Neutrinoless double beta decay and underlying physics

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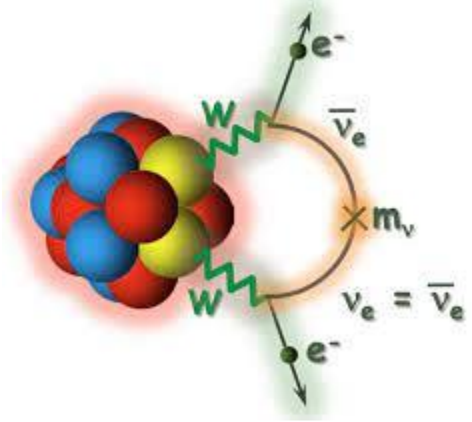
2025年3月21日—24日



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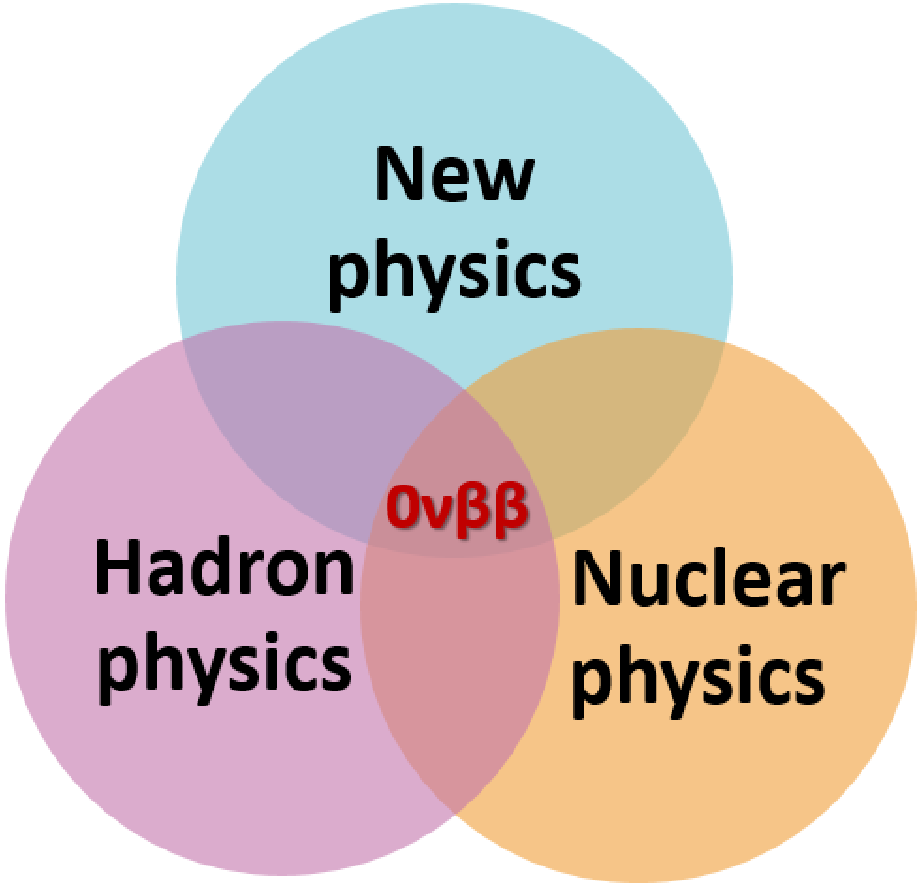
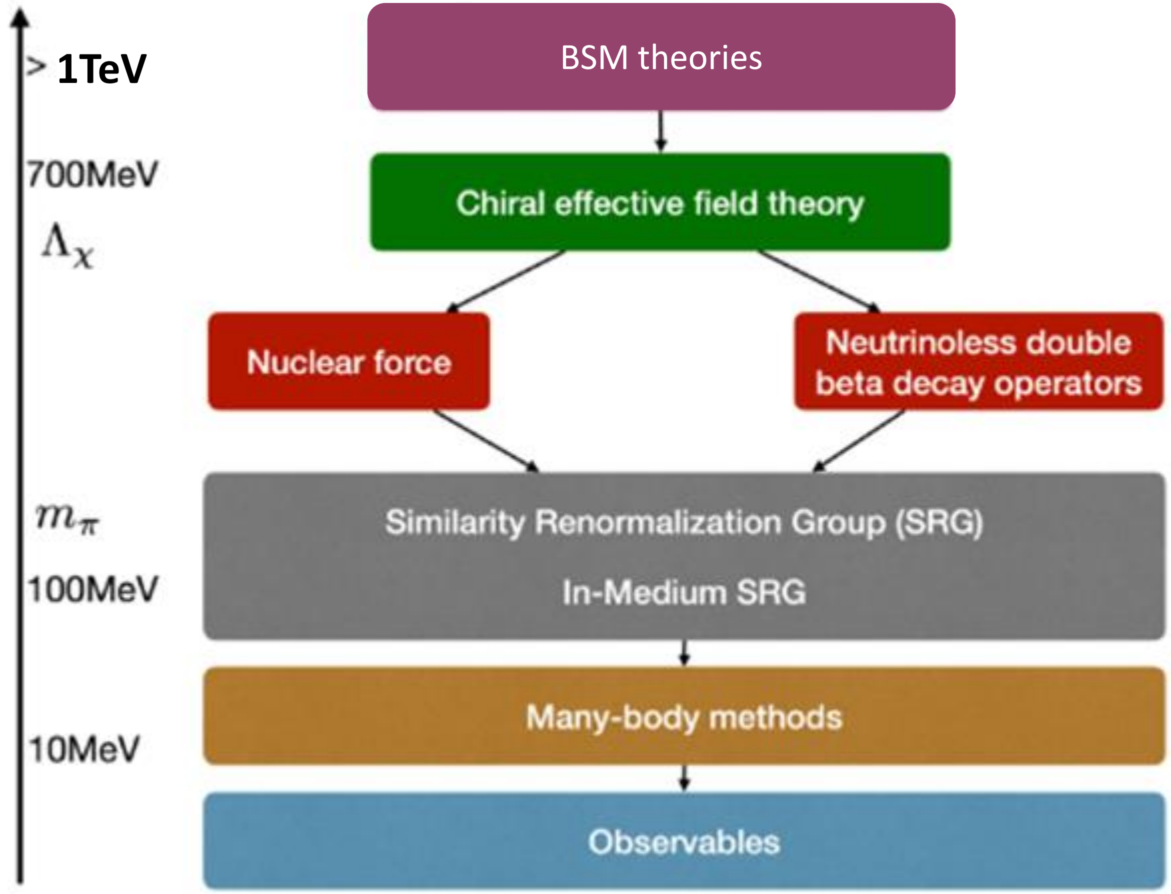
Neutrinoless double beta (0νββ) decay: **intersection of new physics, hadron physics and nuclear physics**



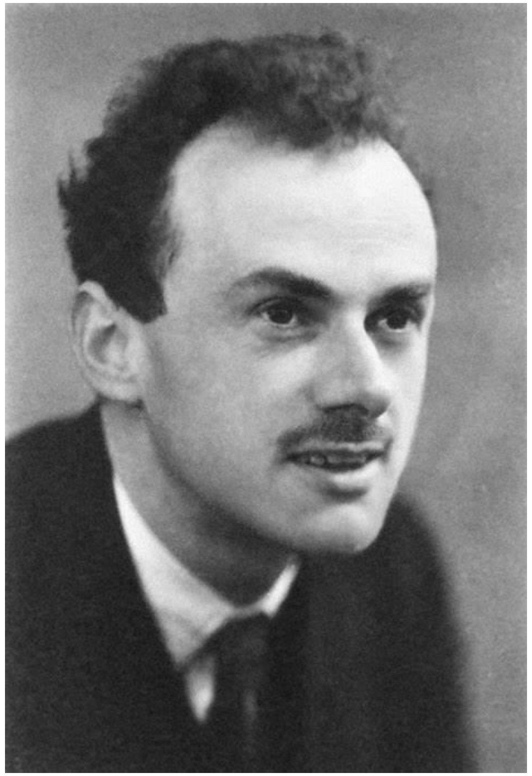


Massive neutrinos: Dirac or Majorana?

$\nu \neq \nu^c$

Left & right handed ν's

Lepton number conservation



vs.

$\nu = \nu^c$

Only left handed ν's

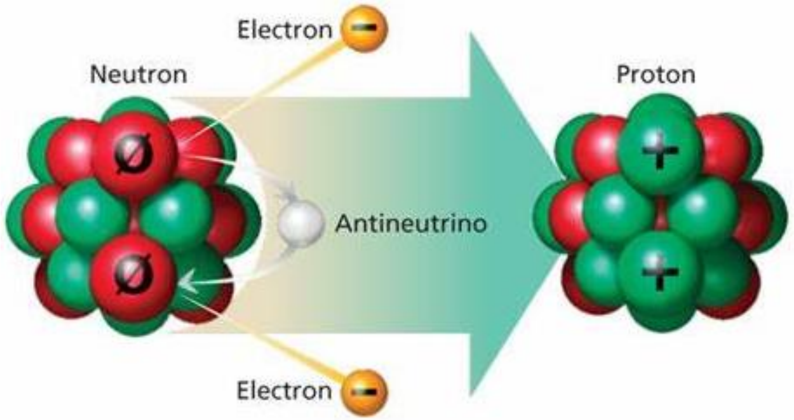
Lepton number violation

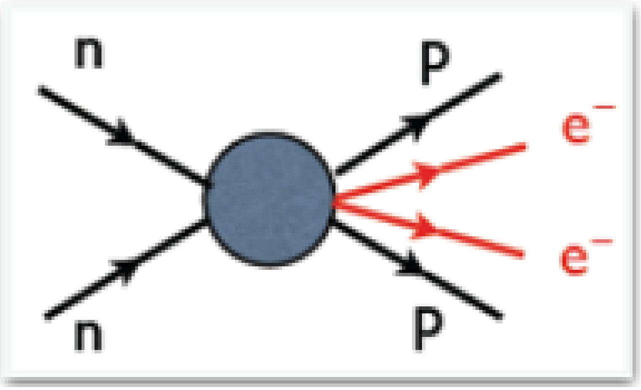
0νββ decay is the most sensitive known experimental method to verify whether neutrinos are Majorana particles.

0νββ-decays: signature and candidate nuclei

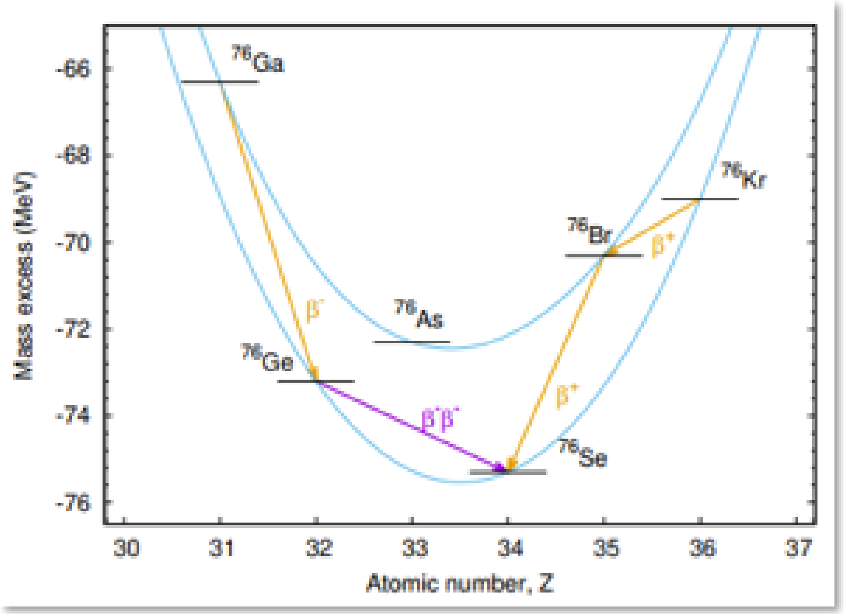
0νββ is potentially observable in certain even-even nuclei (9 isotopes including ^{48}Ca, **^{76}Ge**, ^{100}Mo, ^{130}Te, **^{136}Xe**) for which single beta decay is energetically forbidden. The decay rate is less than 1 event per ton and per year.

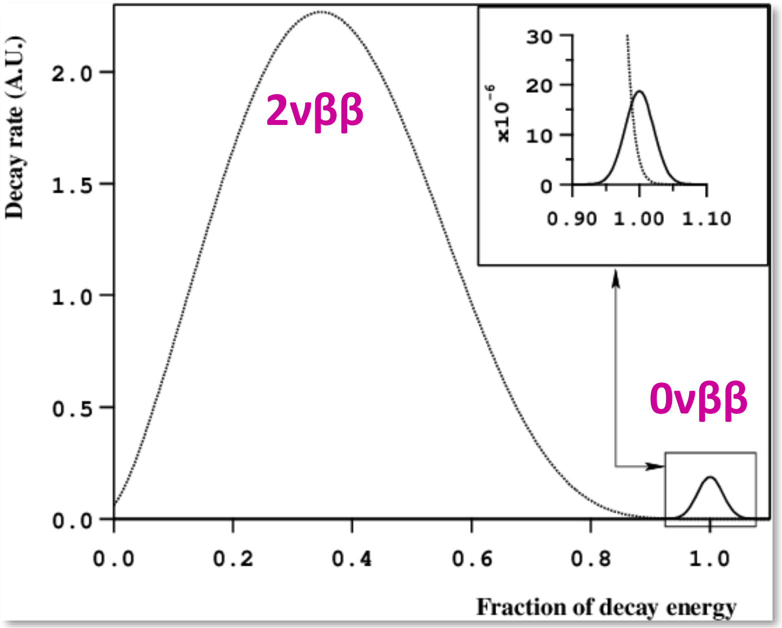
$0\nu\beta\beta\!: \ (A, Z) \rightarrow (A, Z+2) + 2e^{-}$





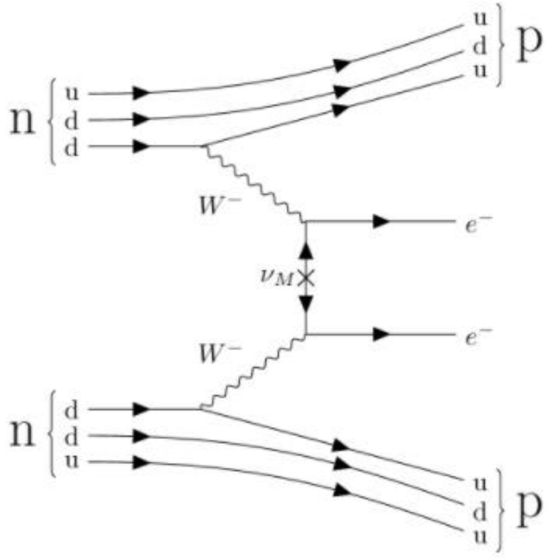
$T_{1/2} > 10^{25}\,\mathrm{yr}$





Standard mass mechanism of 0νββ decay

Mass mechanism: 0νββ decay is usually assumed to be dominantly mediated by light and massive Majorana neutrinos.



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

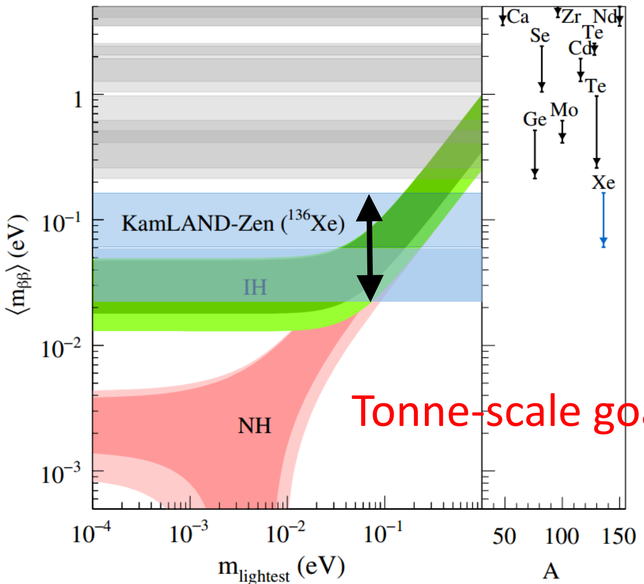
PMNS

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

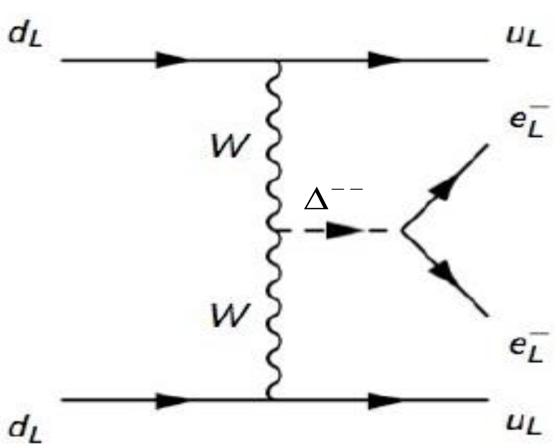


Tonne-scale goal 10^{28} yrs

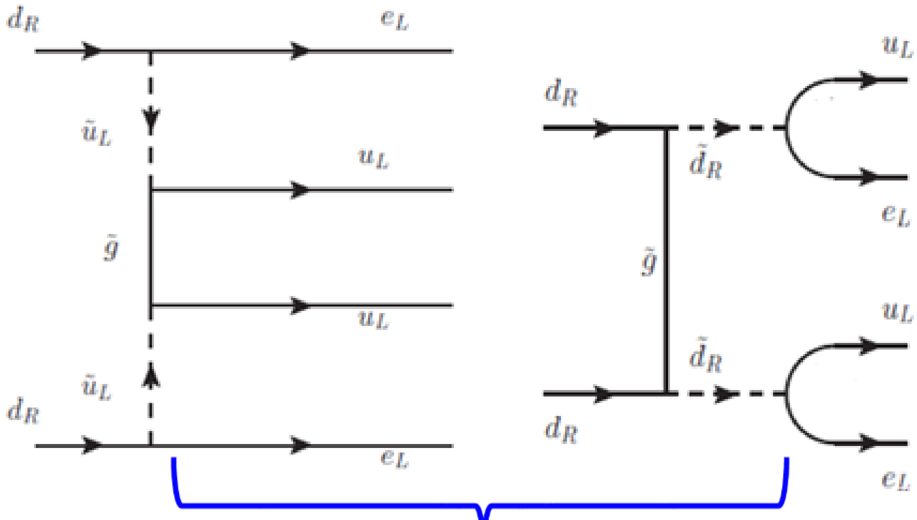
- **Unknown**: lightest mass, hierarchy and Majorana phases
- **Large theoretical uncertainties** in the nuclear matrix elements

Possible BSM physics in 0νββ decay

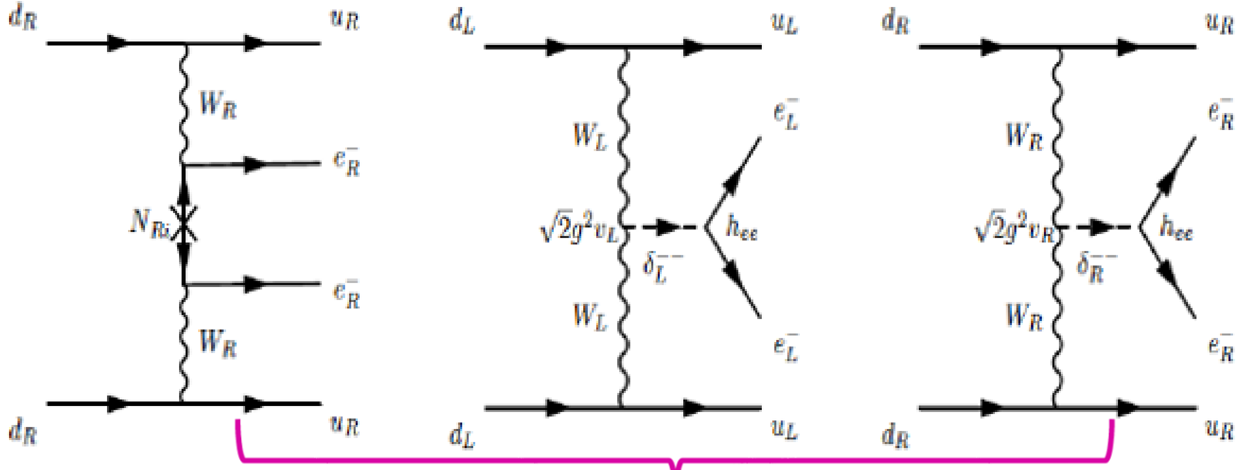
The 0νββ decay can also be induced by other ΔL=2 physics besides the Majorana neutrino mass. There are many possible scenarios:



Type II seesaw



R-parity violating SUSY

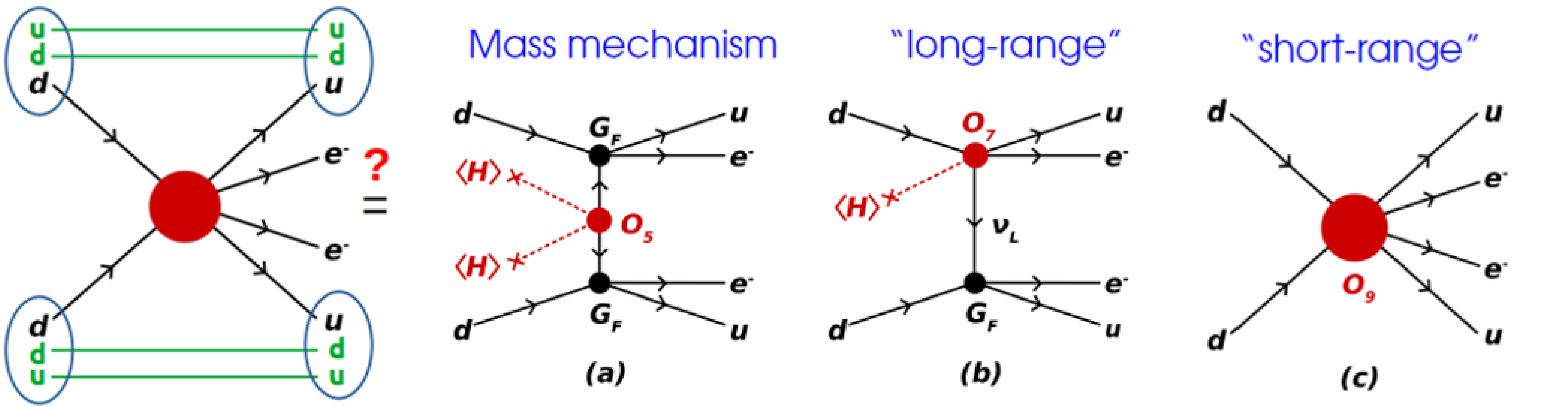


Left-right model

- 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:



EFT:

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

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

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

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

[Pas, Hirsch, Klapdor, Kovalenko, hep-ph/0008182, hep-ph/9804374, PLB; Graesser,1606.04549, JHEP]

Decomposing the short-range 0νββ operators

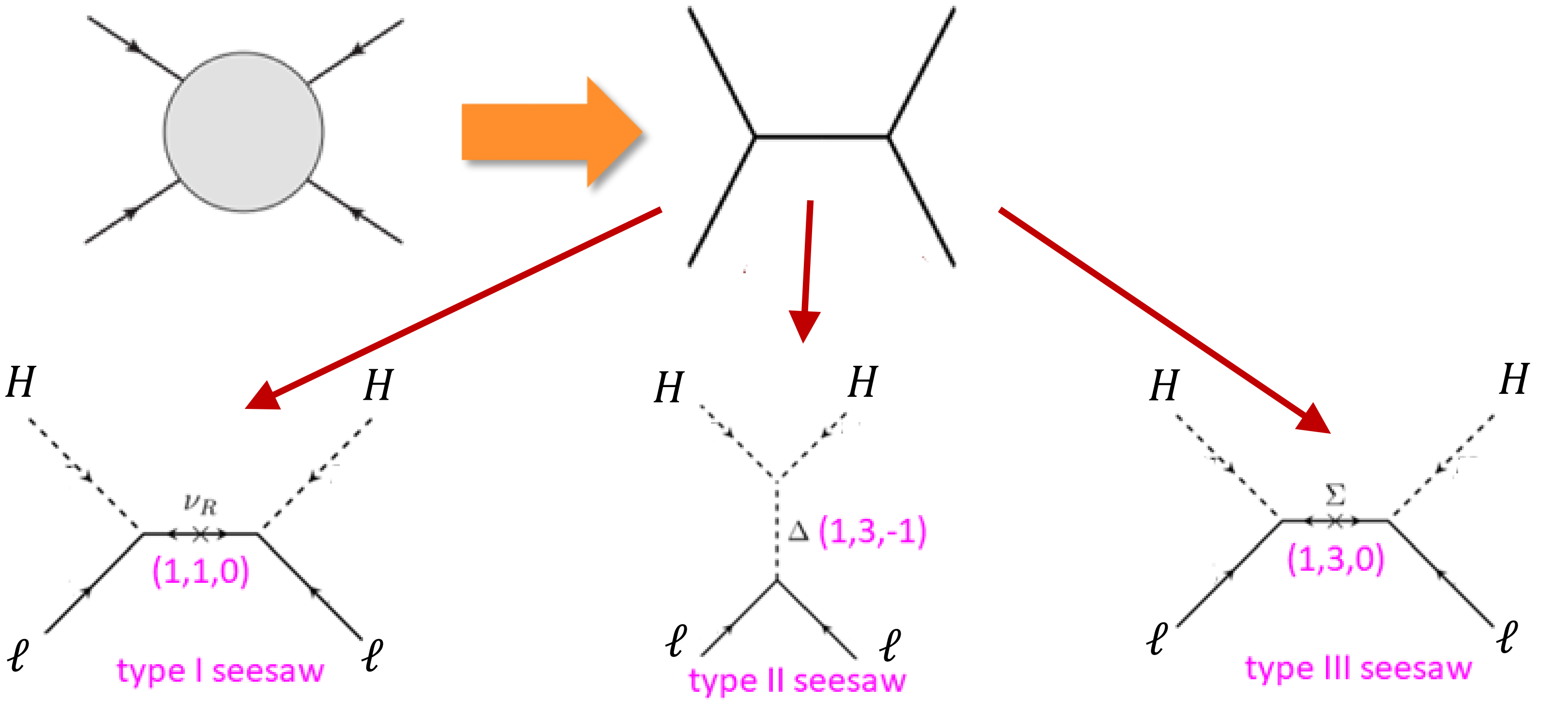
① **Topolopies**: identify the L−loop connected topologies with 6 external legs

② **Diagrams**: assign the fields of 0νββ operators to external lines, and specify the Lorentz nature (spinor or scalar) of each internal line.

③ **Models**: fix the $SU(3)_C \times SU(2)_L \times U(1)_Y$ quantum numbers of the internal fields by gauge invariance of each interaction vertex

- Example: decompose Weinberg operator

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

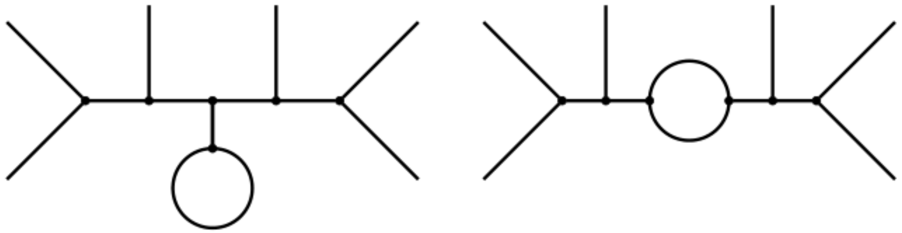


Topologies for short-range 0νββ

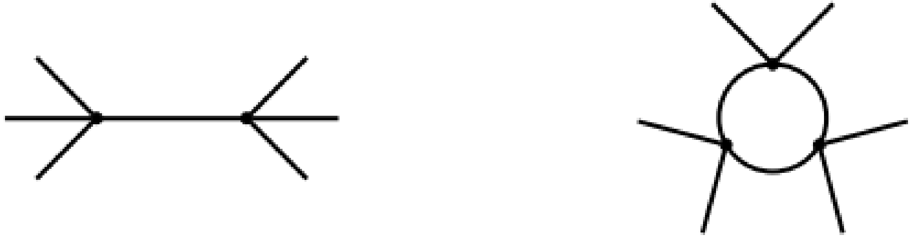
Topolopies: Feynman diagrams where no property of fields is considered

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

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

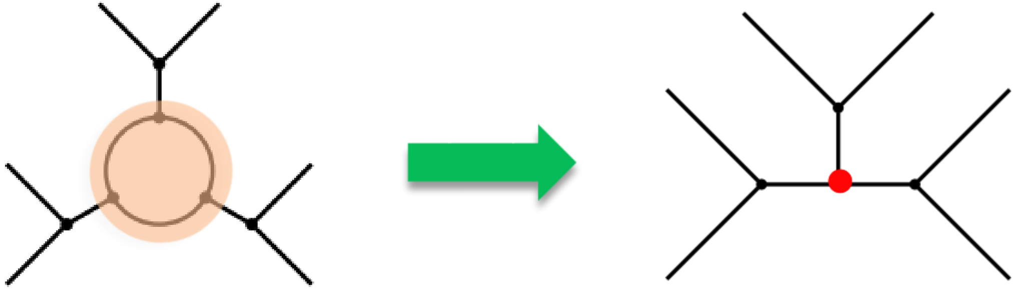


(iii) Exclude non-renormalizable topologies



The 6 external legs are quark and lepton fields for short-range 0νββ

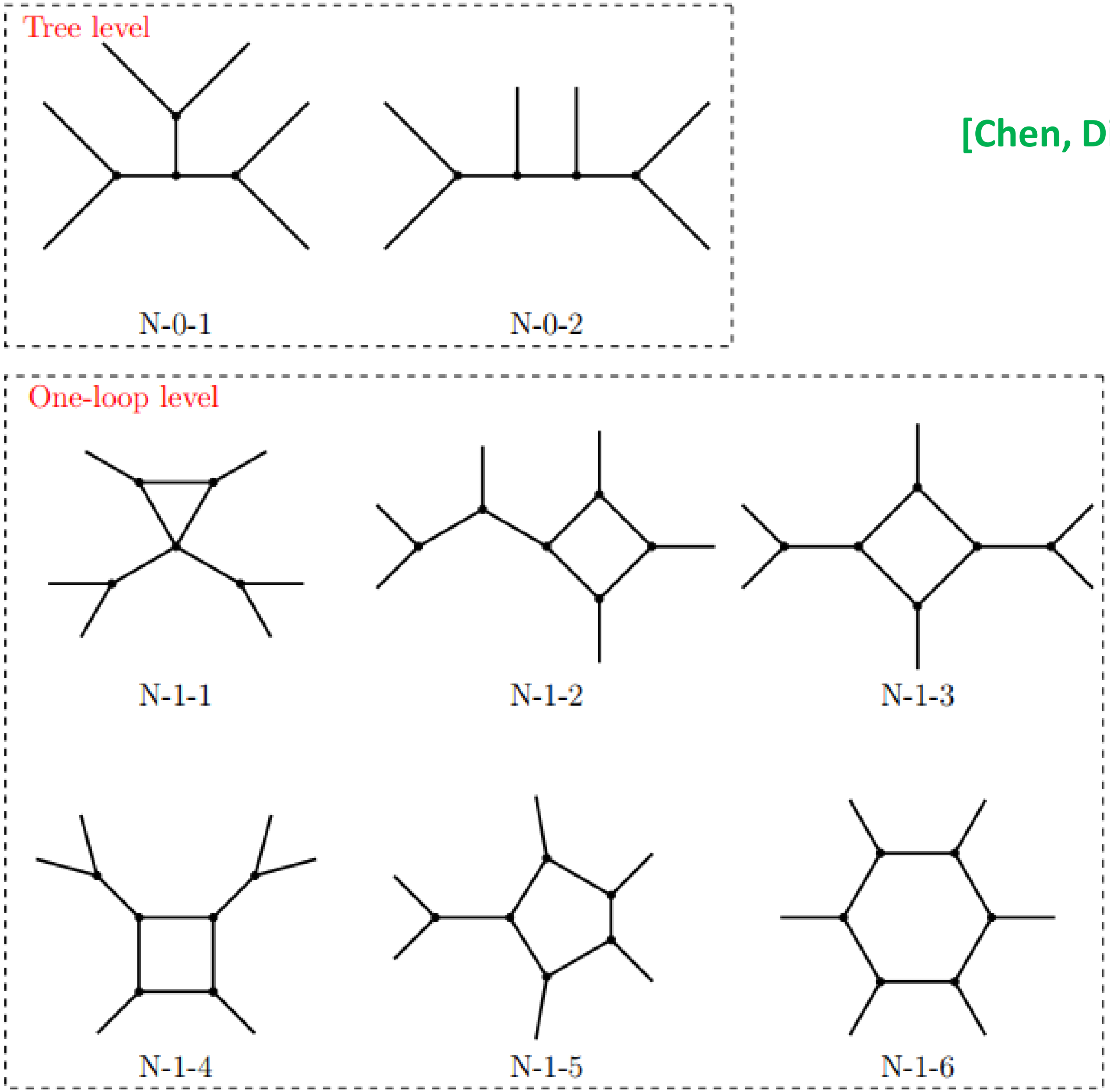
(iv) Discard topologies with 3-point loop vertices



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

➢ 2 tree + 6 one-loop renormalizable topologies

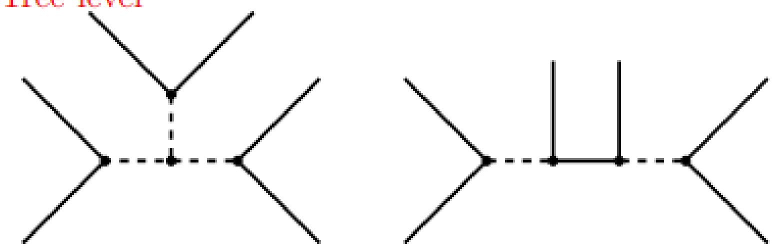
[Chen, Ding, Yao, 2110.15347, JHEP]



Field insertions: topologies → diagrams

Focusing only on fermion and scalar boson mediators [Not considering gauge bosons]

Tree level

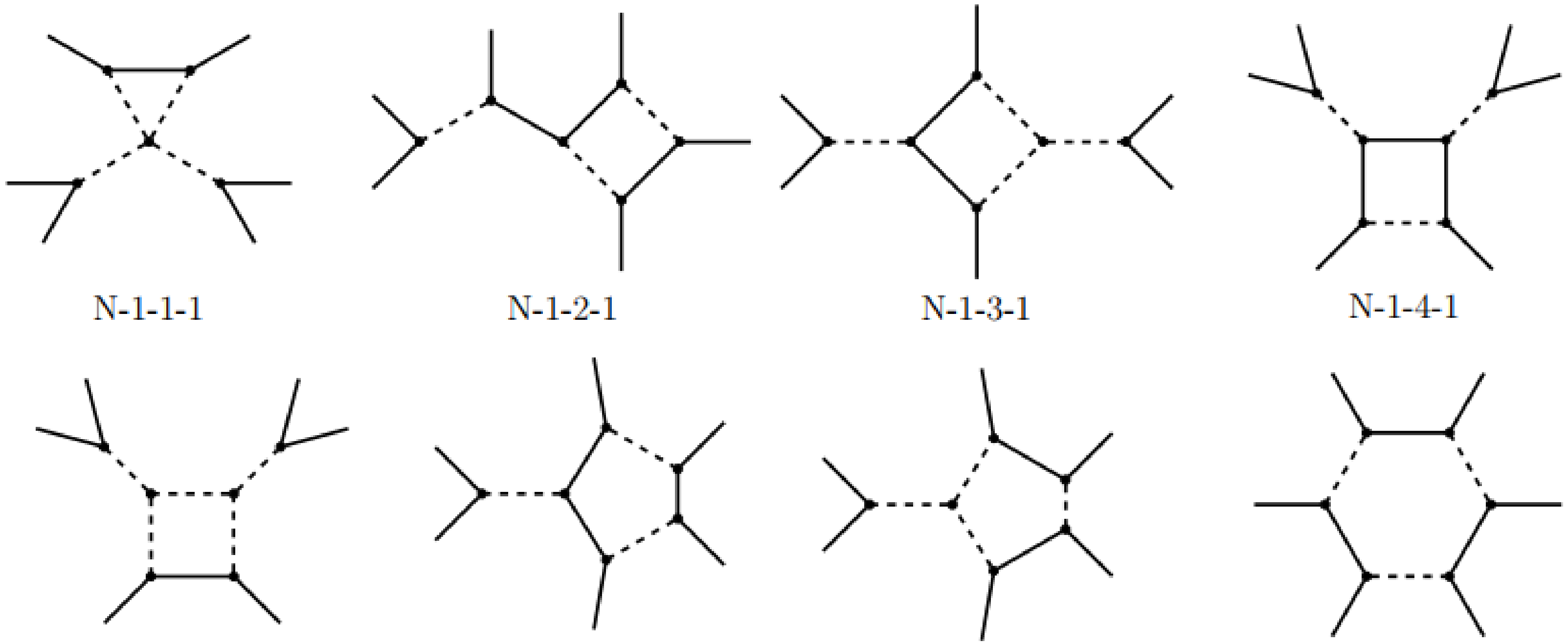


N-0-1-1 N-0-2-1

- Three kinds of renormalizable vertices
  - ①fermion-fermion-scalar (**FFS**)
  - ②scalar-scalar-scalar (**SSS**)
  - ③scalar-scalar-scalar-scalar (**SSSS**)

[Chen, Ding, Yao, 2110.15347,JHEP]

One-loop level

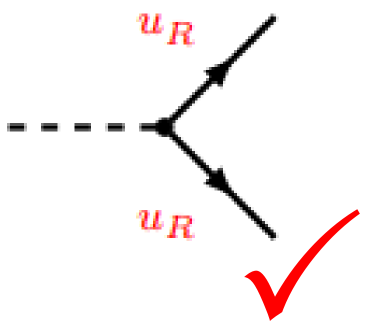


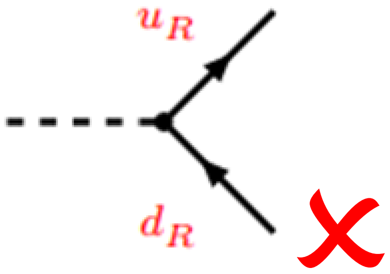
N-1-1-1 N-1-2-1 N-1-3-1 N-1-4-1

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	$\mathcal{O}_{10}^{SR},\ \mathcal{O}_{11}^{SR}$	$\bar{u}_R, \bar{u}_R, Q, d_R, \overline{\ell}, e_R^c$

- **A large 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.

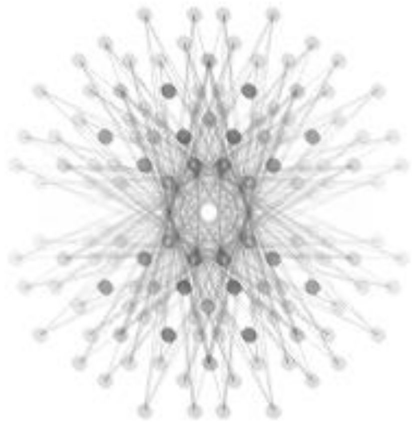
Determine quantum numbers of mediators: diagrams→models

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:** $S_1 S_2 S_3 S_4$

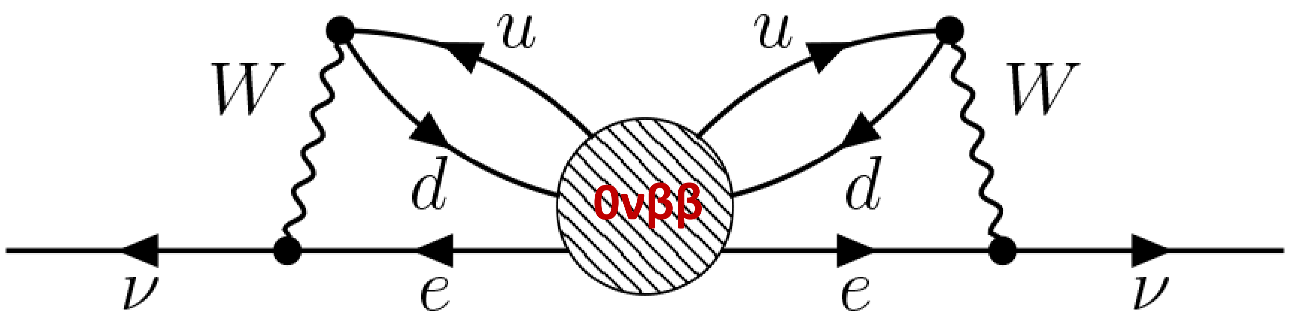
$$n_{S_1} \otimes n_{S_2} \otimes n_{S_3} \otimes n_{S_4} \supset \mathbf{1}, \qquad \sum_i Y_{S_i} = 0$$

GROUPMATH

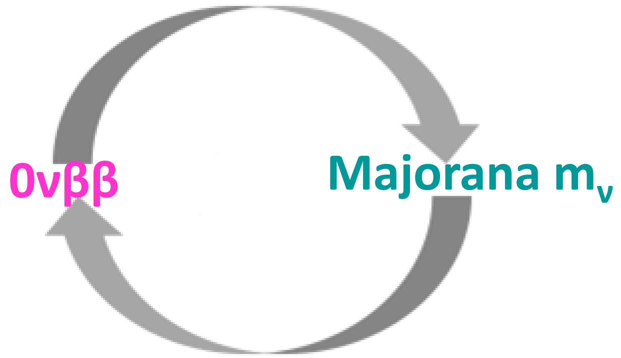
Mathematica package **GroupMath** can help to determine the SM quantum numbers

Short-range contribution versus mass mechanism

- **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, PRD25(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 **higher one-loop** order.

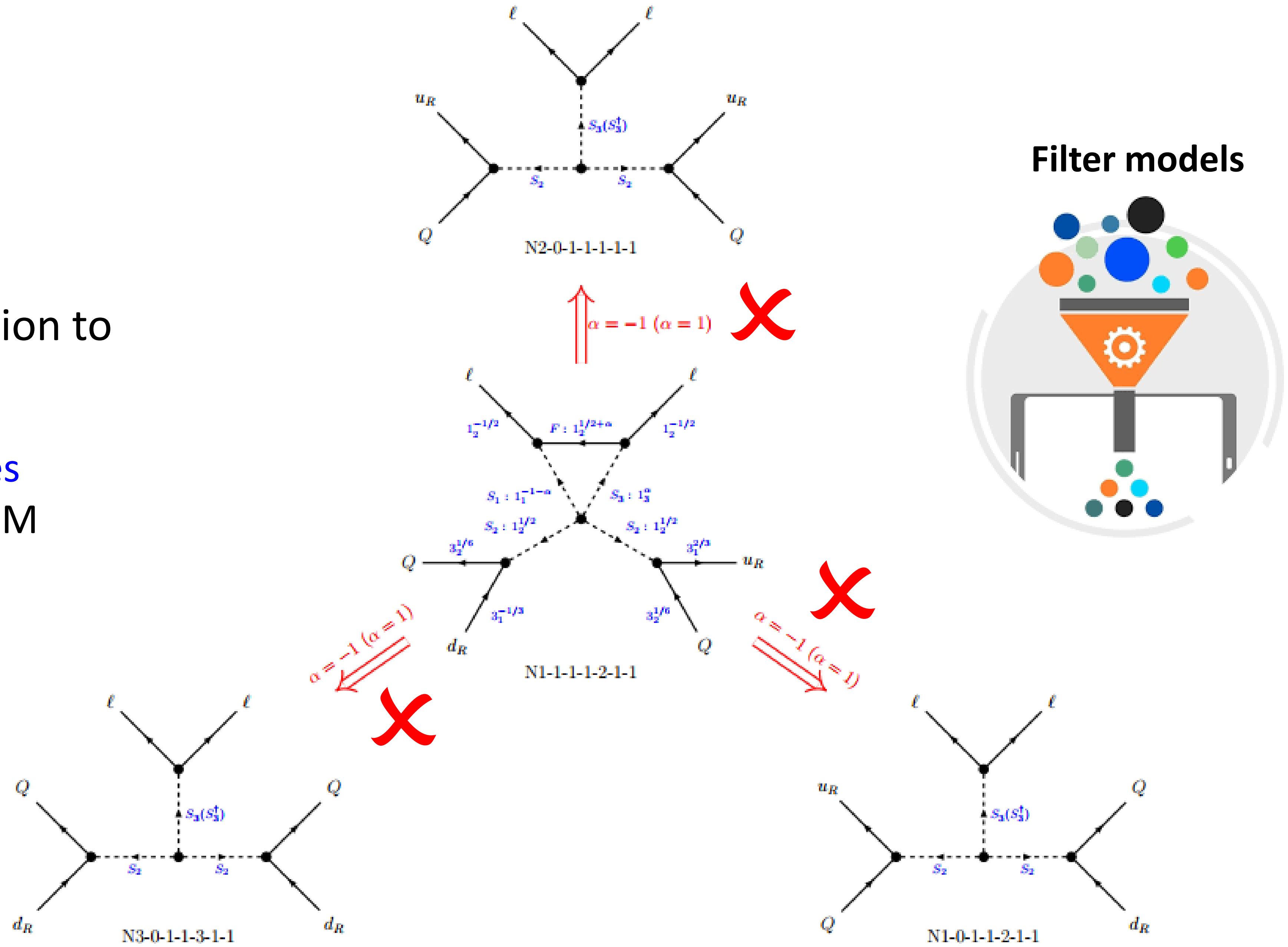
Genuine models

"genuine" models：

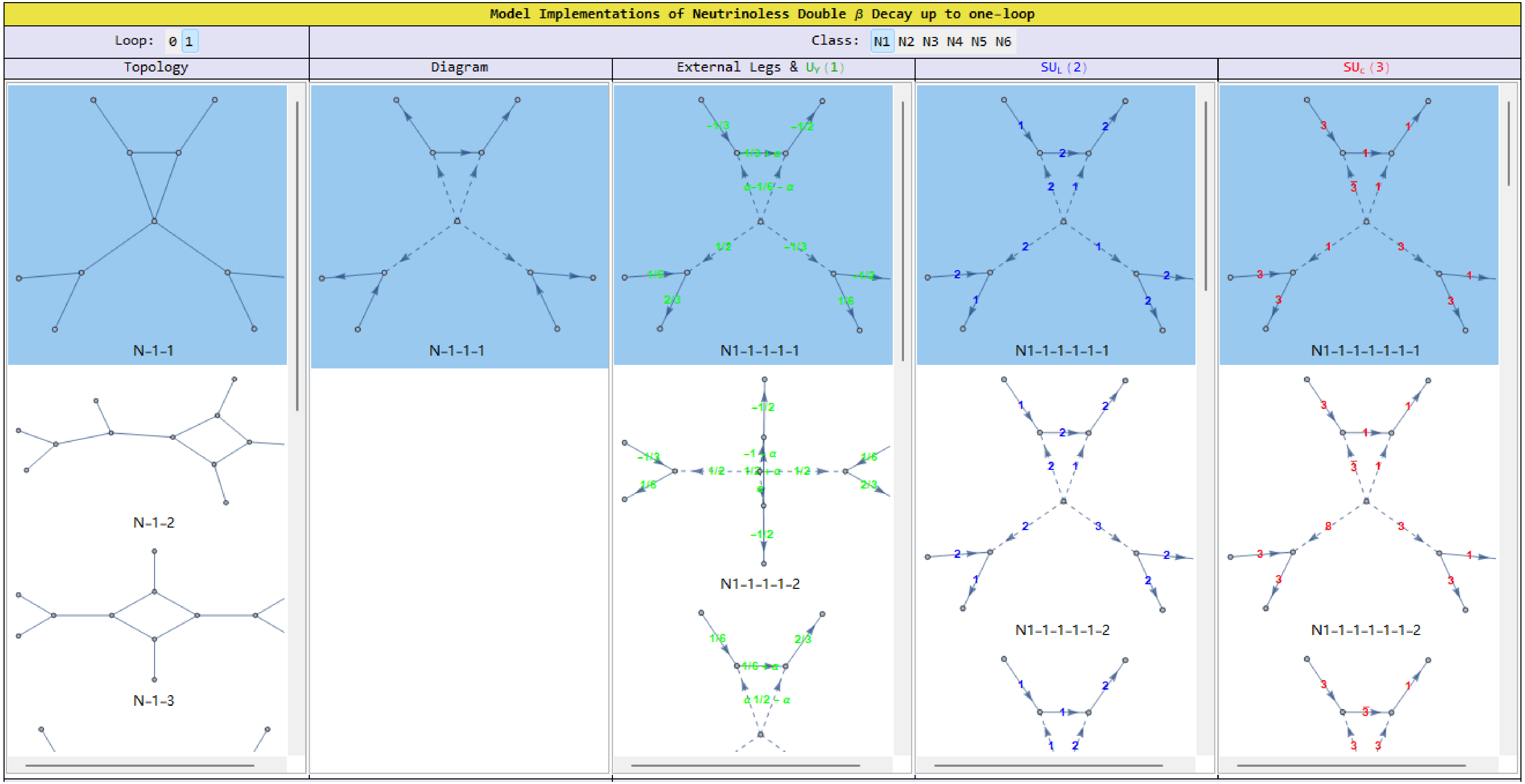
① leading contribution to 0νββ decay

②no extra symmetries beyond these of the SM

Filter models



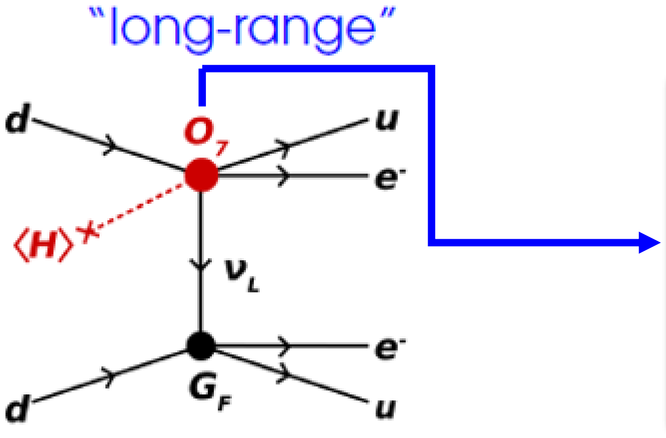
Bird’s-eye view of short-range 0νββ models



A large number of possible diagrams. For detail, see the attachment
http://staff.ustc.edu.cn/~dinggj/supplementary_materials/0nbb.zip

Decomposing the long-range 0νββ operators

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



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

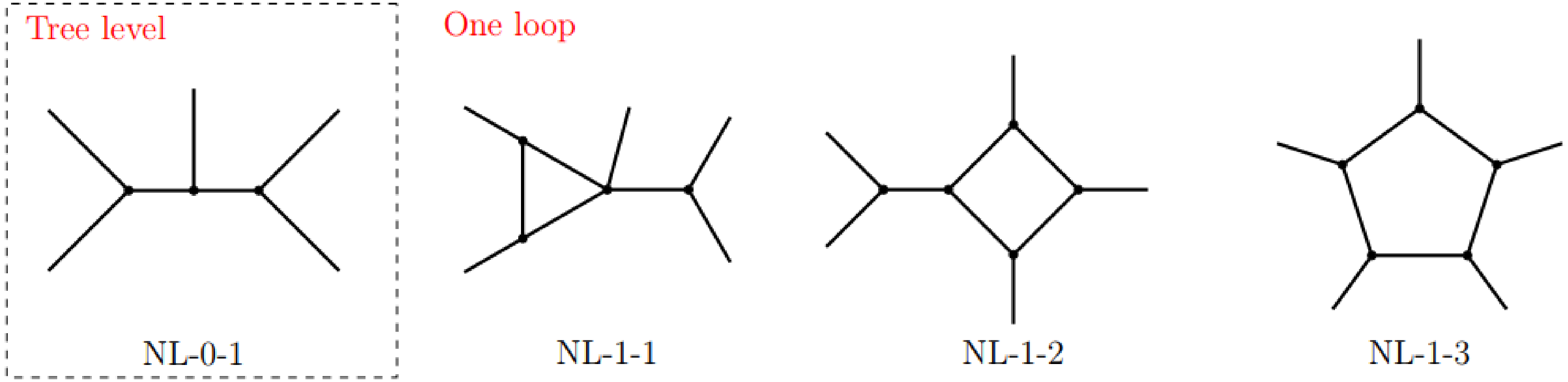
[Babu,Leung,hep-ph/0106054, NPB; Helo, Hirsch, Ota,1602.03362, JHEP; Lehman,1410.4193, PRD]

topologies

diagrams

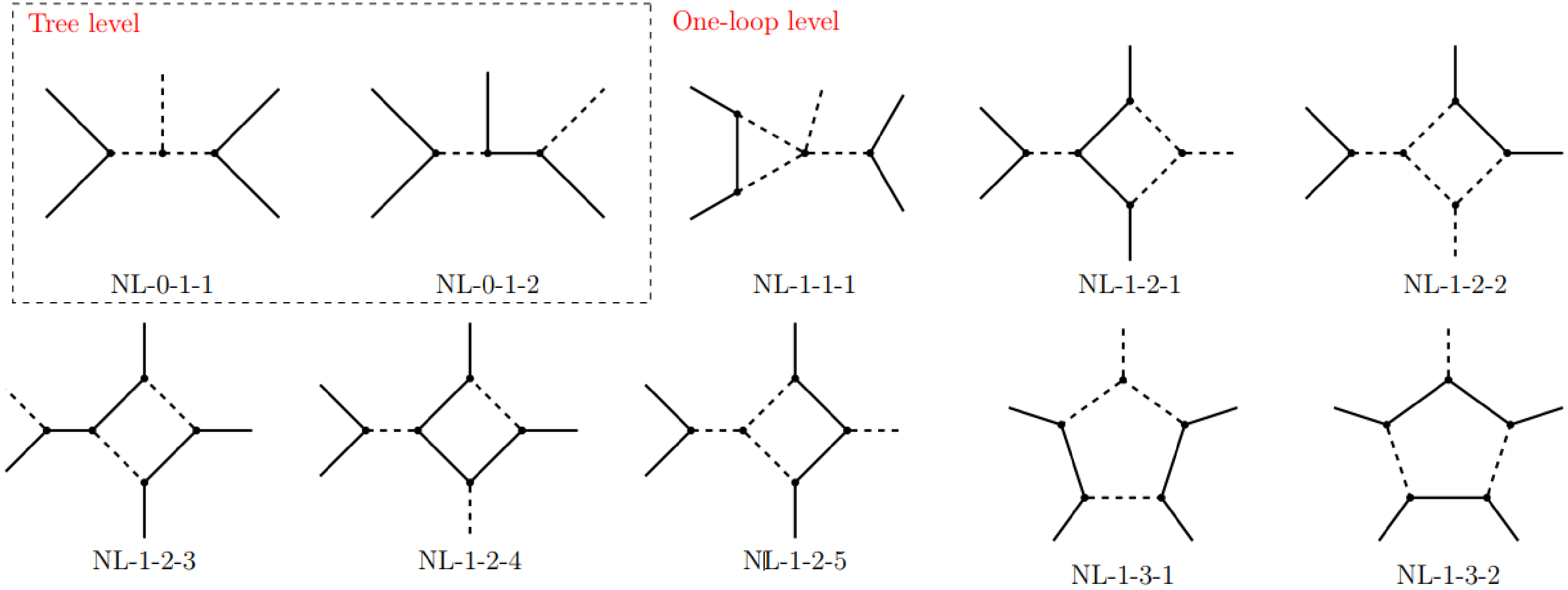
models

- Topologies

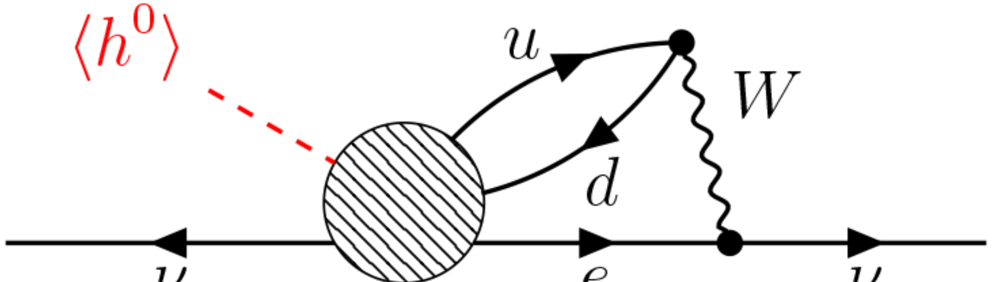


[Chen, Ding, Yao, 2301.02503, JHEP]

Diagrams



- 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: $\Delta L = 2$ operators $\rightarrow 0\nu\beta\beta$ & ν mass



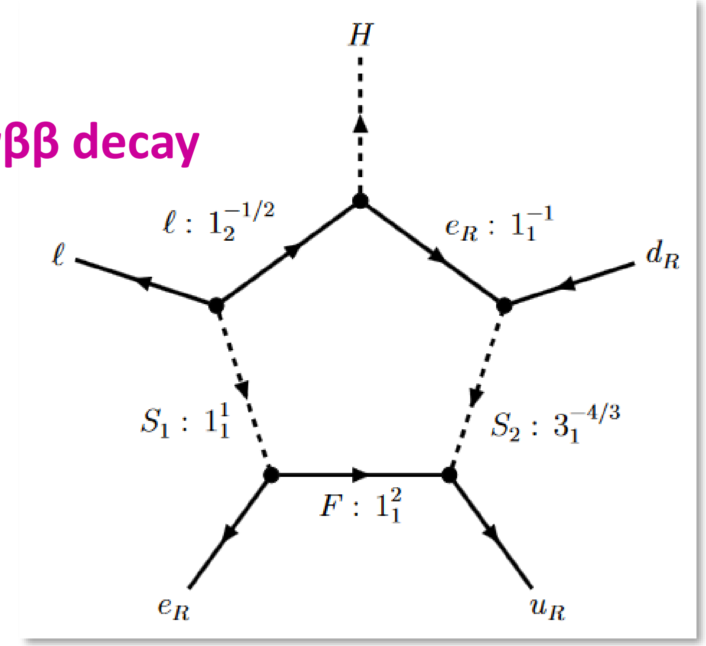
Majorana neutrino masses are generated at least at the 2-loop order, regardless of long-range 0νββ operators

An example model of long-range 0νββ decay

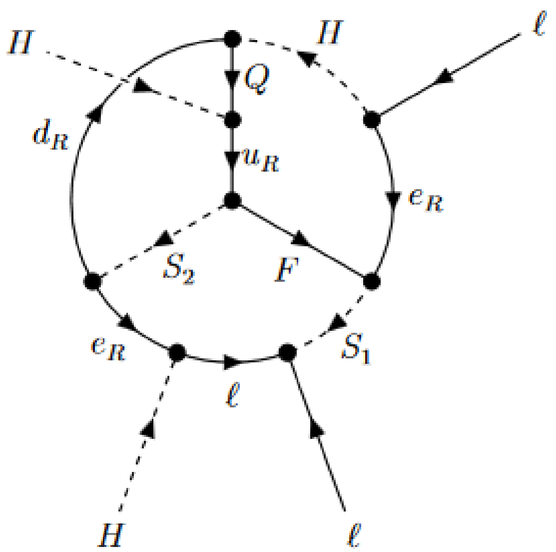
- **3 new fields**: two scalars S_1, S_2 and a vector-like fermion F

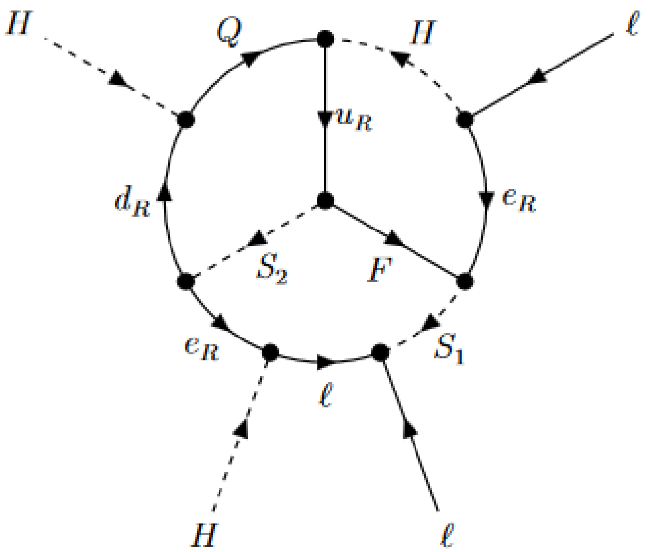
Fields	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
S_1	**1**	**1**	1
S_2	**3**	**1**	$-4/3$
F	**1**	**1**	2

1-loop 0νββ decay



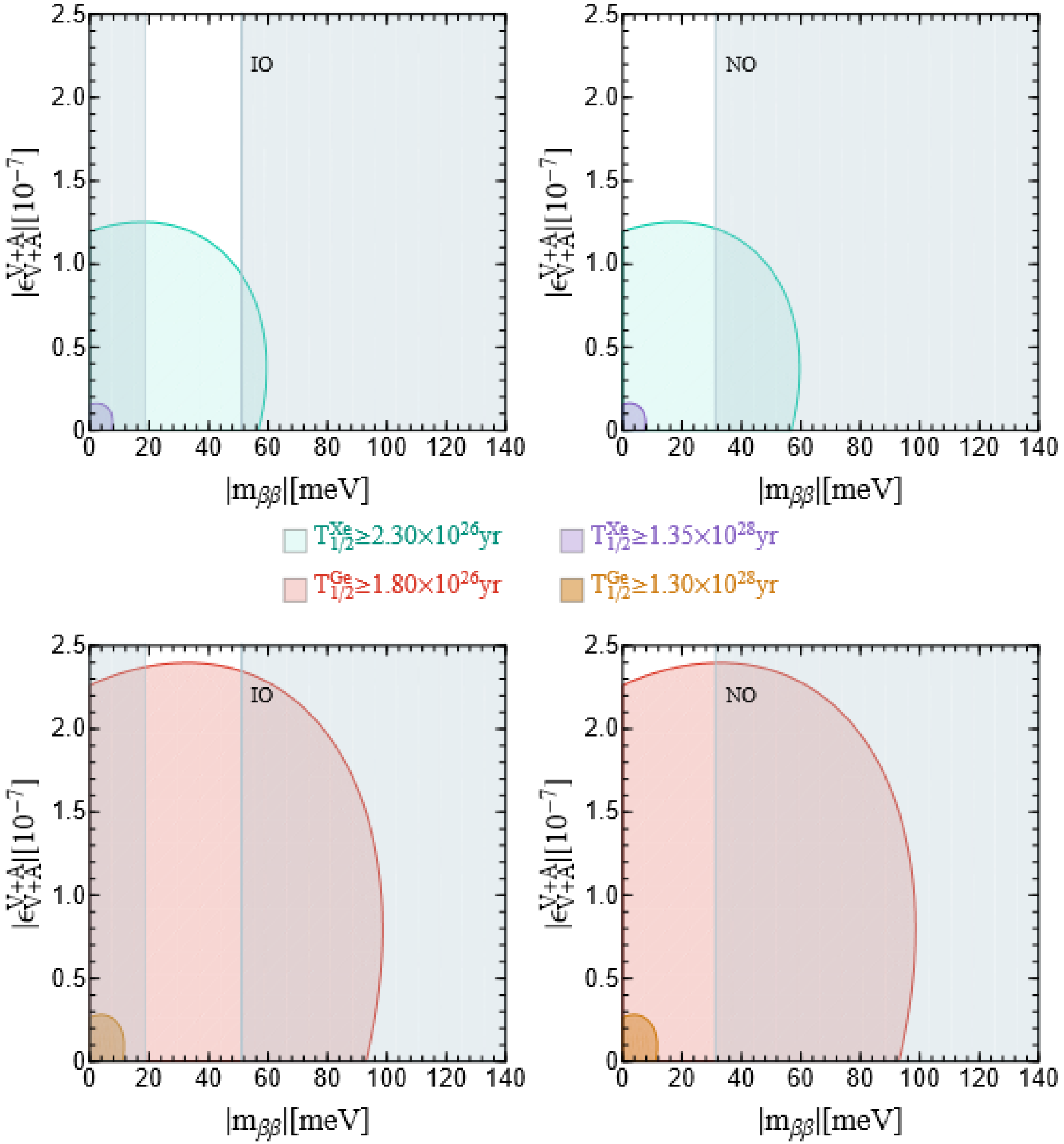
- Majorana neutrino masses generated at **3-loop**

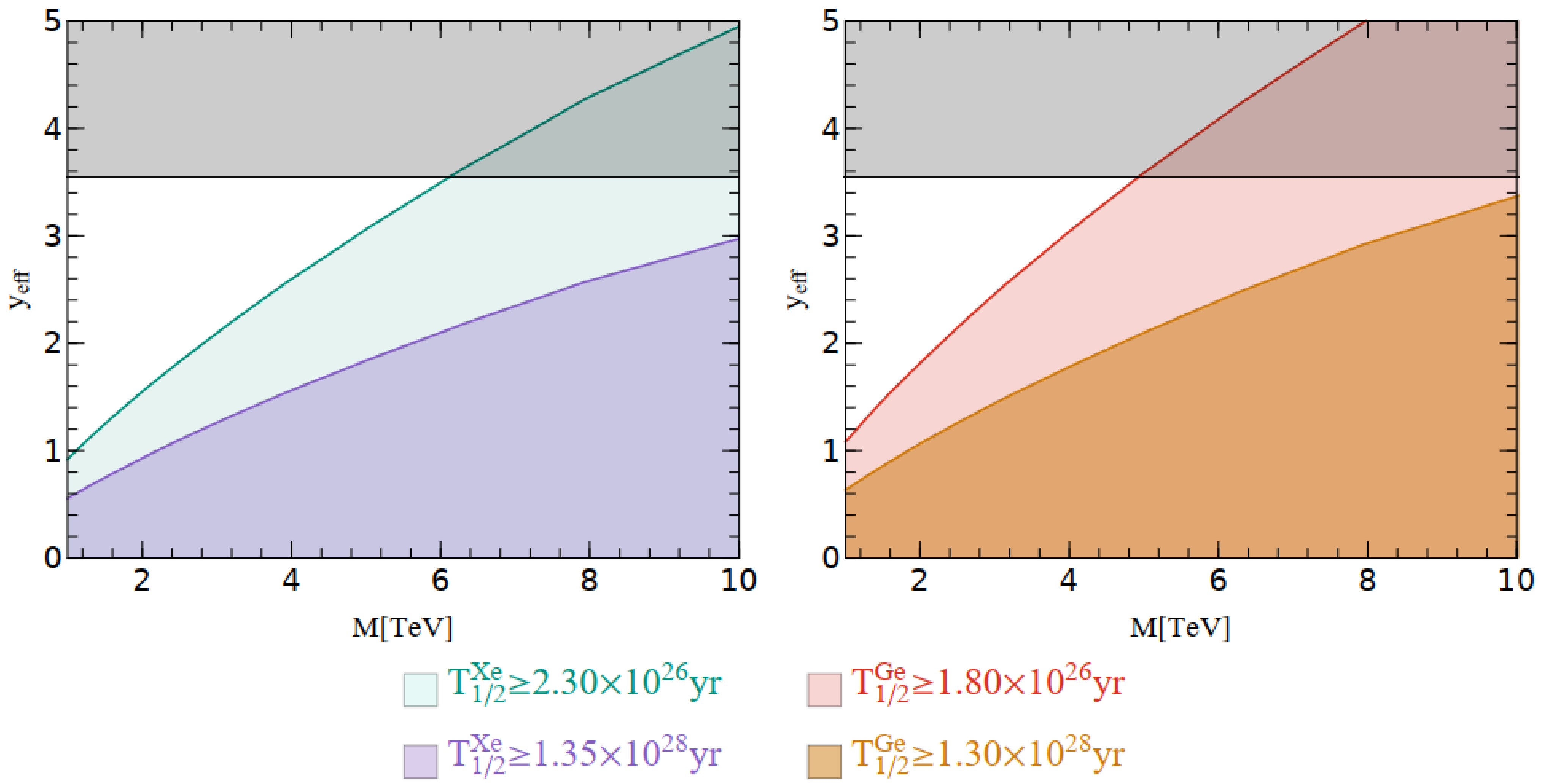




[Chen, Ding, Yao, 2301.02503, JHEP]

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





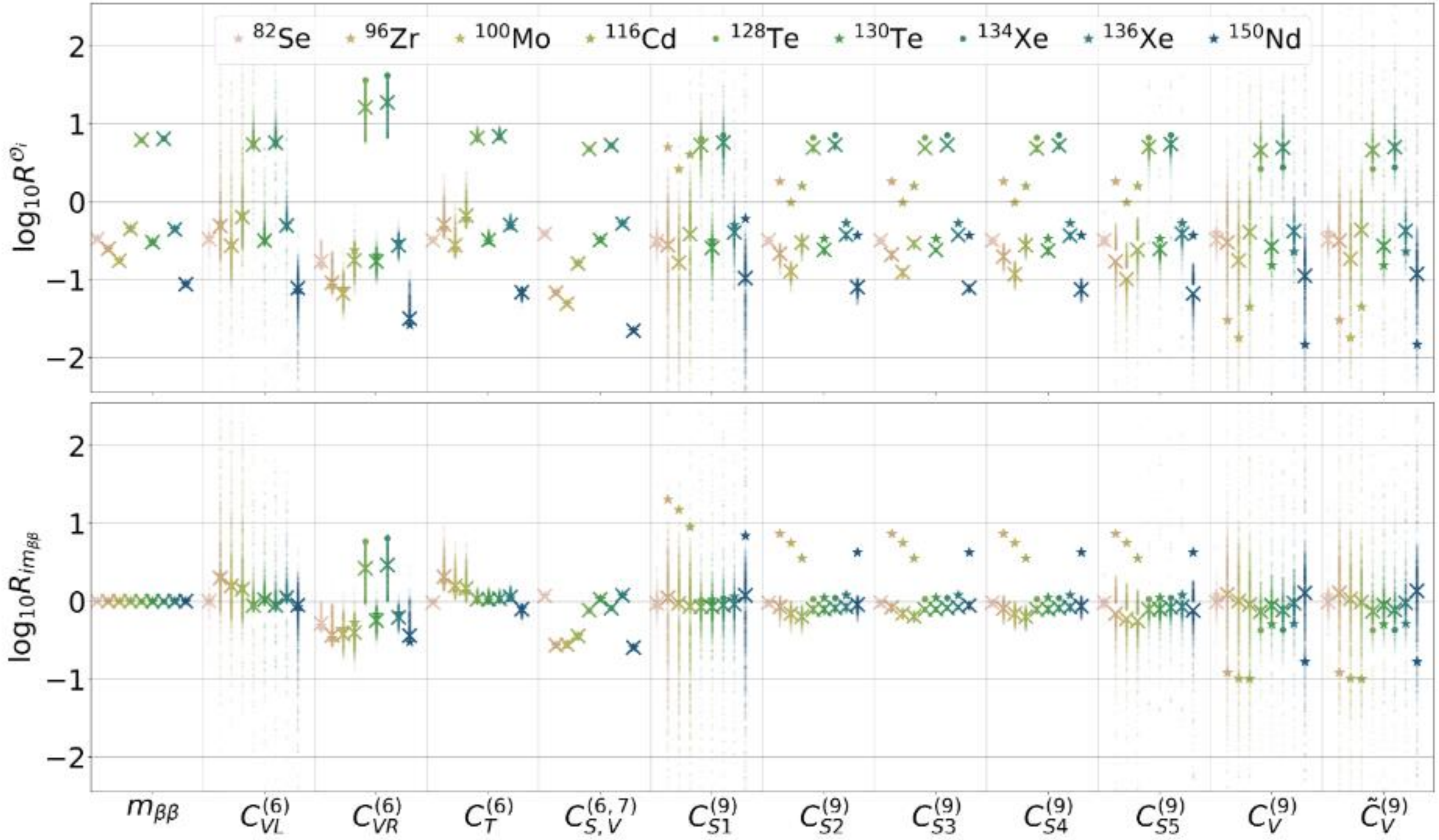
5
4
3
2
1
0
2
4
6
8
10
y_eff
M[TeV]
5
4
3
2
1
0
2
4
6
8
10
y_eff
M[TeV]
$T_{1/2}^{Xe} \geq 2.30\times10^{26}$yr
$T_{1/2}^{Ge} \geq 1.80\times10^{26}$yr
$T_{1/2}^{Xe} \geq 1.35\times10^{28}$yr
$T_{1/2}^{Ge} \geq 1.30\times10^{28}$yr

Distinguishing different 0νββ mechanisms

- Comparison of the decay rates obtained using **different isotopes**

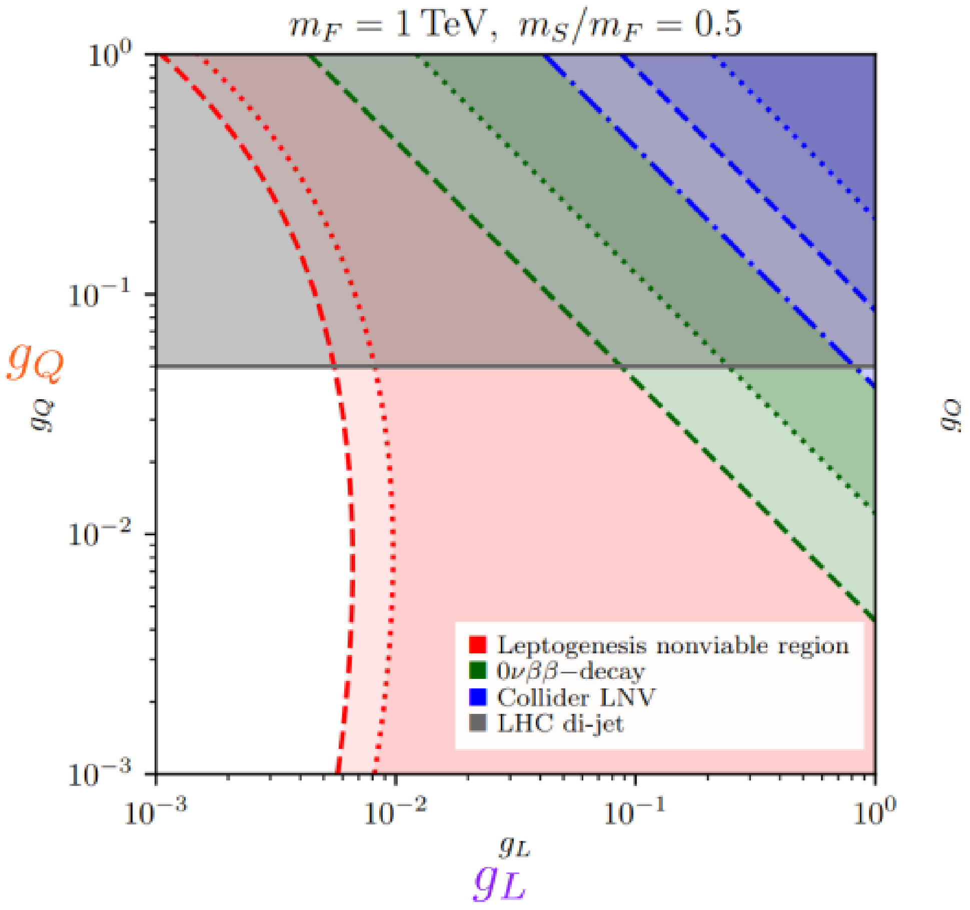
$$R^{\mathcal{O}_i}({}^{A}\mathrm{X}) \equiv \frac{T_{1/2}^{\mathcal{O}_i}({}^{A}\mathrm{X})}{T_{1/2}^{\mathcal{O}_i}({}^{76}\mathrm{Ge})} = \frac{\sum_j |\mathcal{M}_j^{\mathcal{O}_i}({}^{76}\mathrm{Ge})|^2 G_j^{\mathcal{O}_i}({}^{76}\mathrm{Ge})}{\sum_k |\mathcal{M}_k^{\mathcal{O}_i}({}^{A}\mathrm{X})|^2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

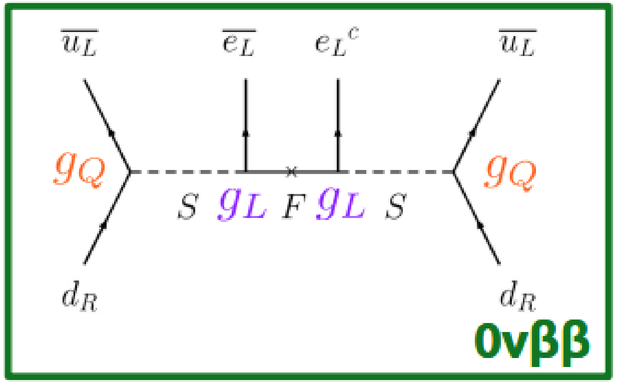
[Graf,Lindner,Scholer,2204.10845,PRD]

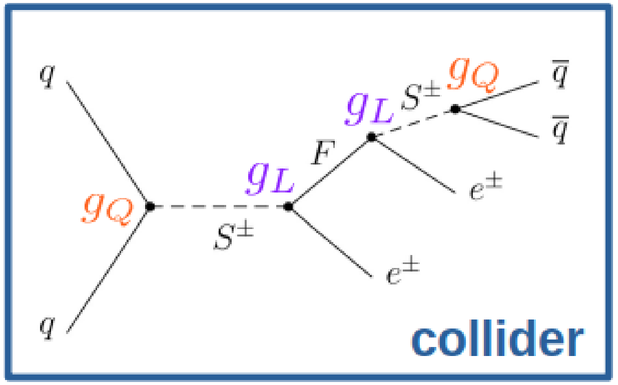


➢ Combining 0νββ decay, collider measurements and cosmology

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





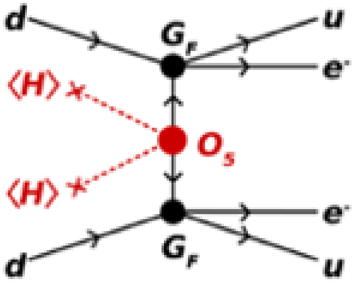


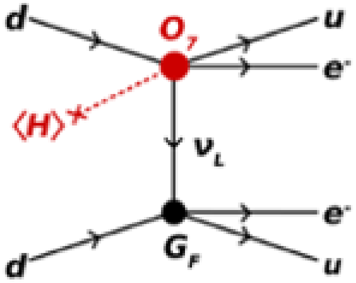
Collider signature: same-sign dilepton +2 jets + no E_T^{miss}

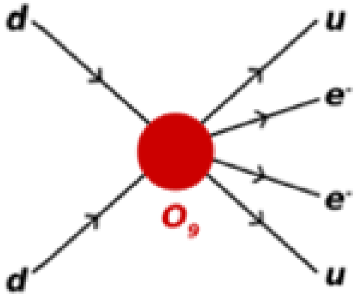
[Harz, Ramsey-Musolf, Shen, Urrutia-Quiroga, 2106.10838,PRD; Graesser,Li,Ramsey-Musolf, Shen,Urrutia-Quiroga, 2202.01237,JHEP]

Summary

- $0\nu\beta\beta$ is the most sensitive probe to the Majorana nature of neutrinos. However, there are many possible sources divided into mass mechanism, long-range mechanism and short-range mechanism.







- Systematic decomposition $0\nu\beta\beta$ operators: **topologies→diagrams → models**

- Many open problems: the $0\nu\beta\beta$ models in future colliders and LFV searches, implications in cosmology and leptogenesis….

- Both **theoretical and experimental efforts** are needed to fix the $0\nu\beta\beta$ signal and underling mechanism.

Thank you for your attention!

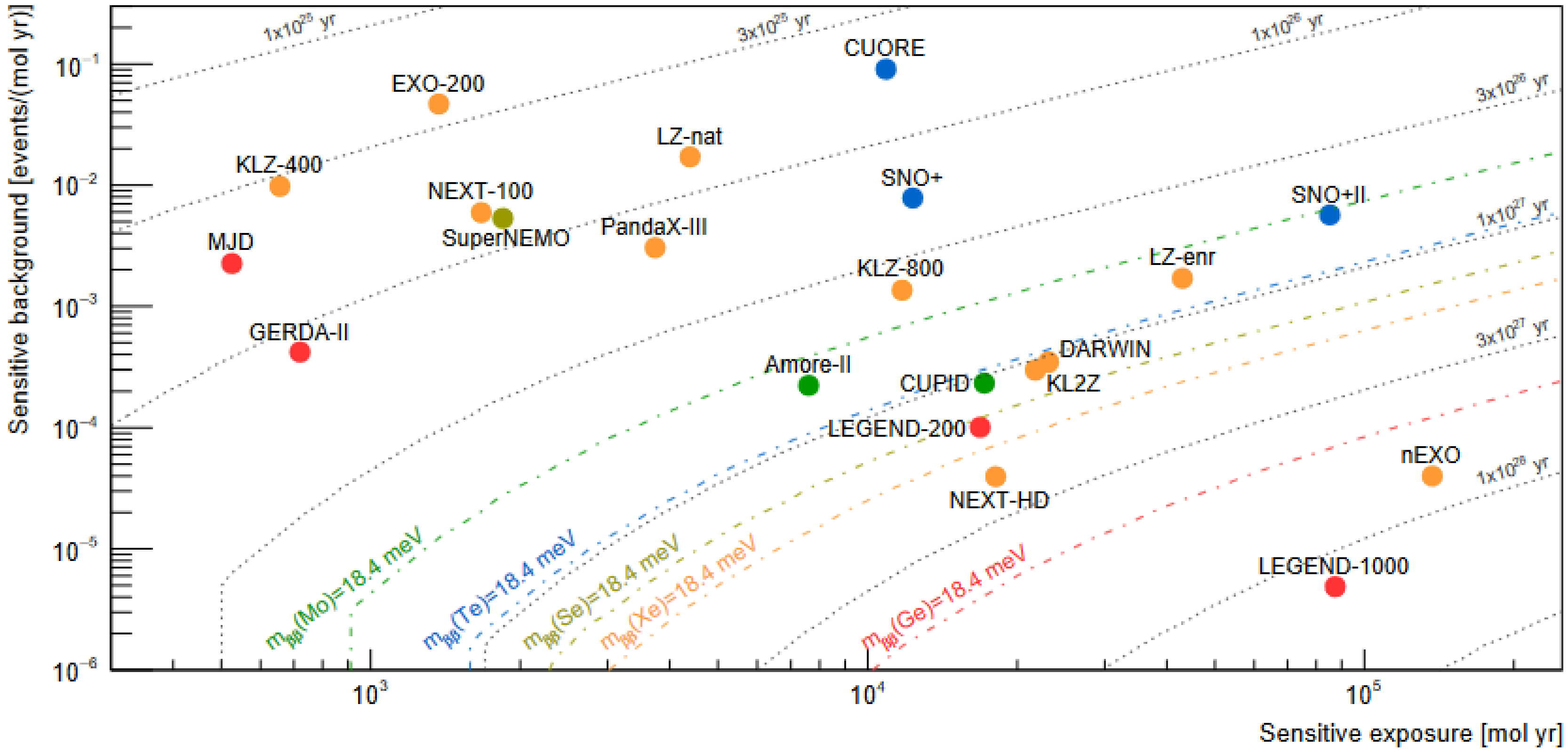
Backup

Current and future 0νββ experiments

Most stringent constraints on the half life:

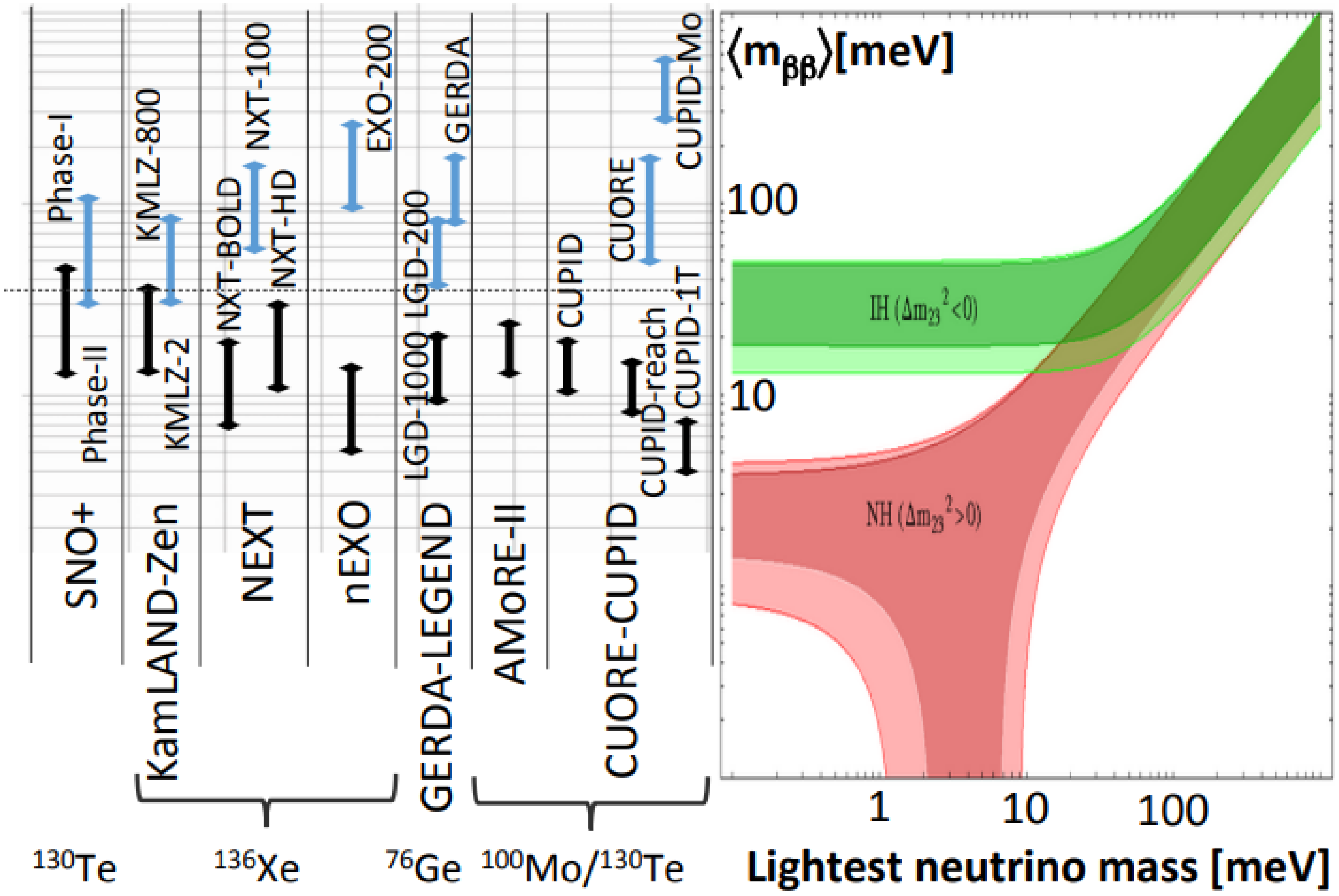
- ^{136}Xe (KamLAND-Zen): $T_{1/2}> 3.8\text{x}10^{26}$ yrs [KamLAND-Zen Collaboration, 2406.11438]
- ^{76}Ge (GERDA): $T_{1/2}> 1.8\text{x}\ 10^{26}$ yrs [GERDA collaboration, 2009.06079,PRL]
- ^{130}Te (CUORE): $T_{1/2}> 3.8\text{x}\ 10^{25}$ yrs [CUORE collaboration, 2404.04453]

There are many 0νββ decay experiments in plan and construction

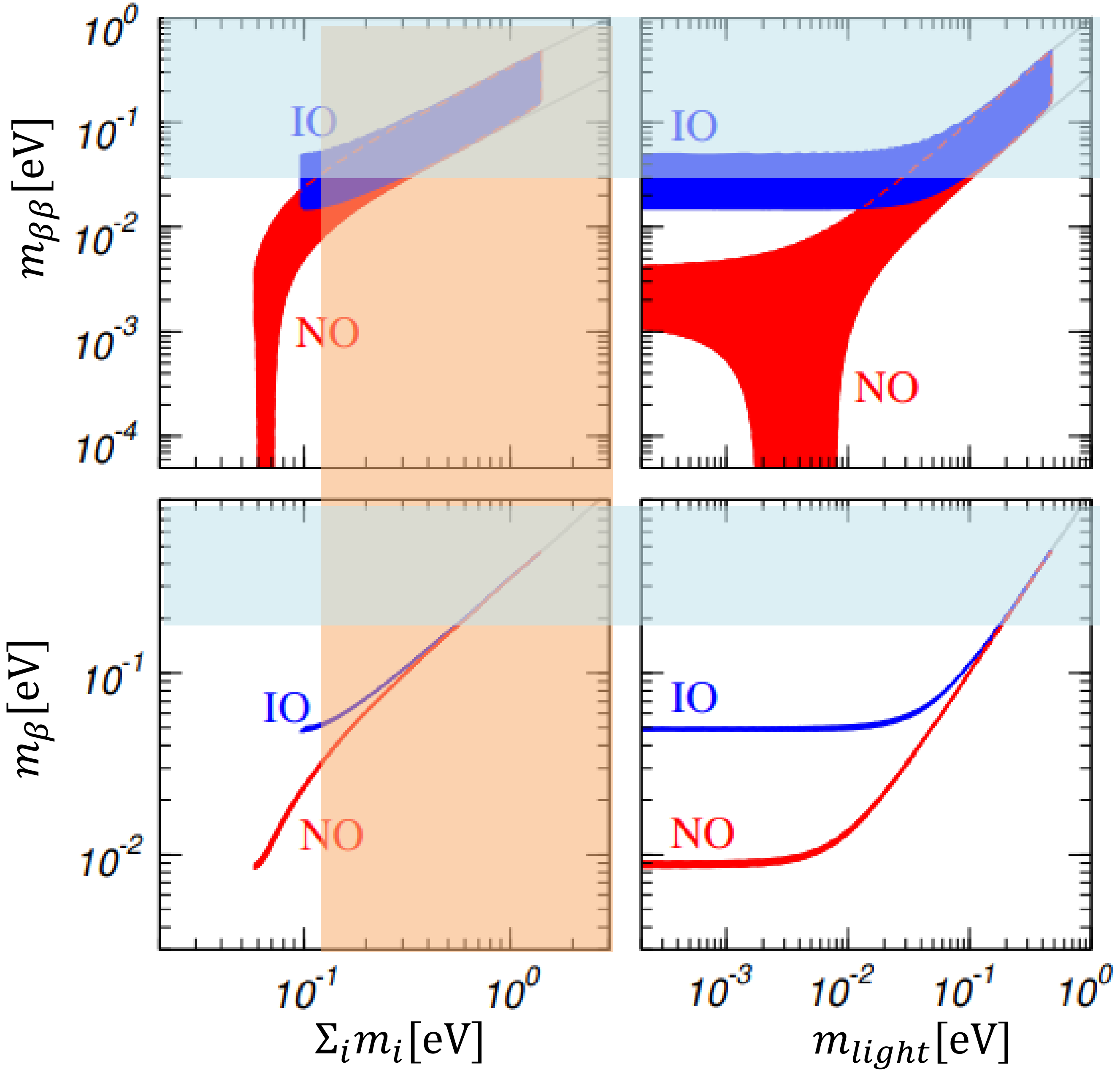


[Agostini, Benato, Detwiler, Menendez, Vissani, 2202.01787, Rev.Mod.Phys.]

Prospects of 0νββ experiments

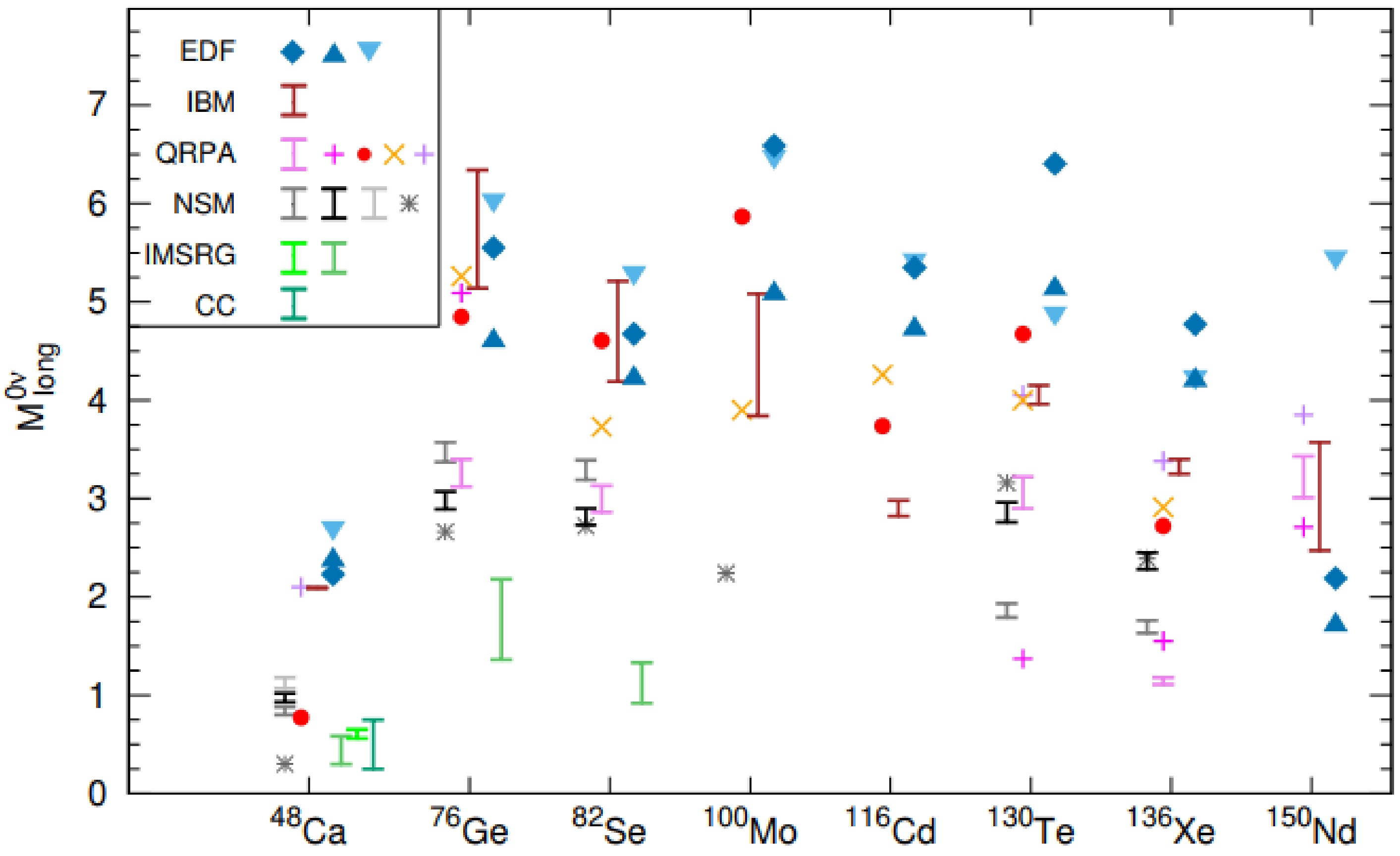


Absolute neutrino masses from synergies of neutrino facilities



Next generation of ton-scale 0νββ experiments will cover the IO region.

Nuclear matrix elements



[Agostini, Benato, Detwiler, Menendez, Vissani, 2202.01787, Rev.Mod.Phys.]

EDF: large NMEs

QRPA: wider range

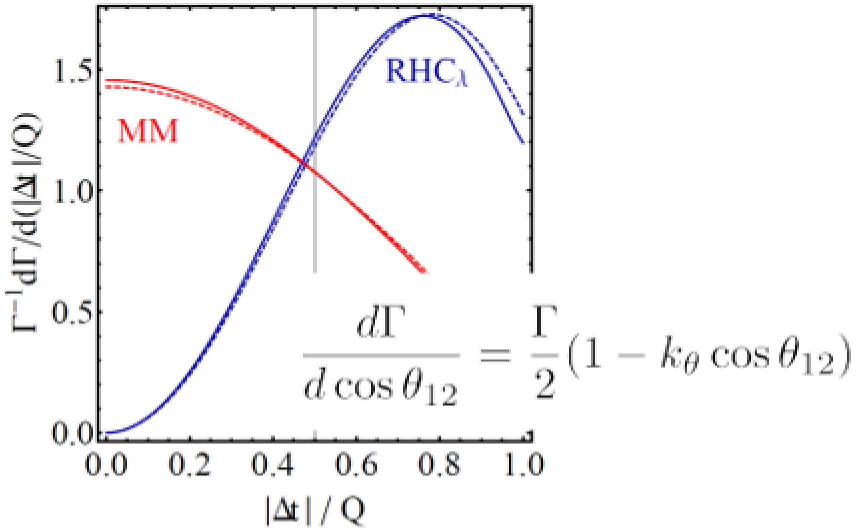
NSM: small NMEs

IMSRG ab initio 48Ca NME: quite small (no 2b currents)

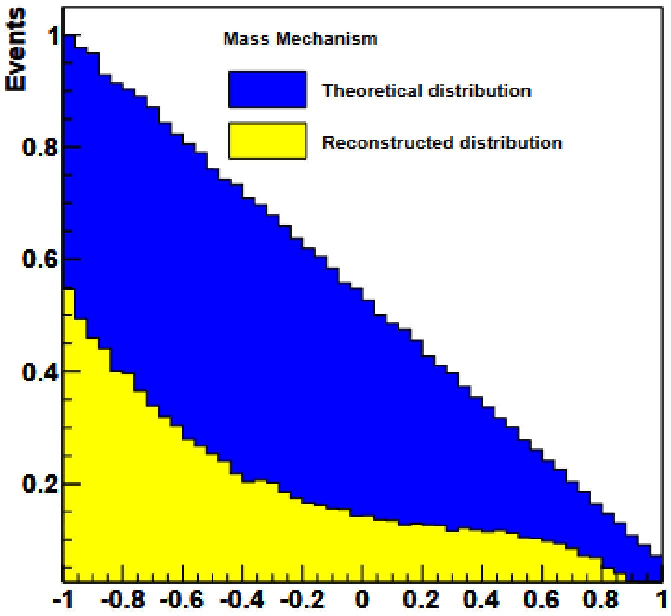
Unfortunately, nuclear matrix elements can be calculated only based on some models which describe many-body interactions of nucleons in nuclei. Since different models focus on different aspects of nuclear physics, large uncertainties (a factor of 2 or 3) are unavoidable.

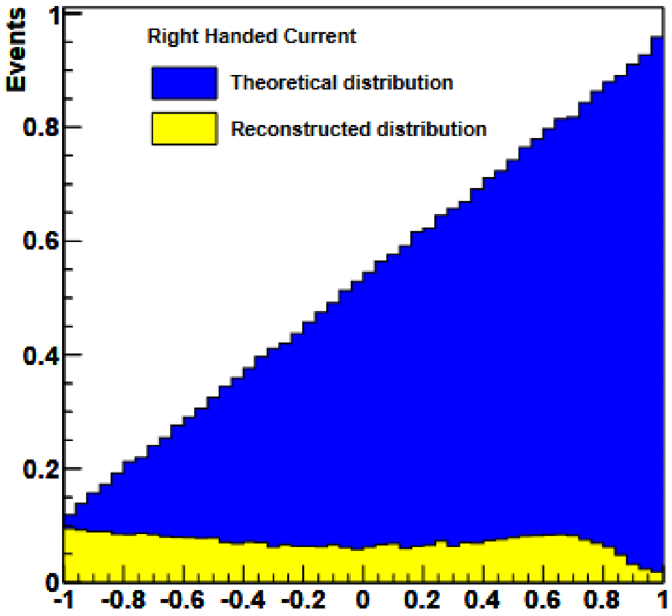
Determine 0νββ mechanisms by measuring electron

- measure the angular and energy distributions of electron

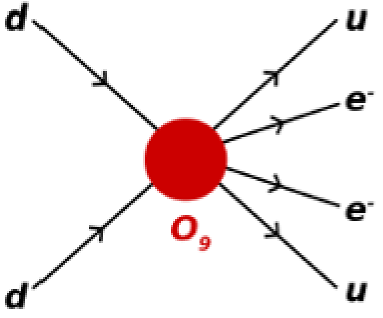


[Ali, Borisov, Zhuridov, 0706.4165,PRD; SuperNEMO Collaborarion,1005.1241,EPJC]





Tree-level decomposition of short-range 0νββ operators



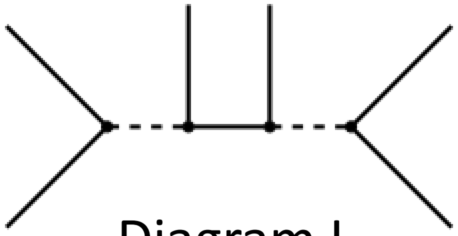


Diagram I

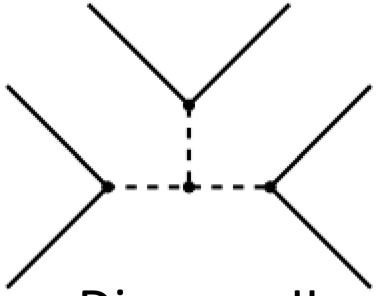
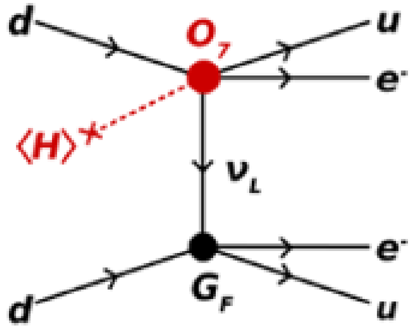


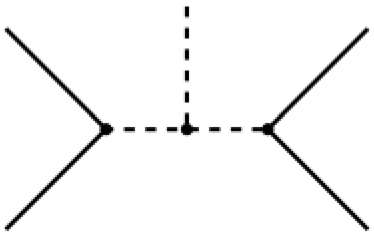
Diagram II

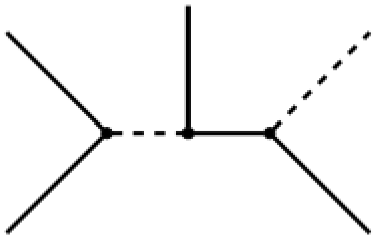
#	Decomposition	Long Range?	Mediator $(U(1)_{em}, SU(3)_c)$ S or V_ρ	ψ	S' or V'_ρ	Models/Refs./Comments
1-i	$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$	(a)	$(+1,\mathbf{1})$	$(0,\mathbf{1})$	$(-1,\mathbf{1})$	Mass mechan., RPV [58–60], LR-symmetric models [39], Mass mechanism with ν_S [61], TeV scale seesaw, 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, JHEP]

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.$\overline{\ell_R}LS'^\dagger$	$T2_4^{\mathrm{B}}(\alpha\neq\beta)$ $\mathcal{O}_3^7$ 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	$(L_\alpha Q)(H)(\overline{d_R}L_\beta)$	$S(\overline{\mathbf{3}},\mathbf{1})_{+\frac{1}{3}}$	$S'(\overline{\mathbf{3}},\mathbf{2})_{-\frac{1}{6}}$	$\frac{1}{2}\mathcal{O}_{3b}(\alpha,\beta)-\frac{1}{2}\mathcal{O}_{3b}^{\mathrm{ten.}}(\alpha,\beta)$	—	TνI-ii [53] $\mathcal{O}_3^8$ in [38]	[14, 68]
		$S(\overline{\mathbf{3}},\mathbf{3})_{+\frac{1}{3}}$	$S'(\overline{\mathbf{3}},\mathbf{2})_{-\frac{1}{6}}$	$\frac{1}{2}\mathcal{O}_{3a}(\alpha,\beta)-\frac{1}{2}\mathcal{O}_{3a}^{\mathrm{ten.}}(\alpha,\beta)$ $-\frac{1}{2}\mathcal{O}_{3b}(\beta,\alpha)-\frac{1}{2}\mathcal{O}_{3b}^{\mathrm{ten.}}(\beta,\alpha)$	—	TνI-ii [53] $\mathcal{O}_3^9$ in [38]	[14]
#3	$(L_\alpha L_\beta)(Q)(\overline{d_R}H)$	$S(\mathbf{1},\mathbf{1})_{+1}$	$\psi_{L,R}(\mathbf{3},\mathbf{2})_{-\frac{5}{6}}$	$-\mathcal{O}_{3a}(\alpha,\beta)$	—	$\left[\begin{array}{c}\text{T}\nu\text{I-ii}\\ \text{w.}S^\dagger HH'\end{array}\right]$	$T2_1^{\mathrm{B}}(\alpha\neq\beta)$ $\mathcal{O}_3^1$ 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	$(L_\alpha H)(Q)(\overline{d_R}L_\beta)$	$\psi_R(\mathbf{1},\mathbf{1})_0$	$S(\overline{\mathbf{3}},\mathbf{2})_{-\frac{1}{6}}$	$\frac{1}{2}\mathcal{O}_{3b}(\beta,\alpha)+\frac{1}{2}\mathcal{O}_{3b}^{\mathrm{ten.}}(\beta,\alpha)$	type I		
		$\psi_R(\mathbf{1},\mathbf{3})_0$	$S(\overline{\mathbf{3}},\mathbf{2})_{-\frac{1}{6}}$	$-\frac{1}{2}\mathcal{O}_{3a}(\alpha,\beta)+\frac{1}{2}\mathcal{O}_{3a}^{\mathrm{ten.}}(\alpha,\beta)$ $-\frac{1}{2}\mathcal{O}_{3b}(\alpha,\beta)+\frac{1}{2}\mathcal{O}_{3b}^{\mathrm{ten.}}(\alpha,\beta)$	type III		
#5	$(L_\alpha L_\beta)(\overline{d_R})(QH)$	$S(\mathbf{1},\mathbf{1})_{+1}$	$\psi_{L,R}(\mathbf{3},\mathbf{1})_{+\frac{2}{3}}$	$\mathcal{O}_{3a}(\alpha,\beta)$	—	$\left[\begin{array}{c}\text{T}\nu\text{I-ii}\\ \text{w.}S^\dagger HH'\end{array}\right]$	$T2_2^{\mathrm{B}}(\alpha\neq\beta)$ $\mathcal{O}_3^2$ 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	$(L_\alpha Q)(\overline{d_R})(L_\beta H)$	$S(\overline{\mathbf{3}},\mathbf{1})_{+\frac{1}{3}}$	$\psi_R(\mathbf{1},\mathbf{1})_0$	$-\frac{1}{2}\mathcal{O}_{3b}(\alpha,\beta)+\frac{1}{2}\mathcal{O}_{3b}^{\mathrm{ten.}}(\alpha,\beta)$	type I		
		$S(\overline{\mathbf{3}},\mathbf{3})_{+\frac{1}{3}}$	$\psi_R(\mathbf{1},\mathbf{3})_0$	$\frac{1}{2}\mathcal{O}_{3a}(\alpha,\beta)-\frac{1}{2}\mathcal{O}_{3a}^{\mathrm{ten.}}(\alpha,\beta)$ $-\frac{1}{2}\mathcal{O}_{3b}(\beta,\alpha)-\frac{1}{2}\mathcal{O}_{3b}^{\mathrm{ten.}}(\beta,\alpha)$	type III		
#7	$(L_\alpha Q)(L_\beta)(\overline{d_R}H)$	$S(\overline{\mathbf{3}},\mathbf{1})_{+\frac{1}{3}}$	$\psi_{L,R}(\mathbf{3},\mathbf{2})_{-\frac{5}{6}}$	$\frac{1}{2}\mathcal{O}_{3b}(\alpha,\beta)-\frac{1}{2}\mathcal{O}_{3b}^{\mathrm{ten.}}(\alpha,\beta)$	—	TνI-iii $\mathcal{O}_3^4$ in [38]	
		$S(\overline{\mathbf{3}},\mathbf{3})_{+\frac{1}{3}}$	$\psi_{L,R}(\mathbf{3},\mathbf{2})_{-\frac{5}{6}}$	$\frac{1}{2}\mathcal{O}_{3a}(\alpha,\beta)-\frac{1}{2}\mathcal{O}_{3a}^{\mathrm{ten.}}(\alpha,\beta)$ $-\frac{1}{2}\mathcal{O}_{3b}(\beta,\alpha)-\frac{1}{2}\mathcal{O}_{3b}^{\mathrm{ten.}}(\beta,\alpha)$	—	TνI-iii $\mathcal{O}_3^5$ in [38]	
#8	$(\overline{d_R}L_\alpha)(L_\beta)(QH)$	$S(\mathbf{3},\mathbf{2})_{+\frac{1}{6}}$	$\psi_{L,R}(\mathbf{3},\mathbf{1})_{+\frac{2}{3}}$	$-\frac{1}{2}\mathcal{O}_{3a}(\alpha,\beta)-\frac{1}{2}\mathcal{O}_{3a}^{\mathrm{ten.}}(\alpha,\beta)$	—	—	$T2_2^{\mathrm{B}}(m_\nu)_{\alpha\neq\beta}$ $\mathcal{O}_3^3$ in [38], [43]
		$S(\mathbf{3},\mathbf{2})_{+\frac{1}{6}}$	$\psi_{L,R}(\mathbf{3},\mathbf{3})_{+\frac{2}{3}}$	$\frac{1}{2}\mathcal{O}_{3b}(\alpha,\beta)+\frac{1}{2}\mathcal{O}_{3b}^{\mathrm{ten.}}(\alpha,\beta)$ $+\frac{1}{2}\mathcal{O}_{3b}(\beta,\alpha)-\frac{1}{2}\mathcal{O}_{3b}^{\mathrm{ten.}}(\beta,\alpha)$	—	TνI-iii $\mathcal{O}_3^6$ 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,JHEP]