Radiative Neutrino Mass in Extended Zee Model with Dark Matter

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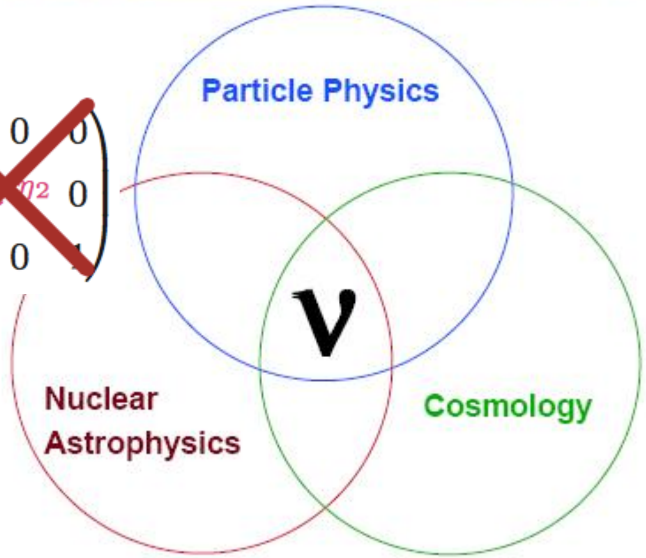
- Radiative Neutrino Mass
- Is Zee Model Ruled Out by Current Data?
- A New Extended Zee Model
- Outlook

Neutrino Oscillations and Mixing

- Standard model is too good with data before neutrino oscillations
- But neutrino oscillations → neutrino mixing → neutrino masses!
- How to expend the Standard model to generate neutrino mass?
- Much small masses and much larger mixing comparing with quarks: not natural if only Dirac masses with υ_R
- Mixing matrix

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

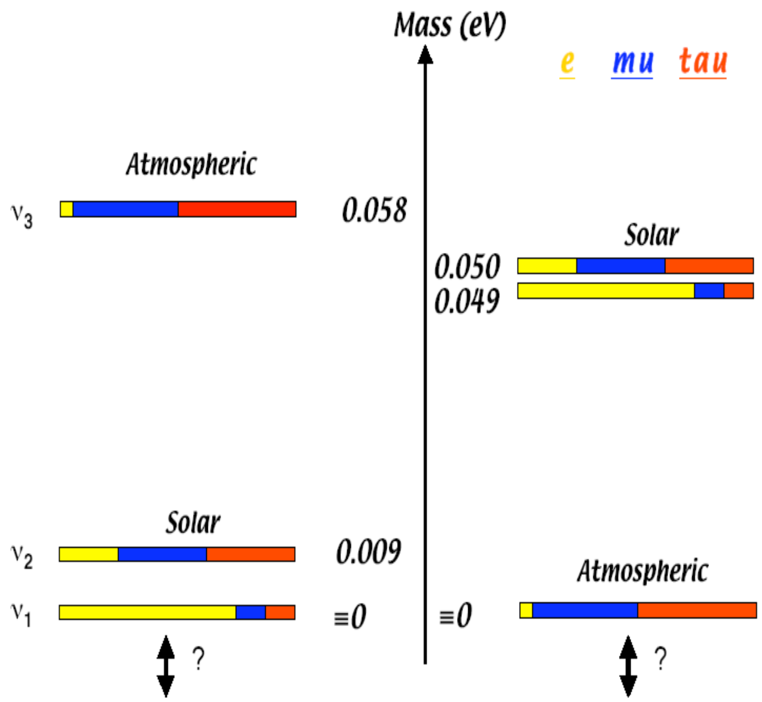
- Anti-neutrinos are the same as neutrinos? Majorana or Dirac?



Neutrino Oscillations and Mixing

❖ More precise neutrino data

parameter	best fit	1σ range	2σ range
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	7.60	7.42–7.79	7.26–7.99
			Reactor LBL (KamLAND)
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (NH)	2.48	2.41–2.53	2.35–2.59
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (IH)	2.38	2.32–2.43	2.26–2.48
			Accelerator LBL ν_μ Disapp (Minos)
$\sin^2\theta_{12}/10^{-1}$	3.23	3.07–3.39	2.92–3.57
			Solar Experiments
$\sin^2\theta_{23}/10^{-1}$ (NH)	5.67 (4.67)[a]	4.39–5.99	4.13–6.23
$\sin^2\theta_{23}/10^{-1}$ (IH)	5.73	5.30–5.98	4.32–6.21
			Atmospheric Experiments
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.34	2.14–2.54	1.95–2.74
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.40	2.21–2.59	2.02–2.78
			Reactor MBL (Daya-Bay, Reno
δ/π (NH)	1.34	0.96–1.98	0.0–2.0
δ/π (IH)	1.48	1.16–1.82	0.0–0.14 & 0.81-2.0



Predictive models?
May be ruled out by experiments!

❖ Normal ordering or inverted ordering?

Why Neutrinos Have Masses?

- God should use natural way to generate neutrinos masses
- Sea-saw: tree level Majorana masses of υ_R & no fine-tuning Dirac

$$\mathcal{L} = -\phi^{\dagger}\overline{\ell_L} y_\nu N_R - \frac{1}{2}\overline{N_R^c} M N_R + \mathrm{h.c.}$$

$$\rightarrow -\overline{\nu_L} m_D N_R - \frac{1}{2}\overline{N_R^c} M N_R + \mathrm{h.c.} \qquad m_D = y_\nu \langle\phi\rangle \qquad \begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix} \rightarrow \begin{array}{l} m_\nu = -m_D M^{-1} m_D^T + \cdots \\ (\text{if } m_D \ll M) \end{array}$$

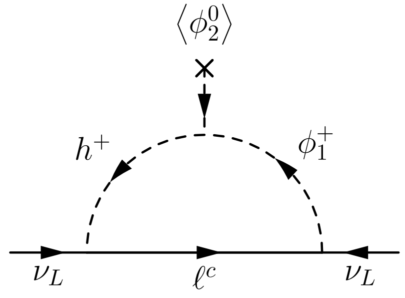
  very heavy neutrinos
- Radiative neutrino masses: naturally small due to the loop corrections, less parameters and thus predictive
  - Simple and clean: only Majorana Masses of υ_L
  - Renormalizable, no counter-term and thus calculable

Radiative Neutrino Masses

- Zee model (1980)
  - 2HDM+charged singlet
  - Majorana Yukawa couplings
  - Was studied extensively

	$SU(2)_L$	$U(1)_Y$
ϕ_2	**2**	1
h^+	**1**	1

· neutrino mass (1-loop level)

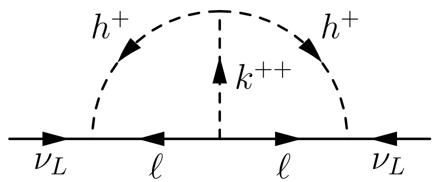


$$\mathcal{V} = \mu\phi_1^T\phi_2 h^-$$

- Zee-Babu model
  - Majorana Yukawa couplings of both L & R leptons
  - Still compatible with data

	$SU(2)_L$	$U(1)_Y$
h^+	**1**	1
k^{++}	**1**	2

· neutrino mass (2-loop level)



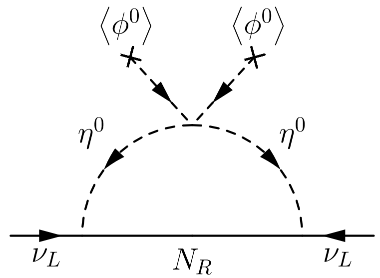
$$\mathcal{V} = \mu h^{-2} k^{++}$$

- Ma model
  - R neutrinos are odd under Z_2
  - Inert doublet scalar
  - Both can be dark matter candidates

	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_2$
N_i	**1**	0	-1
η	**2**	$1/2$	-1

· neutrino mass (1-loop level)

· DM candidates (N_1 or η^0)



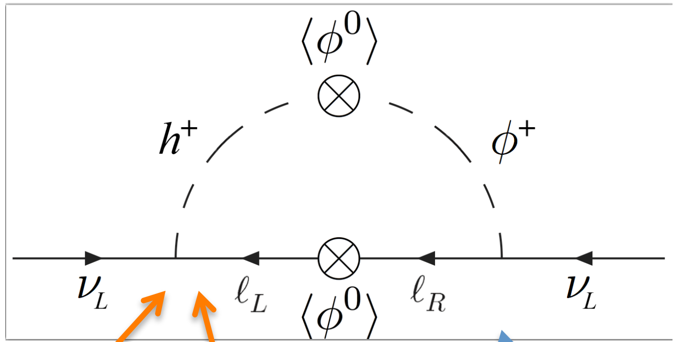
$$\mathcal{V} = \frac{\lambda_5}{2}\left(\phi^\dagger\eta\right)^2$$

Zee Model

- The general Zee model: both doublets have Yukawa: the Yukawa couplings matrix cannot be diagonized
- Neutrino mass matrix

$$M_\nu = \kappa\left(\hat{f} M_\ell^{\text{diag}} \hat{Y}^T + \hat{Y} M_\ell^{\text{diag}} \hat{f}^T\right)$$

- There are non-zero diagonal elements
- But tree level FCNC: Wolfenstein Suggest a Z_2 to prevent the second Yukawa
- Mass matrix with vanishing diagonal elements
- Phases of f_{ab} are absorbed to l_R



flavor can change

$$2f_{e\mu}\left[\overline{\nu_{eL}}(\mu_L)^c - \bar{e}_L(\nu_{\mu L})^c\right]h^- + 2f_{e\tau}\left[\overline{\nu_{eL}}(\tau_L)^c - \bar{e}_L(\nu_{\tau L})^c\right]h^-$$
$$+ 2f_{\mu\tau}\left[\overline{\nu_{\mu L}}(\tau_L)^c - \bar{\mu}_L(\nu_{\tau L})^c\right]h^- + \mu\left(\Phi_1^+\Phi_2^0 - \Phi_1^0\Phi_2^+\right)h^- + \text{h.c.},$$

$$\begin{pmatrix} 0 & m_{e\mu} & m_{e\tau} \\ m_{e\mu} & 0 & m_{\mu\tau} \\ m_{e\tau} & m_{\mu\tau} & 0 \end{pmatrix}$$

$$m_{ab} = f_{ab}(m_b^2 - m_a^2)\frac{\kappa v_2}{v_1}F(M_1^2, M_1^2), \quad F(M_1^2, M_1^2) = \frac{1}{16\pi^2}\frac{1}{M_1^2 - M_1^2}\ln\frac{M_1^2}{M_2^2}$$

couplings f_{ab} are anti-symmetric

Zee Model

- Zee-Wolfenstein model was ruled out by data
- Even when f_{ab} are complex, the mass matrix predicts bimaximal mixing, thus is not compatible with $\theta_{12} = 33.5^{\circ}{}^{+0.8}_{-0.7}\ \left({}^{+2.5}_{-2.1}\right)$
- Symmetric mass matrix $U_\nu^T M_\nu U_\nu = D_\nu \equiv \mathrm{diag}(m_1, m_2, m_3)$

Koide (2001)
X.G. He (2004)

$$H_\nu = M_\nu^\dagger M_\nu \quad U_\nu^\dagger H_\nu U_\nu = D_\nu^* D_\nu = \mathrm{diag}(|m_1|^2, |m_2|^2, |m_3|^2)$$

- Only solution of inverted ordering is possible, but it give large $\sin^2 2\theta_{solar}$ <≈1, far from the current data
- Babu and Julio imposed a family-dependent Z_4 symmetry acting on the leptons

$$L_i : (-i, i, i); \qquad e_i^c : (-i, -i, -i);$$

$$H_1 : +1; \qquad H_2 : -1; \qquad h^+ : -1.$$

$$\begin{pmatrix} X & a & b \\ a & Y & c \\ b & c & \varepsilon \end{pmatrix}$$

Babu, Lulio (2014)

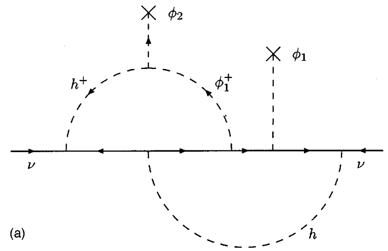
- Non-zero diagonal but avoid FCNC, somehow save Zee model

Extension of Zee Model without Flavor Sym?

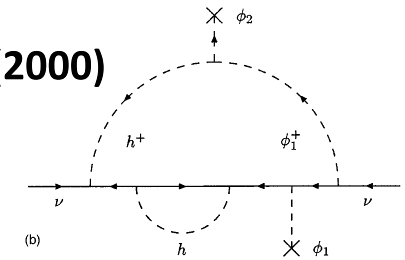
- Can we extended the Zee model without imposing a flavor symmetry?
- 2-loop corrections can generate diagonal masses
- To be compatible with data, $|f_{e\mu}|m_\mu^2 \simeq |f_{e\tau}|m_\tau^2 \gg |f_{\mu\tau}|m_\tau^2$
- 2-loop correction $(m_\nu^{(2)})_{ab} = \gamma \sum_{c,d} f_{ac} f^*_{cd} f_{db}(m_c^2 - m_d^2) = \gamma(f[m^2, f^*]f)_{ab}$
- Correction to $\sin^2 2\theta_{solar}$:

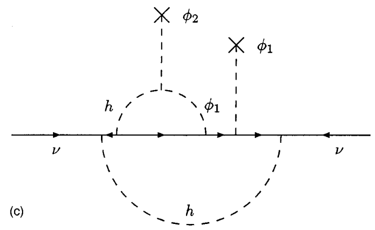
$$\left|\frac{M_{\nu 11}}{M_{\nu 23}}\right| \sim \frac{|f_{e\mu}||f_{\mu\tau}||f_{\tau e}|}{16\pi^2 |f_{\mu\tau}|} \simeq \frac{|f_{e\mu}|^2}{16\pi^2}\left(\frac{m_\mu}{m_\tau}\right)^2 < 10^{-5}$$

- Even 2-loop corrections can't help to save the model



Chang, Zee (2000)





A New Extended Zee Model

- Type-I 2HDM with 2 extra charged and neutral singlets as the 2 Higgs doublets

$$\Phi_1 = \begin{pmatrix} \varphi_1^+ \\ \varphi_1^0 \end{pmatrix} = \begin{pmatrix} \varphi_1^+ \\ \frac{(v_1+\eta_1+i\phi_1)}{\sqrt{2}} \end{pmatrix} \quad \Phi_2 = \begin{pmatrix} \varphi_2^+ \\ \varphi_2^0 \end{pmatrix} = \begin{pmatrix} \varphi_2^+ \\ \frac{(v_2+\eta_2+i\phi_2)}{\sqrt{2}} \end{pmatrix} \quad \chi_1^+ \quad \chi_1^0 = \frac{(u_1+\chi_1+i\chi_2)}{\sqrt{2}} \quad \chi_2^+ \quad \chi_2^0 = \frac{(u_i+\chi_3+i\chi_4)}{\sqrt{2}}$$

$$\mathcal{L}_{H,kim} = (D_\mu\Phi_1)^\dagger(D^\mu\Phi_1) + (D_\mu\Phi_2)^\dagger(D^\mu\Phi_2) + D^\chi_\mu\chi_1^- D^{\chi,\mu}\chi_1^+ + \partial_\mu(\chi_1^0)^*\partial^\mu\chi_1^0 + D^\chi_\mu\chi_2^- D^{\chi,\mu}\chi_2^+ + \partial_\mu(\chi_2^0)^*\partial^\mu\chi_2^0$$

- Both doublets & neutral singlets can get VEV, and no mixing of $\chi_1^\pm, \chi_2^\pm$

$$\tan\beta = v_2/v_1 \qquad \alpha = u_2/u_1 \qquad \tilde{\chi} = \cos\alpha\chi_1^0 + \sin\alpha\chi_2^0 \qquad \rho = sin\alpha\chi_1^0 + \cos\alpha\chi_2^0$$

- Symmetry

	l_L	l_R	Q_L	u_R	d_R	Φ_1	Φ_2	$\chi_1^\pm$	$\chi_2^\pm$	$\tilde{\chi}$	ρ
Z_4	g_3(-1)	g_3(-1)	g_3(-1)	g_3 (−1)	g_3(-1)	g_2(+1)	e(-2)	g_2(+1)	g_2(+1)	g_2(+1)	g_2(+1)
$SU(2)_L$	2	1	2	1	1	2	2	1	1	1	1
Lepton L	1	1	0	0	0	0	0	±2	±2	0	0
Z_2						1	1	1	1	1	-1

- $$\mathcal{L}_{lepsig} = f^1_{ab}L^{aT}_{iL}\,C\,L^b_{jL}\epsilon^{ij}\chi_1^+ + f^1_{ab}L^{b\dagger}_{iL}\,C\,L^{a*}_{jL}\epsilon^{ij}\chi_1^- + f^2_{ab}L^{aT}_{iL}\,C\,L^b_{jL}\epsilon^{ij}\chi_2^+ + f^2_{ab}L^{b\dagger}_{iL}\,C\,L^{a*}_{jL}\epsilon^{ij}\chi_2^-$$

$$\begin{aligned} \mathcal{L}_{12\chi} &= \kappa_1(\Phi_2^{c\dagger}\Phi_1 - \Phi_1^{c\dagger}\Phi_2)\chi_1^-\tilde{\chi} + \kappa_2(\Phi_2^{c\dagger}\Phi_1 - \Phi_1^{c\dagger}\Phi_2)\chi_2^-\tilde{\chi} + h.c. \\ &= 2\kappa_1 u(\varphi_1^+\varphi_2^0 - \varphi_2^+\varphi_1^0)\chi_1^- + 2\kappa_2 u(\varphi_1^+\varphi_2^0 - \varphi_2^+\varphi_1^0)\chi_2^- + h.c. + \cdots \end{aligned}$$

A New Extended Zee Model

- Mass Matrix is complex, but…

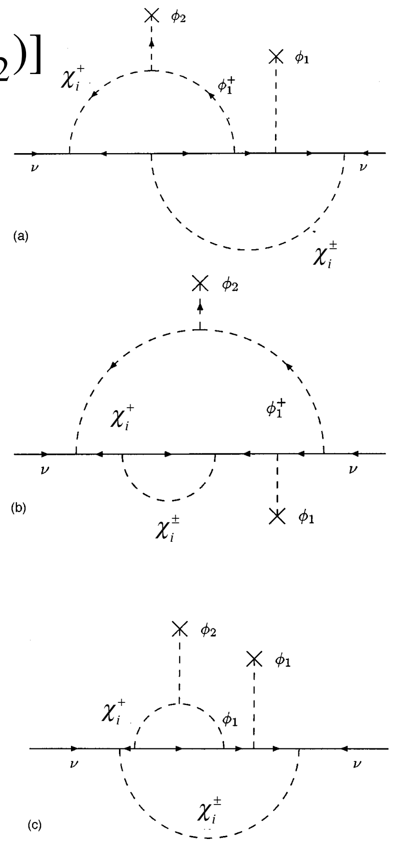
$$m_{ab} = \frac{(m_b^2 - m_a^2)}{16\pi^2} u \tan\beta [f_{ab}^1 \kappa_1 F(M_{11}^2, M_{12}^2) + f_{ab}^2 \kappa_2 F(M_{21}^2, M_{22}^2)]$$

- 2-loop correction to the diagonal

$$m_{ab}^{(2)} = \frac{\mathcal{O}(1)}{(16\pi^2)^2} u \sum_{i,j=1,2} \sum_{c,d=e,\mu,\tau} [f_{ac}^i f_{cd}^{j*} f_{db}^j (m_c^2 - m_d^2) \kappa_i F(M_{\chi 1}^2, M_{\chi 2}^2)]$$

- The ratio contributing to $\sin^2 2\theta_{solar}$ becomes

$$\frac{|M_{\nu 11}|}{|M_{\nu 23}|} = \frac{1}{16\pi^2} |f_{\mu\tau}^{1*} f_{e\tau}^1 + f_{\mu\tau}^{2*} f_{e\tau}^2| \frac{|f_{e\mu}^1 \kappa_1 + f_{e\mu}^2 \kappa_2|}{|f_{\mu\tau}^1 \kappa_1 + f_{\mu\tau}^2 \kappa_2|} \neq \frac{1}{16\pi^2} \frac{m_{\tau^2}}{m_{\mu^2}} |f_{e\tau}^1 + f_{e\mu}^2|$$



- There's room to make our prediction consistent with the solar mixing angle and there's CP phase!
- Fit the parameters f_{ab}^i, κ_i and constraint from FCNF and $0\nu\beta\beta$ decay

A New Extended Zee Model

- There's also scalar dark matter candidate!

$$\rho = sin\alpha\chi_1^0 + \cos\alpha\chi_2^0, \qquad <\rho>= 0$$

- It's constrained by the neutrino part directly
- But $\rho\rho \to \chi^+\chi^- \to l^+l^-\nu\nu$ can be sensitive to the neutrino parameters
- Maybe we can also consider a $SU_D(2)$ extension of Ma model

Outlook

- We will fit the parameters to constrain our model with the current neutrino data
- Interesting LHC phenomenology, e.g. 2 TeV heavy resonance
- Relic density for the dark matter candidate

Thank you!