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Probing Lepton Flavor Triality with Higgs Boson Decay

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Abstract

If neutrino tribimaximal mixing is explained by a non-Abelian discrete symmetry such as A_4, T_7, $\Delta(27)$, etc., the charged-lepton Higgs sector has a Z_3 residual symmetry (lepton flavor triality), which may be observed directly in the decay chain $H^0 \to \psi_2^0 \bar{\psi}_2^0$, then $\psi_2^0(\bar{\psi}_2^0) \to l_i^+ l_j^-$ $(i \neq j)$, where H^0 is a standard-model-like Higgs boson and ψ_2^0 is a scalar particle needed for realizing the original discrete symmetry. If kinematically allowed, this unusual and easily detectable decay is observable at the LHC with 1 fb^{-1} for $E_{\rm cm} = 7$ TeV.

I. INTRODUCTION

In recent years, a theoretical understanding of the observed pattern of neutrino mixing, i.e. the 3×3 matrix $U_{l\nu}$ which links charged-lepton mass eigenstates to neutrino mass eigenstates, has been achieved in terms of non-Abelian discrete symmetries. In particular, the tetrahedral symmetry A_4 [1] has been shown to be successful [2] in explaining tribimaximal mixing [3], i.e.

$$U_{l\nu} = \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & -1/\sqrt{2} \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}, \tag{1}$$

which is very close to what is experimentally observed. However, a specific testable prediction of this idea is so far lacking. Recently, a model based on T_7 and gauged $B-L$ has been shown [4] to be testable at the Large Hadron Collider (LHC), but it depends on observing the Z'_{B-L} gauge boson, which may be too heavy to be produced. In this paper, we show that it is not necessary to extend the gauge symmetry of the standard model (SM). All one needs is to find a standard-model-like Higgs boson H^0 whose decay may reveal the residual Z_3 symmetry, i.e. lepton flavor triality [5], coming from A_4, T_7, $\Delta(27)$, and possibly other non-Abelian discrete symmetries [6]. If kinematically allowed, this unusual and easily detectable decay is predicted to be observable at the LHC and perhaps at the Tevatron as well. Specifically, $H^0 \to \psi_2^0 \bar{\psi}_2^0$ should be searched for, where ψ_2^0 is a light scalar with dominant decays to $\tau^+\mu^-$ and τ^-e^+, resulting thus for example in the easily detectable configuration $H^0 \to (\tau^-e^+)(\tau^-\mu^+)$. (The idea of using the decay of H^0 to two exotic scalars to discover the underlying flavor symmetry has been explored recently [7], using a previously proposed S_3 model [8].)

In Sec. II we reiterate how the notion of lepton triality is realized in the lepton Higgs Yukawa interactions. In Sec. III we analyze the general scalar potential of four Higgs electroweak doublets transforming as an irreducible triplet plus a singlet of A_4, T_7, and $\Delta(27)$. We show that they share a common solution which is useful for proving lepton triality experimentally. In Sec. IV we obtain all the Higgs boson masses in a specific scenario which is also consistent with present phenomenological bounds. In Sec. V we show that the decay $H^0 \to \psi_2\bar{\psi}_2$ has a significant branching fraction for a wide range of m_H values. In Sec. VI we discuss how H^0 itself may be observed through lepton triality at the Large Hadron Collider and its discovery reach. In Sec.VII we have some concluding remarks.

II. CHARGED-LEPTON HIGGS INTERACTIONS

The first thing to notice is that if $L_i = (\nu, l)_i \sim \underline{3}$, $l^c_i \sim \underline{1}_i$, $i = 1, 2, 3$, and $\Phi_i = (\phi^+, \phi^0)_i \sim \underline{3}$ under A_4, T_7, or $\Delta(27)$, the Yukawa couplings $L_i l^c_j \tilde{\Phi}_k$, where $\tilde{\Phi}_k = (\bar{\phi}^0, -\phi^-)_k$, are of the same form, leading to the charged-lepton mass matrix [1]

$$m_l = \begin{pmatrix} y_1 v_1 & y_2 v_1 & y_3 v_1 \\ y_1 v_2 & \omega^2 y_2 v_2 & \omega y_3 v_2 \\ y_1 v_3 & \omega y_2 v_3 & \omega^2 y_3 v_3 \end{pmatrix} = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 1 & 1 \\ 1 & \omega^2 & \omega \\ 1 & \omega & \omega^2 \end{pmatrix} \begin{pmatrix} y_1 & 0 & 0 \\ 0 & y_2 & 0 \\ 0 & 0 & y_3 \end{pmatrix} v, \tag{2}$$

where $\omega = \exp(2\pi i/3) = -1/2 + i\sqrt{3}/2$, and the condition

$$v_1 = v_2 = v_3 = v/\sqrt{3} \tag{3}$$

has been imposed. Note that this condition is not *ad hoc* because it corresponds to a residual Z_3 symmetry and is thus protected against arbitrary corrections. As first shown [2] for A_4, then also recently [4] for T_7, this leads naturally to neutrino tribimaximal mixing, provided that the neutrino mass matrix has a special form, which is realized differently for A_4 and T_7. In either case, as well as that of $\Delta(27)$, the charged-lepton Higgs interactions are completely fixed to be the following:

$$\begin{aligned} \mathcal{L}_{int} &= v^{-1}[m_\tau \bar{L}_\tau \tau_R + m_\mu \bar{L}_\mu \mu_R + m_e \bar{L}_e e_R]\phi_0 \\ &+ v^{-1}[m_\tau \bar{L}_\mu \tau_R + m_\mu \bar{L}_e \mu_R + m_e \bar{L}_\tau e_R]\phi_1 \\ &+ v^{-1}[m_\tau \bar{L}_e \tau_R + m_\mu \bar{L}_\tau \mu_R + m_e \bar{L}_\mu e_R]\phi_2 + H.c., \end{aligned} \tag{4}$$

where $v = \langle \phi^0_0 \rangle$ and

$$\begin{pmatrix} \Phi_1 \\ \Phi_2 \\ \Phi_3 \end{pmatrix} = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 1 & 1 \\ 1 & \omega^2 & \omega \\ 1 & \omega & \omega^2 \end{pmatrix} \begin{pmatrix} \phi_0 \\ \phi_1 \\ \phi_2 \end{pmatrix}, \tag{5}$$

displaying thus explicitly the important residual Z_3 symmetry, i.e. lepton triality [5], under which

$$e,\ \mu,\ \tau \sim 1,\ \omega^2,\ \omega, \qquad \phi_{0,1,2} \sim 1,\ \omega,\ \omega^2. \tag{6}$$

Whereas $\phi^\pm_{1,2}$ are degenerate in mass, the $\phi^0_{1,2}(\bar{\phi}^0_{1,2})$ sector is more complicated. As already shown [9], the mass eigenstates here are not $\phi^0_{1,2}$ but rather

$$\psi^0_{1,2} = \frac{1}{\sqrt{2}}(\phi^0_1 \pm \bar{\phi}^0_2), \tag{7}$$

with different masses $m_{1,2}$. Note that $\phi_1^0 \sim \omega$ and $\phi_2^0 \sim \omega^2$, hence $\psi_{1,2}^0 \sim \omega$ and $\bar{\psi}_{1,2}^0 \sim \omega^2$. As a result of lepton triality, the rare decay $l_1^+ \to l_2^+ l_3^+ l_4^-$ allows only two possibilities [5]

$$\tau^+ \to \mu^+\mu^+e^-, \quad \tau^+ \to e^+e^+\mu^-, \tag{8}$$

and the radiative decay $l_1 \to l_2\gamma$ is not allowed. The present experimental upper limit of the branching fraction of $\tau^+ \to \mu^+\mu^+e^-$ is 2.3×10^{-8}, implying thus only the bound

$$\frac{m_1 m_2}{\sqrt{m_1^2 + m_2^2}} > 22 \text{ GeV} \left(\frac{174 \text{ GeV}}{v}\right). \tag{9}$$

On the other hand, the Z gauge boson couples to $\psi_1^0\bar{\psi}_2^0 + \psi_2^0\bar{\psi}_1^0$, i.e. the analog of AH in the two-Higgs-doublet model, hence the condition

$$m_1 + m_2 > 209 \text{ GeV} \tag{10}$$

also applies. Otherwise, $e^+e^- \to Z \to \psi_1^0\bar{\psi}_2^0 + \psi_2^0\bar{\psi}_1^0$ would have been detected at LEPII which reached a peak energy of 209 GeV. In the following, we will show in detail how m_2 may be small enough, say 50 GeV, so that $m_H > 2m_2$ and H^0 will decay into $\psi_2^0\bar{\psi}_2^0$ and be observed.

III. HIGGS STRUCTURE IN A_4, T_7, AND $\Delta(27)$

For each of the three non-Abelian discrete symmetries A_4, T_7 and $\Delta(27)$, there are four Higgs doublets to be considered: $\eta \sim \underline{1}_1$ and $\Phi_{1,2,3} \sim \underline{3}$. We assume that quarks are all singlets, so they couple only to η, whereas leptons transform nontrivially and couple to Φ_i, as already discussed. The quartic scalar potential of n Higgs doublets has in general $n^2(n^2+1)/2$ terms. For $n = 4$, without any symmetry, there would be 136 terms. However, there are only 10, 7, and 8 terms respectively for A_4, T_7, and $\Delta(27)$. We will show that a common solution exists for all 3 cases, involving only 5 quartic couplings, which will provide us with the desirable scenario of observable $H^0 \to \psi_2^0\bar{\psi}_2^0$ decay.

Consider the following quartic Higgs potential:

$$\begin{aligned} V_4 &= \frac{1}{2}\lambda_0(\eta^\dagger\eta)^2 + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1 + \Phi_2^\dagger\Phi_2 + \Phi_3^\dagger\Phi_3)^2 \\ &+ \lambda_2|\Phi_1^\dagger\Phi_1 + \omega\Phi_2^\dagger\Phi_2 + \omega^2\Phi_3^\dagger\Phi_3|^2 + \lambda_3(|\Phi_1^\dagger\Phi_2|^2 + |\Phi_2^\dagger\Phi_3|^2 + |\Phi_3^\dagger\Phi_1|^2) \\ &+ \frac{1}{2}\lambda_4[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_3)^2 + (\Phi_3^\dagger\Phi_1)^2] + H.c. + \lambda_5|\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_3 + \Phi_3^\dagger\Phi_1|^2 \end{aligned}$$

$$
\begin{aligned}
&+ \; \lambda_6|\Phi_1^\dagger\Phi_2 + \omega\Phi_2^\dagger\Phi_3 + \omega^2\Phi_3^\dagger\Phi_1|^2 + \lambda_7|\Phi_1^\dagger\Phi_2 + \omega^2\Phi_2^\dagger\Phi_3 + \omega\Phi_3^\dagger\Phi_1|^2 \\
&+ \; f_1(\eta^\dagger\eta)(\Phi_1^\dagger\Phi_1 + \Phi_2^\dagger\Phi_2 + \Phi_3^\dagger\Phi_3) + f_2(|\eta^\dagger\Phi_1|^2 + |\eta^\dagger\Phi_2|^2 + |\eta^\dagger\Phi_3|^2) \\
&+ \; f_3[(\eta^\dagger\Phi_1)(\Phi_2^\dagger\Phi_1) + (\eta^\dagger\Phi_2)(\Phi_3^\dagger\Phi_2) + (\eta^\dagger\Phi_3)(\Phi_1^\dagger\Phi_3)] + H.c. \\
&+ \; \frac{1}{2}f_4[(\eta^\dagger\Phi_1)^2 + (\eta^\dagger\Phi_2)^2 + (\eta^\dagger\Phi_3)^2] + H.c. \\
&+ \; f_5[(\eta^\dagger\Phi_1)(\Phi_2^\dagger\Phi_3) + (\eta^\dagger\Phi_2)(\Phi_3^\dagger\Phi_1) + (\eta^\dagger\Phi_3)(\Phi_1^\dagger\Phi_2)] + H.c. \\
&+ \; f_6[(\eta^\dagger\Phi_1)(\Phi_3^\dagger\Phi_2) + (\eta^\dagger\Phi_2)(\Phi_1^\dagger\Phi_3) + (\eta^\dagger\Phi_3)(\Phi_2^\dagger\Phi_1)] + H.c. \qquad (11)
\end{aligned}
$$

For A_4, $\lambda_5 = \lambda_6 = \lambda_7 = f_3 = 0$. For T_7, $\lambda_4 = \lambda_5 = \lambda_6 = \lambda_7 = f_4 = f_5 = f_6 = 0$. For $\Delta(27)$, $\lambda_3 = \lambda_4 = f_3 = f_4 = f_5 = f_6 = 0$. The common terms are then $\lambda_{0,1,2}$ and $f_{1,2}$. However, there is an identity, i.e. $\lambda_5 = \lambda_6 = \lambda_7$ for $\Delta(27)$ is equivalent to having the λ_3 term in A_4 and T_7. Hence we can look for a desirable solution applicable to all three with nonzero values of $\lambda_{0,1,2,3}$ and $f_{1,2}$. It turns out that $f_2 = 0$ may also be assumed for simplicity, so our following analysis involves only five quartic couplings. Of course, this may not be the true structure of the correct (and presumably much more complicated) model of lepton flavor symmetry, but it is a starting point to demonstrate phenomenologically that this idea can be tested experimentally.

We now rotate to the $\phi_{0,1,2}$ basis using Eq. (5), anticipating the breaking of A_4, T_7 or $\Delta(27)$ into Z_3 with $\langle\phi_0^0\rangle \neq 0$, but $\langle\phi_1^0\rangle = \langle\phi_2^0\rangle = 0$.

$$
\begin{aligned}
V_4 \;=\; & \frac{1}{2}\lambda_0(\eta^\dagger\eta)^2 + \frac{1}{2}\lambda_1(\phi_0^\dagger\phi_0 + \phi_1^\dagger\phi_1 + \phi_2^\dagger\phi_2)^2 \\
&+ \; \lambda_2|\phi_0^\dagger\phi_1 + \phi_1^\dagger\phi_2 + \phi_2^\dagger\phi_0|^2 + \frac{1}{3}\lambda_3(|\phi_0^\dagger\phi_0 + \omega\phi_1^\dagger\phi_1 + \omega^2\phi_2^\dagger\phi_2|^2 \\
&+ \; |\phi_0^\dagger\phi_1 + \omega\phi_1^\dagger\phi_2 + \omega^2\phi_2^\dagger\phi_0|^2 + |\phi_0^\dagger\phi_1 + \omega^2\phi_1^\dagger\phi_2 + \omega\phi_2^\dagger\phi_0|^2) \\
&+ \; f_1(\eta^\dagger\eta)(\phi_0^\dagger\phi_0 + \phi_1^\dagger\phi_1 + \phi_2^\dagger\phi_2). \qquad (12)
\end{aligned}
$$

To this we add the bilinear terms which break A_4, T_7, or $\Delta(27)$, but preserve Z_3.

$$
V_2 \;=\; m_0^2(\eta^\dagger\eta) + \mu_0^2(\phi_0^\dagger\phi_0) + \mu_1^2(\phi_1^\dagger\phi_1) + \mu_2^2(\phi_2^\dagger\phi_2) + m_{12}^2(\eta^\dagger\phi_0) + H.c. \qquad (13)
$$

We note that the non-Abelian discrete symmetry is assumed to be broken both spontaneously and explicitly by soft terms. Without the latter, unwanted massless Goldstone bosons may appear and severe constraints on the physical masses of the Higgs bosons may result, as discussed in two recent studies [10, 11], where A_4 only is considered. We now extract the masses of all the physical scalar particles and show that our desired scenario is indeed possible for a wide range of parameters.

IV. HIGGS BOSON MASSES

Let $\langle\eta^0\rangle = v\cos\beta$ and $\langle\phi_0^0\rangle = v\sin\beta$, where $v = (2\sqrt{2}G_F)^{-1/2} = 174$ GeV, then the two stability conditions for the minimum of $V_2 + V_4$ are given by

$$0 = m_0^2 + m_{12}^2\tan\beta + \lambda_0 v^2\cos^2\beta + f_1 v^2\sin^2\beta, \tag{14}$$

$$0 = \mu_0^2 + m_{12}^2\cot\beta + [\lambda_1 + (2/3)\lambda_3]v^2\sin^2\beta + f_1 v^2\cos^2\beta, \tag{15}$$

The masses of the five physical Higgs bosons in this sector are given by

$$m^2(H^\pm) = m^2(A) = \frac{-m_{12}^2}{\sin\beta\cos\beta}, \tag{16}$$

$$m^2(H^0, h^0) = \begin{pmatrix} -m_{12}^2\tan\beta + 2\lambda_0 v^2\cos^2\beta & m_{12}^2 + 2f_1 v^2\sin\beta\cos\beta \\ m_{12}^2 + 2f_1 v^2\sin\beta\cos\beta & -m_{12}^2\cot\beta + 2[\lambda_1 + (2/3)\lambda_3]v^2\sin^2\beta \end{pmatrix}. \tag{17}$$

For simplicity, we will assume

$$2f_1 v^2 = \frac{-m_{12}^2}{\sin\beta\cos\beta}, \tag{18}$$

so that H^0 does not mix with h^0. We will also assume $\sin\beta = \cos\beta = 1/\sqrt{2}$, then the masses become

$$m^2(H^\pm) = m^2(A) = 2f_1 v^2, \quad m^2(H^0) = (\lambda_0 + f_1)v^2, \quad m^2(h^0) = \left(\lambda_1 + \frac{2}{3}\lambda_3 + f_1\right)v^2. \tag{19}$$

Since $H^0 = \sqrt{2}Re(\eta)$, it will couple to quarks as in the standard model, except for the enhanced Yukawa coupling by the factor $1/\cos\beta = \sqrt{2}$. This allows it to be produced by the usual one-loop gluon-gluon process at the LHC [12].

In the $\phi_{1,2}$ sector, we will make another simplifying assumption, i.e. $\mu_1^2 = \mu_2^2 = \mu_{12}^2$. Then their masses are given by

$$m^2(\phi_{1,2}^\pm) = \mu_{12}^2 + \left(\frac{1}{2}\lambda_1 - \frac{1}{6}\lambda_3 + \frac{1}{2}f_1\right)v^2, \tag{20}$$

$$m^2(\psi_1^0) = \mu_{12}^2 + \left(\frac{1}{2}\lambda_1 + \lambda_2 + \frac{1}{2}f_1\right)v^2, \tag{21}$$

$$m^2(\psi_2^0) = \mu_{12}^2 + \left(\frac{1}{2}\lambda_1 + \frac{1}{3}\lambda_3 + \frac{1}{2}f_1\right)v^2. \tag{22}$$

Since H^+H^-, AH^0, Ah^0, $\phi_{1,2}^+\phi_{1,2}^-$, and $\psi_{1,2}^0\bar{\psi}_{2,1}^0$ all couple to the Z, their nonobservation at LEPII implies

$$\sqrt{2f_1}v > 104.5 \text{ GeV}, \tag{23}$$

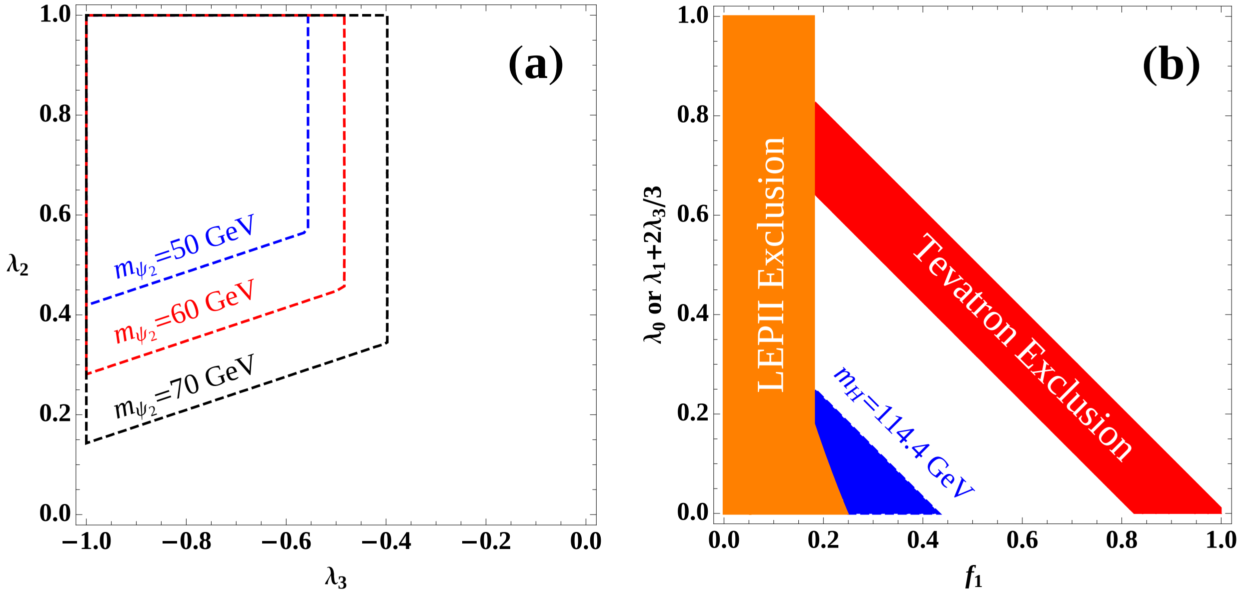

FIG. 1: (a) Allowed region in the plane of λ_2 and λ_3 for $m_{\psi_2} = (50, 60, 70)$ GeV where the region inside each dashed box is allowed. (b) Allowed region in the plane of λ_0 (or $\lambda_1 + (2/3)\lambda_3$) and f_1 where the shaded regions are ruled out by several experiments as explained in the text.

$$(\sqrt{2f_1} + \sqrt{\lambda_0 + f_1})v > 209 \text{ GeV}, \tag{24}$$

$$(\sqrt{2f_1} + \sqrt{\lambda_1 + (2/3)\lambda_3 + f_1})v > 209 \text{ GeV}, \tag{25}$$

$$-\frac{1}{2}\lambda_3 v^2 = m^2(\phi^\pm_{1,2}) - m^2(\psi^0_2) > (104.5 \text{ GeV})^2 - m^2(\psi^0_2), \tag{26}$$

$$\left(\lambda_2 - \frac{1}{3}\lambda_3\right) v^2 = m^2(\psi^0_1) - m^2(\psi^0_2) > (209 \text{ GeV})(209 \text{ GeV} - 2m(\psi^0_2)). \tag{27}$$

In Fig. 1, we show the allowed region of values for λ_2 and $-\lambda_3$, for $m_{\psi_2} = 50, 60, 70$ GeV. We show also the allowed region of values for either λ_0 or $\lambda_1 + (2/3)\lambda_3$ and f_1. The constraints coming from the nonobservation of the standard-model Higgs boson at LEPII, i.e.

$$m_{H,h} > 114.4 \text{ GeV}, \tag{28}$$

as well as the Tevatron exclusion, i.e. [13]

$$158 \text{ GeV} < m_{H,h} < 175 \text{ GeV}, \tag{29}$$

are also shown. It is clear that there is a wide range of parameter space for our desired scenario. It should of course be added that the analysis which obtained these bounds are

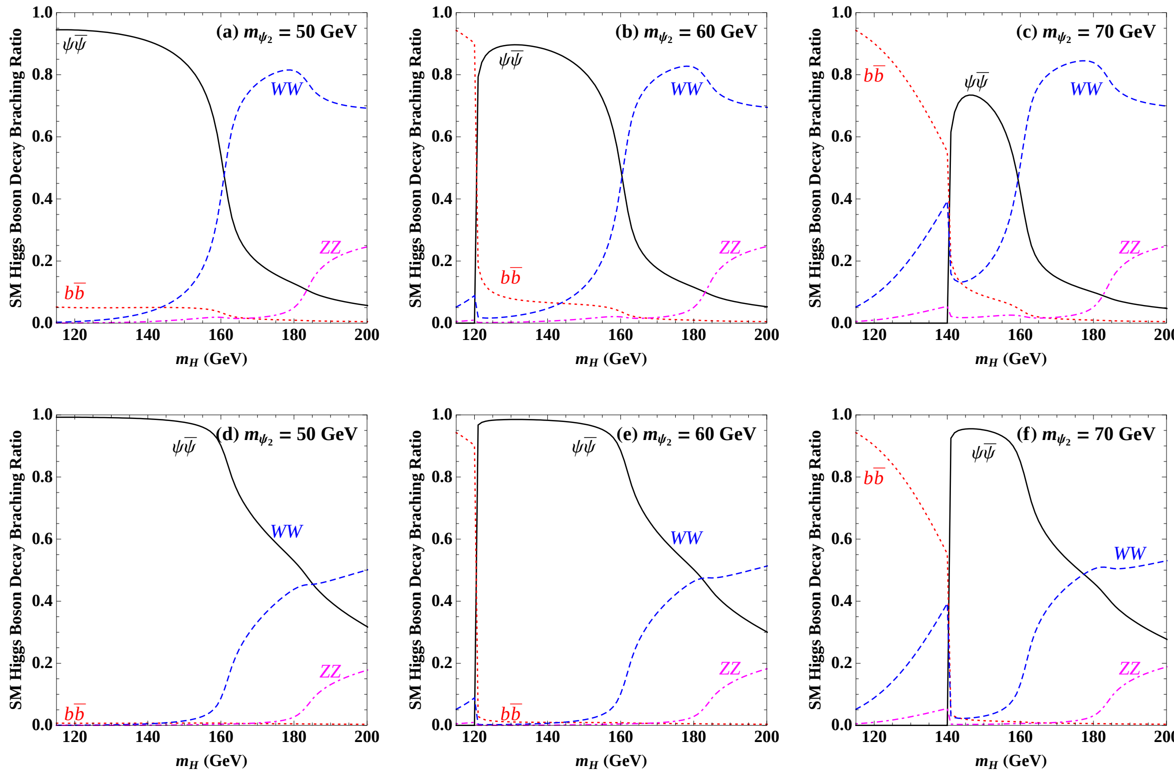

FIG. 2: Decay branching fractions of the Higgs boson H^0 as a function of m_H for $m_\psi = 50$, 60, 70 GeV with $f_1 = 0.18$ (a,b,c) and $f_1 = 0.5$ (d,e,f).

based on the SM. Here, H^0 has other decay modes, so these bounds are not necessarily obeyed. Thus Fig. 1 is merely an illustration that the allowed parameter space for this model is not closed.

V. HIGGS BOSON H^0 DECAY BRANCHING FRACTIONS

The production of H^0 is similar to that of the standard-model Higgs boson. Since it couples to quarks (in particular the t quark) with $\sqrt{2}$ times the standard-model coupling, the gluon-gluon production of H^0 has 2 times the expected cross section. Once produced, it will decay into the usual channels, such as $b\bar{b}$, W^-W^+, ZZ, etc. However, the $H^0 \to \psi_2^0 \bar{\psi}_2^0$ decay rate is substantial if kinematically allowed. Its coupling is $f_1 v$, hence

$$\Gamma_\psi = \frac{f_1^2 v^2}{16\pi m_H}\sqrt{1 - \frac{4m_{\psi_2}^2}{m_H^2}}, \tag{30}$$

TABLE I: Total width of H^0 and its decay branching ratio to $\psi_2^0\bar{\psi}_2^0$ for $f_1 = 0.18$ and 0.5.

m_H	$f_1 = 0.18$						$f_1 = 0.5$					
(GeV)	$m_{\psi_2} = 50$ GeV		$m_{\psi_2} = 60$ GeV		$m_{\psi_2} = 70$ GeV		$m_{\psi_2} = 50$ GeV		$m_{\psi_2} = 60$ GeV		$m_{\psi_2} = 70$ GeV	
	Γ	Br	Γ	Br	Γ	Br	Γ	Br	Γ	Br	Γ	Br
110	0.080	0.942	0.005	0.000	0.005	0.000	0.588	0.996	0.005	0.000	0.005	0.000
150	0.118	0.841	0.099	0.810	0.067	0.718	0.784	0.988	0.635	0.985	0.388	0.975
200	1.516	0.057	1.509	0.053	1.500	0.048	2.096	0.478	2.045	0.462	1.979	0.431
250	4.123	0.018	4.120	0.017	4.116	0.016	4.614	0.219	4.590	0.210	4.560	0.200
300	8.571	0.007	8.569	0.007	8.567	0.007	8.993	0.102	8.979	0.099	8.963	0.096

whereas below (and above) threshold, there is also a contribution from the virtual decay of ψ_2 or $\bar{\psi}_2$ to leptons, with a three-body decay rate given by

$$\Gamma_{\psi*} = \frac{f_1^2 m_\tau^2}{64\pi^3 m_H} \int_{2r-1}^{r^2} \frac{dy(r^2 - y)\sqrt{(1+y)^2 - 4r^2}}{y^2 + r^4\Gamma_2^2/m_{\psi_2}^2}, \tag{31}$$

where $r = m_{\psi_2}/m_H$ and

$$\Gamma_2 = \frac{m_\tau^2 m_{\psi_2}}{8\pi v^2} \tag{32}$$

is the decay width of ψ_2. However, this 3-body contribution is very small and can be safely neglected. The other non-negligible decay modes are as in the SM for $H^0 \to WW, ZZ$ and 2 times as large for $H^0 \to b\bar{b}$. We plot in Fig. 2 the branching fraction of $H^0 \to \psi_2\bar{\psi}_2$ as a function of m_H from 115 to 200 GeV for $m_2 = 50$, 60, 70 GeV, using the minimum value of $f_1 = 0.18$ from Eq. (23), and also $f_1 = 0.5$. In Table I we list the total widths (Γ) of H^0 as well as its branching ratios (Br) to $\psi_2\bar{\psi}_2$ for five values of m_H using $f_1 = 0.18$ and 0.5. We see that $H^0 \to \psi_2\bar{\psi}_2$ is easily observable in a wide range of m_H values for $f_1 = 0.18$ and much better for $f_1 = 0.5$. Once ψ_2^0 and $\bar{\psi}_2^0$ are produced, ψ_2^0 will decay equally into $\tau^+\mu^-$ and τ^-e^+ according to Eq. (4), and $\bar{\psi}_2^0$ into $\tau^-\mu^+$ and τ^+e^-. Thus 25% of the events will be $(\tau^-\mu^+)(\tau^-e^+)$, an unmistakable signature at the LHC. It also has much less background than $b\bar{b}$, which is a serious obstacle to the detection of the standard-model Higgs boson at a hadron collider, but not in our scenario.

VI. COLLIDER PHENOMENOLOGY AT 7 TEV

A. Discovery potential

We now study in detail the process $gg \to H^0 \to \psi_2\bar{\psi}_2$ with the subsequent decay $\psi_2 \to \tau^- e^+$ and $\bar{\psi}_2 \to \tau^-\mu^+$ at the LHC with $E_{\rm cm} = 7$ TeV. The collider signature of interest is

$$e^+\mu^+\ell^-\ell^- + \not{E}_T, \tag{33}$$

where $\ell = e, \mu$ and the missing transverse energy ($\not{E}_T$) originates from the unobserved neutrinos from the two τ decays. The dominant backgrounds yielding the same signature are the processes (generated by MadEvent/MadGraph [14]):

$$\begin{aligned} ZZ &: pp \to ZZ, Z \to \ell^+\ell^-, Z \to \tau^+\tau^-, \tau^\pm \to \ell^\pm\nu\bar{\nu} \\ WWZ &: pp \to W^+W^-Z, W^\pm \to \ell^\pm\nu, Z \to \ell^+\ell^-, \\ t\bar{t} &: pp \to t\bar{t} \to b(\to \ell^-)\bar{b}(\to \ell^+)W^+W^-, W^\pm \to \ell^\pm\nu, \\ Zb\bar{b} &: pp \to Zb(\to \ell^-)\bar{b}(\to \ell^+), Z \to \ell^+\ell^-. \end{aligned}$$

We require no jet tagging and focus on only events with both e^+ and μ^+ in the final state. The first two processes are the irreducible background, while the last two are reducible as they only contribute when some observable particles escape detection, carrying away small transverse momentum (p_T) or falling out of the detector rapidity coverage.

In our analysis, all events are required to pass the following basic acceptance cuts:

$$\begin{aligned} &n_\ell = 4, \qquad n_{e^+} = 1, \qquad n_{\mu^+} = 1, \qquad n_{\ell^-} = 2 \\ &p_T(e^+, \mu^+) > 15 \text{ GeV}, \quad p_T(\ell^-) > 10 \text{ GeV}, \quad \not{E}_T > 15 \text{ GeV}, \\ &|\eta_\ell| < 2.5, \quad \Delta R_{\ell\ell'} \geq 0.4, \end{aligned} \tag{34}$$

where ΔR_{ij} is the separation in the plane spanned by the azimuthal angle (ϕ) and the pseudorapidity (η) between i and j, defined as

$$\Delta R_{ij} \equiv \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}. \tag{35}$$

We also model detector resolution effects by smearing the final-state lepton energies using

$$\frac{\delta E}{E} = \frac{10\%}{\sqrt{E/\text{GeV}}} \oplus 0.7\%. \tag{36}$$

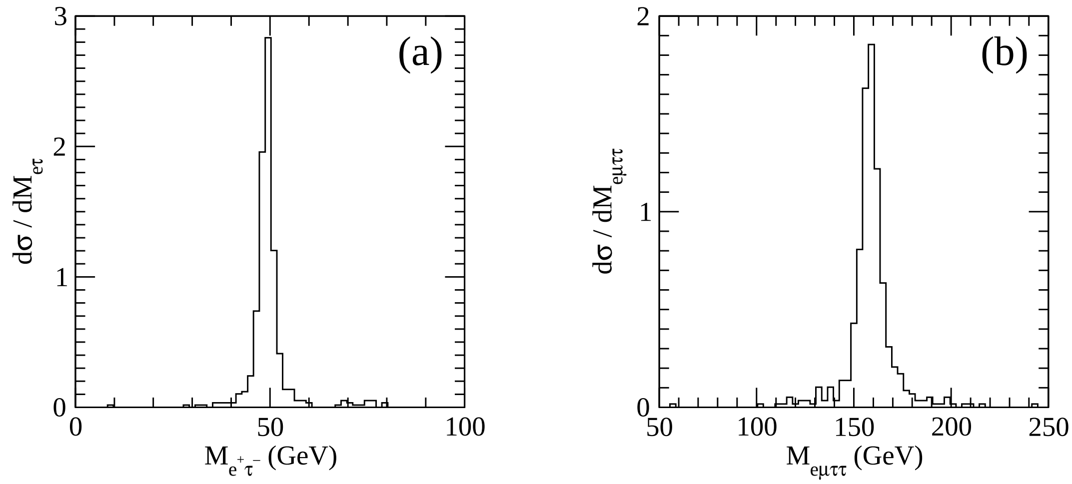

FIG. 3: (a) Reconstructed m_{ψ_2} from $e^+\tau^-$ and (b) m_H from $e^+\mu^+\tau^-\tau^-$ for $m_{\psi_2} = 50$ GeV and $m_H = 160$ GeV.

Note that a soft cut is imposed on the negatively charged leptons because they originate from τ decay. Since the Higgs boson decays predominantly into the $\psi_2\bar{\psi}_2$ pair only just above the threshold region, these scalars are not boosted. The leptons from their decays would then exhibit only small p_T. The charged lepton from the subsequent τ decay becomes even softer.

To reconstruct the scalar ψ, we adopt the collinear approximation that the charged lepton and neutrinos from τ decays are parallel due to the large boost of the τ. Such a condition is satisfied to an excellent degree because the τ leptons originate from a heavy scalar decay in the signal event. Denoting by x_{τ_i} the fraction of the parent τ energy which each observable decay particle carries, the transverse momentum vectors are related by [15]

$$\vec{\not{E}}_T = \left(\frac{1}{x_{\tau_1}} - 1\right)\vec{p}_1 + \left(\frac{1}{x_{\tau_2}} - 1\right)\vec{p}_2. \tag{37}$$

When the decay products are not back-to-back, Eq. (37) gives two conditions for x_{τ_i} with the τ momenta as $\vec{p}_1/x_{\tau_1}$ and $\vec{p}_2/x_{\tau_2}$, respectively. We further require the calculated x_{τ_i} to be positive to remove the unphysical solutions. There are two possible combinations of $e^+\ell^-$ clusters for reconstructing the scalar ψ and Higgs boson. To choose the correct combination, we require the $e^+\ell^-$ pairing to be such that $\Delta R_{e^+\ell^-}$ is minimized. The mass spectra of the reconstructed ψ and Higgs boson are plotted in Fig. 3(a) and (b), respectively, which clearly display sharp peaks around m_ψ and m_H.

TABLE II: Cross sections (fb) of signal and SM backgrounds before and after cuts, using $f_1 = 0.5$, for five values of m_H (GeV) and three values of ψ_2 mass (m_{ψ_2}) after the restriction to $e^+\mu^+\ell^-\ell^-$ and with tagging efficiencies included.

m_H	$m_{\psi_2} = 50\,\text{GeV}$			$m_{\psi_2} = 60\,\text{GeV}$			$m_{\psi_2} = 70\,\text{GeV}$			SM backgrounds			
(GeV)	no cut	basic	$x_i > 0$	no cut	basic	$x_i > 0$	no cut	basic	$x_i > 0$		no cut	basic	$x_i > 0$
110	428.3	11.99	11.91	3.71	0.26	0.25	0.80	0.09	0.09	$t\bar{t}$	0.21	0.14	0.04
150	216.4	8.22	8.18	216.47	13.51	13.42	214.1	21.46	21.33	ZZ	10.14	0.12	0.09
200	54.09	4.65	4.60	52.23	4.94	4.87	47.98	5.99	5.94	$Zb\bar{b}$	0.83	0.13	0.06
250	14.82	2.17	2.13	14.37	2.17	2.14	13.81	2.38	2.35	WWZ	0.06	0.03	0.01
300	4.90	0.92	0.90	4.70	0.92	0.90	4.46	0.93	0.92				

In Table II we show the signal and background cross sections (in fb units) before and after our cuts, with $f_1 = 0.5$, for ten values of m_H and three values of m_ψ. Due to the narrow-width approximation, the signal process can be factorized, i.e. as the simple product of the production of H and its decay as follows:

$$\sigma(gg \to H \to \psi_2\bar{\psi}_2) = \sigma(gg \to H) \times \text{Br}(H \to \psi_2\bar{\psi}_2), \tag{38}$$

where

$$\text{Br}(H \to \psi_2\bar{\psi}_2) \approx \frac{\Gamma_{\psi_2}}{\Gamma_{\psi_2} + \Gamma_{\text{SM}}}. \tag{39}$$

Since $\Gamma_{\psi_2} \propto f_1^2$, one can extract the corresponding signal cross section for values of f_1 other than 0.5 (those displayed in Teble I) easily from Tables I and II and Eq. 30.

In Fig. 4 we display the discovery potential of the signal process in the plane of f_1 and m_H as well as m_H and m_{ψ_2} at the LHC for $E_{\text{cm}} = 7$ TeV with an integrated luminosity of 1 fb^{-1}. Since there is no background after all cuts, one can claim a 5σ discovery once 5 signal events are observed.

B. Impact on the SM Higgs search in WW mode

The cross section of H production via gluon-gluon fusion is doubled because the Yukawa coupling of H to the top quark is enhanced by a factor of $\sqrt{2}$. Below we explore the impact of the new decay channel $H \to \psi_2\bar{\psi}_2$ on the SM Higgs boson search. In Ref. [16] the SM

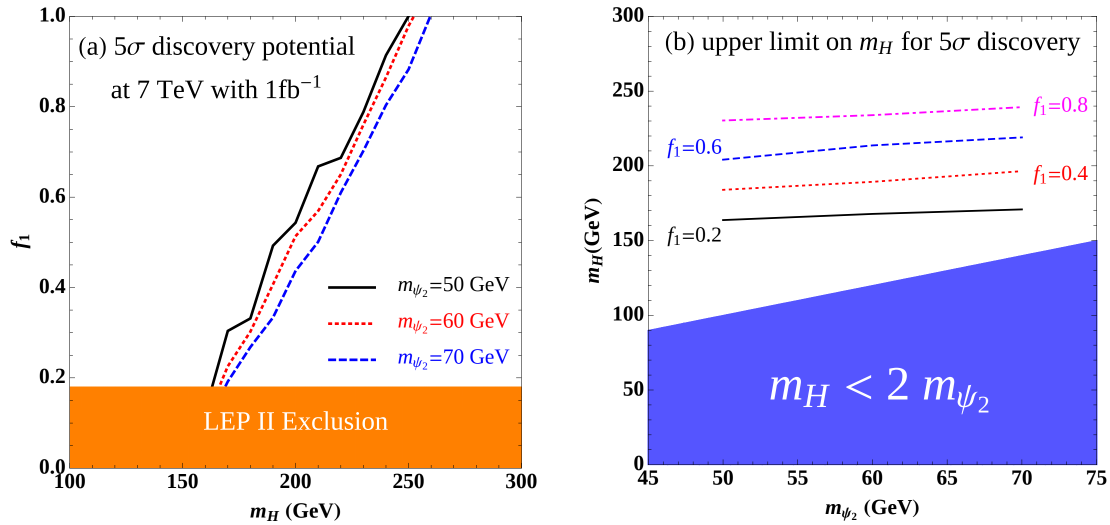

FIG. 4: Discovery potential of signal (a) in the plane of f_1 and m_H where the region above each curve is good for a 5σ discovery, and (b) in the plane of m_H and m_{ψ_2}.

Higgs discovery potential at 7 TeV in the WW mode was studied in detail. Compared to that, the discovery potential of H in our model can be extracted easily via the following relation:

$$\frac{\mathcal{S}}{\mathcal{S}_{SM}} = \frac{\sigma(gg \to H) \times \mathrm{Br}(H \to WW)}{\sigma(gg \to H)_{SM} \times \mathrm{Br}(H \to WW)_{SM}} = 2 \times \frac{\Gamma_{\mathrm{SM}}}{\Gamma_{\mathrm{SM}} + \Gamma(H \to \psi_2 \bar{\psi}_2)}. \tag{40}$$

In Fig. 5 we display the discovery significance $S/\sqrt{B}$ at 7 TeV with an integrated luminosity of 1 fb^{-1} for the ATLAS (a) and CMS (b) detectors with $f_1 = 0.2$ and also with $f_1 = 0.5$ for ATLAS (c) and CMS (d). If the $\psi_2\bar{\psi}_2$ mode is forbidden by kinematics, i.e. $m_H < 2m_{\psi_2}$, the SM Higgs search in the WW mode is unaffected. However, once the $\psi_2\bar{\psi}_2$ channel is open, the discovery potential of the SM Higgs boson in the WW mode is significantly lowered. For large values of f_1, the WW mode is so much suppressed that it will be difficult to discover H in this conventional way.

VII. CONCLUSION

We have shown that the routine search of the standard-model Higgs boson at the LHC may reveal more than just the standard model. It may show evidence of the underlying Z_3

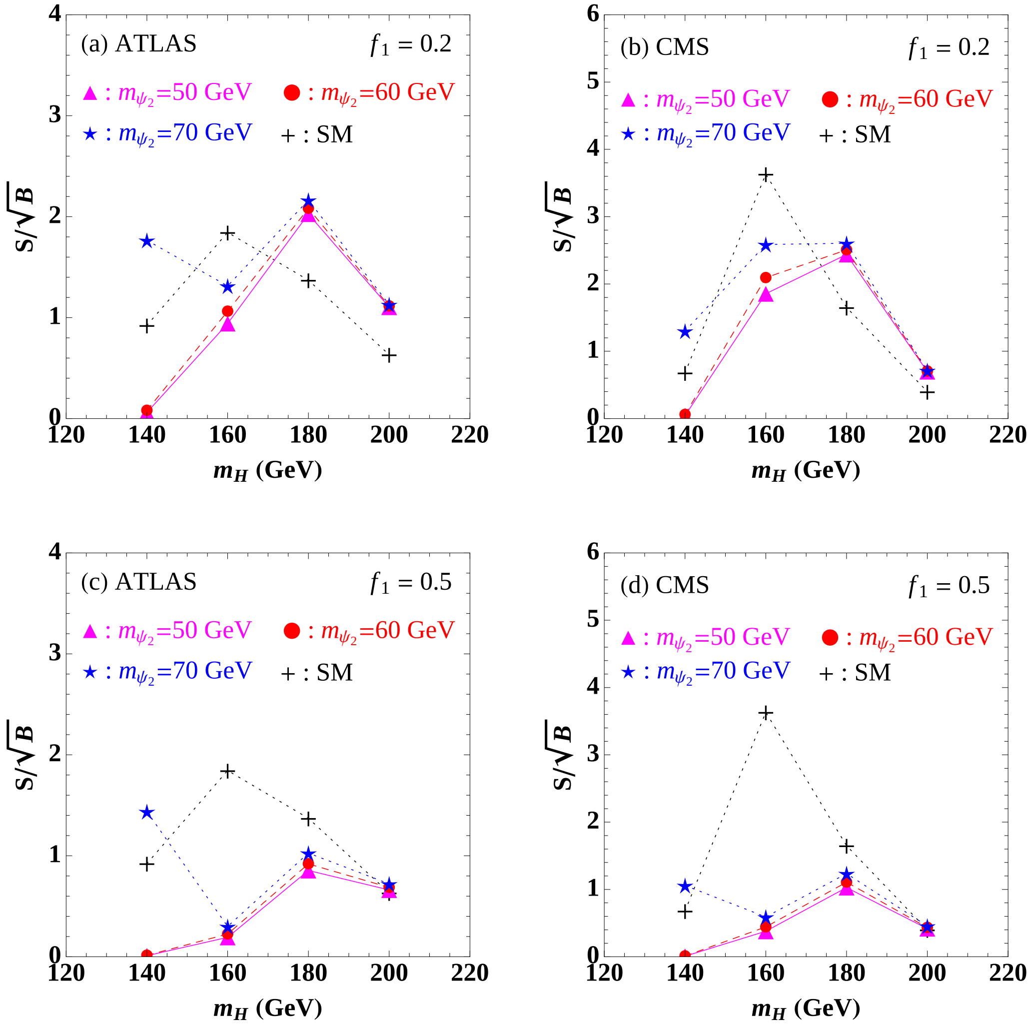

FIG. 5: Discovery potential of H compared to the SM Higgs boson in the WW mode at 7 TeV with an integrated luminosity of 1 fb^{-1}: (a) ATLAS and (b) CMS for $f_1 = 02$; (c) ATLAS and (d) CMS for $f_1 = 0.5$.

lepton flavor symmetry predicted by non-Abelian discrete symmetries, such as A_4, T_7, and $\Delta(27)$, which explain successfully the observed pattern of neutrino tribimaximal mixing. The key is the possible decay $H^0 \to \psi_2^0 \bar{\psi}_2^0$ with the unusual and easily detectable $(\tau^-\mu^+)(\tau^-e^+)$ final state. In a specific and much simplified scenario, we show that a 5σ discovery is possible at the LHC with 1 fb^{-1} for $E_{\rm cm} = 7$ TeV, up to $m_H \sim 200$ GeV. We show that the conventional WW mode in the search for the SM Higgs boson may be impacted significantly as well.

Acknowledgments

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[1] E. Ma and G. Rajasekaran, Phys. Rev **D64**, 113012 (2001).

[2] E. Ma, Phys. Rev. **D70**, 031901 (2004).

[3] P. F. Harrison, D. H. Perkins, and W. G. Scott, Phys. Lett. **B530**, 167 (2002).

[4] Q.-H. Cao, S. Khalil, E. Ma, and H. Okada, Phys. Rev. Lett. **106**, 131801 (2011) [arXiv:1009.5415 [hep-ph]].

[5] E. Ma, Phys. Rev. **D82**, 037301 (2010).

[6] For a recent review, see for example H. Ishimori, T. Kobayashi, H. Ohki, H. Okada, Y. Shimizu, and M. Tanimoto, Prog. Theor. Phys. Suppl. **183**, 1 (2010).

[7] G. Bhattacharyya, P. Leser, and H. Pas, Phys. Rev. **D83**, 011701 (2011).

[8] S.-L. Chen, M. Frigerio, and E. Ma, Phys. Rev. **D70**, 073008 (2004).

[9] E. Ma, Phys. Lett. **B671**, 366 (2009).

[10] A. C. B. Machado, J. C. Montero, and V. Pleitez, Phys. Lett. **B697**, 318 (2011) [arXiv:1011.5855 [hep-ph]].

[11] R. de Adelhart Toorop, F. Bazzocchi, L. Merlo, and A. Paris, JHEP **1103**, 035 (2011) [arXiv:1012.1791 [hep-ph]]; JHEP **1103**, 040 (2011) [arXiv:1012.2091 [hep-ph]].

[12] For a recent update, see J. Buglio and A. Djouadi, JHEP **1103**, 055 (2011) [arXiv:1012.0530 [hep-ph]].

[13] The TEVNPH Working Group for the CDF and D0 Collaborations, arXiv:1007.4587 [hep-ex].

[14] J. Alwall *et al.*, JHEP **0709**, 028 (2007) [arXiv:0706.2334 [hep-ph]].

[15] D. L. Rainwater, D. Zeppenfeld and K. Hagiwara, Phys. Rev. D **59**, 014037 (1999).

[16] E. L. Berger, Q. -H. Cao, C. B. Jackson, T. Liu, G. Shaughnessy, Phys. Rev. **D82**, 053003 (2010).