Phenomenology In a Zee-Babu type model with Local $U(1)_{L\mu-L\tau}$ symmetry

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T.N., H. Okada, PRD 97 (2018) no. 9, 095023

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1. Introduction

Local $U(1)_{L\mu-L\tau}$ gauge symmetry has interesting properties

- Anomaly free, less constrained gauge interaction
- Possible explanation for muon g-2 anomaly

  By light Z' with small gauge coupling

$$\Delta a_\mu^{Z'} = \frac{g'^2}{8\pi^2}\int_0^1 dx \frac{2m_\mu^2 x^2(1-x)}{x^2 m_\mu^2 + (1-x)m_{Z'}^2}$$

- Explaining B-physics anomalies with some extensions

  W.Altmannshofer, S.Gori, M.Pospelov, PRD 89, 095033 (2014)
  A. Crivellin, G.D'Ambrosio, J. Heeck PRL 114, 151801, etc..

- High energy neutrino spectrum observed by IceCube

  T. Araki, F. Kaneko, Y. Konishi, T. Ota, J. Sato, T. Shimomura PRD 91, 037301 (2015)

Flavor dependent charge would restrict structure of neutrino mass

➡ It is interesting to investigate neutrino mass generation with $U(1)_{L\mu-L\tau}$

Some neutrino mass models with $U(1)_{L\mu-L\tau}$

- **Type-I seesaw case**

K. Asai, K. Hamaguchi, N. Nagata, EPJC 77, 763 (2017)

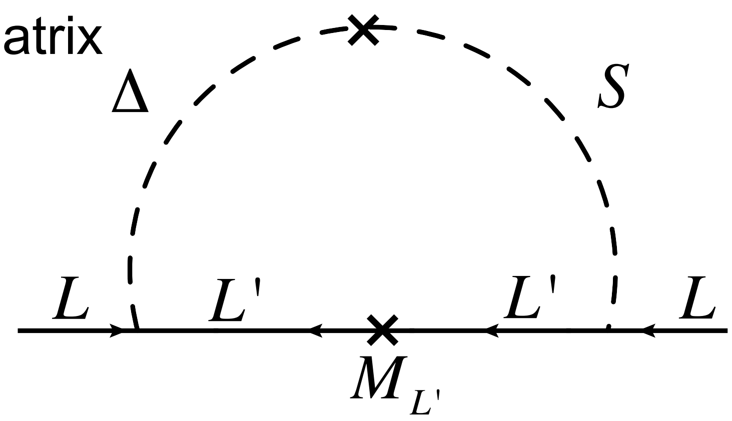
Right-handed neutrino with $U(1)_{L\mu-L\tau}$ charge and scalar φ with charge 1

⇒ **Some prediction for neutrino mass due to two-zero texture of $M_{\nu R}$**

❖ Relation among neutrino masses m_1, m_2, m_3 and Dirac CP-phase

- **One loop generation model** S. Lee, T. N., H. Okada, NPB 931, 179 (2018)

❖ Two-zero texture for exotic lepton mass matrix
❖ Some correlation among CP-phases



- **Etc.**

In this talk, we discuss two loop neutrino mass model

➡ **Zee-Babu type model with $U(1)_{L\mu-L\tau}$ gauge symmetry**

T.N., H. Okada, PRD 97 (2018) no. 9, 095023

Some prediction for Yukawa coupling with charged scalars

Let us explore phenomenology of the model

1. Introduction
2. A two-loop model
3. Phenomenology
4. Summary

Two-loop Zee-Babu type model with $U(1)_{L\mu-L\tau}$

Fields	H	h^+_{-1}	h^+_0	h^+_{+1}	k^{++}	φ	L_e	L_μ	L_τ	e_R	μ_R	τ_R
$SU(2)_L$	**2**	**1**	**1**	**1**	**1**	**1**	**2**	**2**	**2**	**1**	**1**	**1**
$U(1)_Y$	$\frac{1}{2}$	1	1	1	2	0	$-\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{2}$	-1	-1	-1
$U(1)_{L_\mu - L_\tau}$	0	-1	0	1	0	1	0	1	-1	0	1	-1

- For neutrino mass generation, we introduce iso-singlet charged Higgs fields
- At least 3 singly charged Higgs + 1 doubly charged Higgs
- One SM singlet scalar for U(1) breaking

$$H = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG^0) \end{pmatrix}, \quad \varphi = \frac{1}{\sqrt{2}}(v_\varphi + \varphi_R + iG_{Z'})$$

2. A two-loop model

◆ New Yukawa interactions

$$L_Y = f_{e\mu} \bar{L}^c_{L_e} (i\sigma_2) L_{L_\mu} h^+_{-1} + f_{\mu\tau} \bar{L}^c_{L_\mu} (i\sigma_2) L_{L_\tau} h^+_0 + f_{e\tau} \bar{L}^c_{L_e} (i\sigma_2) L_{L_\tau} h^+_{+1}$$
$$+ g_{ee} \bar{e}^c_R e_R k^{++} + g_{\mu\tau} \bar{\mu}^c_R \tau_R k^{++} + h.c. \,,$$

◆ Scalar potential

$$\begin{aligned}
V =& \mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 + \mu_\varphi^2 |\varphi|^2 + \lambda_\varphi |\varphi|^4 \\
&+ M^2_{k^{++}} k^{++} k^{--} + M^2_{h^+_{-1}} h^+_{-1} h^-_{+1} + M^2_{h^+_0} h^+_0 h^-_0 + M^2_{h^+_{+1}} h^+_{+1} h^-_{-1} \\
&+ \underline{(\mu_{kh} k^{++} h^-_0 h^-_0 + \tilde{\mu}_{kh} k^{++} h^-_{-1} h^-_{+1} + \mu_{\varphi h} \varphi h^+_{-1} h^-_0 + \tilde{\mu}_{\varphi h} \varphi^* h^+_{+1} h^-_0 + c.c.)} \\
&+ \underline{(\lambda_{\varphi hk} \varphi k^{++} h^-_{-1} h^-_0 + \tilde{\lambda}_{\varphi hk} \varphi^* k^{++} h^-_{+1} h^-_0 + c.c.)} + \lambda_{Hk^{++}} (H^\dagger H)(k^{++} k^{--}) \\
&+ \lambda_{Hh^+_{-1}} (H^\dagger H)(h^+_{-1} h^-_{+1}) + \lambda_{Hh^+_{+1}} (H^\dagger H)(h^+_{+1} h^-_{-1}) + \lambda_{Hh^+_0} (H^\dagger H)(h^+_0 h^-_0) \\
&+ \lambda_{\varphi k^{++}} |\varphi|^2 (k^{++} k^{--}) + \lambda_{\varphi h^+_{-1}} |\varphi|^2 (h^+_{-1} h^-_{+1}) + \lambda_{\varphi h^+_{+1}} |\varphi|^2 (h^+_{+1} h^-_{-1}) + \lambda_{\varphi h^+_0} |\varphi|^2 (h^+_0 h^-_0) \\
&+ \lambda_{H\varphi} |\varphi|^2 (H^\dagger H) + (\text{quartic terms for charged scalars }), \qquad \text{(II.3)}
\end{aligned}$$

◆ Mass terms for charged Higgs bosons

$$L_M = \left(M^2_{h^+_{-1}} + \frac{1}{2}\lambda_{Hh^+_{-1}} v_H^2 + \frac{1}{2}\lambda_{\varphi h^+_{-1}} v_\varphi^2 \right) h^+_{-1} h^-_{+1} + \left(M^2_{h^+_0} + \frac{1}{2}\lambda_{Hh^+_0} v_H^2 + \frac{1}{2}\lambda_{\varphi h^+_0} v_\varphi^2 \right) h^+_0 h^-_0$$

$$+ \left(M^2_{h^+_{+1}} + \frac{1}{2}\lambda_{Hh^+_{+1}} v_H^2 + \frac{1}{2}\lambda_{\varphi h^+_{+1}} v_\varphi^2 \right) h^+_{+1} h^-_{-1} + \frac{1}{\sqrt{2}} \left(\mu_{\varphi h} v_\varphi h^+_{-1} h^-_0 + \tilde{\mu}_{\varphi h} v_\varphi h^+_{+1} h^-_0 + c.c. \right)$$

$$+ \left(M^2_{k^{\pm\pm}} + \frac{1}{2}\lambda_{Hk^{++}} v_H^2 + \frac{1}{2}\lambda_{\varphi k^{++}} v_\varphi^2 \right) k^{++} k^{--}$$

In our scenario, we require small mixing among singly charged bosons

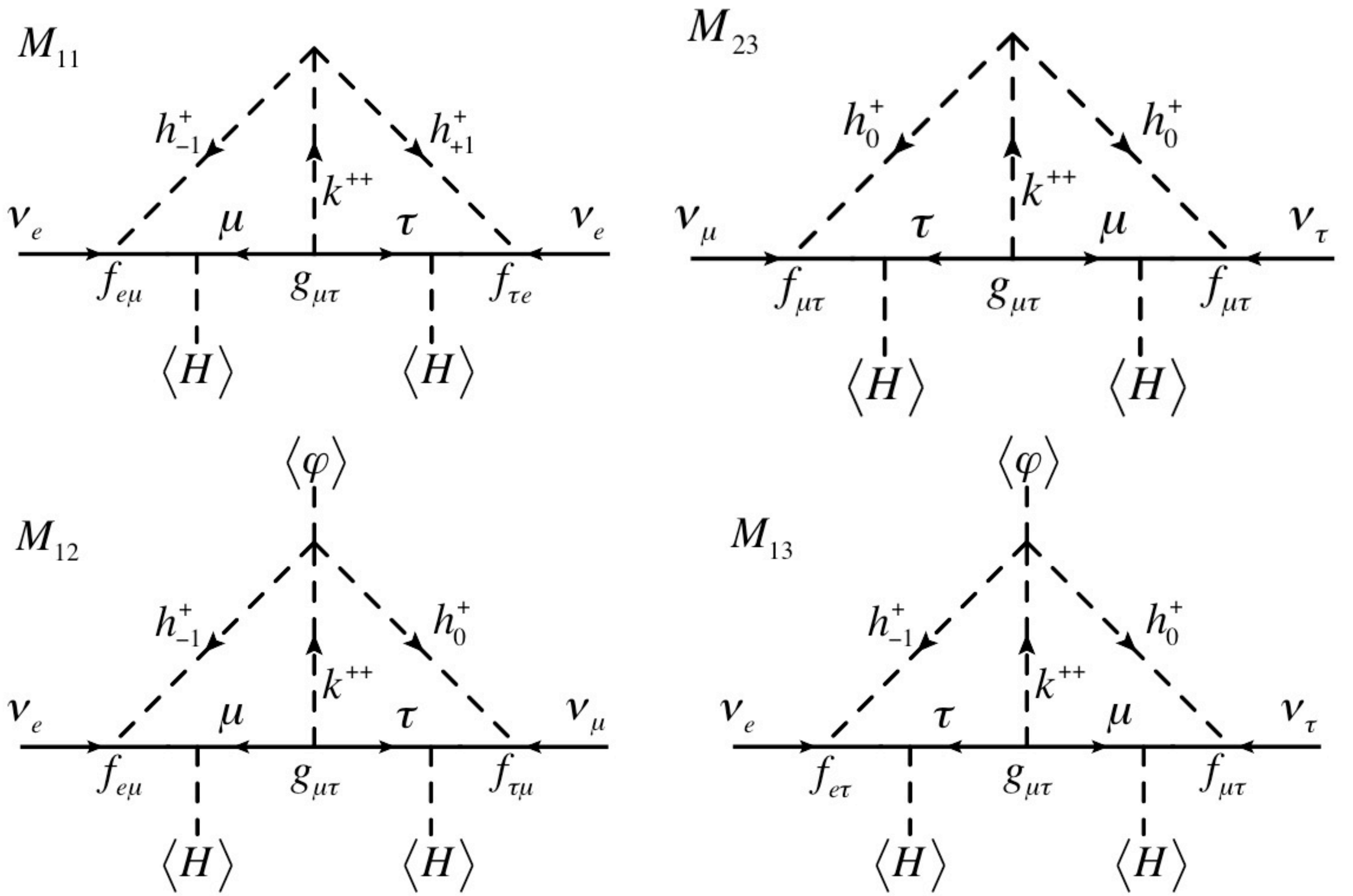
➡ $$\mu_{\varphi h}, v_\varphi, \tilde{\mu}_{\varphi h}, v_\varphi << M_{h^+_{-1}}, M_{h^+_0}, M_{h^+_{+1}}$$

✓ This limit is preferred to suppress LFV

✓ We can obtain predictive neutrino mass structure

2. A two-loop model

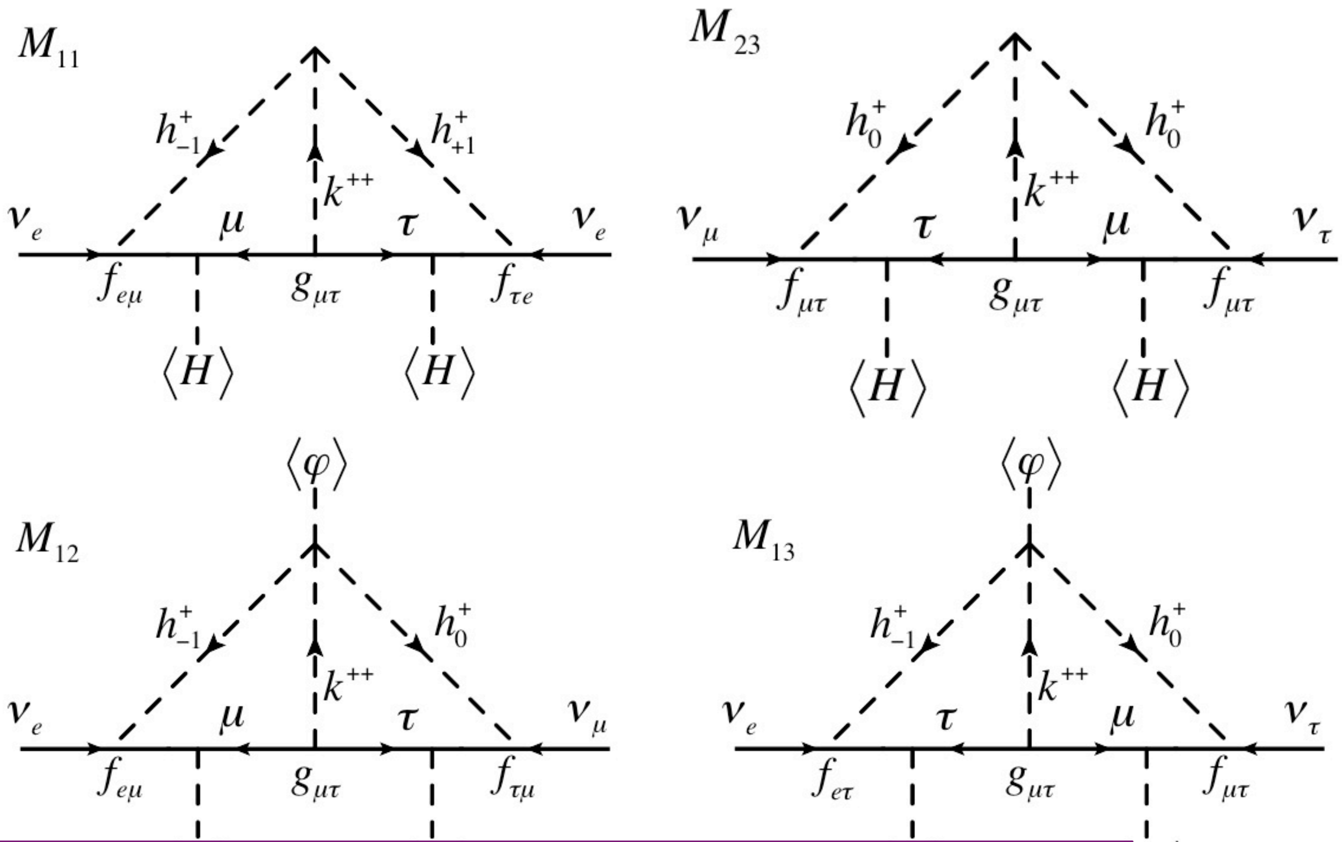
Neutrino mass generation (dominant contributions)



Structure of neutrino mass

$$\Rightarrow \quad M_\nu \approx \begin{pmatrix} M_{11} & M_{12} & M_{13} \\ M_{12} & 0 & M_{23} \\ M_{13} & M_{23} & 0 \end{pmatrix}, \quad (\mu_{\varphi h} v_\varphi, \tilde{\mu}_{\varphi h} v_\varphi << M_{h^+_{-1}}, M_{h^+_0}, M_{h^+_{+1}})$$

Neutrino mass generation (dominant contributions)



$$M_{11} = 8\tilde{\mu}_{kh} f_{e\mu} m_\mu g^*_{\mu\tau} m_\tau f_{\tau e} I\left(m_{h^+_{-1}}, m_{h^+_{+1}}, m_{k^{++}}, m_\mu, m_\tau\right),$$

$$M_{12} = 4\sqrt{2}\lambda_{\varphi hk} v_\varphi f_{e\mu} m_\mu g^*_{\mu\tau} m_\tau f_{\tau\mu} I\left(m_{h^+_{-1}}, m_{h^+_0}, m_{k^{++}}, m_\mu, m_\tau\right),$$

$$M_{13} = 4\sqrt{2}\tilde{\lambda}_{\varphi hk} v_\varphi f_{e\tau} m_\tau g^*_{\mu\tau} m_\mu f_{\mu\tau} I\left(m_{h^+_{+1}}, m_{h^+_0}, m_{k^{++}}, m_\tau, m_\mu\right),$$

$$M_{23} = 8\mu_{kh} f_{\mu\tau} m_\mu g^*_{\mu\tau} m_\tau f_{\mu\tau} I\left(m_{h^+_0}, m_{h^+_0}, m_{k^{++}}, m_\mu, m_\tau\right),$$

I(m1,m2,m3,m4,m5): Loop function

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Implication from neutrino mass

$$M_{11} = 8\tilde{\mu}_{kh} f_{e\mu} m_\mu g^*_{\mu\tau} m_\tau f_{\tau e} I\left(m_{h^+_{-1}}, m_{h^+_{+1}}, m_{k^{++}}, m_\mu, m_\tau\right),$$
$$M_{12} = 4\sqrt{2}\lambda_{\varphi hk} v_\varphi f_{e\mu} m_\mu g^*_{\mu\tau} m_\tau f_{\tau\mu} I\left(m_{h^+_{-1}}, m_{h^+_0}, m_{k^{++}}, m_\mu, m_\tau\right),$$
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$$M_{23} = 8\mu_{kh} f_{\mu\tau} m_\mu g^*_{\mu\tau} m_\tau f_{\mu\tau} I\left(m_{h^+_0}, m_{h^+_0}, m_{k^{++}}, m_\mu, m_\tau\right),$$

$$M \approx \begin{pmatrix} M_{11} & M_{12} & M_{13} \\ M_{12} & 0 & M_{23} \\ M_{13} & M_{23} & 0 \end{pmatrix}$$

Two zero texture (in small mixing limit)

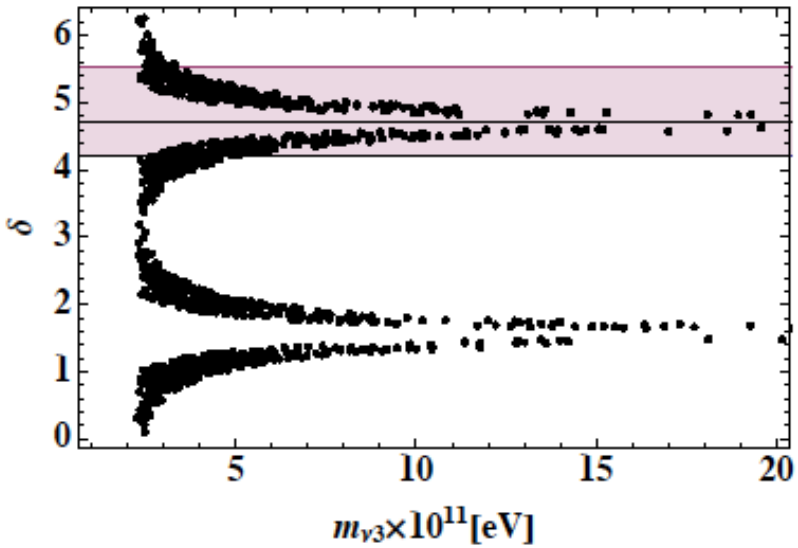
$$m_1^* = \frac{U_{22}^2 U_{33}^2 - U_{23}^2 U_{32}^2}{U_{21}^2 U_{32}^2 - U_{22}^2 U_{31}^2} m_3^*, \quad m_2^* = \frac{U_{21}^2 U_{33}^2 - U_{23}^2 U_{31}^2}{U_{21}^2 U_{32}^2 - U_{22}^2 U_{31}^2} m_3^*,$$

U_{ij} : PMNS matrix

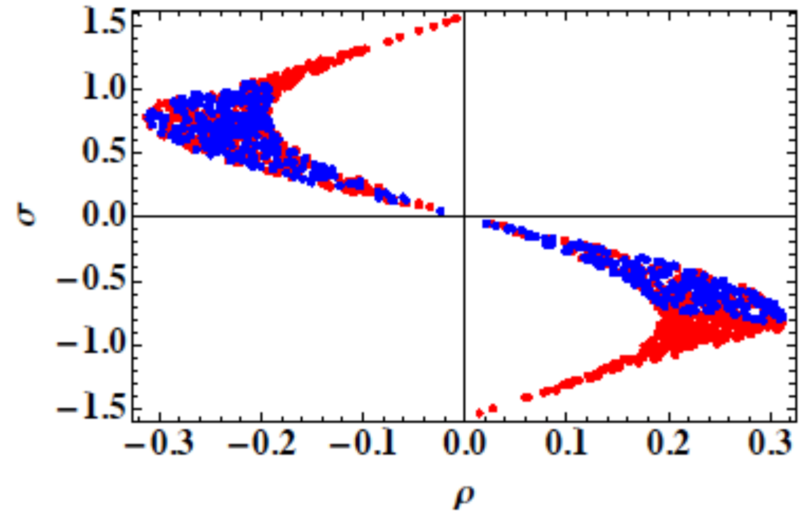
$$\left[\; m_1 = |m_1| e^{-i\rho}, \quad m_2 = |m_2| e^{-i\sigma} \;\right]$$

- ✓ Inverted mass ordering is predicted ($|m_2| > |m_1| > |m_3|$)
- ✓ $M_{ij} \sim O(10^{-11})$ GeV

Implication from neutrino mass



Correlations in the two-zero texture



$$m_1^* = \frac{U_{22}^2 U_{33}^2 - U_{23}^2 U_{32}^2}{U_{21}^2 U_{32}^2 - U_{22}^2 U_{31}^2} m_3^*, \quad m_2^* = \frac{U_{21}^2 U_{33}^2 - U_{23}^2 U_{31}^2}{U_{21}^2 U_{32}^2 - U_{22}^2 U_{31}^2} m_3^*,$$

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Implication from neutrino mass

$$|M_{23}| \sim 2 \times 10^{-10}\ \mathrm{GeV} \times \frac{|f_{\mu\tau}|}{0.1}\frac{|g^*_{\mu\tau}|}{0.4}\frac{|f_{\mu\tau}|}{0.1} C_I \frac{\mu_{kh}}{\mathrm{TeV}} \left(\frac{\mathrm{TeV}}{M}\right)^2$$

- Couplings f_{ij}, g_{ij}, should be sizable (O(0.1))
- Charged Higgs mass scale ~ TeV or less
- Coupling μ_{kh} should be around ~ TeV

$$|g_{ee}| < 0.41 \frac{m_{k^{\pm\pm}}}{TeV}$$

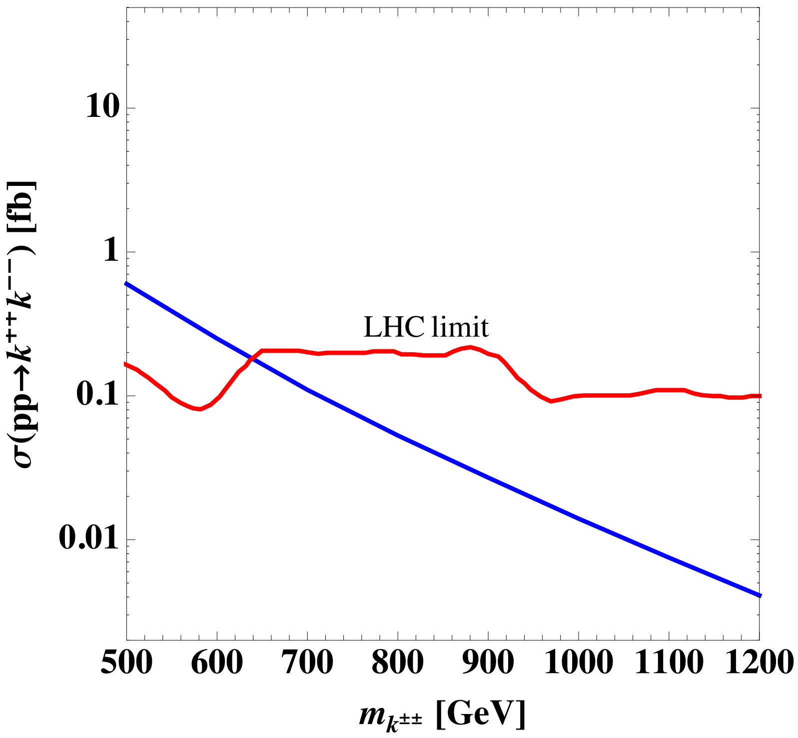
From LEP

Sizable coupling of doubly charged Higgs will be tested

Let us discuss collider physics of doubly charged Higgs bosons

Doubly charged Higgs at the LHC

Production process: $pp \to Z^* / \gamma^* \to k^{++}k^{--}$



- ✓ Assuming decay mode e+e+(e-e-)
- ✓ Mass should be > ~640 GeV
- ✓ Cross section 0.01~0.1 fb for O(1) TeV mass

LHC limit: ATLAS(2017)

Up to ~TeV scale can be tested at the HL-LHC with 3000 fb^{-1}

Doubly charged Higgs at the ILC

Testing effective Lagrangian: $L_{eff} = \frac{g_{ee}^2}{2m_{k^{++}}^2}(\bar{e}\gamma^\mu P_R e)(\bar{e}\gamma_\mu P_R e),$

At the ILC, polaraized beam can be used

➡ Test of chirality structure of the interaction

T. N., H. Okada, H. Yokoya, NPB 929, 193 (2018)

Process: $e^-(k_1,\sigma_1)e^+(k_2,\sigma_2) \to e^-(k_3,\sigma_3)e^+(k_4,\sigma_4)$

(k: momentum, σ: helicity)

Partially-polarized cross section:

$$\frac{d\sigma(P_{e^-},P_{e^-})}{d\cos\theta} = \sum_{\sigma_{e^-},\sigma_{e^+}=\pm} \frac{1+\sigma_{e^-}P_{e^-}}{2}\frac{1+\sigma_{e^+}P_{e^+}}{2}\frac{d\sigma_{\sigma_{e^-}\sigma_{e^+}}}{d\cos\theta}$$

$$\left(\frac{d\sigma_{\sigma_{e^-}\sigma_{e^+}}}{d\cos\theta} = \frac{1}{32\pi s}\sum_{\sigma_3,\sigma_4}\left|M_{\{\sigma_1,\sigma_2,\sigma_3,\sigma_4\}}\right|\right)$$

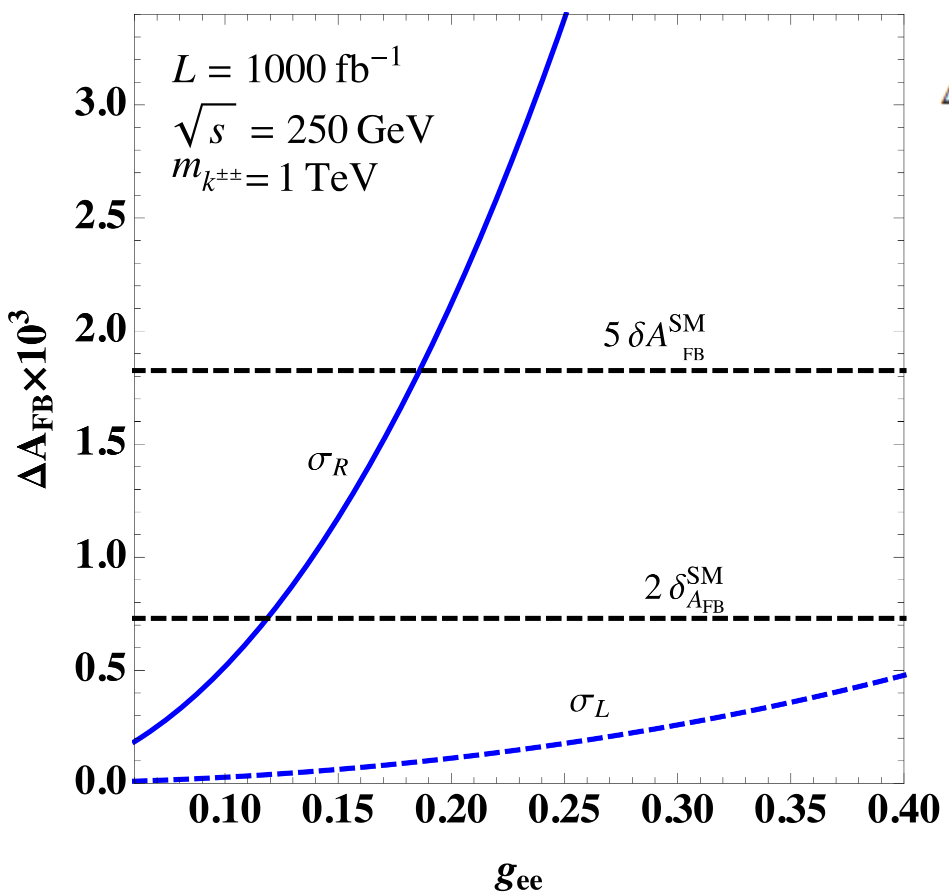
P: polarization of e^+/e^- beam

Forward-backward assymetry

Polarized CX: $$\frac{d\sigma_R}{d\cos\theta} = \frac{d\sigma(0.8,-0.3)}{d\cos\theta}, \quad \frac{d\sigma_L}{d\cos\theta} = \frac{d\sigma(-0.8,0.3)}{d\cos\theta}.$$

$$A_{FB}(\sigma_{L,R}) = \frac{N_F(\sigma_{L,R}) - N_B(\sigma_{L,R})}{N_F(\sigma_{L,R}) + N_B(\sigma_{L,R})},$$

$$\left(N_{F(B)}(\sigma_{L,R}) = L\int_{0(-0.5)}^{0.5(0)} d\cos\theta \frac{d\sigma_{L,R}}{d\cos\theta}, \right)$$



$$\Delta A_{FB}(\sigma_{L,R}) = |A_{FB}^{SM+k^{\pm\pm}}(\sigma_{L,R}) - A_{FB}^{SM}(\sigma_{L,R})|.$$

$$\delta^{SM}_{A_{FB}}(\sigma_{L,R}) = \sqrt{\frac{1-(A^{SM}_{FB}(\sigma_{L,R}))^2}{N^{SM}_F(\sigma_{L,R}) + N^{SM}_B(\sigma_{L,R})}}.$$

- ✓ Test of right-handed interaction
- ✓ We can test around $0.1 < g_{ee}$

Summary and Discussions

- ☐ Neutrino mass models with $U(1)_{L\mu-L\tau}$ gauge symmetry
  - ✓ Neutrino mass matrix could be restricted by the symmetry
  - ✓ Structures of the matrix depends on types of model
  - ✓ Prediction for neutrino oscillation data
- ☐ A specific model: Zee-Babu type model
  - ✓ Two zero texture in small scalar mixing limit for charged Higgs bosons
  - ✓ Phenomenology of doubly charged Higgs

Appendix

Helicity specified amplitudes

$$\mathcal{M}(+-+-) = -e^2(1+\cos\theta)\left[1+\frac{s}{t}+c_R^2\left(\frac{s}{s_Z}+\frac{s}{t_Z}\right)+\frac{2s}{\alpha(\Lambda_{RR}^e)^2}\right],$$
$$\mathcal{M}(-+-+) = -e^2(1+\cos\theta)\left[1+\frac{s}{t}+c_L^2\left(\frac{s}{s_Z}+\frac{s}{t_Z}\right)\right],$$
$$\mathcal{M}(+--+) = \mathcal{M}(-++-) = e^2(1-\cos\theta)\left[1+c_Rc_L\frac{s}{s_Z}\right],$$
$$\mathcal{M}(++++) = \mathcal{M}(----) = 2e^2\frac{s}{t}\left[1+c_Rc_L\frac{t}{t_Z}\right],$$

$$\Lambda_{RR}^e \equiv \frac{4\pi m_{k^{\pm\pm}}^2}{g_{ee}^2}$$

$$t = (k_1-k_3)^2 = (k_2-k_4)^2 = -s(1-\cos\theta)/2$$

$$s_Z = s - m_Z^2 + i m_Z \Gamma_Z$$

$$t_Z = t - m_Z^2 + i m_Z \Gamma_Z$$