Global constraints on Seesaw neutrino mixing

Josu Hernandez-Garcia

Based on:

- JHEP **1608** (2016) 033: E. Fernandez-Martinez, JHG and J. Lopez-Pavon
- JHEP **1510** (2015) 130: E. Fernandez-Martinez, JHG, J. Lopez-Pavon and M. Lucente

Outline

- Motivation
- Introduction
- The two scenarios: G-SS & 3N-SS
- Parametrizations
- Observables
- Results of the Global Fit
- 1-loop effect
- Summary

Motivation

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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.

$$\mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{1}{2}\overline{N_{\text{R}}^{i}}(M_N)_{ij}N_{\text{R}}^{cj} - (Y_N)_{i\alpha}\overline{N_{\text{R}}^{i}}\phi^\dagger \ell_{\text{L}}^{\alpha} + \text{h.c.}$$

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

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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:

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

$\hat{m}$ violates L

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

Introduction

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

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

η → 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

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

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

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

→ Inverse or Lienar 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:

$$
m_D = \frac{v_{\rm EW}}{\sqrt{2}} \begin{pmatrix} Y_e & Y_\mu & Y_\tau \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}
\qquad
\begin{matrix} & \nu_e & \nu_\mu & \nu_\tau \\ L = & 1 & 1 & 1 \end{matrix}
\qquad
\begin{matrix} 1 & N_1 \\ -1 & N_2 \\ 0 & N_3 \end{matrix}
$$

$$
M_N = \begin{pmatrix} 0 & \Lambda & 0 \\ \Lambda & 0 & 0 \\ 0 & 0 & \Lambda' \end{pmatrix}
\qquad
\begin{matrix} & N_1 & N_2 & N_3 \\ L = & 1 & -1 & 0 \end{matrix}
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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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$$m_D = \frac{v_{\rm EW}}{\sqrt{2}} \begin{pmatrix} Y_e & Y_\mu & Y_\tau \\ \epsilon_1 Y'_e & \epsilon_1 Y'_\mu & \epsilon_1 Y'_\tau \\ \epsilon_2 Y''_e & \epsilon_2 Y''_\mu & \epsilon_2 Y''_\tau \end{pmatrix} \quad M_N = \begin{pmatrix} \mu_1 & \Lambda & \mu_3 \\ \Lambda & \mu_2 & \mu_4 \\ \mu_3 & \mu_4 & \Lambda' \end{pmatrix}$$

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 $\Rightarrow \begin{cases} \hat{m} \neq 0 \\ m_i \sim \mathcal{O}\,(\mathrm{eV}) \end{cases}$

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

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We have studied 2 different scenarios:

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  - they are heavier than Λ_{EW}
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  - SM is extended with an arbitrary number of ν_R
  - they are heavier than Λ_{EW}
  - no further assumptions
- 3N-SS: a 3 heavy neutrino scenario
  - SM is only extended with 3 ν_R
  - they are heavier than Λ_{EW}
  - large New Physics effects in spite of the smallness of m_ν
  - m_ν radiatively stable

Parametrizations

Parametrizations

- G-SS: a completely general scenario

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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Since $|\eta_{\alpha\beta}| \leq \sqrt{\eta_{\alpha\alpha}\eta_{\beta\beta}}$ → Schwarz inequality

→ indirect constraints on the off-diagonal entries

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Parametrizations

- 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

$$\Theta \simeq \frac{1}{\sqrt{2}} \begin{pmatrix} -i\theta_e & \theta_e & 0 \\ -i\theta_\mu & \theta_\mu & 0 \\ -i\theta_\tau & \theta_\tau & 0 \end{pmatrix} \text{ with } \theta_\alpha \equiv \frac{vY_\alpha}{\sqrt{2}\Lambda}$$

Since $\eta = \frac{\Theta\Theta^\dagger}{2}$ → $\eta = \frac{1}{2} \begin{pmatrix} |\theta_e|^2 & \theta_e\theta_\mu^* & \theta_e\theta_\tau^* \\ \theta_\mu\theta_e^* & |\theta_\mu|^2 & \theta_\mu\theta_\tau^* \\ \theta_\tau\theta_e^* & \theta_\tau\theta_\mu^* & |\theta_\tau|^2 \end{pmatrix}$

$|\eta_{\alpha\beta}| = \sqrt{\eta_{\alpha\alpha}\eta_{\beta\beta}}$ → 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

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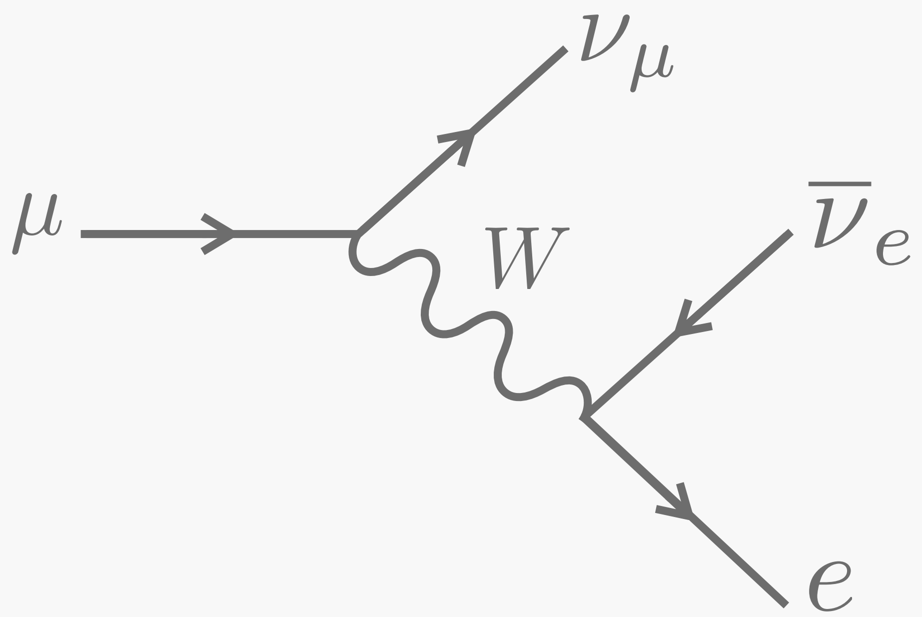
The 28 observables are computed in terms of α, G_μ and M_Z.

- The W boson mass M_W

  G_F measured in the μ decay



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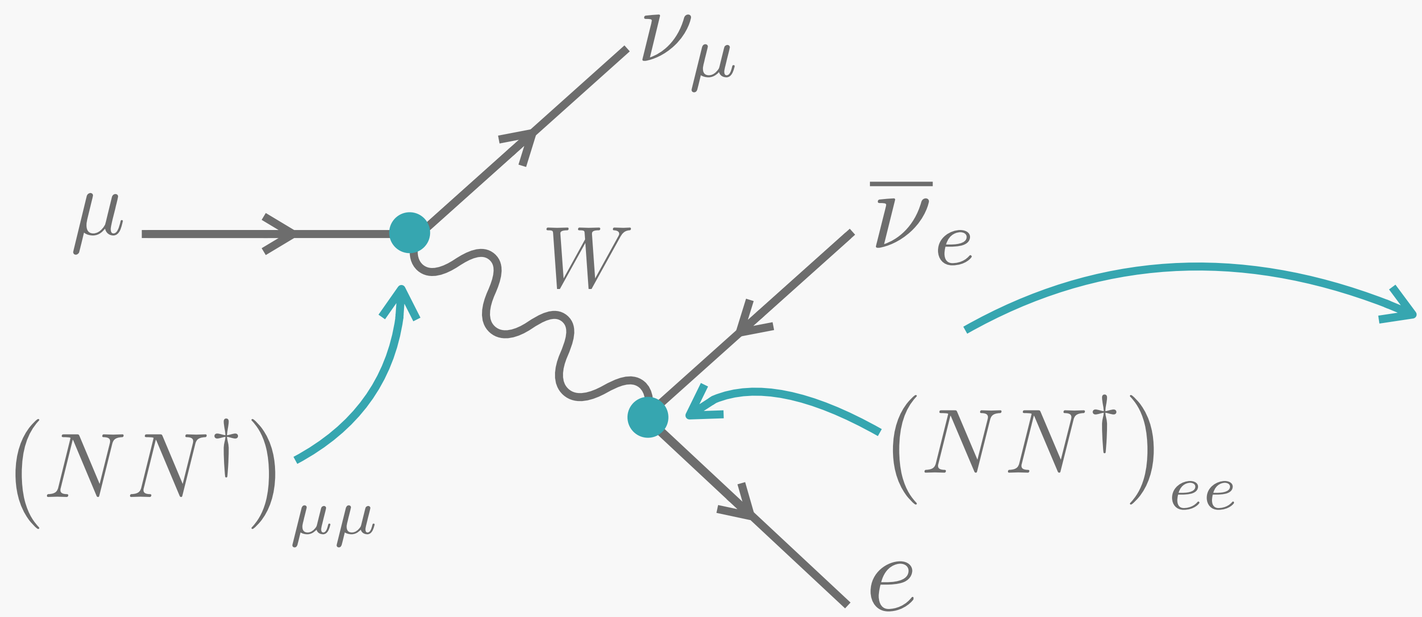

$$G_F^2\left(1-2\eta_{ee}-2\eta_{\mu\mu}\right)=G_\mu^2$$

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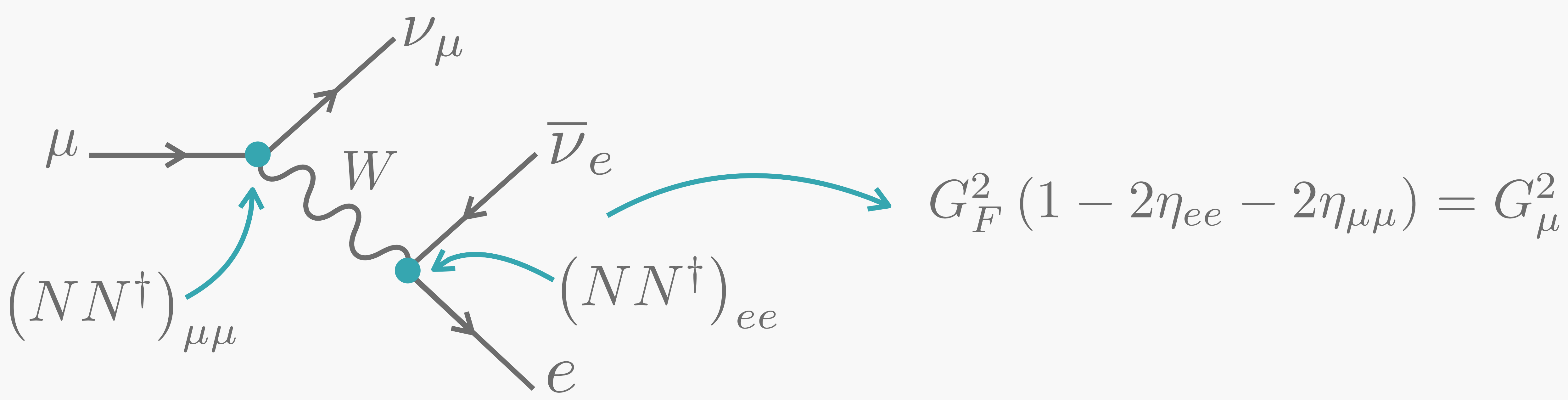

$$M_W^2=\frac{\pi\alpha}{\sqrt{2}G_F s_{\rm W}^2(1-\Delta r)}=\frac{\pi\alpha(1-\eta_{ee}-\eta_{\mu\mu})}{\sqrt{2}G_\mu s_{\rm W}^2(1-\Delta r)}$$

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

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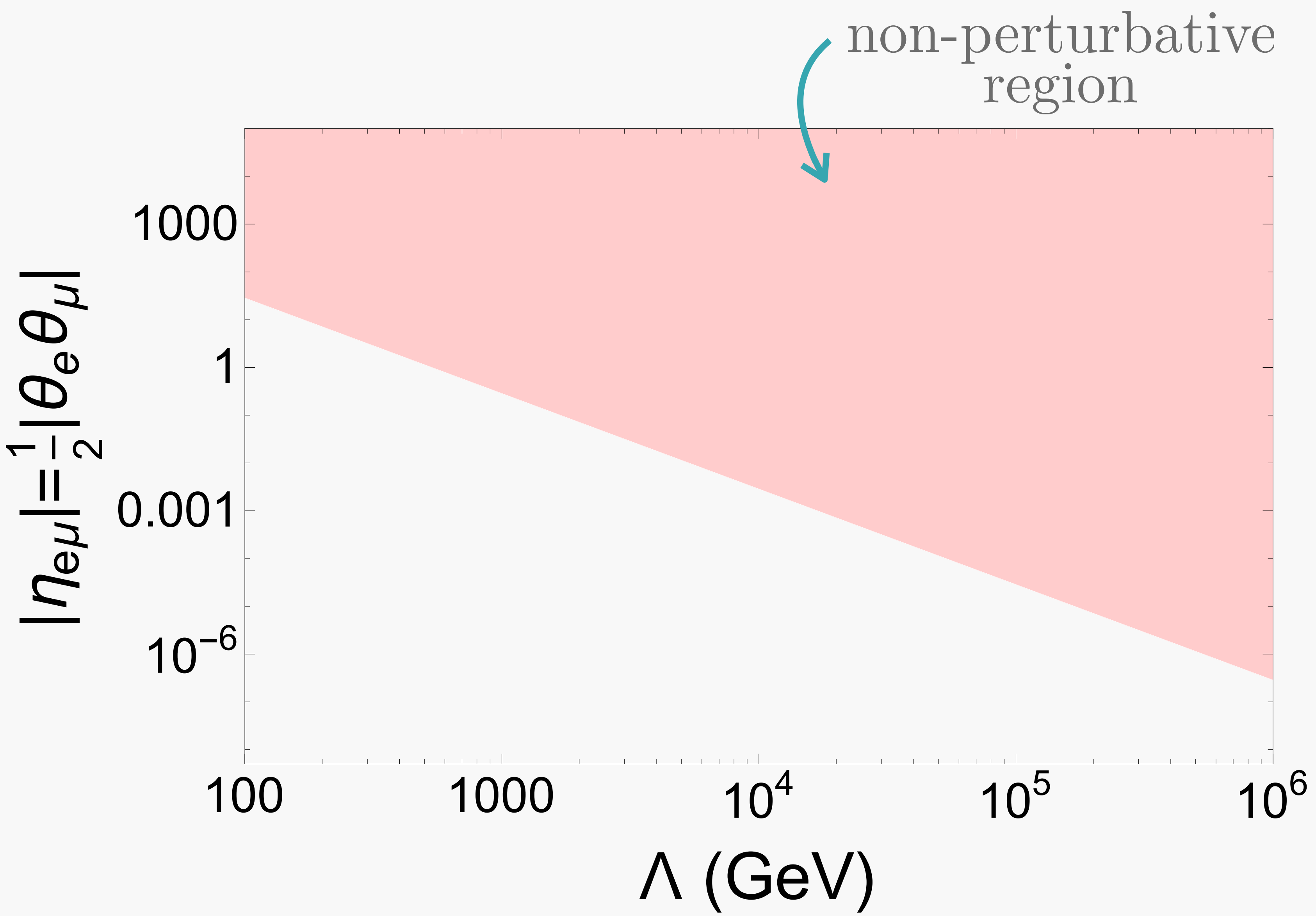
The 28 observables are computed in terms of α, G_μ and M_Z.

- 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



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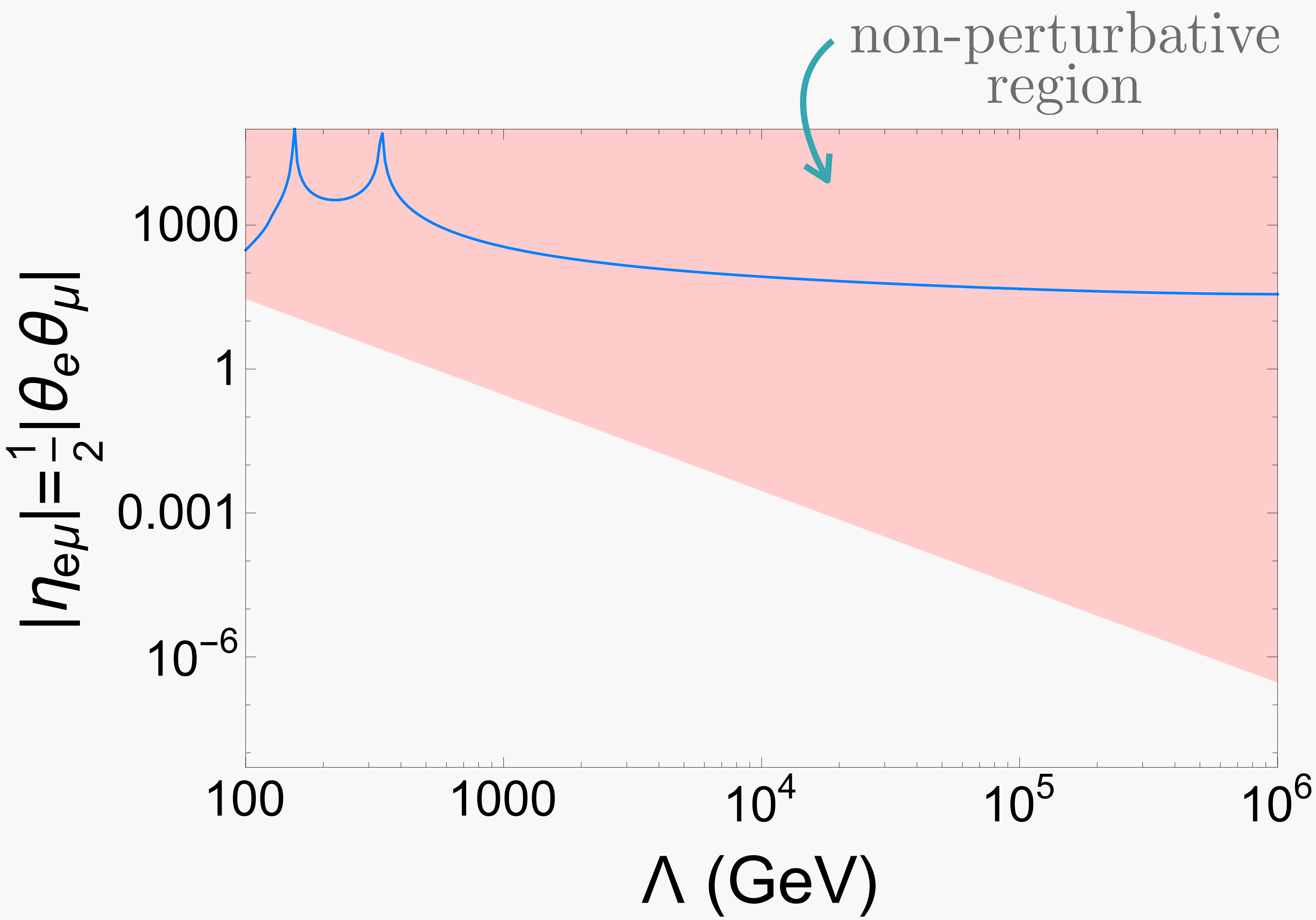

- $h \to e\mu$

Observables

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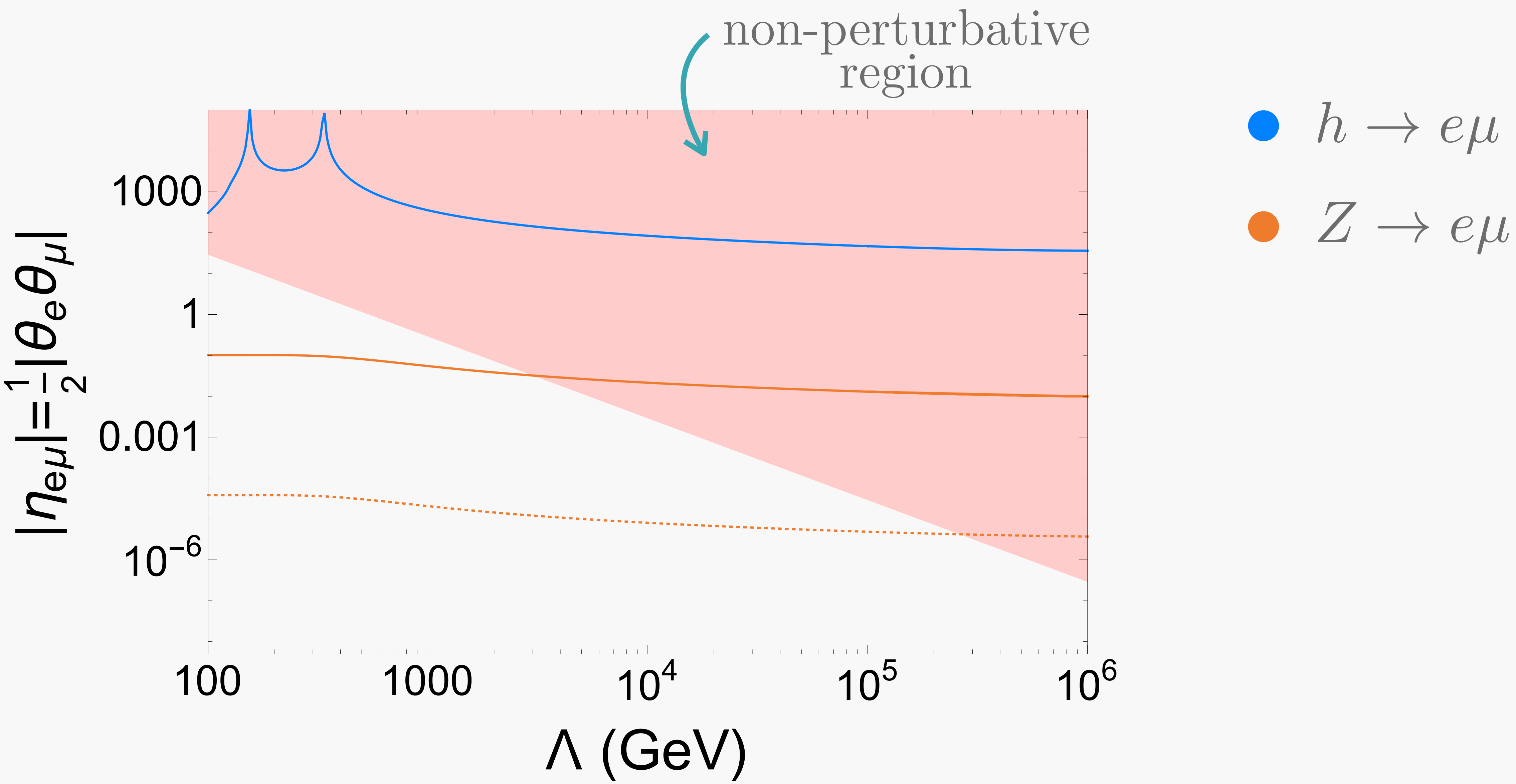

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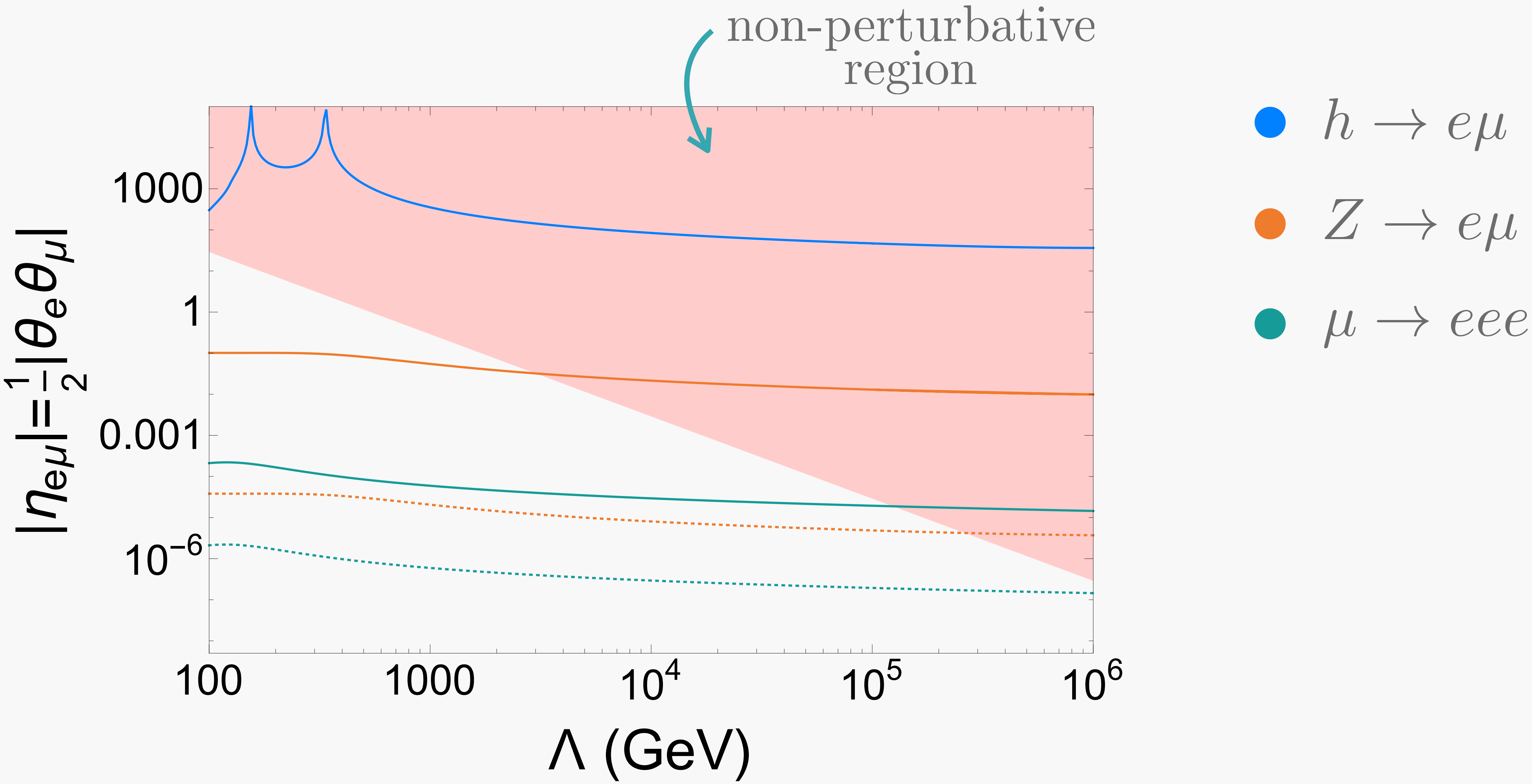

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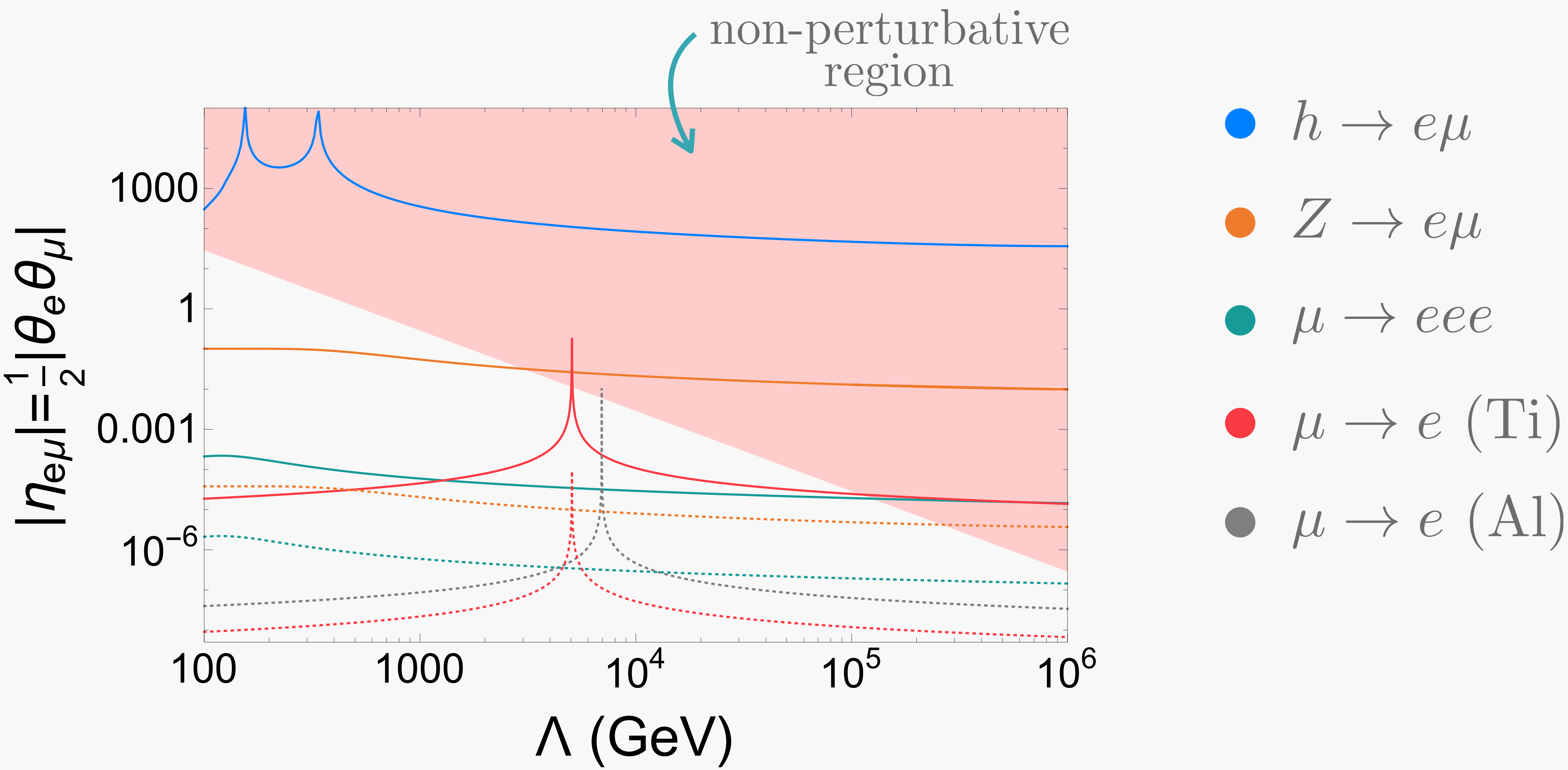

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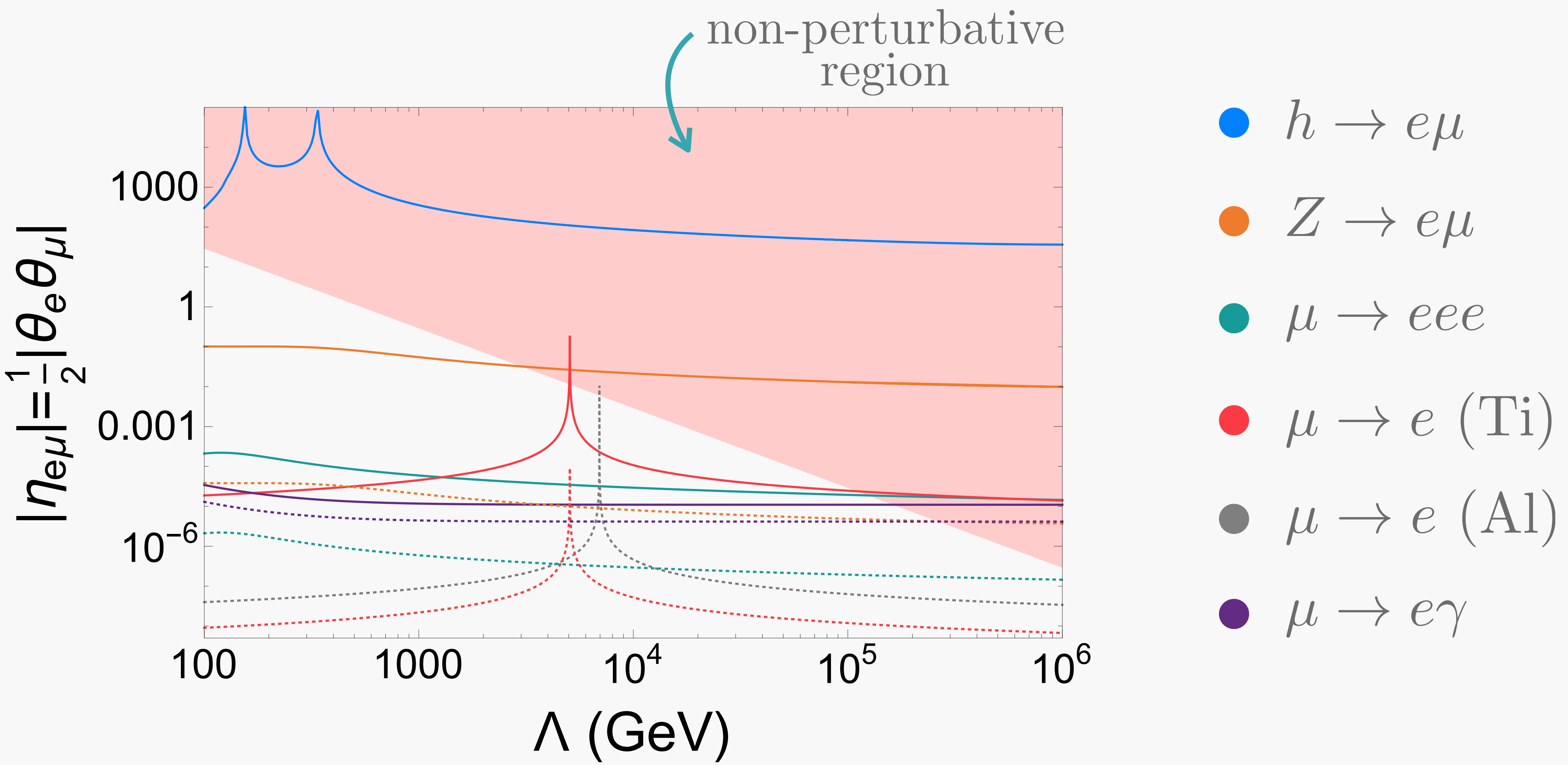
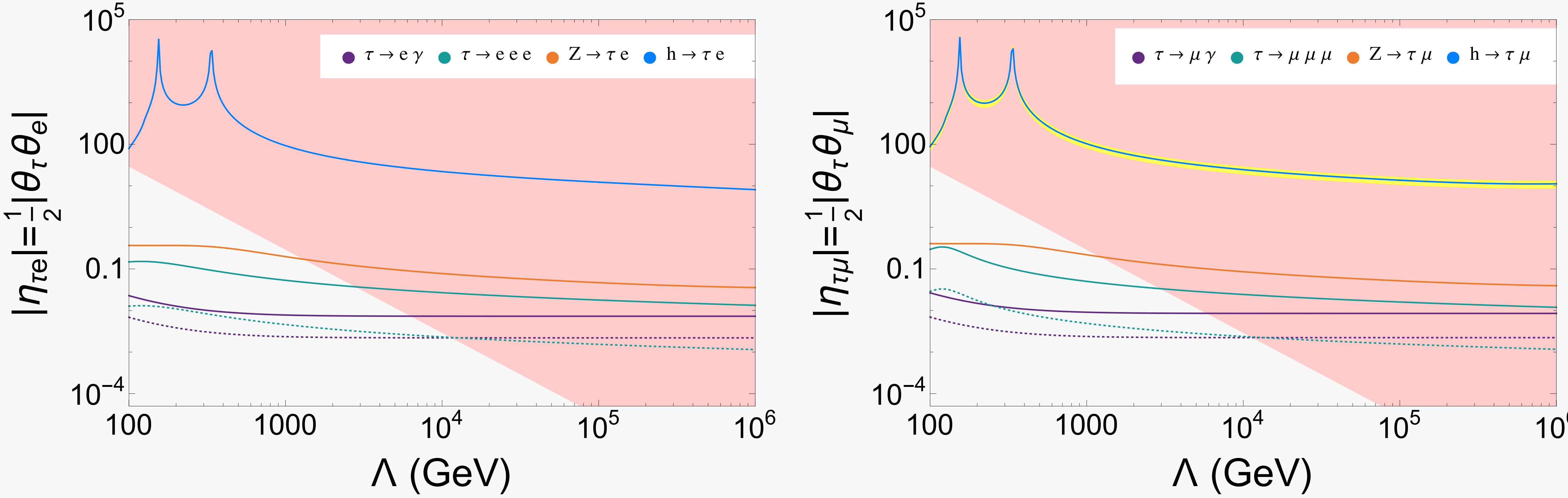


Observables

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 of the Global Fit

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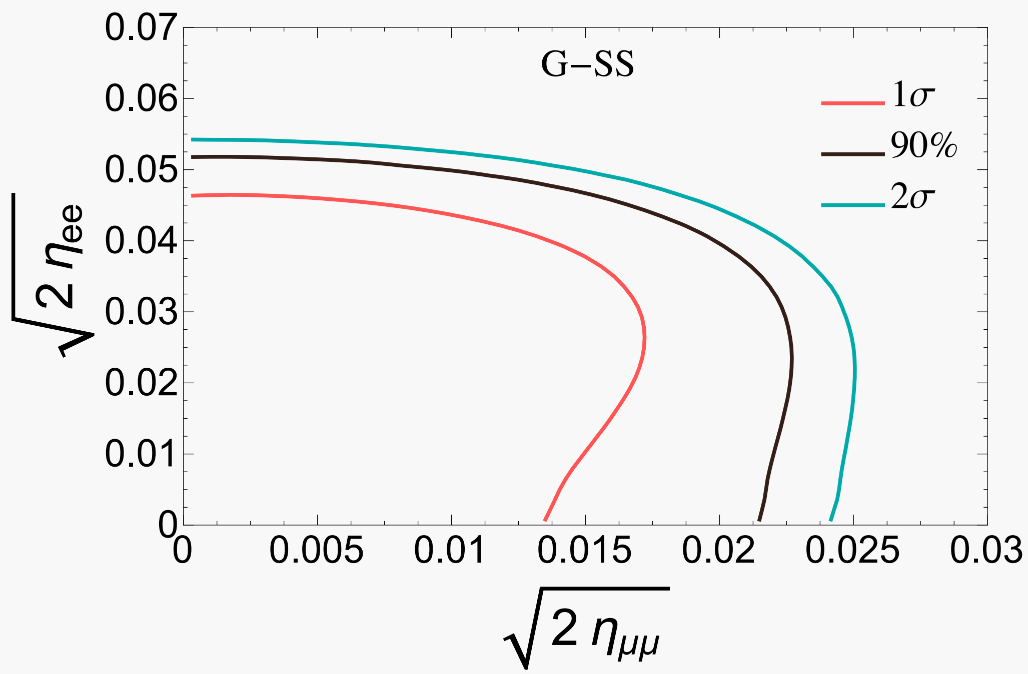
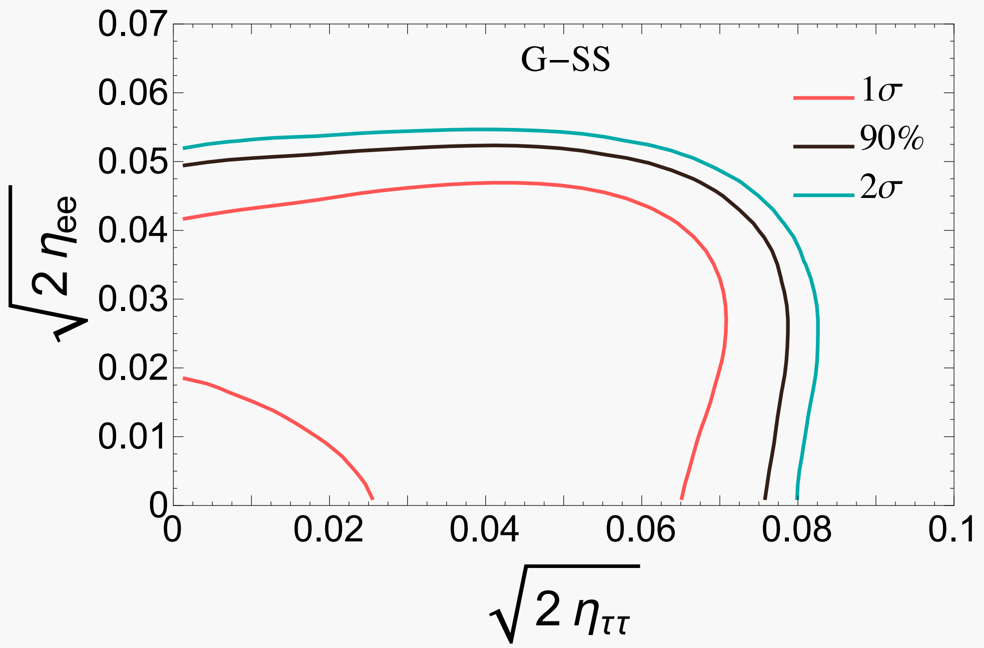
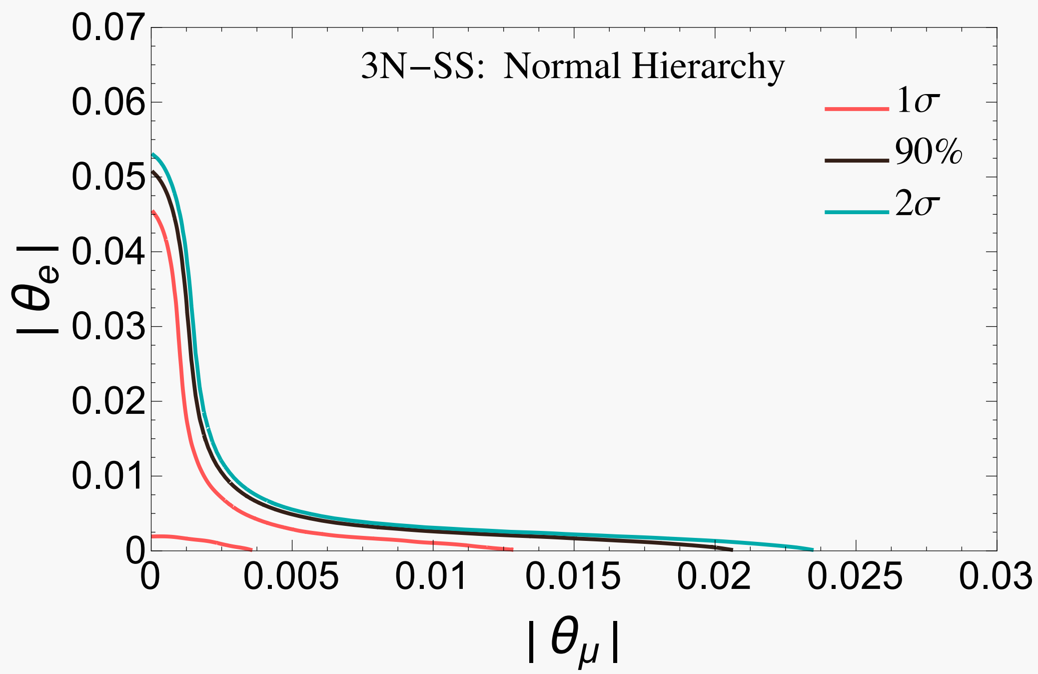
MCMC with the 28 observables scanning over the free parameters

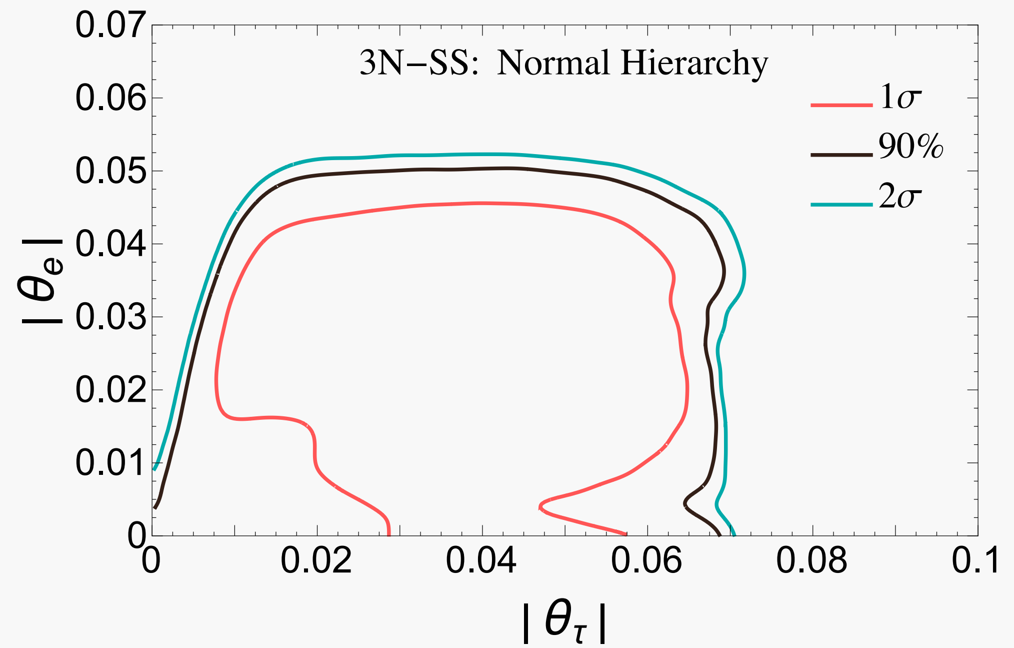
G-SS:





3N-SS: Normal Hierarchy





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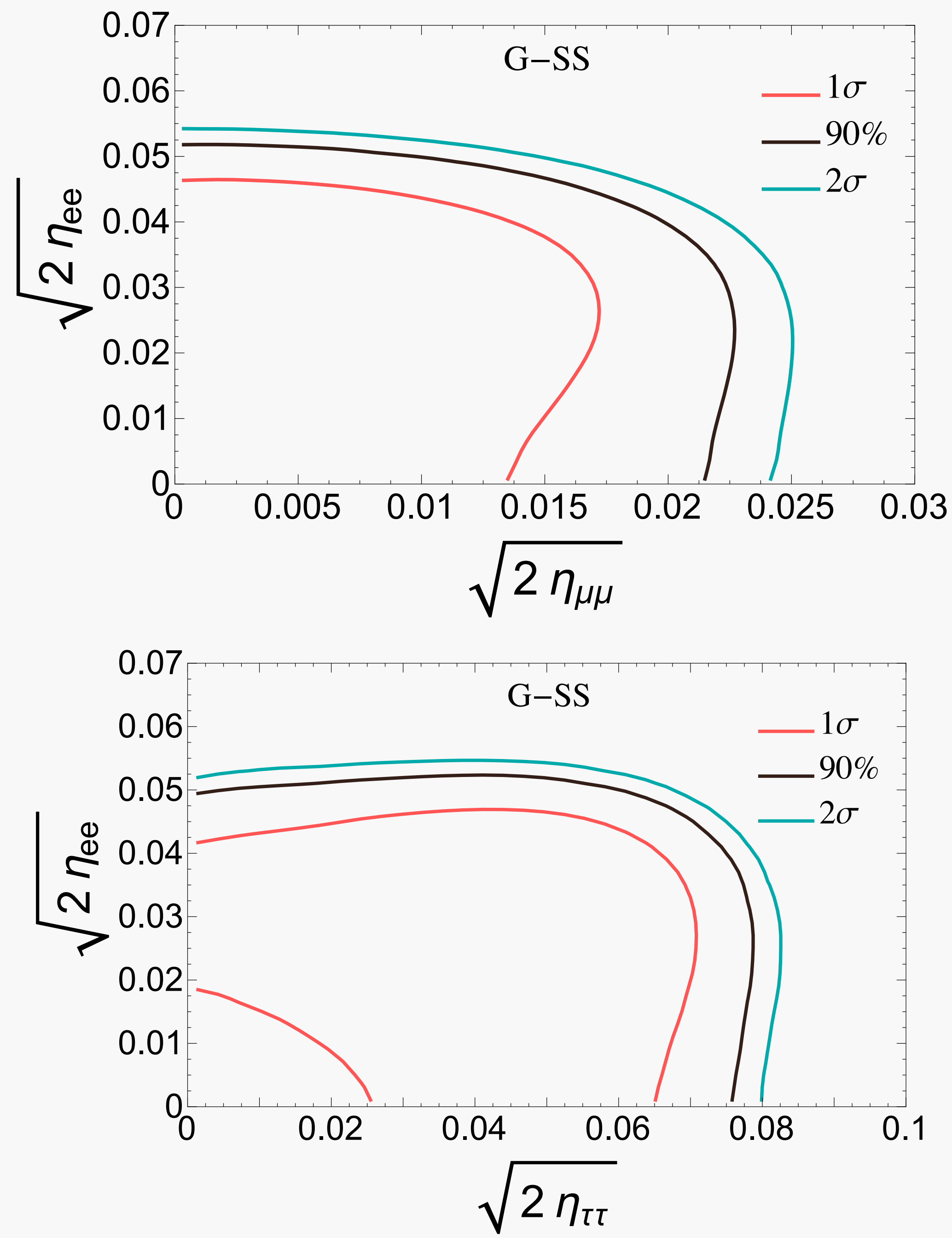
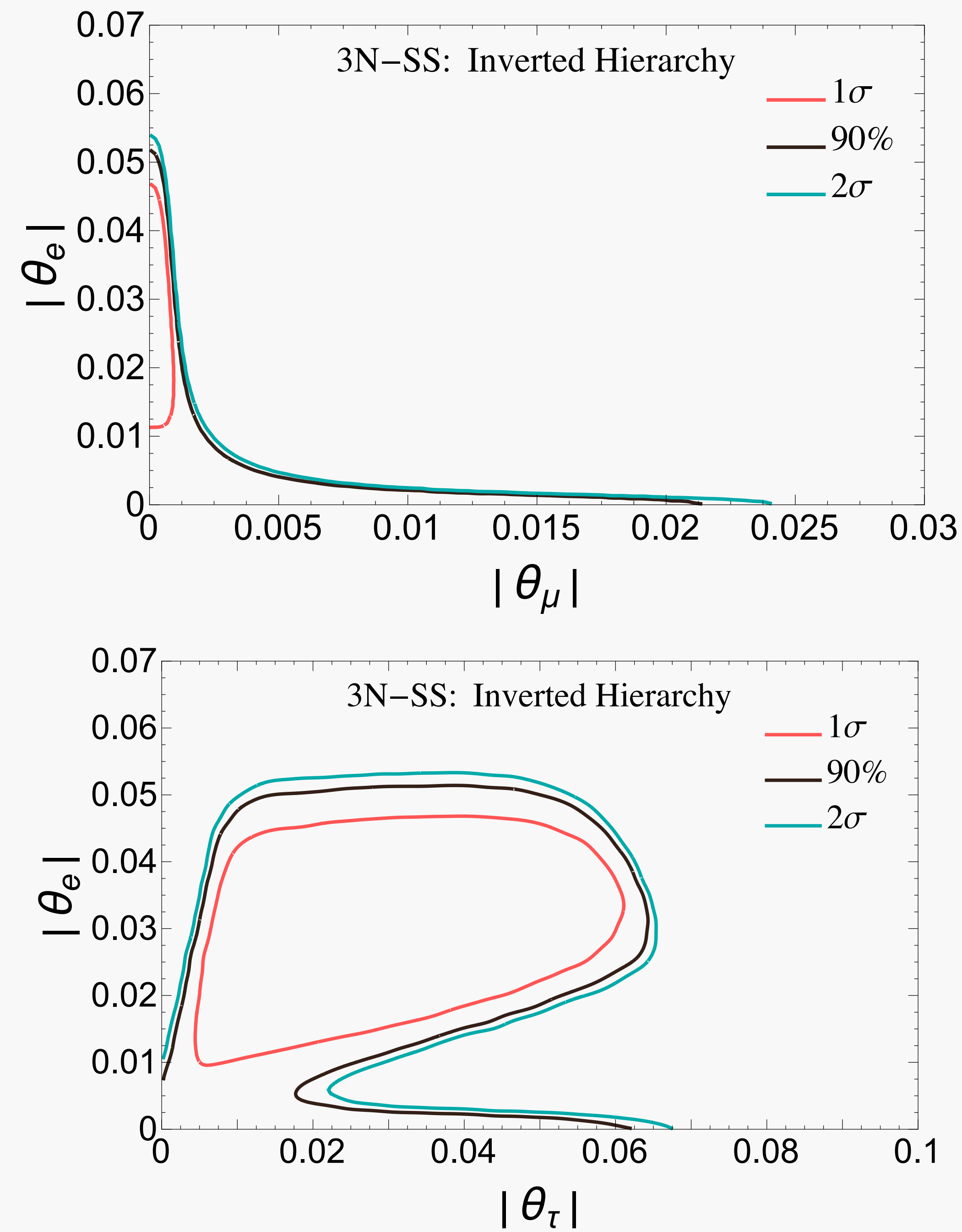
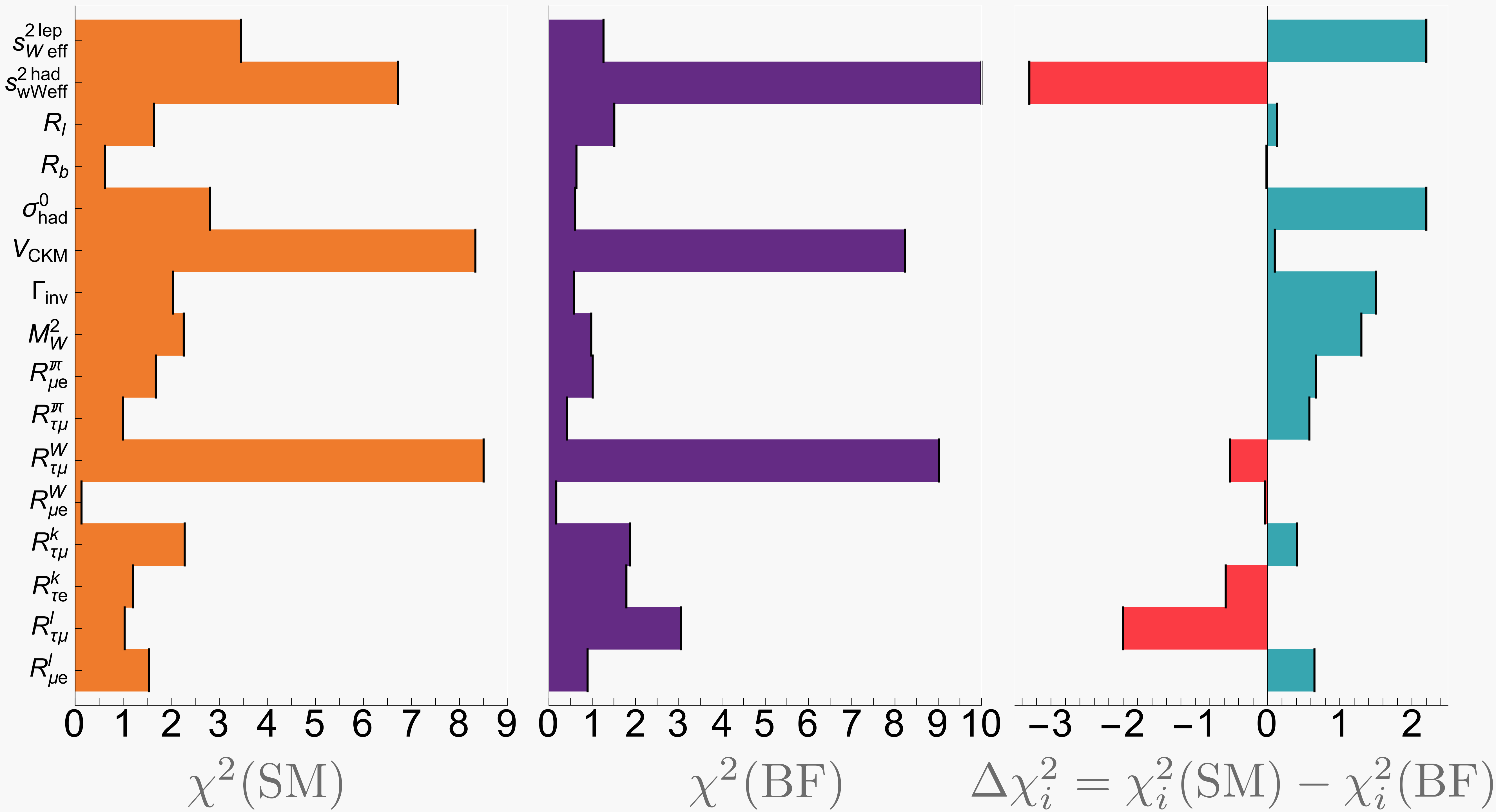


3N-SS: Inverted Hierarchy



Results of the Global Fit

Contributions from the different observables to the χ^2:



Results of the Global Fit

Global fit: diagonal entries of the mixing matrix

G-SS:	3N-SS:	
	NH	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 of the Global Fit

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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Global fit: off-diagonal entries of the mixing matrix

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LFC	LFV	NH	IH
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$\sqrt{2\lvert\eta_{e\tau}\rvert} < 0.045$	$\sqrt{2\lvert\eta_{e\tau}\rvert} < 0.107$	$\sqrt{\lvert\theta_e\theta_\tau\rvert} = 0.036^{+0.010}_{-0.016}$	$\sqrt{\lvert\theta_e\theta_\tau\rvert} = 0.036^{+0.010}_{-0.023}$
$\sqrt{2\lvert\eta_{\mu\tau}\rvert} < 0.024$	$\sqrt{2\lvert\eta_{\mu\tau}\rvert} < 0.115$	$\sqrt{\lvert\theta_\mu\theta_\tau\rvert} < 0.007$	$\sqrt{\lvert\theta_\mu\theta_\tau\rvert} < 0.005$

Schwarz inequality

1-loop effect

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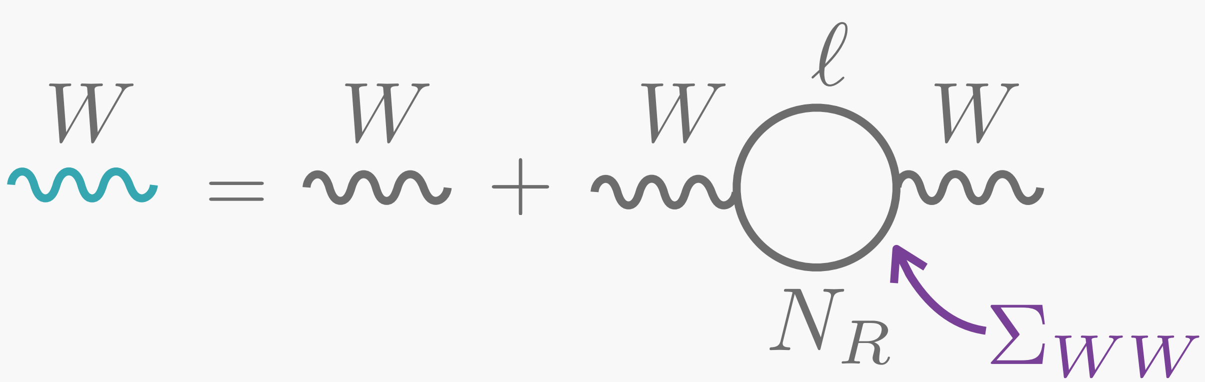
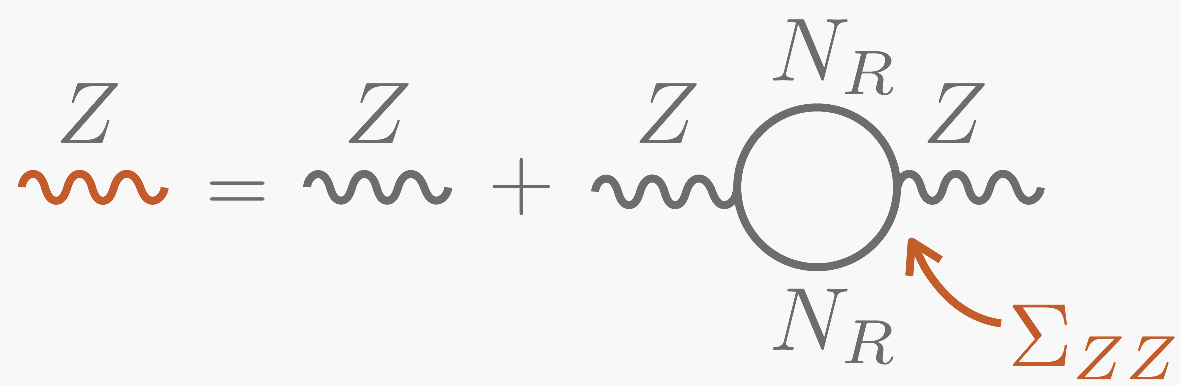
Several observables go with:

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

W and Z boson propagators corrected by the heavy ν_R:





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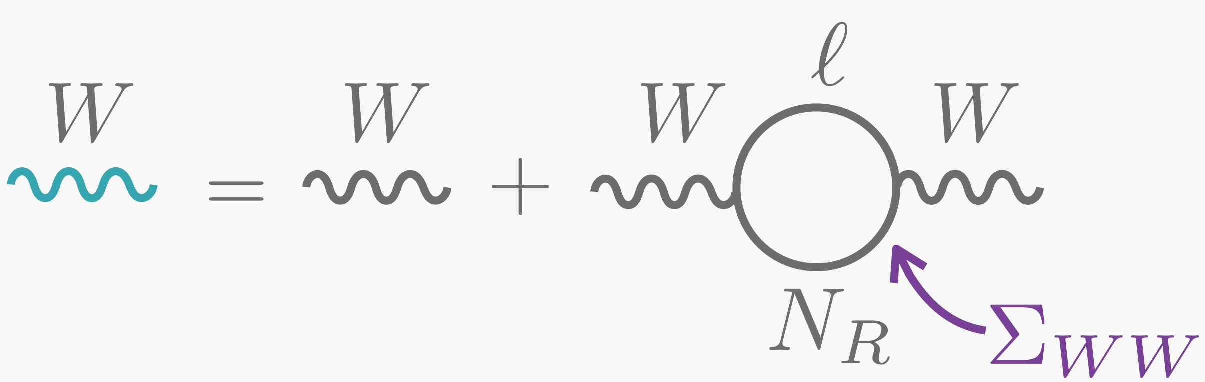
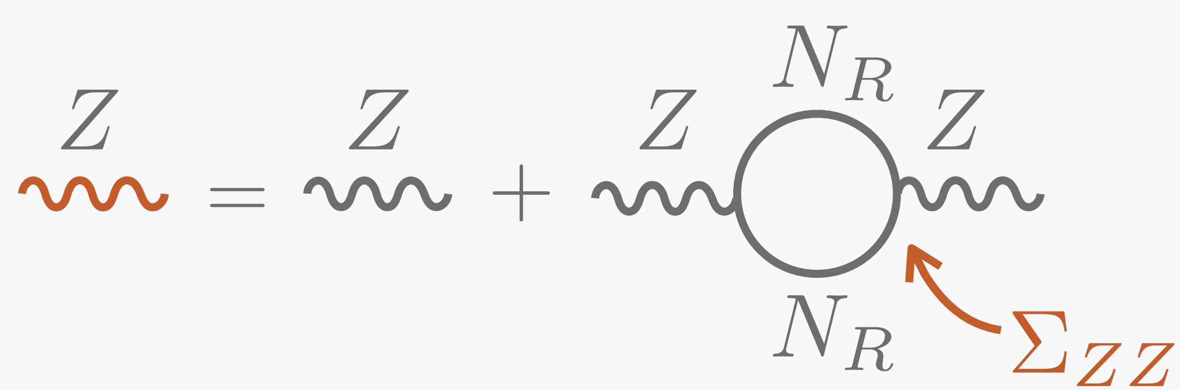
$$\frac{|\theta_e|^2}{2} + \frac{|\theta_\mu|^2}{2} + 2\alpha T \qquad T = \frac{\Sigma_{WW}(0)}{M_W^2} - \frac{\Sigma_{ZZ}(0)}{M_Z^2}$$

W and Z boson propagators corrected by the heavy ν_R:





A cancellation between tree and loop level could be posible.

This relaxes some bounds allowing to fit some anomalies.

E. Akhmedov *et al.* JHEP **1305** (2013) 081

1-LOOP EFFECT

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

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

large $\not{L}$ driven by μ_1 and μ_3

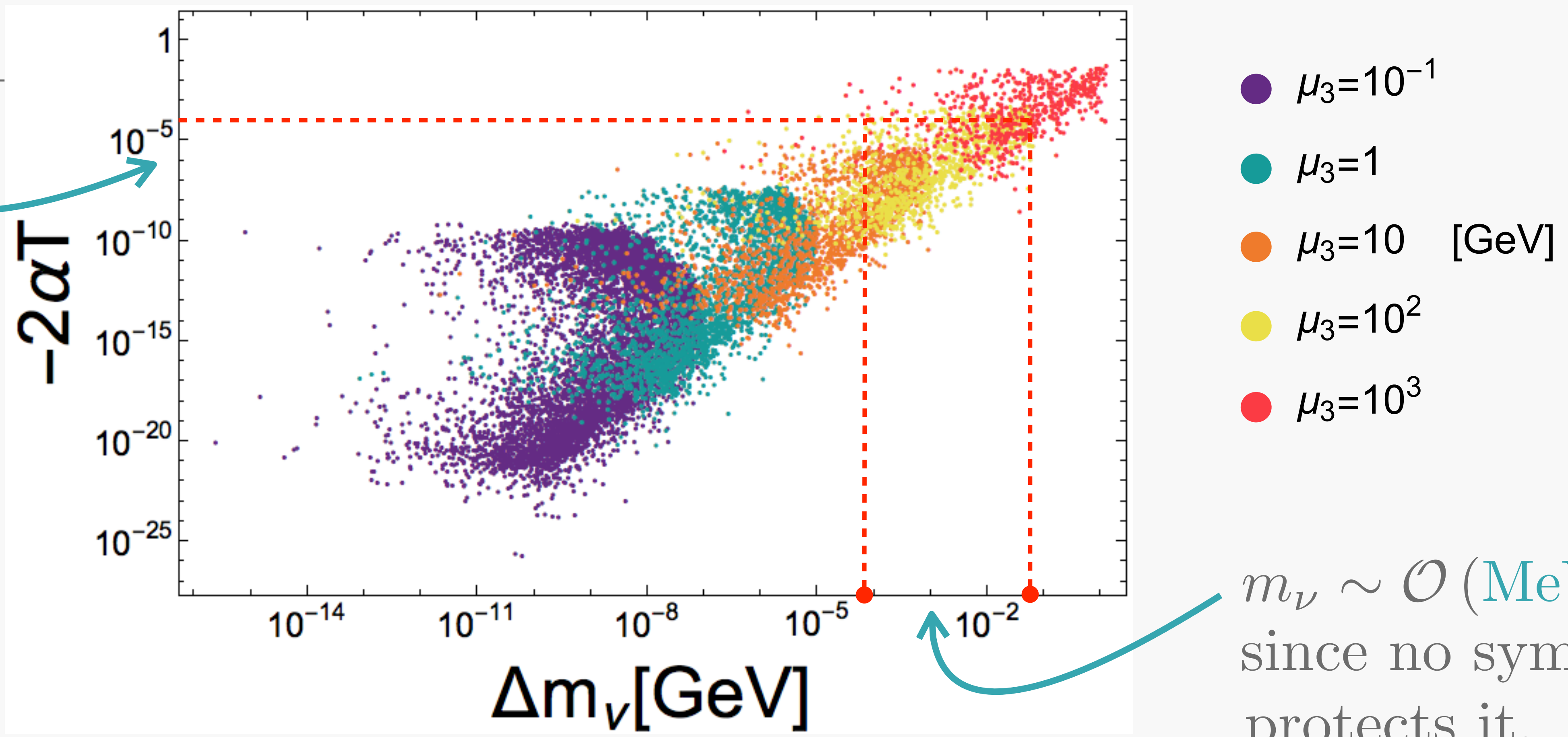
$$T \simeq \frac{v_{\text{EW}}^4}{64\pi s_{\text{W}}^2 M_W^2} \left(\sum_\alpha |Y_\alpha|^2 \right)^2 f\left(\mu_1, \mu_3\right)$$

1-LOOP EFFECT

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

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

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



$m_\nu \sim \mathcal{O}\left(\text{MeV}\right)$!!
since no symmetry protects it.

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 e and τ mixings with a significance of 2σ and an upper bound for μ mixing found in both scenarios.

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

In a L-conserving Seesaw model loop effects are negligible.

Thanks