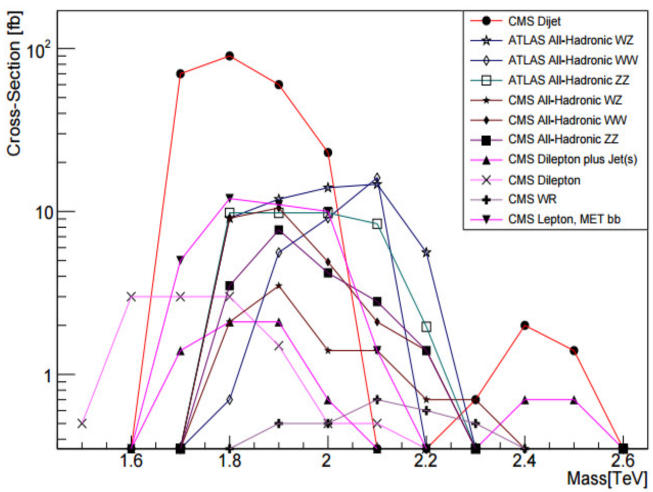
LNV & LFV in LR Models @ the TeV Scale



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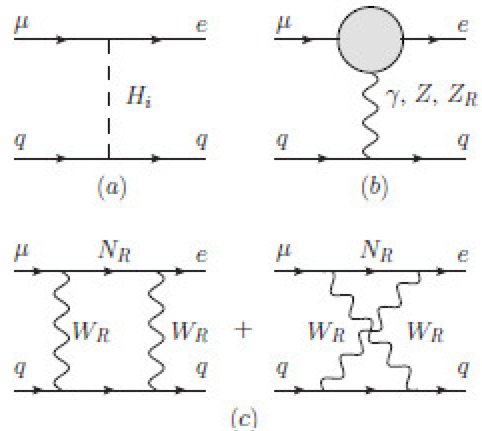

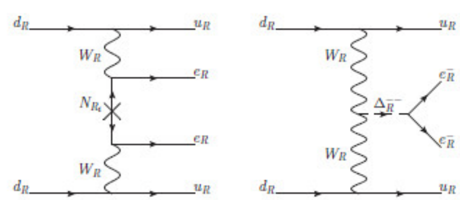

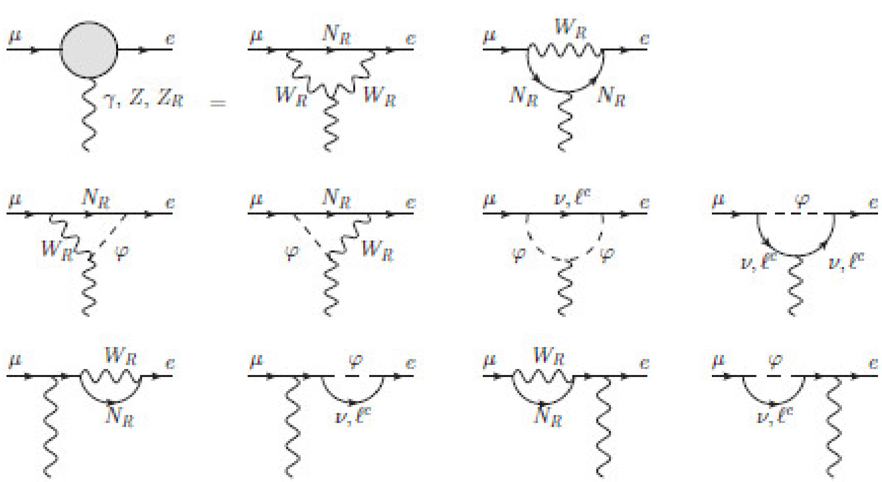

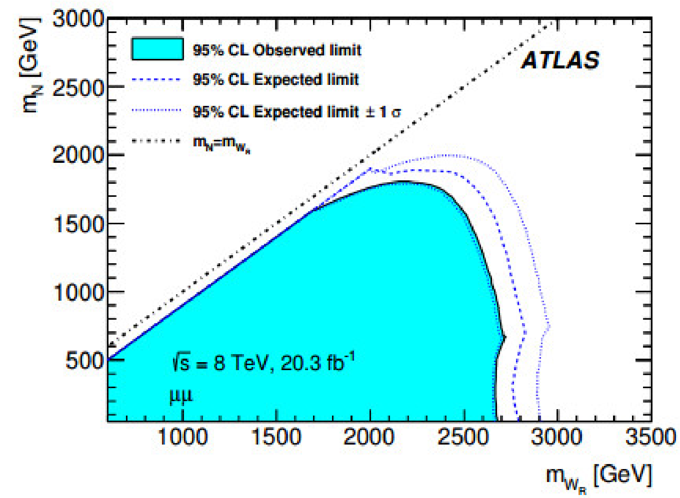

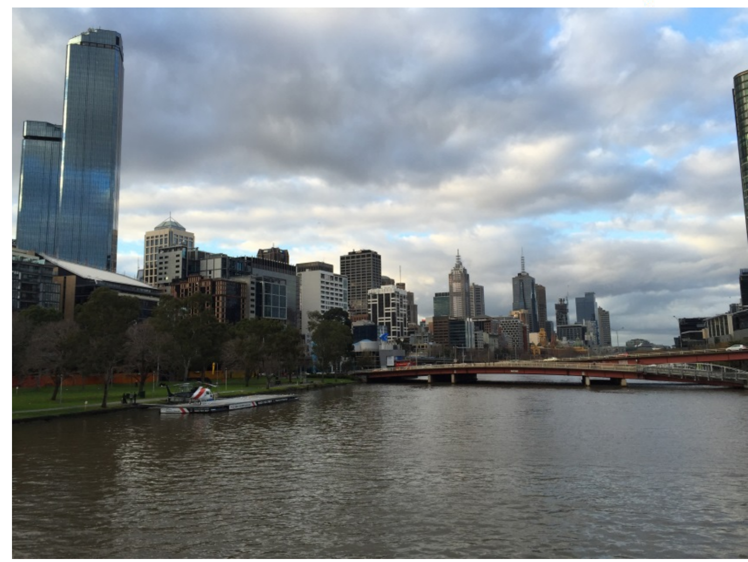

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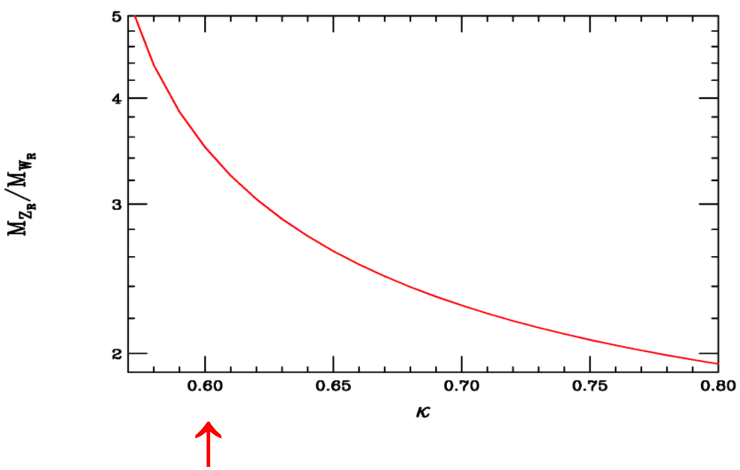
- The LR Model +RH Majorana neutrinos + Higgs triplets, broken at the ~TeV scale, has important implications for colliders & low-energy experiments, e.g., $\mu \to e$ conversion, $\mu \to 3e$, $\mu \to e\gamma$ & $\beta\beta_{0\nu}$.

- Initially motivated by the LR Model interpretation of the diboson excess, we performed 3 detailed scans over the relevant multi-dimensional parameter space.

- Fix the W_R mass & gauge coupling to specific values then scan : 3 RH neutrino masses (+2 relative Majorana signs), 3 RH neutrino mixing angles (omitting CP violation for simplicity), 2 masses of doubly-charged triplet states $\Delta_{L,R}^{++}$, 2 masses for the singly charged Higgs Δ_L^+ (triplet) & H^+ (bi-doublet) + tan β.

- The chosen ranges of the parameters depend on the scan. (see below)



Note: the Z' mass is a calculable quantity in terms of the input parameters & must satisfy LHC dilepton search constraints

- We generate (up to 10^{10}) pts in this space & compare predictions with experimental constraints from LHC, LEP, LFV, $\beta\beta_{0\nu}$, μonium-antiμonium conversion, g-2 & μ-decay -- keep only 'survivors'. (see backups for precise numerical constraints)
- Study the predictions of the (~few 10^6) model points that remain valid after applying the constraints

- We considered 3 scenarios:

(i) Motivated by the LHC di-boson excess fits: $M_R = 1.9$ TeV, $\kappa = g_R/g_L = 0.6$, $\phi_w \approx (1.0\text{-}1.5)10^{-3} \rightarrow \tan\beta \approx 1 \rightarrow$ the bi-doublet charged Higgs is decoupled.

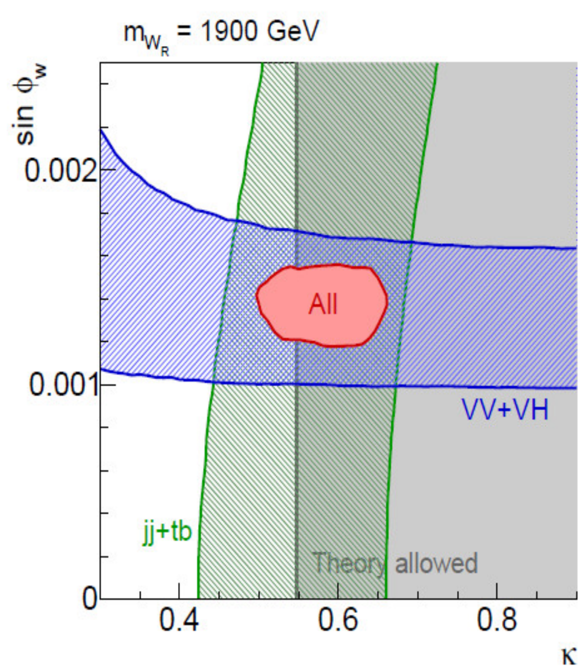
flat priors: $1 \leq m_i \equiv M_{N_i}/M_{W_R} \leq 10$ & $0 \leq s_{12}, s_{13}, s_{23} \leq 1,$

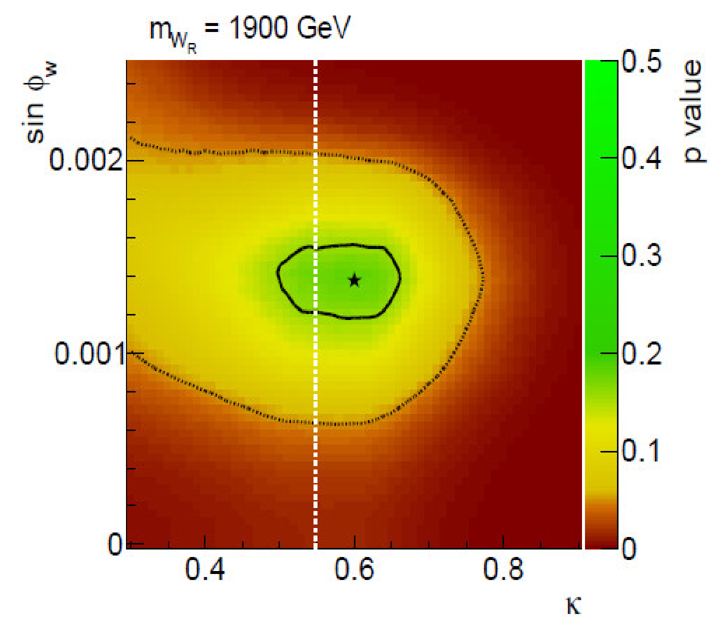
logarithmic prior

$0.2 \leq m/M_{W_R} \leq 10$

for the doubly-charged Higgs and Δ_L^+

Lower limit set by LHC searches





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(ii) & (iii) : Two more general scans w/ M_R =5(10) TeV & κ=1 taking log priors (since the ranges are large):

$100 \text{ GeV} \leq M_{N_R^i} \leq 20 \text{ TeV}.$ $\quad 0.5 \leq \tan\beta \leq 50$

$400 \text{ GeV} \lesssim M_{\Delta_L^\pm,\ \Delta_{L,R}^{\pm\pm}} \leq 20 \text{ TeV}.$ & similarly for M_H^+

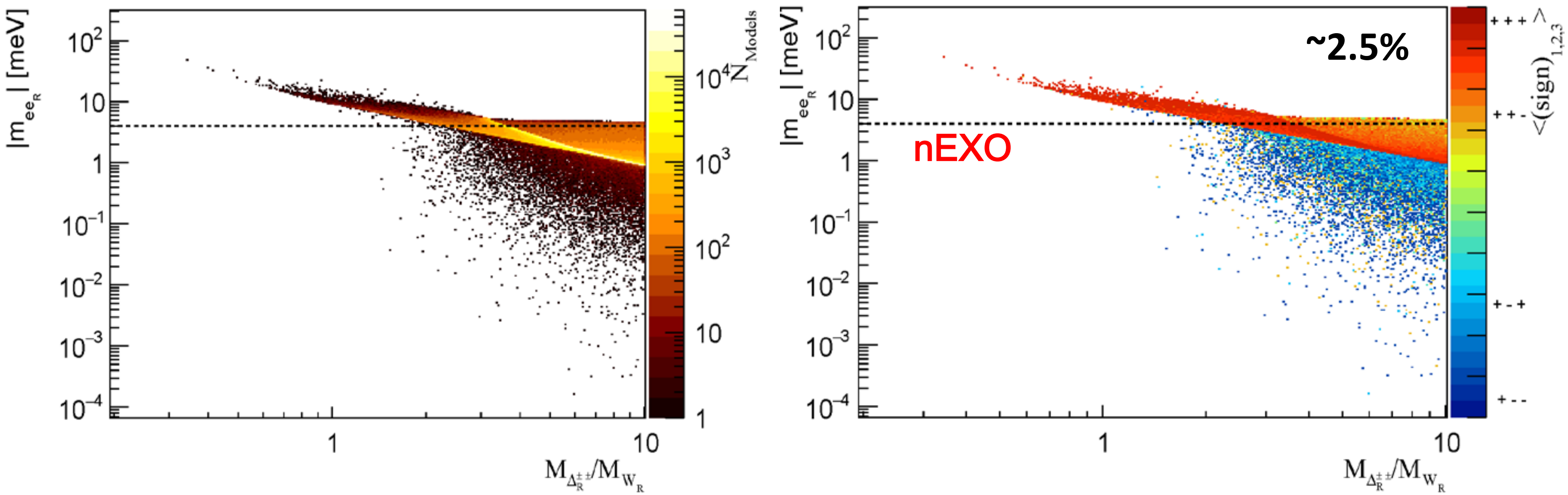
These probe W_R masses at the top of the LHC discovery range at 13/4 TeV & values beyond the reach of the LHC which remain 'phenomenologically' interesting

Given time constraints I will concentrate only on scan (i)… see paper for more details & results for the others

We'll look at one observable at a time & then compare

$\beta\beta_{0\nu}$

PURE LRM predictions (we ignore the possible incoherent LH neutrino contributions here!) …note ‘conventional’ units

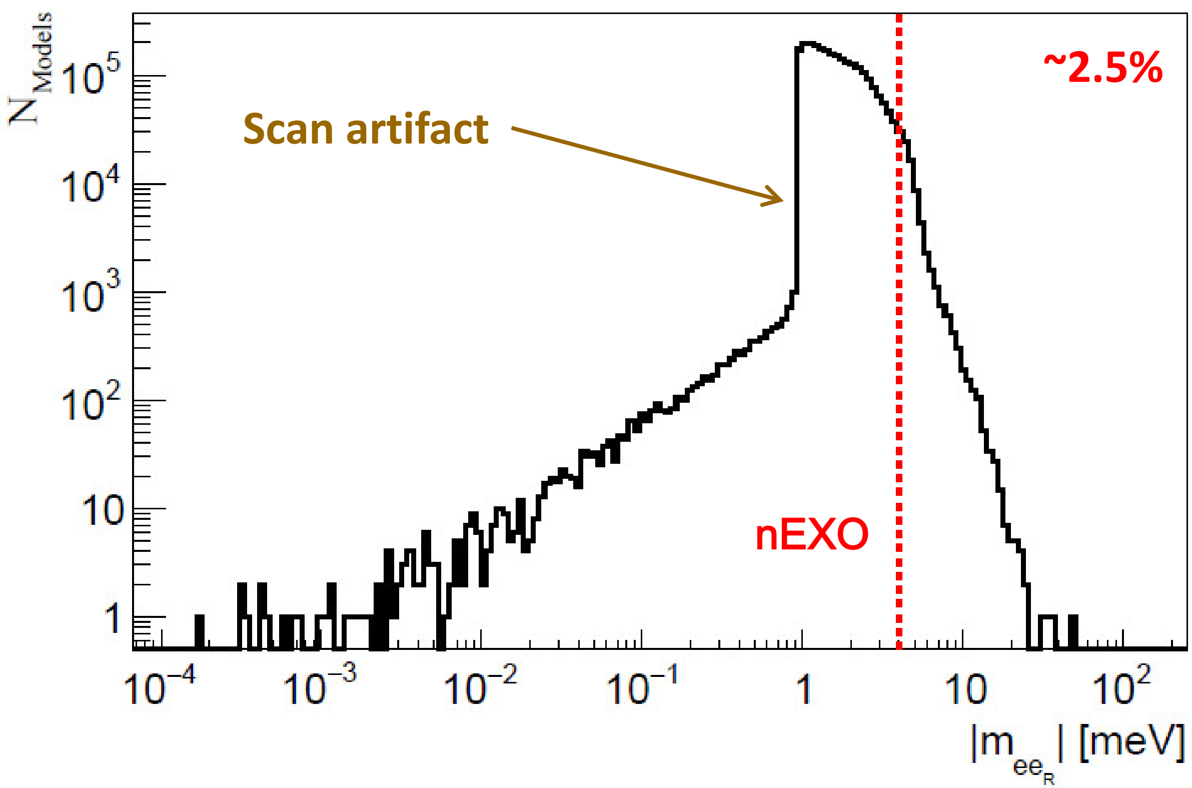


Mostly lie (i) far from present constraints, (ii) highly correlated with Δ_R^{++} mass-this exchange can dominate, (iii) strongly dependent on Majorana masses but ↔ correlated with the relative Majorana mass signs, (iv) some suppression from requirement that N_i be heavier than W_R

The LRM parameter dependence is rather simple in this (tree-level) case

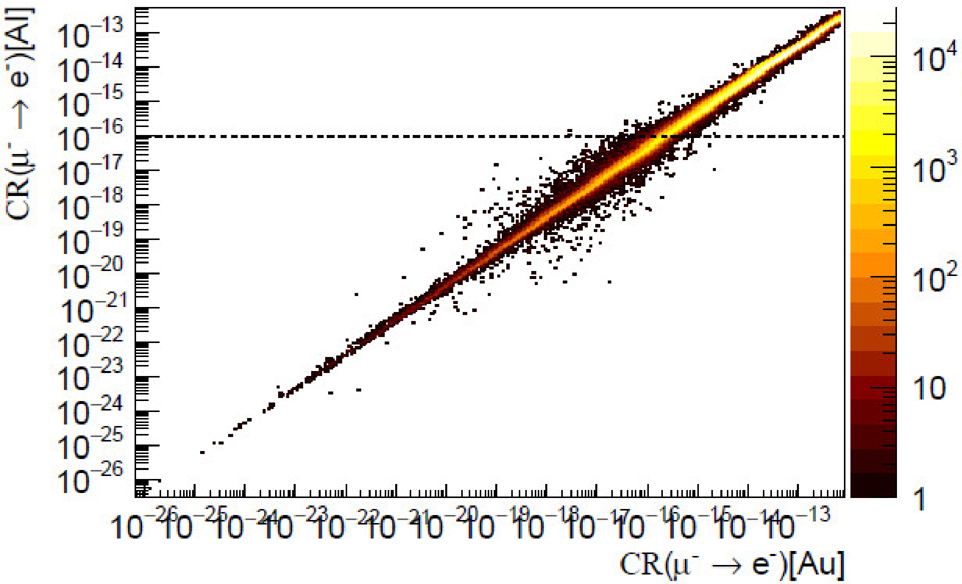
$$m_{ee_R} = \left(\frac{250\ \text{meV}}{1.1\times 10^{-8}}\right)\frac{m_p}{M_{W_R}}\left(\frac{\kappa M_W}{M_{W_R}}\right)^4 \sum_i (sign)_i\, V_{ei}^2 \left(\frac{1}{\sqrt{x_i}} + \frac{\sqrt{x_i}}{x_{\Delta_R^{\pm\pm}}}\right)$$

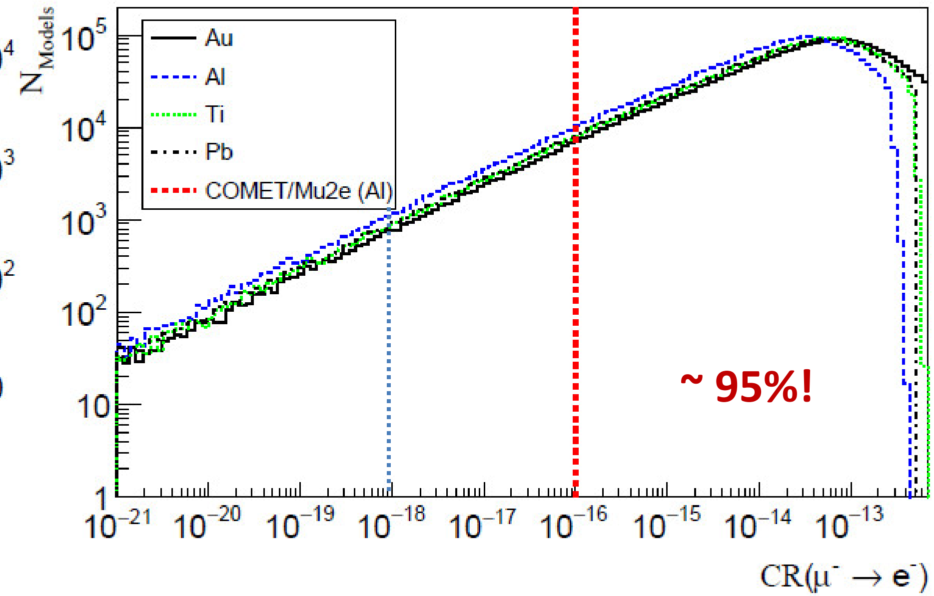
where $x_{\Delta_R^{\pm\pm}} \equiv M^2_{\Delta_R^{\pm\pm}}/M^2_{W_R}$ and $x_i \equiv M^2_{N_i}/M^2_{W_R}$ as before.



μ→e

Complex mix of gauge & scalar +RH neutrino contributions with essentially all LRM particles participating somewhere in loops /exchanges





(i) Powerful in terms of model parameter coverage…minor sensitivity to the specific nucleus, e.g., Au vs Al.

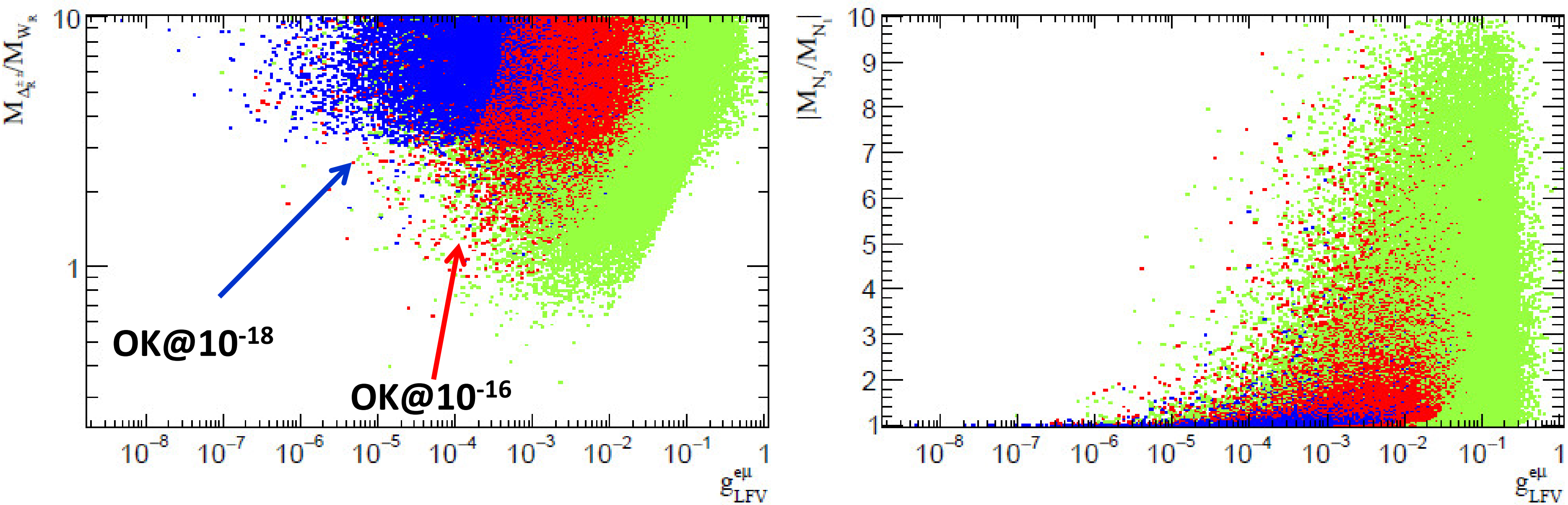
(ii) Log-enhanced $\Delta_{L,R}^{++}$ contributions important & possibly dominating

General scalar contributions are proportional to →

$$g_{\rm LFV}^{\mu e} = \sum_{n\in{\rm heavy}} (V_R^\dagger)_{en}(V_R)_{n\mu}x_n$$

$$x_n = M_{N_n}^2/M_{W_R}^2$$

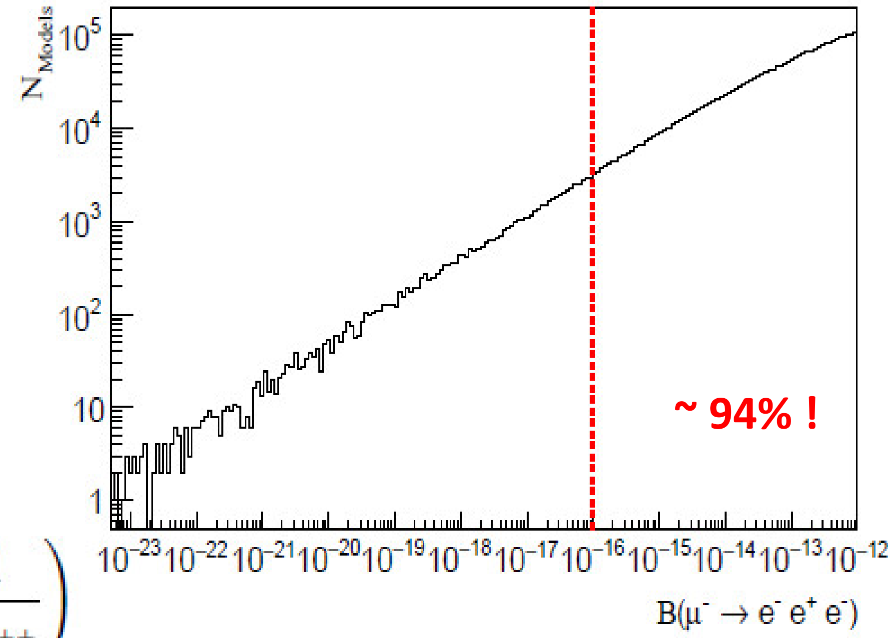
with V_R being the RH-neutrino mixing matrix



Exclusion @ 10^{-18} → no doubly charged Higgs below 1 TeV & degenerate RH neutrinos

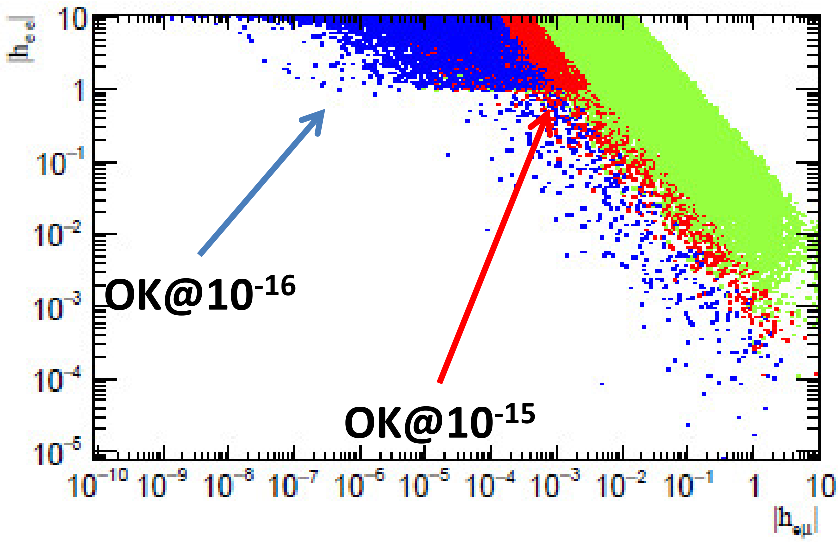
μ→3e

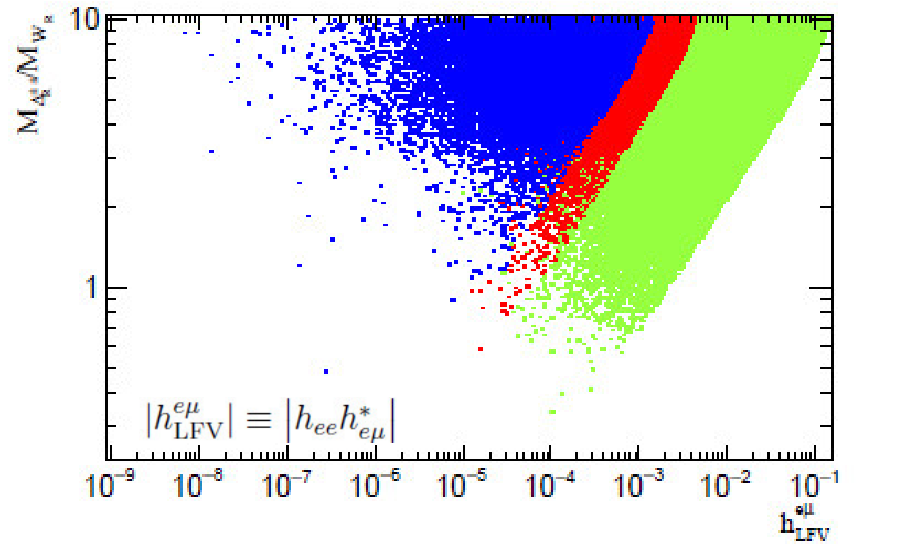
Dominated by tree-level doubly-charged Higgs exchanges but Yukawa couplings probe Majorana neutrino masses & signs



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

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



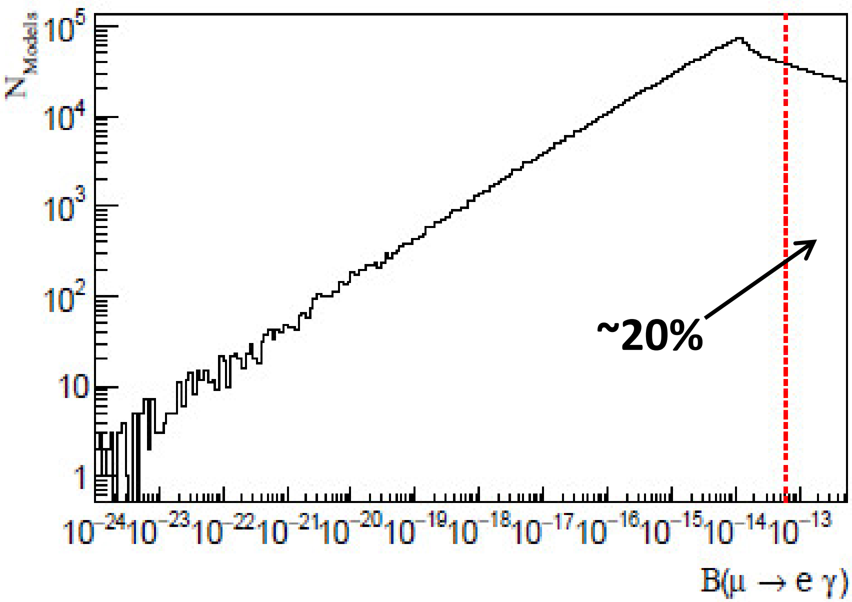


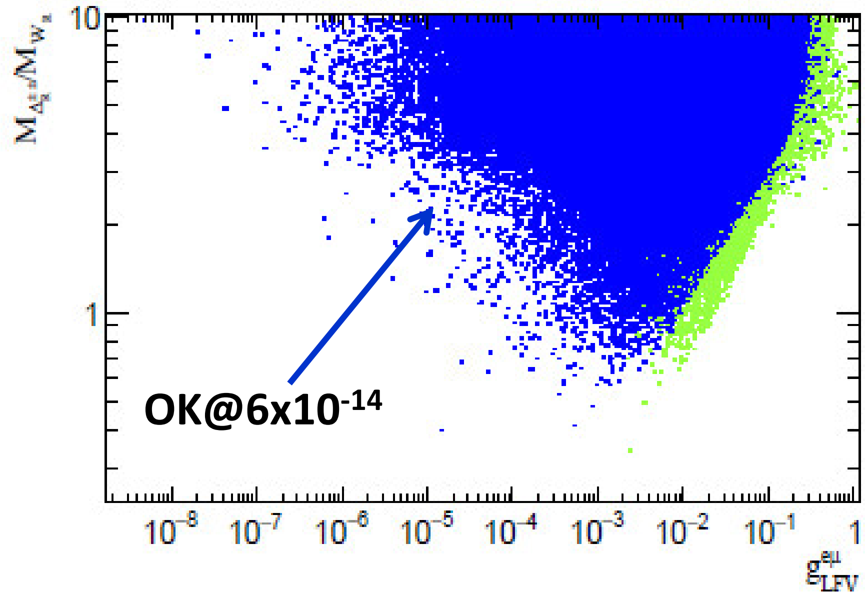
$\mu \to e\gamma$

Multiple loop contributions from both charged scalars & W_R with RH-neutrinos

Order of magnitude increase in sensitivity not as useful as future $\mu \to e$ conversion or $\mu \to 3e$

Does provide complementary information

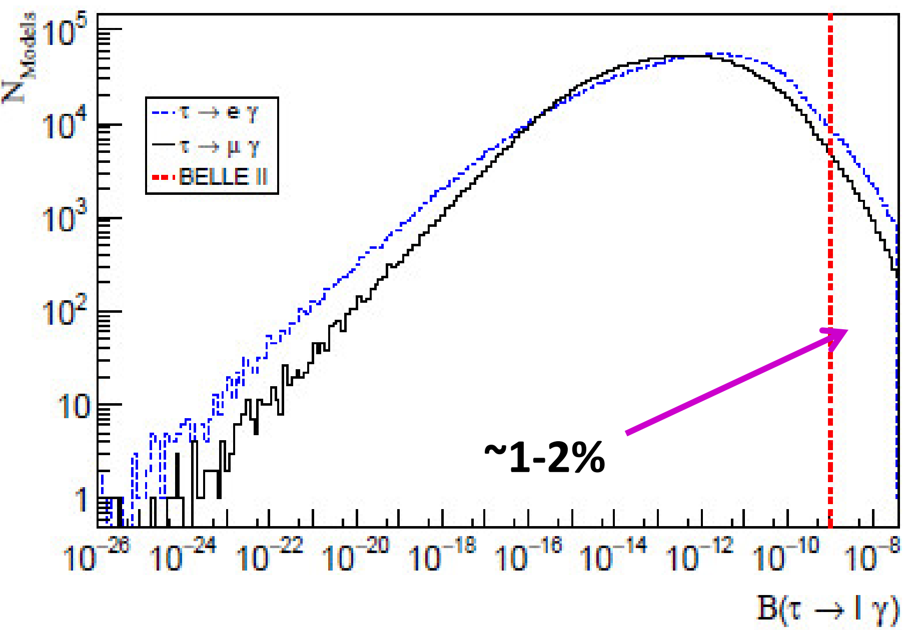


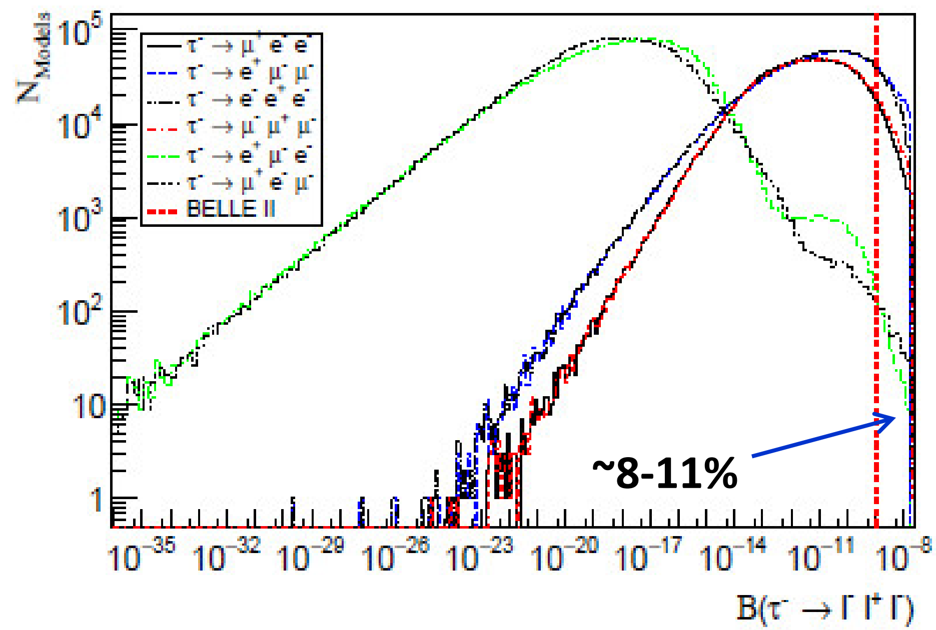


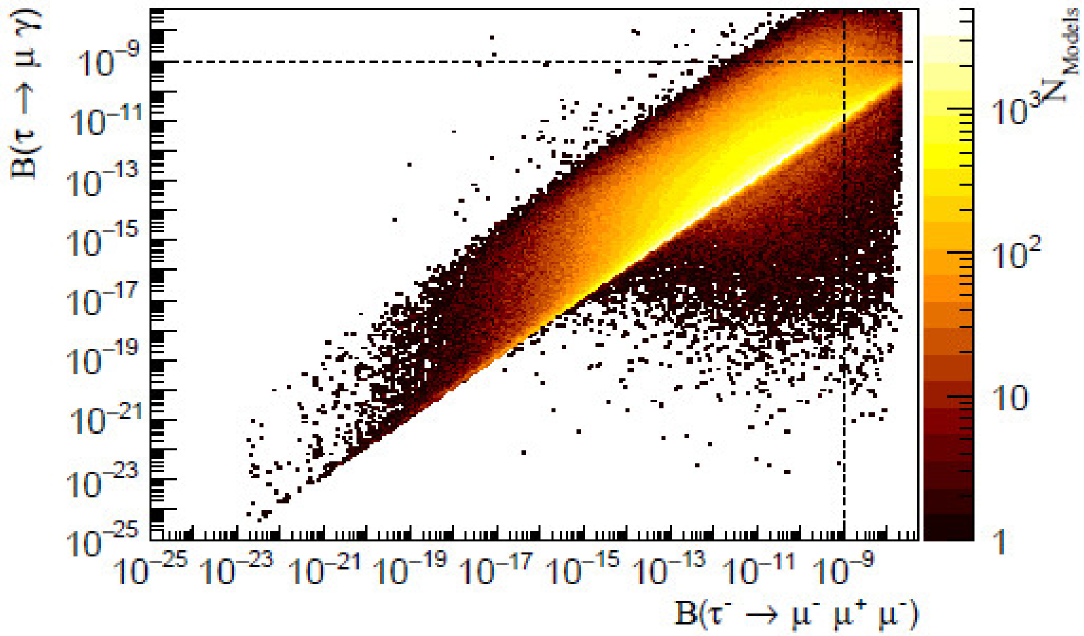
$\tau \to l\gamma$ (loops) + 3l (tree level)

(i) Multiple modes but improvements in sensitivity by (only) ~50 will not cover a substantial amount of model space.

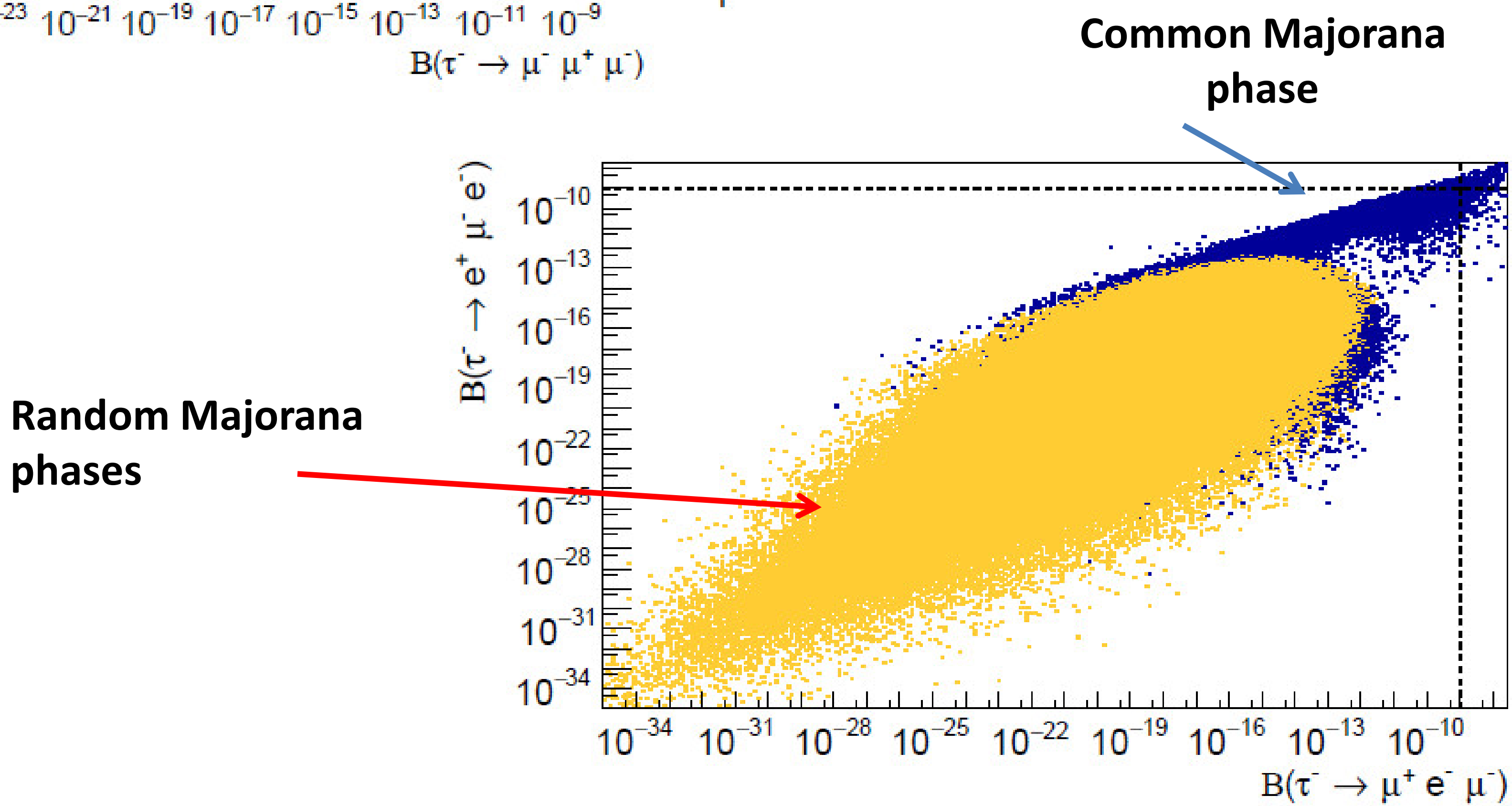
(ii) Correlations between measurements might be used to get info about Majorana mass signs



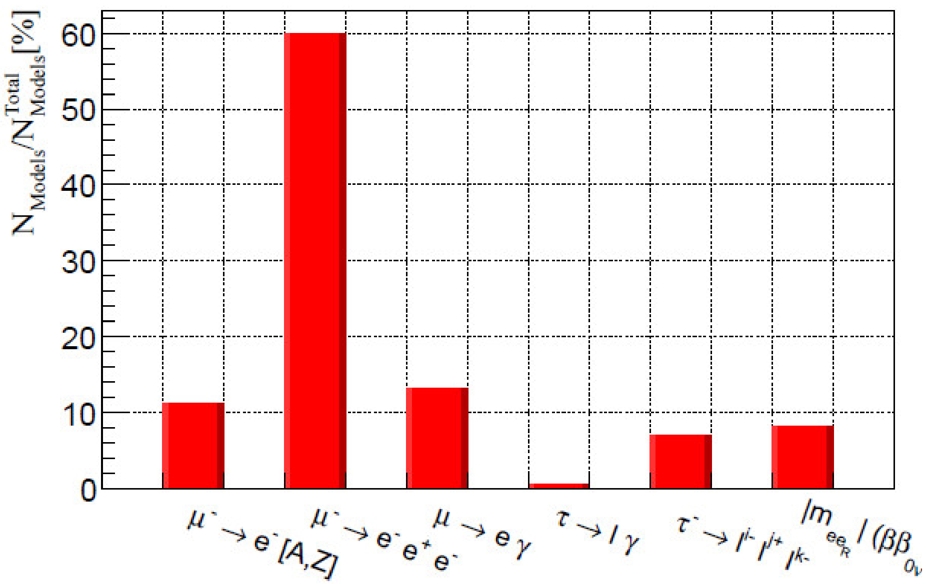


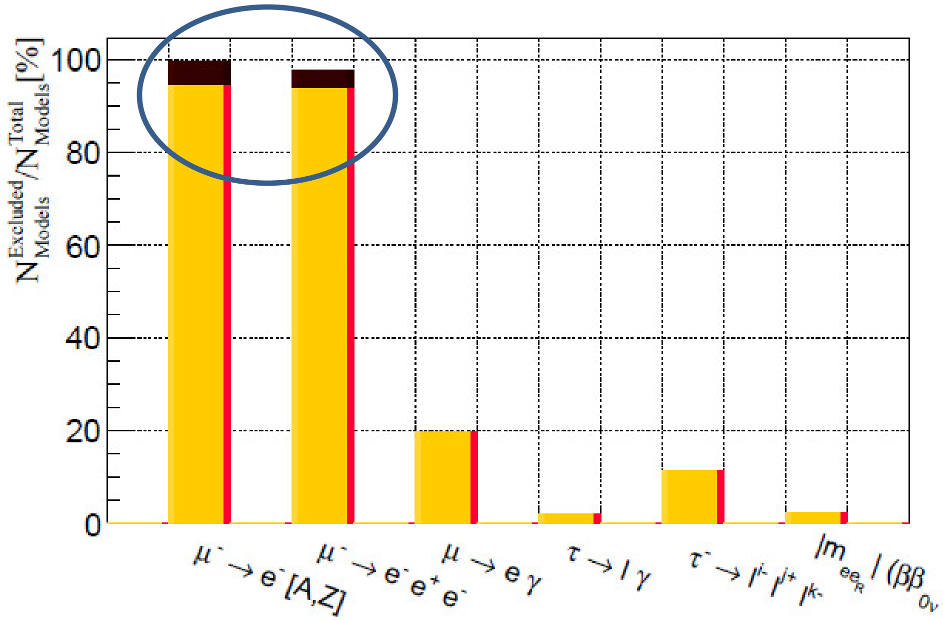


Most rate predictions are far below the anticipated BELLE sensitivities



Correlations & Comparisons

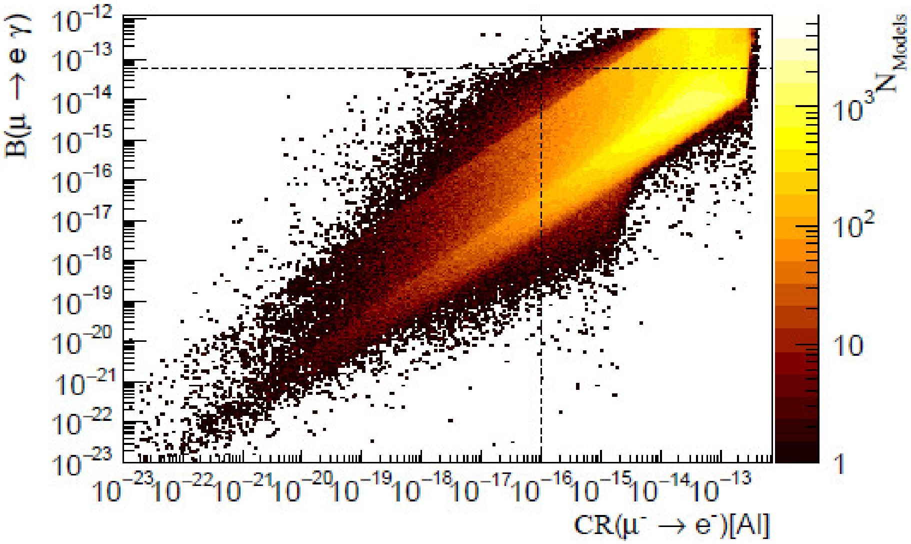


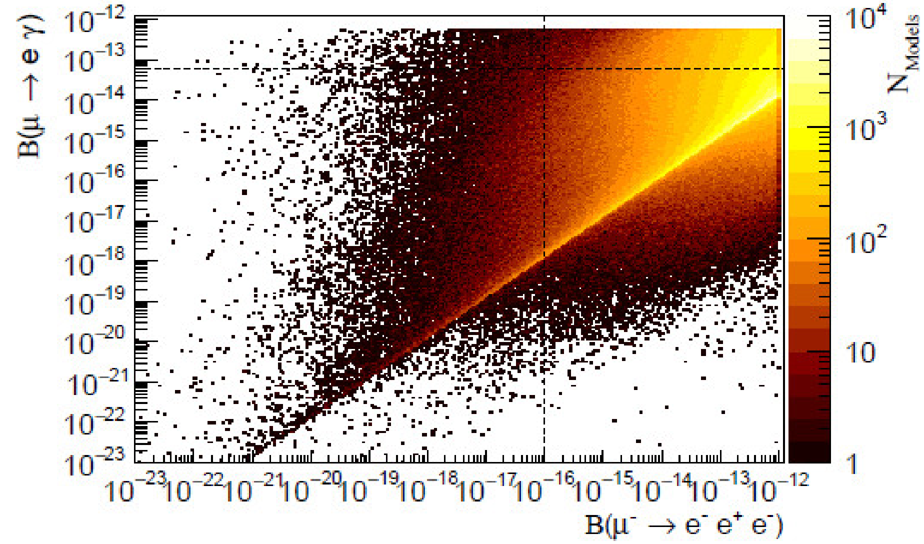


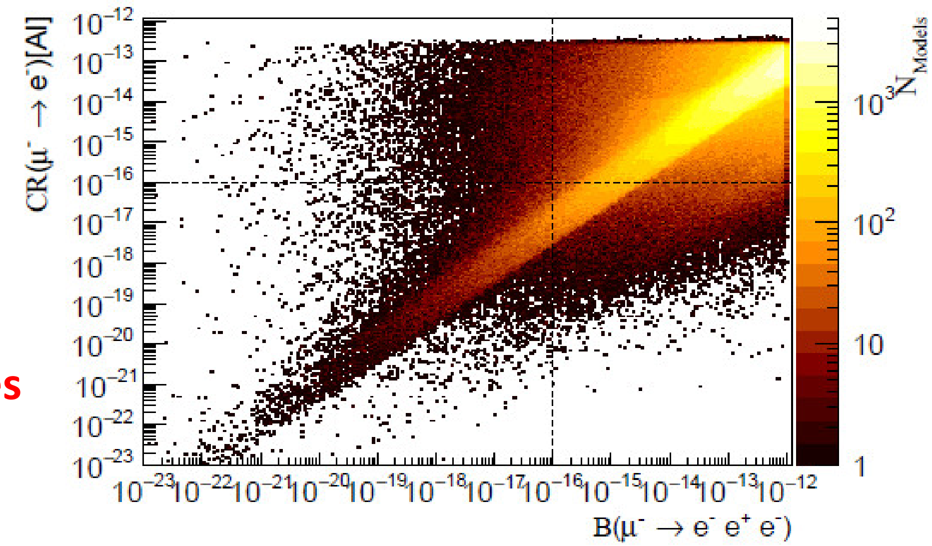
Fraction of models predicting a given observable to be the closest one to the present experimental limit

Fraction of the LRM parameter space accessible to future measurements by a given observable

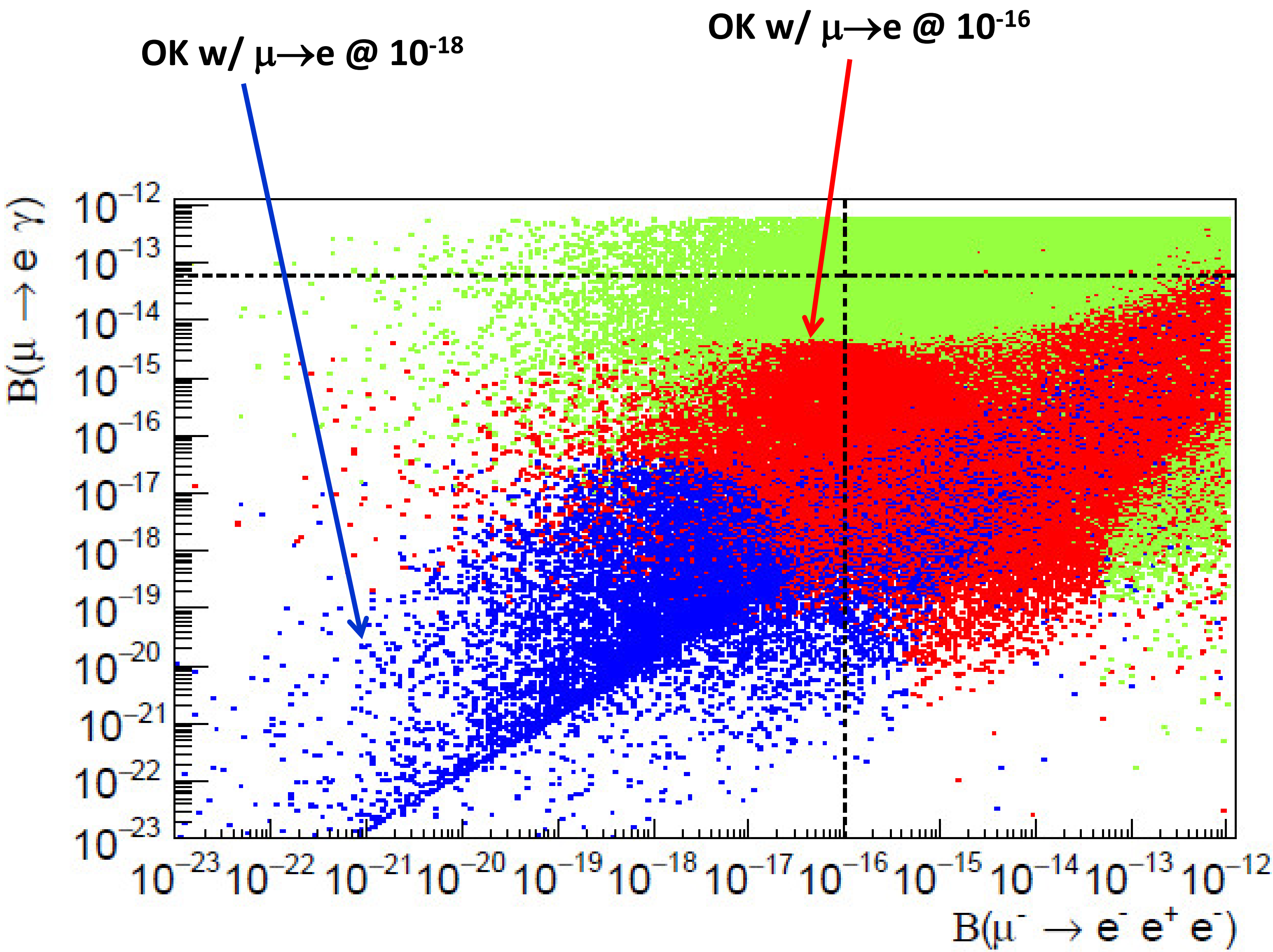
μ Observable Correlations





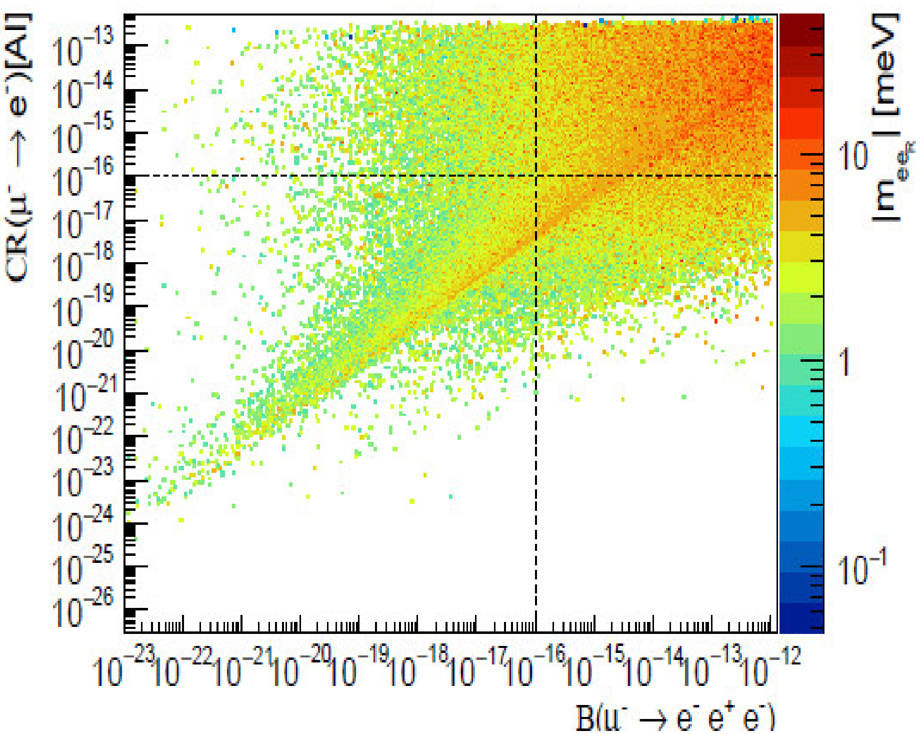


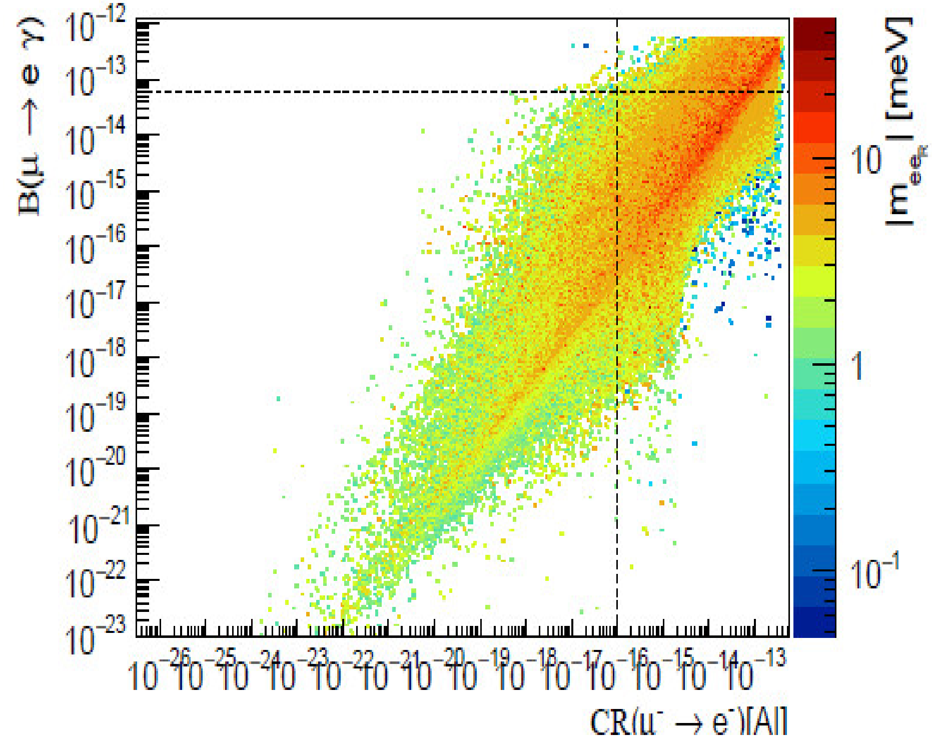
'Diagonals' → a common dominant exchange in both cases



$\mu \to e$ measurement impact

Correlation of $\beta\beta_{0\nu}$ effective $|m_{ee}|$ with rates for rare μ processes





Summary & Conclusions

- The LRM broken at the ~TeV scale can lead to visible LFV & LNV processes at low-energy as well as new signals at the LHC (that I haven't had time to discuss here)
- $\mu \rightarrow e$ conversion & $\mu \rightarrow 3e$ seem to provide the deepest probes of this parameter space (in all three scans). Note that $\beta\beta_{0\nu}$ becomes much more important when RH-neutrinos can be lighter than W_R .
- However all observables can provide some important complementary information especially if/when a signal is observed
- Hopefully we'll see some signatures of new physics soon

Backup

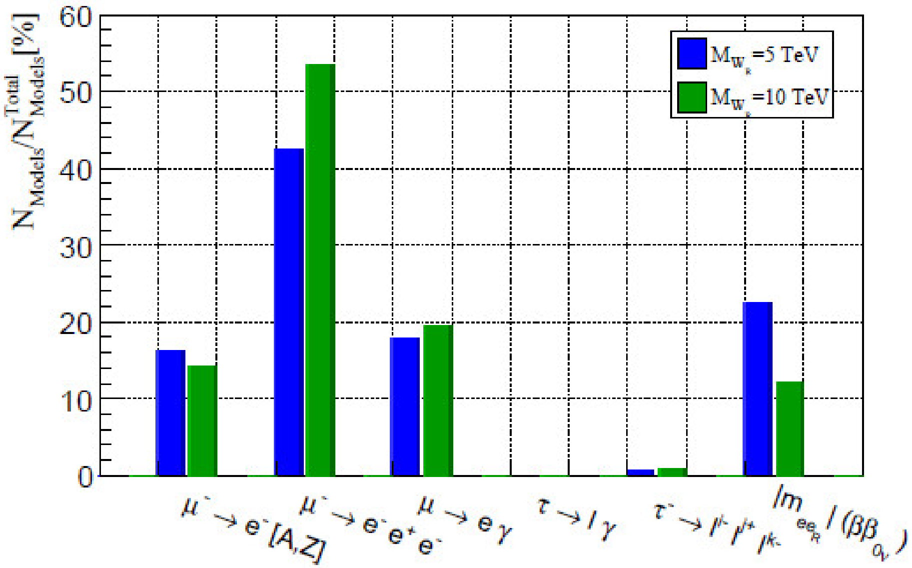
Observable	Experimental bound		Future limit	
$B(\mu^- \to e^-\gamma)$	$< 5.7 \times 10^{-13}$	[64]	$< 6 \times 10^{-14}$	[85]
$B(\tau^- \to \mu^-\gamma)$	$< 4.4 \times 10^{-8}$	[65]	$< 10^{-9}$	[78]
$B(\tau^- \to e^-\gamma)$	$< 3.3 \times 10^{-8}$	[65]	$< 10^{-9}$	[78]
$B(\mu^- \to e^-e^+e^-)$	$< 10^{-12}$	[66]	$< 10^{-15} - 10^{-16}$	[84]
$B(\tau^- \to e^-e^+e^-)$	$< 2.7 \times 10^{-8}$	[67]	$< 10^{-9} - 10^{-10}$	[78]
$B(\tau^- \to \mu^-\mu^+\mu^-)$	$< 2.1 \times 10^{-8}$	[67]	$< 10^{-9} - 10^{-10}$	[78]
$B(\tau^- \to e^-\mu^+\mu^-)$	$< 2.7 \times 10^{-8}$	[67]	$< 10^{-9} - 10^{-10}$	[78]
$B(\tau^- \to e^+\mu^-\mu^-)$	$< 1.7 \times 10^{-8}$	[67]	$< 10^{-9} - 10^{-10}$	[78]
$B(\tau^- \to \mu^-e^+e^-)$	$< 1.8 \times 10^{-8}$	[67]	$< 10^{-9} - 10^{-10}$	[78]
$B(\tau^- \to \mu^+e^-e^-)$	$< 1.5 \times 10^{-8}$	[67]	$< 10^{-9} - 10^{-10}$	[78]
$CR(\mu^- \to e^-)$ [Au]	$< 7 \times 10^{-13}$	[68]		
$CR(\mu^- \to e^-)$ [Ti]	$< 4.3 \times 10^{-12}$	[69]	$< 10^{-18}$	[76, 77]
$CR(\mu^- \to e^-)$ [Pb]	$< 4.6 \times 10^{-11}$	[70]		
$CR(\mu^- \to e^-)$ [Al]	–		$< 10^{-16} - 10^{-18}$	[72–77]
$P(M \to \overline{M})$	$< 8.2 \times 10^{-11}$	[71]		
$T_{1/2}^{\beta\beta_{0\nu}}$ [^{76}Ge]	$> 3.0 \times 10^{25}$ yr	[79]		
$T_{1/2}^{\beta\beta_{0\nu}}$ [^{136}Xe]	$> 1.9 \times 10^{25}$ yr	[80]		

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

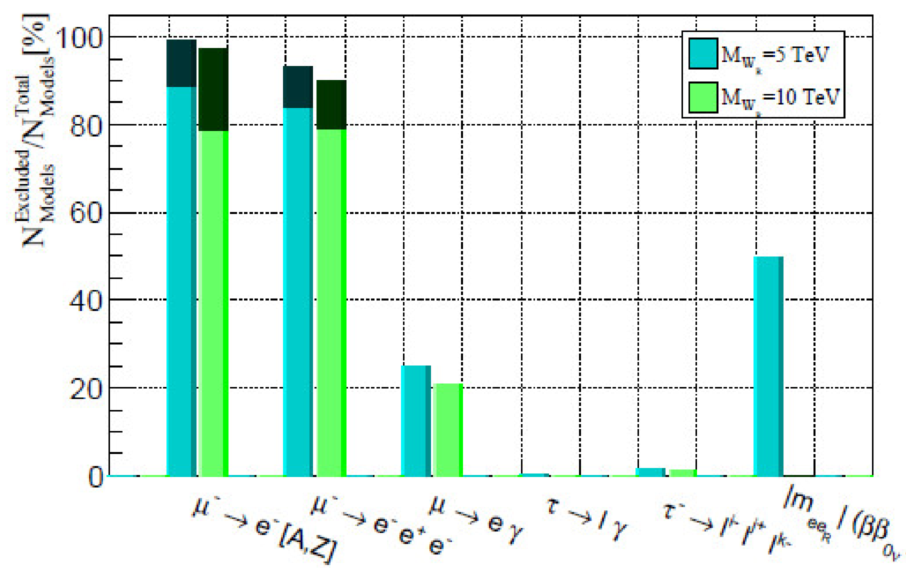
$$\mathcal{L}_{\Delta^{\pm\pm}\ell\ell} = \frac{g_L \kappa}{2} h_{ij} \left\{ \Delta_L^{++}\, \overline{\ell_L^{c\,i}}\, \ell_L^j + \Delta_R^{++}\, \overline{\ell_R^{c\,i}}\, \ell_R^j + \text{h.c.} \right\} \qquad \mathcal{L}_{\Delta^{\pm}\nu\ell} = \frac{g_L \kappa}{\sqrt{2}} \left\{ \tilde{h}_{ij}\,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

$$\frac{g_L}{c_w} [\kappa^2 - (1+\kappa^2) s_w^2]^{-1/2} [s_w^2 T_{3L} + \kappa^2 (1 - s_w^2) T_{3R} - s_w^2 Q]$$

$$\frac{M_{Z_R}^2}{M_{W_R}^2} = \frac{\kappa^2 (1 - s_w^2) \rho_R}{\kappa^2 (1 - s_w^2) - s_w^2} > 1\,,$$



$N_{Models}/N_{Models}^{Total}$[%]
M_{W_R}=5 TeV
M_{W_R}=10 TeV
0
10
20
30
40
50
60
$\mu^- \to e^-[A,Z]$
$\mu^- \to e^-e^+e^-$
$\mu \to e\gamma$
$\tau \to l\gamma$
$\tau^- \to l^{i-} l^{j+} l^{k-}$
$|m_{ee_R}| (\beta\beta_{0\nu})$



$N_{Models}^{Excluded}/N_{Models}^{Total}$[%]
M_{W_R}=5 TeV
M_{W_R}=10 TeV
0
20
40
60
80
100
$\mu^- \to e^-[A,Z]$
$\mu^- \to e^-e^+e^-$
$\mu \to e\gamma$
$\tau \to l\gamma$
$\tau^- \to l^{i-} l^{j+} l^{k-}$
$|m_{ee_R}| (\beta\beta_{0\nu})$