Discrimination of Models Including Doubly Charged Scalar Bosons by Using Tau Lepton Decay Distributions

Hiroaki Sugiyama

Maskawa Institute for Science and Culture, Kyoto Sangyo University, Kyoto 603-8555, Japan

1 Introduction

Measurements of neutrino oscillations have shown the existence of non-zero masses of neutrinos which are regarded as massless particles in the standard model of particle physics (SM). The SM must be extended such that the non-zero neutrino masses are accommodated. Some of such extended models for the neutrino mass involve the doubly-charged scalar boson $H^{--}$.

In the Higgs triplet model (HTM) [2], for example, an SU(2)$_L$-triplet scalar field $\Delta$ with the hypercharge $Y = 1$ is introduced to the SM in order to accommodate non-zero neutrino masses. The $\Delta$ can be expressed in an adjoint representation as

$$\Delta \equiv \left( \begin{array}{c} \Delta^+ / \sqrt{2} \\ \Delta^0 \\ -\Delta^+ / \sqrt{2} \end{array} \right). \quad (1)$$

The scalar field $\Delta$ has the following Yukawa interaction with the SU(2)$_L$-doublet field $L_\ell \equiv (\nu_\ell L, \ell_L)^T$ of left-handed leptons in the flavor basis ($\ell = e, \mu, \tau$):

$$\mathcal{L}^\text{HTM}_{\text{Yukawa}} = -(h_M)_{\ell\ell'} \bar{L}_\ell \epsilon \Delta L_{\ell'} + \text{h.c.}, \quad (2)$$

where $h_M$ is a symmetric matrix of Yukawa coupling constants, and $\epsilon$ denotes the completely antisymmetric tensor for the SU(2)$_L$ indices. The Majorana neutrino mass matrix $M^\text{HTM}_\nu$ in the flavor basis is simply given by $M^\text{HTM}_\nu = 2(h_M) \langle \Delta^0 \rangle$, where $\langle \Delta^0 \rangle$ is the vacuum expectation value of $\Delta^0$. It is clear that the doubly-charged scalar $\Delta^{--}$ has an interaction $\Delta^{--} L_\ell L_{\ell'}$, and the leptonic decay is $\Delta^{--} \rightarrow \ell_\ell' \ell_{\ell'}$.

The Zee-Babu model (ZBM) [3] is another simple example of models to generate neutrino masses, where doubly-charged scalar boson is introduced. In the ZBM, the SM is extended by introducing two SU(2)$_L$-singlet scalar bosons $s^{++}$ and $s^+$ whose hypercharges are $Y = 2$ and 1, respectively. Yukawa interactions of these new scalar bosons with leptons are given by

$$\mathcal{L}^\text{ZBM}_{\text{Yukawa}} = -(Y_s)_{\ell\ell'} \bar{L}_\ell \epsilon \ell^c R \ell^c R \epsilon \Delta L_{\ell'} + \text{h.c.}, \quad (3)$$

where $Y_s$ ($Y_a$) is a symmetric (an antisymmetric) matrix of Yukawa coupling constants. Tiny Majorana neutrino masses are generated at the two-loop level where charged leptons and new

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scalar bosons are involved in the loop. In contrast with the HTM, the leptonic decay of the doubly-charged scalar boson is $s^{--} \rightarrow \ell_R \ell'_R$.

In general, there are two possibilities for the Yukawa interaction of $H^{--}$ with charged leptons, $H_X^{--} (\ell_X')^c$ ($X = L, R$), where $H_L^{--} (H_R^{--})$ stands for $H^{--}$ whose Yukawa interaction is only with left-handed (right-handed) charged leptons. A simple example of $H_L^{--}$ is $\Delta^{--}$ in the HTM while $s^{--}$ in the ZBM is a simple example of $H_R^{--}$. It will be important to distinguish between $H_L^{--}$ and $H_R^{--}$, namely between $\ell_L$ and $\ell_R$ produced by the $H^{--}$ decay, in order to discriminate models for generating neutrino masses when a $H^{--}$ is discovered in the future.

The tau lepton decays within a detector in a collider experiment while the muon is too light to decay within the detector. It is known that decay products have information on the polarization of the parents tau lepton [4, 5, 6]. Since the tau lepton is heavier than the pion, it has a simple two-body decay channel which is especially useful for the extraction of information on the polarization of the tau lepton. The angular distribution of the daughter pions in the rest frame of the tau lepton is translated into the energy distribution of the pion in the collinear limit, $E_{\tau} \gg m_{\tau}$, where $E_{\tau}$ and $m_{\tau}$ are the energy and the mass of the tau lepton, respectively. In the collinear limit, energy distributions $F_{\pi}^X(z)$ for $\pi^-$ produced via the two-body decay of the polarized tau lepton $\tau_X$ ($X = L, R$) are known well as

$$F_{L}^\pi(z) = 2(1-z), \quad F_{R}^\pi(z) = 2z, \quad (4)$$

where $z \equiv E_{\pi}/E_{\tau}$ for the pion energy $E_{\pi}$. As it is naively expected, $\tau_L \rightarrow \nu_L \pi^-$ tends to produce a soft pion while a pion produced via $\tau_R \rightarrow \nu_R \pi^-$ tends to be a hard one. Note that the collinear limit is always reliable when the tau lepton is produced by the decay of $H^{--}$ because $H^{--}$ is much heavier than the tau lepton. In this talk, we see that $H_L^{--}$ and $H_R^{--}$ can be distinguished by measuring energy distributions of daughter charged pions of tau leptons produced by decays of $H^{--}$.

2 Results

Hereafter, $\ell$ denotes $e$ and $\mu$, and $\ell\ell$ means not only $ee$ and $\mu\mu$ but also $e\mu$. We deal only with the pair production of $H^{--}$.

Let us consider first the case where $H^{--}$ decays into $\ell\ell$ and $\ell\tau$ with sizable branching ratios. The $H^{--}$ can be discovered by using a pair of same-signed $\ell$ whose invariant mass $M_{\ell\ell}$ has a peak at the mass $m_{H^{\pm\pm}}$ of $H^{--}$. Then, $pp \rightarrow H^{++} H^{--} \rightarrow \ell\ell \ell\tau \rightarrow \ell\ell \ell\pi^- \nu$ is the most useful mode to determine the tau polarization. The background for the signal will be significantly removed by requiring the existence of a pair of same-signed charged leptons with $M_{\ell\ell} \simeq m_{H^{\pm\pm}}$. We see that the pion energy fraction $z (\equiv E_{\pi}/E_{\tau})$ can be calculated as $z = M_{\pi\ell}^2/m_{H^{\pm\pm}}^2$ in the collinear limit, where $M_{\pi\ell}$ is the invariant mass of a same-singed charged pair of a pion and a charged
lepton. The distribution of charged pions with respect to $z = (M_{π\ell}/m_{H^{±±}})$ in our simulation is shown in Fig. 1 (left). There remains a remarkable difference between distributions for $H_L^{−−}$ (red dashed line) and $H_R^{−−}$ (blue solid line) even after the event selection in our simulation. In order to distinguish between $H_L^{−−}$ and $H_R^{−−}$, it is sufficient to observe the difference between numbers of events for $z < 0.5$ and $0.5 < z$. The difference of these numbers is about 2000 in Fig. 1 (left) where we generated $3 \times 10^4$ events of $pp \to H^{++}H^{−−} \to π\pi\ell\ell\tau$ followed only by the hadronic $τ$ decays. The difference will be $O(10)$ events even if the LHC produces only $O(100)$ events of $pp \to H^{++}H^{−−} \to π\pi\ell\ell\tau$, where $10.8\%$ of $τ$ decays into $π^−ν$.

Next, we consider the case where $H^{−−} \to \ellτ$ has too small branching ratio to be reliable. Then, we utilize $pp \to H^{++}H^{−−} \to π\pi\ell\ell\tau$. As in the first case, a pair of the same-signed $\ell$ with $M_{ℓℓ} \simeq m_{H^{±±}}$ helps to reduce background events. For $H^{−−} \to ττ \to π^−π^−νν$, the distributions in the collinear limit with respect to a product $z \equiv z_1z_2$ of pion energy fractions ($z_1 \equiv E_{π_1}/E_{π_1}$ and $z_2 \equiv E_{π_2}/E_{π_2}$) are given by

$$D^{ππ}_{LL}(z) = \int_1\frac{dz_1}{z_1}F^π_L(z_1)F^π_L(z/z_1) = 4 \left( (1 + z) \log \frac{1}{z} + 2z - 2 \right), \quad (5)$$

$$D^{ππ}_{RR}(z) = \int_1\frac{dz_1}{z_1}F^π_R(z_1)F^π_R(z/z_1) = 4z \log \frac{1}{z}, \quad (6)$$

where $D^{ππ}_{LL}(z)$ ($D^{ππ}_{RR}(z)$) is for $H_L^{−−}$ ($H_R^{−−}$). We see that the $z$ can be obtained by $z = M^2_{π\ell}/m^2_{H^{±±}}$, where $M_{π\ell}$ is the invariant mass of a pair of same-signed charged pions. Note

The actual branching ratio of the hadronic $τ$ decays is 64.8%, and the branching ratio for $τ \to π^−ν$ is 10.8%. Thus, 17% of the tau lepton in our simulation decays into $π^−ν$.

Distributions for $H^{−−} \to ττ \to ℓπ^−νν$ and $H^{−−} \to ττ \to ℓπ^−νν$ do not have a large difference between decays of $H_L^{−−}$ and $H_R^{−−}$. The $ℓπ$ denotes the $ℓ$ produced via the $τ$ decay.
that $D_{LL}^{\pi\pi}(z) = D_{RR}^{\pi\pi}(z)$ at $z \simeq 0.2$. Figure 1 (middle) shows the result of our simulation for this decay process. We see that there is a clear difference between distributions for $H_L^{-}$ (red dashed line) and $H_R^{-}$ (blue solid line) even in this process.

Finally, we discuss about the case where the branching ratio for $H^{-} \rightarrow \ell\ell$ is tiny. The fruitful process in this case is $pp \rightarrow H^{++}H^{-} \rightarrow \ell\tau\ell\tau$. The momentum of two tau leptons can be reconstructed in the collinear limit for their decays [7]. The $H^{-}$ can be discovered by using the invariant mass $M_{\ell\tau}$ of $\ell$ and $\tau$, which has a peak at $m_{H^{\pm\pm}}$. We require that a tau lepton decays into $\ell$ for the background reduction and the other tau lepton decays into $\pi$ for the determination of the $\tau$ polarization. As in the first case, the pion energy fraction $z \equiv E_{\pi}/E_\tau$ can be given by $z = M_{\ell\pi}^2/m_{H^{\pm\pm}}^2$. The generated number of $pp \rightarrow H^{++}H^{-} \rightarrow \ell\tau\ell\tau$ is again $3 \times 10^4$, but the $\tau$ decay here is not restricted to the hadronic ones. The distribution of charged pions is shown in Fig. 1 (right). It would be possible to distinguish between $H_L^{-}$ (red dashed line) and $H_R^{-}$ (blue solid line) in this case also.

In conclusion, we can determine the chiral structure of the Yukawa interaction of $H^{-}$ by using distributions of daughter charged pions of tau leptons produced by the $H^{-}$ decays if pair-produced $H^{-}$ can sufficiently decay as $H^{++}H^{-} \rightarrow \ell\tau\ell\tau$ or $\ell\tau\tau\tau$ or $\ell\tau\ell\tau$. The information on the Yukawa interaction will help to discriminate new physics models in which neutrino masses are generated.

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