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Phenomenology in a Zee-Babu type model with local $U(1)_{L_\mu - L_\tau}$ symmetry

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We discuss the Zee-Babu model with local $U(1)_{L_\mu - L_\tau}$ symmetry in which several singly-charged bosons are introduced. We find a predictive neutrino mass texture in a simple hypothesis where mixings among singly-charged bosons are negligible. Then we explore testability of the model focussing on a doubly-charged boson physics at the International Linear Collider.

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1. Introduction

The Zee-Babu model is one of the attractive approaches to generate neutrino mass at two-loop level without introducing extra fermion degrees of freedom [1]. It is then interesting to introduce $U(1)_{L_\mu - L_\tau}$ gauge symmetry in the Zee-Babu model so that neutrino mass structure is more restricted and we would get more prediction in neutrino physics. In addition, introduction of local $U(1)_{L_\mu - L_\tau}$ symmetry is motivated to explain anomalous muon magnetic dipole moment (muon $g-2$) [2]. In this presentation, we review a Zee-Babu type model with $U(1)_{L_\mu - L_\tau}$ and discuss phenomenology focusing on doubly charged Higgs at the International Linear Collider (ILC).

2. A model

Here we introduce our model based on $U(1)_{L_\mu - L_\tau}$ gauge symmetry in which neutrino masses are generated at two-loop level; for more details see Ref. [3]. Fermion sector is the same as the SM one where leptons have $U(1)_{L_\mu - L_\tau}$ charge; muon(-neutrino) and tauon(-neutrino) have charge 1 and -1 respectively. In scalar sector, we introduce three singly charged and one doubly charged scalar fields which are $SU(2)$ singlet; singly charged scalar fields have $U(1)_{L_\mu - L_\tau}$ charge $+1$, 0 and -1 while doubly charged scalar field $k^{\pm\pm}$ does not have $L_\mu - L_\tau$ charge. Then we write singly charged scalars as $h^+_{Q_{L_\mu - L_\tau}}$ with electric $(L_\mu - L_\tau)$ charge $+1(Q_{L_\mu - L_\tau})$ and complex conjugate is defined as $(h^+_{Q_{L_\mu - L_\tau}})^* = h^-_{-Q_{L_\mu - L_\tau}}$. In addition we introduce SM singlet scalar φ with $L_\mu - L_\tau$ charge 1 to break $U(1)_{L_\mu - L_\tau}$ gauge symmetry and to give mass to Z' boson from the new $U(1)$. The SM Higgs H and φ develop VEVs as $< H >= v/\sqrt{2}$ and $< \varphi >= v_\varphi/\sqrt{2}$ breaking electroweak and $U(1)_{L_\mu - L_\tau}$ symmetry spontaneously.

The Yukawa interactions associated with charged scalars are given by

$$\begin{aligned} L_Y =& f_{e\mu} \bar{L}^c_{L_e}(i\sigma_2) L_{L_\mu} h^+_{-1} + f_{\mu\tau} \bar{L}^c_{L_\mu}(i\sigma_2) L_{L_\tau} h^+_0 + f_{e\tau} \bar{L}^c_{L_e}(i\sigma_2) L_{L_\tau} h^+_{+1} \\ &+ g_{ee} \bar{e}^c_R e_R k^{++} + g_{\mu\tau} \bar{\mu}^c_R \tau_R k^{++} + h.c., \end{aligned} \tag{2.1}$$

where σ_2 is the second Pauli matrix. Note that the coupling f_{ab} is anti-symmetric due to nature of anti-symmetry under $SU(2)_L$ indices in the corresponding operators [1]. We also write interactions relevant to neutrino mass generation in the scalar potential:

$$\begin{aligned} V \supset &+ (\mu_{kh} k^{++} h^-_0 h^-_0 + \tilde{\mu}_{kh} k^{++} h^-_{-1} h^-_{+1} + \mu_{\varphi h} \varphi h^+_{-1} h^-_0 + \tilde{\mu}_{\varphi h} \varphi^* h^+_{+1} h^-_0 + c.c.) \\ &+ (\lambda_{\varphi hk} \varphi k^{++} h^-_{-1} h^-_0 + \tilde{\lambda}_{\varphi hk} \varphi^* k^{++} h^-_{+1} h^-_0 + c.c.), \end{aligned} \tag{2.2}$$

where the coupling constants are assumed to be real for simplicity.

In our scenario we choose parameters so that mixing among scalar fields are small. Then we write mass of $h^\pm_{-1,0,1}$ and $k^{\pm\pm}$ as $m_{h^\pm_{-1,0,1}}$ and $m_{k^{\pm\pm}}$. In this presentation, neutral scalar bosons are not discussed since it is irrelevant in generating neutrino mass; some details of neutral scalar sector can be referred to Ref. [4].

Neutrino mass matrix: In our model, neutrino masses are generated at two loop level as the original Zee-Babu model [1]. From two loop diagrams, non-zero components of neutrino mass matrix are obtained such that

$$M_{11[23]} \simeq 8\tilde{\mu}_{kh} f_{e\mu[\mu\tau]} m_\mu g^*_{\mu\tau} m_\tau f_{\tau e[\mu\tau]} I\left(m_{h^+_{-1}}, m_{h^+_{+1}}, m_{k^{++}}, m_\mu, m_\tau\right), \quad (2.3)$$

$$M_{12[13]} \simeq 4\sqrt{2}\lambda_{\varphi hk}[\tilde{\lambda}_{\varphi hk}] v_\varphi f_{e\mu[e\tau]} m_\mu g^*_{\mu\tau} m_\tau f_{\tau\mu[\mu\tau]} I\left(m_{h^+_{-1}}, m_{h^+_0}, m_{k^{++}}, m_\mu, m_\tau\right), \quad (2.4)$$

where the $I(m_1, m_2, m_3, m_{\ell_i}, m_{\ell_j})$ is the loop integral factor which has $O(1)$ value [5]. We thus obtain two-zero texture of the neutrino mass matrix in which $M_{33} \simeq M_{22} \simeq 0$ for small mixing among singly charged scalar bosons [6].

3. Collider physics

Here we discuss test of doubly charged Yukawa coupling at the ILC with $\sqrt{s} = 250$ GeV. Although doubly charged scalar can not be produced directly at the ILC, we can test the coupling observing deviation from the SM prediction for the $e^+e^- \to e^+e^-$ scattering. The relevant effective interaction is written by

$$L_{eff} = \frac{g^2_{ee}}{2m^2_{k^{++}}}(\bar{e}\gamma^\mu P_R e)(\bar{e}\gamma_\mu P_R e), \quad (3.1)$$

where Fierz transformation is applied to get the operator. We then apply the analysis in ref. [7] based on polarized initial state at the ILC for $e^-(k_1, \sigma_1)e^+(k_2, \sigma_2) \to \ell^-(k_3, \sigma_3)\ell^+(k_4, \sigma_4)$ process where k_i indicates 4-momentum of each particle and we explicitly show the helicities of initial- and final-state leptons $\sigma_i = \pm$.

The partially-polarized differential cross section is defined as

$$\frac{d\sigma(P_{e^-}, P_{e^+})}{d\cos\theta} = \sum_{\sigma_{e^-}, \sigma_{e^+} = \pm} \frac{1+\sigma_{e^-}P_{e^-}}{2} \frac{1+\sigma_{e^+}P_{e^-}}{2} \frac{d\sigma_{\sigma_{e^-}\sigma_{e^+}}}{d\cos\theta}, \quad (3.2)$$

where $d\sigma_{\sigma_{e^-}\sigma_{e^+}}/d\cos\theta$ is The differential cross-section for purely-polarized initial-state $\sigma_{1,2} = \pm 1$, and $P_{e^-(e^+)}$ is the degree of polarization for the electron(positron) beam summing up the helicity of final states. We then apply the following two cases as realistic values at the ILC for polarized cross sections $\sigma_{L,R}$ [8]:

$$\frac{d\sigma_R}{d\cos\theta} = \frac{d\sigma(0.8, -0.3)}{d\cos\theta}, \quad \frac{d\sigma_L}{d\cos\theta} = \frac{d\sigma(-0.8, 0.3)}{d\cos\theta}. \quad (3.3)$$

Applying the polarized cross sections, we study the sensitivity to $k^{\pm\pm}$ boson in $e^+e^- \to e^+e^-$ scattering via the measurement of a forward-backward asymmetry at the ILC, which is given by

$$A_{FB}(\sigma_{L,R}) = \frac{N_F(\sigma_{L,R}) - N_B(\sigma_{L,R})}{N_F(\sigma_{L,R}) + N_B(\sigma_{L,R})}, \quad N_{F(B)}(\sigma_{L,R}) = L\int_{0(-0.5)}^{0.5(0)} d\cos\theta \frac{d\sigma_{L,R}}{d\cos\theta}, \quad (3.4)$$

where L is an integrated luminosity, and a bound of integral ± 0.5 is chosen to maximize the sensitivity. Then the forward-backward asymmetry is estimated for cases with only the SM gauge boson contributions, and with both SM and $k^{\pm\pm}$ boson contributions, in order to explore the sensitivity to $k^{\pm\pm}$ interaction. We thus obtain $N^{SM}_{F(B)}(\sigma_{L,R})$ and $A^{SM}_{FB}(\sigma_{L,R})$ for the former case, and $N^{SM+k^{\pm\pm}}_{F(B)}(\sigma_{L,R})$ and $A^{SM+k^{\pm\pm}}_{FB}(\sigma_{L,R})$ for the latter case. Finally the sensitivity to $k^{\pm\pm}$ interaction is estimated by

$$\Delta A_{FB}(\sigma_{L,R}) = |A^{SM+k^{\pm\pm}}_{FB}(\sigma_{L,R}) - A^{SM}_{FB}(\sigma_{L,R})|. \quad (3.5)$$

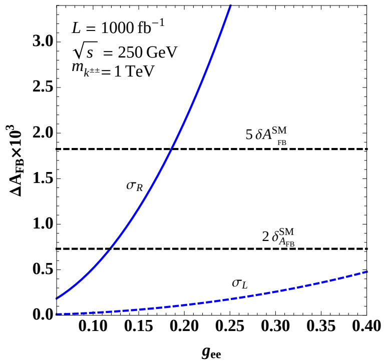

Figure 1: The blue solid(dashed) curve shows ΔA_{FB} as a function of g_{ee} for $\sigma_{R(L)}$. The statistical error in the SM, $\delta^{\rm SM}_{A_{\rm FB}}$, is estimated to be $\sim 0.36\times 10^{-3}$ both σ_R and σ_L.

Then we compare this quantity with a statistical error of the asymmetry which is given by assuming only SM contribution:

$$\delta^{SM}_{A_{FB}}(\sigma_{L,R}) = \sqrt{\frac{1-(A^{SM}_{FB}(\sigma_{L,R}))^2}{N^{SM}_F(\sigma_{L,R})+N^{SM}_B(\sigma_{L,R})}}. \tag{3.6}$$

In Fig. 1, we show $\Delta A_{FB}(\sigma_R)$ and $\Delta A_{FB}(\sigma_L)$ by solid and dashed curves respectively as a function of g_{ee} where we apply integrated luminosity of 1000 fb^{-1} as a reference value. The curves are compared with the values $5\delta^{SM}_{A_{FB}}$ and $2\delta^{SM}_{A_{FB}}$ which are respectively given by $\sim 7.2\times 10^{-3}$ and $\sim 1.8\times 10^{-3}$. Thus we find that $g_{ee} \gtrsim 0.12$ can be tested with the integrated luminosity of 1000 fb^{-1} with 2 σ level and 5 σ significance can be obtained for $g_{ee} \gtrsim 0.18$ for polarized cross section σ_R. On the other hand, $\Delta A_{FB}(\sigma_L)$ is much smaller than that for σ_R.

4. Summary

We have discussed Zee-Babu type model with $U(1)_{L_\mu - L_\tau}$ gauge symmetry in which neutrino mass matrix has two-zero texture in our scenario of small scalar mixing. Then we have considered doubly charged scalar at the ILC. Remarkably we can test chirality structure of Yukawa coupling of doubly charged scalar and electron in use of polarized cross section at the ILC.

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