Various bounds on a three-loop radiative seesaw model

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§ Introduction

Radiative seesaw models

- Non-vanishing neutrino mass
- Dark matter
- Baryon asymmetric Universe
- …, R(K), m_W , g-2, …

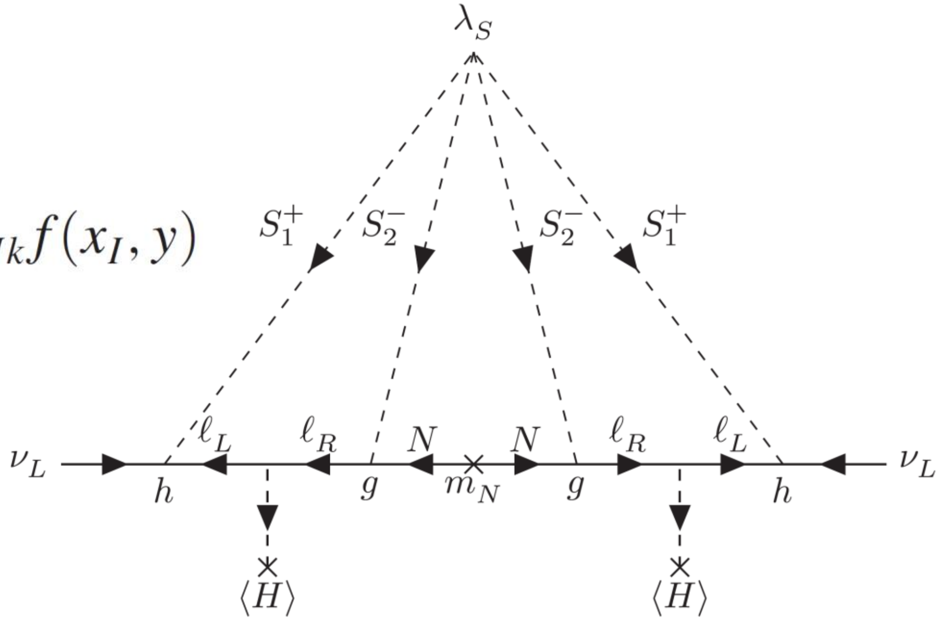
- Small neutrino mass as quantum corrections
  - TeV scale new particles
- Extra Parity
  - Primarily to forbid tree-level terms
  - Stability of DM as a bonus

A three loop model [Krauss, Nasri and Trodden (2003)]

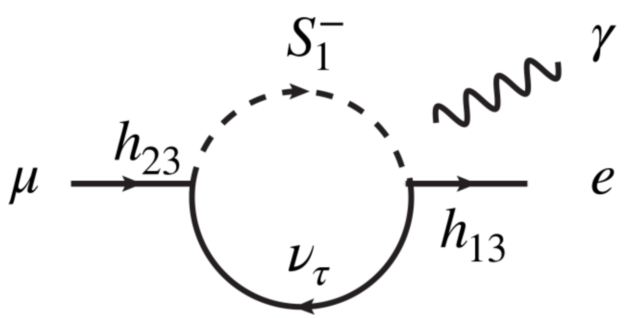
- Neutrino mass

$$M_{ab} = \frac{\lambda_S}{4(4\pi)^3 m_{S_1}} \sum_{I,j,k} m_{\ell_j} m_{\ell_k} h_{aj} h_{bk} g_{Ij} g_{Ik} f(x_I, y)$$

$$x_I \equiv \frac{m_{N_I}^2}{m_{S_2}^2}, \qquad y \equiv \frac{m_{S_1}^2}{m_{S_2}^2},$$



- Lepton flavor violation
  - Anti-symmetric tensor h_{ai}
    - Inevitably induce flavor violation
    - Constraints on h_{ai} and m_{S1}



[Cheung and Seto (2004), Ahrich and Nasri (2013),…]

  - Prescription of h was developed [Irie, Seto, Shindou (2021)]

Mass to couplings [Irie, Seto and Shindou (2021)]

- In a class of radiative neutrino mass models, neutrino mass [Kanemura and Sugiyama (2016)]

$$M_\nu \propto h\, m_l X_S\, m_l h^T$$

  h : anti-symmetric Yukawa

  m_l: charged lepton mass

  X_S: symmetric Yukawa

  – e.g., Zee-Babu model [Zee (1986), Babu (1987)], KNT model

- The ratios of Yukawa couplings

$$k := \frac{h_{12}}{h_{23}}, \quad k' := \frac{h_{13}}{h_{23}},$$

$$k = \frac{M_{e\mu}M_{\mu\tau} - M_{e\tau}M_{\mu\mu}}{M_{\mu\mu}M_{\tau\tau} - M_{\mu\tau}^2}, \quad k' = \frac{M_{e\mu}M_{\mu\tau} - M_{e\tau}M_{\mu\mu}}{M_{\mu\mu}M_{\tau\tau} - M_{\mu\tau}^2}$$

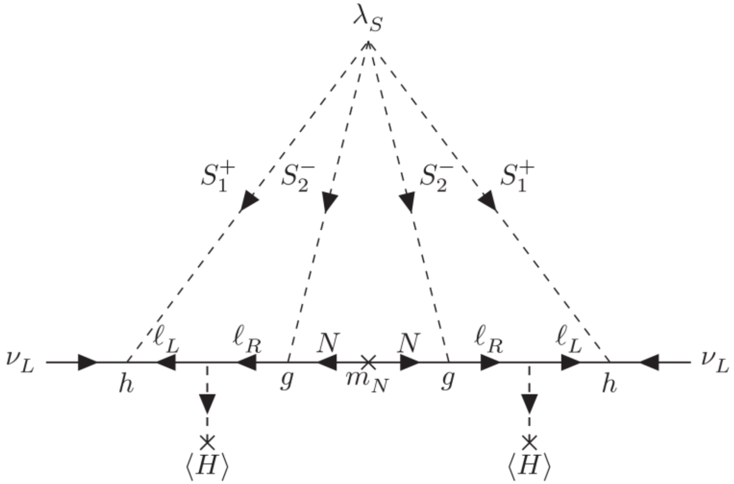
- Revisiting the KNT model

Neutrino mass

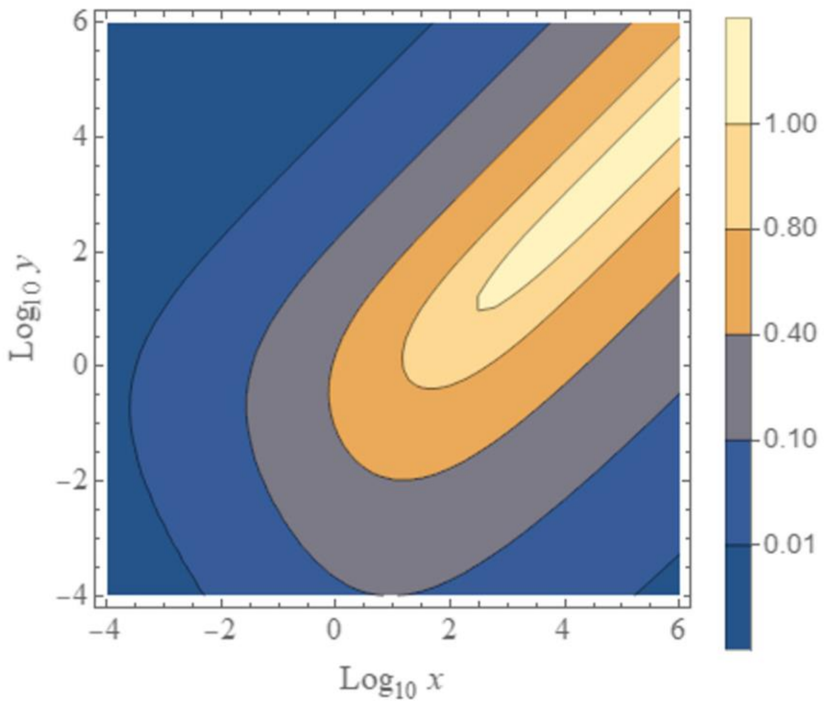
- Neutrino mass

$$M_{ab} = \frac{\lambda_S}{4(4\pi)^3 m_{S_1}} \sum_{I,j,k} m_{\ell_j} m_{\ell_k} h_{aj} h_{bk} g_{Ij} g_{Ik} f(x_I, y)$$

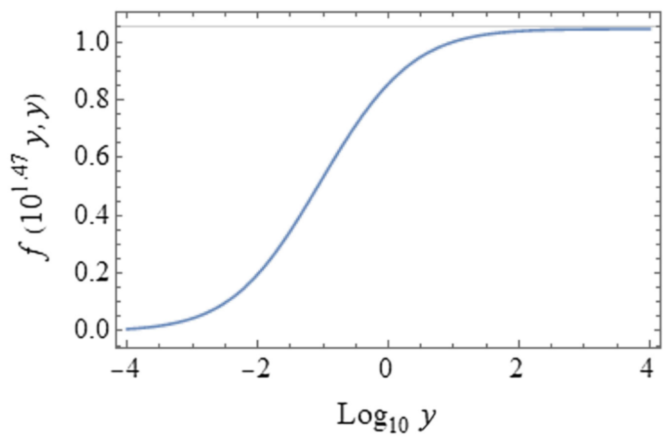
$$x_I \equiv \frac{m_{N_I}^2}{m_{S_2}^2}$$



- Loop function $f(x_I, y)$



The maximal of $f(x_I, y)$



Upper bound on S_1 mass

- The maximal of $f(x_I, y)$ and $|g| < 1$,

$$\left|\sum_I g_{I2}^2 f(x_I, y)\right| < 1.05\, n_{\mathrm{eff}}$$

  - n_{eff} : the number of RH neutrinos effectively contributing neutrino mass

- With $\lambda_S < 1$, we obtain

$$m_{S_1} < 3.4 \times 10^4 \mathrm{GeV} \left(\frac{0.02\ \mathrm{eV}}{|M_{\tau\tau}|}\right) |h_{23}|^2 n_{\mathrm{eff}}$$

- Other components also give similar bounds.

LFV

- S_1 inevitably induces LFV

$$\mathrm{Br}(\mu \to e\gamma) \cong \frac{\alpha^2}{768 G_F^2 m_{S_1}^4} |h_{13} h_{23}^*|^2$$

but the mass is bounded from above by the maximal of m_{S_1}

- Normal ordering (NO)

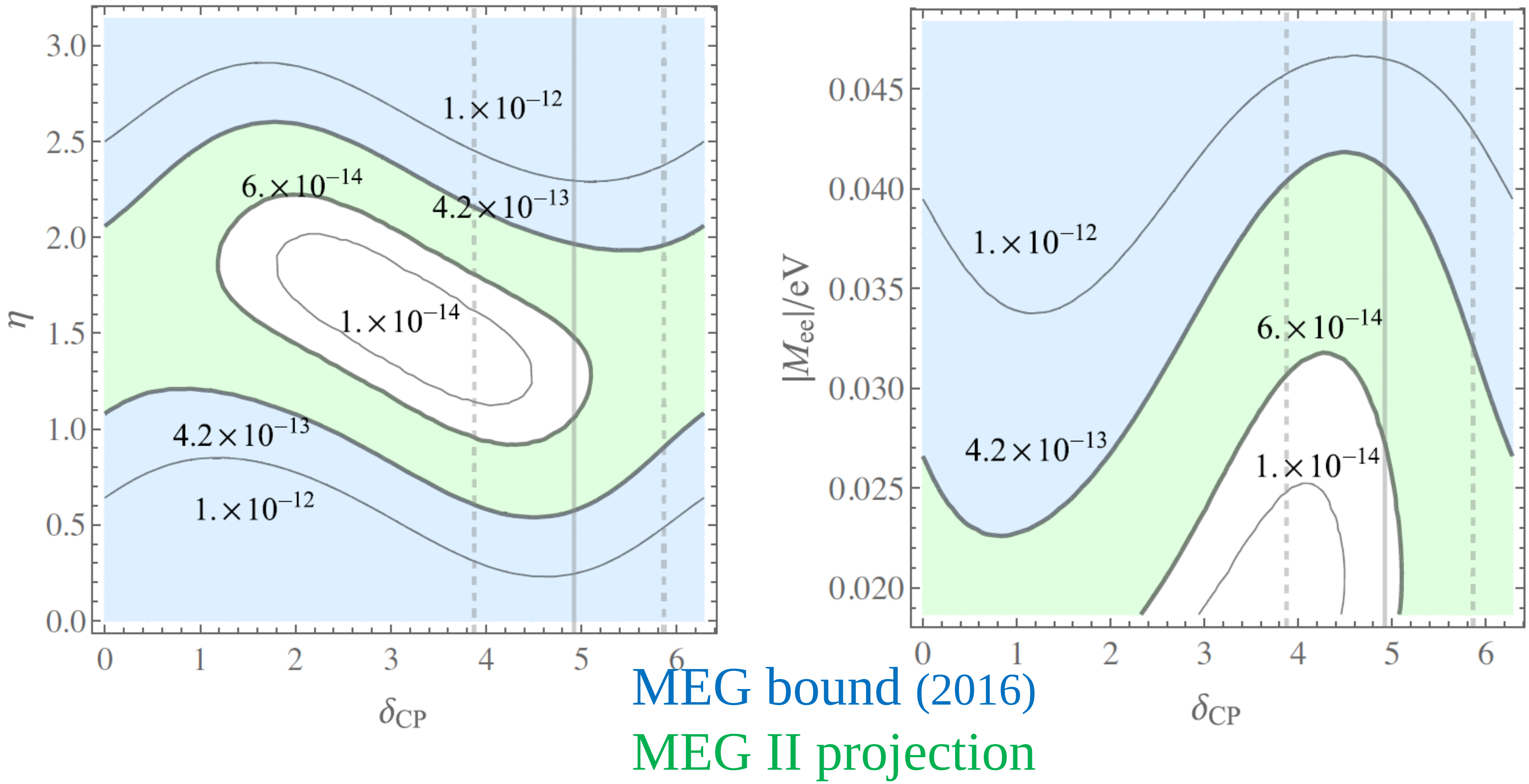
$$\mathrm{Br}(\mu \to e\gamma) > 5.0 \times 10^{-18} \left(\frac{n_{\mathrm{eff}}}{2}\right)^{-4} \left(\frac{|k\prime|}{0.329}\right)^2$$

- Inverted ordering (IO)

$$\mathrm{Br}(\mu \to e\gamma) > 7.4 \times 10^{-13} \left(\frac{n_{\mathrm{eff}}}{2}\right)^{-4} \left(\frac{|k\prime|}{5.01}\right)^2$$

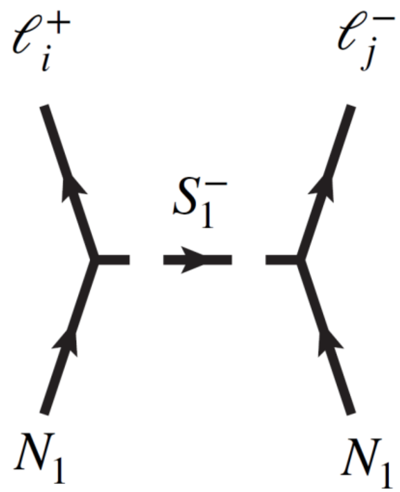
CP phases in neutrino oscillation

- No constraints on NO
- Constraints on IO   for $n_{\mathrm{eff}} = 2$, 2σ in osc. params.



DM and Br$(\tau \to \mu\gamma)$

- N_1 is DM candidate

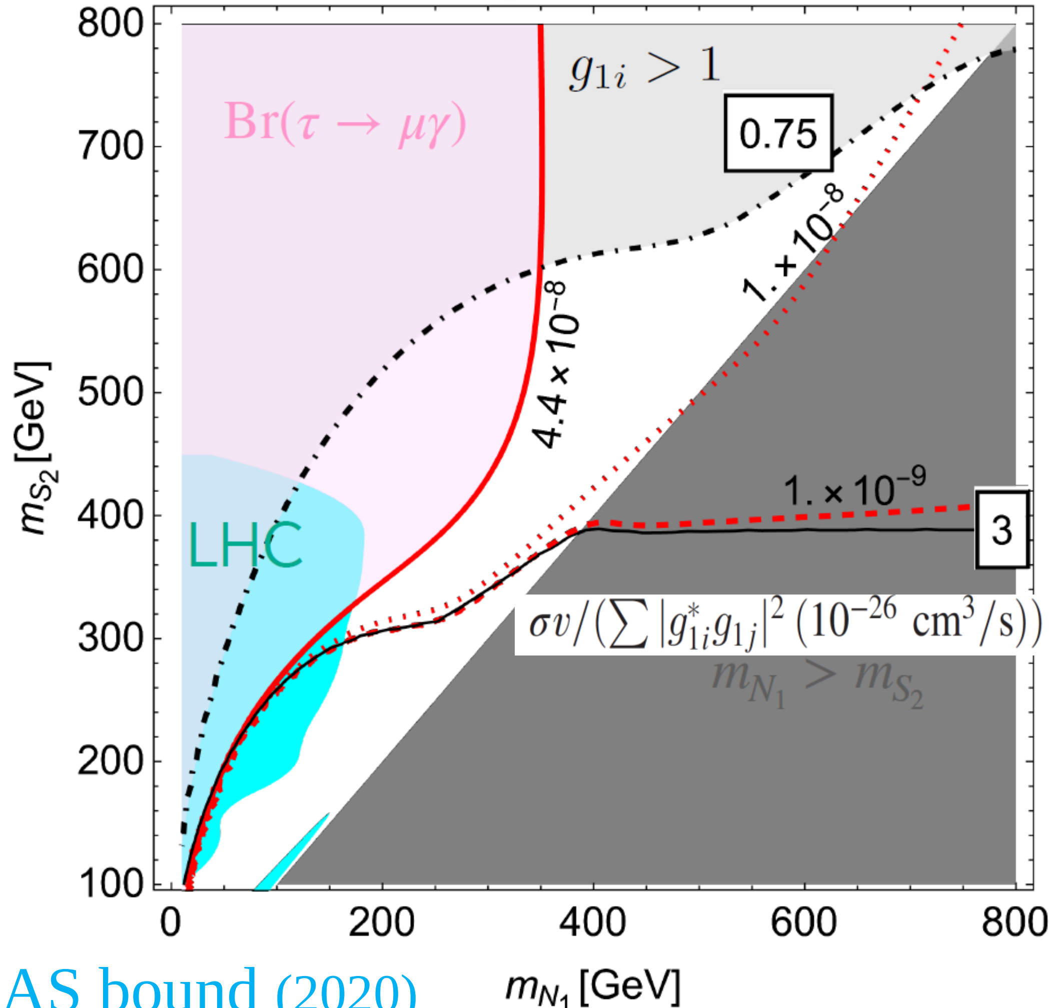


$$\boldsymbol{g} = \begin{array}{c} \\ \\ \\ \end{array}\begin{array}{ccc} e & \mu & \tau \\ \end{array}$$

$$\boldsymbol{g} = \begin{pmatrix} 0 & g_{12} & g_{13} \\ 0 & 1 & g_{23} \\ 0 & 1 & g_{33} \end{pmatrix} \begin{array}{l} N_1 \\ N_2 \\ N_3 \end{array}$$

BABAR bound (2010)

Belle II projection



ATLAS bound (2020)

§ Summary

- We have studied the KNT model
  - Perturbativity
  - Experimental constraints
- We found
  - $m_{S_1} <$ several $\times$ 10 TeV
  - CP phases will be well constrained by LFV for IO
  - $m_{S_2} \lesssim 700$ GeV is predicted
  - The model will be tested by $\tau \to \mu\gamma$ experiments