



GLOBAL FIT TO RIGHT-HANDED NEUTRINO MIXING AT 1 LOOP

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MOTIVATION

EW obs. used to constrain additional ν mixing in Seesaw model.

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Sizeable phenomenology requires $\begin{cases} M_i \sim \mathcal{O}(\Lambda_{EW}) \\ Y_N \sim \mathcal{O}(1) \end{cases} \Rightarrow m_i \text{ too large}$

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$$m_D = \frac{v_{EW}}{\sqrt{2}} \begin{pmatrix} \nu_e & \nu_\mu & \nu_\tau \\ Y_e & Y_\mu & Y_\tau \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \begin{matrix} N_1 \\ N_2 \\ N_3 \end{matrix} \quad M_N = \begin{pmatrix} N_1 & N_2 & N_3 \\ 0 & \Lambda & 0 \\ \Lambda & 0 & 0 \\ 0 & 0 & \Lambda' \end{pmatrix} \begin{matrix} N_1 \\ N_2 \\ N_3 \end{matrix}$$

If L exact $\Rightarrow m_i = 0$

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If L softly broken $\Rightarrow m_i \neq 0$ but small.

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$M_1 = M_2 = \Lambda$ (Dirac pair), $M_3 = \Lambda'$ (decoupled) but **large mixing**.

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The full neutrino mass matrix diagonalized by:

$$U_{\text{tot}} \simeq \begin{pmatrix} \left(\mathbb{1} - \frac{\Theta\Theta^\dagger}{2} \right) U_{\text{PMNS}} & \Theta \\ -\Theta^\dagger U_{\text{PMNS}} & \mathbb{1} - \frac{\Theta\Theta^\dagger}{2} \end{pmatrix} \quad \text{where} \quad \Theta \equiv \frac{1}{\sqrt{2}} \begin{pmatrix} -i\theta_e & \theta_e & 0 \\ -i\theta_\mu & \theta_\mu & 0 \\ -i\theta_\tau & \theta_\tau & 0 \end{pmatrix}$$

$\theta_i \simeq \frac{v_{\text{EW}} Y_i^*}{\sqrt{2}\Lambda}$

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Fixing ν osc. data: θ_{ij} , Δm_{21}^2 and $\Delta m_{31}^2 \Rightarrow Y_\tau = Y_\tau(m_1, \delta, \alpha_1, \alpha_2) \Rightarrow$

9 free parameters

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Parameter	$ Y_e $ & $ Y_\mu $	m_1 [eV]	Λ [GeV]	Phases: $\alpha_e, \alpha_\mu, \delta, \alpha_1$ & α_2	Osc. data
Range	(0, 4)	$(10^{-5}, 1)$	$(10^3, 10^4)$	$(0, 2\pi)$	fixed

OBSERVABLES

The 13 observables computed* at 1 loop in terms of M_Z , α and G_μ .
 Z and W boson propagators corrected by the new dof:

$$\begin{aligned} \text{W propagator} &= \text{tree} + \text{loop} \\ \text{Z propagator} &= \text{tree} + \text{loop} \end{aligned}$$

The diagrams show the correction to the W and Z boson propagators at one loop. The W propagator correction is represented by a loop of W bosons with a self-energy insertion Σ_{WW} (labeled with l and N). The Z propagator correction is represented by a loop of Z bosons with a self-energy insertion Σ_{ZZ} (labeled with N and N).

which directly enter in the list of obs.:

*in the Equivalence Theorem regime

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The diagrams show the tree-level propagators (wavy lines) and the one-loop corrections (circles with N internal lines). The loop corrections are labeled Σ_{WW} and Σ_{ZZ} .

which directly enter in the list of obs.:

- Universality ratios: $R_{\mu e}^\pi$, $R_{\tau\mu}^\pi$, $R_{e\mu}^W$, $R_{\tau\mu}^W$, $R_{\mu e}^K$, $R_{\tau\mu}^K$, $R_{\mu e}^l$ and $R_{\tau\mu}^l$

$$R_{\mu e}^\pi = \frac{\left| \begin{aligned} &\pi \rightarrow W \rightarrow \nu_\mu^\mu \\ &\pi \rightarrow W \rightarrow \nu_\mu^\mu \text{ (with } N \text{ loop)} \\ &\pi \rightarrow W \rightarrow \nu_\mu^\mu \text{ (with } H \text{ loop)} \end{aligned} \right|^2}{\left| \begin{aligned} &\pi \rightarrow W \rightarrow \nu_e^e \\ &\pi \rightarrow W \rightarrow \nu_e^e \text{ (with } N \text{ loop)} \\ &\pi \rightarrow W \rightarrow \nu_e^e \text{ (with } H \text{ loop)} \end{aligned} \right|^2}$$

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 Z and W boson propagators corrected by the new dof:

$$\begin{aligned} \text{Wavy } W &= \text{Wavy } W + \text{Wavy } W \text{ (loop)} \text{ Wavy } W \\ &\quad \text{with } l \text{ external lines and } N \text{ internal lines, labeled } \Sigma_{WW} \\ \text{Wavy } Z &= \text{Wavy } Z + \text{Wavy } Z \text{ (loop)} \text{ Wavy } Z \\ &\quad \text{with } N \text{ external lines and } N \text{ internal lines, labeled } \Sigma_{ZZ} \end{aligned}$$

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- Invisible Z decay

$$\Gamma_{\text{inv}} = \left| Z \text{ (wavy)} \begin{cases} n_i \\ n_j \end{cases} + Z \text{ (wavy)} \begin{matrix} \phi \\ H \end{matrix} \begin{matrix} N \\ N \end{matrix} \begin{cases} n_i \\ n_j \end{cases} + Z \text{ (wavy)} \begin{matrix} N \\ N \end{matrix} \begin{matrix} \phi \\ H \end{matrix} \begin{cases} n_i \\ n_j \end{cases} \right|^2$$

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$$\begin{aligned} \text{Wavy } W &= \text{Wavy } W + \text{Wavy } W \text{---} \text{Circle } W \text{---} \text{Wavy } W \\ &\hspace{15em} \uparrow \Sigma_{WW} \\ \text{Wavy } Z &= \text{Wavy } Z + \text{Wavy } Z \text{---} \text{Circle } Z \text{---} \text{Wavy } Z \\ &\hspace{15em} \uparrow \Sigma_{ZZ} \end{aligned}$$

which directly enter in the list of obs.:

- Universality ratios: $R_{\mu e}^\pi$, $R_{\tau\mu}^\pi$, $R_{e\mu}^W$, $R_{\tau\mu}^W$, $R_{\mu e}^K$, $R_{\tau\mu}^K$, $R_{\mu e}^l$ and $R_{\tau\mu}^l$
- Invisible Z decay
- M_W through μ decay

$$\Gamma_\mu = \left| \begin{array}{c} \mu \text{---} W \text{---} e \\ \nu_\mu \text{---} \nu_e \end{array} + \begin{array}{c} \mu \text{---} W \text{---} \phi \\ \nu_\mu \text{---} \phi H \text{---} N \text{---} e \\ \nu_e \end{array} + \begin{array}{c} \mu \text{---} \phi \\ N \text{---} \phi H \text{---} W \text{---} e \\ \nu_\mu \text{---} \nu_e \end{array} + \begin{array}{c} \mu \text{---} \phi \\ N \text{---} \phi H \text{---} N \text{---} e \\ \nu_\mu \text{---} \nu_e \end{array} \right|^2$$

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 Z and W boson propagators corrected by the new dof:

$$\begin{aligned} \text{W propagator} &= \text{tree} + \text{loop} \\ \text{Z propagator} &= \text{tree} + \text{loop} \end{aligned}$$

The diagram shows two equations. The first equation is for the W boson propagator: a wavy line labeled 'W' is equal to a tree-level wavy line plus a one-loop correction. The loop consists of two particles, labeled 'l' and 'N', connected by a circle. A blue arrow points to the loop with the label Σ_{WW} . The second equation is for the Z boson propagator: a wavy line labeled 'Z' is equal to a tree-level wavy line plus a one-loop correction. The loop consists of two particles, both labeled 'N', connected by a circle. An orange arrow points to the loop with the label Σ_{ZZ} .

which directly enter in the list of obs.:

- Universality ratios: $R_{\mu e}^\pi$, $R_{\tau\mu}^\pi$, $R_{e\mu}^W$, $R_{\tau\mu}^W$, $R_{\mu e}^K$, $R_{\tau\mu}^K$, $R_{\mu e}^l$ and $R_{\tau\mu}^l$
- Invisible Z decay
- M_W through μ decay
- Rare decays: $\mu \rightarrow e\gamma$, $\tau \rightarrow \mu\gamma$ and $\tau \rightarrow e\gamma$

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Several observables go with:

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

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]

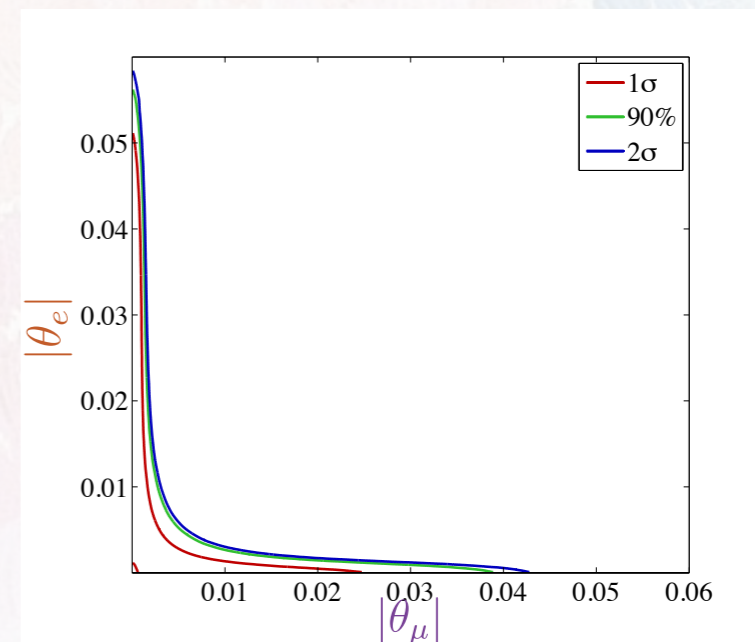
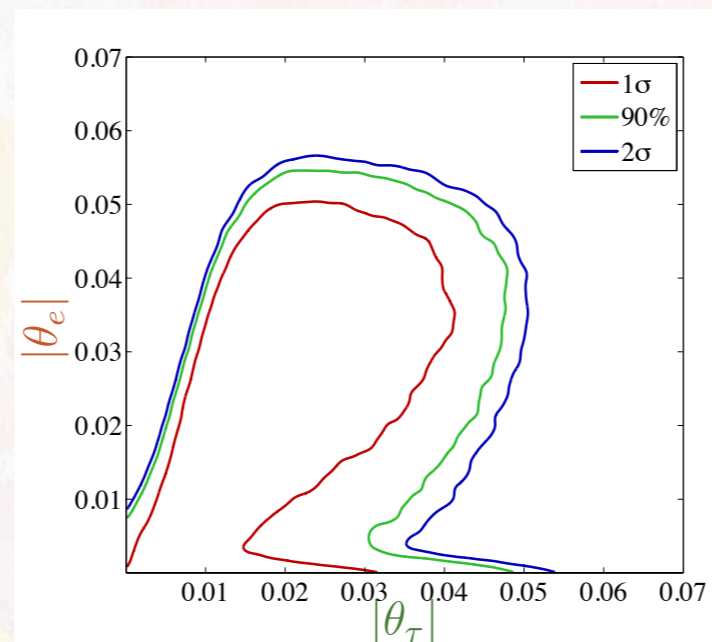
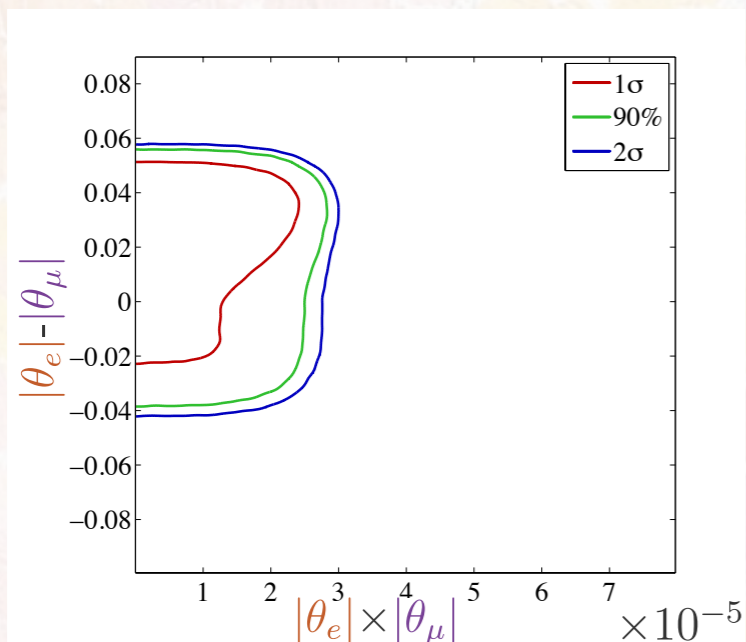
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RESULTS

- Global fit and constraints

MCMC with the 13 observables scanning over the 9 parameters.

Frequentist constraints and values in the BF point of $|\theta_e|$, $|\theta_\mu|$ and $|\theta_\tau|$:



$$\begin{aligned} |\theta_e| &= 0.037^{+0.012}_{-0.014} \\ |\theta_\mu| &< 0.0006 \\ |\theta_\tau| &= 0.021^{+0.016}_{-0.010} \end{aligned}$$

RESULTS

- Loop effect

If L is softly broken $\Rightarrow T \geq 0 \Rightarrow$ NO cancellation allowed.

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

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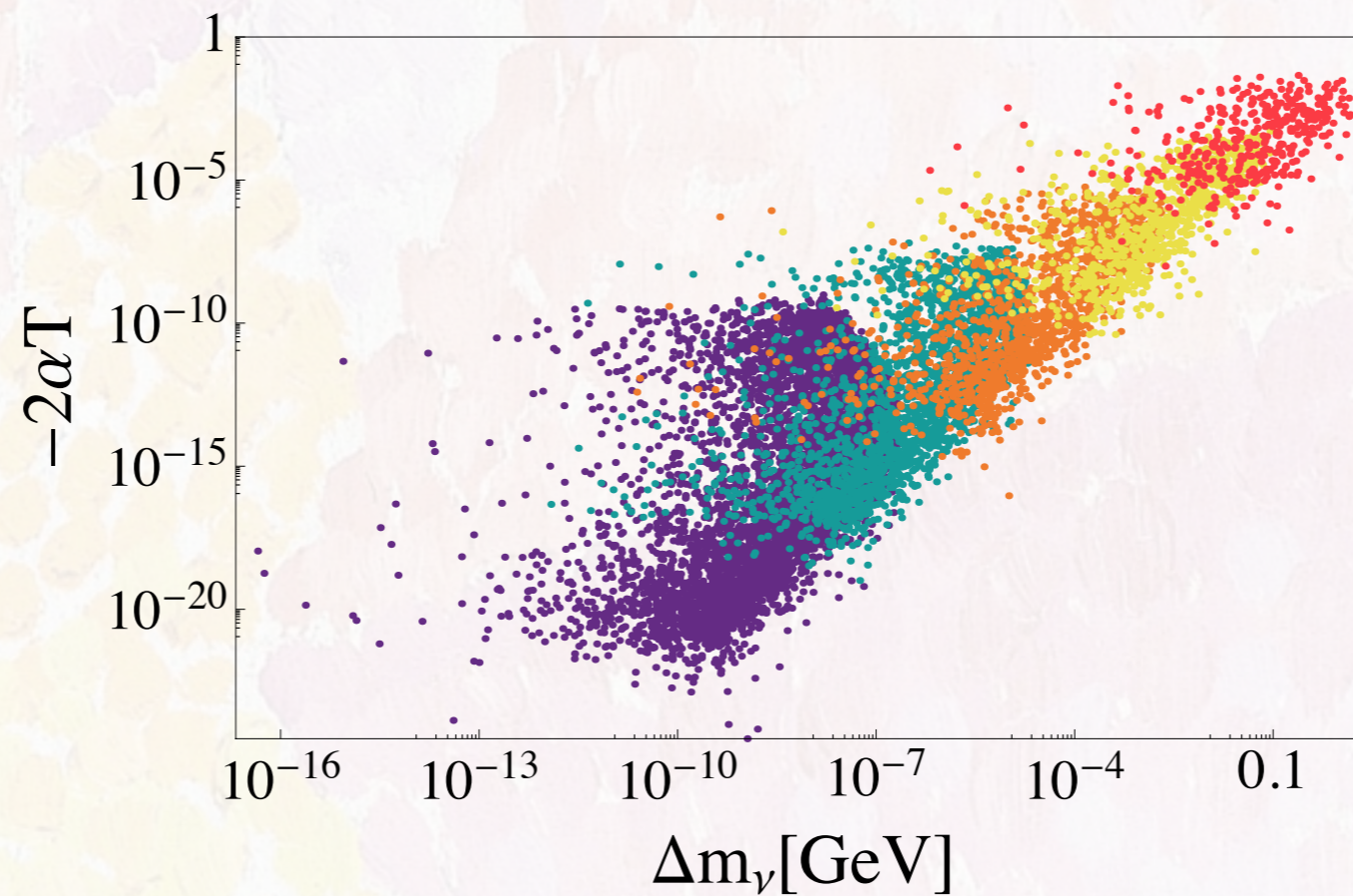
$T < 0$ only possible for large L .

$$m_i^{\text{tree}} \sim v_{EW}^2 Y_i^2 \left(\frac{1}{\Lambda} \mathcal{O}(\epsilon_1, \frac{\mu}{2\Lambda}) + \frac{1}{\Lambda'} \mathcal{O}(\epsilon_2^2, \frac{\mu''^2}{4\Lambda^2}, \frac{\mu'''^2}{4\Lambda^2}) \right) \Rightarrow L \text{ driven by } \mu'$$

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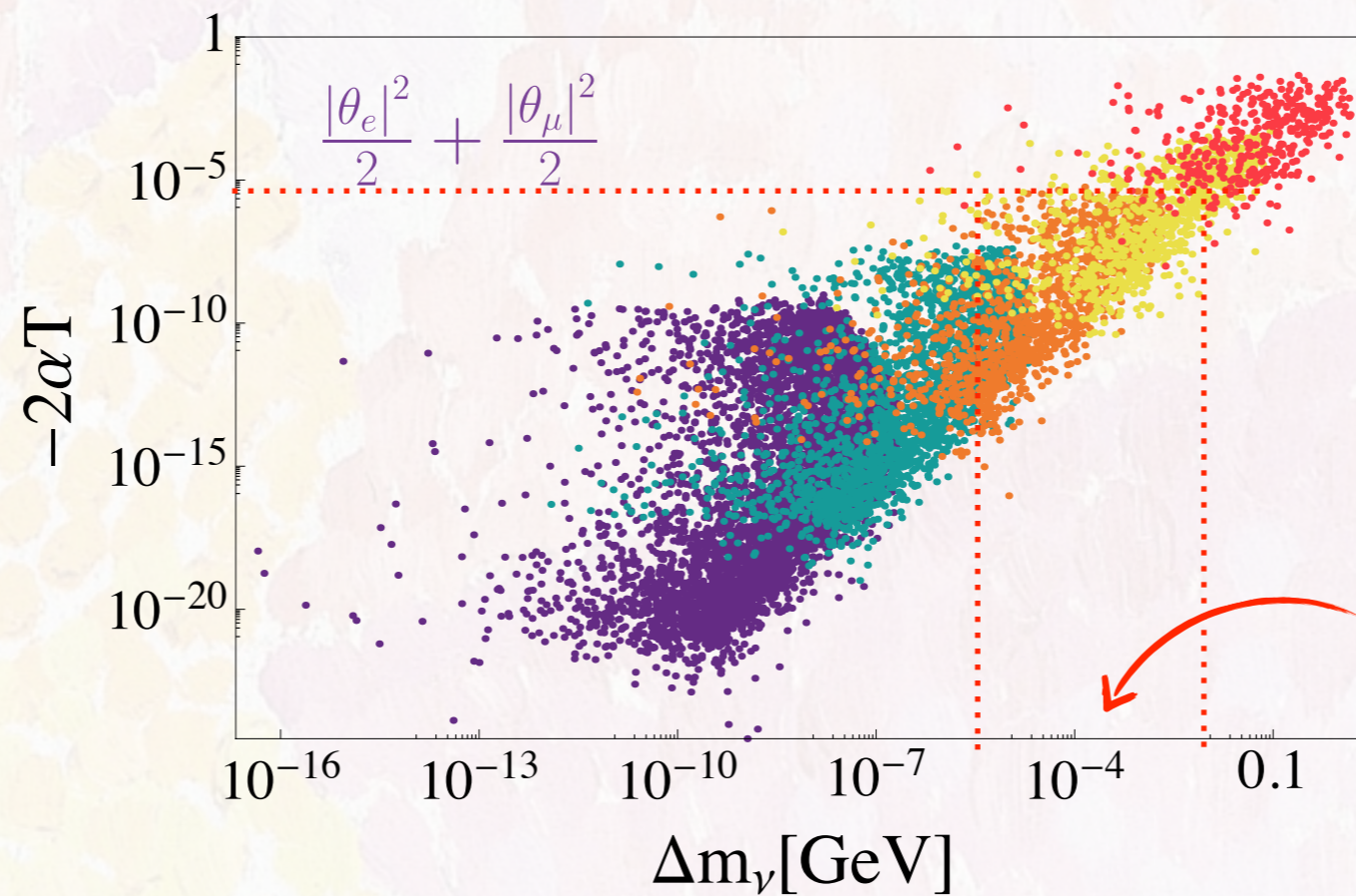
Loop corrections of μ' to m_i should be taken into account:



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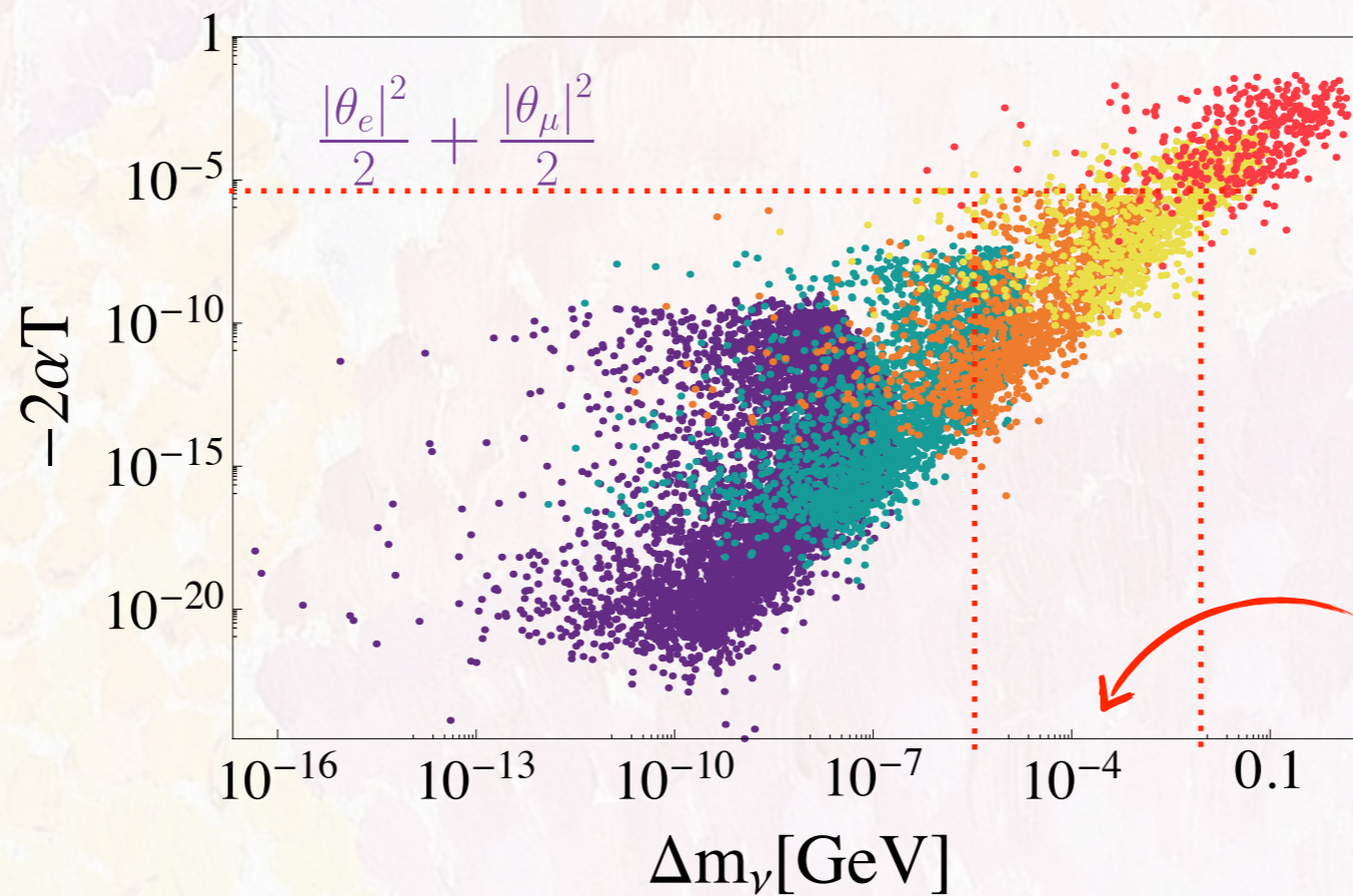


$m_\nu \sim 100$ MeV!!
since no symmetry
protects it

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THANKS



BACK-UP

For $|\mu'| \gg \Lambda$, $Y_\alpha v_{\text{EW}}$:

$$T \simeq \frac{v_{\text{EW}}^4}{32\pi s_W^2 M_W^2 \mu'^2} \left(\sum_\alpha |Y_\alpha|^2 \right)^2 \left(3 - 8 \log \left(\frac{\mu'}{\Lambda} \right) \right)$$

But **loop level** correction to m_ν should be taken into account:

$$\Delta m_{\nu_{\alpha\beta}} \simeq \frac{\mu' Y_\alpha Y_\beta}{16\pi^2} \left(\frac{3M_Z^2}{\mu'^2 - M_Z^2} \log \left(\frac{\mu'}{M_Z} \right) + \frac{M_H^2}{\mu'^2 - M_H^2} \log \left(\frac{\mu'}{M_H} \right) \right)$$