Neutrinoless double β decay with small neutrino masses

An effective field theory point of view

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IFIC/Univ. València

Corfu Summer School, September 12, 2012

Content

Content

Content

Content

Content

Is Lepton Number Conserved?

Much is known on ν's: Δm^2_{21}, $|\Delta m^2_{31}|$, θ_{12}, θ_{23}, θ_{13}
Still do not know: $\mathrm{sign}(\Delta m^2_{31})$, δ, absolute mass scale , … but

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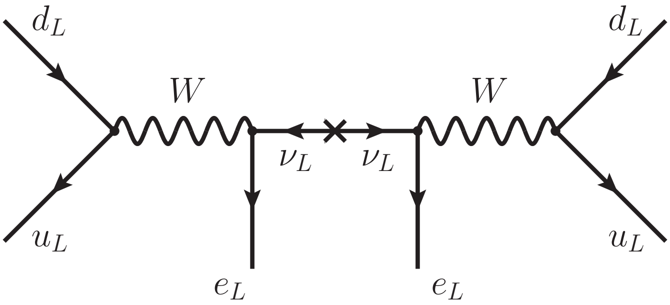
Can we test for LN violation ?

Many processes ($K^+ \to \pi^- \mu^+ \mu^- \dots$) but
only $0\nu\beta\beta$ can match, perhaps, the precision of ν masses

How are $0\nu\beta\beta$ and Majorana ν masses related?

Majorana $m_\nu \Longrightarrow 0\nu\beta\beta$



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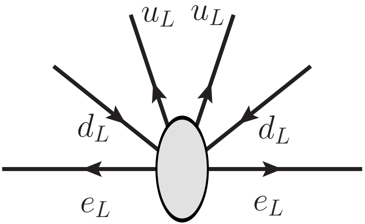
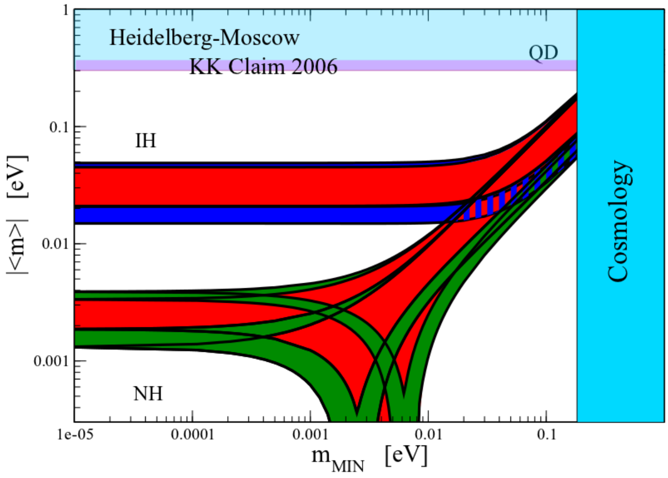


But depends on the ν spectrum,

$(M_\nu)_{ee}$ could be zero even if $m_{\nu_1,\nu_2,\nu_3} \neq 0$

m_ν Contribution to $0\nu\beta\beta$



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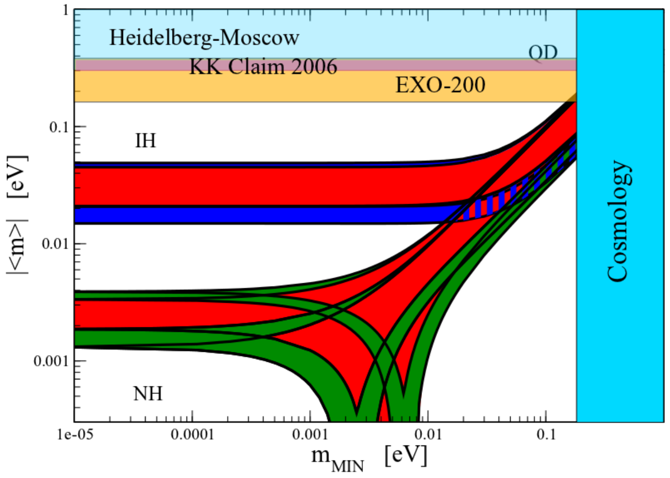

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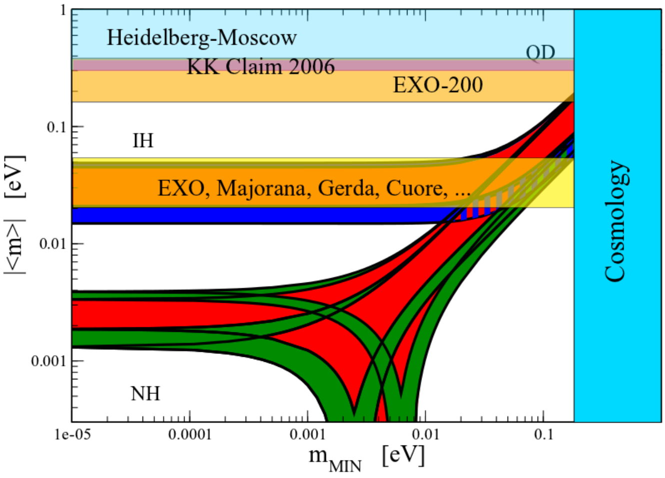

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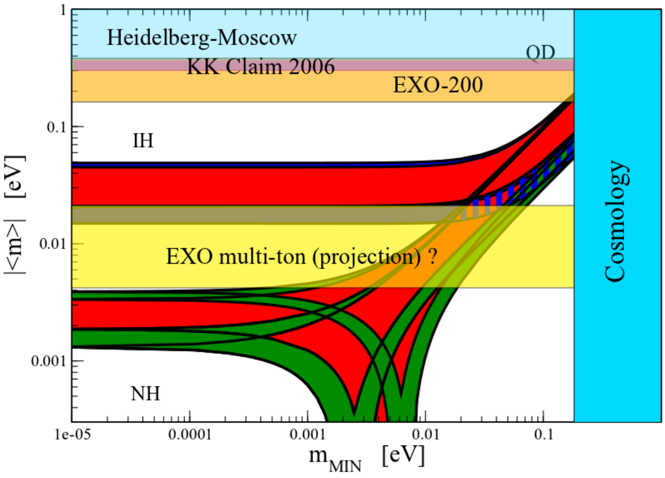
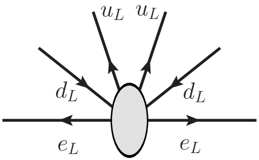


Schechter-Valle "theorem"

$0\nu\beta\beta \Longrightarrow$ Majorana m_ν



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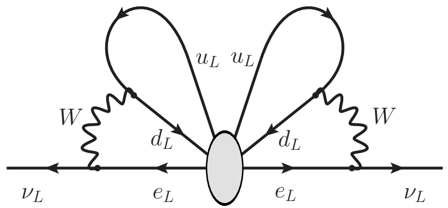

Extremely suppresed (4 loops)

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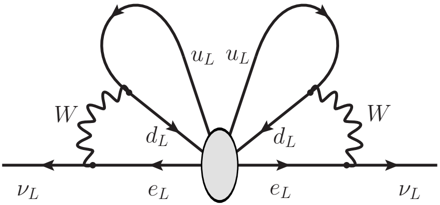


Extremely suppresed (4 loops)

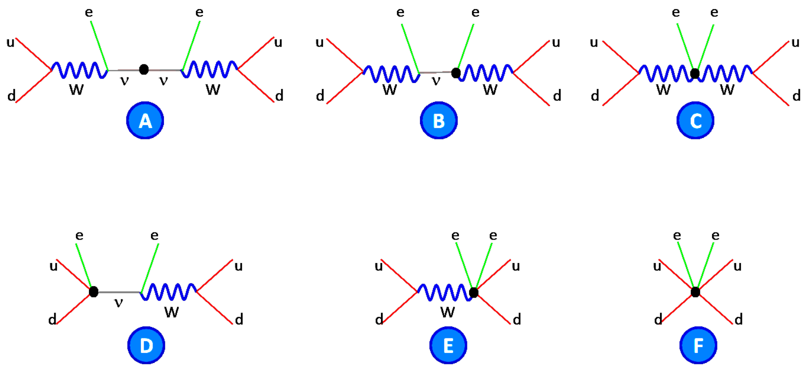
Fermion chirality

$$\text{Majorana } \nu : \quad \nu_L \nu_L , \qquad 0\nu\beta\beta : \begin{cases} e_L e_L \\ e_L e_R \\ e_R e_R \end{cases}$$

Break **different quantum numbers**, only linked by m_e

Vertices contributing to $0\nu\beta\beta$

Classification of possible $0\nu\beta\beta$ contributions



Operators with quarks widely considered:
K. Babu & C.N. Leung; K. Choi, K.S. Jeong & W.Y. Song; J. Engel & P. Vogel; A. de Gouvea & J. Jenkins

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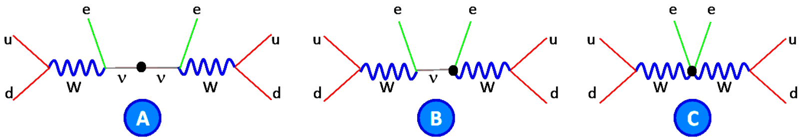

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Effective Lagrangian Approach

Assumptions:

- The SM is a low-energy approximation of a more complete theory
- The only light particles ($m \lesssim 250\,\mathrm{GeV}$) are those of the SM (excluding ν_R)

then

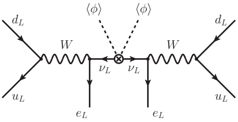
$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + \sum_{n=5}^{\infty} \sum_{i} \left(\frac{C_i^{(n)}}{\Lambda^{n-4}} \mathscr{O}_i^{(n)} + \mathrm{h.c.} \right).$$

$$\mathscr{L}_{\mathrm{SM}} = i\bar{\ell} \not{D} \ell + i\overline{e_R} \not{D} e_R - (\bar{\ell} Y_e e_L \phi + \mathrm{h.c.}) + \cdots$$

$\mathscr{O}_i^{(n)}$ are dim-n gauge invariant operators built with the SM fields

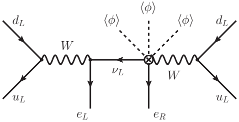
$\mathscr{O}_i^{(n)}$ effects suppressed by $1/\Lambda^n$, being Λ the scale of new physics.

The Operators



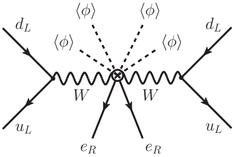
$$\mathcal{O}^{(5)} = \left(\bar{\tilde{\ell}}\phi\right)\left(\tilde{\phi}^\dagger \ell\right)$$

LL



$$\mathcal{O}^{(7)} = \left(\phi^\dagger D_\mu \tilde{\phi}\right)\left(\phi^\dagger \overline{e_{\mathrm{R}}}\gamma^\mu \tilde{\ell}\right)$$

LR



$$\mathcal{O}^{(9)} = \overline{e_{\mathrm{R}}} e^{\mathrm{c}}_{\mathrm{R}}\left(\phi^\dagger D_\mu \tilde{\phi}\right)\left(\phi^\dagger D^\mu \tilde{\phi}\right)$$

RR

Physical content

LL

$$\mathcal{O}^{(5)} = \left(\overline{\tilde{\ell}_\alpha}\phi\right)\left(\tilde{\phi}^\dagger \ell_\beta\right) = -v^2\,\overline{\nu^c_{\alpha L}}\,\nu_{\beta L} + \dots$$

Physical content

LL

$$\mathcal{O}^{(5)} = \left(\overline{\tilde{\ell}_\alpha} \phi\right) \left(\tilde{\phi}^\dagger \ell_\beta\right) = -v^2\, \overline{\nu^c_{\alpha\mathrm{L}}} \nu_{\beta\mathrm{L}} + \ldots$$

LR

$$\mathcal{O}^{(7)} = \left(\phi^\dagger D_\mu \tilde{\phi}\right) \left(\phi^\dagger \overline{e_{\alpha\mathrm{R}}} \gamma^\mu \tilde{\ell}_\beta\right) = i\, \frac{g v^3}{\sqrt{2}} W^-_\mu\, \overline{e_{\alpha\mathrm{R}}} \gamma^\mu \nu^c_{\beta\mathrm{L}} + \ldots$$

Physical content

LL

$$\mathcal{O}^{(5)} = \left(\overline{\tilde{\ell}_\alpha} \phi\right) \left(\tilde{\phi}^\dagger \ell_\beta\right) = -v^2\, \overline{\nu^c_{\alpha \mathrm{L}}}\, \nu_{\beta \mathrm{L}} + \dots$$

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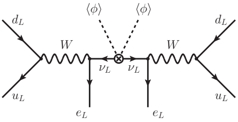
RR

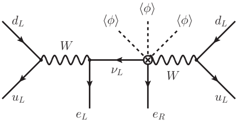
$$\mathcal{O}^{(9)} = \overline{e_{\alpha \mathrm{R}}} e^c_{\beta \mathrm{R}} \left(\phi^\dagger D \tilde{\phi}\right)^2 = -\frac{g^2 v^4}{2} W^-_\mu W^{-\mu}\, \overline{e_{\alpha \mathrm{R}}} e^c_{\beta \mathrm{R}} + \dots$$

Amplitudes ($v = \langle\phi\rangle \sim 174\,\mathrm{GeV}$, $p_{\mathrm{eff}} \sim 100\,\mathrm{MeV}$)



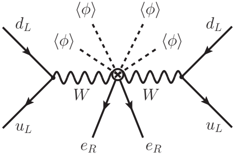
$$\mathscr{A}^{(5)}_{0\nu 2\beta} \sim \frac{C^{(5)}_{ee}}{\Lambda p_{\mathrm{eff}}^2 v^2}$$

LL



$$\mathscr{A}^{(7)}_{0\nu 2\beta} \sim \frac{C^{(7)}_{ee}}{\Lambda^3 p_{\mathrm{eff}} v}$$

LR



$$\mathscr{A}^{(9)}_{0\nu 2\beta} \sim \frac{C^{(9)}_{ee}}{\Lambda^5}$$

RR

The relevant $0\nu\beta\beta$ scales

From present $0\nu\beta\beta$ experiments (HM,IGEX)
$T_{1/2} > 1.9 \times 10^{25}\,\mathrm{years}$

$$\frac{p_{\rm eff}}{G_F^2}\left|\mathscr{A}_{0\nu\beta\beta}\right| \lesssim 5\times 10^{-9}$$

(EXO has improved it recently in about a factor of 2)

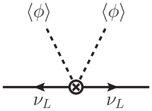
$0\nu\beta\beta$ limits on Λ

- $$\mathrm{LL} \quad \Lambda > 10^{11}\,|C_{ee}^{(5)}|\ \mathrm{TeV}$$
- $$\mathrm{LR} \quad \Lambda > 106\,|C_{ee}^{(7)}|^{1/3}\ \mathrm{TeV}$$
- $$\mathrm{RR} \quad \Lambda > 2.7\,|C_{ee}^{(9)}|^{1/5}\ \mathrm{TeV}$$

Contribution to ν masses

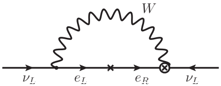
Neutrino masses ($v = \langle \phi \rangle \sim 174\,\mathrm{GeV}$)

$\mathcal{O}^{(5)}$



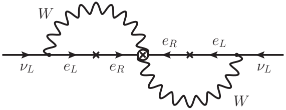
$$(m_\nu)_{ab} \sim \frac{v^2}{\Lambda} C^{(5)}_{ab}$$

$\mathcal{O}^{(7)}$



$$\frac{v}{16\pi^2\Lambda}\left(m_a C^{(7)}_{ab} + m_b C^{(7)}_{ba}\right)$$

$\mathcal{O}^{(9)}$



$$\frac{1}{(16\pi^2)^2\Lambda} m_a C^{(9)}_{ab} m_b$$

The scales

Assuming that the dominant contribution to ν masses comes from these operators we can relate $\mathscr{A}_{0\nu\beta\beta}$ with $(m_\nu)_{ee}$

- LL

$$\mathscr{A}_{0\nu\beta\beta} \propto (m_\nu)_{ee}$$

- LR

$$\mathscr{A}_{0\nu\beta\beta} \propto (m_\nu)_{ee}(4\pi)^2 \frac{v^2}{\Lambda^2}\frac{p_{\rm eff}}{m_e}$$

- RR

$$\mathscr{A}_{0\nu\beta\beta} \propto (m_\nu)_{ee} \left((4\pi)^2 \frac{v^2}{\Lambda^2}\frac{p_{\rm eff}}{m_e} \right)^2$$

If we require the new contributions dominate the standard ones we should require for LR and RR

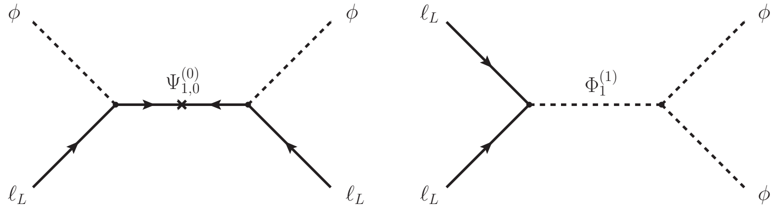
$$\Lambda < 4\pi v \sqrt{\frac{p_{\rm eff}}{m_e}} \sim 30\,\mathrm{TeV}$$

The new physics scale should be low, perhaps accessible!

Renormalizable Completions

The $O^{(5)}$, $O^{(7)}$, $O^{(9)}$ obtained from renormalizable interactions by adding a variety of new particles ($\Phi_I^{(Y)}$, $\Psi_I^{(Y)}$, $X_I^{(Y)}$)

LL



Many possibilities for LR and RR (Classified arXiv:1204.5986), for instance

- LR: $\{\Psi_{1/2}^{(1/2)}, \Phi_1^{(1)}\}; \{\Psi_0^{(0)}, \Phi_0^{(1)}\}, \cdots$
- RR: $\{\Phi_0^{(2)}, \Phi_1^{(1)}\}; \{\Psi_1^{(0)}, \Phi_1^{(1)}\}, \cdots$

To forbid $\mathscr{O}^{(5)}$ at tree level: need chiral LN and/or discrete symmetries

An example of LR-type model

Spectrum of new particles

	L_{La}	L_{Ra}	χ	ϕ'
$SU(2)_L$	$\frac{1}{2}$	$\frac{1}{2}$	1	$\frac{1}{2}$
$U(1)_Y$	$-\frac{1}{2}$	$-\frac{1}{2}$	1	$\frac{1}{2}$
Z_2	$-$	$-$	$-$	$-$

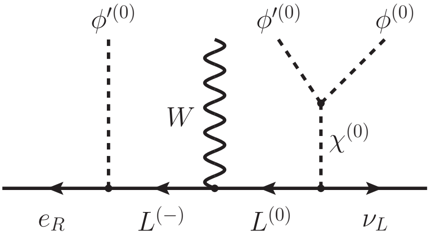
Lagrangian

$$\mathscr{L}_{\rm H}^{L} = \overline{L_a}(i\not{D} - M_a)L_a + \{y^{e}_{ab}\overline{L_{aL}}\phi' e_{bR} + y^{\nu}_{ab}\overline{\tilde{L}_{aL}}\chi\ell_{bL} + {\rm h.c.}\}$$

- $L_a \Longrightarrow$ cannot give see-saw types I-III
- No $\chi\ell_L\ell_L$ coupling $\Longrightarrow$ No see-saw II

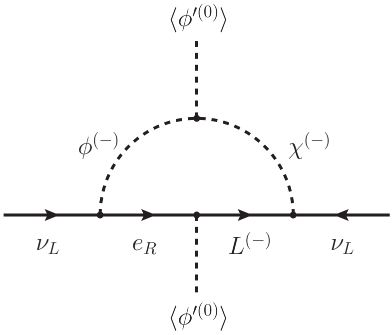
The LR operator in $0\nu\beta\beta$

The LR Operator



$$\frac{C^{(7)}_{ab}}{\Lambda^3} = -i\frac{\mu\, y^{e*}_{ca}\, y^{\nu *}_{cb}}{m^2_\chi M^2_c}$$

The neutrino mass



$$(m_\nu)_{ab} \simeq \frac{v'^2 \mu}{32\pi^2 v} \left(m_a y^{e*}_{ca} y^{\nu*}_{cb} + m_b y^{e*}_{cb} y^{\nu*}_{ca} \right) \frac{1}{M_c^2 - m_\chi^2} \log \frac{M_c^2}{m_\chi^2}$$

m_a and loops not enough suppression, small couplings needed.

Relevant Phenomenology

- Large $0\nu\beta\beta$ (enough to be seen) and small m_ν favor small couplings and relativelly light new particles.
- L_a, χ and ϕ' can be descovered at LHC if light enough ($\lesssim 800\,\mathrm{GeV}$)
- LFV is always small at tree level (new scalars do no couple to SM lepton pairs and mixings L_a-SM fermions are small)
- LFV at one loop provide some constraints but can be easily satisfied

An example of RR-type model

Spectrum of new particles

	χ	κ	σ
$SU(2)_L$	$\frac{1}{2}$	0	0
$U(1)_Y$	1	2	0
Z_2	$-$	$+$	$-$

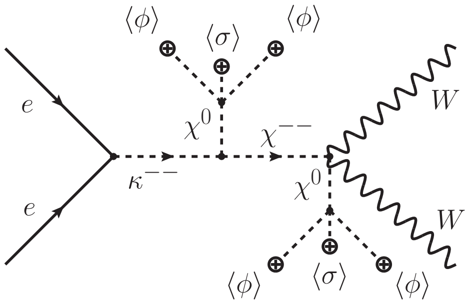
Lagrangian

$$\mathscr{L} = g_{\alpha\beta}\, \overline{e_{\alpha \mathrm{R}}}^{\mathrm{c}} e_{\beta \mathrm{R}}\, \kappa - \mu_\kappa\, \kappa \mathrm{Tr}\left\{\chi^\dagger \chi^\dagger\right\} - \lambda_6\, \sigma\, \phi^\dagger \chi \tilde{\phi} + \cdots$$

- No new fermions $\Longrightarrow$ No see-saw I-III
- No $\chi \ell_L \ell_L$ coupling $\Longrightarrow$ No see-saw II

The RR operator in $0\nu\beta\beta$

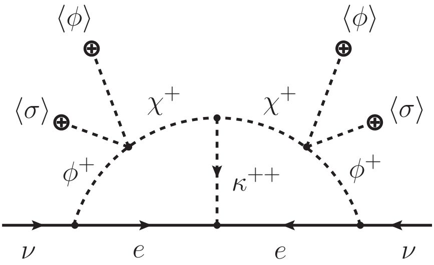
The LR Operator



$$\frac{C^{(9)}_{ab}}{\Lambda^5} = -i\frac{4(\lambda_6\langle\sigma\rangle)^2\mu_\kappa}{m_\kappa^2 M_\chi^6} g^*_{ab}$$

The neutrino mass

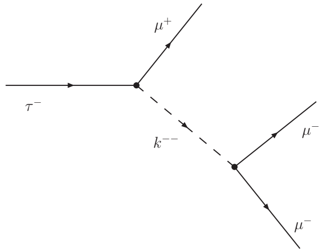
The neutrino mass



$$(m_\nu)_{\alpha\beta} = \frac{\mu_\kappa v_\chi^2}{2(2\pi)^4 v_\phi^4} m_\alpha g^*_{\alpha\beta} m_\beta \, I_\nu$$

LFV in the RR model

$\ell_a^- \to \ell_b^+ \ell_c^- \ell_d^-$: limits on g_{ab}



Strong constraints

- $\mathrm{BR}(\mu^- \to e^+ e^- e^-) < 1.0 \times 10^{-12}$

  $$|g_{\mu e} g^*_{ee}| < 2.3 \times 10^{-5} \left(m_\kappa/\mathrm{TeV}\right)^2$$

- $\mathrm{BR}(\tau^- \to e^+ \mu^- \mu^-) < 1.7 \times 10^{-8}$

  $$|g_{\tau e} g^*_{\mu\mu}| < 0.007 \left(m_\kappa/\mathrm{TeV}\right)^2$$

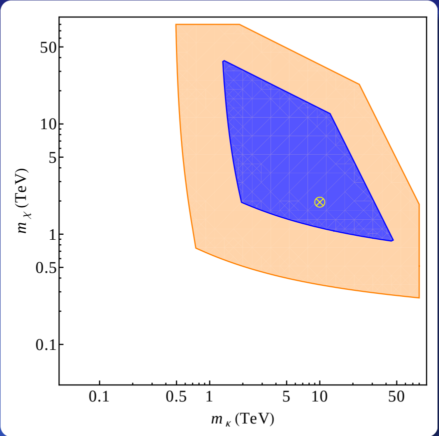
Constraints on the doubly-charged scalars

If scalar masses too large:

- $0\nu\beta\beta$ too small
- Too small ν masses

If scalar masses too small:

- Too large ν masses
- Problems with LFV
- Problems with LEP, LHC (not included in plot)

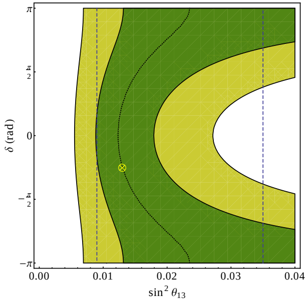


Constraints on the ν mass matrix

- Large $0\nu\beta\beta$: relatively large g_{ee} and small scalar masses
- m_{ee} highly suppressed by the factor m_e^2
- $m_{e\mu}$ also suppressed because the $\mu \to 3e$ bound on $g_{e\mu}$

ν mass matrix highly constrained

$$|m_\nu| = \begin{pmatrix} < 10^{-4} & < 10^{-4} & \sim 0.01 \\ < 10^{-4} & \sim 0.01 & \sim 0.01 \\ \sim 0.01 & \sim 0.01 & \sim 0.01 \end{pmatrix} \text{eV}$$



- Only NH allowed
- Predicction for $m_{\rm light} = m_1$
- Prediction for $\sin^2\theta_{13}$

2012: $\sin^2\theta_{13} \sim 0.02 - 0.026$

Conclusions

- We have used effective field theory language to classify new physics contributions to $0\nu\beta\beta$ involving operators without quarks
- For the lowest order operators, charged lepton chiralities, operator dimension and the order at which m_ν should appear are linked
  - $e_L e_L$ $0\nu 2\beta$ appears at dim 5: m_ν tree-level
  - $e_L e_R$ $0\nu 2\beta$ appears at dim 7: m_ν one loop
  - $e_R e_R$ $0\nu 2\beta$ appears at dim 9: m_ν two loops
- Large $0\nu 2\beta \Longrightarrow m_\nu$ small (supressed by loops) possible
- Models complicated and tighly constrained but could give a rich phenomenology in LFV processes and LHC (especially if a doubly charged scalar is discovered!)

Thanks for your attention

BACKUP SLIDES