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Discrimination of models including $H^{\pm\pm}$ by using tau decay

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Abstract. The doubly charged scalar boson ($H^{\pm\pm}$) is introduced in several models of the new physics beyond the standard model. The $H^{\pm\pm}$ can have Yukawa interactions with two left-handed charged leptons or two right-handed charged leptons. We study kinematical properties of $H^{\pm\pm}$ decay products through tau leptons in order to discriminate the chiral structures of the new Yukawa interaction. The chirality of tau leptons can be measured by the energy distributions of the tau decay products, and thus the chiral structure of the new Yukawa interaction can be traced in the invariant-mass distributions of the $H^{\pm\pm}$ decay products [1].

1 Introduction

The doubly charged scalar boson $H^{\pm\pm}$, which has a twice electrical charge of the electron, exists in several models to generate Majorana neutrino masses. For instance, the particle is a member of an $SU(2)_L$ triplet scalar field in the Higgs triplet model (HTM) [2]. The triplet field develops a tiny vacuum expectation value (VEV), which breaks the lepton number conservation and is the source of the neutrino mass. On the other hand, a doubly charged scalar boson is introduced as an $SU(2)_L$ singlet scalar field in the Zee-Babu model (ZBM) [3] which generates Majorana neutrino masses at the two-loop level. In these models with $H^{\pm\pm}$, its Yukawa interactions with charged leptons depend on the $SU(2)_L$ property of $H^{\pm\pm}$. Namely, $H^{\pm\pm}$ from an $SU(2)_L$ triplet field couples only with left-handed charged leptons ℓ_L^\pm while the one from an $SU(2)_L$ singlet field interacts only with right-handed charged leptons ℓ_R^\pm . The discrimination of the chiral structure of the Yukawa interaction plays an important role to distinguish these models.

The $H^{\pm\pm}$ can be produced by the pair creation process, $pp \rightarrow \gamma^*/Z^* \rightarrow H^{\pm\pm}H^{\mp\mp}$. For $SU(2)_L$ non-singlet representations, the associated production $pp \rightarrow W^{\pm*} \rightarrow H^\pm H^{\mp\pm}$ with a singly charged scalar boson (H^\pm) is also possible [4]. Theoretical studies for $H^{\pm\pm}$ decaying into same-signed leptons and weak gauge bosons can be found in, e.g., Refs. [5, 6]. The experimental search results for $H^{\pm\pm}$ have been available, where purely leptonic decay channels are assumed [7–9].

In this paper, we study the consequence of the chiral structure of the Yukawa interaction (of the doubly charged scalar boson with two charged leptons) to the kinematical distribution involving the decay of tau leptons. In Section II, models of neutrino masses with $H^{\pm\pm}$ are introduced. In Section III, the polarization dependences of the decay distributions of τ leptons are reviewed, and the

invariant-mass distributions of final-state particles in the decay $H^{\pm\pm} \rightarrow \tau^\pm \ell^\pm$ are discussed. Simulation results including τ -tagging and simple kinematical cuts are also presented. Conclusions are given in Section IV.

2 Models with $H^{\pm\pm}$

In this section, we briefly present examples of models which include the doubly charged scalar boson.

The first example is the HTM [2]. In this model, an $SU(2)_L$ adjoint scalar field Δ with hypercharge $Y = 1$ is introduced in order to generate masses of neutrinos via the triplet Yukawa interaction. The new Yukawa interaction is given by

$$\mathcal{L}_{\text{HTM}}^{\text{Yukawa}} = -\bar{L}^c h_M i\sigma_2 \Delta L + \text{H.c.}, \quad (1)$$

where $L = (\nu_L, \ell_L)^T$ is the lepton doublet field, the Yukawa coupling matrix is symmetric $h_M = h_M^T$, $\sigma_i (i = 1-3)$ are the Pauli matrices, and

$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}. \quad (2)$$

In the HTM, the doubly charged scalar boson interacts with a pair of *left-handed* charged leptons. The neutrino mass matrix in the flavor basis is obtained as $M_\nu^{\text{HTM}} = 2h_M^\dagger \langle \Delta^0 \rangle = U_{\text{MNS}} \widehat{M}_\nu U_{\text{MNS}}^T$, where $\langle \Delta^0 \rangle$ is the VEV of the triplet field, \widehat{M}_ν is the neutrino mass matrix in the diagonal basis, and U_{MNS} is the Maki-Nakagawa-Sakata (MNS) matrix for the lepton flavor mixing. Since the neutrino mass matrix is directly related to the Yukawa matrix, the decay patterns of the doubly charged scalar boson are constrained by observed neutrino oscillation data. By assuming the realistic values of decay branching ratios, constraints on the mass of $\Delta^{\pm\pm}$ are obtained as $m_{\Delta^{\pm\pm}} \gtrsim 400 \text{ GeV}$ [8].

The next example is the ZBM [3]. Two $SU(2)_L$ singlet scalar bosons, k^- ($Y = -1$) and k^{--} ($Y = -2$), are introduced in the ZBM to generate tiny neutrino masses at the

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two-loop level. The new interaction terms which relevant to the radiative neutrino mass are

$$\mathcal{L}_{\text{ZBM}} = -\bar{L}^c Y_a i\sigma_2 L k^+ - (\bar{\ell}_R^c)^c Y_s \ell_R^- k^{++} - \mu k^- k^- k^{++} + \text{H.c.}, \quad (3)$$

where $Y_a = -Y_a^T$ and $Y_s = Y_s^T$. The doubly charged scalar boson in this model interacts with *right-handed* charged leptons. If a lepton number 2 is assigned to k^- and k^{--} , a coupling constant μ is the soft breaking parameter of the lepton number conservation. The neutrino mass matrix is calculated as $(M_{\nu}^{\text{ZBM}})_{\alpha\beta} = 16\mu(Y_a^*)_{\alpha\ell} m_{\ell}(Y_s)_{\ell\ell'} I_{\ell\ell'} m_{\ell'}(Y_a^{\dagger})_{\ell'\beta}$, where the loop function $I_{\ell\ell'}$ is given in Ref. [10]. Assuming purely muonic decay mode, the mass of $k^{\pm\pm}$ is constrained to be $m_{k^{\pm\pm}} \gtrsim 250 \text{ GeV}$ [9].

3 Tau polarizations and $H^{\pm\pm}$ decays

In this section, we review the polarization dependence of decays of τ 's, and discuss how that could be traced in the case of $H^{\pm\pm}$ decay through τ 's. In the following discussion, we assume that the leptonic decays of doubly charged scalar bosons occur via the Yukawa interactions, e.g., $H_X^{\pm\pm} \bar{\ell}_X(\tau_X)^c$ ($X = L, R$), where $H_L^{\pm\pm}(H_R^{\pm\pm})$ denotes $H^{\pm\pm}$ only with the left-handed (right-handed) interaction. Hereafter, ℓ denotes e or μ .

Let us consider the lepton flavor violating (LFV) decay $H^{\pm\pm} \rightarrow \ell^{\pm} \tau^{\pm}$ followed by $\tau^{\pm} \rightarrow \pi^{\pm} \nu$. The invariant-mass of $\ell\pi$ is expressed as $M_{\ell\pi}^2 = z m_{H^{\pm\pm}}^2$ in the collinear limit, where $m_{H^{\pm\pm}}$ is the mass of $H^{\pm\pm}$ and $z \equiv E_{\pi}/E_{\tau}$; the E_{π} and E_{τ} are energies of a pion and a τ lepton in the laboratory frame, respectively. This relation between the invariant-mass and the energy fraction is a good approximation for an energetic τ lepton, e.g., a τ lepton produced by a heavy particle decay.

The distributions of the pion energy fraction z (namely, of the invariant-mass $M_{\ell\pi}^2$) are given as

$$\mathcal{D}_L^{\pi}(z) = F_L^{\pi}(z) = 2(1-z), \quad (4a)$$

$$\mathcal{D}_R^{\pi}(z) = F_R^{\pi}(z) = 2z, \quad (4b)$$

where $F_{L,R}^{\pi}(z)$ are the fragmentation functions of $\tau_{L,R}^{\pm} \rightarrow \pi^{\pm} \nu$ decay in the collinear limit [11].

In Fig. 1, we plot the distributions of the invariant-masses of $\ell\pi$. for the LFV decay $H^{\pm\pm} \rightarrow \ell^{\pm} \tau^{\pm}$ followed by the pionic decays of the τ . The invariant-mass distributions via the decay of τ_L (τ_R) are plotted in the dashed (solid) curves. For the pionic decay channel, the distributions are linear in z and have an opposite behavior between τ_L and τ_R .

In order to perform realistic studies for collider experiments, we examine a Monte-Carlo simulation for the $H^{++}H^{--}$ pair production and their decays up to parton-showering and hadronizations. We generate signal events of $pp \rightarrow H^{++}H^{--}$ by using Pythia with handling the τ decay by TAUOLA incorporating the chiral properties of the Yukawa interactions of $H^{\pm\pm}$. The $m_{H^{\pm\pm}}$ is set to be 400 GeV, and the collider energy to $\sqrt{s} = 14 \text{ TeV}$. For the reference, the $H^{++}H^{--}$ production cross-sections is 4.6 fb

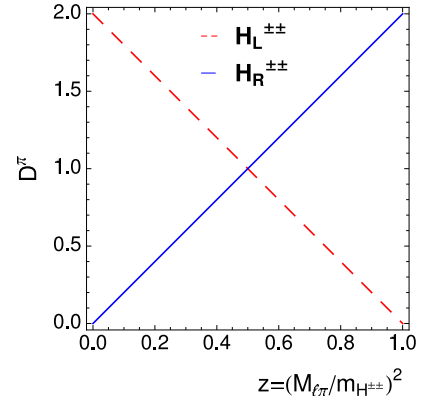


Figure 1. Distributions of the invariant-mass of $\ell\pi$ (left panel) from the LFV decay $H^{\pm\pm} \rightarrow \ell^{\pm} \tau^{\pm}$. The invariant-mass distributions through the decay of τ_L (τ_R) are plotted in the dashed (solid) curves.

for the HTM and 1.9 fb for the ZBM. For the analysis, we use lighter leptons (e and μ) with $p_T^{\ell} > 15 \text{ GeV}$ and $|\eta_{\ell}| < 2.5$, where p_T is the transverse momentum and η is the pseudo rapidity. To find the hadronically decaying τ 's, we perform τ -tagging for every jets with $p_T^j > 25 \text{ GeV}$ and $|\eta_j| < 2.5$ which are constructed by the anti- k_T algorithm with $R = 0.4$. For the τ -tagging, we use two methods. The first method is devoted to extract the $\tau \rightarrow \pi\nu$ decay. Namely, it is tagged as the pionic τ -jet (π_{τ}) if a jet has only 1 charged hadron and its transverse energy dominates more than 0.95 of the jet. The second method is a more general-purpose; we define j_{τ} as a jet which contains 1 or 3 charged tracks in a small cone ($R = 0.15$) centered at the jet momentum direction with the transverse energy deposit to this small cone more than 0.95 of the jet. The second method could tag the τ decay into 2π and 3π originated from $\tau \rightarrow \rho\nu$ and $a_1\nu$ decays, in addition to the single π . Thus the tagging efficiency is better than the first method, but the spin analysis power is weakened.

The extensive signal-to-background studies including τ 's can be found, for example, in Ref. [5, 6]. Following their results, a clear signal extraction is expected by the requirement of the same-signed dilepton and possibly a peak in their invariant-mass. Thus, we present the simulation results only for the signal events, but not for the background events. Expected background processes are diboson production, $t\bar{t}$ plus one boson production, etc.

We deal with $pp \rightarrow H^{++}H^{--} \rightarrow \ell^+\ell^+\ell^-\tau^-$. This decay pattern can be easily identified by requiring the same-signed dilepton with a sharp peak in their invariant-mass distribution. The mass of $H^{\pm\pm}$ can be clearly obtained from the peak. Then, the invariant-mass distribution of the remaining ℓ^- and decay products of τ^- can be used for the polarization discriminant.

In Fig. 2, the invariant-mass distributions of $\ell\pi_{\tau}$ (left panel) and those of ℓj_{τ} (right panel) from $H^{\pm\pm} \rightarrow \ell^{\pm} \tau^{\pm}$ are shown for the events with 3ℓ and one τ -tagged jet. Results for the decay of $H_L^{\pm\pm}$ ($H_R^{\pm\pm}$) are plotted in the dashed (solid) histograms. Corresponding integrated luminosity of our simulation depends on the branching ratio of $H^{\pm\pm}$,

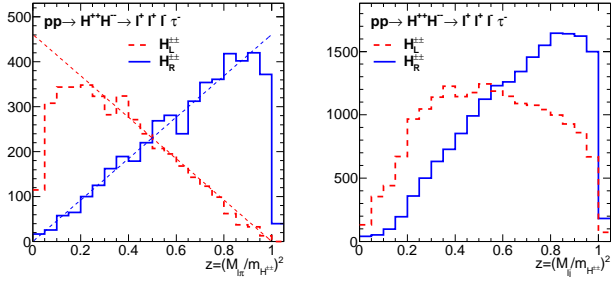


Figure 2. Invariant-mass distributions of $\ell\pi_\tau$ (left) and ℓj_τ (right) in the $pp \rightarrow H^{\pm\pm}H^{\mp\mp} \rightarrow \ell^+\ell^+\ell^-\tau^-$ process followed by hadronic decays of τ^- , after the requirement of the same-signed dilepton with $M_{\ell\ell} \simeq m_{H^{\pm\pm}}$. Dashed (Solid) histograms are for $H_L^{\pm\pm}$ ($H_R^{\pm\pm}$). Smooth lines in the left panel are theoretical expectations by using Eqs. (4) with some normalization.

which however we don't specify in this study. The signal selection efficiencies with the π_τ method and the j_τ method in Fig. 2 are about 13% (15%) and 62% (62%), for $H_L^{\pm\pm}$ ($H_R^{\pm\pm}$) events in our simulation, respectively.

The distributions in the left panel roughly reproduce the linear dependence on z given in Eqs. (4) which are superimposed with some normalization. Thus, the pionic τ -tagging method seems to be working well to catch the pionic τ decay products. The effect of the kinematical cuts can appear in the small z region due to the p_T cut. The discrimination of the two distributions may be possible with just a small number of events. When we employ the general τ -tagging method, the expected number of events becomes 5 times larger than that for the case with pionic τ -tagging method. Since the distributions for $H_L^{\pm\pm}$ and $H_R^{\pm\pm}$ still differ from each other, although the difference is weakened, this general τ -tagging method works as well for our purpose. The distributions are scaled by the mass of $H^{\pm\pm}$, thus it is expected that these distributions does not depend on the value of the mass so much.

4 Conclusions

The doubly charged scalar boson $H^{\pm\pm}$ appears in several new physics models, especially in the models to generate Majorana neutrino masses. The $H^{\pm\pm}$ has characteristic Yukawa interactions with two *left-handed* charged leptons (e.g., $\Delta^{\pm\pm}$ from an $SU(2)_L$ triplet field in the HTM) or two *right-handed* charged leptons (e.g., $k^{\pm\pm}$ from an $SU(2)_L$ singlet field in the ZBM) depending on the model. We have studied the kinematical consequences of the Yukawa interactions in order to discriminate these models through the determination of the chiral structure of the Yukawa interaction.

At collider experiments, it is known that the polarization of the τ lepton is analyzed by the energy fraction distributions of its decay products (π^\pm , ℓ^\pm , etc.). We have seen

that the invariant-mass distributions are good analyzers of the τ polarization especially for the hadronic τ decays. We have performed a simple Monte-Carlo simulation for decays of τ 's made from the decays of pair-produced $H^{\pm\pm}$. If $H^{\pm\pm}H^{\mp\mp} \rightarrow \ell^+\ell^+\ell^-\tau^-$ mode exists ($\ell = e, \mu$), the invariant-mass distribution of $\ell^-\pi_\tau^-$ gives the best analysis power on τ polarization. The background contribution can be highly reduced by requiring $\ell^+\ell^+$ whose invariant-mass is $\simeq m_{H^{\pm\pm}}$. Therefore, we can determine the chiral structure of the Yukawa interaction of $H^{\pm\pm}$, and it will help to discriminate new physics models beyond the SM.

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