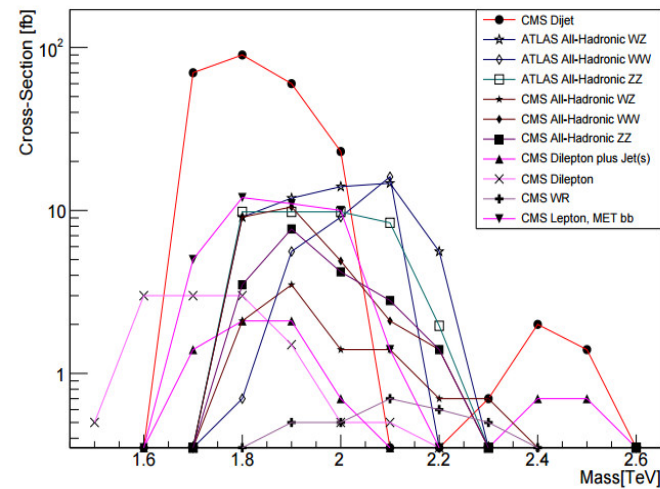
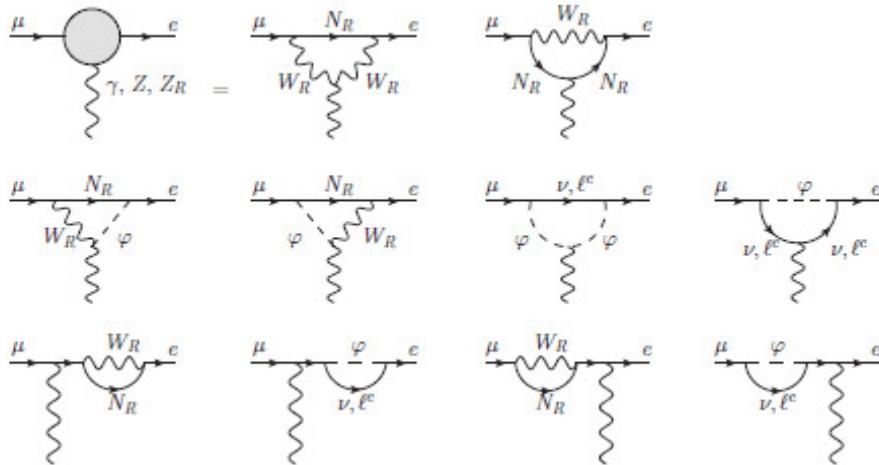
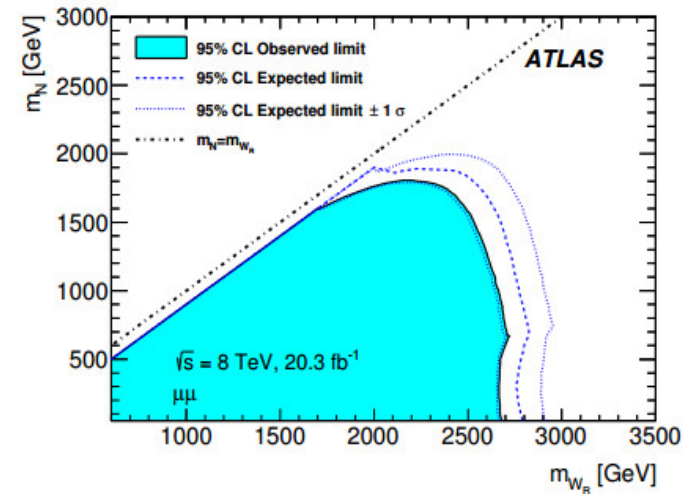
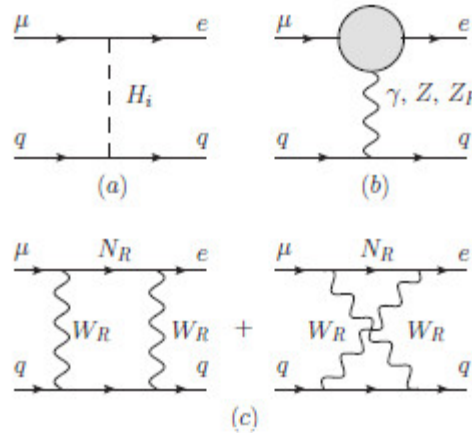


LVN & LFV in LR Models @ the TeV Scale



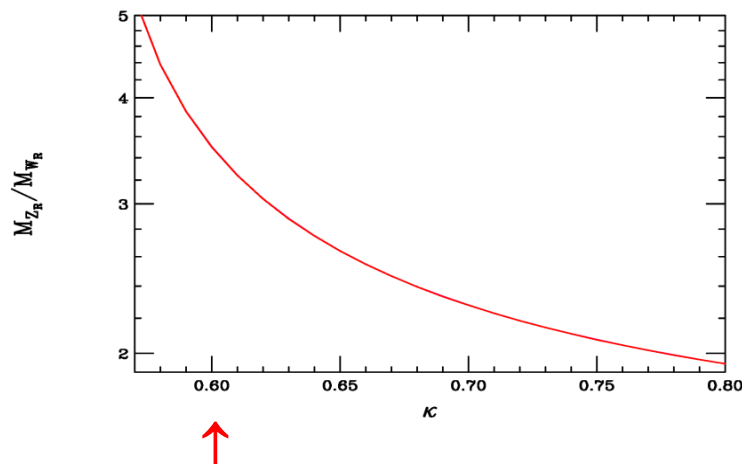
1512.04357



J. de Blas, J. L. Hewett, T. D. Rueter & TGR
1607.0asap 7/5/16

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

- 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**, $\beta\beta_{0\nu}$, **μ onium-anti μ onium conversion**, **g-2** & μ -decay -- keep only 'survivors'. (see backups for precise numerical constraints)
- Study the predictions of the (\sim 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: $M_R = 1.9 \text{ TeV}$, $\kappa = g_R/g_L = 0.6$, $\phi_w \approx (1.0-1.5)10^{-3} \rightarrow \tan \beta \approx 1 \rightarrow$ the bi-doublet charged Higgs is decoupled.

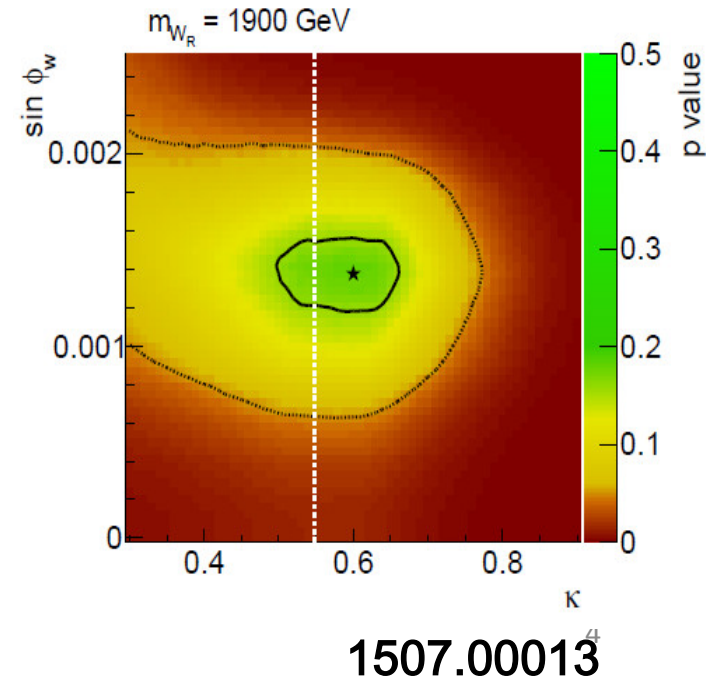
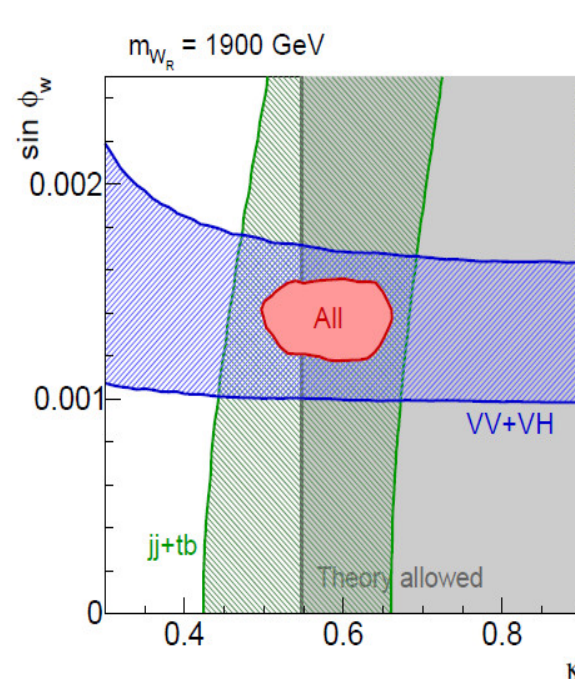
flat priors: $1 \leq m_i \equiv M_{N_i}/M_{W_R} \leq 10$ & $0 \leq s_{12}, s_{13}, s_{23} \leq 1$,

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



1507.00013

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

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

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

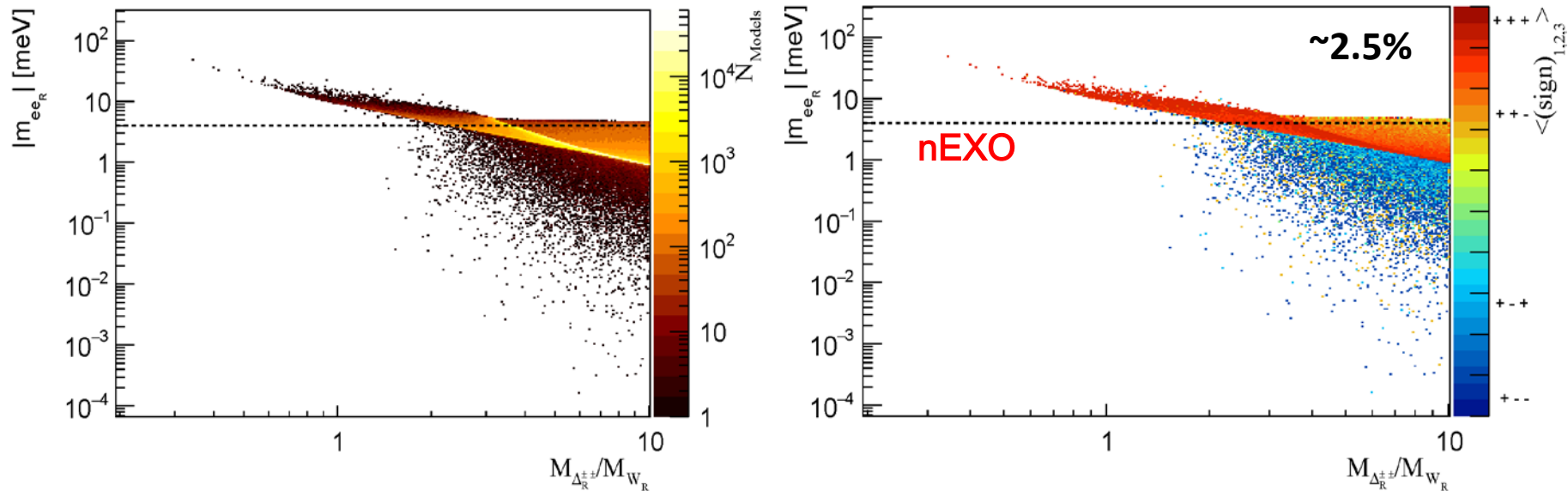
These probe W_R masses at the top of the LHC discovery range at 13/4 TeV & values beyond the reach of the LHC which remain ‘phenomenologically’ interesting

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

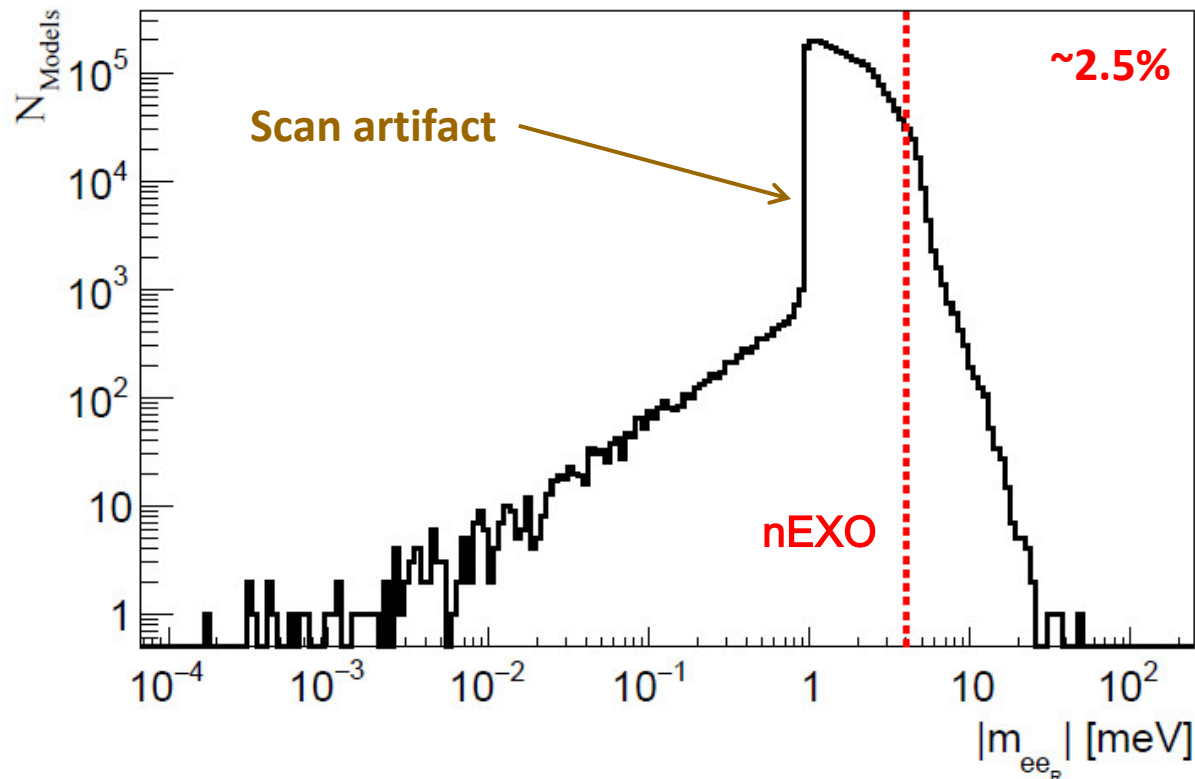


Mostly lie (i) far from present constraints, **(ii)** highly correlated with Δ_R^{++} mass-this exchange can dominate, **(iii)** strongly dependent on Majorana masses but \leftrightarrow correlated with the relative Majorana mass signs, **(iv)** some suppression from requirement that N_i be heavier than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

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

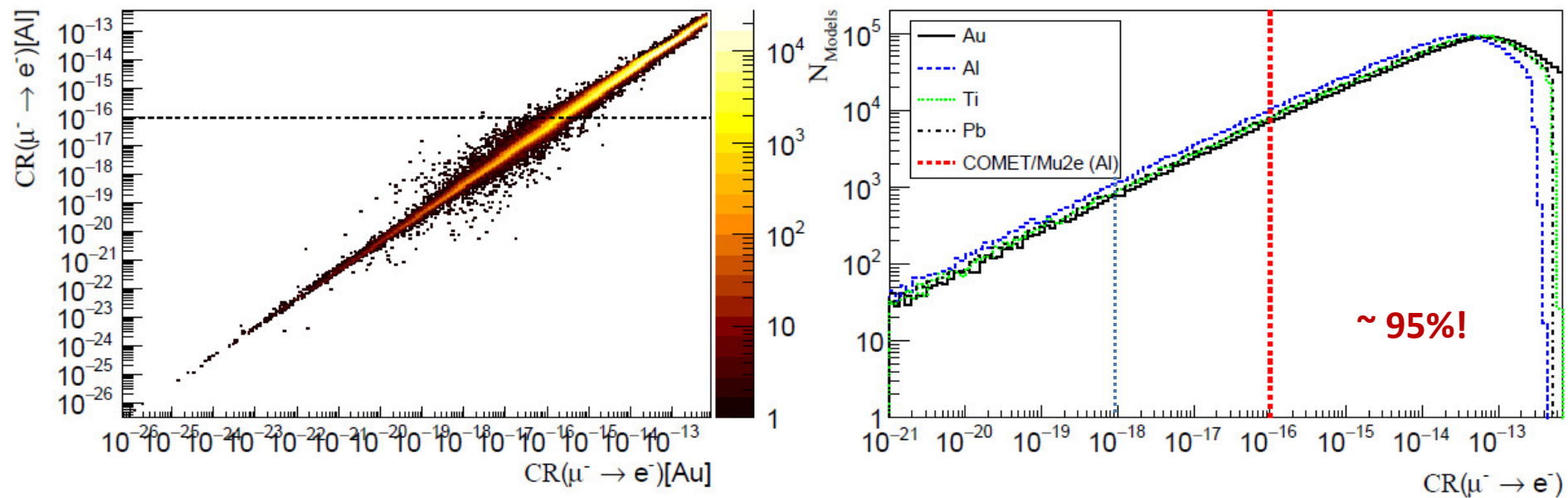
$$m_{ee_R} = \left(\frac{250 \text{ meV}}{1.1 \times 10^{-8}} \right) \frac{m_p}{M_{W_R}} \left(\frac{\kappa M_W}{M_{W_R}} \right)^4 \sum_i (\text{sign})_i V_{ei}^2 \left(\frac{1}{\sqrt{x_i}} + \frac{\sqrt{x_i}}{x_{\Delta_R^{\pm\pm}}} \right)$$

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



$\mu \rightarrow e$

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

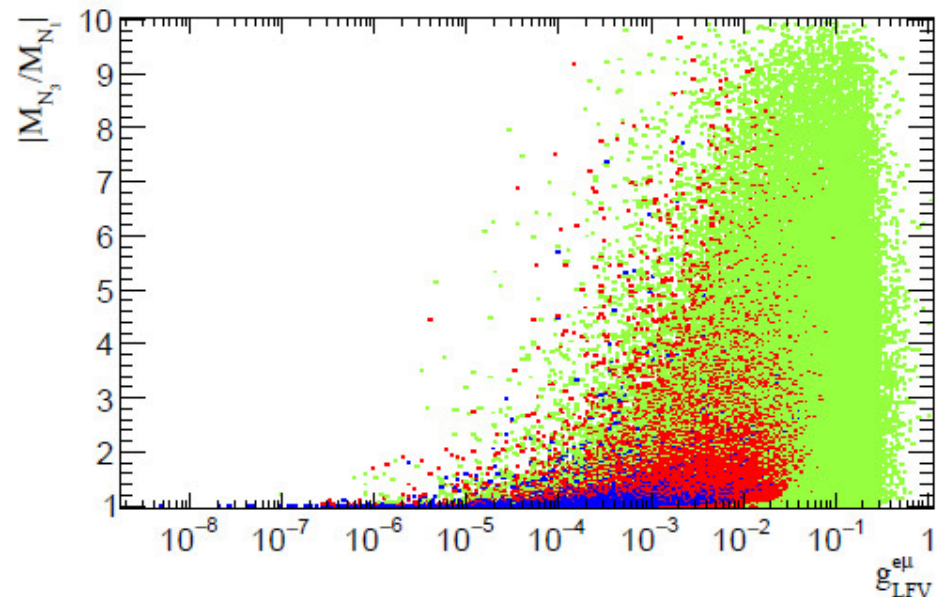
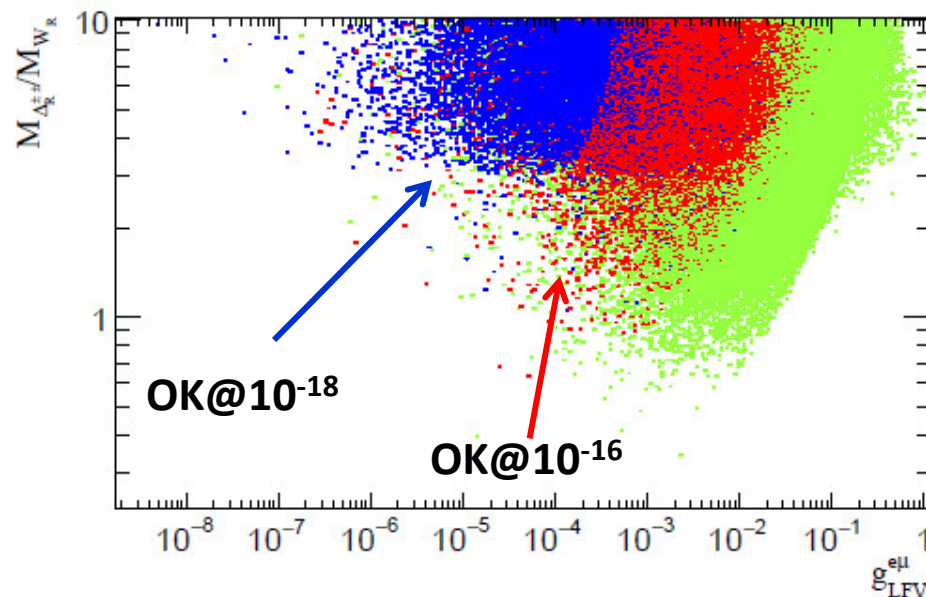


General scalar contributions
are proportional to \rightarrow

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

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

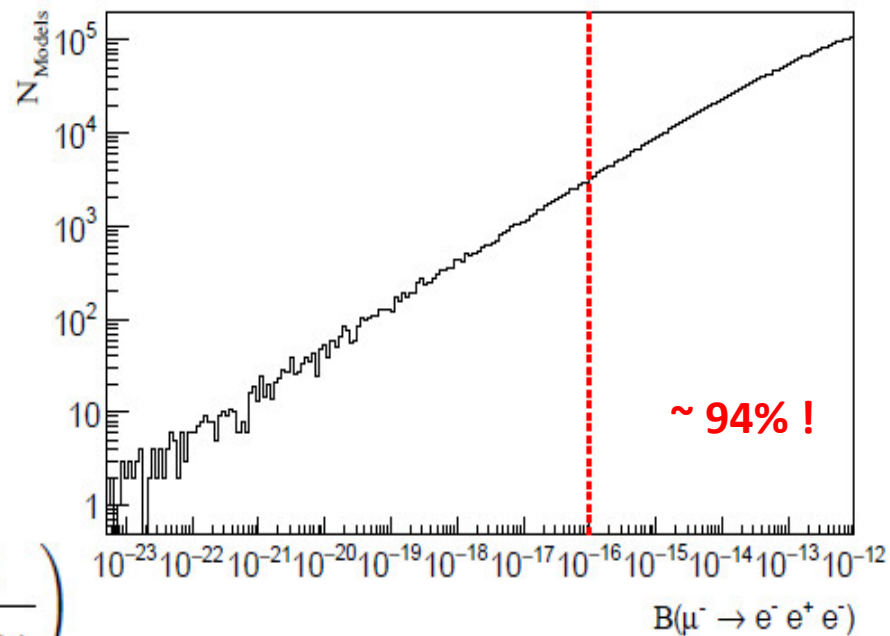
with V_R being the RH-neutrino mixing matrix



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

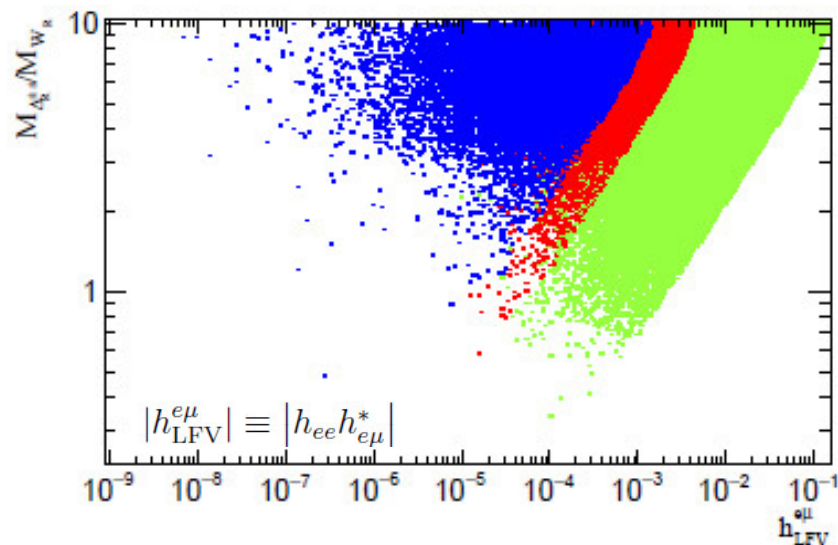
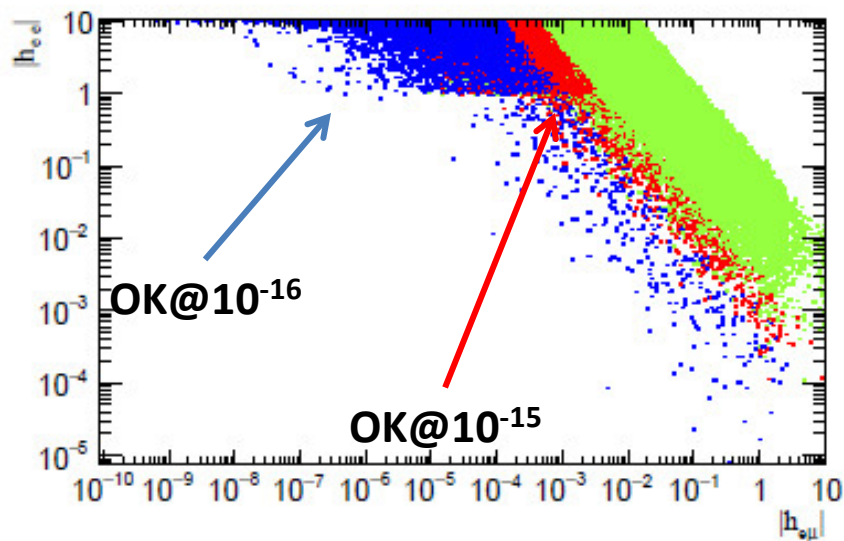
$\mu \rightarrow 3e$

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



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

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

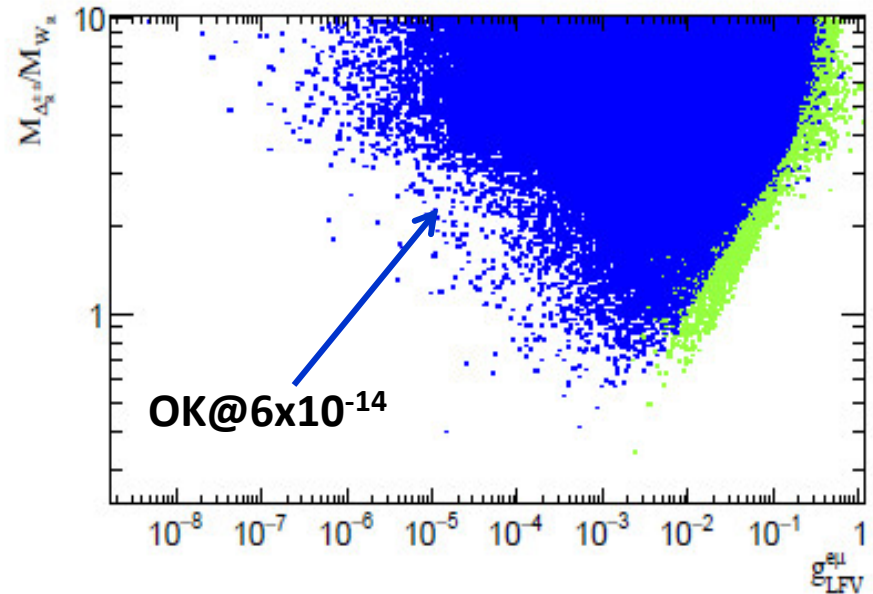
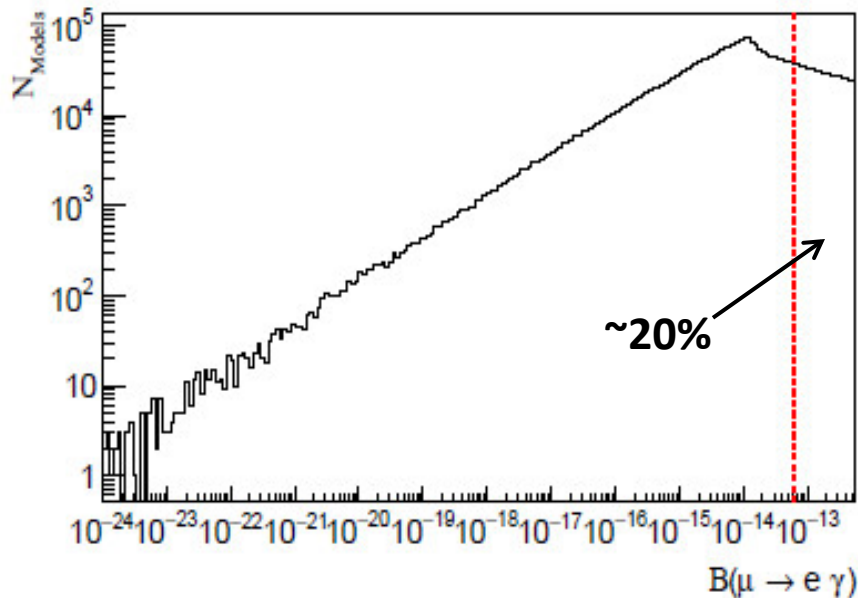


$$\mu \rightarrow e \gamma$$

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

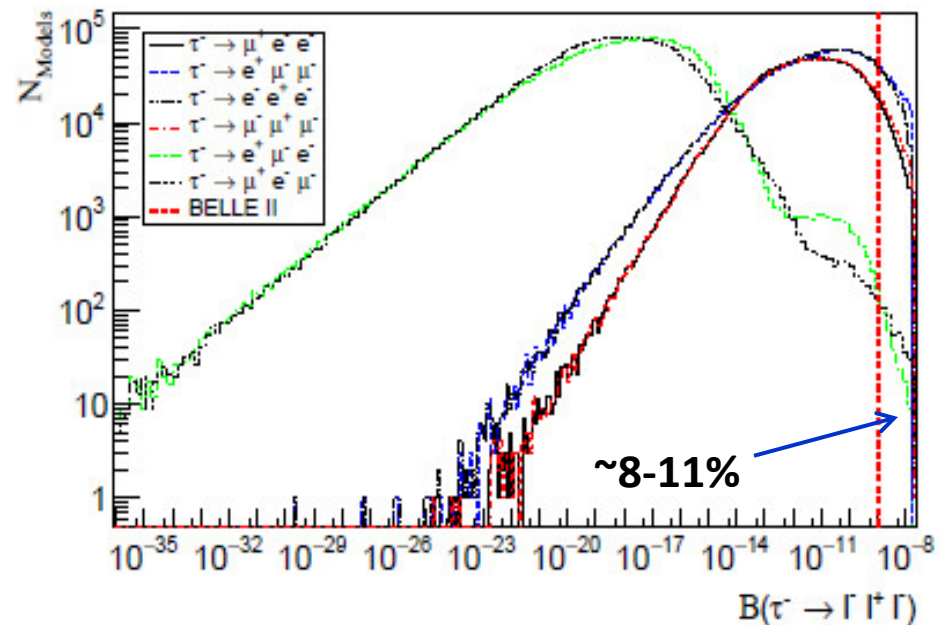
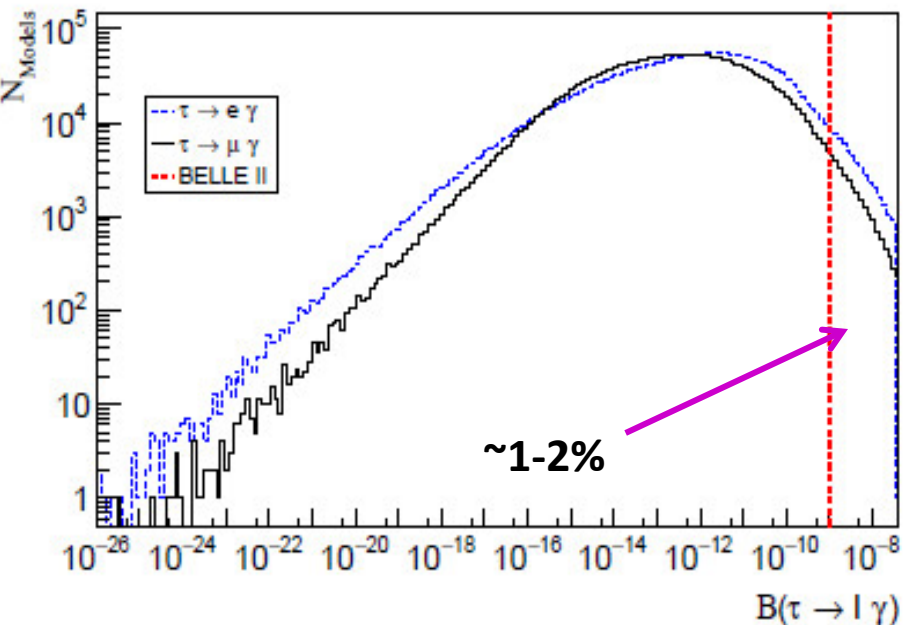
Order of magnitude increase in sensitivity **not** as useful as future $\mu \rightarrow e$ conversion or $\mu \rightarrow 3e$

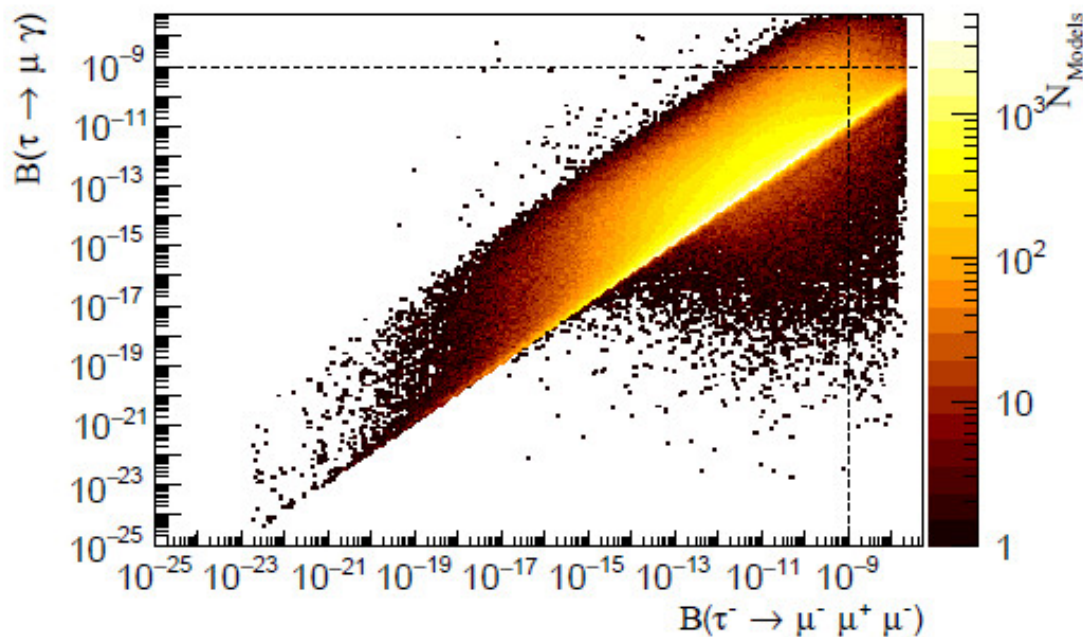
Does provide complementary information



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

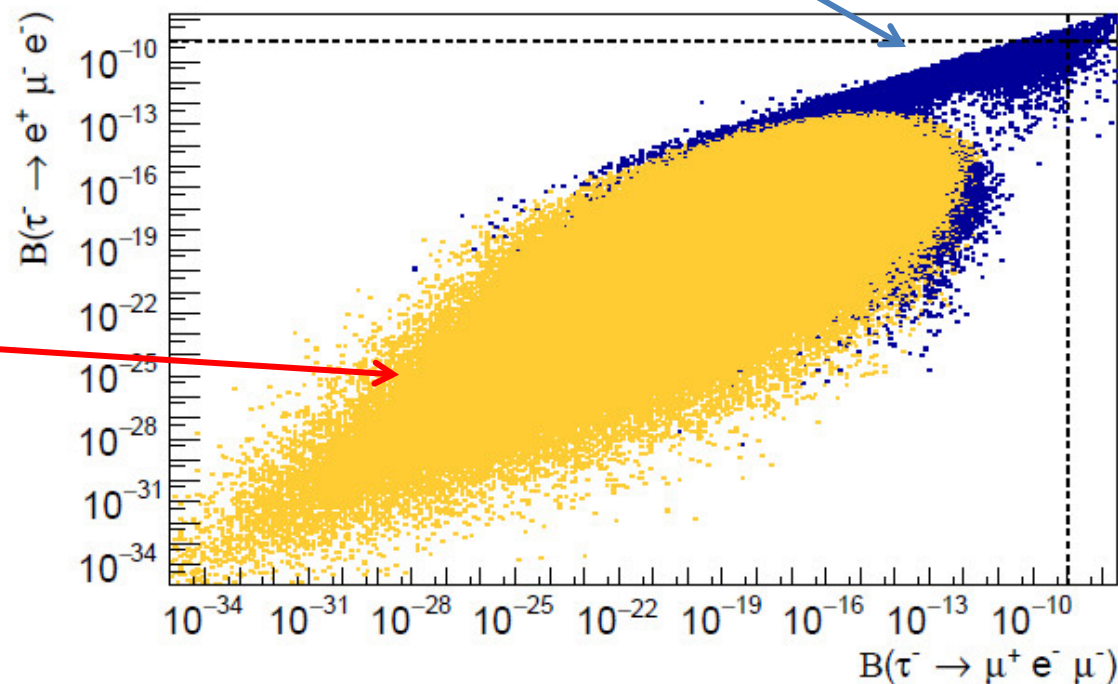
- (i) Multiple modes but improvements in sensitivity by (only) ~ 50 will not cover a substantial amount of model space.
- (ii) Correlations between measurements might be used to get info about Majorana mass signs



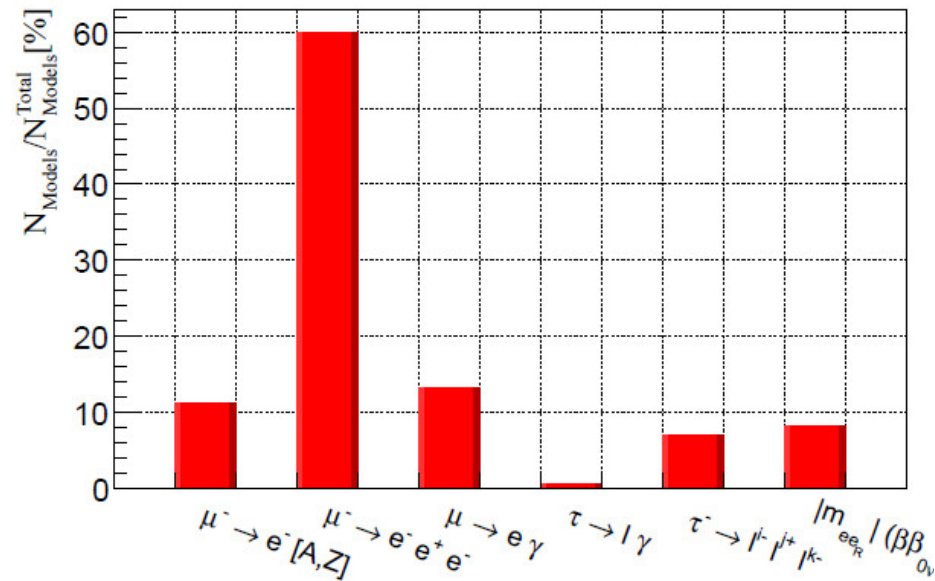


Most rate predictions are far below the anticipated BELLE sensitivities

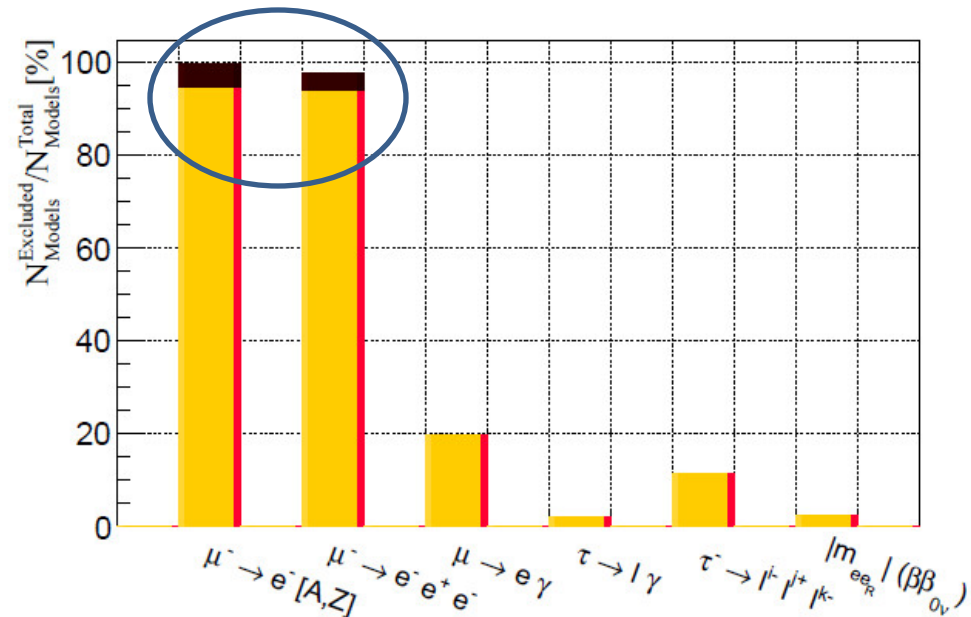
Random Majorana phases



Correlations & Comparisons

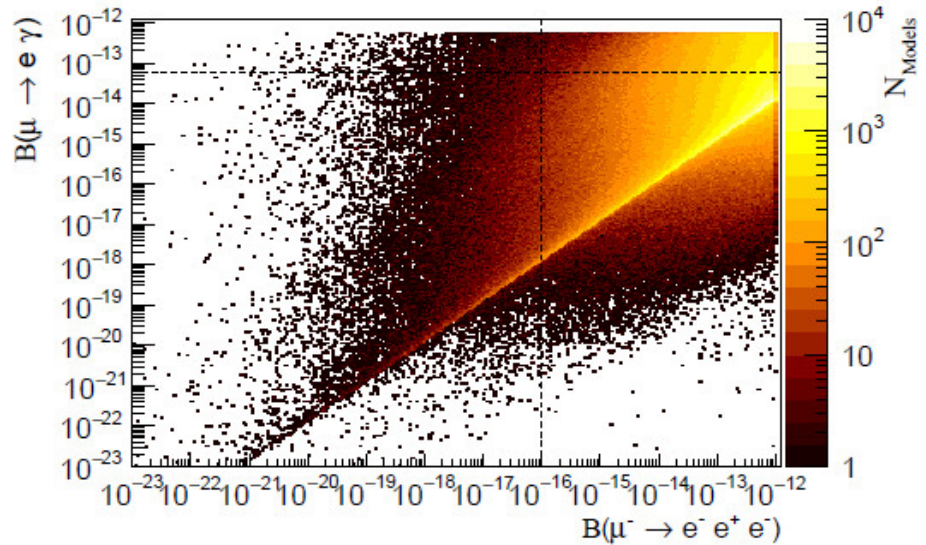
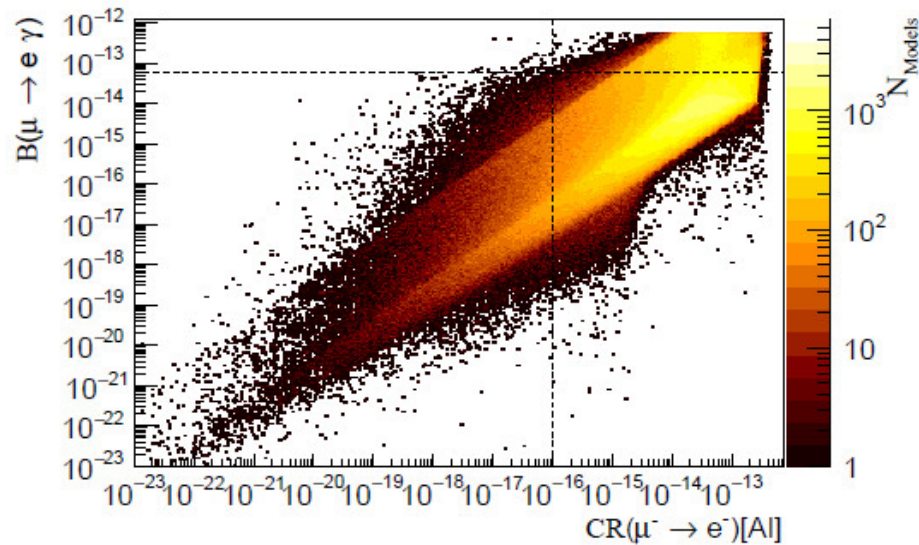


Fraction of models predicting a given observable to be the closest one to the present experimental limit

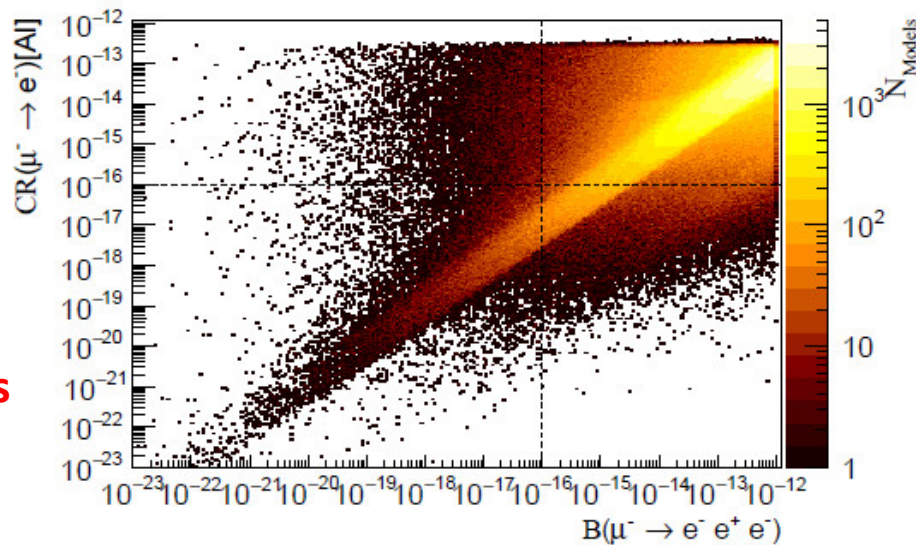


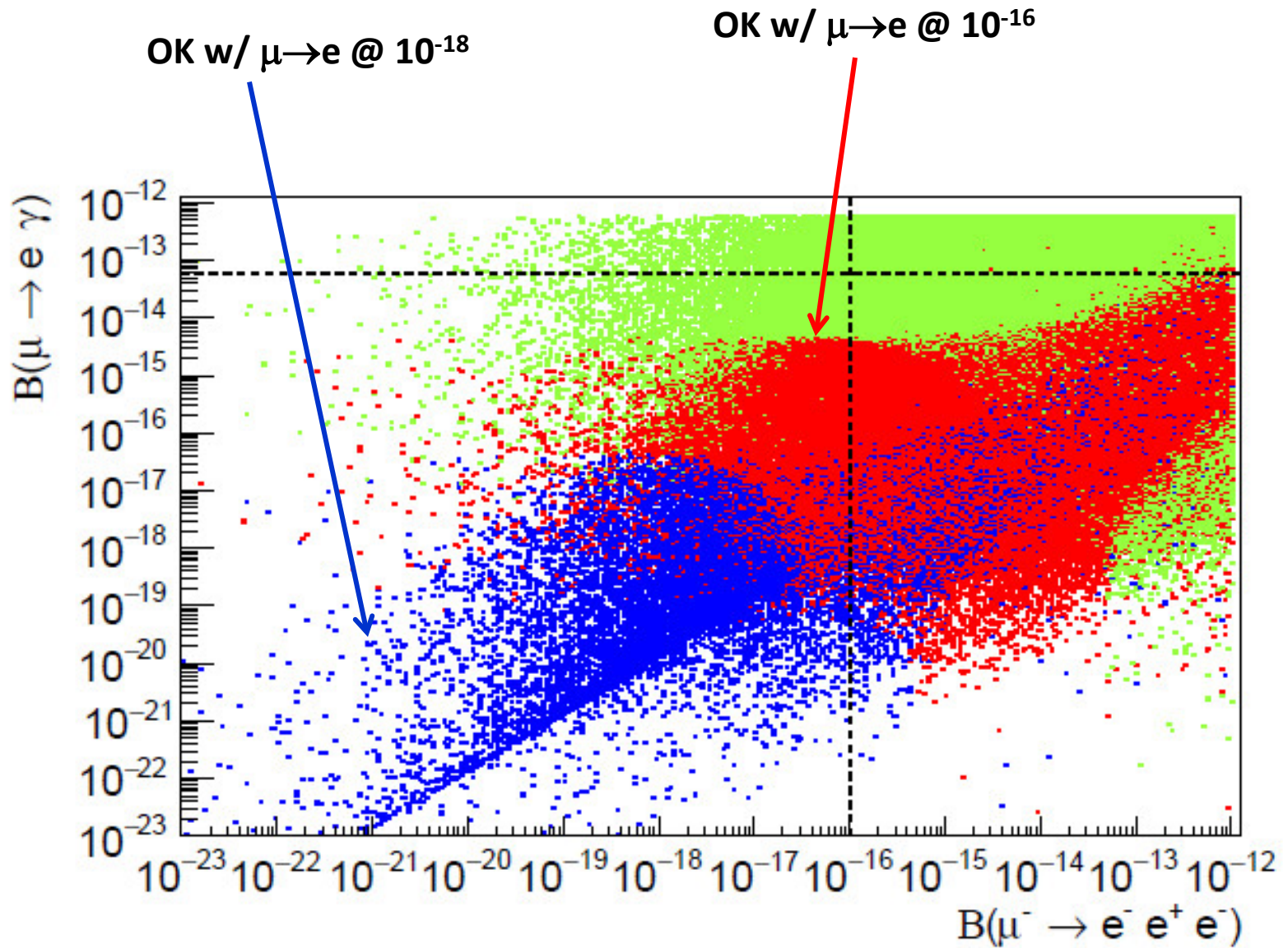
Fraction of the LRM parameter space accessible to future measurements by a given observable

μ Observable Correlations



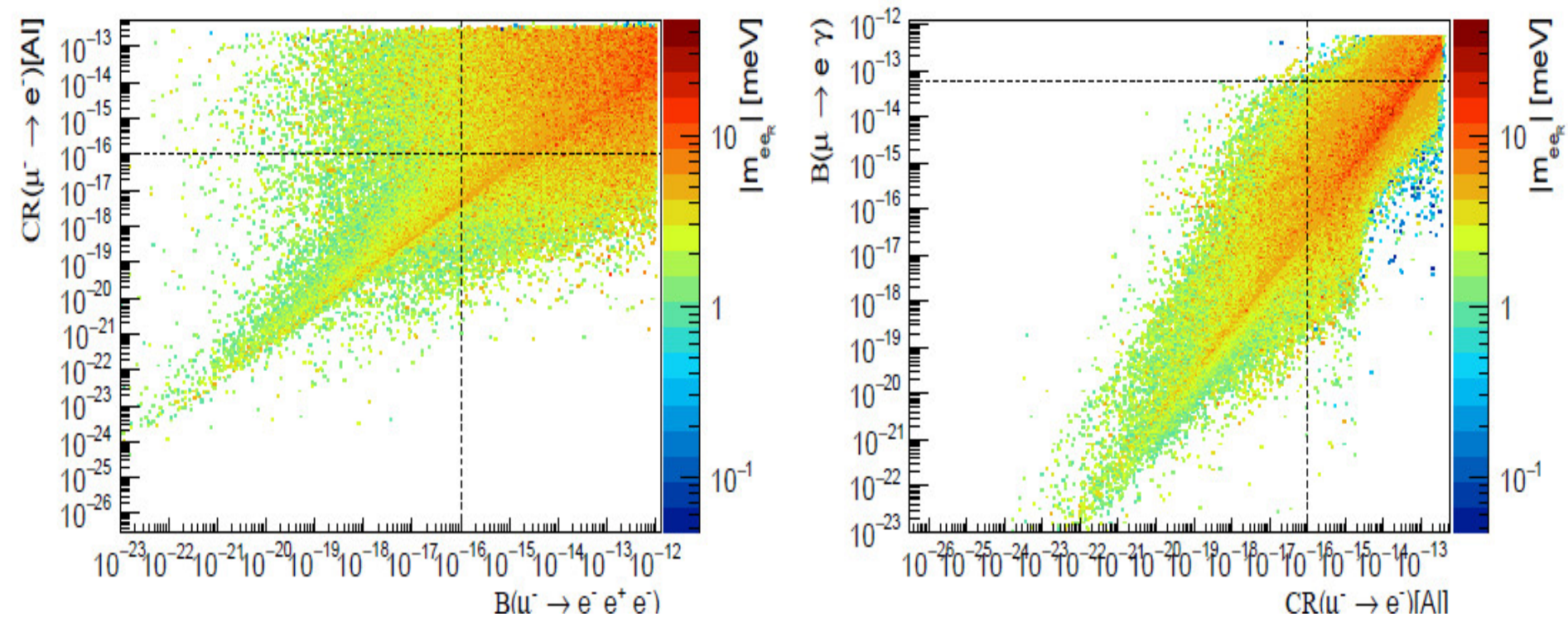
‘Diagonals’ → a common dominant exchange in both cases





$\mu \rightarrow e$ measurement impact

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



Summary & Conclusions

- The LRM broken at the $\sim\text{TeV}$ 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	
$B(\mu^- \rightarrow e^- \gamma)$	$< 5.7 \times 10^{-13}$	[64]	$< 6 \times 10^{-14}$	[85]
$B(\tau^- \rightarrow \mu^- \gamma)$	$< 4.4 \times 10^{-8}$	[65]	$< 10^{-9}$	[78]
$B(\tau^- \rightarrow e^- \gamma)$	$< 3.3 \times 10^{-8}$	[65]	$< 10^{-9}$	[78]
$B(\mu^- \rightarrow e^- e^+ e^-)$	$< 10^{-12}$	[66]	$< 10^{-15} - 10^{-16}$	[84]
$B(\tau^- \rightarrow e^- e^+ e^-)$	$< 2.7 \times 10^{-8}$	[67]	$< 10^{-9} - 10^{-10}$	[78]
$B(\tau^- \rightarrow \mu^- \mu^+ \mu^-)$	$< 2.1 \times 10^{-8}$	[67]	$< 10^{-9} - 10^{-10}$	[78]
$B(\tau^- \rightarrow e^- \mu^+ \mu^-)$	$< 2.7 \times 10^{-8}$	[67]	$< 10^{-9} - 10^{-10}$	[78]
$B(\tau^- \rightarrow e^+ \mu^- \mu^-)$	$< 1.7 \times 10^{-8}$	[67]	$< 10^{-9} - 10^{-10}$	[78]
$B(\tau^- \rightarrow \mu^- e^+ e^-)$	$< 1.8 \times 10^{-8}$	[67]	$< 10^{-9} - 10^{-10}$	[78]
$B(\tau^- \rightarrow \mu^+ e^- e^-)$	$< 1.5 \times 10^{-8}$	[67]	$< 10^{-9} - 10^{-10}$	[78]
$CR(\mu^- \rightarrow e^-)$ [Au]	$< 7 \times 10^{-13}$	[68]		
$CR(\mu^- \rightarrow e^-)$ [Ti]	$< 4.3 \times 10^{-12}$	[69]	$< 10^{-18}$	[76, 77]
$CR(\mu^- \rightarrow e^-)$ [Pb]	$< 4.6 \times 10^{-11}$	[70]		
$CR(\mu^- \rightarrow e^-)$ [Al]	—		$< 10^{-16} - 10^{-18}$	[72–77]
$P(M \rightarrow \bar{M})$	$< 8.2 \times 10^{-11}$	[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]		

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

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

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

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

