Heavy Particle Contributions to Double Beta Decay

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Contents

- Introduction
- Lorentz-invariant $0\nu\beta\beta$ decay
- Limits on BSM
- Distinguishing $\langle m_\nu \rangle$ from BSM?
- Conclusions

$\mathcal{I}.$

Introduction:

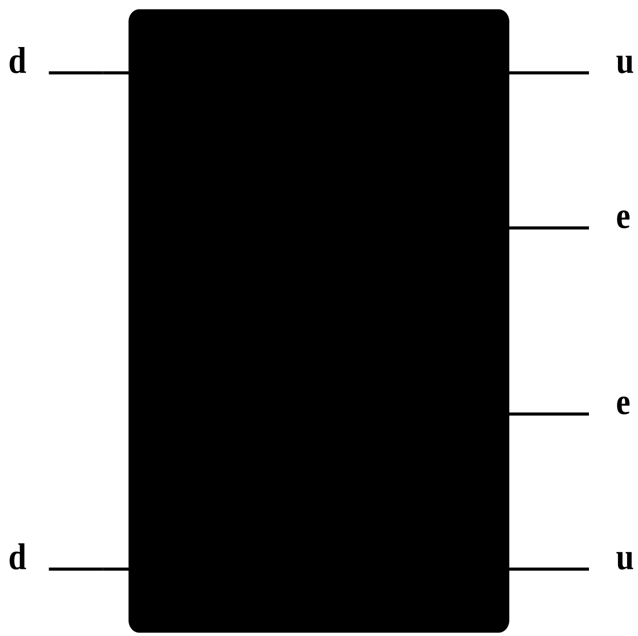
$0\nu\beta\beta$ is a black box

Black Box I.

An ideal experiment detects appearance of two electrons:

$$L = 0 \quad \Rightarrow \quad L = 2?$$

Observables?

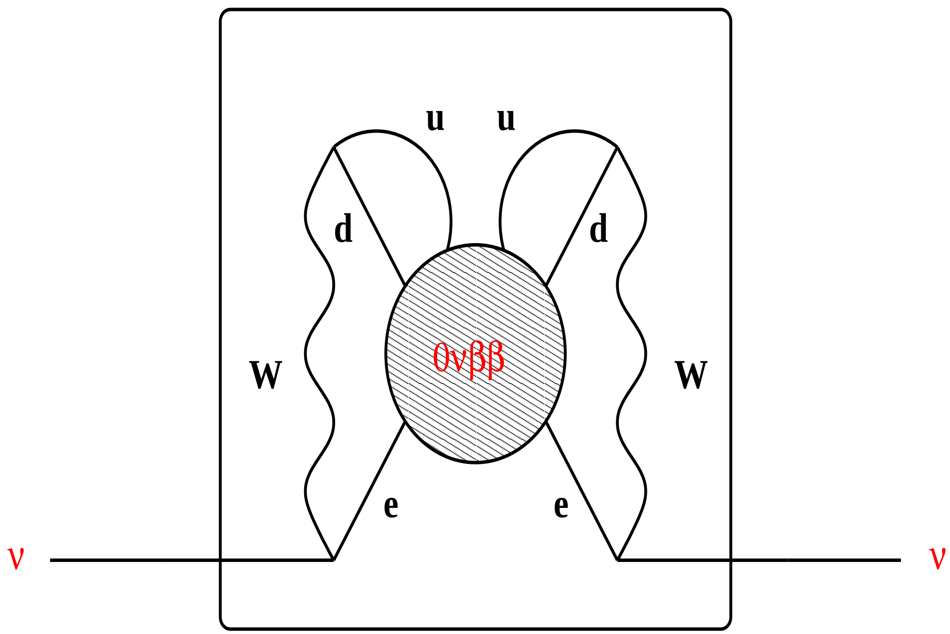


i) Sum energy $\Rightarrow 0\nu\beta\beta$

ii) $\#$ Events $\Rightarrow$ Half-life

iii) - ?) ... Others ... (?)

Black Box Theorem



Schechter & Valle, PRD 1982

Takasugi, PLB 1984

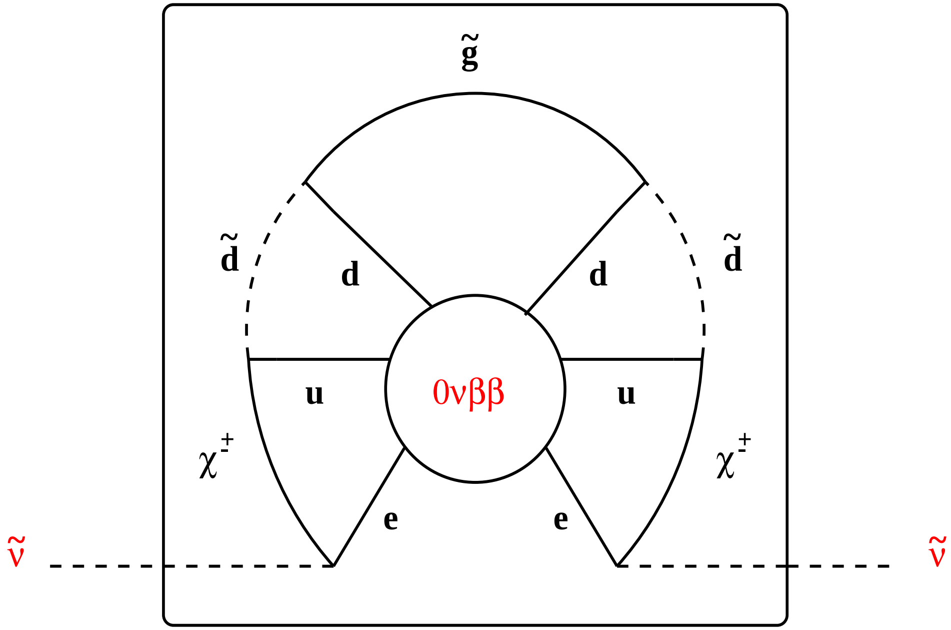
If $0\nu\beta\beta$ is observed the neutrino is a Majorana particle!

$\Rightarrow$ Qualitative statement only: Value of m_ν depends on model

SUSY Black Box

In any supersymmetric gauge theory:

Hirsch et al., PLB 1997



If $0\nu\beta\beta$ observed
the scalar neutrino
has a $\not{L}$ mass!

$\Rightarrow$ $0\nu\beta\beta$ decay, Majorana neutrinos and $\not{L}$
in scalar sector inseparably connected.

$\mathcal{II}.$

Lorentz-invariant $0\nu\beta\beta$ decay

Mass mechanism

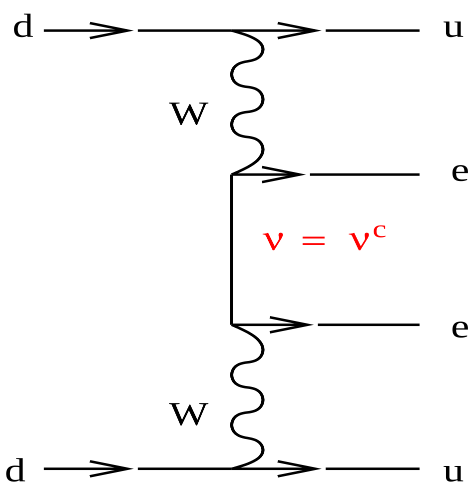
Standard model weak current at low energy:

$$\mathcal{L}^{\rm SM} = \frac{G_F}{\sqrt{2}} j^{\mu}_{V-A} J^{\dagger}_{V-A,\mu}$$

with $J^{\dagger}_{V-A,\mu} = \bar{u}\gamma_\mu P_L d$, $j^{\mu}_{V-A} = \bar{e}\gamma^\mu P_L \nu$

$\Rightarrow$ Product of two $\mathcal{L}$

$+$ Majorana neutrino mass:



Neutrino propagator:

$$P_L \int \frac{d^4p}{(2\pi)^4} \frac{m_\nu + \not{p}}{p^2 - m_\nu^2} P_L$$

$$= P_L \int \frac{d^4p}{(2\pi)^4} \frac{m_\nu}{p^2 - m_\nu^2}$$

$$\sim m_\nu$$

Lorentz-invariant Lagrangian

Consider all possible currents (V, A, S, P, T):

$$\begin{aligned} J_\alpha^\dagger &= \bar{u}\mathcal{O}_\alpha d \\ j_\alpha &= \bar{e}\mathcal{O}_\alpha \nu \\ j_\alpha^{\text{short}} &= \bar{e}\mathcal{O}_\alpha e^C \end{aligned}$$

Define operators $\mathcal{O}_{\alpha,\beta}$ with definite helicity:

$$\begin{aligned} \mathcal{O}_{V-A} = \gamma^\mu P_L & \qquad \mathcal{O}_{V+A} = \gamma^\mu P_R \\ \mathcal{O}_{S-P} = P_L & \qquad \mathcal{O}_{S+P} = P_R \\ \mathcal{O}_{T_L} = \frac{i}{2}[\gamma_\mu, \gamma_\nu] P_L & \qquad \mathcal{O}_{T_R} = \frac{i}{2}[\gamma_\mu, \gamma_\nu] P_R \end{aligned}$$

Lorentz-invariant Lagrangian

Write down most general $\mathcal{L}$:

$$\mathcal{L} = \mathcal{L}^{\mathrm{SM}} + \mathcal{L}^{\mathrm{long}} + \mathcal{L}^{\mathrm{short}}$$

Standard model:

$$\mathcal{L}^{\mathrm{SM}} = \frac{G_F}{\sqrt{2}} j^{\mu}_{V-A} J^{\dagger}_{V-A,\mu}$$

Long-range part:

$$\mathcal{L}^{\mathrm{long}} = \frac{G_F}{\sqrt{2}} \sum_{\alpha,\beta} \epsilon^{\beta}_{\alpha} j_\beta J^{\dagger}_{\alpha}$$

with:

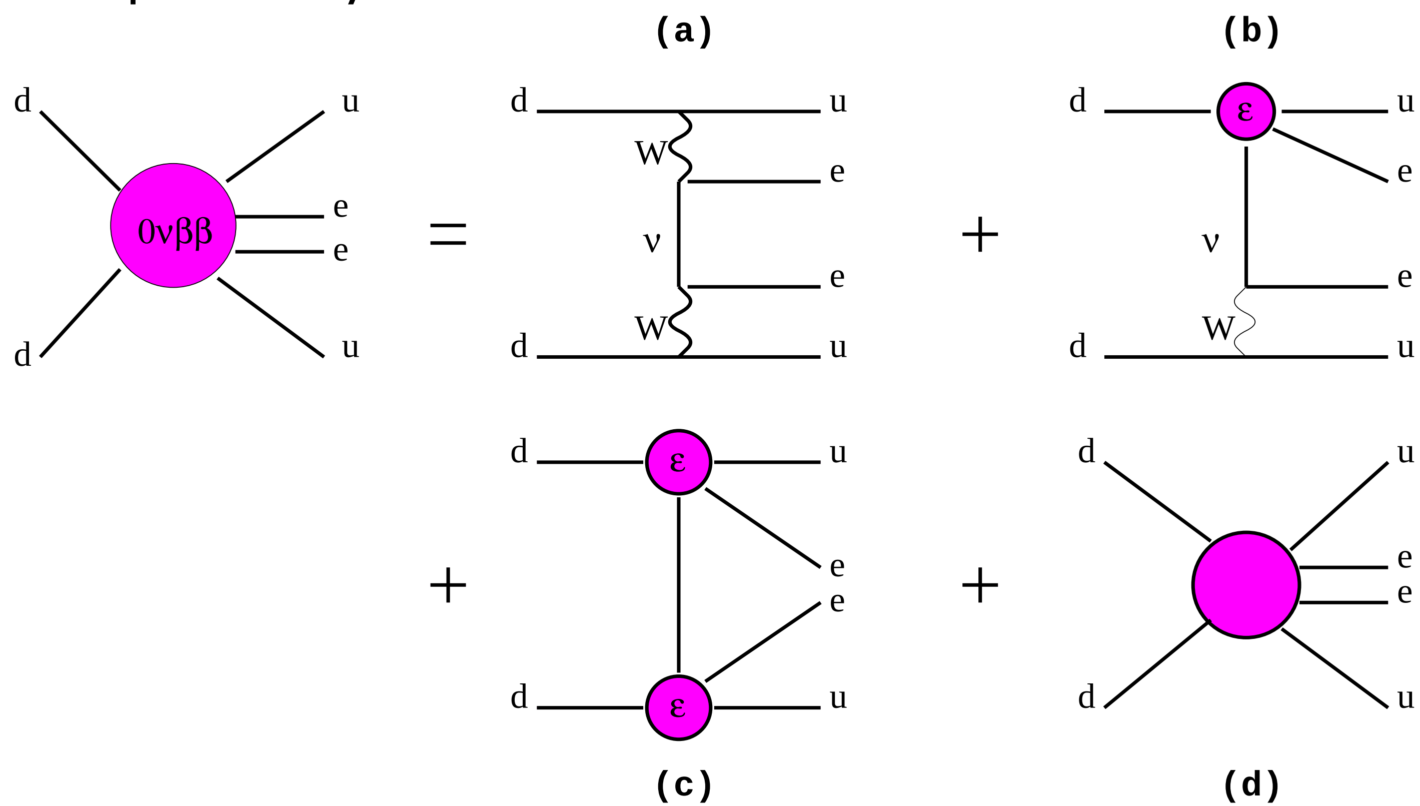
$$J^{\dagger}_{\alpha} = \bar{u}\mathcal{O}_\alpha d,$$
$$j_\beta = \bar{e}\mathcal{O}_\beta \nu$$
$$j^{\mathrm{short}}_\beta = \bar{e}\mathcal{O}_\beta e^C$$

Short-range part:

$$\mathcal{L}^{\mathrm{short}} = \frac{G_F^2}{2m_P} \sum_{\alpha,\beta\gamma} \epsilon^{\alpha\beta\gamma} j^{\mathrm{short}}_{\alpha} J^{\dagger}_{\beta} J^{\dagger}_{\gamma}$$

Lorentz-invariant Lagrangian

Graphically:



$\Rightarrow$ Neglect terms proportional ϵ^2

$\Rightarrow$ For limits, consider only helicity enhanced terms, i.e. $\sim \not{p}$

Neutrino propagator:

$$P_L \int \frac{d^4p}{(2\pi)^4} \frac{m_\nu + \not{p}}{p^2 - m_\nu^2} P_R$$
$$= P_L \int \frac{d^4p}{(2\pi)^4} \frac{\not{p}}{p^2 - m_\nu^2}$$

Limits: $T_{1/2}(^{76}Ge) \geq 1.2 \cdot 10^{25}$ *ys*

H. Päs et al., PLB 1999 and 2001:

Long range part: Short range part:

ϵ^{V+A}_{V-A}	$4.3 \cdot 10^{-9}$		$\epsilon^{S/P,S/P,S/P}$	$4 \cdot 10^{-7}$
ϵ^{V+A}_{V+A}	$7.9 \cdot 10^{-7}$		$\epsilon^{T,T,S/P}$	$2.5 \cdot 10^{-9}$
ϵ^{S+P}_{S-P}	$1.1 \cdot 10^{-8}$		$\epsilon^{V\pm A,V\pm A,S/P}$	$5 \cdot 10^{-8}$
ϵ^{S+P}_{S+P}	$1.1 \cdot 10^{-8}$		$\epsilon^{V\pm A,V\mp A,S/P}$	$1.4 \cdot 10^{-8}$
ϵ^{TR}_{TL}	$6.4 \cdot 10^{-10}$		$\epsilon^{V/A,T,V/A}$	$2.5 \cdot 10^{-8}$
ϵ^{TR}_{TR}	$1.7 \cdot 10^{-9}$		$\epsilon^{V/A,S/P,V/A}$	$2.5 \cdot 10^{-7}$

$\Rightarrow$ Limits are “on-axis”, i.e. one ϵ non-zero

$\mathcal{III}.$

Limits on

physics beyond the SM

Left-right symmetric models

Translation table:

Päs et al.	DKT		limit
ϵ^{V+A}_{V-A}	$\langle\eta\rangle$	$\sim \sum_j U_{ej} V_{ej} \tan\zeta$	$4.3 \cdot 10^{-9}$
ϵ^{V+A}_{V+A}	$\langle\lambda\rangle$	$\sim \sum_j U_{ej} V_{ej} (m_{W_L}/m_{W_R})^2$	$7.9 \cdot 10^{-7}$
$\epsilon^{V\pm A, V\mp A, S/P}$	$\langle\xi\rangle^*$	$\sim \sum_j V_{ej}^2 / m_N (m_{W_L}/m_{W_R})^2$	$1.4 \cdot 10^{-8}$

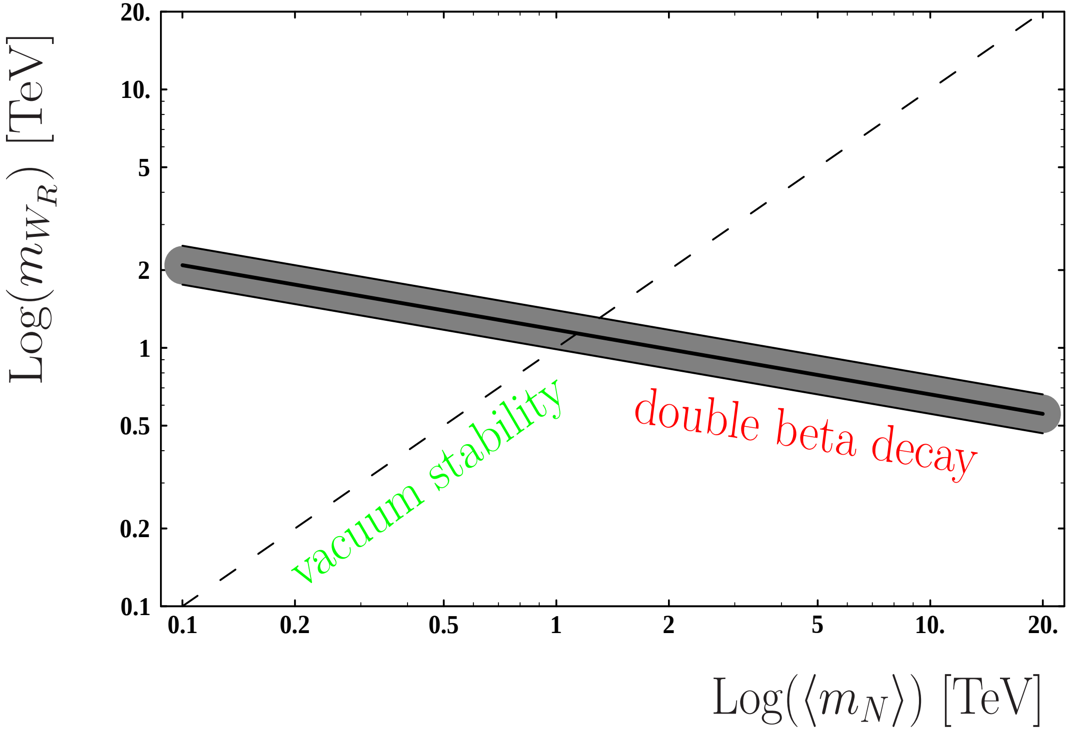
* Notation of Hirsch et al., PLB 1996

Note:

$\Rightarrow$ $\langle\eta\rangle$ and $\langle\lambda\rangle$ are long-range

$\Rightarrow$ $\langle\xi\rangle$ is short-range

Limit on m_{W_R} from $0\nu\beta\beta$



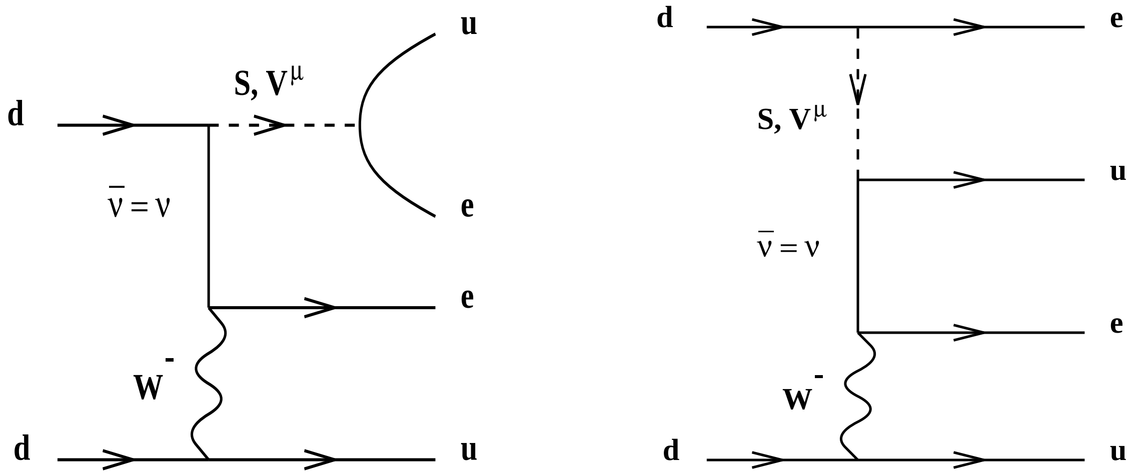
Mohapatra, PRD 1986

Hirsch et al., PLB 1996

Note: Width of band indicates NME uncertainty of ~ 2

$$\langle \xi \rangle \Rightarrow \quad m_{W_R} \gtrsim 1.3 \left(\frac{\langle m_N \rangle}{[1\mathrm{TeV}]} \right)^{-1/4} \mathrm{TeV}$$

Leptoquarks



LQs are hypothetical particles, coupling to a quark-lepton pair

LQs can be scalars (S) or vectors (V^{μ})

LQs can violate L (in LQ-Higgs interaction) if conserve B

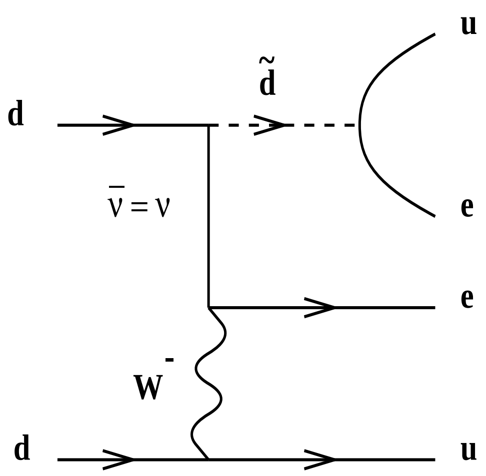
$$
\begin{aligned}
\mathcal{L}^{eff}_{LQ} \quad &= \quad (\bar{\nu}_n P_R e^c) \left[\frac{\epsilon_S}{M_S^2} (\bar{u} P_R d) + \frac{\epsilon_V}{M_V^2} (\bar{u} P_L d) \right] - \\
&- \quad (\bar{\nu}_n \gamma^{\mu} P_L e^c) \\
&\times \quad \left[\left(\frac{\alpha_S^{(R)}}{M_S^2} + \frac{\alpha_V^{(R)}}{M_V^2} \right) (\bar{u} \gamma_{\mu} P_R d) - \sqrt{2} \left(\frac{\alpha_S^{(L)}}{M_S^2} + \frac{\alpha_V^{(L)}}{M_V^2} \right) (\bar{u} \gamma_{\mu} P_L d) \right],
\end{aligned}
$$

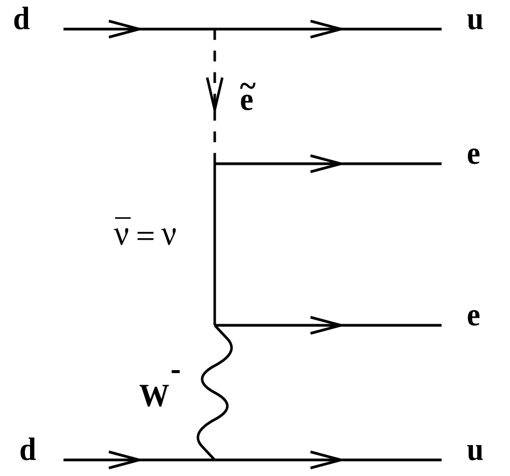
$\Rightarrow$ ϵ and α products of LQ couplings times mixing angle

$\Rightarrow$ Example: $\alpha_{S,V}^{(L)} \leq 2.5 \cdot 10^{-10} \left(\frac{M_{S;V}}{100\text{GeV}} \right)^2$

Hirsch et al. PRD 1996

Long-range RPV SUSY





Babu & Mohapatra, PRL 1995

Päs et al., PLB 1999

$\Rightarrow T(^{76}Ge) \geq 1.2 \cdot 10^{25}$ ys

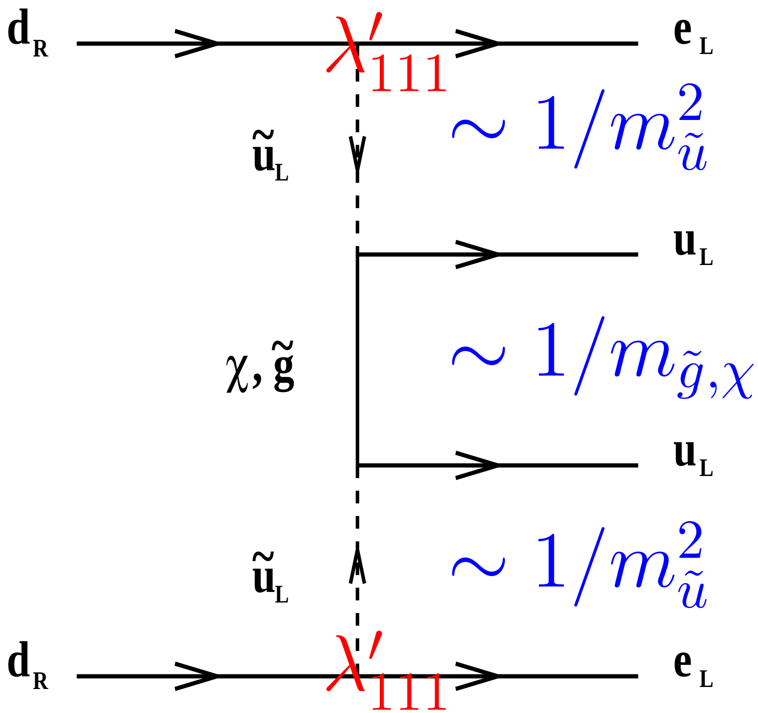
$\Rightarrow$ Including tensor matrix element:

$$\lambda'_{113}\lambda'_{131} \leq 3.8 \cdot 10^{-8} \left(\frac{m_{SUSY}}{100\text{GeV}} \right)^3$$

Short-range RPV SUSY

Only one example:

Mohapatra, PRD 1986
Vergados, PLB 1987
Hirsch et al., PRL 1995



Amplitude
$\sim$ 2 RPV vertices,
but limit
very stringent

From gluino graph:

$$\lambda'_{111} \leq 3 \times 10^{-4} \left(\frac{m_{\tilde{q}}}{100\mathrm{GeV}}\right)^2 \left(\frac{m_g}{100\mathrm{GeV}}\right)^{1/2}$$

$$\mathcal{IV}.$$

$\langle m_\nu \rangle$ or BSM?

Angular correlation

Calculate differential width:

For LR-models:
Doi, Kotani & Takasugi, 1985

$$\frac{d\Gamma}{d\cos\theta} \sim (1 - K\cos\theta)$$

For general LI Lagrangian:
Ali, Borisov & Zhuridov, 2007

⇒ Advantage: K depends strongly on mechanism, but weakly on nuclear matrix elements (i.e. weakly on isotope)

⇒ Disadvantage: Many terms in general Lagrangian lead to same (or very similar) angular dependence

⇒ Disadvantage: Most experiments calorimetric measurements only, exception: NEMO-III

Double beta plus decays

In $\beta^+\beta^+$ three principle decay modes:

$0\nu\beta^+\beta^+$: $(Z,N) \Rightarrow (Z-2,N) + 2e^+$

$0\nu\beta^+/EC$: $(Z,N) + e^- \Rightarrow (Z-2,N) + e^+$

$0\nu EC/EC$: $(Z,N) + 2e^- \Rightarrow (Z-2,N)^*$

For LR-models:
Hirsch et al., Z. Phys. A 1994

For general LI Lagrangian:
no publication exists

Numerical example: ^{124}Xe using pn-QRPA

Mode:	C_{mm}	$C_{\lambda\lambda}$	$C_{\lambda\lambda}/C_{mm}$
$0\nu\beta^+\beta^+$	$8.7 \cdot 10^{-17}$	$8.5 \cdot 10^{-18}$	0.098
$0\nu\beta^+/EC$	$1.6 \cdot 10^{-15}$	$2.2 \cdot 10^{-14}$	13.75

$\Rightarrow$ Advantage: Ratios (nearly) independent from nuclear matrix elements uncertainty

$\Rightarrow$ Disadvantage: Only $\langle\lambda\rangle$ enhanced

$\Rightarrow$ Disadvantage: Even best isotopes (at least) one order of magnitude slower than best $\beta^-\beta^-$

Others?

$\Rightarrow$ Compare rates ground state to 2^+

- Doi, Kotani & Takasugi, 1985: YES
- Tomoda, PLB 2000: NO for $\langle\eta\rangle$, maybe for $\langle\lambda\rangle$
- Disadvantage: several o.m. slower than g.s. transitions

$\Rightarrow$ Compare rates ground state to 0_1^+

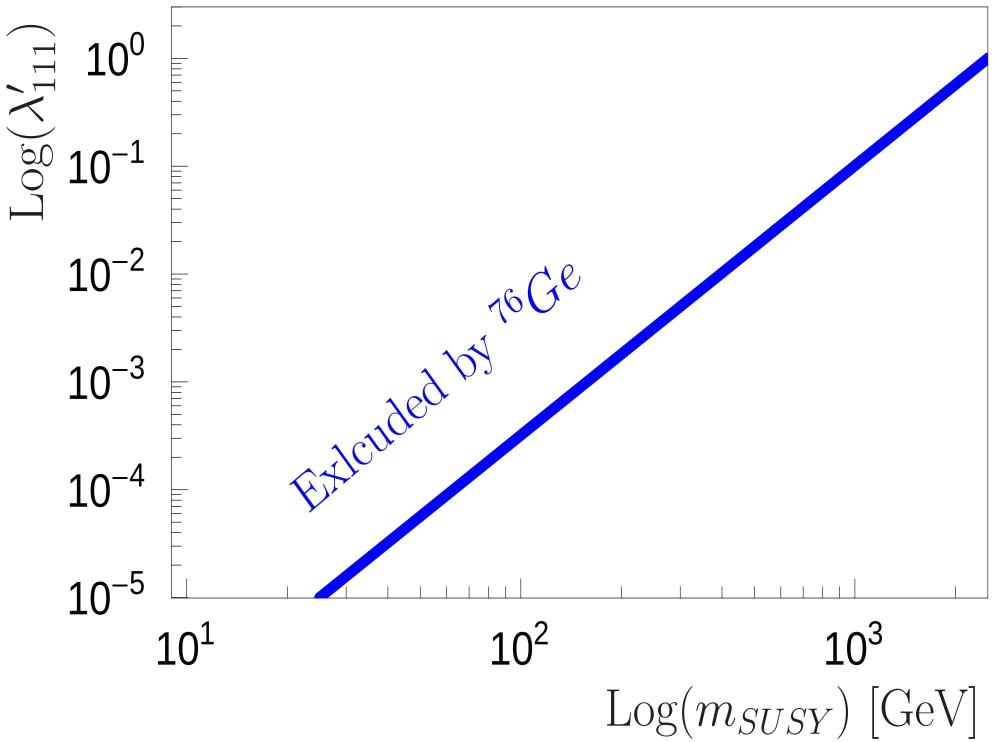
- Simkovic & Fäßler, Prog. Part. Nucl. Phys, 2002
- Disadvantage: (a) (about) 2 o.m. slower than g.s. transitions
- Disadvantage: (b) need to know matrix elements: $\Delta M \ll 40\%$

$\Rightarrow$ Compare rates, different nuclei

- Päs & Deppisch, PRL 2007; Gehman & Elliott, J. Phys. G 2007
- Disadvantage: need to know matrix elements: $\Delta M \ll x$,
  x differs for different particle physics, but is
  $x = (10 - 25)\%$, depending on number of isotopes

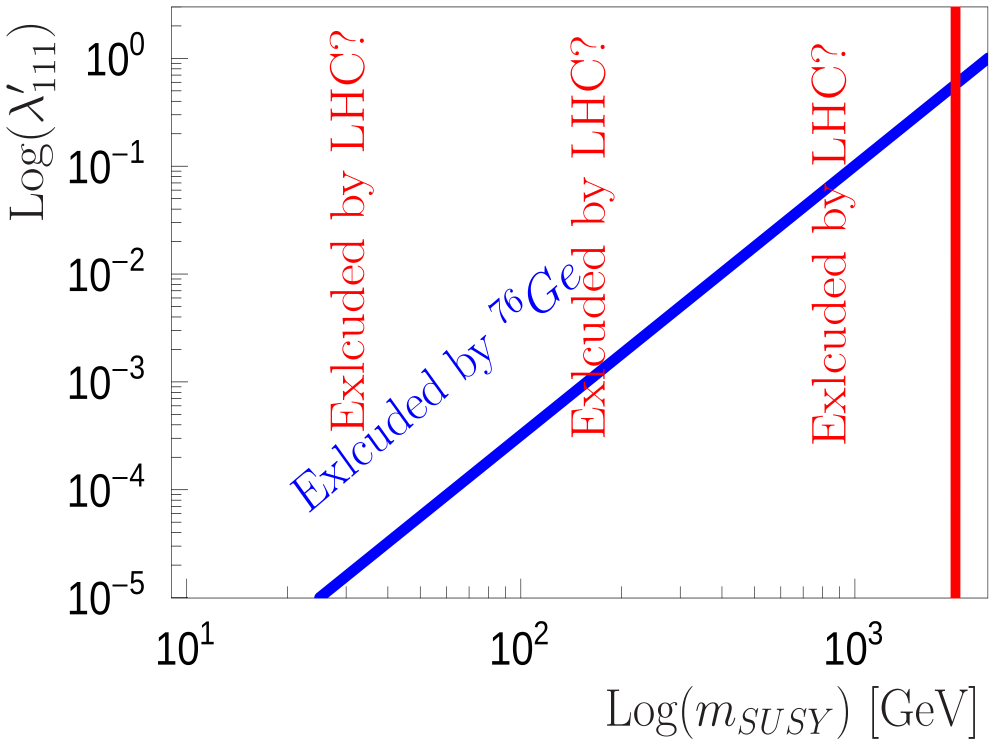
From accelerators?

In trilinear RPV SUSY, limit from ^{76}Ge excludes:



From accelerators?

In trilinear RPV SUSY, limit from ^{76}Ge excludes:



No SUSY @ LHC?
RPV $0\nu\beta\beta$ decay
(nearly) excluded

$\Rightarrow$ Disadvantage: Only RPV SUSY?

Conclusions

$\Rightarrow$ All models with lepton number violation contribute to $0\nu\beta\beta$ decay

$\Rightarrow$ Discovery of $0\nu\beta\beta$ decay $\equiv$ Majorana neutrinos

$\Rightarrow$ IF $0\nu\beta\beta$ decay is discovered:
Which is the dominant mechanism?