Neutrinoless double decay and left-right symmetry

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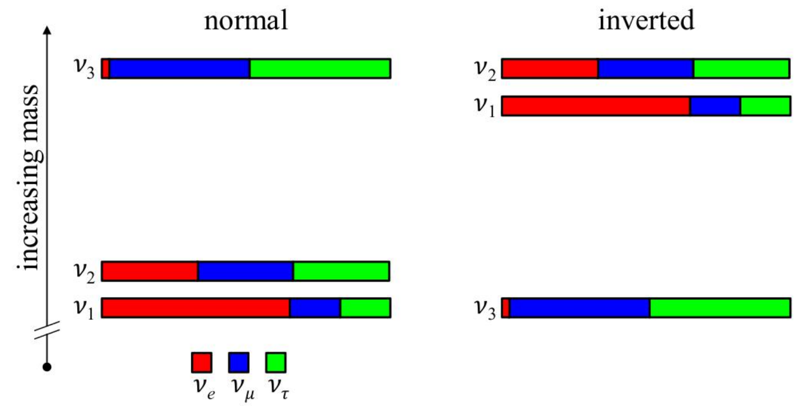
arXiv: 2009.01257 (PRL)
GL, Michael Ramsey-Musolf and Juan Carlos Vasquez

BSM-2021, Mar. 30, 2021

Neutrinos: Dirac or Majorana?

Neutrino oscillation experiments imply that neutrinos are massive

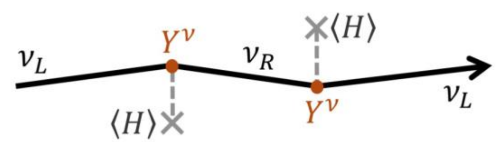


$$\Delta m^2_{21} \approx 7.5 \times 10^{-5}\ \mathrm{eV}^2$$

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

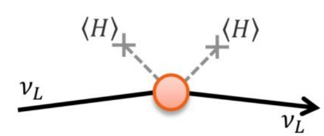
Dirac mass term

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



Majorana mass term

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



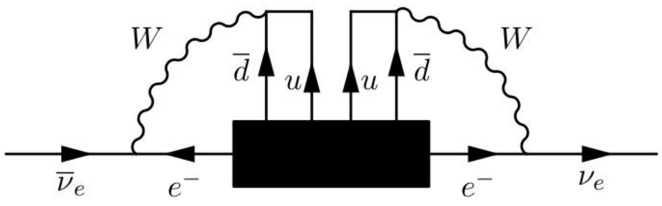
credit: J. Harz

breaks the lepton number by two units

0vbb-decay: experiment

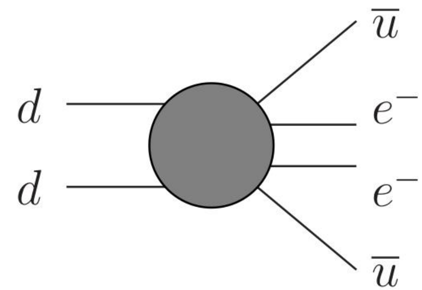
An observation of 0vbb-decay implies the Majorana nature of neutrinos

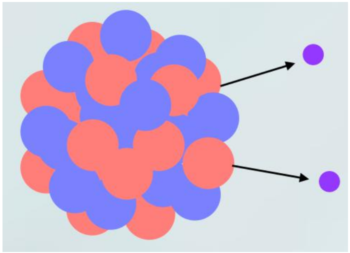
Majorana neutrino mass:



Schechter, Valle
Phys.Rev. D25 (1982) 774;
Duerr, Lindner, Merle, 1105.0901 (JHEP)

0vbb-decay:





credit: Z. Davoudi

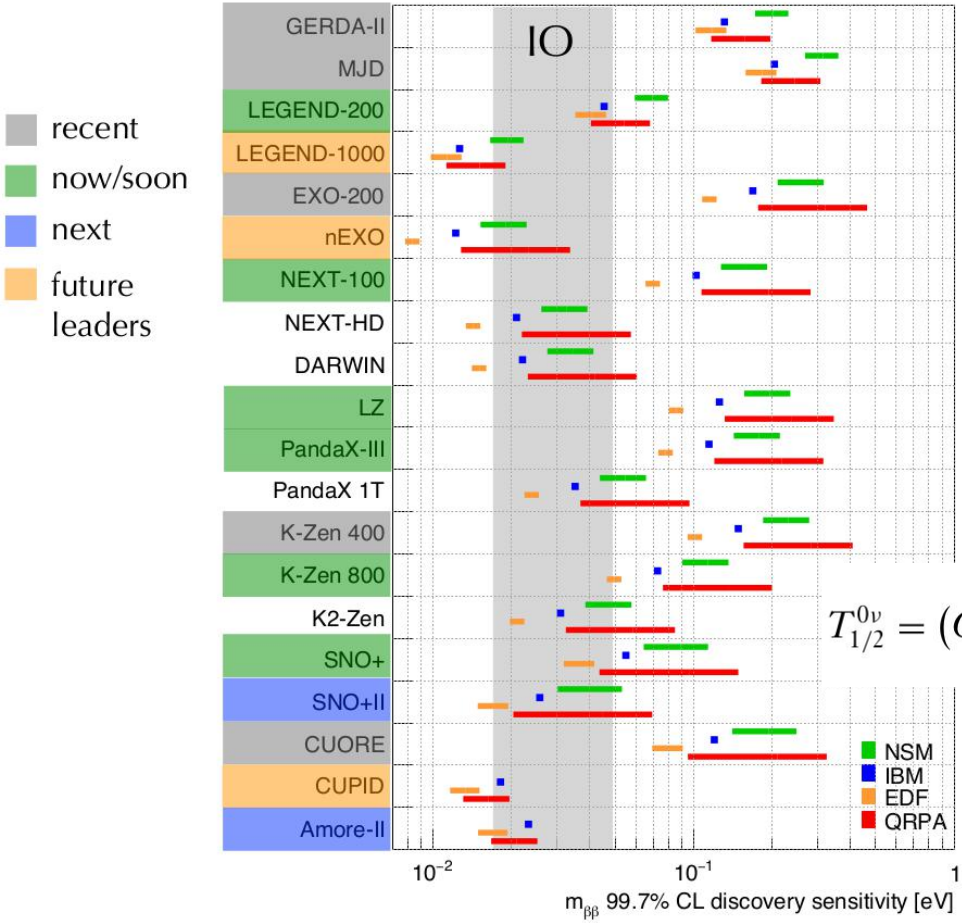
$$(A,Z) \to (A,Z+2) + e^- + e^-$$

$T^{0\nu}_{1/2} > 1.07 \times 10^{26}$ yr KamLAND-Zen (^{136}Xe)

PRL 117 (2016) 082503

$T^{0\nu}_{1/2} \gtrsim 10^{28}$ yr ton-scale experiments

0vbb-decay: experiment



$$T^{0\nu}_{1/2} = \left(G\,|\mathcal{M}|^2\,\langle m_{\beta\beta}\rangle^2\right)^{-1} \simeq 10^{27-28}\left(\frac{0.01\text{ eV}}{\langle m_{\beta\beta}\rangle}\right)^2 \text{ years.}$$

taken from A. Pocar BLV circa 2020

0vbb-decay: interpretation

Half life

nuclear matrix element (NME)

$$T_{1/2}^{0\nu} = \left(G\,|\mathcal{M}|^2\,\langle m_{\beta\beta}\rangle^2\right)^{-1} \simeq 10^{27-28}\left(\frac{0.01\,\mathrm{eV}}{\langle m_{\beta\beta}\rangle}\right)^2 \text{years.}$$

phase space factor

effective Majorana mass

0vbb-decay: interpretation

Half life

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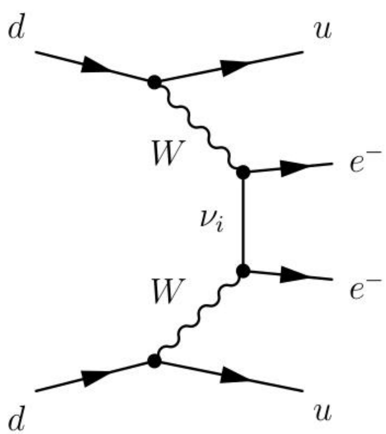
phase space factor

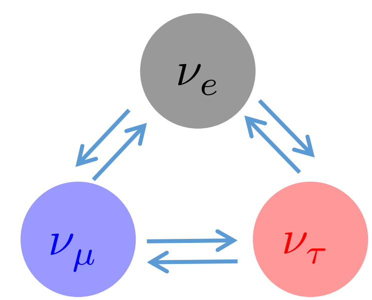
effective Majorana mass

Standard mechanism

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



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



0vbb-decay: interpretation

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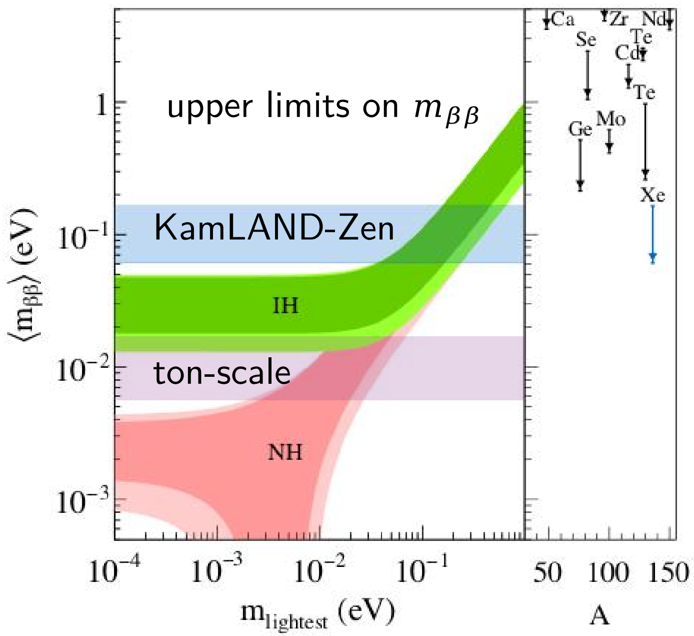
effective Majorana mass



blue and purple bands: uncertainties in NMEs

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

NH is favored over IH at at 2.7σ by neutrino oscillation expts.

F. Capozzi et al, Phys.Rev.D 95 (2017) 096014, Phys.Rev.D 101 (2020) 116013
P.F. de Salas et al, 2006.11237 (JHEP)

0vbb-decay: interpretation

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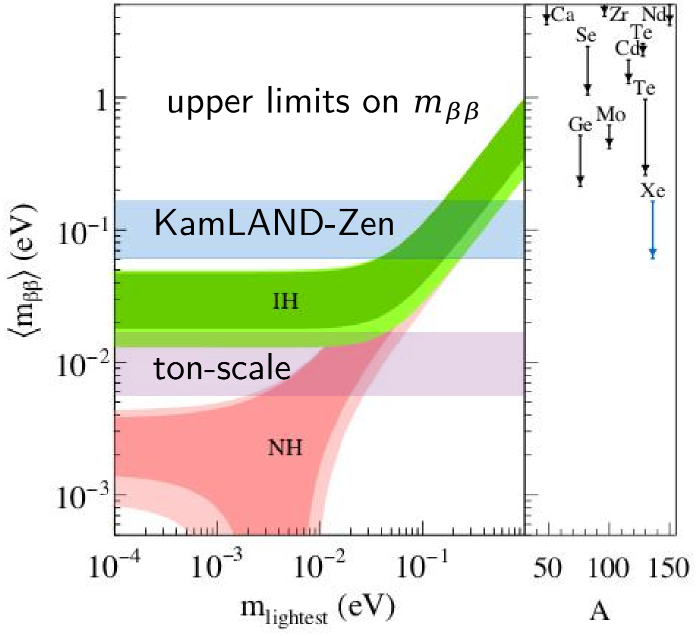
phase space factor

effective Majorana mass



We may live in the "nightmare" region

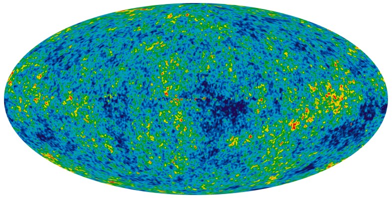
$$10^{-3}\ \mathrm{eV} \lesssim m_{\mathrm{lightest}} \lesssim 10^{-2}\ \mathrm{eV}$$

cosmological surveys

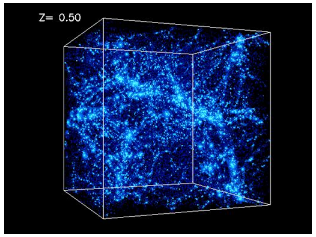
0vbb-decay meets cosmology

Cosmological experiments:

- Cosmic Microwave Background (CMB)



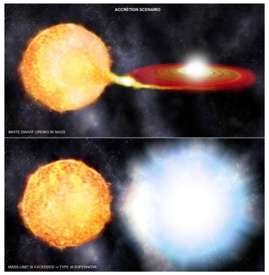
  Planck, CMB-S4, CORE-M5, LiteBIRD



- Large Scale Structure (LSS) surveys

  BOSS, DESI, Euclid

- Type Ia supernova



Massive neutrinos affect the <u>expansion rate of the Universe (CMB)</u> and <u>clustering of matter (LSS)</u>

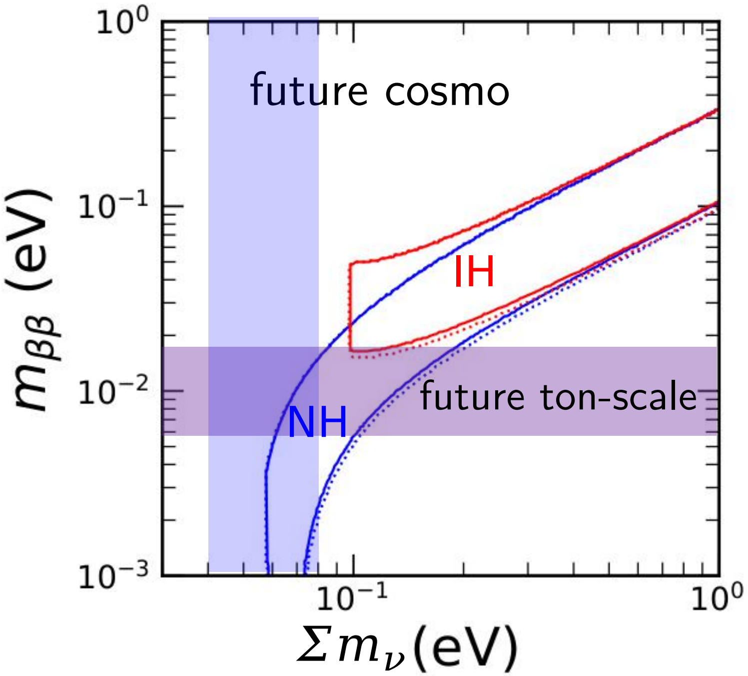
0vbb-decay meets cosmology

Cosmology bounds the sum of neutrino masses directly

$$\sum m_\nu = m_1 + m_2 + m_3$$

$$\sigma(\Sigma \mathrm{m}_\nu \lesssim 0.02 \text{ eV})$$

Lesgourgues et al, 1808.05955



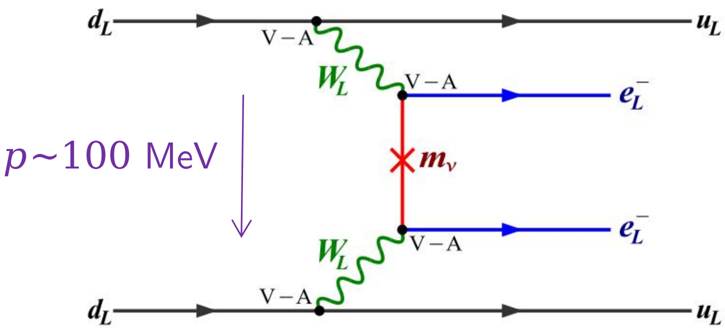
Future ton-scale 0vbb-decay experiments may be in vain!

arXiv: 2009.01257 (PRL) G. Li, M. Ramsey-Musolf and J. C. Vasquez

➡ SM+3 light massive neutrinos are NOT the end of the world

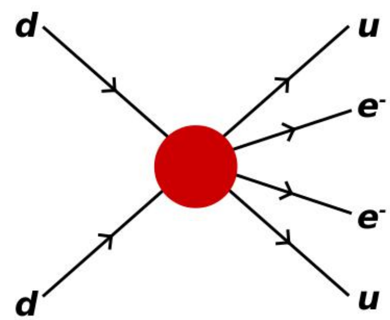
New mechanisms of 0vbb-decay

Standard mechanism:



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

New mechanisms:



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

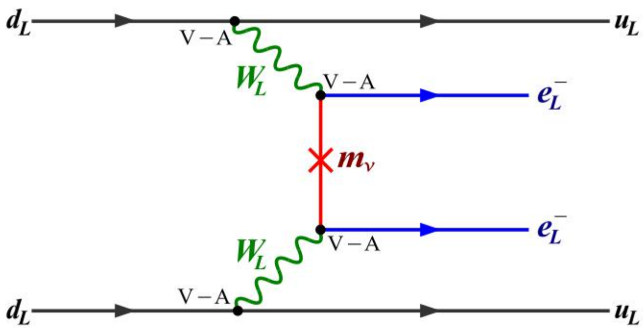
$$\frac{c/\Lambda^5}{G_F^2 m_\nu^{ee}/p^2} = c\left(\frac{3.7\ \mathrm{TeV}}{\Lambda}\right)^5 \frac{0.1\ \mathrm{eV}}{m_\nu^{ee}}$$

TeV scale new physics contribution could be comparable if $c \sim O(1)$

taken from Deppisch et, al

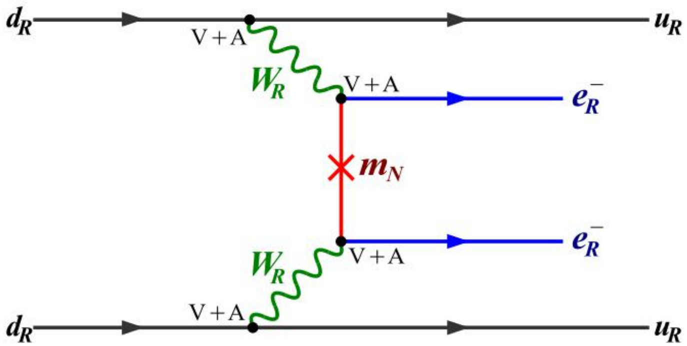
New mechanisms of 0vbb-decay

Standard mechanism:



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

Right-handed counterpart:



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

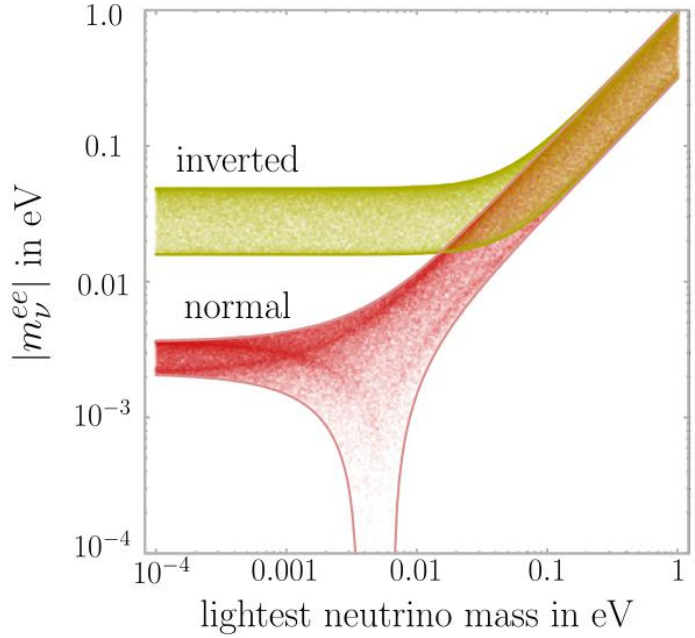
$$g_R = g_L = g \quad M_{W_R},\, m_N \sim \mathrm{O(TeV)}$$

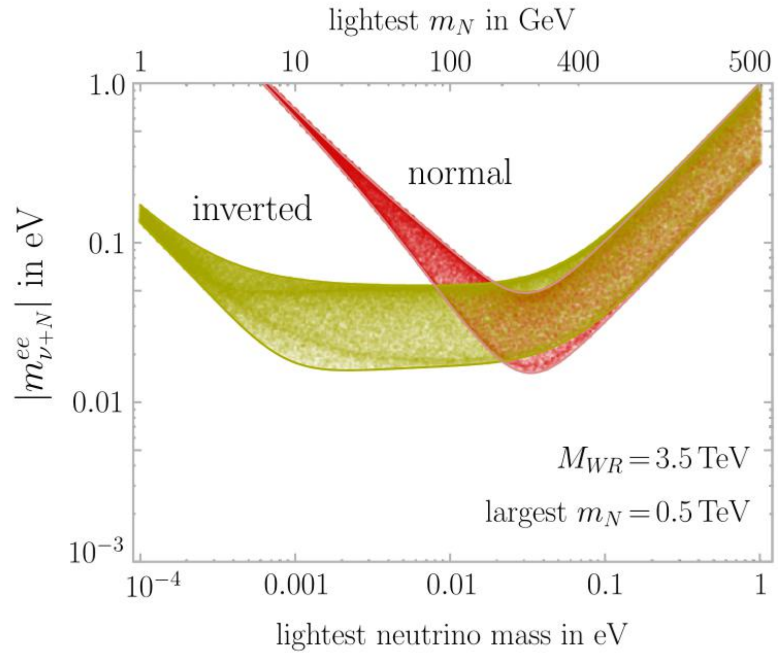
M. Doi, et al, Prog.Theor.Phys. 66 (1981) 1739; Prog.Theor.Phys. 69 (1983) 602; Prog.Theor.Phys.Suppl. 83 (1985) 1

Mohapatra and Senjanovic, Phys.Rev.Lett. 44 (1980) 912, Phys.Rev.D 23 (1981) 165
Riazuddin, Marshak, Mohapatra Phys. Rev. D 24, 1310 (1981)

the most natrual way to incorporate RH current is the minimal left-right symmetric model

$W_R - W_R$ contribution

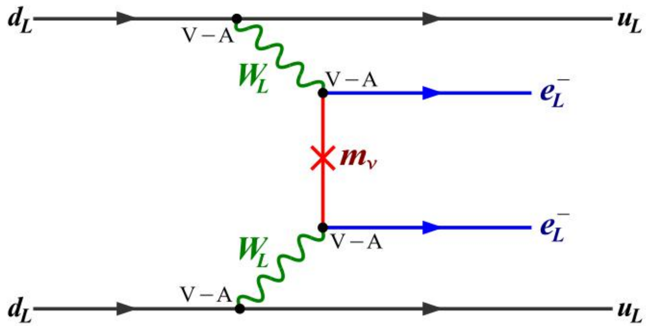


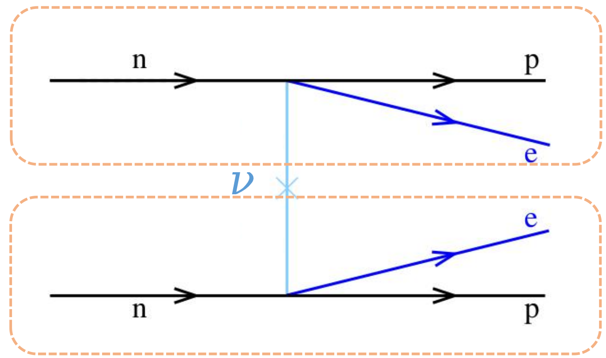


Tello et al, Phys.Rev.Lett. 106 (2011) 151801
Bhupal Dev, Goswami, Mitra Phys.Rev.D 91 (2015) 113004

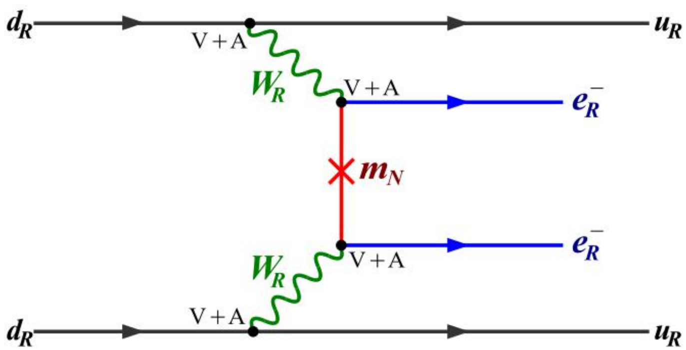
“old” calculation of 0vbb-decay

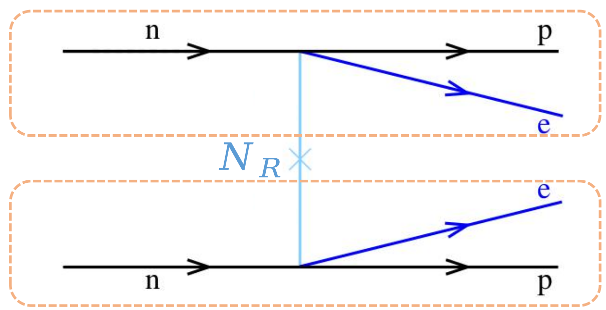
Map quark bilinear to nucleon current





p^{-2}

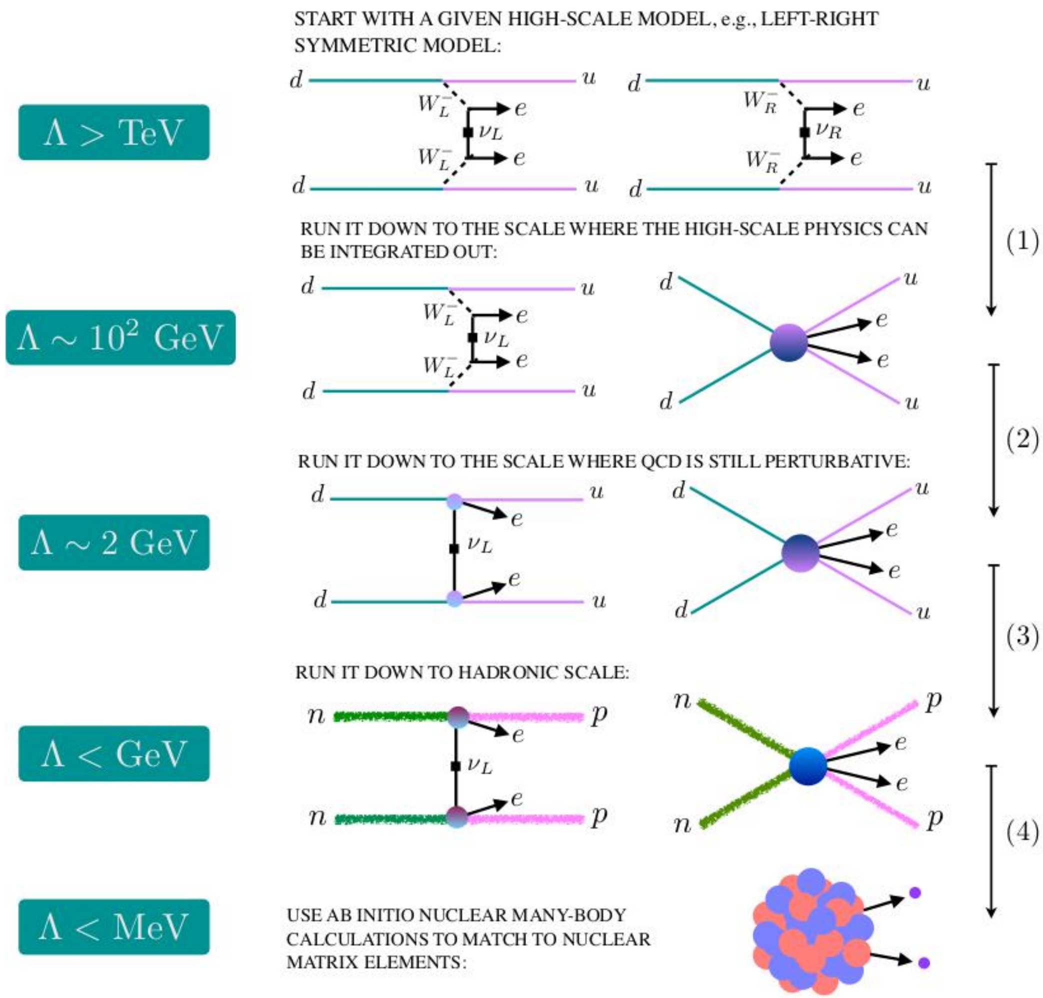




p^0

inconsistent since $m_{N_R} \gg m_p, m_n$

0vbb-decay: multi-scale $\mathrm{TeV} \rightarrow \mathrm{MeV}$



SMEFT

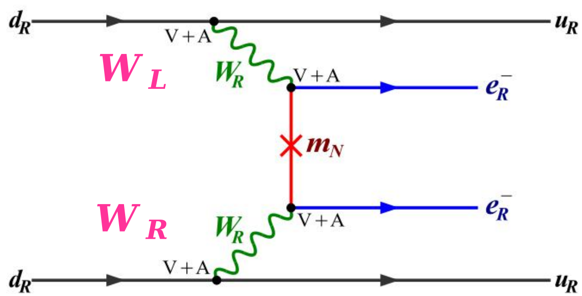
LEFT

chiral perturbation theory

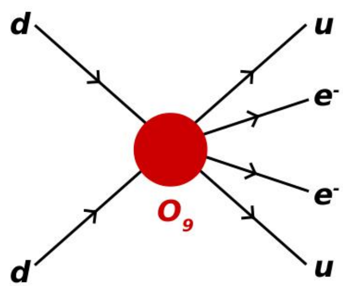
many-body methods

New leading contribution: $W_L - W_R$

New calcualtion using EFT



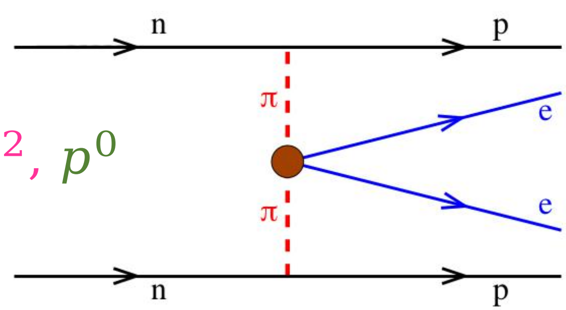
Mohapatra and Senjanovic, Phys.Rev.Lett. 44 (1980) 912, Phys.Rev.D 23 (1981) 165



Prezeau, Ramsey-Musolf, Vogel, Phys.Rev.D 68 (2003) 034016
Cirigliano, Dekens, de Vries, Graesser, Mereghetti, JHEP 12 (2018) 097

long-range $\pi\pi ee$ interaction

p^{-2}, p^0



GL, M. Ramsey-Musolf and J. C. Vasquez, arXiv: 2009.01257 (PRL)

$(\Lambda_\chi / p)^2 \sim 20$

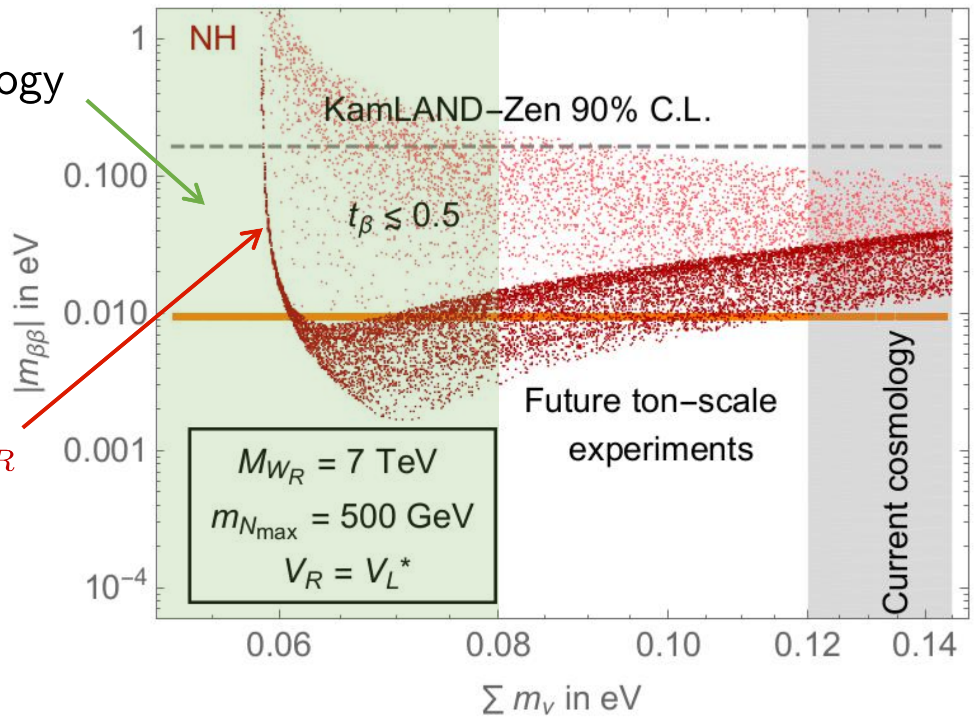
A. Nicholson et al, 1805.02634 (PRL)

Left-right mixing may be the key

Shaking off nightmare region with left-right mixing even confronting with future cosmological surveys and neutrino oscillation experiments

cosmology

$W_R - W_R$



$$\tan\xi = \frac{v_1 v_2}{v_R^2} = \lambda \sin(2\beta)$$

$$\lambda \equiv \frac{M_W^2}{M_{W_R}^2}$$

$$\tan\beta = \frac{v_2}{v_1}$$

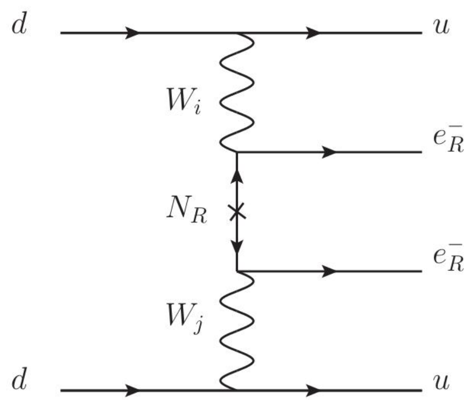
Constraints from collider, flavor, CKM unitarity, perturbativity are considered

GL, M. Ramsey-Musolf and J. C. Vasquez, arXiv: 2009.01257 (PRL)

Thank you!

Minimal LRSM

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



left-right mixing:

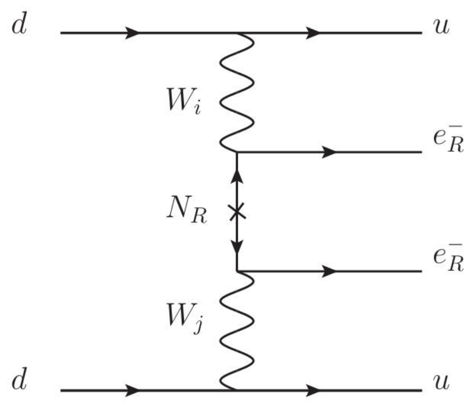
$$W_L = \cos\xi\, W^+_{1\mu} - \sin\xi\; e^{-i\alpha}\, W^+_{2\mu},$$
$$W_R = \sin\xi\, e^{i\alpha}\, W^+_{1\mu} + \cos\xi\, W^+_{2\mu}.$$

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

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

Minimal LRSM

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



left-right mixing:

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

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

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

$$\mathcal{O}^{++}_{1+} = (\bar{q}^\alpha_L\tau^+\gamma^\mu q^\alpha_L)(\bar{q}^\beta_R\tau^+\gamma_\mu q^\beta_R) \qquad C_1 = -4\lambda\xi$$

Constraints on minimal LRSM

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

Constraints on minimal LRSM

- Remarkably, there is no experimental bound on β in the mLRSM

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

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

the only constraint on β

Finally,

$$\lambda \leq 2.8 \times 10^{-4} \qquad \xi \lesssim 0.8\lambda \lesssim 2.2 \times 10^{-4}$$

the left-right mixing ξ is not negligibly small

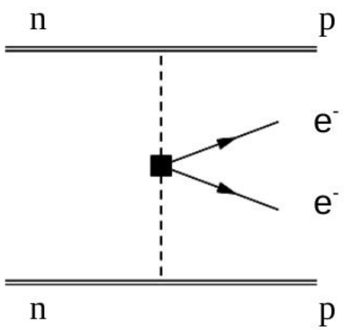
EFT approach to 0vbb-decay

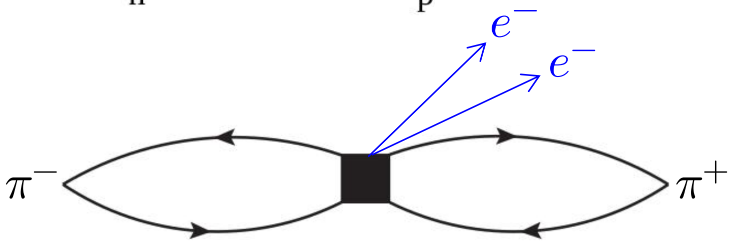
LECs: non-perturbative QCD effects

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

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

$$\mathcal{O}_{3\pm}^{++} = (\bar{q}_L^\alpha \tau^+ \gamma^\mu q_L^\alpha)(\bar{q}_L^\beta \tau^+ \gamma_\mu q_L^\beta) \pm (\bar{q}_R^\alpha \tau^+ \gamma^\mu q_R^\alpha)(\bar{q}_R^\beta \tau^+ \gamma_\mu q_R^\beta)$$





LECs $\ell_1^{\pi\pi}, \ell_1^{\pi\pi'}, \ell_3^{\pi\pi}$ are obtained by computing the matrix elements of $\pi^- \to \pi^+$ induced by $O_{1+}^{++}, O_{1+}^{++'}, O_{3+}^{++}$

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

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

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

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