Neutrinoless Double Beta Decay

Max-Planck-Institut für Kernphysik

Werner Rodejohann

XVIII LNF Spring School

May 2016

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

MANITOP

Massive Neutrinos: Investigating their Theoretical Origin and Phenomenology

INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Frascati

XVIII Frascati Spring School

"BRUNO TOUSCHEK"

in nuclear, subnuclear and astroparticle physics

LNF, May 9 - 13, 2016, Frascati (Italy)

Heisenberg-Programm

DFG Deutsche Forschungsgemeinschaft

Contents

Interpretation of Experiments

Master formula:

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

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

Interpretation of Experiments

Master formula:

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- $G_x(Q,Z)$: phase space factor, typically Q^5
- $\mathcal{M}_x(A,Z)$: nuclear physics; factor 2-3 uncertainty
- η_x: particle physics; many possibilities

Contents

III1) Basics

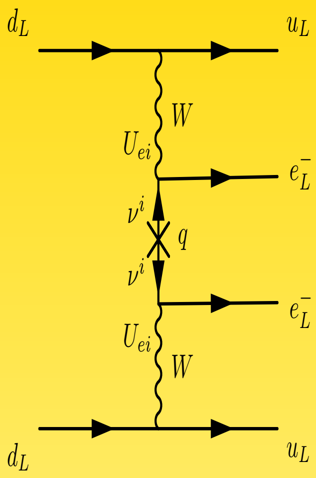
- **Standard Interpretation:**

  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

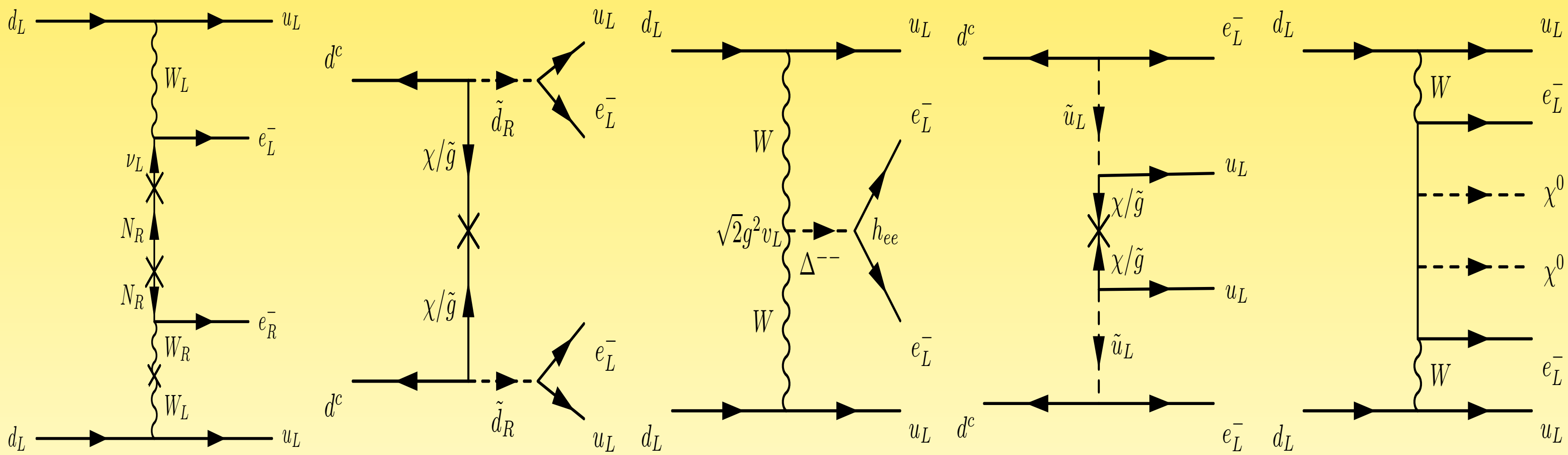
- **Non-Standard Interpretations:**

  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

- **Standard Interpretation:**



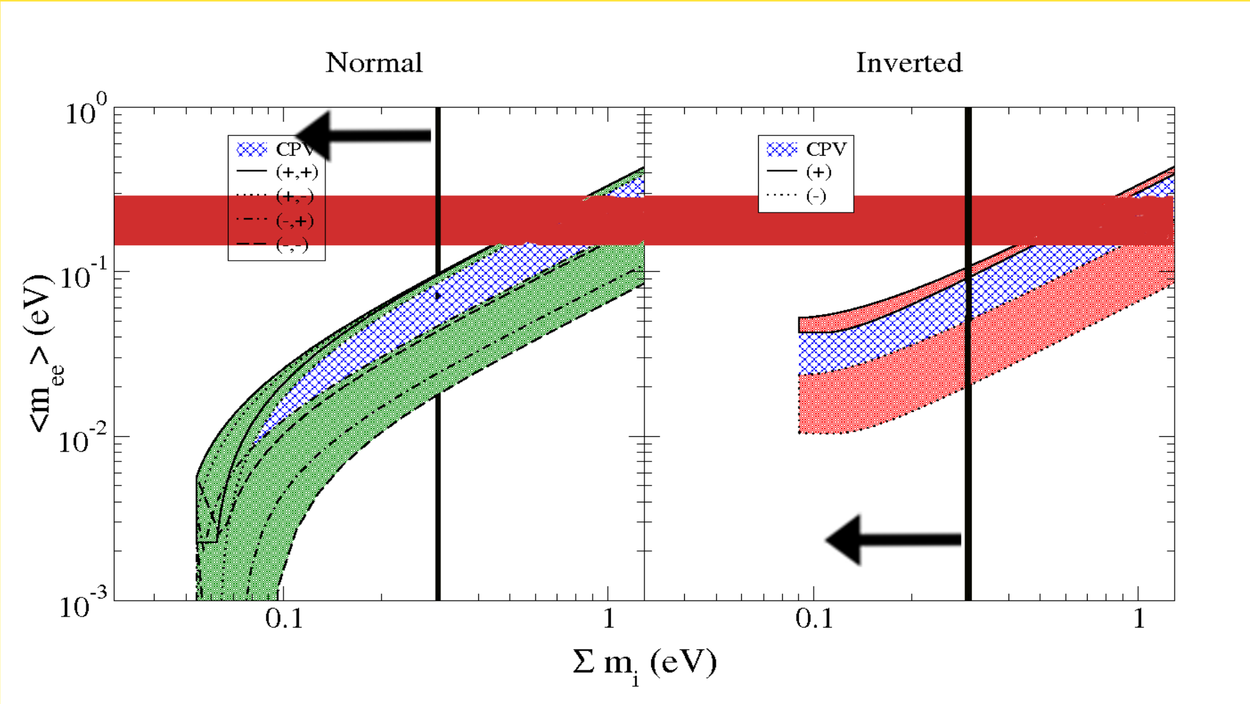
- **Non-Standard Interpretations:**



Non-Standard Interpretations

clear experimental signature:

KATRIN (or cosmology) sees nothing but "$|m_{ee}| > 0.5$ eV"



$0\nu\beta\beta$ decoupled from cosmology limits on neutrino mass!

Energy Scale:

- *standard amplitude* for light Majorana neutrino exchange:

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

-

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- if new heavy particles are exchanged:

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

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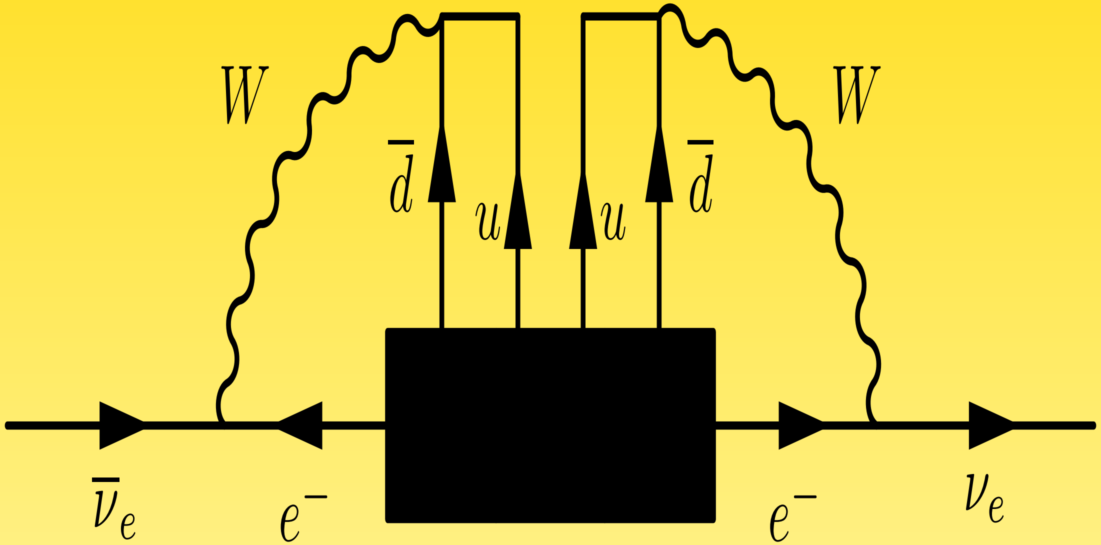
$\Rightarrow$ for $0\nu\beta\beta$ holds:

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

$\Rightarrow$ Phenomenology in colliders, LFV

Schechter-Valle theorem: observation of $0\nu\beta\beta$ implies Majorana neutrinos



is 4 loop diagram: $m_\nu^{\rm BB} \sim \frac{G_F^2}{(16\pi^2)^4}\,{\rm MeV}^5 \sim 10^{-25}\,{\rm eV}$

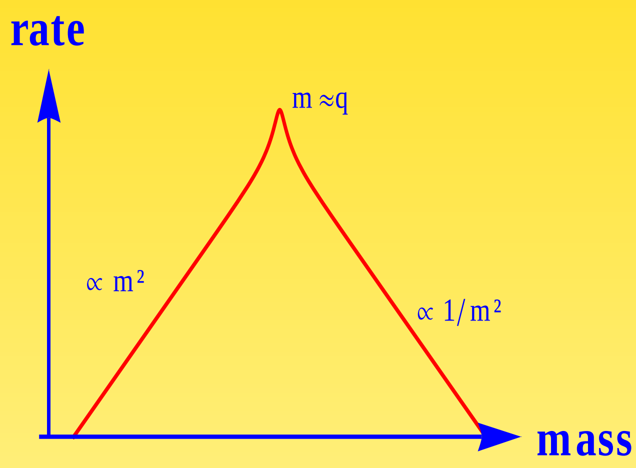
explicit calculation: `Duerr, Lindner, Merle, 1105.0901`

mechanism	physics parameter	current limit	test
light neutrino exchange	$\left\| U_{ei}^2 \, m_i \right\|$	0.5 eV	oscillations, cosmology, neutrino mass
heavy neutrino exchange	$\left\| \frac{S_{ei}^2}{M_i} \right\|$	2×10^{-8} GeV^{-1}	LFV, collider
heavy neutrino and RHC	$\left\| \frac{V_{ei}^2}{M_i \, M_{W_R}^4} \right\|$	4×10^{-16} GeV^{-5}	flavor, collider
Higgs triplet and RHC	$\left\| \frac{(M_R)_{ee}}{m_{\Delta_R}^2 \; M_{W_R}^4} \right\|$	10^{-15} GeV^{-1}	flavor, collider e^- distribution
λ-mechanism with RHC	$\left\| \frac{U_{ei} \, \tilde{S}_{ei}}{M_{W_R}^2} \right\|$	1.4×10^{-10} GeV^{-2}	flavor, collider, e^- distribution
η-mechanism with RHC	$\tan\zeta \, \left\| U_{ei} \, \tilde{S}_{ei} \right\|$	6×10^{-9}	flavor, collider, e^- distribution
short-range $\not R$	$\frac{\left\| \lambda'^2_{111} \right\|}{\Lambda^5_{SUSY}}$ $\Lambda_{SUSY} = f(m_{\tilde{g}}, m_{\tilde{u}_L}, m_{\tilde{d}_R}, m_{\chi_i})$	7×10^{-18} GeV^{-5}	collider, flavor
long-range $\not R$	$\left\| \sin 2\theta^b \, \lambda'_{131} \, \lambda'_{113} \left(\frac{1}{m^2_{\tilde{b}_1}} - \frac{1}{m^2_{\tilde{b}_2}} \right) \right\|$ $\sim \frac{G_F}{q} m_b \frac{\left\| \lambda'_{131} \, \lambda'_{113} \right\|}{\Lambda^3_{SUSY}}$	2×10^{-13} GeV^{-2} 1×10^{-14} GeV^{-3}	flavor, collider
Majorons	$\|\langle g_\chi \rangle\|$ or $\|\langle g_\chi \rangle\|^2$	$10^{-4} \ldots 1$	spectrum, cosmology

Some features

- Majoranas and no RHC:

$$\mathcal{A} \propto \frac{m}{q^2 - m^2} \rightarrow \begin{cases} m & \text{for } q^2 \gg m^2 \\ \frac{1}{m} & \text{for } q^2 \ll m^2 \end{cases}$$



Note: maximum $\mathcal{A}$ corresponds to $m \simeq \langle q \rangle$: limits on $\mathcal{O}(m_K)$ Majorana neutrinos from $K^+ \rightarrow \pi^- \mu^+ e^+$

- heavy scalar/vector boson:

$$\mathcal{A} \propto \frac{1}{q^2 - m^2} \rightarrow \frac{1}{m^2}$$

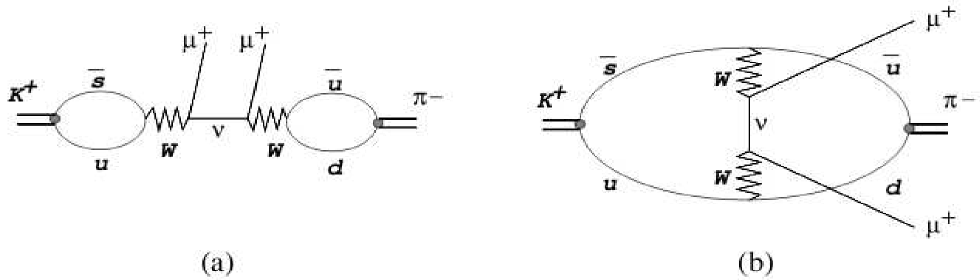
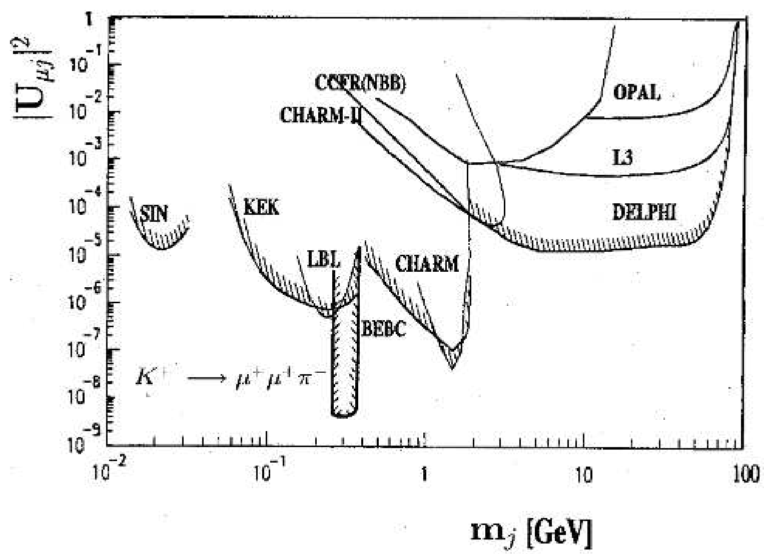
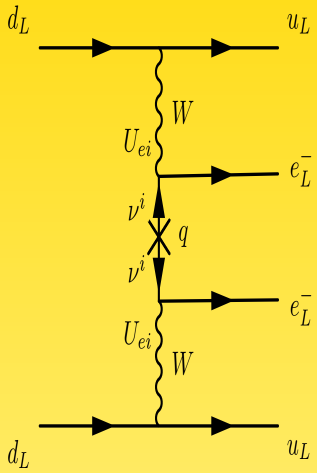


Figure 1: The lowest order diagrams contributing to $K^+ \to \mu^+\mu^+\pi^-$ decay.

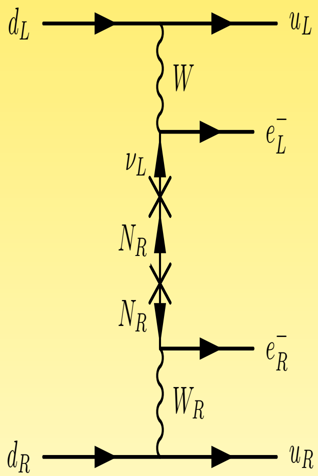


Dib *et al.*, hep-ph/0006277

Chiralities

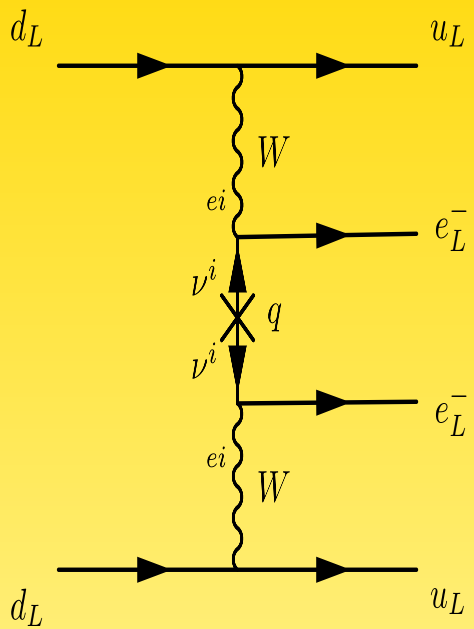


$$\mathcal{A} \propto P_L \frac{\not{q} + m_i}{q^2 - m_i^2} P_L \propto \frac{m_i}{q^2 - m_i^2} \simeq \begin{cases} m_i/q^2 & (m_i^2 \ll q^2) \\ 1/m_i & (m_i^2 \gg q^2) \end{cases}$$



$$\mathcal{A} \propto P_R \frac{\not{q} + m_i}{q^2 - m_i^2} P_L \propto \frac{\not{q}}{q^2 - m_i^2} \simeq \begin{cases} 1/q & (m_i^2 \ll q^2) \\ q/m_i^2 & (m_i^2 \gg q^2) \end{cases}$$

Heavy neutrinos

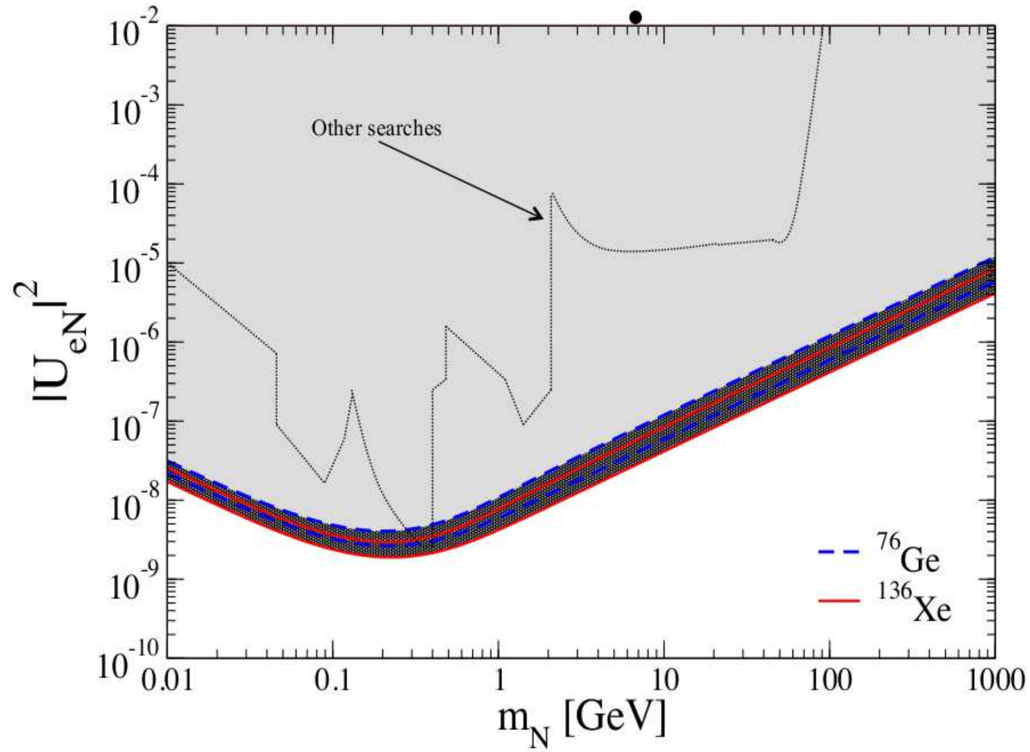


if heavier than 100 MeV:

$$\mathcal{A}_{\rm h} = G_F^2 \frac{S_{ei}^2}{M_i} \equiv G_F^2 \, \langle \frac{1}{m} \rangle \;\Rightarrow \langle \frac{1}{m} \rangle \;\lesssim 10^{-8}\ {\rm GeV}^{-1}$$

dimensionless LNV parameter:

$$\eta_{\rm h} = m_p \, \langle \frac{1}{m} \rangle \leq 1.7 \times 10^{-8}$$



Faessler, Gonzalez, Kovalenko, Simkovic, 1408.6077

An exact See-Saw Relation

Full mass matrix:

$$\mathcal{M} = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} = \mathcal{U} \begin{pmatrix} m_\nu^{\rm diag} & 0 \\ 0 & M_R^{\rm diag} \end{pmatrix} \mathcal{U}^T \text{ with } \mathcal{U} = \begin{pmatrix} N & S \\ T & V \end{pmatrix}$$

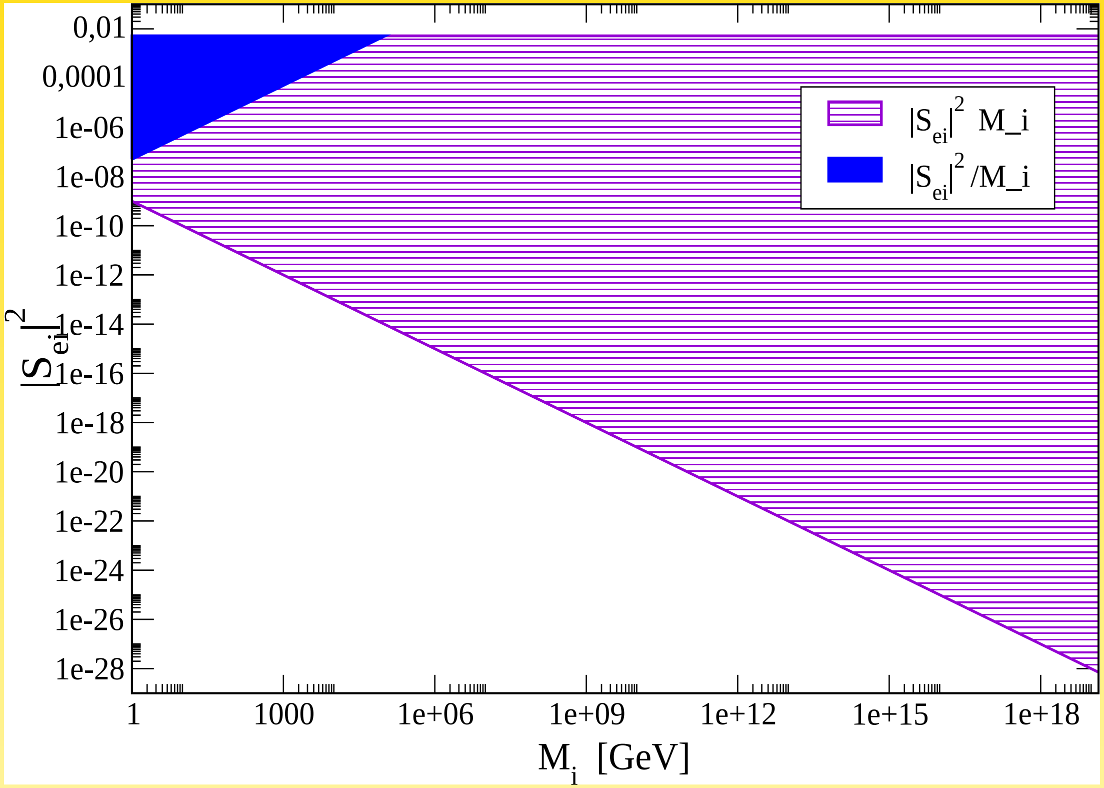
- N is the PMNS matrix: non-unitary
- $S = m_D^\dagger \, (M_R^*)^{-1}$ describes mixing of heavy neutrinos with SM leptons

upper left 0 in $\mathcal{M}$ gives exact see-saw relation $\mathcal{U}_{\alpha i} \, (m_\nu)_i \mathcal{U}_{i\beta} = 0$, or:

$$|N_{ei}^2 \, m_i| = |S_{ei}^2 \, M_i| \lesssim 0.3 \text{ eV}$$

compare with $\dfrac{S_{ei}^2}{M_i} \lesssim 10^{-8} \, \text{GeV}^{-1}$ and $|S_{ei}|^2 \leq 0.0052$

exact see-saw relation gives stronger constraints!



$\Rightarrow$ cancellations required to make heavy neutrinos contribute significantly to $0\nu\beta\beta$

TeV scale seesaw with sizable mixing

$$m_\nu = m_D^2/M_R \simeq v^2/M_R$$

with $m_\nu \simeq \sqrt{\Delta m_{\rm A}^2}$ it follows that $M_R \simeq 10^{15}$ GeV and

$$S = m_D/M_R = \sqrt{m_\nu/M_R} \simeq 10^{-13}$$

then, heavy neutrino contribution to $0\nu\beta\beta$ negligible:

$$S^2/M_R = m_D^2/M_R^3 \simeq 10^{-41} \text{ GeV}^{-1}$$

can make M_R TeV, but then mixing $\sqrt{m_\nu/M_R} \simeq 10^{-7}$ and still

$$m_D^2/M_R^3 \simeq 10^{-17} \text{ GeV}^{-1}$$

TeV scale seesaw with sizable mixing

not necessarily correct, m_D and M_R are matrices and cancellations can occur...

e.g. $$m_D = v \begin{pmatrix} h_1 & h_2 & h_3 \\ \omega\, h_1 & \omega\, h_2 & \omega\, h_3 \\ \omega^2\, h_1 & \omega^2\, h_2 & \omega^2\, h_3 \end{pmatrix} \quad M_R = M_0 \mathbb{1}$$ (here $\omega = e^{2i\pi/3}$)

gives $m_\nu = 0$, add (very) small corrections...

$m_D = v$, $M_R =$ TeV, mixing m_D/M_R large, $0\nu\beta\beta$ contribution large

TeV scale seesaw with sizable mixing

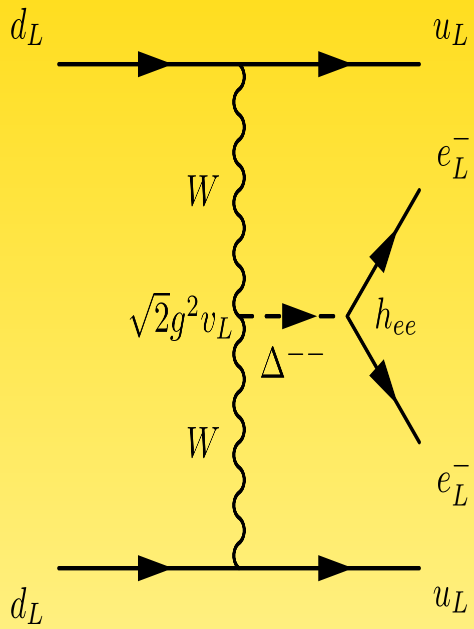
can also make everything smaller:

$$M_D = m \begin{pmatrix} f\epsilon^2 & 0 & 0 \\ 0 & g\epsilon & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad , \quad M_R^{-1} = M^{-1} \begin{pmatrix} a & b & k \\ b & c & d\epsilon \\ k & d\epsilon & e\epsilon^2 \end{pmatrix}$$

M/GeV	m/MeV	ϵ	a	k	b	c	d	e	f	g
5.00	0.935	0.02	1.00	1.35	0.90	1.4576	0.7942	0.2898	0.0948	0.485

$$\left| \frac{\mathcal{A}_{\rm l}}{\mathcal{A}_{\rm h}} \right| = \frac{\frac{G_F^2}{q^2} \, |m_{ee}|}{G_F^2 \, \langle \frac{1}{m} \rangle} \simeq \frac{10^{-4} \text{ GeV}^2}{q^2} \simeq 10^{-2}$$

Higgs triplets (type II seesaw)



$$\mathcal{A}_\Delta \simeq G_F^2 \, \frac{h_{ee}\, v_L}{m_\Delta^2} \lesssim G_F^2 \, \frac{(m_\nu)_{ee}}{m_\Delta^2} = G_F^2 \, \frac{|m_{ee}|}{m_\Delta^2}$$

plays no role in $0\nu\beta\beta$

Inverse Neutrinoless Double Beta Decay

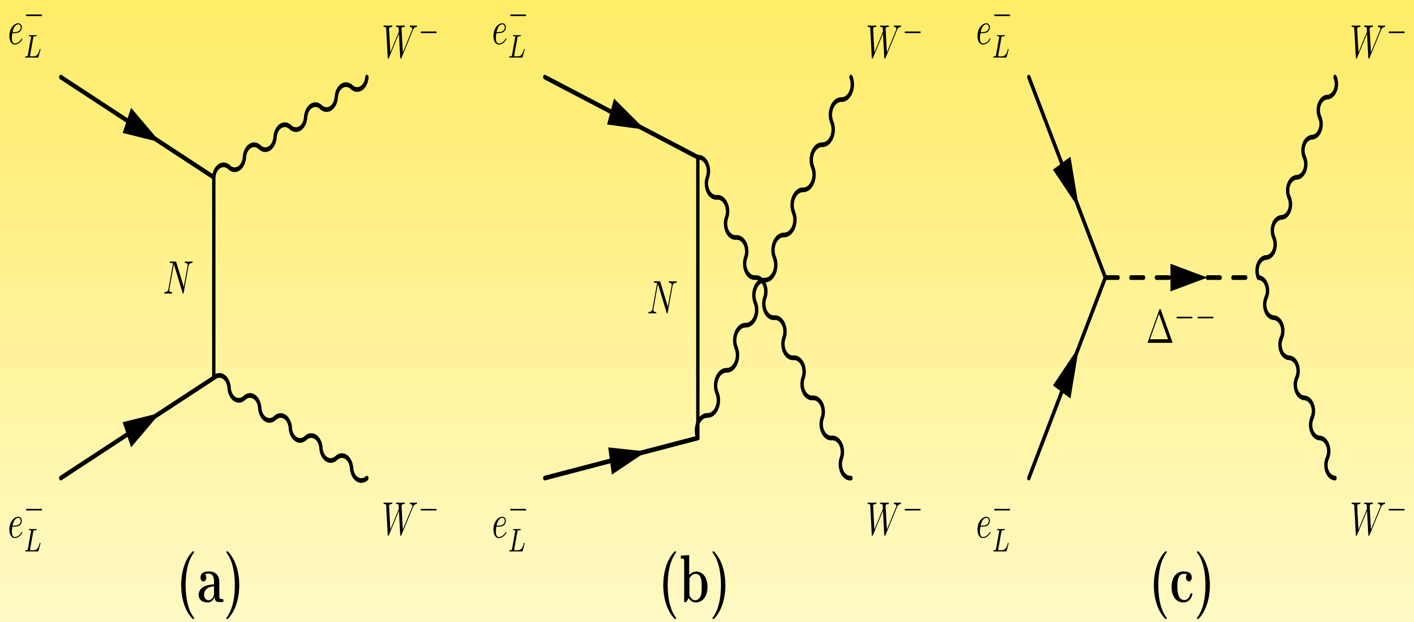
this is not

$$^{76}\mathrm{Se}^{++} + e^- + e^- \to \ ^{76}\mathrm{Ge}$$

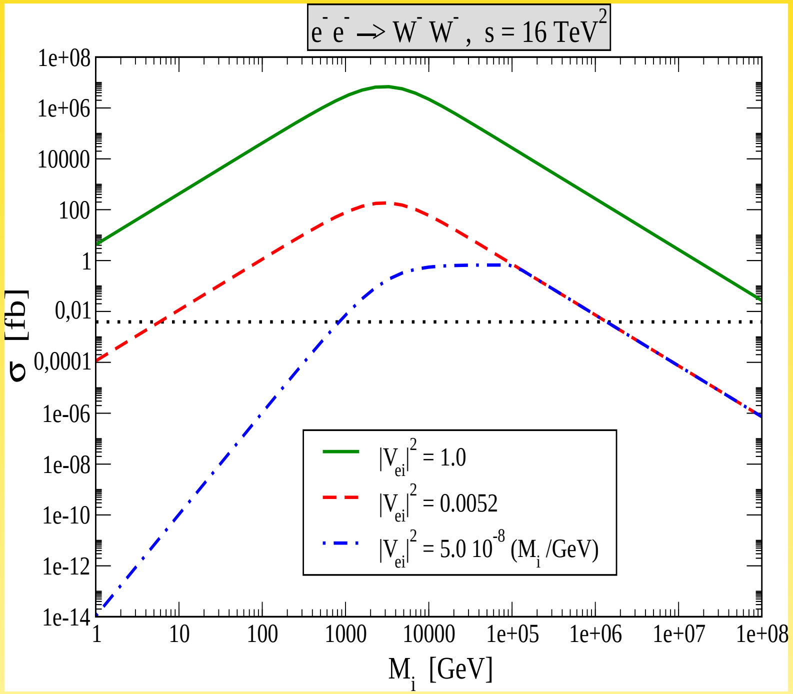
but rather

$$e^- + e^- \to W^- + W^-$$

Rizzo; Heusch, Minkowski; Gluza, Zralek; Cuypers, Raidal;...



Inverse Neutrinoless Double Beta Decay



$$\frac{d\sigma}{d\cos\theta} = \frac{G_F^2}{32\,\pi}\left\{\sum (m_\nu)_i\,\mathcal{U}_{ei}^2\left(\frac{t}{t-(m_\nu)_i}+\frac{u}{u-(m_\nu)_i}\right)\right\}^2$$

Inverse Neutrinoless Double Beta Decay

Extreme limits:

- light neutrinos:

$$\sigma(e^-e^- \to W^-W^-) = \frac{G_F^2}{4\,\pi}\,|m_{ee}|^2 \leq 4.2 \cdot 10^{-18} \left(\frac{|m_{ee}|}{1\,\mathrm{eV}}\right)^2 \mathrm{fb}$$

$\Rightarrow$ way too small

- heavy neutrinos:

$$\sigma(e^-e^- \to W^-W^-) = 2.6 \cdot 10^{-3} \left(\frac{\sqrt{s}}{\mathrm{TeV}}\right)^4 \left(\frac{S_{ei}^2/M_i}{5 \cdot 10^{-8}\,\mathrm{GeV}^{-1}}\right)^2 \mathrm{fb}$$

$\Rightarrow$ too small

- $\sqrt{s} \to \infty$:

$$\sigma(e^-e^- \to W^-W^-) = \frac{G_F^2}{4\pi} \left(\sum \mathcal{U}_{ei}^2\,(m_\nu)_i\right)^2$$

$\Rightarrow$ amplitude grows with $\sqrt{s}$? Unitarity??

Unitarity

high energy limit $\sqrt{s} \to \infty$:

$$\sigma(e^- e^- \to W^- W^-) = \frac{G_F^2}{4\pi} \left(\sum \mathcal{U}_{ei}^2 \, (m_\nu)_i \right)^2$$

$\leftrightarrow$ amplitude grows with $\sqrt{s}$?

Answer: exact see-saw relation $\mathcal{U}_{ei}^2 \, (m_\nu)_i = 0$

$$\mathcal{M} = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} = \mathcal{U} \begin{pmatrix} m_\nu^{\rm diag} & 0 \\ 0 & M_R^{\rm diag} \end{pmatrix} \mathcal{U}^T$$

if Higgs triplet is present: unitarity also conserved

$$\sigma(e^- e^- \to W^- W^-) = \frac{G_F^2}{4\pi} \left((\mathcal{U}_{ei}^2 \, (m_\nu)_i - (m_L)_{ee} \right)^2 = 0$$

W.R., PRD **81**

Contents

III2) Left-right symmetric theories

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
  $M_{Z'} = \sqrt{\frac{2}{1-\tan^2\theta_W}} M_{W_R} \simeq 1.7\, M_{W_R}$
- 'sterile' neutrinos ν_R
- type I + type II seesaw for neutrino mass
- right-handed currents with strength $G_F \left(\frac{g_R}{g_L}\right)^2 \left(\frac{m_W}{M_{W_R}}\right)^2$
- $m_\nu \propto 1/v_R \propto 1/M_{W_R}$: 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, flavor states $n'_L = (\nu'_L, {\nu_R}^c)^T$, 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 $f_L = f_R = f$)

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

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

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

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

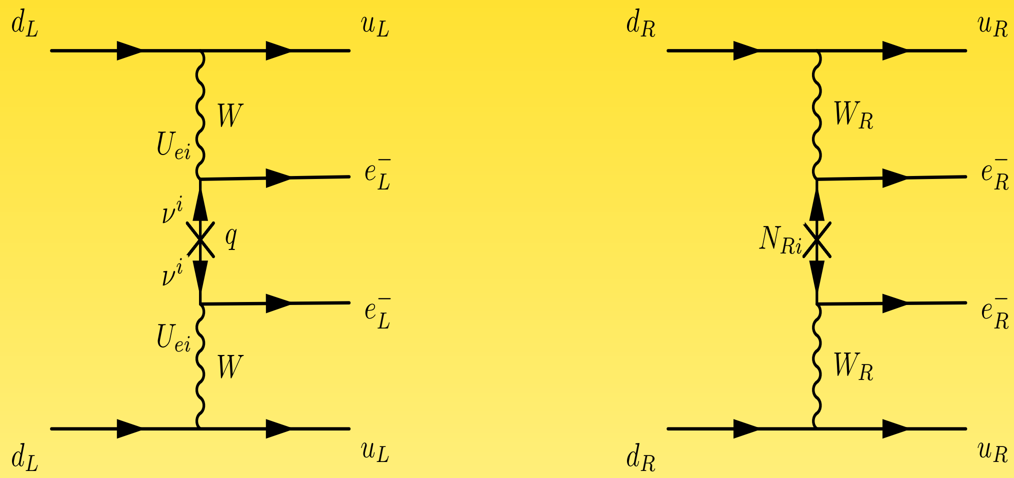
$$\mathcal{L}_Y^\ell = -\overline{L}_L^{\prime c} i\sigma_2 \Delta_L f_L L_L^\prime - \overline{L}_R^{\prime c} i\sigma_2 \Delta_R f_R L_R^\prime$$

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 both right-handed: leading diagrams:



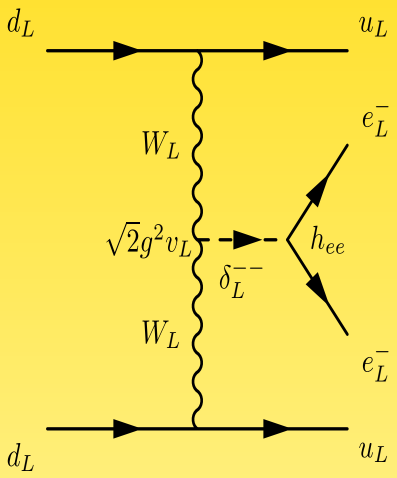
$$\mathcal{A}_\nu \simeq G_F^2 \frac{m_{ee}}{q^2} \qquad \mathcal{A}_{N_R}^R \simeq G_F^2 \left(\frac{m_{W_L}}{M_{W_R}}\right)^4 \sum_i \frac{{V_{ei}^*}^2}{M_i}$$

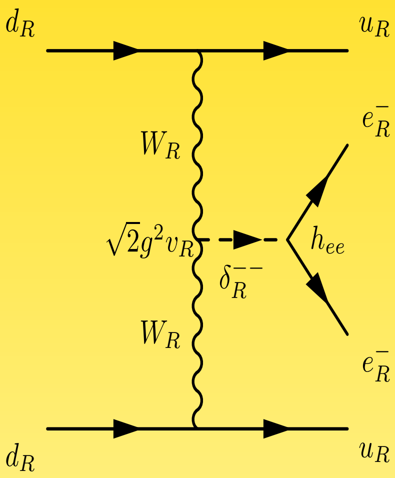
$$\lesssim 0.3\,\mathrm{eV} \qquad \lesssim 4 \cdot 10^{-16}\,\mathrm{GeV}^{-5}$$

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

Triplet exchange diagrams

leading diagrams:





$$\mathcal{A}_{\delta_L} \simeq G_F^2 \frac{h_{ee} v_L}{m_{\delta_L}^2}$$

$$--$$

(negligible)

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

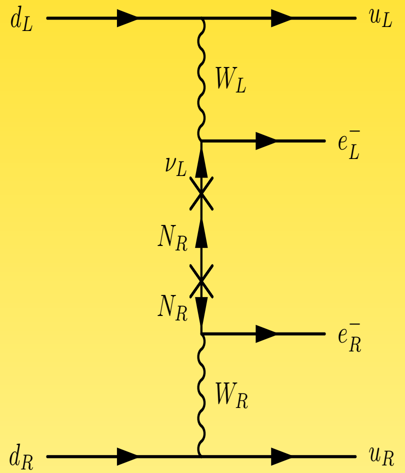
$$\lesssim 4 \cdot 10^{-16}\,\mathrm{GeV}^{-5}$$

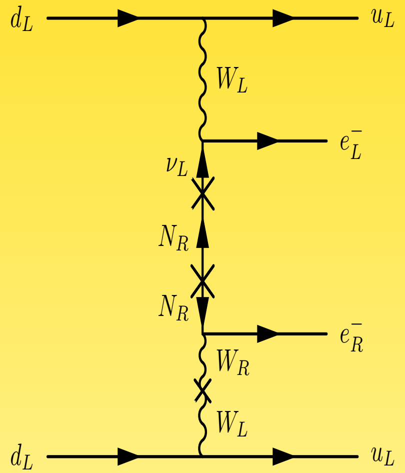
$$\propto \frac{L^4}{R^5}$$

Momentum Dependent Diagrams

electrons with opposite helicity leading diagrams

(light neutrino exchange, long range):





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

$$\lesssim 1 \cdot 10^{-10}\,\mathrm{GeV}^{-2}$$

$$\propto \frac{L^3}{R^3 q}$$

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

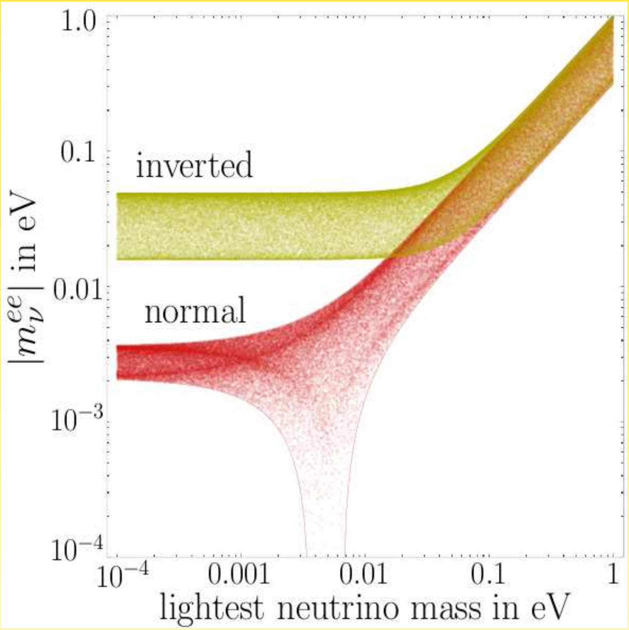
$$\lesssim 6 \cdot 10^{-9}$$

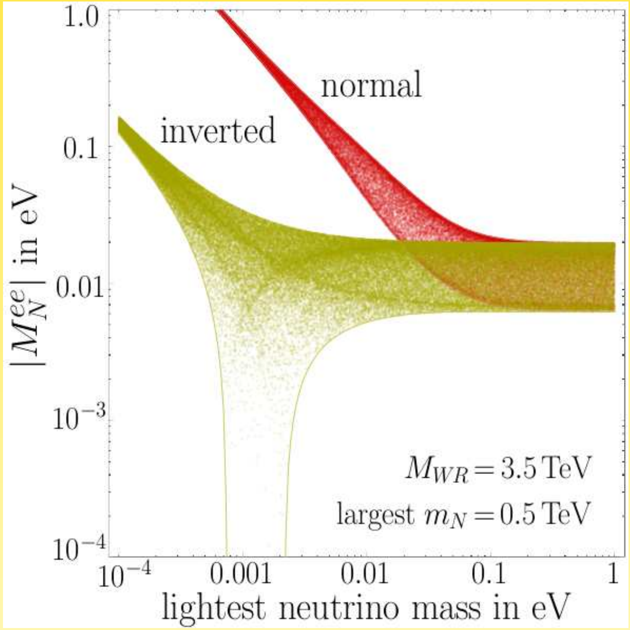
$$\propto \frac{L^3}{R^3 q}$$

Tests of left-right symmetric diagrams

suppose M_L dominates in m_ν and $h = f$: $\Rightarrow M_R \propto m_\nu$

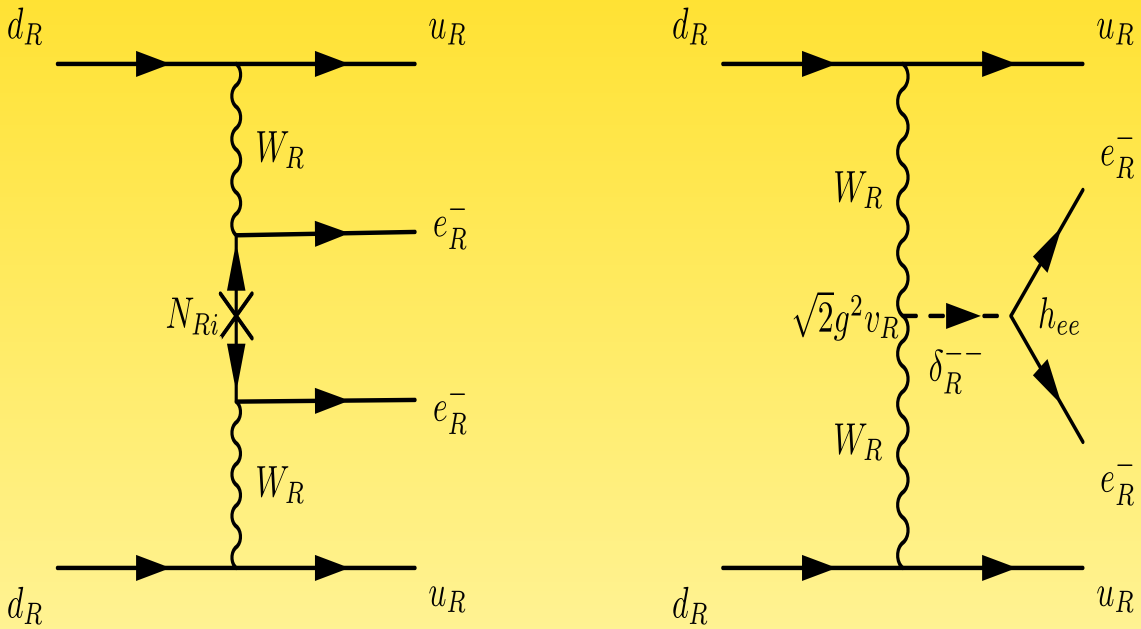
$$\Rightarrow \mathcal{A}_{N_R} \simeq G_F^2 \left(\frac{m_W}{M_{W_R}}\right)^4 \sum \frac{V_{ei}^2}{M_i} \propto \sum \frac{U_{ei}^2}{m_i}$$





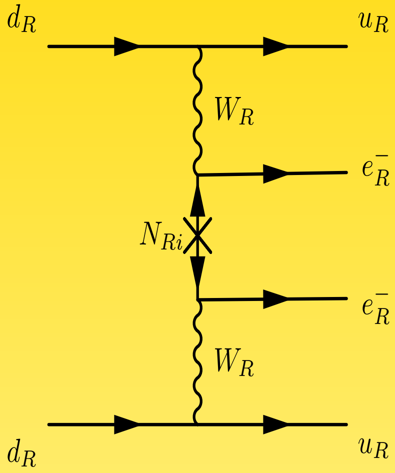
Tello *et al.*, 1011.3522

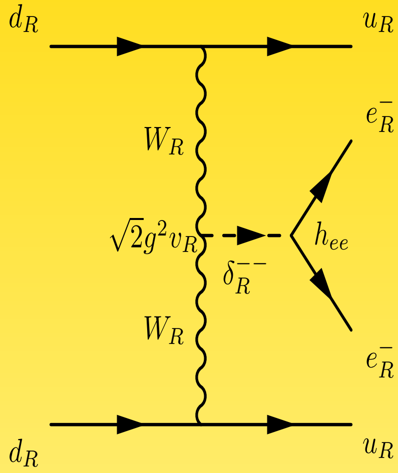
Tests of left-right symmetric diagrams

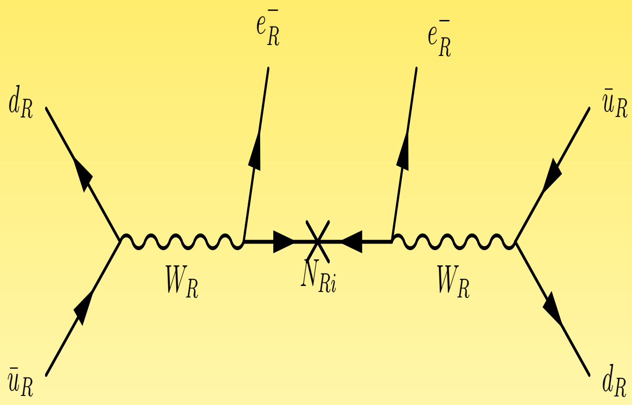


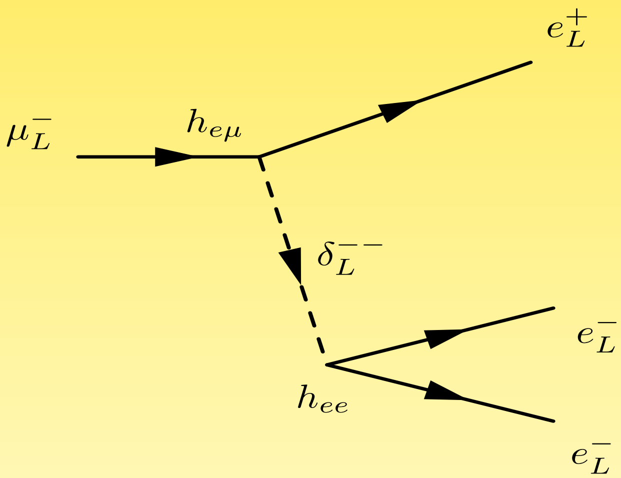
Keung, Senjanovic, 1983

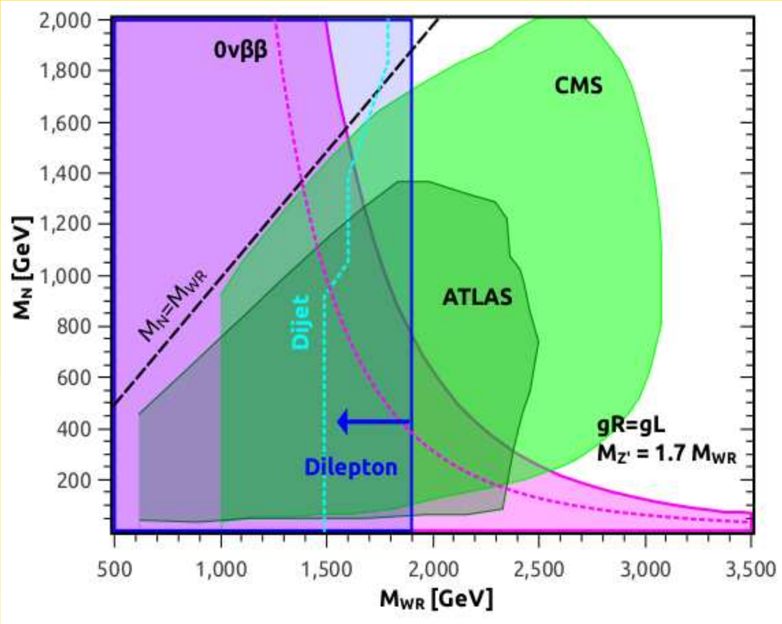
Example: Left-right symmetric theories

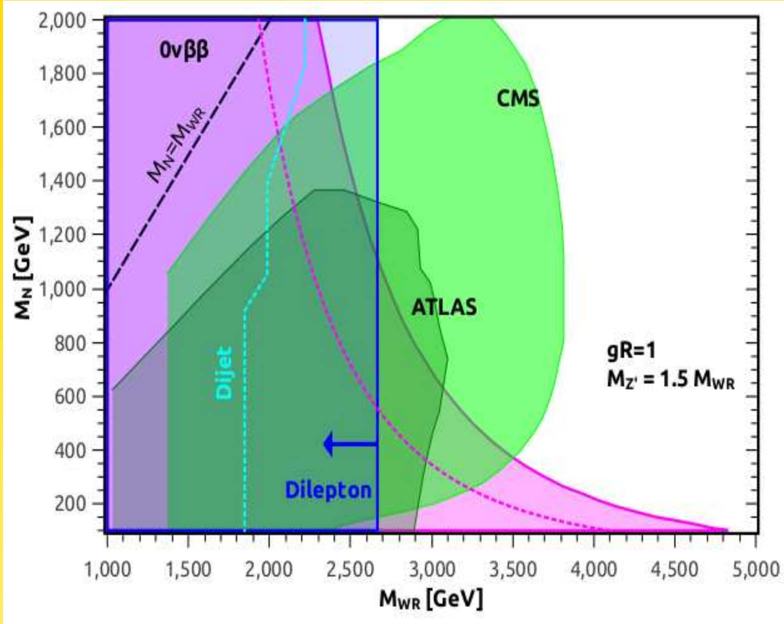












Lindner, Queiroz, W.R., 1604.07419

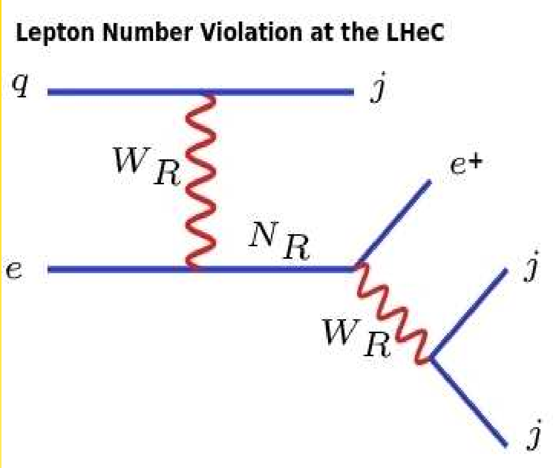
LHC assumes that $M_{W_R} > M_N$, BR $= 1$, cuts don't see low M_N regime

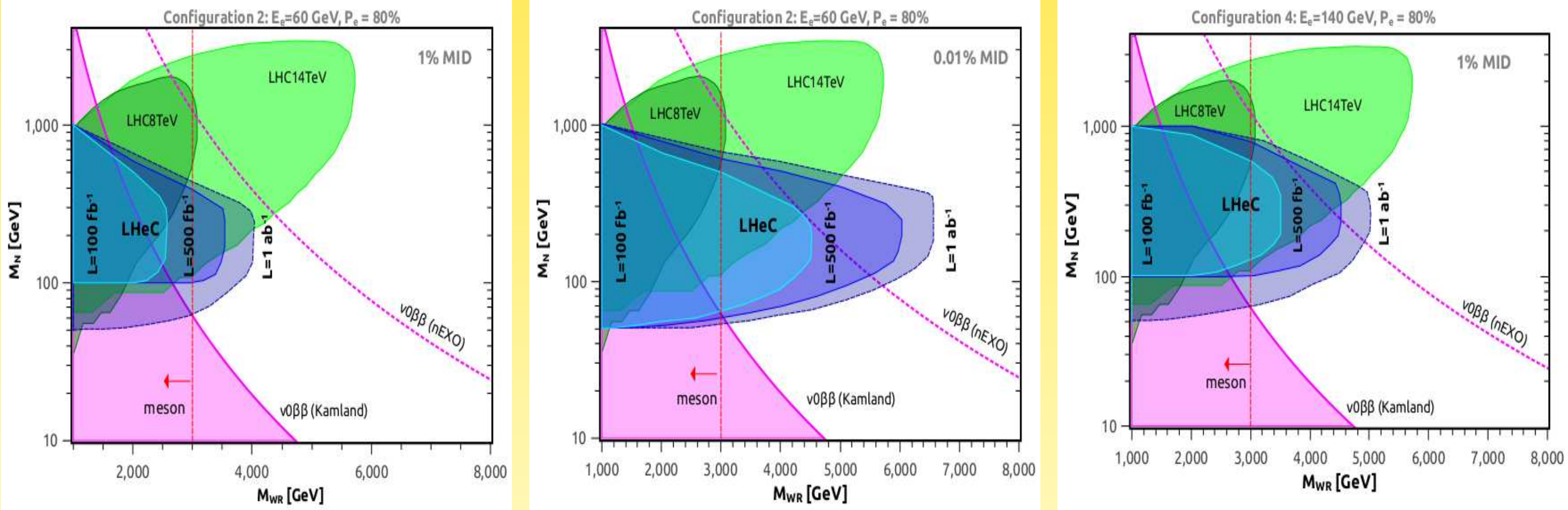
indirect limits from $W_R \to jj$ (Helo, Hirsch, 1509.00423) and $Z' \to \ell\ell$

$$\frac{M_{Z'}}{M_{W_R}} = \frac{\sqrt{2}\delta}{\sqrt{\delta^2 - \tan^2\theta_W}} \text{ and } \frac{g_R}{\sqrt{1-\delta^2\tan^2\theta_W}} Z'_\mu \bar{f}\left(T_3^R + (T_3^L - Q)\delta^2\tan^2\theta_W\right) f$$

where $\delta = g_L/g_R$

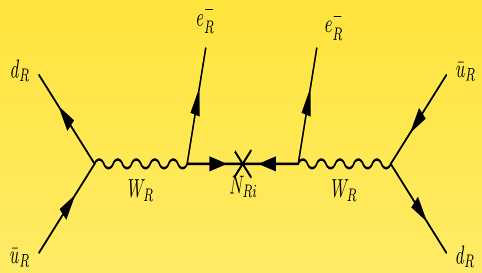
Da (far and uncertain) future:

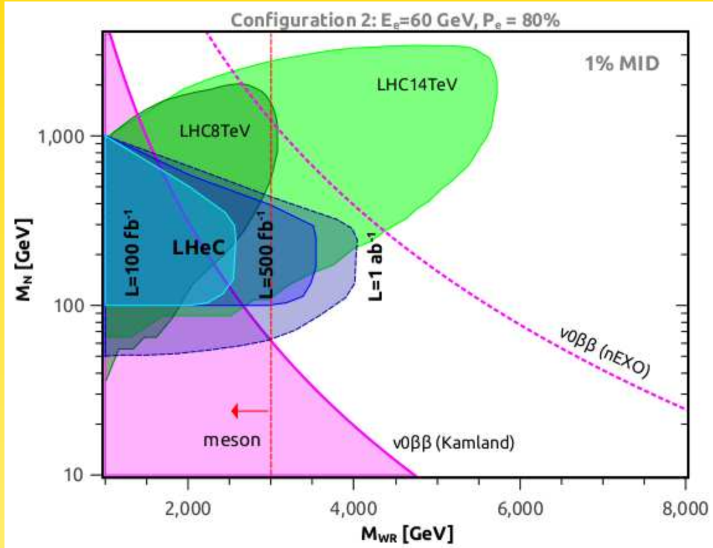




Lindner, Queiroz, W.R., Yaguna, 1604.08596

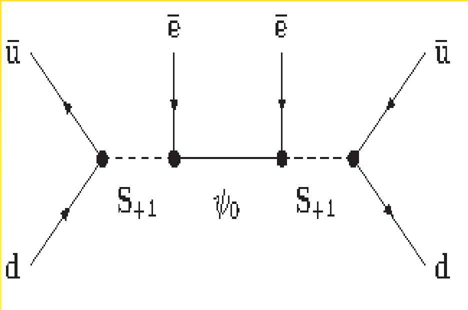
LHC vs. $0\nu\beta\beta$

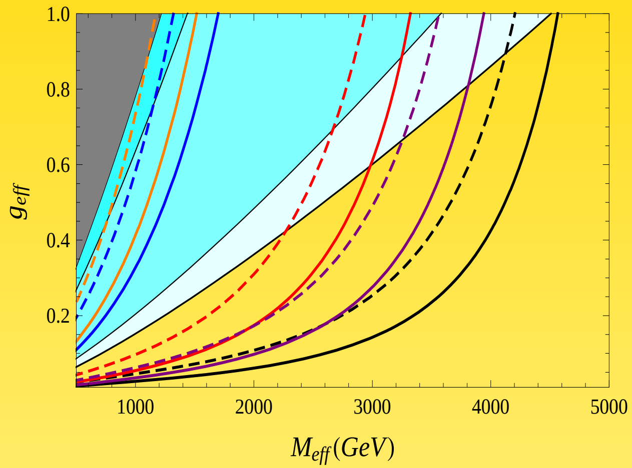




- LHC assumptions: $M_N < M_{W_R}$, BR$(M_N \to ee) = 1$, $g_R = g_L$
- cuts result in weak sensitivities for low M_N
- background processes?
- QCD corrections?
- (LNV at LHC and baryogenesis)

Background





Helo *et al.*, PRD **88**

one should include e.g.

- "jet fake" (high-p_T jet registered as electron)
- "charge flip" (e^- from opposite sign pair transfer p_T to e^+ via conversion)

Peng, Ramsey-Musolf, Winslow, 1508.04444

Background

one should include e.g.

- "jet fake" (high-p_T jet registered as electron)
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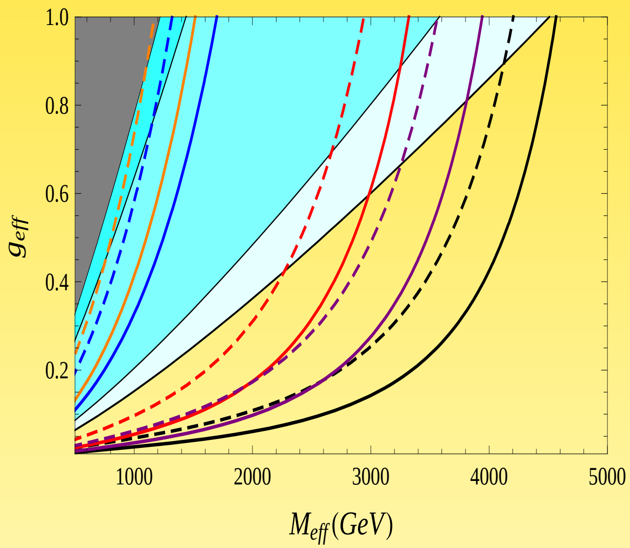
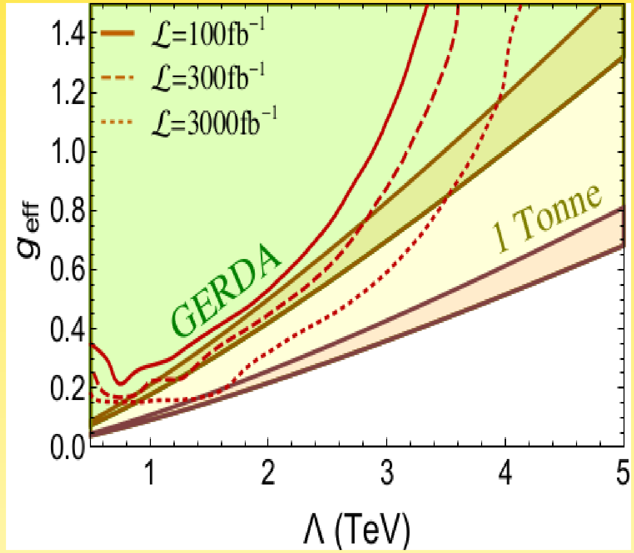
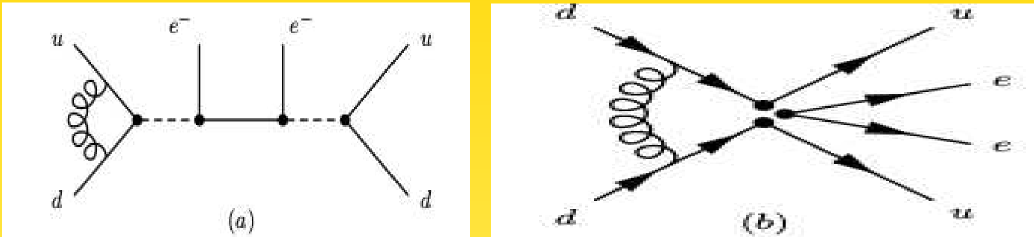




Peng, Ramsey-Musolf, Winslow, 1508.04444

QCD corrections



- matrix element multiplied with $\alpha_s/(4\pi)\ln M_W^2/\mu^2$, match with eff. diagram
- run that down to $0\nu\beta\beta$ scale $p^2 = (100$ MeV$)^2 \Rightarrow \alpha_s/(4\pi)\ln M_W^2/p^2 = 10\%$
- creates color non-singlet operators, ('operator mixing'), Fierz them for NMEs
- creates new operator with different matrix element, e.g.
  $(V-A)\times(V+A)\rightarrow(S-P)\times(S+P)$
- can give for alternative mechanisms large effect in either direction...
- (makes limit on right-handed diagrams slightly weaker)

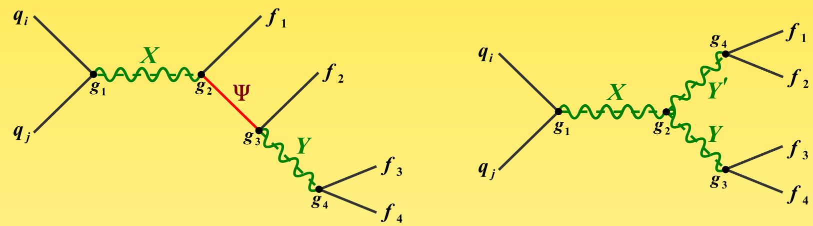
Mahajan, PRL **112**; Gonzalez, Kovalenko, Hirsch, PRD **93**

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):

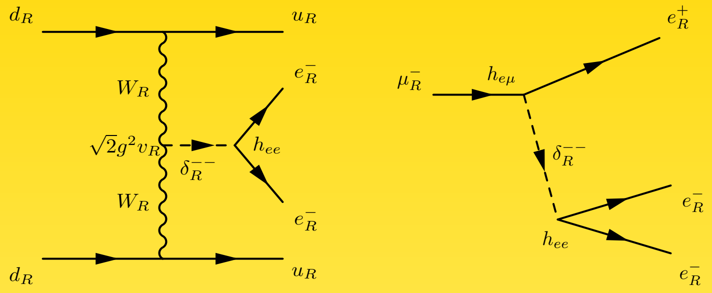


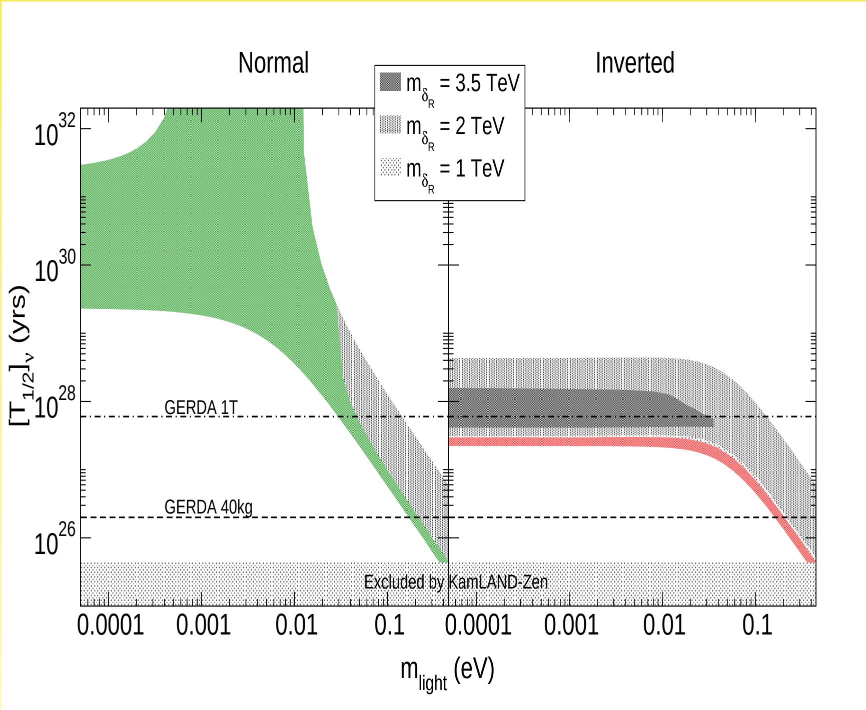
washout: $$\log_{10} \frac{\Gamma_W(qq \to \ell^+ \ell^+ qq)}{H} \gtrsim 6.9 + 0.6 \left(\frac{M_X}{\text{TeV}} - 1\right) + \log_{10} \frac{\sigma_{\text{LHC}}}{\text{fb}}$$

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

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

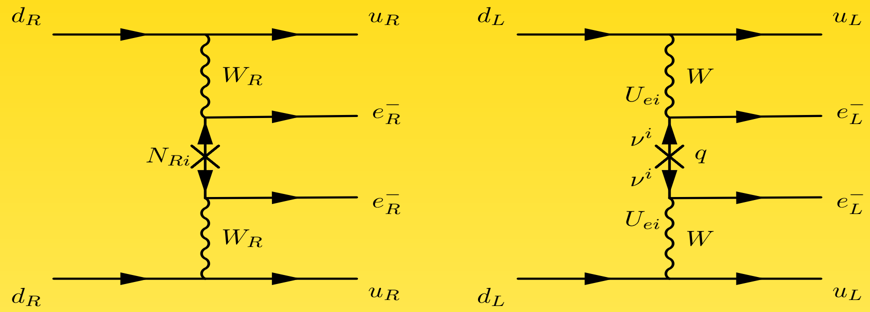
Constraints from Lepton Flavor Violation

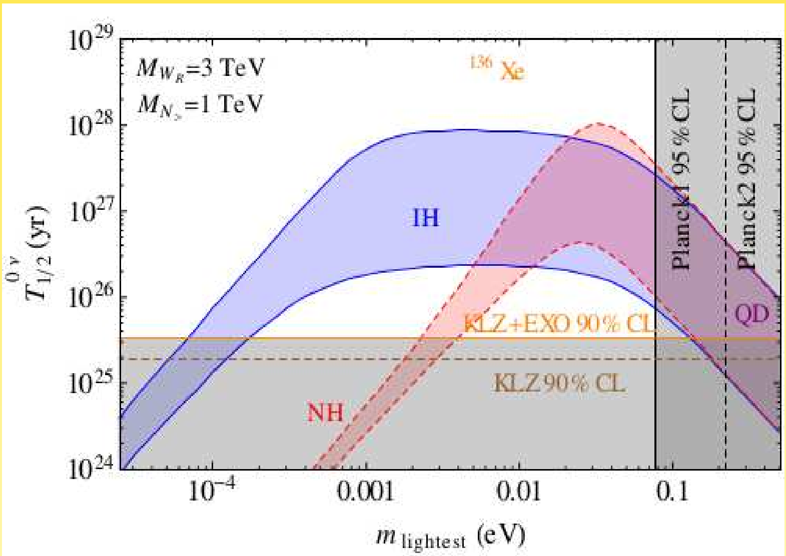




Barry, W.R., JHEP **1309**

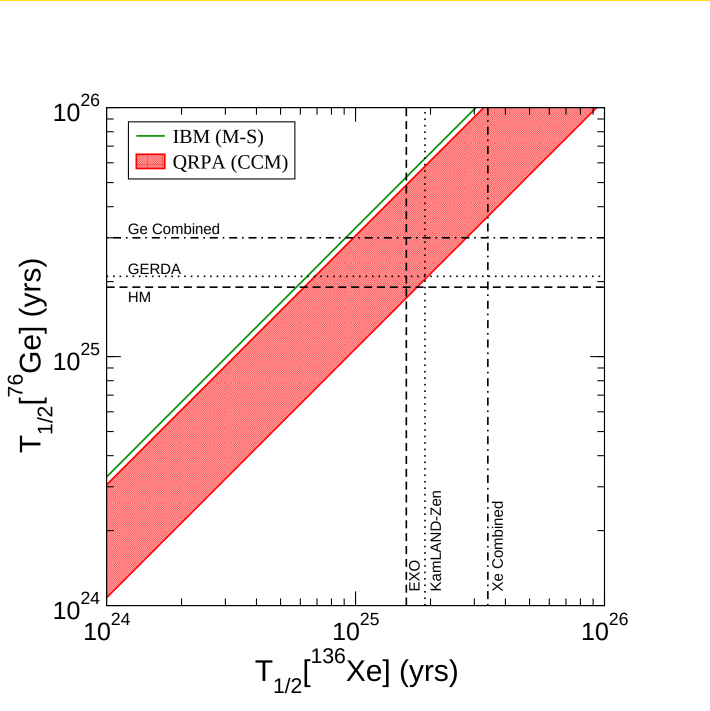
Adding diagrams

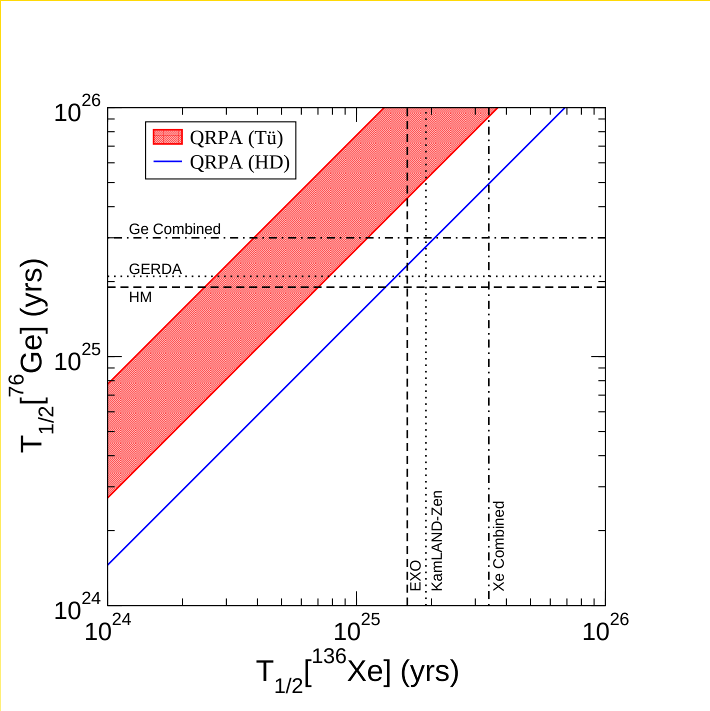


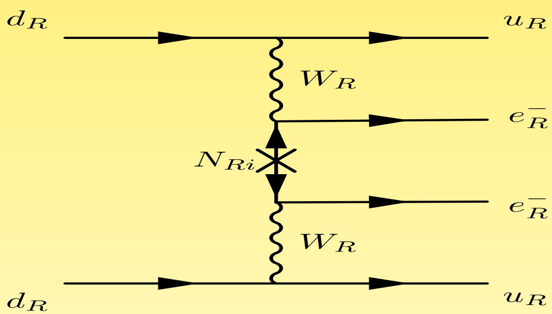


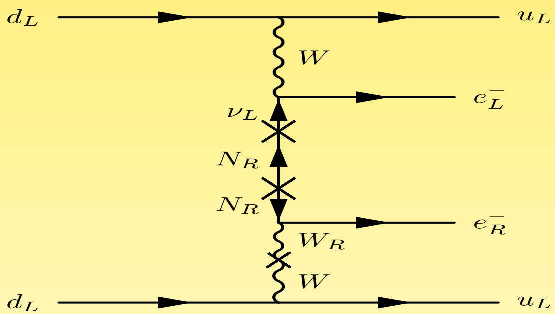
$\Rightarrow$ lower bound on $m(\text{lightest}) \gtrsim$ meV

Xe vs. Ge



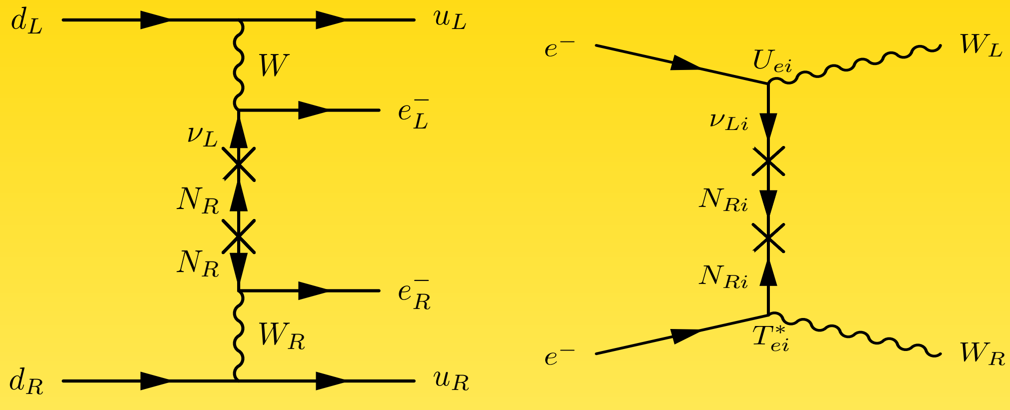




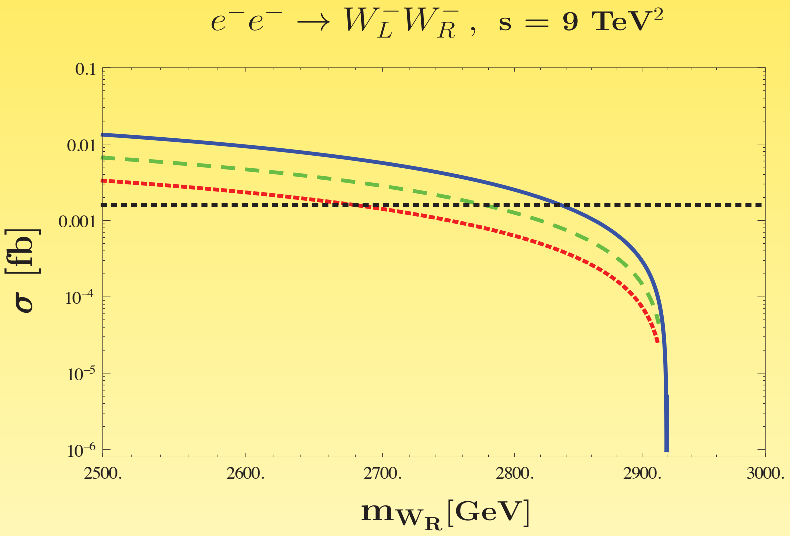


Barry, W.R., JHEP **1309**

λ-diagram and inverse $0\nu\beta\beta$



$0\nu\beta\beta$ $\quad$ W-W_R production



Barry, Dorame, W.R., 1204.3365

Contents

III3) Supersymmetry

$$\mathcal{L}_{\not R} = \lambda_{ijk}\,\hat{L}_i\,\hat{L}_j\,\hat{e}^c_k + \lambda'_{ijk}\,\hat{L}_i\,\hat{Q}_j\,\bar{d}^c_k + \lambda''_{ijk}\hat{u}^c_i\,\hat{d}^c_j\,\hat{d}^c_k + \epsilon_i\,\hat{L}_i\hat{H}_u$$

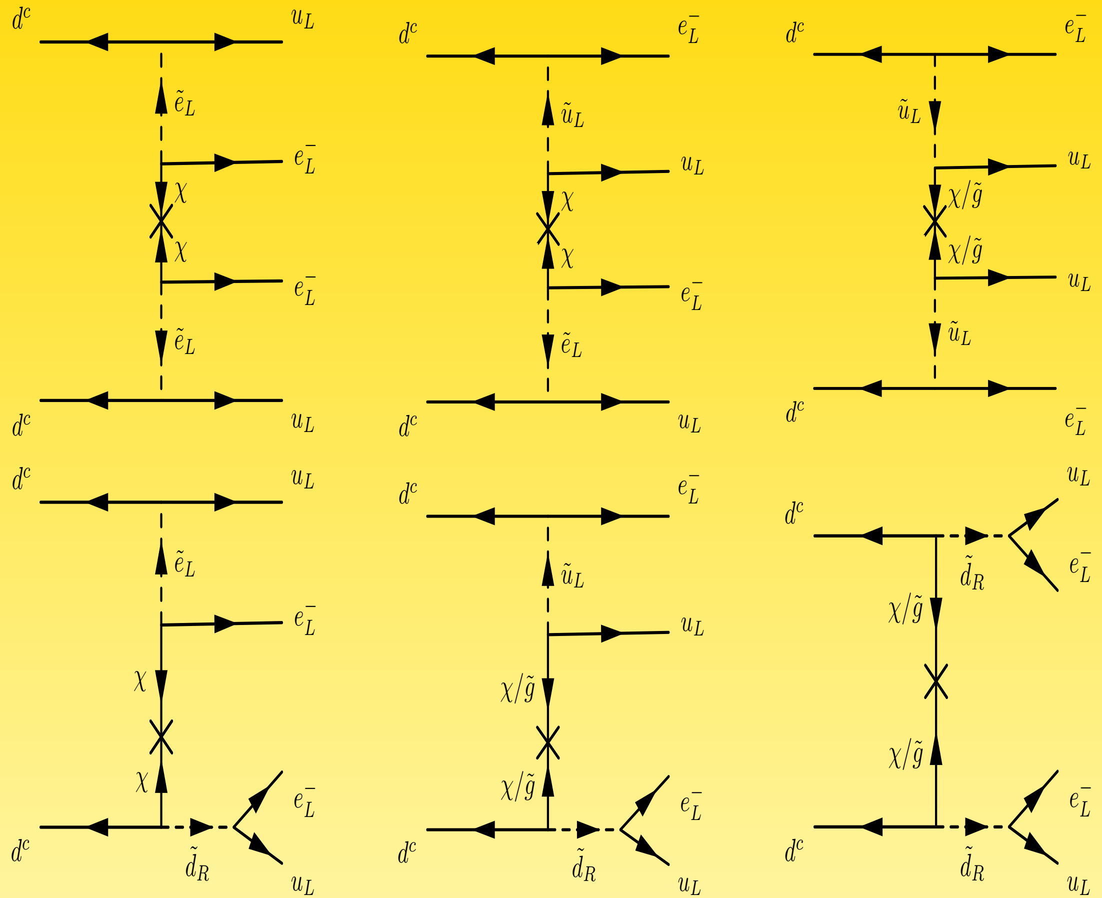
λ'' violates B, the rest violates L by one unit

gives rise to two mechanisms for $0\nu\beta\beta$:

- short range, or neutralino/gluino exchange, or λ'_{111} mechanism
- long-range, or squark exchange, or $\lambda'_{131}\,\lambda'_{113}$ mechanism

Hirsch, Kovalenko, Paes, Klapdor, Babu, Mohapatra, Vergados,...

Supersymmetry: short range



$$\mathcal{A}_{\not R_1} \simeq \frac{\lambda'^2_{111}}{\Lambda^5_{\rm SUSY}}$$

Supersymmetry: short range

Actually...

$$\eta_{\tilde g} = \frac{\pi\alpha_3}{6}\frac{\lambda'^2_{111}}{G_F^2}\frac{m_p}{m_{\tilde g}}\left(\frac{1}{m^4_{\tilde u_L}}+\frac{1}{m^4_{\tilde d_R}}-\frac{1}{2m^2_{\tilde u_L}m^2_{\tilde d_R}}\right)$$

$$\eta_{\chi} = \frac{\pi\alpha_2}{2}\frac{\lambda'^2_{111}}{G_F^2}\sum_{i=1}^{4}\frac{m_p}{m_{\chi_i}}\left(\frac{V^2_{L_i}(u)}{m^4_{\tilde u_L}}+\frac{V^2_{R_i}(d)}{m^4_{\tilde d_R}}-\frac{V_{L_i}(u)V_{R_i}(d)}{m^2_{\tilde u_L}m^2_{\tilde d_R}}\right)$$

$$\eta'_{\tilde g} = \frac{2\pi\alpha_3}{3}\frac{\lambda'^2_{111}}{G_F^2}\frac{m_p}{m_{\tilde g}}\frac{1}{m^2_{\tilde u_L}m^2_{\tilde d_R}}$$

$$\eta_{\chi\tilde e} = 2\pi\alpha_2\frac{\lambda'^2_{111}}{G_F^2}\sum_{i=1}^{4}\frac{m_p}{m_{\chi_i}}\frac{V^2_{L_i}(e)}{m^4_{\tilde e_L}}$$

$$\eta_{\chi\tilde f} = \pi\alpha_2\frac{\lambda'^2_{111}}{G_F^2}\sum_{i=1}^{4}\frac{m_p}{m_{\chi_i}}\left(\frac{V_{L_i}(u)V_{R_i}(d)}{m^2_{\tilde u_L}m^2_{\tilde d_R}}-\frac{V_{L_i}(u)V_{L_i}(e)}{m^2_{\tilde u_L}m^2_{\tilde e_L}}-\frac{V_{L_i}(e)V_{R_i}(d)}{m^2_{\tilde e_L}m^2_{\tilde d_R}}\right)$$

Supersymmetry: short range

gluino dominance:

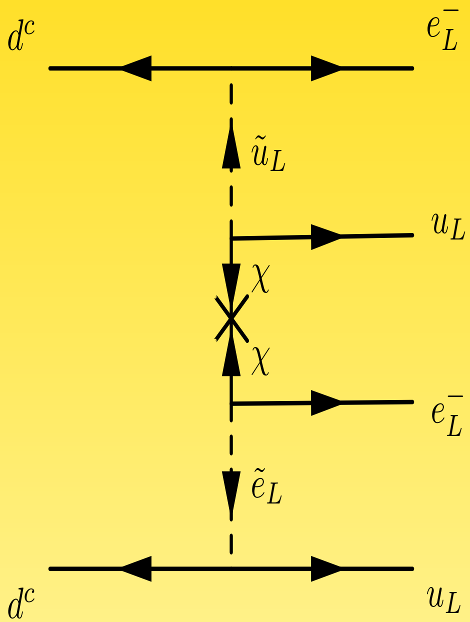
$$\eta^{\tilde{g}}_{\not{R}_1} \simeq \frac{\pi\alpha_3}{6}\frac{\lambda'^2_{111}}{G_F^2}\frac{m_p}{m_{\tilde{g}}\, m^4_{\tilde{d}_R}}\left(1+\left(\frac{m_{\tilde{d}_R}}{m_{\tilde{u}_L}}\right)^2\right)^2 \leq 7.5\times 10^{-9}$$

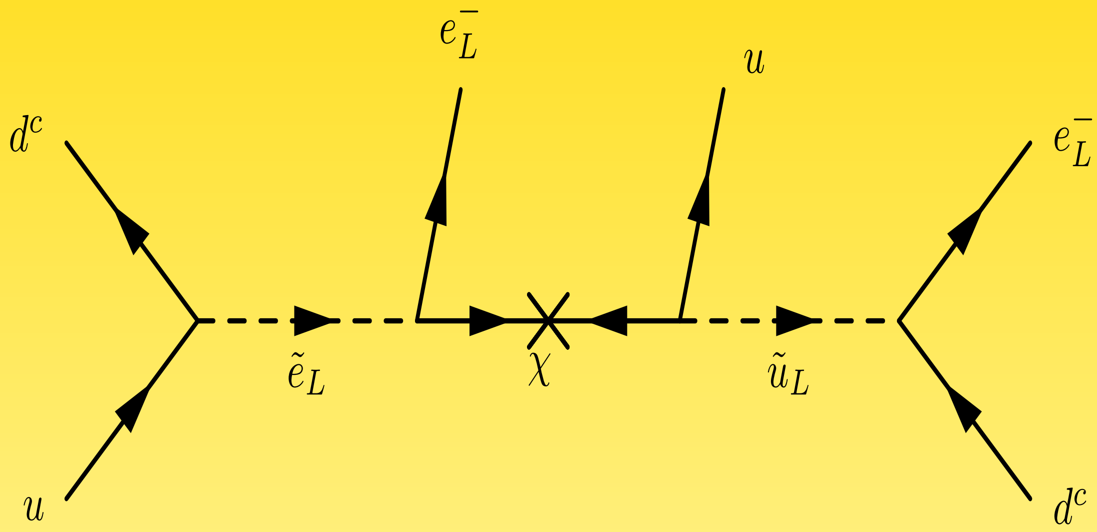
translates into

$$\frac{\lambda'^2_{111}}{m_{\tilde{g}}\, m^4_{\tilde{d}_R}(1+m^2_{\tilde{d}_R}/m^2_{\tilde{u}_L})^2} \lesssim 1.8\times 10^{-17}\ \mathrm{GeV}^{-5}$$

Supersymmetry: short range

interplay with LHC:



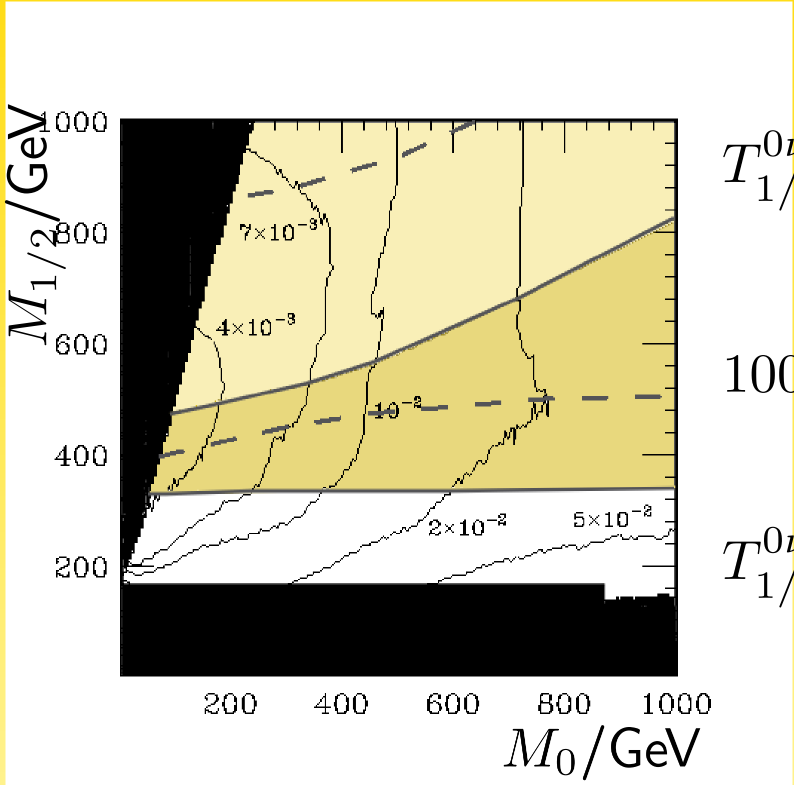


"resonant selectron production"

$$\hat{\sigma} \propto \frac{\lambda'^2_{111}}{\hat{s}}$$

Allanach, Kom, Paes, 0903.0347

$\tan\beta = 10,\ A_0 = 0,$ 10 fb^{-1}



$T^{0\nu\beta\beta}_{1/2}(\mathrm{Ge}) > 1 \times 10^{27}$ yrs

$100 > T^{0\nu\beta\beta}_{1/2}(\mathrm{Ge})/10^{25}$ yrs > 1.9

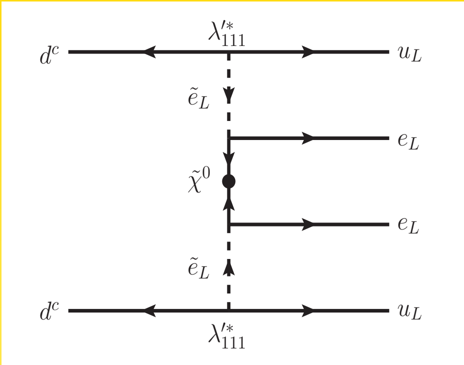
$T^{0\nu\beta\beta}_{1/2}(\mathrm{Ge}) < 1.9 \times 10^{25}$ yrs

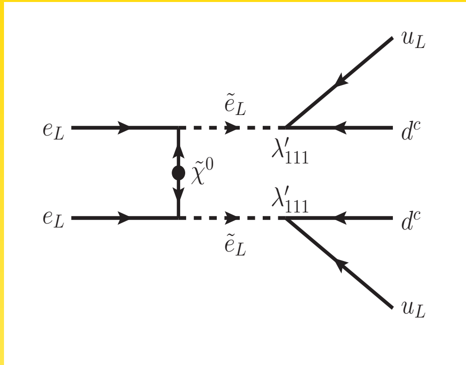
$\rightarrow$ observation in white region in conflict with $0\nu\beta\beta$

$\rightarrow$ if $0\nu\beta\beta$ observed: dark yellow region tests $R\!\!\!/$ SUSY mechanism

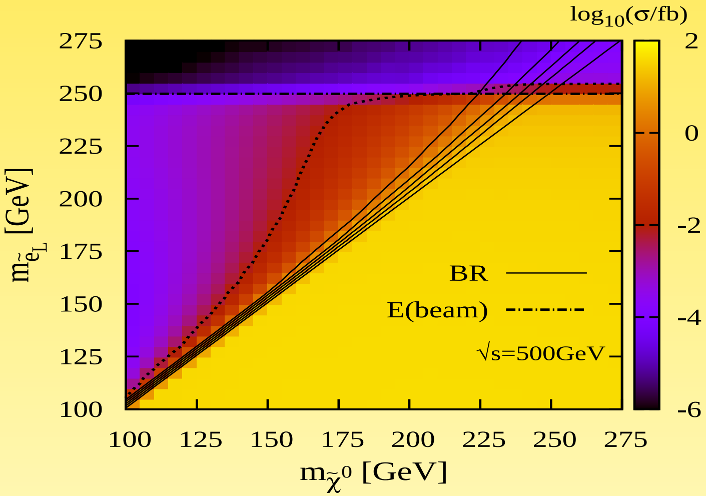
$\rightarrow$ light yellow region: no significant $R\!\!\!/$ contribution to $0\nu\beta\beta$

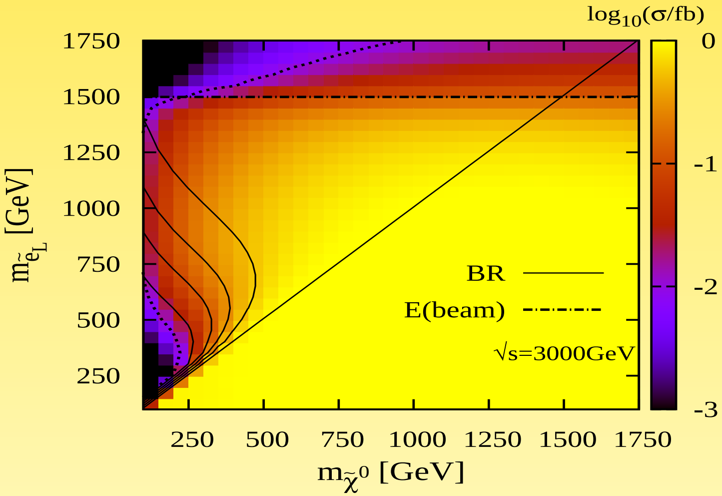
RPV SUSY and inverse $0\nu\beta\beta$





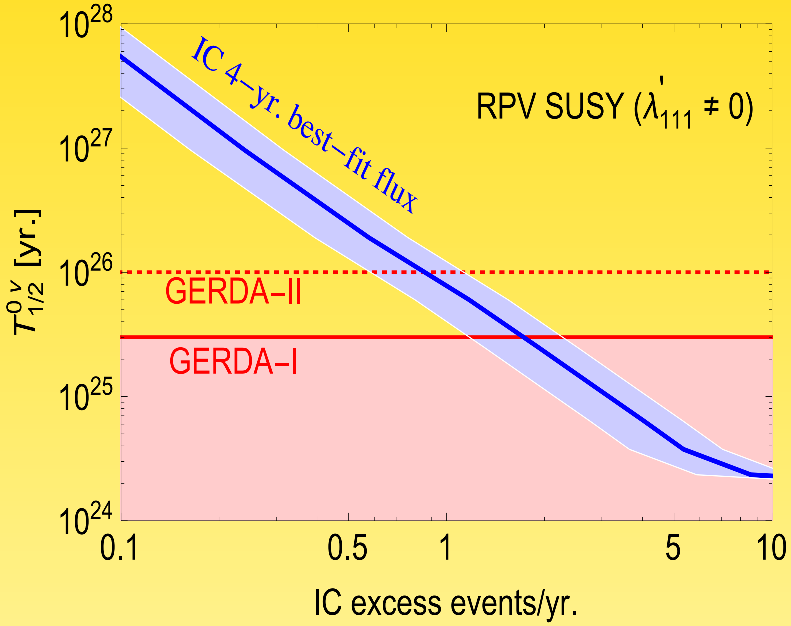
$0\nu\beta\beta$ *resonant* $\tilde{e}_L$ production $\to 4j$





Kom, W.R., 1110.3220

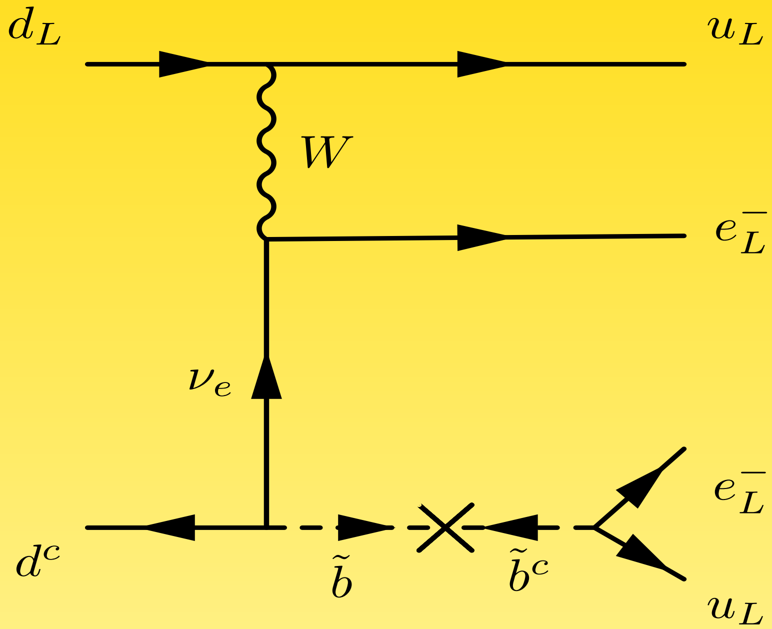
Cool effect somewhere else



d-squarks resonantly produced $\nu_e d_L \to \tilde{d}_R \to \nu_e d_L,\, e u_L$

Dev, W.R.

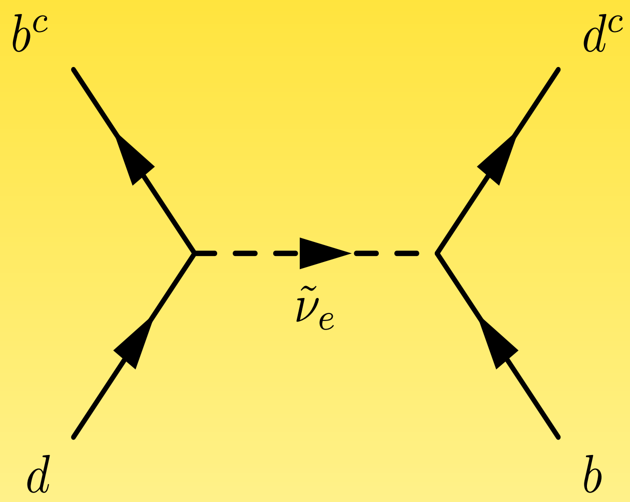
Supersymmetry: long range



$$\mathcal{A}^b_{\not R_2} \simeq G_F \, \frac{1}{q} \, U_{ei} \, \frac{m_b}{\Lambda^3_{\rm SUSY}} \, \lambda'_{131} \, \lambda'_{113}$$

Supersymmetry: long range

Test with B^0-$\bar{B}^0$ mixing



constrains $\lambda'_{131}\,\lambda'_{113}/\Lambda^4_{\mathrm{SUSY}}$

gives currently stronger constraint than $0\nu\beta\beta$

Contents

III4) The inverse problem

identify mechanism via

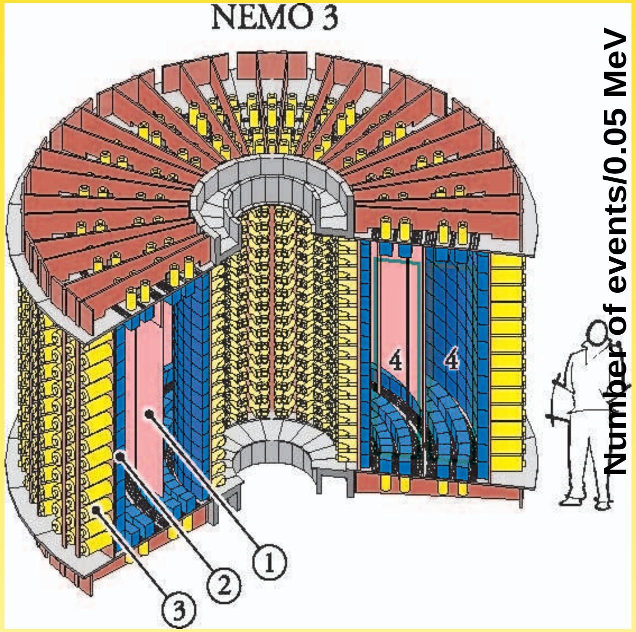
1.) other observables (LHC, LFV, KATRIN, cosmology,...)

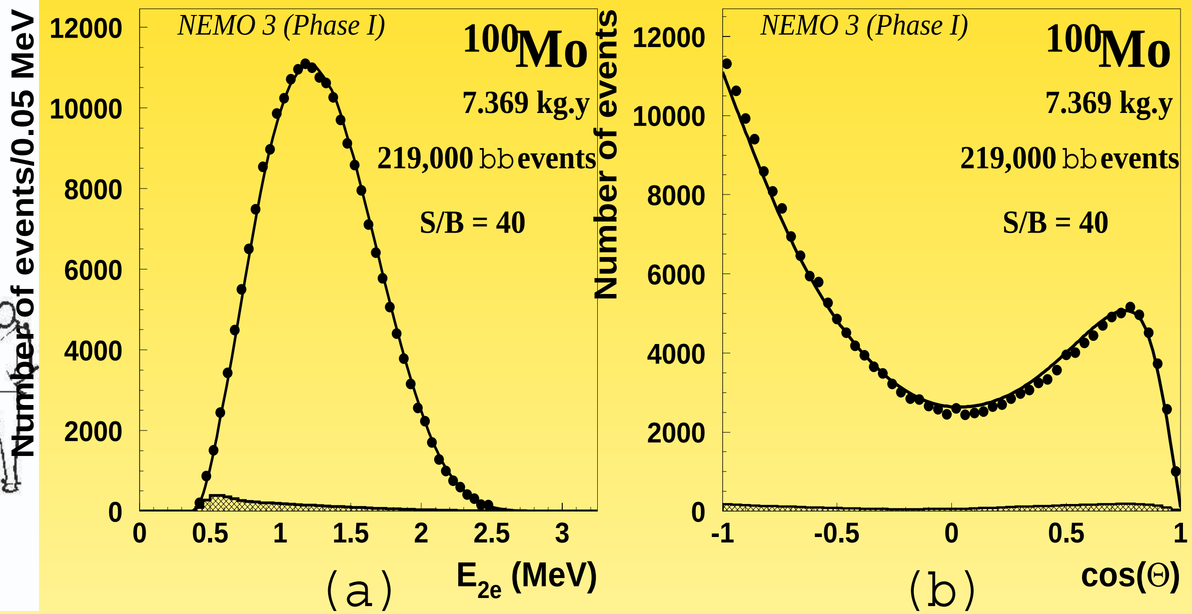
2.) decay products (individual e^- energies, angular correlations, spectrum,...)

3.) nuclear physics (multi-isotope, 0νECEC, $0\nu\beta^+\beta^+$,...)

Distinguishing via decay products

SuperNEMO

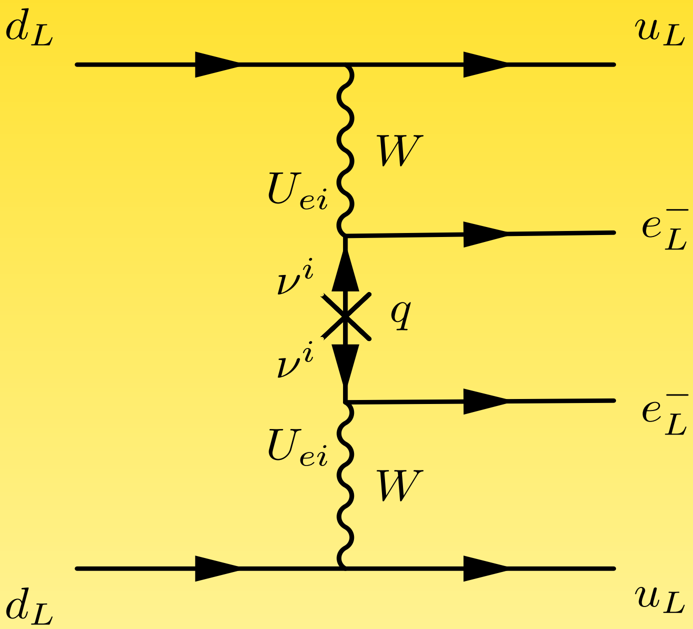


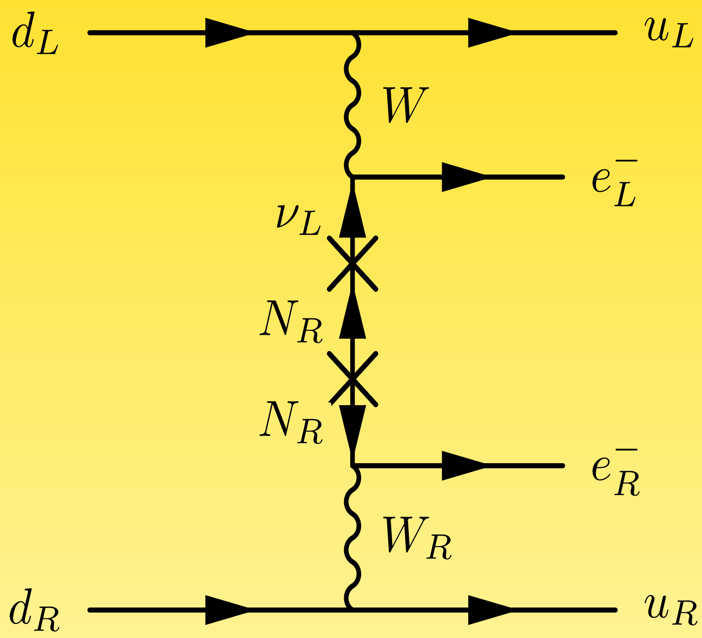


- source foils in between plastic scintillators
- individual electron energy, and their relative angle!

Distinguishing via decay products

Consider standard plus λ-mechanism





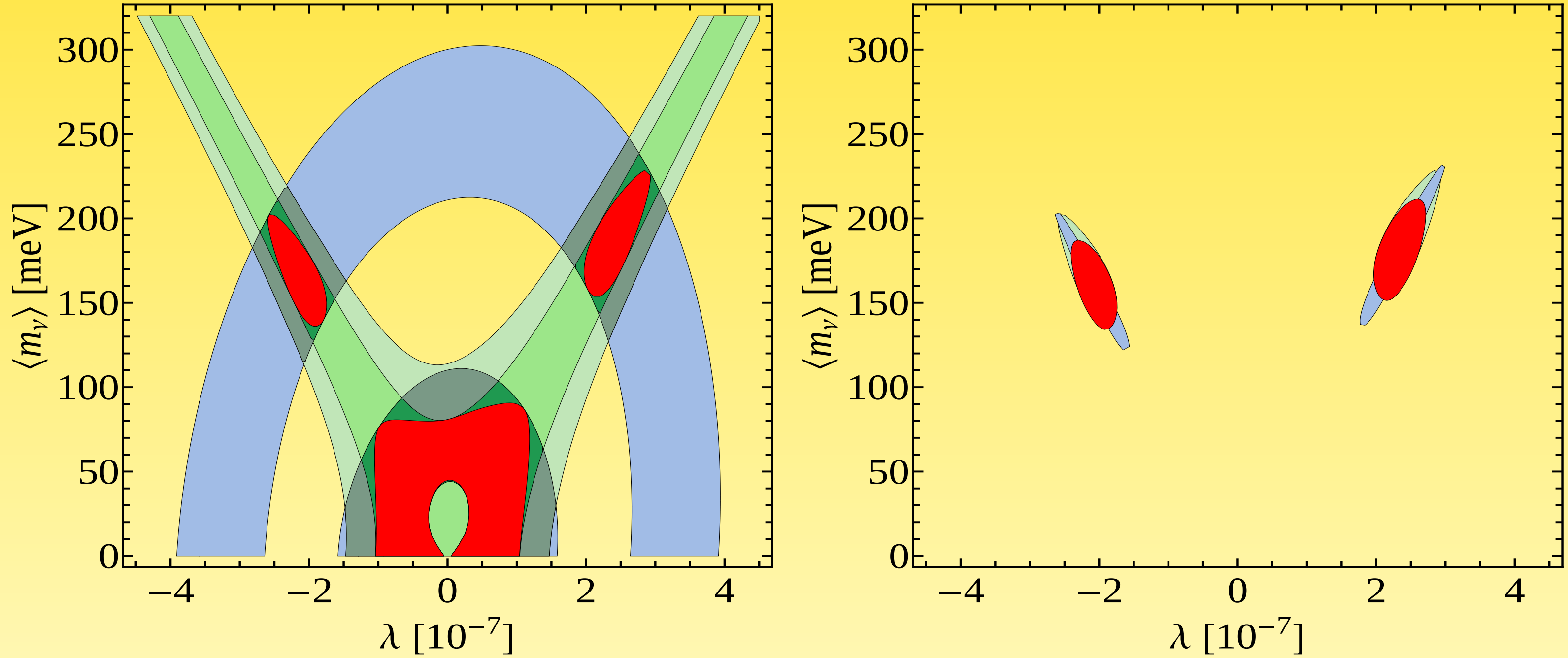
$$\frac{d\Gamma}{dE_1\, dE_2\, d\cos\theta} \propto (1 - \beta_1\, \beta_2\, \cos\theta) \qquad \frac{d\Gamma}{dE_1\, dE_2\, d\cos\theta} \propto (E_1 - E_2)^2\, (1 + \beta_1\, \beta_2\, \cos\theta)$$

Arnold *et al.*, 1005.1241

Distinguishing via decay products

Defining asymmetries

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



Distinguishing via nuclear physics

challenging, but possible if nuclear physics is under control (sic!)

recall:

$$\frac{1}{T_{1/2}^{0\nu}(A,Z)} = G(Q,Z)\,|\mathcal{M}(A,Z)\,\eta|^2$$

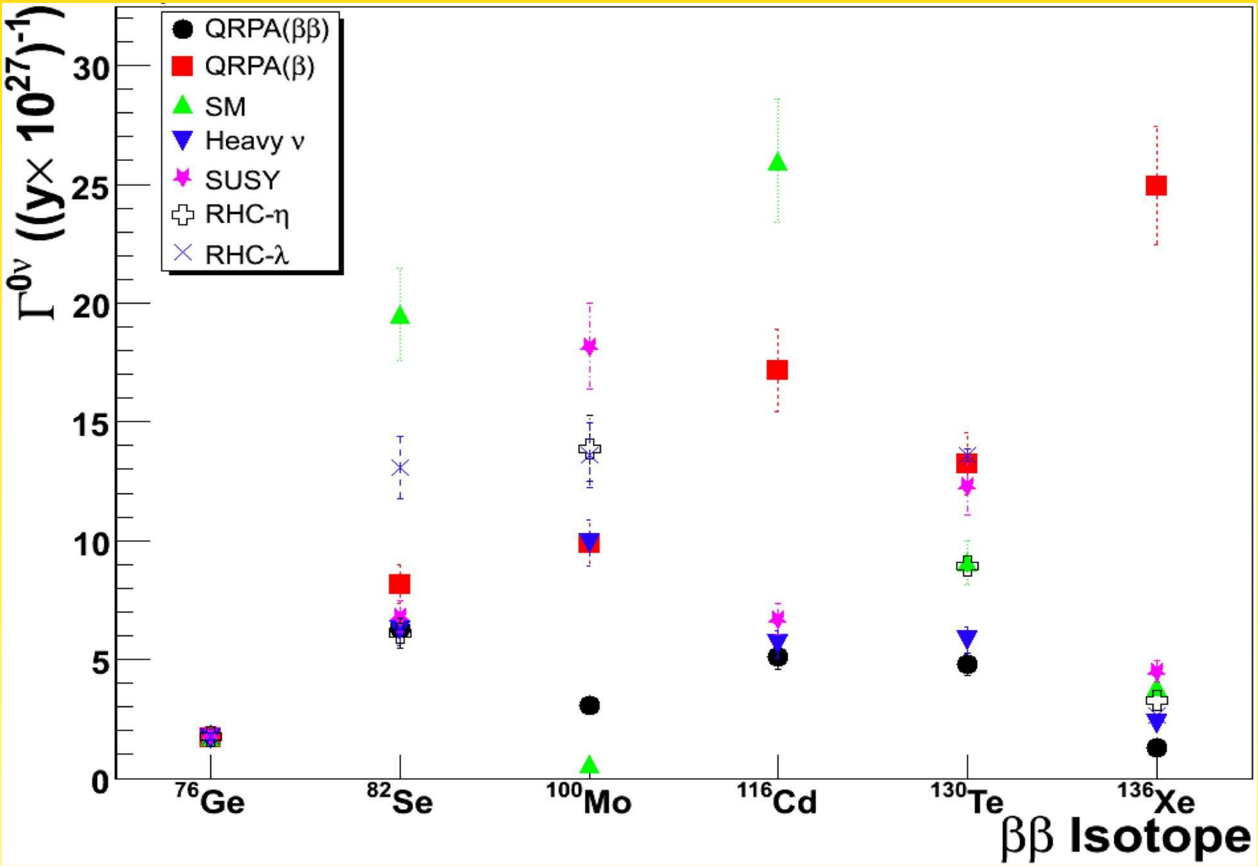
if you measured two isotopes:

$$\frac{T_{1/2}^{0\nu}(A_1,Z_1)}{T_{1/2}^{0\nu}(A_2,Z_2)} = \frac{G_x(Q_2,Z_2)\,|\mathcal{M}_x(A_2,Z_2)|^2}{G_x(Q_1,Z_1)\,|\mathcal{M}_x(A_1,Z_1)|^2}$$

particle physics drops out, *ratio of NMEs sensitive to mechanism*

$\Rightarrow$ **third reason for multi-isotope determination**

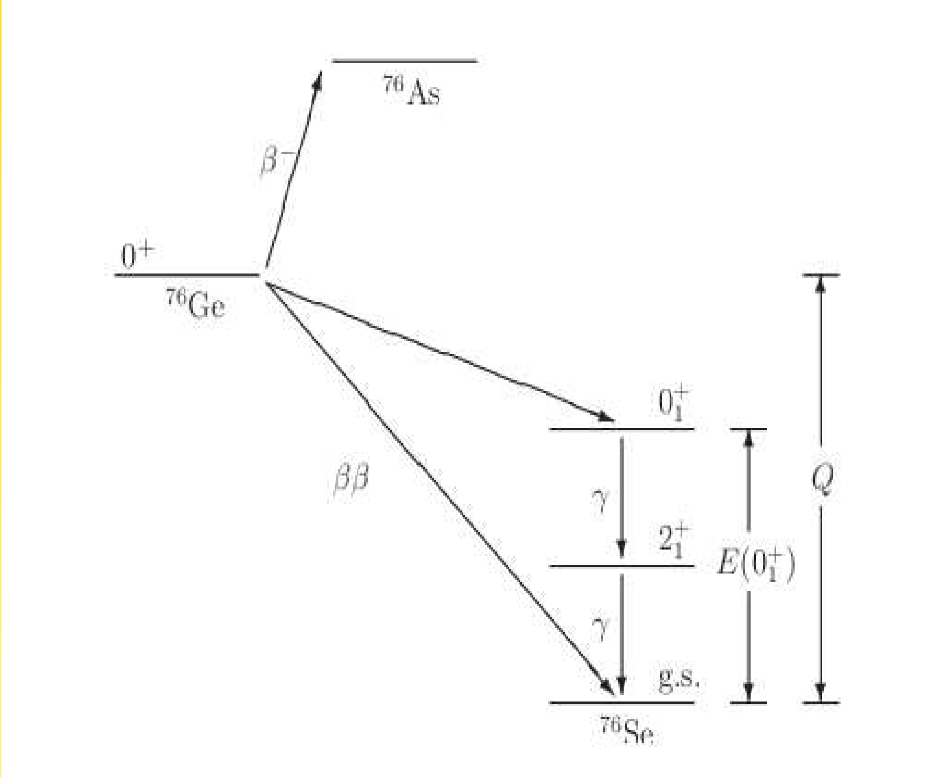
Distinguishing via nuclear physics



Gehman, Elliott, hep-ph/0701099

3 to 4 isotopes necessary to disentangle mechanism

Distinguishing via nuclear physics



- standard interpretation: suppressed by 2 to 3 orders of magnitude
- ratio sensitive to mechanism
- 0_1^+ easier to identify; 2_1^+ very sensitive to RHC

Distinguishing via nuclear physics

Observation of

$$(A,Z) \to (A,Z-2) + 2\,e^+ \qquad (0\nu\beta^+\beta^+)$$

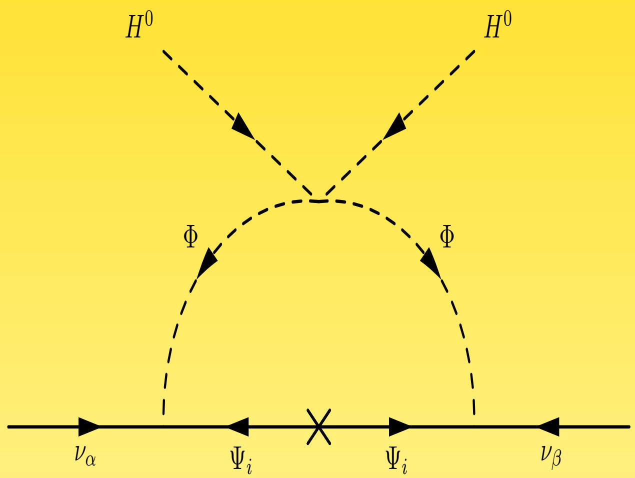
$$e_b^- + (A,Z) \to (A,Z-2) + e^+ \qquad (0\nu\beta^+\mathrm{EC})$$

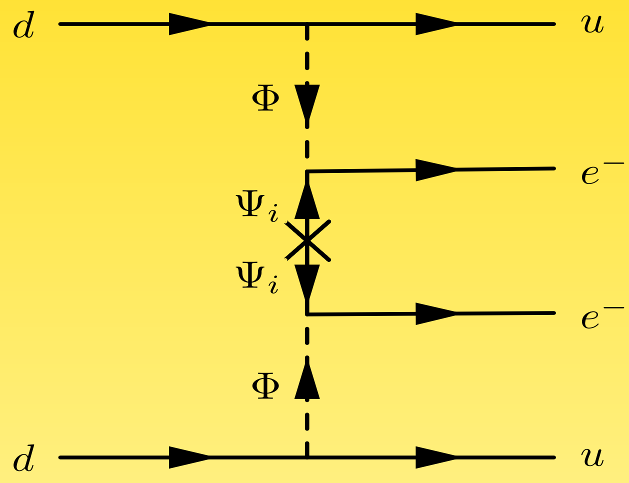
$$2\,e_b^- + (A,Z) \to (A,Z-2)^* \qquad (0\nu\mathrm{ECEC})$$

rate to $0\nu\beta\beta$ is sensitive to mechanism

Dircet vs. indirect contribution

Example: introduce $\Psi_i = (8,1,0)$ and $\Phi = (8,2,\frac{1}{2})$





$$m_\nu \propto \lambda_{\Phi H}\, y_{\alpha i} y_{\beta i}$$

indirect contribution to $0\nu\beta\beta$:

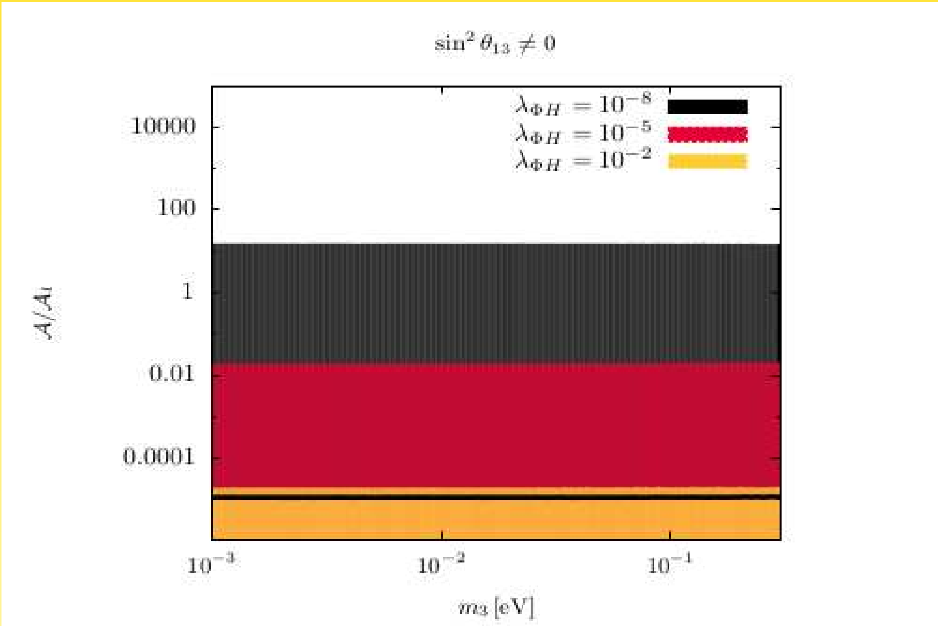
$$\mathcal{A}_l \simeq G_F^2 \, \frac{|m_{ee}|}{q^2}$$

direct contribution to $0\nu\beta\beta$:

$$\mathcal{A} \simeq c_{ud}^2 \, \frac{y_{e\alpha}^2}{M_{\Psi_i}\, M_\Phi^4}$$

Dircet vs. indirect contribution

new contribution can dominate over standard one:



Choubey, Dürr, Mitra, W.R., JHEP **1205**

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.