Improving electroweak fits

with TeV-scale sterile neutrinos

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EWPO	Theory (Standard Model)	Experiment
Γ_{lept} (MeV)	84.005 ± 0.015	83.984 ± 0.086
$\Gamma_{\text{inv}}/\Gamma_{\text{lept}}$	5.9721 ± 0.0002	5.942 ± 0.016
$\sin^2 \theta_{\text{W}}$	0.23150 ± 0.0001	0.2324 ± 0.0012
g_{L}^2	0.3040 ± 0.0002	0.3026 ± 0.0012
g_{R}^2	0.0300 ± 0.0002	0.0303 ± 0.0010
M_{W} (GeV)	80.359 ± 0.011	80.385 ± 0.015

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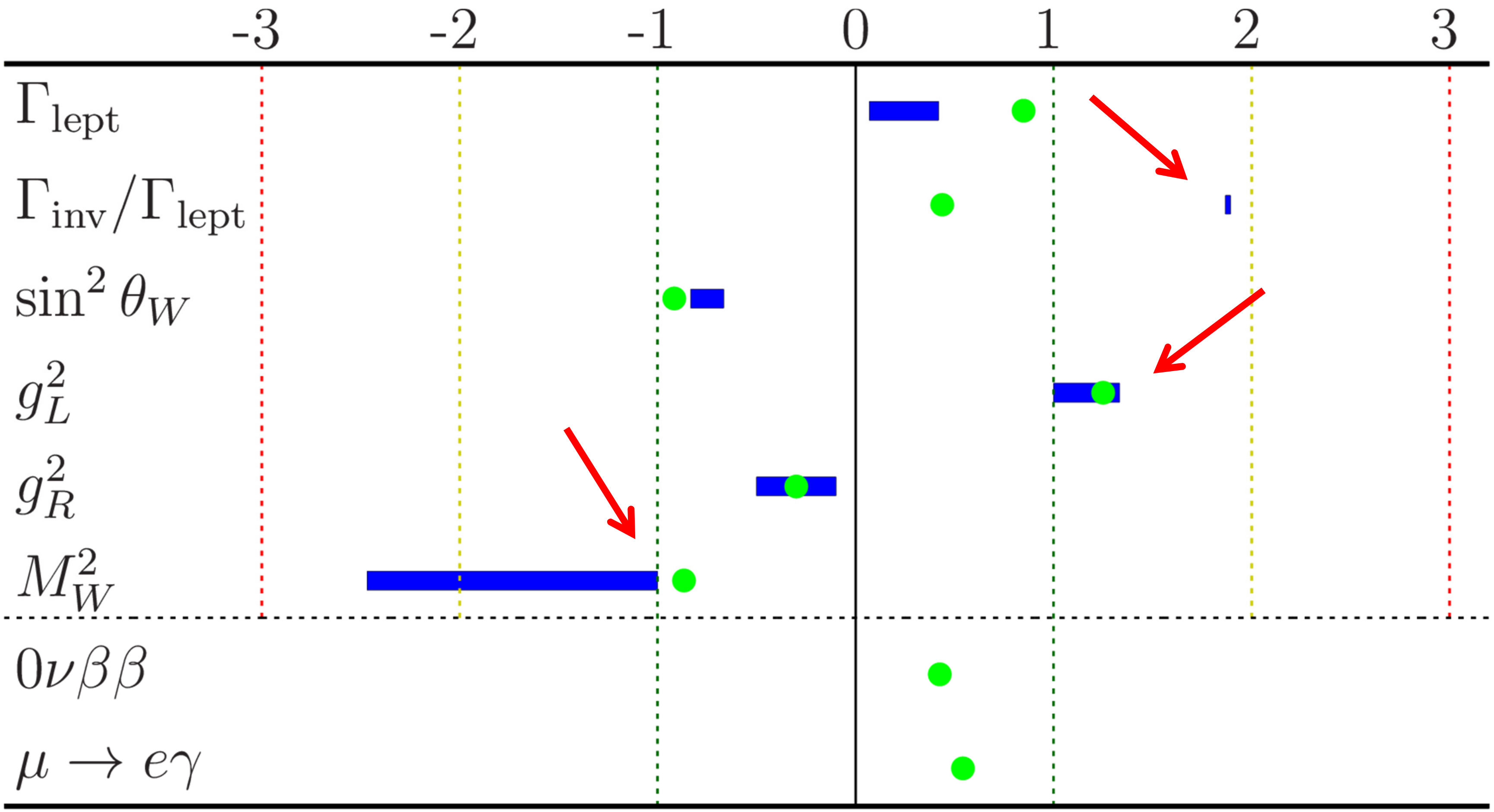
Improved electroweak fit



Outline

1. Why are low energy observables affected ?
2. Which observables are affected ?
3. Parameter scan
4. What comes out ?
5. Summary

Why are SM observables affected?

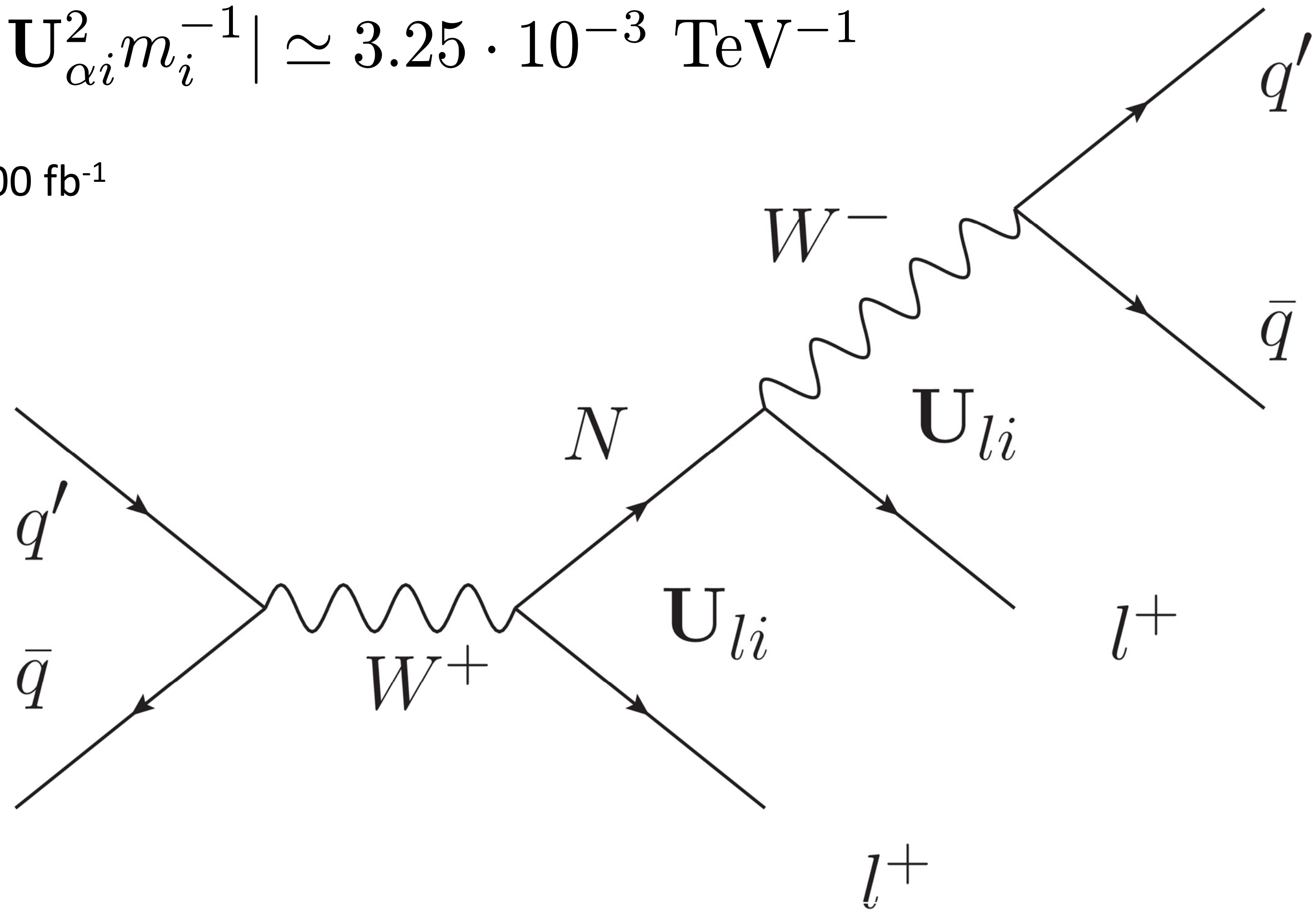
PMNS matrix → $\begin{pmatrix} \mathscr{U} & \mathscr{R} \\ \mathscr{W} & \mathscr{V} \end{pmatrix}$

$$\mathscr{L}_{\text{int}} = -\frac{e}{2c_w s_w} Z_\mu \sum_{i,j=1}^{3+n} \sum_{\alpha=e,\mu,\tau} \bar{\nu}_i \mathbf{U}^\dagger_{i\alpha} \gamma^\mu P_L \mathbf{U}_{\alpha j} \nu_j$$
$$- \frac{e}{\sqrt{2} s_w} W_\mu \sum_{i=1}^{3+n} \sum_{\alpha=e,\mu,\tau} \bar{\nu}_i \mathbf{U}^\dagger_{i\alpha} \gamma^\mu P_L e_\alpha + \text{h.c.}$$

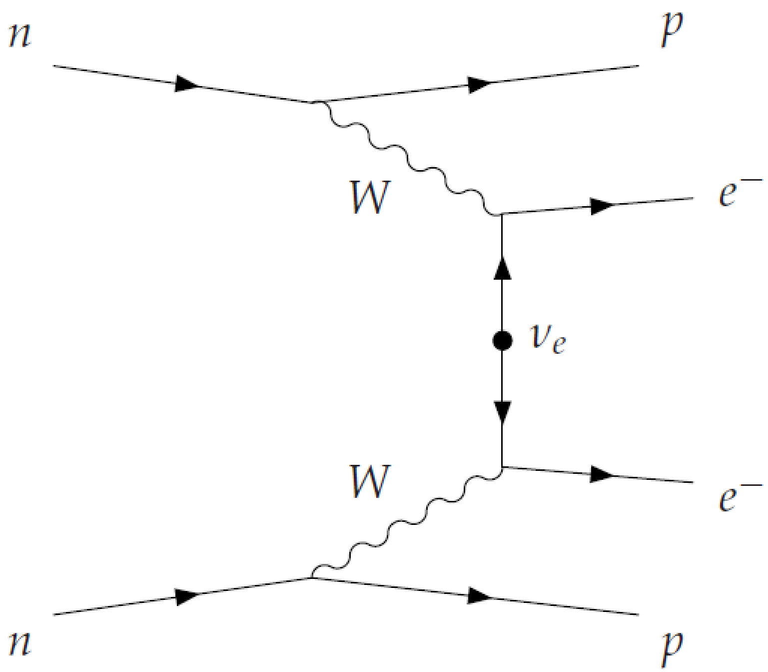
Heavy neutrinos in colliders

$$|\sum_i \mathbf{U}^2_{\alpha i} m_i^{-1}| \simeq 3.25 \cdot 10^{-3}\ \mathrm{TeV}^{-1}$$

for 400 fb^{-1}



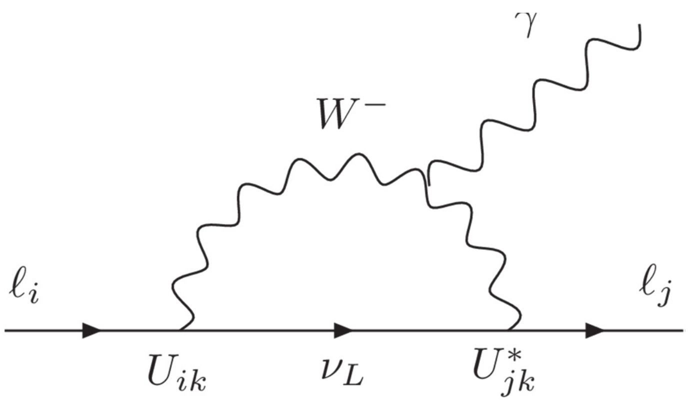
Neutrinoless double-beta decay



$$|\langle m_{ee}\rangle| \approx \left|\sum_{i=1}^{3} \mathbf{U}_{ei}^2 m_i - \sum_{i=4}^{3+n} F(A, M_i)\mathbf{U}_{ei}^2 m_i\right|$$

$$|\langle m_{ee}\rangle| < 0.2\, -\, 0.4 \text{ eV}$$

Lepton-flavor violating decays



Abada, arXiv:1110.6507

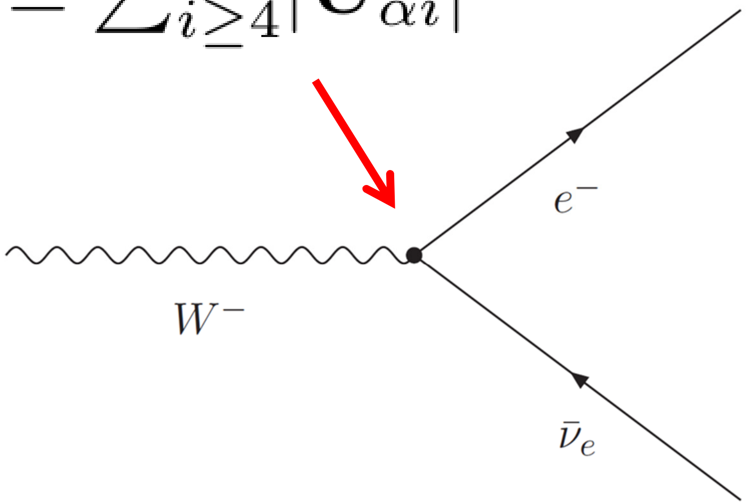
$$\mathrm{BR}(\mu \to e\gamma) = \frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to e\nu\bar{\nu})} = \frac{3\alpha}{32\pi}|\delta_\nu|^2$$

$$\delta_\nu = 2\sum_{i=4}^{3+n} \mathbf{U}_{ei}^* \mathbf{U}_{\mu i} \left[g\left(m_i^2/M_W^2\right) - 5/3\right]$$

$$\mathrm{BR}(\mu^+ \to e^+\gamma) \leq 5.7 \cdot 10^{-13}$$

Lepton universality constraints

$$\epsilon_\alpha \equiv \sum_{i\geq 4} |\mathbf{U}_{\alpha i}|^2$$



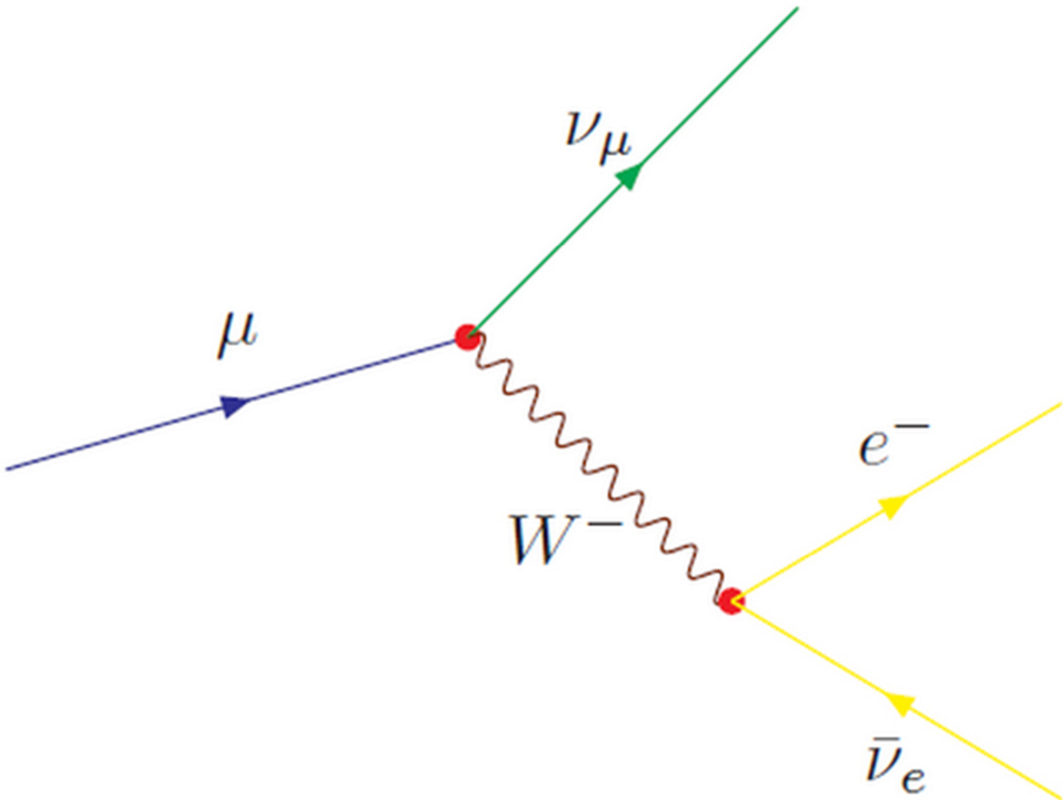
$$\epsilon_e - \epsilon_\mu = 0.0022 \pm 0.0025$$
$$\epsilon_\mu - \epsilon_\tau = 0.0017 \pm 0.0038$$
$$\epsilon_e - \epsilon_\tau = 0.0039 \pm 0.0040$$

Loinaz et. al., hep-ph/0403306

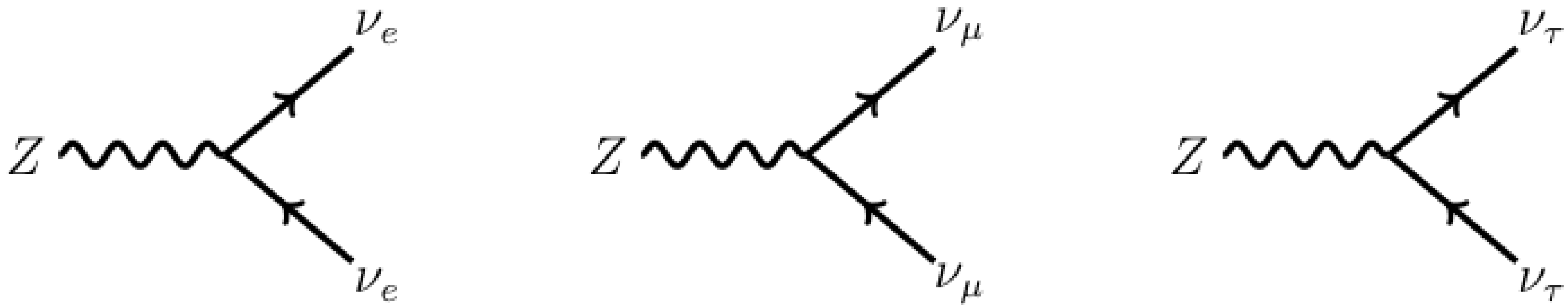
Non-unitarity in oscillations

$$P_{\alpha\beta}(L=0) = \frac{\delta_{\alpha\beta}\left(1-2\epsilon_\alpha\right)+\epsilon_\alpha\epsilon_\beta}{(1-\epsilon_\alpha)(1-\epsilon_\beta)}$$

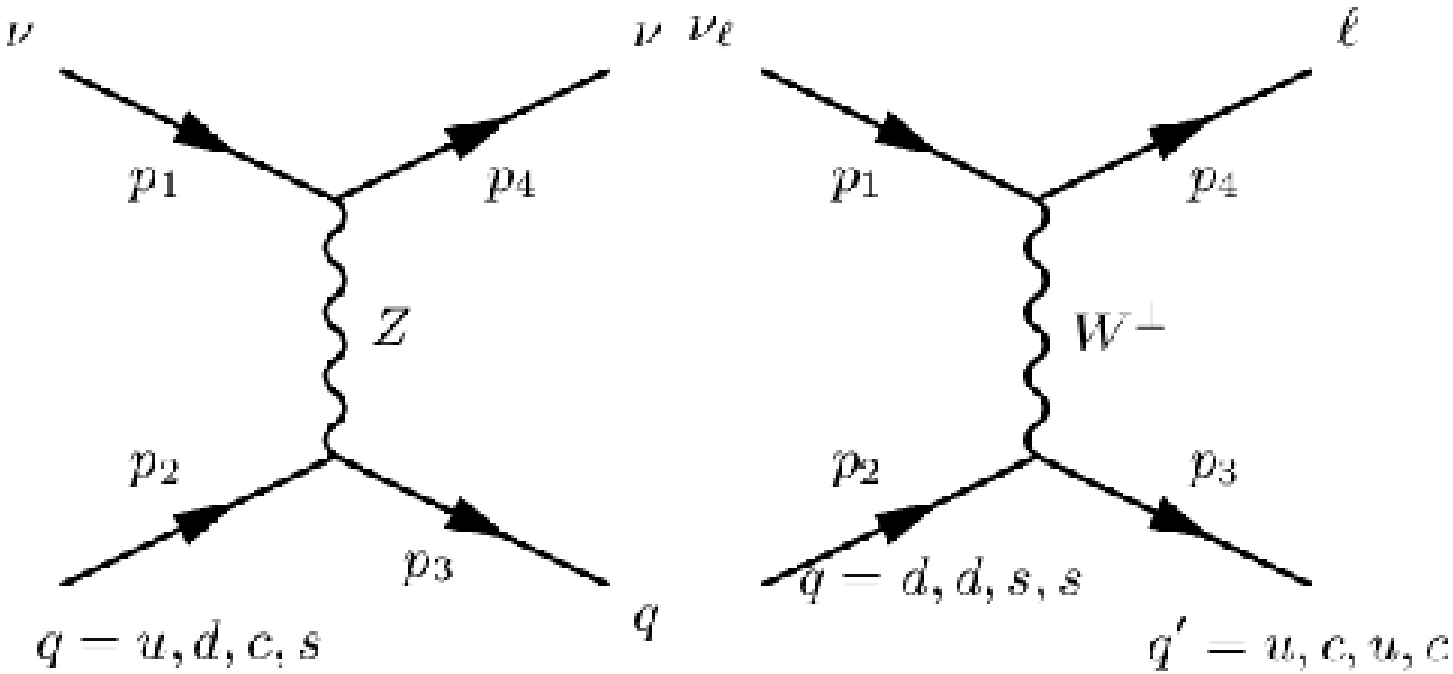
Fermi constant



Invisible Z-decay width

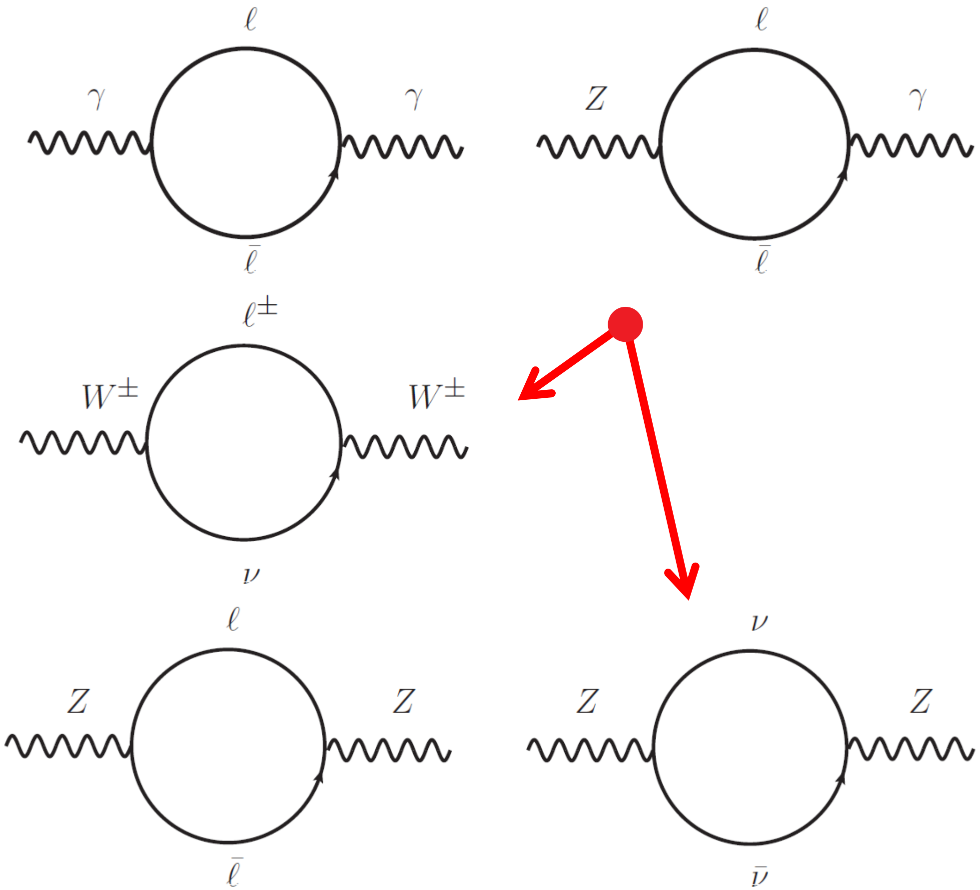


Charged to neutral current ratio



Park, Kwangwoo et al. arXiv:0910.5013

Loop corrections



Tree-level and loop corrections

$$\frac{\Gamma_{\rm lept}}{[\Gamma_{\rm lept}]_{\rm SM}} = 1 + 0.6\,(\epsilon_e + \epsilon_\mu + 0.0145\,T) - 0.0021\,S\,,$$

$$\frac{\Gamma_{\rm inv}/\Gamma_{\rm lept}}{[\Gamma_{\rm inv}/\Gamma_{\rm lept}]_{\rm SM}} = 1 - 0.67\,(\epsilon_e + \epsilon_\mu + \epsilon_\tau) + 0.0021\,S - 0.0015\,T\,,$$

$$\frac{\sin^2\theta_{\rm w}^{\rm lept}}{\left[\sin^2\theta_{\rm w}^{\rm lept}\right]_{\rm SM}} = 1 - 0.72\,(\epsilon_e + \epsilon_\mu + 0.0145\,T) + 0.0016\,S\,,$$

$$\frac{g_L^2}{[g_L^2]_{\rm SM}} = 1 + 0.41\,\epsilon_e - 0.59\,\epsilon_\mu - 0.0090\,S + 0.0022\,T\,,$$

$$\frac{g_R^2}{[g_R^2]_{\rm SM}} = 1 - 1.4\,\epsilon_e - 2.4\,\epsilon_\mu + 0.031\,S - 0.0067\,T\,,$$

$$\frac{M_{\rm W}}{[M_{\rm W}]_{\rm SM}} = 1 + 0.11\,\epsilon_e + 0.11\,\epsilon_\mu - 0.0036\,S + 0.0056\,T + 0.0042\,U\,.$$

Loinaz et. al., hep-ph/0403306

Parameter scan

$$\mathscr{R} = -i\,\mathcal{U}\,\hat{m}_{\text{light}}^{\frac{1}{2}}\,O^{*}\,\hat{m}_{\text{heavy}}^{-\frac{1}{2}}\,,$$

$$\mathscr{U} = \left(1 - \mathscr{R}\,\mathscr{R}^{\dagger}\right)^{\frac{1}{2}}\mathcal{U}\,,$$

M1		S		~~S~~	
M2	3	T		T	
M3		U		~~U~~	
			6		4
α1		ε1		ε1	
α2	6	ε2		ε2	
α3		ε3		ε3	

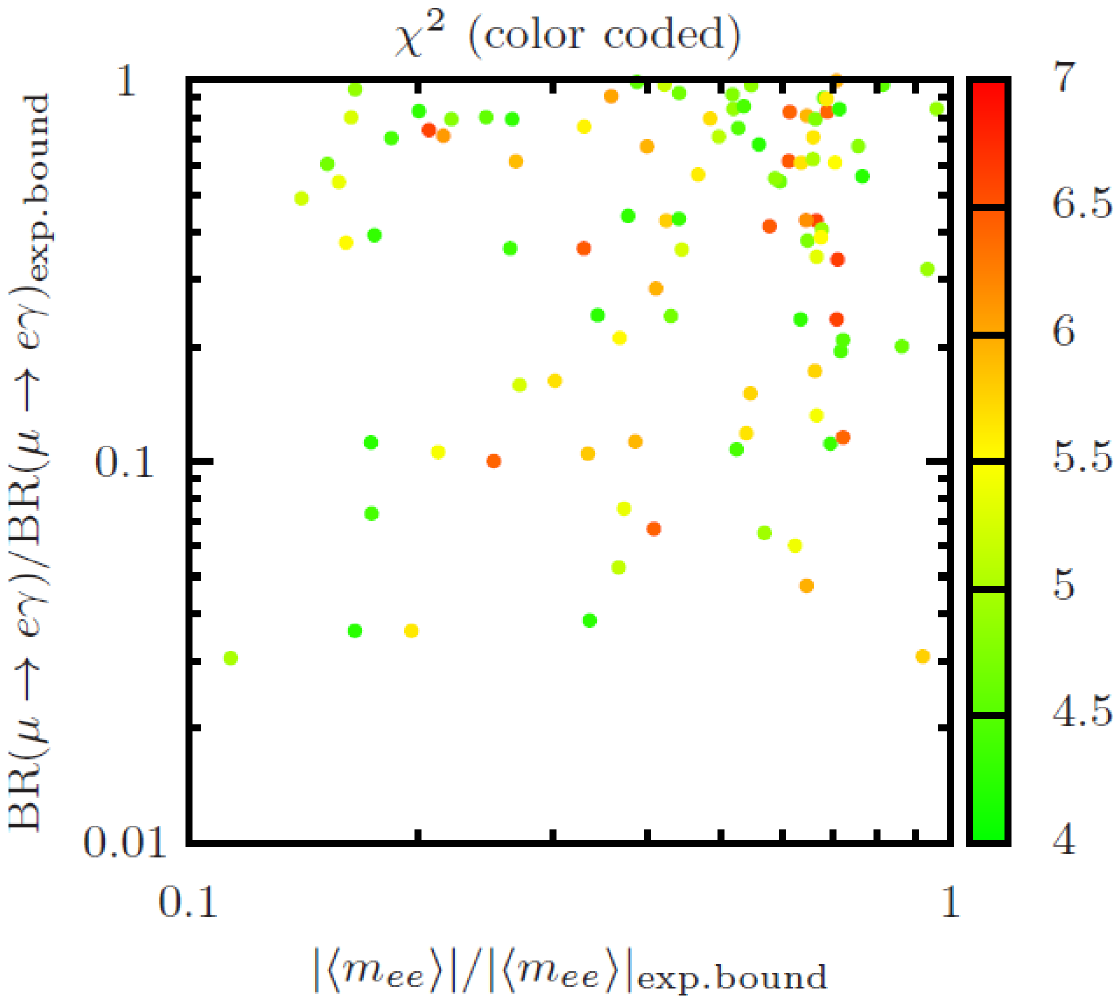
χ^2

$$\chi^2_{\mu\to e\gamma} \equiv \left(\frac{\mathrm{BR}^{th}(\mu\to e\gamma) - \mathrm{BR}^{exp}(\mu\to e\gamma)}{\mathrm{BR}^{exp}(\mu\to e\gamma)}\right)^2 \times \theta(\mathrm{BR}^{th}(\mu\to e\gamma) - \mathrm{BR}^{exp}(\mu\to e\gamma))\,,$$

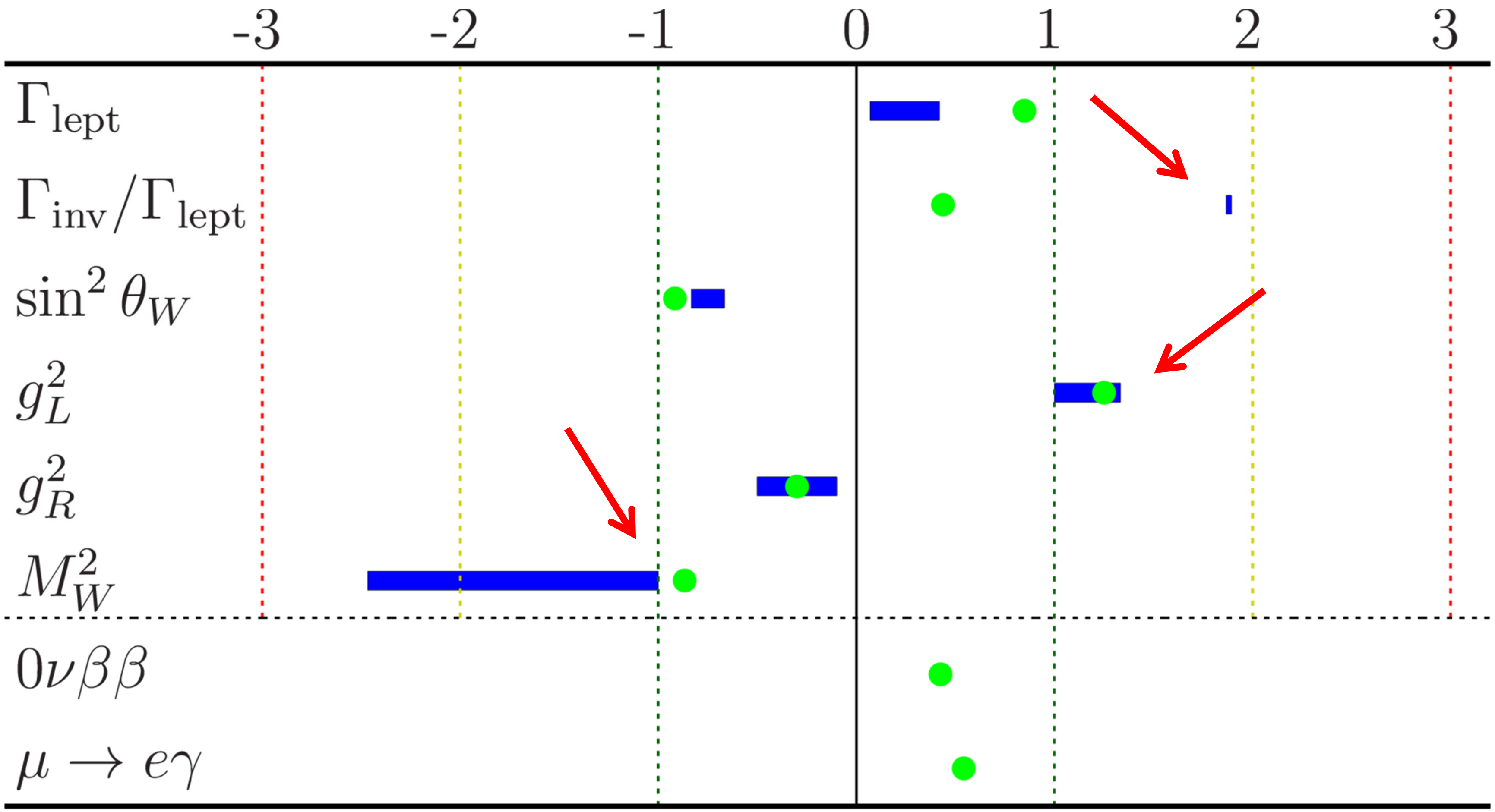
$$\chi^2_{0\nu\beta\beta} \equiv \left(\frac{|\langle m_{ee}^{th}\rangle| - |\langle m_{ee}^{exp}\rangle|}{|\langle m_{ee}^{exp}\rangle|}\right)^2 \times \theta(|\langle m_{ee}^{th}\rangle| - |\langle m_{ee}^{exp}\rangle|)\,,$$

$$\chi^2_{\mathrm{EWPO}} = \sum_i \frac{(O_i - O_{i,\mathrm{SM}})^2}{(\delta O_i)^2 + (\delta O_{i,\mathrm{SM}})^2}$$

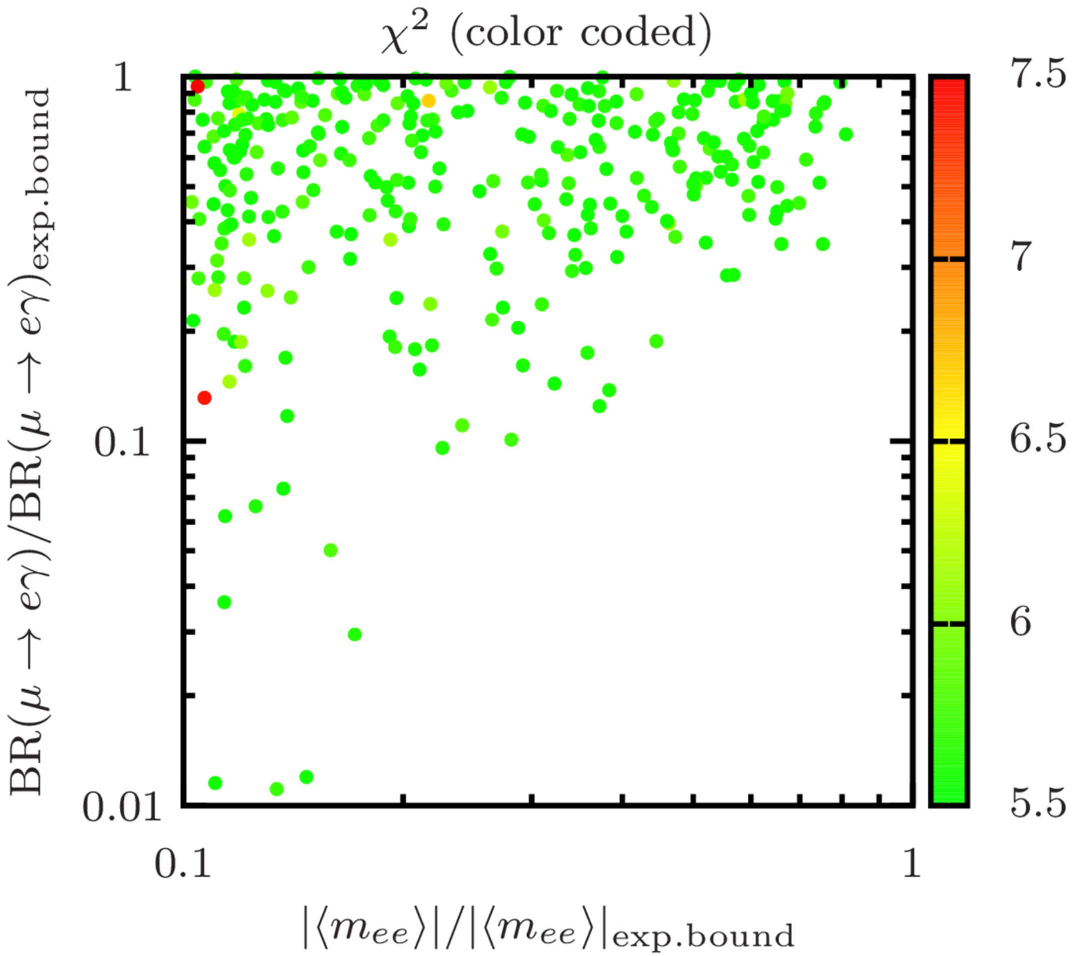
Normal hierarchy: rare processes



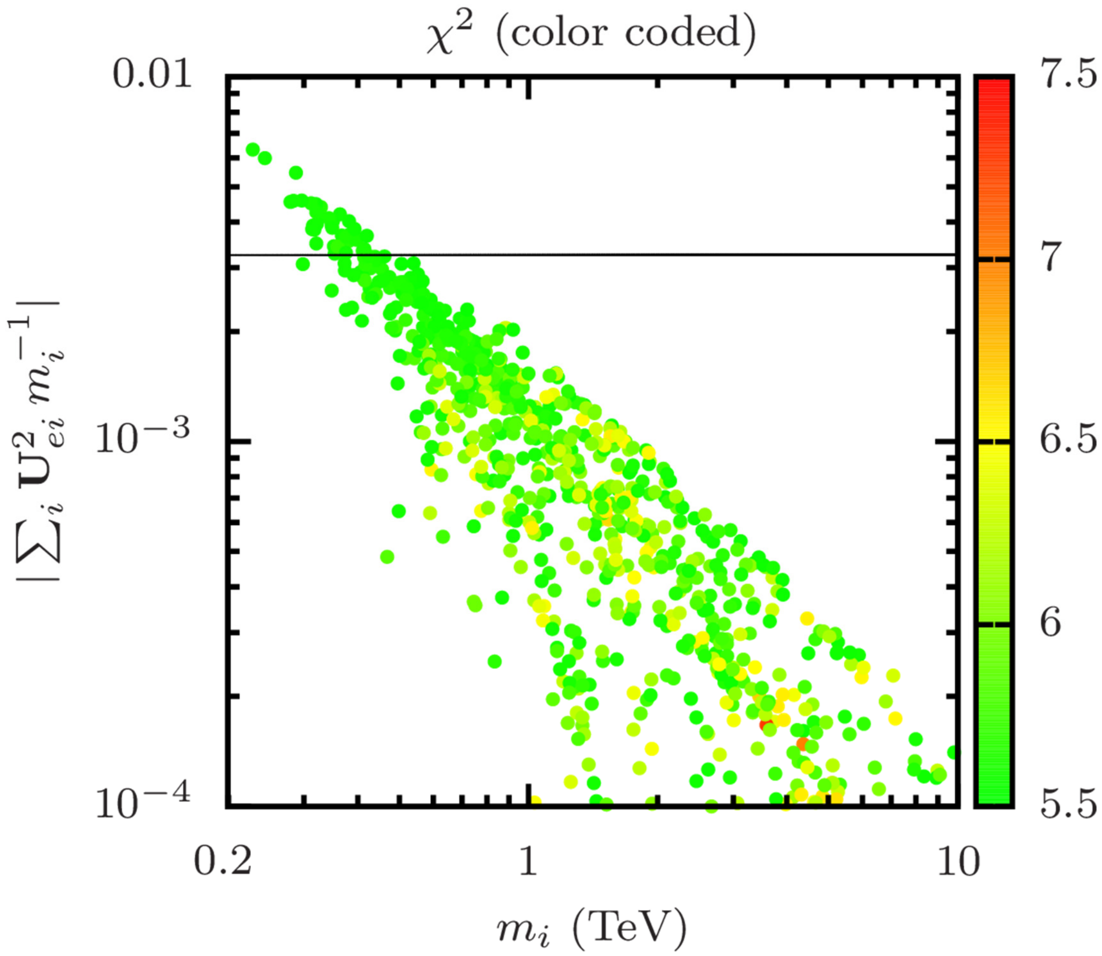
Normal hierarchy: EW fit



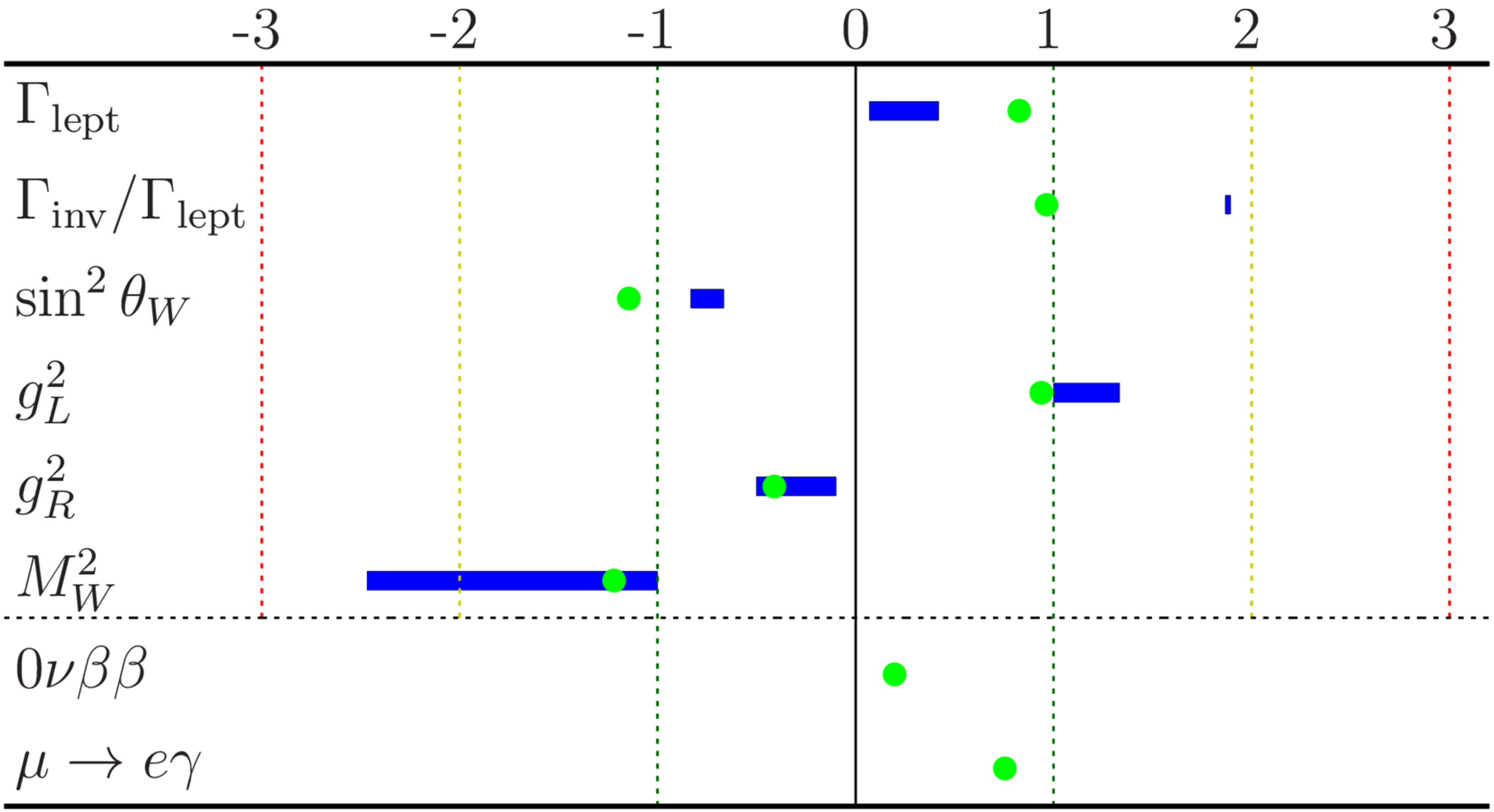
Inverted hierarchy: rare processes



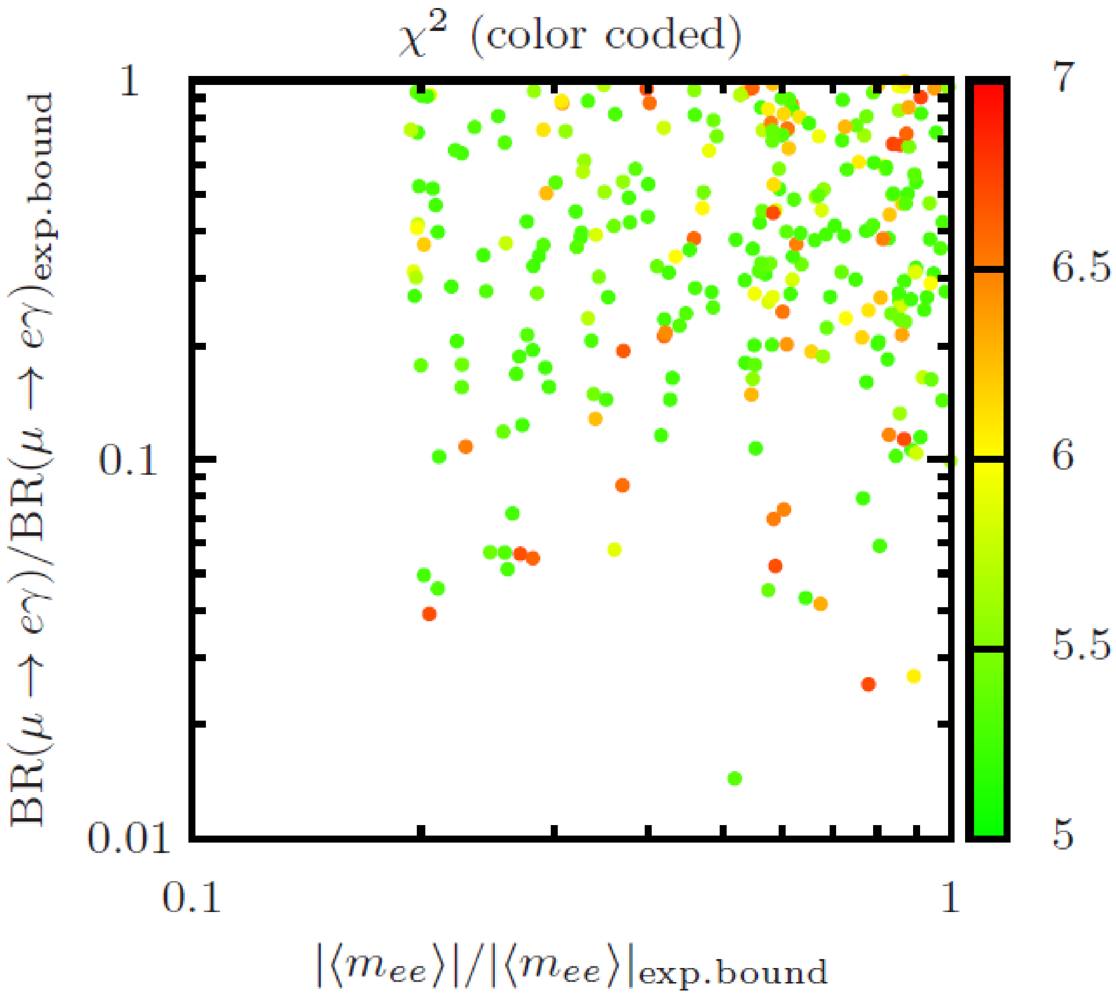
Inverted hierarchy: LHC



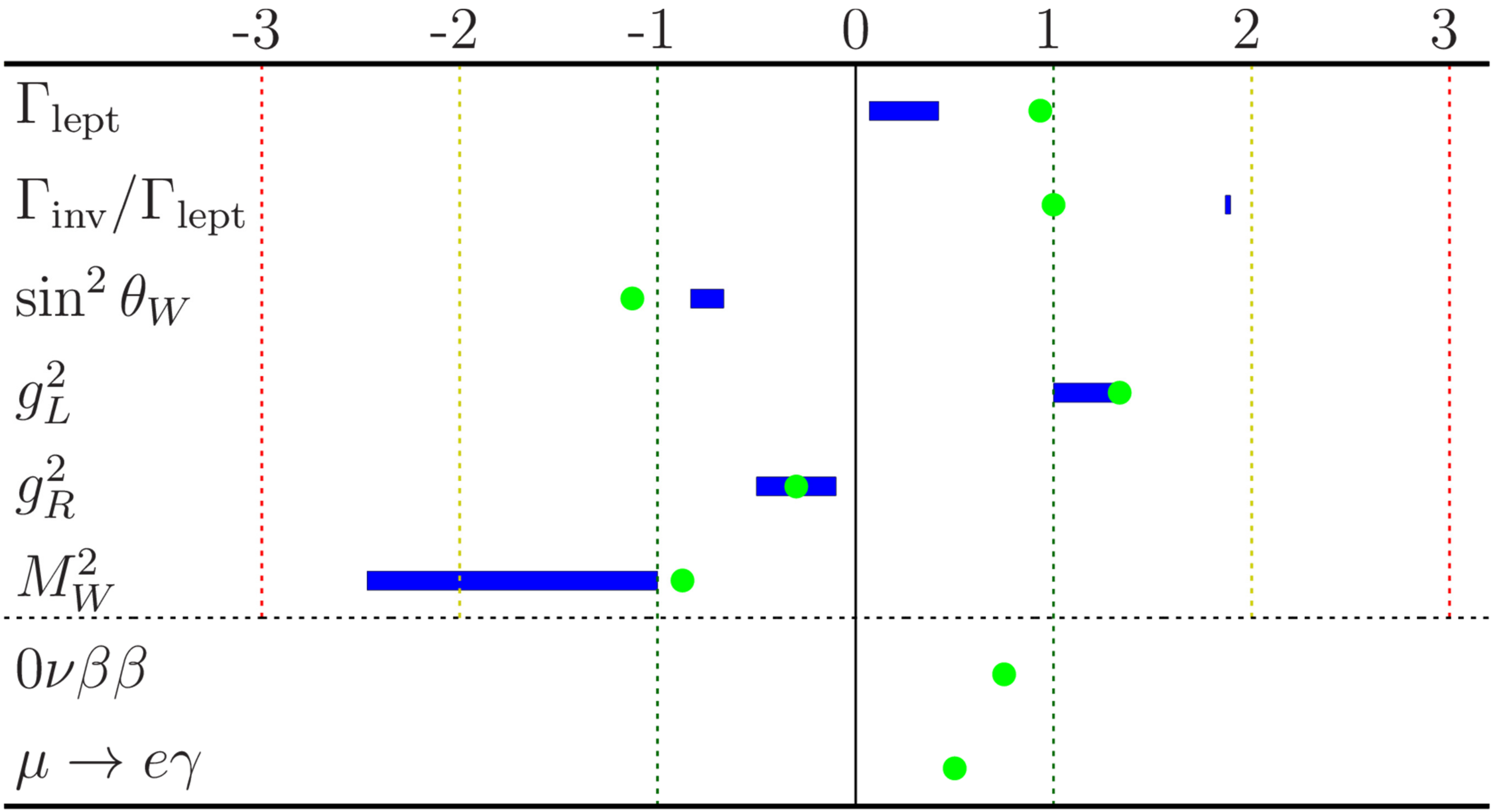
Inverted hierarchy: EW fit



Quasidegenerate: rare processes



Quasidegenerate: EW fit



Summary

RH neutrinos affect low energy observables

- via induced non-unitarity of PMNS matrix
- via loop corrections

With some fine tuning the fit can be improved

- neutral-to-charged current ratio
- W-boson mass
- to a lesser extent invisible Z-decay width

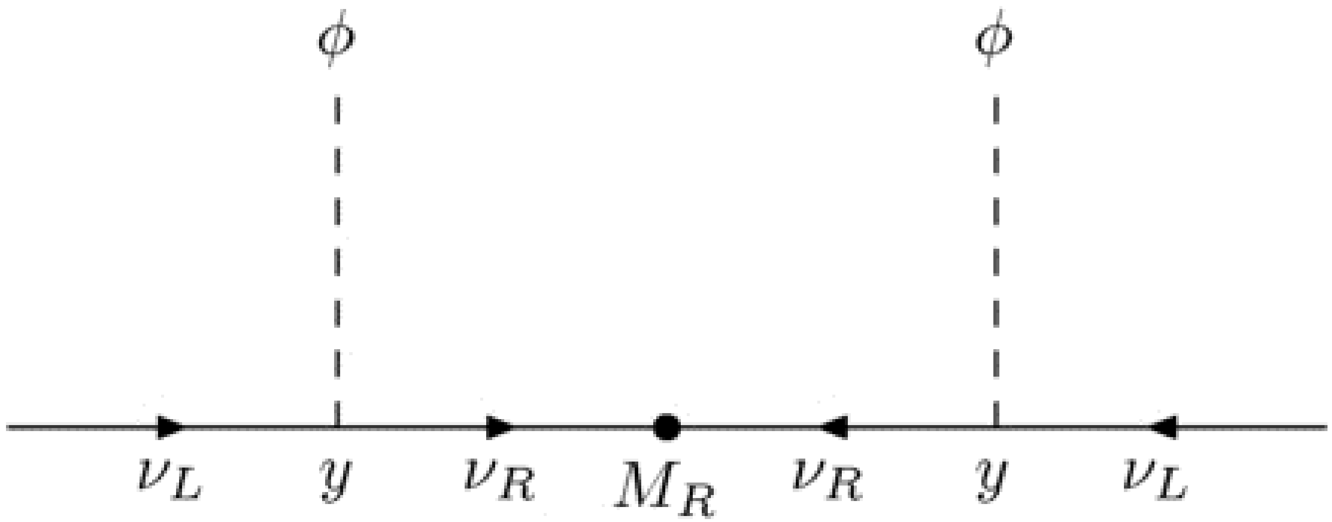
STU parameters

$$S = \frac{4s_w^2 c_w^2}{M_Z^2}\left[\Pi_{ZZ}(0) - \Pi_{ZZ}(M_Z^2) + \Pi_{\gamma\gamma}(M_Z^2) - \frac{c_w^2 - s_w^2}{c_w s_w}\Pi_{Z\gamma}(M_Z^2)\right]$$

$$T = \frac{\Pi_{ZZ}(0)}{M_Z^2} - \frac{\Pi_{WW}(0)}{M_W^2}$$

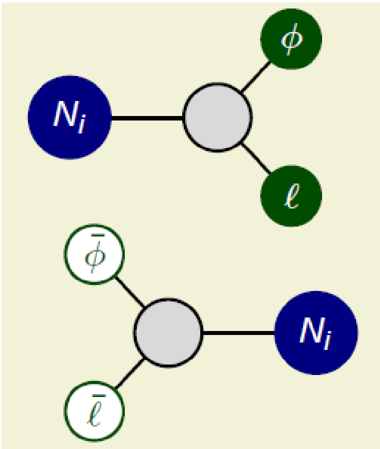
$$U = 4s_w^2 c_w^2\left[\frac{\Pi_{WW}(0) - \Pi_{WW}(M_W^2)}{c_w^2 M_W^2} - \frac{\Pi_{ZZ}(0) - \Pi_{ZZ}(M_Z^2)}{M_Z^2} + \frac{s_w^2}{c_w^2}\frac{\Pi_{\gamma\gamma}(M_Z^2)}{M_Z^2} - 2\frac{s_w}{c_w}\frac{\Pi_{Z\gamma}(M_Z^2)}{M_Z^2}\right]$$

See-saw mechanism

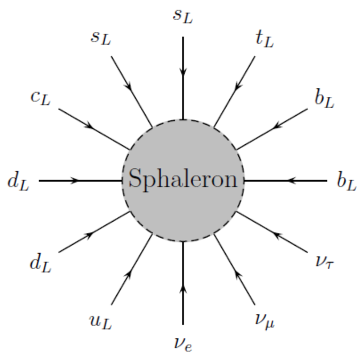


$$\mathcal{M}_\nu = \mathcal{M}_D^T \mathcal{M}_M^{-1} \mathcal{M}_D$$

Baryogenesis via leptogenesis



→ ΔL →



→ ΔB →