Neutrinoless Double Beta Decay and Particle Physics

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Portoroz 2015

09/04/15

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MANITOP
Massive Neutrinos: Investigating their Theoretical Origin and Phenomenology

Portorož 2015
Particle Phenomenology From the Early Universe to High Energy Colliders

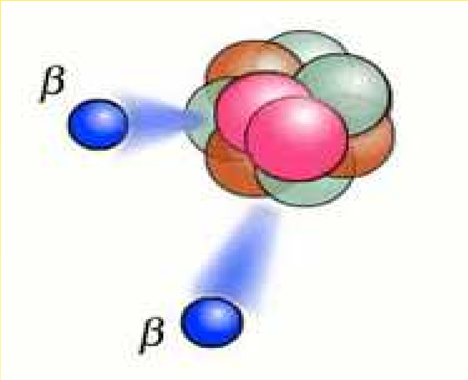
Heisenberg-Programm
DFG Deutsche Forschungsgemeinschaft

Neutrinoless Double Beta Decay

$\boxed{(A, Z) \to (A, Z+2) + 2\,e^- \quad (0\nu\beta\beta) \Rightarrow \text{Lepton Number Violation}}$

- **Standard Interpretation** (neutrino physics)
- **Non-Standard Interpretations** (BSM $\neq$ neutrino physics)

Int. J. Mod. Phys. **E20**, 1833 (2011); J. Phys. **G39**, 124008 (2012)



Why should we probe Lepton Number Violation?

- L and B *accidentally* conserved in SM
- effective theory: $\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\,\mathcal{L}_{\rm LNV} + \frac{1}{\Lambda^2}\,\mathcal{L}_{\rm LFV,\,BNV,\,LNV} + \ldots$
- baryogenesis: B is violated
- B, L often connected in GUTs
- GUTs have seesaw and Majorana neutrinos
- (chiral anomalies: $\partial_\mu J^\mu_{B,L} = c\, G_{\mu\nu}\,\tilde{G}^{\mu\nu} \neq 0$ with $J^B_\mu = \sum \overline{q_i}\,\gamma_\mu\,q_i$ and $J^L_\mu = \sum \overline{\ell_i}\,\gamma_\mu\,\ell_i$)

$\Rightarrow$ Lepton Number Violation as important as Baryon Number Violation

(0$\nu\beta\beta$ is much more than a neutrino mass experiment)

Upcoming/running experiments: exciting time!!

best limit was from 2001, improved 2012

Name	Isotope	Source = Detector; calorimetric with			Source ≠ Detector
		high $\triangle E$	low $\triangle E$	topology	topology
AMoRE	^{100}Mo	✓	–	–	–
CANDLES	^{48}Ca	–	✓	–	–
COBRA	^{116}Cd (and ^{130}Te)	–	–	✓	–
CUORE	^{130}Te	✓	–	–	–
DCBA/MTD	^{82}Se / ^{150}Nd	–	–	–	✓
EXO	^{136}Xe	–	–	✓	–
GERDA	^{76}Ge	✓	–	–	–
IHE	^{82}Se / ^{100}Mo / ^{116}Cd / ^{130}Te	✓	–	–	–
KamLAND-Zen	^{136}Xe	–	✓	–	–
LUCIFER	^{82}Se / ^{100}Mo / ^{130}Te	✓	–	–	–
LUMINEU	^{100}Mo	✓	–	–	–
MAJORANA	^{76}Ge	✓	–	–	–
MOON	^{82}Se / ^{100}Mo / ^{150}Nd	–	–	–	✓
NEXT	^{136}Xe	–	–	✓	–
SNO+	^{130}Te	–	✓	–	–
SuperNEMO	^{82}Se / ^{150}Nd	–	–	–	✓
XMASS	^{136}Xe	–	✓	–	–

Interpretation of Experiments

Master formula:

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

- $G_x(Q,Z)$: phase space factor
- $\mathcal{M}_x(A,Z)$: nuclear physics
- η_x: particle physics

Interpretation of Experiments

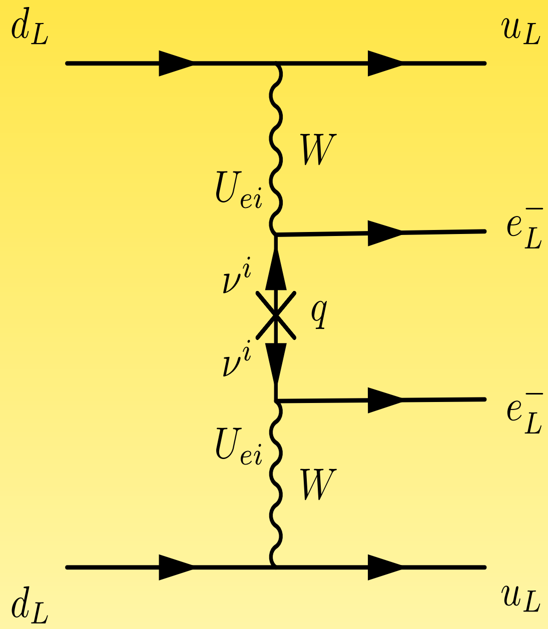
Master formula:

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

- $G_x(Q,Z)$: phase space factor; calculable
- $\mathcal{M}_x(A,Z)$: nuclear physics; problematic
- η_x: particle physics; interesting

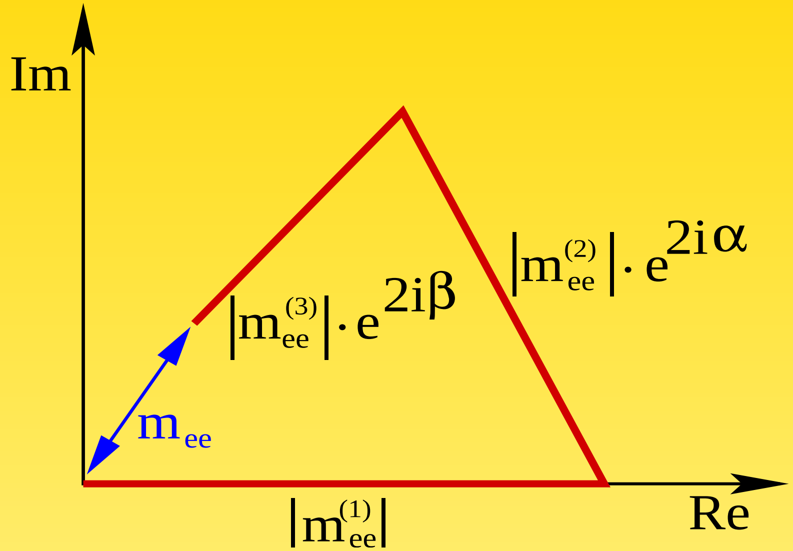
Standard Interpretation

Neutrinoless Double Beta Decay is mediated by light and massive Majorana neutrinos (the ones which oscillate) and all other mechanisms potentially leading to $0\nu\beta\beta$ give negligible or no contribution



prediction of $(100 - \epsilon)$ % of all neutrino mass mechanisms

The effective mass



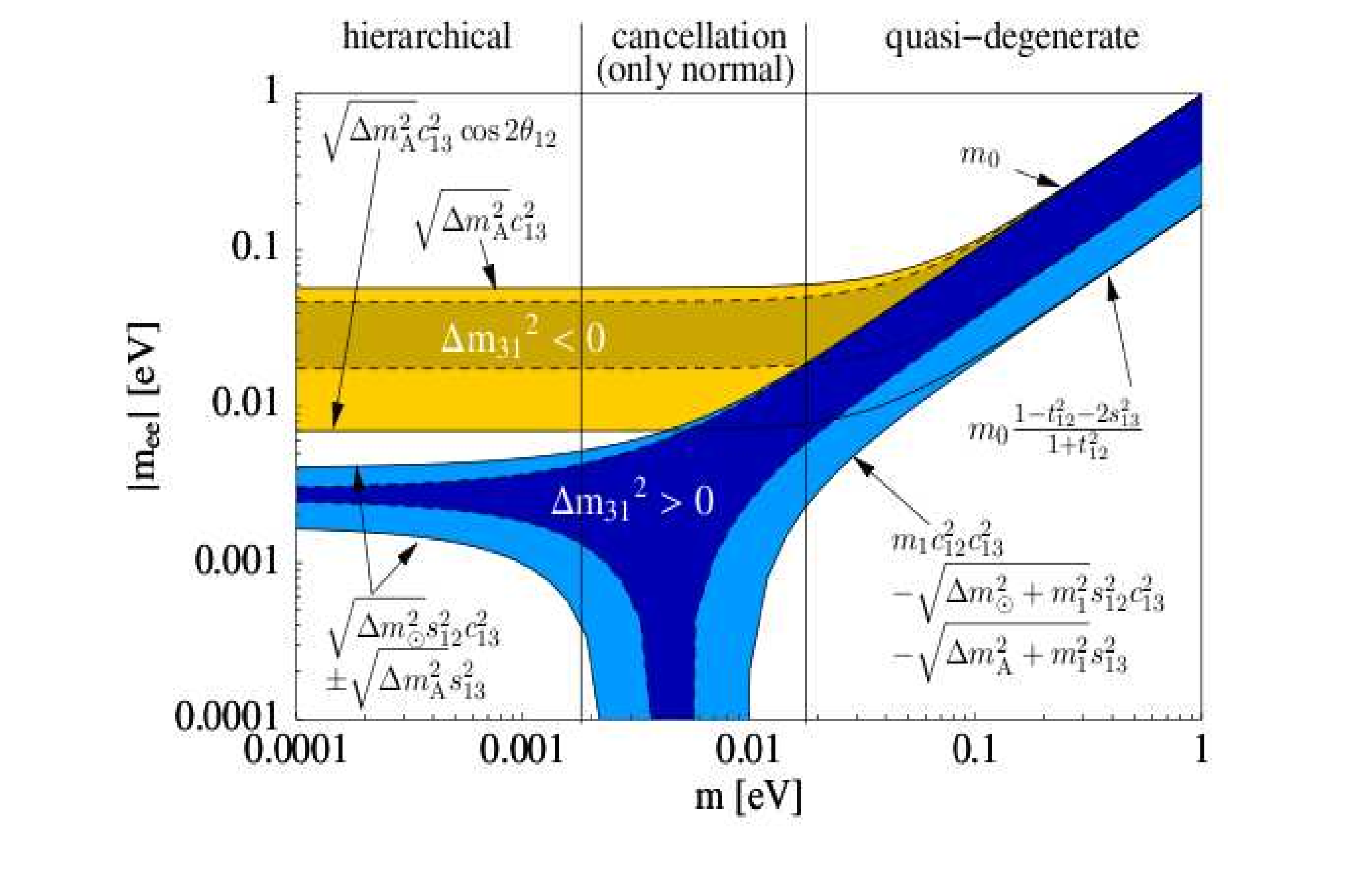
Amplitude proportional to coherent sum ("effective mass"):

$$\boxed{|m_{ee}| \equiv \left|\sum U_{ei}^2\, m_i\right| = \left||U_{e1}|^2\, m_1 + |U_{e2}|^2\, m_2\, e^{2i\alpha} + |U_{e3}|^2\, m_3\, e^{2i\beta}\right|}$$

$$\boxed{= f\left(\theta_{12}, |U_{e3}|, m_i, \mathrm{sgn}(\Delta m_{\mathrm{A}}^2), \alpha, \beta\right)}$$

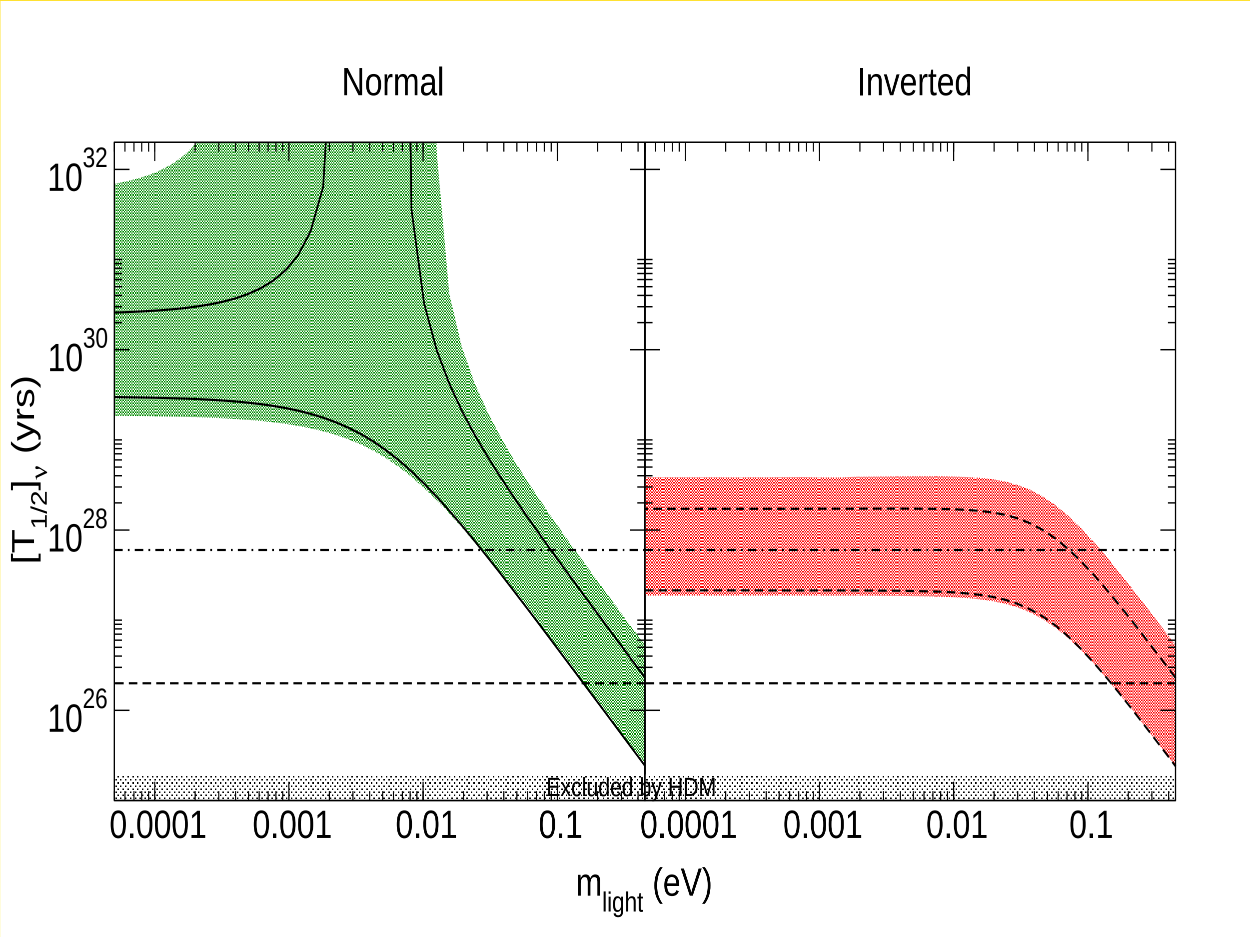
7 out of 9 parameters of neutrino physics!

The usual plot

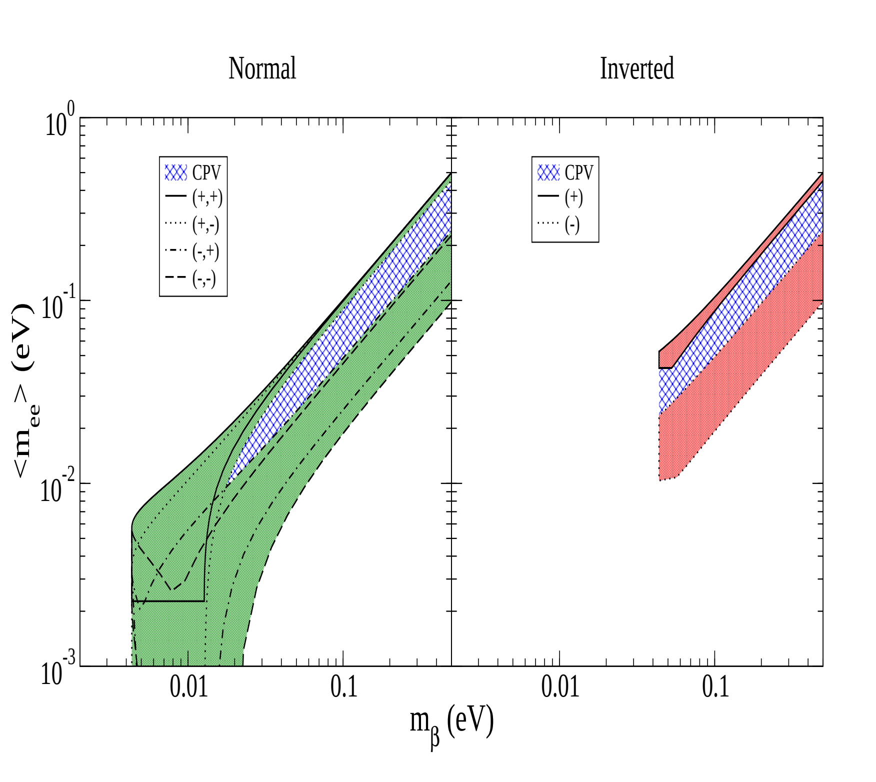


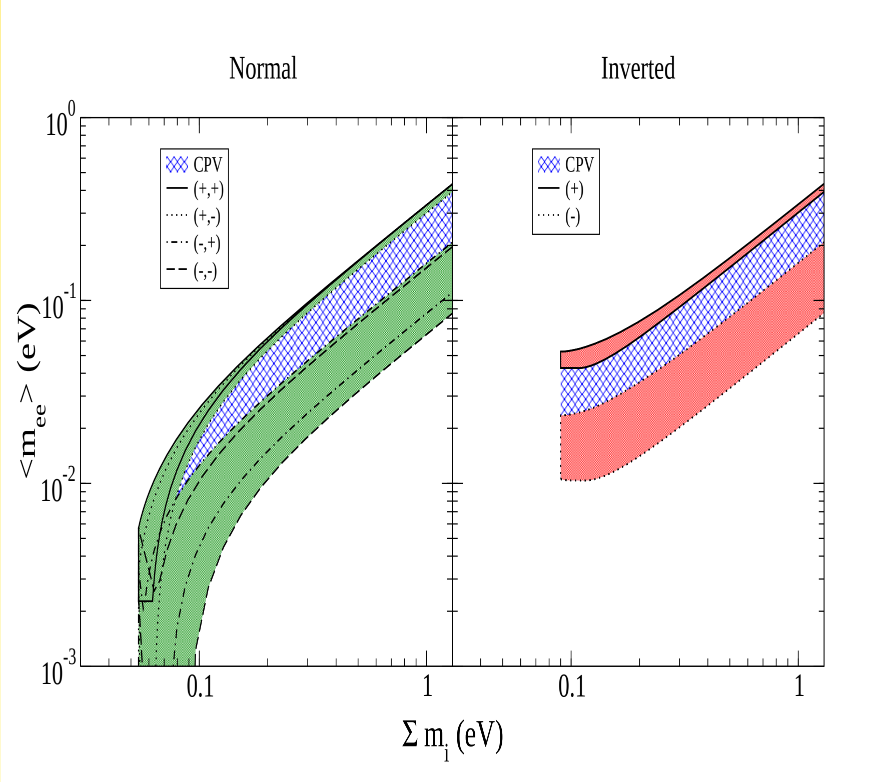
The usual plot

(life-time instead of $|m_{ee}|$)



Plot against other observables

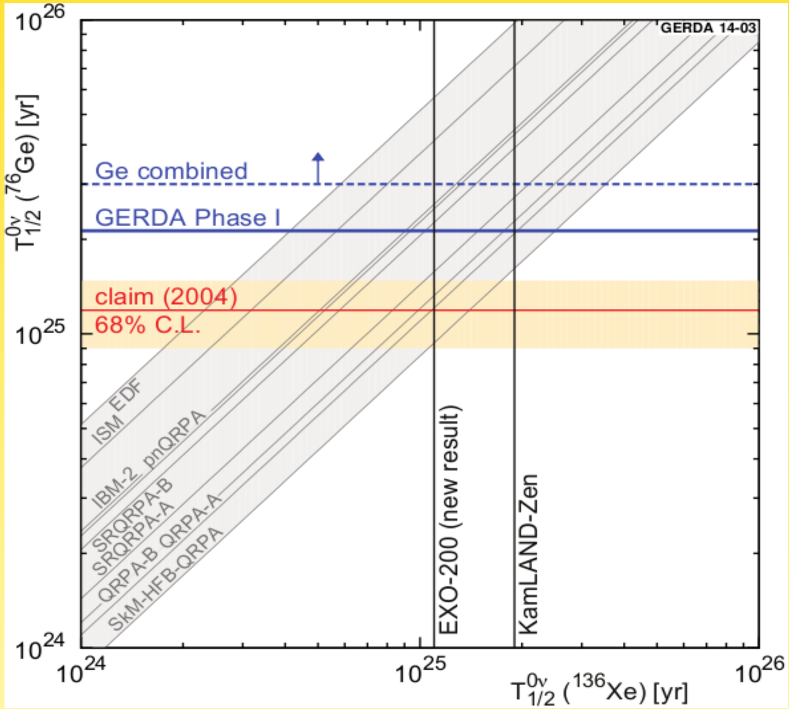




Complementarity of $|m_{ee}| = U_{ei}^2\, m_i$, $m_\beta = \sqrt{|U_{ei}|^2\, m_i^2}$ and $\Sigma = \sum m_i$

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*	–



Predictions of $SO(10)$ theories

Yukawa structure of $SO(10)$ models depends on Higgs representations

10_H $(\leftrightarrow H)$, $\overline{126}_H$ $(\leftrightarrow F)$, 120_H $(\leftrightarrow G)$

Gives relation for mass matrices:

$$
\begin{aligned}
m_{\rm up} &\propto r(H + sF + it_u\, G)\\
m_{\rm down} &\propto H + F + iG\\
m_D &\propto r(H - 3sF + it_D\, G)\\
m_\ell &\propto H - 3F + it_l\, G\\
M_R &\propto r_R^{-1} F
\end{aligned}
$$

Numerical fit including RG, Higgs, θ_{13}

$10_H + \overline{126}_H$: 19 free parameters

$10_H + \overline{126}_H + 120_H$: 18 free parameters

20 (19) observables to be fitted

Predictions of $SO(10)$ theories

Model	Fit	$\lvert m_{ee}\rvert$ [meV]	m_0 [meV]	M_3 [GeV]	χ^2
$10_H + \overline{126}_H$	NH	0.49	2.40	3.6×10^{12}	23.0
$10_H + \overline{126}_H$ + SS	NH	0.44	6.83	1.1×10^{12}	3.29
$10_H + \overline{126}_H + 120_H$	NH	2.87	1.54	9.9×10^{14}	11.2
$10_H + \overline{126}_H + 120_H$ + SS	NH	0.78	3.17	4.2×10^{13}	6.9×10^{-6}
$10_H + \overline{126}_H + 120_H$	IH	35.52	30.2	1.1×10^{13}	13.3
$10_H + \overline{126}_H + 120_H$ + SS	IH	24.22	12.0	1.2×10^{13}	0.6

Dueck, W.R., JHEP **1309**

Sterile Neutrinos and $0\nu\beta\beta$

- recall: $|m_{ee}|_{\rm NH}^{\rm act}$ can vanish and $|m_{ee}|_{\rm IH}^{\rm act} \sim 0.03$ eV cannot vanish
- $|m_{ee}| = |\underbrace{|U_{e1}|^2\, m_1 + |U_{e2}|^2\, m_2\, e^{2i\alpha} + |U_{e3}^2|\, m_3\, e^{2i\beta}}_{m_{ee}^{\rm act}} + \underbrace{|U_{e4}|^2\, m_4\, e^{2i\Phi_1}}_{m_{ee}^{\rm st}}|$
- sterile contribution to $0\nu\beta\beta$ (assuming 1+3):

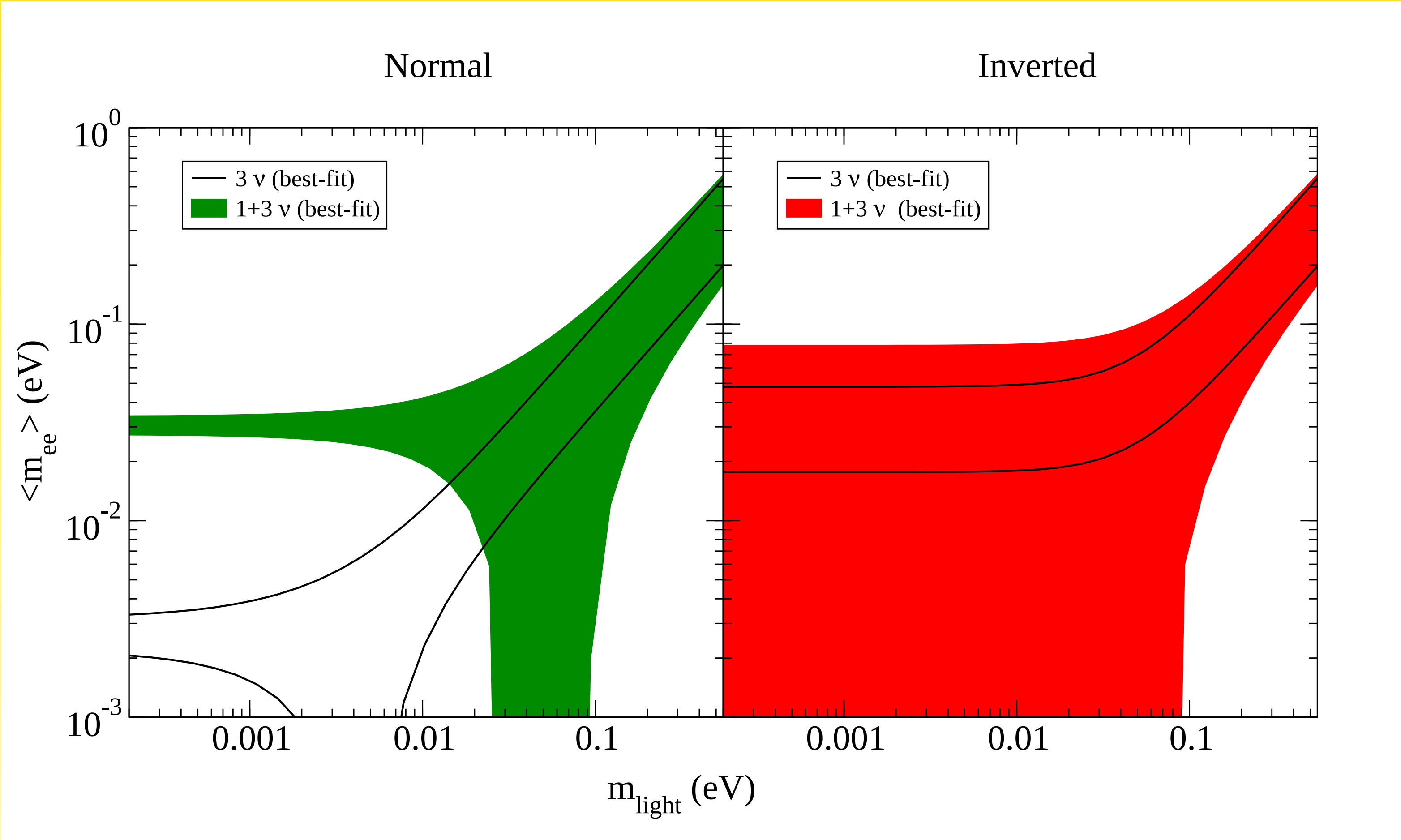
$$|m_{ee}|^{\rm st} \simeq \sqrt{\Delta m_{\rm st}^2}\, |U_{e4}|^2 \left\{ \begin{array}{l} \gg |m_{ee}|_{\rm NH}^{\rm act} \\ \simeq |m_{ee}|_{\rm IH}^{\rm act} \end{array} \right.$$

$\Rightarrow$ $|m_{ee}|_{\rm NH}$ cannot vanish and $|m_{ee}|_{\rm IH}$ can vanish!

$\Rightarrow$ usual phenomenology gets completely turned around!

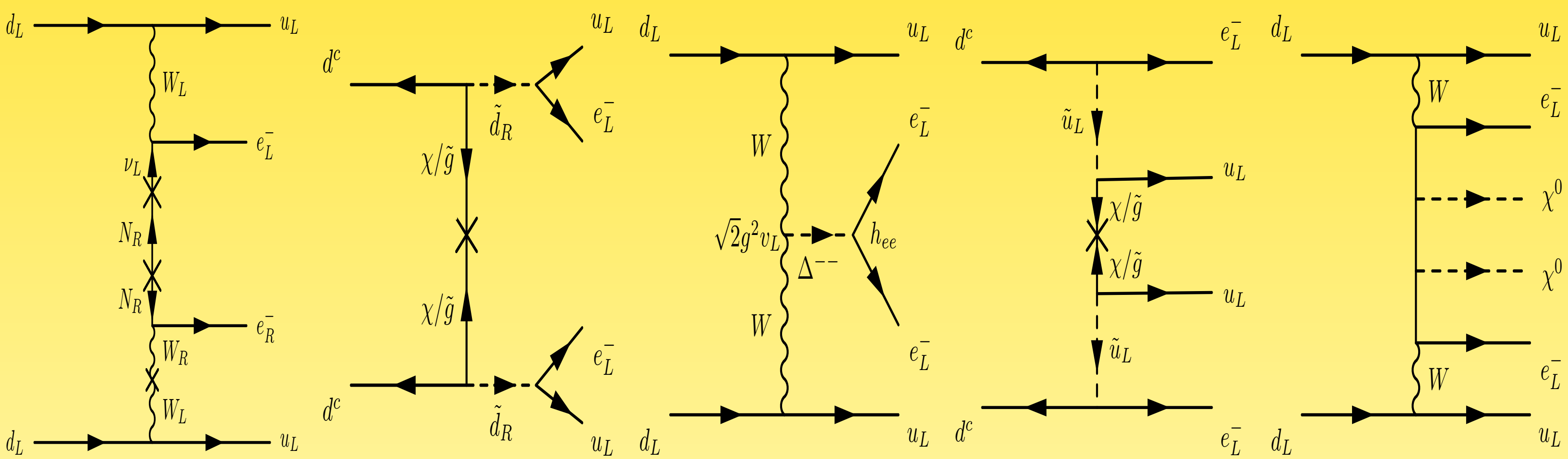
Barry, W.R., Zhang, JHEP **1107**; Giunti *et al.*, PRD **87**; Girardi, Meroni, Petcov, JHEP **1311**

Usual plot gets completely turned around!



Non-Standard Interpretations:

There is at least one other mechanism leading to Neutrinoless Double Beta Decay and its contribution is at least of the same order as the light neutrino exchange mechanism



Clear experimental signature:

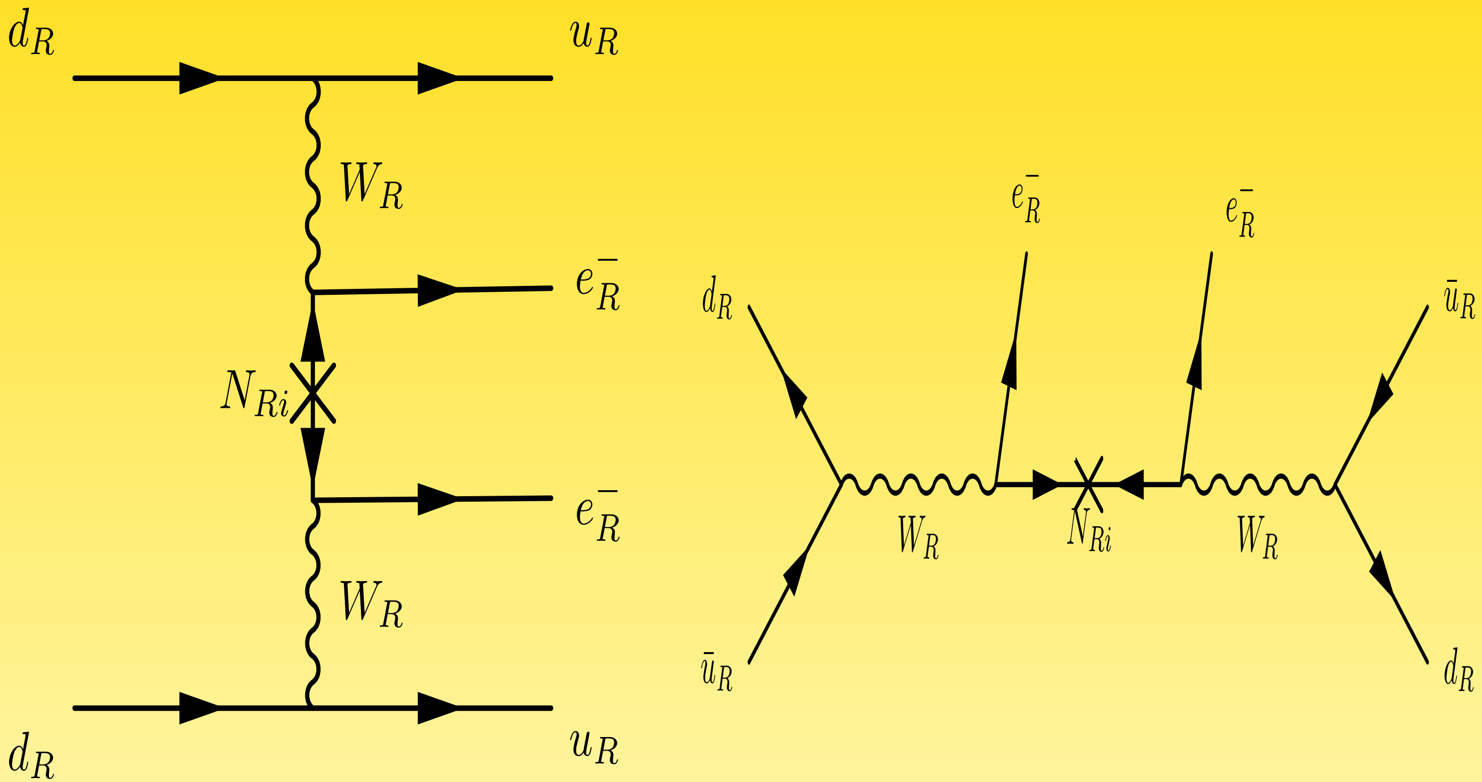
KATRIN and/or cosmology see nothing but $0\nu\beta\beta$ does

$$T^{0\nu}(1\ \text{eV}) = T^{0\nu}(1\ \text{TeV})$$

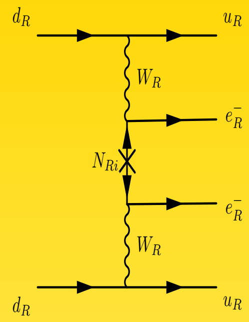
- RPV Supersymmetry
- left-right symmetry
- heavy neutrinos
- color octets
- leptoquarks
- effective operators
- extra dimensions
- ...

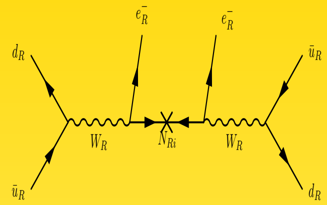
$\Rightarrow$ need to solve the inverse problem...

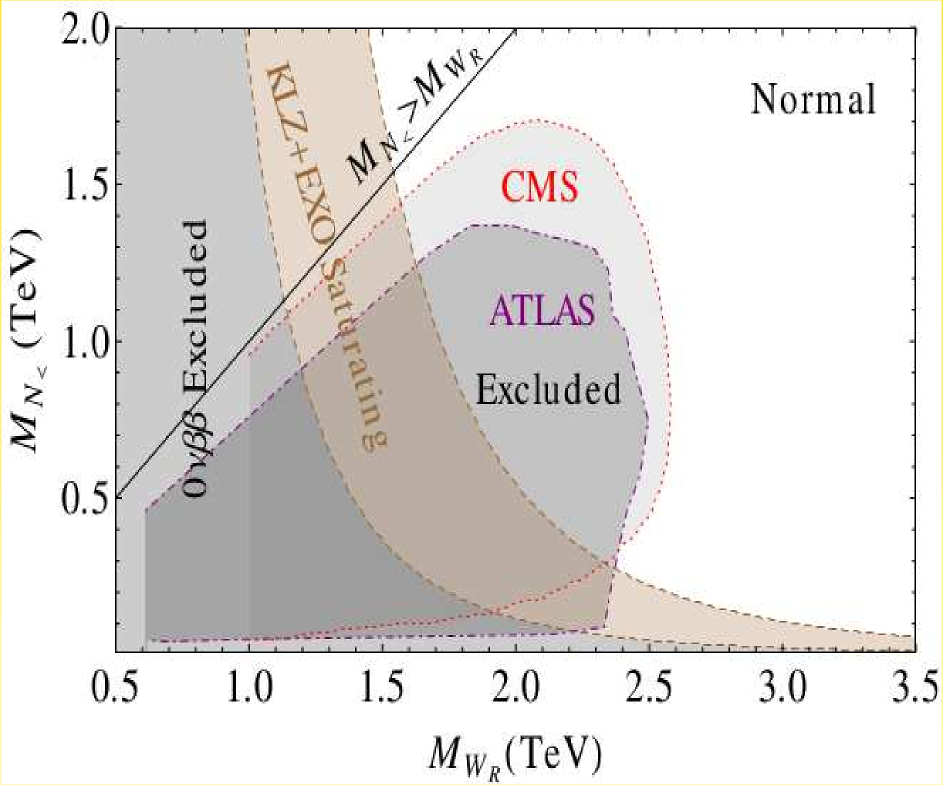
Left-right symmetry



Senjanovic, Keung, 1983; Tello *et al.*; Nemevsek *et al.*







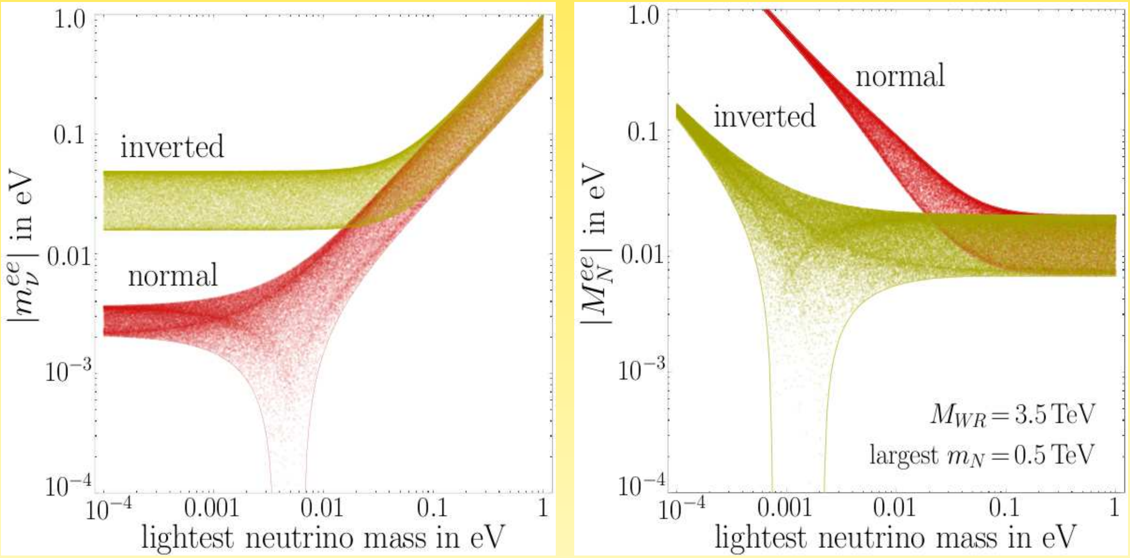
Bhupal Dev, Goswami, Mitra, W.R.

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

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

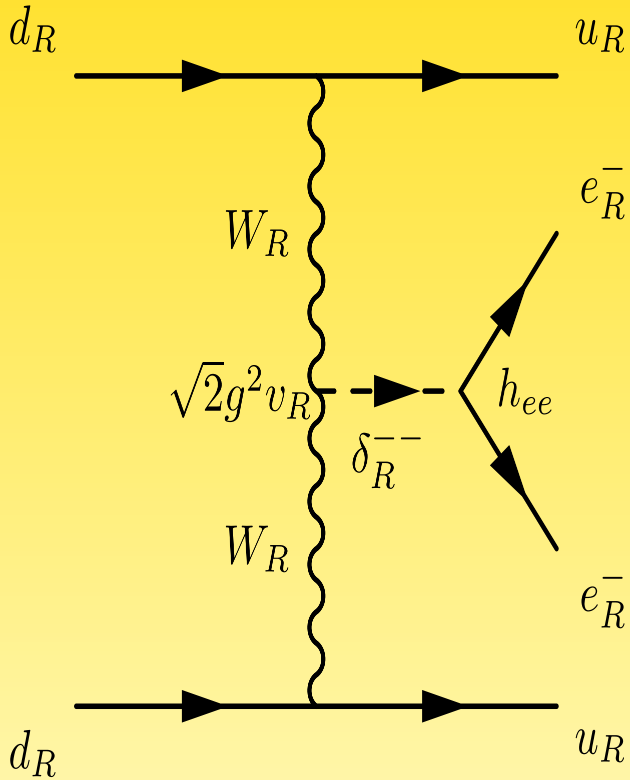
$\Rightarrow m_\nu$ fixes M_R and exchange of N_R with W_R fixed in terms of PMNS:

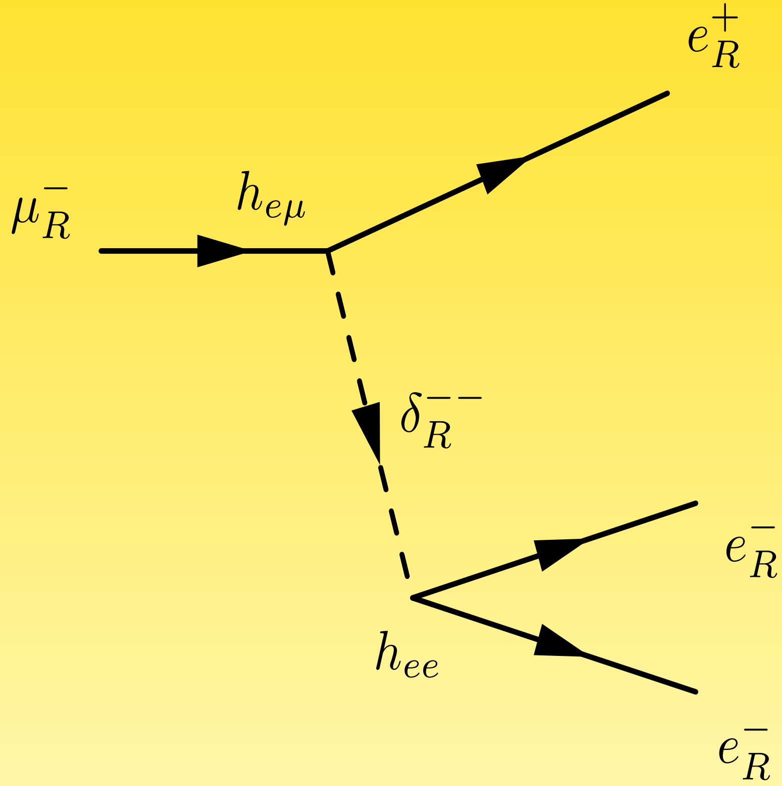
$$\Rightarrow \mathcal{A}_{N_R} \simeq G_F^2 \left(\frac{m_W}{M_{W_R}}\right)^4 \sum \frac{V_{ei}^2}{M_i} \propto \sum \frac{U_{ei}^2}{m_i}$$



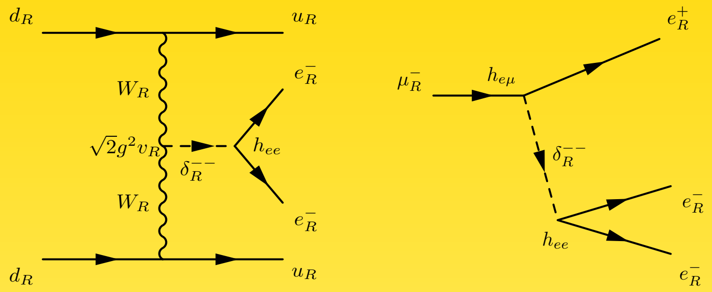
* **(for leptogenesis**: Joshipura, Paschos, W.R., JHEP **0108)**

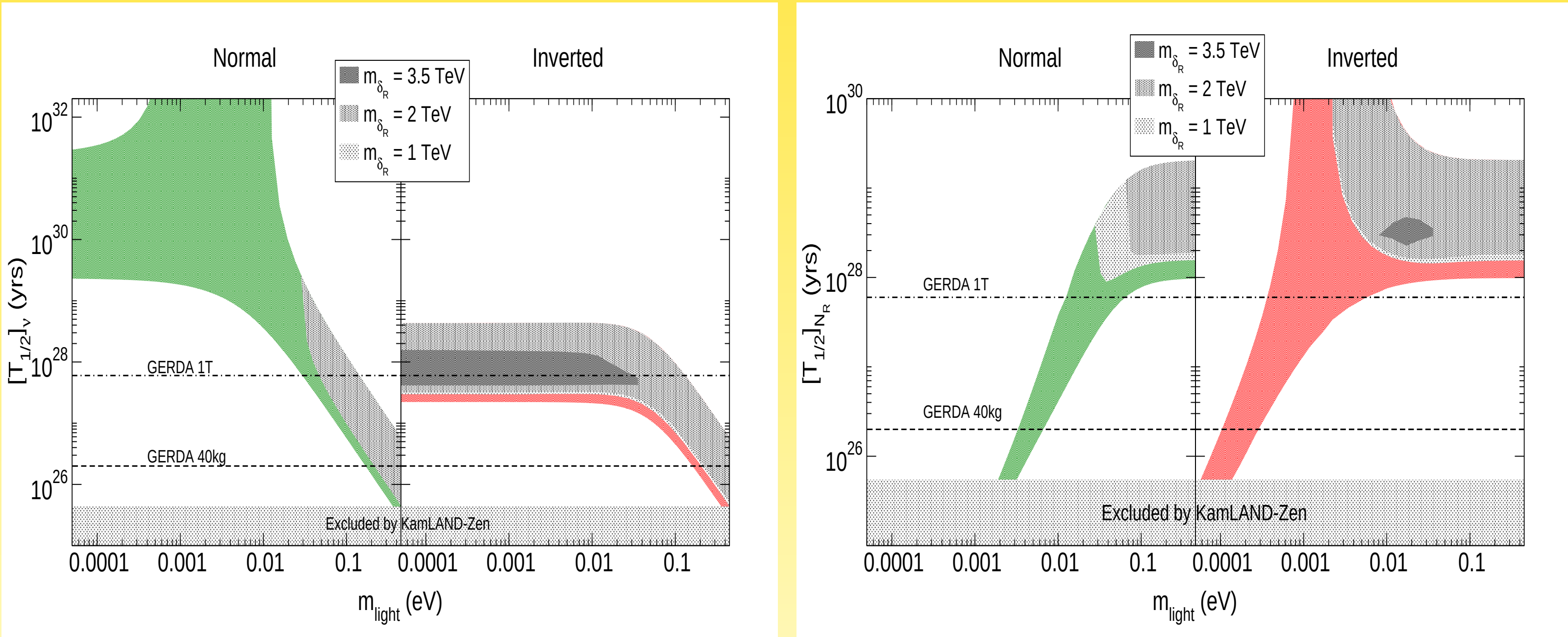
Constraints from Lepton Flavor Violation





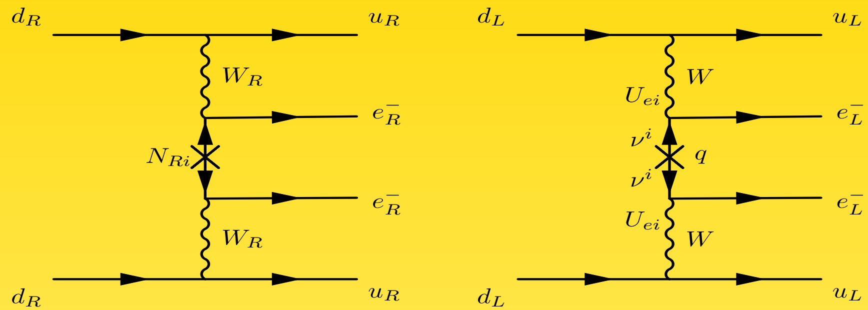
Constraints from Lepton Flavor Violation

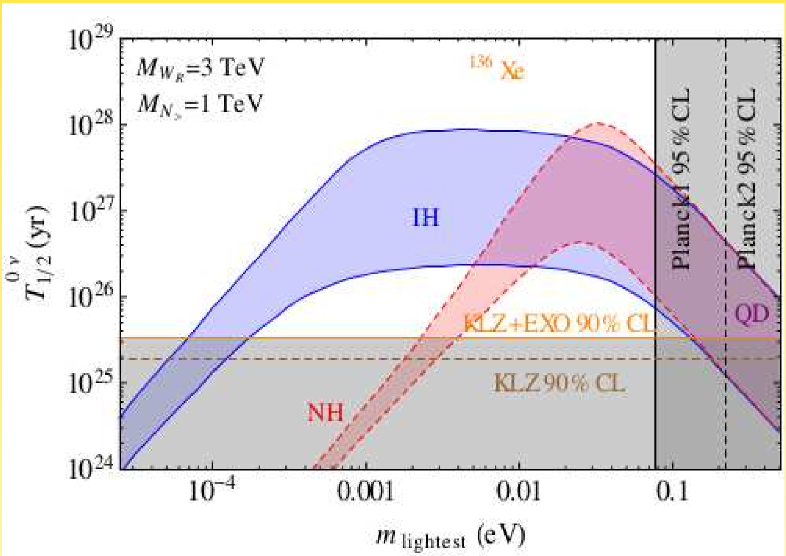




Barry, W.R., JHEP **1309**

Adding diagrams

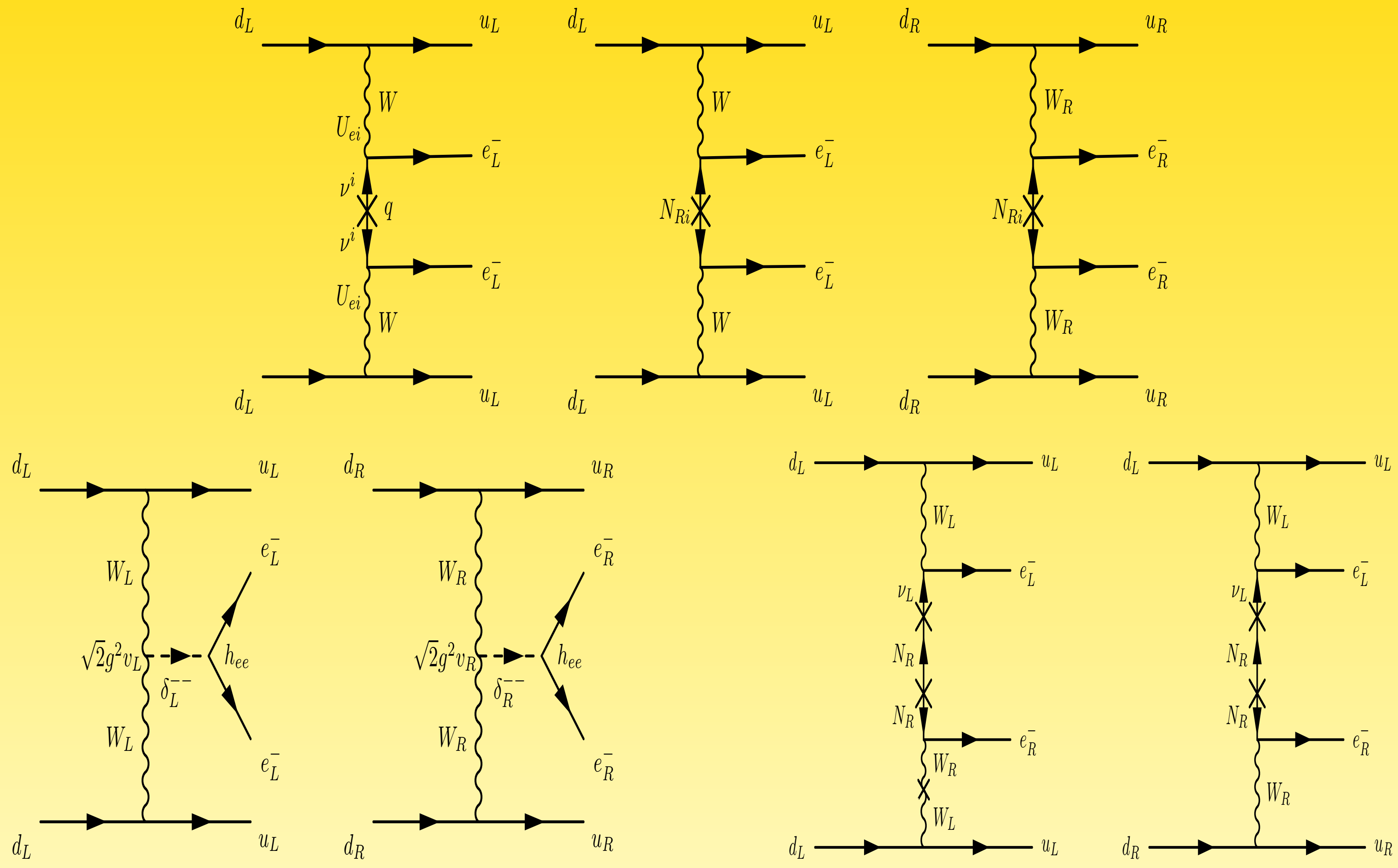




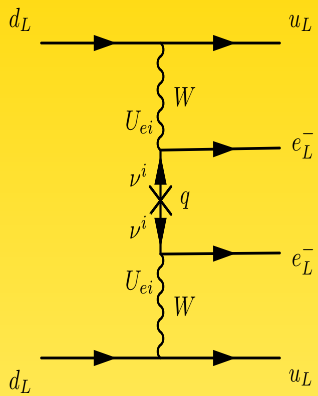
$\Rightarrow$ lower bound on $m(\text{lightest}) \gtrsim$ meV

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

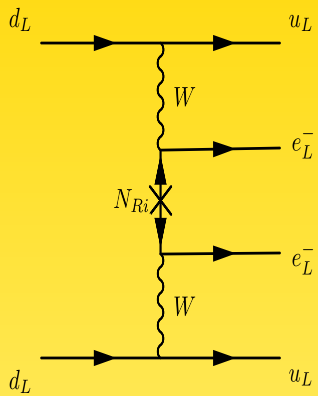
Left-right symmetry



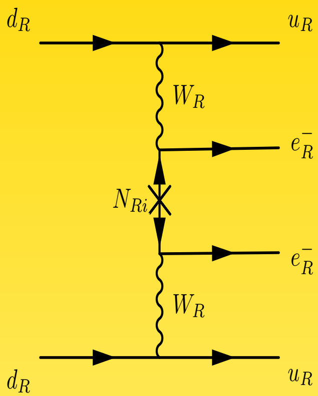
Left-right symmetry



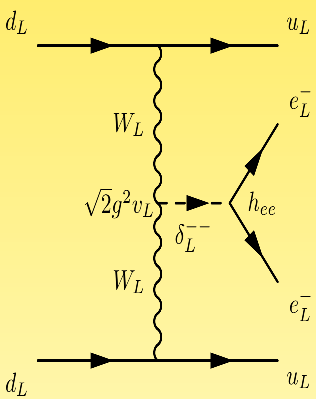
$$U_{ei}^2\, m_i$$



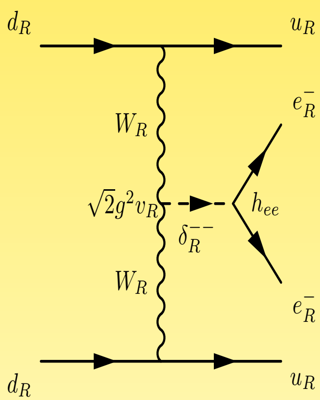
$$\frac{S_{ei}^2}{M_i}$$



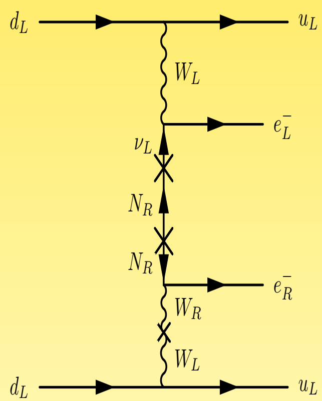
$$\frac{V_{ei}^2}{M_{W_R}^4\, M_i}$$



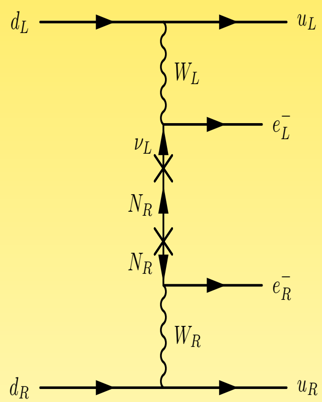
$$\frac{U_{ei}^2\, m_i}{M_{\Delta_L}^2}$$



$$\frac{V_{ei}^2\, M_i}{M_{W_R}^4\, M_{\Delta_R}^2}$$

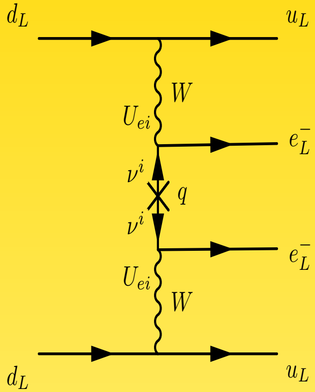


$$U_{ei}\, T_{ei}\, \tan\zeta$$

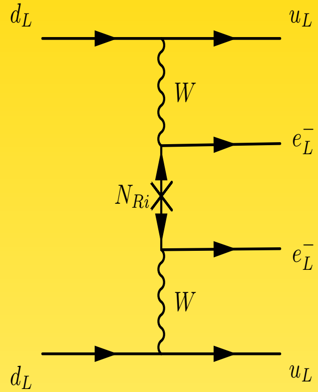


$$\frac{U_{ei}\, T_{ei}}{M_{W_R}^2}$$

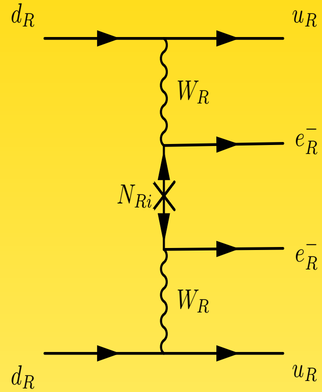
Left-right symmetry



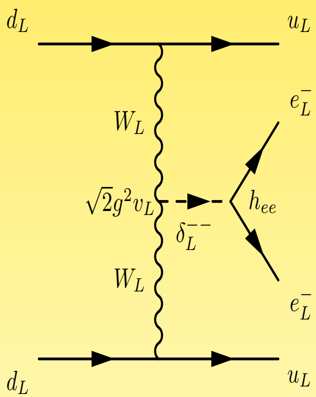
0.4 eV



2×10^{-8} GeV^{-1}



4×10^{-16} GeV^{-5}



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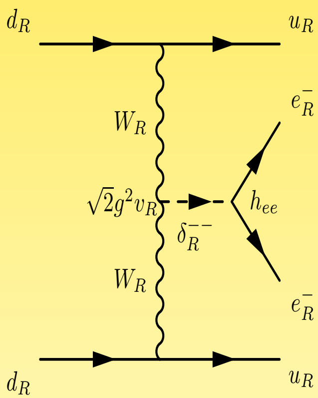
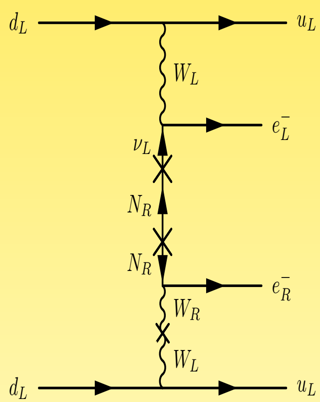
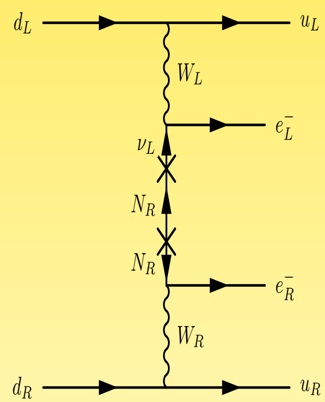


10^{-15} GeV^{-5}

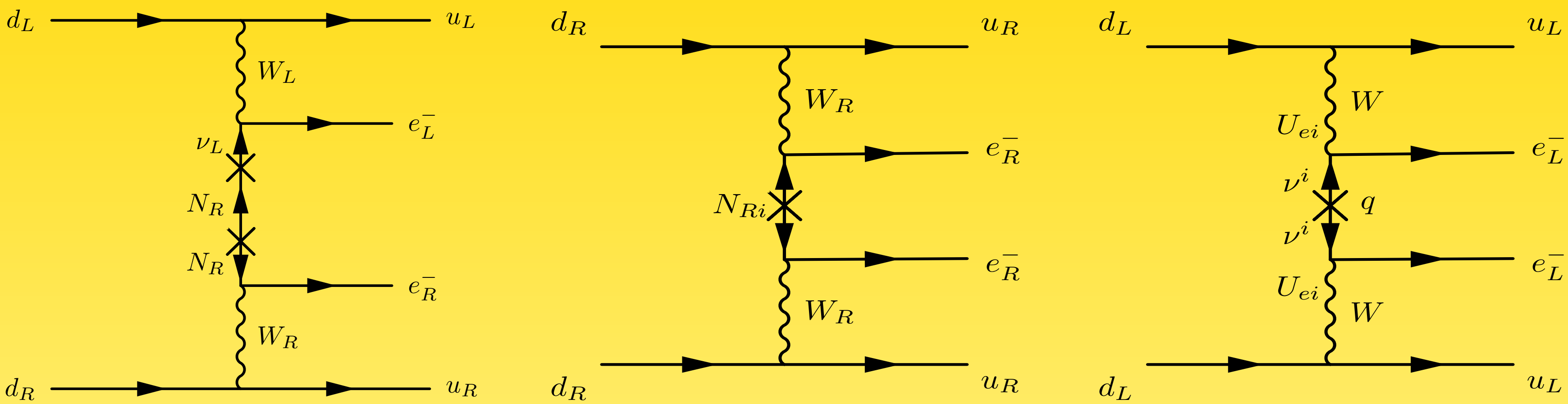


6×10^{-9}



1.4×10^{-10} GeV^{-2}

Mixed Diagrams can dominate



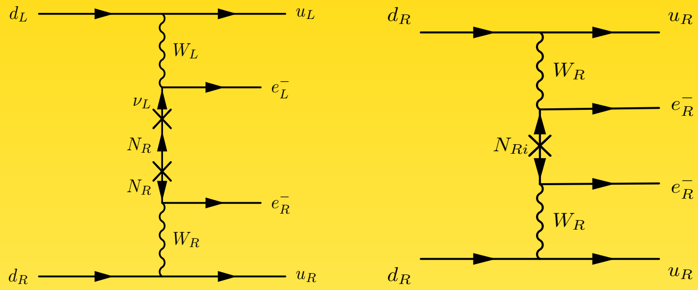
$$\mathcal{A}_\lambda \sim \left(\frac{m_W}{M_{W_R}}\right)^2 \frac{U\,T}{q} \qquad \mathcal{A}_{N_R} \sim \left(\frac{m_W}{M_{W_R}}\right)^4 \frac{V^2}{M_R} \qquad \mathcal{A}_\nu \sim U^2 \frac{m_i}{q^2}$$

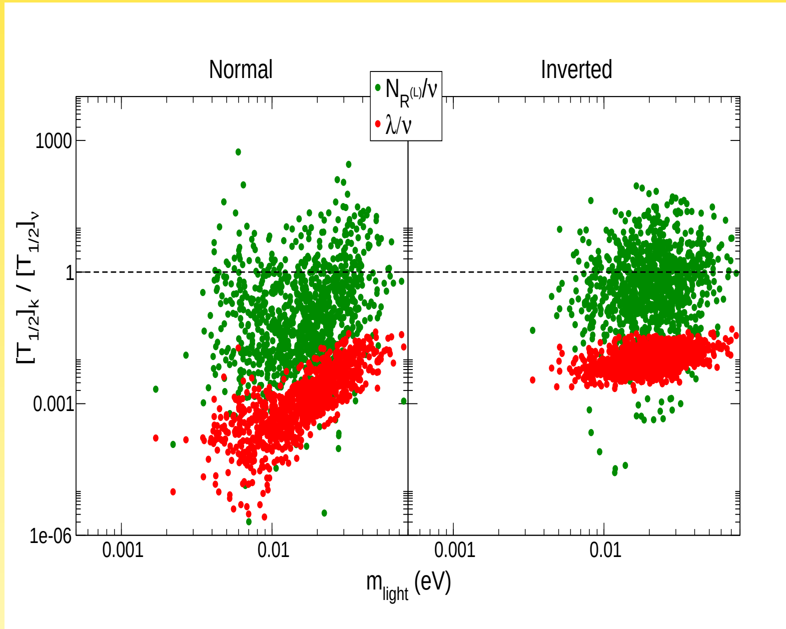
with $T \simeq \sqrt{\frac{m_\nu}{M_R}} \sim 10^{-7}$ (or huge enhancements up to 10^{-2})

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

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

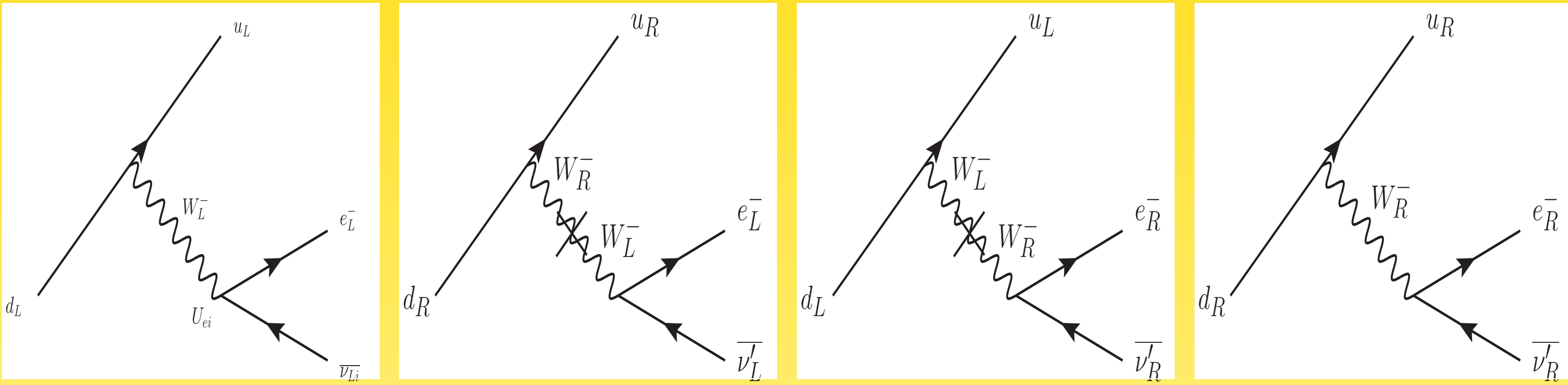
Mixed Diagrams can dominate





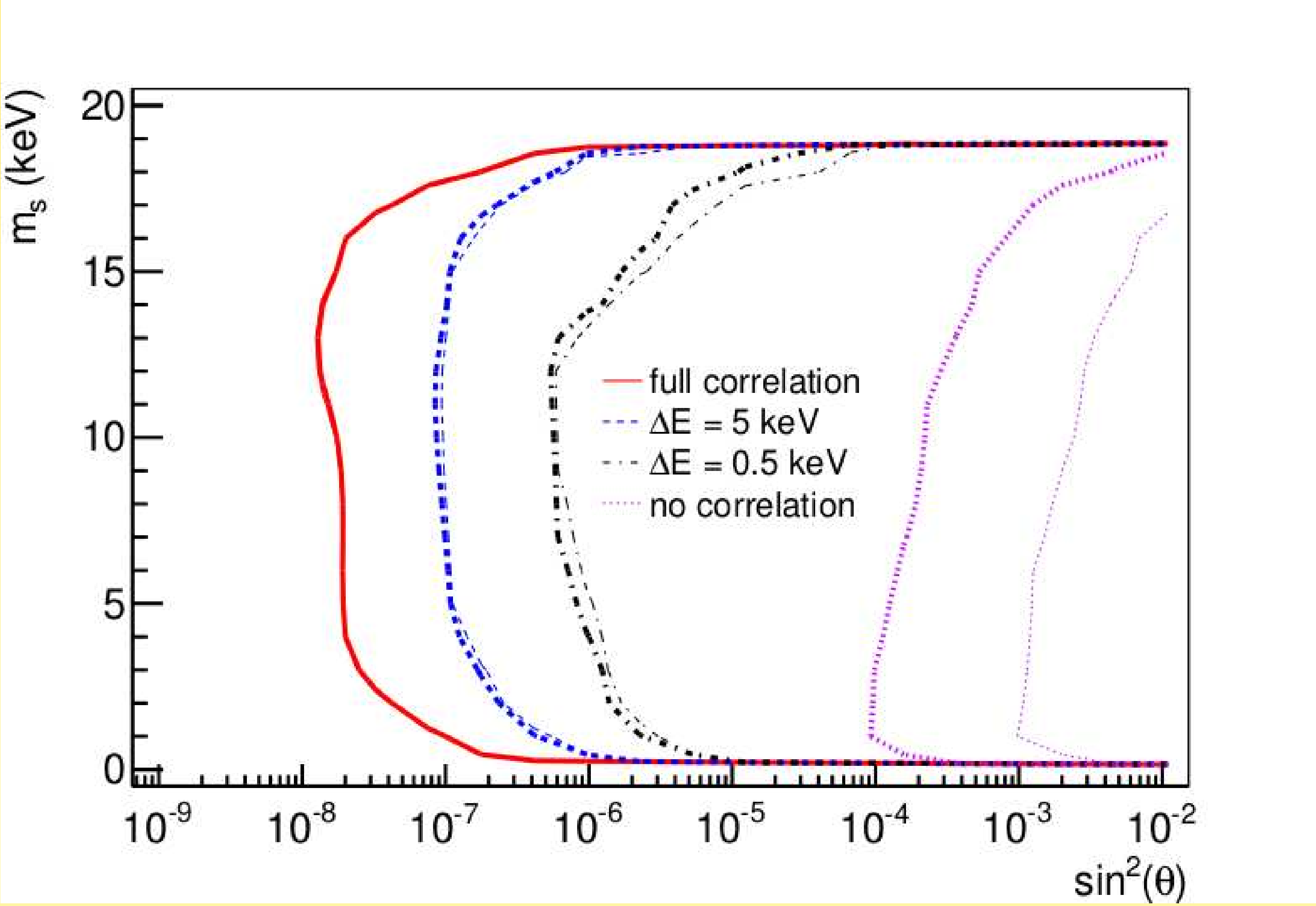
Barry, W.R., 1303.6324

KATRIN and right-handed currents



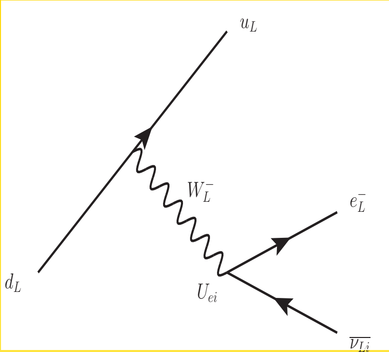
- left-handed contribution
- right-handed contribution
- interference contribution

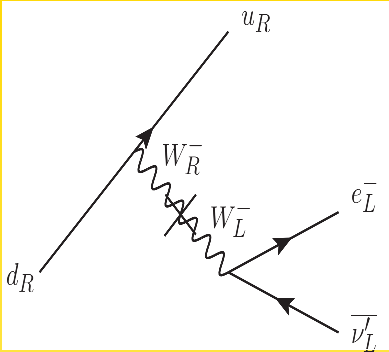
Neutrino masses up to $m = 18.6$ keV testable

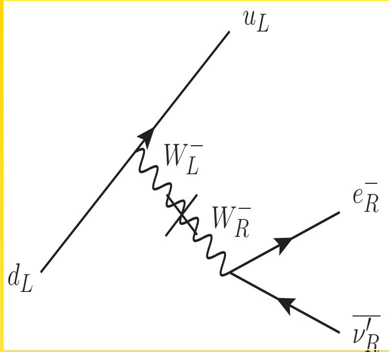


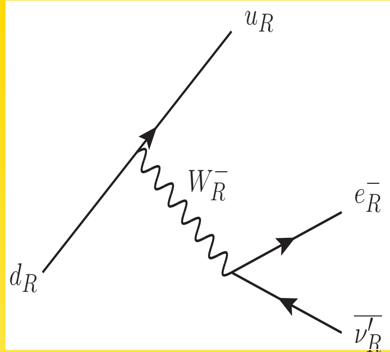
$\Rightarrow$ mixing down to 10^{-7} in reach!?

`Mertens` *et al.*, `1409.0920`









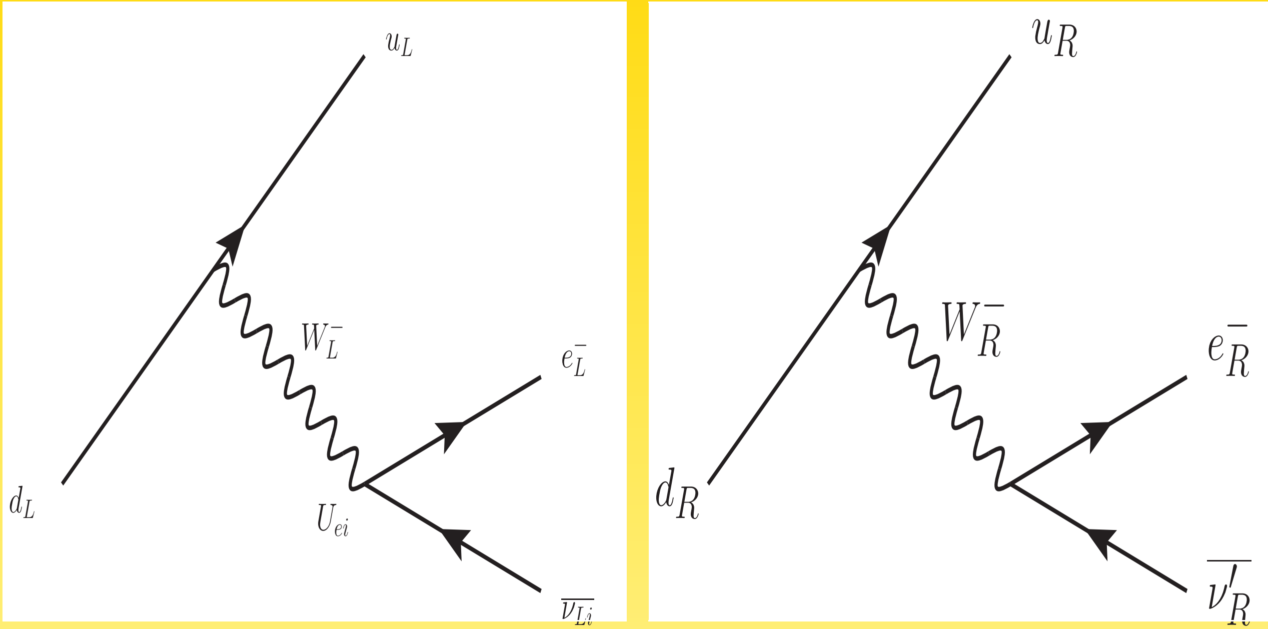
$$\left(\frac{\mathrm{d}\Gamma}{\mathrm{d}E}\right)_{LL} = K'(E+m_e)p_e X[1+2C\tan\xi]$$
$$\times\left[|U_{ei}|^2\sqrt{X^2-m_i^2}\,\Theta(X-m_i)+|S_{ei}|^2\sqrt{X^2-M_i^2}\,\Theta(X-M_i)\right]$$

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

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

with $X = E_0 - E$

Focus for simplicity on



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

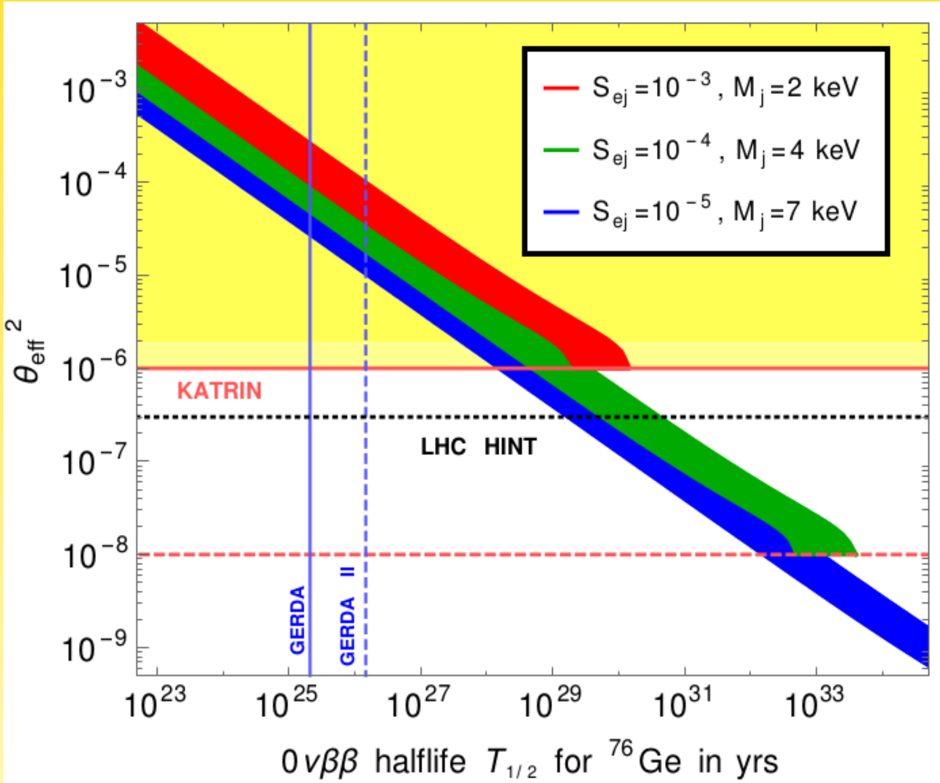
$$\theta_{\text{eff}}^2 \simeq |S_{ej}|^2 + 1.1 \times 10^{-6}\, |V_{ej}|^2 \left(\frac{2.5\,\text{TeV}}{m_{W_R}}\right)^4$$

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: $\dfrac{\Gamma_{\mathrm{RHC}}(N_j \to \bar{\nu}\gamma)}{\Gamma_{\mathrm{SM}}(N_j \to \nu\gamma)} \simeq \dfrac{m_{W_L}^4\,|S_{ei}|^2}{m_{W_R}^4\,|T_{ei}|^2} \simeq \dfrac{m_{W_L}^4}{m_{W_R}^4}$
- beta decay: $\theta_{\mathrm{eff}}^2 \simeq |S_{ej}|^2 + 1.1 \times 10^{-6}\,|V_{ej}|^2 \left(\frac{2.5\,\mathrm{TeV}}{m_{W_R}}\right)^4 > |S_{ej}|^2$

Do Dirac neutrinos imply that there is no Lepton Number Violation?

possible to construct $U(1)_{B-L}$ model with $\chi \sim -2$ and $\phi \sim 4$

$$\mathcal{L} = \left(y_{\alpha\beta}\overline{L}_\alpha H \nu_{R,\beta} + \kappa_{\alpha\beta}\chi\,\overline{\nu}_{R,\alpha}\nu^c_{R,\beta} + h.c.\right) + \sum_{X=H,\phi,\chi}\left(\mu_X^2|X|^2 + \lambda_X|X|^4\right)$$
$$+\lambda_{H\phi}|H|^2|\phi|^2 + \lambda_{H\chi}|H|^2|\chi|^2 + \lambda_{\chi\phi}|\chi|^2|\phi|^2 \quad - \left(\mu\phi\chi^2 + h.c.\right)$$

break it by allowing only scalar ϕ to obtain VEV:

$\Rightarrow$ neutrinos are Dirac particles, and Lepton Number violated by 4 units!

$\Rightarrow$ neutrinoless double beta decay forbidden...

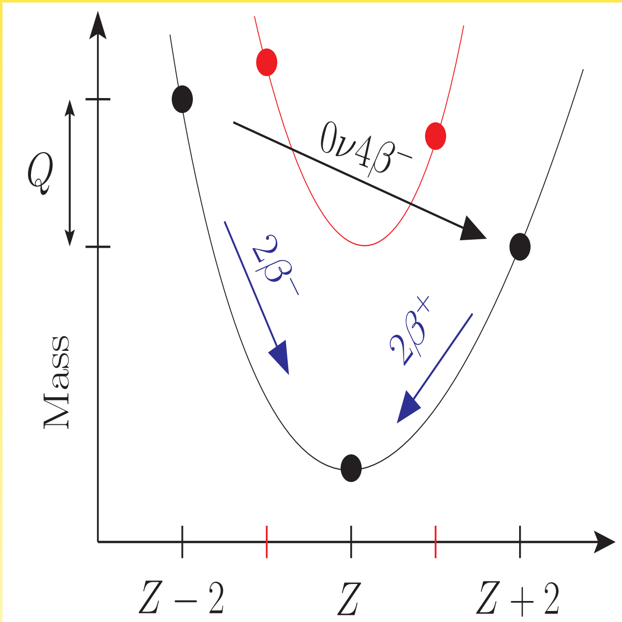
Heeck, W.R., EPL 103

Do Dirac neutrinos mean there is no Lepton Number Violation?

Model based on gauged $B - L$, broken by 4 units

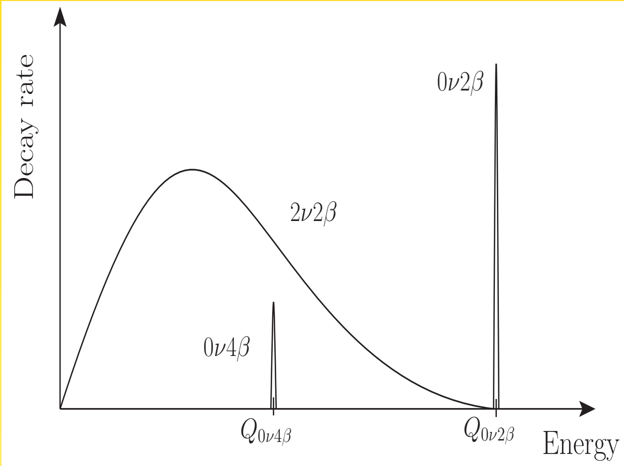
$\Rightarrow$ Neutrinos are Dirac particles, $\Delta L = 2$ forbidden, but $\Delta L = 4$ allowed...

$\Rightarrow$ observable: neutrinoless quadruple beta decay $(A, Z) \to (A, Z+4) + 4\,e^-$



Heeck, W.R., EPL **103**

Candidates for neutrinoless quadruple beta decay



	$Q_{0\nu4\beta}$	Other decays	NA
${}^{96}_{40}\mathrm{Zr} \to {}^{96}_{44}\mathrm{Ru}$	0.629	$\tau^{2\nu2\beta}_{1/2} \simeq 2 \times 10^{19}$	2.8
${}^{136}_{54}\mathrm{Xe} \to {}^{136}_{58}\mathrm{Ce}$	0.044	$\tau^{2\nu2\beta}_{1/2} \simeq 2 \times 10^{21}$	8.9
${}^{150}_{60}\mathrm{Nd} \to {}^{150}_{64}\mathrm{Gd}$	2.079	$\tau^{2\nu2\beta}_{1/2} \simeq 7 \times 10^{18}$	5.6

Heeck, W.R., EPL **103**

Summary

Chi l'ha visto?

Ettore Majorana, ordinario di fisica teorica all'Università di Napoli, è misteriosamente scomparso dagli ultimi di marzo. Di anni 31, alto metri 1,70, snello, con capelli neri, occhi scuri, una lunga cicatrice sul dorso di una mano. Chi ne sapesse qualcosa è pregato di scrivere al R. P. E. Marianecci, Viale Regina Margherita 66 - Roma.

Experimental Aspect

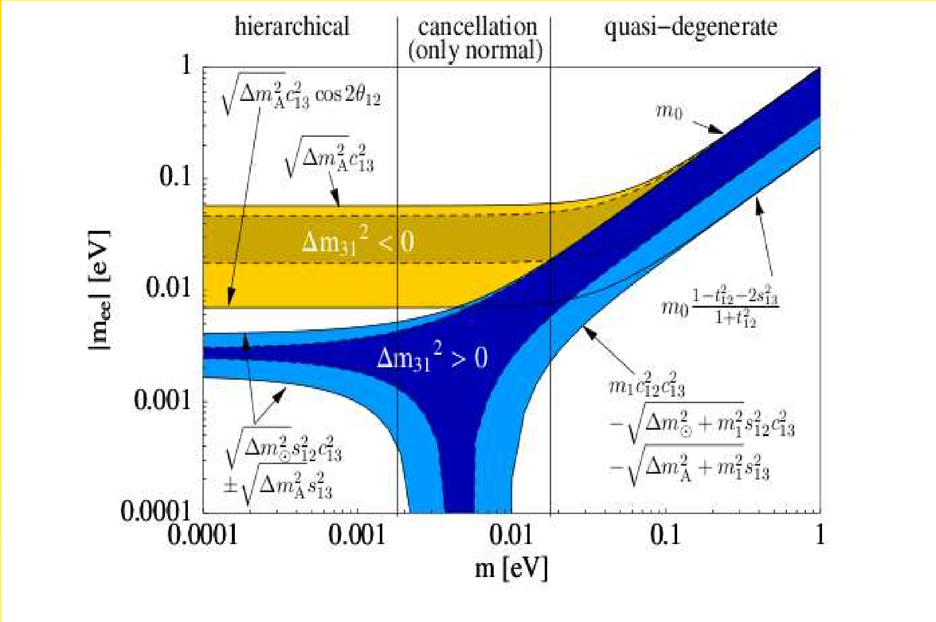
$$(T_{1/2}^{0\nu})^{-1} \propto \begin{cases} a\, M\, \varepsilon\, t & \text{without background} \\ a\, \varepsilon \sqrt{\dfrac{M\, t}{B\, \Delta E}} & \text{with background} \end{cases}$$

with

- B is background index in counts/(keV kg yr)
- ΔE is energy resolution
- ϵ is efficiency
- $(T_{1/2}^{0\nu})^{-1} \propto$ (particle physics)^2

Note: factor 2 in particle physics is combined factor of 16 in $M \times t \times B \times \Delta E$

Inverted Ordering



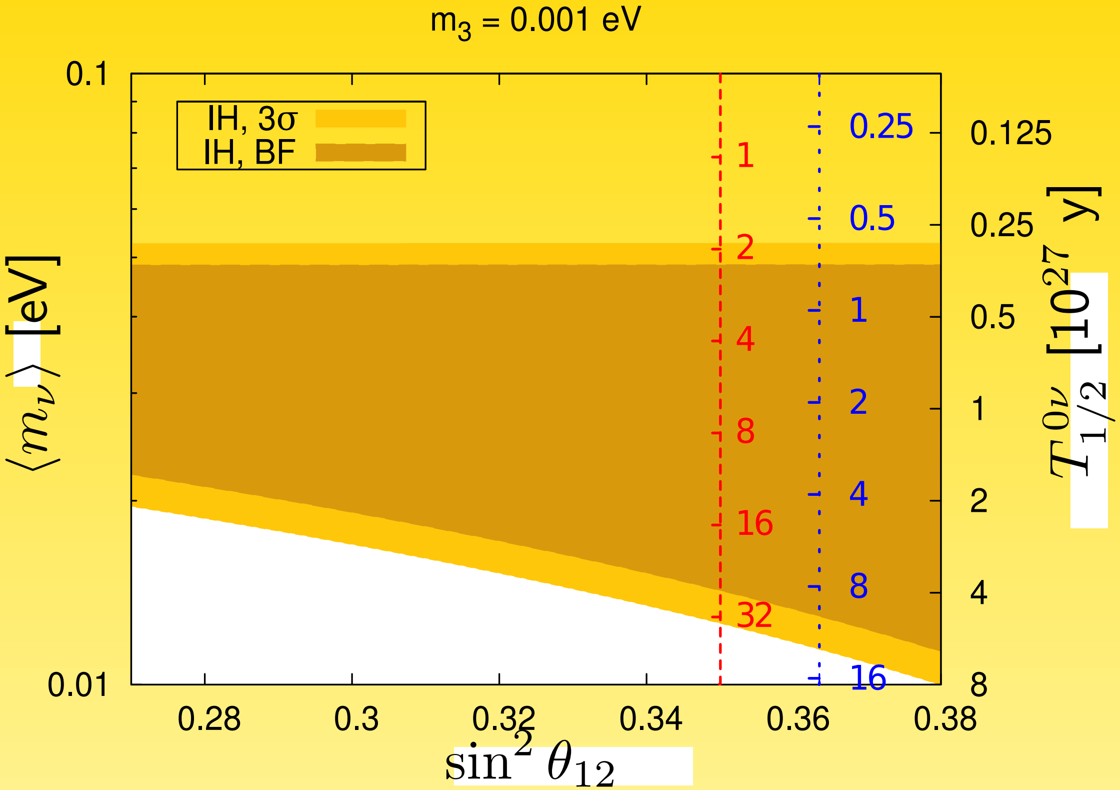
Nature provides 2 scales:

$$|m_{ee}|^{\text{IH}}_{\text{max}} \simeq c_{13}^2 \sqrt{\Delta m_A^2} \quad \text{and} \quad |m_{ee}|^{\text{IH}}_{\text{min}} \simeq c_{13}^2 \sqrt{\Delta m_A^2} \cos 2\theta_{12}$$

requires $\mathcal{O}(10^{26} \ldots 10^{27})$ yrs

is the lower limit $|m_{ee}|^{\text{IH}}_{\text{min}}$ fixed?

Inverted Hierarchy



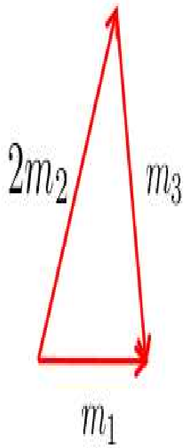
Current 3σ range of $\sin^2\theta_{12}$ gives factor of ~ 2 uncertainty for $|m_{ee}|^{\rm IH}_{\rm min}$

$\Rightarrow$ combined factor of ~ 16 in $M \times t \times B \times \Delta E$

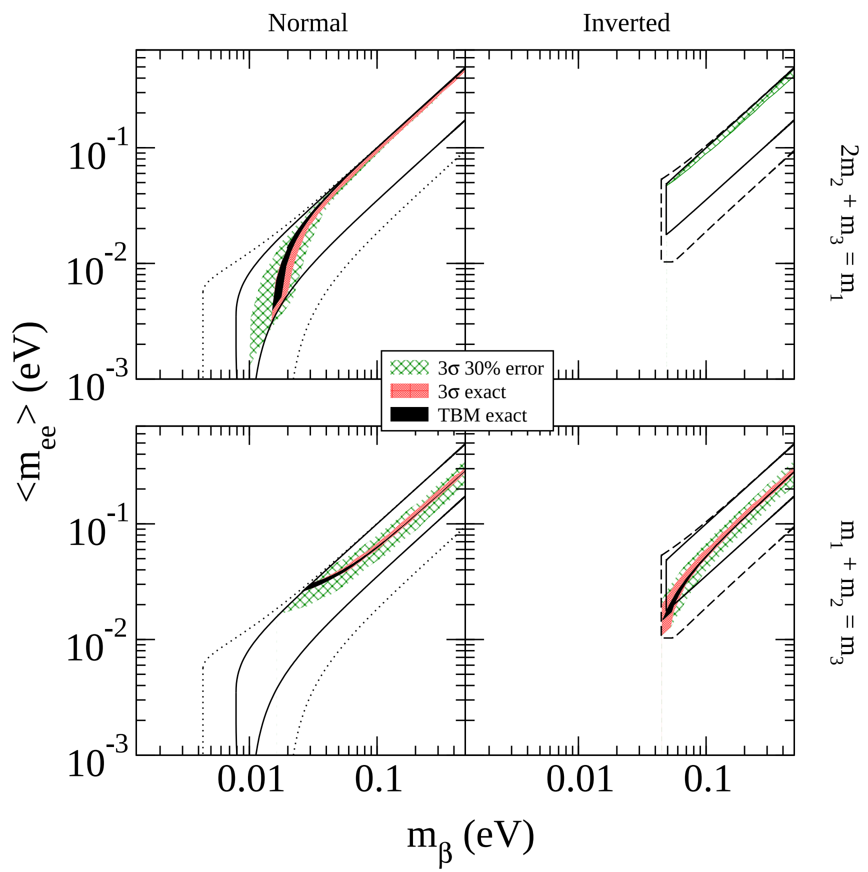
$\Rightarrow$ need precision determination of θ_{12}! $\leftrightarrow$ JUNO

Dueck, W.R., Zuber, PRD **83**

Flavor Symmetry Models: sum-rules



Sum-rule	Flavour symmetry
$2m_2 + m_3 = m_1$	$A_4, T', (S_4)$
$m_1 + m_2 = m_3$	$S_4, (A_4)$
$\frac{2}{m_2} + \frac{1}{m_3} = \frac{1}{m_1}$	A_4, T'
$\frac{1}{m_1} + \frac{1}{m_2} = \frac{1}{m_3}$	S_4



constrains masses and Majorana phases

Barry, W.R., Nucl. Phys. **B842**

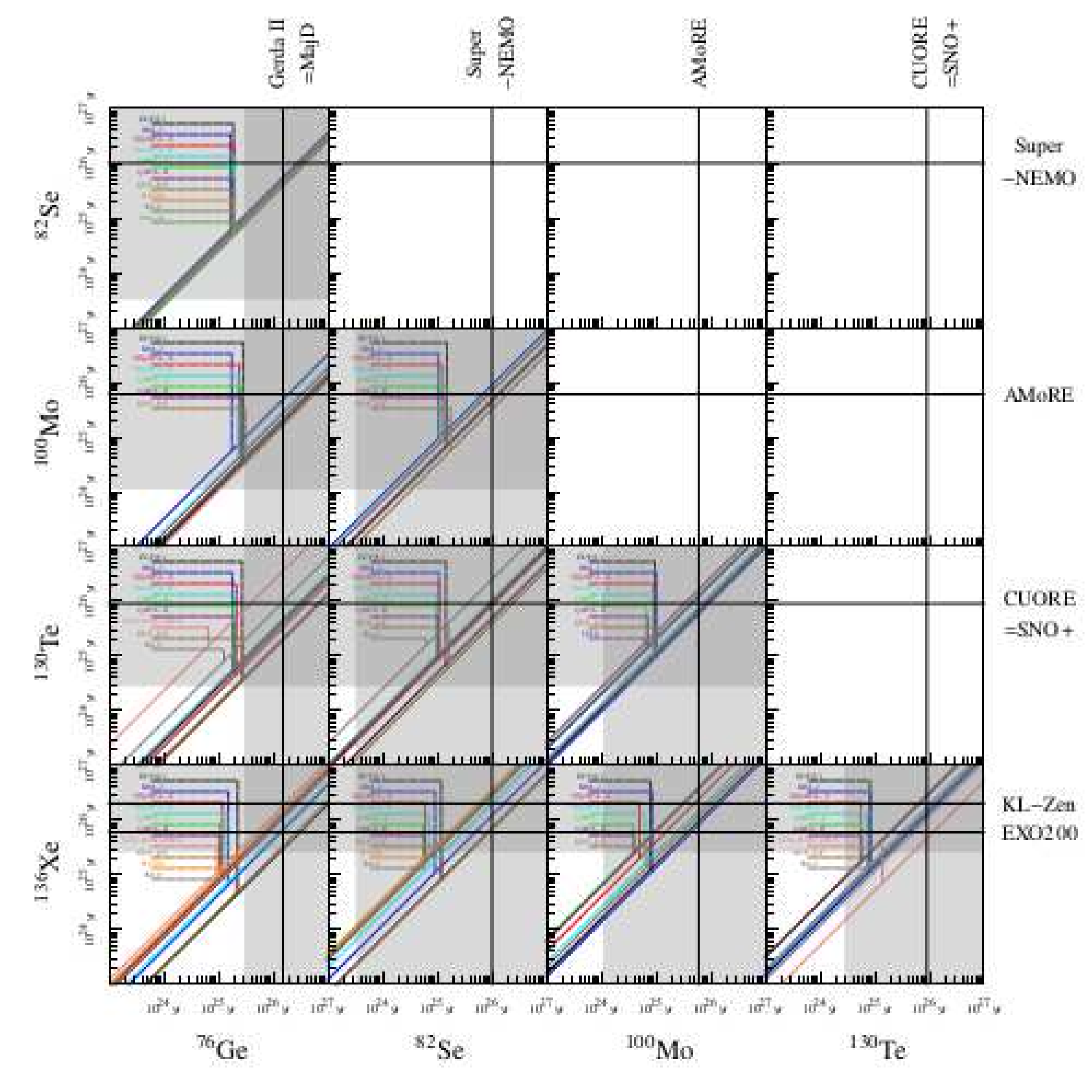
Neutrino Mass

$$m(\text{heaviest}) \gtrsim \sqrt{|m_3^2 - m_1^2|} \simeq 0.05 \text{ eV}$$

3 **complementary** methods to measure neutrino mass:

Method	observable	now [eV]	near [eV]	far [eV]	pro	con
Kurie	$\sqrt{\sum \lvert U_{ei}\rvert^2 \, m_i^2}$	2.3	0.2	0.1	model-indep.; theo. clean	final?; worst
Cosmo.	$\sum m_i$	0.7	0.3	0.05	best; NH/IH	systemat.; model-dep.
$0\nu\beta\beta$	$\lvert \sum U_{ei}^2 m_i \rvert$	0.3	0.1	0.05	fundament.; NH/IH	model-dep.; theo. dirty

Generalization. . .



Sterile Neutrinos??

- LSND/MiniBooNE/gallium
- cosmology
- BBN
- r-process nucleosynthesis in Supernovae
- reactor anomaly

	$\Delta m^2_{41}[\mathrm{eV}^2]$	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	$\Delta m^2_{51}[\mathrm{eV}^2]$	$\lvert U_{e5}\rvert$	$\lvert U_{\mu 5}\rvert$
3+2/2+3	0.47	0.128	0.165	0.87	0.138	0.148
1+3+1	0.47	0.129	0.154	0.87	0.142	0.163

or $\Delta m^2_{41} = 1.78$ eV^2 and $|U_{e4}|^2 = 0.151$

Kopp, Maltoni, Schwetz, 1103.4570

Note on TeV scale left-right symmetry

Usual relation between VEVs:

$$v_L\, v_R \simeq \gamma\, v^2 \Rightarrow \gamma \simeq 10^{-10}$$

(or strong cancellations in $m_D^T\, M_R^{-1}\, m_D$)

possible to break discrete left-right parity P at high scale:

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times P \xrightarrow{\langle \sigma_P \rangle} SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

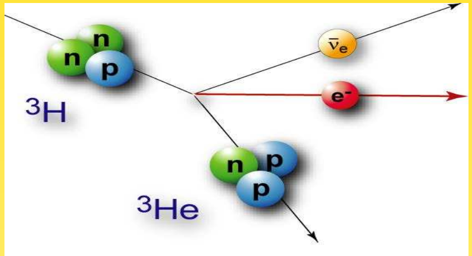
and break gauge symmetry later (Chang, Mohapatra, Parida, PRL **52**); results in

$$v_L = \beta \frac{v^2\, v_R}{M_\Delta\, \langle \sigma_P \rangle}$$

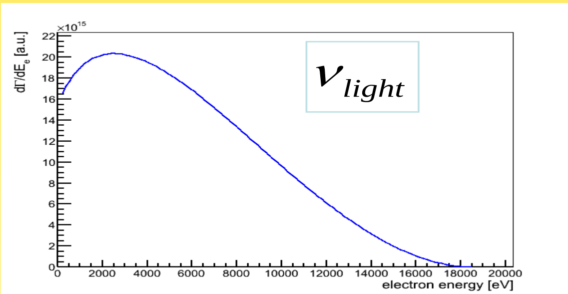
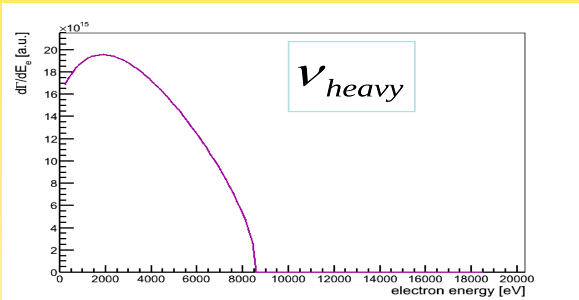
gives $g_R/g_L \neq 1$, weaker M_{W_R} limits, etc.

(recent use for $eejj$ excess: Deppisch *et al.*, PR **D91**)

Imprint of keV neutrinos on ß-spectrum

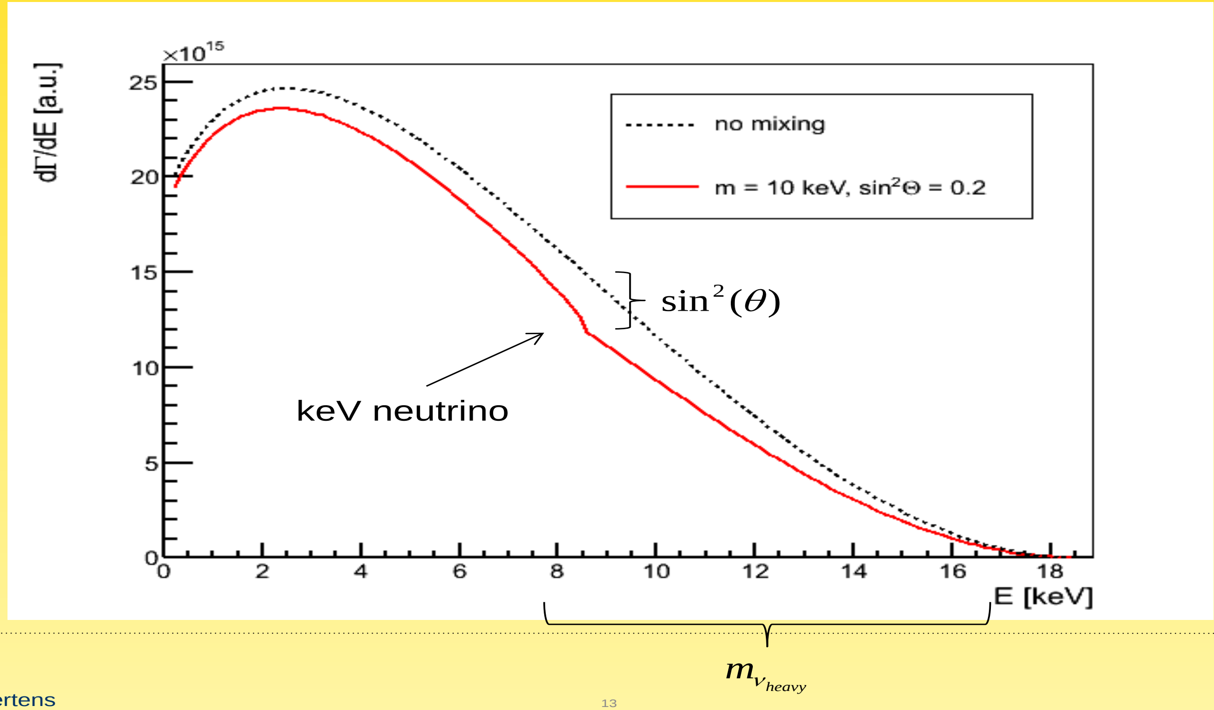


$$\begin{pmatrix} \nu_e \\ \nu_s \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_{light} \\ \nu_{heavy} \end{pmatrix}$$

$\cos^2(\theta)$  $+ \sin^2(\theta)$ 

Mertens *et al.*, 1409.0920

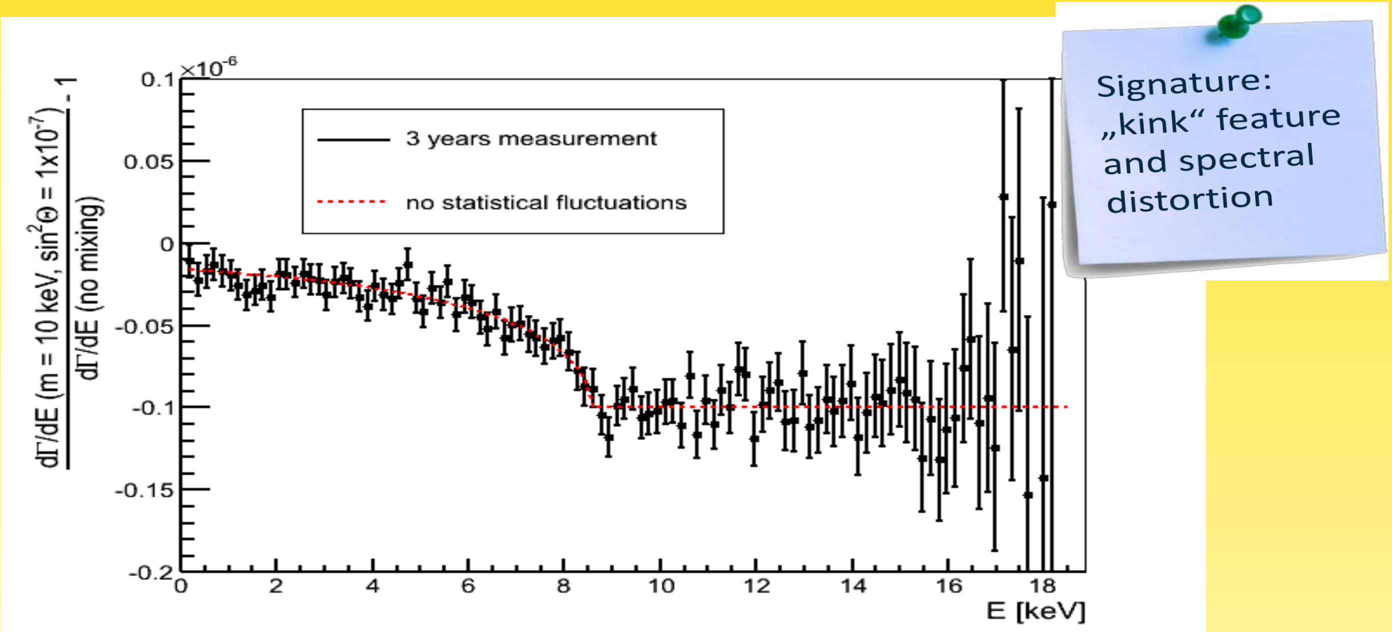
Imprint of keV neutrinos on ß-spectrum



Susanne Mertens 13

Mertens *et al.*, 1409.0920

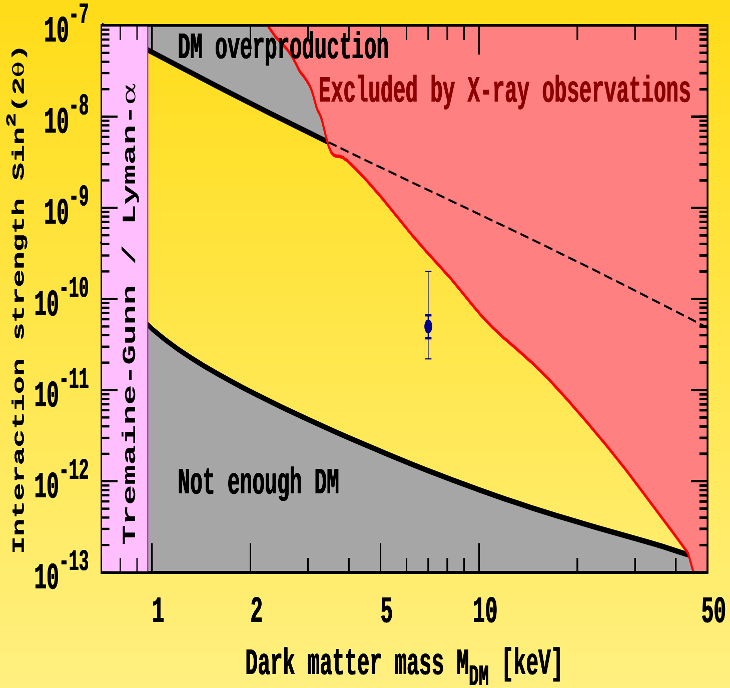
Imprint of keV neutrinos on ß-spectrum



Susanne Mertens

15

Mertens *et al.*, 1409.0920

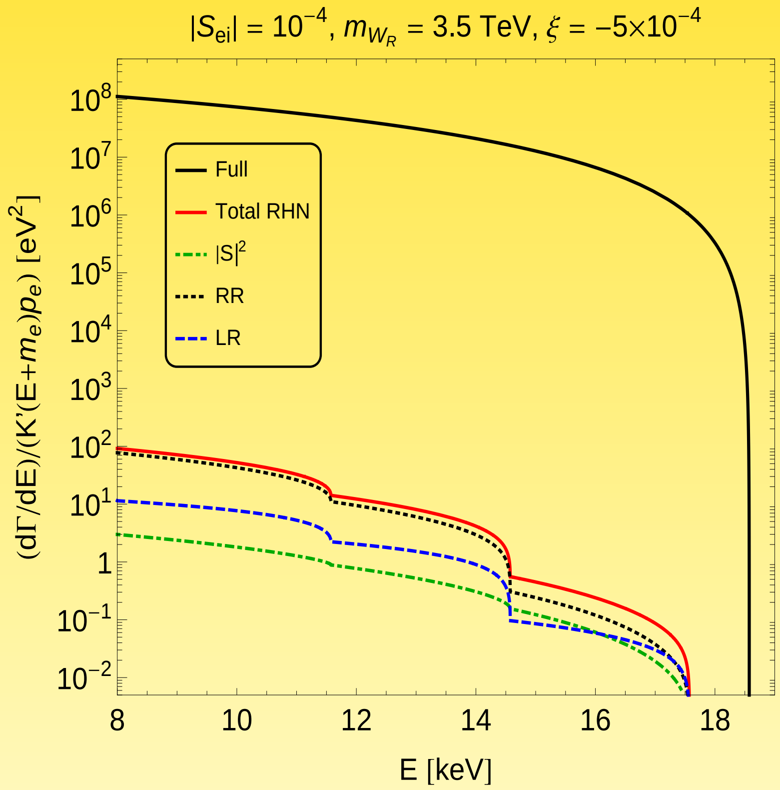


$\Rightarrow$ mixing down to 10^{-7} in reach!?

hard for KATRIN to see something...

...can increase signal with additional interactions, e.g. right-handed currents in total one has

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E} = \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}E}\right)_{LL} + \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}E}\right)_{RR} + \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}E}\right)_{LR}$$



Energy Scale:

Note: *standard amplitude* for light Majorana neutrino exchange:

$$\mathcal{A}_{\rm l} \simeq G_F^2 \, \frac{|m_{ee}|}{q^2} \simeq 7 \times 10^{-18} \left(\frac{|m_{ee}|}{0.5 \text{ eV}} \right) \text{GeV}^{-5} \simeq 2.7 \text{ TeV}^{-5}$$

if new heavy particles are exchanged:

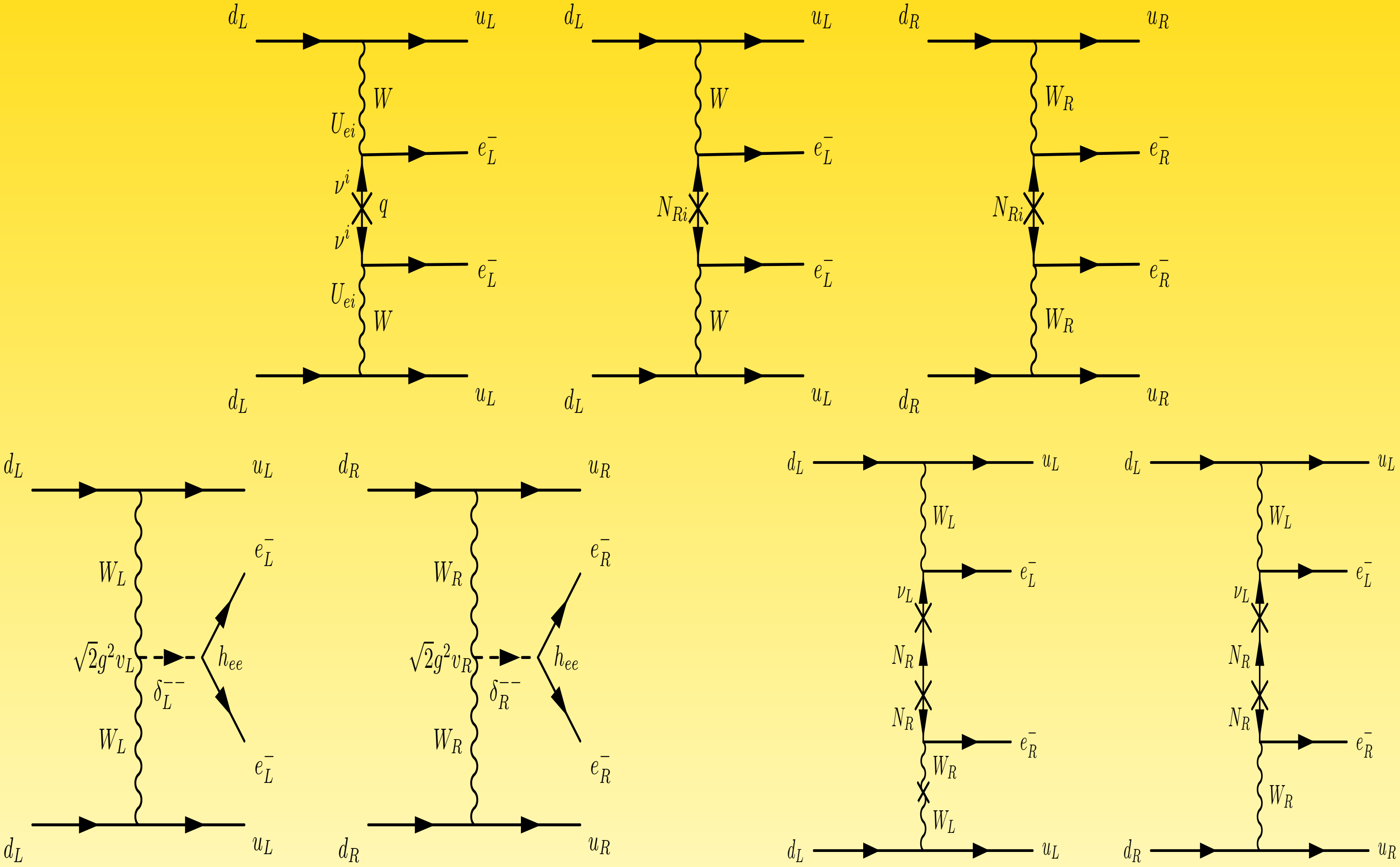
$$\mathcal{A}_{\rm h} \simeq \frac{c}{M^5}$$

$\Rightarrow$ for $0\nu\beta\beta$ holds:

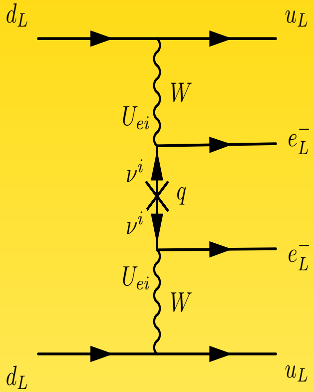
$$\boxed{1 \text{ eV} = 1 \text{ TeV}}$$

$\Rightarrow$ Phenomenology in colliders, LFV

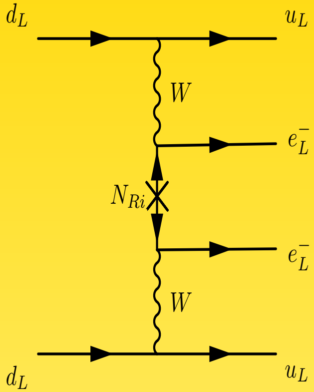
Left-right symmetry



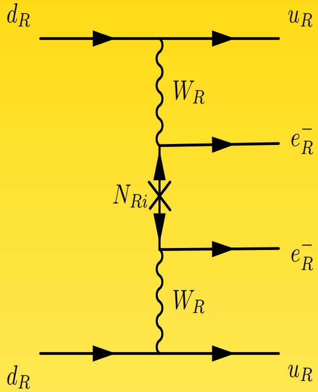
Left-right symmetry



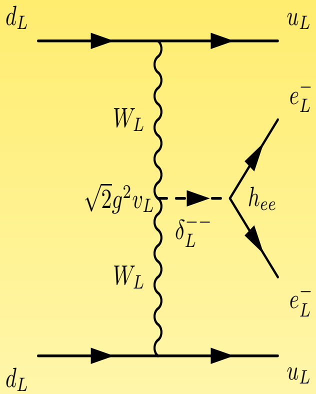
$$U_{ei}^2\, m_i$$



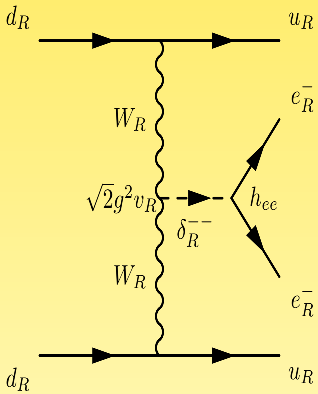
$$\frac{S_{ei}^2}{M_i}$$



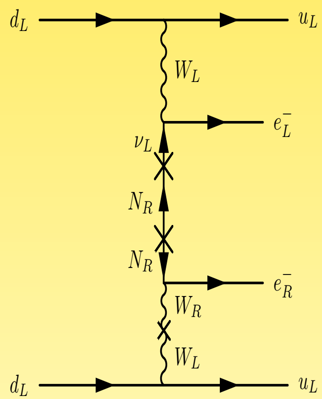
$$\frac{V_{ei}^2}{M_{W_R}^4\, M_i}$$



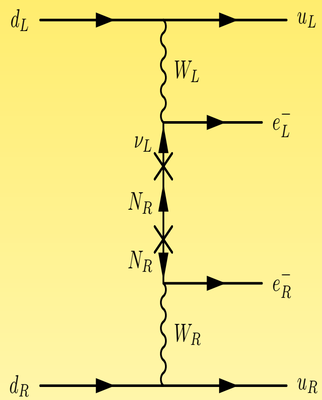
$$\frac{U_{ei}^2\, m_i}{M_{\Delta_L}^2}$$



$$\frac{V_{ei}^2\, M_i}{M_{W_R}^4\, M_{\Delta_R}^2}$$

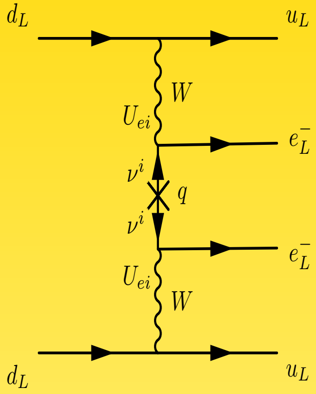


$$U_{ei}\, T_{ei} \tan\zeta$$

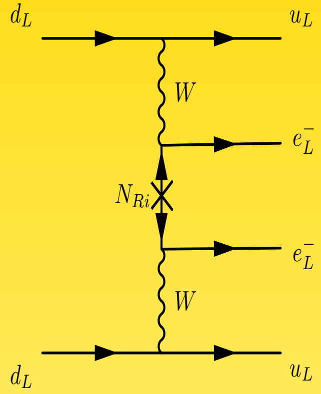


$$\frac{U_{ei}\, T_{ei}}{M_{W_R}^2}$$

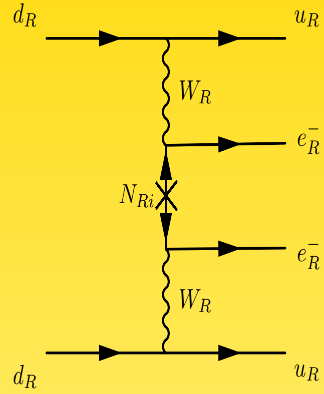
Left-right symmetry



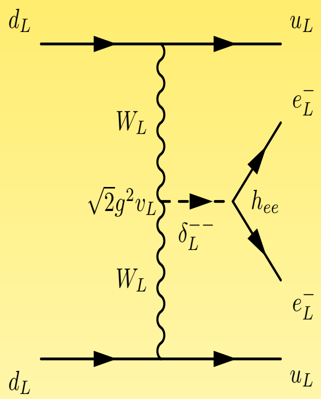
0.4 eV



2×10^{-8} GeV^{-1}



4×10^{-16} GeV^{-5}



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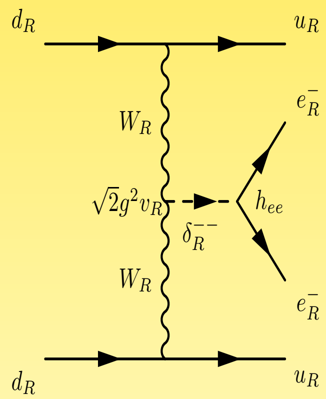
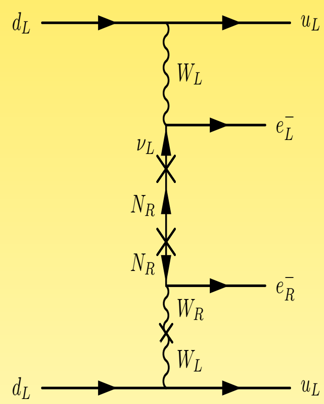
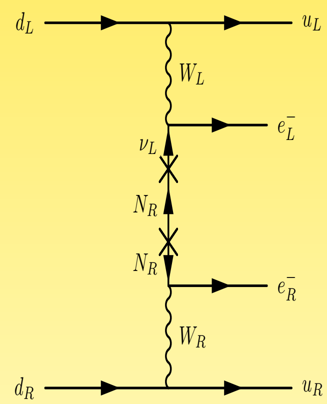


10^{-15} GeV^{-5}



6×10^{-9}



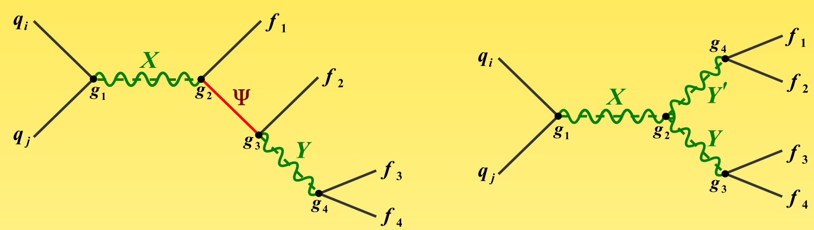
1.4×10^{-10} GeV^{-2}

Observation of LNV at LHC implies washout effects in early Universe!

Example TeV-scale W_R: leading to washout $e^\pm_R\, e^\pm_R \to W^\pm_R W^\pm_R$ and $e^\pm_R\, W^\mp_R \to e^\mp_R\, W^\pm_R$. Further, $e^\pm_R W^\mp_R \to e^\mp_R\, W^\pm_R$ stays long in equilibrium

(Frere, Hambye, Vertongen; Bhupal Dev, Lee, Mohapatra; U. Sarkar *et al.*)

More model-independent (Deppisch, Harz, Hirsch):



washout: $$\log_{10} \frac{\Gamma_W(qq \to \ell^+\ell^+\, qq)}{H} \gtrsim 6.9 + 0.6 \left(\frac{M_X}{\text{TeV}} - 1\right) + \log_{10} \frac{\sigma_{\text{LHC}}}{\text{fb}}$$

(TeV-$0\nu\beta\beta$, LFV and Y_B: Deppisch, Harz, Huang, Hirsch, Päs)

$\leftrightarrow$ post-Sphaleron mechanisms, τ flavor effects,...

Paths to Neutrino Mass

approach	ingredient	quantum number of messenger	$\mathcal{L}$	m_ν	scale
"SM" **(Dirac mass)**	**RH** ν	$N_R \sim (1,0)$	$h\overline{N_R}\Phi L$	hv	$h = \mathcal{O}(10^{-12})$
"effective" **(dim 5 operator)**	**new scale** **+ LNV**	–	$h\,\overline{L^c}\,\Phi\,\Phi\,L$	$\frac{h\,v^2}{\Lambda}$	$\Lambda = 10^{14}$ **GeV**
"direct" **(type II seesaw)**	**Higgs triplet** **+ LNV**	$\Delta \sim (3,-2)$	$h\overline{L^c}\Delta L + \mu\Phi\Phi\Delta$	hv_T	$\Lambda = \frac{1}{h\mu}M_\Delta^2$
"indirect 1" **(type I seesaw)**	**RH** ν **+ LNV**	$N_R \sim (1,0)$	$h\overline{N_R}\Phi L + \overline{N_R}M_R N_R^c$	$\frac{(hv)^2}{M_R}$	$\Lambda = \frac{1}{h}M_R$
"indirect 2" **(type III seesaw)**	**fermion triplets** **+ LNV**	$\Sigma \sim (3,0)$	$h\overline{\Sigma}\,L\Phi + \mathrm{Tr}\overline{\Sigma}M_\Sigma\Sigma$	$\frac{(hv)^2}{M_\Sigma}$	$\Lambda = \frac{1}{h}M_\Sigma$

plus seesaw variants (linear, double, inverse,...)

plus radiative mechanisms

plus extra dimensions

plusplusplus

Recent Results

- ^{76}Ge:
  - GERDA: $T_{1/2} > 2.1 \times 10^{25}$ yrs
  - GERDA + IGEX + HDM: $T_{1/2} > 3.0 \times 10^{25}$ yrs
- ^{136}Xe:
  - EXO-200: $T_{1/2} > 1.1 \times 10^{25}$ yrs **(first run with less exposure:** $T_{1/2} > 1.6 \times 10^{25}$ **yrs. . .)**
  - KamLAND-Zen: $T_{1/2} > 2.6 \times 10^{25}$ yrs

Xe-limit is stronger than Ge-limit when:

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