$0\nu\beta\beta$-decay: Non-standard Mechanisms and Long-range contributions

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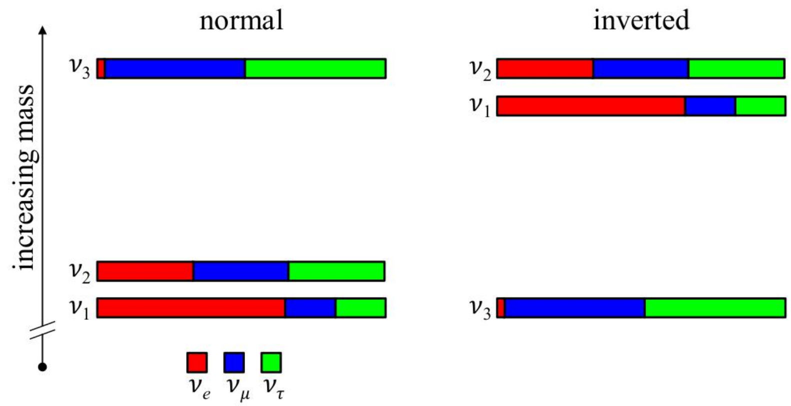
ACFI, University of Massachusetts, Amherst

Workshop on neutrinoless double-β decay
Zhuhai, May 21, 2021

Neutrinos: Dirac or Majorana?

Neutrino oscillation experiments imply that neutrinos are massive



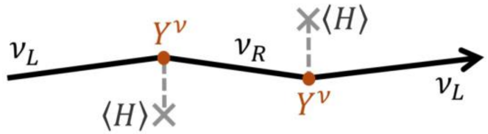
$$\Delta m^2_{21} \approx 7.5 \times 10^{-5}\ \mathrm{eV}^2$$

$$|\Delta m^2_{31}| \approx 2.5 \times 10^{-3}\ \mathrm{eV}^2$$

$m_2 > m_1$ through solar neutrino oscillation (with matter effects)

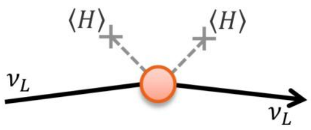
Dirac mass term

$$\mathcal{L}_D = -m_D(\bar{\nu}_L \nu_R + \mathrm{h.c.})$$



Majorana mass term

$$\mathcal{L}_M = -\frac{m_M}{2}(\bar{\nu}_L \nu^c_L + \mathrm{h.c.})$$



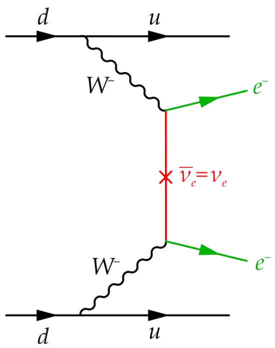
breaks the lepton number by two units

$0\nu\beta\beta$-decay in a nutshell

- In order to probe the nature of massive neutrinos (are they their own anti-particles?), we need to study processes in which the total lepton number is not conserved

$0\nu\beta\beta$-decay:

$L = 0$



$L = 2$

Furry, Phys. Rev. 56 (1939) 1184

$0\nu\beta\beta$-decay in a nutshell

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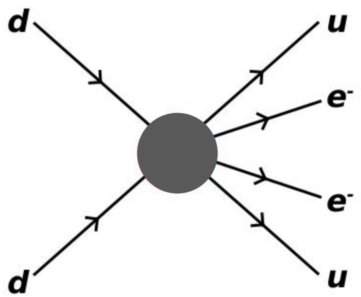
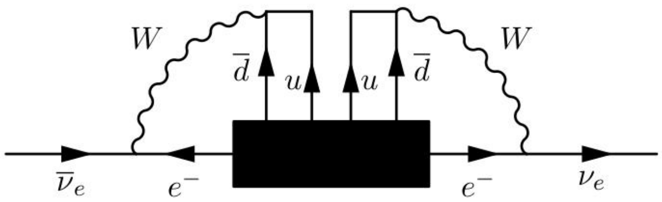
$0\nu\beta\beta$-decay:

$L = 0$



$L = 2$

Majorana neutrino mass:



Schechter, Valle
Phys.Rev. D25 (1982) 774

An observation of $0\nu\beta\beta$-decay implies

Majorana nature of neutrinos and lepton number violation

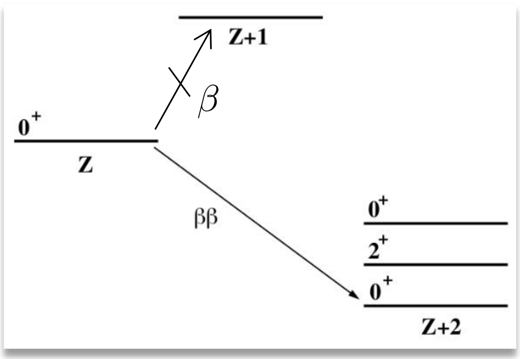
regardless of the origin of the "black box"

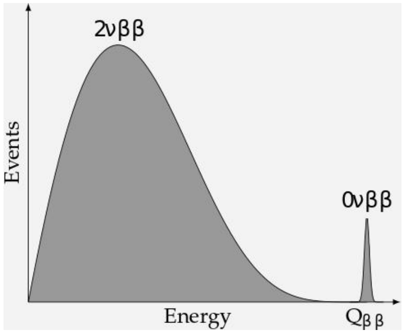
$0\nu\beta\beta$-decay in a nutshell

- In nuclei ^{136}Xe, ^{76}Ge, et al,

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

$^A_Z X$ *A: mass number, # of p, n*
Z: atomic number, # of p





summed energy of electrons $Q_{\beta\beta}$~2MeV

- β-decay is forbidden
- $0\nu\beta\beta$-decay and $2\nu\beta\beta$-decay are distinguishable

$0\nu\beta\beta$-decay in a nutshell

- $0\nu\beta\beta$-decay has not been observed yet
- The most stringent limit comes from KamLAND-Zen (^{136}Xe)

$$T^{0\nu}_{1/2} > 1.07 \times 10^{26} \text{ year}$$

Phys.Rev.Lett. 117 (2016) 082503

- Plenty of future tonne-scale experiments are sensitive to $T^{0\nu}_{1/2} \gtrsim 10^{28}$ year

Experiment	Isotope	Mass	Technique	Present Status	Location
CANDLES-III	^{48}Ca	300 kg	CaF_2 scint. crystals	Prototype	Kamioka
GERDA	^{76}Ge	≈35 kg	^{enr}Ge semicond. det.	Operating	LNGS
MAJORANA	^{76}Ge	26 kg	^{enr}Ge semicond. det.	Operating	SURF
CDEX-1T	^{76}Ge	1 ton	^{enr}Ge semicond. det.	Prototype	CJPL
LEGEND-200	^{76}Ge	200 kg	^{enr}Ge semicond. det.	Construction	LNGS
LEGEND-1000	^{76}Ge	ton	^{enr}Ge semicond. det.	Proposal	
CUPID-0	^{82}Se	5 kg	Zn^{enr}Se scintillating bolometers	Prototype	LNGS
SuperNEMO-Dem	^{82}Se	7 kg	^{enr}Se foils/tracking	Construction - 2019	Modane
SuperNEMO	^{82}Se	100 kg	^{enr}Se foils/tracking	Proposal	Modane
CMOS Imaging	^{82}Se		^{enr}Se, CMOS	Development	
AMoRE-Pilot	^{100}Mo	1 kg	^{40}Ca^{100}MoO$_4$ Bolometers	Operation	YangYang
AMoRE-I	^{100}Mo	6 kg	^{40}Ca^{100}MoO$_4$ Bolometers	Construction - 2019	YangYang
AMoRE-II	^{100}Mo	200 kg	^{40}Ca^{100}MoO$_4$ Bolometers	Construction - 2020	Yemi
CROSS	^{100}Mo	5 kg	Li$_2$^{100}MoO$_4$ surface coated Bolometers	Construction - 2020	Canfranc
LUMINEU	^{100}Mo		Li^{enr}MoO$_4$, Zn^{enr}MoO$_4$ scint. bolometers	Development	LNGS, LSM
Aurora	^{116}Cd	1 kg	^{enr}CdWO$_4$ scintillating crystals	Development	LNGS
COBRA-dem	^{116}Cd	0.38 kg	^{nat}Cd CZT semicond. det.	Operation	LNGS
Tin.Tin	^{124}Sn	1 kg	Tin bolometers	Development	INO
CALDER	^{130}Te		TeO_2 bolometers with Cerenkov Light	Development	LNGS
CUORE	^{130}Te	1 ton	TeO_2 bolometers	Operating	LNGS
SNO+	^{130}Te	1.3 t	0.5% ^{enr}Te loaded liq. scint.	Construction - 2020	SNOLab
nEXO	^{136}Xe	5 t	Liq. ^{enr}Xe TPC/scint.	Proposal	
NEXT-100	^{136}Xe	100 kg	gas TPC	Prototype	Canfranc
AXEL	^{136}Xe		gas TPC	Prototype	
KamLAND-Zen	^{136}Xe	800 kg	^{enr}Xe disolved in liq. scint.	Operating	Kamioka
LZ	^{136}Xe		Dual phase Xe TPC	Construction - 2020	SURF
PANDAX-III	^{136}Xe	1 ton	Dual phase Xe TPC	Construction - 2019	CJPL
XENON1T	^{136}Xe	1 ton	Dual phase Xe TPC	Operating	LNGS
DARWIN	^{136}Xe	50 ton	Dual phase Xe TPC	Proposal	LNGS
NuDot	Various		Cherenkov and scint. detection in liq. scint.	Development	
FLARES	Various		Scint. crystals with Si photodetectors	Development	

May 28, 2020 Elliott, BB Theory Workshop

incomplete list

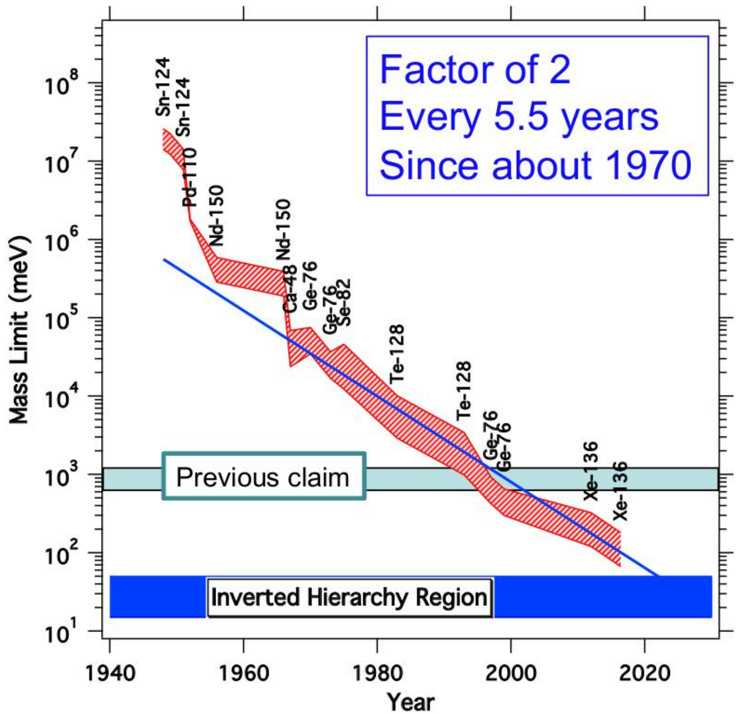
$0\nu\beta\beta$-decay in a nutshell

- Connection to particle physics

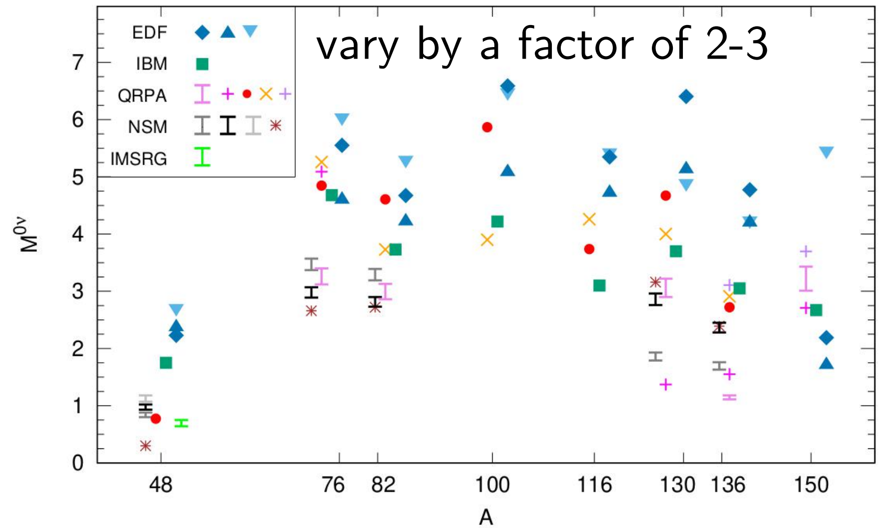
$$\left(T^{0\nu}_{1/2}\right)^{-1} = G_{0\nu}|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

$G_{0\nu}$: phase space factor
$M_{0\nu}$: nuclear matrix element

half-life → effective Majorana mass $\langle m_{\beta\beta}\rangle$



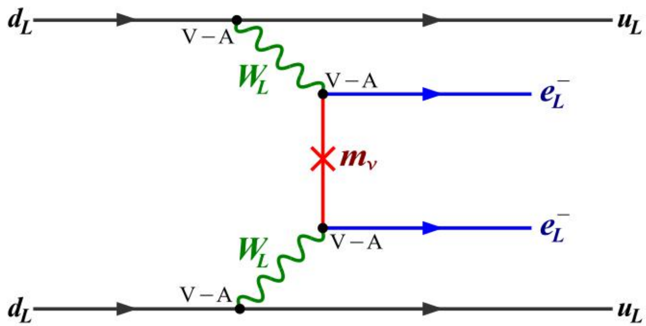
S. Elliott, BB Theory Workshop '20



Engel, Menndez, Rept. Prog. Phys. 80 (2017) 046301

$0\nu\beta\beta$-decay in a nutshell

- Well-known Majorana mass (standard) mechanism



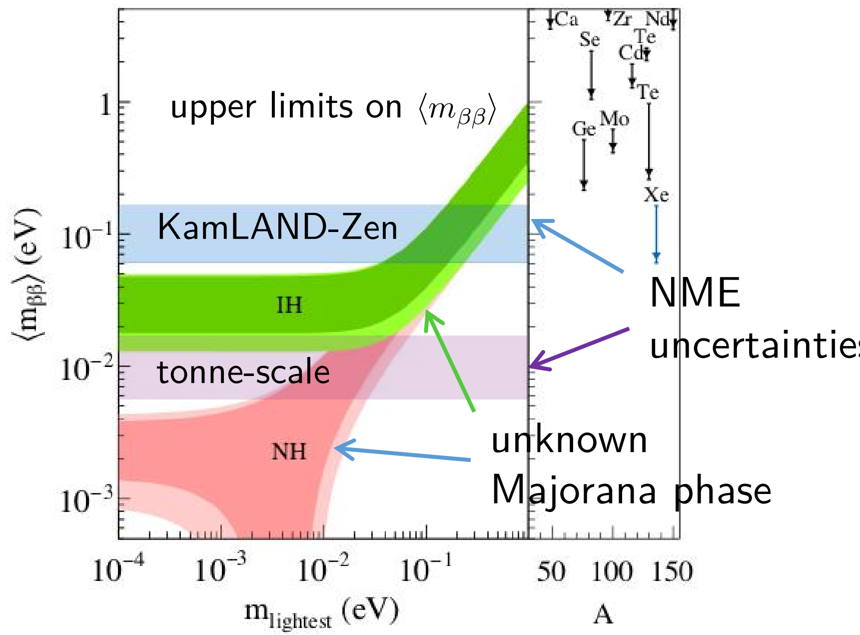
$$m_{\beta\beta} = |\sum_i m_i U_{ei}^2|$$

absolute neutrino masses

PMNS matrix

$$\Delta m_{21}^2, |\Delta m_{31}^2|$$

accidental cancellation in NH



Phys.Rev.Lett. 117 (2016) 082503; Phys.Rev.Lett. 125 (2020) 25, 252502

KamLAND-Zen (^{136}Xe): $\langle m_{\beta\beta} \rangle <$ 61-165 meV

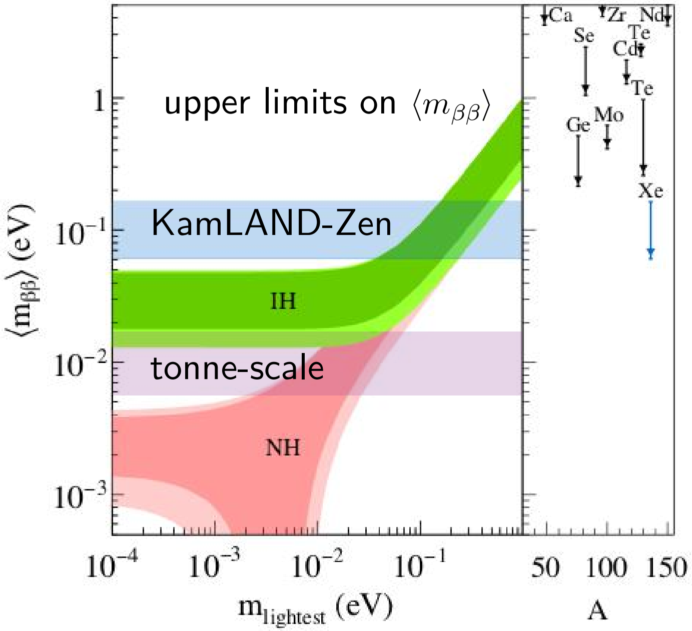
GERDA (^{76}Ge): $\langle m_{\beta\beta} \rangle <$ 79-180 meV

$0\nu\beta\beta$-decay in a nutshell

- Issues for interpretation of $0\nu\beta\beta$-decay results
  - sizable NME uncertainties
  - value of lightest neutrino mass
  - discrimination of mass hierarchy

NH is favored over IH
at 2.7σ with current neutrino
oscillation data

P.F. de Salas et al, 2006.11237 (JHEP)



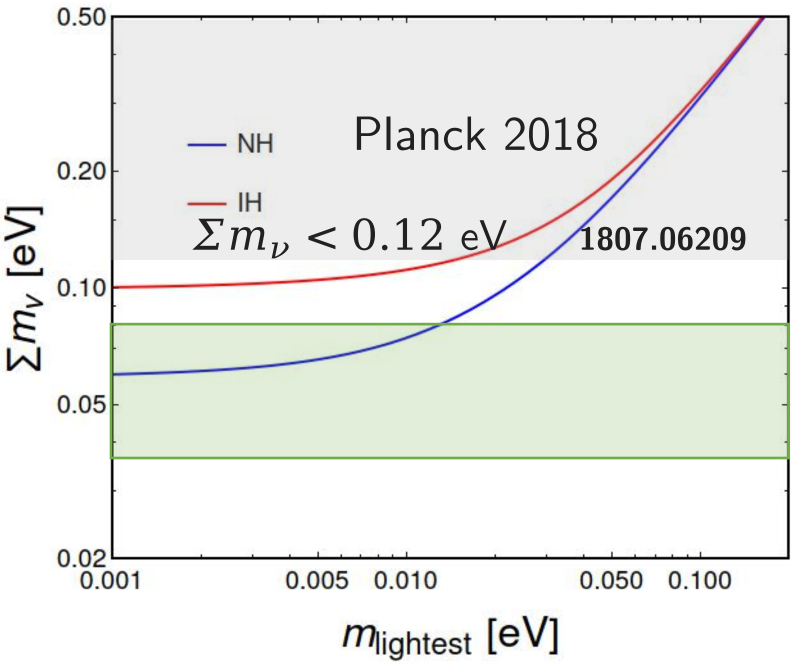
- An observation of $0\nu\beta\beta$-decay is challenging in tonne-scale experiments
- It is even more worrying confronted with cosmological surveys

Cosmological bound

Sum of neutrino masses $\sum m_\nu = m_1 + m_2 + m_3$

affect expansion rate of the Universe or clustering of matter

Σm_ν depends on the lightest neutrino mass and $\Delta m^2_{21}, |\Delta m^2_{31}|$



Oscillation (+Planck): NH is favored over IH at $2.7\sigma (3.3\sigma)$

P.F. de Salas et al, 2006.11237 (JHEP)

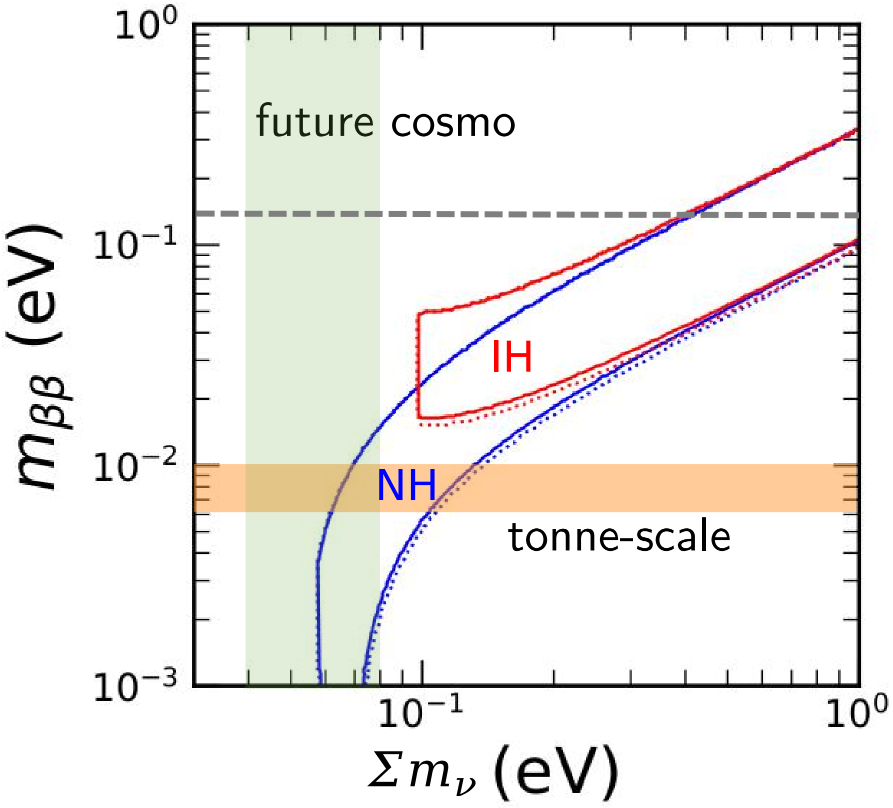
CMB-S4 (operate in 2027), DESI (commissioning) et al: $\sigma(\Sigma \mathrm{m}_\nu \lesssim 0.02\ \mathrm{eV})$

NH and IH can be discriminated at 95% C.L.

Lesgourgues et al, 1808.05955 (JCAP)

$0\nu\beta\beta$-decay infronted with cosmology

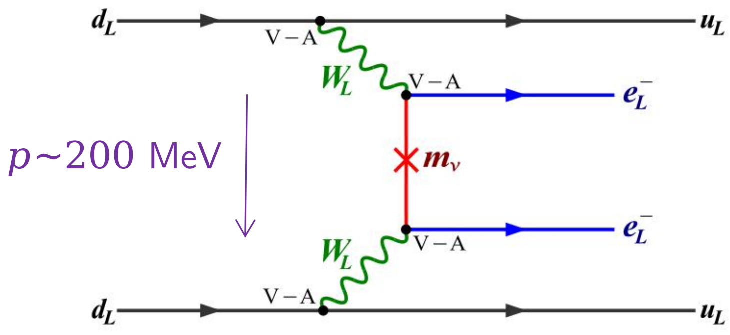
challenging for a positive signal in $0\nu\beta\beta$-decay experiments



F. Capozzi et al, 2003.08511 (PRD)

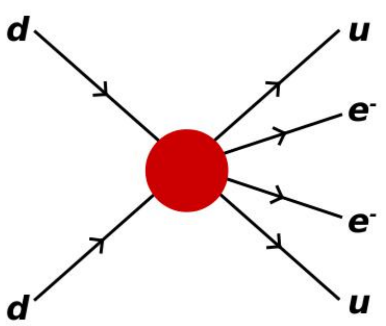
We need new mechanisms of $0\nu\beta\beta$-decay

Standard mechanism:



$\sim G_F^2 m_\nu / p^2$

Heavy BSM mechanisms:



$\sim c/\Lambda^5$ c: new coupling

$$\frac{c/\Lambda^5}{G_F^2 m_\nu^{ee}/p^2} = c\left(\frac{3.3\ \text{TeV}}{\Lambda}\right)^5 \frac{0.1\ \text{eV}}{m_\nu^{ee}}$$

Contribution from heavy BSM mechanisms could be comparable if $c \sim O(1)$, $\Lambda \sim \text{TeV}$

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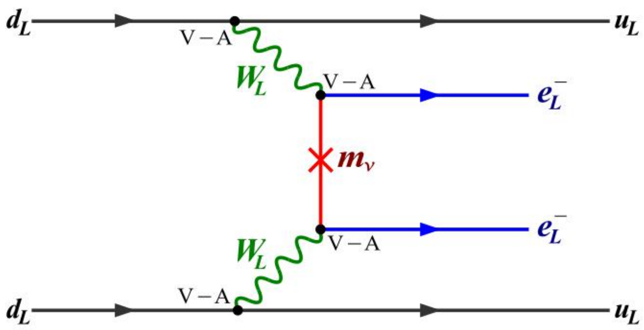
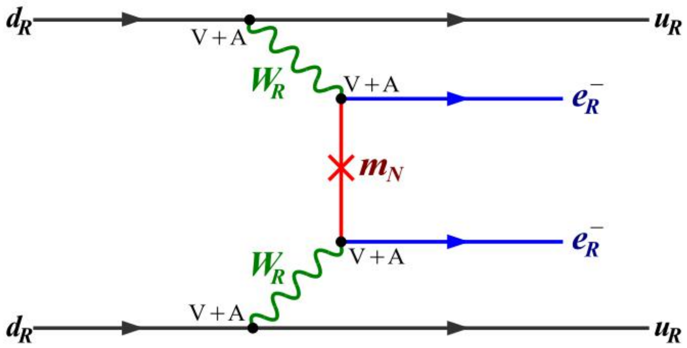


$\sim G_F^2 m_\nu / p^2$

long-range contribution

Right-handed counterpart:



$\sim G_F^2 M_W^2 / M_{W_R}^2 1/m_N$

Mohapatra, Senjanovic, Marshak, Doi, et. al

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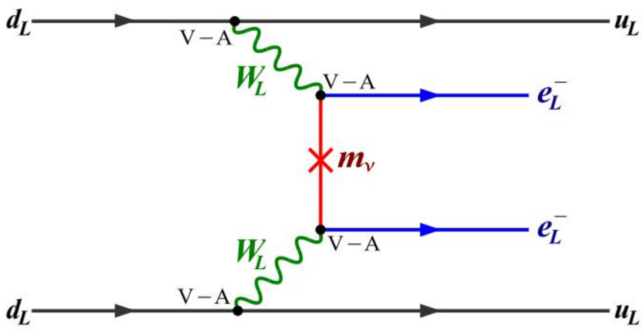

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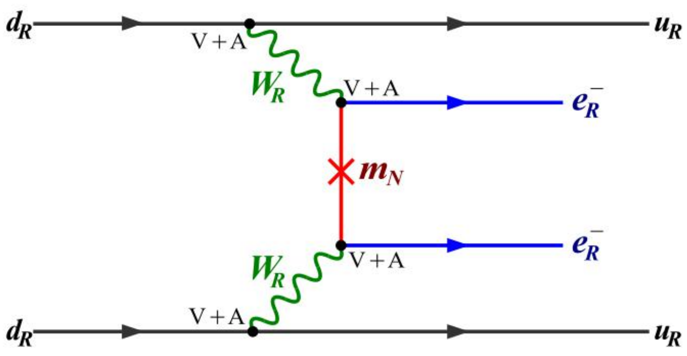


$\sim G_F^2 M_W^2 / M_{W_R}^2 1/m_N$

Mohapatra, Senjanovic, Marshak, Doi, et. al

Many possible scenarios:

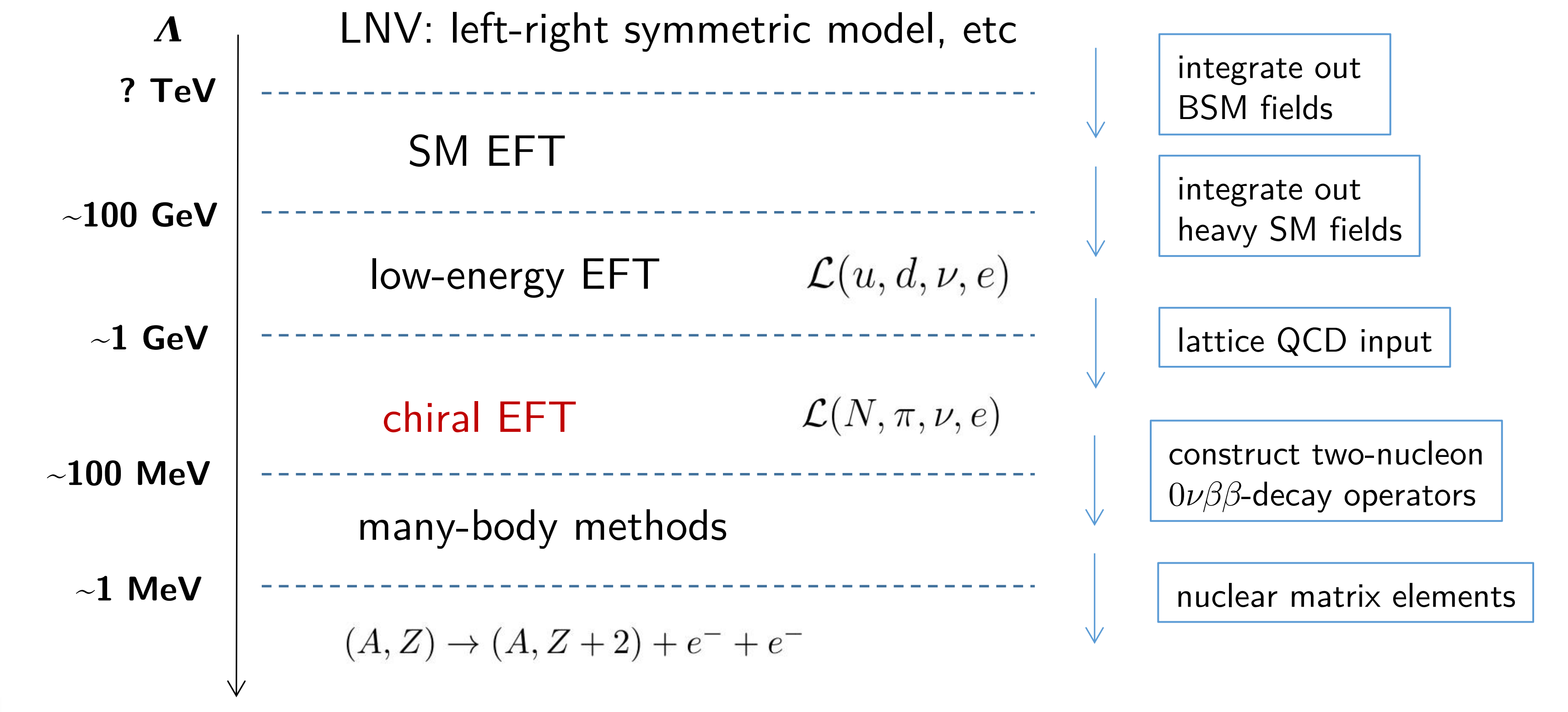
- left-right symmetric model
- R-parity violating SUSY
- ...

Roadmap for model-dependent studies:

effective field theory approach

EFT approach to $0\nu\beta\beta$-decay

- systematical way: all LNV sources
- multi-scale involved: $\mathrm{TeV} \rightarrow \mathrm{MeV}$
- long-range contribution from heavy BSM mechanisms



EFT approach to $0\nu\beta\beta$-decay

Below the EW scale, $\mathrm{SU}(3)_\mathrm{C} \times \mathrm{U}(1)_\mathrm{em}$ invariant operators

dimension-9: $O_i \; \bar{e}(1 \pm \gamma_5)e^c$

In total, 24 non-redundant operators for $0\nu\beta\beta$-decay

Prezeau, Ramsey-Musolf, Vogel, Phys.Rev.D 68 (2003) 034016; Graesser JHEP 08 (2017) 099

$$\mathcal{O}_{1+}^{++} = (\bar{q}_\mathrm{L}^\alpha \tau^+ \gamma^\mu q_\mathrm{L}^\alpha)(\bar{q}_\mathrm{R}^\beta \tau^+ \gamma_\mu q_\mathrm{R}^\beta), \quad \mathcal{O}_{1+}^{++\prime} = (\bar{q}_L^\alpha \tau^+ \gamma^\mu q_L^\beta)(\bar{q}_R^\beta \tau^+ \gamma_\mu q_R^\alpha)$$

$$\mathcal{O}_{3\pm}^{++} = (\bar{q}_\mathrm{L}^\alpha \tau^+ \gamma^\mu q_\mathrm{L}^\alpha)(\bar{q}_\mathrm{L}^\beta \tau^+ \gamma_\mu q_\mathrm{L}^\beta) \pm (\bar{q}_\mathrm{R}^\alpha \tau^+ \gamma^\mu q_\mathrm{R}^\alpha)(\bar{q}_\mathrm{R}^\beta \tau^+ \gamma_\mu q_\mathrm{R}^\beta)$$

left-right symmetric model

$$\mathcal{O}_{2\pm}^{++} = (\bar{q}_\mathrm{R}^\alpha \tau^+ q_\mathrm{L}^\alpha)(\bar{q}_\mathrm{R}^\beta \tau^+ q_\mathrm{L}^\beta) \pm (\bar{q}_\mathrm{L}^\alpha \tau^+ q_\mathrm{R}^\alpha)(\bar{q}_\mathrm{L}^\beta \tau^+ q_\mathrm{R}^\beta)$$

RPV SUSY

α, β are color indices, $q = (u, d)^T$, $\tau^+ = (\tau^1 + i\tau^2)/2$
subscript $\pm$ denotes parity-even(odd)

+ more operators

EFT approach to $0\nu\beta\beta$-decay

Map quark operators to hadronic operators using chiral effective field theory, which transform in the same way under chiral $\mathrm{SU(2)_L} \times \mathrm{SU(2)_R}$

$$\xi = \exp\left(\frac{i\Pi}{\sqrt{2}F_\pi}\right) \qquad \Pi = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} & \pi^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} \end{pmatrix}$$

$$X_R^a = \xi\tau^a\xi^\dagger, \quad X_L^a = \xi^\dagger\tau^a\xi, \quad X^a = \xi\tau^a\xi$$

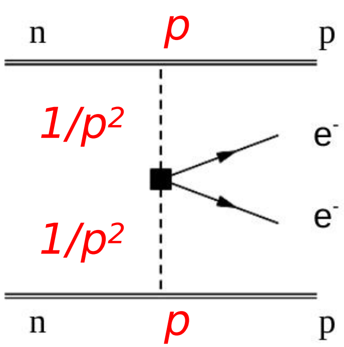
Prezeau, Ramsey-Musolf, Vogel, Phys.Rev.D 68 (2003) 034016

LO $\pi\pi ee$

$\bar{e}(1 \pm \gamma_5)e^c$

$$\mathcal{O}_{1+}^{++}, \mathcal{O}_{1+}^{++\prime} \to \mathrm{tr}[X_L^+ X_R^+ + X_R^+ X_L^+] = \frac{4}{F_\pi^2}\pi^-\pi^- + \cdots$$

$$\mathcal{O}_{2+}^{++} \to \mathrm{tr}[X^+ X^+ + X^{+\dagger} X^{+\dagger}] = -\frac{4}{F_\pi^2}\pi^-\pi^- + \cdots$$



$\mathcal{A}^{\mathrm{LO}} \sim p^{-2}$

long-range contribution

Notice: for light neutrino exchange $\sim G_F^2 m_\nu / p^2$

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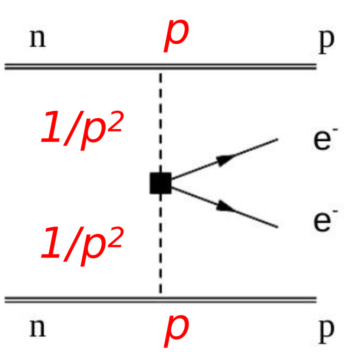
Prezeau, Ramsey-Musolf, Vogel, Phys.Rev.D 68 (2003) 034016

NNLO $\pi\pi ee$

$$\mathcal{O}_{3+}^{++} \to \mathrm{tr}[X_L^+ X_L^+ + X_R^+ X_R^+] = 0$$

$$\mathcal{O}_{3+}^{++} \to \frac{1}{2}\mathrm{tr}[D^\mu X_L^+ D_\mu X_L^+ + D^\mu X_R^+ D_\mu X_R^+]$$
$$= -\frac{1}{F_\pi^2}(\partial_\mu \pi^-)^2 + \cdots ,$$



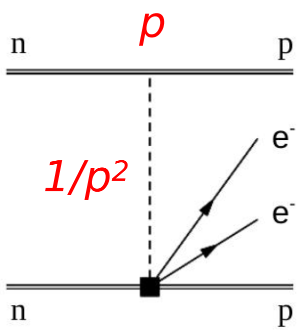
$$\mathcal{A}^{\mathrm{NNLO}} \sim p^0$$

EFT approach to $0\nu\beta\beta$-decay

$NN\pi ee$

$$\mathcal{O}_{3+}^{++} \rightarrow \frac{i2\sqrt{2}m_N}{F_\pi}\bar{N}\gamma_5\tau^+\pi^-N + \cdots$$

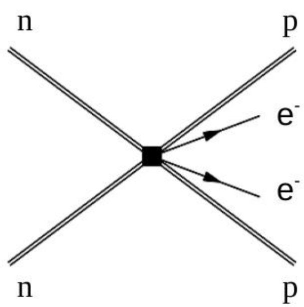
$$\mathcal{A}^{\rm NNLO} \sim p^0$$



$NNNNee$

$$\mathcal{O}_{3+}^{++} \rightarrow \bar{N}\tau^+N\bar{N}\tau^+N$$

$$\mathcal{A}^{\rm NNLO} \sim p^0$$



$$\frac{\mathcal{A}^{\rm LO}}{\mathcal{A}^{\rm NNLO}} \simeq \mathcal{O}\left(\frac{\Lambda_\chi^2}{p^2}\right), \quad \Lambda_\chi \sim 1 \text{ GeV} \qquad p \sim 200 \text{ MeV}$$

a factor of 20 !!

Notice: an equal formalism based on HBChPT

V. Cirigliano, W. Dekens, J. de Vries, M. L. Graesser, E. Mereghetti 1806.02780 (JHEP)

Long-range contributions from LO $\pi\pi ee$ are the leading ones

EFT w/o chiral EFT approach

- Map quark bilinear to single-nucleon current

consistent ChPT to NNLO for one-nucleon system

- It works well the standard mechanism with the exchange of light neutrinos

factorize the amplitude of $0\nu\beta\beta$-decay into two β-decay

- Use vacuum saturation approximation to factorize four-quark operators into two quark bilinears

LECs could be a factor of 2 different

LRSM: **Doi, Kotani, Nishiura, Takasugi '81; Barry, Rodejohann 1303.6324 (JHEP)**
SUSY&EFT: **Hirsch, Klapdor-Kleingrothaus, Kovalenko, Pas '95-'98**
EFT: **Graf, Deppisch, Iachello, Kotila 1806.06058 (PRD)**

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- Map quark bilinear to single-nucleon current

consistent ChPT to NNLO for one-nucleon system

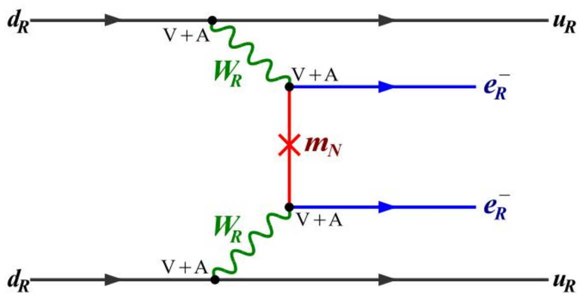
- It works well the standard mechanism with the exchange of light neutrinos

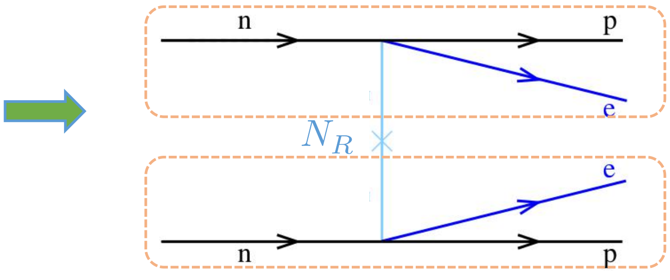
factorize the amplitude of $0\nu\beta\beta$-decay into two β-decay

- Use vacuum saturation approximation to factorize four-quark operators into two quark bilinears

LECs could be a factor of 2 different

- The failure of applying single-nucleon current to the non-standard mechanism: no $\pi\pi ee$; inconsistent by itself





Minimal left-right symmetric model

Gauge group: $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

Doublets:

$$q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L \qquad q_R = \begin{pmatrix} u \\ d \end{pmatrix}_R$$

$$L_L = \begin{pmatrix} \nu \\ l \end{pmatrix}_L \qquad L_R = \begin{pmatrix} N \\ l \end{pmatrix}_R$$

Mohapatra and Senjanovic, Phys.Rev.Lett. 44 (1980) 912, Phys.Rev.D 23 (1981) 165

Bidoublet:

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \Rightarrow \langle \Phi \rangle = \begin{pmatrix} v_1 & 0 \\ 0 & v_2 e^{i\alpha} \end{pmatrix}$$

Triplets:

$$\Delta_{L,R} = \begin{pmatrix} \delta_{L,R}^+/\sqrt{2} & \delta_{L,R}^{++} \\ \delta_{L,R}^0 & -\delta_{L,R}^+/\sqrt{2} \end{pmatrix}$$

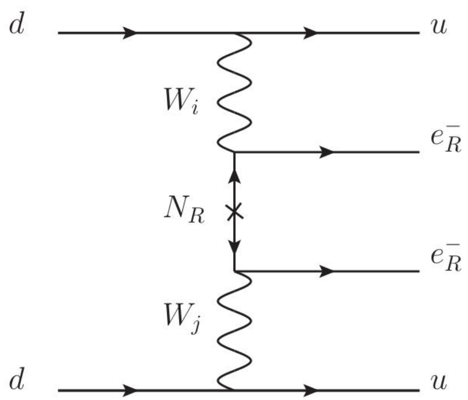
$$\Rightarrow \langle \Delta_R \rangle = \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix}, \qquad \langle \Delta_L \rangle = \begin{pmatrix} 0 & 0 \\ v_L e^{i\theta_L} & 0 \end{pmatrix}$$

provide a natural origin of neutrino masses

Leading contribution from $W_L - W_R$ mixing

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}}\bar{u}_{Li}V^{\rm CKM}_{Lij}\not{W}_L d_{Lj} - \frac{g}{\sqrt{2}}\bar{u}_{Ri}V^{\rm CKM}_{Rij}\not{W}_R d_{Rj}$$
$$-\frac{g}{\sqrt{2}}\bar{e}_{Li}V^{\rm PMNS}_{Lij}\not{W}_L \nu_{Lj} - \frac{g}{\sqrt{2}}\bar{e}_{Ri}V^{\rm PMNS}_{Rij}\not{W}_R N_{Rj}$$
$$+ \text{ h.c. } ,$$

$0\nu\beta\beta$-decay:



left-right $(W_L - W_R)$ mixing:

$$W_L = \cos\xi\, W^+_{1\mu} - \sin\xi\; e^{-i\alpha}\, W^+_{2\mu},$$
$$W_R = \sin\xi\, e^{i\alpha}\, W^+_{1\mu} + \cos\xi\, W^+_{2\mu}.$$

$$W_L \simeq W_1,\; W_R \simeq W_2$$

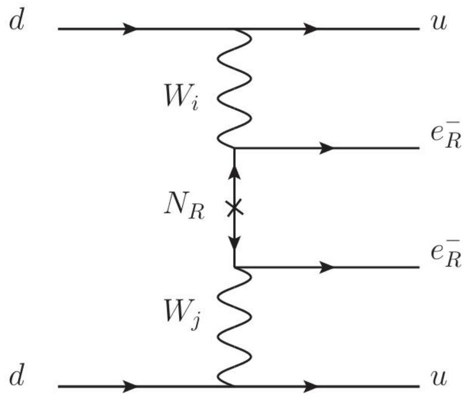
No $W_L - W_R$ mixing (i,j)=(R,R) $u_R d_R u_R d_R e_R e_R$

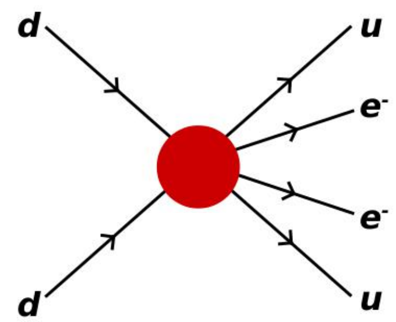
$W_L - W_R$ mixing (i,j)=(1,2) $u_L d_L u_R d_R e_R e_R$

Leading contribution from $W_L - W_R$ mixing

$$
\begin{aligned}
\mathcal{L}_{CC} = &- \frac{g}{\sqrt{2}} \bar{u}_{Li} V^{\rm CKM}_{Lij} \not{W}_L d_{Lj} - \frac{g}{\sqrt{2}} \bar{u}_{Ri} V^{\rm CKM}_{Rij} \not{W}_R d_{Rj} \\
&- \frac{g}{\sqrt{2}} \bar{e}_{Li} V^{\rm PMNS}_{Lij} \not{W}_L \nu_{Lj} - \frac{g}{\sqrt{2}} \bar{e}_{Ri} V^{\rm PMNS}_{Rij} \not{W}_R N_{Rj} \\
&+ \text{h.c.} \;,
\end{aligned}
$$

$0\nu\beta\beta$-decay:





No $W_L - W_R$ mixing (i,j)=(R,R) $u_R d_R u_R d_R e_R e_R \sim O^{++}_{3\pm}$

$\mathcal{A}^{\rm NNLO} \sim p^0$

$W_L - W_R$ mixing (i,j)=(1,2) $u_L d_L u_R d_R e_R e_R \sim O^{++}_{1+}$

$\mathcal{A}^{\rm LO} \sim p^{-2}$

Leading contribution from $W_L - W_R$ mixing

After integrating out W_1, W_2 and N_R

$$\mathcal{L}_{\text{eff}} = \frac{G_F^2}{\Lambda_{\beta\beta}}\left[C_{3R}(\mathcal{O}_{3+}^{++} - \mathcal{O}_{3-}^{++})(\bar{e}e^c - \bar{e}\gamma_5 e^c) + C_1\mathcal{O}_{1+}^{++}(\bar{e}e^c - \bar{e}\gamma_5 e^c)\right]$$

$$\mathcal{O}_{3+}^{++} - \mathcal{O}_{3-}^{++} = 2(\bar{q}_R^\alpha \tau^+ \gamma^\mu q_R^\alpha)(\bar{q}_R^\beta \tau^+ \gamma_\mu q_R^\beta) \qquad C_{3R} = \lambda^2 \qquad \lambda \equiv \frac{M_W^2}{M_{W_R}^2}$$

$$\mathcal{O}_{1+}^{++} = (\bar{q}_L^\alpha \tau^+ \gamma^\mu q_L^\alpha)(\bar{q}_R^\beta \tau^+ \gamma_\mu q_R^\beta) \qquad C_1 = -4\lambda\xi$$

$$\boxed{\tan\xi = \frac{v_1 v_2}{v_R^2} = \lambda\sin(2\beta)} \qquad \lambda \equiv \frac{M_W^2}{M_{W_R}^2} \qquad \tan\beta = \frac{v_2}{v_1}$$

LHC direct searches, kaon and B meson mass mixing

$$M_{W_R} \geq 4.8 \text{ TeV} \Longrightarrow \lambda \leq 2.8 \times 10^{-4}$$

perturbativity bound, CKM unitarity, EW precision

$$\tan\beta \lesssim 0.5 \quad \text{or} \quad \sin 2\beta \lesssim 0.8$$

$0\nu\beta\beta$-decay in minimal LRSM

Inverse of half-life for $0\nu\beta\beta$-decay:

$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu} \cdot \mathcal{M}_\nu^2 \left(|m_\nu^{ee}|^2 + |m_N^{ee}|^2\right) \qquad |m_{\beta\beta}| = \sqrt{|m_\nu^{ee}|^2 + |m_N^{ee}|^2}$$

$$m_\nu^{ee} = \sum_{i=1}^{3} |V_{Lei}|^2 m_{\nu_i}$$ contribution from the standard mechanism

$$|m_N^{ee}|^2 = \frac{\Lambda_\chi^4}{72\Lambda_{\beta\beta}^2} \frac{\mathcal{M}_0^2}{\mathcal{M}_\nu^2} \times \Big[(\beta_1 - \zeta_5\delta_{N\pi} - \beta_3\delta_{\pi\pi} + \xi_1\delta_{NN})^2 + (\beta_2 - \zeta_6\delta_{N\pi} - \beta_4\delta_{\pi\pi} + \xi_4\delta_{NN})^2\Big]$$

$$\delta_{\pi\pi} = \frac{2m_\pi^2}{\Lambda_\chi^2}\frac{\mathcal{M}_2}{\mathcal{M}_0}, \qquad \delta_{N\pi} = \frac{\sqrt{2}m_\pi^2}{g_A\Lambda_\chi m_N}\frac{\mathcal{M}_1}{\mathcal{M}_0},$$

$$\delta_{NN} = \frac{12m_\pi^2}{g_A^2\Lambda_\chi^2}\frac{\mathcal{M}_{NN}}{\mathcal{M}_0}.$$

Notice: recent development in NME/contact term for standard mechanism, see works by V. Cirigliano et al; J. M. Yao, et al.; $\sim +40\%$

GL, Ramsey-Musolf and Vasquez, 2009.01257 (PRL)

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$$\beta_1 = -\beta_2 = \ell_1^{\pi\pi} C_1 + \ell_1^{\pi\pi\prime} C_1'$$

LO $\pi\pi ee$ interaction from W_L-W_R mixing

sub-leading terms

$$\delta_{\pi\pi} = \frac{2m_\pi^2}{\Lambda_\chi^2} \frac{\mathcal{M}_2}{\mathcal{M}_0}, \qquad \delta_{N\pi} = \frac{\sqrt{2} m_\pi^2}{g_A \Lambda_\chi m_N} \frac{\mathcal{M}_1}{\mathcal{M}_0},$$

$$\delta_{NN} = \frac{12 m_\pi^2}{g_A^2 \Lambda_\chi^2} \frac{\mathcal{M}_{NN}}{\mathcal{M}_0}.$$

GL, Ramsey-Musolf and Vasquez, 2009.01257 (PRL)

$0\nu\beta\beta$-decay in minimal LRSM

Inverse of half-life for $0\nu\beta\beta$-decay:

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu} \cdot \mathcal{M}_\nu^2 \left(|m_\nu^{ee}|^2 + |m_N^{ee}|^2\right) \qquad |m_{\beta\beta}| = \sqrt{|m_\nu^{ee}|^2 + |m_N^{ee}|^2}$$

$$m_\nu^{ee} = \sum_{i=1}^{3} |V_{Lei}|^2 m_{\nu_i}$$

$$|m_N^{ee}|^2 = \frac{\Lambda_\chi^4}{72\Lambda_{\beta\beta}^2}\frac{\mathcal{M}_0^2}{\mathcal{M}_\nu^2} \times \left[(\beta_1 - \zeta_5\delta_{N\pi} - \beta_3\delta_{\pi\pi} + \xi_1\delta_{NN})^2 + (\beta_2 - \zeta_6\delta_{N\pi} - \beta_4\delta_{\pi\pi} + \xi_4\delta_{NN})^2\right]$$

$$\beta_1 = -\beta_2 = \ell_1^{\pi\pi} C_1 + \ell_1^{\pi\pi\prime} C_1'$$

LECs:

$$\ell_1^{\pi\pi} = -(0.71 \pm 0.07)$$

$$\ell_1^{\pi\pi\prime} = -(2.98 \pm 0.22)$$

$$\ell_3^{\pi\pi} = 0.60 \pm 0.03$$

Nicholson et al., Phys. Rev. Lett. 121, 172501 (2018)

$$\delta_{\pi\pi} = \frac{2m_\pi^2}{\Lambda_\chi^2}\frac{\mathcal{M}_2}{\mathcal{M}_0}, \qquad \delta_{N\pi} = \frac{\sqrt{2}m_\pi^2}{g_A\Lambda_\chi m_N}\frac{\mathcal{M}_1}{\mathcal{M}_0},$$

$$\delta_{NN} = \frac{12m_\pi^2}{g_A^2\Lambda_\chi^2}\frac{\mathcal{M}_{NN}}{\mathcal{M}_0}.$$

NMEs for ^{136}Xe:

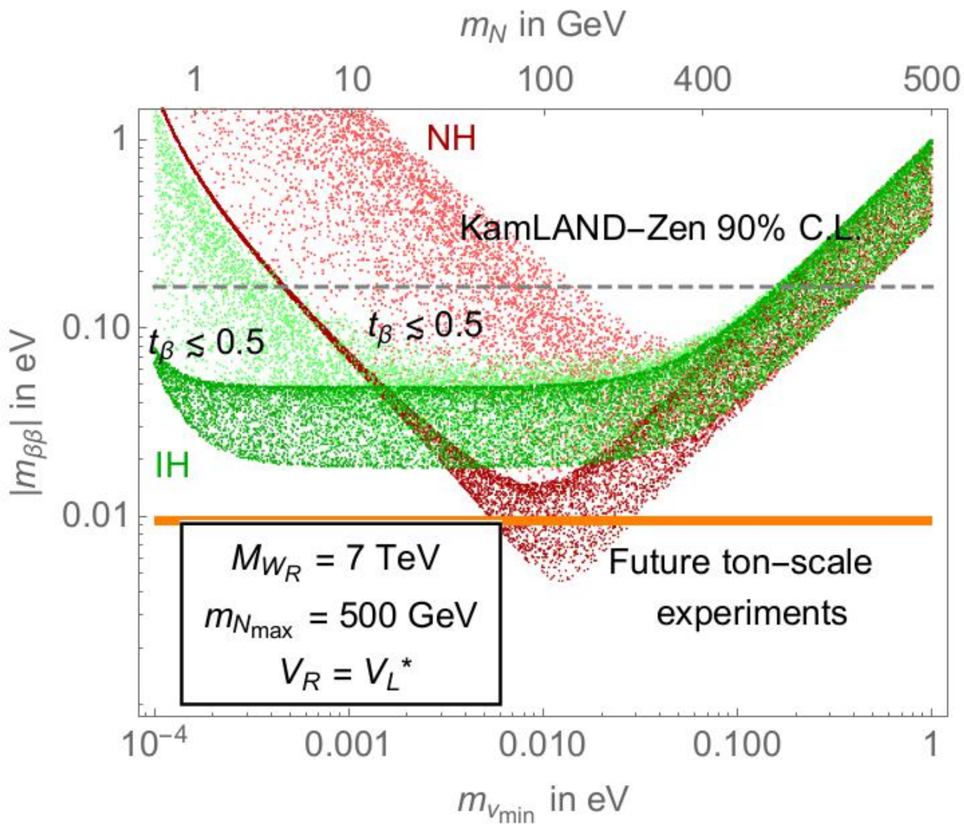
M_0	M_1	M_2	M_ν	M_{NN}
-2.64	-5.52	-4.20	2.91	-1.53

Hyvarinen, Suhonen Phys.Rev.C 91 (2015) 024613

$$\delta_{\pi\pi} = 0.046,\ \delta_{N\pi} = 0.042,\ \ \delta_{NN} = 0.063$$

$\approx$ chiral power counting $\sim 1/20$

$0\nu\beta\beta$-decay in minimal LRSM



dark red, dark green:
$\tan\beta = 0$

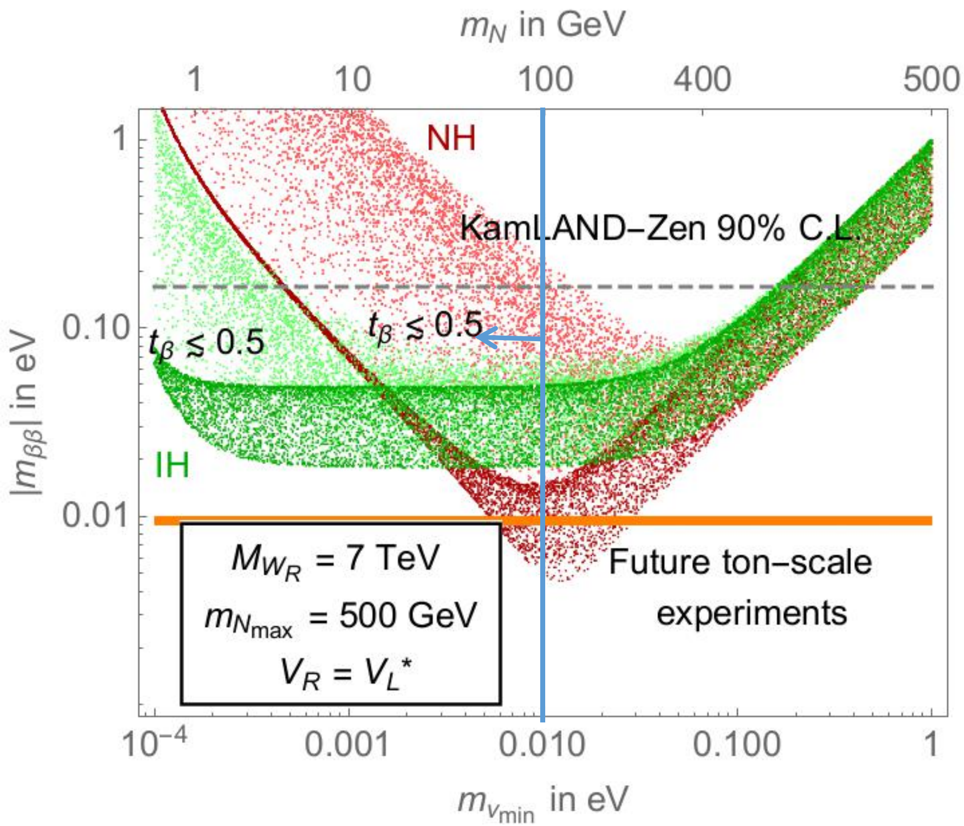
see for example, Tello et al, Phys.Rev.Lett. 106 (2011) 151801; S.-F. Ge, M. Lindner, S. Patra, 1508.07286 (JHEP); Bhupal Dev, Goswami, Mitra Phys.Rev.D 91 (2015) 113004 and many more

light red, light green:
$\tan\beta \lesssim 0.5$

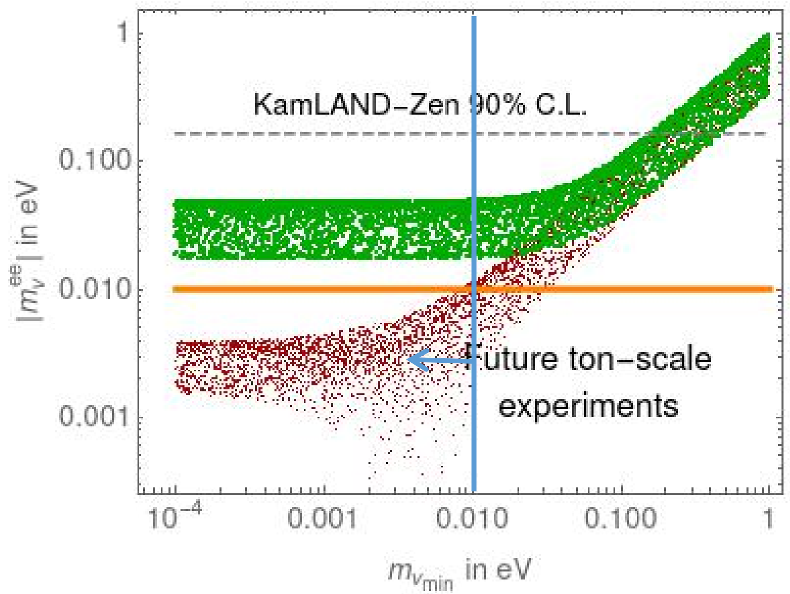
GL, Ramsey-Musolf and Vasquez, 2009.01257 (PRL)

A large portion of parameter space could give a positive signal after including leading contribution from LO $\pi\pi ee$ interaction from W_L-W_R mixing

$0\nu\beta\beta$-decay in minimal LRSM



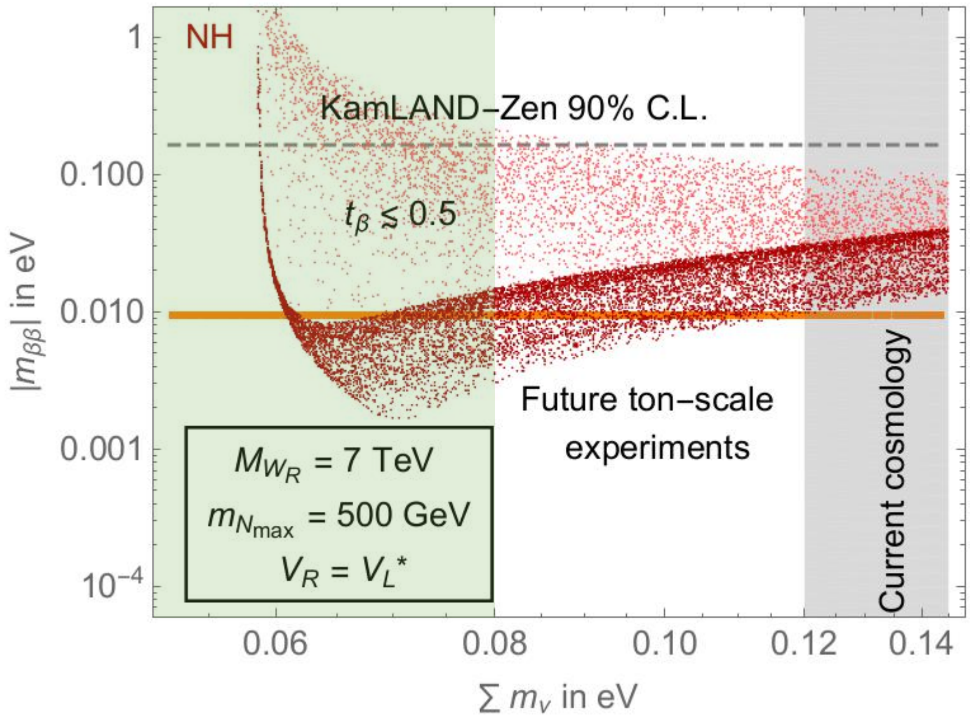
SM+3ν:

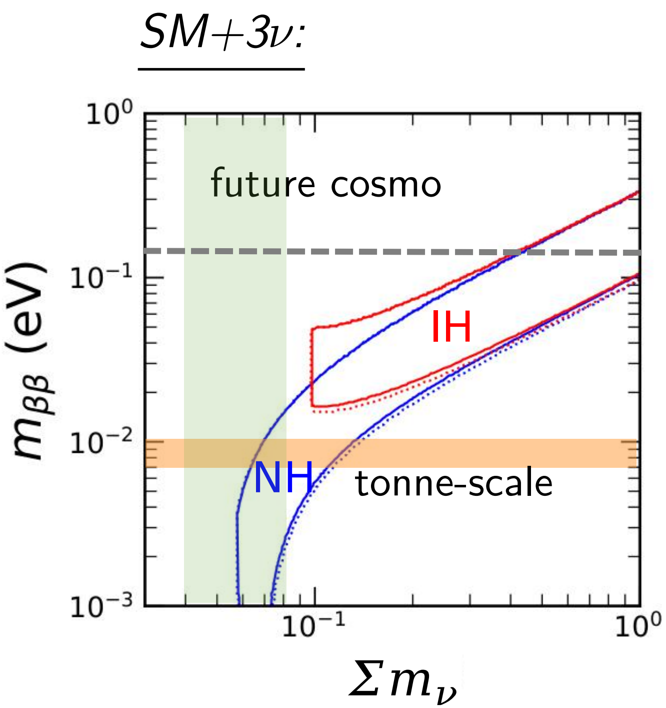


A large portion of parameter space could give a positive signal after including leading contribution from LO $\pi\pi ee$ interaction from W_L-W_R mixing

$0\nu\beta\beta$-decay in minimal LRSM

Including cosmological constraints:



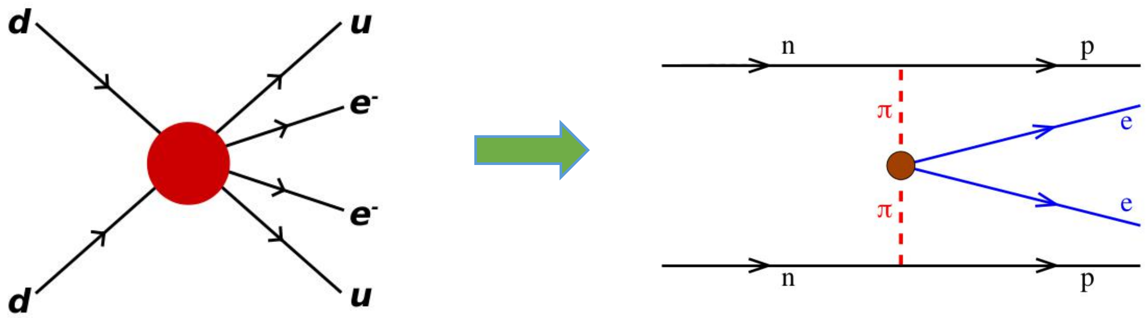


Good prospects for a positive signal even confronted with future cosmological surveys

GL, Ramsey-Musolf and Vasquez, 2009.01257 (PRL)

Intermediate summary

- We show the importance of long-range contribution from heavy BSM mechanism in neutrino mass models with minimal left-right symmetric model as an example

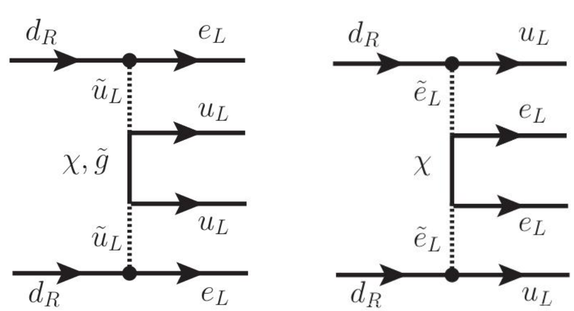


$$\mathcal{A}^{\mathrm{LO}} \sim p^{-2}$$

- More generally, it is necessary to use chiral EFT to deal with $0\nu\beta\beta$-decay in non-standard mechanisms

$$\mathcal{O}_{2\pm}^{++} = (\bar{q}_{\mathrm{R}}^{\alpha}\tau^{+}q_{\mathrm{L}}^{\alpha})(\bar{q}_{\mathrm{R}}^{\beta}\tau^{+}q_{\mathrm{L}}^{\beta}) \pm (\bar{q}_{\mathrm{L}}^{\alpha}\tau^{+}q_{\mathrm{R}}^{\alpha})(\bar{q}_{\mathrm{L}}^{\beta}\tau^{+}q_{\mathrm{R}}^{\beta})$$

$$\mathcal{A}^{\mathrm{LO}} \sim p^{-2}$$



RPV SUSY

Faessler, et al, Phys.Rev.Lett. 78 (1997) 183; Phys.Rev.D 58 (1998) 115004; Peng, Ramsey-Musolf, Winslow, 1508.04444 (PRD); Dekens, et al, 2002.07182 (JHEP)

General procedure

Approach to $0\nu\beta\beta$-decay in non-standard mechanisms:

- start with a given BSM model
- integrate out heavy fields and obtain LNV operators (matching)
- map quark operators onto hadronic operators using chiral EFT

LECs are obtained using lattice QCD
or naive dimensional analysis

- calculate inverse half-life and compare with experimental limits

$$(T_{1/2}^{0\nu})^{-1} \sim G_{0\nu} |\langle 0^+ | \sum_{m,n} \int \frac{d^3\mathbf{p}}{(2\pi)^3} e^{i\mathbf{p}\cdot\mathbf{r}} \mathcal{A}(\mathbf{p}^2) | 0^+ \rangle|^2$$

Fourier transformation
sum over all nucleons

$$\text{Wilson Coeff}^2 \times \text{LEC}^2 \times \text{NME}^2$$

NMEs are obained using many-body methods: QRPA, IBM, shell, etc

Prezeau, Ramsey-Musolf, Vogel, Phys.Rev.D 68 (2003) 034016
V. Cirigliano, W. Dekens, J. de Vries, M. L. Graesser, E. Mereghetti 1806.02780 (JHEP); 1708.09390 (JHEP)

General procedure

Approach to $0\nu\beta\beta$-decay in non-standard mechanisms:

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it may involve several steps

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$$(T_{1/2}^{0\nu})^{-1} \sim G_{0\nu} |\langle 0^+ | \sum_{m,n} \int \frac{d^3\mathbf{p}}{(2\pi)^3} e^{i\mathbf{p}\cdot\mathbf{r}} \mathcal{A}(\mathbf{p}^2) | 0^+ \rangle|^2$$

Fourier transformation
sum over all nucleons

$$\text{Wilson Coeff}^2 \times \text{LEC}^2 \times \text{NME}^2$$

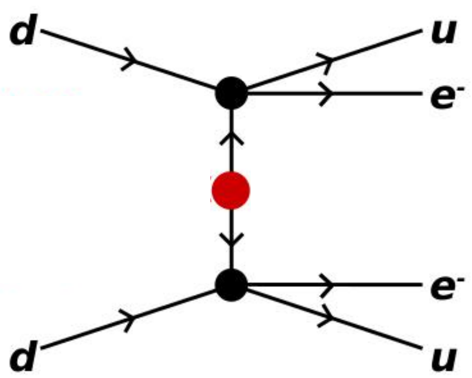
it depends on the LNV interactions

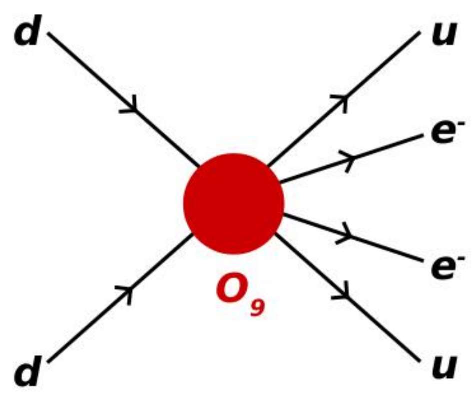
NMEs are obained using many-body methods: QRPA, IBM, shell, etc

Prezeau, Ramsey-Musolf, Vogel, Phys.Rev.D 68 (2003) 034016
V. Cirigliano, W. Dekens, J. de Vries, M. L. Graesser, E. Mereghetti 1806.02780 (JHEP); 1708.09390 (JHEP)

$0\nu\beta\beta$-decay: intermediate mass region

Two regions: $p^2 \gg m^2$ and $p^2 \ll m^2$ with the mean momentum transfer $p \sim 200$ MeV





$p^2 \gg m^2$

e.g.: standard mechanism

V. Cirigliano, et al
1806.02780 (JHEP)

9 basic NMEs M_l

8/9 are known

$p^2 \ll m^2$

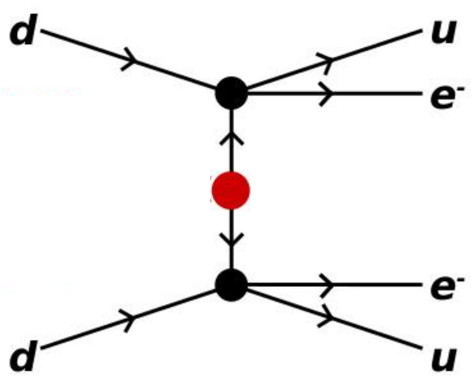
heavy BSM mechanism

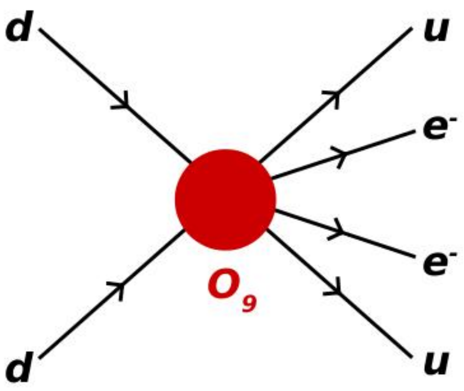
6 basic NMEs M_h

6/6 are known

$0\nu\beta\beta$-decay: intermediate mass region

Two regions: $p^2 \gg m^2$ and $p^2 \ll m^2$ with the mean momentum transfer $p \sim 200$ MeV





$p^2 \gg m^2$ | $p^2 \ll m^2$

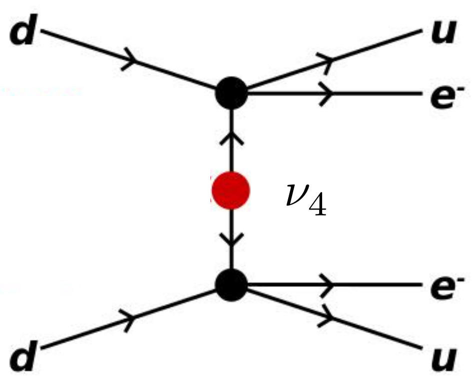
e.g.: standard mechanism | heavy BSM mechanism

V. Cirigliano, et al 1806.02780 (JHEP) 9 basic NMEs M_l | 6 basic NMEs M_h

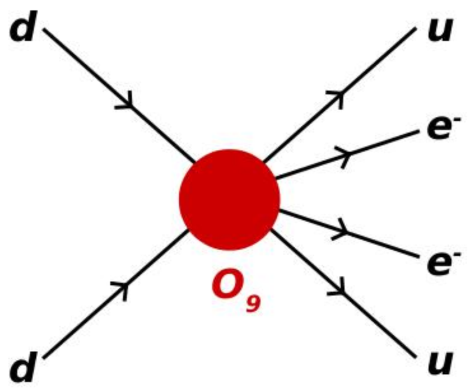
How about the intermediate mass region $m^2 \sim p^2$?

$0\nu\beta\beta$-decay: intermediate mass region

For illustration, consider sterile neutrino ν_4

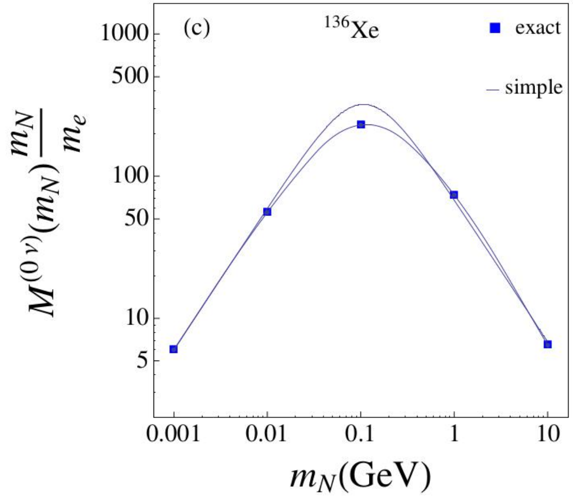


m_{ν_4} ⟷



- ν_4 is not integrated out
- include the mass dependence in LECs and NMEs

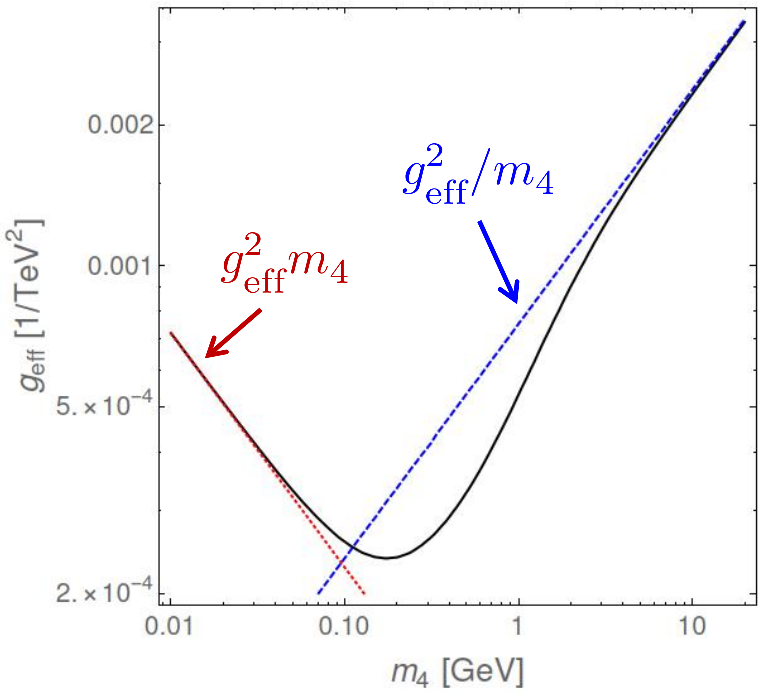
interpolation of NMEs



Faessler, et al, 1408.6077 (PRD); J. Barea, et al, 1509.01925 (PRD); Dekens,et al, 2002.07182 (JHEP)

$0\nu\beta\beta$-decay: intermediate mass region

Smooth transition with the increase of m_4



$$P_{L,R}\frac{\not{q}+m_i}{q^2-m_i^2}P_{L,R}=\frac{m_i}{q^2-m_i^2}\,P_{L,R}$$

Also in well-motivated UV complete models

Jordy de Vries, GL, Michael Ramsey-Musolf, Shufang Su, Juan Carlos Vasquez, in preparation

Summary

- $0\nu\beta\beta$-decay can provide direct evidence for Majorana neutrino mass and lepton number violation, hence physics beyond the SM

- We show that in the EFT approach, the long-range contribution from non-standard mechanism can dominate over other contributions

- If new particle contributing to $0\nu\beta\beta$-decay is in the intermediate mass region, mass dependence captured by the LECs and NMEs should be dealt with consistently in EFT approach

- An interplay of $0\nu\beta\beta$-decay with other probes (yet not be covered)

Summary

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Thanks for your attention!

Neutrino masses

Yukawa interactions

$$\mathcal{L}_Y = \bar{L}_L(Y_\Phi \Phi + \tilde{Y}_\Phi \tilde{\Phi})L_R + \frac{1}{2}(L_L^T C i\sigma_2 Y_{\Delta_L} \Delta_L L_L + L_R^T C i\sigma_2 Y_{\Delta_R} \Delta_R L_R) + \text{H.c.},$$

provide a natural origin of neutrino masses:

$$M_D \equiv v_1 Y_\Phi + \tilde{Y}_\Phi v_2 e^{-i\alpha}$$

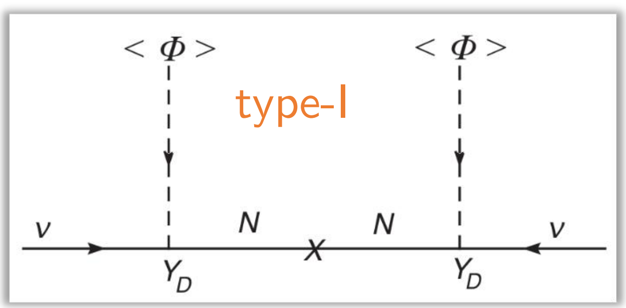
$$M_L \equiv Y_{\Delta_L} v_L e^{i\theta_L} \qquad M_R \equiv Y^*_{\Delta_R} v_R$$

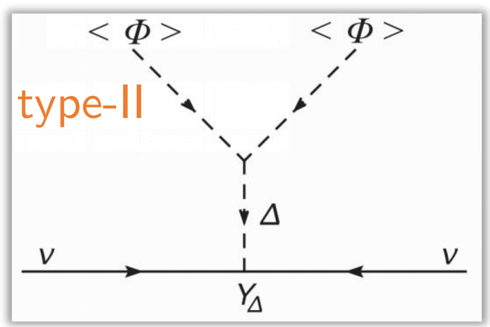
$$M_\nu \simeq M_L - M_D^* \frac{1}{M_N} M_D^\dagger$$

$$M_N \simeq M_R$$

type-I seesaw

type-II seesaw





Left-right mixing

ξ and λ are related:

$$\tan\xi = \frac{v_1 v_2}{v_R^2} = \lambda \sin(2\beta) \qquad \lambda \equiv \frac{M_W^2}{M_{W_R}^2} \quad \tan\beta = \frac{v_2}{v_1}$$

- ξ alone is constrained with the CKM unitarity, using mostly precise $|V_{ud}|$, $\xi \leq 1.25 \times 10^{-3}$

  C.-Y. Seng, et al, Phys. Rev. Lett. 121, 241804 (2018)

- The most severe flavor constraints comes from kaon and B meson mass mixing, excluding $M_{W_R} < 2.9$ TeV

  Bertolini, Maiezza, Nesti Phys.Rev.D 89 (2014) 095028

- Direct searches for W_R exclude $M_{W_R} < 4.8$ TeV, which imples $\lambda \leq 2.8 \times 10^{-4}$ (set stronger bound on ξ)

  CMS JHEP 05 (2018) 148

the upper bound on ξ depends on the value of β

Left-right mixing

- There is no experimental bound on β in the minimal LRSM

Senjanovic and Tello Phys. Rev. Lett. 114, 071801 (2015); Phys. Rev. D 94, 095023 (2016)

- The theoretical bound is obtained requring perturbativity of Yukawa coupling of heavy Higgs boson

$$\frac{m_t}{v\cos(2\beta)} \lesssim 1 \quad \Rightarrow \quad \tan\beta \lesssim 0.5$$