Right-handed Currents in Single and Double Beta Decay

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NDM 2015

03/06/15

$m_\nu = m_L - m_D^T M_R^{-1} m_D$

MANITOP

Massive Neutrinos: Investigating their Theoretical Origin and Phenomenology

Heisenberg-Programm
DFG Deutsche Forschungsgemeinschaft

Left-right Symmetry

very simple extension of SM gauge group to $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

usual particle content:

$$L_{Li} = \begin{pmatrix} \nu'_L \\ \ell_L \end{pmatrix}_i \sim (\mathbf{2}, \mathbf{1}, -\mathbf{1}) \,, \quad L_{Ri} = \begin{pmatrix} \nu_R \\ \ell_R \end{pmatrix}_i \sim (\mathbf{1}, \mathbf{2}, -\mathbf{1})$$

$$Q_{Li} = \begin{pmatrix} u_L \\ d_L \end{pmatrix}_i \sim (\mathbf{2}, \mathbf{1}, \tfrac{\mathbf{1}}{\mathbf{3}}) \,, \quad Q_{Ri} = \begin{pmatrix} u_R \\ d_R \end{pmatrix}_i \sim (\mathbf{1}, \mathbf{2}, \tfrac{\mathbf{1}}{\mathbf{3}})$$

for symmetry breaking:

$$\Delta_L \equiv \begin{pmatrix} \delta_L^+/\sqrt{2} & \delta_L^{++} \\ \delta_L^0 & -\delta_L^+/\sqrt{2} \end{pmatrix} \sim (\mathbf{3}, \mathbf{1}, \mathbf{2}) \,, \quad \Delta_R \equiv \begin{pmatrix} \delta_R^+/\sqrt{2} & \delta_R^{++} \\ \delta_R^0 & -\delta_R^+/\sqrt{2} \end{pmatrix} \sim (\mathbf{1}, \mathbf{3}, \mathbf{2})$$

$$\phi \equiv \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \sim (\mathbf{2}, \mathbf{2}, \mathbf{0})$$

Left-right Symmetry

- very rich Higgs sector (13 extra scalars)
- rich gauge boson sector ($Z', M_{W_R^\pm}$) with
  $M_{Z'} = \sqrt{\frac{2}{1-\tan^2\theta_W}} M_{W_R} \simeq 1.7\, M_{W_R} \gtrsim 4.3\,\mathrm{TeV}$
- 'sterile' neutrinos ν_R
- type I + type II seesaw for neutrino mass
- right-handed currents with strength $G_F \left(\frac{g_R}{g_L}\right)^2 \left(\frac{m_W}{M_{W_R}}\right)^2$
- $m_\nu \propto 1/M_{W_R}$: maximal parity violation $\leftrightarrow$ smallness of neutrino mass

(Note: in case of modified symmetry breaking $g_L \neq g_R$ and $M_{Z'} < M_{W_R}$ possible...)

Left-right Symmetry

6 neutrinos with flavor states n'_L and mass states $n_L = (\nu_L, N_R^c)^T$

$$n'_L = \begin{pmatrix} \nu'_L \\ {\nu_R}^c \end{pmatrix} = \begin{pmatrix} K_L \\ K_R \end{pmatrix} n_L = \begin{pmatrix} U & S \\ T & V \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R^c \end{pmatrix}$$

Right-handed currents:

$$\mathcal{L}_{CC}^{\rm lep} = \frac{g}{\sqrt{2}} \left[\overline{\ell_L} \gamma^\mu K_L n_L (W_{1\mu}^- + \xi e^{i\alpha} W_{2\mu}^-) + \overline{\ell_R} \gamma^\mu K_R n_L^c (-\xi e^{-i\alpha} W_{1\mu}^- + W_{2\mu}^-) \right]$$

(K_L and K_R are 3×6 mixing matrices)

plus: gauge boson mixing

$$\begin{pmatrix} W_L^\pm \\ W_R^\pm \end{pmatrix} = \begin{pmatrix} \cos\xi & \sin\xi \, e^{i\alpha} \\ -\sin\xi \, e^{-i\alpha} & \cos\xi \end{pmatrix} \begin{pmatrix} W_1^\pm \\ W_2^\pm \end{pmatrix}$$

Connection to Neutrinos

Majorana mass matrices $M_L = f_L\, v_L$ from $\langle \Delta_L \rangle$ and $M_R = f_R\, v_R$ from $\langle \Delta_R \rangle$
(with $f_L = f_R = f$)

$$\mathcal{L}^{\nu}_{\rm mass} = -\frac{1}{2} \left(\overline{\nu'_L} \;\; \overline{{\nu'_R}^c} \right) \begin{pmatrix} M_L & M_D \\ M_D^T & M_R \end{pmatrix} \begin{pmatrix} {\nu'_L}^c \\ \nu'_R \end{pmatrix} \Rightarrow m_\nu = M_L - M_D\, M_R^{-1}\, M_D^T$$

useful special cases

(i) type I dominance: $m_\nu = M_D\, M_R^{-1}\, M_D^T = M_D\, f_R^{-1}/v_R\, M_D^T$

(ii) type II dominance: $m_\nu = f_L\, v_L$

for case (i): mixing of light neutrinos with heavy neutrinos of order

$$|S_{\alpha i}| \simeq |T^T_{\alpha i}| \simeq \sqrt{\frac{m_\nu}{M_i}} \lesssim 10^{-7} \left(\frac{\rm TeV}{M_i} \right)^{1/2}$$

small (or enhanced up to 10^{-2} by cancellations)

Right-handed Currents in Double Beta Decay

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

$$\mathcal{L}_{CC}^{\rm lep} = \frac{g}{\sqrt{2}} \sum_{i=1}^{3} \Big[\overline{e_L}\gamma^\mu (U_{ei}\nu_{Li} + S_{ei}N_{Ri}^c)(W_{1\mu}^- + \xi e^{i\alpha} W_{2\mu}^-)$$

$$+ \overline{e_R}\gamma^\mu (T_{ei}^*\nu_{Li}^c + V_{ei}^* N_{Ri})(-\xi e^{-i\alpha} W_{1\mu}^- + W_{2\mu}^-)\Big]$$

$$\mathcal{L}_Y^\ell = -\overline{L}_L^{\prime c} i\sigma_2 \Delta_L f_L L_L^\prime - \overline{L}_R^{\prime c} i\sigma_2 \Delta_R f_R L_R^\prime$$

classify diagrams:

- mass dependent diagrams (same helicity of electrons)
- triplet exchange diagrams (same helicity of electrons)
- momentum dependent diagrams (different helicity of electrons)

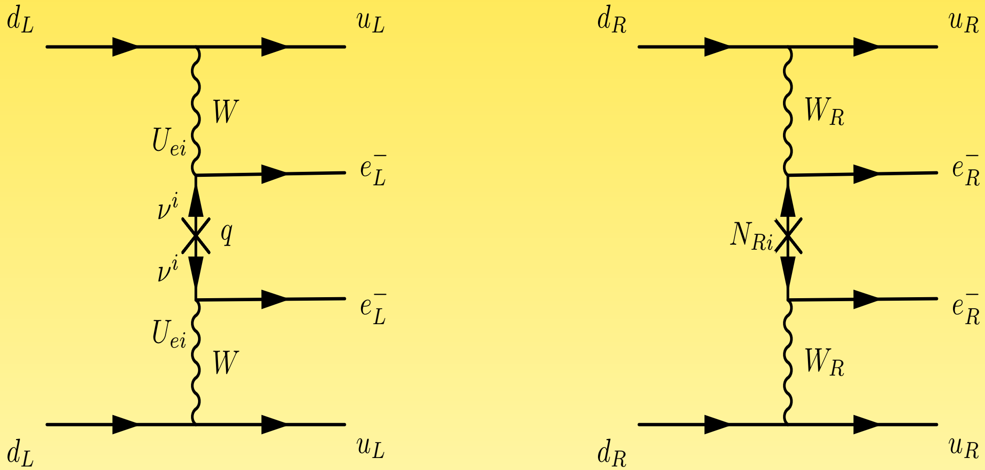
Mass Dependent Diagrams

electrons either both left- or right-handed:

$$\mathcal{A}_{LL} \simeq G_F^2 \left(1 + 2\tan\xi + \tan^2\xi\right) \sum_i \left(\frac{U_{ei}^2 m_i}{q^2} - \frac{S_{ei}^2}{M_i}\right)$$

$$\mathcal{A}_{RR} \simeq G_F^2 \left(\frac{m_{W_L}^4}{M_{W_R}^4} + 2\frac{m_{W_L}^2}{M_{W_R}^2}\tan\xi + \tan^2\xi\right) \sum_i \left(\frac{T_{ei}^{*\,2} m_i}{q^2} - \frac{V_{ei}^{*\,2}}{M_i}\right)$$

leading diagrams:

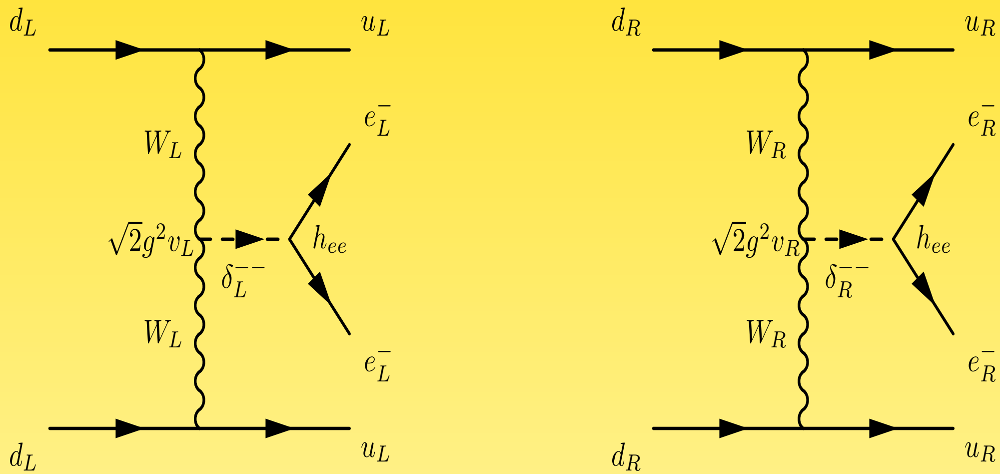


$$\mathcal{A}_\nu \simeq G_F^2 \frac{m_{ee}}{q^2} \qquad \mathcal{A}_{N_R}^R \simeq G_F^2 \left(\frac{m_{W_L}}{M_{W_R}}\right)^4 \sum_i \frac{V_{ei}^{*\,2}}{M_i}$$

$$\propto \frac{L^2}{R} \qquad\qquad \propto \frac{L^4}{R^5}$$

Triplet Exchange Diagrams

leading diagrams:



$$\mathcal{A}_{\delta_L} \simeq G_F^2 \frac{h_{ee} v_L}{m^2_{\delta_L}} \qquad \mathcal{A}_{\delta_R} \simeq G_F^2 \left(\frac{m_{W_L}}{M_{W_R}}\right)^4 \sum_i \frac{V_{ei}^2 M_i}{m^2_{\delta_R}}$$

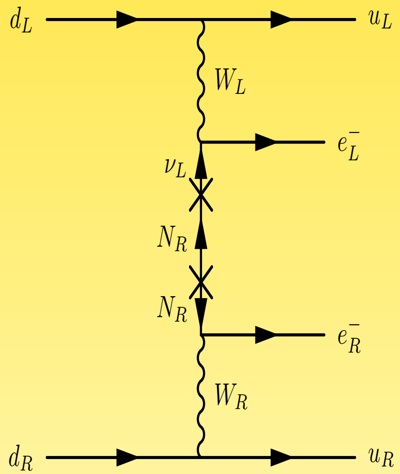
(negligible) $\qquad \propto \frac{L^4}{R^5}$

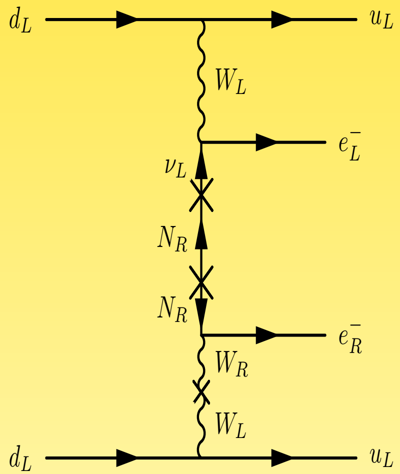
Momentum Dependent Diagrams

electrons with opposite helicity

$$\mathcal{A}_{LR} \simeq G_F^2 \left(\frac{m_{W_L}^2}{M_{W_R}^2} + \tan\xi + \frac{m_{W_L}^2}{M_{W_R}^2} \tan\xi + \tan^2\xi \right) \sum_i \left(U_{ei} T_{ei}^* \frac{1}{q} - S_{ei} V_{ei}^* \frac{q}{M_i^2} \right)$$

leading diagrams (long range):





$$\mathcal{A}_\lambda \simeq G_F^2 \left(\frac{m_{W_L}}{M_{W_R}} \right)^2 \sum_i U_{ei} T_{ei}^* \frac{1}{q} \propto \frac{L^3}{R^3 q}$$

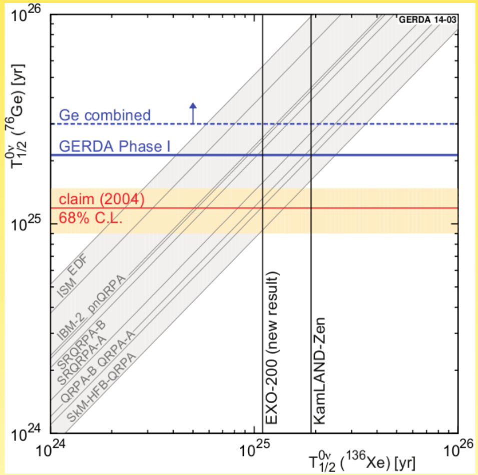
$$\mathcal{A}_\eta \simeq G_F^2 \tan\xi \sum_i U_{ei} T_{ei}^* \frac{1}{q} \propto \frac{L^3}{R^3 q}$$

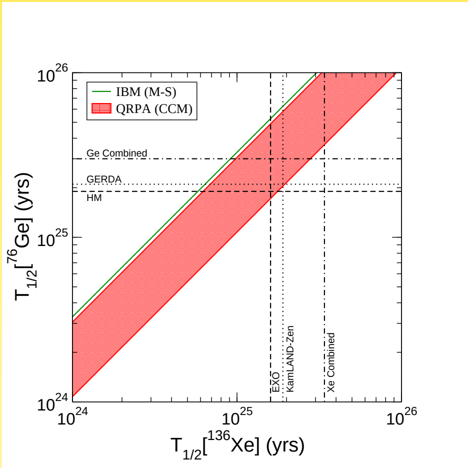
Limits

$$\Gamma^{0\nu} = G_x(Q,Z)\,|\mathcal{M}_x(A,Z)\,\eta_x|^2$$

Xe-limit is stronger than Ge-limit when:

$$T_{\rm Xe} > T_{\rm Ge}\,\frac{G_{\rm Ge}}{G_{\rm Xe}}\,\left|\frac{\mathcal{M}_{\rm Ge}}{\mathcal{M}_{\rm Xe}}\right|^2\ \text{yrs}$$

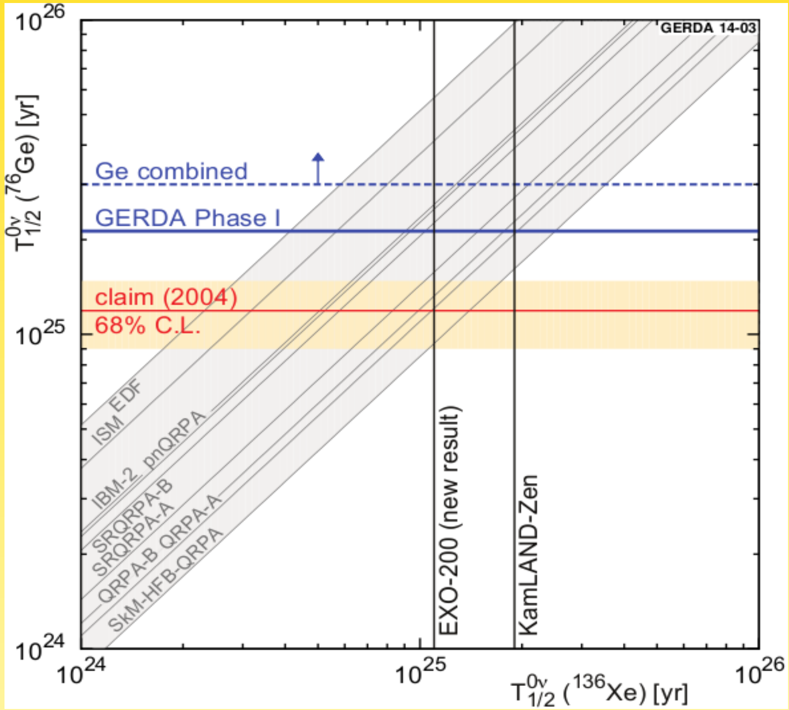




GERDA Barry, W.R., JHEP **1309**

Current Limits on $|m_{ee}|$

NME	^{76}Ge		^{136}Xe	
	GERDA	comb	KLZ	comb
EDF(U)	**0.32**	**0.27**	**0.13**	–
ISM(U)	**0.52**	**0.44**	**0.24**	–
IBM-2	**0.27**	**0.23**	**0.16**	–
pnQRPA(U)	**0.28**	**0.24**	**0.17**	–
SRQRPA-A	**0.31**	**0.26**	**0.23**	–
QRPA-A	*0.28*	*0.24*	*0.25*	–
SkM-HFB-QRPA	*0.29*	*0.24*	*0.28*	–



GERDA

Bhupal Dev, Goswami, Mitra, W.R., Phys. Rev. **D88**

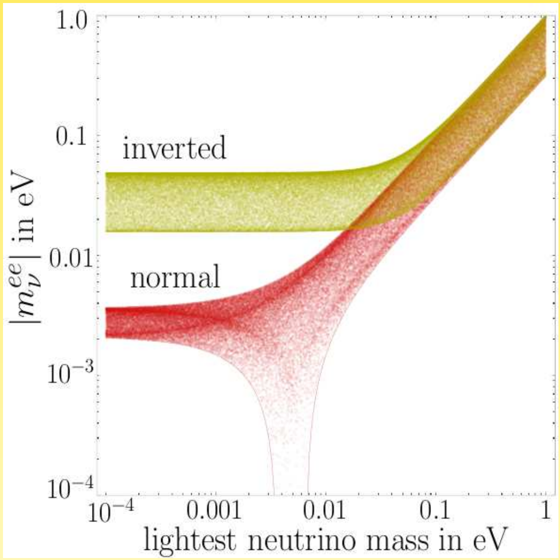
mechanism	amplitude	current limit
light neutrino exchange ($\mathcal{A}_\nu$)	$\frac{G_F^2}{q^2}\left\lvert \boldsymbol{U_{ei}^2 m_i} \right\rvert$	0.3 eV
heavy neutrino exchange ($\mathcal{A}_{N_R}^L$)	$G_F^2 \left\lvert \frac{\boldsymbol{S_{ei}^2}}{\boldsymbol{M_i}} \right\rvert$	$7.4 \times 10^{-9}\ \mathrm{GeV}^{-1}$
heavy neutrino exchange ($\mathcal{A}_{N_R}^R$)	$G_F^2 m_{W_L}^4 \left\lvert \frac{\boldsymbol{V_{ei}^{*\,2}}}{\boldsymbol{M_i M_{W_R}^4}} \right\rvert$	$1.7 \times 10^{-16}\ \mathrm{GeV}^{-5}$
Higgs triplet exchange ($\mathcal{A}_{\delta_R}$)	$G_F^2 m_{W_L}^4 \left\lvert \frac{\boldsymbol{V_{ei}^2 M_i}}{\boldsymbol{m_{\delta_R}^2 M_{W_R}^4}} \right\rvert$	$1.7 \times 10^{-16}\ \mathrm{GeV}^{-5}$
λ-mechanism ($\mathcal{A}_\lambda$)	$G_F^2 \frac{m_{W_L}^2}{q} \left\lvert \frac{\boldsymbol{U_{ei} T_{ei}^*}}{\boldsymbol{M_{W_R}^2}} \right\rvert$	$8.8 \times 10^{-11}\ \mathrm{GeV}^{-2}$
η-mechanism ($\mathcal{A}_\eta$)	$G_F^2 \frac{1}{q} \left\lvert \boldsymbol{\tan\xi \sum_i U_{ei} T_{ei}^*} \right\rvert$	3.0×10^{-9}

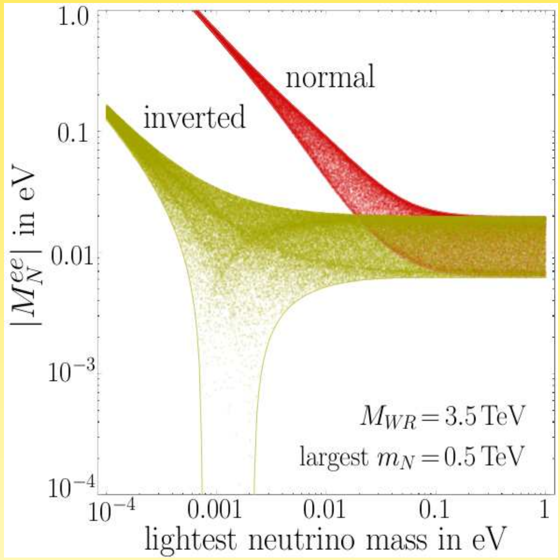
Type II dominance (Senjanovic *et al.*, 1011.3522)

$$m_\nu = M_L - M_D\, M_R^{-1}\, M_D^T = v_L\, f - \frac{v^2}{v_R}\, Y_D\, f^{-1}\, Y_D^T \xrightarrow{*} v_L\, f$$

$\Rightarrow m_\nu$ fixes $M_R = f v_R$ and exchange of N_R with W_R fixed in terms of PMNS:

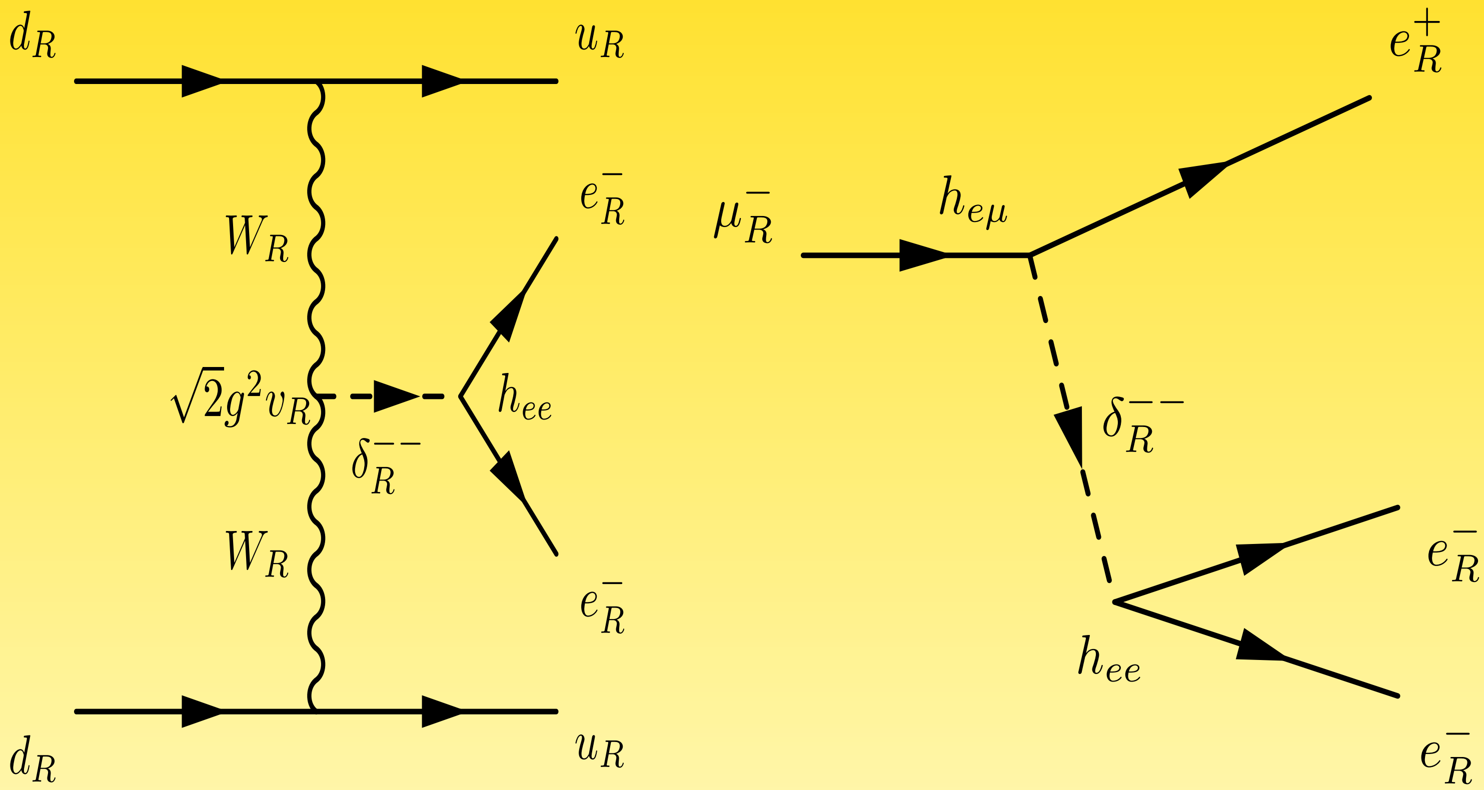
$$\Rightarrow \mathcal{A}_{N_R} \simeq G_F^2 \left(\frac{m_W}{M_{W_R}}\right)^4 \sum \frac{V_{ei}^2}{M_i} \propto \sum \frac{U_{ei}^2}{m_i}$$



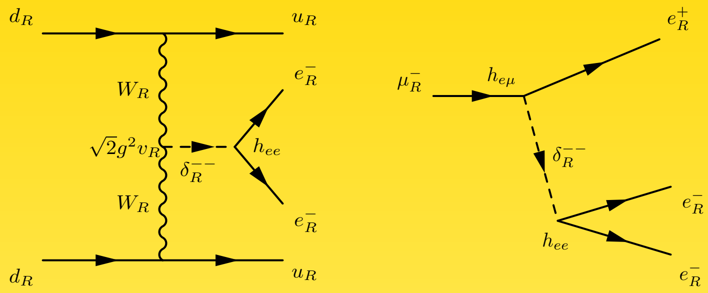


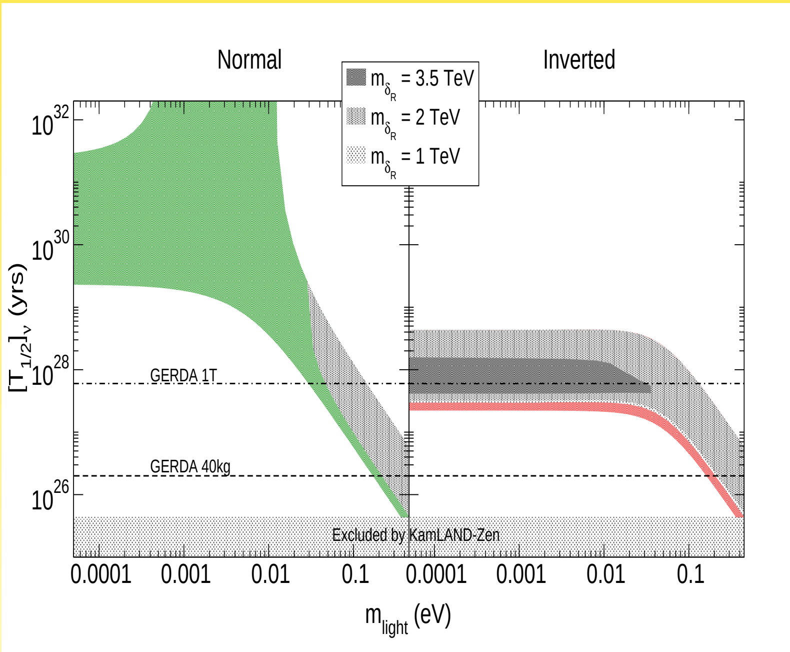
* **(for leptogenesis**: Joshipura, Paschos, W.R., JHEP **0108)**

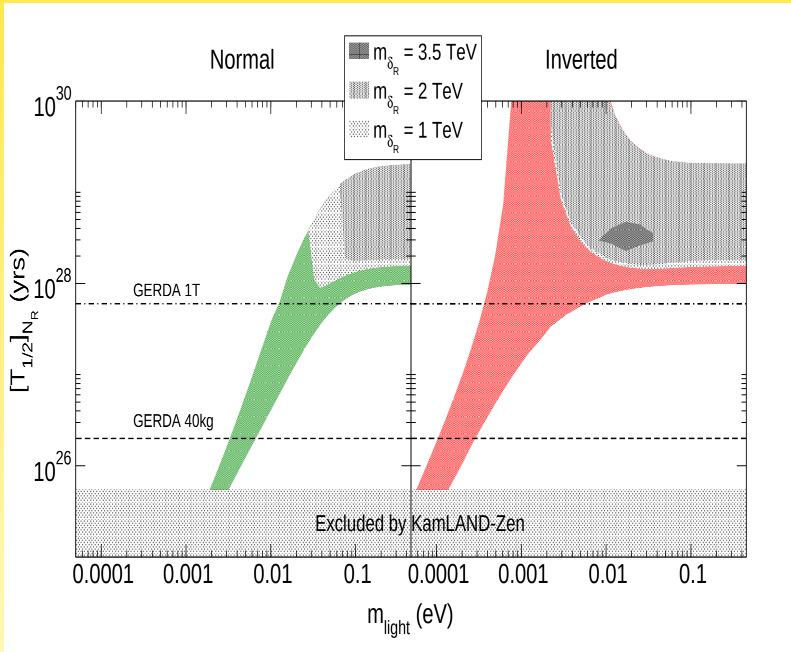
Constraints from Lepton Flavor Violation



Constraints from Lepton Flavor Violation

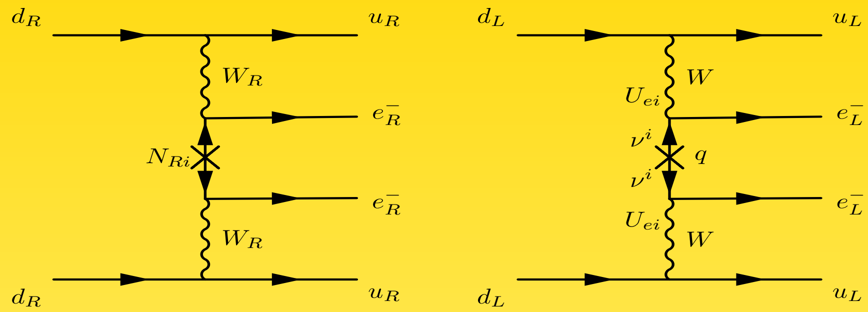


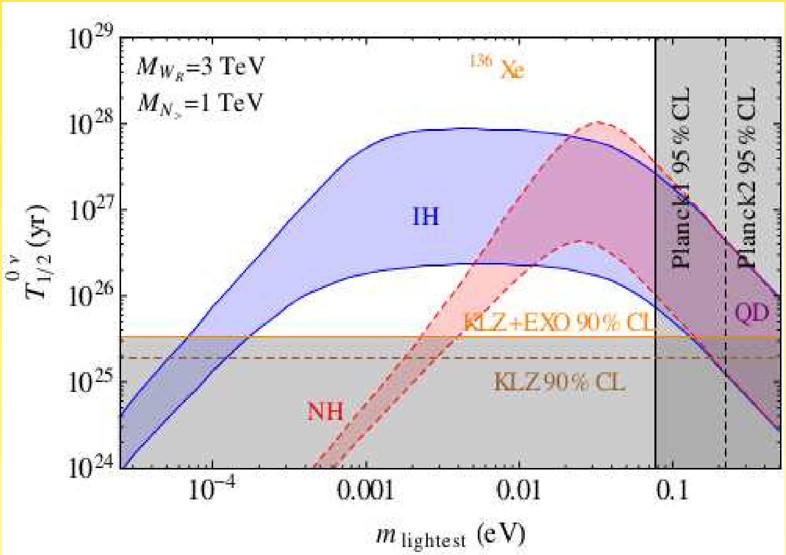




Barry, W.R., JHEP **1309**

Adding diagrams





$\Rightarrow$ lower bound on $m(\text{lightest}) \gtrsim$ meV

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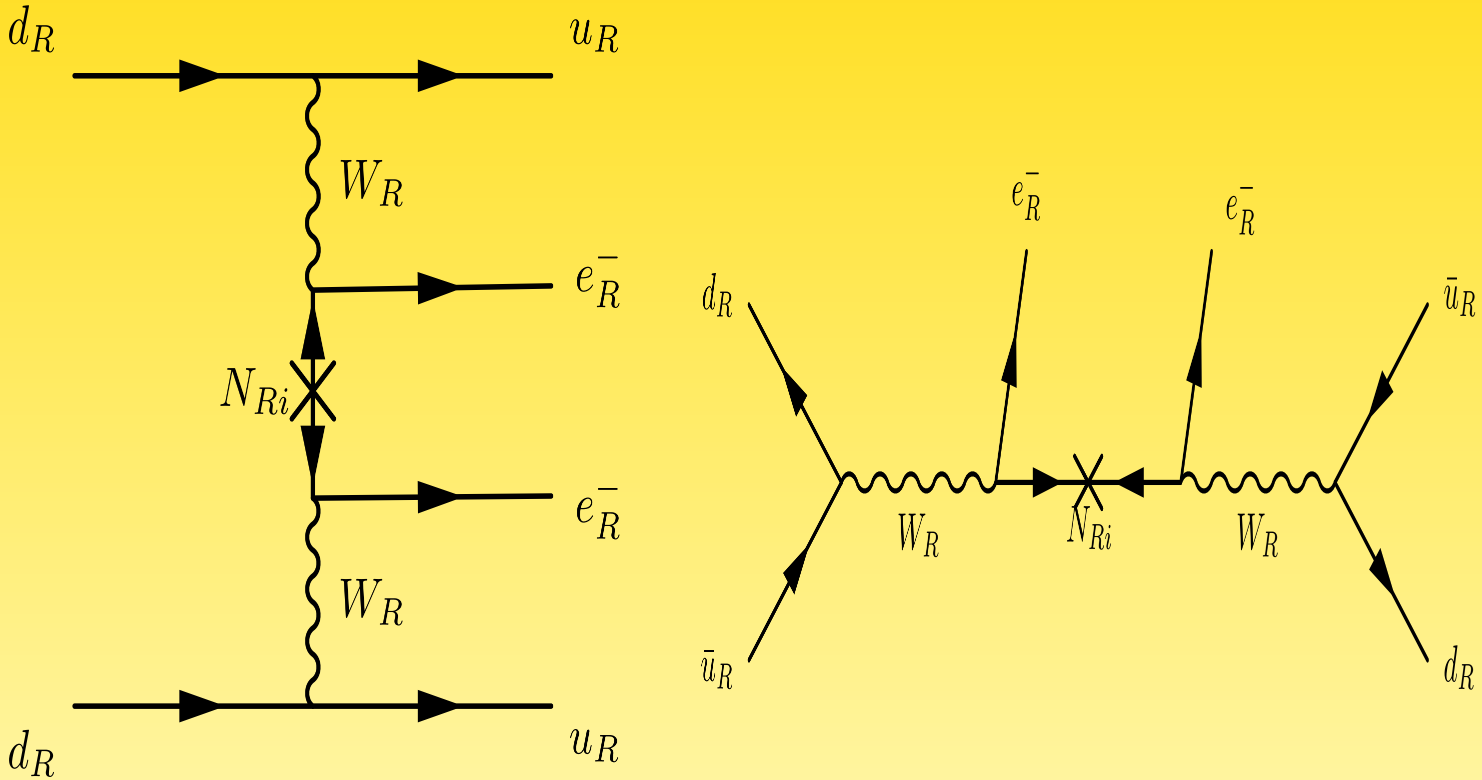
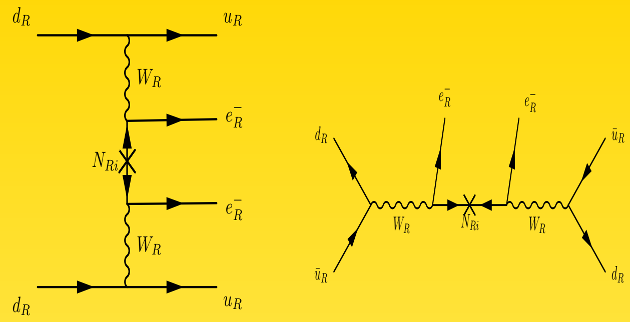
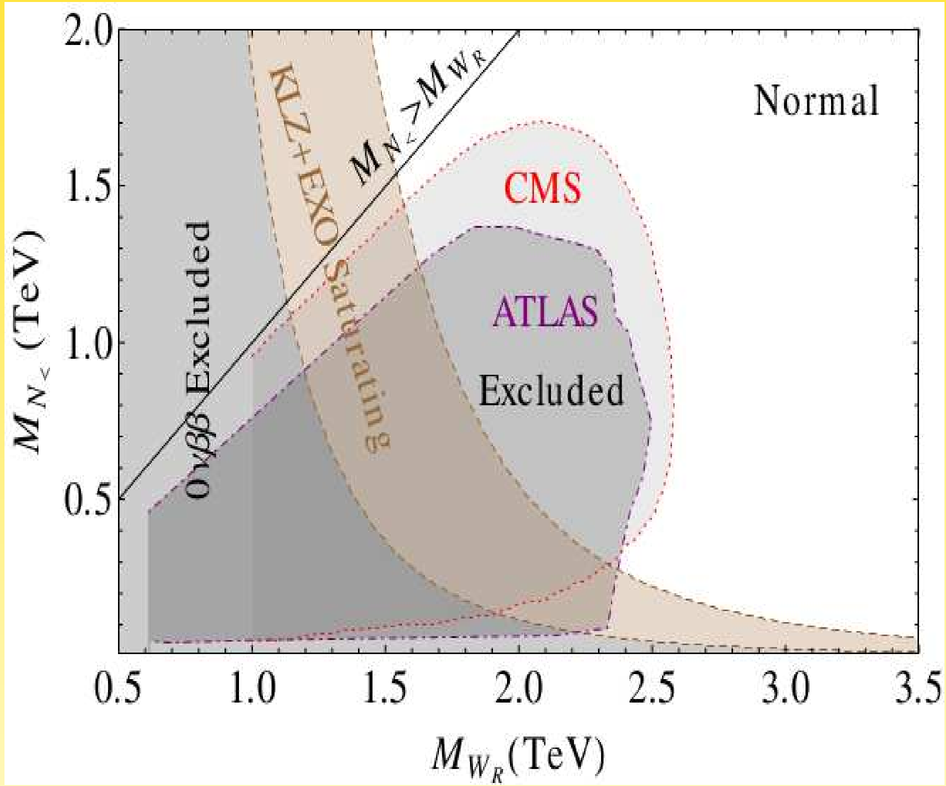
LHC Tests



Senjanovic, Keung, 1983





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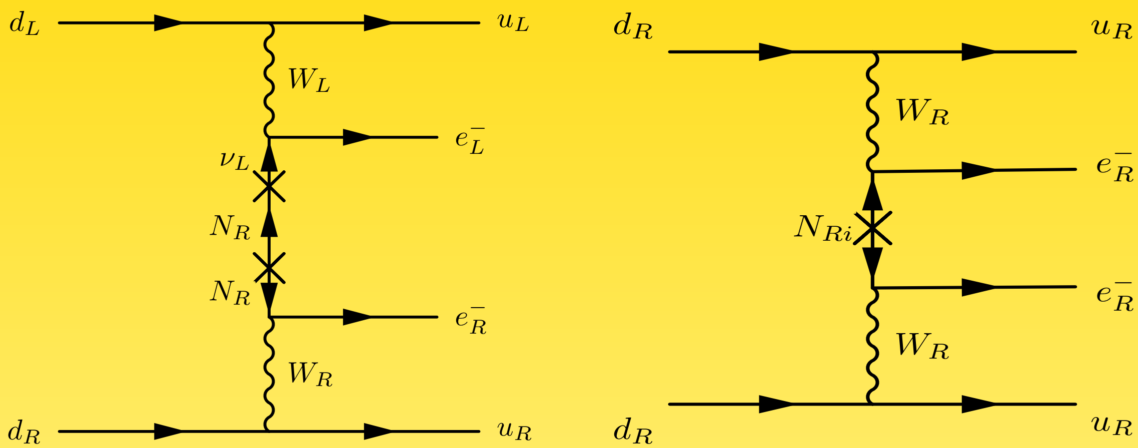
Type I Dominance: Mixed Diagrams can dominate



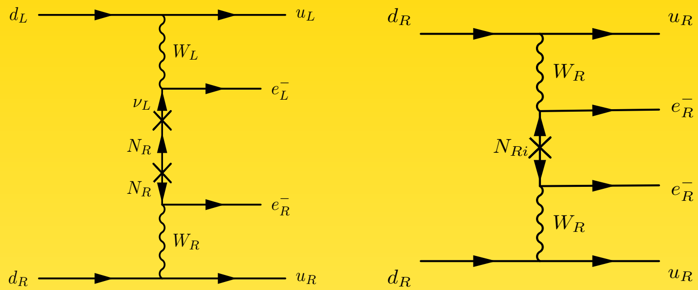
$$\mathcal{A}_\lambda \sim \left(\frac{m_W}{M_{W_R}}\right)^2 \frac{U\,T}{q} \qquad \mathcal{A}_{N_R} \sim \left(\frac{m_W}{M_{W_R}}\right)^4 \frac{V^2}{M_R}$$

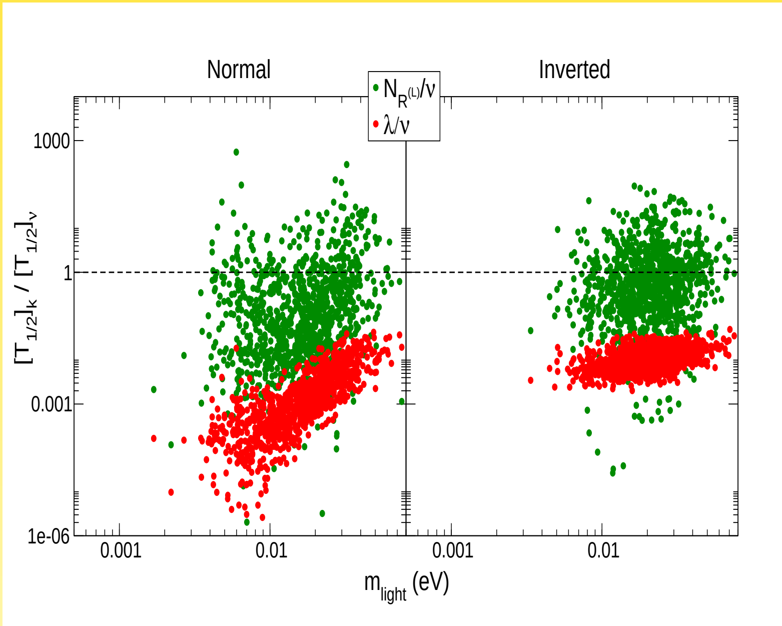
with $T \simeq \sqrt{\frac{m_\nu}{M_R}} \sim 10^{-7}$ (or huge enhancements up to 10^{-2})

$$\Rightarrow \frac{\mathcal{A}_\lambda}{\mathcal{A}_{N_R}} \simeq \frac{M_R}{q} \left(\frac{M_{W_R}}{m_W}\right)^2 T \simeq 10^{5\,(\to 3)}\, T$$

Barry, W.R., JHEP **1309**

Type I Dominance: Mixed Diagrams can dominate

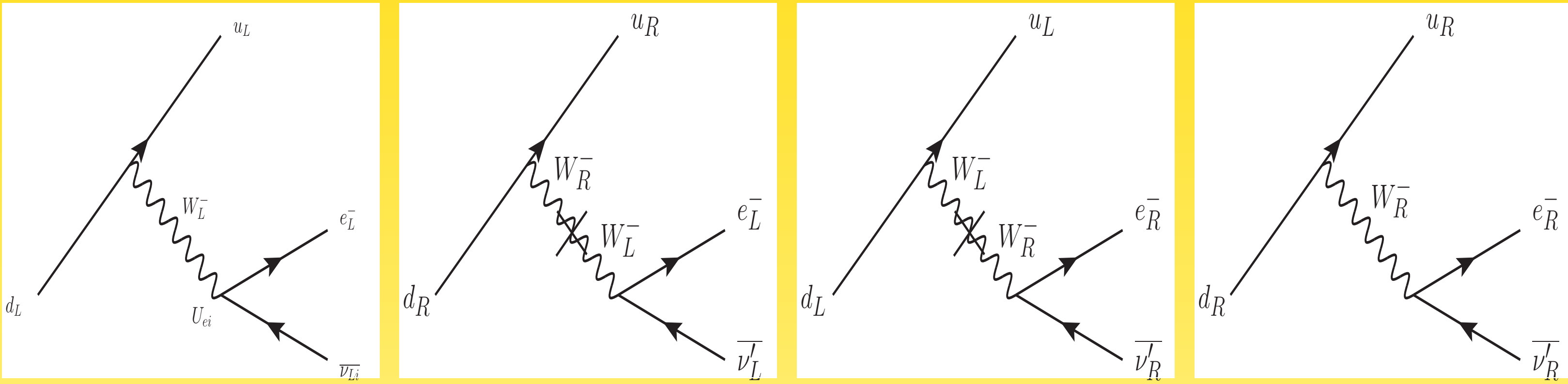




Barry, W.R., JHEP **1309**

(tests with SuperNEMO and $e^- e^-$ colliders)

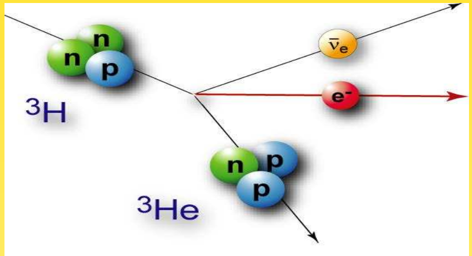
KATRIN and right-handed currents



- left-handed contribution
- right-handed contribution
- interference contribution

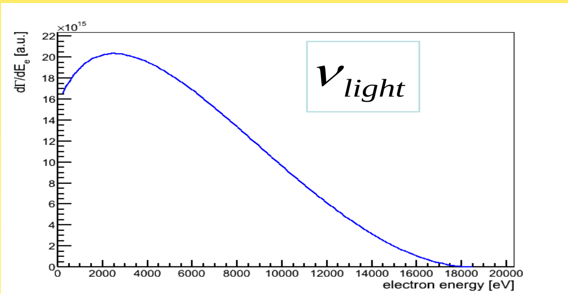
Neutrino masses up to $m = 18.6$ keV testable

Imprint of keV neutrinos on ß-spectrum

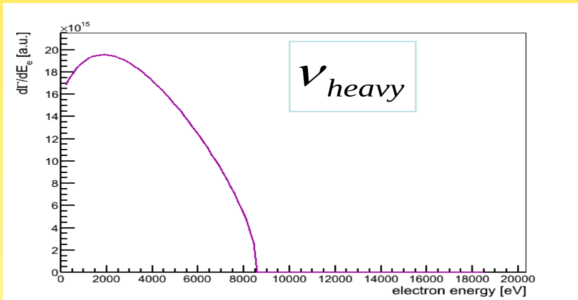


$$\begin{pmatrix} \nu_e \\ \nu_s \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_{light} \\ \nu_{heavy} \end{pmatrix}$$

$\cos^2(\theta)$

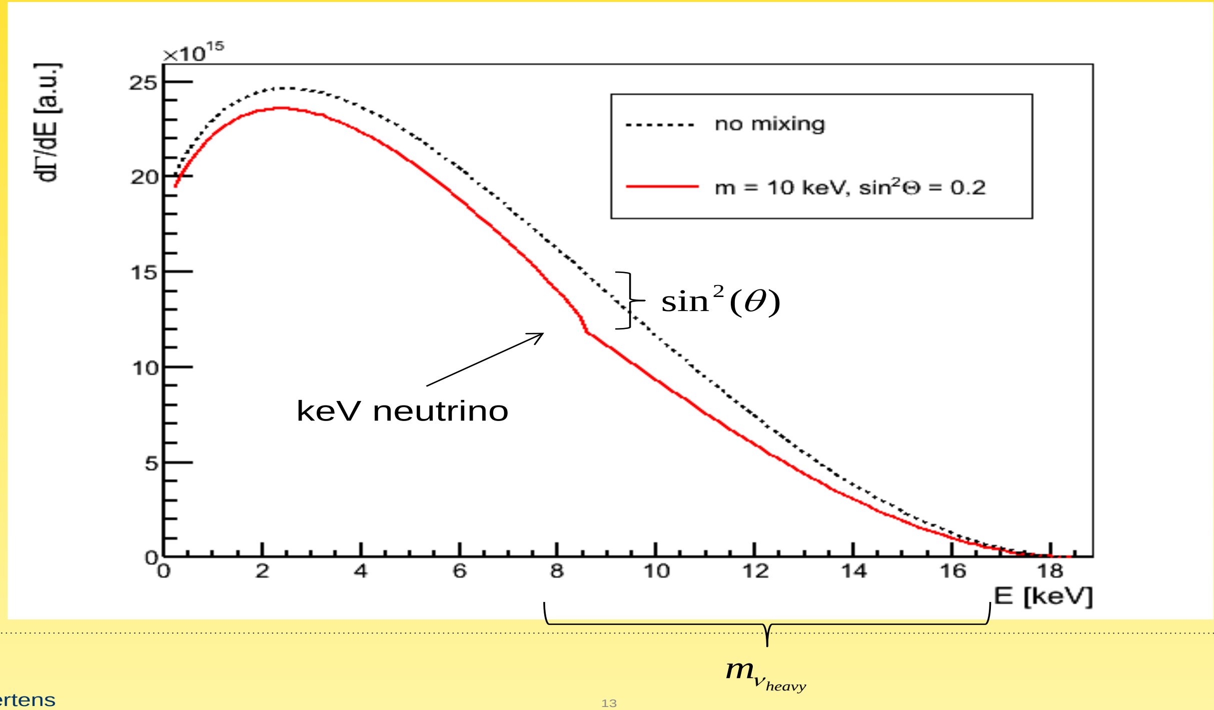


$+ \sin^2(\theta)$

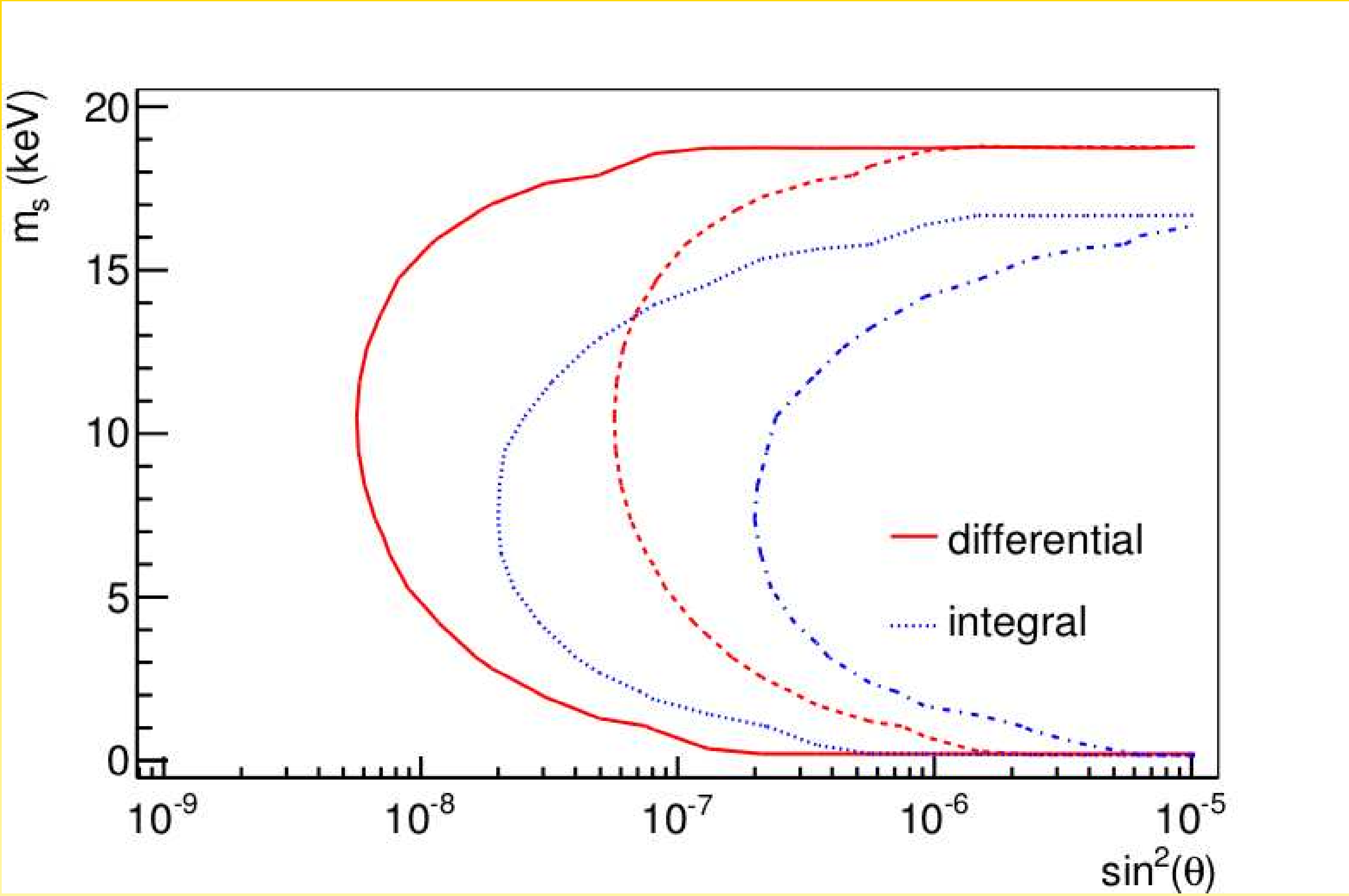


Mertens *et al.*, 1409.0920

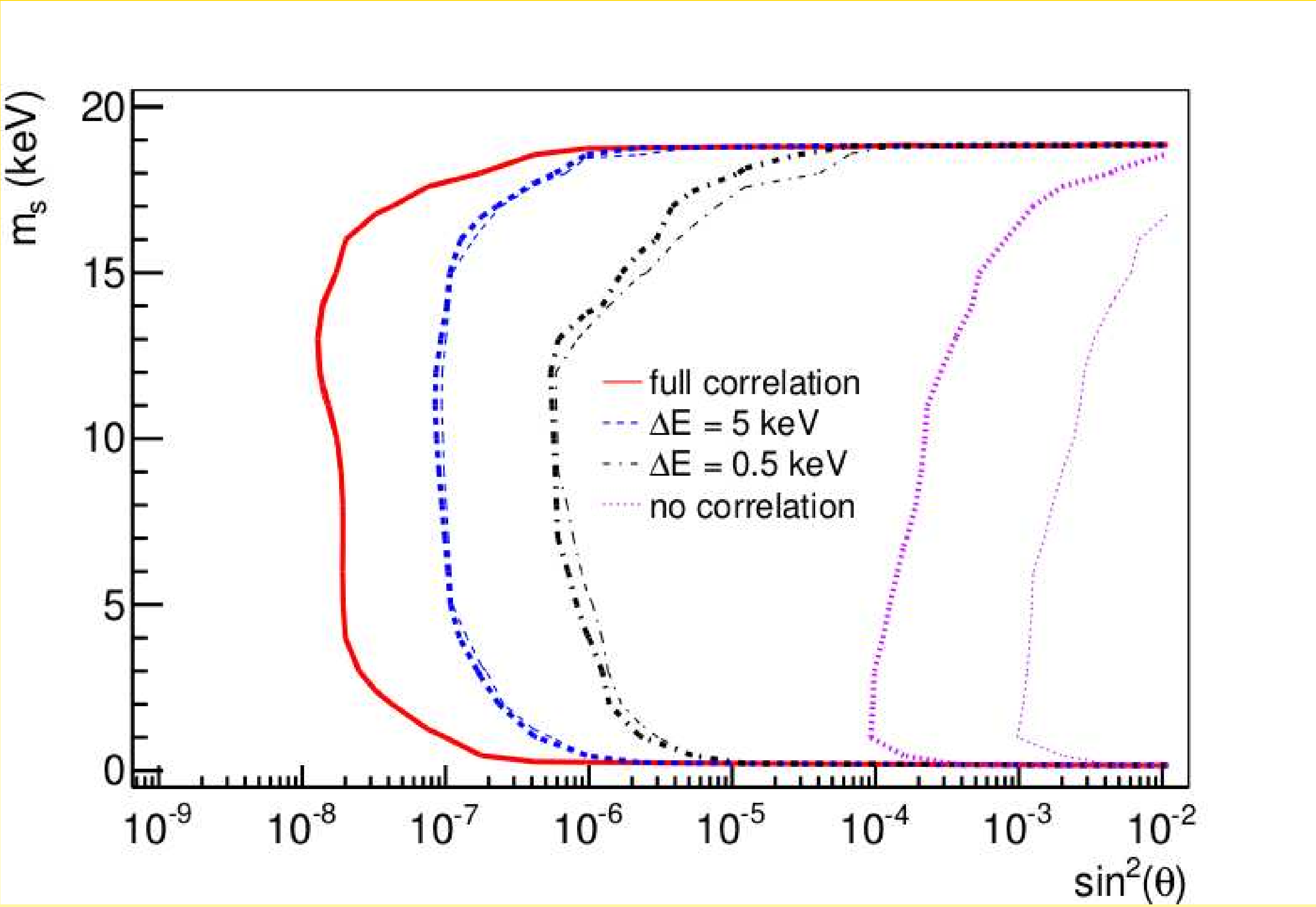
Imprint of keV neutrinos on ß-spectrum



Mertens *et al.*, 1409.0920

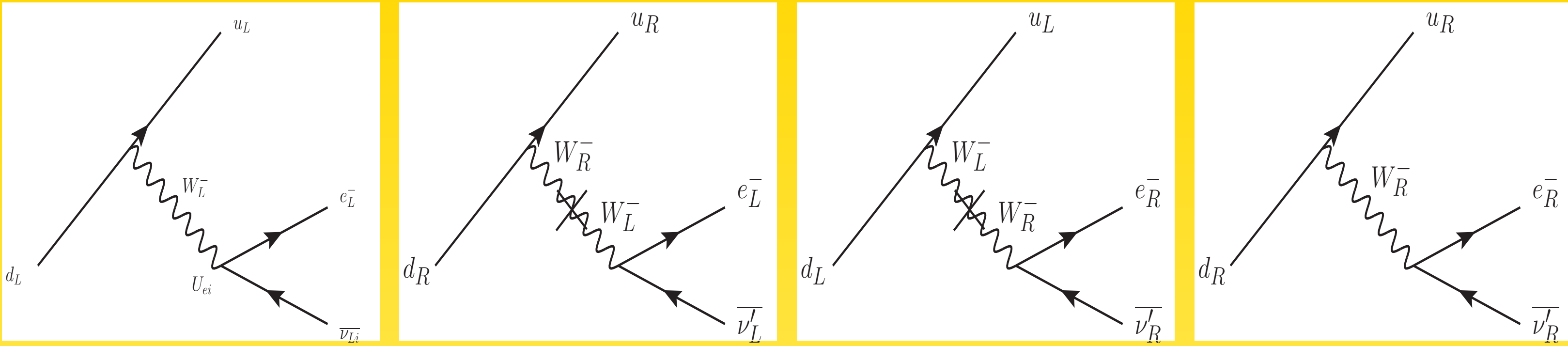


(i) energy resolving detector (differential) or (ii) counting detector (integral) or (iii) time-of-flight



$\Rightarrow$ mixing down to 10^{-7} in reach!?

Mertens *et al.*, 1409.0920



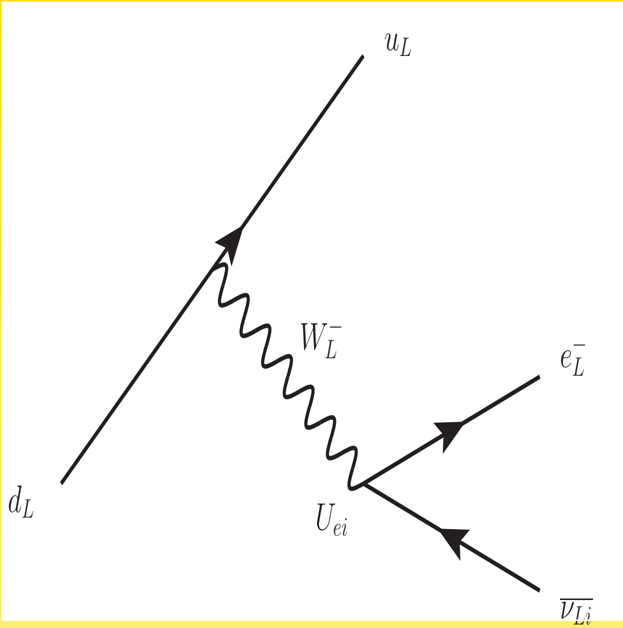
$$\left(\frac{\mathrm{d}\Gamma}{\mathrm{d}E}\right)_{LL} = K'(E+m_e)p_e X[1+2C\tan\xi] \times \left[|U_{ei}|^2\sqrt{X^2-m_i^2}\,\Theta(X-m_i) + |S_{ei}|^2\sqrt{X^2-M_i^2}\,\Theta(X-M_i)\right]$$

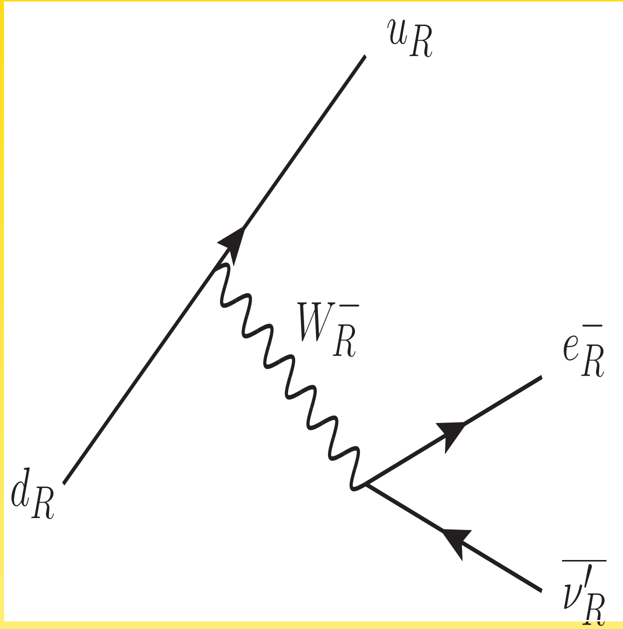
$$\left(\frac{\mathrm{d}\Gamma}{\mathrm{d}E}\right)_{RR} \simeq K'(E+m_e)p_e X\left[\frac{m_{W_L}^4}{M_{W_R}^4} + \tan^2\xi + 2C\frac{m_{W_L}^2}{M_{W_R}^2}\tan\xi\right] \times |V_{ei}|^2\sqrt{X^2-M_i^2}\,\Theta(X-M_i)$$

$$\left(\frac{\mathrm{d}\Gamma}{\mathrm{d}E}\right)_{LR} = -2K' m_e p_e \mathrm{Re}\left\{\left[\left(\frac{m_{W_L}}{M_{W_R}}\right)^2 + C\tan\xi\right] \times \left[U_{ei}T_{ei}m_i\sqrt{X^2-m_i^2}\,\Theta(X-m_i) + S_{ei}V_{ei}M_i\sqrt{X^2-M_i^2}\,\Theta(X-M_i)\right]\right\}$$

with $X = E_0 - E$

Focus for simplicity on





total contribution of keV neutrino with mass M to beta decay:

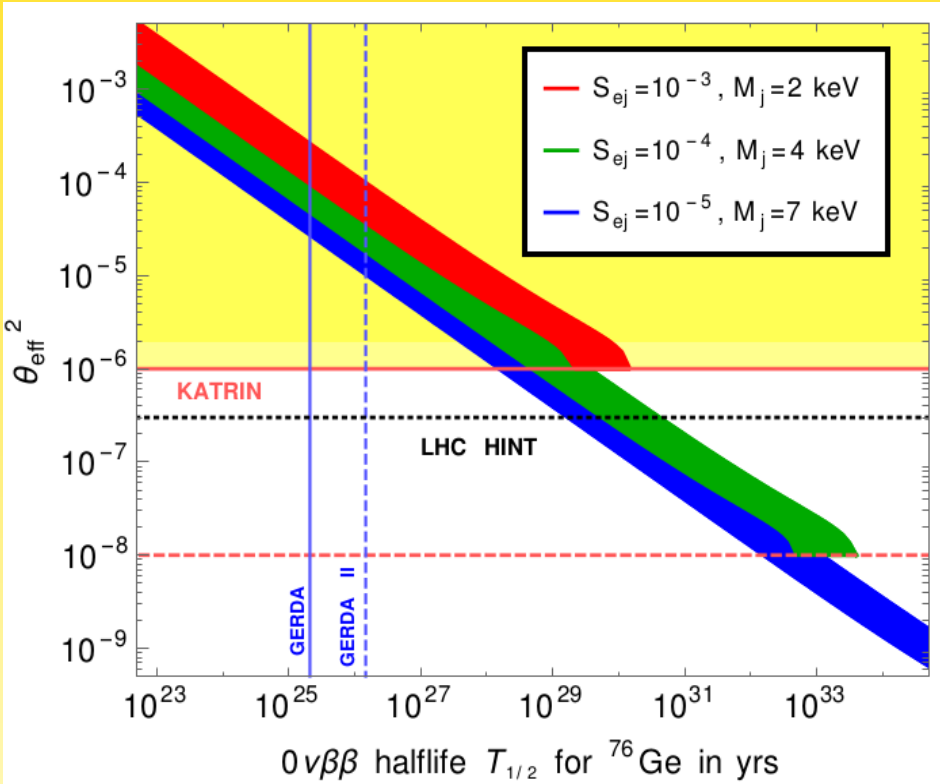
$$\theta^2_{\rm eff} \simeq |S_{ej}|^2 + 1.1 \times 10^{-6}\, |V_{ej}|^2 \left(\frac{2.5\,\text{TeV}}{M_{W_R}}\right)^4 > |S_{ej}|^2 \quad (X\text{-rays}\ldots)$$

and note that M does $0\nu\beta\beta$ with amplitude $\propto |V_{ej}|^2\,(m_W/M_{W_R})^4\, M$

$\Rightarrow$ connection to $0\nu\beta\beta$ constraints!

connection to $0\nu\beta\beta$ constraints:

$$\theta_{\rm eff}^2 = |S_{ej}|^2 + \frac{m_e}{M_j}\left[|\mathcal{M}_\nu^{0\nu}|^{-2}\left(G_{01}^{0\nu}\right)^{-1}\left(T_{1/2}^{0\nu}\right)^{-1} - |S_{ej}^2 M_j/m_e|^2\right]^{\frac{1}{2}}$$



Barry, Heeck, W.R., JHEP **1407**

How the additional interactions save the day

- double beta decay without RHC: $\theta^2 M = 7 \times 10^{-10}\,\mathrm{keV} = 70\,\mu\mathrm{eV}$
- double beta decay with RHC: $(m_{W_L}/M_{W_R})^4\,|V_{ei}|^2 M = 8\,\mathrm{meV}$
- decay: $\dfrac{\Gamma_{\rm RHC}(N_j \to \bar{\nu}\gamma)}{\Gamma_{\rm SM}(N_j \to \nu\gamma)} \simeq \dfrac{m_{W_L}^4\,|S_{ei}|^2}{M_{W_R}^4\,|T_{ei}|^2} \simeq \dfrac{m_{W_L}^4}{M_{W_R}^4}$
- beta decay: $\theta_{\rm eff}^2 \simeq |S_{ej}|^2 + 1.1 \times 10^{-6}\,|V_{ej}|^2 \left(\frac{2.5\,\mathrm{TeV}}{M_{W_R}}\right)^4 > |S_{ej}|^2$

Energy Spectrum

$$\left(\frac{\mathrm{d}\Gamma}{\mathrm{d}E_e}\right) = p_e\,\sqrt{(Q-E_e)^2 - m_\nu^2}\,\left(a\,(Q-E_e)\,(E_e+m_e) + b\,m_e\,m_\nu\right)$$

`Jackson, Treiman, Wyld; Lee, Yang; Cirigliano` *et al.*; `Severijns` *et al.*

b from interference with scalar or tensor (here right-handed) interactions is derived actually in non-relativistic limit...(relativistic: see e.g. `Valle, Weinheimer` *et al.*; `Simkovic, Dvornicky, Faessler`)

Goal (`Ludl, W.R.`): relativistic calculation of process, full spectrum, include all possible neutrino masses...

Energy Spectrum

most general matrix element

$$\left|\mathcal{M}(\mathcal{A}\to\mathcal{B}+e^-+\overline{\nu_j})\right|^2 = A + B_1 E_e + B_2 E_j + C E_e E_j + D_1 E_e^2 + D_2 E_j^2$$

and energy spectrum

$$\left(\frac{d\Gamma}{dE_e}\right)_{\overline{\nu_j}} = \frac{1}{64\pi^3 m_{\mathcal{A}}}\times$$

$$\Big\{(A + B_1 E_e + D_1 E_e^2)(E_{j+} - E_{j-}) + \frac{1}{2}(B_2 + C E_e)(E_{j+}^2 - E_{j-}^2)$$

$$+\frac{1}{3} D_2 (E_{j+}^3 - E_{j-}^3)\Big\}$$

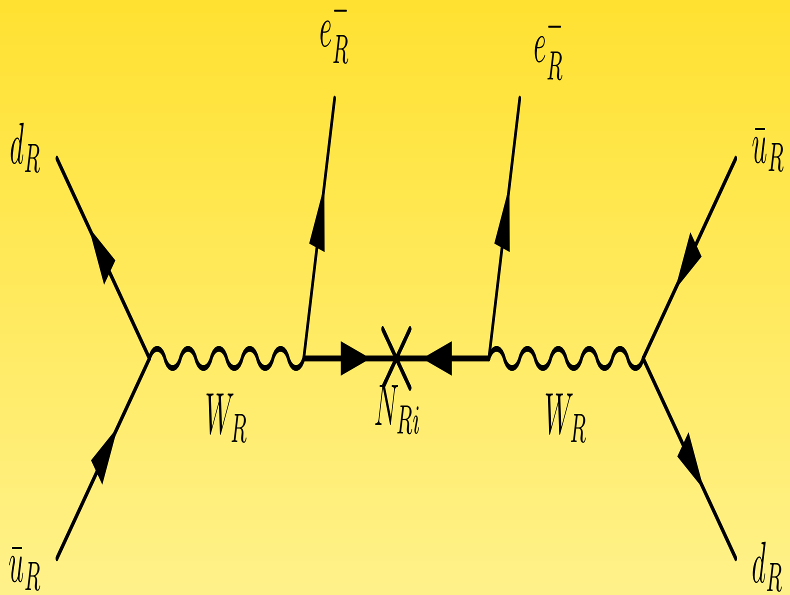
with maximal/minimal neutrino energy $(2\alpha = m_{\mathcal{A}}^2 - m_{\mathcal{B}}^2 + m_e^2 + m_j^2)$

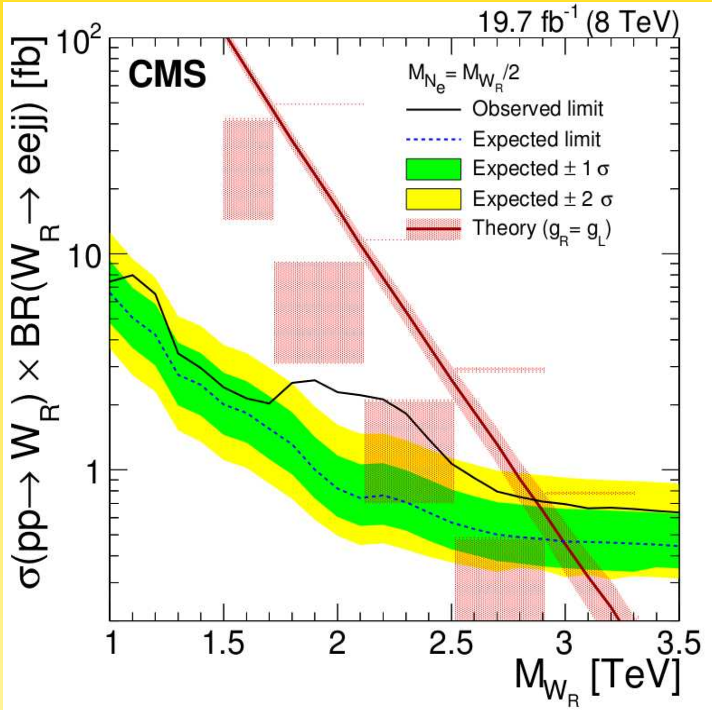
$$E_{j\pm} = \frac{-(m_{\mathcal{A}} - E_e)(E_e m_{\mathcal{A}} - \alpha) \pm |\vec{p}_e|\sqrt{(E_e m_{\mathcal{A}} - \alpha + m_j^2)^2 - m_{\mathcal{B}}^2 m_j^2}}{m_{\mathcal{A}}^2 - 2m_{\mathcal{A}} E_e + m_e^2}$$

Summary

- Left-right symmetry has rich phenomenology in various areas
- Many possibilities to influence single and double beta decay
- allows connecting single and double beta decay different from standard light neutrino exchange

LHC signal in $eejj$? (1407.3683)

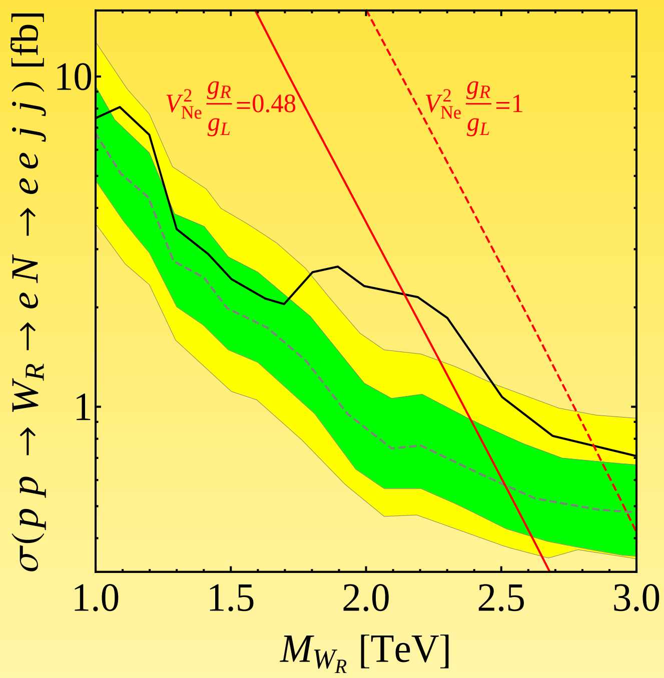


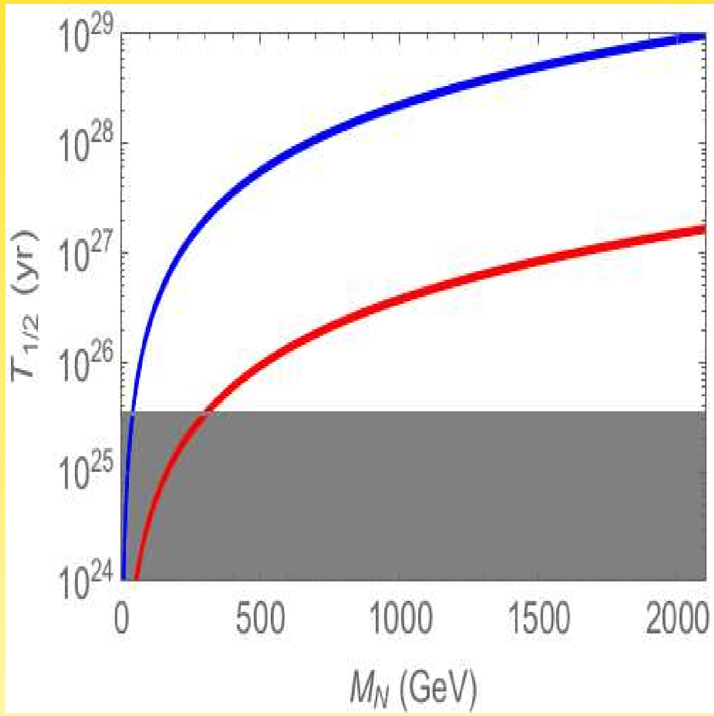


local 2.8σ at $M_{W_R} = 2.1$ TeV, only in ee-channel

Interpretation

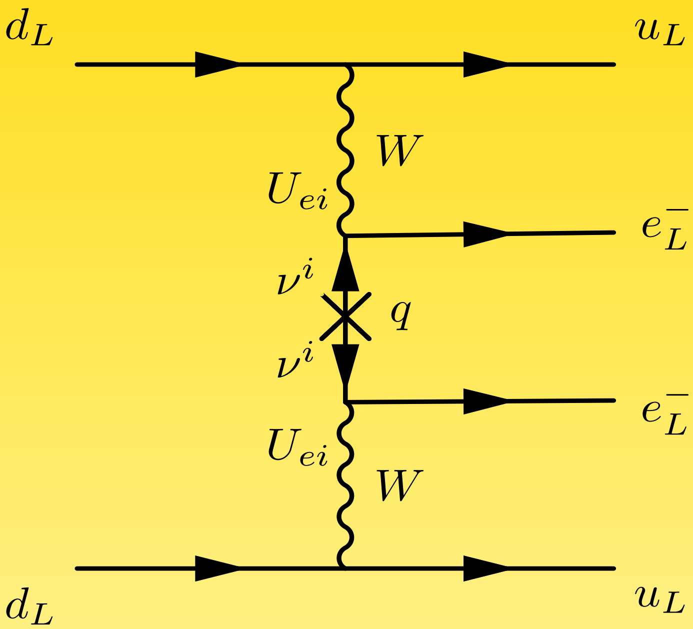
Modified LRSM, $g_R = 0.6\, g_L$ (scalar fields of $SU(2)_L$ have different masses than scalar fields of $SU(2)_R$)

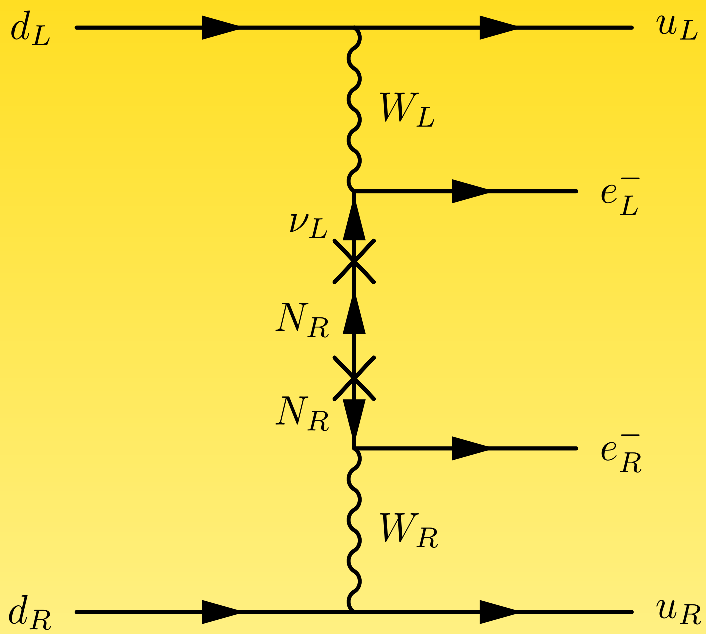




Deppisch *et al.*, 1407.5384

Tests of the λ diagram





$\frac{d\Gamma}{dE_1\, dE_2\, d\cos\theta} \propto (1 - \beta_1\, \beta_2\, \cos\theta)$ $\quad$ $\frac{d\Gamma}{dE_1\, dE_2\, d\cos\theta} \propto (E_1 - E_2)^2\, (1 + \beta_1\, \beta_2\, \cos\theta)$

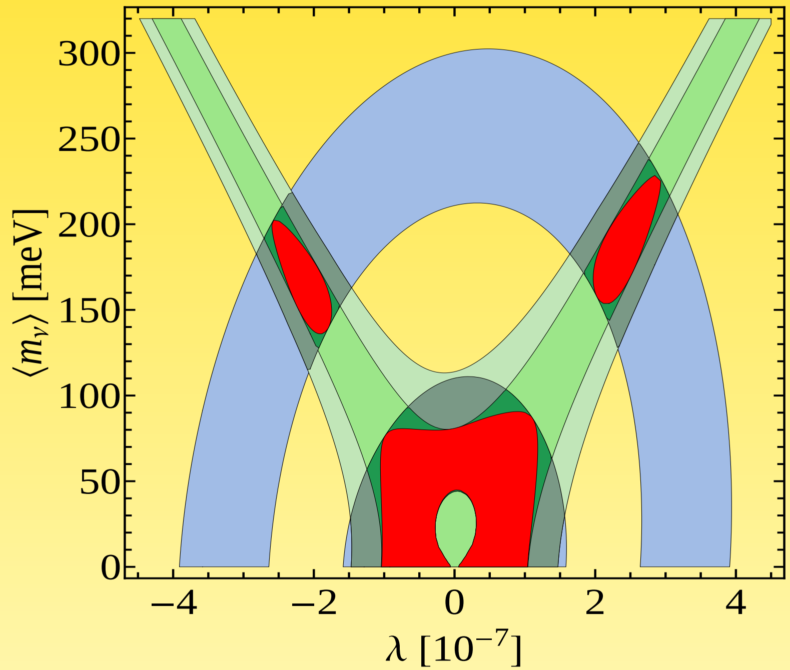
Defining asymmetries

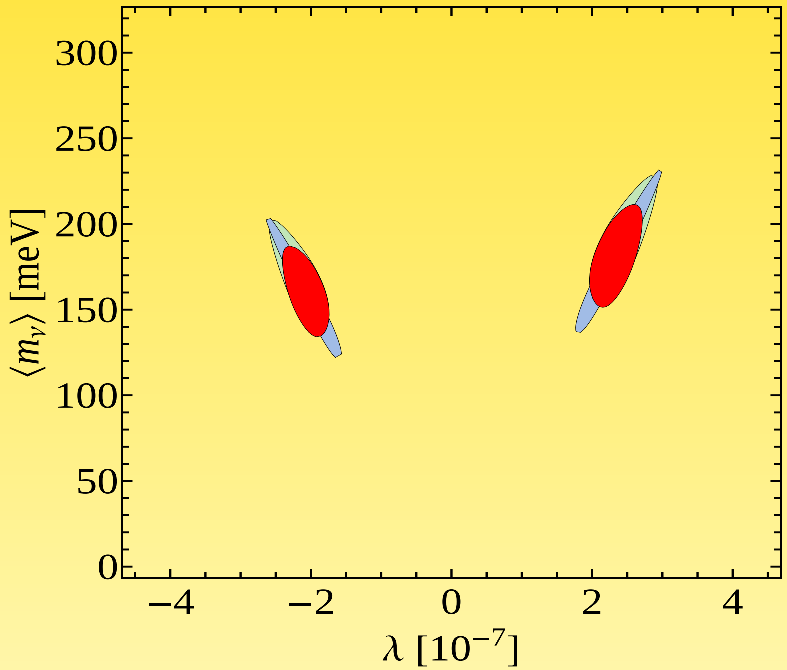
$A_\theta = (N_+ - N_-)/(N_+ + N_-)$ and $A_E = (N_> - N_<)/(N_> + N_<)$

Tests of the λ diagram

Defining asymmetries

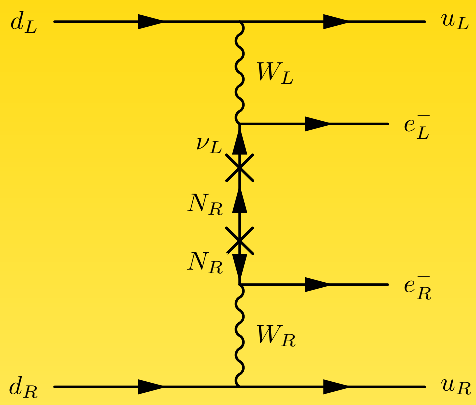
$A_\theta = (N_+ - N_-)/(N_+ + N_-)$ and $A_E = (N_> - N_<)/(N_> + N_<)$



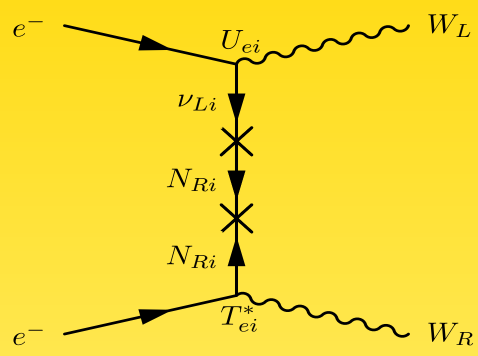


SuperNEMO *et al.*, 1005.1241

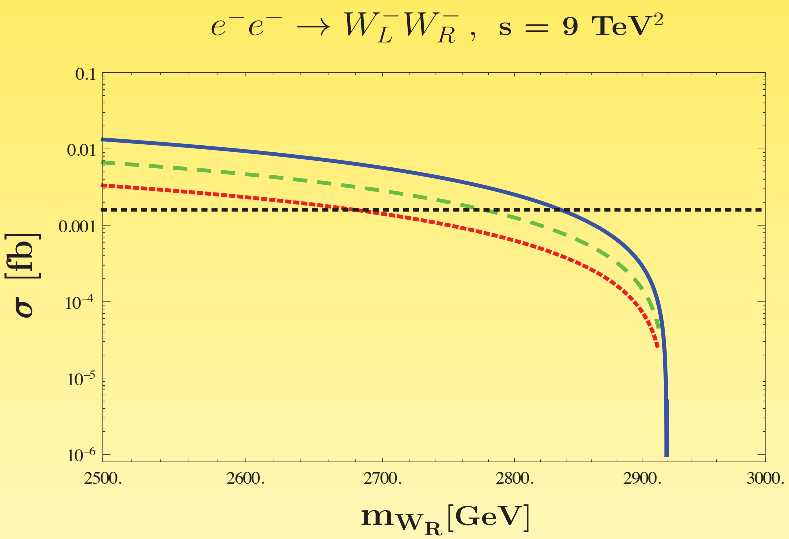
Tests of the λ diagram



$0\nu\beta\beta$



W-W_R production



Barry, Dorame, W.R., EPJ **C72**