UV completions of 0νββ decay operators at one-loop level

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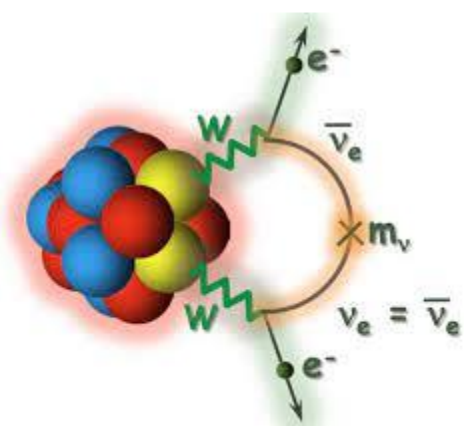
The 2nd conference on neutrinoless double beta decay and relevant physics, Zhuhai, 20th May 2023

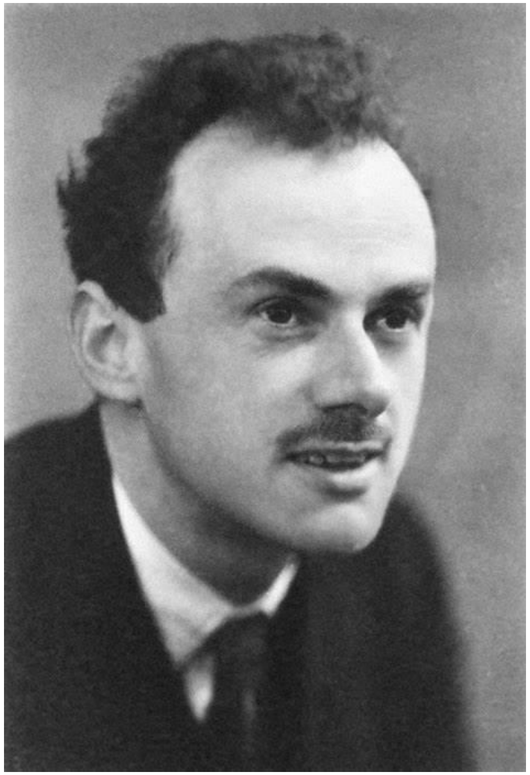
Based on arXiv: 2110.15347, 2301.02503, in collaboration with Ping-Tao Chen, Chang-Yuan Yao



Massive neutrinos: Dirac or Majorana?

$\nu \neq \bar{\nu}$

$\nu = \bar{\nu}$



vs.

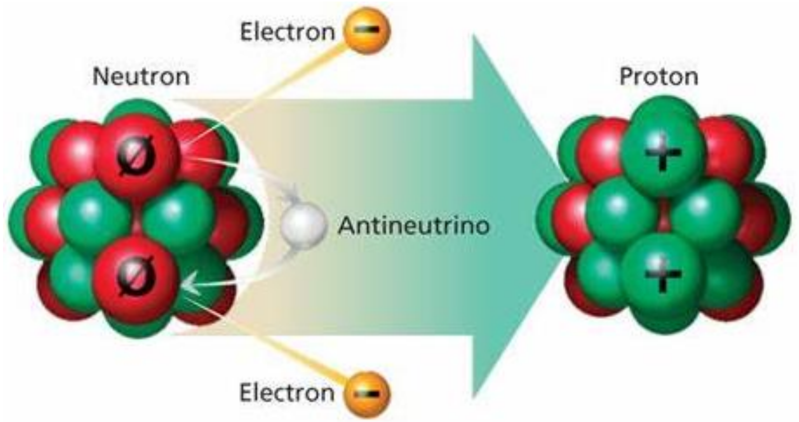
- **neutrinoless double beta decay**
- lepton number violation at collider
- cosmology

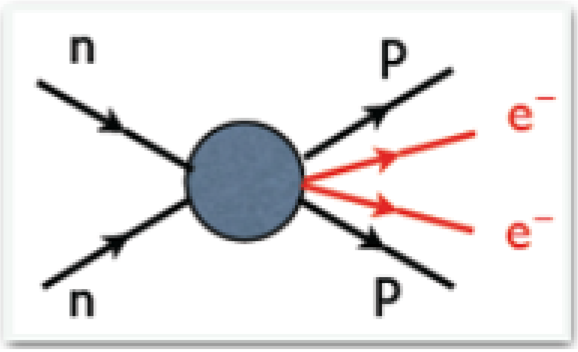
The 0νββ decays

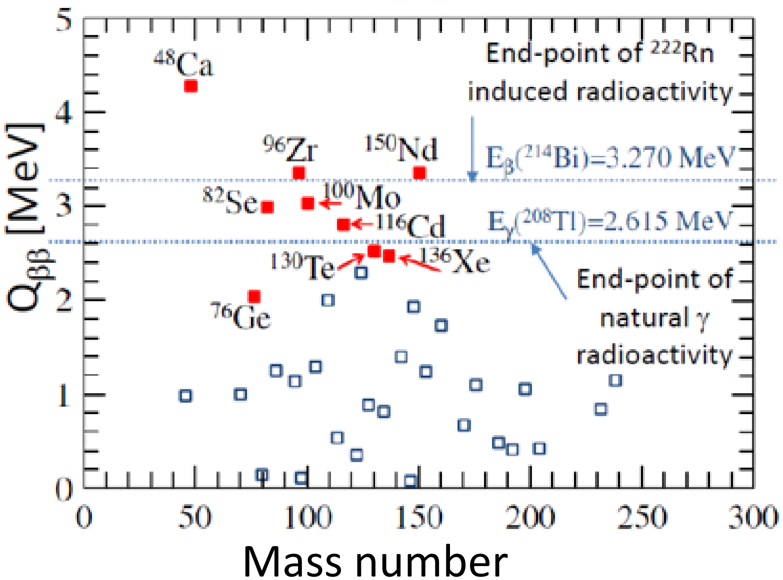
0νββ is potentially observable in certain even-even nuclei (^{48}Ca, **^{76}Ge**, ^{100}Mo, ^{130}Te, **^{136}Xe**) for which single beta decay is energetically forbidden. The decay rate is less than 1 event per ton and year.

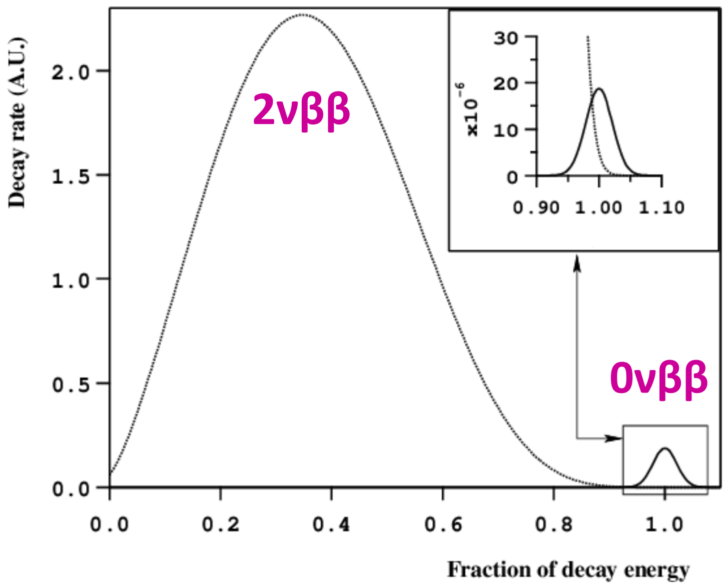
$$0\nu\beta\beta:\ (A,Z) \rightarrow (A,Z+2) + 2e^-$$

$$T_{1/2} > 10^{25}\ \text{yr}$$



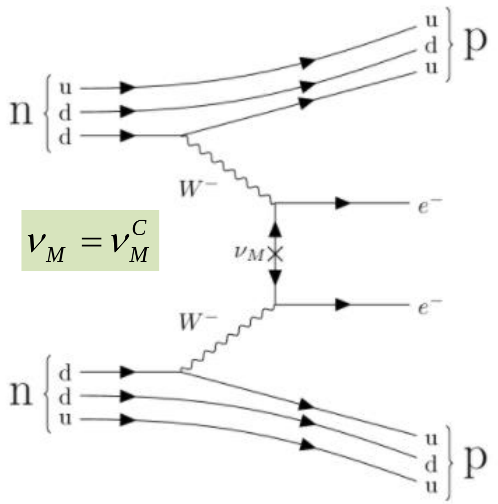






Standard mass mechanism of 0νββ decay

0νββ decay is mediated by light and massive Majorana neutrinos (the ones which oscillate) and all other mechanisms potentially leading to 0νββ give negligible or no contribution



- **The decay amplitude is proportional to the effective mass**

PMNS

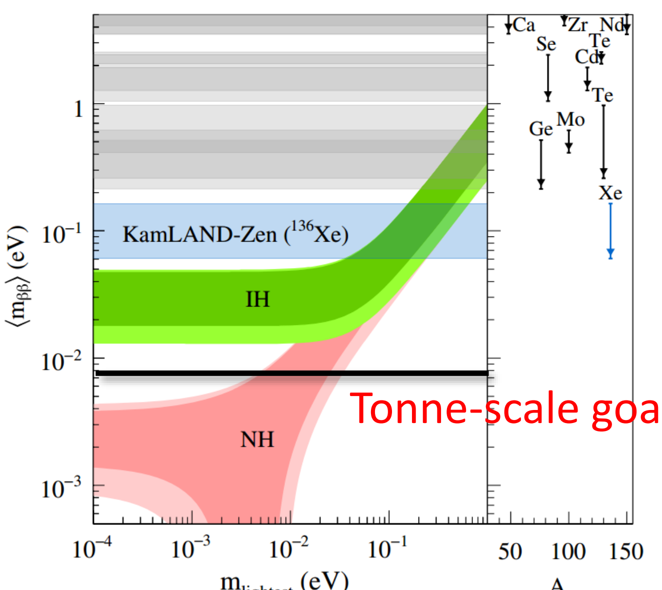
neutrino masses

Majorana phases

$$|m_{\beta\beta}| = \left|\sum_k U_{ek}^2\, m_k\right|$$

$$= \left|c_{12}^2\, c_{13}^2\, m_1 + s_{12}^2\, c_{13}^2\, e^{i\alpha_{21}}\, m_2 + s_{13}^2\, e^{i\alpha_{31}}\, m_3\right|$$

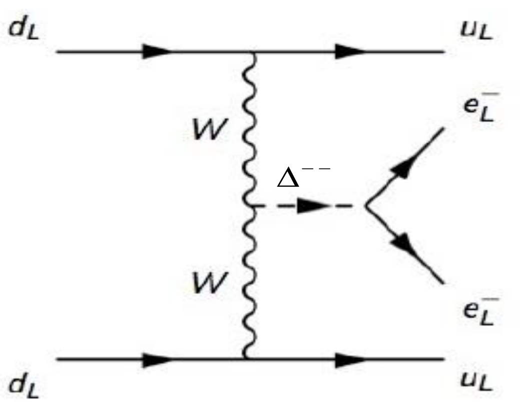
cosines and sines of the mixing angles



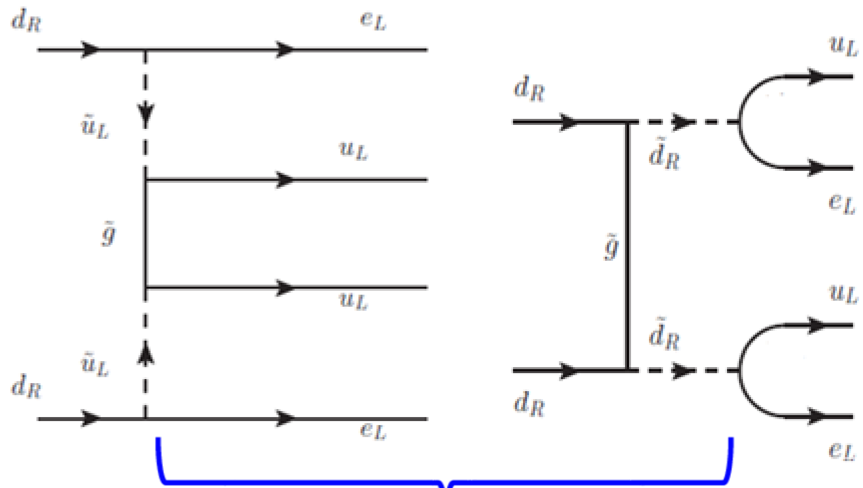
- Unknown: lightest mass, hierarchy and Majorana phases
- Large theoretical uncertainties in the nuclear matrix elements

Possible BSM physics in 0νββ decay

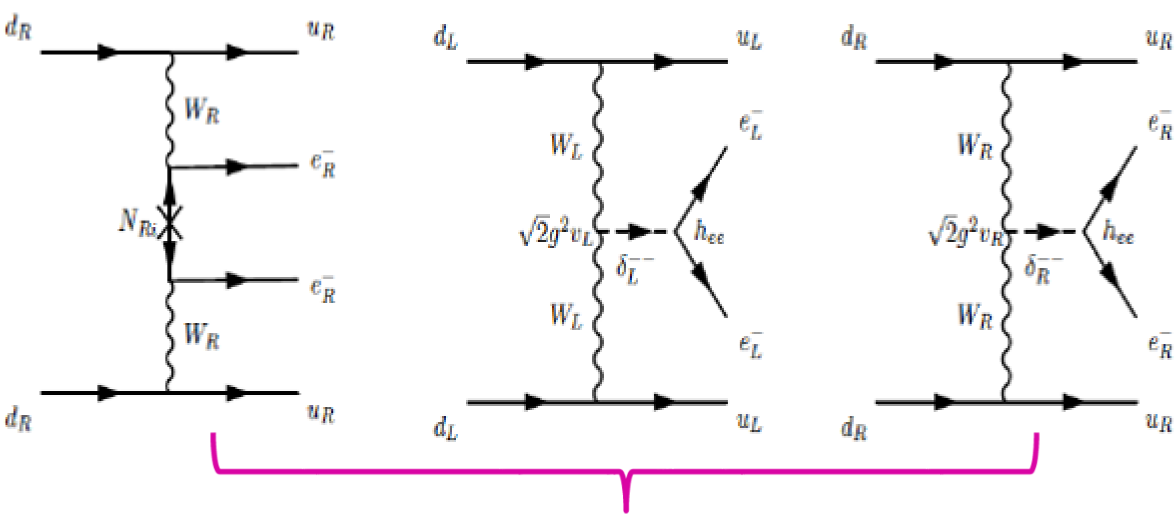
The 0νββ decay can also be induced by other ΔL=2 physics besides the Majorana neutrino mass. There are many possible scenarios:



Type II seesaw



R-parity violating SUSY

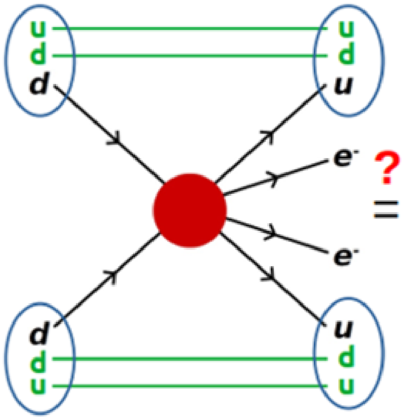


Left-right model

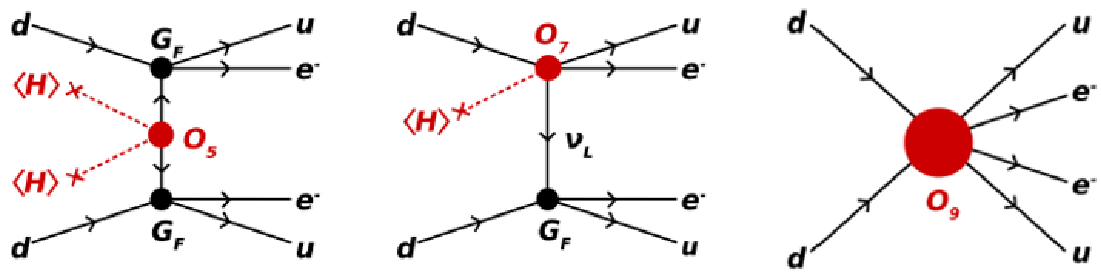
- 0νββ decay is connected to TeV scale physics and LFV.
- **A systematical classification is necessary!**

Classification of 0νββ mechanisms from SMEFT

The amplitude of 0νββ decay can be generally divided into: [Pas, Hirsch, Klapdor, Kovalenko, hep-ph/0008182, hep-ph/9804374]



Mass mechanism — "long-range" — "short-range"



(a) (b) (c)

EFT:

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{c_i^{(5)}}{\Lambda}\mathcal{O}_i^{MM} + \frac{c_i^{(7)}}{\Lambda^3}\mathcal{O}_i^{LR} + \frac{c_i^{(9)}}{\Lambda^5}\mathcal{O}_i^{SR} + \dots$$

[Graesser,1606.04549; Liao,Ma,2007.08125; Yu et al,2007.07899]

See Jiang-Hao Yu's talk

$$\mathcal{O}_1^{MM} = \epsilon^{ik}\epsilon^{jl}(\overline{\ell_i^c}\ell_j)H_k H_l$$

$$\begin{aligned}
\mathcal{O}_1^{LR} &= \epsilon^{ik}\epsilon^{jl}(\overline{\ell_i^c}\ell_j)(\overline{d_R}Q_k)H_l\,,\\
\mathcal{O}_2^{LR} &= \epsilon^{ik}\epsilon^{jl}(\overline{\ell_i^c}\gamma^{\mu\nu}\ell_j)(\overline{d_R}\gamma_{\mu\nu}Q_k)H_l\,,\\
\mathcal{O}_3^{LR} &= \epsilon^{jk}(\overline{\ell_i^c}\ell_j)(\overline{Q}^i u_R)H_k\,,\\
\mathcal{O}_4^{LR} &= (\overline{\ell_i^c}\gamma^\mu e_R)(\overline{d_R}\gamma_\mu u_R)\epsilon^{ij}H_j
\end{aligned}$$

$$\begin{aligned}
\mathcal{O}_1^{SR} &= \epsilon_{ij}(\overline{Q}_i\gamma^\mu Q_m)(\overline{u}_R\gamma_\mu d_R)(\overline{\ell}_j\ell_m^c)\,,\\
\mathcal{O}_2^{SR} &= \epsilon_{ij}(\overline{Q}_i\gamma^\mu\lambda^A Q_m)(\overline{u}_R\gamma_\mu\lambda^A d_R)(\overline{\ell}_j\ell_m^c)\,,\\
\mathcal{O}_3^{SR} &= (\overline{u}_R Q_i)(\overline{u}_R Q_j)(\overline{\ell}_i\ell_j^c)\,,\\
\mathcal{O}_4^{SR} &= (\overline{u}_R\lambda^A Q_i)(\overline{u}_R\lambda^A Q_j)(\overline{\ell}_i\ell_j^c)\,,\\
\mathcal{O}_5^{SR} &= \epsilon_{ij}\epsilon_{mn}(\overline{Q}_i d_R)(\overline{Q}_m d_R)(\overline{\ell}_j\ell_n^c)\,,\\
\mathcal{O}_6^{SR} &= \epsilon_{ij}\epsilon_{mn}(\overline{Q}_i\lambda^A d_R)(\overline{Q}_m\lambda^A d_R)(\overline{\ell}_j\ell_n^c)\,,\\
\mathcal{O}_7^{SR} &= (\overline{u}_R\gamma^\mu d_R)(\overline{u}_R\gamma_\mu d_R)(\overline{e}_R e_R^c)\,,\\
\mathcal{O}_8^{SR} &= \epsilon_{ij}(\overline{u}_R\gamma^\mu d_R)(\overline{Q}_i d_R)(\overline{\ell}_j\gamma_\mu e_R^c)\,,\\
\mathcal{O}_9^{SR} &= \epsilon_{ij}(\overline{u}_R\gamma^\mu\lambda^A d_R)(\overline{Q}_i\lambda^A d_R)(\overline{\ell}_j\gamma_\mu e_R^c)\,,\\
\mathcal{O}_{10}^{SR} &= (\overline{u}_R\gamma^\mu d_R)(\overline{u}_R Q_i)(\overline{\ell}_i\gamma_\mu e_R^c)\,,\\
\mathcal{O}_{11}^{SR} &= (\overline{u}_R\gamma^\mu\lambda^A d_R)(\overline{u}_R\lambda^A Q_i)(\overline{\ell}_i\gamma_\mu e_R^c)
\end{aligned}$$

Decomposing the short-range 0νββ operators

A systematic classification (at a given loop order) of the possible realizations is feasible through the following "**recipe**" [Gavela et al,0809.3451; Hirsch et al,1204.5862]

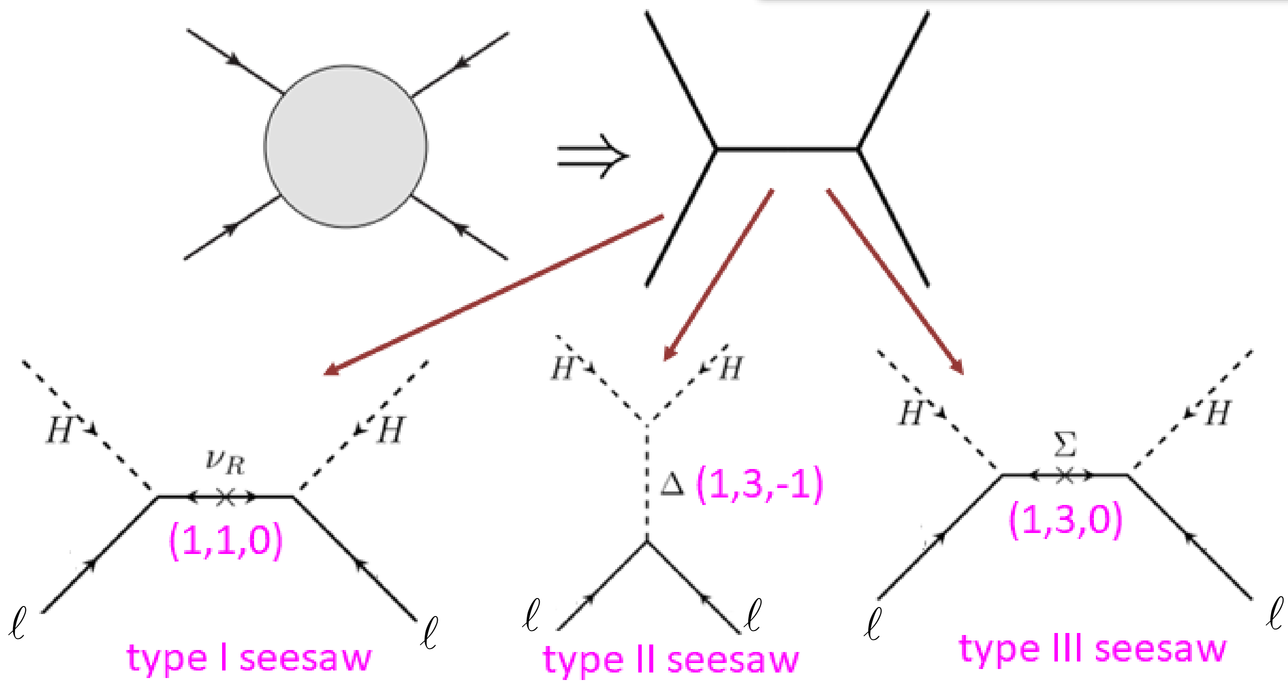
① **Topologies**: identify all possible L−loop connected topologies and 6 external legs

② **Diagrams**: assign the fields involved in the concerned operators to the external lines, and specify the Lorentz nature (spinor or scalar) of each internal line.

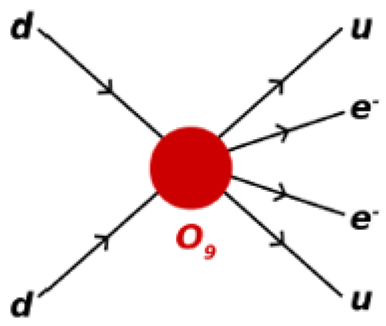
③ **Models**: fix the **$SU(3)_C$ x $SU(2)_L$ x $U(1)_Y$** quantum numbers of the internal fields, and each vertex should be invariant under the SM gauge symmetry.

- Example: decompose Weinberg operator

$$\mathcal{O}_W = \frac{c_{\alpha\beta}}{\Lambda}\,\epsilon^{ik}\epsilon^{jl}(\overline{\ell^c_{\alpha i}}\ell_{\beta j})H_k H_l$$



Tree-level decomposition



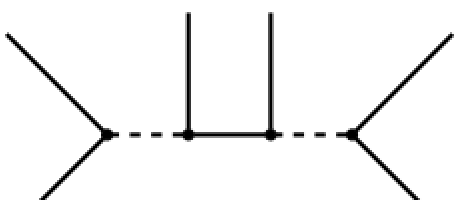


Diagram I

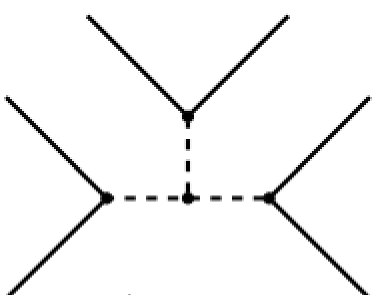


Diagram II

#	Decomposition	Long Range?	Mediator $(U(1)_{em}, SU(3)_c)$ S or V_ρ	ψ	S' or V'_ρ	Models/Refs./Comments
1-i	$(\bar u d)(\bar e)(\bar e)(\bar u d)$	(a)	$(+1,\mathbf{1})$	$(0,\mathbf{1})$	$(-1,\mathbf{1})$	Mass mechan., RPV [58-60], LR-symmetric models [39], Mass mechanism with ν_S [61], TeV scale seesaw, e.g., [62, 63]
			$(+1,\mathbf{8})$	$(0,\mathbf{8})$	$(-1,\mathbf{8})$	[64]
1-ii-a	$(\bar u d)(\bar u)(d)(\bar e\bar e)$		$(+1,\mathbf{1})$	$(+5/3,\mathbf{3})$	$(+2,\mathbf{1})$	
			$(+1,\mathbf{8})$	$(+5/3,\mathbf{3})$	$(+2,\mathbf{1})$	
1-ii-b	$(\bar u d)(d)(\bar u)(\bar e\bar e)$		$(+1,\mathbf{1})$	$(+4/3,\overline{\mathbf{3}})$	$(+2,\mathbf{1})$	
			$(+1,\mathbf{8})$	$(+4/3,\overline{\mathbf{3}})$	$(+2,\mathbf{1})$	
2-i-a	$(\bar u d)(d)(\bar e)(\bar u\bar e)$		$(+1,\mathbf{1})$	$(+4/3,\overline{\mathbf{3}})$	$(+1/3,\overline{\mathbf{3}})$	
			$(+1,\mathbf{8})$	$(+4/3,\overline{\mathbf{3}})$	$(+1/3,\overline{\mathbf{3}})$	
2-i-b	$(\bar u d)(\bar e)(d)(\bar u\bar e)$	(b)	$(+1,\mathbf{1})$	$(0,\mathbf{1})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58-60], LQ [65, 66]
			$(+1,\mathbf{8})$	$(0,\mathbf{8})$	$(+1/3,\overline{\mathbf{3}})$	
2-ii-a	$(\bar u d)(\bar u)(\bar e)(d\bar e)$		$(+1,\mathbf{1})$	$(+5/3,\mathbf{3})$	$(+2/3,\mathbf{3})$	
			$(+1,\mathbf{8})$	$(+5/3,\mathbf{3})$	$(+2/3,\mathbf{3})$	
2-ii-b	$(\bar u d)(\bar e)(\bar u)(d\bar e)$	(b)	$(+1,\mathbf{1})$	$(0,\mathbf{1})$	$(+2/3,\mathbf{3})$	RPV [58-60], LQ [65, 66]
			$(+1,\mathbf{8})$	$(0,\mathbf{8})$	$(+2/3,\mathbf{3})$	
2-iii-a	$(d\bar e)(\bar u)(d)(\bar u\bar e)$	(c)	$(-2/3,\overline{\mathbf{3}})$	$(0,\mathbf{1})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58-60]
			$(-2/3,\overline{\mathbf{3}})$	$(0,\mathbf{8})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58-60]
2-iii-b	$(d\bar e)(d)(\bar u)(\bar u\bar e)$		$(-2/3,\overline{\mathbf{3}})$	$(-1/3,\mathbf{3})$	$(+1/3,\overline{\mathbf{3}})$	
			$(-2/3,\overline{\mathbf{3}})$	$(-1/3,\overline{\mathbf{6}})$	$(+1/3,\overline{\mathbf{3}})$	
3-i	$(\bar u\bar u)(\bar e)(\bar e)(dd)$		$(+4/3,\overline{\mathbf{3}})$	$(+1/3,\overline{\mathbf{3}})$	$(-2/3,\overline{\mathbf{3}})$	only with V_ρ and V'_ρ
			$(+4/3,\mathbf{6})$	$(+1/3,\mathbf{6})$	$(-2/3,\mathbf{6})$	
3-ii	$(\bar u\bar u)(d)(d)(\bar e\bar e)$		$(+4/3,\overline{\mathbf{3}})$	$(+5/3,\mathbf{3})$	$(+2,\mathbf{1})$	only with V_ρ
			$(+4/3,\mathbf{6})$	$(+5/3,\mathbf{3})$	$(+2,\mathbf{1})$	
3-iii	$(dd)(\bar u)(\bar u)(\bar e\bar e)$		$(+2/3,\mathbf{3})$	$(+4/3,\overline{\mathbf{3}})$	$(+2,\mathbf{1})$	only with V_ρ
			$(+2/3,\overline{\mathbf{6}})$	$(+4/3,\overline{\mathbf{3}})$	$(+2,\mathbf{1})$	
4-i	$(d\bar e)(\bar u)(\bar u)(d\bar e)$	(c)	$(-2/3,\overline{\mathbf{3}})$	$(0,\mathbf{1})$	$(+2/3,\mathbf{3})$	RPV [58-60]
			$(-2/3,\overline{\mathbf{3}})$	$(0,\mathbf{8})$	$(+2/3,\mathbf{3})$	RPV [58-60]
4-ii-a	$(\bar u\bar u)(d)(\bar e)(d\bar e)$		$(+4/3,\overline{\mathbf{3}})$	$(+5/3,\mathbf{3})$	$(+2/3,\mathbf{3})$	only with V_ρ
			$(+4/3,\mathbf{6})$	$(+5/3,\mathbf{3})$	$(+2/3,\mathbf{3})$	see Sec. 4 (this work)
4-ii-b	$(\bar u\bar u)(\bar e)(d)(d\bar e)$		$(+4/3,\overline{\mathbf{3}})$	$(+1/3,\overline{\mathbf{3}})$	$(+2/3,\mathbf{3})$	only with V_ρ
			$(+4/3,\mathbf{6})$	$(+1/3,\mathbf{6})$	$(+2/3,\mathbf{3})$	
5-i	$(\bar u\bar e)(d)(d)(\bar u\bar e)$	(c)	$(-1/3,\mathbf{3})$	$(0,\mathbf{1})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58-60]
			$(-1/3,\mathbf{3})$	$(0,\mathbf{8})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58-60]
5-ii-a	$(\bar u\bar e)(\bar u)(\bar e)(dd)$		$(-1/3,\mathbf{3})$	$(+1/3,\overline{\mathbf{3}})$	$(-2/3,\overline{\mathbf{3}})$	only with V'_ρ
			$(-1/3,\mathbf{3})$	$(+1/3,\mathbf{6})$	$(-2/3,\mathbf{6})$	
5-ii-b	$(\bar u\bar e)(\bar e)(\bar u)(dd)$		$(-1/3,\mathbf{3})$	$(-4/3,\mathbf{3})$	$(-2/3,\overline{\mathbf{3}})$	only with V'_ρ
			$(-1/3,\mathbf{3})$	$(-4/3,\mathbf{3})$	$(-2/3,\mathbf{6})$	

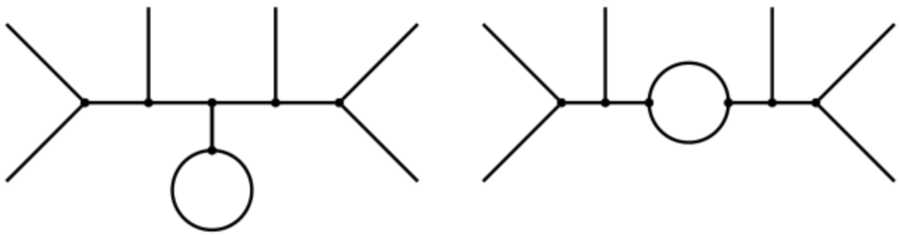
[Bonnet, Hirsch, Ota, Winter, 1212.3045]

Topologies for short-range $0\nu\beta\beta$

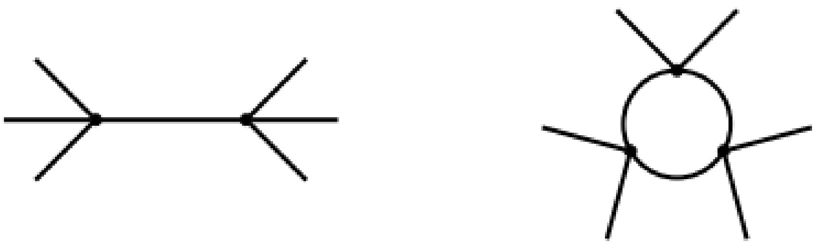
Topolopies: Feynman diagrams where no property of the fields is considered

(i) All connected topologies with 3- and 4- point vertices and 6 external legs

(ii) Remove tadpoles and self-energies (**divergent**)

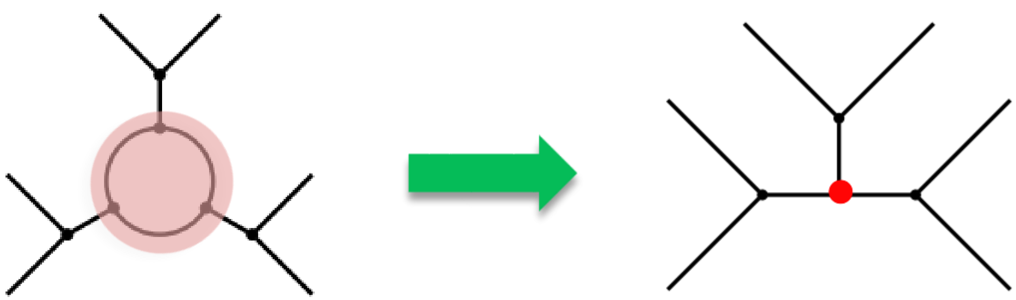


(iii) Exclude non-renormalizable topologies



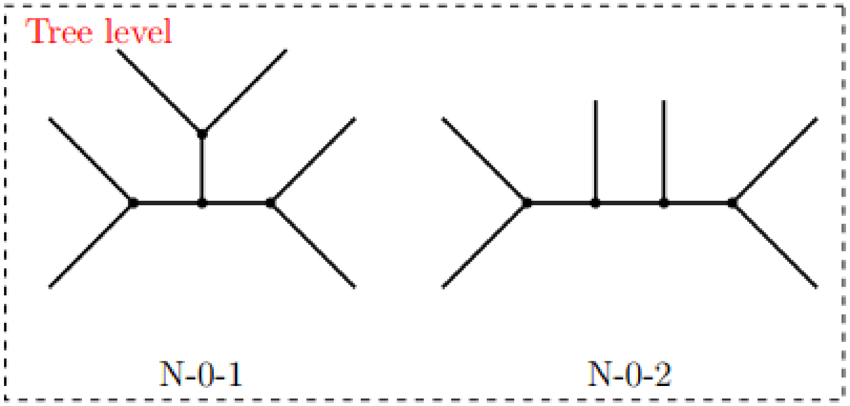
The 6 external legs are quark and lepton fields for short-range $0\nu\beta\beta$

(iv) Discard topologies with 3-point loop vertices

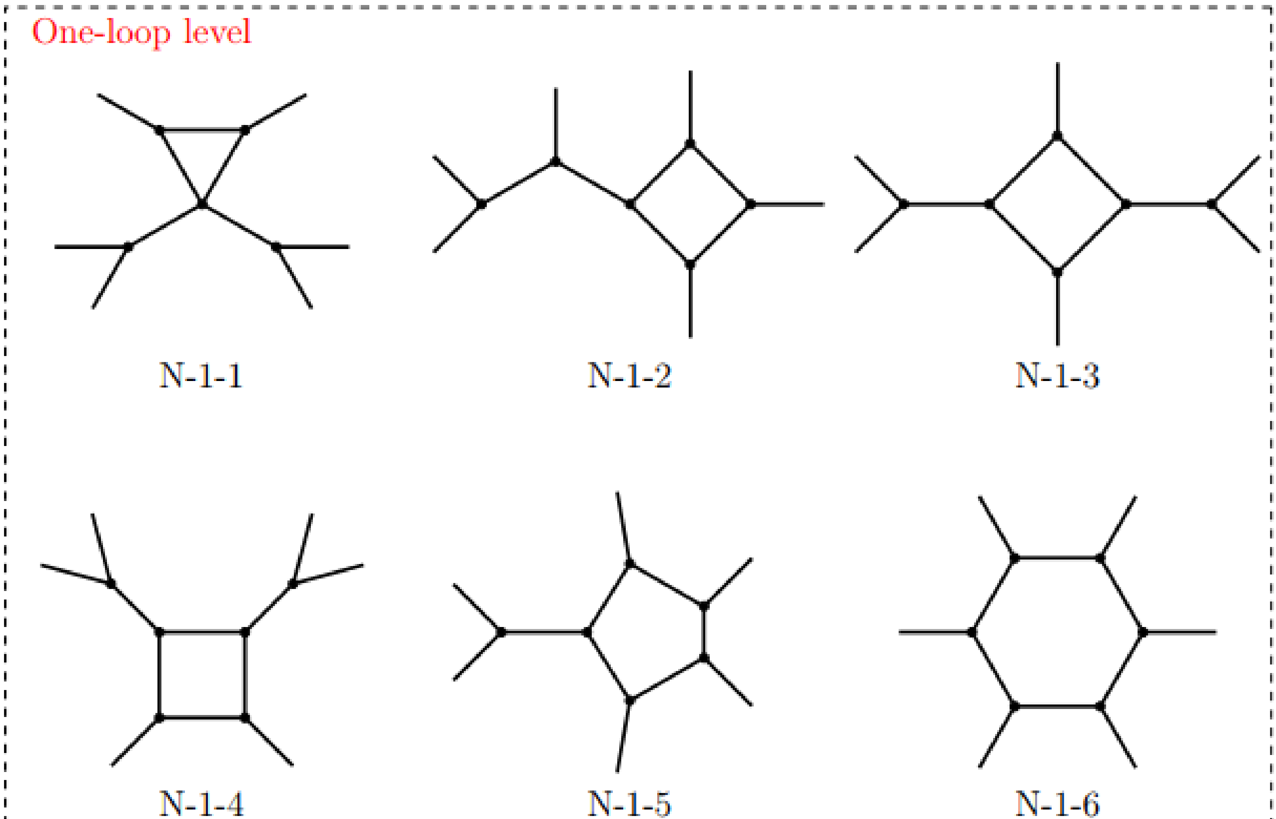


any loop with 3 external legs can be compressible to a renormalizable trilinear vertex

➢ 2 tree + 6 one-loop renormalizable topologies



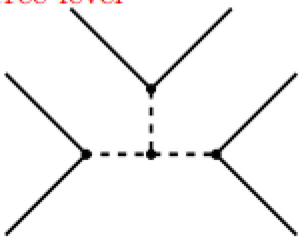
[Chen, Ding, Yao, 2110.15347]



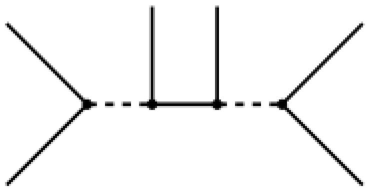
field insertions: topologies→diagrams

Focusing only on fermions and scalar bosons [**Not considering new gauge bosons**]:

Tree level



N-0-1-1



N-0-2-1

- Three kinds of renormalizable vertices

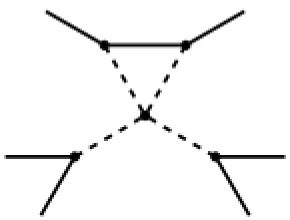
  ①fermion-fermion-scalar (FFS)

  ②scalar-scalar-scalar (SSS)

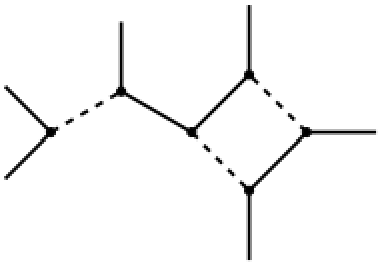
  ③scalar-scalar-scalar-scalar (SSSS)

[Chen, Ding, Yao, 2110.15347]

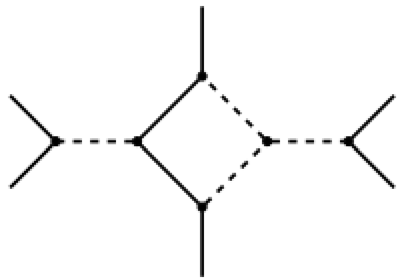
One-loop level



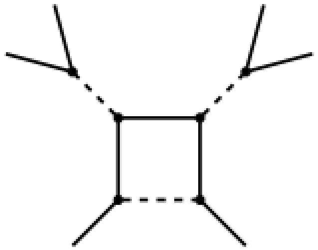
N-1-1-1



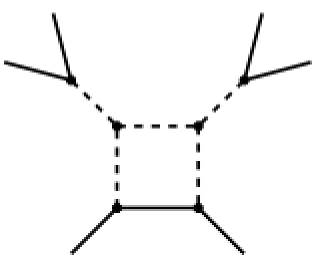
N-1-2-1



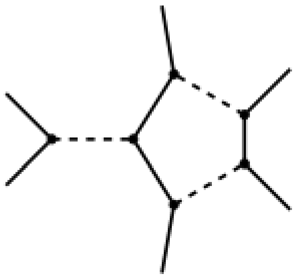
N-1-3-1



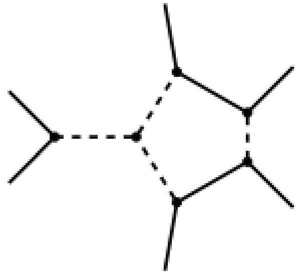
N-1-4-1



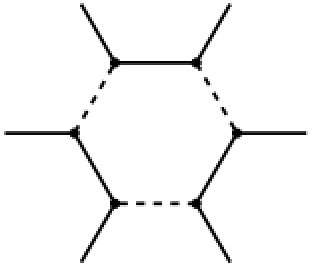
N-1-4-2



N-1-5-1



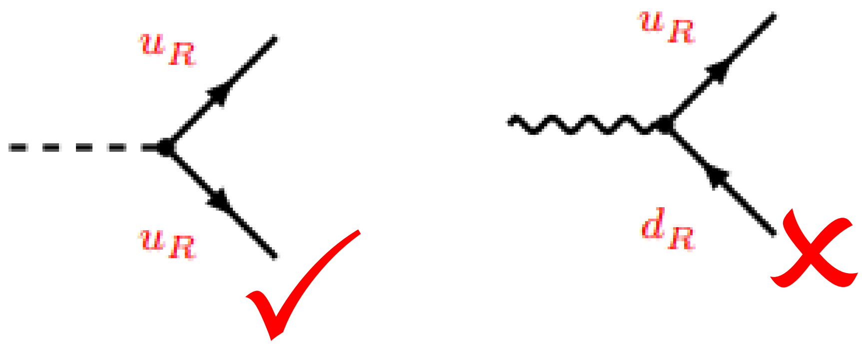
N-1-5-2



N-1-6-1

➢ Diagrams continuum: attach external fields

Lorentz invariance fixes the mediator to be **scalar or vector** by chirality of external fermions



Classify 0νββ operators

Notation	$0\nu\beta\beta$ decay operators	External fields
N1	$\mathcal{O}_1^{SR},\ \mathcal{O}_2^{SR}$	$\overline{Q}, Q, \bar{u}_R, d_R, \overline{\ell}, \ell^c$
N2	$\mathcal{O}_3^{SR},\ \mathcal{O}_4^{SR}$	$Q, Q, \bar{u}_R, \bar{u}_R, \overline{\ell}, \ell^c$
N3	$\mathcal{O}_5^{SR},\ \mathcal{O}_6^{SR}$	$\overline{Q}, \overline{Q}, d_R, d_R, \overline{\ell}, \ell^c$
N4	$\mathcal{O}_7^{SR}$	$\bar{u}_R, \bar{u}_R, d_R, d_R, \bar{e}_R, e_R^c$
N5	$\mathcal{O}_8^{SR},\ \mathcal{O}_9^{SR}$	$\bar{u}_R, \overline{Q}, d_R, d_R, \overline{\ell}, e_R^c$
N6	$\mathcal{O}_{10}^{SR},\ \mathcal{O}_{11}^{SR}$	$\bar{u}_R, \bar{u}_R, Q, d_R, \overline{\ell}, e_R^c$

The number of possible diagrams

	TOPO \ $\mathcal{O}_i^{SR}$	N1	N2	N3	N4	N5	N6
Tree	N-0-1-1	2	2	5	2	2	2
	N-0-2-1	11	6	18	6	11	11
One-loop	N-1-1-1	6	5	12	5	6	6
	N-1-2-1	96	30	54	30	96	96
	N-1-3-1	11	9	21	9	12	12
	N-1-4-1	11	6	18	6	11	11
	N-1-4-2	11	6	18	6	11	11
	N-1-5-1	48	18	30	18	48	48
	N-1-5-2	48	18	30	18	48	48
	N-1-6-1	60	18	18	18	60	60

The redundant diagrams should be removed.

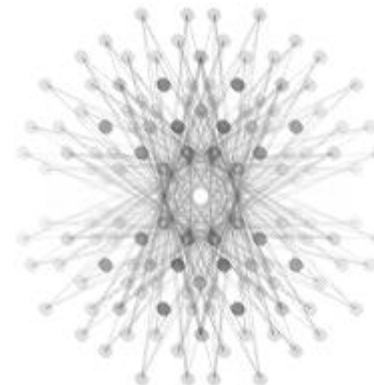
Determine quantum numbers: diagrams→models

The **SU(3)$_C$ x SU(2)$_L$ x U(1)$_Y$** quantum numbers of the mediators fields are fixed by gauge invariance of each interaction vertex

- 3-point vertex: $\bar{F}_1 F_2 S,\ S_1 S_2 S_3$

$$n_{\bar{F}_1} \otimes n_{F_2} \otimes n_S \supset \mathbf{1}, \qquad Y_{\bar{F}_1} + Y_{F_2} + Y_S = 0$$

$$n_{S_1} \otimes n_{S_2} \otimes n_{S_3} \supset \mathbf{1}, \qquad Y_{S_1} + Y_{S_2} + Y_{S_3} = 0$$



n_X denotes the SU(2)$_L$ or SU(3)$_C$ representation of the field X

- 4-point vertex: $S_1 S_2 S_3 S_4$

$$n_{S_1} \otimes n_{S_2} \otimes n_{S_3} \otimes n_{S_4} \supset \mathbf{1}, \qquad \sum_i Y_{S_i} = 0$$

GROUPMATH

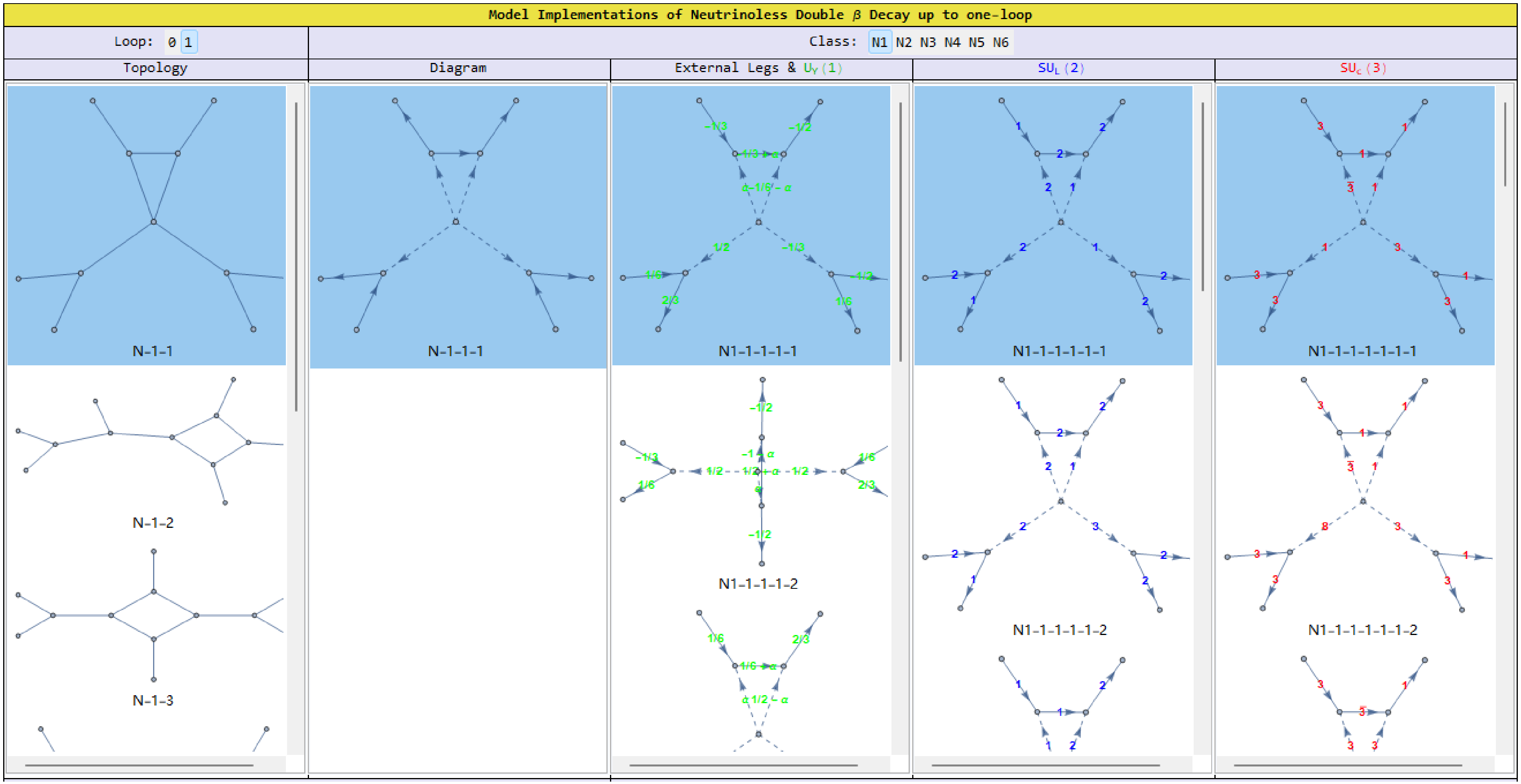
- The tensor products of SU(3)$_C$ representations are a bit complex

$$\mathbf{3} \otimes \mathbf{3} = \bar{\mathbf{3}} \oplus \mathbf{6}, \quad \mathbf{3} \otimes \bar{\mathbf{3}} = \mathbf{1} \oplus \mathbf{8}, \quad \mathbf{3} \otimes \mathbf{6} = \mathbf{8} \otimes \mathbf{10}, \quad \mathbf{3} \otimes \bar{\mathbf{6}} = \bar{\mathbf{3}} \oplus \overline{\mathbf{15}},$$

$$\mathbf{3} \otimes \mathbf{8} = \mathbf{3} \oplus \bar{\mathbf{6}} \oplus \mathbf{15}, \quad \mathbf{3} \otimes \mathbf{10} = \mathbf{15} \oplus \mathbf{15}, \quad \mathbf{3} \otimes \overline{\mathbf{10}} = \bar{\mathbf{6}} \oplus \overline{\mathbf{24}},$$

The Mathematica package **GroupMath** can facilitate the determination of SM quantum numbers.

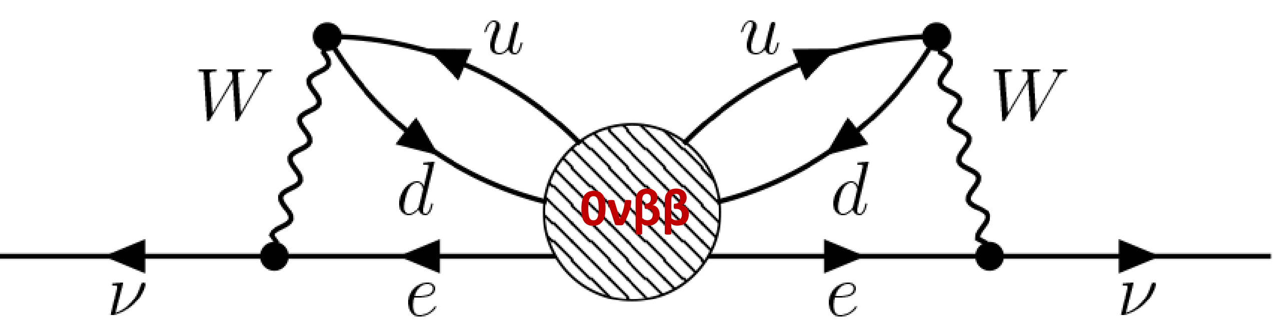
The possible short-range 0νββ models of at 1-loop level are collected in the attachment http://staff.ustc.edu.cn/~dinggj/supplementary_materials/0nbb.zip



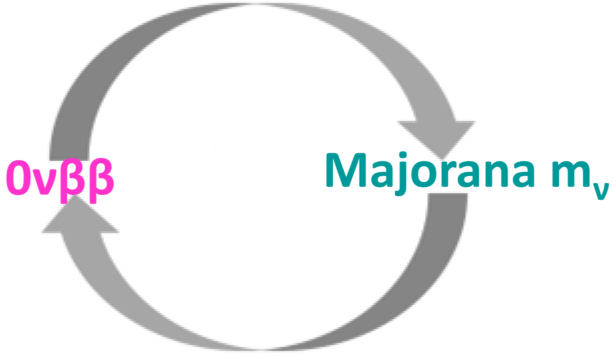
Genuine models

Genuine： A one-loop 0νββ model of is called "genuine" if it fulfills the conditions:
①It is renormalizable
② The leading contribution to 0νββ decay arises at 1-loop
③No need for extra symmetries beyond those of the SM

- Black box theorem implies that the mass mechanism is always present in 0νββ decay. In 0νββ models, Majorana neutrino masses usually are generated at less than four-loop order.



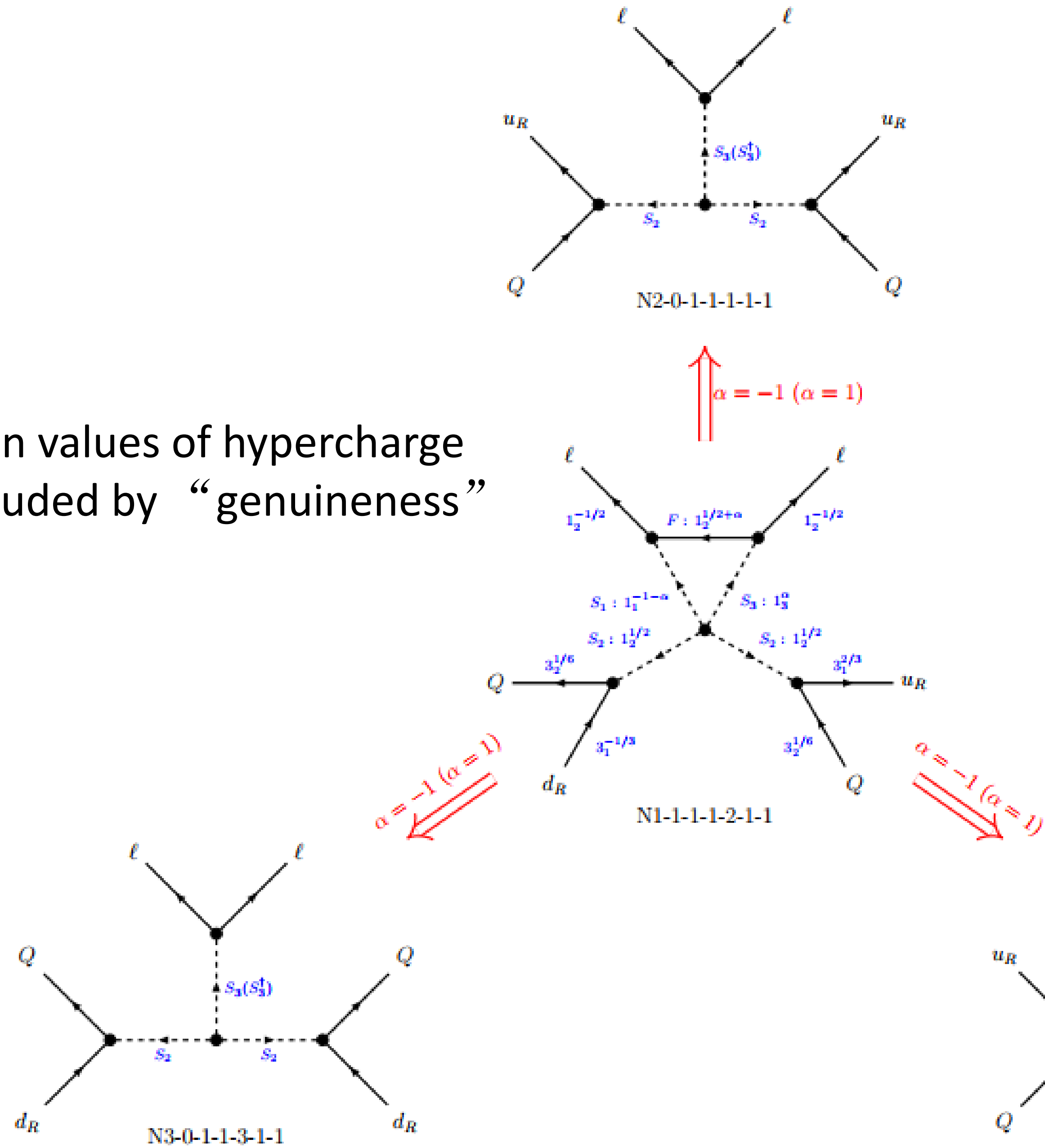
[Schechter, Valle, 1982']



- The short range contribution could dominate over the mass mechanism without fine-tuning in some parameter space, if the neutrino mass is generated at least at two-loop order.

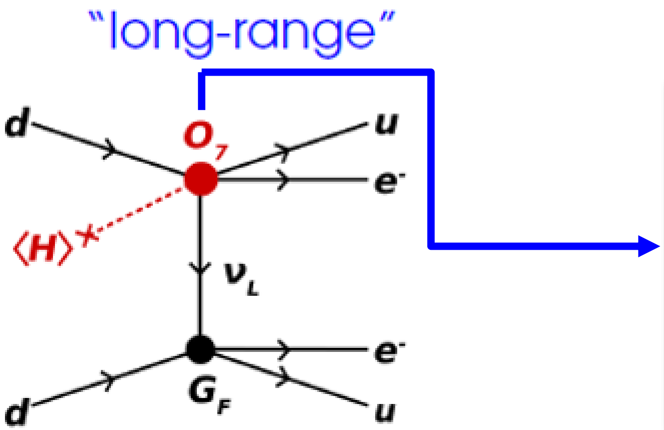
Filter models

Certain values of hypercharge is excluded by “genuineness”



Decomposing the long-range 0νββ operators

➢ Long-range mechanism is **not subject to helicity suppression**!



$\Delta L = 2$

$$\mathcal{O}_1^{LR} = \epsilon^{ik}\epsilon^{jl}(\overline{\ell_i^c}\ell_j)(\overline{d_R}Q_k)H_l\,,$$
$$\mathcal{O}_2^{LR} = \epsilon^{ik}\epsilon^{jl}(\overline{\ell_i^c}\gamma^{\mu\nu}\ell_j)(\overline{d_R}\gamma_{\mu\nu}Q_k)H_l\,,$$
$$\mathcal{O}_3^{LR} = \epsilon^{jk}(\overline{\ell_i^c}\ell_j)(\overline{Q}^i u_R)H_k\,,$$
$$\mathcal{O}_4^{LR} = (\overline{\ell_i^c}\gamma^\mu e_R)(\overline{d_R}\gamma_\mu u_R)\epsilon^{ij}H_j$$

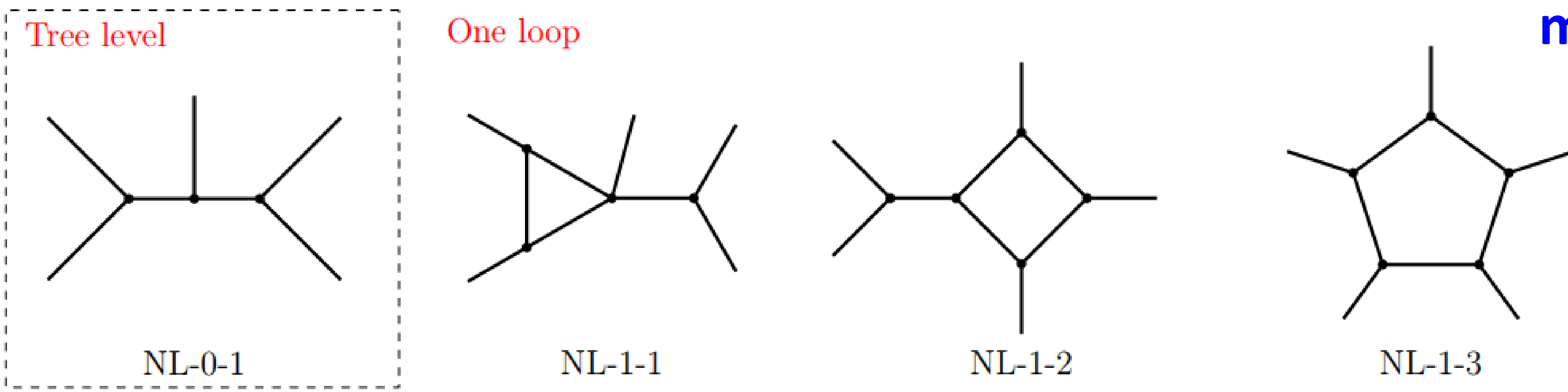
[Babu,Leung,hep-ph/0106054; Helo, Hirsch,Ota,1602.03362; Lehman,1410.4193]

topologies

diagrams

models

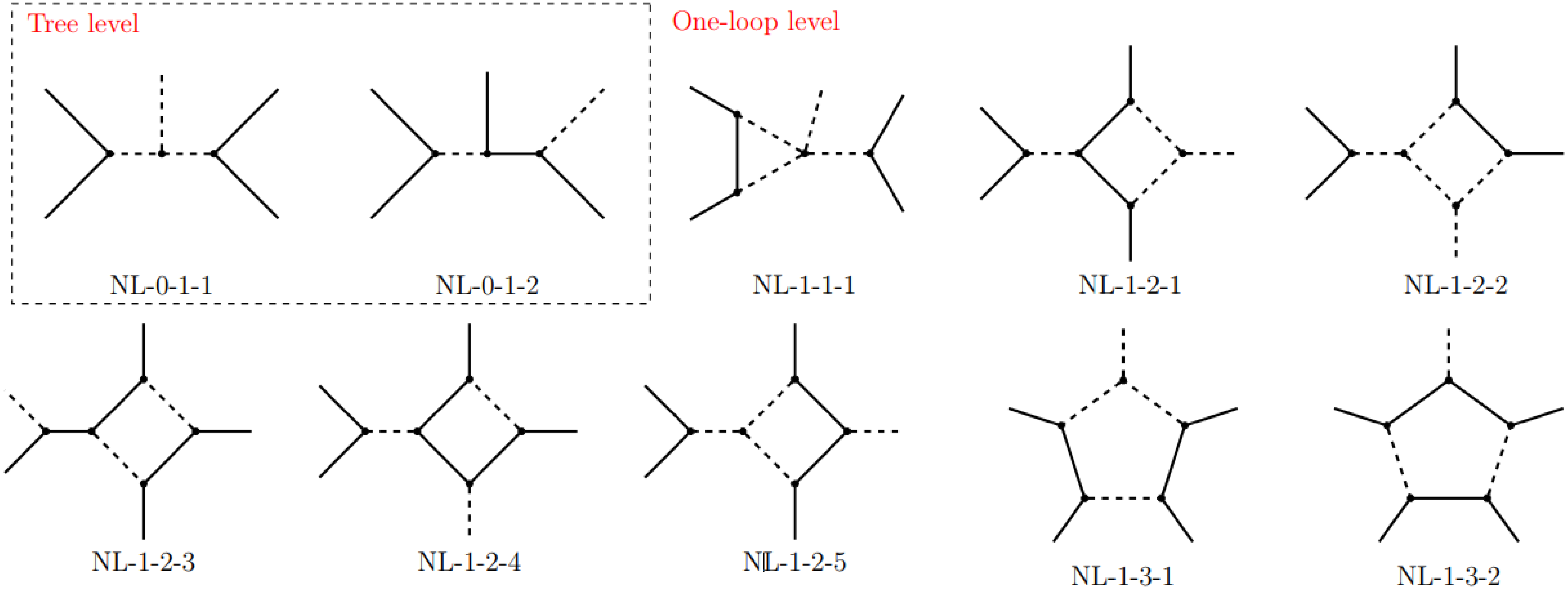
➢ Topologies



[Chen, Ding, Yao, 2301.02503]

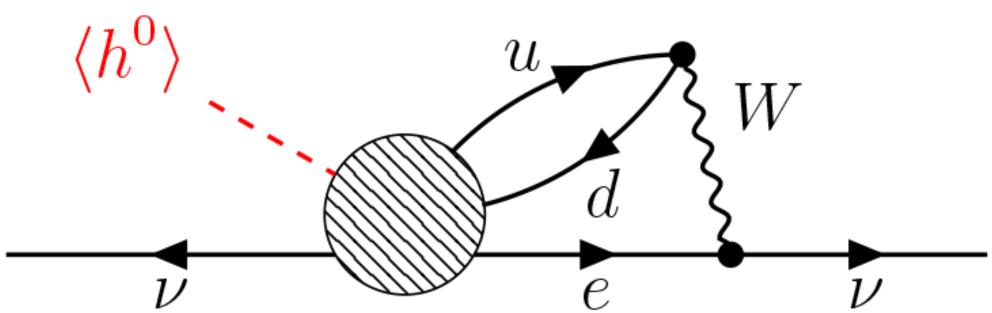
➢ Diagrams

[Chen, Ding, Yao, 2301.02503]



- Models: large variety of possible realizations accessible at high-energy colliders and high-intensity facilities, all genuine long-range 0νββ models up to 1-loop in the file http://staff.ustc.edu.cn/~dinggj/supplementary_materials/Long_range_0nbb.zip

- Black box theorem in long-range 0νββ decay: $\Delta L = 2$ operators $\rightarrow 0\nu\beta\beta$ & ν mass



Majorana neutrino masses are generated at least at the 2-loop order, regardless of long-range 0νββ operators

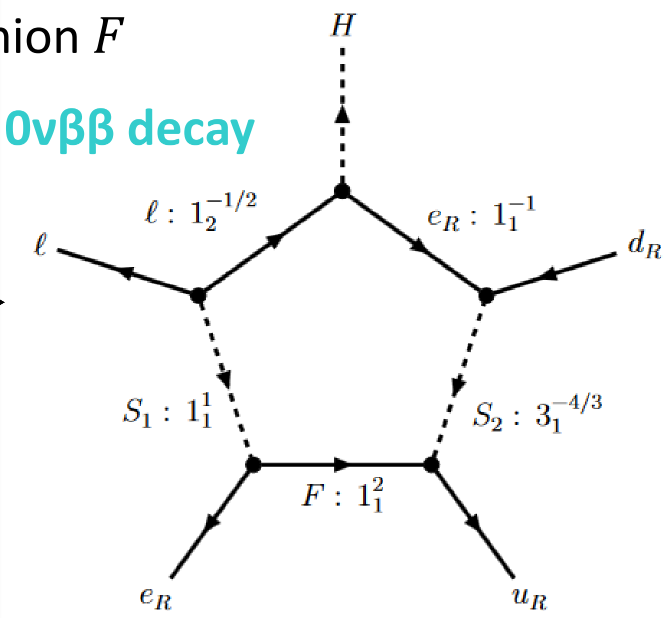
An example model of long-range 0νββ decay

There are many realizations, and a benchmark model is presented here

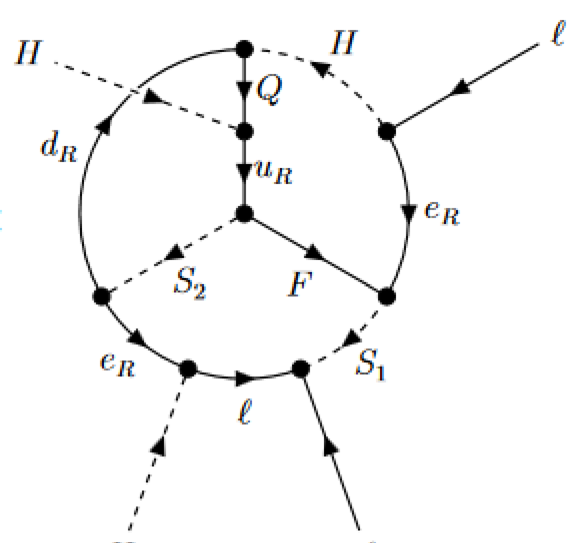
- 3 new fields: two scalars S_1, S_2 and a vector-like fermion F

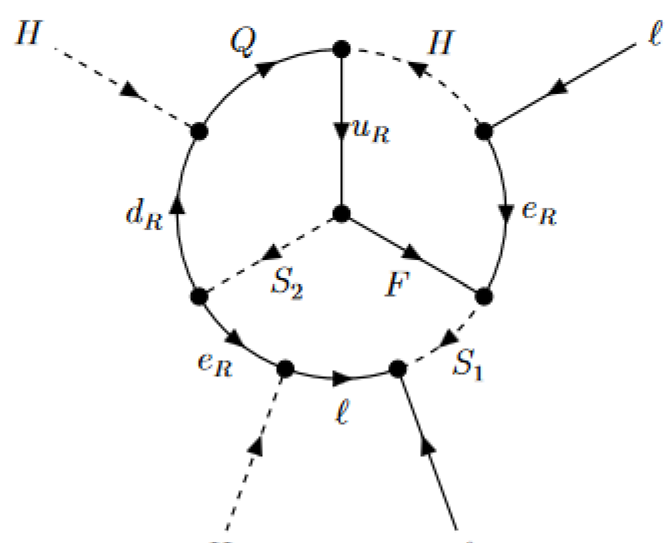
Fields	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
S_1	**1**	**1**	1
S_2	**3**	**1**	$-4/3$
F	**1**	**1**	2

1-loop 0νββ decay

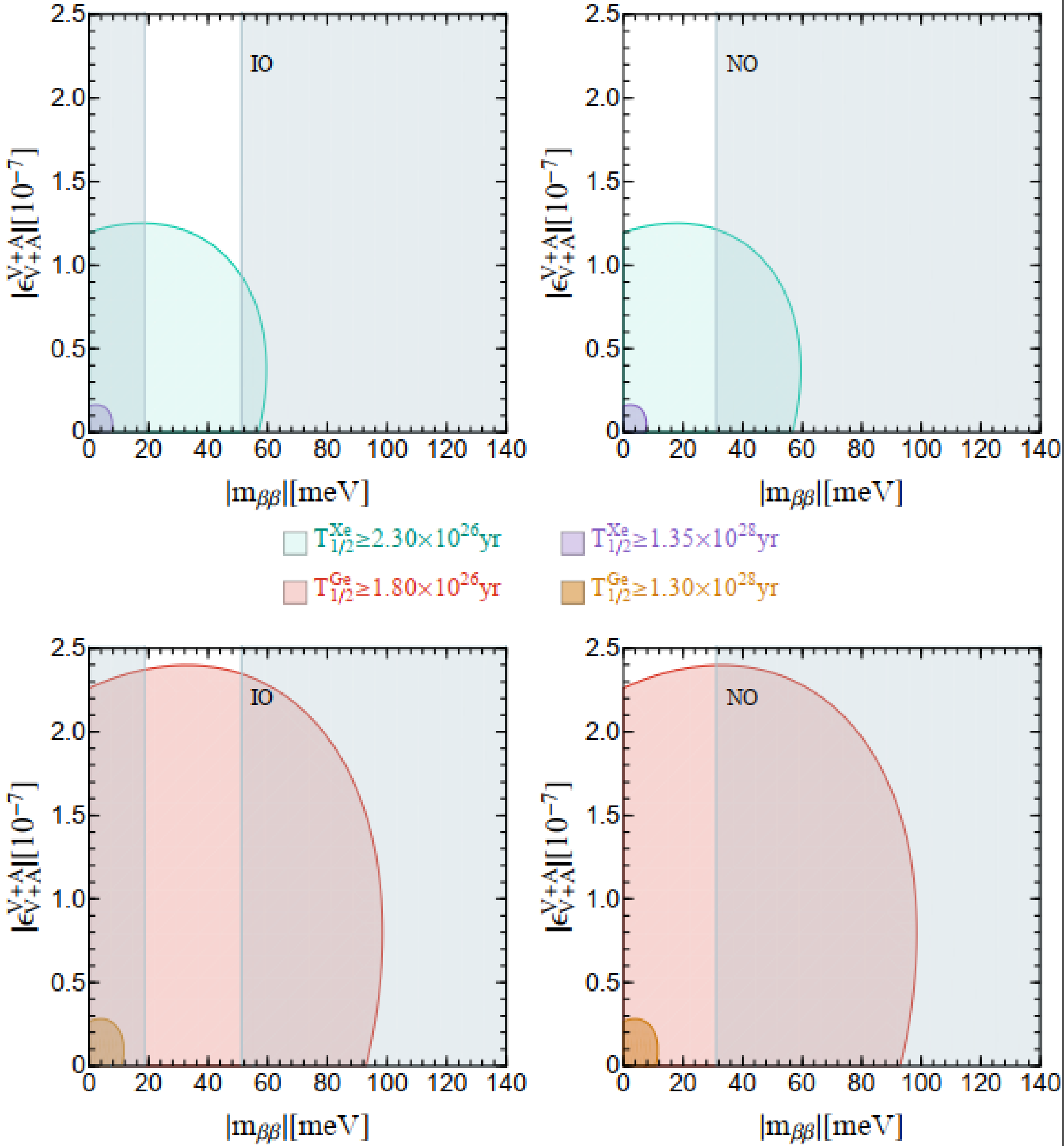


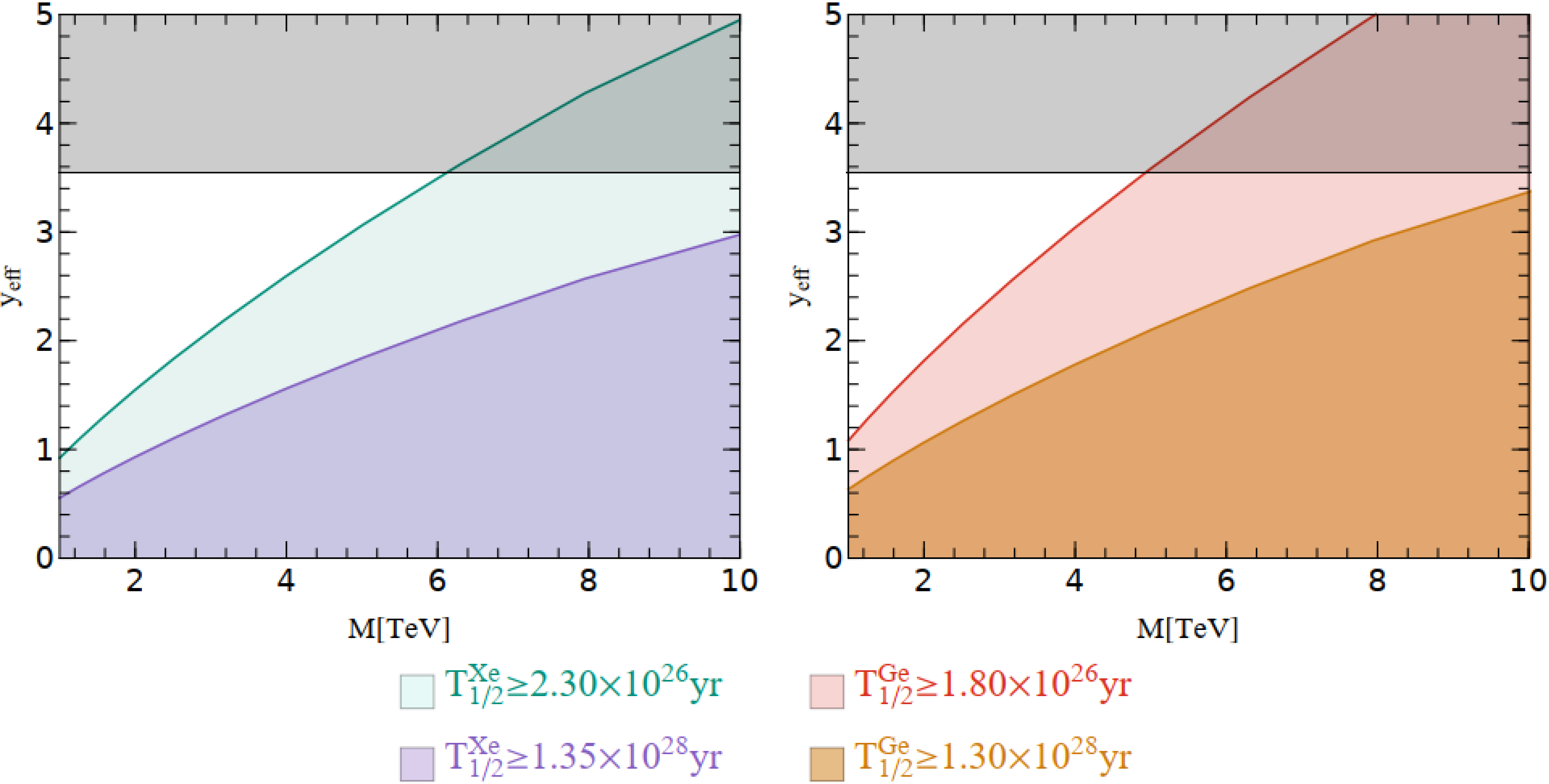
- Majorana neutrino masses generated at **3-loop**





➢ Future ton-scale experiments impose strong constraint on the model and new physics contribution.





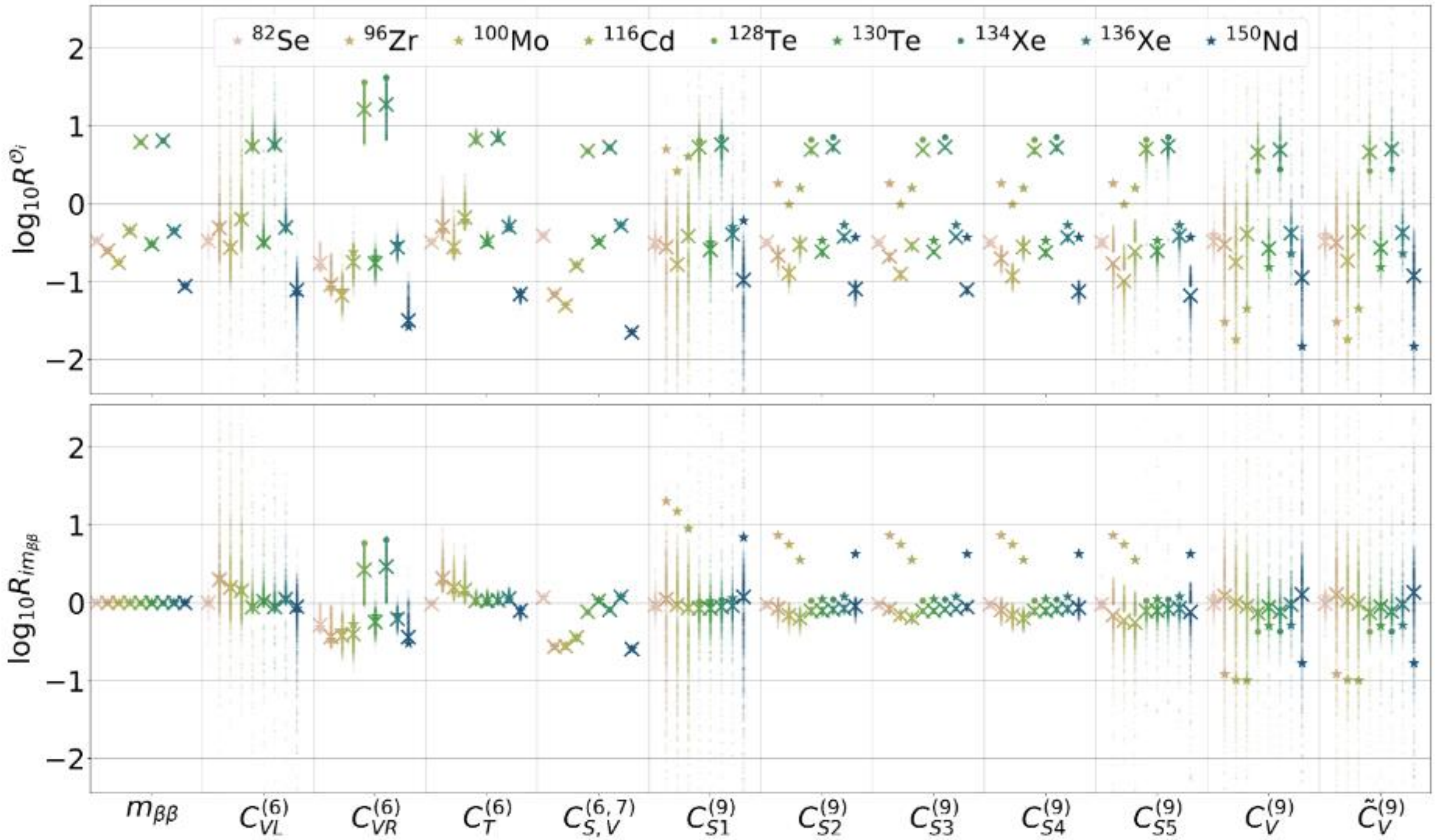
5
4
3
2
1
0
y_{eff}
2
4
6
8
10
M[TeV]
$T^{Xe}_{1/2} \geq 2.30\times10^{26}$yr
$T^{Xe}_{1/2} \geq 1.35\times10^{28}$yr
$T^{Ge}_{1/2} \geq 1.80\times10^{26}$yr
$T^{Ge}_{1/2} \geq 1.30\times10^{28}$yr

Distinguishing different 0νββ mechanisms

- Comparison of the decay rates obtained using different isotopes

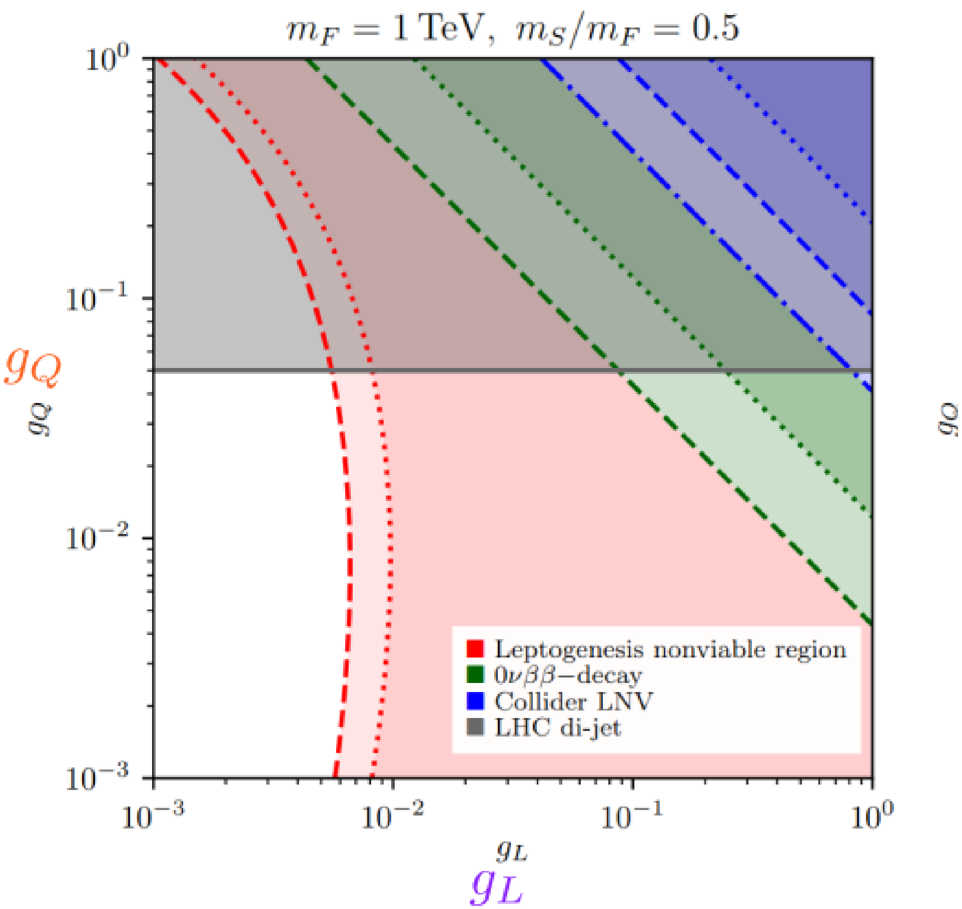
$$R^{\mathcal{O}_i}(^{\mathrm{A}}\mathrm{X}) \equiv \frac{T_{1/2}^{\mathcal{O}_i}(^{\mathrm{A}}\mathrm{X})}{T_{1/2}^{\mathcal{O}_i}(^{76}\mathrm{Ge})} = \frac{\sum_j |\mathcal{M}_j^{\mathcal{O}_i}(^{76}\mathrm{Ge})|^2 G_j^{\mathcal{O}_i}(^{76}\mathrm{Ge})}{\sum_k |\mathcal{M}_k^{\mathcal{O}_i}(^{\mathrm{A}}\mathrm{X})|^2 G_k^{\mathcal{O}_i}(^{\mathrm{A}}\mathrm{X})}$$

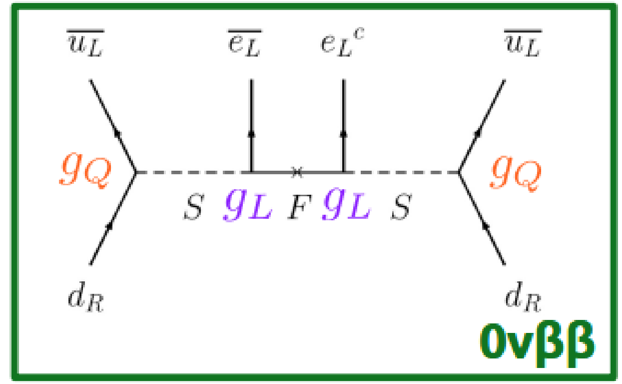
[Graf,Lindner,Scholer,2204.10845]

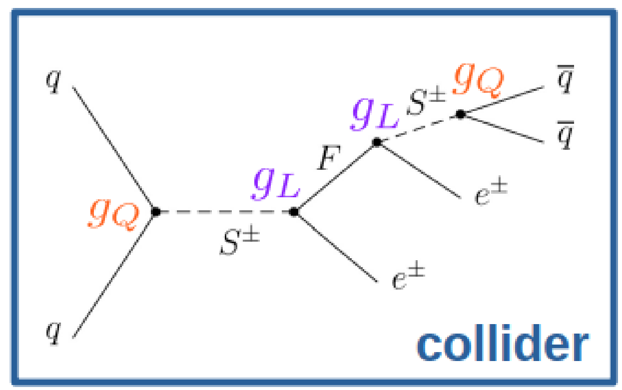


- Combination of 0νββ decay, collider measurement and cosmology

$$\mathcal{L} \supset g_Q \overline{Q} S d_R + g_L \overline{L}(i\tau^2) S^* F + \lambda_{HS}(S^\dagger H)^2 + \text{h.c.}$$







See Michael's Talk

[Harz, Ramsey-Musolf, Shen, Urrutia-Quiroga, 2106.10838; Graesser,Li,Ramsey-Musolf, Shen,Urrutia-Quiroga, 2202.01237]

Summary

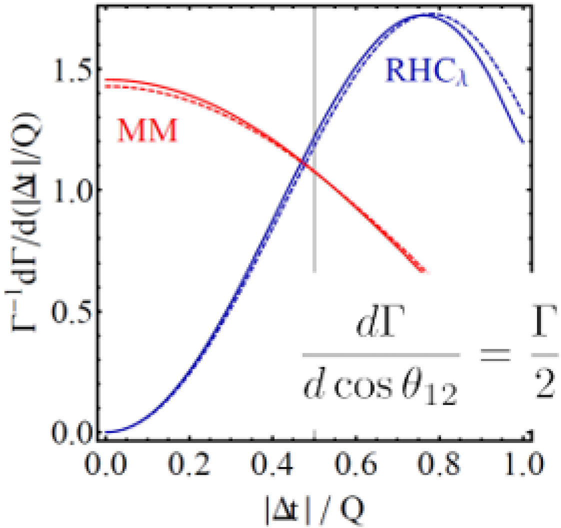
- $0\nu\beta\beta$ is the most sensitive probe to the Majorana nature of neutrinos. However, there are many possible underlying physics mechanisms which can be divided into mass mechanism, short-range mechanism and long-range mechanism.
- We have performed systematic decomposition of both d=7 short-range and d=9 long-range $0\nu\beta\beta$ operators, the possible renormalizable UV realizations are presented. An example model is given.
- Many open questions: the new $0\nu\beta\beta$ models in future colliders and LFV searches, implications in cosmology and leptogenesis....
- Further theoretical and experimental efforts are needed to find out whether $0\nu\beta\beta$ exists and what is the underling mechanism.

Thank you for your attention!

Backup

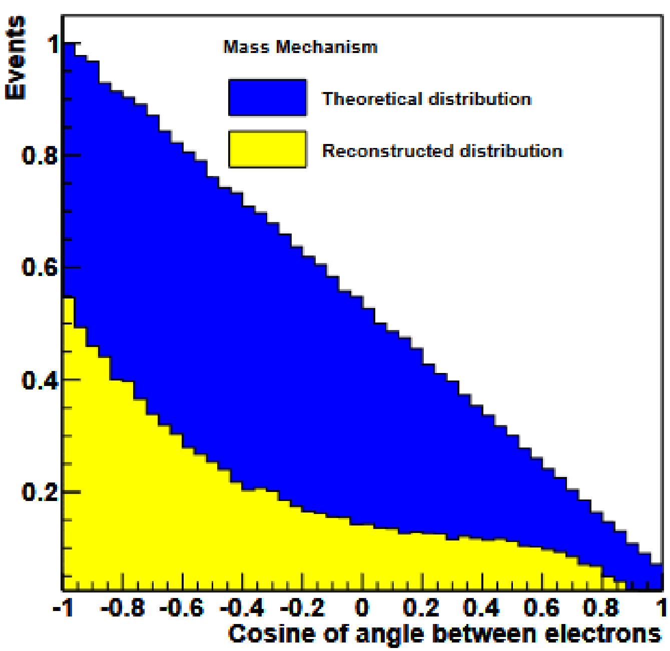
determine 0νββ mechanisms

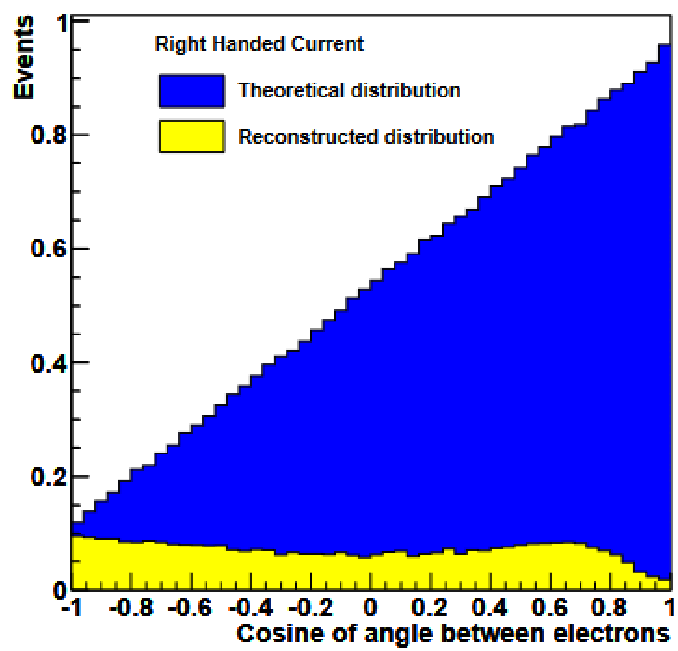
- measure the angular and energy distributions of electron



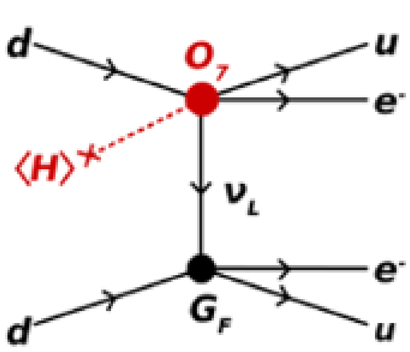
$$\frac{d\Gamma}{d\cos\theta_{12}} = \frac{\Gamma}{2}(1 - k_\theta \cos\theta_{12})$$

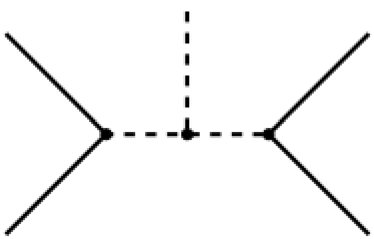
[Ali, Borisov, Zhuridov, 0706.4165;
SuperNEMO Collaborarion,1005.1241]

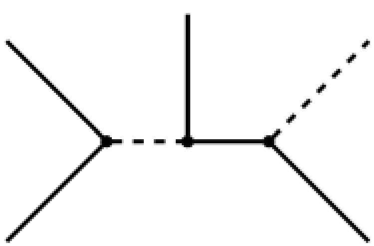




tree-level decomposition of long-range 0νββ operators







# Decompositions	Mediators		Projection to the basis ops.	m_ν@tree	m_ν@1loop	m_ν@2loop
#1 $(L_\alpha L_\beta)(H)(\overline{d_R}Q)$	$S(\mathbf{1},\mathbf{1})_{+1}$	$S'(\mathbf{1},\mathbf{2})_{+\frac{1}{2}}$	$-\mathcal{O}_{3a}(\alpha,\beta)$	—	TνI-ii w.$\overline{\ell_R}LS'^\dagger$	$T2^{\rm B}_4(\alpha\neq\beta)$ $\mathcal{O}^7_3$ in [38]
	$S(\mathbf{1},\mathbf{3})_{+1}$	$S'(\mathbf{1},\mathbf{2})_{+\frac{1}{2}}$	$-\mathcal{O}_{3b}(\alpha,\beta)-\mathcal{O}_{3b}(\beta,\alpha)$	type II		
#2 $(L_\alpha Q)(H)(\overline{d_R}L_\beta)$	$S(\overline{\mathbf{3}},\mathbf{1})_{+\frac{1}{3}}$	$S'(\overline{\mathbf{3}},\mathbf{2})_{-\frac{1}{6}}$	$\frac{1}{2}\mathcal{O}_{3b}(\alpha,\beta)-\frac{1}{2}\mathcal{O}^{\rm ten.}_{3b}(\alpha,\beta)$	—	TνI-ii [53] $\mathcal{O}^8_3$ in [38]	[14, 68]
	$S(\overline{\mathbf{3}},\mathbf{3})_{+\frac{1}{3}}$	$S'(\overline{\mathbf{3}},\mathbf{2})_{-\frac{1}{6}}$	$\frac{1}{2}\mathcal{O}_{3a}(\alpha,\beta)-\frac{1}{2}\mathcal{O}^{\rm ten.}_{3a}(\alpha,\beta)$ $-\frac{1}{2}\mathcal{O}_{3b}(\beta,\alpha)-\frac{1}{2}\mathcal{O}^{\rm ten.}_{3b}(\beta,\alpha)$	—	TνI-ii [53] $\mathcal{O}^9_3$ in [38]	[14]
#3 $(L_\alpha L_\beta)(Q)(\overline{d_R}H)$	$S(\mathbf{1},\mathbf{1})_{+1}$	$\psi_{L,R}(\mathbf{3},\mathbf{2})_{-\frac{5}{6}}$	$-\mathcal{O}_{3a}(\alpha,\beta)$	—	[TνI-ii w.$S^\dagger HH'$]	$T2^{\rm B}_1(\alpha\neq\beta)$ $\mathcal{O}^1_3$ in [38]
	$S(\mathbf{1},\mathbf{3})_{+1}$	$\psi_{L,R}(\mathbf{3},\mathbf{2})_{-\frac{5}{6}}$	$-\mathcal{O}_{3b}(\alpha,\beta)-\mathcal{O}_{3b}(\beta,\alpha)$	type II		
#4 $(L_\alpha H)(Q)(\overline{d_R}L_\beta)$	$\psi_R(\mathbf{1},\mathbf{1})_0$	$S(\overline{\mathbf{3}},\mathbf{2})_{-\frac{1}{6}}$	$\frac{1}{2}\mathcal{O}_{3b}(\beta,\alpha)+\frac{1}{2}\mathcal{O}^{\rm ten.}_{3b}(\beta,\alpha)$	type I		
	$\psi_R(\mathbf{1},\mathbf{3})_0$	$S(\overline{\mathbf{3}},\mathbf{2})_{-\frac{1}{6}}$	$-\frac{1}{2}\mathcal{O}_{3a}(\alpha,\beta)+\frac{1}{2}\mathcal{O}^{\rm ten.}_{3a}(\alpha,\beta)$ $-\frac{1}{2}\mathcal{O}_{3b}(\alpha,\beta)+\frac{1}{2}\mathcal{O}^{\rm ten.}_{3b}(\alpha,\beta)$	type III		
#5 $(L_\alpha L_\beta)(\overline{d_R})(QH)$	$S(\mathbf{1},\mathbf{1})_{+1}$	$\psi_{L,R}(\mathbf{3},\mathbf{1})_{+\frac{2}{3}}$	$\mathcal{O}_{3a}(\alpha,\beta)$	—	[TνI-ii w.$S^\dagger HH'$]	$T2^{\rm B}_2(\alpha\neq\beta)$ $\mathcal{O}^2_3$ in [38]
	$S(\mathbf{1},\mathbf{3})_{+1}$	$\psi_{L,R}(\mathbf{3},\mathbf{3})_{+\frac{2}{3}}$	$-\mathcal{O}_{3b}(\alpha,\beta)-\mathcal{O}_{3b}(\beta,\alpha)$	type II		
#6 $(L_\alpha Q)(\overline{d_R})(L_\beta H)$	$S(\overline{\mathbf{3}},\mathbf{1})_{+\frac{1}{3}}$	$\psi_R(\mathbf{1},\mathbf{1})_0$	$-\frac{1}{2}\mathcal{O}_{3b}(\alpha,\beta)+\frac{1}{2}\mathcal{O}^{\rm ten.}_{3b}(\alpha,\beta)$	type I		
	$S(\overline{\mathbf{3}},\mathbf{3})_{+\frac{1}{3}}$	$\psi_R(\mathbf{1},\mathbf{3})_0$	$\frac{1}{2}\mathcal{O}_{3a}(\alpha,\beta)-\frac{1}{2}\mathcal{O}^{\rm ten.}_{3a}(\alpha,\beta)$ $-\frac{1}{2}\mathcal{O}_{3b}(\beta,\alpha)-\frac{1}{2}\mathcal{O}^{\rm ten.}_{3b}(\beta,\alpha)$	type III		
#7 $(L_\alpha Q)(L_\beta)(\overline{d_R}H)$	$S(\overline{\mathbf{3}},\mathbf{1})_{+\frac{1}{3}}$	$\psi_{L,R}(\mathbf{3},\mathbf{2})_{-\frac{5}{6}}$	$\frac{1}{2}\mathcal{O}_{3b}(\alpha,\beta)-\frac{1}{2}\mathcal{O}^{\rm ten.}_{3b}(\alpha,\beta)$	—	TνI-iii $\mathcal{O}^4_3$ in [38]	
	$S(\overline{\mathbf{3}},\mathbf{3})_{+\frac{1}{3}}$	$\psi_{L,R}(\mathbf{3},\mathbf{2})_{-\frac{5}{6}}$	$\frac{1}{2}\mathcal{O}_{3a}(\alpha,\beta)-\frac{1}{2}\mathcal{O}^{\rm ten.}_{3a}(\alpha,\beta)$ $-\frac{1}{2}\mathcal{O}_{3b}(\beta,\alpha)-\frac{1}{2}\mathcal{O}^{\rm ten.}_{3b}(\beta,\alpha)$	—	TνI-iii $\mathcal{O}^5_3$ in [38]	
#8 $(\overline{d_R}L_\alpha)(L_\beta)(QH)$	$S(\mathbf{3},\mathbf{2})_{+\frac{1}{6}}$	$\psi_{L,R}(\mathbf{3},\mathbf{1})_{+\frac{2}{3}}$	$-\frac{1}{2}\mathcal{O}_{3a}(\alpha,\beta)-\frac{1}{2}\mathcal{O}^{\rm ten.}_{3a}(\alpha,\beta)$	—	—	$T2^{\rm B}_2(m_\nu)_{\alpha\neq\beta}$ $\mathcal{O}^3_3$ in [38], [43]
	$S(\mathbf{3},\mathbf{2})_{+\frac{1}{6}}$	$\psi_{L,R}(\mathbf{3},\mathbf{3})_{+\frac{2}{3}}$	$\frac{1}{2}\mathcal{O}_{3b}(\alpha,\beta)+\frac{1}{2}\mathcal{O}^{\rm ten.}_{3b}(\alpha,\beta)$ $+\frac{1}{2}\mathcal{O}_{3b}(\beta,\alpha)-\frac{1}{2}\mathcal{O}^{\rm ten.}_{3b}(\beta,\alpha)$	—	TνI-iii $\mathcal{O}^6_3$ in [38]	
#9 $(L_\alpha H)(L_\beta)(\overline{d_R}Q)$	$\psi_R(\mathbf{1},\mathbf{1})_0$	$S(\mathbf{1},\mathbf{2})_{+\frac{1}{2}}$	$\mathcal{O}_{3b}(\beta,\alpha)$	type I		
	$\psi_R(\mathbf{1},\mathbf{3})_0$	$S(\mathbf{1},\mathbf{2})_{+\frac{1}{2}}$	$\mathcal{O}_{3a}(\alpha,\beta)+\mathcal{O}_{3b}(\alpha,\beta)$	type III		

[Helo, Hirsch,Ota, 1602.03362]