Lepton Flavor Violating Processes in the Left-Right Symmetric Model

de Blas, JLH, Reuter, Rizzo 1806.ASAP

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U.S. DEPARTMENT OF ENERGY
Office of Science

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Left-Right Symmetric Model Basics

$G_{EW} = SU(2)_L \times SU(2)_R \times U(1)' \rightarrow SU(2)_L \times U(1)_Y$

Pati, Salam '74
Mohapatra, Pati '75

- Right-handed neutrinos
- New gauge fields
  - » W_R & Z_R with couplings $\kappa = g_R/g_L$
- New Higgs fields with vev v_R
  - » Doublet Higgs:
    - Dirac neutrinos
    - Strong constraints from $W_R \rightarrow l\nu$ LHC searches (5.2 TeV for κ=1)
  - » Triplet Higgs: $(\Delta_L^{\pm}, \Delta_{R,L}^{\pm\pm})$
    - Majorana right-handed neutrinos w/ mass N_l ~ mass W_R
    - $W_R \rightarrow lN_l$ avoided if mass N_l > mass W_R
    - U(1)' can be identified as $U(1)_{B-L}$
  - » Bi-Doublet Higgs to generate fermion masses with vevs $k_{1,2}$
- Right-handed CKM, PMNS matrix

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Bounds from Direct LHC Searches: $W_R \rightarrow N_R l$ Channel

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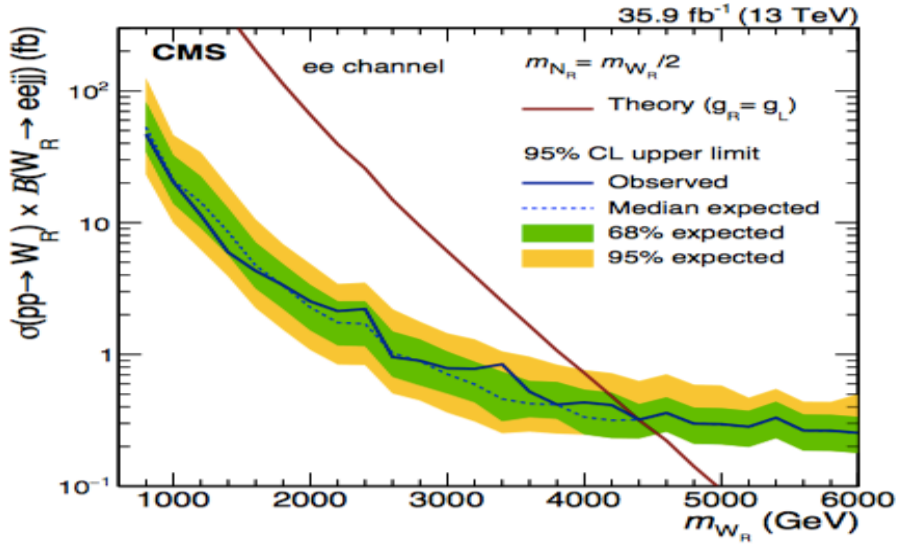

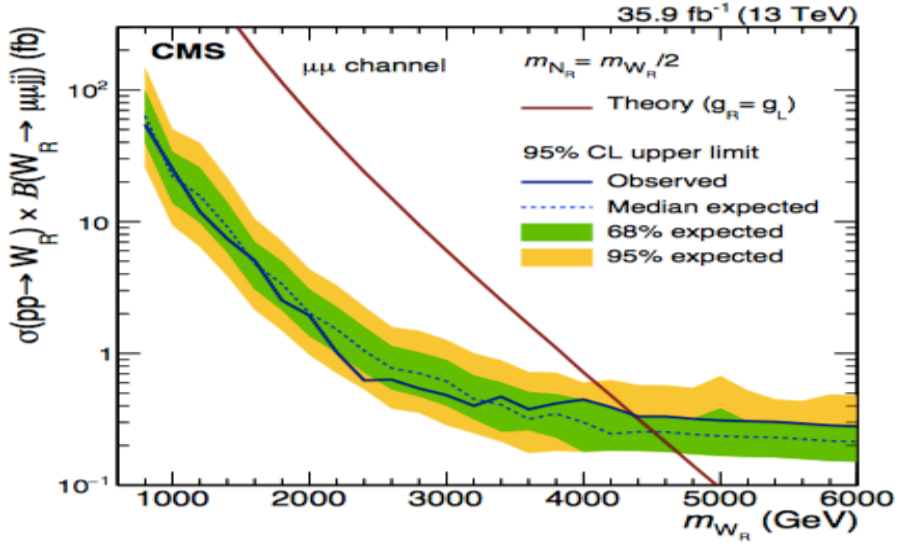

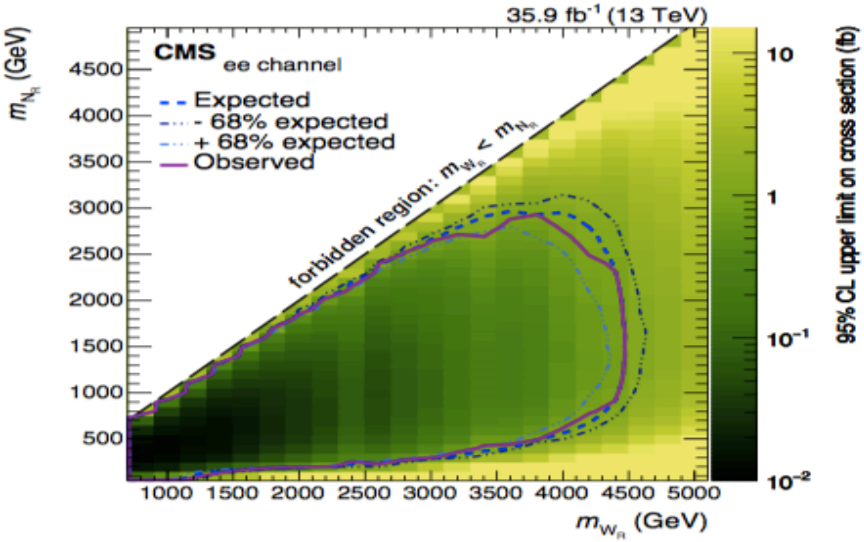

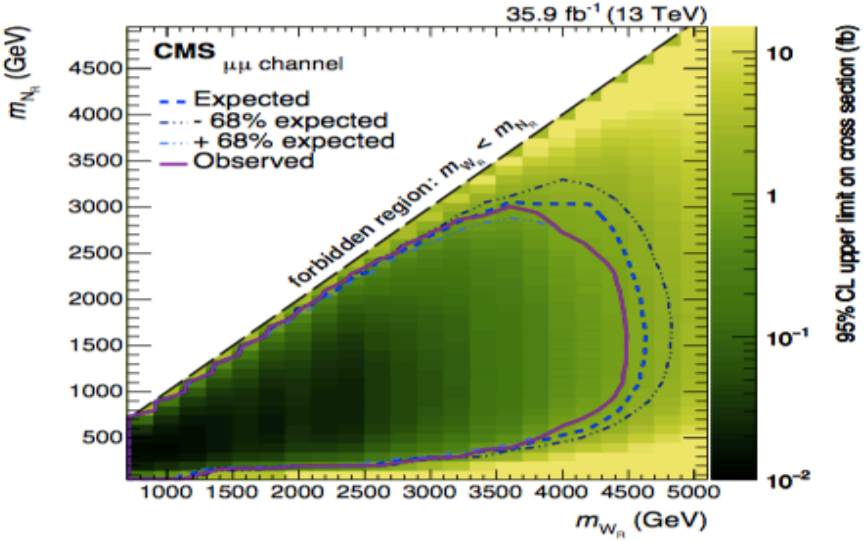

Right-handed gauge sector

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- W_L – W_R mass matrix

$$\mathcal{M}_{\mathcal{W}^2} = \begin{pmatrix} m_W^2 & \beta_w m_W^2 \\ \beta_w m_W^2 & m_{W_R}^2 \end{pmatrix}$$

- Diagonalized by mixing

$$\tan 2\phi_w = \frac{-2\beta_w m_W^2}{m_{W_R}^2 - m_W^2}$$

- W_R/Z_R mass ratio set by theory

$$\frac{m_{Z_R}^2}{m_{W_R}^2} = \frac{\kappa^2(1-x_w)\rho_R}{\kappa^2(1-x_w) - x_w} > 1$$

where κ > 0.55 is physical region

- Lepton Yukawa couplings to triplet Higgs

$$y_R \left[(\Delta_R^0 + \frac{v_R}{\sqrt{2}})\, \overline{N^c} P_R N + \frac{\Delta_R^+}{\sqrt{2}}\, \overline{N} P_R \ell + \frac{\Delta_R^{++}}{2}\, \overline{\ell^c} P_R \ell \right] + \text{h.c.}\,,$$

$$(h_R)_{ij} = \sum_n (V_R)_{ni}\, (V_R)_{nj}\, \frac{M_{N_n}}{M_{W_R}}$$

$$\mathcal{L}_{\Delta^\pm \nu \ell} = \frac{g_L \kappa}{\sqrt{2}} \left\{ \tilde{h}_{ij}\, \Delta_L^+\, \overline{\nu_L^{i\,c}}\, \ell_L^j + \text{h.c.} \right\},$$

$$\mathcal{L}_{\Delta^{\pm\pm} \ell\ell} = \frac{g_L \kappa}{2} h_{ij} \left\{ \Delta_L^{++}\, \overline{\ell_L^{c\,i}}\, \ell_L^j + \Delta_R^{++}\, \overline{\ell_R^{c\,i}}\, \ell_R^j + \text{h.c.} \right\}$$

Scan of parameter space

- Perform a scan of parameter space, two distinct model sets
  - » Gauge sector parameters
    - Fix W_R mass = 5, 10 TeV,
    - $\kappa = 1$,
    - $V_{CKM}{}^R = V_{CKM}{}^L$
  - » Right-handed neutrinos
    - assign $m_1 < m_2 < m_3$ w/ signed $m_{2,3}$

$$100\ \text{GeV} \leq M_{N_R^i} \leq 20\ \text{TeV}.$$

  - » Right-handed PMNS matrix

$$0 \leq s_{12}, s_{13}, s_{23} \leq 1$$

  - » Charged scalars $\Delta_L{}^{\pm}$, $\Delta_{R,L}{}^{\pm\pm}$

$$400\ \text{GeV} \lesssim M_{\Delta_L^{\pm},\ \Delta_{L,R}^{\pm\pm}} \leq 20\ \text{TeV}. \qquad 0.5 \leq \tan\beta \leq 50$$

Generated 3×10^8 models per set

Consistency with current LFV/LNV constraints

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Subject parameter space to constraints:

Rare processes: 0νββ, μ➔eγ, τ➔lγ, μ➔eee, τ➔lll', μ➔e conversion

Muonium oscillations

Observable	Experimental bound		Future limit	
$B(\mu^- \to e^-\gamma)$	$< 4.2 \times 10^{-13}$	[72]	$< 6 \times 10^{-14}$	[96]
$B(\tau^- \to \mu^-\gamma)$	$< 4.4 \times 10^{-8}$	[73]	$< 10^{-9}$	[86]
$B(\tau^- \to e^-\gamma)$	$< 3.3 \times 10^{-8}$	[73]	$< 10^{-9}$	[86]
$B(\mu^- \to e^-e^+e^-)$	$< 10^{-12}$	[74]	$< 10^{-15} - 10^{-16}$	[95]
$B(\tau^- \to e^-e^+e^-)$	$< 2.7 \times 10^{-8}$	[75]	$< 10^{-9} - 10^{-10}$	[86]
$B(\tau^- \to \mu^-\mu^+\mu^-)$	$< 2.1 \times 10^{-8}$	[75]	$< 10^{-9} - 10^{-10}$	[86]
$B(\tau^- \to e^-\mu^+\mu^-)$	$< 2.7 \times 10^{-8}$	[75]	$< 10^{-9} - 10^{-10}$	[86]
$B(\tau^- \to e^+\mu^-\mu^-)$	$< 1.7 \times 10^{-8}$	[75]	$< 10^{-9} - 10^{-10}$	[86]
$B(\tau^- \to \mu^-e^+e^-)$	$< 1.8 \times 10^{-8}$	[75]	$< 10^{-9} - 10^{-10}$	[86]
$B(\tau^- \to \mu^+e^-e^-)$	$< 1.5 \times 10^{-8}$	[75]	$< 10^{-9} - 10^{-10}$	[86]
$CR(\mu^- \to e^-)$ [Au]	$< 7 \times 10^{-13}$	[76]		
$CR(\mu^- \to e^-)$ [Ti]	$< 4.3 \times 10^{-12}$	[77]	$< 10^{-18}$	[84, 85]
$CR(\mu^- \to e^-)$ [Pb]	$< 4.6 \times 10^{-11}$	[78]		
$CR(\mu^- \to e^-)$ [Al]	–		$< 10^{-16} - 10^{-18}$	[80–85]
$P(M \to \overline{M})$	$< 8.2 \times 10^{-11}$	[79]		
$T_{1/2}^{\beta\beta 0\nu}$ [^{136}Xe]	$> 1.07 \times 10^{26}$ yr	[89]		
($\langle m_{ee} \rangle$	$< 61 - 165$ meV		< 3-12 meV)	[92, 93]

Note large improvement in future expt's!!

Consistency with Lepton Flavor Conserving Processes

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- Subject parameter space to LFC constraints
  - » e^+e^- ➔ l^+l^- from LEP2, cross sections and asymmetries
  - » Low-energy parity-violating asymmetry in Moller scattering
  - » Neutrino-electron scattering observables
  - » Muon decay
- 4-Fermion interaction

$$\mathcal{L}_{\rm Eff} \supset a_\ell \frac{g_R^2}{4} \frac{|h_{e\ell}|^2}{M^2_{\Delta_\alpha^{\pm\pm}}} (\overline{e_\alpha}\gamma^\mu e_\alpha)(\overline{\ell_\alpha}\gamma^\mu \ell_\alpha), \qquad \alpha = L, R,$$

- Surviving model set after LFV/LNV & LFC Constraints:
  - » 6.6 x 10^5 models; M_{W_R} = 5 TeV
  - » 2.7 x 10^6 models; M_{W_R} = 10 TeV

Distribution of Models

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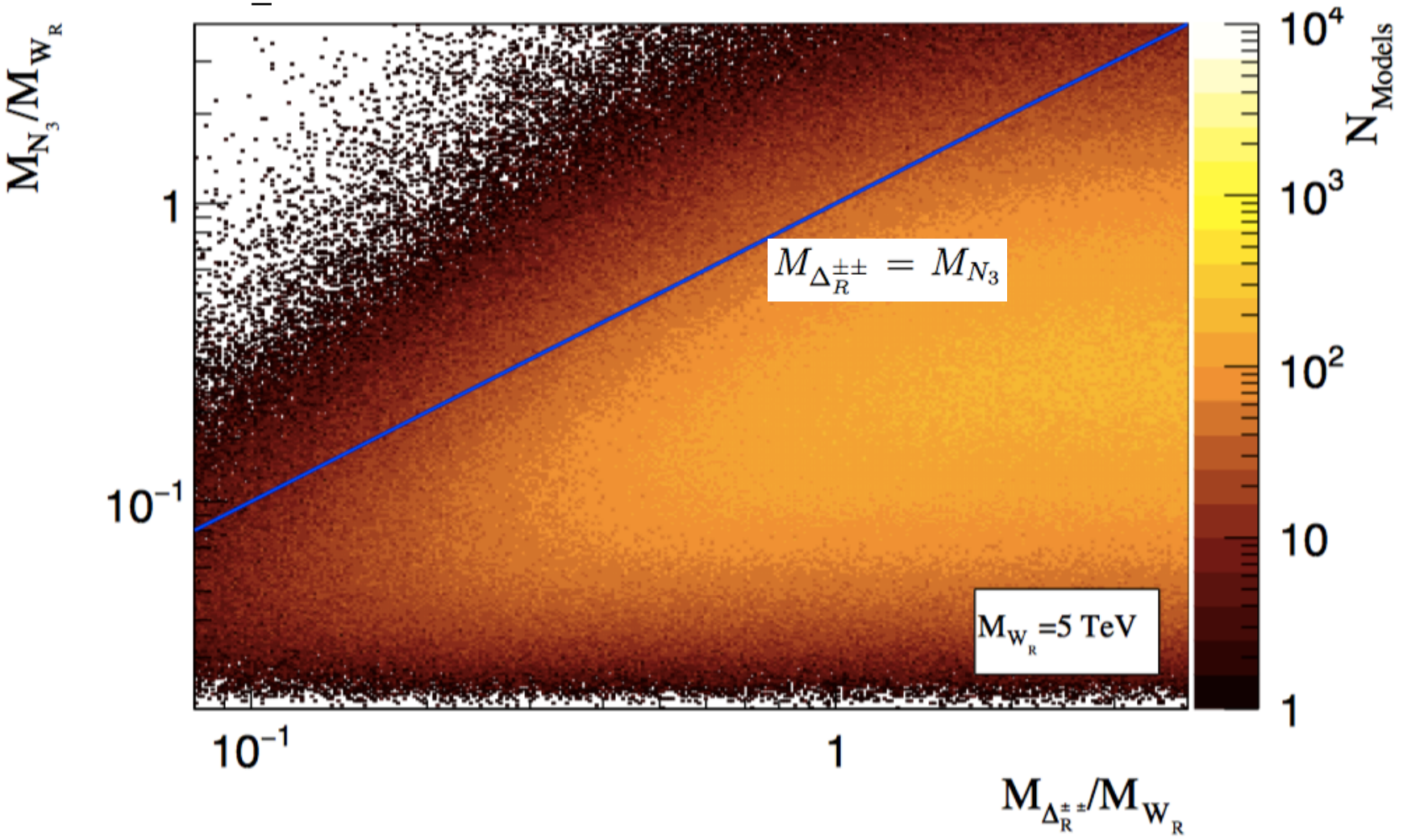
M_{W_R} = 5 TeV



Neutrinoless double-beta decay

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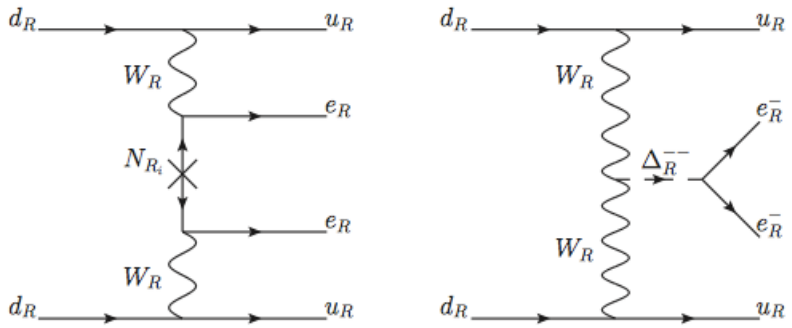
- Current limits in Ge^{76} and Xe^{136} (Gerda, EXO-200, Kamland-Zen)
- Probes effective Majorana neutrino mass

$$|m_{ee}|^2 = |m_{ee_L}|^2 + |m_{ee_R}|^2$$

- Tree-level LNV diagrams with N and $\Delta_R^{\pm\pm}$ exchange



$$x_i = M_{N_i}^2 / M_{W_R}^2$$

$$x_{\Delta_R^{\pm\pm}} \equiv M_{\Delta_R^{\pm\pm}}^2 / M_{W_R}^2$$

$$\eta_R = \frac{m_p}{M_{W_R}} \left(\frac{\kappa M_W}{M_{W_R}}\right)^4 \sum_i (sign)_i \, V_{ei}^2 \left(\frac{1}{\sqrt{x_i}} + \frac{\sqrt{x_i}}{x_{\Delta_R^{\pm\pm}}}\right)$$

Neutrinoless Double-Beta Decay Results

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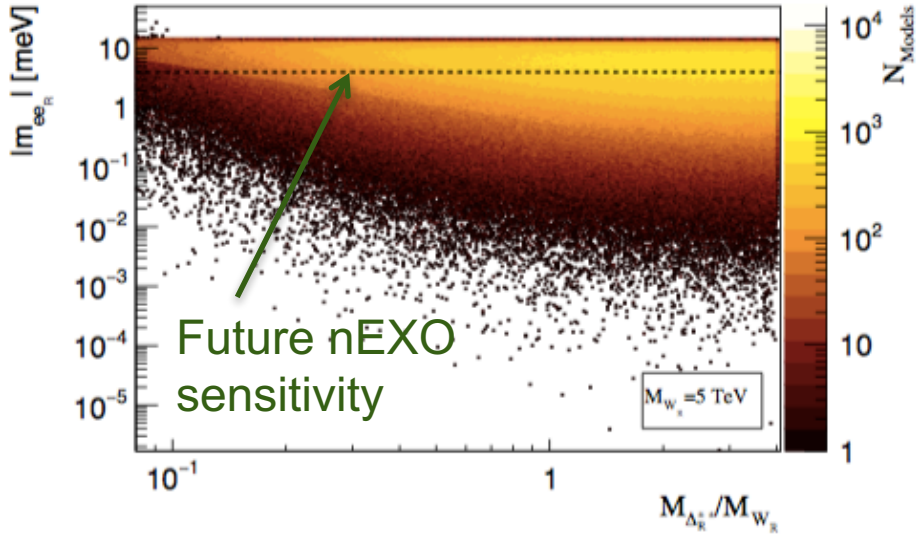

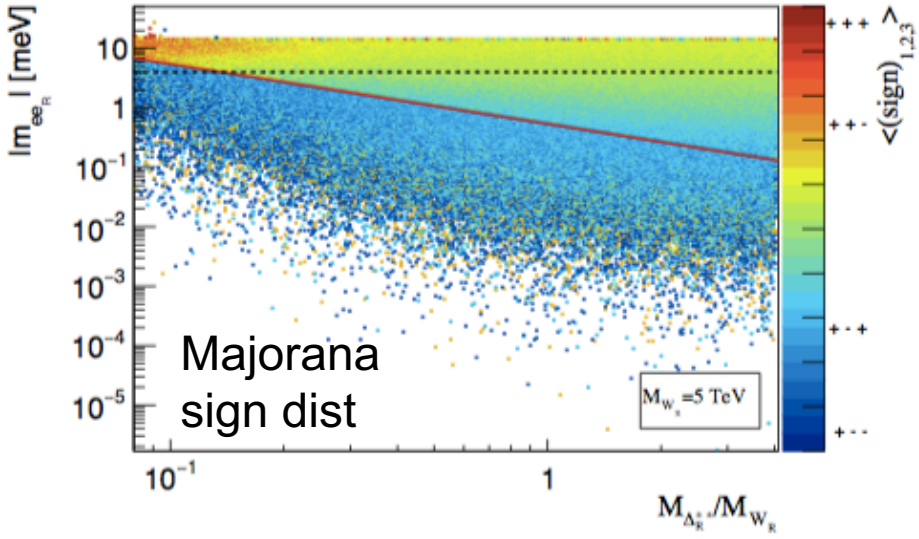

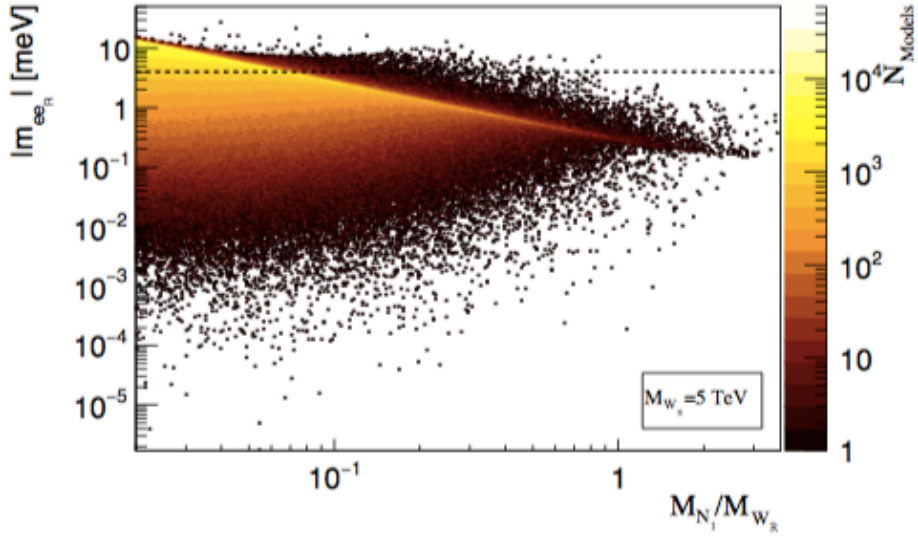

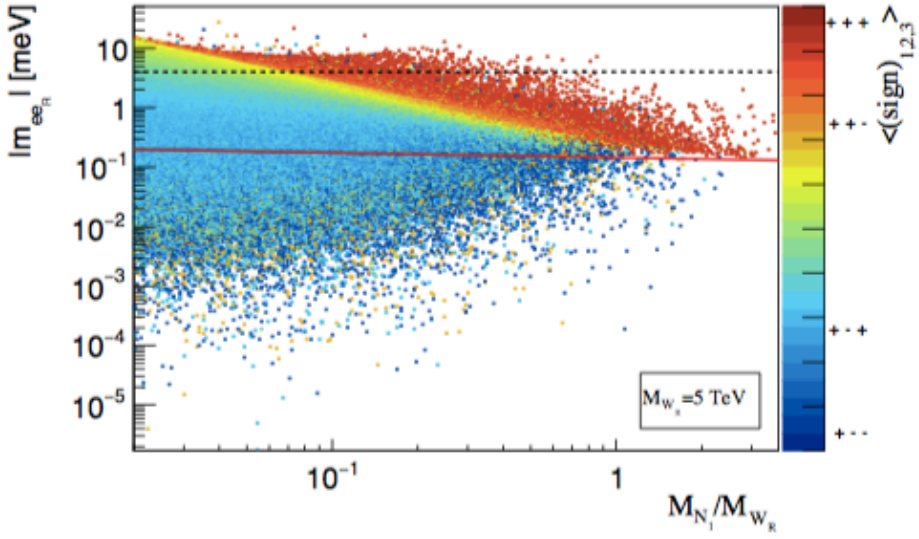

Neutrinoless double-beta decay: histogram of predictions

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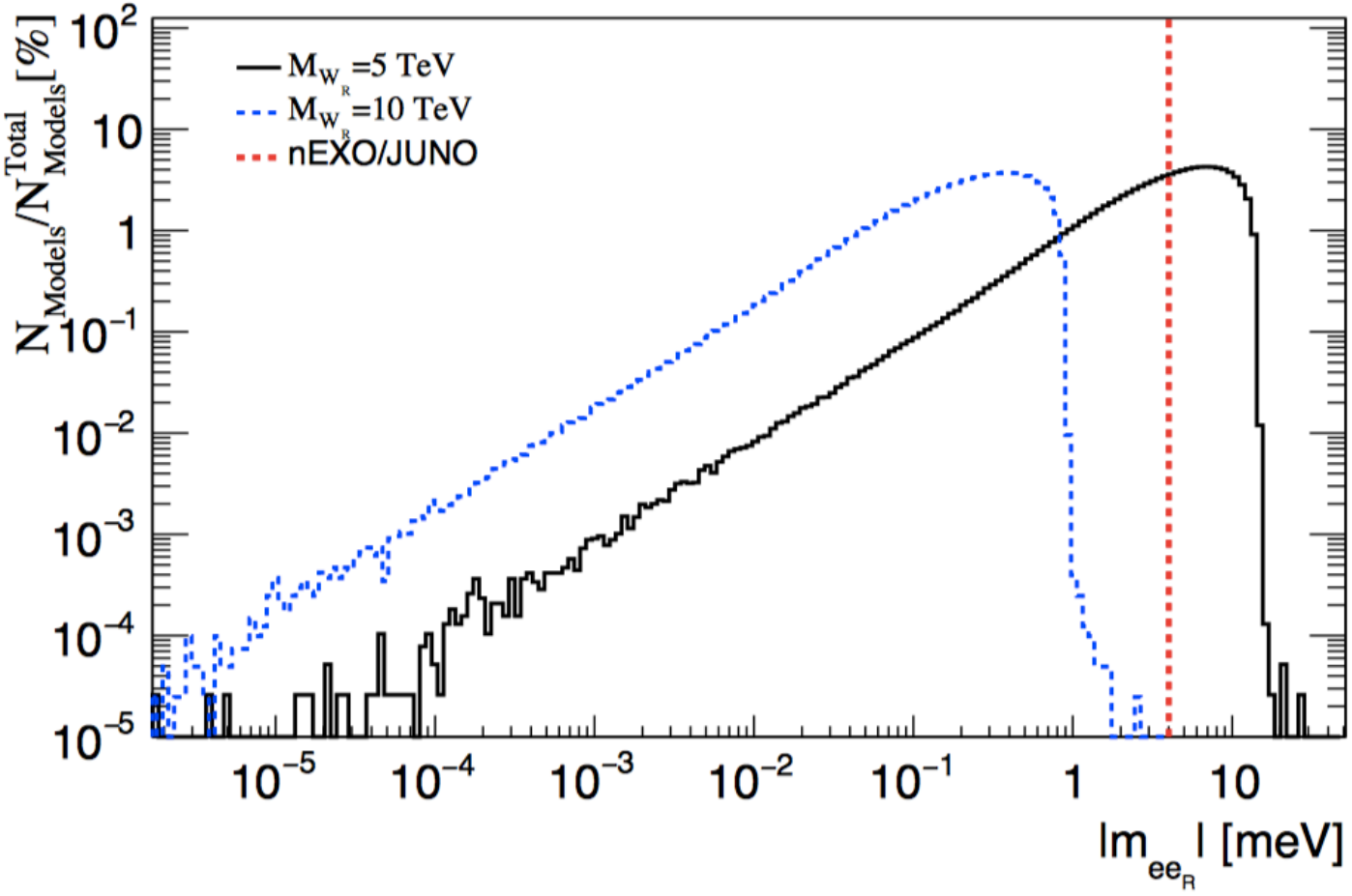
0νββ has sensitivity to M_{W_R} = 5 TeV



Mu2e conversion (μN ➔ eN)

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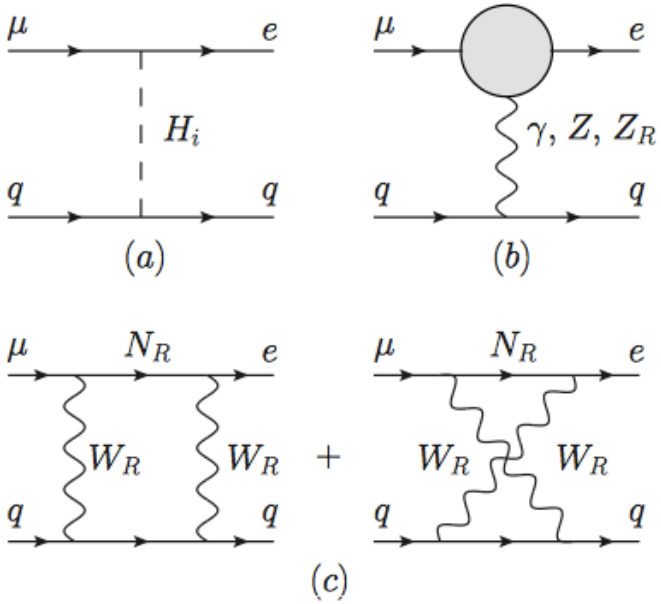
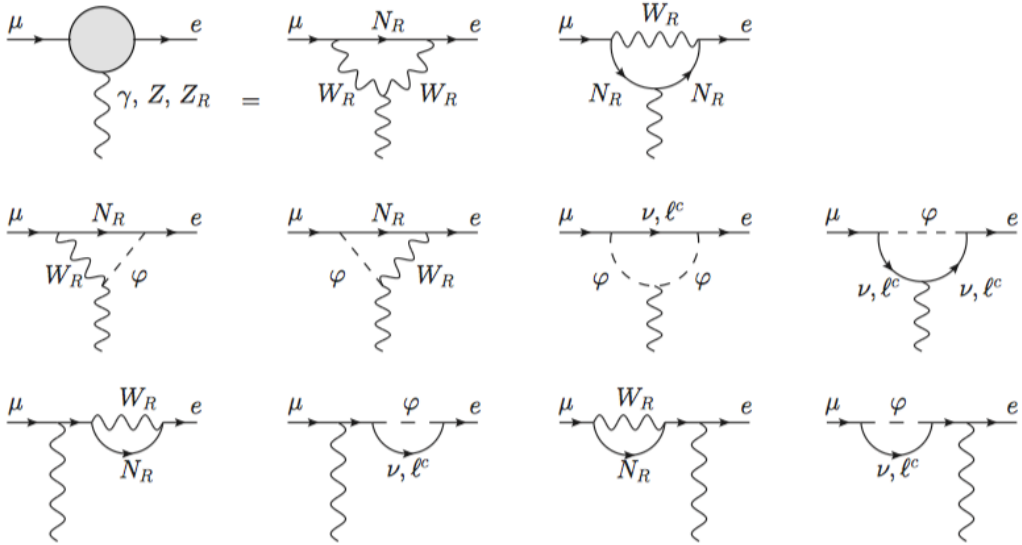
- Current limits for Pb, Ti, Au (SINDRUM II)
- LRM contributions
  - » Tree-level neutral Higgs exchange (small) $y_D/(\alpha/4\pi) \ll 1$
  - » 1-loop W_R, $\Delta_L^{\pm}$, $\Delta_{R,L}^{\pm\pm}$ exchange to anapole/dipole vertices
    - Log enhanced $\sim \log(-q^2/M^2_{\Delta^{\pm\pm}_{L,R}})$
  - » 1-loop W_R exchange in μeZ_i vertices
  - » 1-loop W_R box diagrams





Mu2e Conversion in Al: Results

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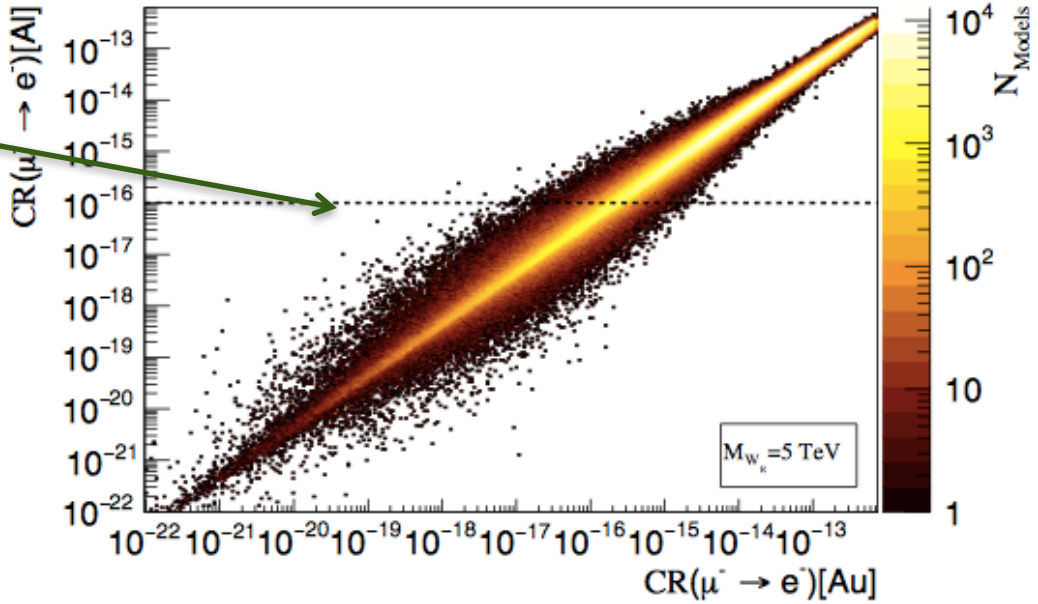
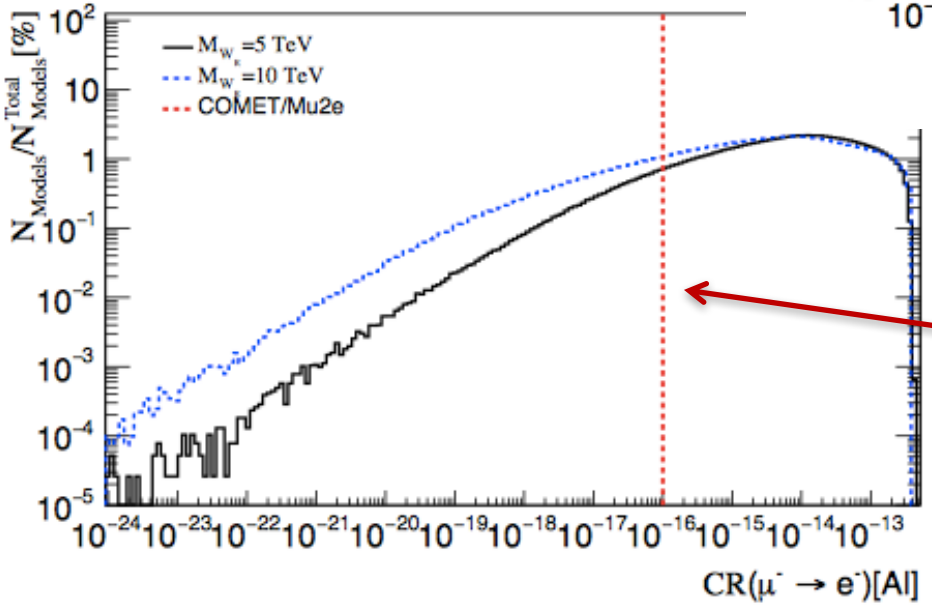
Future Mu2e/COMET sensitivity

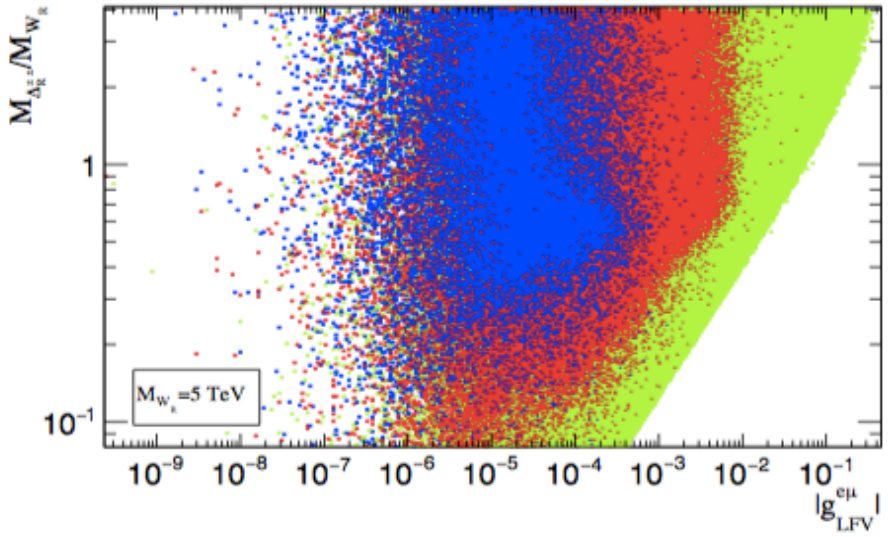


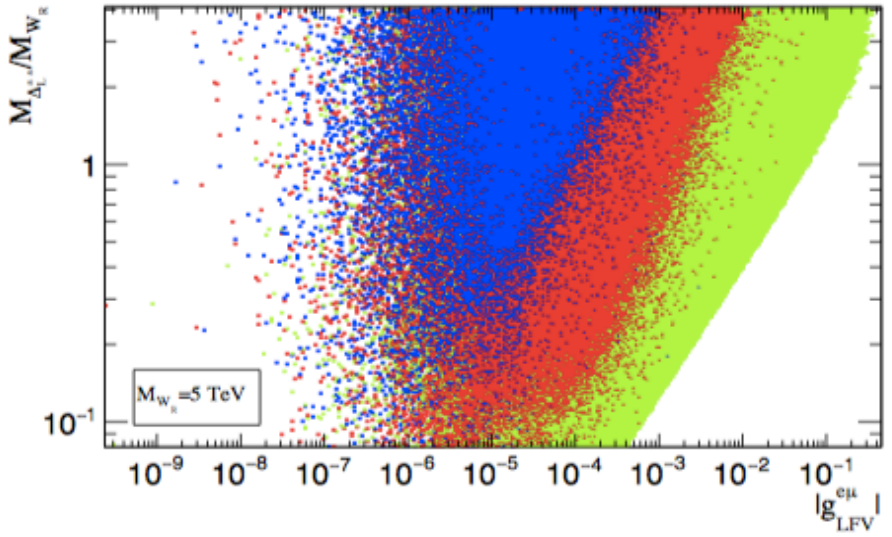
Histogram of predctions

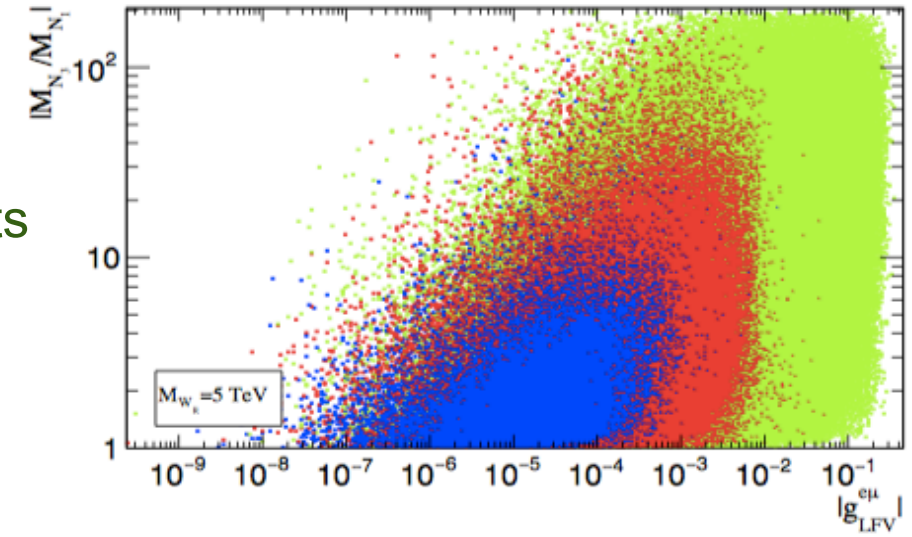


Large fraction of models covered!

Strong Constraints from Mu2e







Current Constraints

CR(μ→e) < 10^{-16}

CR(μ→e) < 10^{-18}

Rare Muon Decays

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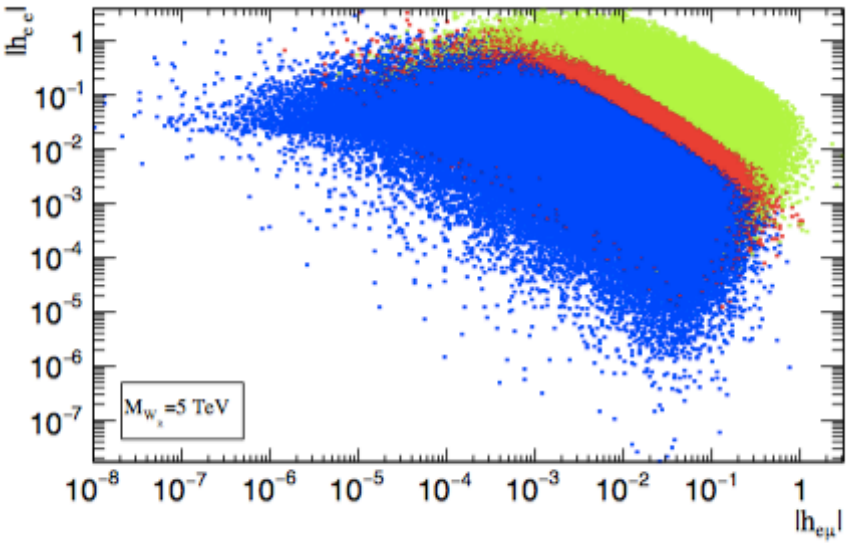
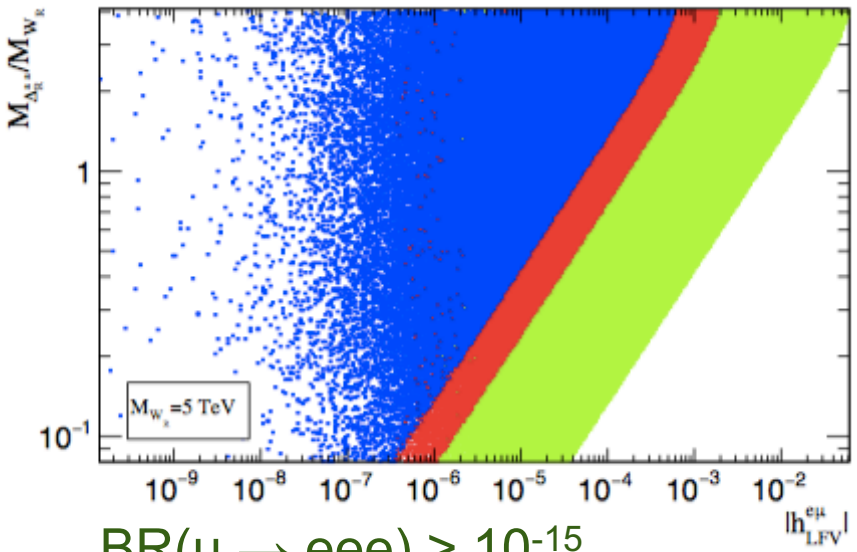
- Strong current bounds on μ➔eγ & μ➔eee (MEG, SINDRUM)
- LRM contributions to μ➔eγ
  - » 1-loop W_R exchange
  - » 1-loop $\Delta_L^{\pm}$, $\Delta_{R,L}^{\pm\pm}$ exchange
- LRM contributions to μ➔eee
  - » Leading contributions: Tree-level $\Delta_{R,L}^{\pm\pm}$ exchange

$$\mathrm{B}(\mu^- \to e^- e^+ e^-) = \frac{1}{2}\left(\frac{\kappa M_W}{M_{W_R}}\right)^4 |h_{\mu e} h_{ee}^*|^2 \left(\frac{1}{x^2_{\Delta_L^{\pm\pm}}} + \frac{1}{x^2_{\Delta_R^{\pm\pm}}}\right)$$

$$x_{\Delta_{L,R}^{\pm\pm}} = M^2_{\Delta_{L,R}^{\pm\pm}}/M^2_{W_R} \qquad (h_R)_{ij} = \sum_n (V_R)_{ni}\,(V_R)_{nj}\,\frac{M_{N_n}}{M_{W_R}}$$

μ → eee Results

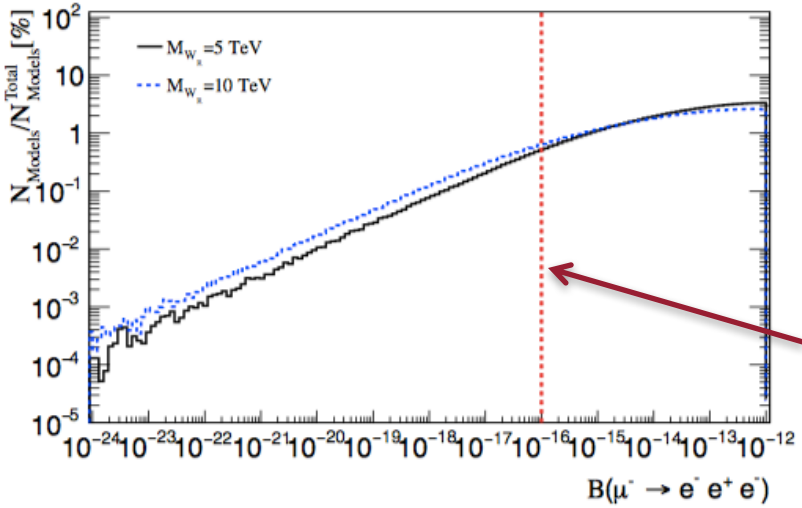




BR(μ → eee) > 10^{-15}

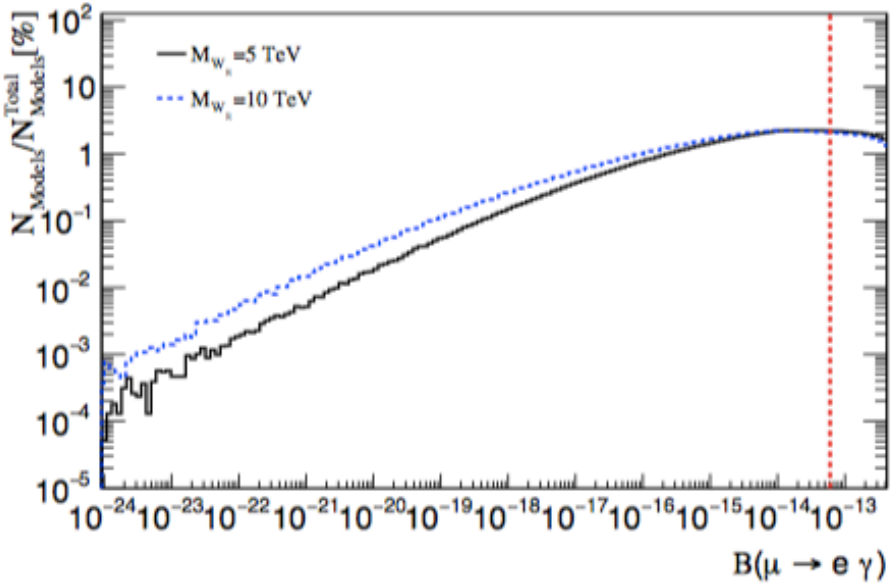
BR(μ → eee) > 10^{-16}

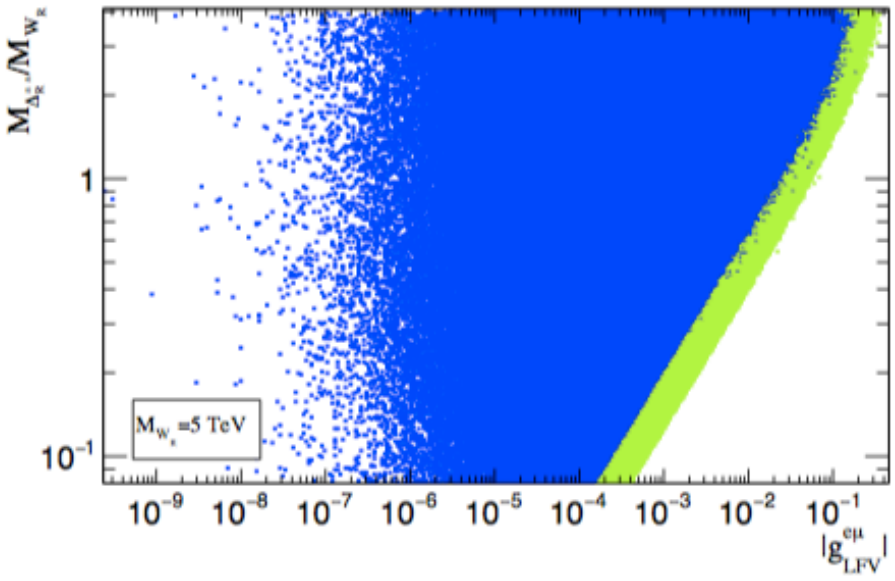
BR(μ → eee) < 10^{-16}



Mu3e would have good sensitivity

μ→ eγ Results



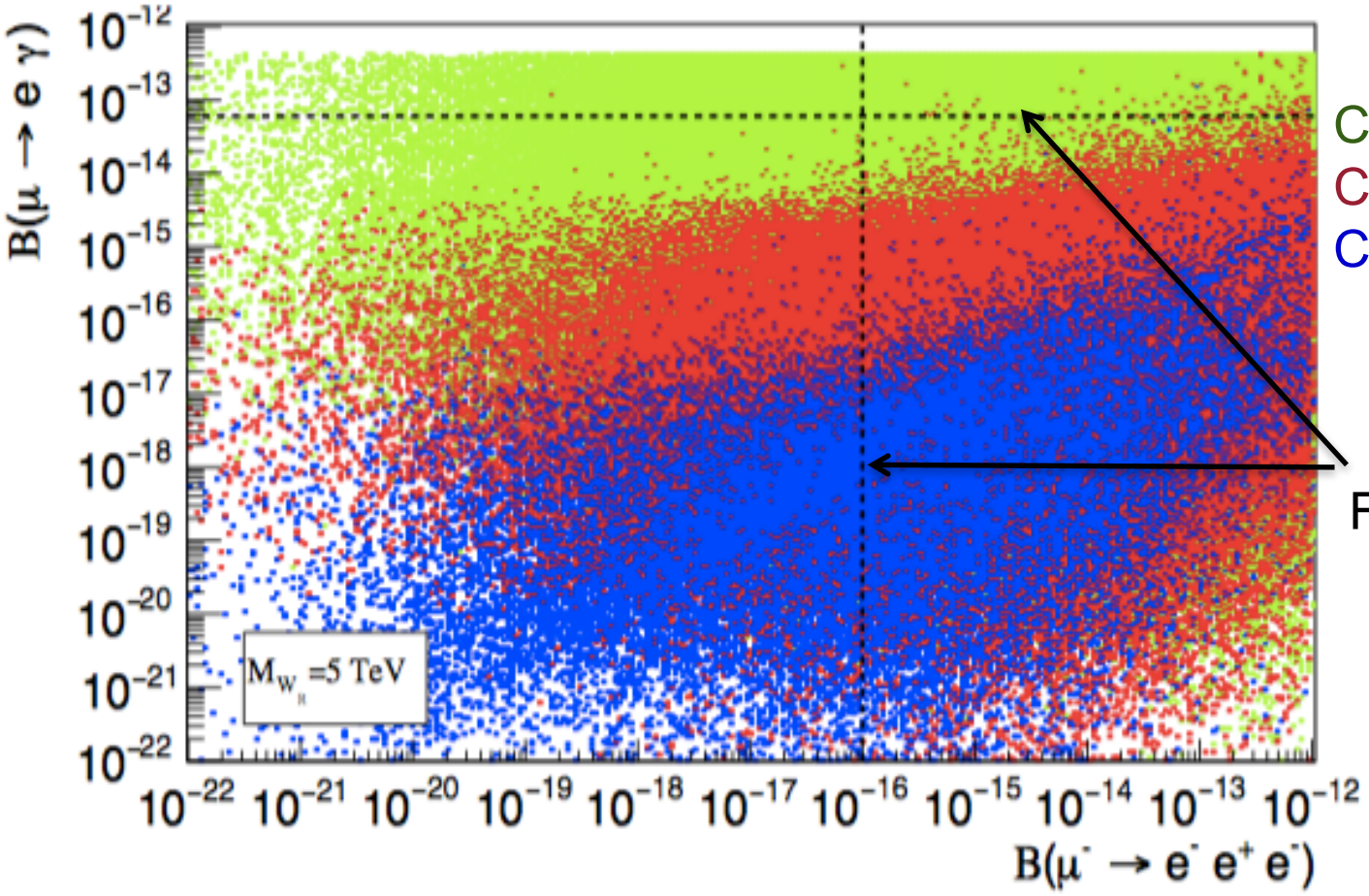


Consistent with current limits

BR(μ→ eγ) < 6 x 10^{-14}

μ→ eγ not a strong probe

Comparison of LFV in the muon sector



Current Constraints

CR(μ→e) < 10^{-16}

CR(μ→e) < 10^{-18}

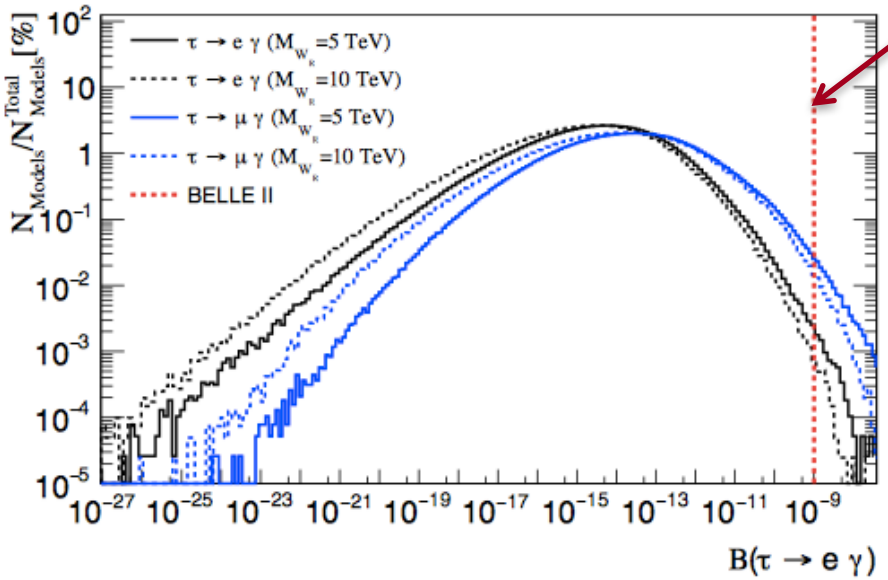
Future sensitivity

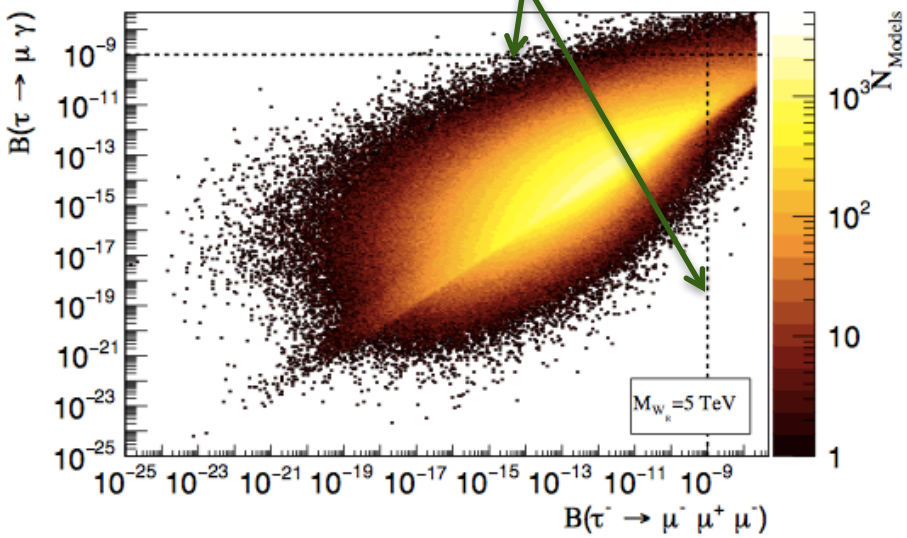
Rare tau decays

- Current limits from BaBar/Belle
- LRM contributions to $\tau \rightarrow e\gamma, \mu\gamma$
  - 1-loop W_R exchange
  - 1-loop $\Delta_L^{\pm}$, $\Delta_{R,L}^{\pm\pm}$ exchange
- LRM contributions to $\tau \rightarrow lll$
  - Tree-level $\Delta_{R,L}^{\pm\pm}$ exchange

Not much sensitivity

Future sensitivity for Belle-II, LHCb

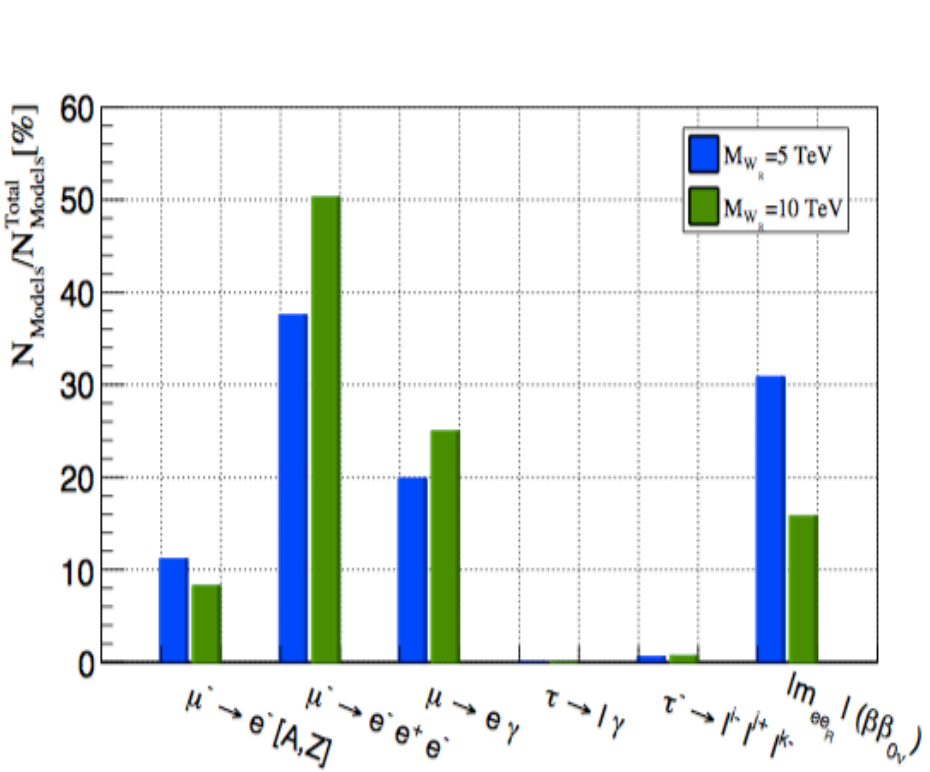




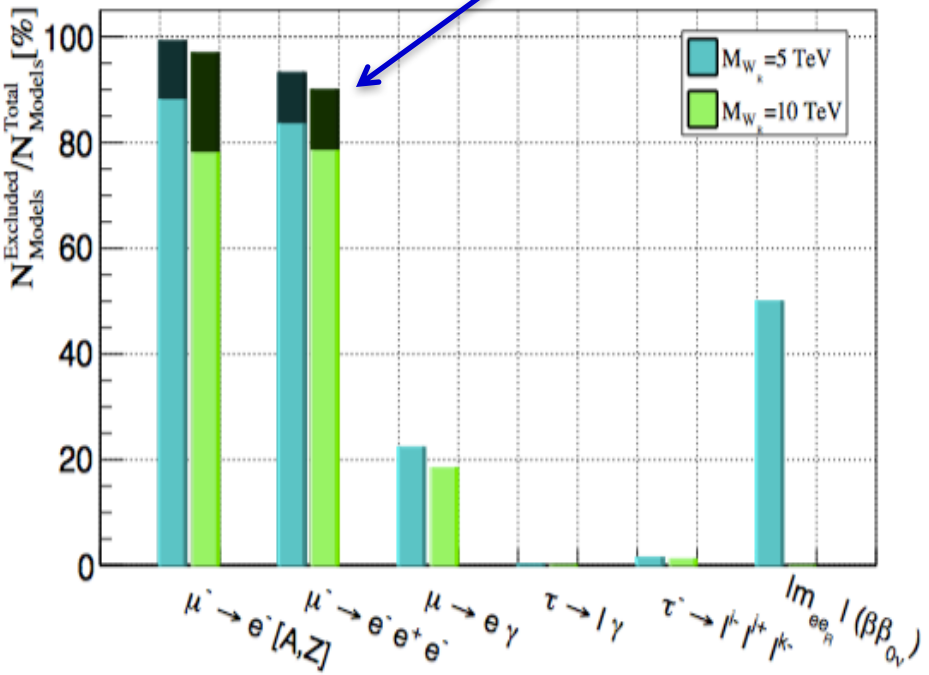
LFV Reach Comparison

- Quantify relative importance of each variable by

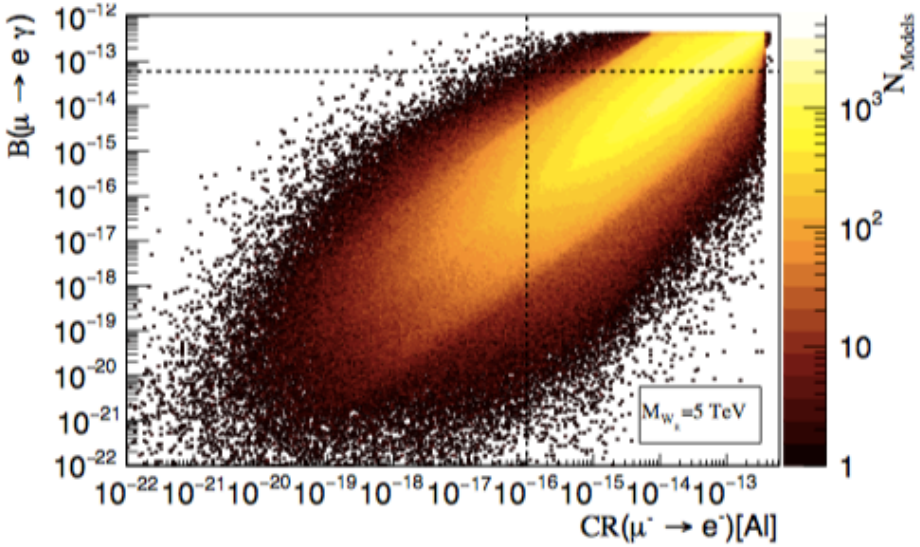
$$R_i \equiv \frac{\mathrm{B}_i}{\mathrm{B}_i^{\mathrm{exp}}}, \frac{\mathrm{CR}_i}{\mathrm{CR}_i^{\mathrm{exp}}},$$

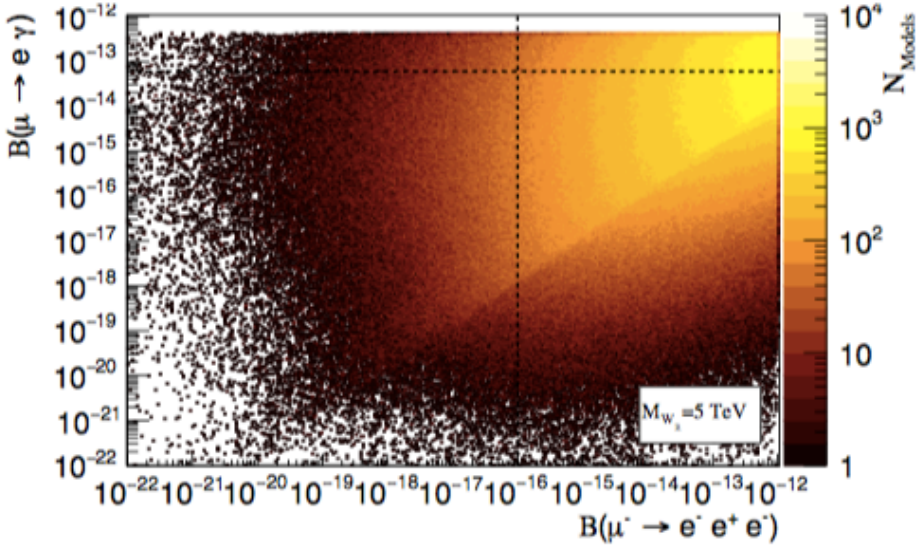


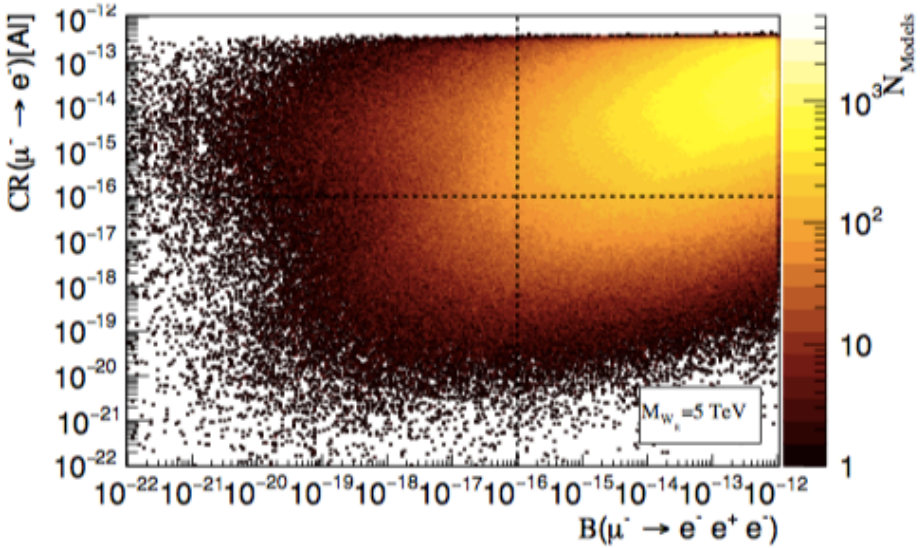
Future upgrade



Correlations Between Observables







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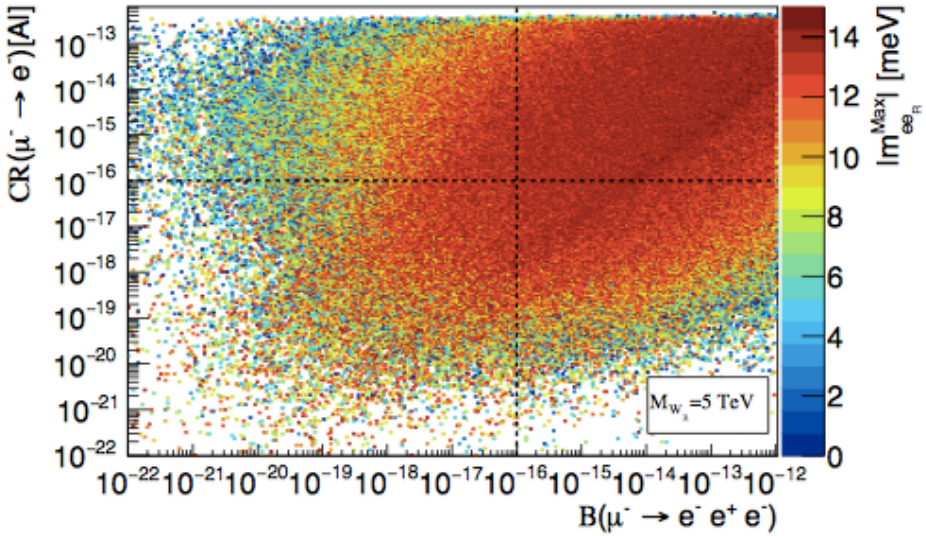

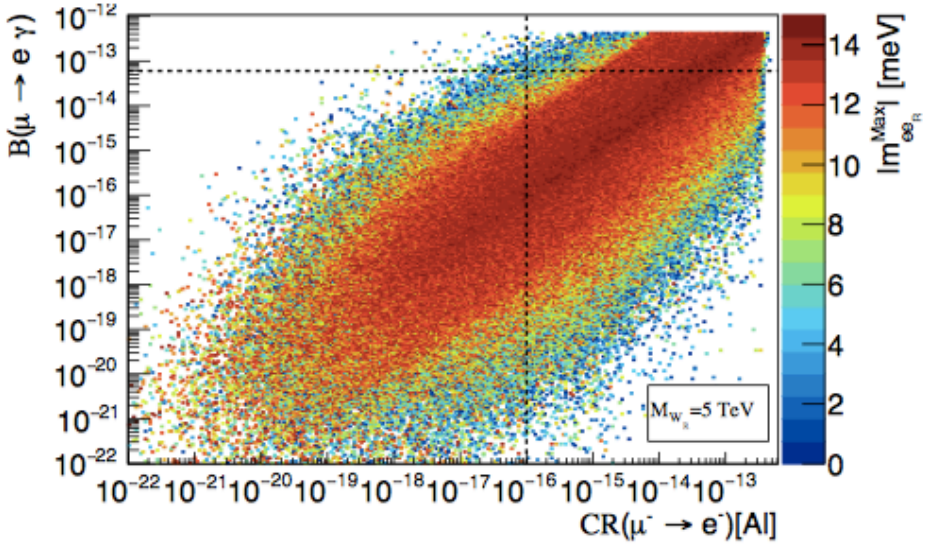

Figure 20: (Left) The maximum effective Majorana mass $|m_{ee_R}^{\mathrm{Max}}|$ in meV as a function of $\mu^- \to e^-$ [Al] and $\mu \to e^-e^+e^-$. (Right) The maximum effective Majorana mass $|m_{ee_R}^{\mathrm{Max}}|$ in meV as a function of $\mu^- \to e^-$ [Al] and $\mu \to e\gamma$. In both panels the dashed lines indicate the expected future sensitivities to each LFV observable.

Summary

- LRM is a highly predictive scenario impacts the other frontiers
- Strong influence in LFV/LNV processes
- Mu2e & $\mu \rightarrow eee$ have significant reach in this parameter space, outpassing direct collider sensitivity
- $0\nu\beta\beta$ has sensitivity to M_{W_R} = 5 TeV