# Neutrinoless double beta decay and left-right symmetry

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arXiv: 2009.01257 (PRL) in collaboration with
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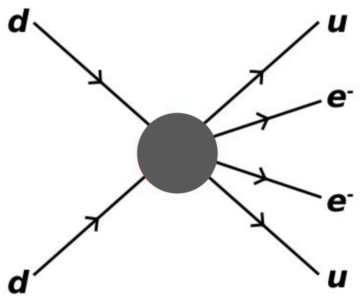
# $0\nu\beta\beta$-decay in a nutshell

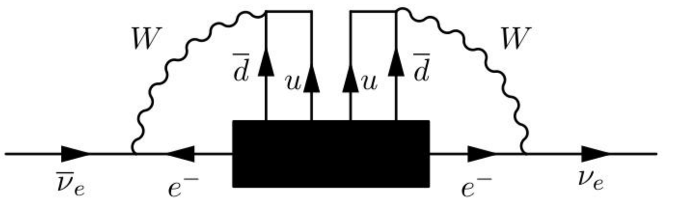
- In order to probe Majorana nature of massive neutrinos, we need to study $0\nu\beta\beta$-decay

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

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




Majorana neutrino mass:




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

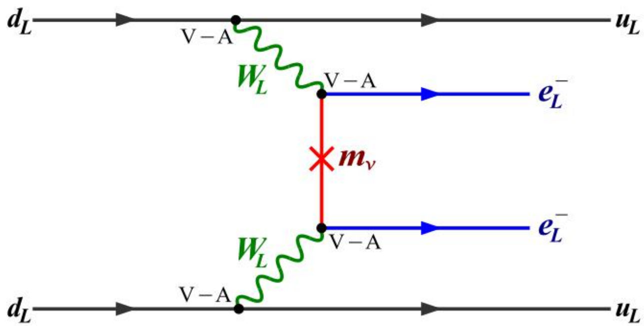
An observation of $0\nu\beta\beta$-decay implies

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 the standard mechanism




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

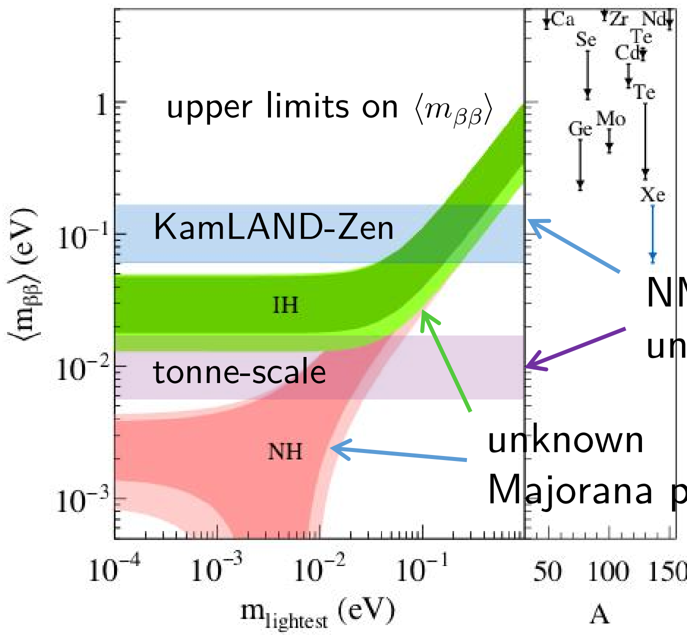
nuclear matrix element (NME)

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

absolute neutrino masses

PMNS matrix

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




**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

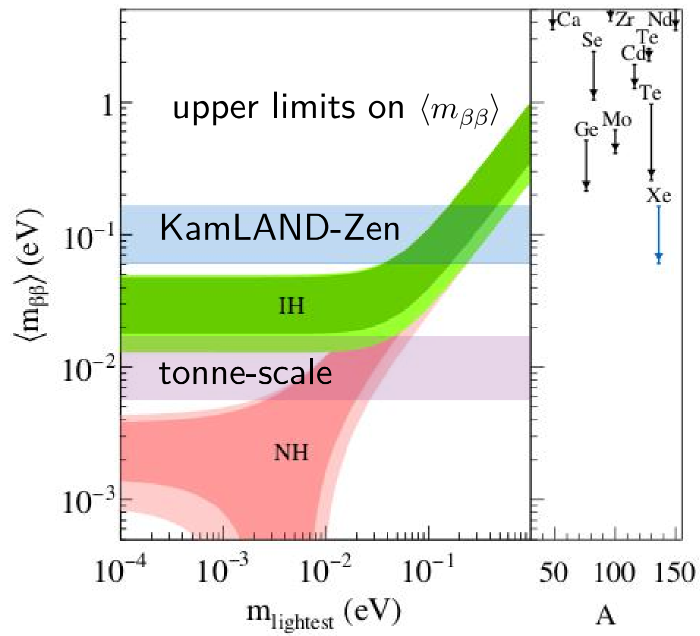
accidental cancellation in NH

# $0\nu\beta\beta$-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 $2.7\sigma$ with current neutrino
oscillation data

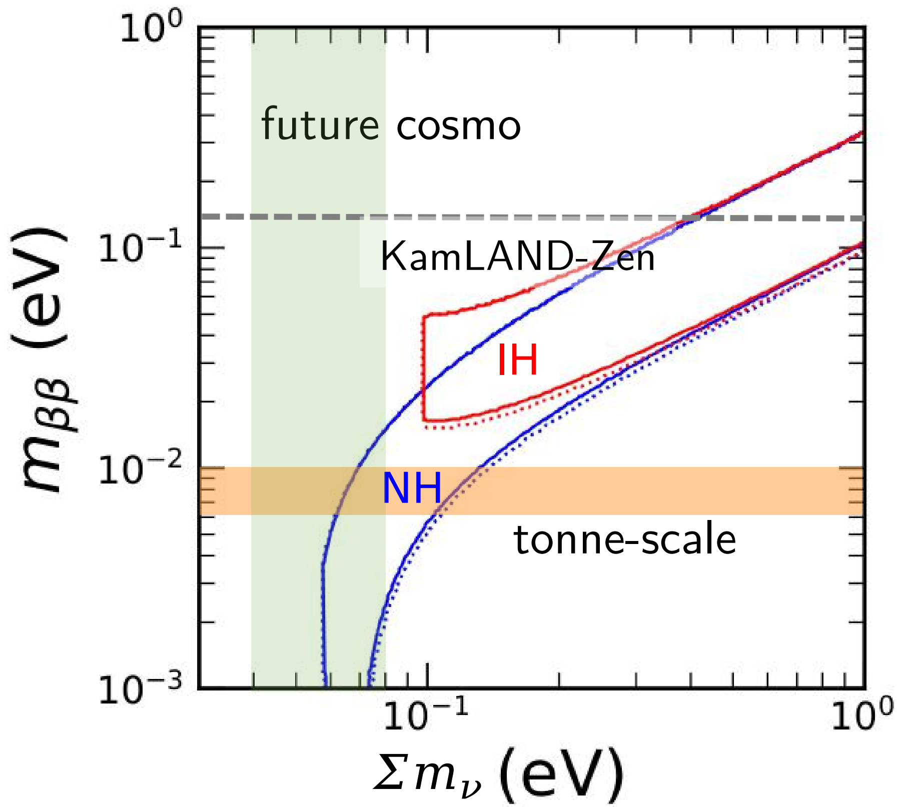
**P.F. de Salas et al, 2006.11237 (JHEP)**




An observation of $0\nu\beta\beta$-decay is challenging in tonne-scale experiments, since neutrinos are more likely to be in the NH

# $0\nu\beta\beta$-decay confronted with cosmology

It is even more worrying ...




**F. Capozzi et al, 2003.08511 (PRD)**

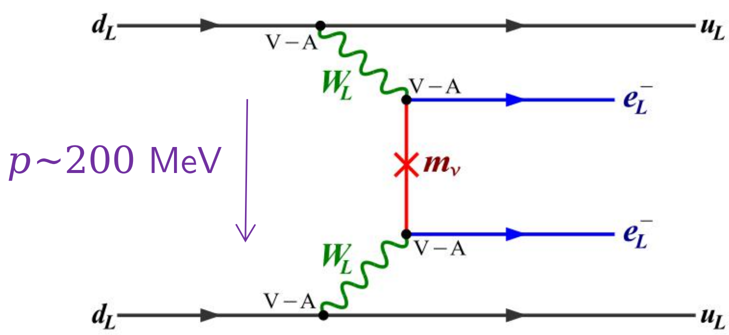
$$\sum m_\nu = m_1 + m_2 + m_3$$

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

Little hope of observing $0\nu\beta\beta$-decay signals in tonne-scale experiments given the standard mechanism

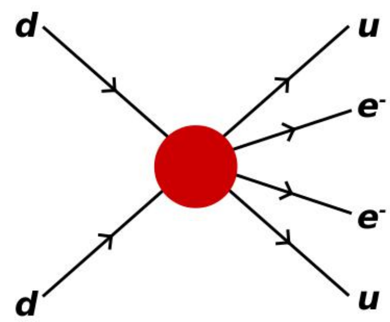
# We need new mechanisms of $0\nu\beta\beta$-decay

Standard mechanism:




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

Heavy BSM mechanisms:




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

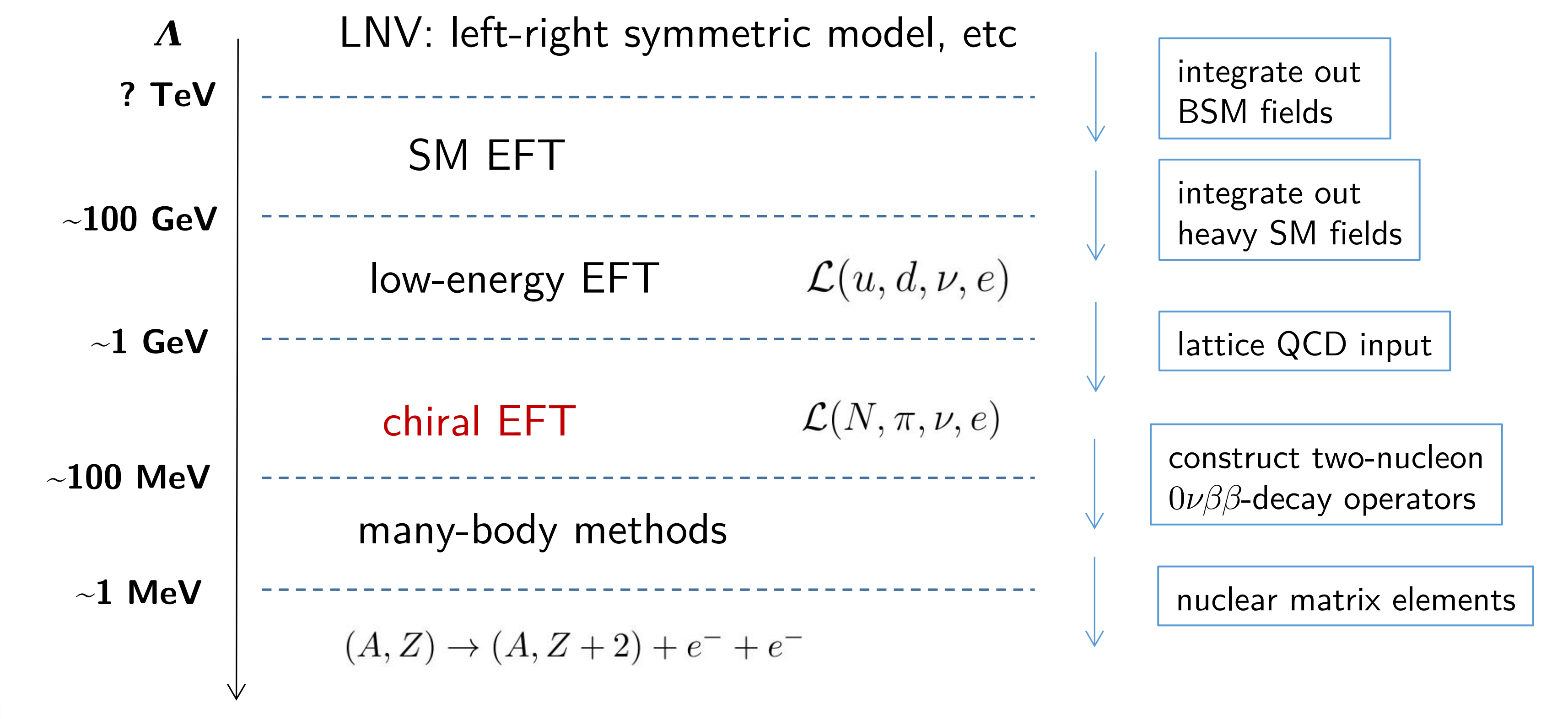
$$\frac{c/\Lambda^5}{G_F^2 m_\nu^{ee}/p^2} = c\left(\frac{3.3 \text{ TeV}}{\Lambda}\right)^5 \frac{0.1 \text{ eV}}{m_\nu^{ee}}$$

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

Many possible scenarios: left-right symmetric model, RPV SUSY, ...

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

- systematical way: all LNV sources
- multi-scale involved: $\mathrm{TeV} \to \mathrm{MeV}$
- 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

$\alpha, \beta$ 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 $\mathrm{SU(2)_L} \times \mathrm{SU(2)_R}$

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

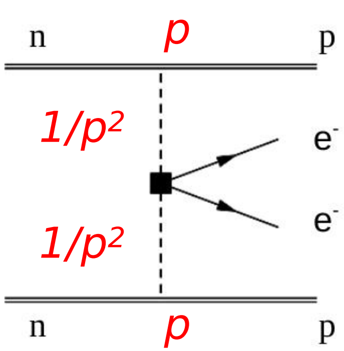
$$X_R^a = \xi\tau^a\xi^\dagger, \quad X_L^a = \xi^\dagger\tau^a\xi, \quad X^a = \xi\tau^a\xi$$

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

LO $\pi\pi ee$

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

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




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

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

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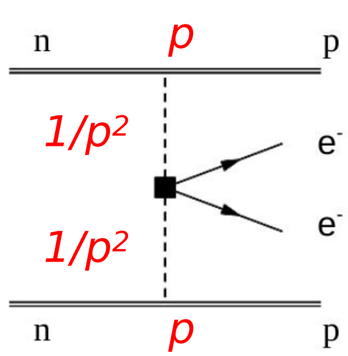
$$X_R^a = \xi\tau^a\xi^\dagger, \quad X_L^a = \xi^\dagger\tau^a\xi, \quad X^a = \xi\tau^a\xi$$

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

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

NNLO $\pi\pi ee$

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



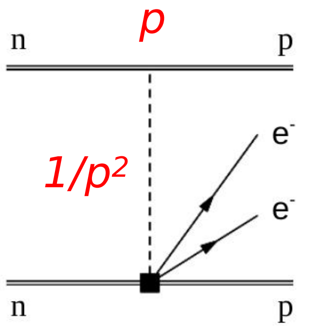

$$\mathcal{A}^{\mathrm{NNLO}} \sim p^0$$

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

$NN\pi ee$

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

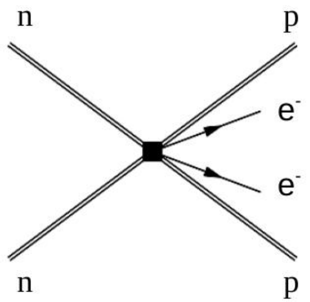
$$\mathcal{A}^{\rm NNLO} \sim p^0$$




$NNNNee$

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

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




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

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

# 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:

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

$N_R, W_R$

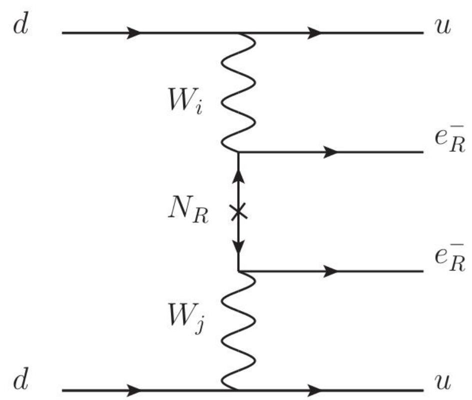
$$\Rightarrow \langle \Delta_R \rangle = \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix}, \qquad \langle \Delta_L \rangle = \begin{pmatrix} 0 & 0 \\ v_L e^{i\theta_L} & 0 \end{pmatrix}$$

provide a natural origin of neutrino masses

# Leading contribution from $W_L - W_R$ mixing

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

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




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

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

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

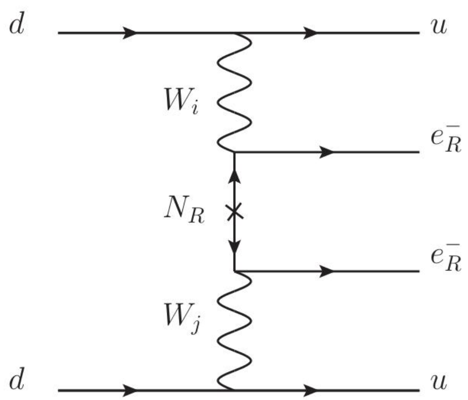
No $W_L - W_R$ mixing (i,j)=(R,R) $u_R d_R u_R d_R e_R e_R$

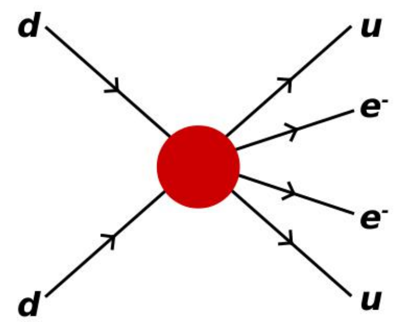
$W_L - W_R$ mixing (i,j)=(1,2) $u_L d_L u_R d_R e_R e_R$

# Leading contribution from $W_L - W_R$ mixing

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

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




| | | |
|---|---|---|
| No $W_L - W_R$ mixing | (i,j)=(R,R) | $u_R d_R u_R d_R e_R e_R \sim O_{3\pm}^{++}$ |
| | | $\mathcal{A}^{\text{NNLO}} \sim p^0$ |
| $W_L - W_R$ mixing | (i,j)=(1,2) | $u_L d_L u_R d_R e_R e_R \sim O_{1+}^{++}$ |
| | | $\mathcal{A}^{\text{LO}} \sim p^{-2}$ |

# Leading contribution from $W_L - W_R$ mixing

After integrating out $W_1$, $W_2$ and $N_R$

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

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

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

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

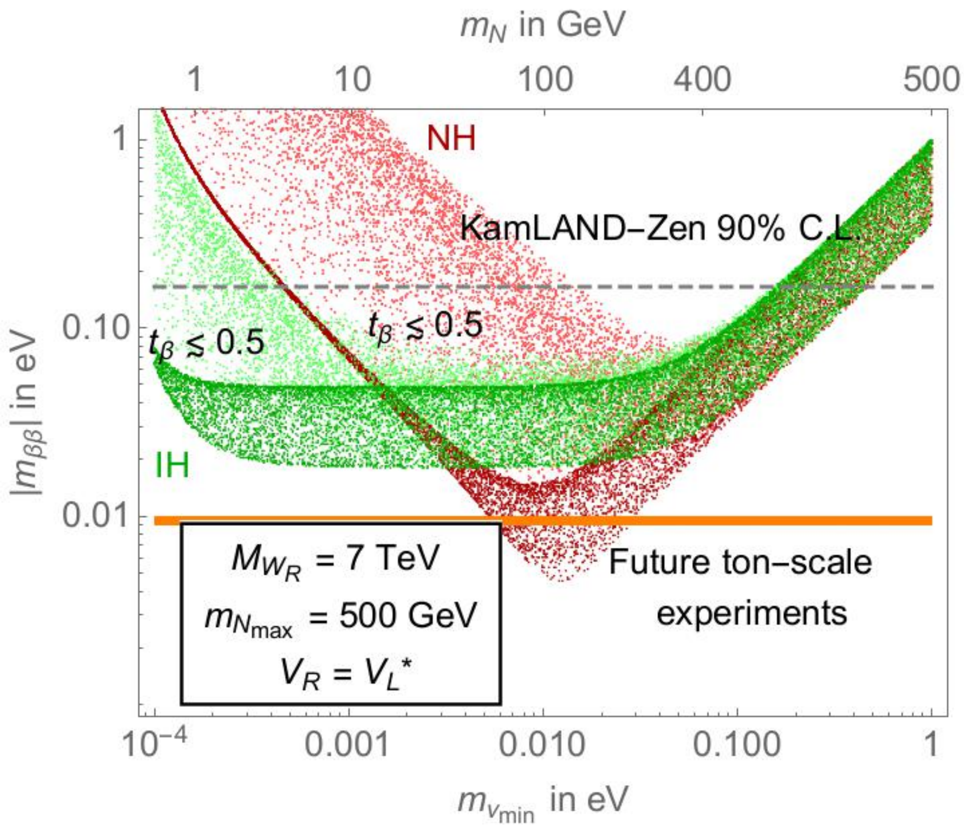
LHC direct searches, kaon and B meson mass mixing

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

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




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

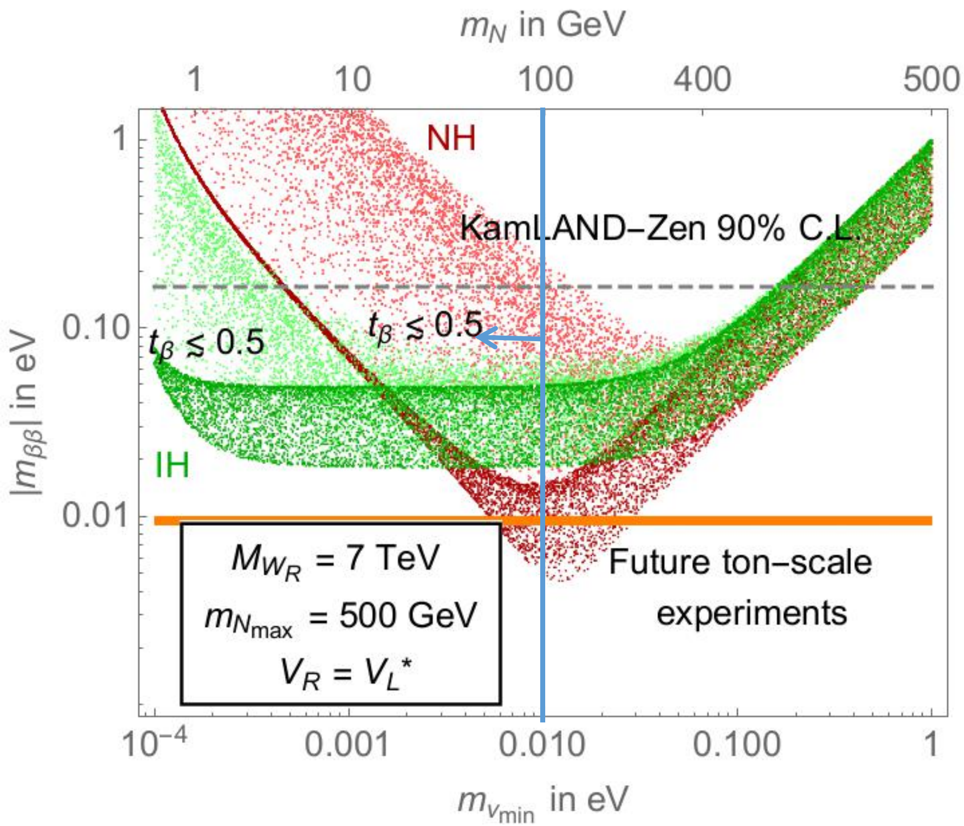
**see for example, Tello et al, Phys.Rev.Lett. 106 (2011) 151801; S.-F. Ge, M. Lindner, S. Patra, 1508.07286 (JHEP); Bhupal Dev, Goswami, Mitra Phys.Rev.D 91 (2015) 113004 and many more**

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

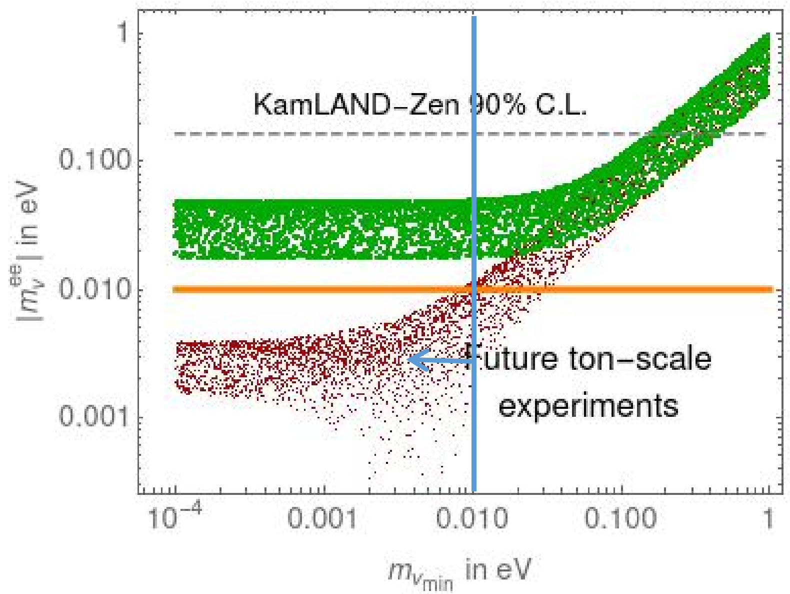
**GL, Ramsey-Musolf and Vasquez, 2009.01257 (PRL)**

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

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




*SM+3ν:*

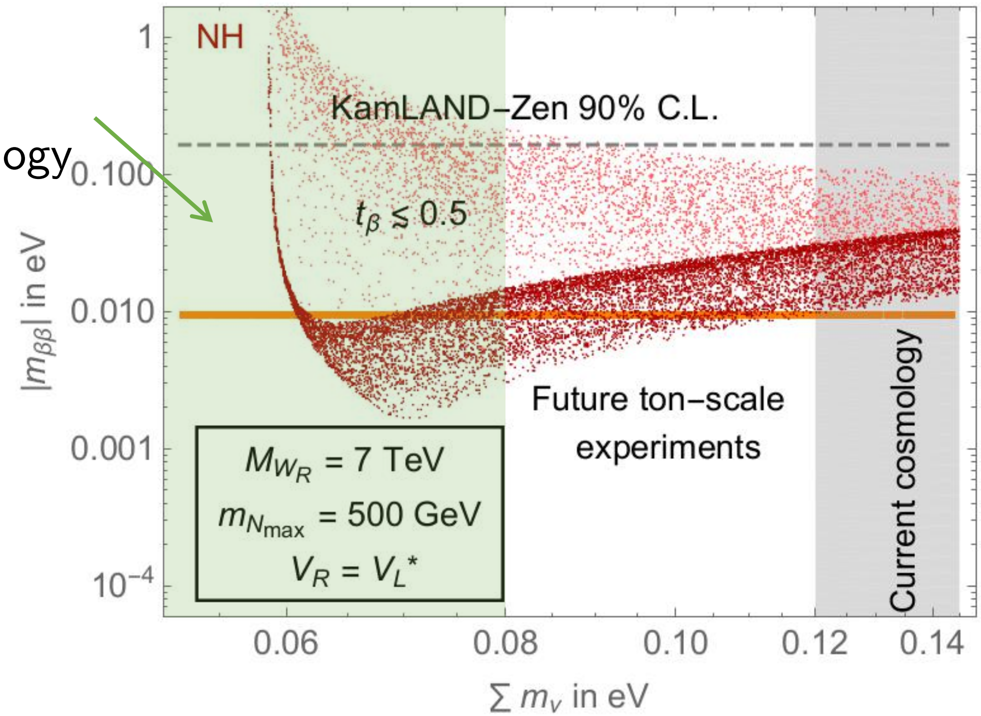



A large portion of parameter space could give a positive signal after including long-range contribution from LO $\pi\pi ee$ interaction from $W_L$-$W_R$ mixing

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

Including cosmological constraints:

future cosmology

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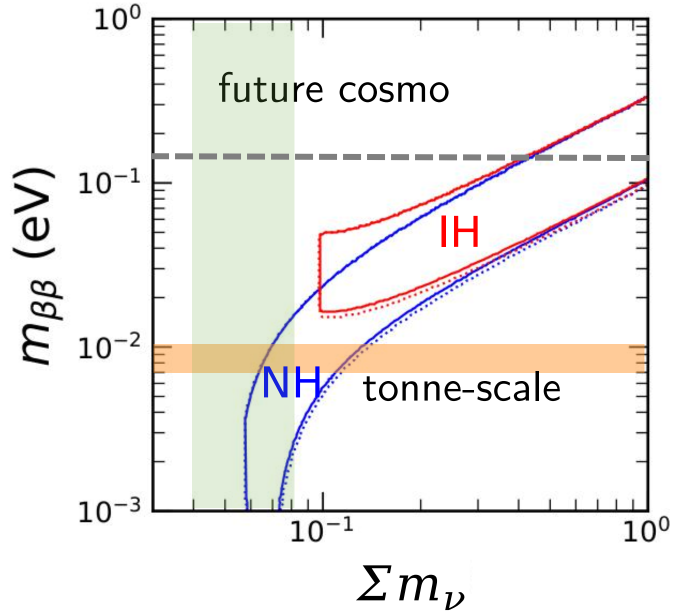


Good prospects for a positive signal even confronted with future cosmological surveys

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

# 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 left-right mixing can dominate over other contributions in the minimal left-right symmetric model