Constraining Neutrino Mass from $0\nu\beta\beta$ decay

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From Majorana to LHC: ICTP, October 2013

Plan of the talk

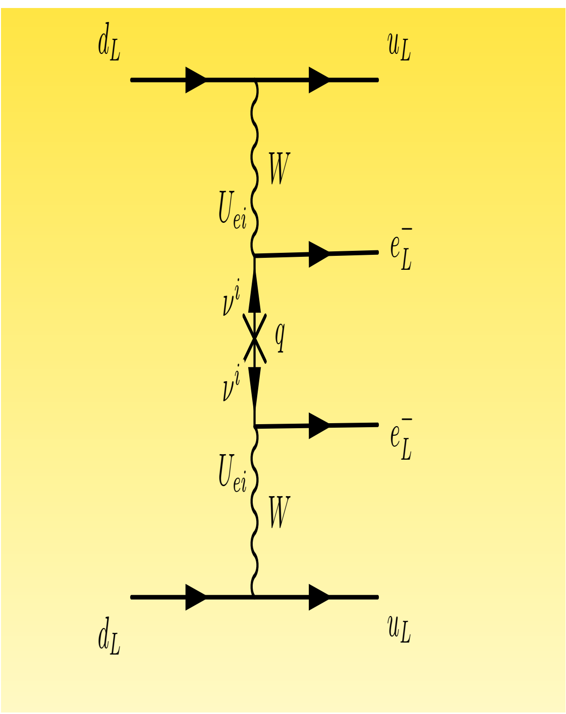
- Implications of recent results for neutrinoless double beta decay and the Planck results
- Implications for the Left-Right Symmetric Model

P. S. Bhupal Dev, S. Goswami, M. Mitra and W. Rodejohann, arXiv:1305.0056

J. Chakrabortty, H. Z. Devi, S. Goswami and S. Patra, JHEP **1208**, 008 (2012)

Neutrinoless Double Beta decay

- $(A, Z) \to (A, Z+2) + 2e^- \implies$ signifies violation of Lepton Number by 2 units
- Standard Picture: $0\nu\beta\beta$ mediated by the light neutrinos



- The half-life for $0\nu\beta\beta$,

$$\frac{1}{T^{0\nu}_{1/2}} = G|\mathcal{M}_\nu|^2 \left|\frac{m^\nu_{ee}}{m_e}\right|^2 ,$$

- $G \to$ contains the phase space factors (calculable)
- $\mathcal{M}_\nu$ is the nuclear matrix element (important and complicated.)

Talk by Civiterase, this workshop

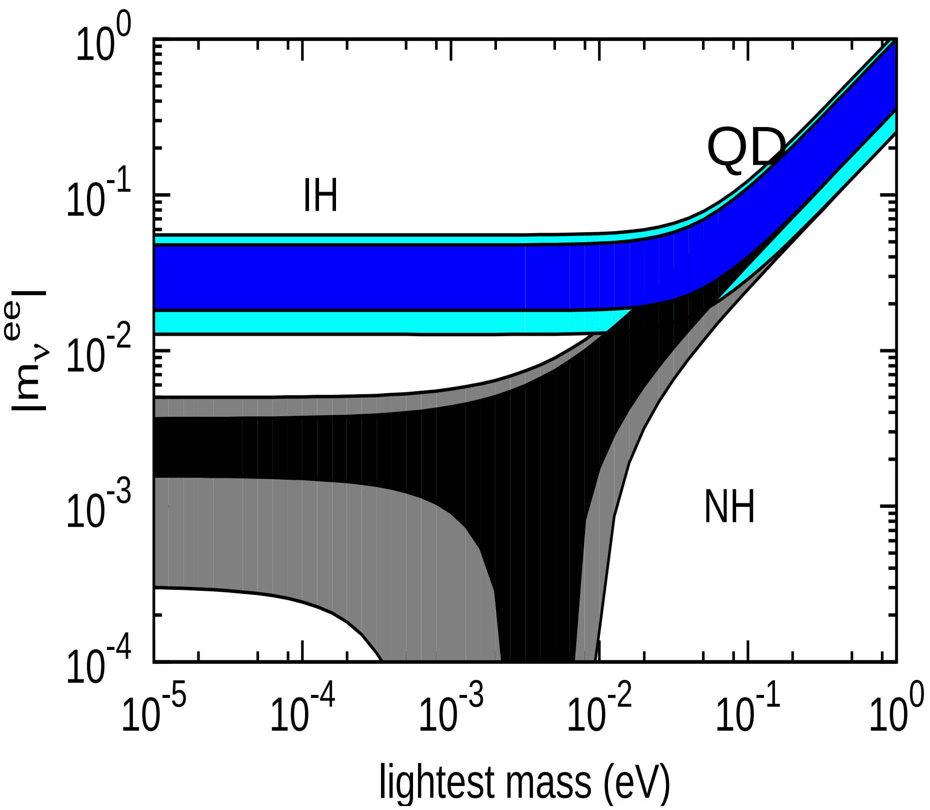
- $|m^{ee}_\nu| = |U^2_{ei}\, m_i| \to$ the effective mass, (interesting)

The effective mass

$$|m_\nu^{ee}| = |m_1 U_{e1}^2 + m_2 U_{e2}^2 e^{2i\alpha_1} + m_3 U_{e3}^2 e^{2i\alpha_2}|$$

• ν Mass Spectrum • Absolute ν Mass Scale • CP phases

- Depends on 7 out of 9 parameters of neutrino mass matrix



NH: $m_1 << m_2 << m_3$

IH: $m_3 << m_1 \approx m_2$

QD: $m_1 \approx m_2 \approx m_3$

$0\nu\beta\beta$: Experimental Results-I

- One Positive claim :

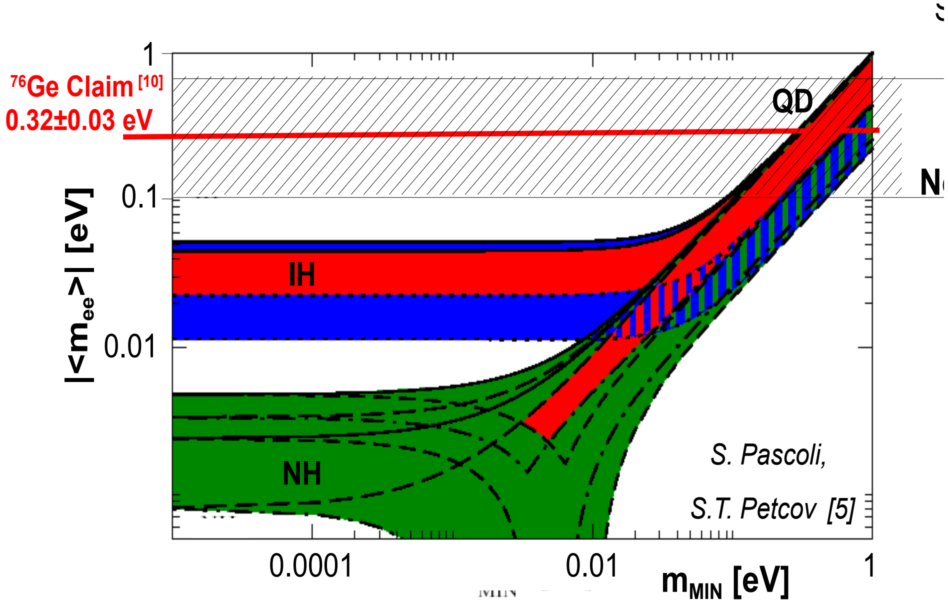
  $T^{0\nu}_{1/2} = 1.19^{+0.37}_{-0.23} \times 10^{25}$ yr at 68% CL using ^{76}Ge

  Klapdor-Kleingrothaus, Krivosheina, Dietz, Chkvorets, Phys. Lett. B **586**, 198 (2004).

  $T^{0\nu}_{1/2} = 2.23^{+0.44}_{-0.31} \times 10^{25}$ yr at 68% CL using ^{76}Ge

  H. V. Klapdor-Kleingrothaus and I. V. Krivosheina, Mod. Phys. Lett. A **21**, 1547 (2006).

- Depending on the NME used: $m^{\nu}_{ee} = 0.21 - 0.58$ eV



- $\Longrightarrow$ neutrinos are quasi-degenerate
- Many new experiments were planned to test this..

$0\nu\beta\beta$: Experimental Results-II

- Results from experiments using ^{136}Xe
- $T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr at 90% CL (KamLAND-ZEN)

  A. Gando *et al.* [KamLAND-Zen Collaboration], Phys. Rev. Lett. **110**, 062502 (2013).
- $T^{0\nu}_{1/2} > 1.6 \times 10^{25}$ yr at 90% C.L. (EXO)

  M. Auger *et al.* [EXO Collaboration], Phys. Rev. Lett. **109**, 032505 (2012).
- $T^{0\nu}_{1/2} > 3.4 \times 10^{25}$ yr at 90% CL (Combined)

  A. Gando *et al.* [KamLAND-Zen Collaboration], Phys. Rev. Lett. **110**, 062502 (2013).

Compatibility between Experimental Results

- To test the compatibility between the results using different isotopes it is useful to study the correlation between their half-lives
- $\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu}|\mathcal{M}_\nu|^2 \left|\frac{m^\nu_{ee}}{m_e}\right|^2 ,$
- Eliminating m^ν_{ee}:
$$T^{0\nu}_{1/2}(^{Z_1}\mathrm{A}) = \frac{G^{\mathrm{B}}_{0\nu}}{G^{\mathrm{A}}_{0\nu}} \left|\frac{\mathcal{M}_{0\nu}(^{76}\mathrm{Ge})}{\mathcal{M}_{0\nu}(^{136}\mathrm{Xe})}\right|^2 T^{0\nu}_{1/2}(^{Z_2}\mathrm{B})$$
- The above can be used to test the compatibility between the positive claim in ^{76}Ge and the null results in ^{136}Xe
- Putting the phase space factors
$$T^{0\nu}_{1/2}(^{136}\mathrm{Xe}) = \left(3.61^{+1.18}_{-0.83} \times 10^{24}\ \mathrm{yr}\right) \left|\frac{\mathcal{M}_{0\nu}(^{76}\mathrm{Ge})}{\mathcal{M}_{0\nu}(^{136}\mathrm{Xe})}\right|^2$$
- Experimental bound on $T^{0\nu}_{1/2}(^{136}\mathrm{Xe}) >$ the predicted value from the above equation $\Longrightarrow$ inconsistency with the positive claim

Compatibility between Experimental Results

NME			$T^{0\nu}_{1/2}(^{136}\mathrm{Xe})$
Method	$\mathcal{M}_{0\nu}(^{76}\mathrm{Ge})$	$\mathcal{M}_{0\nu}(^{136}\mathrm{Xe})$	$[10^{25}$ yr]
EDF(U)	4.60	4.20	0.33 - 0.57
ISM(U)	2.81	2.19	0.46 - 0.79
IBM-2	5.42	3.33	0.74 - 1.27
pnQRPA(U)	5.18	3.16	0.75 - 1.29
SRQRPA-B	5.82	3.36	0.84 - 1.44
SRQRPA-A	4.75	2.29	1.19 - 2.06
QRPA-B	5.571	2.460	1.43 - 2.46
QRPA-A	5.157	2.177	1.56 - 2.69
SkM-HFB-QRPA	5.09	1.89	2.02 - 3.47

- Limits from experiments using Xe:
  - $T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr at 90% CL (KamLAND-ZEN)
  - $T^{0\nu}_{1/2} > 1.6 \times 10^{25}$ yr at 90% C.L. (EXO)
  - $T^{0\nu}_{1/2} > 3.4 \times 10^{25}$ yr at 90% CL (KLZ + EXO)

Inconsistent for most NME's

Dev, S.G, Mitra, Rodejohann,2013

$0\nu\beta\beta$: Experimental Results-III

- Recent results from GERDA :
  $T^{0\nu}_{1/2}(^{76}\mathrm{Ge}) > 2.1 \times 10^{25}$ yr at 90% CL

  GERDA Collaboration, PRL 2013; G. Benato, this workshop

- GERDA + IGEX + HM :
  $T^{0\nu}_{1/2}(^{76}\mathrm{Ge}) > 3.0 \times 10^{25}$ yr at 90% CL

- The postive claim :
  $T^{0\nu}_{1/2} = 1.19^{+0.37}_{-0.23} \times 10^{25}$ yr at 68% CL (2004)
  $T^{0\nu}_{1/2} = 2.23^{+0.44}_{-0.31} \times 10^{25}$ yr at 68% CL using ^{76}Ge (2006)

- GERDA disfavour the 2004 results of Klapdor-Kleingotherus *et al.*
- But the 2006 results are still not ruled out by GERDA alone.
- Strong tension with the combined Ge bound
- Xe experiments provide a complementary way to test this

$0\nu\beta\beta$: Bounds on m_{ee}^{ν}

- The lower bound on half-lives can be translated into upper bound on m_{ee}^{ν}

NME	Limit on m_{ee}^{ν} (eV)				
	^{76}Ge			^{136}Xe	
	GERDA	comb	KK	KLZ	comb
EDF(U)	0.32	0.27	0.27-0.35	0.15	0.11
ISM(U)	0.52	0.44	0.44-0.58	0.28	0.21
IBM-2	0.27	0.23	0.23-0.30	0.19	0.14
pnQRPA	0.28	0.24	0.24-0.31	0.20	0.15
SRQRPA-B	0.25	0.21	0.21-0.28	0.18	0.14
SRQRPA-A	0.31	0.26	0.26-0.34	0.27	0.20
QRPA-B	0.26	0.22	0.22-0.29	0.25	0.19
QRPA-A	0.28	0.24	0.24-0.31	0.29	0.21
SkM-HFB-QRPA	0.29	0.24	0.24-0.32	0.33	0.25

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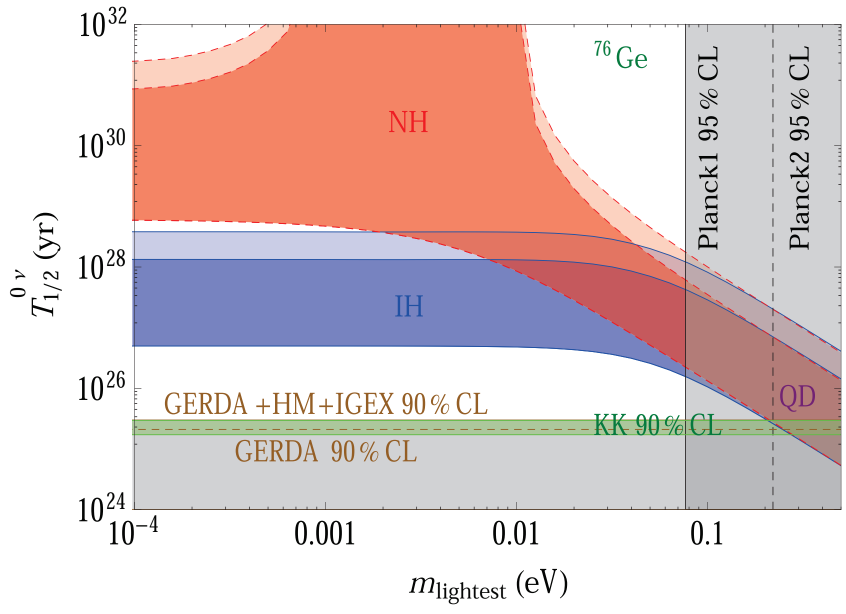
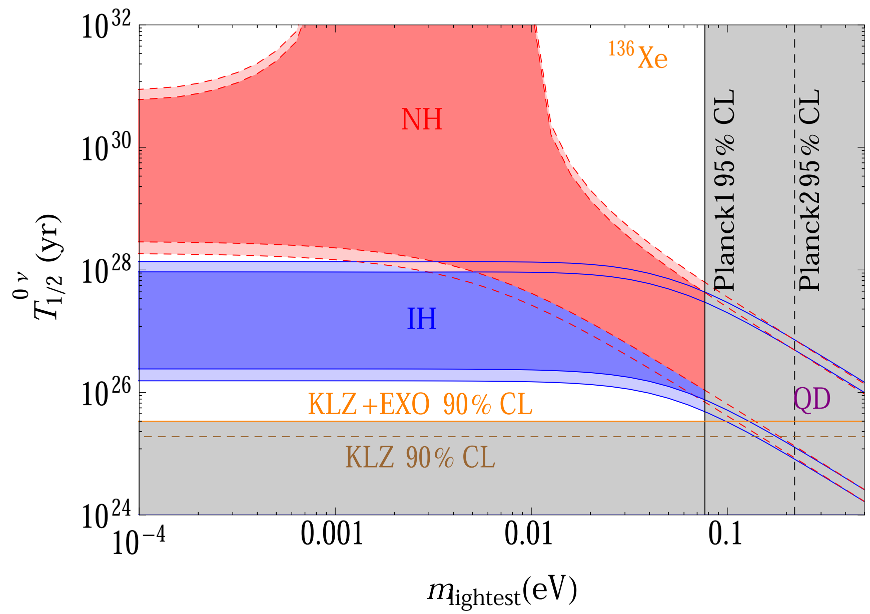
SRQRPA-B	0.25	0.21	0.21-0.28	0.18	0.14
SRQRPA-A	0.31	0.26	0.26-0.34	0.27	0.20
QRPA-B	0.26	0.22	0.22-0.29	0.25	0.19
QRPA-A	0.28	0.24	0.24-0.31	0.29	0.21
SkM-HFB-QRPA	0.29	0.24	0.24-0.32	0.33	0.25

- Combined Ge bounds are barely consistent with KK (2006)
- Inconsistent with combined KLZ+EXO limit for most NME's
- Bounds on m_{ee}^{ν} from KLZ+EXO stronger

Compatibility between Experimental Results





- The cosmological mass bound $\Sigma m_i < 0.23 - 0.63$ eV from Planck + others

  J. Hamnann, this workshop

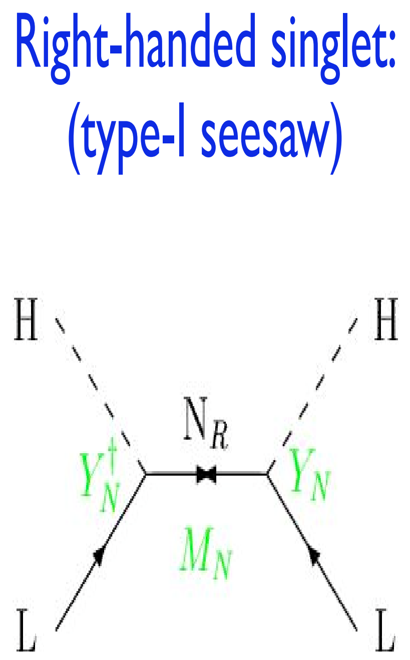
- Tension with the positive $0\nu\beta\beta$ claim of ^{76}Ge experiment
- Current $0\nu\beta\beta$ bounds can be reached only for higher masses
- New physics ??
- TeV scale Left-Right Symmetric model $\rightarrow$ Accessible at LHC

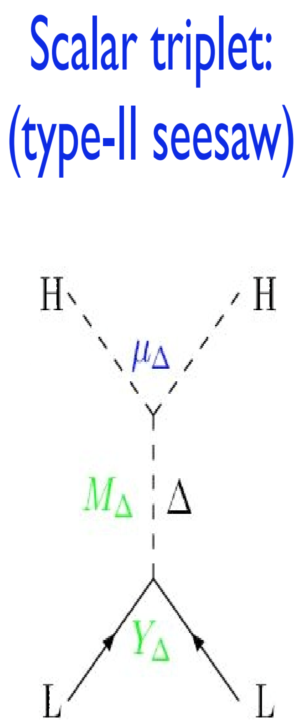
Left-Right Symmetric Model

- The minimal LR symmetric model is based on the gauge group $SU(3)_C \times SU(2)_L \times U(1)_{B-L}$
- B-L because $Q = T_{3L} + T_{3R} + \frac{B-L}{2}$
- Restoration of Parity symmetry at high scale
- The right-handed fields transform as $SU(2)_R$ doublets
- $\Longrightarrow$ existence of right-handed neutrinos N_R
- LR symmetry breaking is achieved by the triplet Higgs fields $\Delta_R \equiv (1, 3, 1)$
- For LR symmetry there is also a $\Delta_L \equiv (3, 1, 1)$
- There are extra gauge bosons W_R and Z'
- Neutrino mass is generated via seesaw mechanism

Seesaw in Left-Right Symmetric Model

- Type-I seesaw heavy particles are right-handed Majorana neutrinos N_R
- Type-II seesaw the heavy particles are Triplet Higgs fields





Neutrino Mass in Left-Right Symmetric Model

- The relevant Lagrangian is
  $\mathcal{L}_Y = f_L \bar{l}_L^C \Delta_L l_L + f_R \bar{l}_R^C \Delta_R l_R + \bar{l}_R (Y_D \phi + y_L \tilde{\Phi}) l_L + h.c.,$
- The Higgs fields acquires vacuum expectation values (vev) as:
  $$< \Phi >= \begin{pmatrix} v & 0 \\ 0 & v' \end{pmatrix}, < \Delta_L >= v_L, < \Delta_R >= v_R.$$
- Presence of $N_R \Longrightarrow$ Dirac mass term $m_D = Y_\nu v.$
- Triplet Higgs $\Longrightarrow$ Majorana Mass term $M_R = f_R v_R \quad m_T = f_L v_L$
- The mass matrix : $M_\nu \equiv \begin{pmatrix} f_L v_L & y_D v \\ y_D^T v & f_R v_R \end{pmatrix},$
- Light and Heavy neutrino masses:

$$(m_\nu)_{3\times 3} = f_L v_L + \frac{v^2}{v_R} y_D^T f_R^{-1} y_D,$$
$$(M_R)_{3\times 3} = f_R v_R,$$

The scale of Left-Right Symmetry Breaking

- Symmetry Breaking in LR model occurs as
  $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \xrightarrow{<\Delta_R>} SU(3)_C \times SU(2)_L \times U(1)_Y$
  $SU(3)_C \times SU(2)_L \times U(1)_Y \xrightarrow{<v>} SU(3)_C \times U(1)_{em}$
- The mass of M_{W_R} is related to v_R
- Usually M_{W_R} is taken as high.. consistent with small neutrino mass
- Can this scale be low $\sim$ TeV ?
- Direct limits :
  From LHC : $M_{W_R} \gtrsim 2.5$ TeV (CMS,ATLAS, 2012)
- Theoretical limits :
  $K_L - K_S$ mass difference $M_{W_R} \gtrsim 1.6$ TeV (Beall,Bander, A. Soni, PRL, 1982)
  Recent analysis improves this bound to $M_{W_R} \gtrsim 2.5$ TeV
  Zhang, Ji, Mohapatra, 2008; Maiezza, Nemevšek, Nesti,Senjanović,2010

Typical values of Dirac Coupling

- The right-handed neutrino mass $M_R = f_R v_R$
- Related to the scale of LR symmetry breaking
- For type-I seesaw $m_\nu = \frac{v^2}{v_R} y_D^T f_R^{-1} y_D \sim \frac{y_D^2 v^2}{f_R v_R}$
- If $f_R v_R \sim 10^{14}$ GeV $\Longrightarrow m_\nu \sim 0.1$ eV for $Y_D \sim \mathcal{O}(1)$ and $v \sim$ 100 GeV
- If $f_R v_R \sim$ 1000 GeV then we need $Y_D \sim 10^{-6}$ for $m_\nu \sim 0.1$ eV
- Defining $m_D = y_D v$, $m_D/M_R \sim 10^{-7}$
- Very small unless one allows for cancellations

$0\nu\beta\beta$ in LR symmetric models : Type-I dominance

- $M_\nu \equiv \begin{pmatrix} f_L v_L & y_D v \\ y_D^T v & f_R v_R \end{pmatrix}$,
- Type-I dominance $\Longrightarrow v_L = 0$ (admitted by minimization of potential)
- $\mathcal{U}^T \begin{pmatrix} 0 & m_D^T \\ m_D & M_R \end{pmatrix} \mathcal{U} = \begin{pmatrix} m_\nu^{diag} & 0 \\ 0 & M_R^{diag} \end{pmatrix}$
- $m_\nu^{diag} =$ diag(m_1, m_2, m_3) and $M_R^{diag} =$ diag(M_1, M_2, M_3)
- $\begin{pmatrix} \nu_L' \\ N_R^{c\prime} \end{pmatrix} = \mathcal{U} \begin{pmatrix} \nu_L \\ N_R^c \end{pmatrix}$,
- $\mathcal{U} = \begin{pmatrix} U_L & T \\ S & U_R \end{pmatrix}$,
- Off diagonal entries $T \approx S \approx m_D\, M_R^{-1}$

$0\nu\beta\beta$ in TypeI LR model : Additional Diagrams

- In flavour basis,

$$\mathcal{L}_{\rm CC} = \left[\overline{\ell}_{\alpha\, L}\,\gamma_\mu {\nu'}_{\alpha\, L}\, W_L^\mu + \overline{\ell}_{\alpha\, R}\,\gamma_\mu {N'}_{\alpha\, R}\, W_R^\mu\right] + \text{h.c.}$$

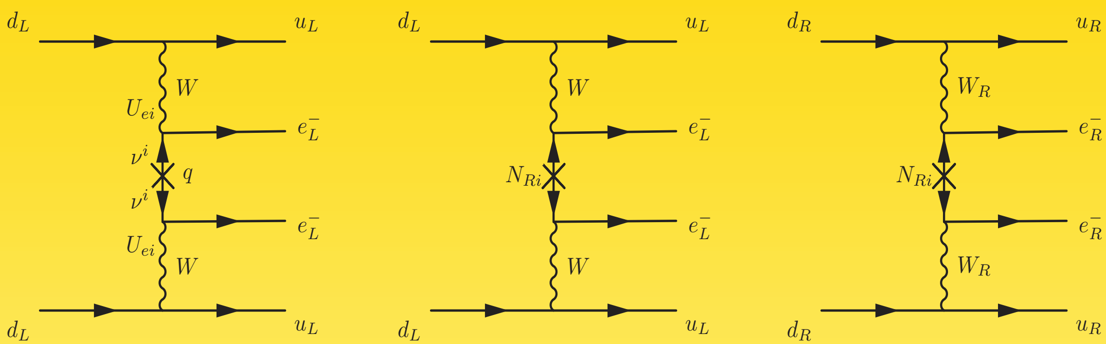
- In mass basis,

$$\begin{aligned}\mathcal{L}_{\rm CC} &= \frac{g}{\sqrt{2}} \sum_\alpha \sum_{i=1}^{3} \Big[\overline{\ell}_{\alpha\, L}\,\gamma_\mu \left\{(U_L)_{\alpha i}\nu_{Li} + (T)_{\alpha i} N^c_{Ri}\right\} W_L^\mu \\ &+ \overline{\ell}_{\alpha\, R}\,\gamma_\mu \left\{(S)^*_{\alpha i}\nu^c_{Li} + (U_R)^*_{\alpha i} N_{Ri}\right\} W_R^\mu\Big] + \text{h.c.}\end{aligned}$$

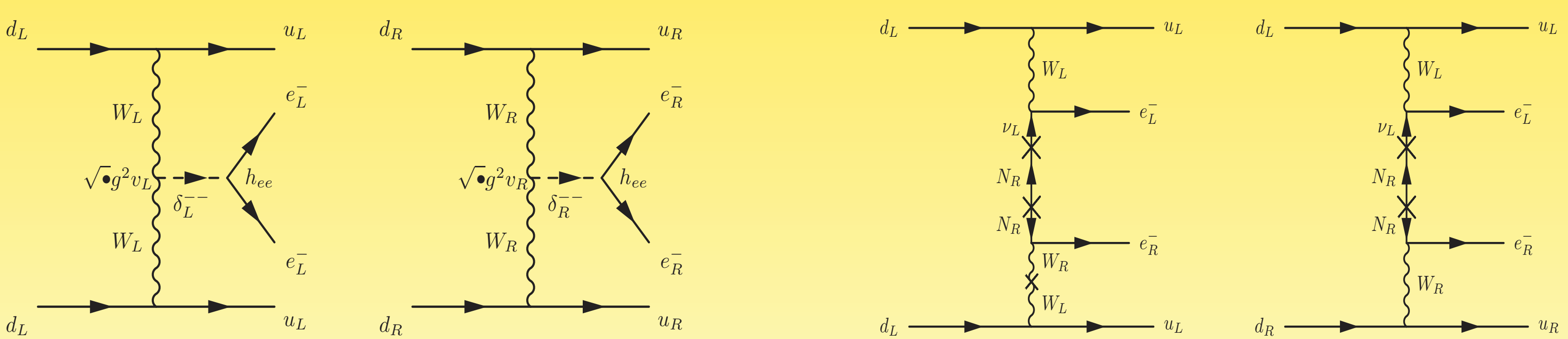
- Extra diagrams due to exchange of W_R and the charged Higgs fields

$0\nu\beta\beta$ in Type-I LR model : Additional Diagrams

Left-right symmetry



$U_{ei}^2\, m_i$ $\qquad \dfrac{S_{ei}^2}{M_i}$ $\qquad \dfrac{V_{ei}^2}{M_{W_R}^4\, M_i}$



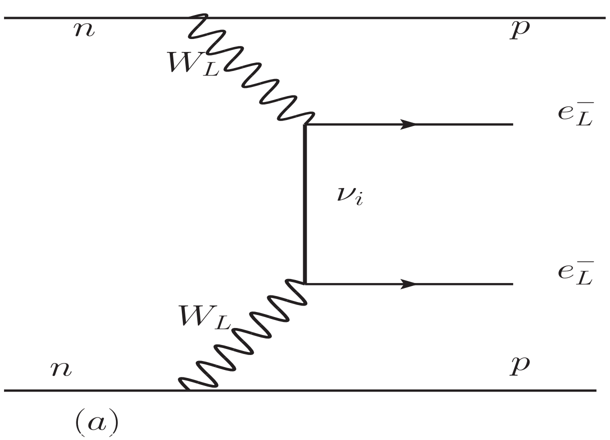
$\dfrac{U_{ei}^2\, m_i}{M_{\Delta_L}^2}$ $\qquad \dfrac{V_{ei}^2\, M_i}{M_{W_R}^4\, M_{\Delta_R}^2}$ $\qquad U_{ei}\, T_{ei} \tan\zeta$ $\qquad \dfrac{U_{ei}\, T_{ei}}{M_{W_R}^2}$

slide courtsey: W. Rodejohann

$0\nu\beta\beta$ in Type-I LR model : Dominant Contributions

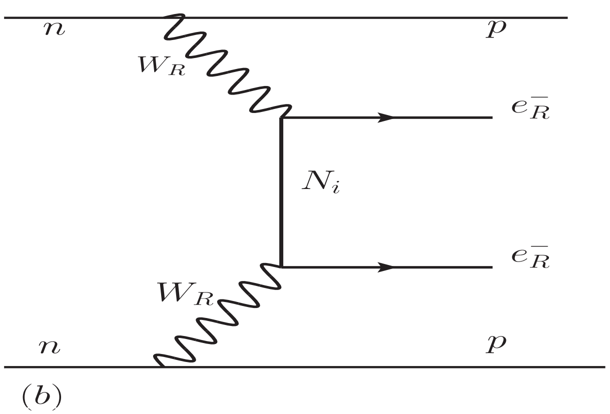
- $T_{ei} \sim S_{ei} \sim m_D/M_R \sim 10^{-6} << U_{Lei}$
- Mixed Diagrams (LR) can be neglected
- Possible to have large T_{ei} and S_{ei} in specific textures with cancellations

Pilaftsis; Kersetn & Smirnov, Adhikari & Raychaudhuri;Barry and Rodejohann



Light neutrino exchange

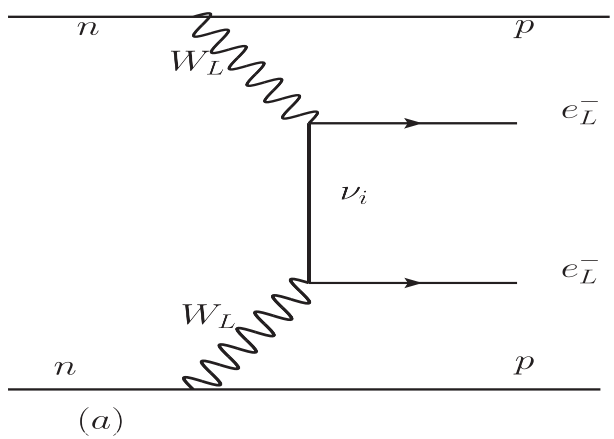
$$\mathcal{A}_{\nu}^{LL} \propto \frac{1}{M_{W_L}^4} \frac{U_{L_{e\,i}}^2\, m_i}{p^2}$$

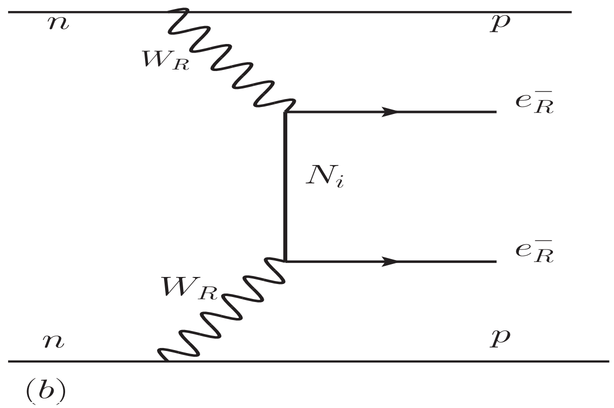


Heavy neutrino exchange

$$\mathcal{A}_{N}^{RR} \propto \frac{1}{M_{W_R}^4} \frac{(U_{R_{e\,i}}^*)^2}{M_i}$$

$0\nu\beta\beta$ in TypeI LR model : Dominant Contributions





Light neutrino exchange

$$\mathcal{A}_\nu^{LL} \propto \frac{1}{M_{W_L}^4} \frac{U_{L_{e\,i}}^2 m_i}{p^2}$$

Heavy neutrino exchange

$$\mathcal{A}_N^{RR} \propto \frac{1}{M_{W_R}^4} \frac{(U_{R_{e\,i}}^*)^2}{M_i}$$

- The different dependence on mass comes since propagator $\sim \frac{m^2}{p^2 - m^2}$ and $m_i << p << M_i$
- $p \sim 10$ MeV, $m_i \sim 0.01 - 0.1$ eV, $M_i \sim 100$ GeV

Type-I dominance and $0\nu\beta\beta$

- $\frac{\Gamma_{0\nu\beta\beta}}{\ln 2} = G\Big(|\mathcal{M}_\nu|^2|\eta_L|^2 + |\mathcal{M}_N|^2|\eta_R|^2\Big)$,
  $|\eta_L| = \frac{|U_{Lei}^2 m_i|}{m_e} = |m_\nu^{ee}|/m_e$
  $|\eta_R| = \frac{M_{W_L}^4}{M_{W_R}^4}|(U_R)_{ei}^2 m_p/M_i|$
- $\mathcal{M}_\nu$ and $\mathcal{M}_N$ $\rightarrow$ the nuclear matrix elements for light and heavy neutrino exchange respectively

Type-I dominance and $0\nu\beta\beta$

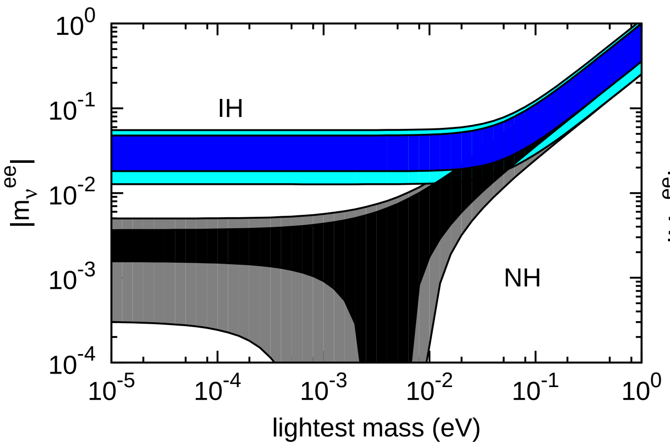
- $$\frac{\Gamma_{0\nu\beta\beta}}{\ln 2} = G\left(|\mathcal{M}_\nu|^2|\eta_L|^2 + |\mathcal{M}_N|^2|\eta_R|^2\right),$$
  $$|\eta_L| = \frac{|U_{Lei}^2 m_i|}{m_e} = |m_\nu^{ee}|/m_e$$
  $$|\eta_R| = \frac{M_{W_L}^4}{M_{W_R}^4}|(U_R)_{ei}^2 m_p/M_i|$$
- $\mathcal{M}_\nu$ and $\mathcal{M}_N \to$ the nuclear matrix elements for light and heavy neutrino exchange respectively
- $$\frac{\Gamma_{0\nu\beta\beta}}{\ln 2} = \frac{G|\mathcal{M}_\nu|^2|}{m_e^2}|m_{ee}^{\rm eff}|^2.$$
- $$|m_{\rm ee}^{\rm eff}|^2 = |m_\nu^{ee}|^2 + |M_N^{ee}|^2$$
- $$|M_N^{ee}| = \left| < p >^2 \frac{M_{W_L}^4}{M_{W_R}^4}\frac{(U_R)_{ei}^2}{M_i}\right|$$
- $\left| < p^2 > \right| = \left|m_e m_p \mathcal{M}_N/\mathcal{M}_\nu\right| \sim 100 - 200$ (MeV)^2
- $< p^2 >$ encapsulates the Nuclear matrix element uncertainties

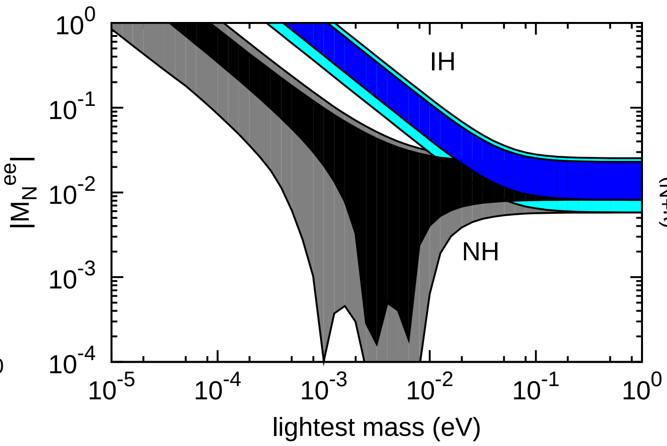
Type-I dominance and $0\nu\beta\beta$

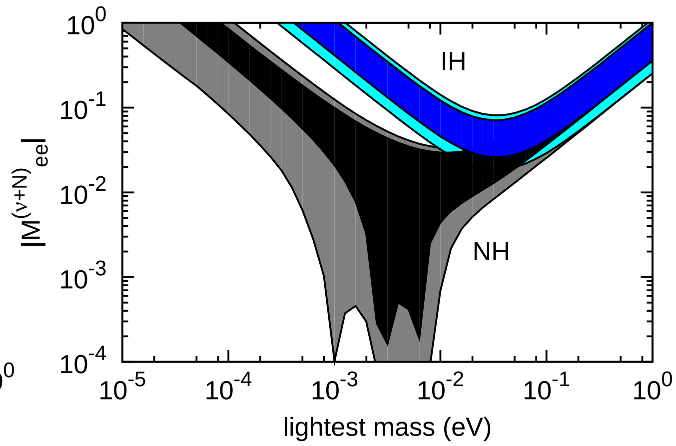
- LR symmetry $\rightarrow f_L = f_R = f$ or $f_L = f_R^*$
- Then $m_\nu = \frac{v^2}{v_R} y_D^T f^{-1} y_D$,
  $M_R = f v_R$
- Assuming y_D diagonal,
- $U_L = U_R, \quad \text{and} \quad m_i \propto \frac{1}{M_i}$
- Hierarchy of the heavy neutrinos is related to that of light neutrinos
- For numerical work we assume $y_{D1} = y_{D2} = y_{D3}$

J. Chakrabortty, H. Zeen Devi, S. Goswami, S, Patra JHEP, 2012

Type-I dominance and $0\nu\beta\beta$







$$|m_\nu^{ee}| = |U_{ei}^2\, m_i|$$

$$|M_N^{ee}| = |C_N \frac{(U_R)_{ei}^2}{M_i}|$$

$$[|m_\nu^{ee}|^2 + |M_N^{ee}|^2]^{1/2}$$

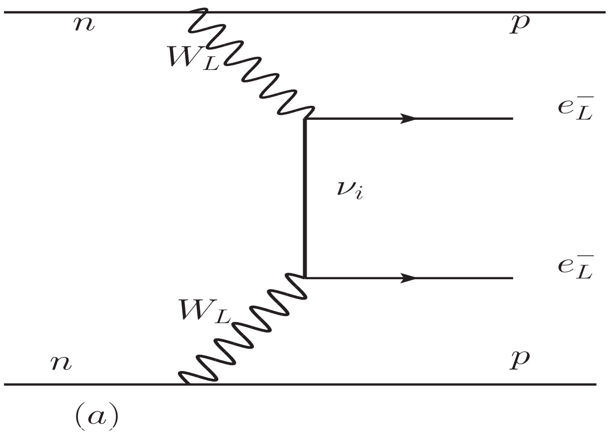
- Right-handed contribution dominates for smaller m_1
- Left-handed contribution dominates in the QD regime
- Large effective mass even for smaller values of masses
- Cancellation region remains the same

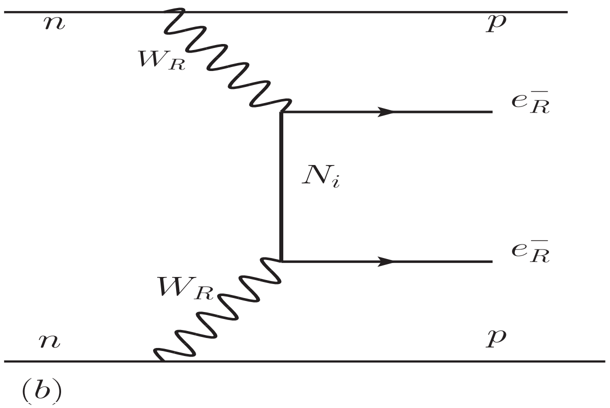
J. Chakrabortty, H. Zeen Devi, S. Goswami, S, Patra JHEP, 2012

Type-II dominance

- $$M_\nu \equiv \begin{pmatrix} f_L v_L & y_D v \\ y_D^T v & f_R v_R \end{pmatrix},$$
- Type-II dominance $\Longrightarrow y_D = 0$
- $(m_\nu)_{3\times 3} = f_L v_L$
- $(M_R)_{3\times 3} = f_R v_R,$
- LR symmetry $\Longrightarrow f_L = f_R$ (parity) or $f_L = f_R^*$ (charge-conjugation)
- $$\begin{pmatrix} \nu_L' \\ N_R^{c\prime} \end{pmatrix} = \mathcal{U} \begin{pmatrix} \nu_L \\ N_R^c \end{pmatrix}, \quad \mathcal{U} = \begin{pmatrix} U_L & 0 \\ 0 & U_R \end{pmatrix}$$

$0\nu\beta\beta$ in Type-II LR model : Additional Diagrams





Light neutrino exchange

$$\mathcal{A}_{\nu}^{LL} \propto \frac{1}{M_{W_L}^4} \frac{U_{L_{e\,i}}^2\, m_i}{p^2}$$

Heavy neutrino exchange

$$\mathcal{A}_{N}^{RR} \propto \frac{1}{M_{W_R}^4} \frac{(U_{R_{e\,i}}^*)^2}{M_i}$$

- The different dependence on mass comes since propagator $\sim \frac{m^2}{p^2 - m^2}$ and $m_i << p << M_i$
- Typical values $p \sim 10$ MeV, $m_i \sim 0.01 - 0.1$ eV, $M_i \sim 100$ GeV

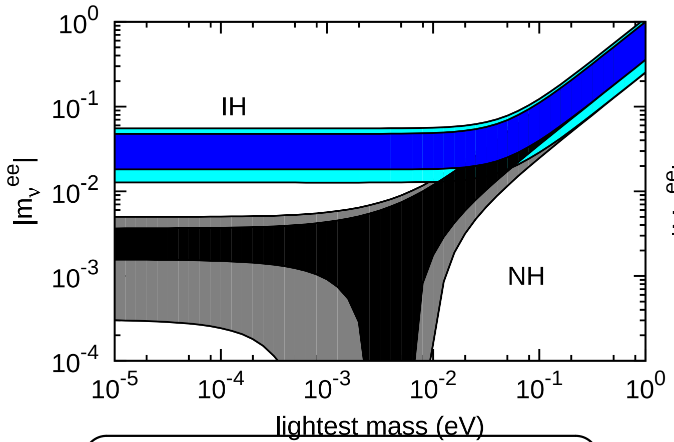
Type-II dominance and $0\nu\beta\beta$

- $$\frac{\Gamma_{0\nu\beta\beta}}{\ln 2} = G\left(|\mathcal{M}_\nu|^2|\eta_L|^2 + |\mathcal{M}_N|^2|\eta_R|^2\right),$$
  $$|\eta_L| = \frac{|U_{Lei}^2 m_i|}{m_e} = |m_\nu^{ee}|/m_e$$
  $$|\eta_R| = \frac{M_{W_L}^4}{M_{W_R}^4}|(U_R)_{ei}^2 m_p/M_i|$$
- $\mathcal{M}_\nu$ and $\mathcal{M}_N \rightarrow$ the nuclear matrix elements for light and heavy neutrino exchange respectively
- $$\frac{\Gamma_{0\nu\beta\beta}}{\ln 2} = \frac{G|\mathcal{M}_\nu|^2|}{m_e^2}|m_{ee}^{\text{eff}}|^2.$$
- $|m_{\text{ee}}^{\text{eff}}|^2 = |m_\nu^{ee}|^2 + |M_N^{ee}|^2$
- $|M_N^{ee}| = \left| < p >^2 \frac{M_{W_L}^4}{M_{W_R}^4}\frac{(U_R)_{ei}^2}{M_i}\right|$ (for $M_j^2 \gg |\langle p^2\rangle|$)
- $\left| < p^2 > \right| = \left|m_e m_p \mathcal{M}_N/\mathcal{M}_\nu\right| \sim 100 - 200$ MeV
- $< p^2 >$ encapsulates the Nuclear matrix element uncertainties

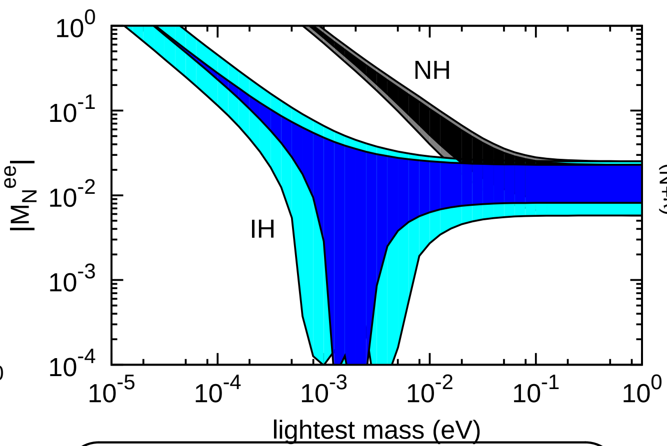
Tello, Nemevsek, Nesti, Senjanovic and Vissani, Phys. Rev. Lett. **106**, 151801 (2011).

Type-II dominance and $0\nu\beta\beta$

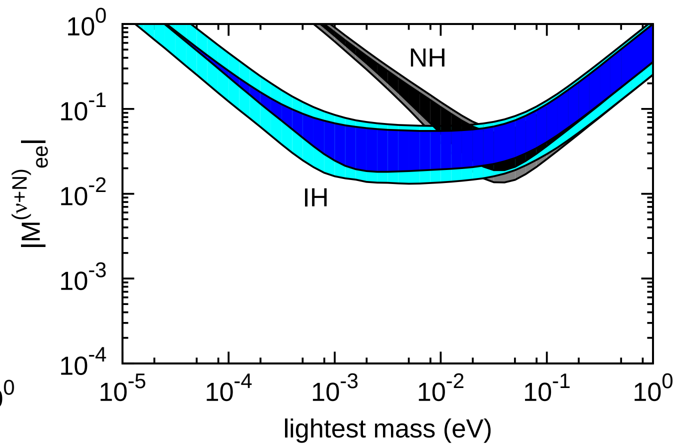
- LR symmetry : $f_L = f_R = f$ (parity)
- Then, $m_\nu = f_L v_L$, $M_R = f_R v_R \Longrightarrow m_i \propto M_i$



$$|m_\nu^{ee}| = |U_{ei}^2\, m_i|$$



$$|M_N^{ee}| = |C_N \frac{(U_R)_{ei}^2}{M_i}|$$

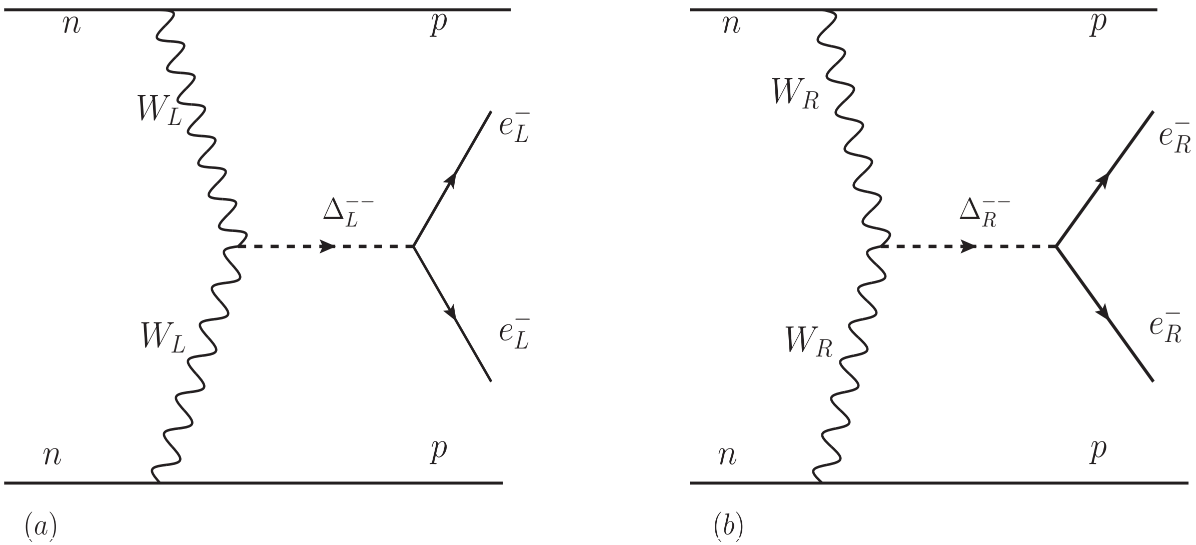


$$[|m_\nu^{ee}|^2 + |M_N^{ee}|^2]^{1/2}$$

- Right-handed contribution dominates for smaller m_1
- Left-handed contribution dominates in the QD regime
- Large effective mass even for smaller values of masses
- Complete role reversal among NH and IH , no cancellation region.

J. Chakrabortty, H. Zeen Devi, S. Goswami, S, Patra JHEP, 2012

Triplet Higgs Contribution



Δ_L exchange

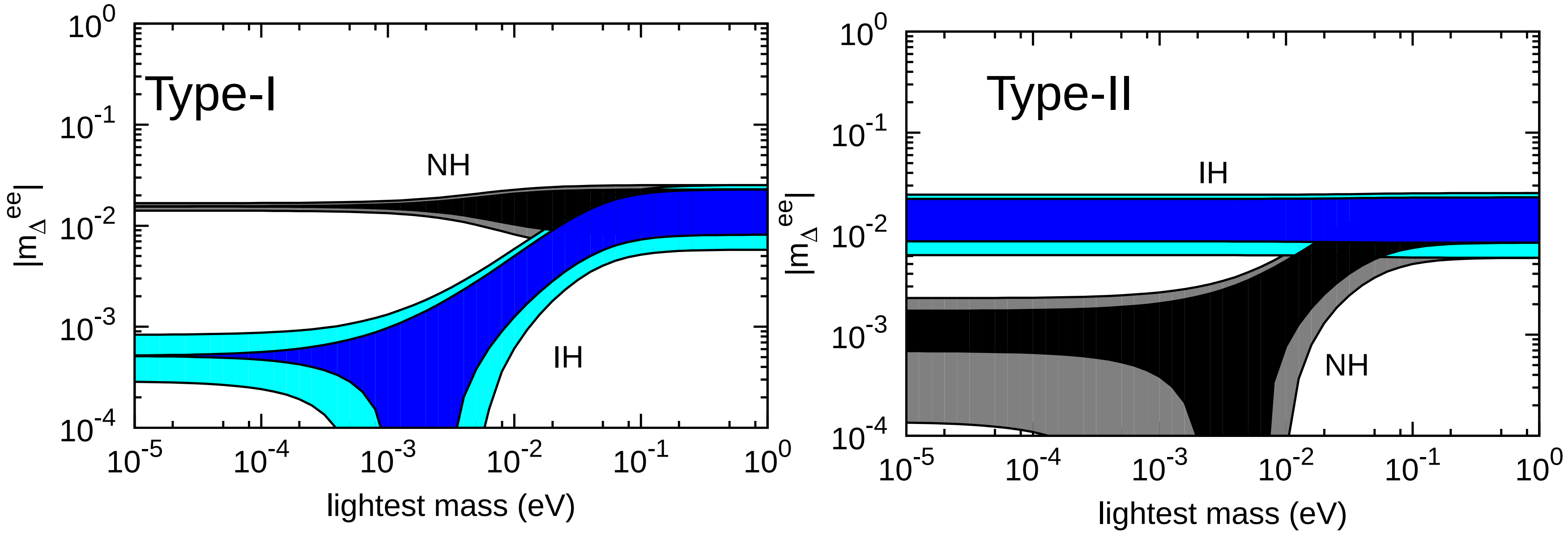
$$\mathcal{A}_{\Delta_L}^{LL} \propto \frac{1}{M_{W_L}^4} \frac{1}{M_{\Delta_L}^2} f_L v_L$$

Δ_R exchange

$$\mathcal{A}_{\Delta_R}^{RR} \propto \frac{1}{M_{W_R}^4} \frac{1}{M_{\Delta_R^2}} f_R v_R$$

- $$\frac{\Gamma^{0\nu\beta\beta}}{\ln 2} = G \frac{|\mathcal{M}_\nu|^2}{m_e^2} \left| \left(\frac{U_{Lei}^2 m_i m_e^2}{M_{\Delta_L}^2} + p^2 \frac{M_{W_L}^4}{M_{W_R}^4} \frac{U_{Rei}^2 M_i}{M_{\Delta_R}^2} \right) \right|^2 .$$
- $$|m_\Delta^{ee}| = \left| p^2 \frac{M_{W_L}^4}{M_{W_R}^4} \frac{2\, M_N}{M_{\Delta_R}^2} \right| .$$
- LFV constraints $\Longrightarrow M_N / M_{\Delta_R} < 0.1$ in most of the parameter space

Triplet Higgs contribution to $0\nu\beta\beta$

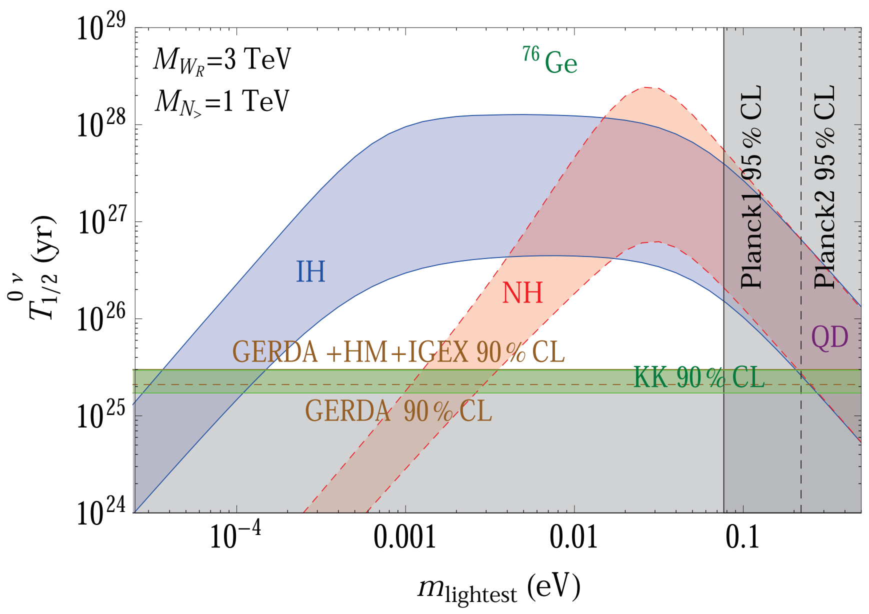


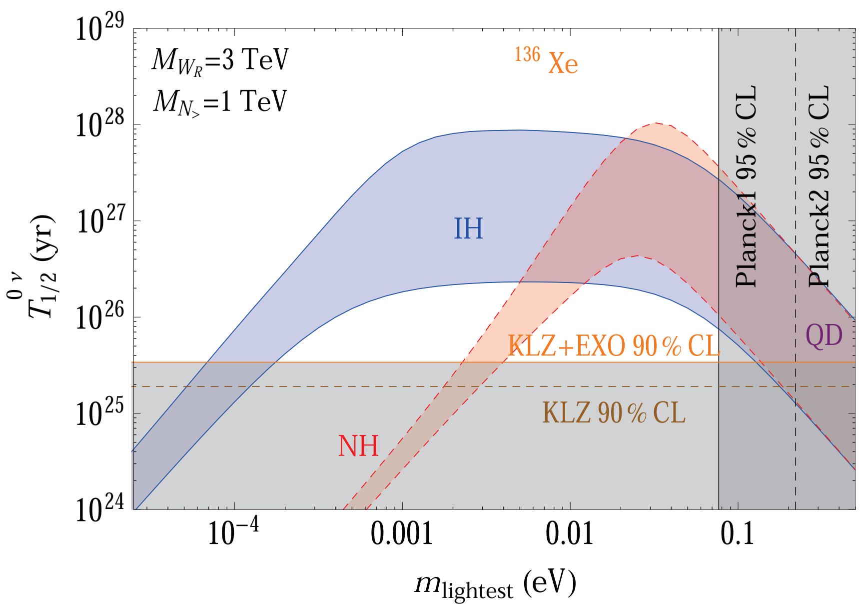
- Assume $M_N/M_{\Delta_R} = 1$
- Can be important for type-I case

J. Chakrabortty, H. Zeen Devi, S. Goswami, S, Patra JHEP, 2012

See also Barry and Rodejohann, 1303.6324

Constraints on neutrino masses: Type-II case





- KK claim can be reached for lower values of masses for some NMEs.
- Current bounds can be staurated by hierarchical neutrinos
- For lower values of masses the experimental limit is crossed $\Longrightarrow$ lower bound on neutrino masses
- Typical bounds are (2-3) meV (NH) and (0.07 -0.2) meV for IH
- Bound depends on the W_R and N_R mass; Valid only in the limit $M_i >> p$

Dev, S.G, Mitra, Rodejohann,2013

Compatibility between Results for Heavy ν case

- $T^{0\nu}_{1/2}({}^{Z_1}\mathrm{A}) = \frac{G^{\mathrm{B}}_{0\nu}}{G^{\mathrm{A}}_{0\nu}} \left| \frac{\mathcal{M}_{0\nu}({}^{76}\mathrm{Ge})}{\mathcal{M}_{0\nu}({}^{136}\mathrm{Xe})} \right|^2 T^{0\nu}_{1/2}({}^{Z_2}\mathrm{B})$
- NME for heavy neutrinos

Meroni, Petcov, Simkovic, JHEP **1302**, 025 (2013).

- Predicted $T^{0\nu}_{1/2}({}^{136}\mathrm{Xe}) : (0.56 - 2.74) \times 10^{25}$ yr, 90% C.L.
- Can be consistent with individual KLZ and EXO but not with their combined limit
- Similar conclusion holds for light+heavy contribution.

Dev, S.G, Mitra, Rodejohann,2013

Compatibility between Results for Heavy ν case

- For the heavy neutrino case one can compare the upper limits on the corresponding effective mass parameter $M_{W_R}^{-4} \sum_j U_{Rej}^2/M_j$

SRQRPA NME method	Limit on $M_{W_R}^{-4} \sum_j U_{Rej}^2/M_j$ (TeV^{-5})				
	^{76}Ge			^{136}Xe	
	GERDA	comb	KK	KLZ	comb
Argonne intm	0.30	0.25	0.24-0.33	0.18	0.13
Argonne large	0.26	0.22	0.22-0.29	0.18	0.14
CD-Bonn intm	0.20	0.16	0.17-0.22	0.17	0.13
CD-Bonn large	0.17	0.14	0.14-0.18	0.17	0.13

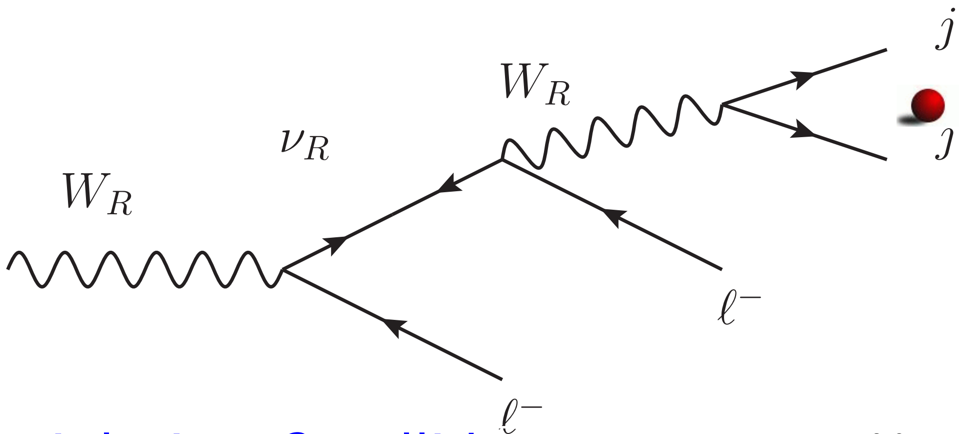
Z

- ‘Argonne’ and “CD-Bonn" $\rightarrow$ different nucleon-nucleon potentials

Meroni, Petcov Simkovic, JHEP **1302**, 025 (2013).

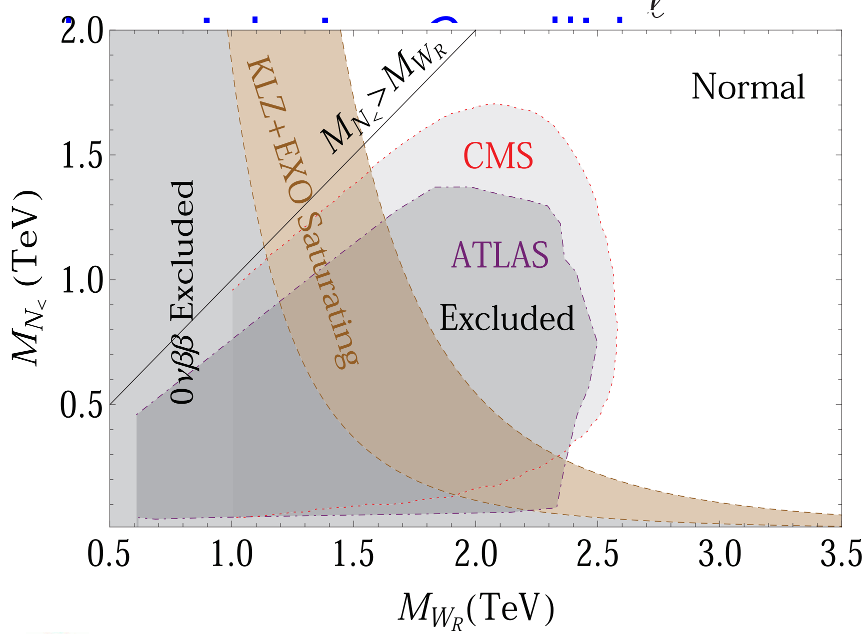
- KLZ+EXO cimbined limits inconsistent with KK results

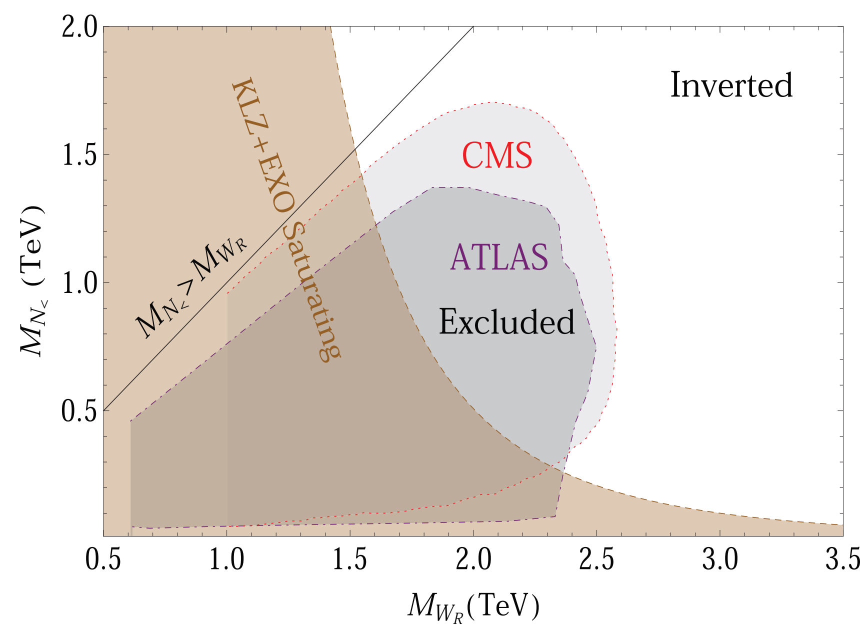
Lepton Number violation at Colliders



- Same sign di-leptons + jet , Golden Channel

[Keung Senjanovic '83]





- Complimentary constraints for NH

Dev, S.G, Mitra, Rodejohann,2013

Conclusion and Outlook

- The 2006 KK results though consistent with GERDA alone – in tension with combined GERDA + IGEX + HM limits.
- The KLZ+EXO combined bound is inconsistent with the KK results for most of the Nuclear Matrix Element calculations.
- A positive signal of $0\nu\beta\beta$ in QD region may be in conflict with cosmology
- The current bounds can also be saturated only in the QD regime.
- New Physics ?
- We consider LR symmetric model with $M_{W_R} \sim$ 3.5 TeV
- Can be accessible at LHC
- Large effective mass even for hierarchical neutrinos
- This can set a lower limit on light neutrino mass
- Signature of TeV scale LR symmetry at LHC can result in a completely different interpretation of effective neutrino mass in $0\nu\beta\beta$ process.