Lepton Flavour Violation and Neutrino Masses

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Flavour Physics at LHC Run II
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Outline

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LFV $\Longrightarrow m_\nu$? Not necessarily!

If Majorana m_ν, need for Lepton Number Violation (LNV)

$$\mathscr{L}_k = \overline{e^c_{aR}} g_{ab}\, e_{bR}\, k^{++}$$

Tree level LFV ($\mu \to eee$) without neutrino masses!

A large class of models have (LNV + LFV): $M_\nu = \mu \dfrac{v^2}{M^2}$

If $\mu \ll M$ large LFV with small M_ν

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$$\Rightarrow \qquad \overline{e_L} \left(\frac{v}{\sqrt{2}} \left(Y_e + C_Y \frac{v^2}{2\Lambda^2} \right) + \frac{h}{\sqrt{2}} \left(Y_e + 3 C_Y \frac{v^2}{2\Lambda^2} \right) + \cdots \right) e_R + \cdots$$

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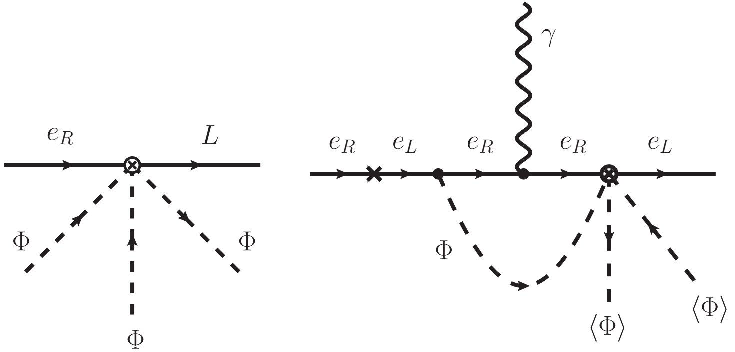
$\overline{C}_Y$	Λ (TeV)
1	5
m_τ / v	0.4
$1/(4\pi)^2$	0.4
$m_\tau / (v(4\pi)^2)$	0.04

Induced $\tau \to \mu\gamma$ by HLFV



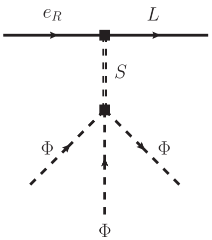
Induced $\tau \to \mu\gamma$ by HLFV

$$\mathscr{L}_{\rm LFV} = \frac{e C^{\gamma}_{ij} v}{16\pi^2 \Lambda^2 \sqrt{2}} \bar{e}_i \sigma_{\mu\nu} P_R e_j F^{\mu\nu} + \text{h.c.}$$

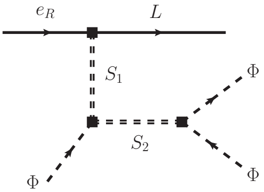
Upper bounds on $\mathrm{BR}(h \to \mu\tau)$

$\overline{C}_Y$ \ $\overline{C}_\gamma$	m_τ^2/v^2	m_τ/v	1
1	1	0.04	10^{-6}
m_τ/v	0.04	10^{-6}	10^{-10}
$1/(16\pi^2)$	0.03	10^{-6}	10^{-10}
$m_\tau/(16\pi^2 v^2)$	10^{-6}	10^{-10}	10^{-14}

Tree-level Topologies



(A)



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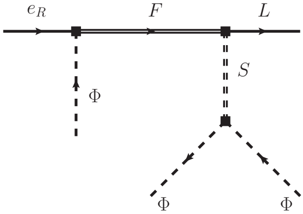

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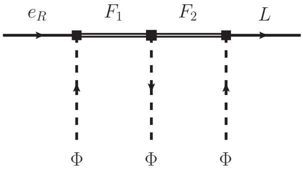

(D)

Representations

Topology	Particles	Representations	Coefficient $\frac{C_Y}{\Lambda^2}$
A	1 S	$S=(2,-1/2)$	$\frac{Y\lambda}{m_S^2}$
B	2 S	$(2,-1/2)_S\oplus(1,0)_S,(3,0)_S,(3,1)_S$	$\frac{Y\mu_1\mu_2}{m_{S_1}^2 m_{S_2}^2}$
C_1	1 F,1 S	$(2,-1/2)_F\oplus(1,0)_S,(3,0)_S$	$\frac{Y_F\, Y_F^S\mu}{m_F m_S^2}$
C_2	1 F,1 S	$(2,-3/2)_F\oplus(3,1)_S$	$\frac{Y_F\, Y_F^S\mu}{m_F m_S^2}$
C_3	1 F,1 S	$(1,-1)_F\oplus(1,0)_S$, $(3,-1)_F\oplus\ (3,0)_S$	$\frac{Y_F\, Y_F^S\mu}{m_F m_S^2}$
C_4	1 F,1 S	$(3,0)_F\oplus(3,1)_S$	$\frac{Y_F\, Y_F^S\mu}{m_F m_S^2}$
D_1	2 F	$(2,-1/2)_F\oplus(3,0)_F,\cancel{(1,0)_F}$	$\frac{Y_{F_1}\, Y_{12}\, Y_{F_2}}{m_{F_1} m_{F_2}}$
D_2	2 F	$(2,-1/2)_F\oplus(1,-1)_F,(3,-1)_F$	$\frac{Y_{F_1}\, Y_{12}\, Y_{F_1}}{m_{F_1} m_{F_2}}$
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Results for HLFV

- Topology A: type III 2HDM can give large HLFV

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- Most of one-loop topologies also proportional to m_τ or contain VL fermions
- Most of neutrino mass models give HLFV at one loop and suppressed by m_τ
- ν–mass models with two Higgs doublets, can give large HLFV
  - Extended Zee model
  - Left-right symmetric models

Neutrino mass models and LFV

Neutrino mass models and LFV

$$M_\nu = U D_\nu U^T \ , \quad \text{with} \ \ D_\nu = \text{diag}(m_1, m_2, m_3) \, , \quad U : \text{PMNS}$$

$(M_\nu)_{ab} \propto g_{ab}$, depend on $s_{12}, s_{13}, \Delta_{21}, \Delta_{31}, s_{23}, \delta, m_{\text{ligth}}, \alpha_1, \alpha_2$

Process	BR upper bound	Couplings limit
$\mu^- \to e^+ e^- e^-$	1.0×10^{-12}	$\lvert g_{e\mu} g_{ee}^* \rvert < 2.3 \times 10^{-5} \left(\frac{m_k}{\text{TeV}}\right)^2$
$\tau^- \to e^+ e^- e^-$	2.7×10^{-8}	$\lvert g_{e\tau} g_{ee}^* \rvert < 0.009 \left(\frac{m_k}{\text{TeV}}\right)^2$
$\tau^- \to e^+ e^- \mu^-$	1.8×10^{-8}	$\lvert g_{e\tau} g_{e\mu}^* \rvert < 0.005 \left(\frac{m_k}{\text{TeV}}\right)^2$
$\tau^- \to e^+ \mu^- \mu^-$	1.7×10^{-8}	$\lvert g_{e\tau} g_{\mu\mu}^* \rvert < 0.007 \left(\frac{m_k}{\text{TeV}}\right)^2$
$\tau^- \to \mu^+ e^- e^-$	1.5×10^{-8}	$\lvert g_{\mu\tau} g_{ee}^* \rvert < 0.007 \left(\frac{m_k}{\text{TeV}}\right)^2$
$\tau^- \to \mu^+ e^- \mu^-$	2.7×10^{-8}	$\lvert g_{\mu\tau} g_{e\mu}^* \rvert < 0.007 \left(\frac{m_k}{\text{TeV}}\right)^2$
$\tau^- \to \mu^+ \mu^- \mu^-$	2.1×10^{-8}	$\lvert g_{\mu\tau} g_{\mu\mu}^* \rvert < 0.008 \left(\frac{m_k}{\text{TeV}}\right)^2$
$\mu \to e\gamma$	4.2×10^{-13}	$\lvert g_{ee}^* g_{e\mu} + g_{e\mu}^* g_{\mu\mu} + g_{e\tau}^* g_{\mu\tau} \rvert < 3 \times 10^{-4} \, (m_k/\text{TeV})^2$
$\tau \to e\gamma$	3.3×10^{-8}	$\lvert g_{ee}^* g_{e\tau} + g_{e\mu}^* g_{\mu\tau} + g_{e\tau}^* g_{\tau\tau} \rvert < 0.2 \, (m_k/\text{TeV})^2$
$\tau \to \mu\gamma$	4.4×10^{-8}	$\lvert g_{e\mu}^* g_{e\tau} + g_{\mu\mu}^* g_{\mu\tau} + g_{\mu\tau}^* g_{\tau\tau} \rvert < 0.2 \, (m_k/\text{TeV})^2$
$Cr(\mu \to e)_{\text{Au}}$	7×10^{-13}	$\lvert g_{ee}^* g_{e\mu} + g_{e\mu}^* g_{\mu\mu} + g_{e\tau}^* g_{\mu\tau} \rvert < 4 \times 10^{-4} \, (m_k/\text{TeV})^2$

The See-Saw type II (tree level)

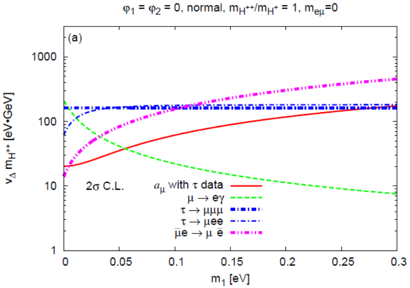
$Y = 1$ scalar triplet χ

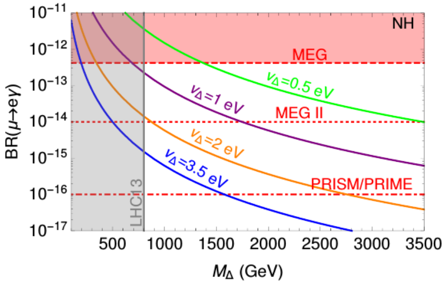
$$\mathscr{L}_\chi = -\left(\bar{\tilde{L}}_L Y_\chi \chi L_L - \mu\, \tilde{\Phi}^\dagger \chi^\dagger \Phi + \text{h.c.}\right), \quad M_\nu \approx Y_\chi v_\chi\,, \quad v_\chi \approx \frac{\mu}{m_\chi^2}\langle\Phi\rangle^2$$

LFV processes controlled by $Y_\chi^2/m_\chi^2 \approx M_\nu^2/(v_\chi m_\chi)^2$

$\ell_a^- \to \ell_b^+ \ell_c^- \ell_d^-$: tree, χ^{++} , $\ell_a^- \to \ell_b^- \gamma$: 1-loop, χ^+,χ^{++}

Limit on $v_\chi m_\chi$ (Fukuyama, Sugiyama, Tsumura. '10, Dev, Miralles, Rodejohann, '17)





Minimal Zee Model (one loop)

Adds to the SM a scalar singlet h^+ and a new doublet Φ'
$h^+ \sim (1,1), \qquad \Phi' \sim (2, \frac{1}{2})$

$$-\mathscr{L}_{\text{Zee}} = \overline{L_L} Y_e^\dagger \Phi e_R + \overline{\tilde{L}_L} f L_L h^+ + \mu h^+ \Phi^\dagger \tilde{\Phi}' + \cdots$$

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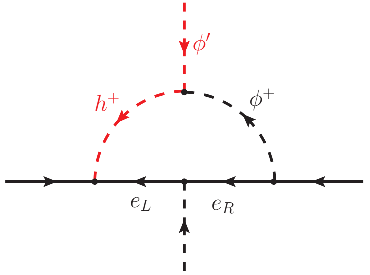

Simplest version gives

$$(M_\nu)_{ab} \approx \frac{1}{(4\pi)^2} \frac{\mu}{M_h^2} f_{ab}(m_a^2 - m_b^2)$$

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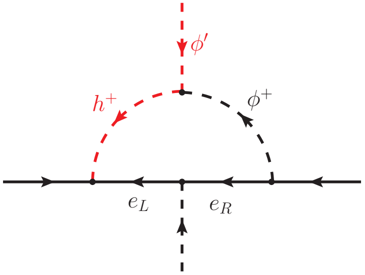

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- "Too predictive": excluded
- Type III 2HDM versions OK
  (Balaji, Grimus, Schwetz '01)
- $H \to \tau\mu$ linked to ν masses?
  (Herrero-Garcia, Rius, AS, '16)

Generalized Zee Model (one loop)

Zee with type III 2HDM (the two doublets coupled to charged leptons)

$$-\mathscr{L}_{\text{Zee}} = \overline{L_L}(Y_1^\dagger \Phi_1 + Y_2^\dagger \Phi_2) e_R + \overline{\tilde{L}_L} f L_L h^+ + \mu h^+ \Phi_1^\dagger \tilde{\Phi}_2 + \cdots$$

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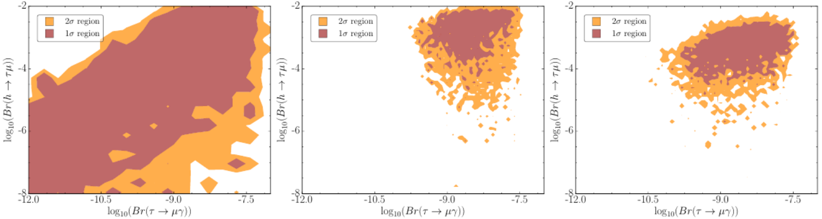
HLFV – LFV correlations

(Herrero-García, Ohlsson, Riad, Wirén, ’17)

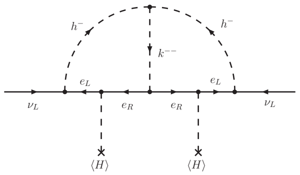


(a) $\mu = 0$ (b) NO (c) IO

The Zee-Babu Model (two loops)

Two scalar singlets h^+, k^{++} (Zee '86, Babu '88, Babu,Macesanu '03)
(Aristizabal,Hirsch '06, Nebot,Oliver,Palao,AS '08, Ohlsson,Schwetz,Zhang '09, Schmidt,Schwetz,Zhang '14)

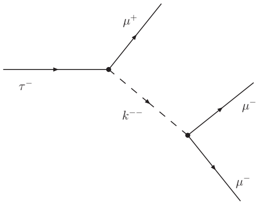
$$\mathscr{L}_{ZB} = \overline{\tilde{L}_L} f L_L h^+ + \overline{e^c_R} g\, e_R\, k^{++} + \mu (h^-)^2 k^{++} + \cdots$$



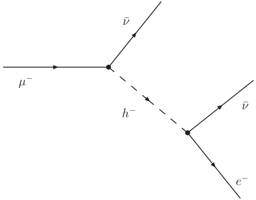
$$M_\nu \sim \frac{\mu}{(4\pi)^4 M_k^2} f\, M_E g^\dagger M_E f^T$$

- Lightest ν is massless
- $f_{e\tau}/f_{\mu\tau}, f_{e\mu}/f_{\mu\tau}$ fixed from mixings

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



$\ell_a \to \ell_b \nu \bar{\nu}$: limits on f_{ab}



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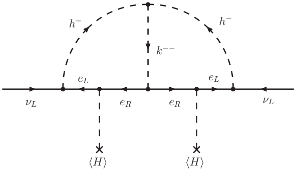

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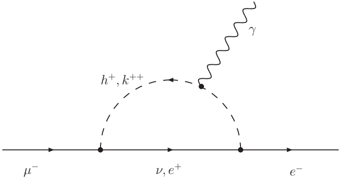
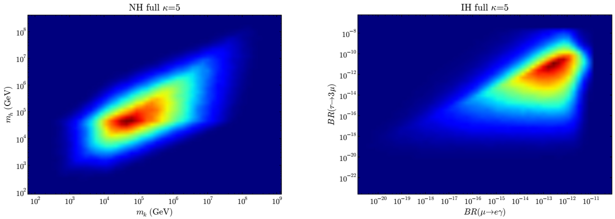
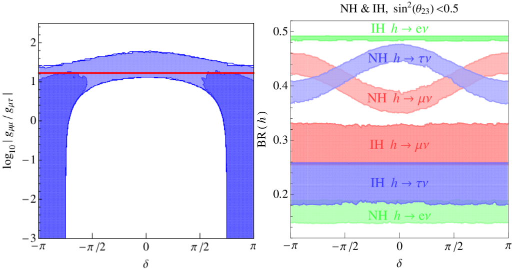
$\ell_a^- \to \ell_b^- \gamma$: bounds g_{ab} and f_{ab}



Constrained Parameter Space

(Nebot,Oliver,Palao,AS ’08, Herrero-Garcia,Nebot,Rius,AS ’14)

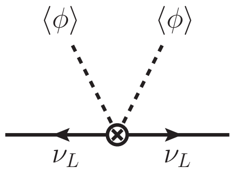




Lepton Number Violation and neutrino masses

$0\nu\beta\beta$ and Majorana m_ν

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



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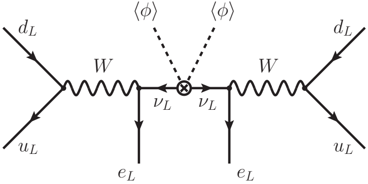

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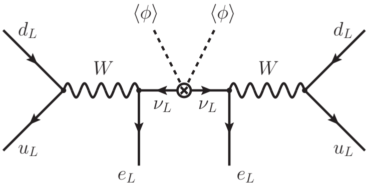

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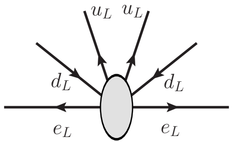

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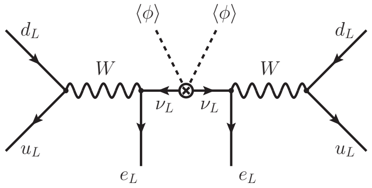

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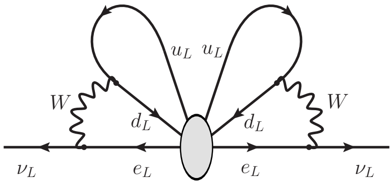

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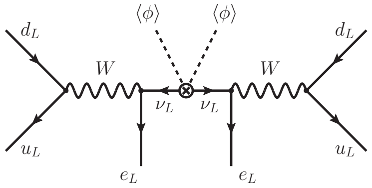
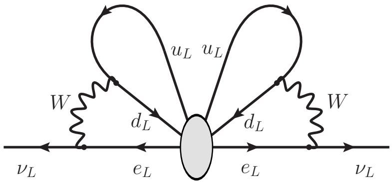


How tight is this connection?

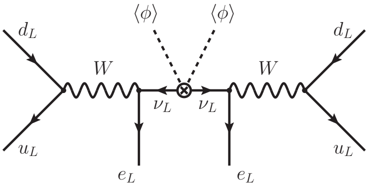
$0\nu\beta\beta \Longrightarrow$ Majorana m_ν



What if $(M_\nu)_{ee} < 10^{-3}$ eV?

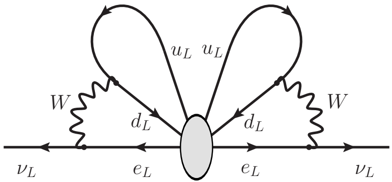
$0\nu\beta\beta$ and Majorana m_ν

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



How tight is this connection?

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



What if $(M_\nu)_{ee} < 10^{-3}$ eV?

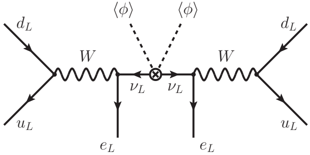
Chiral lepton number

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

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

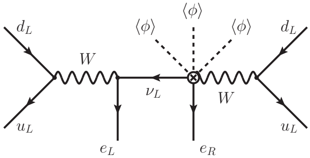
Contributions to $0\nu\beta\beta$

(del Aguila, Aparici, Bhattacharya, AS, Wudka '12)



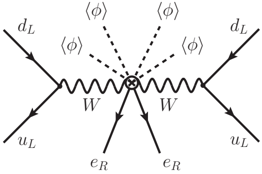
$$\mathcal{O}^{(5)} = \left(\overline{\tilde{L}_L}\Phi\right)\left(\tilde{\Phi}^\dagger L_L\right)$$

$$\mathcal{A}^{(5)}_{0\nu 2\beta} \sim \frac{C^{(5)}_{ee}}{\Lambda p^2_{\rm eff} v^2}$$



$$\mathcal{O}^{(7)} = \left(\Phi^\dagger D_\mu \tilde{\Phi}\right)\left(\Phi^\dagger \overline{e_{\rm R}}\gamma^\mu \tilde{L}_L\right)$$

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

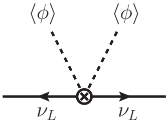


$$\mathcal{O}^{(9)} = \overline{e_{\rm R}} e^c_{\rm R} \left(\Phi^\dagger D_\mu \tilde{\Phi}\right)\left(\Phi^\dagger D^\mu \tilde{\Phi}\right)$$

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

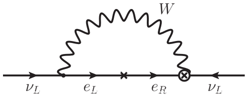
Contributions to ν Masses

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



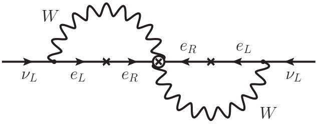
$$(M_\nu)_{ab} \sim \frac{v^2}{\Lambda} C^{(5)}_{ab}$$

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



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

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



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

Contributions to ν Masses

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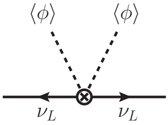

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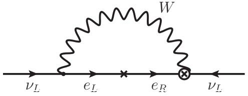

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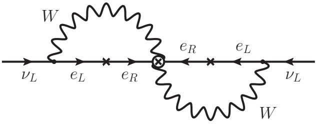

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Need models: C.S. Chen, C.Q. Geng, J.N. Ng, J.M.S. Wu; del Aguila, Aparici, Bhattacharya, AS, Wudka; M. Gustafsson, J.M. No, M.A. Rivera

A model for 1loop $0\nu\beta\beta$, 3loop m_ν with DM
(J. Alcaide, D. Das, A.S. '17)

3 new scalars $\kappa^{++} \sim (1, 2, +)$, $\chi \sim (3, 1, -)$,$\sigma \sim (1, 0, -)$ with Z_2

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- The DM requirement (small mixings large singlet-triplet splittings)

Neutrinoless double beta decay

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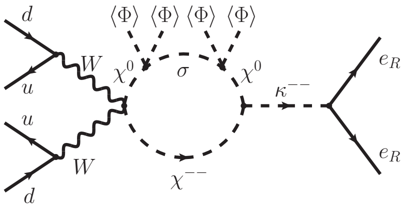
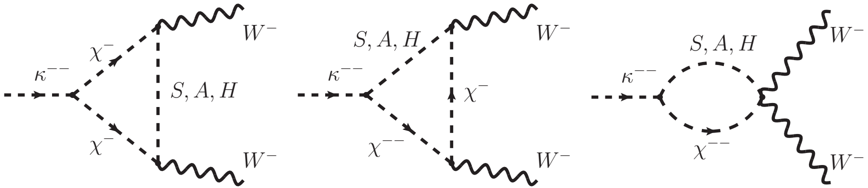


Neutrinoless double beta decay

The effective $\kappa^{--}WW$ vertex



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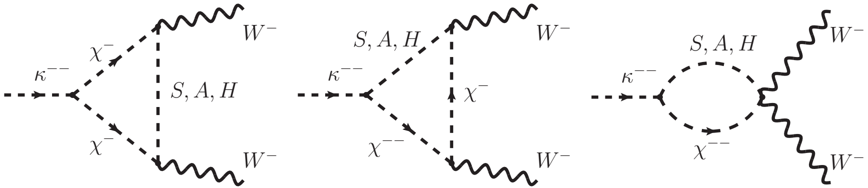


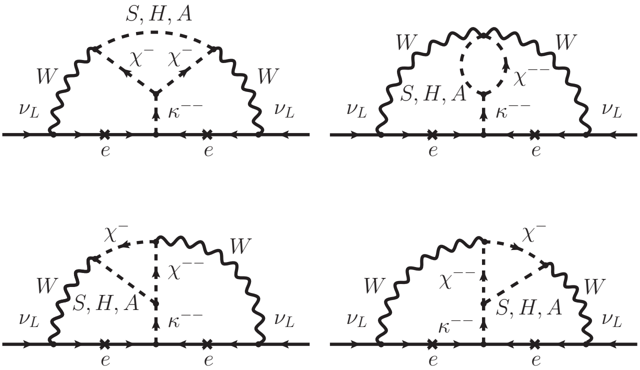
The amplitude

$$\mathscr{L}_{0\nu\beta\beta} = 2\frac{f_{ee}^*}{16\pi^2}\frac{\mu_\kappa \lambda_6^2}{m_\kappa^2 m_A^4} I_\beta \left(\overline{u_L}\gamma^\mu d_L\right)\left(\overline{u_L}\gamma_\mu d_L\right)\overline{e_R}e_R^c$$

$$4\times 10^{-10} < \frac{m_p}{2G_F^2}\frac{f_{ee}^*}{16\pi^2}\frac{\mu_\kappa \lambda_6^2}{m_\kappa^2 m_A^4} I_\beta < 4\times 10^{-9}$$

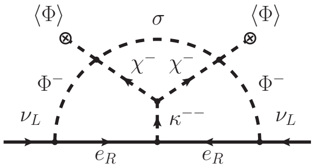
The neutrino masses

Neutrino mass in the unitary gauge



The neutrino masses

Mass insertion approximation



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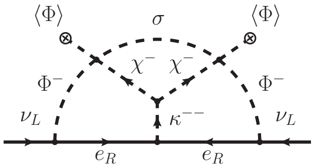

The neutrino mass matrix

$$M_{ab} = \frac{8\mu_\kappa \lambda_6^2}{(4\pi)^6 m_\kappa^2} I_\nu \, m_a f_{ab} m_b = U D_\nu U^T$$

Structure of the ν Mass Matrix

- M_{ee} highly suppressed by the factor m_e^2
- $M_{e\mu}$ also suppressed because the $\mu \to 3e$ bound on $f_{e\mu}$
- $M_{ee}, M_{e\mu} \ll M_{e\tau}, M_{\mu\mu}, M_{\mu\tau}, M_{\tau\tau} \sim 0.02\,\mathrm{eV}$

M_ν strongly constrained

$$M_\nu = \begin{pmatrix} < 10^{-4} & < 10^{-4} & \sim 0.01 \\ < 10^{-4} & \sim 0.02 & \sim 0.02 \\ \sim 0.01 & \sim 0.02 & \sim 0.02 \end{pmatrix} \mathrm{eV}$$

- Only NH allowed
- $\sin^2\theta_{13}$ cannot be zero
- Predicction for $m_{\text{light}} \sim 0.005\,\mathrm{eV}$
- Prediction for Majorana phases: fixed by δ

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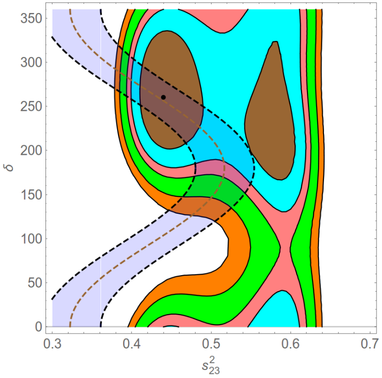

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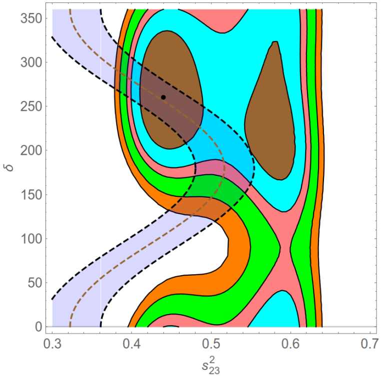
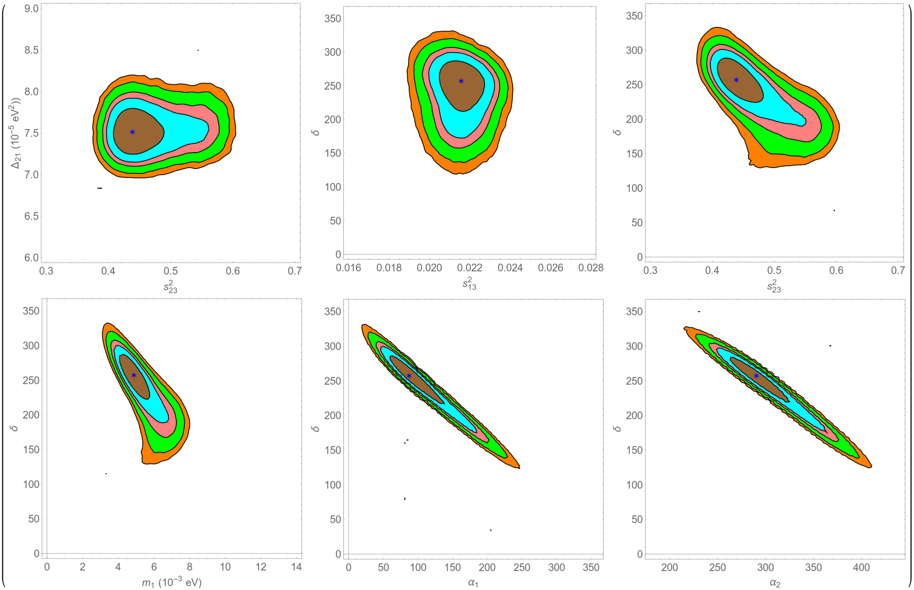


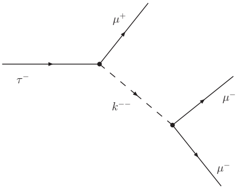
$\delta \sim 260^\circ$ and $s^2_{23} \sim 0.44$

The fit (preliminary)



LFV and LHC

LFV ($\ell_a^- \to \ell_b^+ \ell_c^- \ell_d^-$, $\ell_a^- \to \ell_b^- \gamma$, ...): limits on f_{ab}



Experimental Data (90% CL)	Bounds (90% CL)	Bounds assuming Eq. (28)
$\mathrm{BR}(\mu^- \to e^+e^-e^-) < 1.0 \times 10^{-12}$	$\lvert f_{e\mu} f_{ee}^* \rvert < 2.3 \times 10^{-5} \left(\frac{m_{\kappa^{++}}}{\mathrm{TeV}}\right)^2$	
$\mathrm{BR}(\tau^- \to e^+e^-e^-) < 2.7 \times 10^{-8}$	$\lvert f_{e\tau} f_{ee}^* \rvert < 0.009 \left(\frac{m_{\kappa^{++}}}{\mathrm{TeV}}\right)^2$	$\lvert f_{ee}^* f_{\tau\tau} \rvert \lesssim 7.8 \times 10^{-6} \left(\frac{m_{\kappa^{++}}}{\mathrm{TeV}}\right)^2$
$\mathrm{BR}(\tau^- \to e^+e^-\mu^-) < 1.8 \times 10^{-8}$	$\lvert f_{e\tau} f_{e\mu}^* \rvert < 0.005 \left(\frac{m_{\kappa^{++}}}{\mathrm{TeV}}\right)^2$	$\lvert f_{e\mu}^* f_{\tau\tau} \rvert \lesssim 4.3 \times 10^{-6} \left(\frac{m_{\kappa^{++}}}{\mathrm{TeV}}\right)^2$
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$\mathrm{BR}(\mu \to e\gamma) < 5.7 \times 10^{-13}$	$\lvert f_{ee}^* f_{e\mu} + f_{e\mu}^* f_{\mu\mu} + f_{e\tau}^* f_{\mu\tau} \rvert^2 < 1 \times 10^{-7} \left(\frac{m_{\kappa^{++}}}{\mathrm{TeV}}\right)^4$	$\lvert f_{\tau\tau} \rvert \lesssim 1.2 \times 10^{-4} \left(\frac{m_{\kappa^{++}}}{\mathrm{TeV}}\right)$

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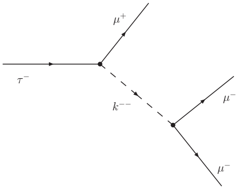

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Corrrelations of BR fixed by ν oscillation data

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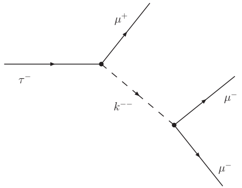

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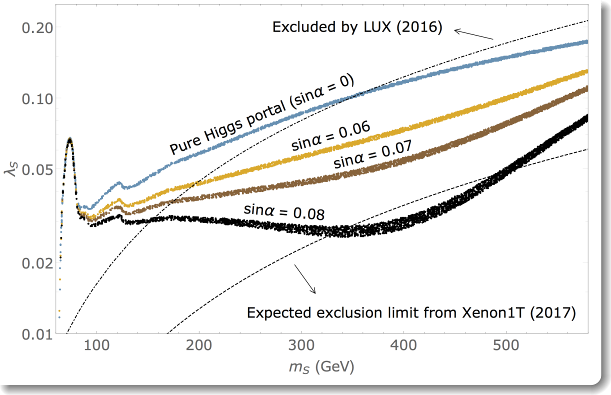
$\mathrm{BR}(\tau^- \to e^+e^-e^-) < 2.7\times10^{-8}$	$\lvert f_{e\tau} f_{ee}^*\rvert < 0.009 \left(\frac{m_{\kappa^{++}}}{\mathrm{TeV}}\right)^2$	$\lvert f_{ee}^* f_{\tau\tau}\rvert \lesssim 7.8\times10^{-6} \left(\frac{m_{\kappa^{++}}}{\mathrm{TeV}}\right)^2$
$\mathrm{BR}(\tau^- \to e^+e^-\mu^-) < 1.8\times10^{-8}$	$\lvert f_{e\tau} f_{e\mu}^*\rvert < 0.005 \left(\frac{m_{\kappa^{++}}}{\mathrm{TeV}}\right)^2$	$\lvert f_{e\mu}^* f_{\tau\tau}\rvert \lesssim 4.3\times10^{-6} \left(\frac{m_{\kappa^{++}}}{\mathrm{TeV}}\right)^2$
$\mathrm{BR}(\tau^- \to e^+\mu^-\mu^-) < 1.7\times10^{-8}$	$\lvert f_{e\tau} f_{\mu\mu}^*\rvert < 0.007 \left(\frac{m_{\kappa^{++}}}{\mathrm{TeV}}\right)^2$	$\lvert f_{\tau\tau}\rvert \lesssim 1.4\times10^{-4} \left(\frac{m_{\kappa^{++}}}{\mathrm{TeV}}\right)$
$\mathrm{BR}(\mu \to e\gamma) < 5.7\times10^{-13}$	$\lvert f_{ee}^* f_{e\mu} + f_{e\mu}^* f_{\mu\mu} + f_{e\tau}^* f_{\mu\tau}\rvert^2 < 1\times10^{-7} \left(\frac{m_{\kappa^{++}}}{\mathrm{TeV}}\right)^4$	$\lvert f_{\tau\tau}\rvert \lesssim 1.2\times10^{-4} \left(\frac{m_{\kappa^{++}}}{\mathrm{TeV}}\right)$

Corrrelations of BR fixed by ν oscillation data

LHC

- $\kappa^{--} \to \ell_a \ell_b$ Easily produced and detected.
  BR fixed by ν oscilaton data
- χ^{--}, χ^- easily produced.
  Interesting phenomenology because the discrete symmetry; have to decay into DM.

Dark Matter (Singlet-triplet scalar Higgs portal)



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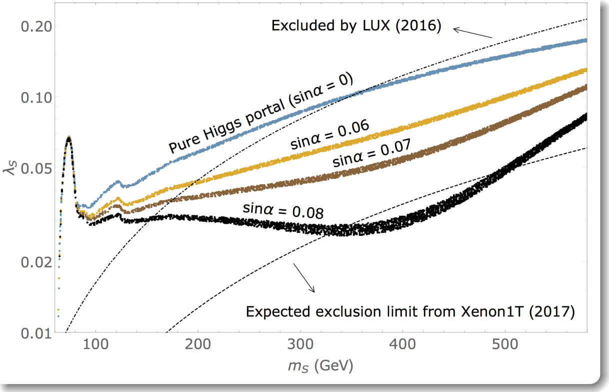

- Adjust the relic density with the mixing singlet-triplet
- Connection with neutrino masses

$$\lambda_6 = \frac{\sin 2\alpha}{\sqrt{2}v^2}\left(m_H^2 - m_S^2\right)$$

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Can be tested NOW!

BACKUP SLIDES

An example of HLFV–LFV correlations