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Global constraints on heavy neutrino Seesaw mixing

Josu Hernandez-Garcia

arXiv: 1605.08774 [hep-ph] E. Fernandez-Martinez, JHG, J. Lopez-Pavon

SEVENTH FRAMEWORK PROGRAMME

MARIE CURIE ACTIONS

invisiblesPlus
neutrinos, dark matter & dark energy physics

Motivation

Neutrino masses are one of the most promising open windows to physics beyond the Standard Model (SM).

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By adding heavy ν_R to SM particle content, neutrino masses arise in a simple and natural way.

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} - \frac{1}{2}\overline{N^i_{\mathrm{R}}}(M_N)_{ij}N^{cj}_{\mathrm{R}} - (Y_N)_{i\alpha}\overline{N^i_{\mathrm{R}}}\phi^\dagger \ell^\alpha_{\mathrm{L}} + \mathrm{h.c.}$$

Motivation

Neutrino masses are one of the most promising open windows to physics beyond the Standard Model (SM).

By adding heavy ν_R to SM particle content, neutrino masses arise in a simple and natural way.

A set of EW and flavor observables are going to be used to constrain the additional neutrino mixing.

Introduction

Once the new heavy states are integrated out, the SM-Seesaw can be considered as a low energy effective theory:

- dim-5 Weinberg op. gives masses to the light ν:

$$\frac{c_{\alpha\beta}^{\text{dim-5}}}{\Lambda}\left(\overline{L^c}_\alpha\tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger L_\beta\right) \longrightarrow \hat{m} = m_D^t M_N^{-1} m_D$$

violates L

S. Weinberg, Phys.Rev.Lett. **43**, 1566 (1979)

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- dim-6 op. induces non-unitarity in the mixing matrix N of lepton charged current interactions:

$$\frac{c^{\text{dim-6}}_{\alpha\beta}}{\Lambda^2}\left(\overline{L}_\alpha\tilde{\phi}\right)i\gamma^\mu\partial_\mu\left(\tilde{\phi}^\dagger L_\beta\right) \longrightarrow \eta = \frac{1}{2}m_D^\dagger M_N^{-2} m_D$$

conserves L

A. Broncano, M.B. Gavela, and E.E. Jenkins, Phys. Lett. **B552**, 177 (2003)

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$$N = (I-\eta)\,U_{\text{PMNS}}$$

since η is Hermitian $\Rightarrow$ the most general parametrization for N.

Introduction

dim-5: $\hat{m} = m_D^t M_N^{-1} m_D$

violates L

dim-6: $\eta = \frac{1}{2} m_D^\dagger M_N^{-2} m_D$

conserves L

If smallness of m_ν comes only from the suppression with M_N

mixing η much more suppressed

experimental verification extremely challenging

Introduction

dim-5: $\hat{m} = m_D^t M_N^{-1} m_D$

violates L

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conserves L

Meaningful bounds imply $\begin{cases} M_i \sim \mathcal{O}(\Lambda_{\mathrm{EW}}) \\ Y_N \sim \mathcal{O}(1) \end{cases}$ $\Rightarrow$ $\hat{m}$ too large

Alternatively, smallness of m_ν may naturally stem from an approximate L instead of a huge hierarchy of masses

→ inverse or linear Seesaw

R. Mohapatra and J. Valle, Phys.Rev. **D34**, 1642 (1986)

J. Bernabeu, A. Santamaria, J. Vidal, A. Mendez, and J. Valle, Phys. Lett. **B187**, 303 (1987)

G.C. Branco, W. Grimus, and L. Lavoura, Nucl. Phys. **B312**, 492 (1989)

Introduction

In particular:

$$m_D = \frac{v_{\rm EW}}{\sqrt{2}} \begin{array}{c} \begin{array}{ccc} \nu_e & \nu_\mu & \nu_\tau \\ L = 1 & 1 & 1 \end{array} \\ \left(\begin{array}{ccc} Y_e & Y_\mu & Y_\tau \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{array} \right) \end{array} \begin{array}{cc} 1 & N_1 \\ -1 & N_2 \\ 0 & N_3 \end{array} \qquad M_N = \begin{array}{c} \begin{array}{ccc} N_1 & N_2 & N_3 \\ L = 1 & -1 & 0 \end{array} \\ \left(\begin{array}{ccc} 0 & \Lambda & 0 \\ \Lambda & 0 & 0 \\ 0 & 0 & \Lambda' \end{array} \right) \end{array} \begin{array}{cc} 1 & N_1 \\ -1 & N_2 \\ 0 & N_3 \end{array}$$

where N_i is an arbitrary number of extra heavy fields.

If L is exact: $\hat{m} = 0$ while $\eta \neq 0$ and arbitrarily large.

R. Alonso, M. Dhen, M. Gavela, and T. Hambye, JHEP **1301**, 118 (2013)
A. Abada, D. Das, A. Teixeira, A. Vicente, and C. Weiland, JHEP **1302**, 048 (2013)

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where N_i is an arbitrary number of extra heavy fields.

If ϵ_i and μ_j small $\not{L}$ terms introduced $\Rightarrow L$ mildly broken $\Rightarrow \begin{cases} \hat{m} \neq 0 \\ m_i \sim \mathcal{O}\,(\text{eV}) \end{cases}$

while $\eta \neq 0$ and arbitrarily large.

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The 2 scenarios: G-SS

We have studied 2 different scenarios:

- G-SS: a completely general scenario
  - SM is extended with an arbitrary number of ν_R
  - they are heavier than $\Lambda_{\rm EW}$
  - no further assumptions

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  Where N parametrized by:

$$N = (I - \eta)\, U_{\text{PMNS}}$$

→ the most general one since η is Hermitian.

$$\eta = \begin{pmatrix} \eta_{ee} & \eta_{e\mu} & \eta_{e\tau} \\ \eta_{e\mu}^* & \eta_{\mu\mu} & \eta_{\mu\tau} \\ \eta_{e\tau}^* & \eta_{\mu\tau}^* & \eta_{\tau\tau} \end{pmatrix} \quad \text{where} \quad \sqrt{2\eta_{\alpha\alpha}} = \sqrt{\sum_i |\Theta_{\alpha i}|^2}$$

represents the total mixing from all N_{R_i} with the flavor α.

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→ Schwarz inequality

The 2 scenarios: 3N-SS

We have studied 2 different scenarios:

- 3N-SS: a 3 heavy neutrino scenario
  - SM is only extended with 3 ν_R
  - they are heavier than $\Lambda_{\rm EW}$
  - large New Physics effects in spite of the smallness of m_ν
  - m_ν radiatively stable

E. Fernandez-Martinez, JHG, J. Lopez-Pavon, and M. Lucente JHEP 1510 (2015) 130

The 2 scenarios: 3N-SS

We have studied 2 different scenarios:

- 3N-SS: a 3 heavy neutrino scenario

  Where the only Seesaw that saturates the bounds:

  $M_{1,2} \sim \Lambda$ (pseudo Dirac pair), $M_3 \sim \Lambda'$ (decoupled) but

$$\eta = \frac{1}{2} \begin{pmatrix} |\theta_e|^2 & \theta_e \theta_\mu^* & \theta_e \theta_\tau^* \\ \theta_\mu \theta_e^* & |\theta_\mu|^2 & \theta_\mu \theta_\tau^* \\ \theta_\tau \theta_e^* & \theta_\tau \theta_\mu^* & |\theta_\tau|^2 \end{pmatrix} \text{ with } \theta_\alpha \equiv \frac{v Y_\alpha}{\sqrt{2}\Lambda}$$

$|\eta_{\alpha\beta}| = \sqrt{\eta_{\alpha\alpha}\eta_{\beta\beta}}$ → Schwarz inequality is saturated

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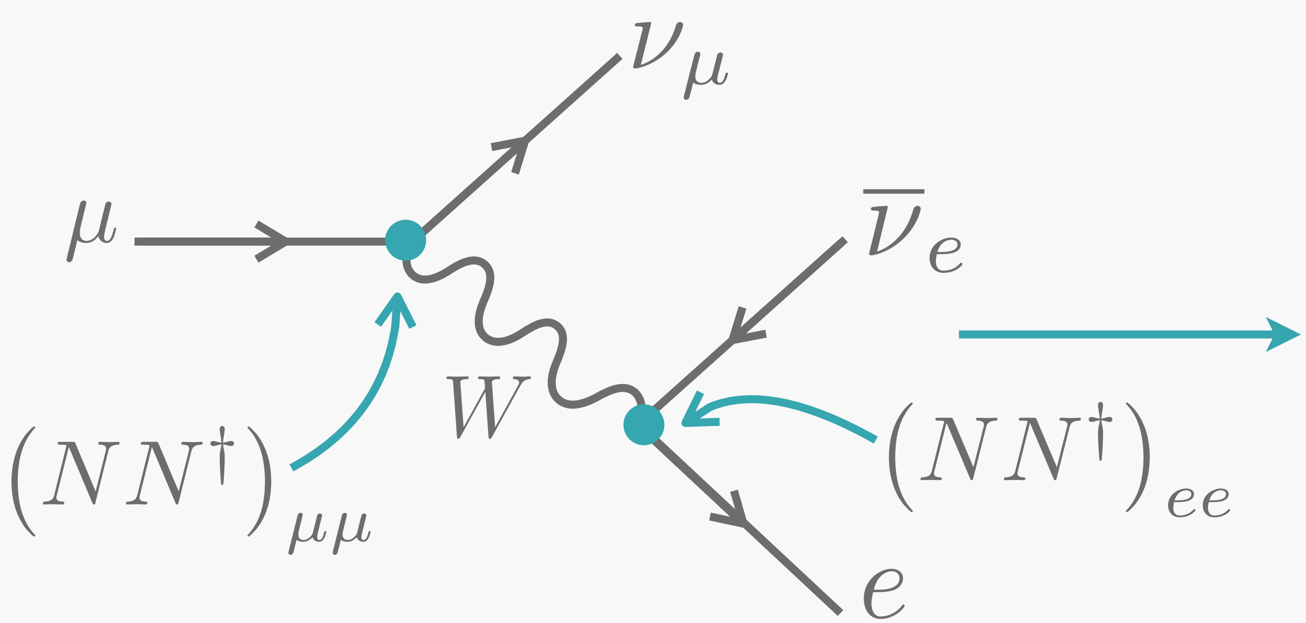
  Fixing ν osc. data: θ_{ij} & $\Delta m^2_{ij} \Rightarrow Y_\tau = Y_\tau(m_{1,3}, \delta, \phi_1, \phi_2)$

Observables

The 28 observables are computed in terms of α, G_μ and M_Z.

- The W boson mass M_W



$$G_F^2\,(1 - 2\eta_{ee} - 2\eta_{\mu\mu}) = G_\mu^2$$

$$M_W^2 = \frac{\pi\alpha}{\sqrt{2}G_F s_W^2(1-\Delta r)} = \frac{\pi\alpha(1-\eta_{ee}-\eta_{\mu\mu})}{\sqrt{2}G_\mu s_W^2(1-\Delta r)}$$

kinematical measurements of M_W constrain η_{ee} and $\eta_{\mu\mu}$

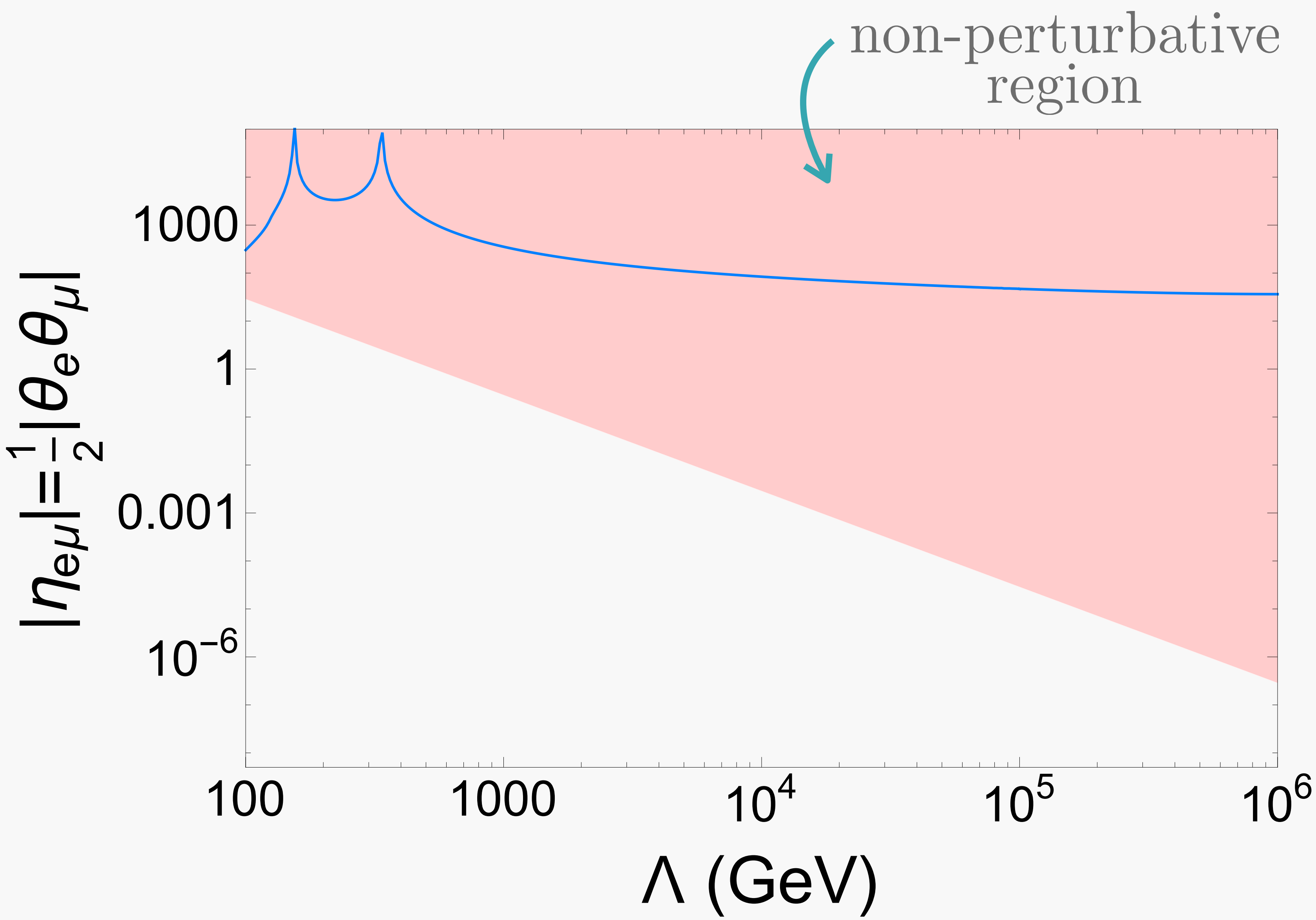
Observables

The 28 observables are computed in terms of α, G_μ and M_Z.

- The W boson mass M_W
- The effective weak mixing angle θ_{W}: $s^{2\ \mathrm{lep}}_{\mathrm{W\ eff}}$ & $s^{2\ \mathrm{had}}_{\mathrm{W\ eff}}$
- 4 ratios of Z fermionic decays: R_l, R_c, R_b & σ^0_{had}
- The invisible Z width Γ_{inv}
- Universality ratios: $R^{\pi}_{\mu e}$, $R^{\pi}_{\tau\mu}$, $R^{W}_{\mu e}$, $R^{W}_{\tau\mu}$, $R^{K}_{\mu e}$, $R^{K}_{\tau\mu}$, $R^{l}_{\mu e}$ & $R^{l}_{\tau\mu}$
- 9 decays constraining the CKM unitarity

OBSERVABLES

LFV decays: $\mu - e$ transitions



- $h \to e\mu$

OBSERVABLES

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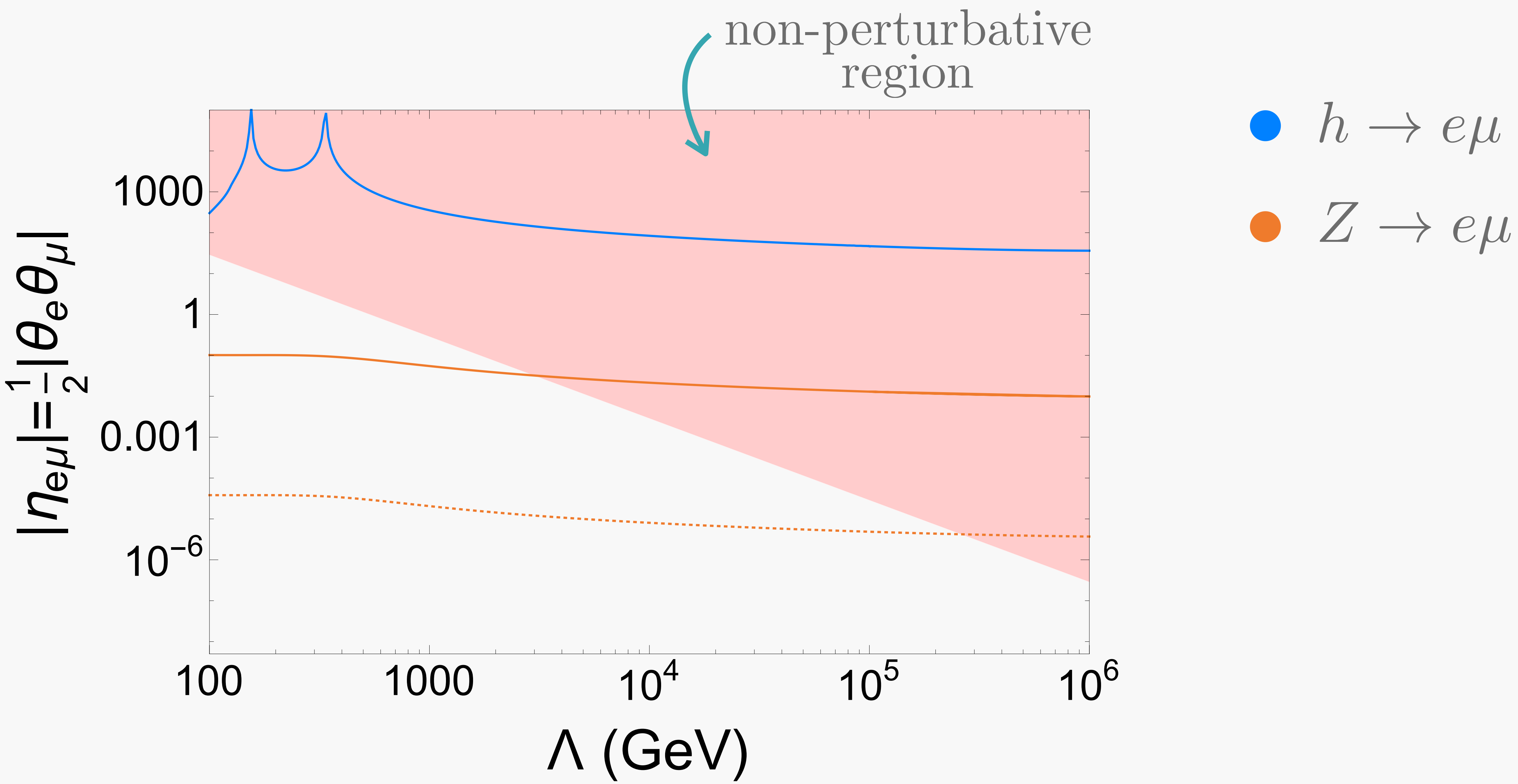

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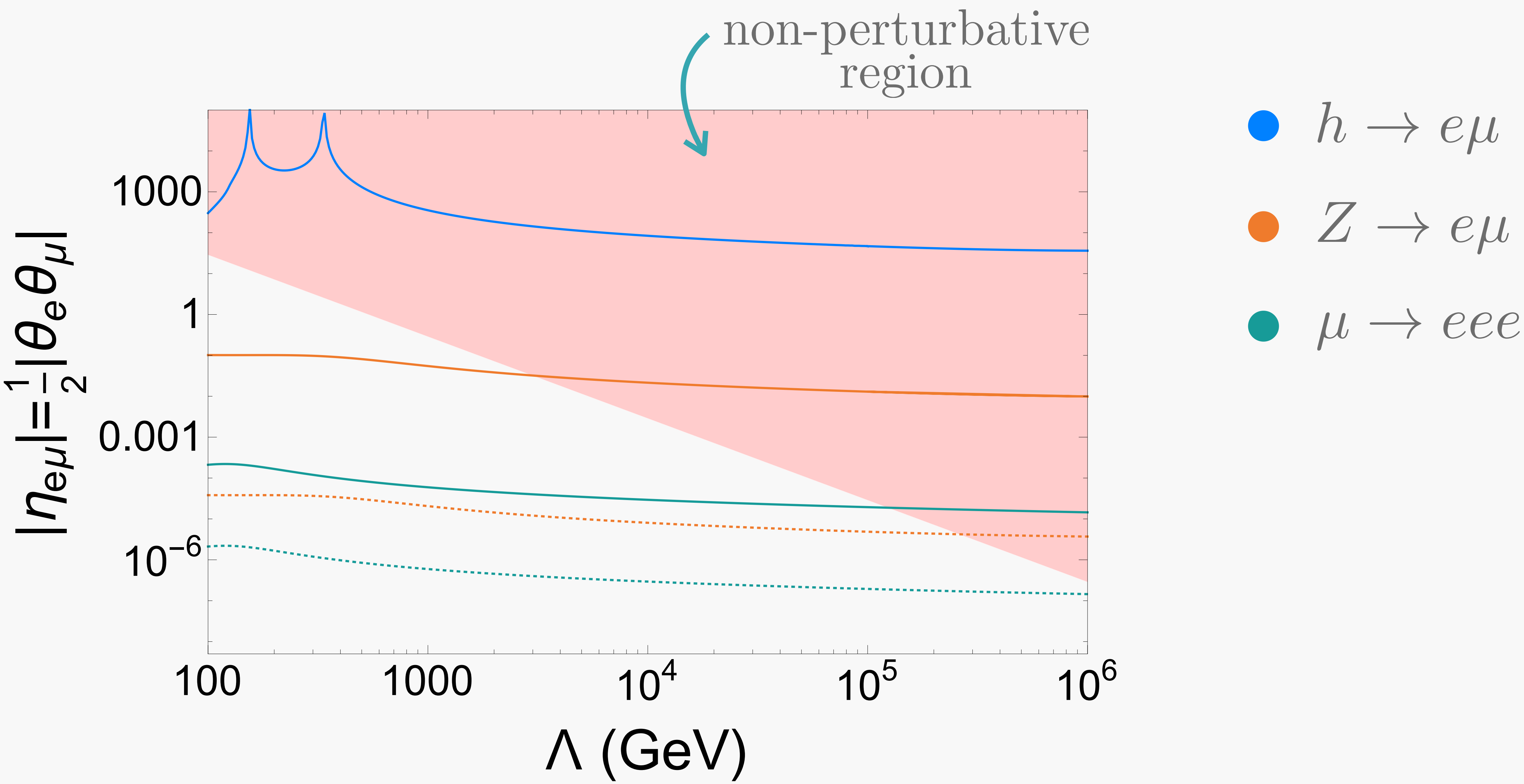

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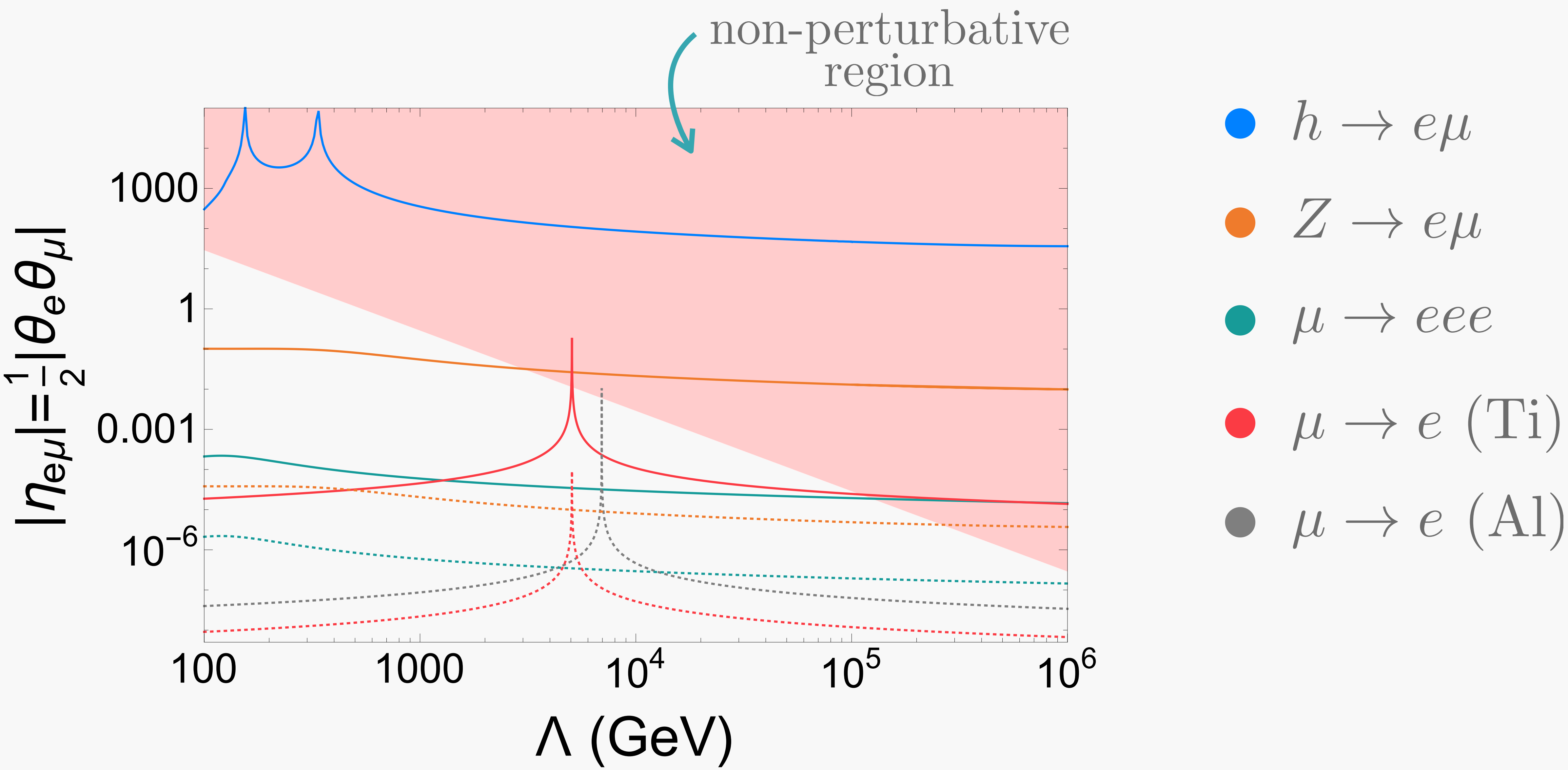

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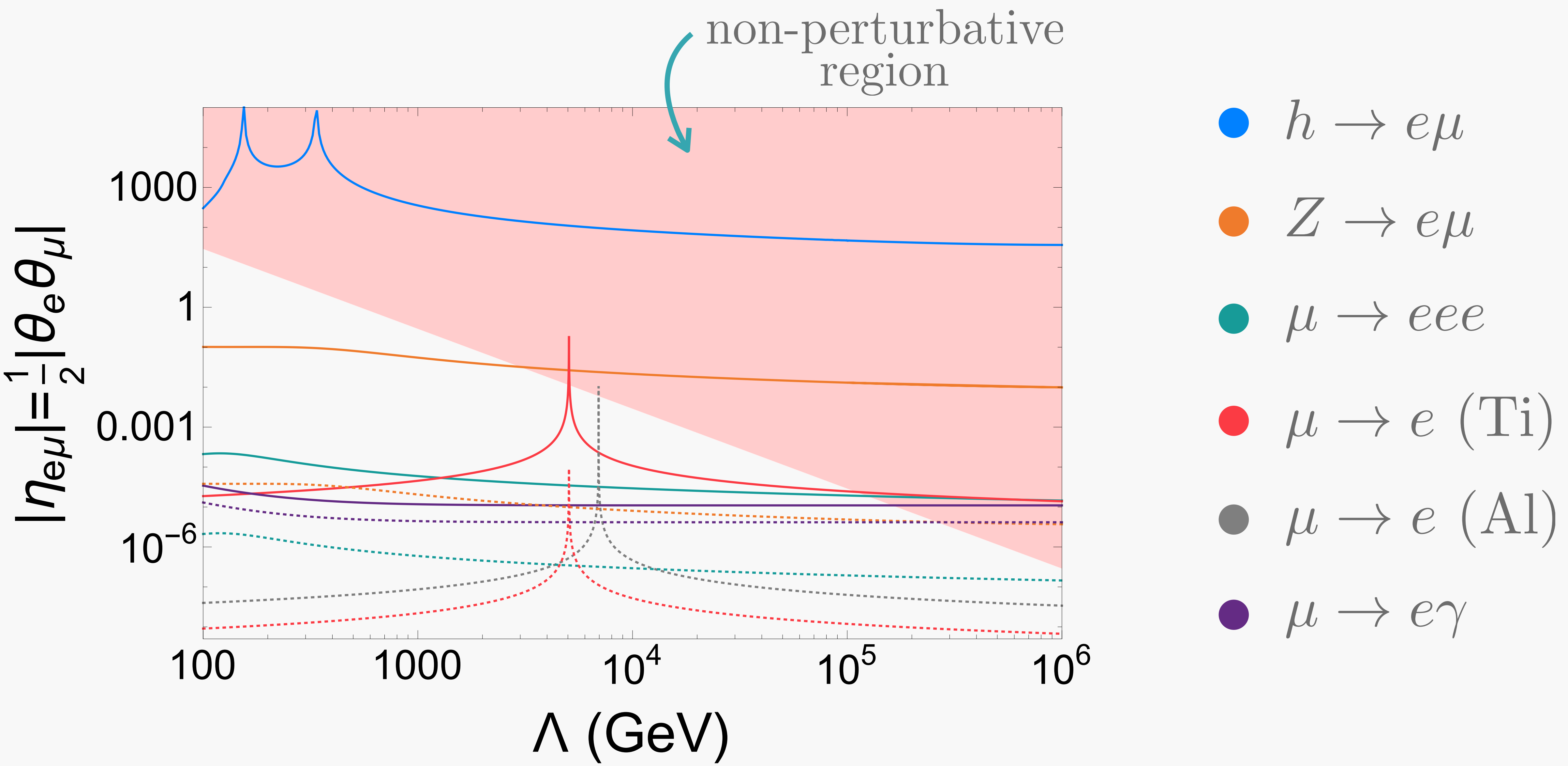
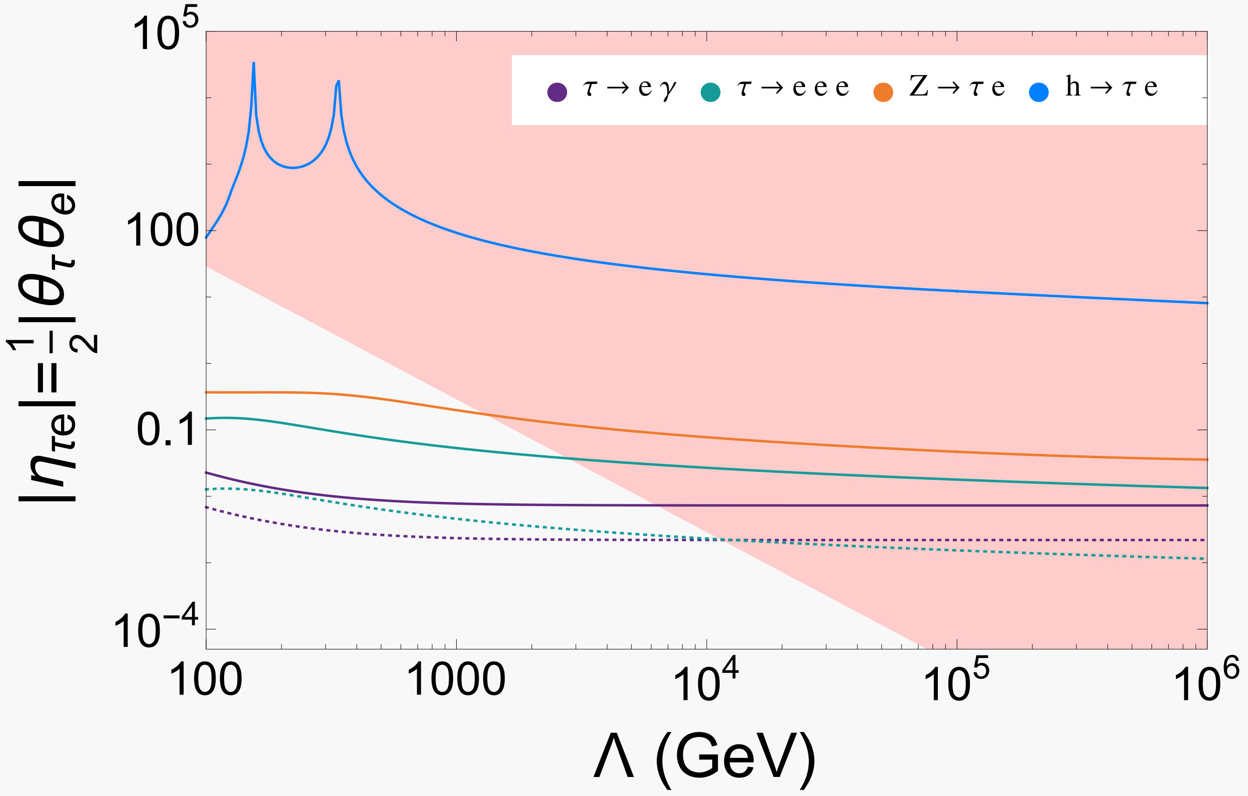
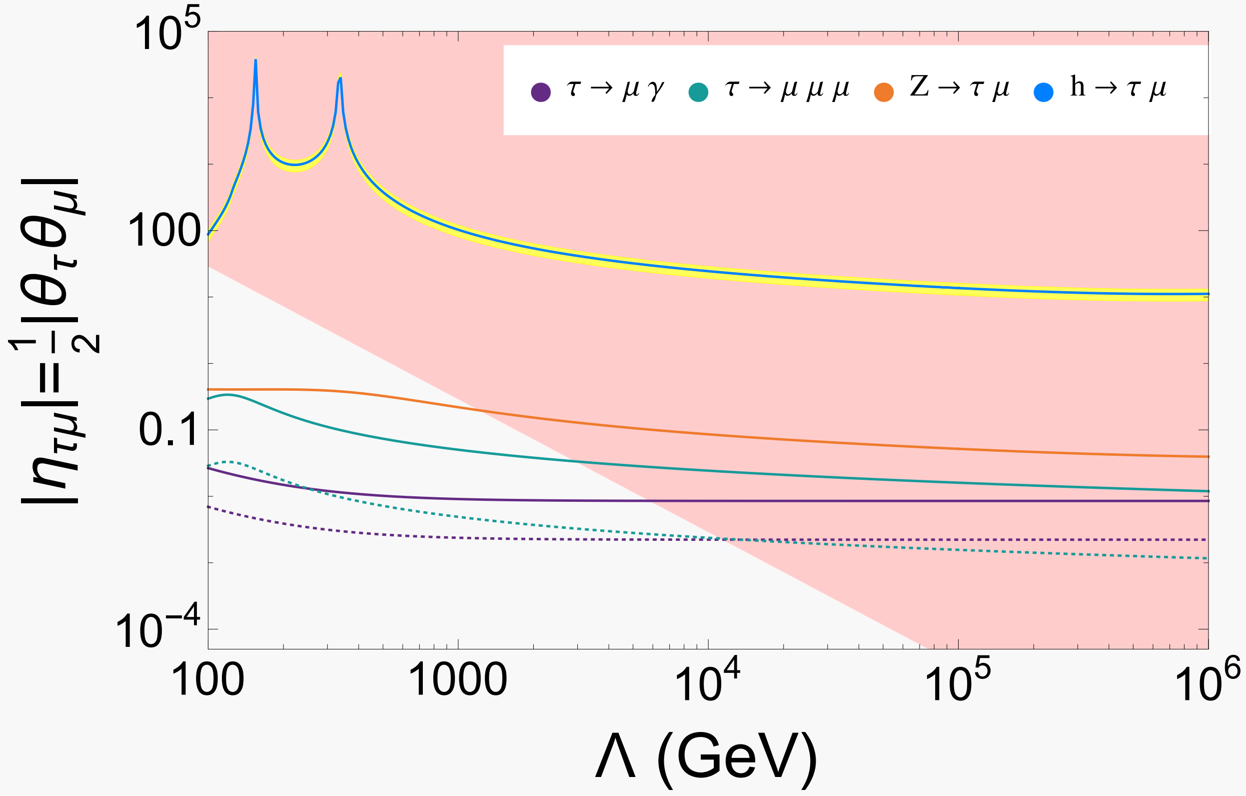


Observables

LFV decays: $\tau - e$ & $\tau - \mu$ transitions





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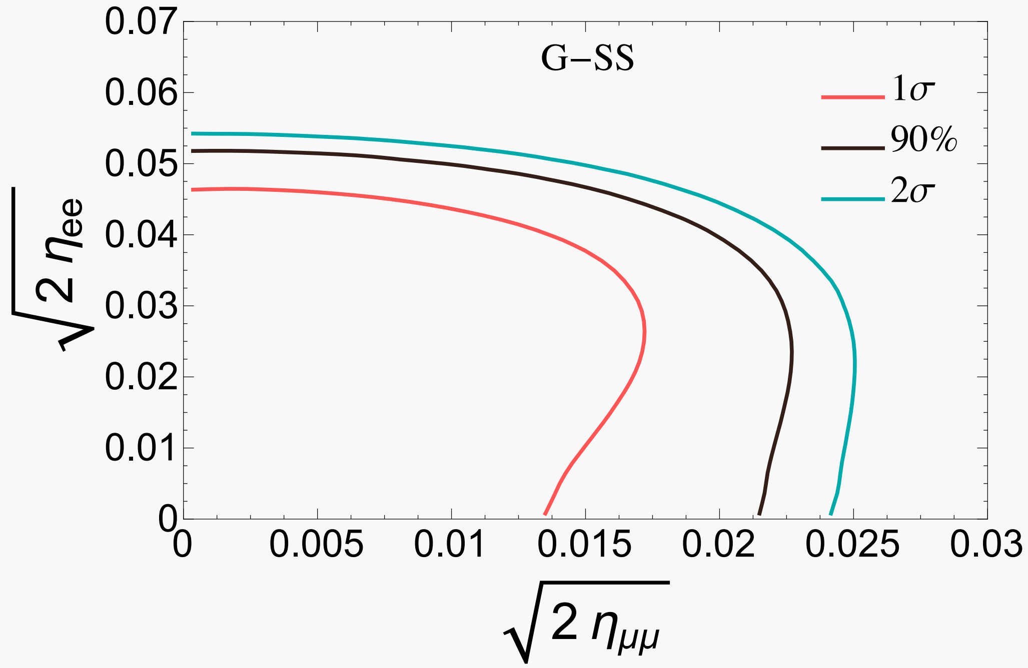
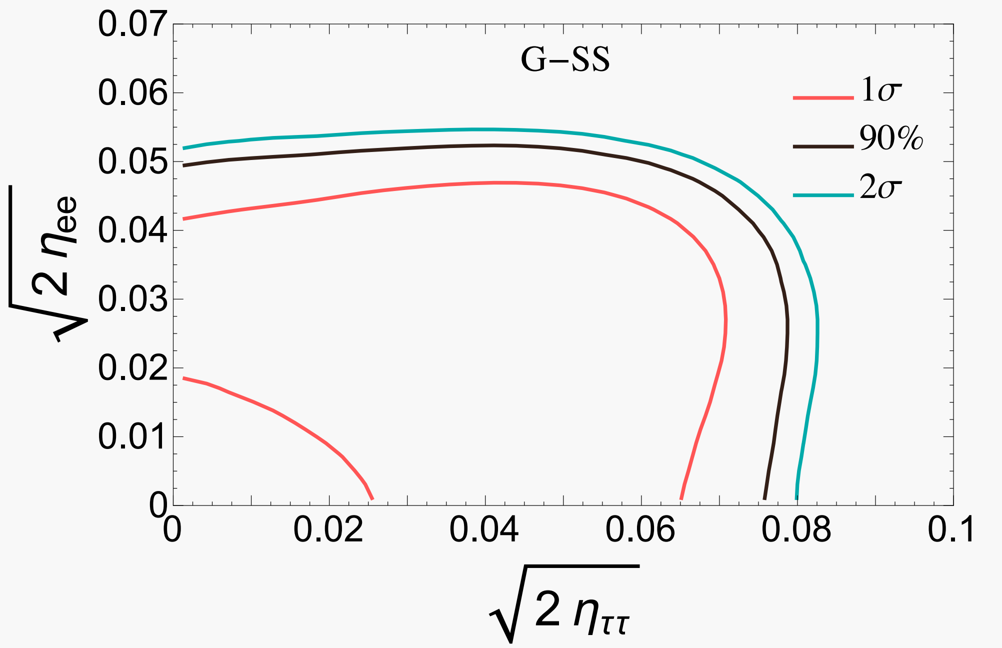
- 9 decays constraining the CKM unitarity
- 3 rare LFV decays: $\mu \to e\gamma$, $\tau \to \mu\gamma$ & $\tau \to e\gamma$

Results

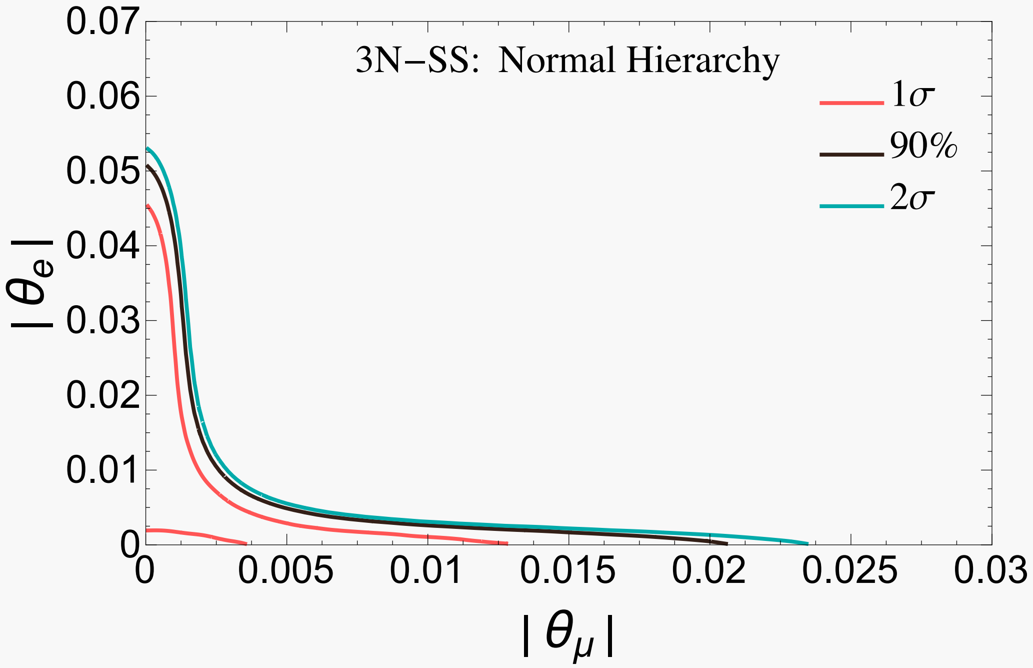
MCMC with the 28 observables scanning over the free parameters

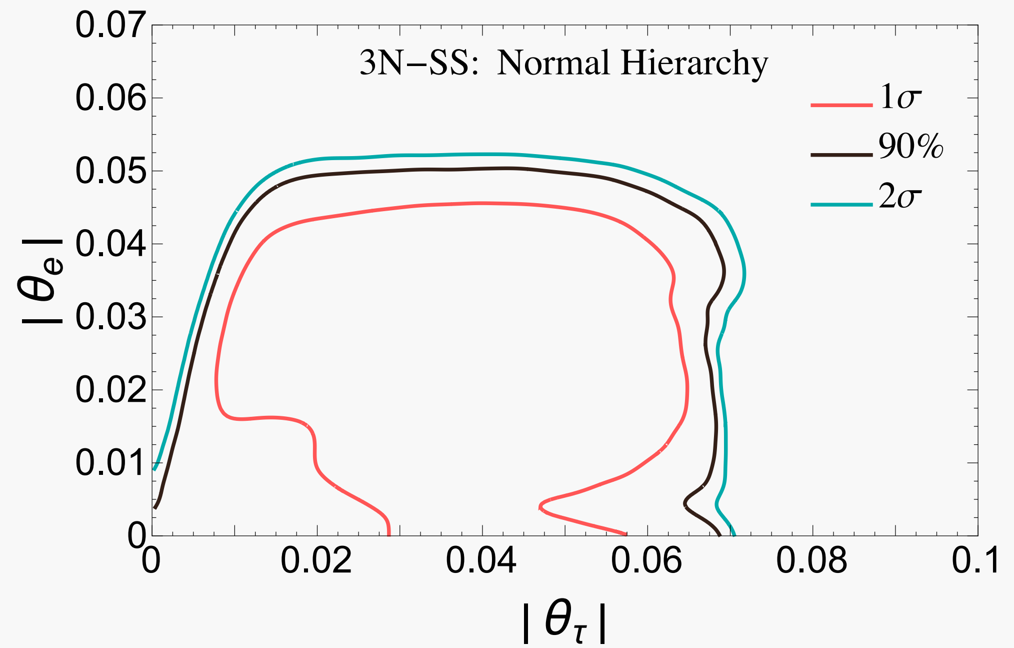
G-SS:





3N-SS: Normal Hierarchy





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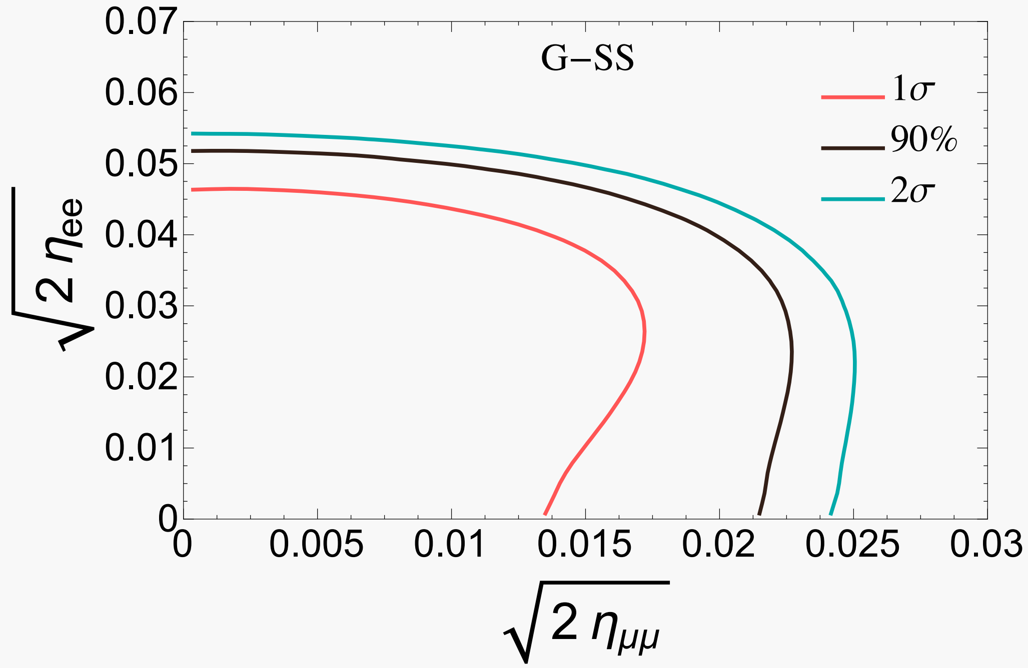
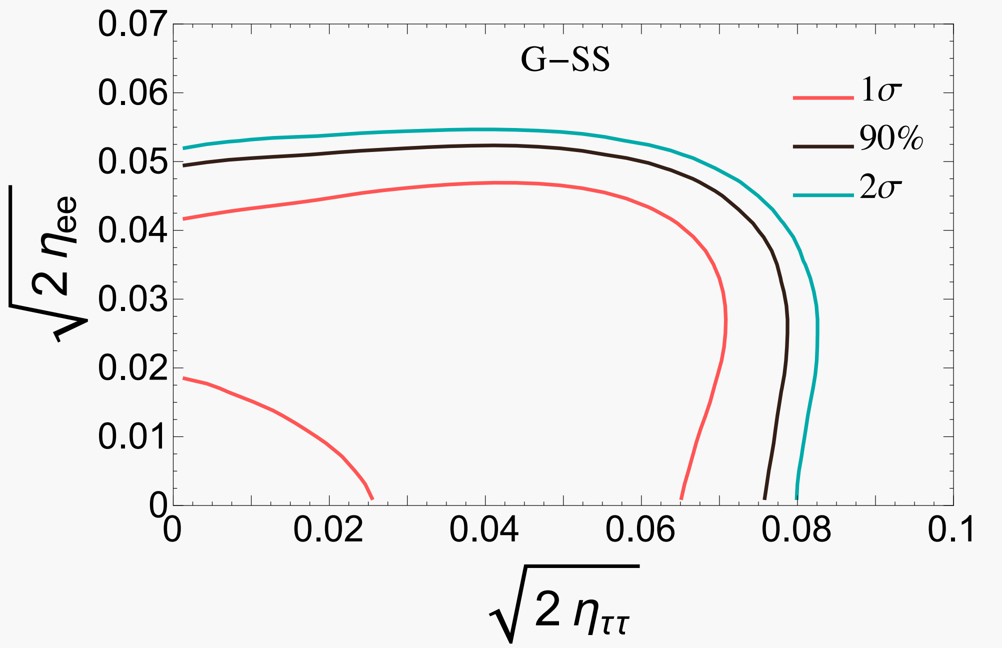
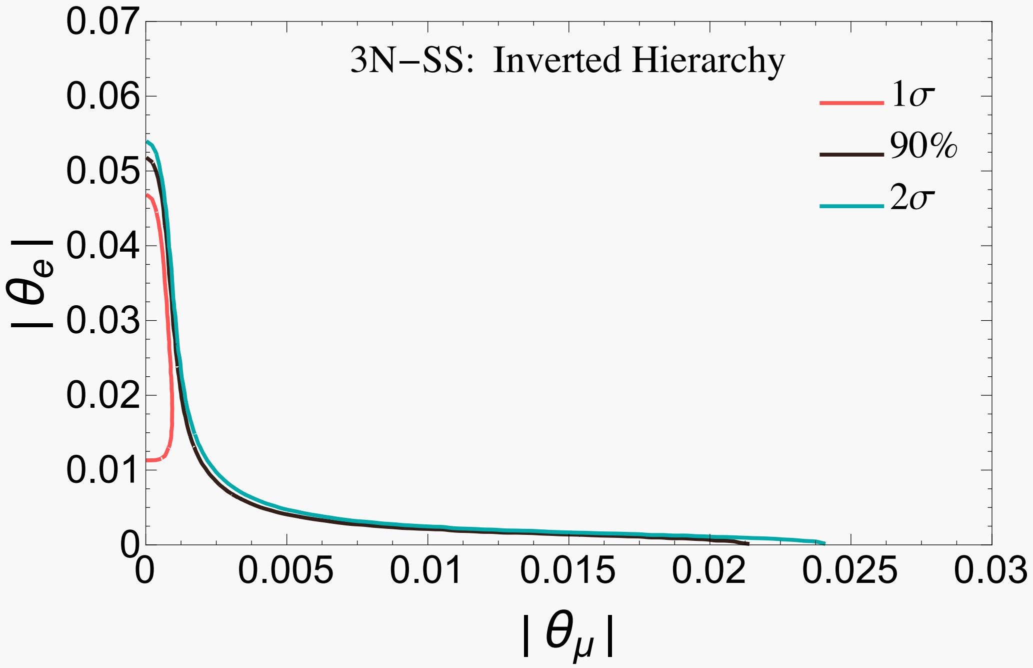
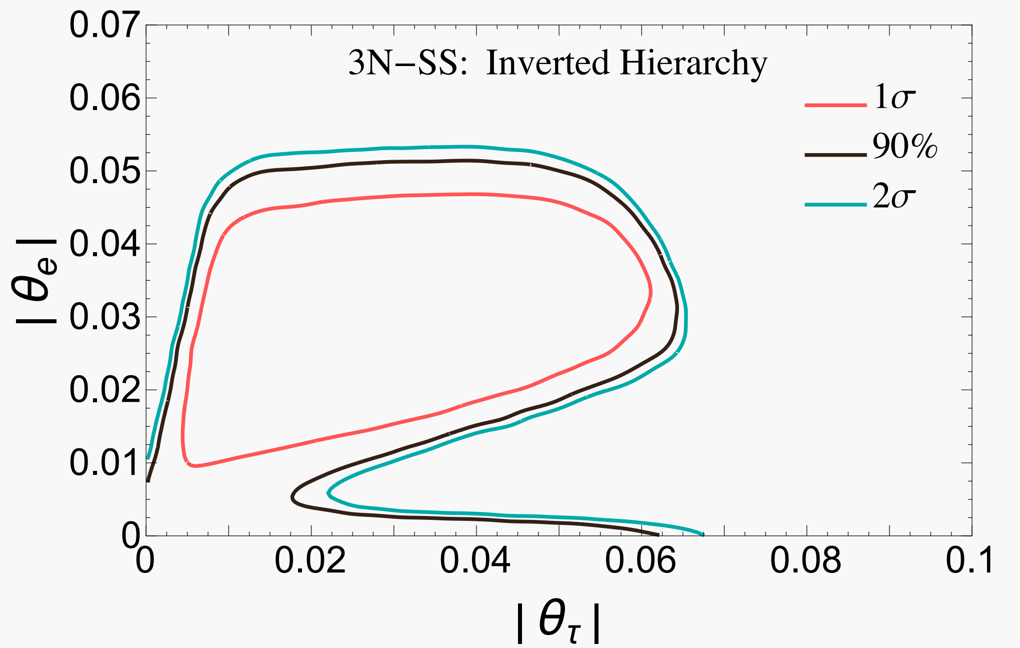




3N-SS: Inverted Hierarchy





Results

Global fit: diagonal entries of the mixing matrix

G-SS:	3N-SS: NH	3N-SS: IH
$\sqrt{2\eta_{ee}} = 0.031^{+0.010}_{-0.020}$	$\lvert\theta_e\rvert = 0.029^{+0.012}_{-0.020}$	$\lvert\theta_e\rvert = 0.031^{+0.010}_{-0.012}$
$\sqrt{2\eta_{\mu\mu}} < 0.011$	$\lvert\theta_\mu\rvert < 7.6 \cdot 10^{-4}$	$\lvert\theta_\mu\rvert < 6.9 \cdot 10^{-4}$
$\sqrt{2\eta_{\tau\tau}} = 0.044^{+0.019}_{-0.027}$	$\lvert\theta_\tau\rvert = 0.043^{+0.018}_{-0.027}$	$\lvert\theta_\tau\rvert = 0.037^{+0.021}_{-0.032}$

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Results

Global fit: off-diagonal entries of the mixing matrix

G-SS:		3N-SS:	
LFC	LFV	NH	IH
$\sqrt{2\lvert\eta_{e\mu}\rvert} < 0.018$	$\sqrt{2\lvert\eta_{e\mu}\rvert} < 4.1\cdot 10^{-3}$	$\sqrt{\lvert\theta_e\theta_\mu\rvert} < 4.1\cdot 10^{-3}$	$\sqrt{\lvert\theta_e\theta_\mu\rvert} < 4.1\cdot 10^{-3}$
$\sqrt{2\lvert\eta_{e\tau}\rvert} < 0.045$	$\sqrt{2\lvert\eta_{e\tau}\rvert} < 0.107$	$\sqrt{\lvert\theta_e\theta_\tau\rvert} = 0.036^{+0.010}_{-0.016}$	$\sqrt{\lvert\theta_e\theta_\tau\rvert} = 0.036^{+0.010}_{-0.023}$
$\sqrt{2\lvert\eta_{\mu\tau}\rvert} < 0.024$	$\sqrt{2\lvert\eta_{\mu\tau}\rvert} < 0.115$	$\sqrt{\lvert\theta_\mu\theta_\tau\rvert} < 0.007$	$\sqrt{\lvert\theta_\mu\theta_\tau\rvert} < 0.005$

Schwarz inequality

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Schwarz inequality

Summary

A set of EW and flavor observables have been used to constrain the additional mixing in two different scenarios.

A non-zero value for the e and τ mixings with a significance of 2σ and an upper bound for the μ mixing have been found in both scenarios.

In the G-SS scenario, $\eta_{e\mu}$ is contained by $\mu \to e\gamma$ while $\eta_{\tau e}$ and $\eta_{\tau\mu}$ are constrained by indirect bounds through Schwarz inequality.

Thanks

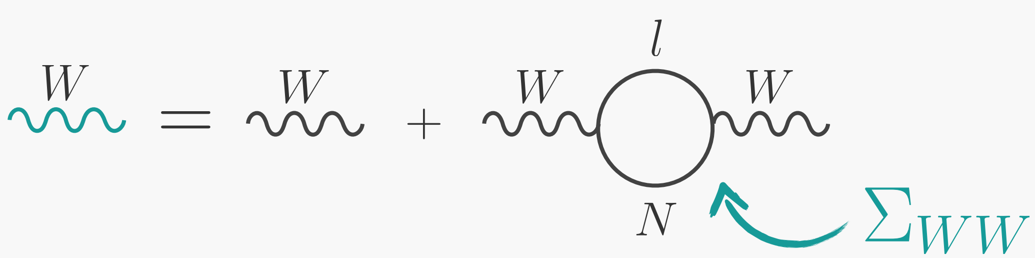
Back-up

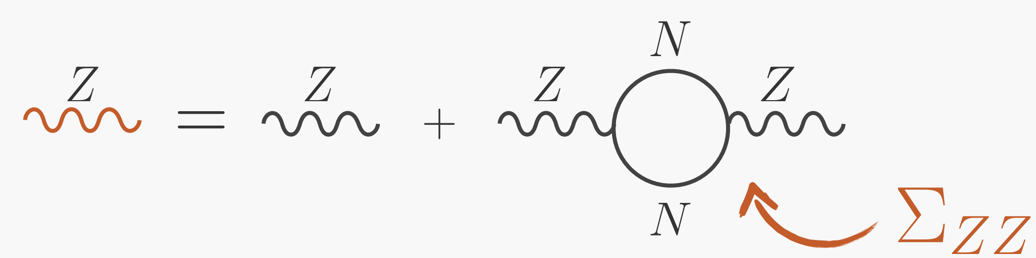
1-loop effect

Several observables go with:

$$\frac{|\theta_e|^2}{2} + \frac{|\theta_\mu|^2}{2} + 2\alpha T \qquad \text{where} \qquad T = \frac{\Sigma_{WW}(0)}{M_W^2} - \frac{\Sigma_{ZZ}(0)}{M_Z^2}$$

W and Z boson propagators corrected by the new dof:





A cancellation between tree and loop level could be possible.

This relaxes some bounds allowing to fit some anomalies.

E. Akhmedov *et al.* arXiv:1302:1872 [hep-ph]

1-LOOP EFFECT

If L is mildly broken $\Rightarrow T \geq 0 \Rightarrow$ No cancellation allowed.

$$\frac{|\theta_e|^2}{2} + \frac{|\theta_\mu|^2}{2} + 2\alpha T$$

$T < 0$ only possible for large $\not{L}$.

$$m_i^{\text{tree}} \sim v_{EW}^2 Y^2 \left(\frac{1}{\Lambda} \mathcal{O}\left(\epsilon_1, \frac{\mu_2}{2\Lambda}\right) + \frac{1}{\Lambda'} \mathcal{O}\left(\epsilon_2^2, \frac{\mu_4}{4\Lambda^2}\right) \right) \Rightarrow$$

$\not{L}$ driven by μ_1 and μ_3

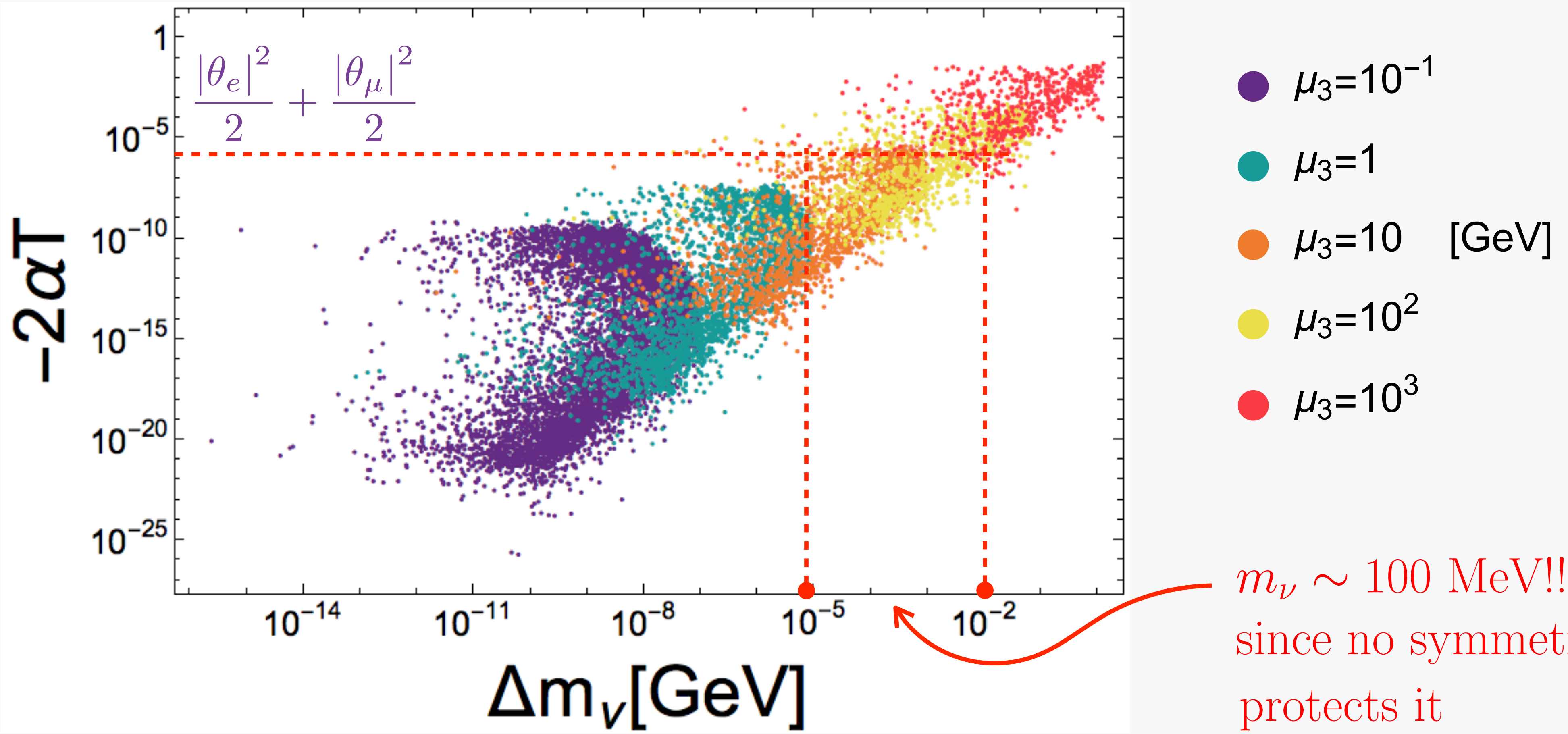
$$\Downarrow$$

$$T \simeq \frac{v_{\text{EW}}^4}{64\pi s_w^2 M_W^2} \left(\sum_\alpha |Y_\alpha|^2 \right)^2 f(\mu_1, \mu_3)$$

1-LOOP EFFECT

Loop corrections of μ_1 and μ_3 to m_i should be taken into account:

$$\Delta m_{\nu_{\alpha\beta}} = \frac{Y_\alpha Y_\beta}{32\pi^2\mu}\left(3M_Z^2 f(\mu_1,\mu_3,M_Z) + M_h^2 f(\mu_1,\mu_3,M_h)\right)$$



$m_\nu \sim 100$ MeV!! since no symmetry protects it