Neutrinoless double beta decay and classification of the mechanisms

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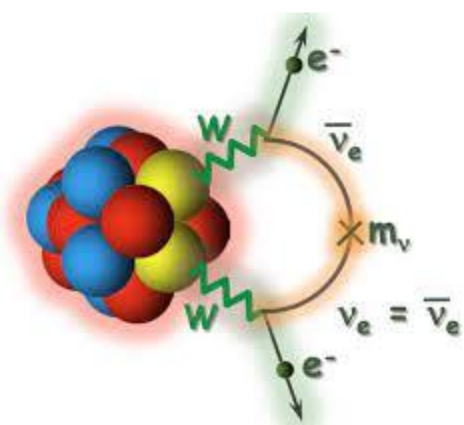
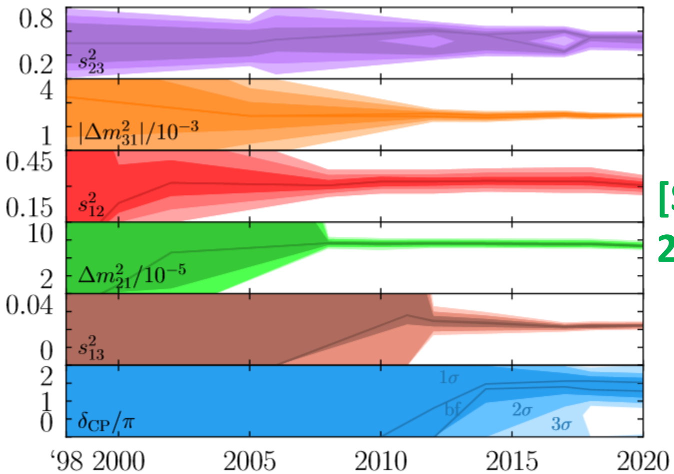


The state of art of neutrino mixing

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



[Snowmass, 2212.00809]

Global fit-Normal hierarchy

Δm^2_{21}=$7.41^{+0.21}_{-0.20} \times 10^{-5}\text{eV}^2$

Δm^2_{31}=$2.507^{+0.026}_{-0.027} \times 10^{-3}\text{eV}^2$

$\theta_{12}= 33.41^{+0.75}_{-0.72}(^\circ)$

$\theta_{23}= 42.2^{+1.1}_{-0.9}(^\circ)$

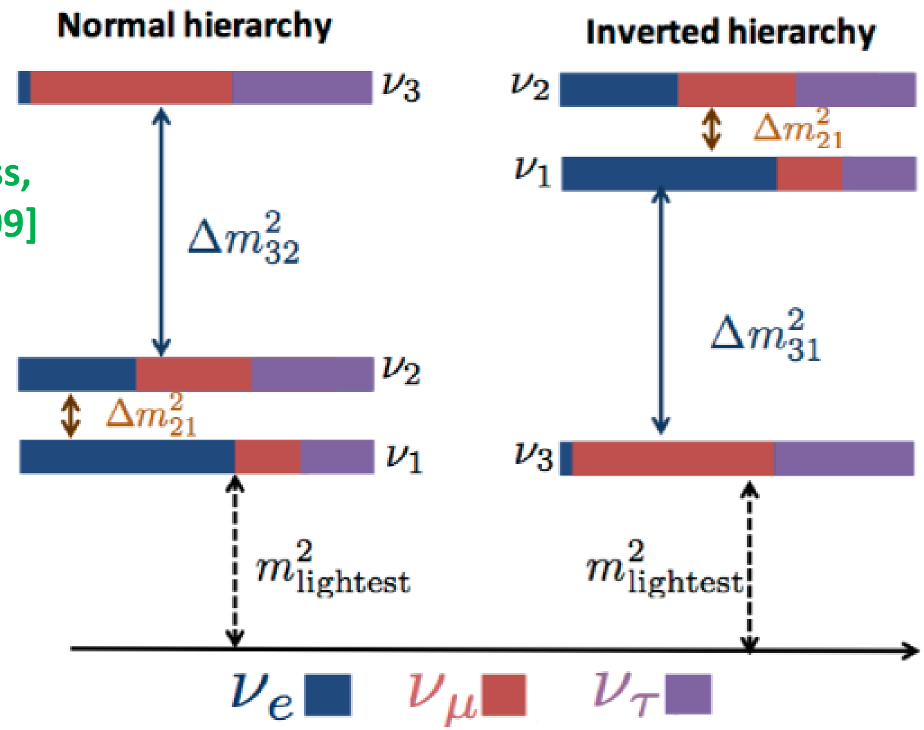
$\theta_{13}= 8.58^{+0.11}_{-0.11}(^\circ)$

sign(Δm^2_{32})=?

$\theta_{23}< 45^\circ$ or $\theta_{23}> 45^\circ$?

δ_{CP}=?

m_{lightest}=?



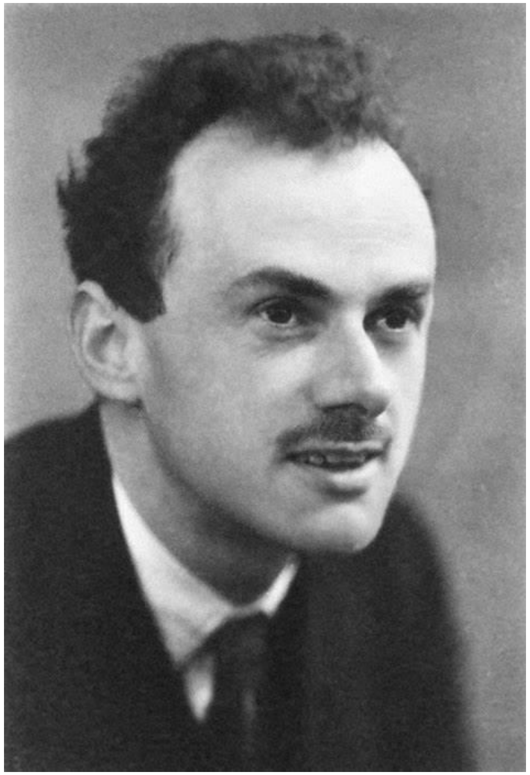
$$\Delta m^2_{ij} \equiv m^2_i - m^2_j$$

[Gonzalez-Garcia et al., NuFIT5.2 (2022)]

Massive neutrinos: Dirac or Majorana?

$\nu \neq \nu^c$

$\nu = \nu^c$



vs.

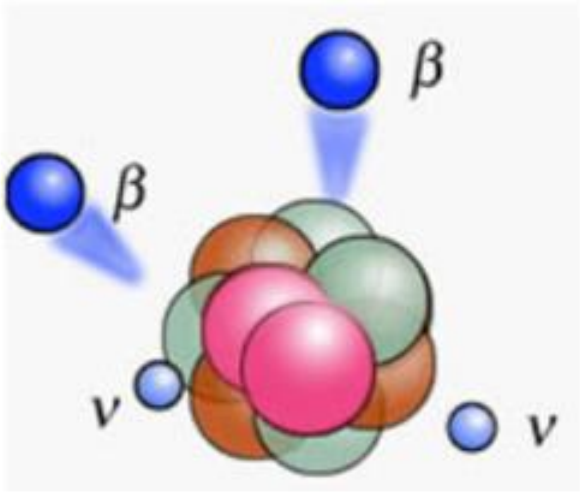
- **neutrinoless double beta decay**
- lepton number violation at collider
- cosmology

The 2β-decays

2νββ decays

$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\overline{\nu}_e$$

$\Delta L = 0$

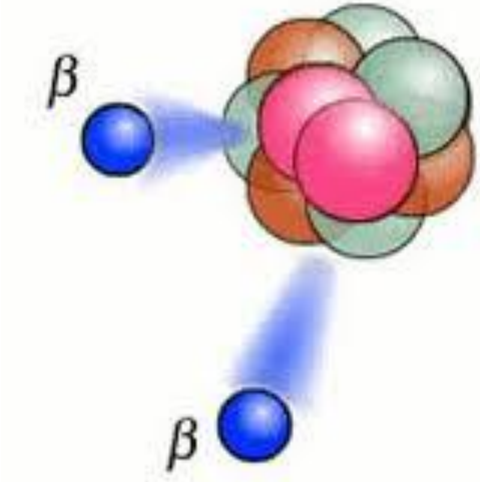


[Goeppert-Mayer, Phys. Rev.48,512(1935)]

- Allowed in SM
- second order in weak interaction
- Natural background for decay

0νββ decays

$$(A,Z) \rightarrow (A,Z+2) + 2e^-$$



$\Delta L = 2$

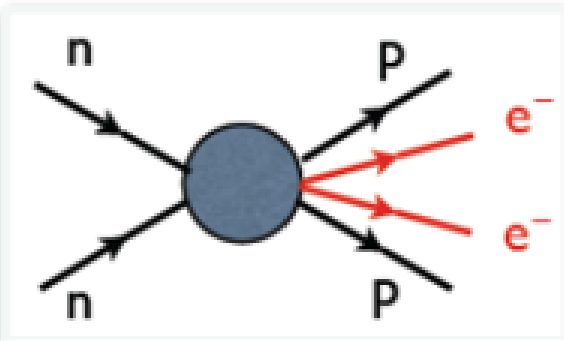
[Furry, Phys.Rev.56,1184(1939)]

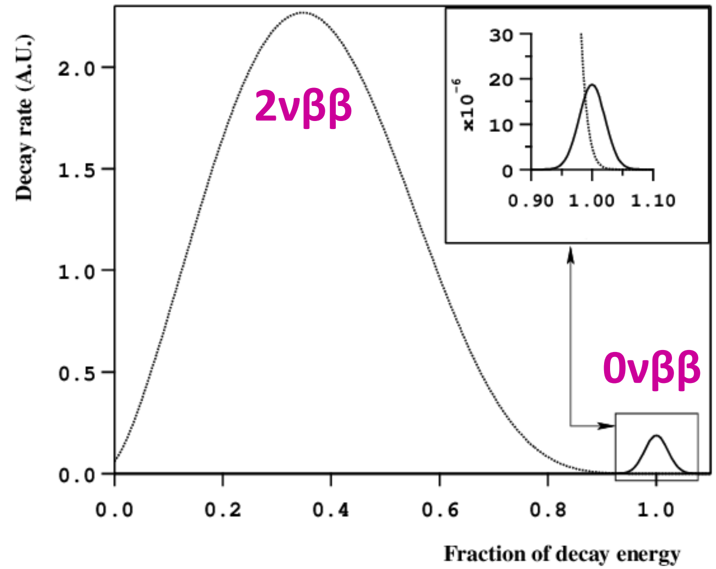
- **NOT** allowed in SM→rare
- Lepton number violation→ neutrinos are Majorana fermions

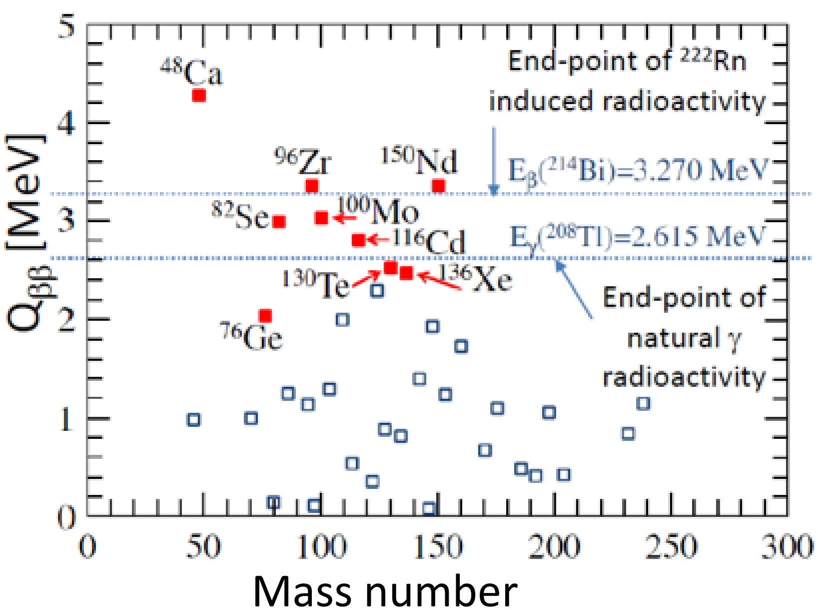
The 0νββ-decays: signature and candidate nuclei

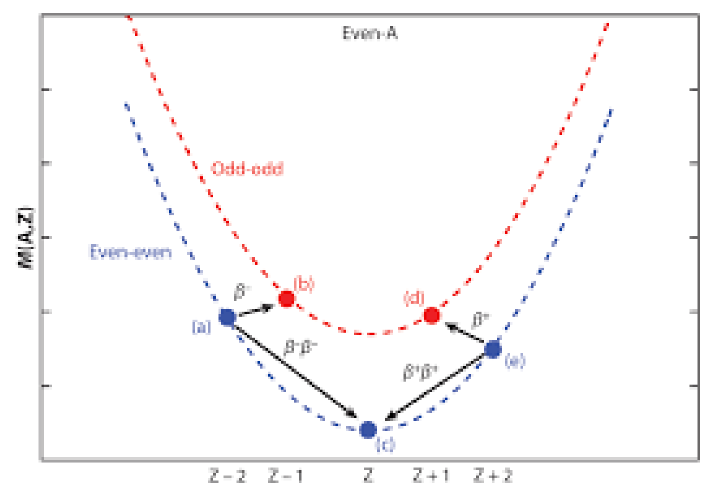
0νββ is potentially observable in certain even-even nuclei (9 isotopes including ^{48}Ca, **^{76}Ge**, ^{100}Mo, ^{130}Te, **^{136}Xe**) for which single beta decay is energetically forbidden. The decay rate is less than 1 event per ton and year.

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







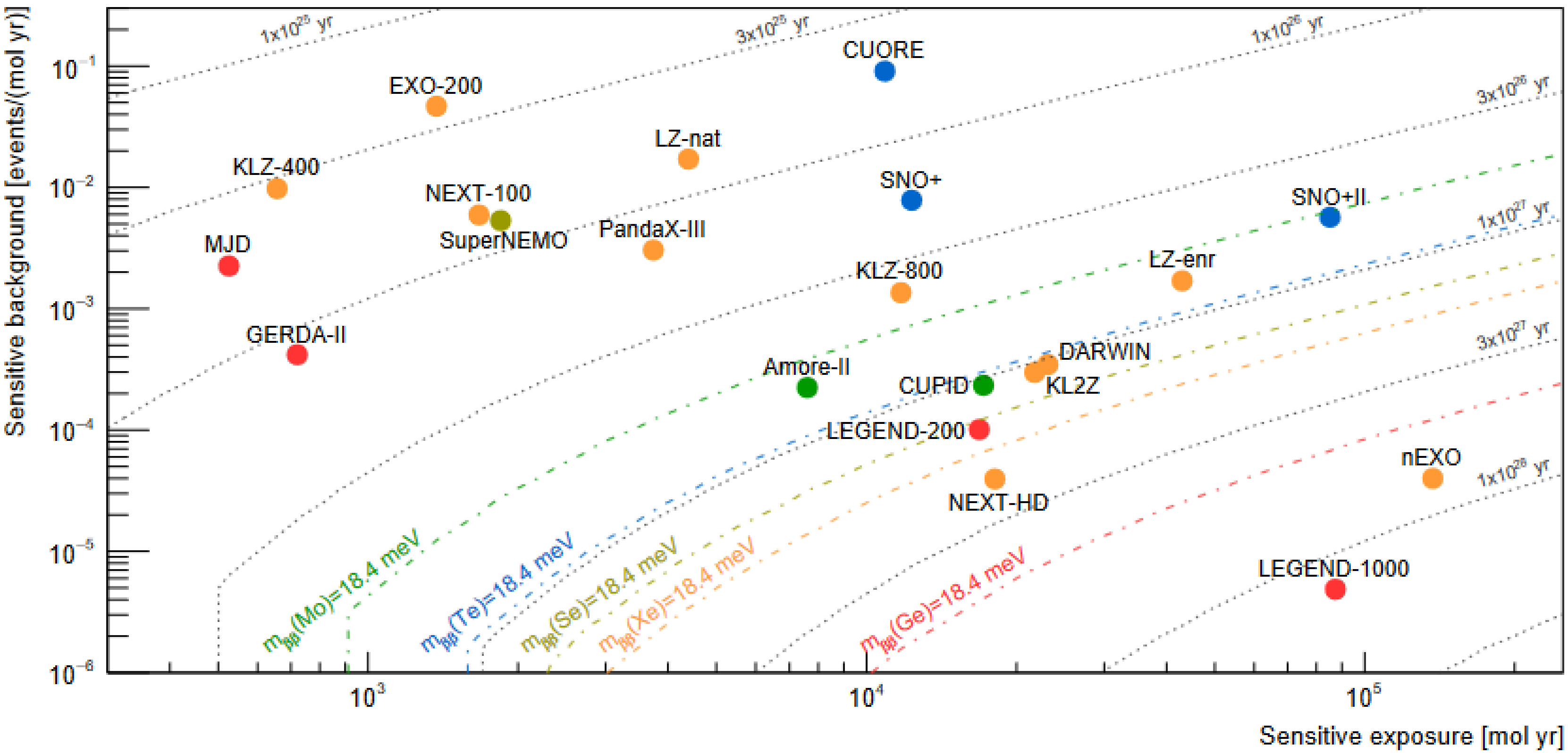


Current and future experiments

Most stringent constraints on the half life:

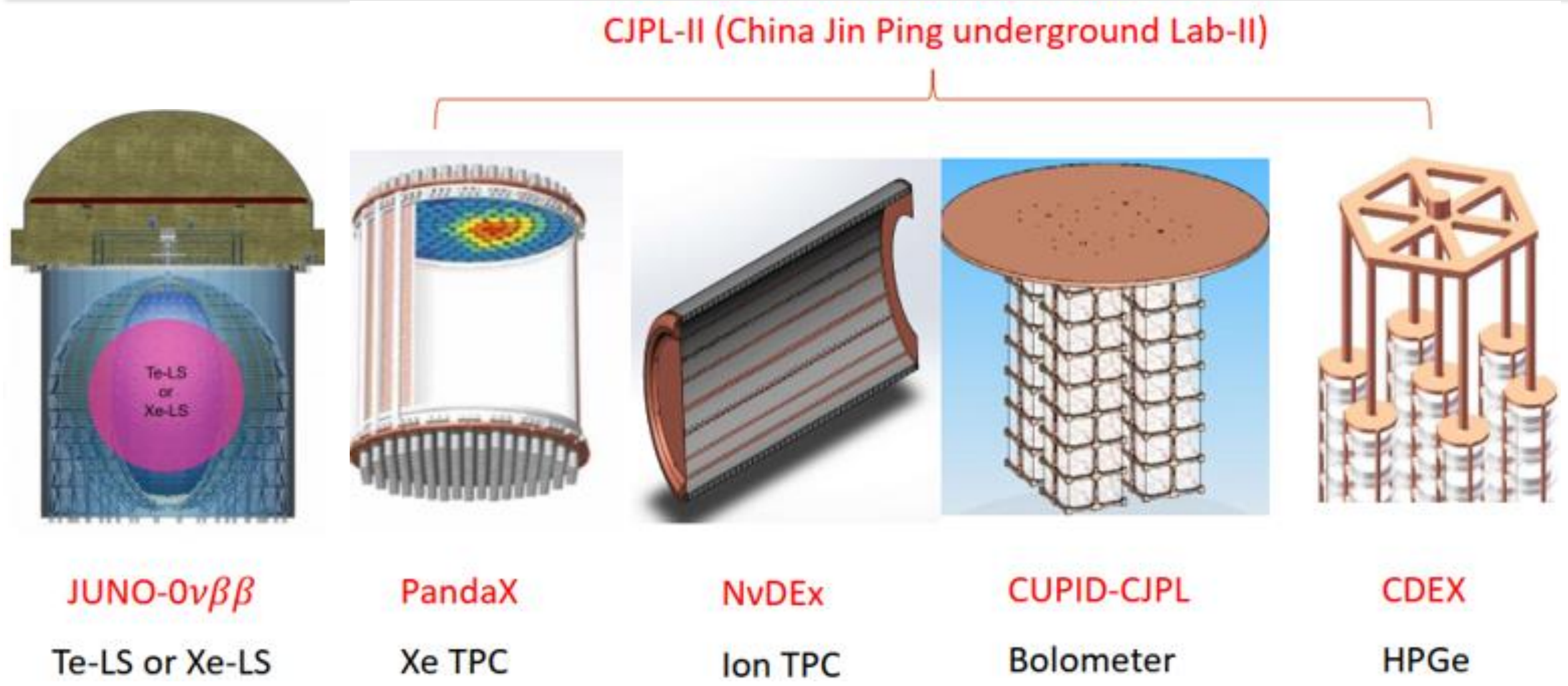
- ^{136}Xe (KamLAND-Zen): $T_{1/2} > 2.3 \times 10^{26}$ yrs **[KamLAND-Zen Collaboration, 2203.02139]**
- ^{76}Ge (GERDA): $T_{1/2} > 1.8 \times 10^{26}$ yrs **[GERDA collaboration, 2009.06079]**
- ^{130}Te (CUORE): $T_{1/2} > 2.2 \times 10^{25}$ yrs **[CUORE collaboration, 2104.06906]**

There are many 0νββ decay experiments in plan and construction



[Agostini, Benato, Detwiler, Menendez, Vissani, 2202.01787]

$0\nu\beta\beta$ experiments in China



$T_{1/2}$> 1.8x10^{28} yrs

[Snowmass, 2209.03340]

$T_{1/2}$ >2.7x10^{26} yrs

[2102.08221, 2211.14992]

$T_{1/2}$ >4x10^{26} yrs

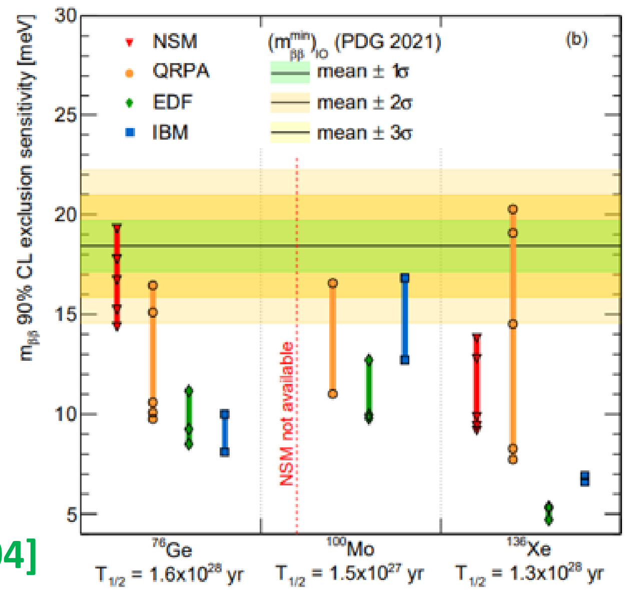
[NvDEx-100 CDR, 2304.08362]

CDEX-1T:
$T_{1/2}$ > 10^{28} yrs

[http://cdex.ep.tsinghua.edu.cn/column/Experiment#cdex1t]

Discovery sensitivities of current and next-generation $0\nu\beta\beta$ experiments

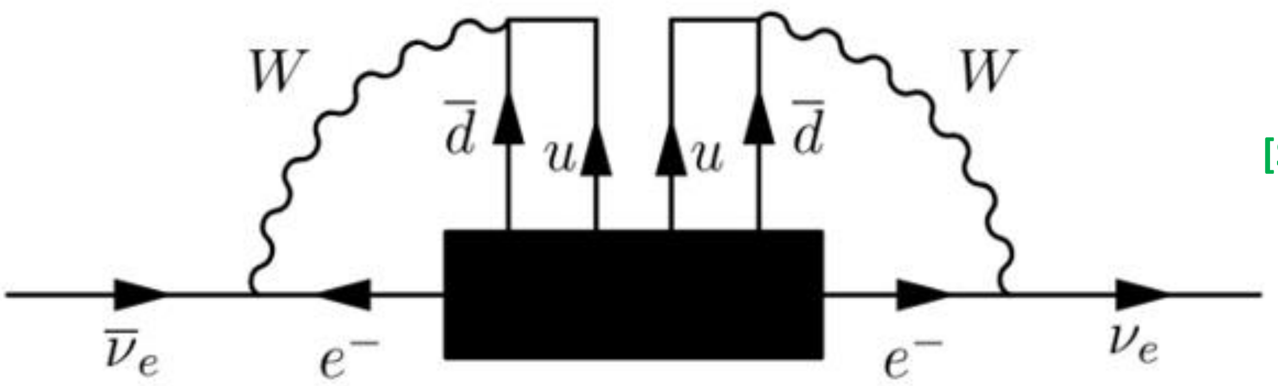
- tonne-scale to multi-tonne scale detectors
- multiple isotopes, multiple techniques: bolometers, scintillators, trackers, TPC, semiconductors
- the discovery sensitivity depends on the matrix elements
- will cover all IO region



[Agostini, et al, 2107.09104]

Black Box theorem (Schechter-Valle theorem)

Whatever is the mechanism of 0νββ decay, if 0νββ decay is observed, it is possible to construct a 4-loop diagram that contributes to the Majorana neutrino mass matrix



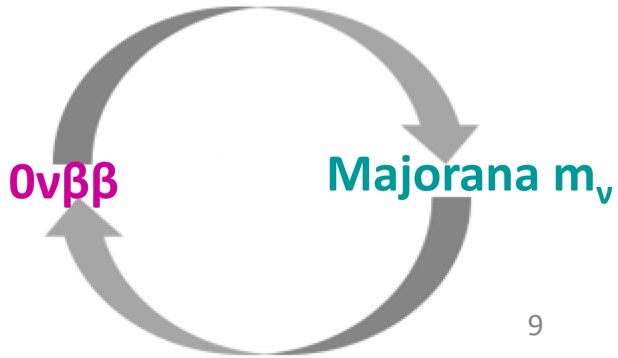
[Schechter, Valle, 1982']

Only very tiny Majorana mass is induced

$$\delta m_\nu \approx 10^{-25}\ \mathrm{eV}$$

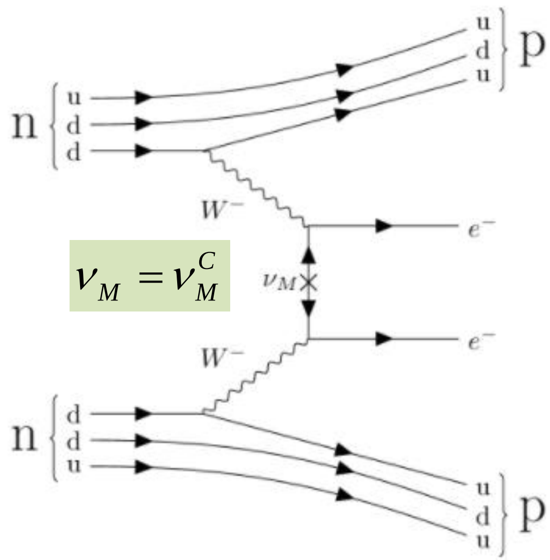
[Duerr, Lindner, Merle, 1105.0901; Liu,Zhang,Zhou,1606.04886]

- It is too small to explain observed neutrino masses and splittings.
- In a concrete model of 0νββ decay, the leading order contribution to neutrino mass can appear at lower order and it can be larger than 10^{-25}eV.



Majorana neutrino interpretation of 0νββ

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



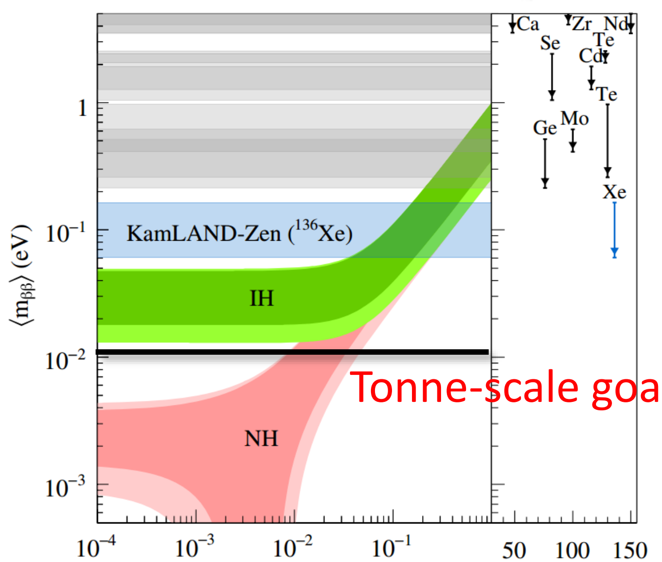
- **The decay amplitude is proportional to the effective mass**

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



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

- $0\nu\beta\beta$ decay, single β decay and cosmology measure different combination of the neutrino masses, they are complementary probes of neutrino mass.

$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right|$$

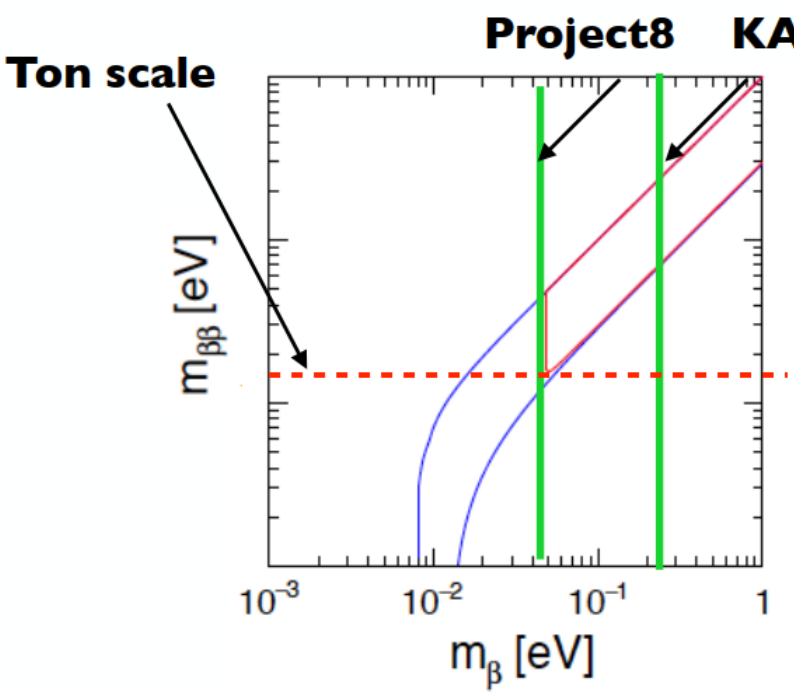
$0\nu\beta\beta$ decay

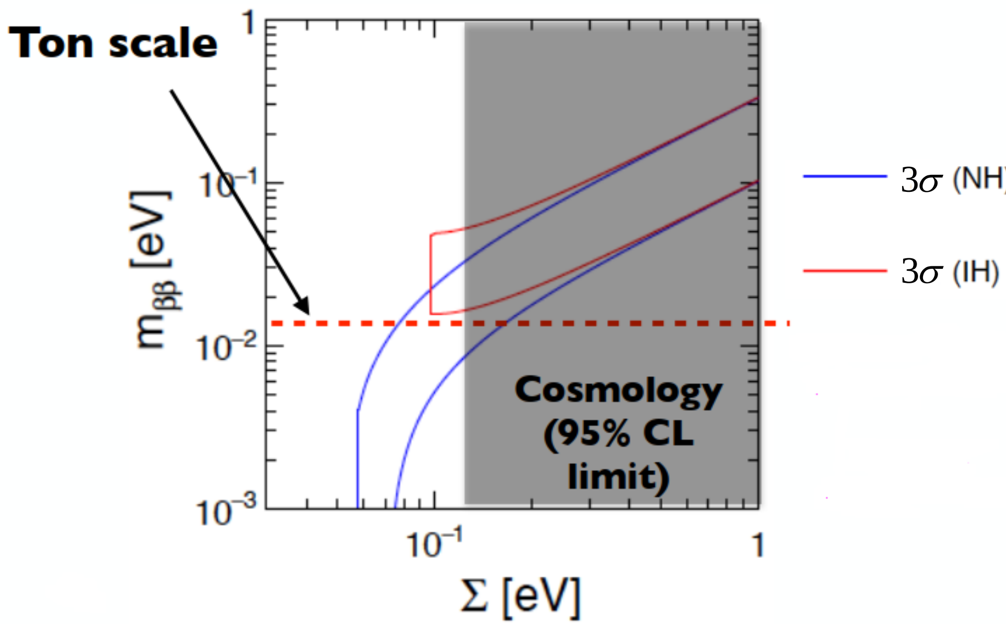
$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

Tritium β decay

$$\Sigma = \sum_i m_i$$

Cosmology

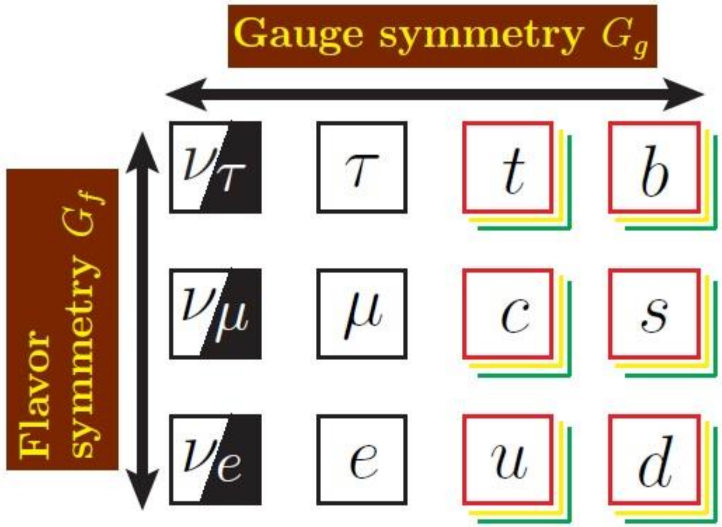


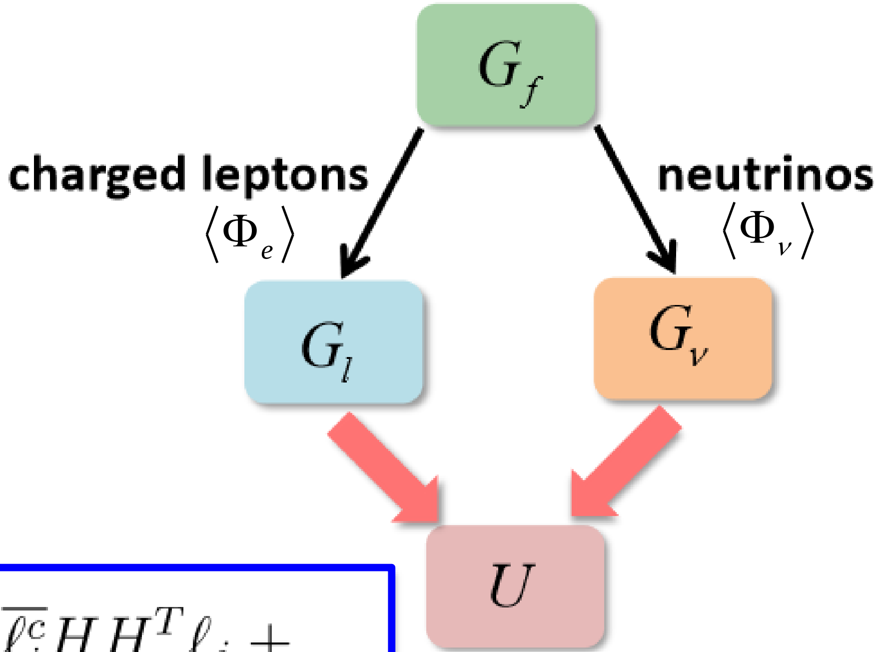


[Capozzi, Valentino, Lisi, Marrone, Melchiorri, Palazzo, 2003.08511]

Flavor symmetry in 0νββ decay

Flavor symmetry: relate three generations of fundamental fermions to explain the origin of fermion of mass hierarchies and mixings.



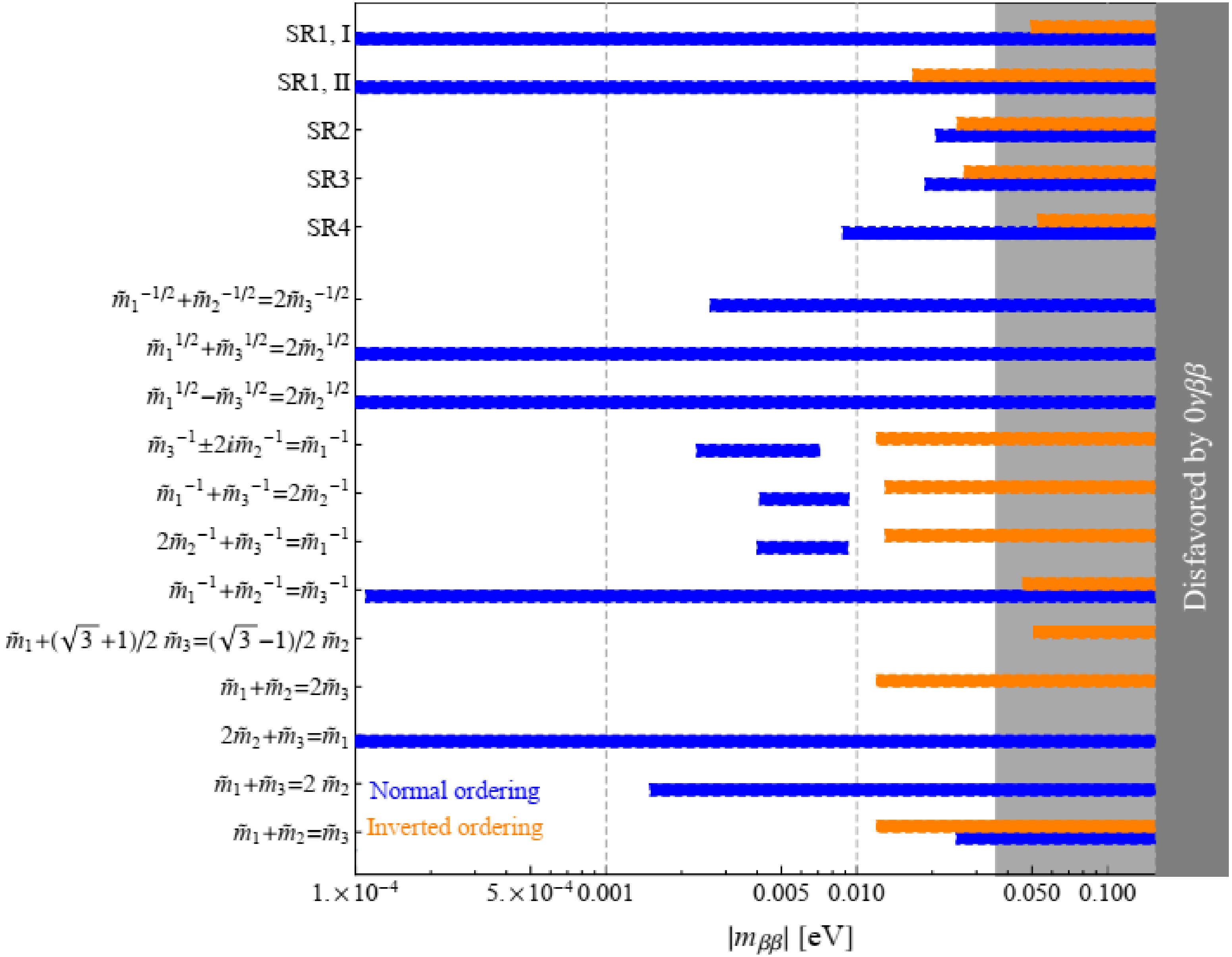


$$\mathcal{L}_m = -Y^e_{ij}(\langle\Phi_e\rangle)\overline{\ell_i}He_{Rj} - \frac{1}{2}Y^\nu_{ij}(\langle\Phi_\nu\rangle)\overline{\ell^c_i}HH^T\ell_j + \ldots$$

Flavor symmetry → specific structure of mass matrices → correlations among ν masses and mixing parameters

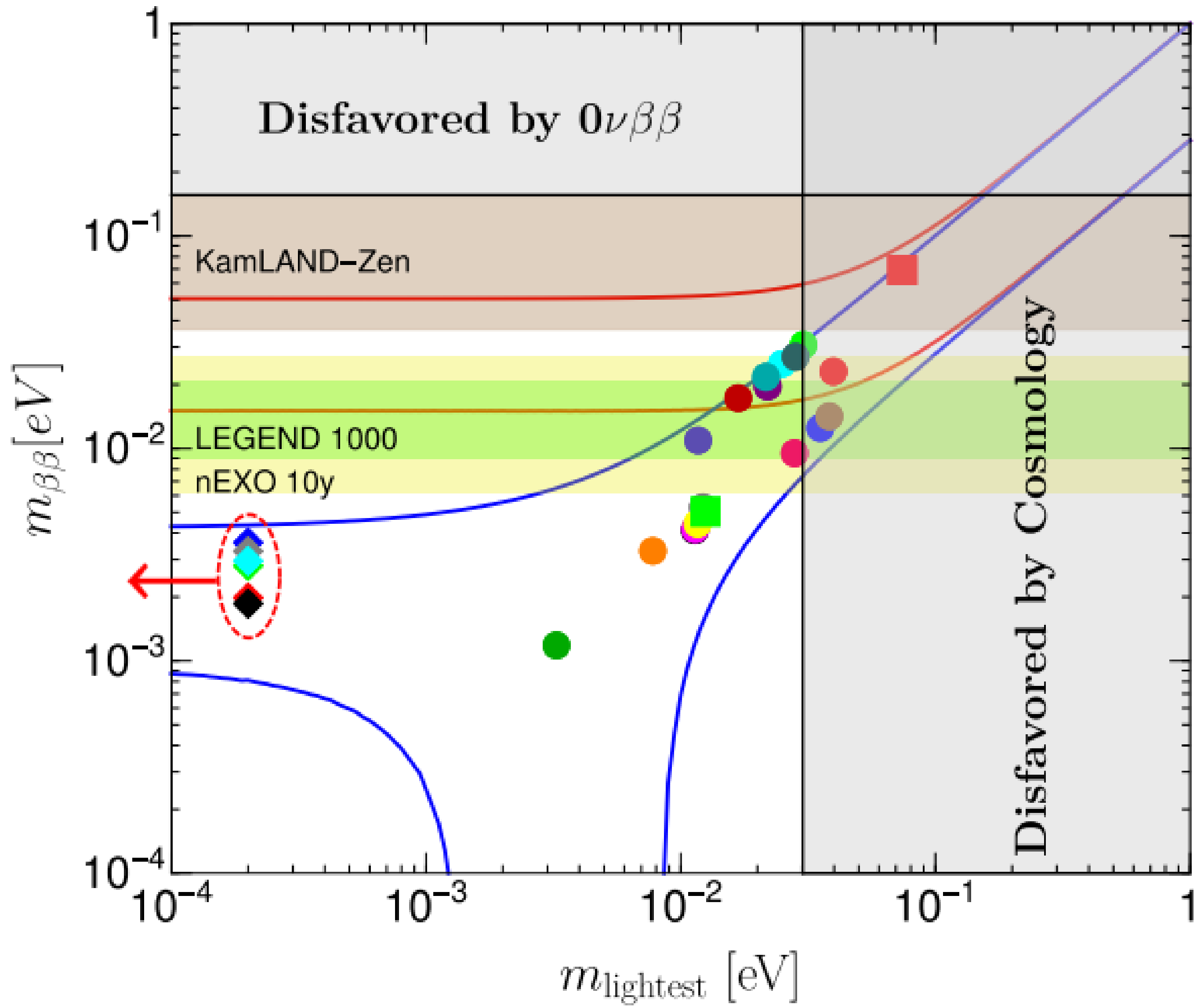
[Xing, 1909.09610; Feruglio,Romanino, 1912.06028; Ding, King, 2311.09282; Ding,Valle, 2402.16963]

➢ Test neutrino mass sum rules of flavor symmetry at 0νββ decay



[Snowmass, 2203.12169]

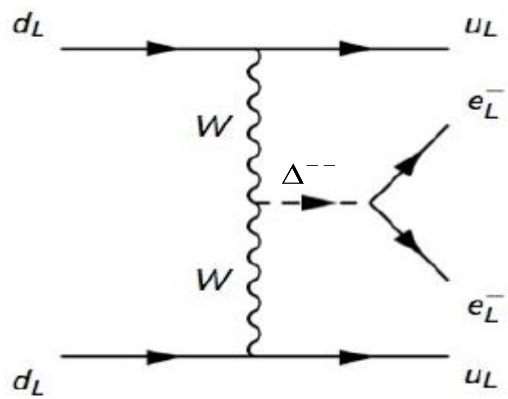
➢ Test modular invariant models at 0νββ



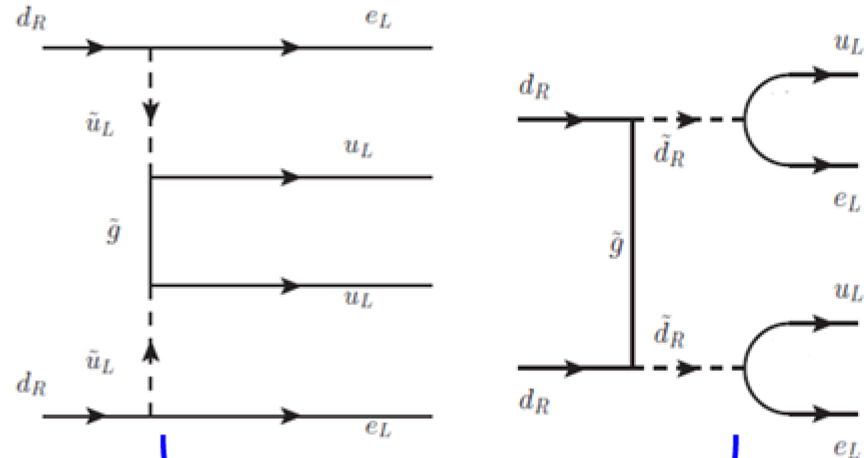
[Chen,Ding,King,2101.12724]

Possible BSM physics in 0νββ decay

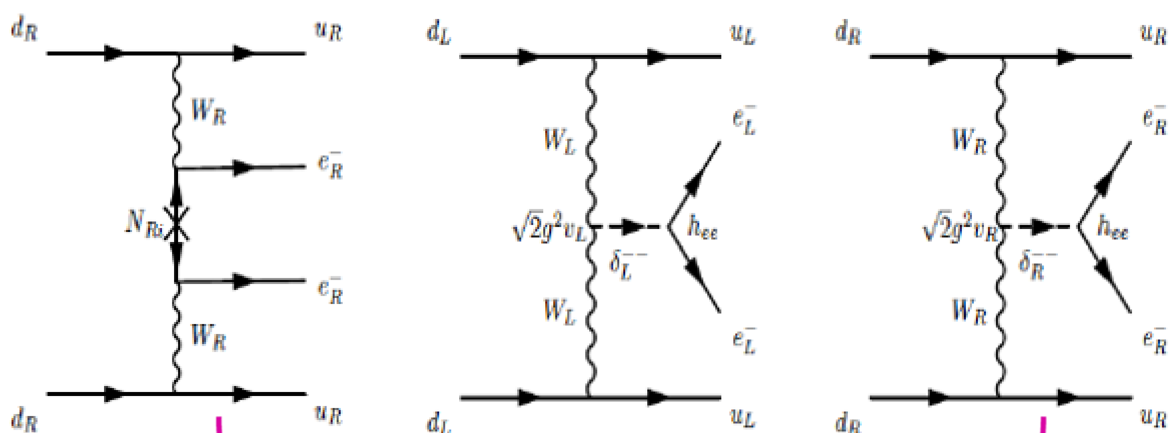
The 0νββ decay can also be induced by other ΔL=2 physics besides the Majorana neutrino mass. There are many possible scenarios:



Type II seesaw



R-parity violating SUSY

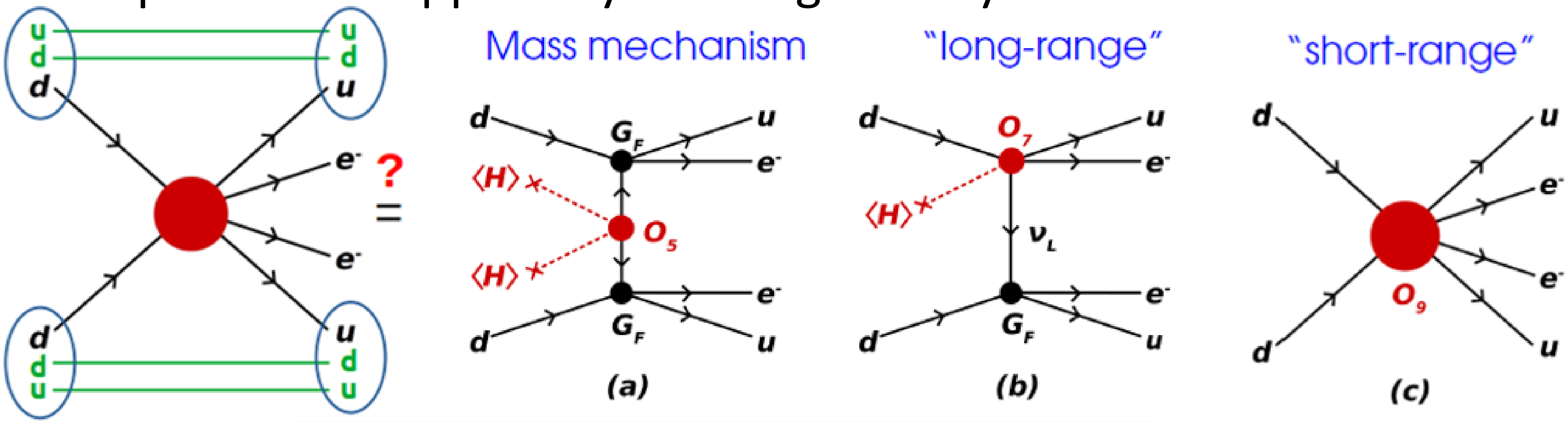


Left-right model

- 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:

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

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

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

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

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

Decomposing the short-range 0νββ operators

"Recipe" for a systematic classification of the possible realizations

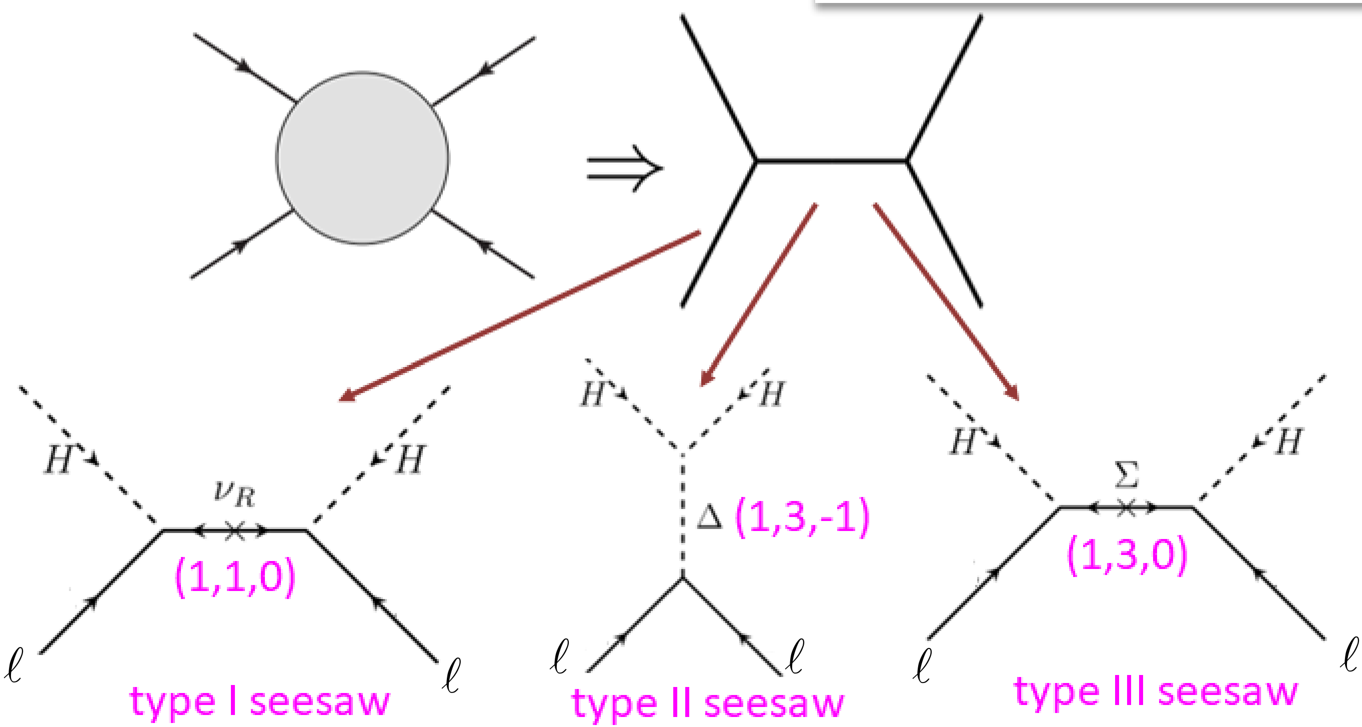
① **Topolopies**: identify the $L-$loop connected topologies with 6 external legs

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

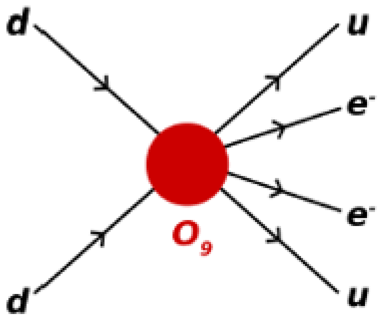
③ **Models**: fix the **$SU(3)_C$ x $SU(2)_L$ x $U(1)_Y$** quantum numbers of the internal fields by gauge invariance of each interaction vertex

➢ Example: decompose Weinberg operator

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



Tree-level decomposition



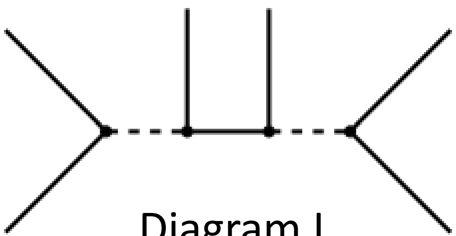


Diagram I

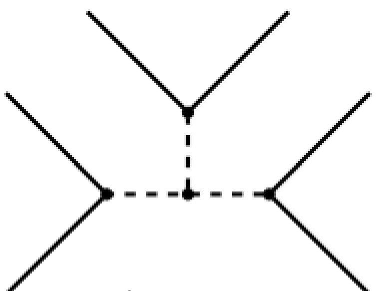


Diagram II

#	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)	$(+1, 1)$	$(0, 1)$	$(-1, 1)$	Mass mechan., RPV [58-60], LR-symmetric models [39], Mass mechanism with ν_S [61], TeV scale seesaw, e.g., [62, 63, 64]
			$(+1, 8)$	$(0, 8)$	$(-1, 8)$	
1-ii-a	$(\bar{u}d)(\bar{u})(d)(\bar{e}\bar{e})$		$(+1, 1)$	$(+5/3, 3)$	$(+2, 1)$	
			$(+1, 8)$	$(+5/3, 3)$	$(+2, 1)$	
1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$		$(+1, 1)$	$(+4/3, \bar{3})$	$(+2, 1)$	
			$(+1, 8)$	$(+4/3, \bar{3})$	$(+2, 1)$	
2-i-a	$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$		$(+1, 1)$	$(+4/3, \bar{3})$	$(+1/3, \bar{3})$	
			$(+1, 8)$	$(+4/3, \bar{3})$	$(+1/3, \bar{3})$	
2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	(b)	$(+1, 1)$	$(0, 1)$	$(+1/3, \bar{3})$	RPV [58-60], LQ [65, 66]
			$(+1, 8)$	$(0, 8)$	$(+1/3, \bar{3})$	
2-ii-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$		$(+1, 1)$	$(+5/3, 3)$	$(+2/3, 3)$	
			$(+1, 8)$	$(+5/3, 3)$	$(+2/3, 3)$	
2-ii-b	$(\bar{u}d)(\bar{e})(\bar{u})(d\bar{e})$	(b)	$(+1, 1)$	$(0, 1)$	$(+2/3, 3)$	RPV [58-60], LQ [65, 66]
			$(+1, 8)$	$(0, 8)$	$(+2/3, 3)$	
2-iii-a	$(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$	(c)	$(-2/3, \bar{3})$	$(0, 1)$	$(+1/3, \bar{3})$	RPV [58-60]
			$(-2/3, \bar{3})$	$(0, 8)$	$(+1/3, \bar{3})$	RPV [58-60]
2-iii-b	$(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$		$(-2/3, \bar{3})$	$(-1/3, 3)$	$(+1/3, \bar{3})$	
			$(-2/3, \bar{3})$	$(-1/3, \bar{6})$	$(+1/3, \bar{3})$	
3-i	$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$		$(+4/3, \bar{3})$	$(+1/3, \bar{3})$	$(-2/3, \bar{3})$	only with V_ρ and V'_ρ
			$(+4/3, 6)$	$(+1/3, 6)$	$(-2/3, 6)$	
3-ii	$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$		$(+4/3, \bar{3})$	$(+5/3, 3)$	$(+2, 1)$	only with V_ρ
			$(+4/3, 6)$	$(+5/3, 3)$	$(+2, 1)$	
3-iii	$(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$		$(+2/3, 3)$	$(+4/3, \bar{3})$	$(+2, 1)$	only with V_ρ
			$(+2/3, \bar{6})$	$(+4/3, \bar{3})$	$(+2, 1)$	
4-i	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	(c)	$(-2/3, \bar{3})$	$(0, 1)$	$(+2/3, 3)$	RPV [58-60]
			$(-2/3, \bar{3})$	$(0, 8)$	$(+2/3, 3)$	RPV [58-60]
4-ii-a	$(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$		$(+4/3, \bar{3})$	$(+5/3, 3)$	$(+2/3, 3)$	only with V_ρ
			$(+4/3, 6)$	$(+5/3, 3)$	$(+2/3, 3)$	see Sec. 4 (this work)
4-ii-b	$(\bar{u}\bar{u})(\bar{e})(d)(d\bar{e})$		$(+4/3, \bar{3})$	$(+1/3, \bar{3})$	$(+2/3, 3)$	only with V_ρ
			$(+4/3, 6)$	$(+1/3, 6)$	$(+2/3, 3)$	
5-i	$(\bar{u}\bar{e})(d)(d)(\bar{u}\bar{e})$	(c)	$(-1/3, 3)$	$(0, 1)$	$(+1/3, \bar{3})$	RPV [58-60]
			$(-1/3, 3)$	$(0, 8)$	$(+1/3, \bar{3})$	RPV [58-60]
5-ii-a	$(\bar{u}\bar{e})(\bar{u})(\bar{e})(dd)$		$(-1/3, 3)$	$(+1/3, \bar{3})$	$(-2/3, \bar{3})$	only with V'_ρ
			$(-1/3, 3)$	$(+1/3, 6)$	$(-2/3, 6)$	
5-ii-b	$(\bar{u}\bar{e})(\bar{e})(\bar{u})(dd)$		$(-1/3, 3)$	$(-4/3, 3)$	$(-2/3, \bar{3})$	only with V'_ρ
			$(-1/3, 3)$	$(-4/3, 3)$	$(-2/3, 6)$	

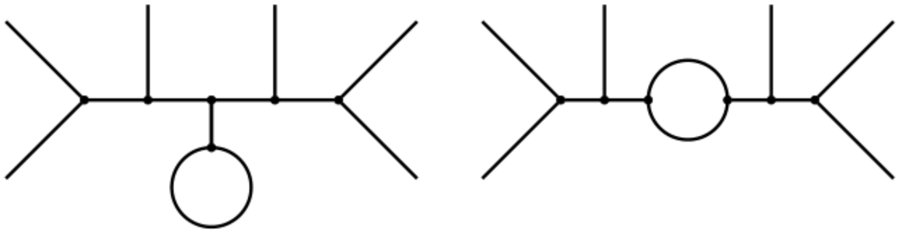
[Bonnet, Hirsch, Ota, Winter, 1212.3045]

Topologies for short-range 0νββ

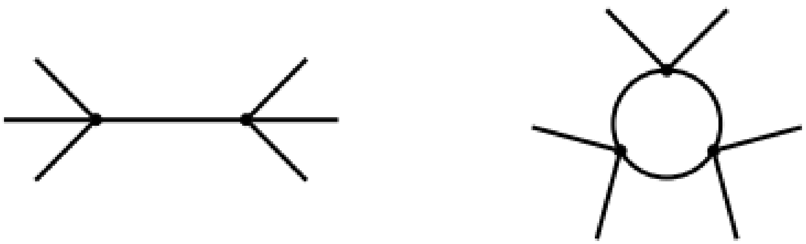
Topolopies: Feynman diagrams where no property of fields is considered

(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

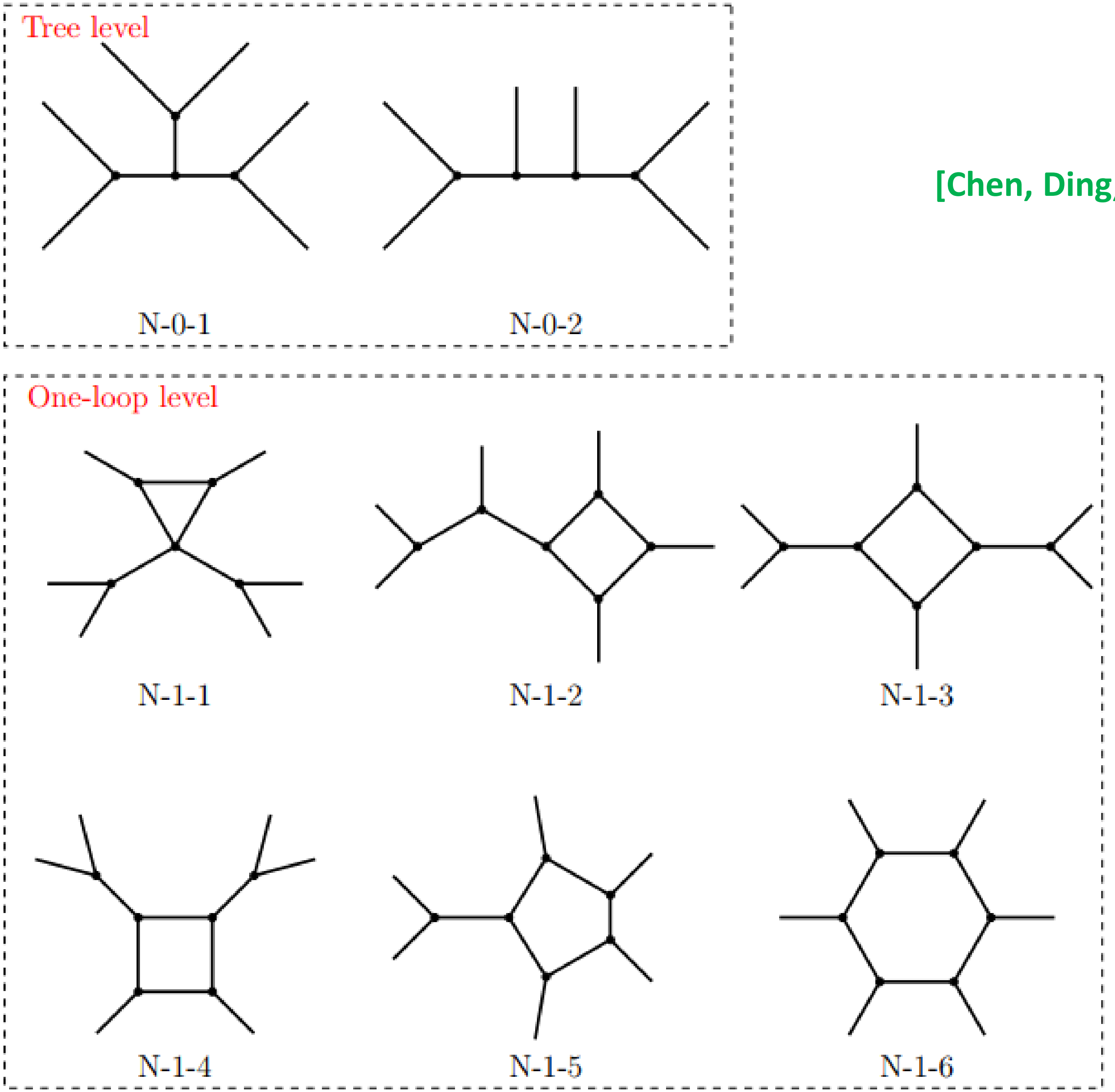


The 6 external legs are quark and lepton fields for short-range 0νββ

(iv) Discard topologies with 3-point loop vertices

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

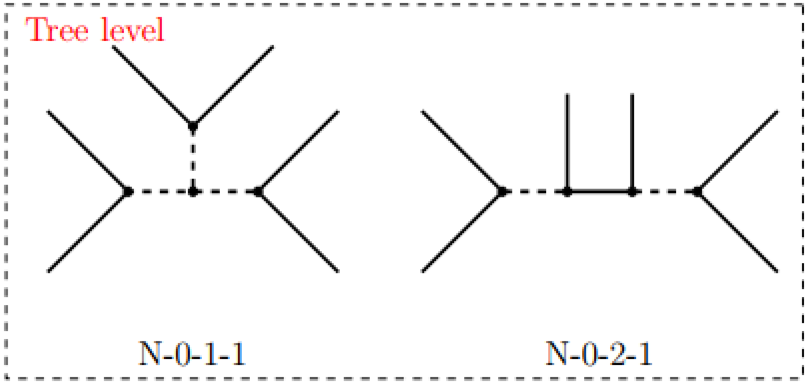
➢ 2 tree + 6 one-loop renormalizable topologies



[Chen, Ding, Yao, 2110.15347]

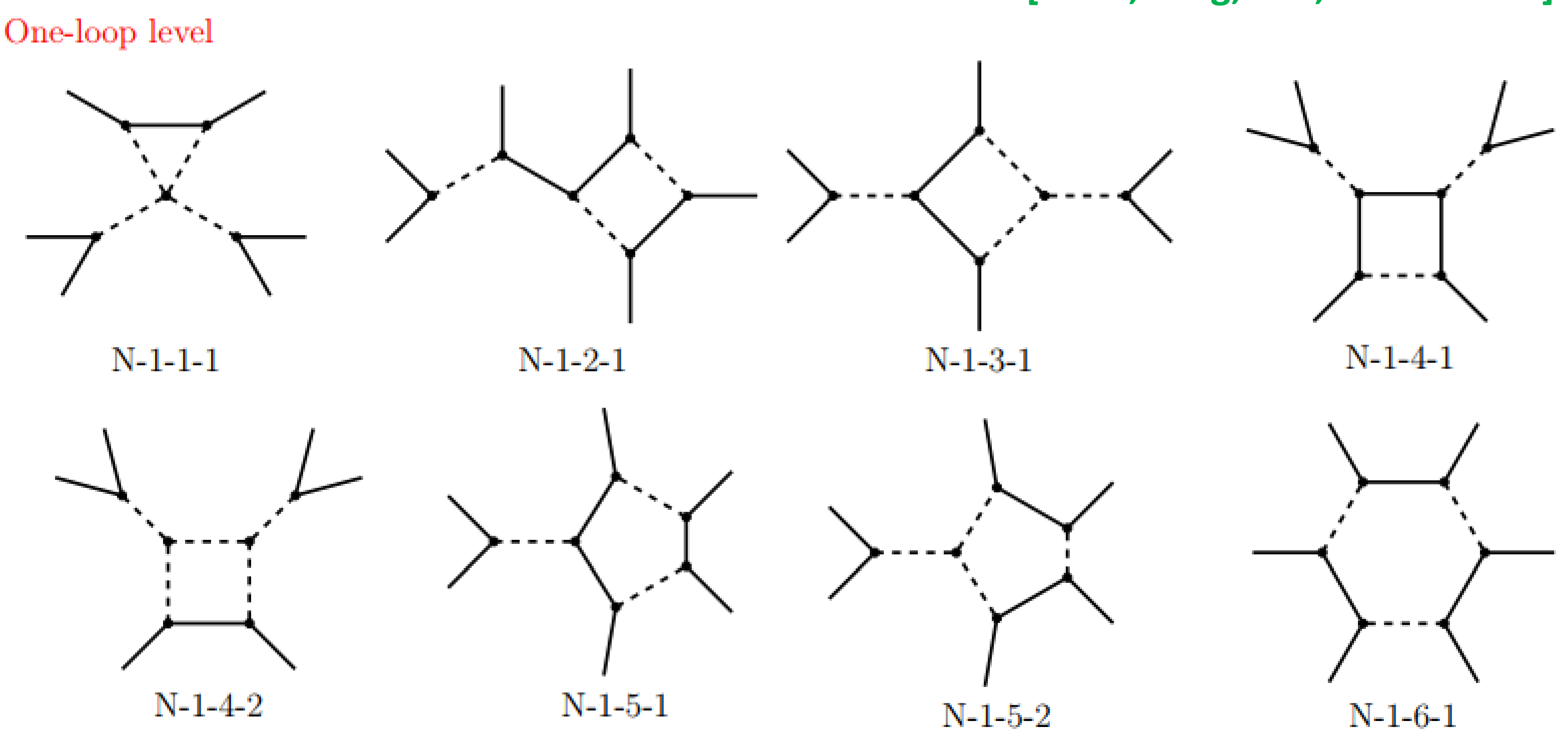
field insertions: topologies→diagrams

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



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

[Chen, Ding, Yao, 2110.15347]



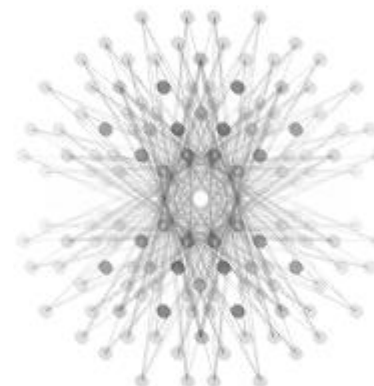
Determine quantum numbers: diagrams→models

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



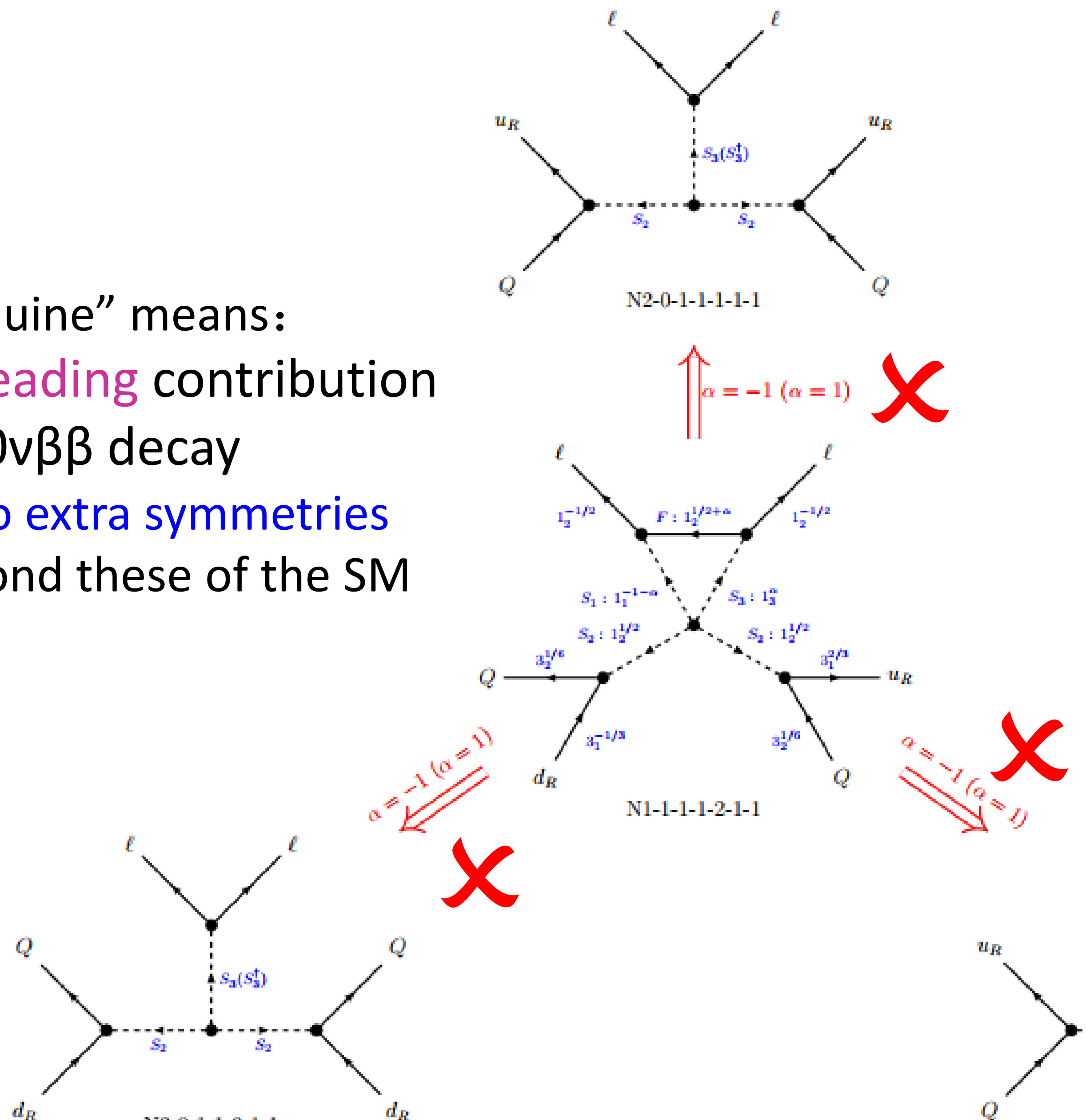
- **4-point vertex:** $S_1 S_2 S_3 S_4$

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

GROUPMATH

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

Genuine models



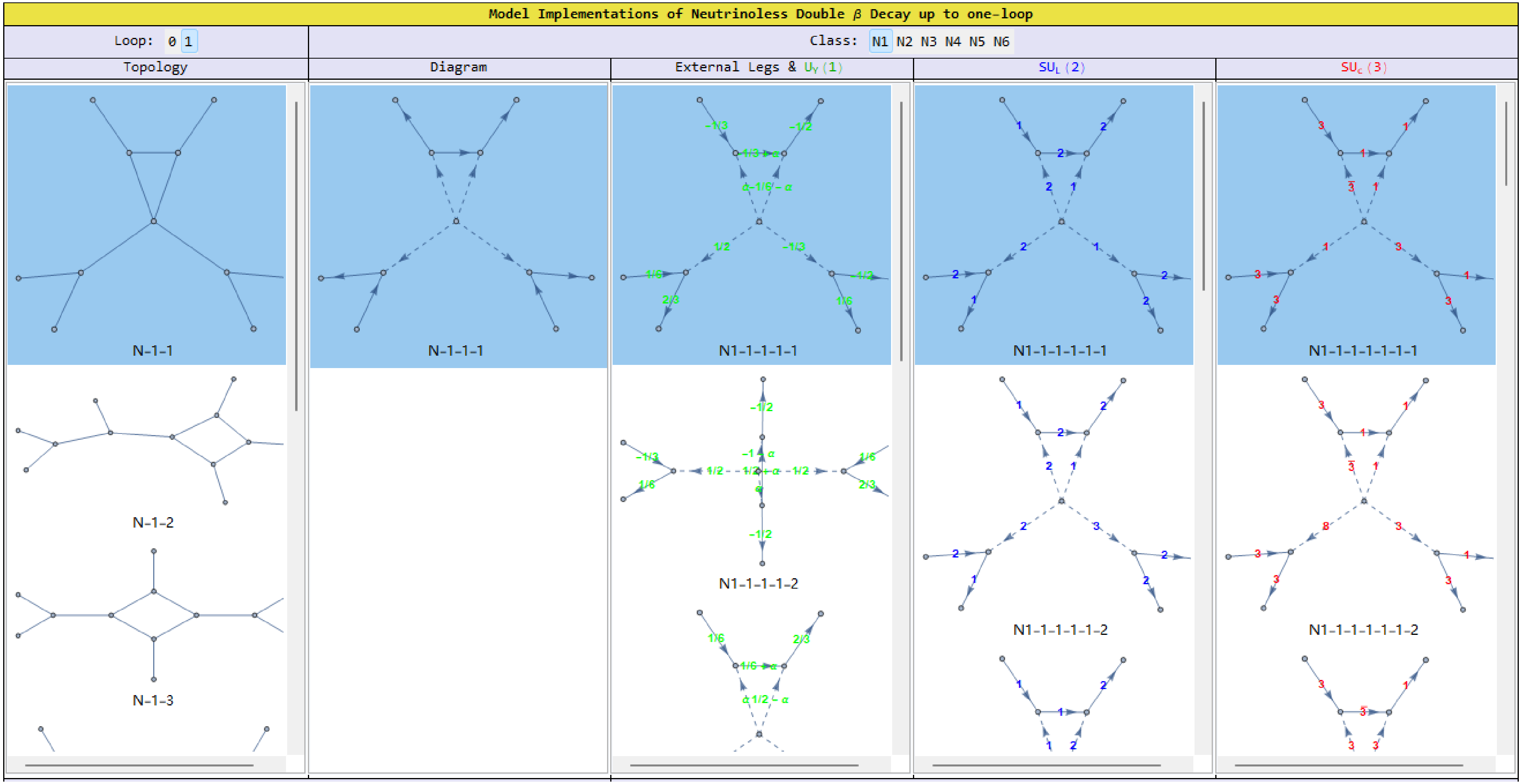
"genuine" means:

① leading contribution to 0νββ decay

②no extra symmetries beyond these of the SM

Filter models

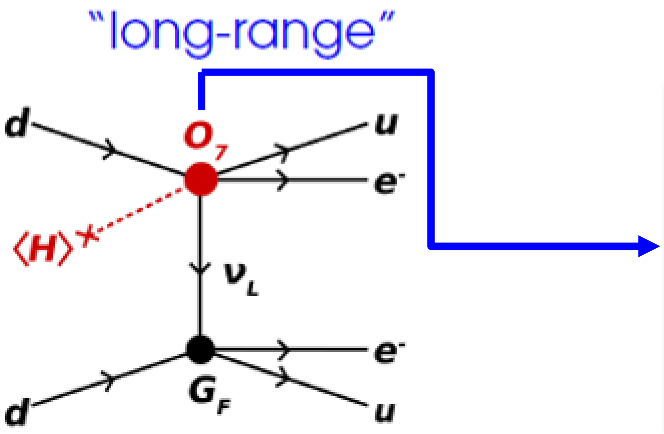
Determine quantum numbers: diagrams→models



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**!



$\Delta L = 2$

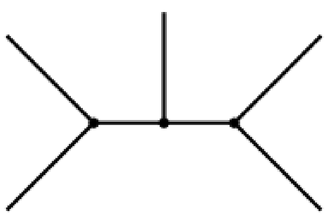
$$\mathcal{O}_1^{LR} = \epsilon^{ik}\epsilon^{jl}(\overline{\ell_i^c}\ell_j)(\overline{d_R}Q_k)H_l\,,$$
$$\mathcal{O}_2^{LR} = \epsilon^{ik}\epsilon^{jl}(\overline{\ell_i^c}\gamma^{\mu\nu}\ell_j)(\overline{d_R}\gamma_{\mu\nu}Q_k)H_l\,,$$
$$\mathcal{O}_3^{LR} = \epsilon^{jk}(\overline{\ell_i^c}\ell_j)(\overline{Q}^i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

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

topologies ↓ **diagrams** ↓ **models**

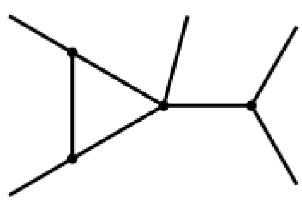
- Topologies

Tree level

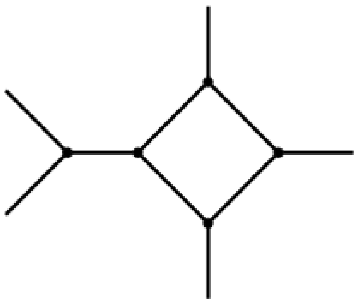


NL-0-1

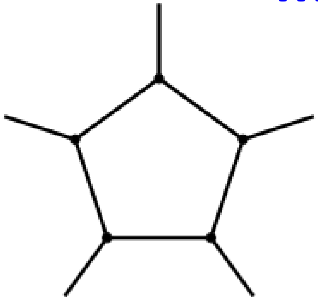
One loop



NL-1-1



NL-1-2

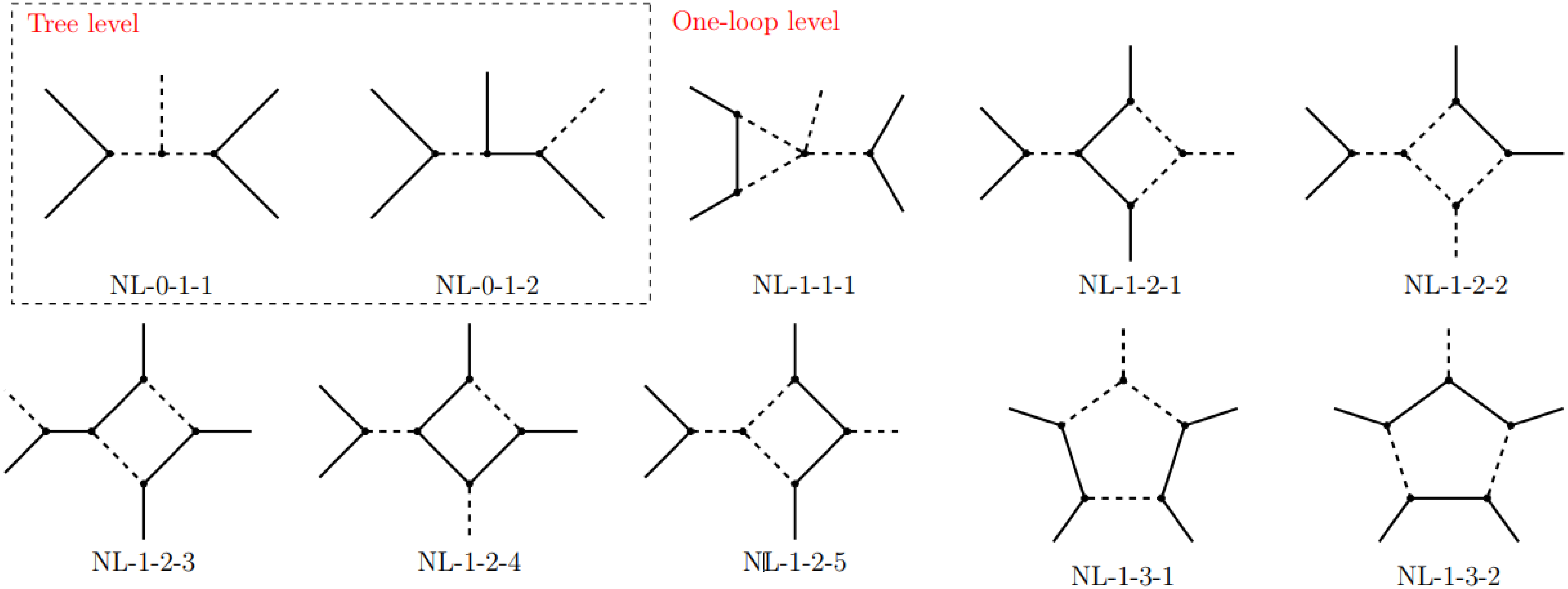


NL-1-3

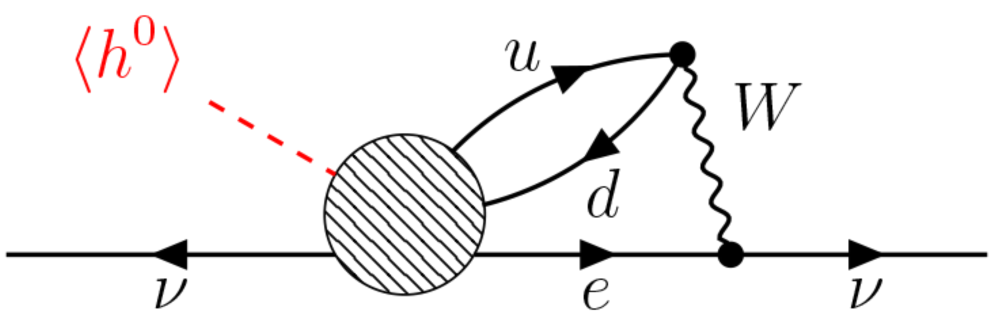
[Chen, Ding, Yao, 2301.02503]

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



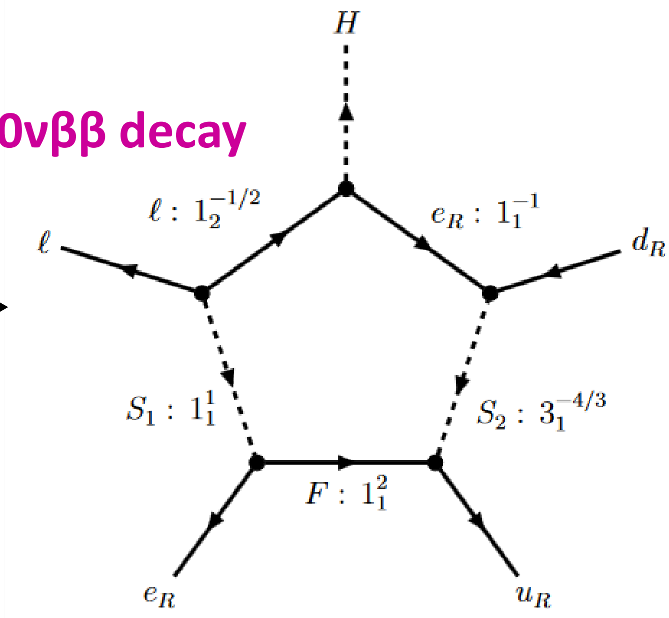
Majorana neutrino masses are generated at least at the 2-loop order, regardless of long-range 0νββ operators

An example model of long-range 0νββ decay

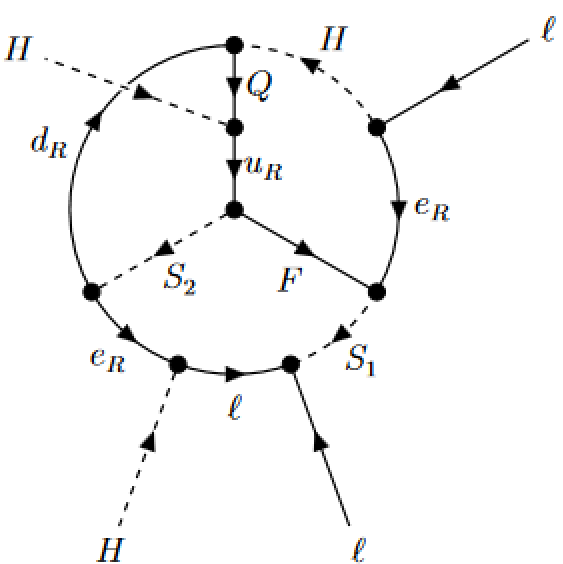
➢ **3** new fields: two scalars S_1, S_2 and a vector-like fermion F

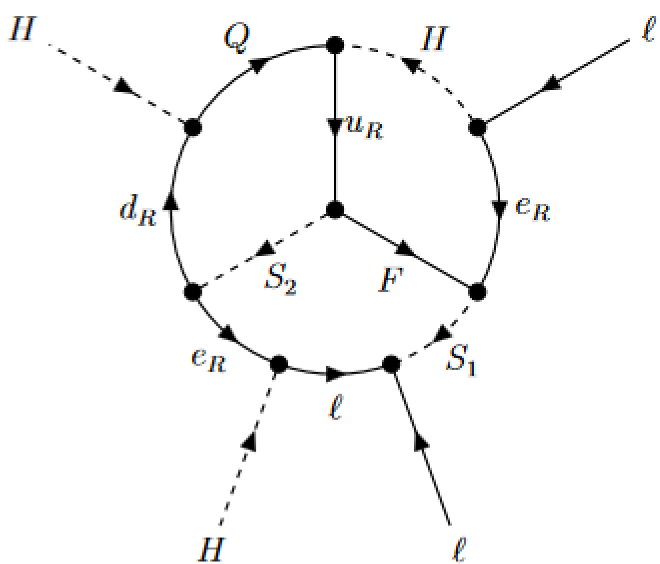
Fields	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
S_1	**1**	**1**	1
S_2	**3**	**1**	$-4/3$
F	**1**	**1**	2

1-loop 0νββ decay

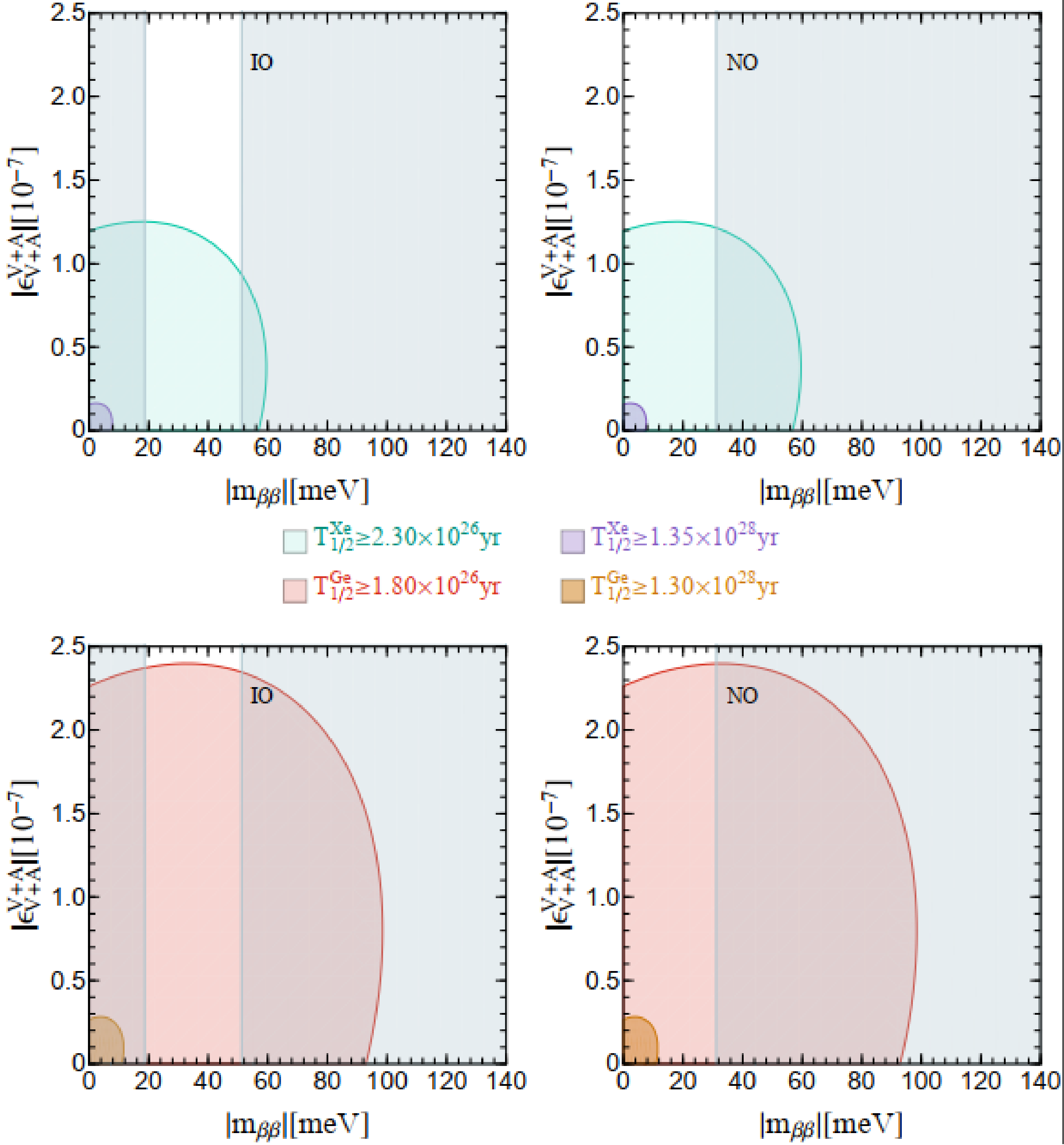


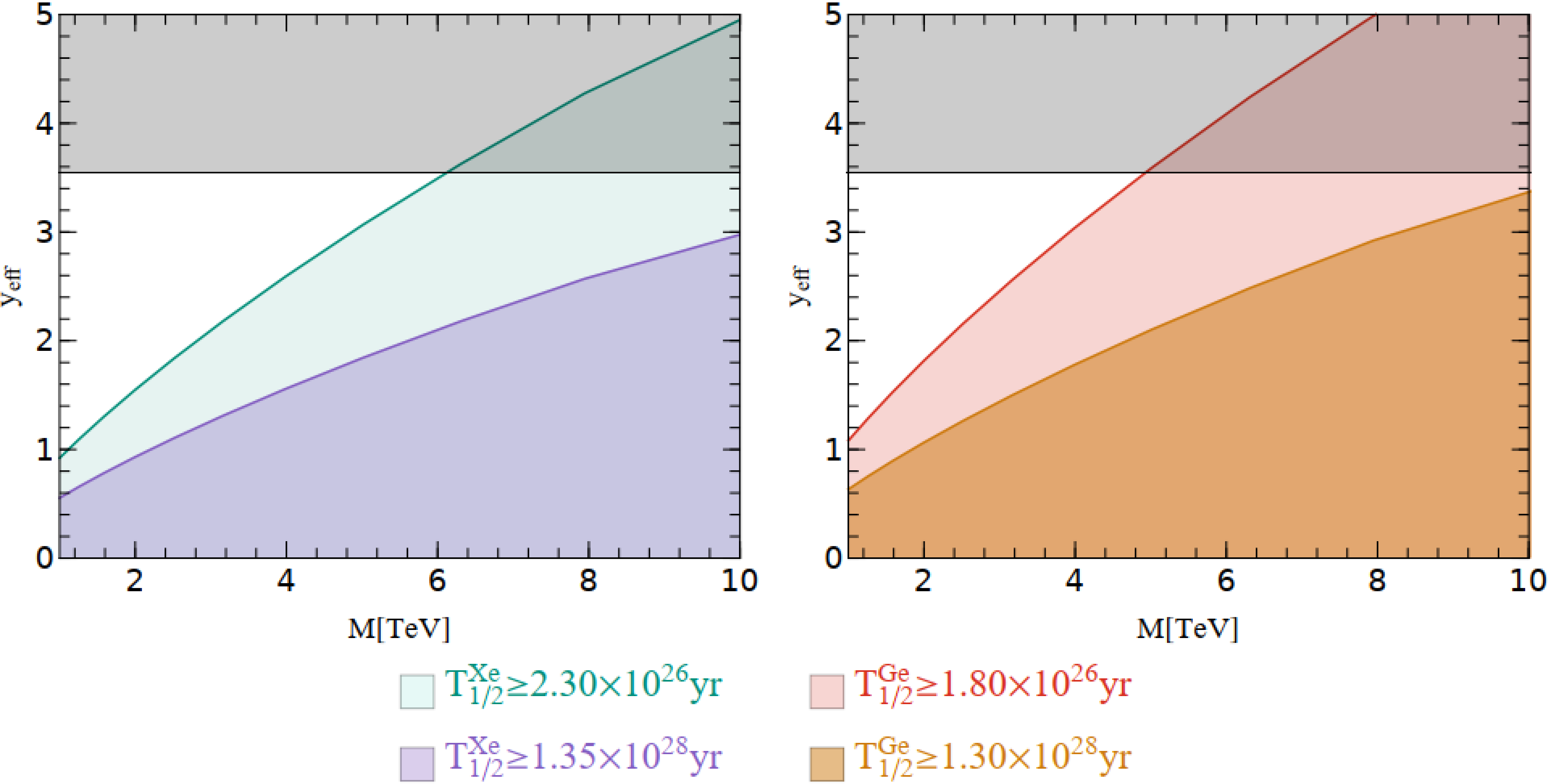
➢ Majorana neutrino masses generated at **3-loop**





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





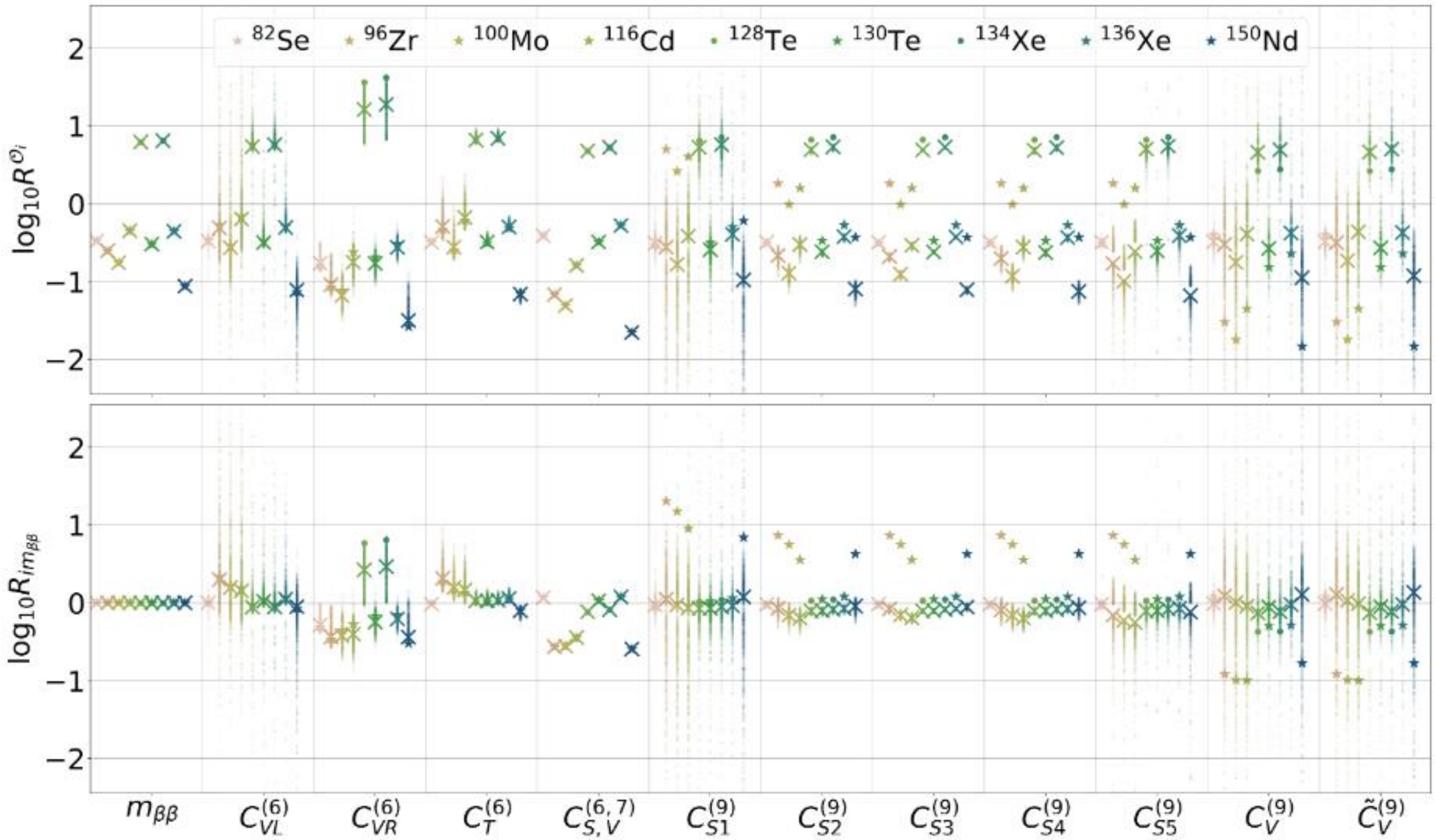
5
4
3
2
1
0
2
4
6
8
10
y_{eff}
M[TeV]
$T_{1/2}^{Xe} \geq 2.30\times10^{26}$yr
$T_{1/2}^{Xe} \geq 1.35\times10^{28}$yr
$T_{1/2}^{Ge} \geq 1.80\times10^{26}$yr
$T_{1/2}^{Ge} \geq 1.30\times10^{28}$yr

Distinguishing different 0νββ mechanisms

- Comparison of the decay rates obtained using different isotopes

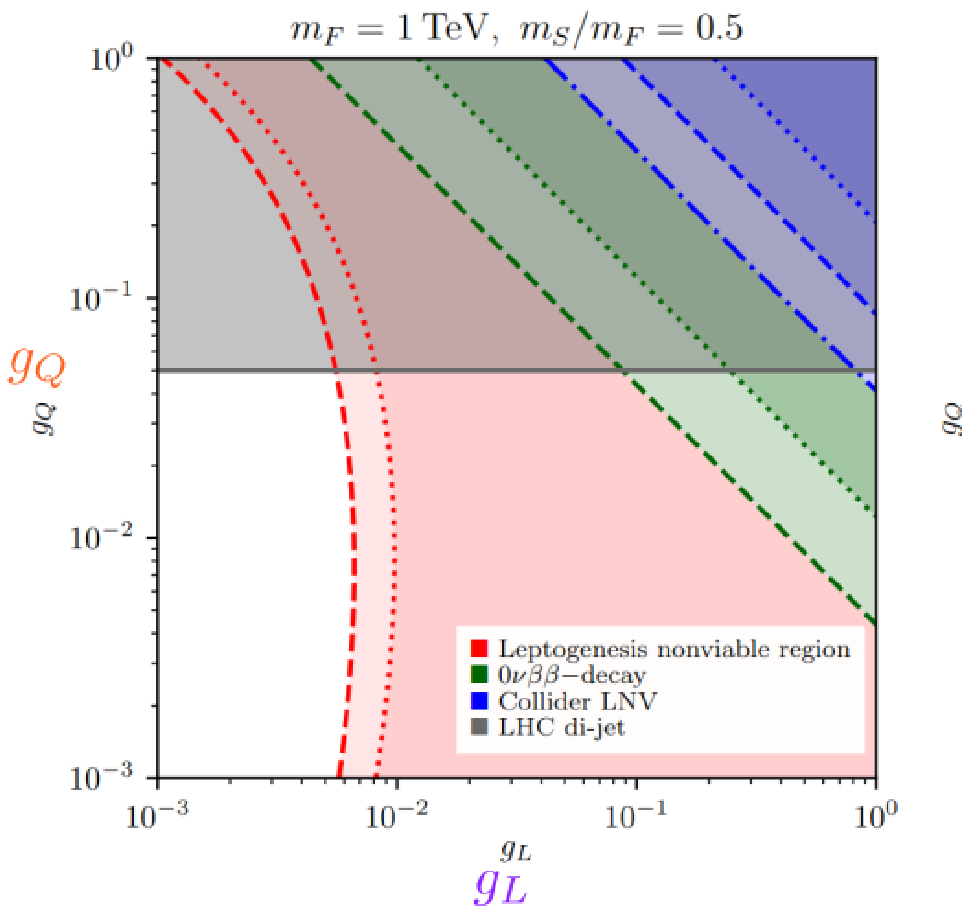
$$R^{\mathcal{O}_i}(^{A}\mathrm{X}) \equiv \frac{T_{1/2}^{\mathcal{O}_i}(^{A}\mathrm{X})}{T_{1/2}^{\mathcal{O}_i}(^{76}\mathrm{Ge})} = \frac{\sum_j |\mathcal{M}_j^{\mathcal{O}_i}(^{76}\mathrm{Ge})|^2 G_j^{\mathcal{O}_i}(^{76}\mathrm{Ge})}{\sum_k |\mathcal{M}_k^{\mathcal{O}_i}(^{A}\mathrm{X})|^2 G_k^{\mathcal{O}_i}(^{A}\mathrm{X})}$$

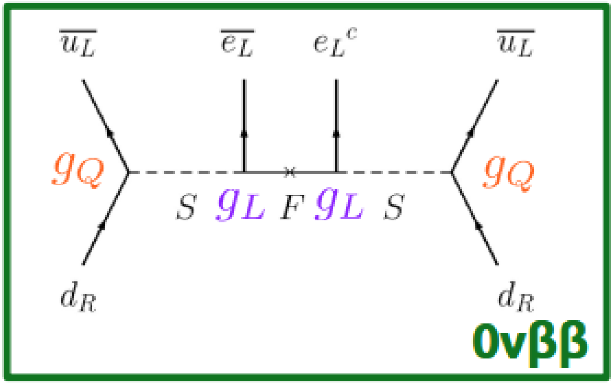
[Graf,Lindner,Scholer,2204.10845]

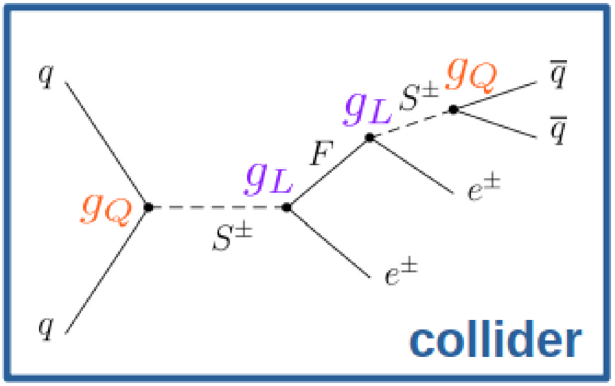


- Combining 0νββ decay, collider measurements and cosmology

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







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

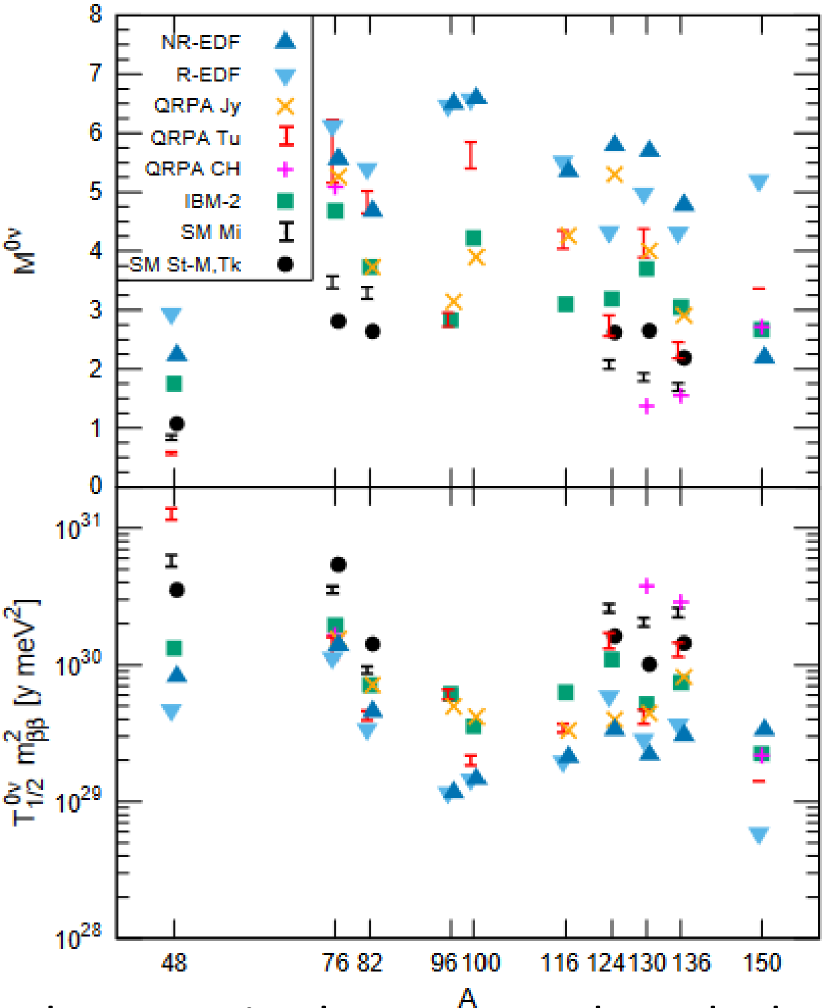
Summary

- $0\nu\beta\beta$ is the most sensitive probe to the Majorana nature of neutrinos. However, there are many possible physics mechanisms divided into mass mechanism, short-range mechanism and long-range mechanism.
- Systematic decomposition $0\nu\beta\beta$ operators: **topologies→diagrams → models**
- Many open questions: 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

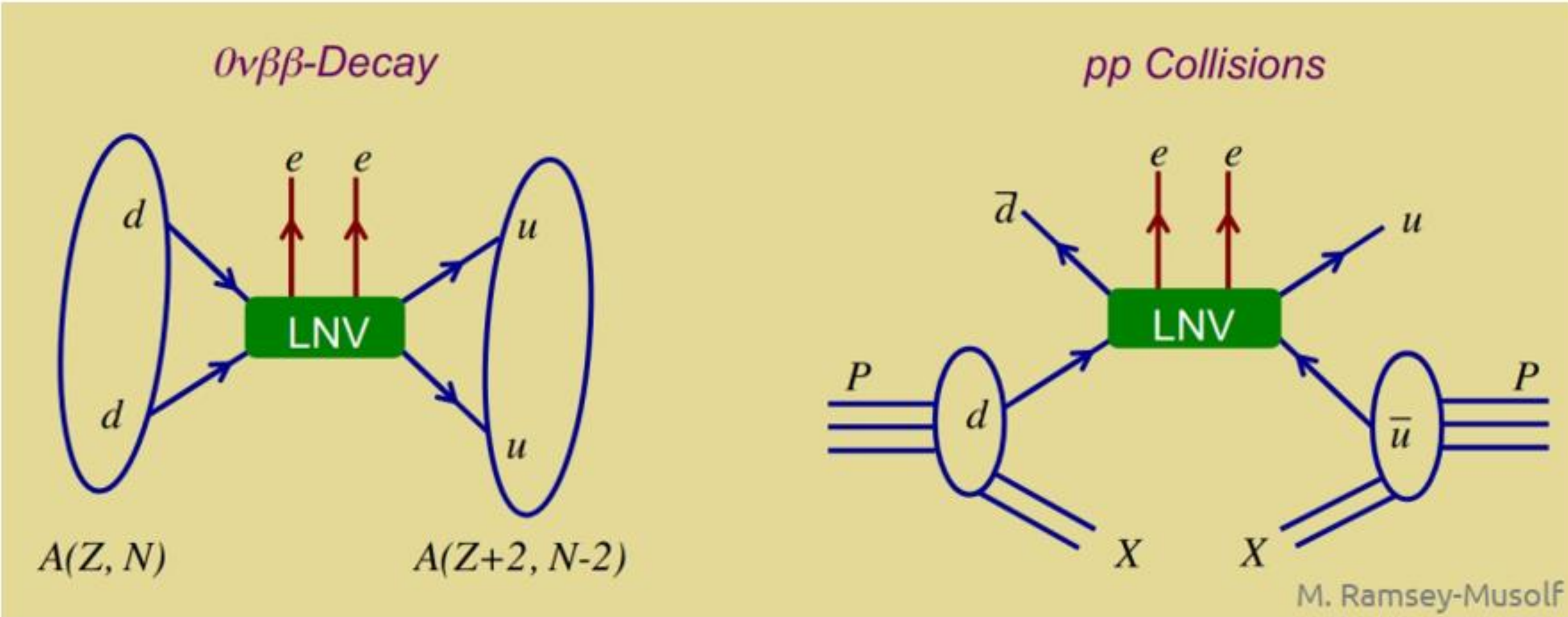
Nuclear matrix elements



[Engel, Menendez, 1610.06548]

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.

0νββ at LHC

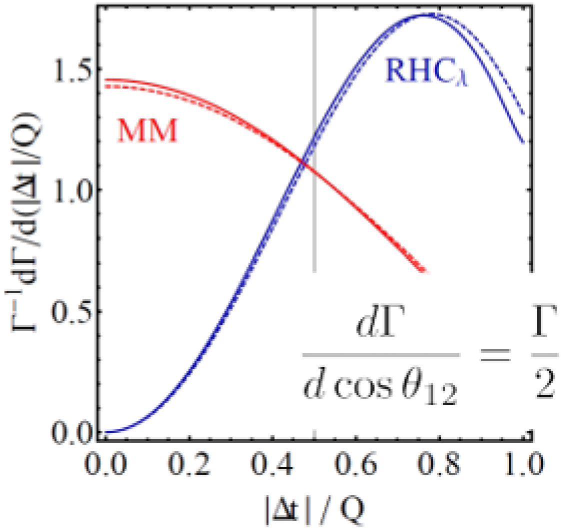


Collider signature: same-sign dilepton +2 jets + no E_T^{miss}

$$p + p \to 2e^{\pm} + 2\,\text{jets}$$

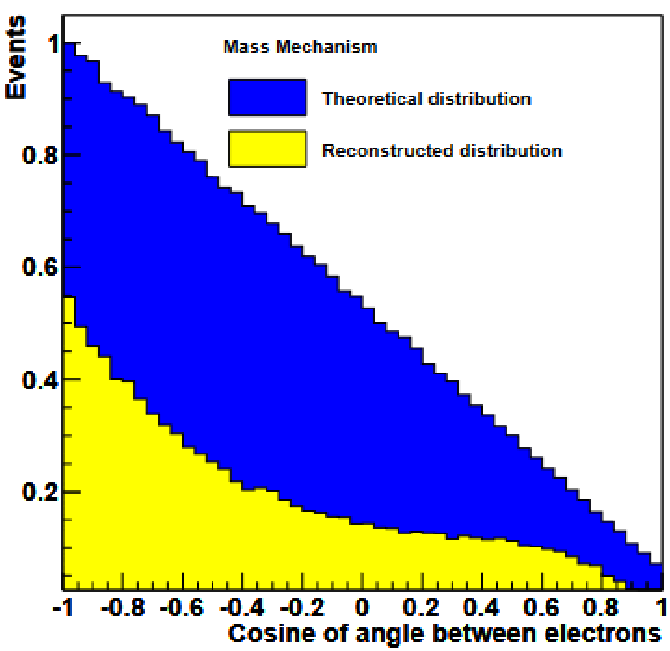
determine 0νββ mechanisms

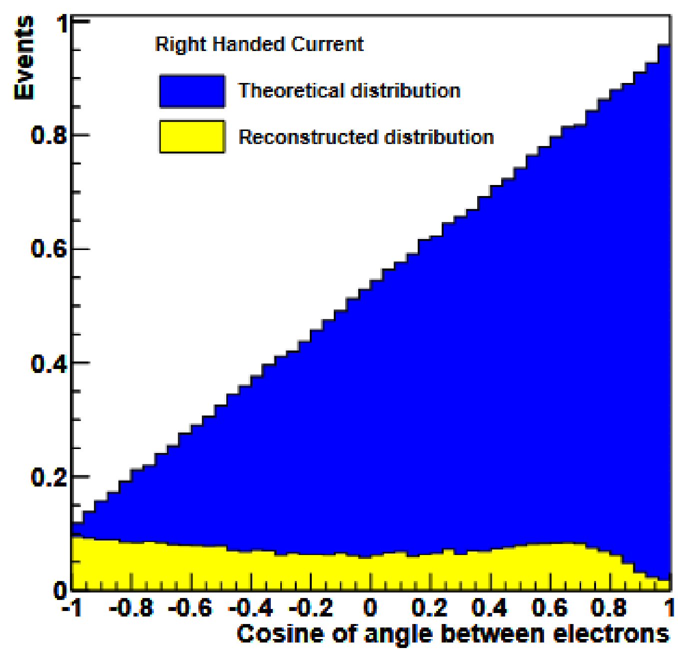
- measure the angular and energy distributions of electron



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

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

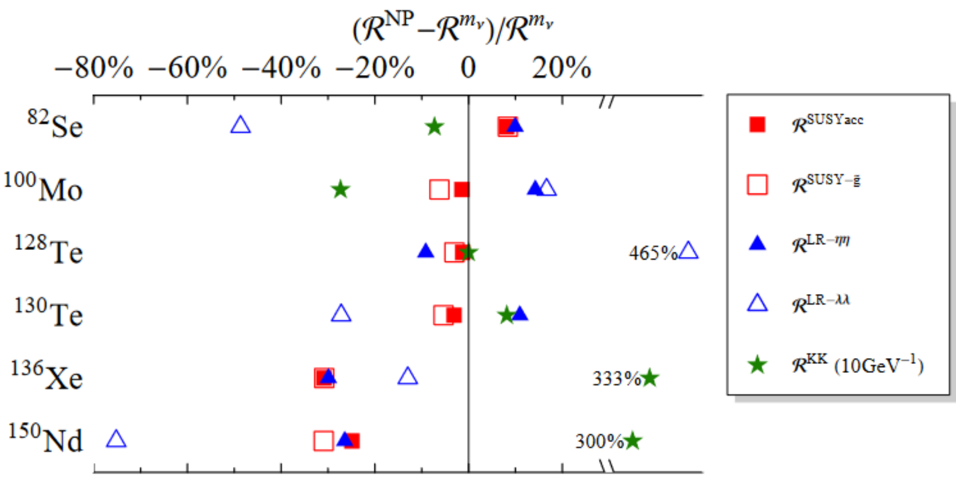




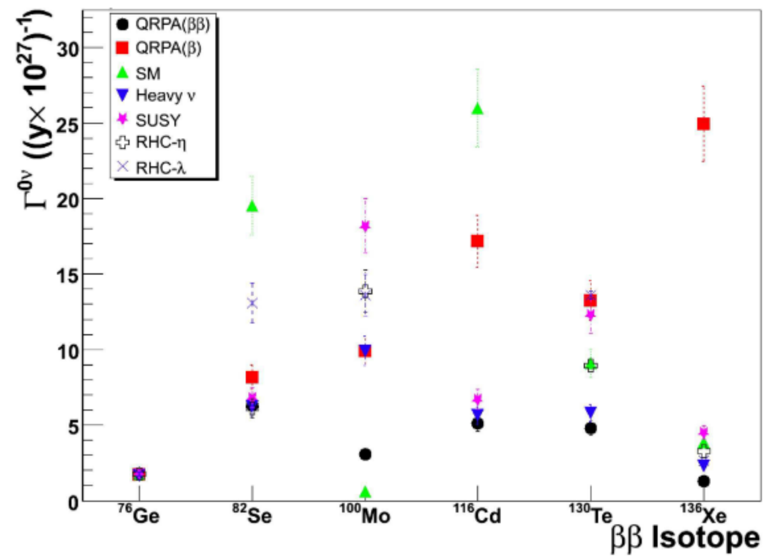
- Distinguish different mechanisms via measurements in different isotopes

$$[T_{1/2}^{NP}]^{-1} = \epsilon_{NP}^2 G_{NP} |\mathcal{M}^{NP}|^2$$

$$\frac{T_{1/2}(^A X)}{T_{1/2}(^{76}\mathrm{Ge})} = \frac{|\mathcal{M}(^{76}\mathrm{Ge})|^2 G(^{76}\mathrm{Ge})}{|\mathcal{M}(^A X)|^2 G(^A X)}$$



[Deppisch, Pas,hep-ph/0612165]



Isotope Ordering	Confidence Level	Number of Isotopes 2	3	4	5	6
Atomic Number	90%	<2%	8%	16%	23%	24%
	68%	<2%	19%	36%	45%	48%
$\Gamma^{0\nu}$ Spread	90%	6%	18%	27%	27%	24%
	68%	13%	29%	41%	42%	47%
Experimental Readiness	90%	3%	11%	24%	24%	24%
	68%	7%	18%	46%	47%	47%
Alternative Ordering	90%	3%	11%	17%	15%	24%
	68%	7%	18%	34%	32%	47%
Experimental Readiness (All 7 models, no ^{116}Cd)	90%	< 2%	6%	14%	16%	
	68%	< 2%	12%	22%	24%	

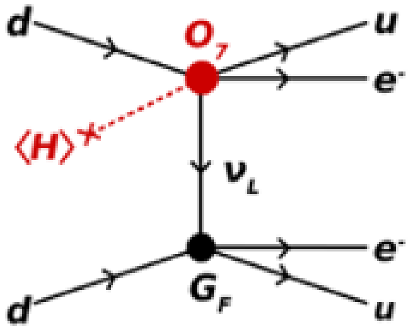
[Gehman,Elliott,hep-ph/0701099]

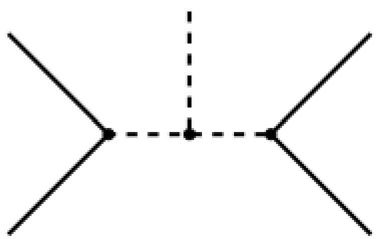
determine 0νββ mechanisms

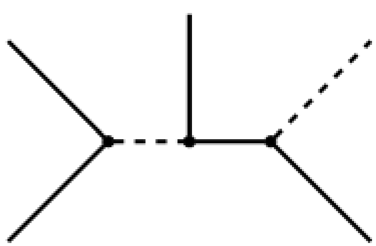
mechanism	amplitude and particle physics parameter	current limit	test
light neutrino exchange	$\frac{G_F^2}{q^2}\left\|U_{ei}^2\, m_i\right\|$	0.5 eV	oscillations, cosmology, neutrino mass
heavy neutrino exchange	$G_F^2 \left\|\frac{S_{ei}^2}{M_i}\right\|$	2×10^{-8} GeV^{-1}	LFV, collider
heavy neutrino and RHC	$G_F^2\, m_W^4 \left\|\frac{V_{ei}^2}{M_i\, M_{W_R}^4}\right\|$	4×10^{-16} GeV^{-5}	flavor, collider
Higgs triplet and RHC	$G_F^2\, m_W^4 \left\|\frac{(M_R)_{ee}}{m_{\Delta_R}^2\, M_{W_R}^4}\right\|$	10^{-15} GeV^{-1}	flavor, collider, e^- distribution
λ-mechanism with RHC	$G_F^2 \frac{m_W^2}{q}\left\|\frac{U_{ei}\, \tilde{S}_{ei}}{M_{W_R}^2}\right\|$	1.4×10^{-10} GeV^{-2}	flavor, collider, e^- distribution
η-mechanism with RHC	$G_F^2 \frac{1}{q} \tan\zeta\, \left\|U_{ei}\, \tilde{S}_{ei}\right\|$	6×10^{-9}	flavor, collider, e^- distribution
short-range $\not{R}$	$\frac{\|\lambda'^2_{111}\|}{\Lambda^5_{\rm SUSY}}$ $\Lambda_{\rm SUSY} = f(m_{\tilde{g}}, m_{\tilde{u}_L}, m_{\tilde{d}_R}, m_{\chi_i})$	7×10^{-18} GeV^{-5}	collider, flavor
long-range $\not{R}$	$\frac{G_F}{q}\left\|\sin 2\theta^b\, \lambda'_{131}\, \lambda'_{113}\left(\frac{1}{m^2_{\tilde{b}_1}} - \frac{1}{m^2_{\tilde{b}_2}}\right)\right\|$ $\sim \frac{G_F}{q} m_b \frac{\|\lambda'_{131}\, \lambda'_{113}\|}{\Lambda^3_{\rm SUSY}}$	2×10^{-13} GeV^{-2} 1×10^{-14} GeV^{-3}	flavor, collider
Majorons	$\propto \|\langle g_\chi \rangle\|$ or $\|\langle g_\chi \rangle\|^2$	$10^{-4} \ldots 1$	spectrum, cosmology

[Rodejohann, 1106.1334]

tree-level decomposition of long-range 0νββ operators





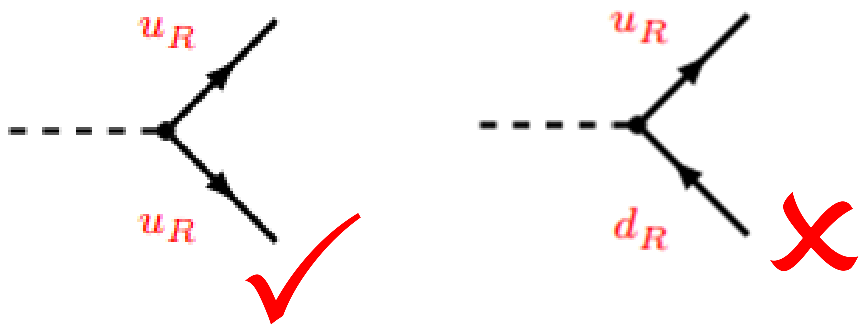


#	Decompositions	Mediators		Projection to the basis ops.	m_ν@tree	m_ν@1loop	m_ν@2loop
#1	$(L_\alpha L_\beta)(H)(\overline{d_R}Q)$	$S(\mathbf{1},\mathbf{1})_{+1}$	$S'(\mathbf{1},\mathbf{2})_{+\frac{1}{2}}$	$-\mathcal{O}_{3a}(\alpha,\beta)$	—	TνI-ii w.$\overline{\ell_R}LS'^\dagger$	$T2^{\rm B}_4(\alpha\neq\beta)$ $\mathcal{O}^7_3$ 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]

➢ 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
Tree	N-0-2-1	11	6	18	6	11	11
One-loop	N-1-1-1	6	5	12	5	6	6
One-loop	N-1-2-1	96	30	54	30	96	96
One-loop	N-1-3-1	11	9	21	9	12	12
One-loop	N-1-4-1	11	6	18	6	11	11
One-loop	N-1-4-2	11	6	18	6	11	11
One-loop	N-1-5-1	48	18	30	18	48	48
One-loop	N-1-5-2	48	18	30	18	48	48
One-loop	N-1-6-1	60	18	18	18	60	60

The redundant diagrams should be removed.