Lepton flavor violation and DM constraints in a radiative seesaw model

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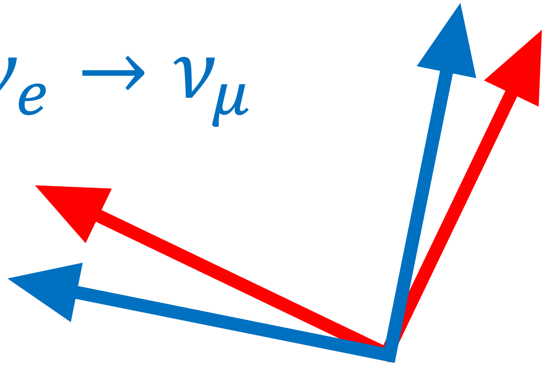
§ Introduction

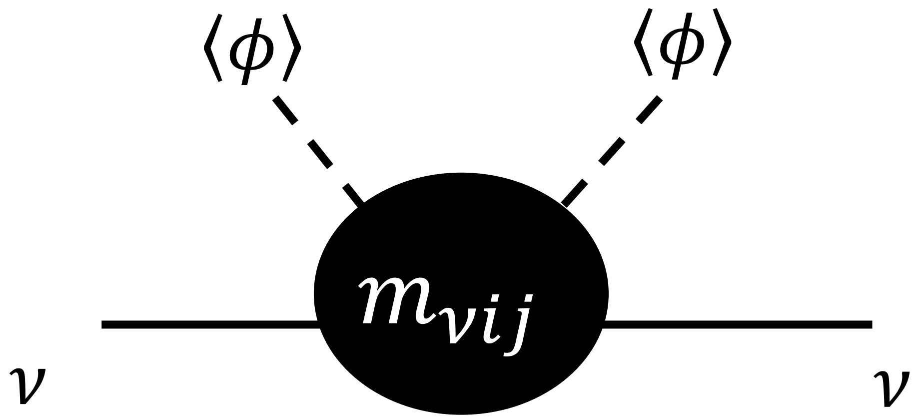
Nonvanishing neutrino mass

- Neutrino flavor oscillation: e.g., $\nu_e \rightarrow \nu_\mu$

  – tiny (< 0.1 eV) but massive neutrino



- Majorana neutrino mass operator



  - How to open ?

Neutrino mass generation

- At Tree level: Smallness due to high scale origin
  - Type-I : Singlet ν_R
  - Type-II : Triplet Higgs [Schechter and Valle, Magg and C. Wetterich, Cheng and Li (1980)]
  - Type-III : Triplet ν_R [Foot et al (1989)]
- At loop level: Smallness due to quantum correction
  - New particles are relatively light: accessible(?)
  - **Without a parity**: Zee model [Zee (1980)], Others…
  - **With a parity** : "radiative seesaw" [Krauss, Nasri and Trodden (2003), Ma (2006), Aoki, Kanemura and Seto (2008), …]

Neutrino mass generation

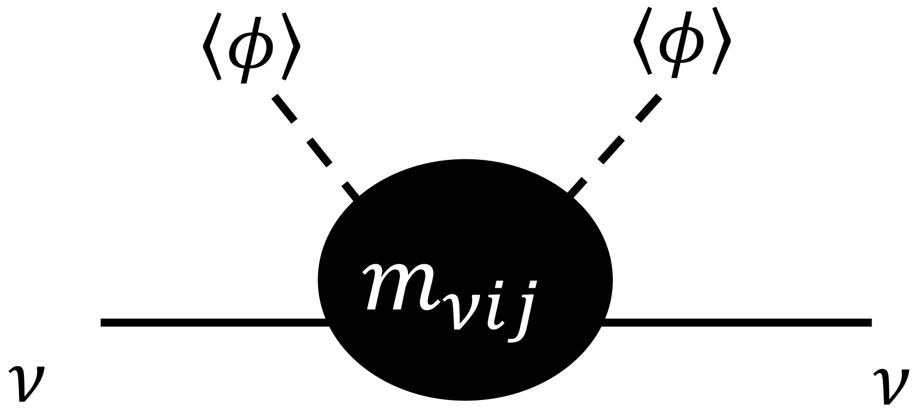
All wrong except one!

- At Tree level: Smallness due to hi[illegible] origin
  - Type-I : Singlet ν_R
  - Type-II : Triplet Higgs [S[illegible]alle, Magg and C. Wetterich, Cheng and Li (1980)]
  - Type-III : Triplet[illegible]al (1989)]
- At loop level[illegible]ess due to quantum correction
  - New p[illegible]e relatively light: accessible(?)
  - W[illegible]parity: Zee model [Zee (1980)], Others…
  - W[illegible]d parity : “radiative seesaw” [Krauss, Nasri and Trodden (20[illegible]3), Ma (2006), Aoki, Kanemura and Seto (2008), …]

§ Radiative generation of neutrino mass

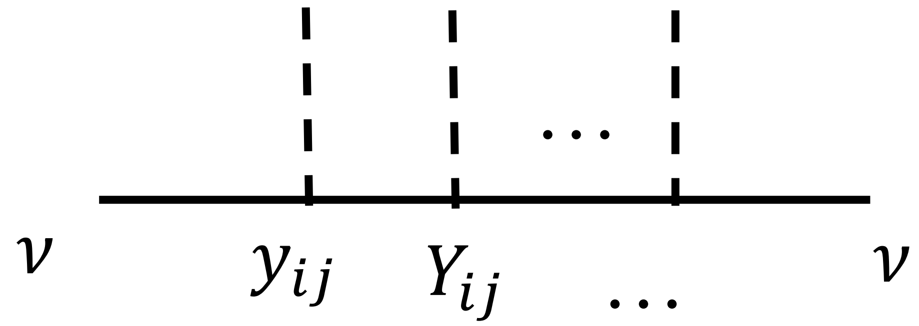
Lepton flavor violation in radiative generation of neutrino mass

- Majorana neutrino mass at loop



flavor mixing is large

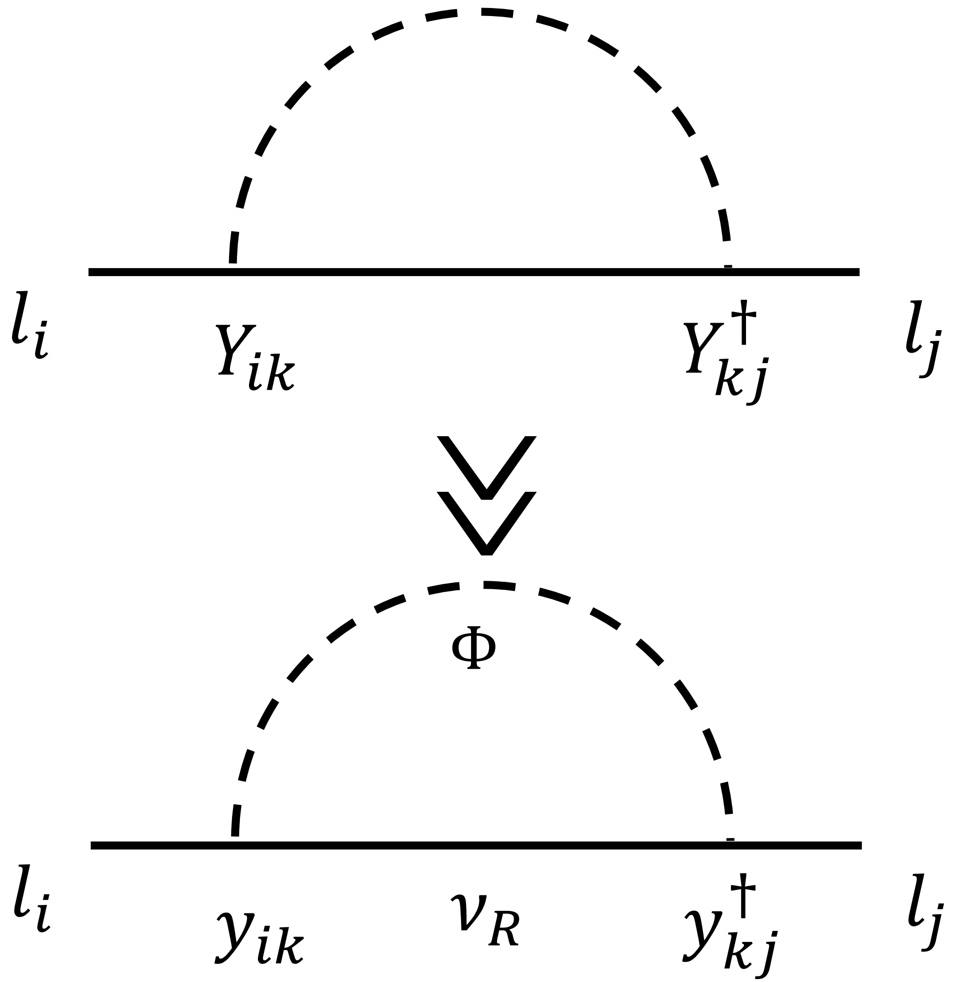
- Whatever it is, the fermion line is connected.



Yukawa couplings are flavor non-diagonal

Lepton flavor violation in radiative generation of neutrino mass

- Charged fermion inside loop



Flavor violation!

§ § Extracting neutrino Yukawa

Exercise: Type-I seesaw case

- Mass $m_\nu = -y_\nu \, v \, \frac{1}{M_N} \, y_\nu^T v$
- Casas-Ibarra [Casas and Ibarra (2001)]

$$y_\nu \frac{v}{\sqrt{2}} = i \, U \left(m_\nu^{\mathrm{diag}} \right)^{1/2} \; R (M_N)^{1/2}$$

U : PMNS

R : complex orthogonal matrix

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 [Krauss, Nasri and Trodden (2003)]

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

- Neutrino mass

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

- Assumption
  - m_e dependent parts are negligible
  - $|M_{\nu 22}| \sim |M_{\nu 23}| \sim |M_{\nu 33}|$
    - Indeed true except certain points of IO case
- 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 Zee-Babu model

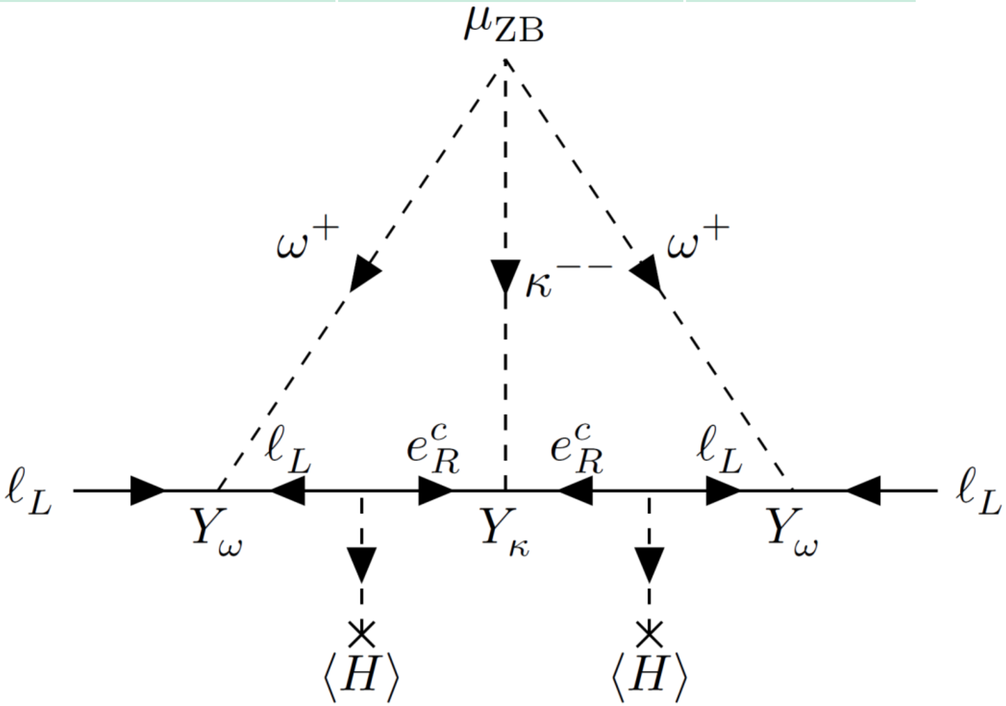
[Irie, Seto and Shindou (2021)]

Zee-Babu model [Zee (1986), Babu (1987)]

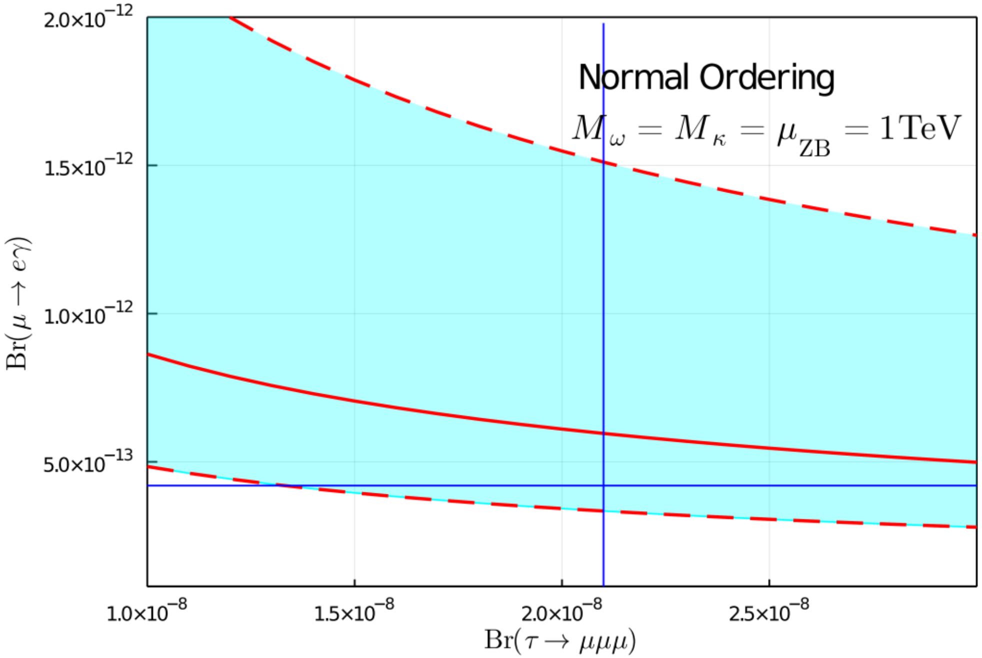
- Content

	$SU(2)_L$	$U(1)_Y$	Spin
SM particles	usual	usual	usual
ω^-	1	-1	0
κ^{--}	1	-2	0

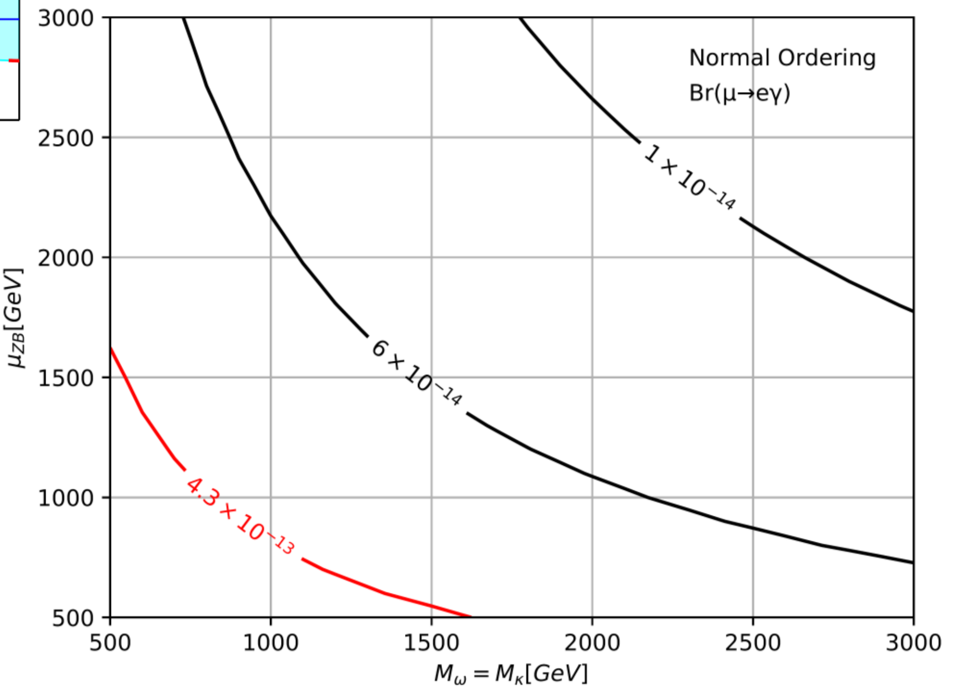
- Neutrino mass
  - Y_ω : anti-symmetric
  - Y_κ : symmetric



LFV in Zee-Babu model



- New scalars with $\mathcal{O}(10^2)$ GeV mass are excluded.
- The MEG-II will probe $\mathrm{Br}(\mu \to e\gamma) > 6 \times 10^{-14}$



- For minimal $\mathrm{Br}(\mu \to e\gamma)$
- 3σ band for ν osc.
- The Bell-II will probe $\mathrm{Br}(\tau \to \mu\mu\mu) > 3.3 \times 10^{-10}$

§ Radiative seesaw models

Radiative seesaw models

- Non-vanishing neutrino mass
- WIMP dark matter by the parity
  - Extra Parity
    - Primarily to forbid tree-level terms $y\bar{L}\Phi N$
    - Stability of DM as a bonus
- Baryon asymmetric Universe
- …

- Small neutrino mass as quantum corrections
  - TeV scale new particles: accessible(?)

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

- Particle content

	$SU(2)_L$	$U(1)_Y$	Z_2	Spin
SM particles	usual	usual	$+$	usual
N_i	1	0	$-$	1/2
S_1^-	1	-1	$+$	0
S_2^-	1	-1	$-$	0

- The lightest is stable

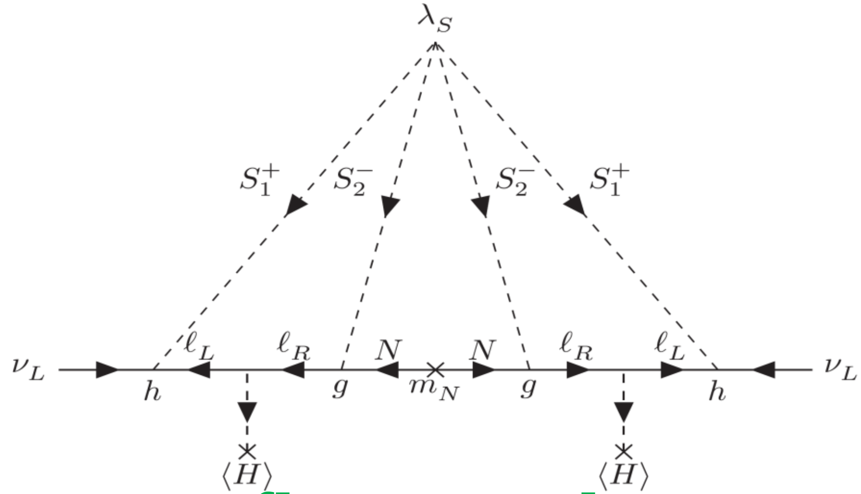
A three loop model [Krauss, Nasri and Trodden (2003)]

- Additional new interactions

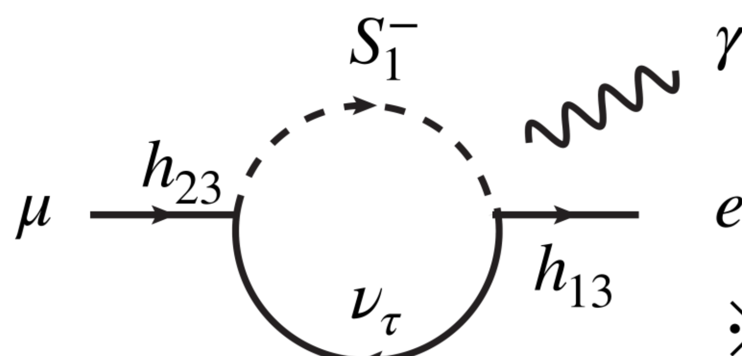
$$\mathcal{L}_{\text{int}} \supset \frac{1}{2} h_{ij} L_i^T C \cdot L_j S_1^+ + g_{ij} N_i^C l_{Rj} S_2^+ + \frac{1}{2} N_i^C M_{N_i} N_i + \text{h.c.} + V$$

$$V \supset \frac{1}{4} \lambda_S (S_1^-)^2 (S_2^+)^2 + \text{h.c.}$$

- Neutrino mass



- Lepton flavor violation
  - Anti-symmetric tensor h_{ai}



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§ § Revisiting the KNT model

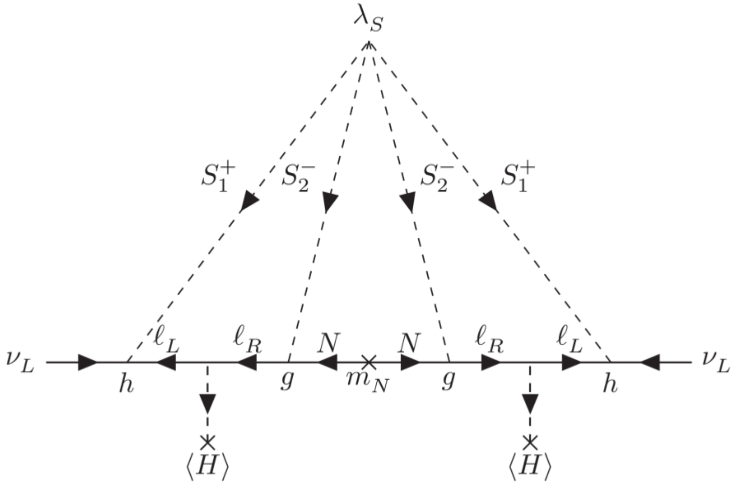
[Seto, Shindou and Tsuyuki (2022)]

Neutrino mass

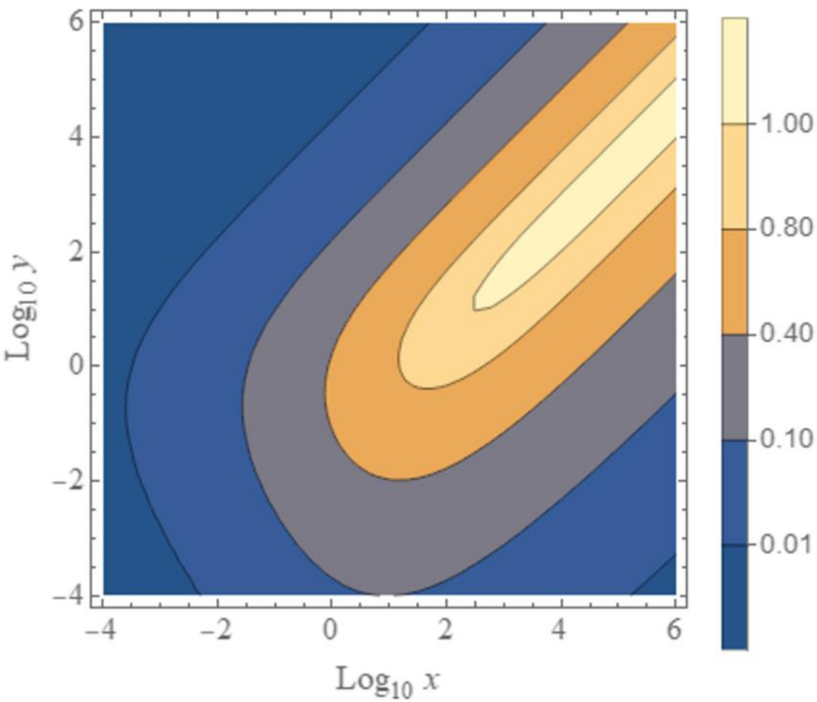
- Neutrino mass

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

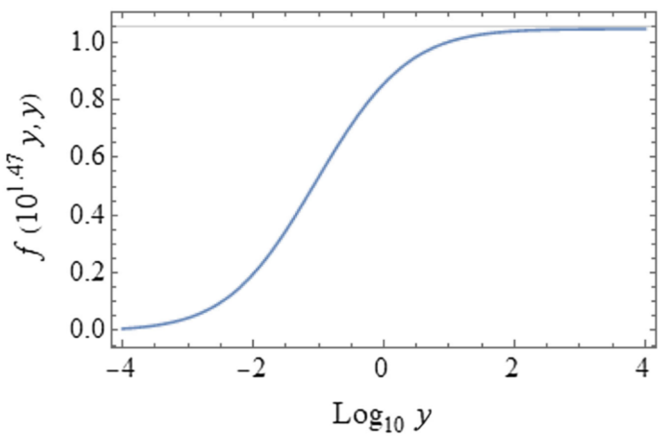
$$x_I \equiv \frac{m_{N_I}^2}{m_{S_2}^2}$$



- 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)

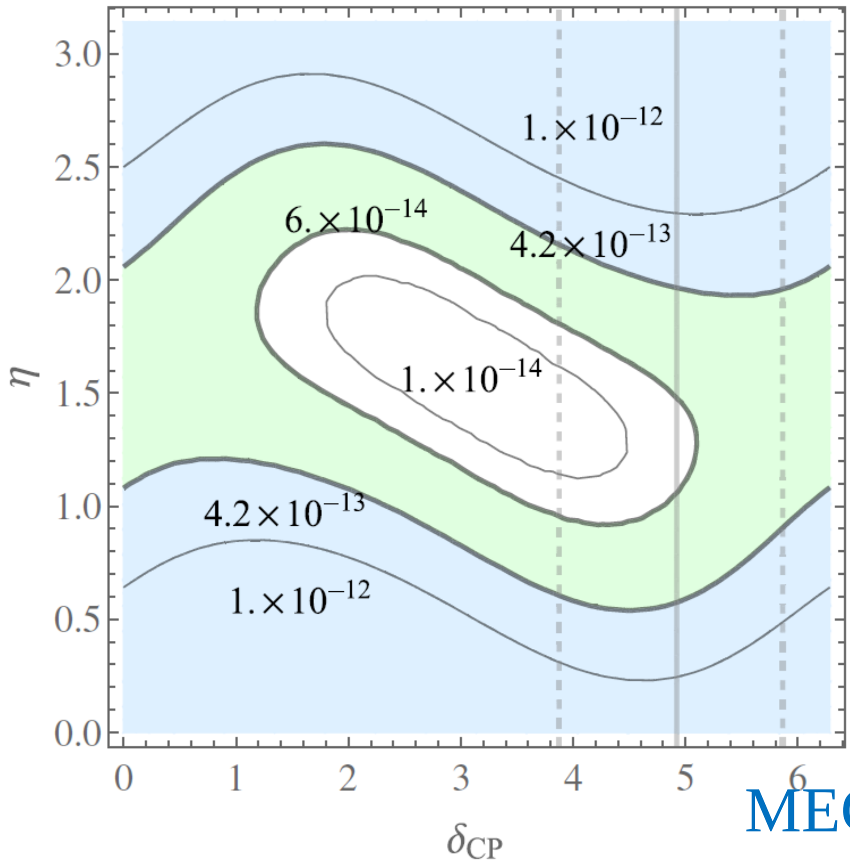
$$\mathrm{Br}(\mu \to e\gamma) > 5.0 \times 10^{-18} \left(\frac{n_{\text{eff}}}{2}\right)^{-4} \left(\frac{|k\prime|}{0.329}\right)^2$$

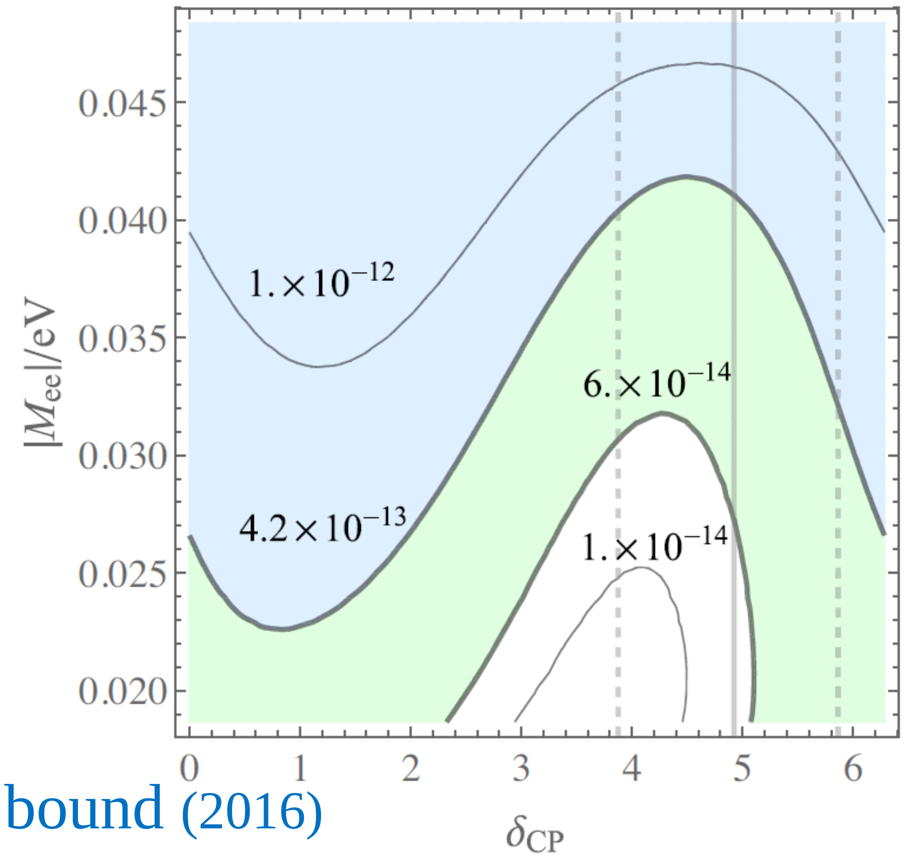
- Inverted ordering (IO)

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

CP phases in neutrino oscillation

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

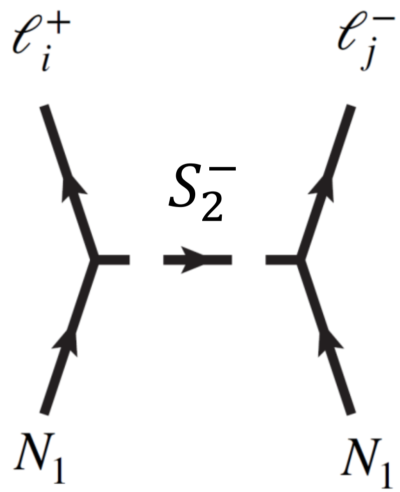




MEG bound (2016)
MEG II projection

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

- N_1 is DM candidate

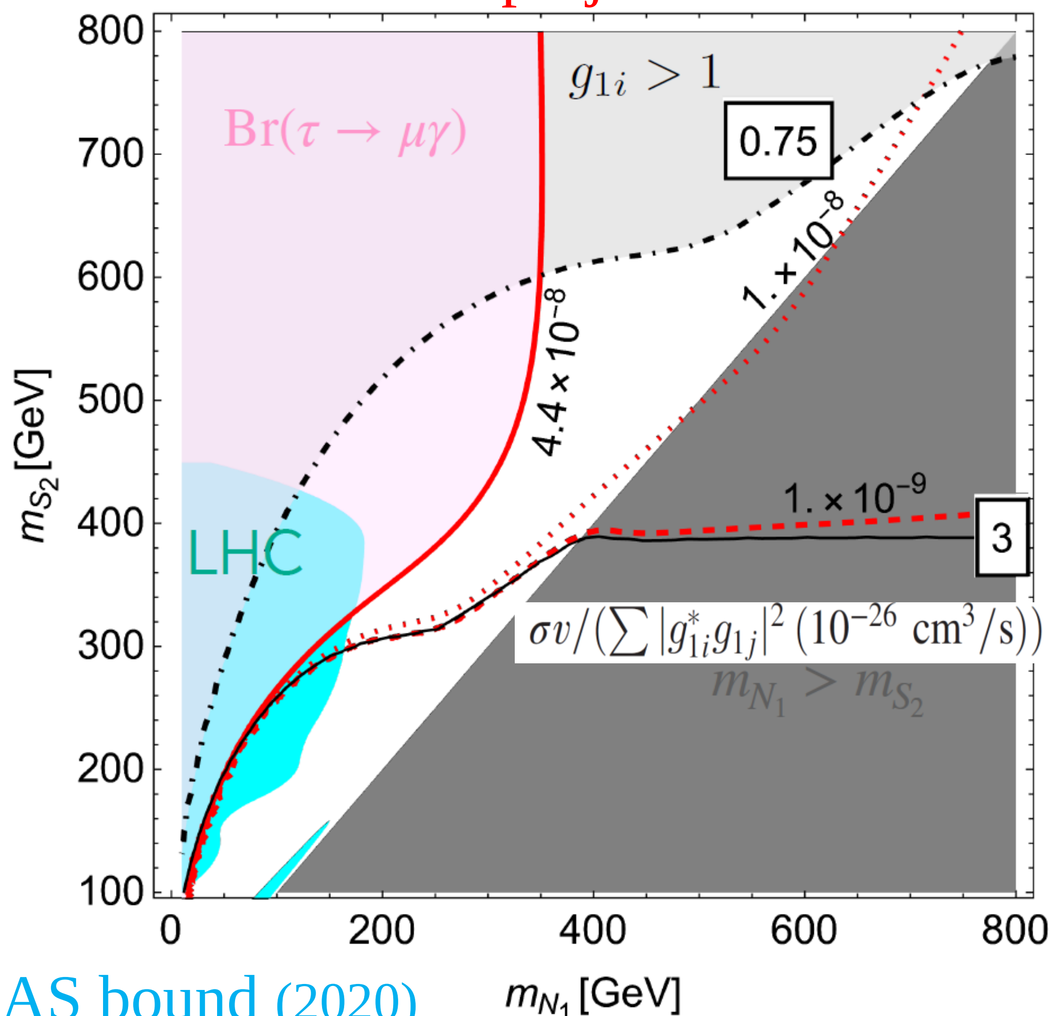


$$\boldsymbol{g} = \begin{array}{c} \\ \end{array}\begin{array}{ccc} e & \mu & \tau \end{array}$$

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

BABAR bound (2010)

Belle II projection



ATLAS bound (2020)

§ Summary

- Yukawa coupling for loop-induced neutrino mass.
  - In certain class of model, the ratio of Yukawa coupling can be rewritten in terms of M_ν
- For Zee-Babu model, we found
  - LFV constraint : the scale of new scalar > 1 TeV
  - The forthcoming experiments will work well.
- For KNT model, 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