Neutrino Masses and the Muon $g - 2$ in a Minimal Zee Model

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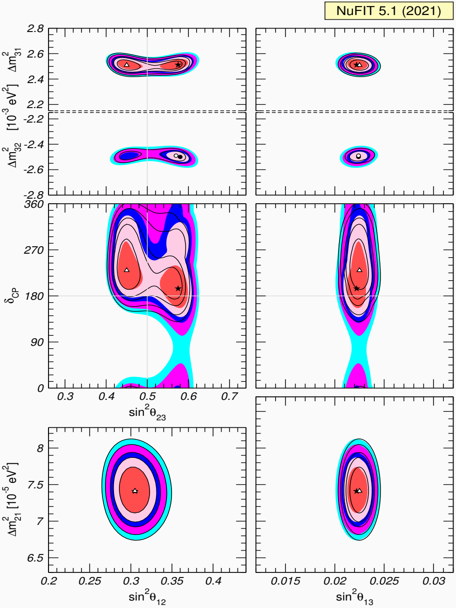
Outline

- Motivation

  Neutrino masses, discrepancy in muon/electron $g-2$

- A minimal Zee model
- Results
- Conclusion

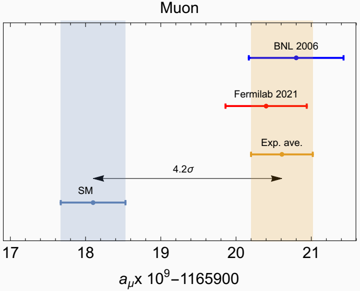
Neutrino masses



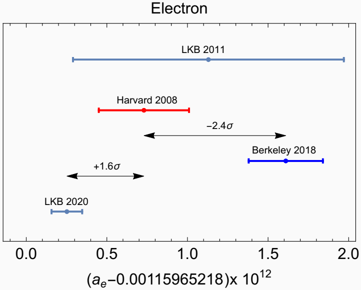
- Neutrinos do have masses, unlike the SM prediction
- Most of neutrino data can be fit into 3-neutrino paradigm
- The origin of neutrino masses, mass hierarchy, the leptonic CP violation, the octant of θ_{23} are yet to be known

NuFit Collaboration (2021)

Anomalous magnetic moment



Abi et al., *Phys. Rev. Lett.* **126** (2021) 14



Morel et al., *Nature* **588** (2020) 62

- A 4.2σ discrepancy in muon $g-2$ measurements has been observed
  $\rightarrow$ signal for a new physics
- A more intriguing is the electron $g-2$ determination from fine-structure constant
  $\rightarrow$ two inferred values go in opposite directions
- Incorporating a new physics is very challenging
  $\rightarrow$ only Berkeley result considered

The origin of neutrino masses

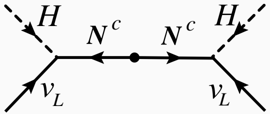
- In the SM neutrinos are massless because
  - no right-handed neutrinos
  - no scalar other than Higgs doublet
  - no nonrenormalizable terms
- To induce neutrino masses, at least one of the above requirements must be present

Seesaw mechanism

Adding an N^c

$$\mathcal{L} \sim Y_\nu L H N^c + \frac{1}{2} M_R N^c N^c$$

Minkowski (1977); Yanagida (1979)
Gell-Mann, Ramond, Slansky (1980)
Mohapatra, Senjanović (1980)



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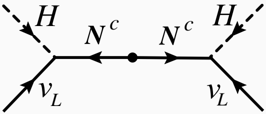
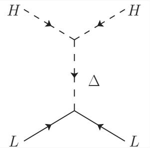


Adding a scalar triplet

$$\mathcal{L} \sim f_\nu L L \Delta + \mu H H \Delta^*$$

Mohapatra & Senjanovic (1980)
Schechter & Valle (1980)
Lazarides, Shafi, & Wetterich (1981)



- Integrating out the heavy states induces effective operator

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{L^i H^j L^k H^l \epsilon_{ij} \epsilon_{kl}}{\Lambda}$$

- To get $m_\nu \sim 0.1$ eV, $\Lambda \sim 10^{14}$ GeV
  $\rightarrow$ very unlikely to be probed in near future

$\Delta L = 2$ operators

$$
\begin{aligned}
\mathcal{O}_1 &= L^i L^j H^k H^l \epsilon_{ik}\epsilon_{jl} \\
\mathcal{O}_2 &= L^i L^j L^k e^c H^l \epsilon_{ij}\epsilon_{kl} \\
\mathcal{O}_3 &= \{L^i L^j Q^k d^c H^l \epsilon_{ij}\epsilon_{kl}, \quad L^i L^j Q^k d^c H^l \epsilon_{ik}\epsilon_{jl}\} \\
\mathcal{O}_4 &= \{L^i L^j \bar{Q}_i \bar{u^c} H^k \epsilon_{jk}, \quad L^i L^j \bar{Q}_k \bar{u^c} H^k \epsilon_{ij}\} \\
\mathcal{O}_5 &= L^i L^j Q^k d^c H^l H^m \bar{H}_i \epsilon_{jl}\epsilon_{km} \\
\mathcal{O}_6 &= L^i L^j \bar{Q}_k \bar{u^c} H^l H^k \bar{H}_i \epsilon_{jl} \\
\mathcal{O}_7 &= L^i Q^j \bar{e^c} \bar{Q}_k H^k H^l H^m \epsilon_{il}\epsilon_{jm} \\
\mathcal{O}_8 &= L^i \bar{e^c} \bar{u^c} d^c H^j \epsilon_{ij} \\
\mathcal{O}_9 &= L^i L^j L^k e^c L^l e^c \epsilon_{ij}\epsilon_{kl}
\end{aligned}
$$

Babu & Leung (2001)

de Gouvea & Jenkins (2008)

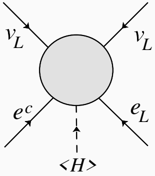
Angel & Volkas (2012)

Bonnet, Hirsch, Ota, Winter (2013)

Operator $\mathcal{O}_2$

- Let's consider operator $\mathcal{O}_2$

$$L^i L^j L^k e^c H^l \epsilon_{ij}\epsilon_{kl} \Rightarrow \nu_L \nu_L e_L e^c H^0$$



- Connecting the e_L and e^c legs, neutrino masses arise at one–loop level
- Because of loop and chirality suppressions the physical scale could be near TeV
- Realized in the Zee model

The Zee model

- A singly-charged scalar $\eta^+(1, 1, +1)$ is introduced

$$\mathcal{L} \supset f_{ab} L_a L_b \eta^+$$

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$\rightarrow$ Two Higgs doublets are required

Zee (1980)

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  Zee (1980)

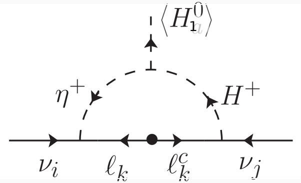
- The rest is like the 2HDM

$$\mathcal{L}_Y \supset y L e^c \tilde{H}_1 + Y L e^c \tilde{H}_2 + \text{h.c.}$$

- The phenomenology of this model has been widely studied in literature

  Smirnov & Tanimoto (1997); He (2004); Fukuyama et al. (2010); Babu & JJ (2014);
  Herrero-Garcia et al. (2017); Nomura & Yagyu (2019); Barman, Dcruz & Thapa (2022);
  Primulando, JJ & Uttayarat (2022)

Neutrino mass



$$M_\nu = \kappa \left(f M_\ell Y^T + Y M_\ell f^T \right)$$

$$16\pi^2 \kappa = \sin 2\gamma \ln m_{H_1^+}^2 / m_{H_2^+}^2$$

Notes

- Work in the so-called Higgs basis

$$H_1 = \begin{pmatrix} G^+ \\ \frac{v+h+iG^0}{\sqrt{2}} \end{pmatrix}; \quad H_2 = \begin{pmatrix} H^+ \\ \frac{H+iA}{\sqrt{2}} \end{pmatrix}$$

- We work in the basis where y is diagonal: $y = M_\ell \sqrt{2}/v$.
- The antisymmetric coupling matrix f can be made real
- Y remains complex

A minimal Zee model

$$M_\nu = \kappa\left(f M_\ell Y^T + Y M_\ell f^T\right)$$

- In order to explain neutrino oscillation data Y cannot be diagonal
  $\rightarrow$ incompatible with solar+KamLAND data
- We need at least 3 complex Y_{ab} to account for neutrino oscillation data (3 mixing angles, 1 CP phase, and $R \equiv \Delta m^2_{sol}/\Delta m^2_{atm}$)

$$f = f_{\mu\tau}\begin{pmatrix} 0 & r & s \\ -r & 0 & 1 \\ -s & -1 & 0 \end{pmatrix}; \quad Y = Y_{\tau\tau}\begin{pmatrix} 0 & \tilde{r} & 0 \\ \tilde{s} & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$r = f_{e\mu}/f_{f\mu\tau};\ s = f_{e\tau}/f_{\mu\tau};\ \tilde{r} = Y_{e\mu}/Y_{\tau\tau};\ \tilde{s} = Y_{\mu e}/Y_{\tau\tau}$$

- Introducing off-diagonal couplings may induce LFVs
  $\rightarrow$ can be avoided in particular texture of Y

The anomalous magnetic moment

$$\delta a_\ell = \frac{m_\ell^2}{96\pi^2}\left[\sum_{\phi=H,A}\frac{|Y_{a\ell}|^2+|Y_{\ell a}|^2}{m_\phi^2} - \frac{|Y_{\ell a}|^2}{m_{H+}^2} - 3\frac{m_a}{m_\ell}\mathrm{Re}(Y_{a\ell}Y_{\ell a})\sum_{\phi=H,A}\frac{(-1)^{CP}}{m_\phi^2}\left(3+2\ln\frac{m_a^2}{m_\phi^2}\right)\right]$$

$$-\frac{4m_\ell^2}{96\pi^2}\frac{(f^\dagger f)^{\ell\ell}}{M_\eta^2}$$

- $(g-2)_{e,\mu}$ arises at one loop
- The contribution induced by singly-charged scalar $\eta^\pm$ is always negative
  $\rightarrow$ it simply is ignored by assuming an heavy $\eta^\pm$ and/or small f_{ij}
- No need to worry about η-induced LFV
- To simultaneously explain both $(g-2)_{e,\mu}$, a sizable mass splitting among scalars is needed
  $\rightarrow$ useful to explain current CDF W-mass result

CDF W–mass result

- Recent CDF measurement on W mass can also be explained within this model

$$m_W^2 = m_W^2\big|_{\mathrm{SM}} \left[1 + \frac{\alpha}{1-2s_W^2}\left(-\frac{1}{2}S + (1-s_W^2)T + \frac{1-2s_W^2}{4s_W^2}U\right)\right]$$

$$m_W = 80.4242 \pm 0.0087 \text{ GeV}, \quad m_W|_{\mathsf{SM}} = 80.357 \pm 0.006 \text{ GeV}$$

$$T = \frac{1}{16\pi^2 \alpha v^2}\left[F(m_{H+}^2, m_H^2) + F(m_{H+}^2, m_A^2) - F(m_A^2, m_H^2)\right]$$

$$F(x,y) = \frac{x+y}{2} - \frac{xy}{x-y}\ln\frac{x}{y}$$

- A significant shift in W mass can be achieved if scalar masses considerably split

A minimal flavor texture

- We consider the following texture

$$Y = \begin{pmatrix} 0 & Y_{e\mu} & 0 \\ Y_{\mu e} & 0 & 0 \\ 0 & 0 & Y_{\tau\tau} \end{pmatrix}$$

- No tree-level or radiative LFV induced, except $\mu \to e + 2\nu$
  $\to$ constrain from Michel decay parameter must be considered
- The neutrino mass matrix

$$M_\nu = \hat{m}_0 \begin{pmatrix} -\frac{m_\mu w}{m_e} & 0 & \frac{m_\mu w}{2m_e x} - \frac{m_\tau y}{2m_e u x} \\ 0 & 1 & \frac{y}{2x} - \frac{m_\tau}{2m_e u x} \\ \frac{m_\mu w}{2m_e x} - \frac{m_\tau y}{2m_e u x} & \frac{y}{2x} - \frac{m_\tau}{2m_e u x} & 0 \end{pmatrix}$$

  $x \equiv f_{e\mu}/f_{\mu\tau},\ y \equiv f_{e\tau}/f_{\mu\tau},\ w \equiv Y_{e\mu}/Y_{\mu e},\ u \equiv Y_{\mu e}/Y_{\tau\tau}$, and
  $\hat{m}_0 \equiv 2m_e f_{\mu\tau} Y_{\tau\tau} \kappa$
- Well known two-zero texture $\to$ admitting both neutrino mass orderings
  $\theta_{23} < \pi/4$ for IO and $\theta_{23} > \pi/4$ for NO. $\delta_{CP} \simeq 270^o$

Result

Input

$f_{e\mu}/f_{\mu\tau}$	$f_{e\tau}/f_{\mu\tau}$	$Y_{e\mu}/Y_{\mu e}$	$Y_{\mu e}/Y_{\tau\tau}$
4.809	22.787	$9.283e \times 10^{-3} e^{i0.0799}$	$2.7084 \times 10^{4} e^{-i0.9956}$

Output

$\sin^2\theta_{23}$	$\sin^2\theta_{13}$	$\sin^2\theta_{12}$	J	R
0.5979	0.022	0.304	-0.03265	0.03167

The central values of $\delta a_{\mu,e}$ can be easily found by solving the $Y_{\tau\tau}$.

Other possible textures

- Turning on $Y_{\tau\tau}, Y_{\mu\tau}, Y_{\tau\mu}$ can also be considered. It induces LFV such as $\tau \to \mu\gamma$. Not able to get good muon $g-2$ because of LFV constraints
- Similarly, other texture $Y_{ee}, Y_{\mu\tau}, Y_{\tau\mu}$ cannot fit neutrino data. It gives zeros in (2,3) and (1,1) entries, not compatible with solar mass splittings
- Other textures may also be interesting to study, albeit facing LFV constraints

Conclusion

- We have introduced a minimal Zee model that can explain simultaneously neutrino masses, AMM of uon and electron, dan CDF W mass
- The minimal example shown admits both normal and inverted orderings of neutrino masses
- The NO scenario prefers θ_{23} in second octant, while NO prefers in first octant
- Central values of both AMM can be obtained within this model
- More textures need to be studied deeply to reveal this kind of scenario

Thank You