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Testing a neutrino mass generation mechanism at the Large Hadron Collider

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The Large Hadron Collider could be a discovery machine for the neutrino mass pattern and its Majorana nature in the context of a well-motivated TeV scale Type II seesaw model. This is achieved by identifying the flavor structure of the lepton-number violating decays of the charged Higgs bosons. The observation of either $H^+ \to \tau^+ \bar{\nu}$ or $H^+ \to e^+ \bar{\nu}$ will be particularly robust to determine the neutrino spectra since they are independent of the unknown Majorana phases, which could be probed via the $H^{++} \to e_i^+ e_j^+$ decays. In a less favorable scenario when the leptonic channels are suppressed, one needs to observe the decays $H^+ \to W^+ H_1$ and $H^+ \to t\bar{b}$ to confirm the triplet-doublet mixing that implies the Type II relation. The associated production $H^{\pm\pm}H^{\mp}$ is crucial in order to test the triplet nature of the Higgs field.

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I. INTRODUCTION

The Large Hadron Collider (LHC) at CERN will soon take us to a new frontier with unprecedented high energy and luminosity. Major discoveries of exciting new physics at the Terascale are highly anticipated. The existence of massive neutrinos clearly indicates the need for new physics beyond the standard model (SM) [1]. It is thus pressing to investigate the physics potential of the LHC in this regard. The leading operator relevant for neutrino masses in the context of the SM [2] is $(\kappa/\Lambda) l_L l_L H H$, where l_L and H stand for the $SU(2)_L$ leptonic and Higgs doublet, respectively. After the electroweak symmetry breaking (EWSB), the neutrino Majorana mass reads as $m_\nu \sim \kappa v_0^2/\Lambda$, where $v_0 \approx 246$ GeV. The crucial issue is to understand the origin of this operator in a given extension of the SM in order to identify the dimensionless coupling κ and the mass scale Λ at which the new physics enters.

There exist several simple renormalizable extensions of the SM to generate neutrino Majorana masses and mixing. (i) The simplest one is perhaps the Type I seesaw mechanism [3], where one adds fermionic gauge singlets N. The resulting neutrino mass is given by $m_\nu \propto v_0^2/M_N$. The smallness of $m_\nu \lesssim 1$ eV is thus understood by the "seesaw" spirit if $M_N \gg v_0$. The interests of searching for heavy Majorana neutrinos N at the LHC have been lately renewed [4]. However, it is believed that any signal of N would indicate a more subtle mechanism beyond the simple Type I seesaw due to the naturally small mixing $V_{N\nu}^2 \sim m_\nu/M_N$. (ii) A more appealing mechanism, at least from the phenomenological point of view, is the Type II seesaw mechanism [5]. In this scenario the Higgs sector of the SM is extended by adding an $SU(2)_L$ Higgs triplet, $\Delta \sim (1, 3, 1)$ under the SM gauge groups. After EWSB the neutrino mass is given by $m_\nu \propto Y_\nu v_\Delta$, where Y_ν and v_Δ are the Yukawa coupling and the vacuum expectation value of the triplet, respectively. If the triplet mass is accessible at the LHC, $M_\Delta \lesssim \mathcal{O}(1)$ TeV, then this scenario may lead to very rich phenomenology. Experimentally verifying this mechanism would be of fundamental importance to understand the neutrino mass generation and its connection to the EWSB. For other proposals with exotic leptonic representations or radiative mass generations, see [6].

In this paper, we explore the feasibility to test the Type II seesaw mechanism at the LHC assuming that the Higgs triplet is kinematically accessible. We focus on the exciting possibility to determinate the neutrino spectrum through the lepton violating Higgs decays in the theory. Recently, several groups [7–9] have studied the possibility to distinguish between the neutrino spectra using the predictions for the decays of the doubly charged Higgs. Unfortunately, this method suffers from the dependence on the unknown Majorana phases. Here we point out for the first time that the best way to determinate the neutrino spectrum in this context is through the lepton-number violating decays $H^+ \to e_i^+ \bar{\nu} (i = e, \mu, \tau)$, since those are independent of the unknown Majorana phases. We advocate that the associated production $H^{\pm\pm}H^{\mp}$ is crucial in order to test the triplet nature of the model. With semirealistic Monte Carlo simulations, we demonstrate how to reconstruct the signal events $H^{\pm\pm}H^{\mp} \to e_i^{\pm} e_j^{\pm} e_k^{\mp} \nu$ and suppress the backgrounds up to 1 TeV of the Higgs mass. We also show how to test this theory when the leptonic channels are suppressed. The discovery of the predicted signals at the LHC would provide us crucial information about the neutrino mass and its connection to the electroweak symmetry breaking mechanism.

II. THE TYPE II SEESAW FOR NEUTRINO MASSES

The Higgs sector of the Type II seesaw scenario is composed of the SM Higgs $H(1, 2, 1/2)$ and a scalar triplet $\Delta(1, 3, 1)$. The crucial terms for the neutrino mass generation in the theory are

$$- Y_\nu l_L^T C i\sigma_2 \Delta l_L + \mu H^T i\sigma_2 \Delta^\dagger H + \text{H.c.}, \qquad (1)$$

where the Yukawa coupling Y_ν is a 3×3 complex symmetric matrix. The lepton number is explicitly broken by two units due to the simultaneous presence of the Yukawa coupling Y_ν and the Higgs term proportional to the μ parameter. From the minimization of the scalar potential one finds $v_\Delta = \mu v_0^2/\sqrt{2}M_\Delta^2$. Therefore, the neutrinos acquire a Majorana mass given by

$$M_\nu = \sqrt{2} Y_\nu v_\Delta = Y_\nu \mu v_0^2 / M_\Delta^2. \qquad (2)$$

This equation is the key relation of the Type II seesaw scenario. The neutrino mass is triggered by the EWSB and its smallness is associated with a large mass scale M_Δ. With appropriate choices of the Yukawa matrix elements, one can easily accommodate the neutrino masses and mixing consistent with the experimental observation. For the purpose of illustration, we adopt the values of the masses and mixing at 2σ level from a recent global fit [10].

A. General properties of the Higgs sector

After the EWSB, there are seven massive physical Higgs bosons: $H_1, H_2, A, H^\pm$, and $H^{\pm\pm}$, where H_1 is SM-like and the rest of the Higgs states are Δ-like. Neglecting the Higgs quartic interactions one finds $M_{H_2} \simeq M_A \simeq M_{H^+} \simeq M_{H^{++}} = M_\Delta$. Since we are interested in a mass scale accessible at the LHC, we thus focus on 110 GeV $< M_\Delta <$ 1 TeV, where the lower bound is from direct searches [11]. Working in the physical basis for the fermions we find that the Yukawa interactions can be written as

$$\nu_L^T C \Gamma_+ H^+ e_L \quad \text{and} \quad e_L^T C \Gamma_{++} H^{++} e_L,$$

$$\Gamma_+ = \frac{c_{\theta_+} m_\nu^{\text{diag}} V_{\text{PMNS}}^\dagger}{v_\Delta}, \qquad \Gamma_{++} = \frac{V_{\text{PMNS}}^* m_\nu^{\text{diag}} V_{\text{PMNS}}^\dagger}{\sqrt{2} v_\Delta},$$

where $c_{\theta_+} = \cos\theta_+$, θ_+ is the mixing angle in the charged Higgs sector and $v_\Delta \lesssim 1$ GeV from the ρ-parameter constraints. $V_{\text{PMNS}} = V_l(\theta_{12}, \theta_{23}, \theta_{13}, \delta) \times K_M$ is the leptonic mixing matrix and $K_M = \text{diag}(e^{i\Phi_1/2}, 1, e^{i\Phi_2/2})$ is the Majorana phase factor. The values of the physical couplings Γ_+ and Γ_{++} are thus governed by the spectrum and mixing angles of the neutrinos, and they in turn characterize the branching fractions of the $\Delta L = 2$ Higgs decays. For a previous study of the doubly charged Higgs decays see [12].

The two leading decay modes for the heavy Higgs bosons are the $\Delta L = 2$ leptonic mode and the (longitudinal) gauge boson pair mode. The ratio between them for the H^{++} decay reads as

$$\frac{\Gamma(H^{++} \to \ell^+ \ell^+)}{\Gamma(H^{++} \to W^+ W^+)} \approx \frac{|\Gamma_{++}|^2 v_0^4}{M_\Delta^2 v_\Delta^2} \approx \left(\frac{m_\nu}{M_\Delta}\right)^2 \left(\frac{v_0}{v_\Delta}\right)^4, \qquad (3)$$

using $m_\nu/M_\Delta \sim 1$ eV/1 TeV, one finds that these two decay modes are comparable when $v_\Delta \approx 10^{-4}$ GeV. It is thus clear that for a smaller value of v_Δ (a larger Yukawa coupling), the leptonic modes dominate, while for larger values, the gauge boson modes take over. In the case of the singly charged Higgs, $H^\pm$, there is one additional mode to a heavy quark pair. The ratio between the relevant channels is

$$\frac{\Gamma(H^+ \to t\bar{b})}{\Gamma(H^+ \to W^+ Z)} \approx \frac{3(v_\Delta m_t/v_0^2)^2 M_\Delta}{M_\Delta^3 v_\Delta^2 / 2v_0^4} = 6\left(\frac{m_t}{M_\Delta}\right)^2. \qquad (4)$$

Therefore, the decays $H^+ \to W^+ Z$, $W^+ H_1$ dominate over $t\bar{b}$ for $M_\Delta > 400$ GeV. We present a more detailed discussion elsewhere [13]. In our discussions thus far, we have assumed the mass degeneracy for the Higgs triplet. Even if there is no tree-level mass difference, the SM gauge interactions generate the splitting of the masses via radiative corrections, leading to $\Delta M = M_{H^{++}} - M_{H^+} = 540$ MeV [14]. The transitions between two heavy triplet Higgs bosons via the SM gauge interactions, such as the three-body decays $H^{++} \to H^+ W^{+*}$, $H^+ \to H^0 W^{+*}$ may be sizable if kinematically accessible. We find [13] that these transitions will not have a significant branching ratio unless $\Delta M > 1$ GeV. In fact, our analyses will remain valid as long as H^{++} and H^+ are the lower-lying states in the triplet and they are nearly degenerate. We will thus ignore the mass-splitting effect in the current study.

B. Higgs decays and the neutrino properties

For $v_\Delta < 10^{-4}$ GeV, the dominant channels for the heavy Higgs boson decay are the $\Delta L = 2$ dileptons. In Fig. 1 we show the predictions for the representative decay branching fractions (BR) to flavor diagonal dileptons versus the lightest neutrino mass where the spread in BR values is due to the current errors in the neutrino masses and mixing. Figure 1(a) is for the H^{++} decay to same-sign dileptons in the normal hierarchy (NH) ($\Delta m_{31}^2 > 0$), and Fig. 1(b) for the H^+ decay in the inverted hierarchy (IH) ($\Delta m_{31}^2 < 0$). In accordance with the NH spectrum and the large atmosphere mixing (θ_{23}), the leading channels are $H^{++} \to \tau^+\tau^+$, $\mu^+\mu^+$, and the channel e^+e^+ is much smaller. When the spectrum is inverted, the dominant channel is $H^{++} \to e^+e^+$ instead. Also is seen in Fig. 1(b) the $H^+ \to e^+\bar{\nu}$ dominance in the IH. In the case of NH the dominant channels are $H^+ \to \mu^+\bar{\nu}$ and $H^+ \to \tau^+\bar{\nu}$. In both cases of NH and IH, the off-diagonal channel $H^{++} \to \tau^+\mu^+$ is dominant due to the large mixing. In the limit of quasidegenerate (QD) neutrinos one finds that the three diagonal channels are quite similar, but the off-diagonal channels are suppressed.

The properties of all leptonic decays of the charged Higgs bosons are summarized in Table. I. The effects of the Majorana phases are neglected so far. The Higgs decays are not very sensitive to the phase Φ_2, with a maximal reduction of $H^{++} \to \tau^+\tau^+$, $\mu^+\mu^+$ and enhancement of $\mu^+\tau^+$ up to a factor of 2 in the NH. The phase Φ_1, however, has a dramatic impact on the H^{++} decay in the

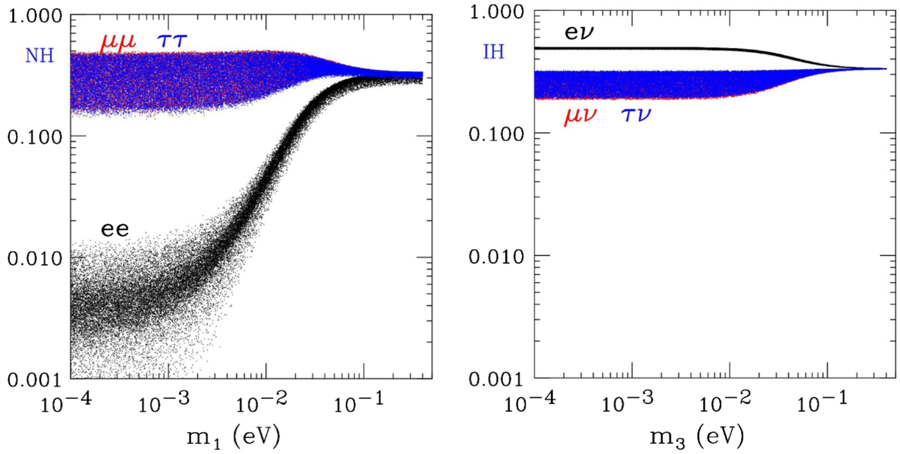

FIG. 1 (color online). Leptonic branching fractions vs the lightest neutrino mass when $\Phi_i = 0$. (a) For H^{++} decay in the NH, and (b) for H^{+} in the IH.

TABLE I. Relations for the $\Delta L = 2$ decays of H^{++}, H^{+} in three different neutrino mass patterns when $\Phi_1 = \Phi_2 = 0$.

Spectrum	Relations
NH	$\mathrm{Br}(\tau^+\tau^+)$, $\mathrm{Br}(\mu^+\mu^+) \gg \mathrm{Br}(e^+e^+)$
$\Delta m^2_{31} > 0$	$\mathrm{Br}(\mu^+\tau^+) \gg \mathrm{Br}(e^+\tau^+)$, $\mathrm{Br}(e^+\mu^+)$
	$\mathrm{Br}(\tau^+\bar{\nu})$, $\mathrm{Br}(\mu^+\bar{\nu}) \gg \mathrm{Br}(e^+\bar{\nu})$
IH	$\mathrm{Br}(e^+e^+) > \mathrm{Br}(\mu^+\mu^+)$, $\mathrm{Br}(\tau^+\tau^+)$
$\Delta m^2_{31} < 0$	$\mathrm{Br}(\mu^+\tau^+) \gg \mathrm{Br}(e^+\tau^+)$, $\mathrm{Br}(e^+\mu^+)$
	$\mathrm{Br}(e^+\bar{\nu}) > \mathrm{Br}(\mu^+\bar{\nu})$, $\mathrm{Br}(\tau^+\bar{\nu})$
QD	$\mathrm{Br}(e^+e^+) \approx \mathrm{Br}(\mu^+\mu^+) \approx \mathrm{Br}(\tau^+\tau^+)$
	$\mathrm{Br}(\mu^+\tau^+) \approx \mathrm{Br}(e^+\tau^+) \approx \mathrm{Br}(e^+\mu^+)$ (suppressed)
	$\mathrm{Br}(e^+\bar{\nu}) \approx \mathrm{Br}(\mu^+\bar{\nu}) \approx \mathrm{Br}(\tau^+\bar{\nu})$

IH. This is shown in Fig. 2. We see that for $\Phi_1 \approx \pi$ the dominant channels switch to $e^+\mu^+$, $e^+\tau^+$ from e^+e^+, $\mu^+\tau^+$ as in the zero phase limit. This provides the best hope to probe the Majorana phase. The decays $H^{\pm} \to e_i^+\bar{\nu}$, on the other hand, are independent of the unknown Majorana phases, leaving the BR predictions robust. Therefore, using the lepton violating decays of the singly charged Higgs one can determinate the neutrino spectrum without any ambiguity. This is one of the main results of our paper.

III. TESTING THE MODEL AT THE LHC

We consider the following production channels:

$$q\bar{q} \to \gamma^*, \quad Z^* \to H^{++}H^{--}, \quad \text{and} \quad q\bar{q}' \to W^* \to H^{\pm\pm}H^{\mp}.$$

The total cross sections versus the mass at the LHC are shown in Fig. 3. The cross sections range in 100–0.1 fb for a mass of 200–1000 GeV, leading to a potentially observable signal with a high luminosity. The associated production $H^{\pm\pm}H^{\mp}$ [15] is crucial to test the triplet nature of $H^{\pm\pm}$ and $H^{\pm}$.

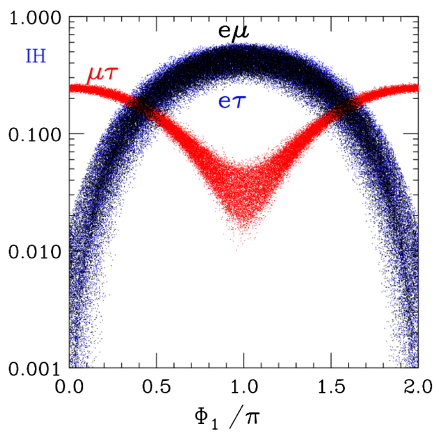

FIG. 2 (color online). Leptonic branching fractions of H^{++} decay versus the Majorana phase Φ_1 in the IH for $m_3 \approx 0$.

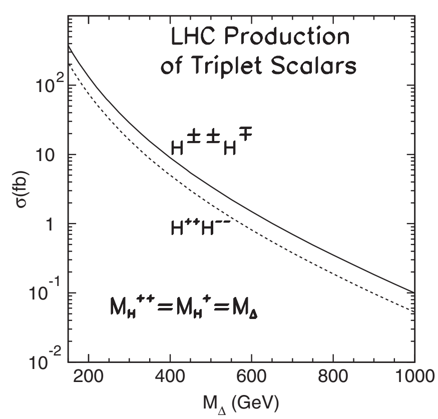

FIG. 3. Total cross sections in units of fb for $pp \to H^{++}H^{--}$ and $H^{\pm\pm}H^{\mp}$ production versus its mass at $\sqrt{s} = 14$ TeV.

A. Purely leptonic modes

For $v_\Delta < 10^{-4}$ GeV, we wish to identify as many channels of leptonic flavor combination as possible to study the neutrino mass pattern. The e's and μ's are experimentally easy to identify, while τ's can be identified via their simple charged tracks (1-prong and 3-prongs). We make use of the important feature that the τ's from the heavy Higgs decays are highly relativistic and the missing neutrinos are collimated along the charged tracks, so that the τ momentum $p(\tau)$ can be reconstructed effectively. In fact, we can reconstruct up to three τ's if we assume the Higgs pair production with equal masses [13]. The fully reconstructible signal events are thus

$$H^{++}H^{--} \to \ell^+\ell^+\ell^-\ell^-, \quad \ell^\pm\ell^\pm\ell^\mp\tau^\mp, \quad \ell^\pm\ell^\pm\tau^\mp\tau^\mp,$$
$$\ell^+\tau^+\ell^-\tau^-, \quad \ell^\pm\tau^\pm\tau^\mp\tau^\mp,$$
$$H^{\pm\pm}H^\mp \to \ell^\pm\ell^\pm\ell^\mp\nu, \quad \ell^\pm\ell^\pm\tau^\mp\nu,$$

where $\ell = e, \mu$. We have performed a full kinematical analysis for those modes, including judicious cuts to separate the backgrounds, energy-momentum smearing to simulate the detector effects, and the $p(\tau)$ and M_Δ reconstruction. We find our kinematical reconstruction procedure highly efficient, with about 50% for $M_\Delta = 200$ GeV and even higher for a heavier mass. With a 300 fb^{-1} luminosity, there will still be several reconstructed events in the leading channels up to $M_\Delta \sim 1$ TeV with negligible backgrounds.

We summarize the leading reconstructible channels and their achievable branching fractions in Table II. The $H^\pm$ decays are robust to determinate the mass pattern since they are independent of the Majorana phases. For more details see [13].

B. Gauge boson and heavy quark modes

For $v_\Delta > 2 \times 10^{-4}$ GeV, the dominant decay modes of the heavy Higgs bosons are the SM gauge bosons. The decay $H^{\pm\pm} \to W^\pm W^\pm$ is governed by v_Δ and $H^\pm \to W^\pm H_1$, $t\bar{b}$ by the mixing μ, and $H^\pm \to W^\pm Z$ by a combination of both. Therefore, systematically studying those channels would provide the evidence of the triplet-doublet mixing and further confirm the seesaw relation $v_\Delta = \mu v_0^2/\sqrt{2}M_\Delta^2$. We have once again performed detailed signal and background analysis at the LHC for those channels. We are able to obtain a 20% signal efficiency and a signal-to-background ratio 1:1 or better. With a 300 fb^{-1} luminosity, we can achieve statistically significant signals up to $M_\Delta \approx 600$ GeV [13].

IV. SUMMARY

The feasibility to test the Type II seesaw mechanism at the LHC has been studied. We first emphasize the importance to observe the associated production $H^{\pm\pm}H^\mp$ to establish the triplet nature of the Higgs field. In the optimistic scenarios, $v_\Delta < 10^{-4}$ GeV, one can test the theory up to $M_\Delta \sim 1$ TeV by identifying the leading decay channels as *either* $H^{++} \to \tau^+\tau^+$, $\mu^+\mu^+$, $\mu^+\tau^+$, $H^+ \to \tau^+\bar{\nu}$ in the normal hierarchy, *or* $H^{++} \to e^+e^+$, $\mu^+\tau^+$, $H^+ \to e^+\bar{\nu}$ in the inverted hierarchy. If the Majorana phases play an important role, then the H^{++} decay channels are much less predictable. Always one can use the $H^\pm$ decays to determinate the neutrino spectrum since those are independent of the Majorana phases. For a special case in the IH, the significant changes in the decay rate of H^{++} with e^+e^+, $\mu^+\tau^+ \leftrightarrow e^+\mu^+$, $e^+\tau^+$ offer the best hope to probe Φ_1. In a less favorable scenario, $v_\Delta > 2 \times 10^{-4}$ GeV, the leptonic channels are suppressed. The decays $H^{\pm\pm} \to W^\pm W^\pm$ indicate the existence of v_Δ, while the decays $H^+ \to t\bar{b}$ and $H^+ \to W^+ H_1$ are due to the mixing between the SM Higgs and the triplet. Statistically significant signals are achievable up to $M_\Delta \approx 600$ GeV. In the most optimistic situation, $v_\Delta \sim 10^{-4}$ GeV, the leptonic and gauge boson channels may be available simultaneously.

TABLE II. Leading fully reconstructible leptonic channels and their achievable branching fractions.

Channels	Modes and BR's (NH)	Modes and BR's (IH)
$H^{++}H^{--}$		
$\Phi_1, \Phi_2 = 0$	$\mu^+\mu^+\mu^-\mu^-(40\%)^2$	$e^+e^+e^-e^-(50\%)^2$
	$\mu^+\mu^+\mu^-\tau^-(40\% \times 35\%)$	$e^+e^+\mu^-\tau^-(50\% \times 25\%)$
	$\mu^+\mu^+\tau^-\tau^-(40\%)^2$	$\mu^+\tau^+\mu^-\tau^-(25\%)^2$
	$\mu^+\tau^+\mu^-\tau^-(35\%)^2$	
	$\mu^+\tau^+\tau^-\tau^-(35\% \times 40\%)$	
$\Phi_1 \approx \pi$	same as above	$ee, \mu\tau \to e\mu, e\tau(50\%)^2$
$\Phi_2 \approx \pi$	$\mu\mu, \tau\tau: \times 1/2, \mu\tau: \times 2$	same as above
$H^{\pm\pm}H^\mp$		
$\Phi_1, \Phi_2 = 0$	$\mu^+\mu^+\mu^-\nu(40\% \times 60\%)$	$e^+e^+e^-\nu(50\%)^2$
	$\mu^+\mu^+\tau^-\nu(40\% \times 60\%)$	
$\Phi_1 \approx \pi$	same as above	$ee \to e\mu, e\tau(60\% \times 50\%)$
$\Phi_2 \approx \pi$	$\mu\mu: \times 1/2$	same as above

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