeudH}$	2L, anti	CLBZ-1
M11	$(S_{3,1,-\frac{1}{3}}, F_{8,1,0})$	$\mathcal{O}^{(9)}_{ddueue}$, $\mathcal{O}^{(9)}_{dQdueL}$, $\mathcal{O}^{(9)}_{dQdQLL}$	$\mathcal{O}^{(7)}_{LLQdH}$, $\mathcal{O}^{(7)}_{LeudH}$	2L, sym	PTBM-1
M12	$(S_{3,3,-\frac{1}{3}}, F_{8,3,0})$	$\mathcal{O}^{(9)}_{dQdQLL}$	$\mathcal{O}^{(7)}_{LLQdH}$	2L, sym	PTBM-1
M13	$(S_{3,2,\frac{1}{6}}, F_{8,1,0})$	$\mathcal{O}^{(9)}_{dQdQLL}$	$\mathcal{O}^{(7)}_{LLQdH}$	2L, sym	PTBM-1
M14	$(S_{3,2,\frac{1}{6}}, F_{8,3,0})$	$\mathcal{O}^{(9)}_{dQdQLL}$	$\mathcal{O}^{(7)}_{LLQdH}$	2L, sym	PTBM-1

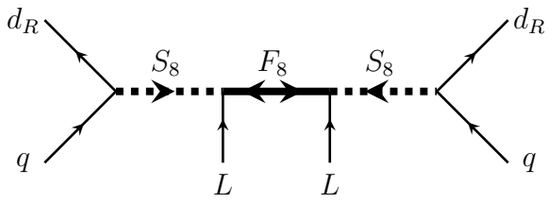
1L Weinberg - $(S_{8,2,1/2}, F_{8,1,0})$

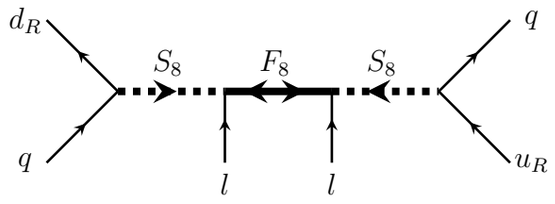
scalar diquark: $S_8 = S_{8,2,\frac{1}{2}}$

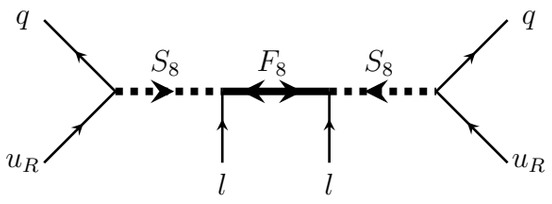
vector-like fermion: $F_8 = F_{8,1,0}$ **or** $F_{8,3,0}$

$$\begin{aligned}\mathcal{L}_{Int}^{UV} =& y_{SQd}^{pr} T_b^{Aa} S_8^{Ai} \left(\bar{q}_{ai}^{p} \cdot P_R \cdot d^{br}\right) + y_{SQu}^{pr} T_b^{Aa} \epsilon^{ij} \bar{S}_{8,j}^{A} \left(\bar{q}_{ai}^{p} \cdot P_R \cdot u^{br}\right) \\ &+ y_{SFL}^{p} \bar{\epsilon}_{ij} S_8^{Aj} \left(F_8^{A,T} \cdot C P_L \cdot l^{ip}\right) + \lambda_S H^i H^j \bar{S}_{8,i}^{A} \bar{S}_{8,j}^{A} + \text{h.c.}\end{aligned}$$

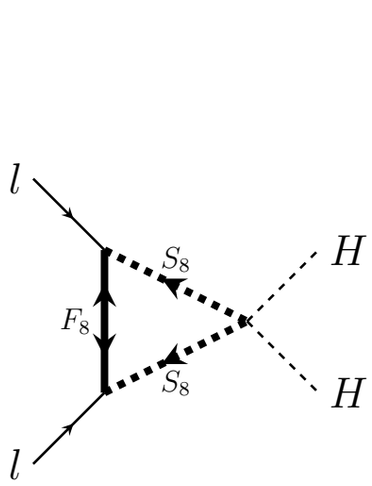
tree-level dim-9:

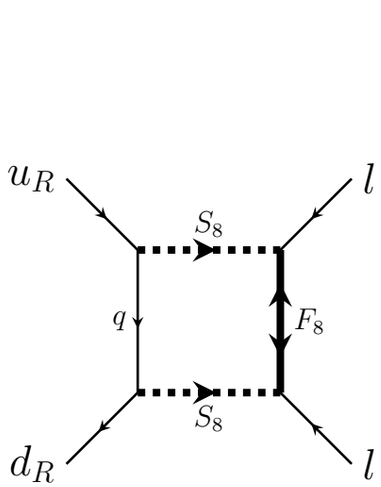


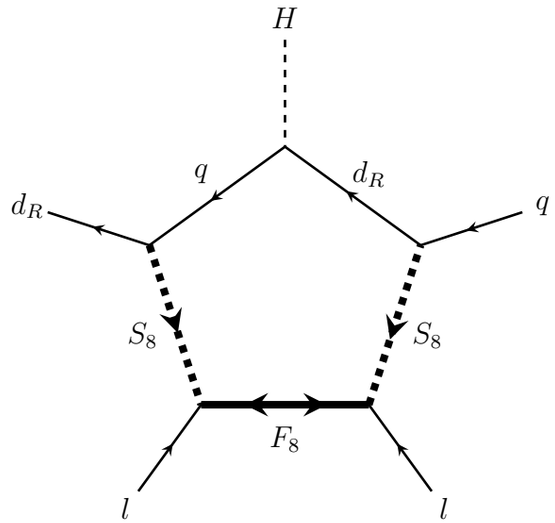


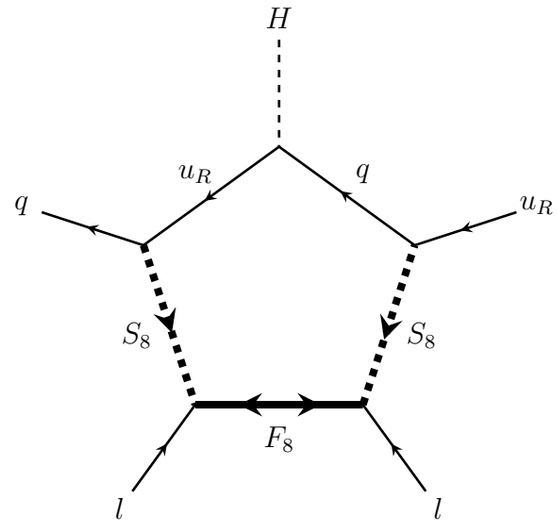


1-loop dim-7:

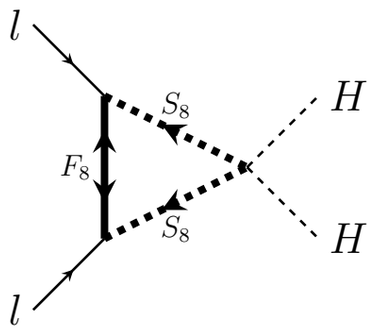




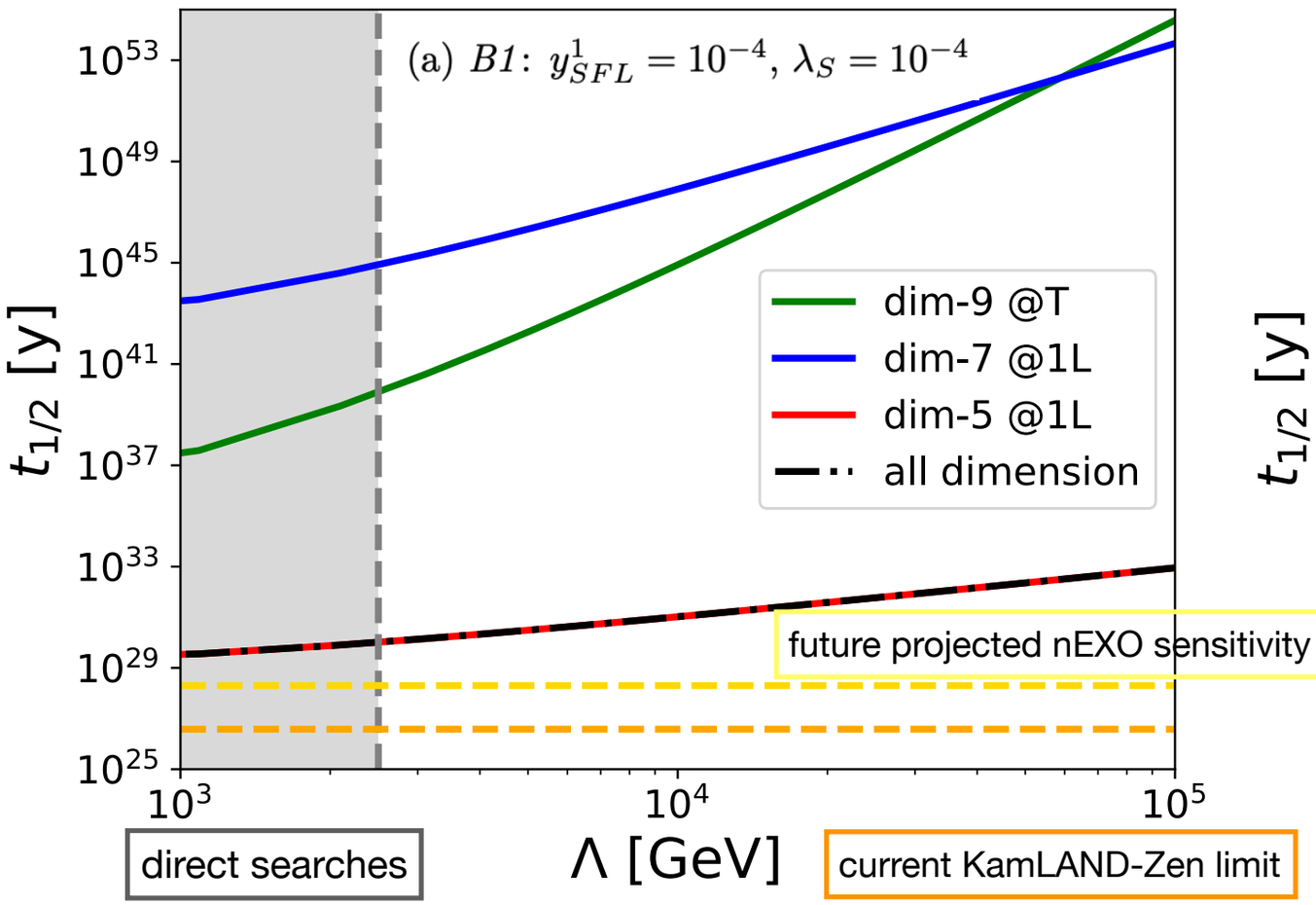


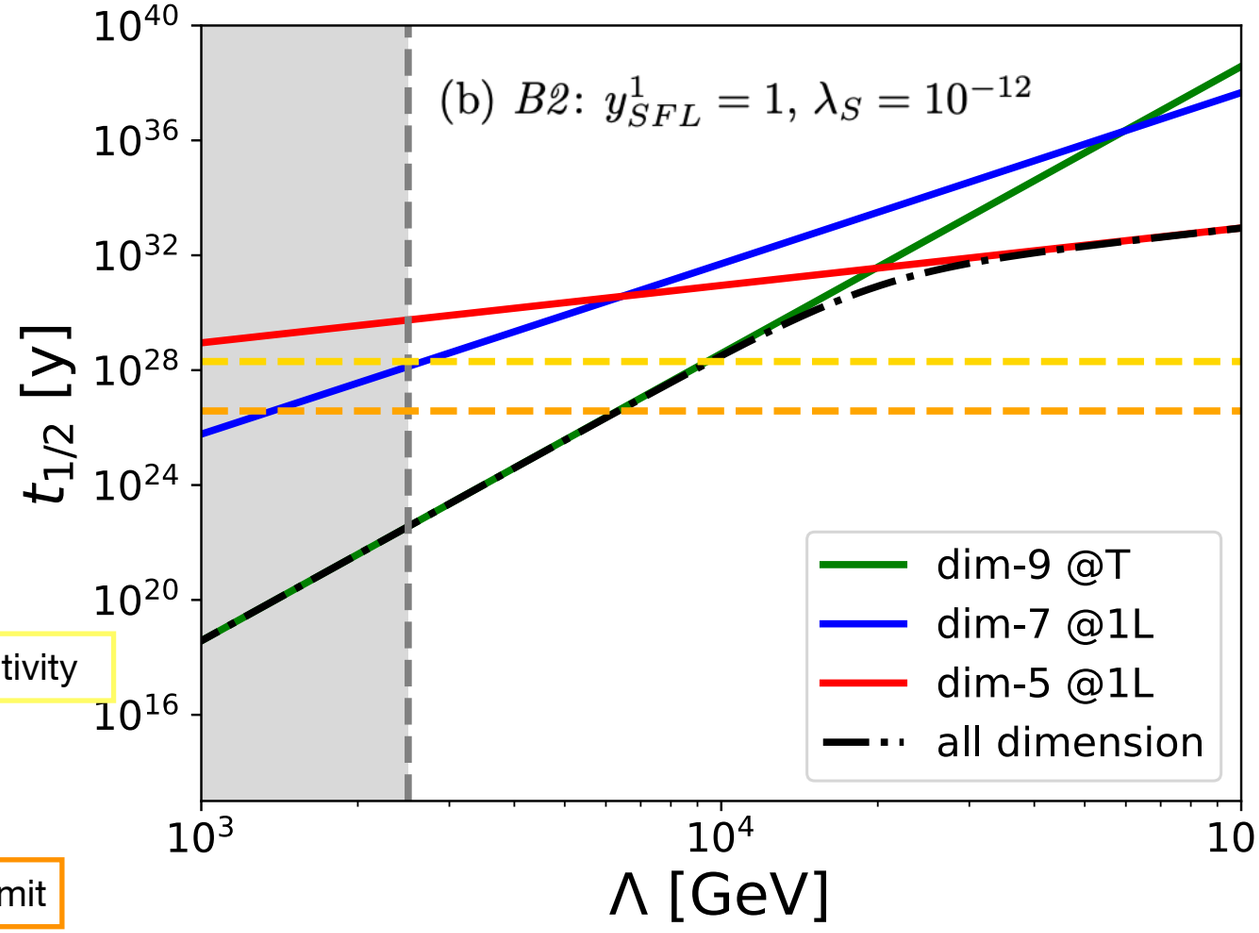


1-loop dim-5 (Weinberg):



$0\nu\beta\beta$ in $(S_{8,2,1/2}, F_{8,1,0})$

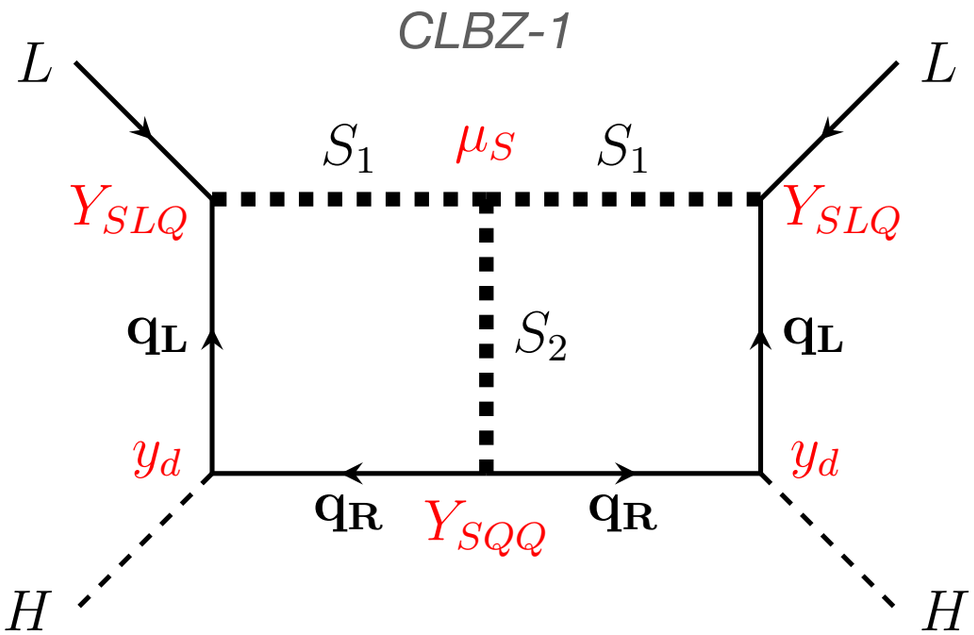


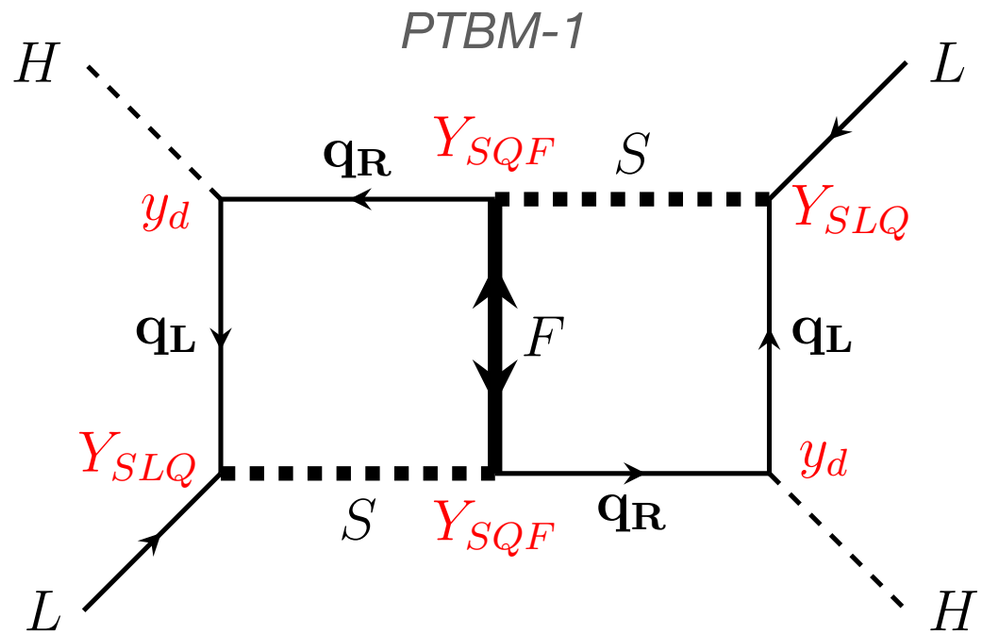


- $(y_{SFL})^2 \lambda_S \sim 10^{-12}$ to get the correct order of magnitude for the neutrino masses ($m_{\beta\beta} \sim 0.1$ eV)
- calculate the half-life in Xe-136 in vDoBe triggered by only one dimension at a time for two benchmarks
- (a) for all possible NP scales Λ the dim-5 contribution will dominate (smaller half-life = larger impact)
  (b) for symmetry-protected λ_S, dim-9 could dominate and be probed for $\Lambda \sim 6 - 9$ TeV

2L Weinberg

names according to [Aristizabal Sierra, Degee, Dorame, Hirsch '14]





$$\Rightarrow$$

$$M_{\nu\nu}^{pt} \propto \sum_{r,s=1}^{3} Y_{SLQ}^{pr} Y_{SLQ}^{ts} Y_{SQQ}^{rs} I_{CLBZ}^{rs}(m_{S_1}, m_{F_1}),$$

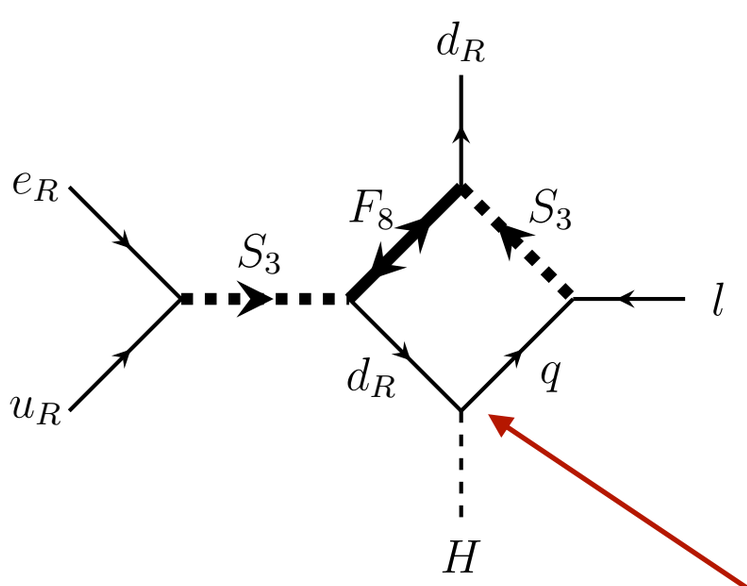
$$M_{\nu\nu}^{pt} \propto \sum_{r,s=1}^{3} Y_{SLQ}^{pr} Y_{SLQ}^{ts} Y_{SQF}^{r} Y_{SQF}^{s} I_{PTBM}^{rs}(m_S, m_F),$$

$$I_{CLBZ}^{rs} = \int \frac{d^4k}{(2\pi)^4} \int \frac{d^4q}{(2\pi)^4} \frac{\mu_S m_{d_r} m_{d_s}}{(k^2 - m_{d_r}^2)(k^2 - m_{S_1}^2)(q^2 - m_{d_s}^2)(q^2 - m_{S_1}^2)((k+q)^2 - m_{S_2}^2)}.$$

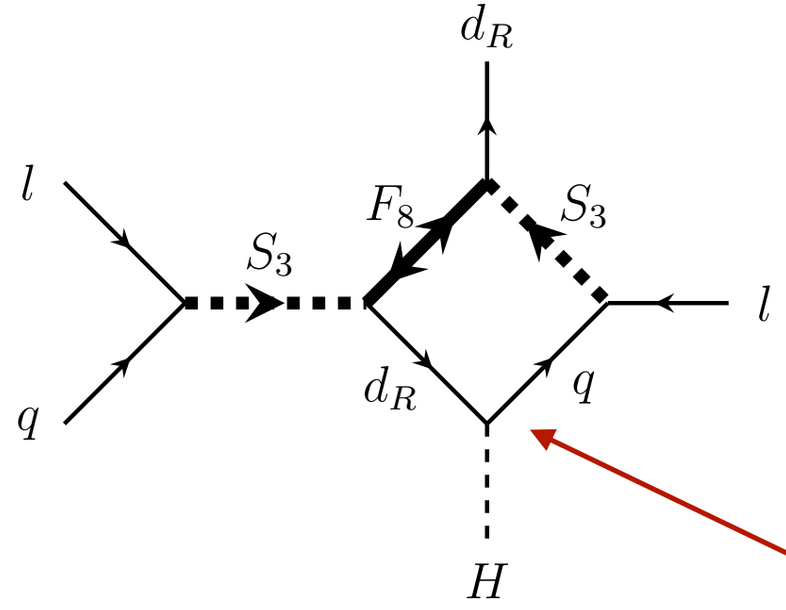
$$I_{PTBM}^{rs} = \int \frac{d^4k}{(2\pi)^4} \int \frac{d^4q}{(2\pi)^4} \frac{m_F m_{d_r} m_{d_s}}{(k^2 - m_{d_r}^2)(k^2 - m_S^2)(q^2 - m_{d_s}^2)(q^2 - m_S^2)((k+q)^2 - m_F^2)}$$

$\Rightarrow$ Same loop factor for both classes

$(S_{3,1,-\frac{1}{3}}, F_{8,1,0})$ - 1-loop dim-7



$$c_{LeudH}^{(7),tvus} = -\frac{1}{16\pi^2}\frac{\sqrt{2}}{\Lambda^3}\overline{y_{SdF}}^{r}\overline{y_{SdF}}^{s}y_{Sue}^{uv}y_{SLQ}^{tp}\overline{y_d}^{pr}$$



$$c_{LLQdH,1}^{(7),tvus} = -\frac{1}{16\pi^2}\frac{2\sqrt{2}}{\Lambda^3}\overline{y_{SdF}}^{r}\overline{y_{SdF}}^{s}y_{SLQ}^{uv}y_{SLQ}^{tp}\overline{y_d}^{pr}$$

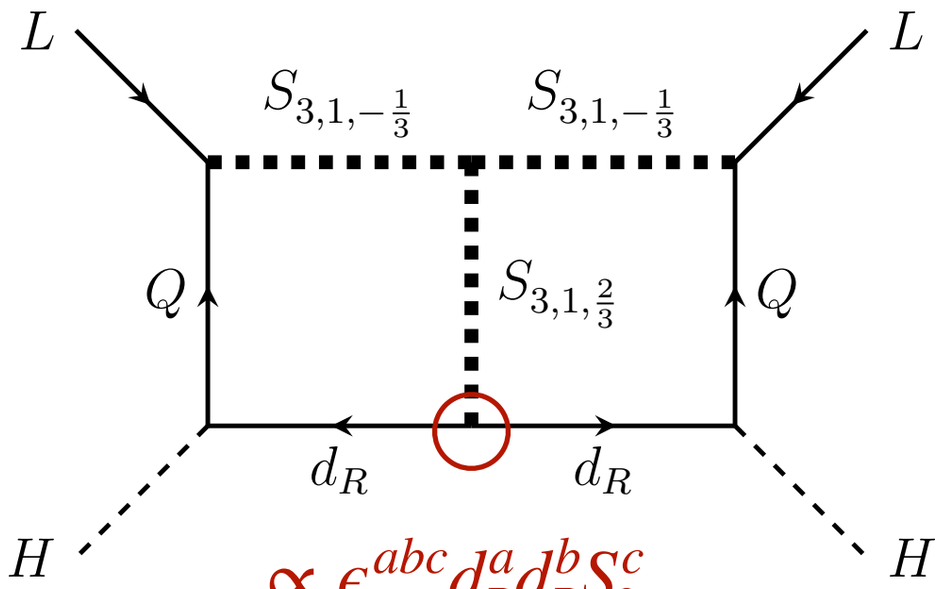
$$c_{LLQdH,2}^{(7),tvus} = \frac{1}{16\pi^2}\frac{2\sqrt{2}}{\Lambda^3}\overline{y_{SdF}}^{r}\overline{y_{SdF}}^{s}y_{SLQ}^{uv}y_{SLQ}^{tp}\overline{y_d}^{pr}$$

Dim-7 1-loop from closing two SM legs.
Which quark generation d_R^i contributes depends on the flavour assumption on y_{SLQ}

Tree-level and 1-loop matching with

MATCHETE [2212.04510]

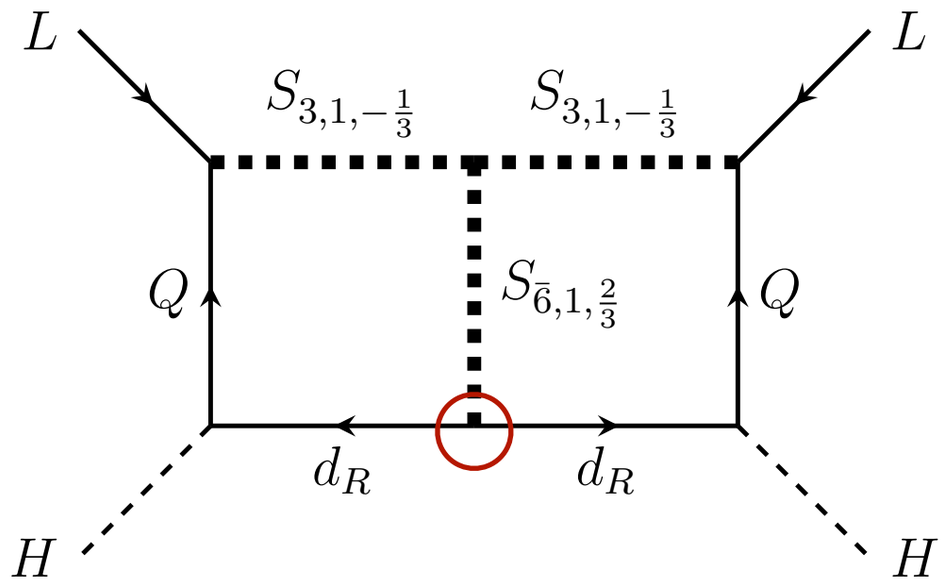
Symmetric vs. antisymmetric 2L Weinberg?



$\propto \epsilon^{abc} d_R^a d_R^b S_3^c$

antisymmetric colour contraction,
must be antisymmetric in flavour

can not give diagonal entries for the neutrino masses



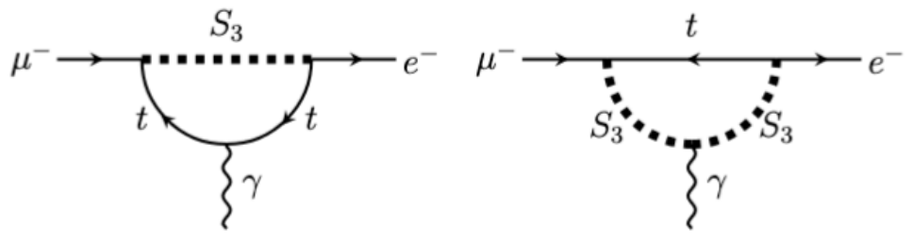
symmetric colour contraction

can give diagonal entries for the neutrino mass

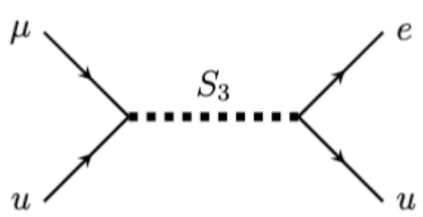
Operator-to-model table

#	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14
Model	$\left(S_{8,2,\frac{1}{2}}, F_{8,1,0}\right)$	$\left(S_{8,2,\frac{1}{2}}, F_{8,3,0}\right)$	$(S_{1,1,1}, S_{1,3,0})$	$\left(S_{1,1,1}, S_{8,2,\frac{1}{2}}\right)$	$\left(S_{3,1,-\frac{1}{3}}, S_{3,1,\frac{2}{3}}\right)$	$\left(S_{3,1,-\frac{1}{3}}, S_{6,1,-\frac{2}{3}}\right)$	$\left(S_{3,3,-\frac{1}{3}}, S_{3,1,\frac{2}{3}}\right)$	$\left(S_{3,3,-\frac{1}{3}}, S_{6,1,-\frac{2}{3}}\right)$	$\left(S_{3,2,\frac{1}{6}}, S_{6,1,\frac{1}{3}}\right)$	$\left(S_{3,2,\frac{1}{6}}, S_{6,3,\frac{1}{3}}\right)$	$\left(S_{3,1,-\frac{1}{3}}, F_{8,1,0}\right)$	$\left(S_{3,3,-\frac{1}{3}}, F_{8,3,0}\right)$	$\left(S_{3,2,\frac{1}{6}}, F_{8,1,0}\right)$	$\left(S_{3,2,\frac{1}{6}}, F_{8,3,0}\right)$
$\mathcal{O}^{(9)}_{dddueue}$					T	T					T			
$\mathcal{O}^{(9)}_{dQdueL}$					T	T					T			
$\mathcal{O}^{(9)}_{dQdQLL}$	T	T		T	T	T	T	T	T	T	T	T	T	T
$\mathcal{O}^{(9)}_{dQQuLL}$	T	T		T										
$\mathcal{O}^{(9)}_{QuQuLL}$	T	T		T										
$\mathcal{O}^{(9)}_{LLH^4(D/W)^2}$			T											
$\mathcal{O}^{(7)}_{LH}$	1L	1L												
$\mathcal{O}^{(7)}_{LHD}$	1L	1L	1L											
$\mathcal{O}^{(7)}_{LLduD}$	1L	1L		1L					1L					
$\mathcal{O}^{(7)}_{LLQdH}$	1L	1L		1L	1L	1L	1L	1L	1L	1L	1L	1L	1L	1L
$\mathcal{O}^{(7)}_{LLQuH}$	1L	1L		1L										
$\mathcal{O}^{(7)}_{LeudH}$					1L	1L	1L	1L	1L	1L	1L			
$\mathcal{O}^{(5)}_{LH}$	1L	1L	2L anti	2L anti	2L anti	2L sym	2L anti	2L sym	2L anti	2L sym	2L sym	2L sym	2L sym	2L sym

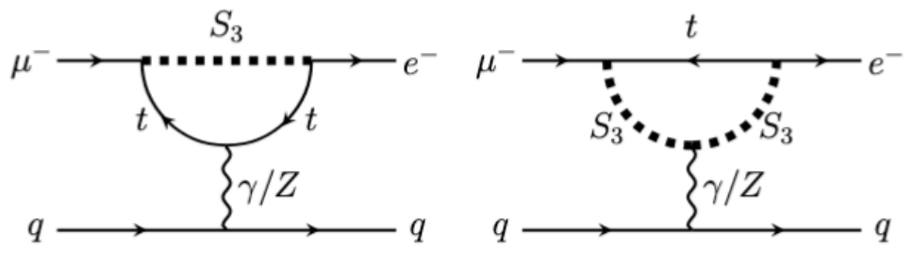
Charged Lepton Flavour violation



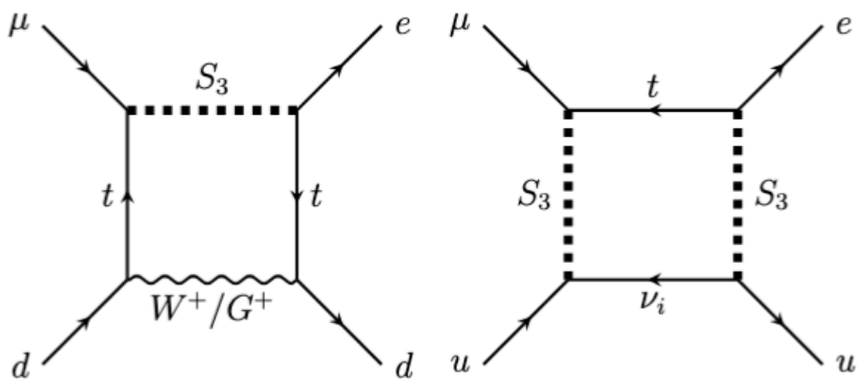
(a) Diagrams for $\mu \to e\gamma$



(b) Tree-level diagram for μ to e conversion



(c) Penguin diagrams for μ to e conversion



(d) Box diagrams for μ to e conversion.

$$\mathrm{BR}(\mu \to e\gamma) \simeq \frac{3s\theta_W^2}{8\pi^3\alpha}|V_{tb}|^2 \sum_{\alpha=1}^{2} \left(y_{SLQ}^{23\alpha}\right)^* y_{SLQ}^{13\alpha} \frac{m_W^2}{m_{S_3}^2} F\left(t_{3\alpha}\right)$$

$$F(t) = \frac{1+4t-5t^2+2t(2+t)\ln(t)}{4(t-1)^4}. \qquad t_{3\alpha} = \frac{m_t^2}{m_{S_\alpha}^2}$$

$$\omega_{\mathrm{conv}} = 4\left|\frac{1}{8}A_2^{R*}D + \tilde{g}_{LV}^{(p)}V^{(p)} + \tilde{g}_{LV}^{(n)}V^{(n)}\right|^2 + 4\left|\frac{1}{8}A_2^{L*}D\right|^2$$

$$A_2^L = \frac{m_e}{16\pi^2 m_\mu}|V_{tb}|^2 \sum_{\alpha=1}^{2} \frac{\left(y_{SLQ}^{23\alpha}\right)^* y_{SLQ}^{13\alpha}}{m_{S_\alpha}^2} F(t_{3\alpha}),$$

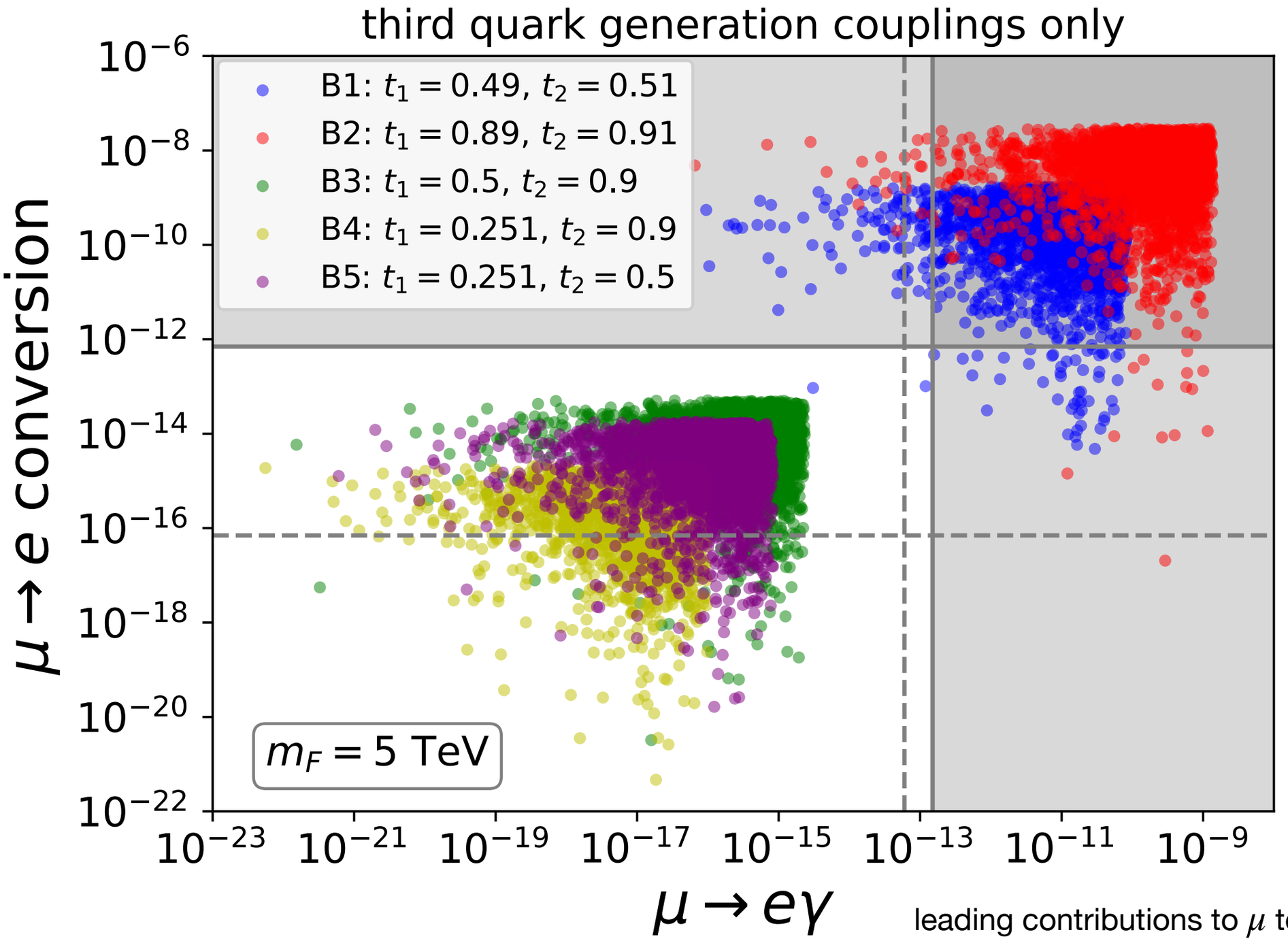
$$A_2^R = \frac{1}{16\pi^2}|V_{tb}|^2 \sum_{\alpha=1}^{2} \frac{\left(y_{SLQ}^{23\alpha}\right)^* y_{SLQ}^{13\alpha}}{m_{S_\alpha}^2} F(t_{3\alpha})$$

$$\begin{aligned} g_{LV(d)}^{box} = -\frac{|V_{tb}|^2|V_{td}|^2}{64\pi^2} \sum_\alpha \left(y_{SLQ}^{23\alpha}\right)^* y_{SLQ}^{13\alpha} \Big\{ & m_t^2 y_t^2 D_0\left(m_W^2, m_{S_\alpha}^2, m_t^2, m_t^2\right) \\ & + g^2\left(C_0\left(m_W^2, 0, m_{S_\alpha}^2\right) + m_t^2 D_0\left(m_W^2, 0, m_{S_\alpha}^2, m_t^2\right)\right. \\ & \left. - 2\left(D_{00}\left(m_W^2, 0, m_{S_\alpha}^2, m_t^2\right) + D_{00}\left(m_W^2, m_{S_\alpha}^2, m_t^2, m_t^2\right)\right)\right) \Big\}, \end{aligned}$$

$$g_{LV(d)}^{\gamma} = -\frac{\alpha|V_{tb}|^2}{144\pi} \sum_\alpha \frac{\left(y_{SLQ}^{23\alpha}\right)^* y_{SLQ}^{13\alpha}}{m_{S_\alpha}^2} \frac{t_{3\alpha}^3 - 18t_{3\alpha}^2 + 27t_{3\alpha} + 2\left(t_{3\alpha}^3 + 6t_{3\alpha} - 4\right)\ln\left(t_{3\alpha}\right) - 10}{\left(t_{3\alpha}-1\right)^4},$$

$$g_{LV(d)}^{(Z)} = \frac{g^2\left(4s_w^2 - 3\right)|V_{tb}|^2}{128\pi^2 m_W^2} \sum_\alpha \left(y_{SLQ}^{23\alpha}\right)^* y_{SLQ}^{13\alpha} \frac{t_{3\alpha}\left(t_{3\alpha} - \ln\left(t_{3\alpha}\right) - 1\right)}{\left(t_{3\alpha}-1\right)^2}.$$

cLFV for only third generation quark couplings



leading contributions to μ to e conversion are CKM suppressed!