第四届高能物理理论与实验融合发展研讨会/大连

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Interplay between Seesaw & Vector-like Lepton

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Based on works with Shuyang Han & Jiang Zhu

The SEESAW^{+}: SEESAW+VECTOR-LIKE LEPTON

Why the SM neutrinos have a tiny mass far below the weak scale?

Hints from $d = 5$ Weinberg operator $\frac{1}{\Lambda}(L_i H)^2$ ⇐type-I/III (singlet/triplet Majorana N_i), inverse seesaw

Change the vacuum: type-II with $L^T C^{-1} L\Delta$ (hypercharge-1 triplet scalar with $\langle\Delta^0\rangle \ll m_W$)

Suppress via dark matter loops for the radiative neutrino masses

Seesaw services as an attractive platform for BSM

As a portal to dark matter, leading to UV-FIMP for very heavy RHN

This talk is to study its interplay with vector-like lepton

The SEESAW$^+$: SEESAW+VECTOR-LIKE LEPTON

Seesaw meets the vector-like leptons (VLL) **doublet with hypercharge -1**, a possible TeV BSM object

A prediction from E_6 GUT?

The Higgsinos in supersymmetry with a term LH_μ

The fourth family, to provide a large CP phase?

To portal dark matter

introduced to cancel anomalies of new gauged symmetries

to realize full neutrino mixings in some models with a family symmetry

The SEESAW$^+$: SEESAW+VECTOR-LIKE LEPTON

A concrete but not elegant example: flavorful gauged $(B-L)_{13}$

Z. Kang and Y. Shigekami, JHEP, 2019

$$-\mathcal{L}_L = Y^e_{22}\bar{\ell}_2 H e_{R2} + Y^e_{ij}\bar{\ell}_i H e_{Rj} + Y^N_{ij}\bar{\ell}_i \tilde{H} N_{Rj} + Y^e_i \overline{L}_L H e_{Ri} + Y^N_i \overline{L}_L \widetilde{H} N_{Ri}$$
$$+ \lambda^\ell_2 \bar{\ell}_2 L_R \mathcal{F}^*_\ell + M^\ell_i \bar{\ell}_i L_R + m_L \overline{L}_L L_R + \frac{\lambda^N_{ij}}{2}\Phi \bar{N}^C_{Ri} N_{Rj} + h.c.\,,$$

Related to $(B-L)_{13}$, the selected LFV pattern for flavon is $\mathcal{F}(= s \pm ia)\bar{\mu}P_R e/\tau$

Occam's razor principle

$$M_e \equiv \begin{pmatrix} \frac{v_h}{\sqrt{2}}Y^e_{11} & 0 & 0 & M^\ell_1 \to 0 \\ 0 & \frac{v_h}{\sqrt{2}}Y^e_{22} & 0 & M^\ell_2 \\ 0 & 0 & \frac{v_h}{\sqrt{2}}Y^e_{33} & M^\ell_3 \to 0 \\ \frac{v_h}{\sqrt{2}}Y^e_1 & 0 & \frac{v_h}{\sqrt{2}}Y^e_3 \to 0 & m_L \end{pmatrix}$$

$M^\ell_2 = \lambda^\ell_2 v_f/\sqrt{2}$ is related to flavor symmetry breaking, to account **for the full neutrino mixing**

At the same time, this mixing element will be adjustable to suppress the charged lepton flavor violating decay

It generates LFV coupling flavon-$e-\mu$ via $(U_R)_{41} \simeq Y^e_1 v_h/m_L$

Alternatively, turn on this element leads to LFV flavon coupling to $\tau\mu$

The SEESAW^{+}: SEESAW+VECTOR-LIKE LEPTON

The new elements in various seesaw are testable, except for N_i which decouples with EW as $\theta \sim \sqrt{m_\nu / M_N}$

Using the possible gauge interactions of N_i like $U(1)_{B-L}$

Zhaofeng Kang, P. Ko and Jinmian Li, PRD 2016

This talk: to explore implications on seesaw from the VLL seesaw^{+}

Light RHN below $m_h/2$: look for Higgs boson exotic decay via $\bar{L}_L \widetilde{H} N_R$

Direct search quasi-EW RHN at various colliders

VLL-RHN & VLL-lepton mixings: investigate prospect of quasi-EW RHN in $0\nu\beta\beta$ signal (another main goal)

VLL-RHN strong mixing: find hints of split VLL in EWPOs (one main goal)

Mixed RHN-VLL: EW precise test

Shuyang Han, ZK and JiangZhu, JHEP 2024

VLL doublet couples to SM leptons are dangerous, but couples to RHNs are hopeful $\lambda_n \bar{L}_L \widetilde{H} N_R + \lambda'_n \overline{L_R^C} H N_R$

$\lambda_n, \lambda'_n \sim O(1)$ leads to mass splitting in doublet thus sizable custodial symmetry breaking

captured in the gauge bosons' vacuum polarization amplitude $\Sigma^{\mu\nu}_{VV'} \equiv \langle J^{\mu}_{V} J^{\nu}_{V'} \rangle$, fully described by the Peskin-Takeuchi oblique parameters S、$T = \frac{4\pi}{M_Z^2 s^2 c^2}(2\Sigma_{11}(0) - \Sigma_{33}(0))$ and U

M. E. Peskin and T. Takeuchi, PRL 1990, PRD, 1992

$$T = \frac{4\pi}{M_Z^2 s^2 c^2}\left[\sum_{m=m_L}^{a=1,2,3}\left(\frac{V_{1a}^2 + V_{2a}^2}{2}\Sigma_{V+A}(m, M_a) + \mathrm{Re}(V_{1a}V_{2a})\Sigma_{V-A}(m, M_a)\right) - \frac{1}{2}\tilde{\Sigma}(m_L, m_L)\right.$$
$$\left. -4\sum_{a,b=1,}^{2,3}\left(\frac{|(g_L)_{ab}|^2 + |(g_R)_{ab}|^2}{2}\Sigma_{V+A}(M_a, M_b) + \mathrm{Re}((g_L)_{ab}(g_R)^*_{ab})\Sigma_{V-A}(M_a, M_b)\right)\right], \quad (3.16)$$

Mixed RHN-VLL: EW precise test

Shuyang Han, ZK and JiangZhu, JHEP 2024

Watchout: To correctly deal with the Majorana loops to get consistent (finite) result

$$\mathcal{L}_{NC} \supset \frac{g}{c} Z_\mu \overline{N_a} \gamma^\mu \left((g_L)_{ab} P_L + (g_R)_{ab} P_R \right) N_b + \frac{g}{2c}(s^2 - c^2) Z_\mu \bar{e}_4 \gamma^\mu e_4,$$

$$(g_L)_{ab} = \frac{V_{1a}V_{1b}^* - V_{2b}^* V_{2a}}{4}, \quad (g_R)_{ab} = \frac{V_{2a}^* V_{2b} - V_{1b} V_{1a}^*}{4}.$$

The correct neutral current coupling to reflect the Majorana property $N_a^C = N_a$; such a system was interested in 1993 when favored **negative S & T**

L. Lavoura and L.-F. Li, PRD, 1993, E. Gates and J. Terning PRL 1993

Mixed RHN-VLL: EWPOs

Shuyang Han, ZK and JiangZhu, JHEP 2024

insensitive to the strong interaction, thus with a quite small theoretical uncertainty

Unlike muon $g-2$, M_W is an attractive EWPO to probe new physics

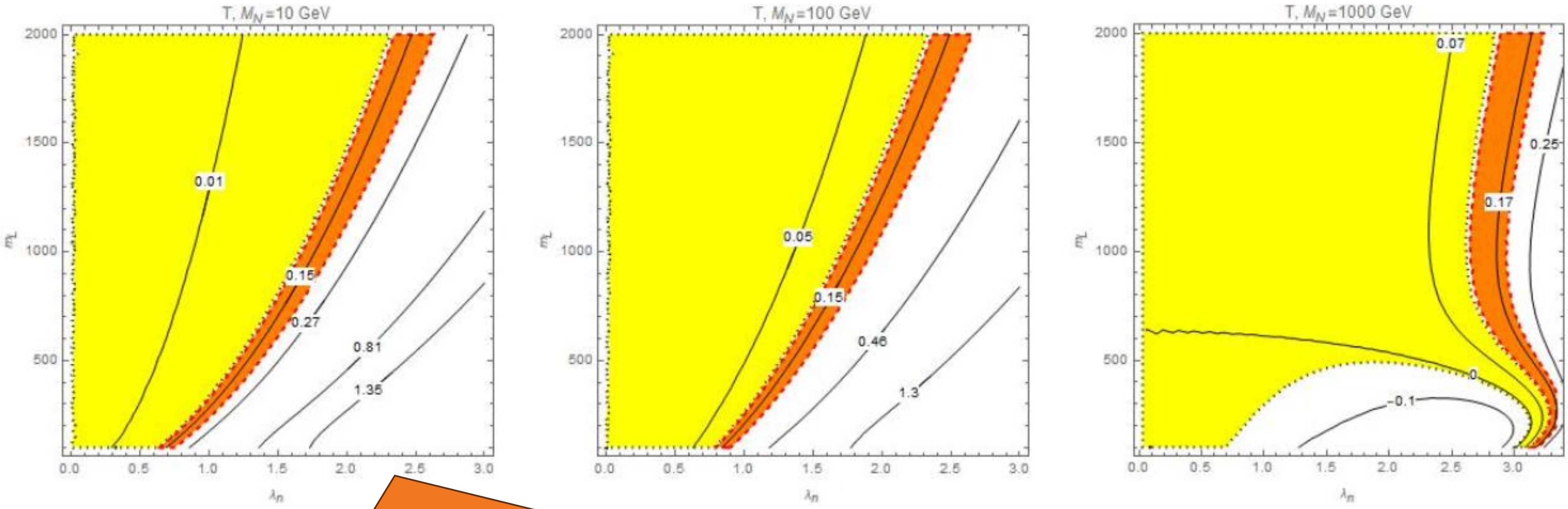
Colliders	experiments	results	SM Prediction
LEP	LEP	$80440 \pm 43(stat.)$ MeV [33]	80373 ± 23 MeV [34]
	LEP combination [35]	80376 ± 33 MeV	80385 ± 15 MeV
Tavetron	D0 (Run 2) [37]	80375 ± 23 MeV	80399 ± 23 MeV [38]
	CDF (Run 2) [22]	80433.5 ± 9.4 MeV	80357 ± 6 MeV
LHC	LHCb 2022 [39]	$80354 \pm 23(stat.)$ MeV	80379 ± 12 MeV [40]
	ATLAS 2017 [41]	80370 ± 19 MeV	80385 ± 15 MeV [42]
	ATLAS 2023 [23]	80360 ± 16 MeV	80377 ± 12 MeV [43]
	ATLAS 2024 [24]	80366.5 ± 15.9 MeV	80355 ± 6 MeV [44]

$$\mathrm{PDG}-2021: -0.010\,819 \leq T \leq 0.116\,374, \quad \mathrm{CDF}-\mathrm{II}: 0.122\,222 \leq T \leq 0.192\,398.$$

C. T. Lu, L. Wu, Y. Wu and B. Zhu, PRD, 2022

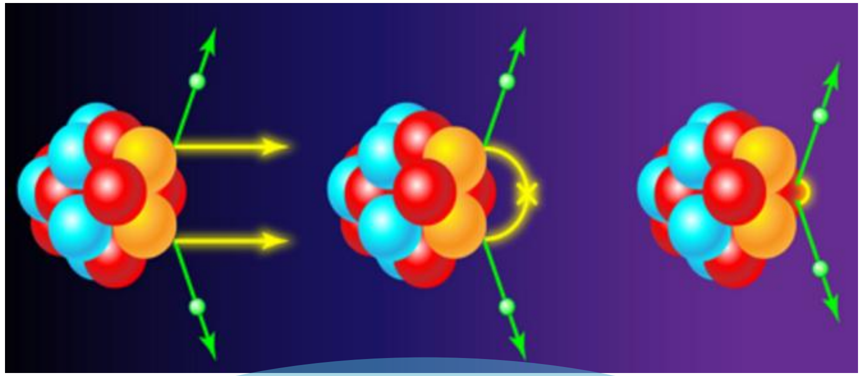
Mixed RHN-VLL: EWPOs

Shuyang Han, ZK and JiangZhu, JHEP 2024



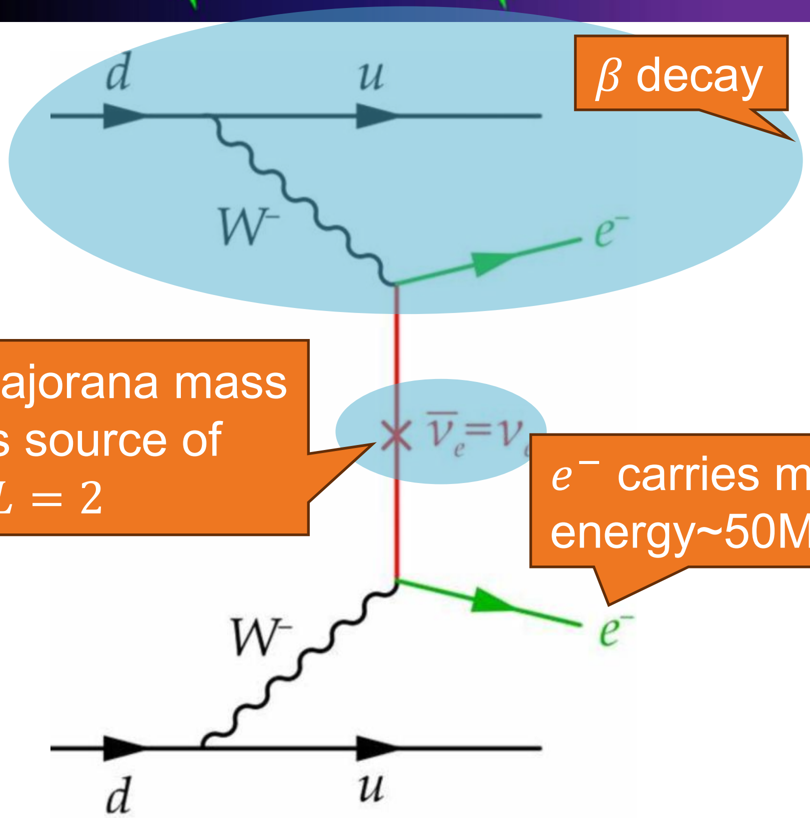
Yellow: the allowed-region of T by PDG-2021； orange: CDF-II

The SEESAW$^+$: new source for $0\nu\beta\beta$ decay



$0\nu\beta\beta$: a signature of lepton number violating +2 in nuclear process

$2\nu\beta\beta$ (1987, M.Moe) as a leading order transition in some special nuclear such as Ge-76 with $10^{20} year$!



β decay

Majorana mass as source of $\Delta L = 2$

e^- carries most energy~50MeV

$$\mathcal{H}_\beta = \frac{G_F \cos\theta_C}{\sqrt{2}} 2(\bar{e}_L \gamma^\mu \nu_{eL}) \mathcal{J}_\mu^+ + h.c.\,,$$

	$M_l'^{0\nu}$	$M_h'^{0\nu}$	$\sqrt{\langle p^2 \rangle}$ (MeV)	$G^{0\nu}$ (y^{-1})
^{76}Ge	3.886	204.0	159.0	2.363×10^{-15}
^{136}Xe	1.643	108.0	178.0	14.58×10^{-15}

$$(T_{1/2}^{0\nu})^{-1} = \frac{\Gamma^{0\nu}}{\ln 2} = G^{0\nu}(Q, Z)\, |\langle m \rangle_{ee}|^2\, g_A^4\, |M'^{0\nu}|^2$$

Axial former factor $g_A = 1.27$

The SEESAW$^+$: new source for $0\nu\beta\beta$ decay

实验名称	主要研究机构/国家	探测技术	使用的同位素	地点/实验室
CUORE	意大利、美国等	低温晶体量热器（TeO_2晶体）	^{130}Te	意大利格兰萨索国家实验室（LNGS）
GERDA/LEGEND	德国、美国、俄等国合作	高纯锗探测器（富集^{76}Ge）	^{76}Ge	意大利格兰萨索国家实验室（LNGS）
EXO	美国、加拿大等	液态氙时间投影室（富集^{136}Xe）	^{136}Xe	美国斯坦福地下研究设施（SUF）
nEXO	国际大型合作	下一代液态氙时间投影室（更大规模的EXO）	^{136}Xe	待定 (计划中)
KamLAND-Zen	日本、美国等	液体闪烁体（富集^{136}Xe）	^{136}Xe	日本神冈实验室（Kamioka）
SNO+	加拿大、英国等	液体闪烁体（富集^{130}Te）	^{130}Te	加拿大萨德伯里中微子观测站（SNOLAB
CUPID	国际合作	低温晶体量热器（采用^{200}Mo等新材料）	^{100}Mo, ^{82}Se, ^{116}Cd等	意大利格兰萨索国家实验室（LNGS）
AMoRE	韩国、俄等国合作	低温晶体量热器（$^{40}Ca^{100}MoO_4$晶体）	^{100}Mo	韩国襄阳地下实验室（Y2L）
中国锦屏实验	中国（清华大学等）	**高纯锗探测器** (CDEX合作组) 6	^{76}Ge	**中国锦屏地下实验室（CJPL）** 6
	中国（复旦大学等）	**低温晶体量热器** (例如钼基晶体) 7	^{100}Mo等	**中国锦屏地下实验室（CJPL）** 6 7

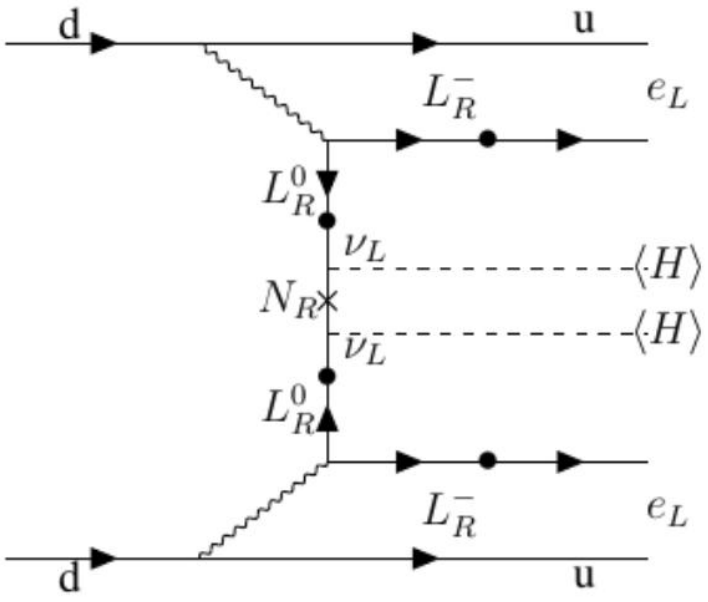
The $\mathbf{SEESAW^+}$: new source for $\boldsymbol{0\nu\beta\beta}$ decay

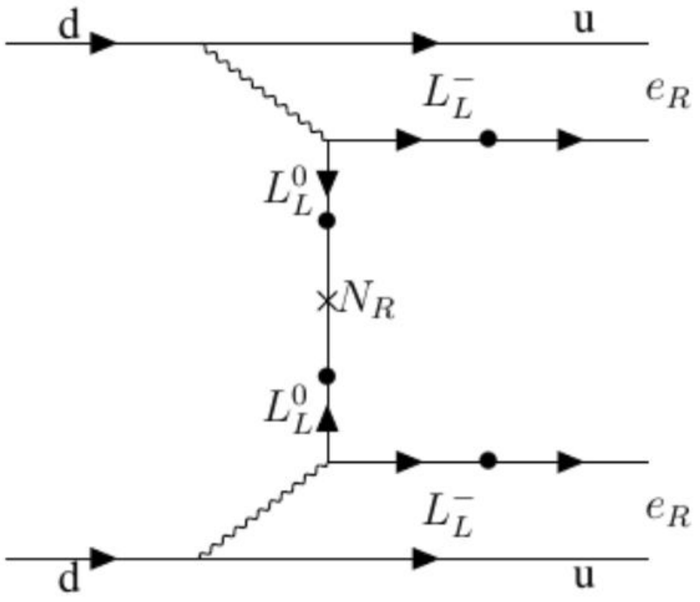
Why not turn on VLL-electron mixing? The cross between $\boldsymbol{0\nu\beta\beta}$ & lepton flavor physics

Unlike the sterile RHNs in seesaw, here the heavy Majorana RHNs gain quasi-EW charge, and may fire the first shot in $0\nu\beta\beta$

VLL mixing with different generations of SM leptons leads to LFV like $\mu \to e\gamma$ (but it can be avoided if only mixes with the 1st generation)

Large right-handed lepton mixing is constrained by university test $Z \to \bar{\ell}_i \ell_i$





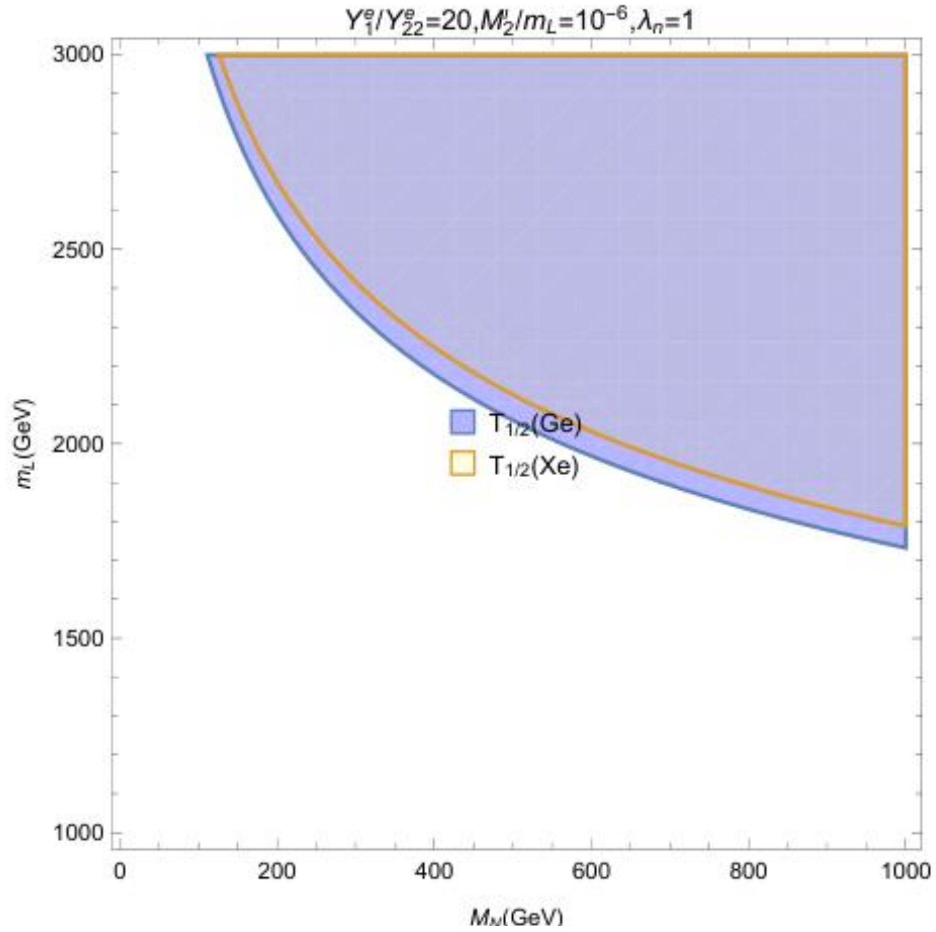
The $SEESAW^+$: new source for $0\nu\beta\beta$ decay

Prospect of quasi-EW heavy Majorana RHN in $0\nu\beta\beta$ decay (preliminary)

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu} g_A^4 \left| \sum_i U_{ei}^2 m_i m_p M'^{0\nu}(m_i, g_A^{eff}) \right|^2$$

$$= G^{0\nu} g_A^4 \begin{cases} \left|\frac{\langle m\rangle_{ee}}{m_e}\right|^2 \left|M'^{0\nu}_l(g_A^{eff})\right|^2, & \text{for } m_i \ll q_F, \\ \left|\frac{m_p}{\langle M\rangle_{ee}}\right|^2 \left|M'^{0\nu}_h(g_A^{eff})\right|^2, & \text{for } m_i \gg q_F. \end{cases}$$

$$M_N < (M'^{0\nu}_h / M'^{0\nu}_l)(m_p m_e / m_\nu) \sim 25 \times (0.01\text{eV}/m_\nu)\text{GeV}.$$



$$(T^{0\nu}_{1/2})(^{76}\text{Ge}) \geq (T^{0\nu}_{1/2})^{exp}(^{76}\text{Ge}) = 1.8 \times 10^{26} \text{ yr } (90\% \text{ C.L.}),$$

$$(T^{0\nu}_{1/2})(^{136}\text{Xe}) \geq (T^{0\nu}_{1/2})^{exp}(^{136}\text{Xe}) = 1.07 \times 10^{26} \text{ yr } (90\% \text{ C.L.})$$

1. Type-I seesaw mechanism is a very promising BSM, but its detection is a bit awkward

2. Its meeting with another popular BSM, VLL, may change the situation

Conclusions & Outlook & Thanks

3. We find the sizable RHN-VLL mixing is testable in EWPOs such as M_W (effect of mass split VLL)

4. The quasi-EW Majorana RHN, due to RHN-VLL plus VLL-electron mixing, is hopeful in $0\nu\beta\beta$ decay