Construction of lepton mass matrices and TeV-scale phenomenology in the minimal left-right symmetric model

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Minimal left-right symmetric model

$$\mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \otimes \mathrm{U}(1)_{B-L}$$

$$L'_{Li} = \begin{pmatrix} \nu'_{Li} \\ \ell'_{Li} \end{pmatrix} \sim (\mathbf{2}, \mathbf{1}, -1), \qquad L'_{Ri} = \begin{pmatrix} \nu'_{Ri} \\ \ell'_{Ri} \end{pmatrix} \sim (\mathbf{1}, \mathbf{2}, -1)$$

Scalar

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \sim (\mathbf{2}, \mathbf{2}, 0)$$

$$\Delta_L = \begin{pmatrix} \delta_L^+/\sqrt{2} & \delta_L^{++} \\ \delta_L^0 & -\delta_L^+/\sqrt{2} \end{pmatrix} \sim (\mathbf{3}, \mathbf{1}, 2), \qquad \Delta_R = \begin{pmatrix} \delta_R^+/\sqrt{2} & \delta_R^{++} \\ \delta_R^0 & -\delta_R^+/\sqrt{2} \end{pmatrix} \sim (\mathbf{1}, \mathbf{3}, 2)$$

$$\mathcal{L}_Y^\ell = -\overline{L'_{Li}}(f_{ij}\Phi + \tilde{f}_{ij}\tilde{\Phi})L'_{Rj} - h_{Lij}\overline{L'^c_{Li}}i\sigma_2\Delta_L L'_{Lj} - h_{Rij}\overline{L'^c_{Ri}}i\sigma_2\Delta_R L'_{Rj} + \mathrm{H.c.}$$

Complex!

VEV

$$\Phi = \begin{pmatrix} \kappa_1/\sqrt{2} & 0 \\ 0 & \kappa_2 e^{i\alpha}/\sqrt{2} \end{pmatrix}, \qquad \Delta_L = \begin{pmatrix} 0 & 0 \\ v_L e^{i\theta_L}/\sqrt{2} & 0 \end{pmatrix}, \qquad \Delta_R = \begin{pmatrix} 0 & 0 \\ v_R/\sqrt{2} & 0 \end{pmatrix}$$

$$M_\ell = \frac{1}{\sqrt{2}}(f\kappa_2 e^{i\alpha} + \tilde{f}\kappa_1)$$

$$\mathcal{L}_\nu^{\mathrm{mass}} = -\frac{1}{2}(\overline{\nu'_L}\ \overline{\nu'^c_R})\begin{pmatrix} M_L & M_D \\ M_D^{\mathsf{T}} & M_R \end{pmatrix}\begin{pmatrix} \nu'^c_L \\ \nu'_R \end{pmatrix} + \mathrm{H.c.}$$

$$M_D = \frac{1}{\sqrt{2}}(f\kappa_1 + \tilde{f}\kappa_2 e^{-i\alpha}), \qquad M_L = \sqrt{2}h_L^* v_L e^{-i\theta_L}, \qquad M_R = \sqrt{2}h_R v_R$$

Seesaw

$$M_\nu \approx M_L - M_D M_R^{-1} M_D^{\mathsf{T}}$$

Type-II <u>Type-I</u>

Parity symmetry

Hermitian matrices

$$L'_{Li} \leftrightarrow L'_{Ri}, \qquad \Delta_L \leftrightarrow \Delta_R, \qquad \Phi \leftrightarrow \Phi^\dagger, \qquad f = f^\dagger, \qquad \tilde{f} = \tilde{f}^\dagger, \qquad h_L = h_R$$

TeV-scale MLRSM

$$M_\ell = \frac{1}{\sqrt{2}}(f\kappa_2 e^{i\alpha} + \tilde{f}\kappa_1), \quad M_D = \frac{1}{\sqrt{2}}(f\kappa_1 + \tilde{f}\kappa_2 e^{-i\alpha})$$

$$M_\nu \approx -M_D M_R^{-1} M_D^{\mathsf{T}}$$

1. The largest component of M_l ~ m_τ ~ O(1) GeV

→ The largest component of M_D ~ O(1) GeV

2. m_ν < O(0.1) eV (Planck)

→ m_N > O(10^{10}) GeV

For **TeV-scale** m_N, we need $|M_{Dij}|$ < O(10^{-3}) GeV.

→ **Fine-tuning** in M_D?

Conditions for the TeV-scale MLRSM **without fine-tuning**

(i) $\kappa_1 \gg \kappa_2$, $f_{ij} \ll \tilde{f}_{ij}$, and $V_L^\ell \approx V_R^\ell$, or (ii) $\kappa_1 \ll \kappa_2$, $f_{ij} \gg \tilde{f}_{ij}$, and $V_L^\ell \approx V_R^\ell e^{-i\alpha}$.

Previous works on CLFV and 0νββ in the MLRSM

[8] E.Kh. Akhmedov and M. Frigerio, *Duality in Left-Right Symmetric Seesaw Mechanism*, *Phys. Rev. Lett.* **96** (2006) 061802.

← Mass matrix construction for real EW VEV's

[9] M. Nemevšek, G. Senjanović and V. Tello, *Connecting Dirac and Majorana Neutrino Mass Matrices in the Minimal Left-Right Symmetric Model*, *Phys. Rev. Lett.* **110** (2013) 151802.

[10] J. Barry and W. Rodejohann, *Lepton number and flavour violation in TeV-scale left-right symmetric theories with large left-right mixing*, *JHEP* **09** (2013) 153.

[11] G. Bambhaniya, P.S. Bhupal Dev, S. Goswamia, and M. Mitrad, *The scalar triplet contribution to lepton flavour violation and neutrinoless double beta decay in Left-Right Symmetric Model*, *JHEP* **04** (2016) 046.

[12] D. Borah and A. Dasgupta, *Charged lepton flavour violation and neutrinoless double beta decay in left-right symmetric models with type I+II seesaw*, *JHEP* **07** (2016) 022.

[13] C. Bonilla, M.E. Krauss, T. Opferkuch, and W. Porod, *Perspectives for detecting lepton flavour violation in left-right symmetric models*, *JHEP* **03** (2017) 027.

CLFV, 0νββ

1. **Real electroweak VEV's** were explicitly or implicitly assumed.

2. M_D or M_R was chosen without considering the issue of **fine-tuning**.

3. μ → eee: the **type-I contribution** was neglected.

Construction of lepton mass matrices

Gauge basis

Charged lepton mass basis

$$M_\ell = V_L^\ell M_\ell^c V_R^{\ell\dagger} = Ae^{i\alpha} + B \; (A \equiv f\kappa_2/\sqrt{2},\; B \equiv \tilde{f}\kappa_1/\sqrt{2})$$

Choose $|A_{11}| > \left|\mathrm{Im}[M_{11}]\right|$ (*M* = *M*$_l$)

$$\sin\alpha = \pm\frac{\left|\mathrm{Im}[M_{11}]\right|}{|A_{11}|}$$

Hermitian matrices

$$A_{ij} = \pm\frac{|A_{11}|}{2\left|\mathrm{Im}[M_{11}]\right|}\left(\mathrm{Im}[M_{ji} + M_{ij}] + i\mathrm{Re}[M_{ji} - M_{ij}]\right)$$

$$B_{ij} = \frac{1}{2}\left(\mathrm{Re}[M_{ji} + M_{ij}] - i\mathrm{Im}[M_{ji} - M_{ij}]\right) - A_{ij}\cos\alpha$$

Experimental constraints

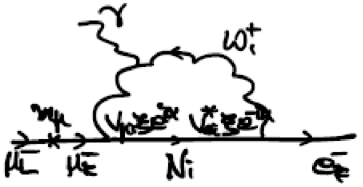
	Present bound	Future sensitivity
$\mathrm{BR}_{\mu\to e\gamma}$	$< 4.2 \cdot 10^{-13}$ (MEG)	$< 5.0 \cdot 10^{-14}$ (Upgraded MEG)
$\mathrm{BR}_{\tau\to\mu\gamma}$	$< 4.4 \cdot 10^{-8}$ (BaBar)	$< 1.0 \cdot 10^{-9}$ (Super B factory)
$\mathrm{BR}_{\tau\to e\gamma}$	$< 3.3 \cdot 10^{-8}$ (BaBar)	$< 3.0 \cdot 10^{-9}$ (Super B factory)
$\mathrm{BR}_{\mu\to eee}$	$< 1.0 \cdot 10^{-12}$ (SINDRUM)	$< 1.0 \cdot 10^{-16}$ (PSI)
$\mathrm{R}^{\mathrm{Al}}_{\mu\to e}$	·	$< 3.0 \cdot 10^{-17}$ (COMET)
$\mathrm{R}^{\mathrm{Ti}}_{\mu\to e}$	$< 6.1 \cdot 10^{-13}$ (SINDRUM II)	$< 1.0 \cdot 10^{-18}$ (PRISM/PRIME)
$\mathrm{R}^{\mathrm{Au}}_{\mu\to e}$	$< 6.0 \cdot 10^{-13}$ (SINDRUM II)	·
$\mathrm{R}^{\mathrm{Pb}}_{\mu\to e}$	$< 4.6 \cdot 10^{-11}$ (SINDRUM II)	·
$T^{0\nu}_{1/2}\big\|_{\mathrm{Ge}}$	$> 2.1 \cdot 10^{25}$ yrs. (GERDA)	$> 1.35 \cdot 10^{26}$ yrs. (GERDA II)
$T^{0\nu}_{1/2}\big\|_{\mathrm{Te}}$	·	$> 2.1 \cdot 10^{26}$ yrs. (CUORE)
$T^{0\nu}_{1/2}\big\|_{\mathrm{Xe}}$	$> 1.9 \cdot 10^{25}$ yrs. (KamLAND-Zen)	·
$\|d_e\|$	$< 8.7 \cdot 10^{-29}$ e·cm (ACME)	$< 5.0 \cdot 10^{-30}$ e·cm (PSU)
$\|d_\mu\|$	$< 1.9 \cdot 10^{-19}$ e·cm (Muon $(g-2)$)	·
$\|d_\tau\|$	$\lesssim 5.0 \cdot 10^{-17}$ e·cm (Belle)	·
$\sum_i^3 m_{\nu_i}$	< 0.23 eV (Planck)	·

CLFV

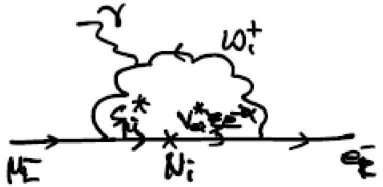
$\mu \to e\gamma$

(1) G_L^γ

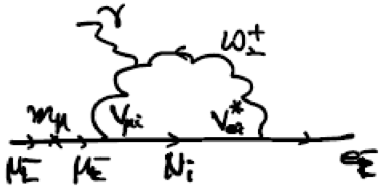
① $V_{\mu i} V^*_{ei} |\xi|^2 G_1^\gamma(x_i)$



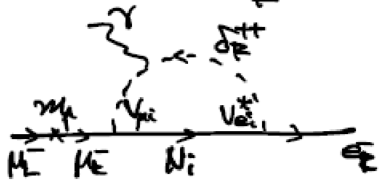
② $-S^*_{\mu i} V^*_{ei} \xi e^{-i\alpha} G_2^\gamma(x_i) \frac{M_i}{m_\mu}$



③ $V_{\mu i} V^*_{ei} \frac{m_{W_L}^2}{m_{W_R}^2} G_1^\gamma(y_i)$

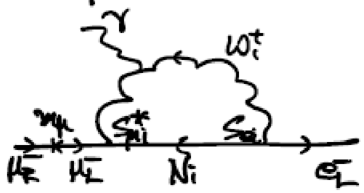


④ $V_{\mu i} V^*_{ei} \frac{2}{3} y_i \frac{m_{W_L}^2}{m_{\delta_R^{++}}^2}$

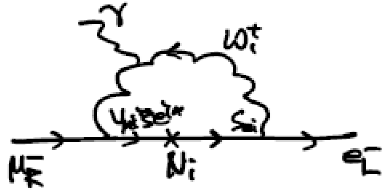


(2) G_R^γ

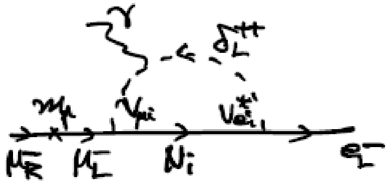
① $S^*_{\mu i} S_{ei} G_1^\gamma(x_i)$



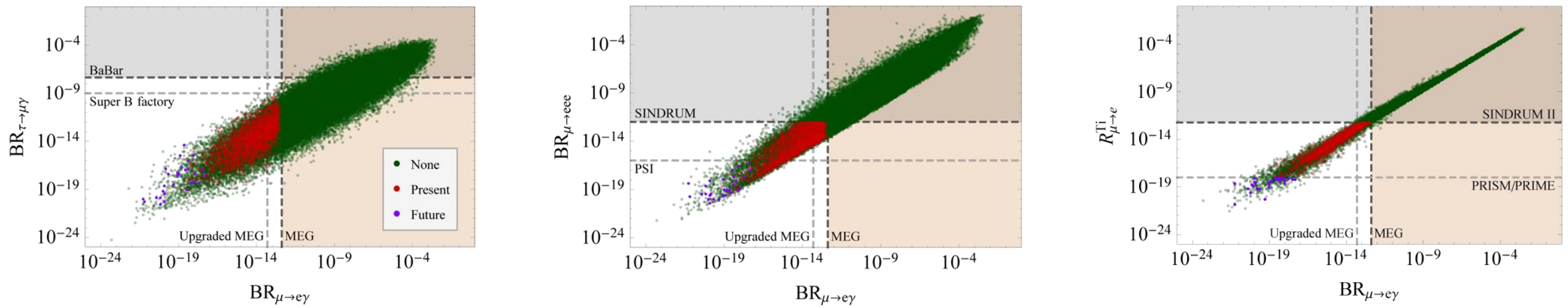
② $-V_{\mu i} S_{ei} \xi e^{i\alpha} G_2^\gamma(x_i) \frac{M_i}{m_\mu}$

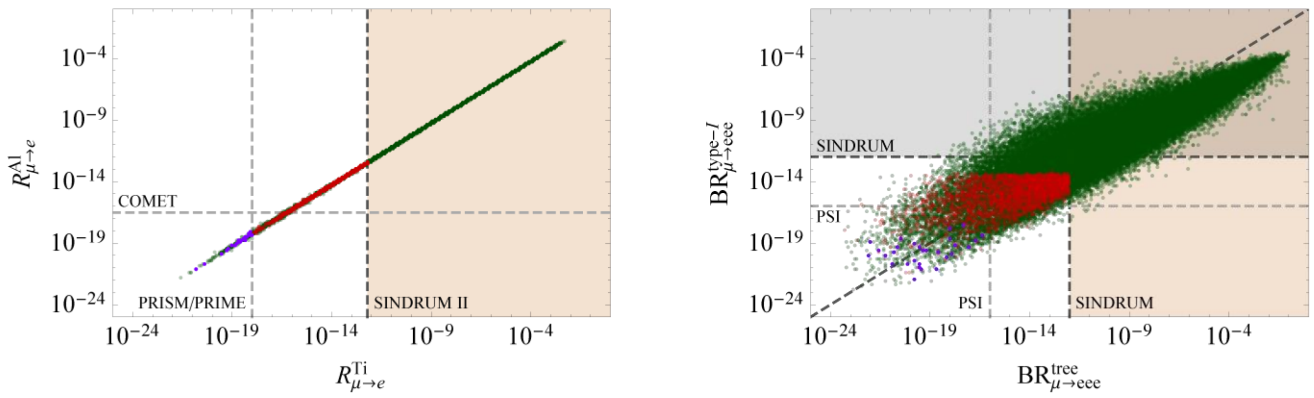


③ $V_{\mu i} V^*_{ei} \frac{2}{3} y_i \frac{m_{W_L}^2}{m_{\delta_L^{++}}^2}$



CLFV





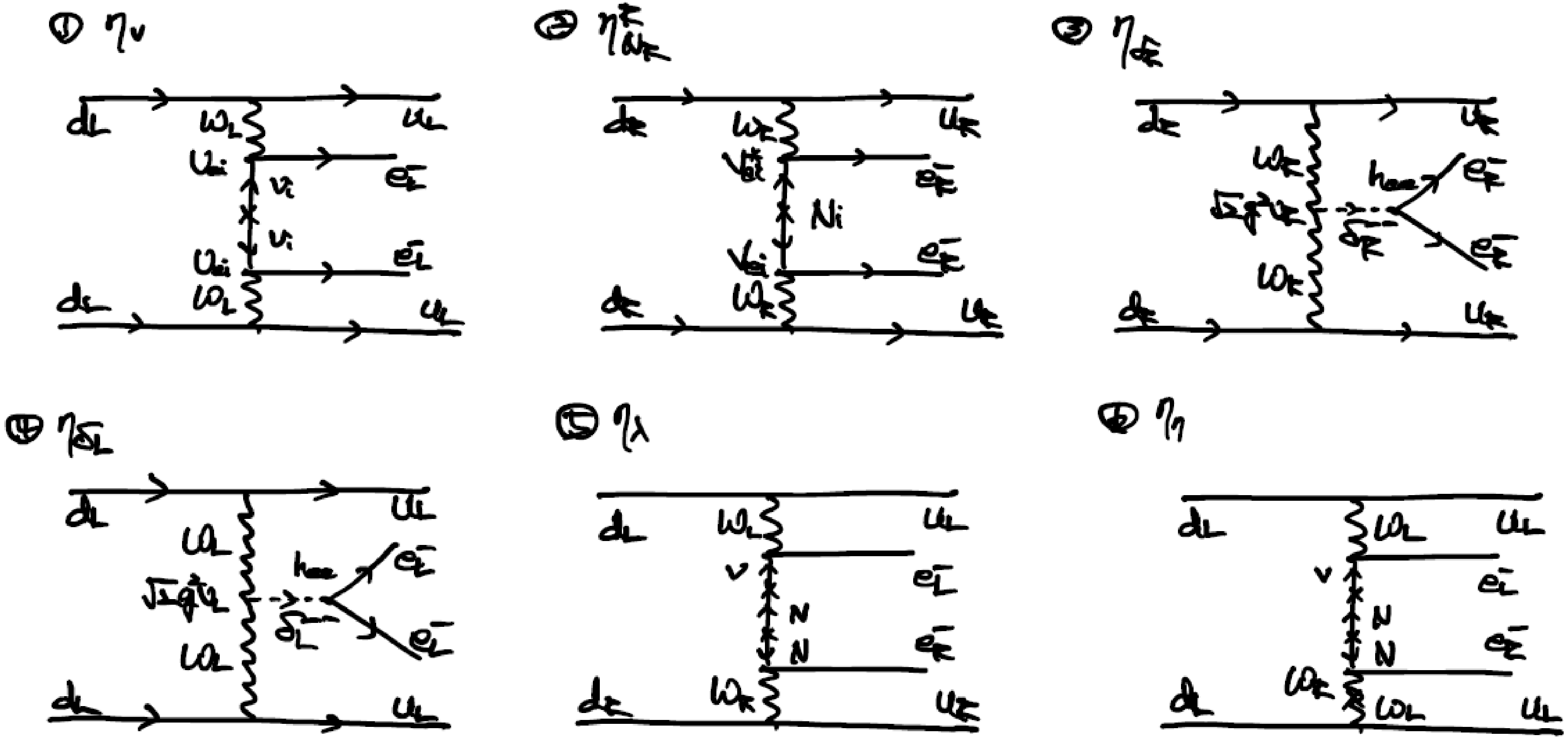
2 TeV < m_{WR} < 30 TeV

1. ***τ* decay** rates are **small** compared with experimental bounds.

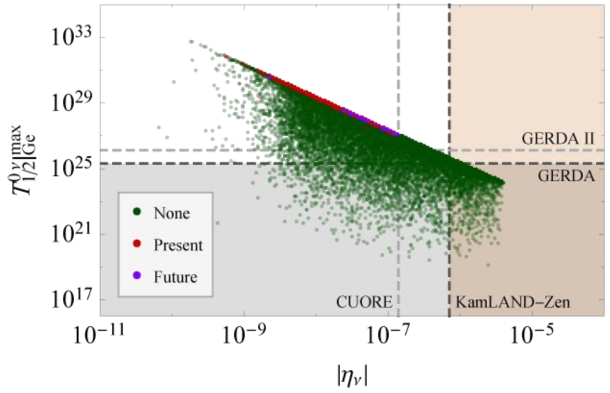
2. Strong/weak **linear correlations** among μ decay BR's.

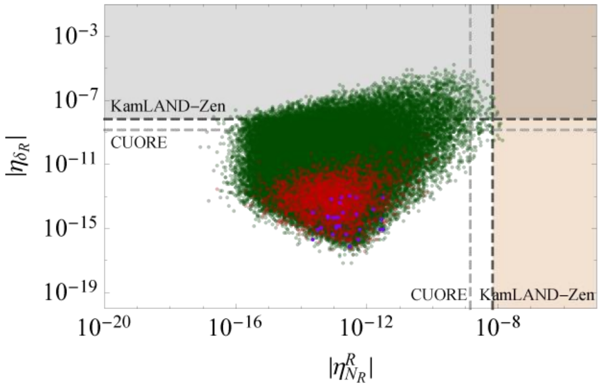
3. **Both tree-level and type-I** contributions should be considered for μ → eee.

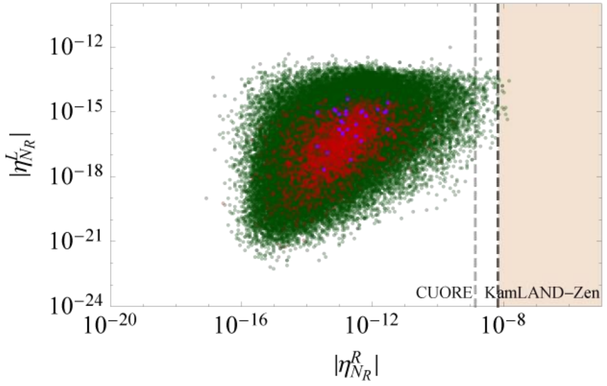
0νββ

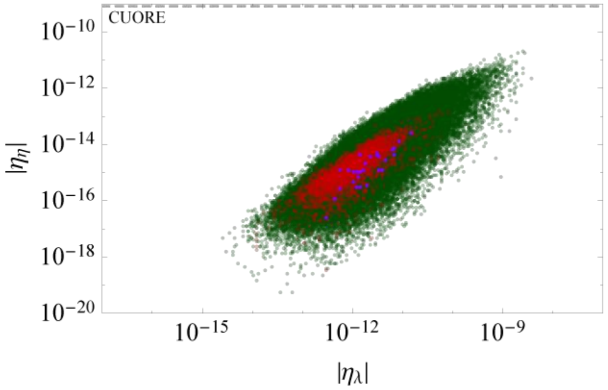


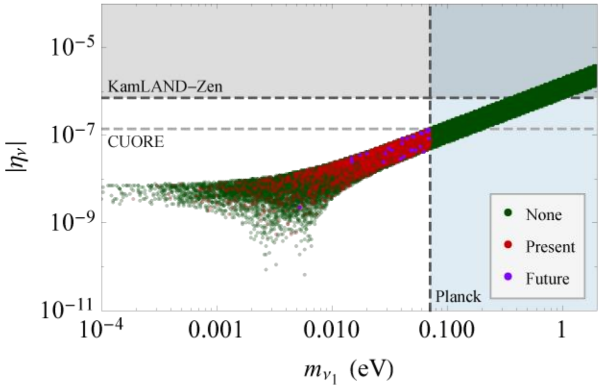
0νββ











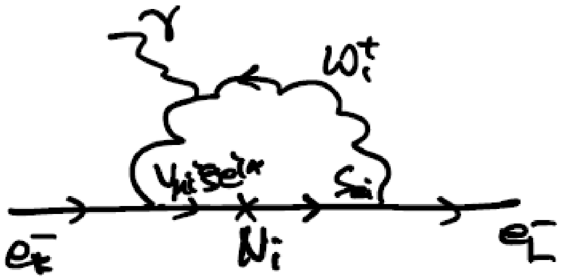
2 TeV < m_{W_R} < 30 TeV

1. The contribution from $\boldsymbol{\eta_\nu}$ **is dominant** since all the others are small by themselves or suppressed by **CLFV** constraints.

2. $\boldsymbol{\eta_\nu}$ **is suppressed** by the **Planck** constraint.

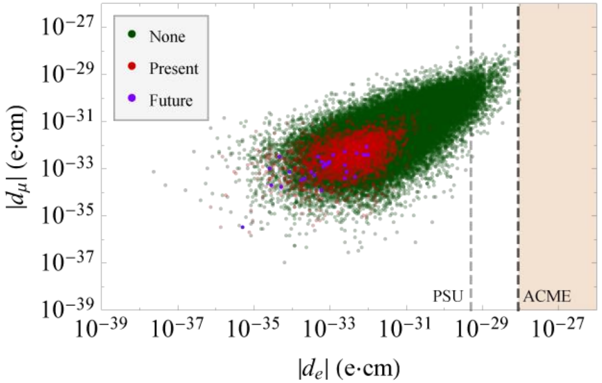
3. Consequently, **0νββ is almost unobservable** in near-future experiments.

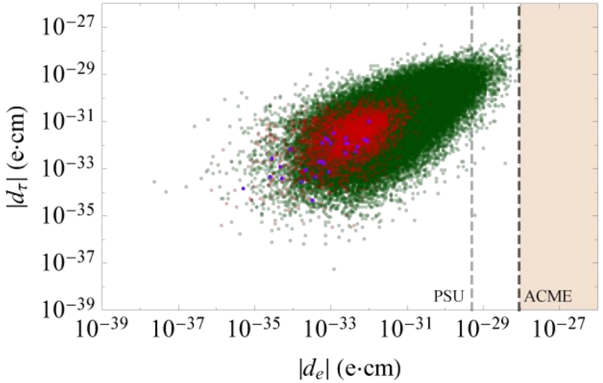
EDM's of charged leptons

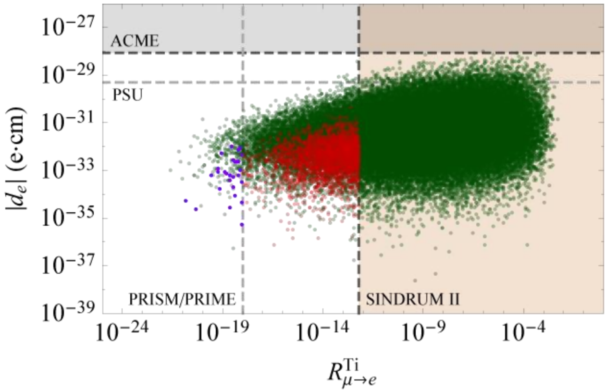


2 TeV < m_{WR} < 30 TeV

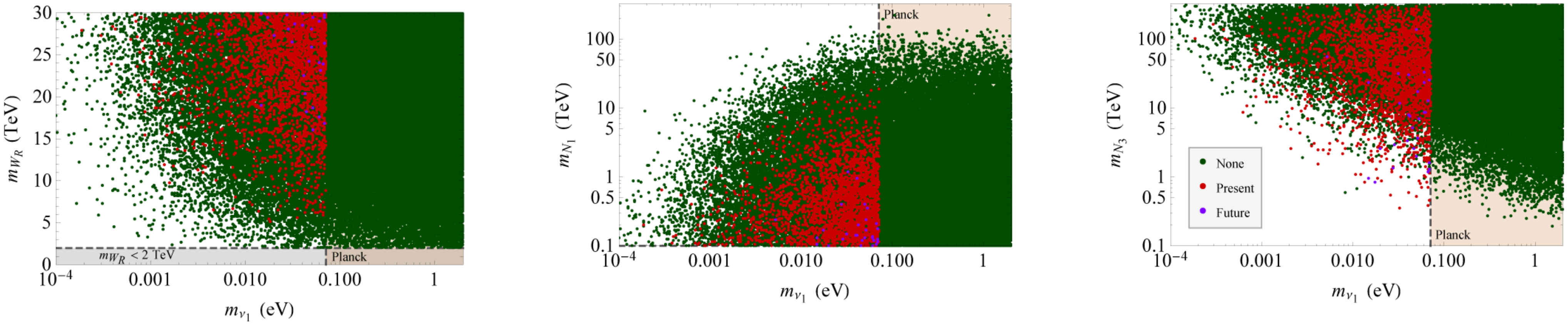
EDM's are **too small** due to the **CLFV** constraints.







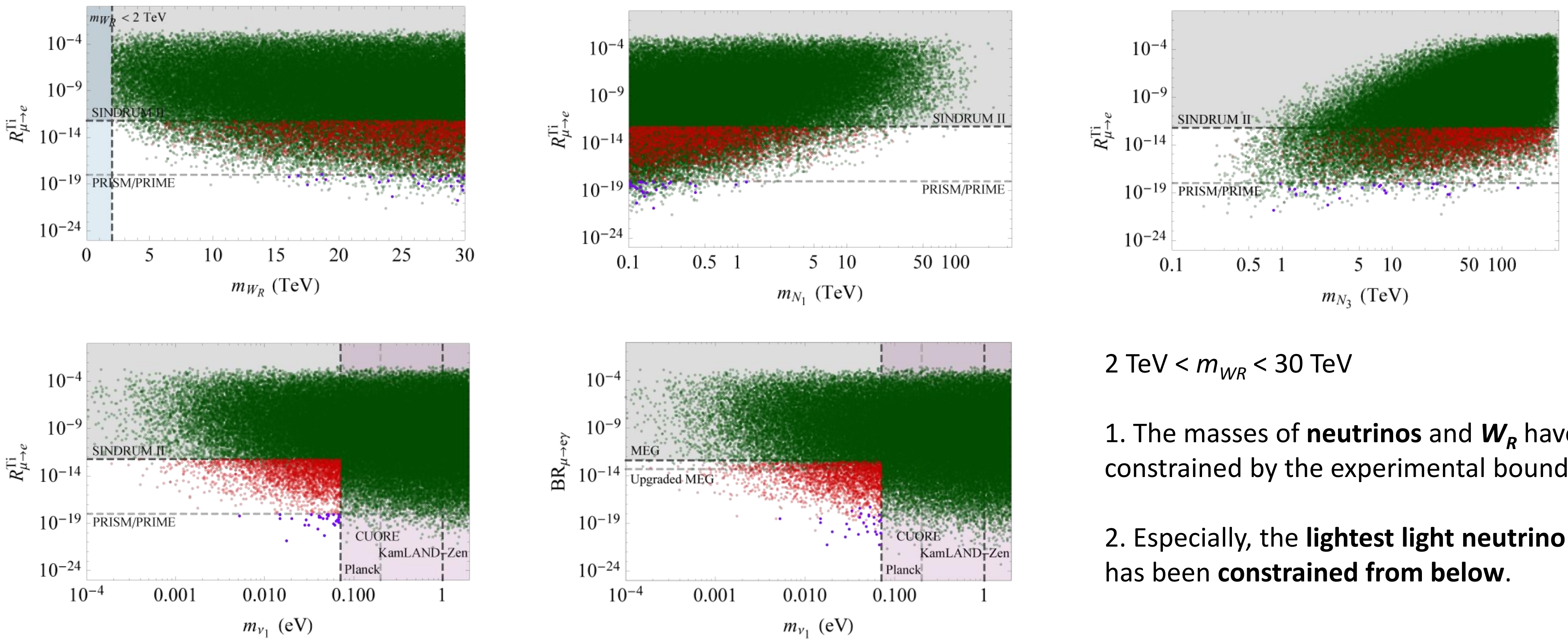
Correlations in the masses of neutrinos and W_R



1. A **large hierarchy in light neutrino masses** generally requires a **large hierarchy in heavy neutrino masses**. (General feature of **type-I seesaw**, as shown by green dots.)

2. The discovery of **light W_R** and any improved **CLFV bounds** will **largely constrain** the parameter space of the **normal hierarchy**.

CLFV and the masses of neutrinos and W_R

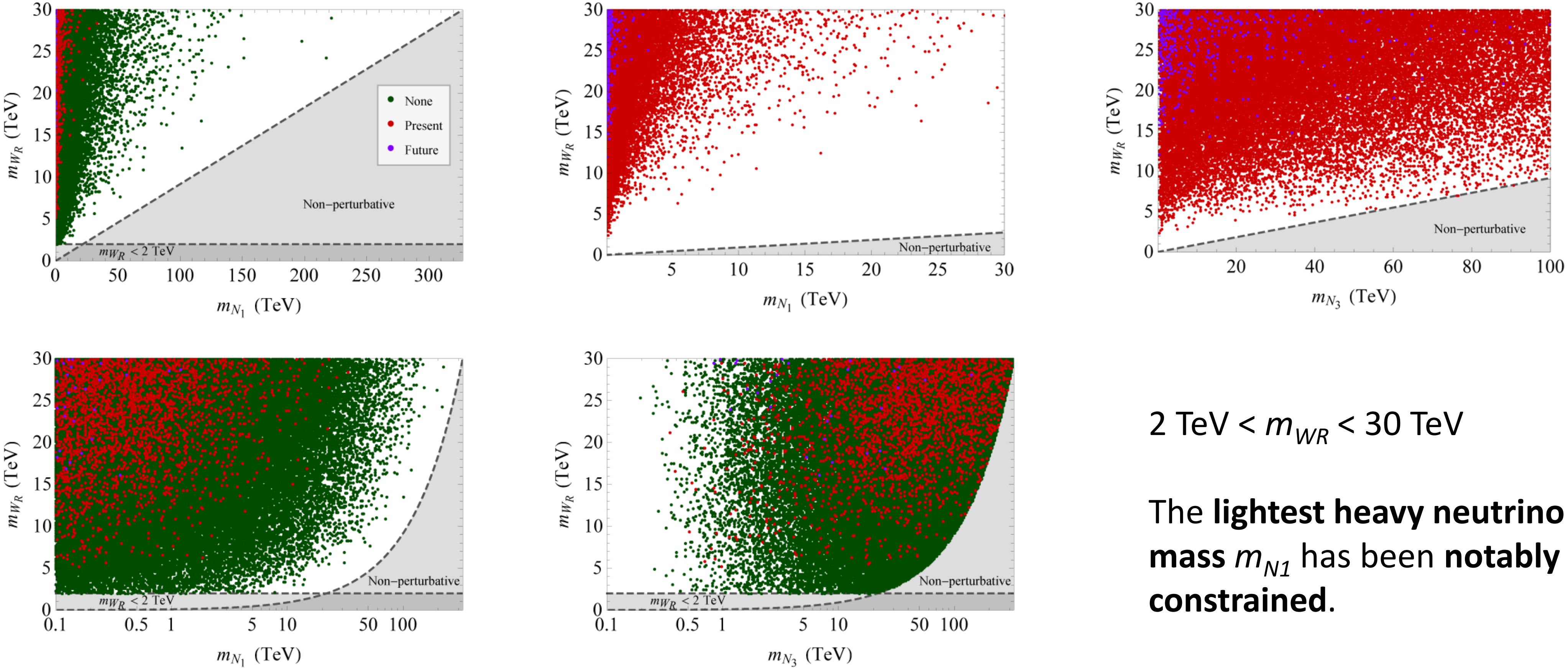


2 TeV < m_{WR} < 30 TeV

1. The masses of **neutrinos** and ***W*$_R$** have been constrained by the experimental bounds on **CLFV**.

2. Especially, the **lightest light neutrino mass** $m_{\nu 1}$ has been **constrained from below**.

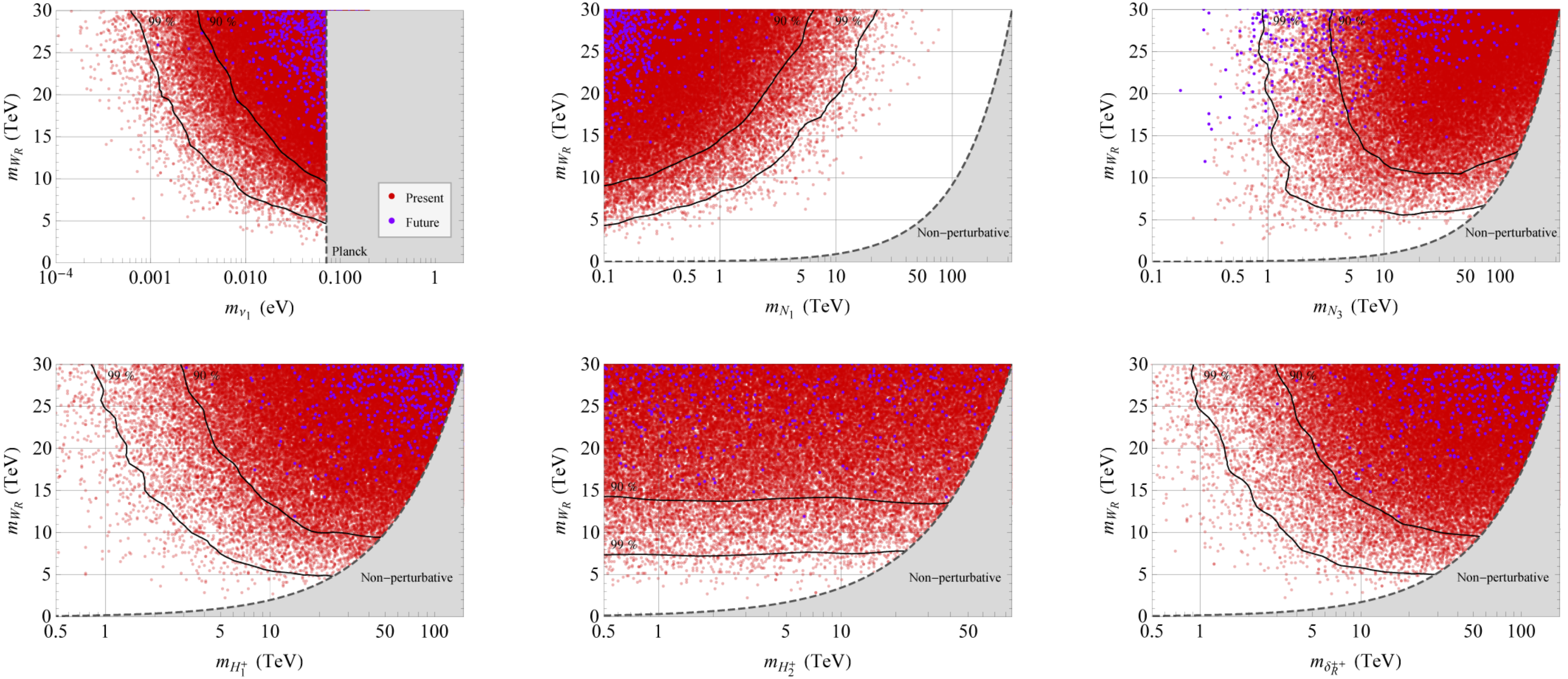
Neutrino masses



2 TeV < m_{WR} < 30 TeV

The **lightest heavy neutrino mass** m_{N1} has been **notably constrained**.

Neutrino masses



Conclusion

- Procedure to **construct lepton mass matrices** in the MLRSM of type-I dominance with the parity symmetry
- Conditions for the **TeV-scale** MLRSM without fine-tuning:

  (i) $\kappa_1 \gg \kappa_2$, $f_{ij} \ll \tilde{f}_{ij}$, and $V_L^\ell \approx V_R^\ell$, or (ii) $\kappa_1 \ll \kappa_2$, $f_{ij} \gg \tilde{f}_{ij}$, and $V_L^\ell \approx V_R^\ell e^{-i\alpha}$.
- Numerical results ($m_{WR} <$ 30 TeV)
  - **Light neutrino masses** have been constrained from below. ($m_{\nu 1} > 10^{-3}$ eV)
  - **Lightest heavy neutrino masses** have been notably constrained.

    (e.g. m_{N1} < a few TeV for m_{WR} = 10 TeV)
  - **0νββ** processes are found to be **too small** due to the CLFV and Planck constraints.
  - **EDM's of charged leptons** are also found to be **too small** due to the CLFV constraints.