Multi-Higgs doublet models with local $U(1)_H$ gauge symmetry and neutrino physics therein

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Abstract. Multi-Higgs doublet models appear in many interesting extensions of the standard model (SM). But they suffer from Higgs-mediated flavor changing neutral current (FCNC) problem which is very generic. In this talk, I describe that this problem can be resolved or mitigated if we introduce local $U(1)_H$ Higgs flavor gauge symmetry. As examples, I describe chiral $U(1)_H$ models where the right-handed up-type quarks also carry $U(1)_H$ charges and discuss the top forward-backward asymmetry (FBA) and $B \to D^{(*)}\tau\nu$ puzzle. Next I describe the two-Higgs doublet models where the usual $Z_2$ symmetry is implemented to $U(1)_H$ and show how the Type-I and Type-II models are extended. One possible extension of Type-II has the same fermion contents with the leptonphobic $E_6 Z'$ model by Rosner, and I discuss the neutrino sector in this model briefly.

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INTRODUCTION

The long-sought-for Higgs boson has been finally discovered at the LHC. Still the Higgs sector is the least understood part of the standard model (SM), both theoretically and experimentally. There are still many questions about the electroweak symmetry breaking (EWSB) sector:

• Is it exactly the same as the SM Higgs boson or is there any (slight) deviation from the SM Higgs boson ?
• How many Higgs doublets are there ?
• Is there any singlet scalar that could mix with the SM Higgs boson ?
• Are there Higgs multiplets with weak isospin larger than 1/2 ?

The upcoming LHC @ 13, 14 TeV and the future linear collider will provide us with invaluable information about the origin of electroweak symmetry breaking (EWSB) and (partial) answers to the questions listed above.

Among many extensions of the SM Higgs sector, multi-Higgs doublet models are well motivated in various extensions beyond the SM (BSM). In this talk, I first discuss how my collaborators and I came up with the idea of Higgs flavor in the context of chiral $U(1)'$ flavor models with multi-Higgs doublets invented for the top forward-backward asymmetry at the Tevatron. Then I describe our proposal to implement the softly broken $Z_2$ symmetry in 2 Higgs doublet models (2HDMs) to a spontaneously broken $U(1)_H$ symmetry, and show how the usual Type-I and Type-II 2HDMs are generalized into new 2HDMs with $U(1)_H$ symmetry. In particular one extension of the Type-II 2HDM is exactly the same as the leptonphobic $Z'$ models derived from $E_6$ by J.L. Rosner [1]. In this model, there are new sterile neutrinos whose mass matrix is fixed by gauge quantum numbers of the SM fermions and the new sterile neutrinos, which I briefly touch upon.

CHIRAL $U(1)'$ FLAVOR MODELS FOR THE TOP FBA

Motivations

The top forward-backward asymmetry ($A_{FB}'$) has been one of the most interesting observables recently, since there have been some discrepancies between theoretical predictions in the standard model (SM) and experimental results at the Tevatron. The most recent measurement for $A_{FB}'$ at CDF is $A_{FB}' = 0.162 \pm 0.047$ in the lepton+jets channel with a
left-handed quarks and right-handed down-type quarks are not charged under and we consider an extra leptophobic U(1) in Ref. [12]. Our model is an extension of the of Ref. [10]. The original \( A_{FB}' \) model of events with the positive and negative \( \Delta |y| = |y| - |\bar{y}| \) divided by their sum. The current values for \( A_C' \) are \( A_C' = -0.018 \pm 0.028 \pm 0.023 \) at ATLAS [6] and \( A_C' = 0.004 \pm 0.010 \pm 0.012 \) at CMS [7], respectively, which are consistent with the SM prediction \( \sim 0.01 \) [4]. Another interesting observable at the LHC is the cross section for the same-sign top-quark pair production, \( \sigma^{tt} \), which is not allowed in the SM. The current upper bound on \( \sigma^{tt} \) is about 0.39 pb at 95 % C.L.. [8] and 2 pb or 4 pb at ATLAS depending on the model [9]. Some models which were proposed to account for \( A_{FB}' \) at the Tevatron, predict large \( A_C' \), and/or \( \sigma^{tt} \) so that they are already disfavored by present experiments at the LHC. However the story is not that simple if there is a new chiral gauge boson, which is a main theme of this section.

**The original \( Z' \) model by Jung et al. [10]**

Let us consider a \( Z' \) model first proposed by Jung, Murayama, Pierce and Wells [10], who assume that there is a flavor changing \( Z' \) couplings to the right-handed (RH) \( u \) and \( t \) quarks:

\[
\mathcal{L} = -g_X Z'_\mu [\bar{R} Y u_R + \text{H.c.}].
\]

The \( t \)-channel exchange of \( Z' \) leads to the Rutherford peak in the forward direction and generates the desired amount of the top FBA if \( Z' \) is around 150 – 250 GeV and \( g_X \) is not too small. Here \( Z' \) is assumed to couple only to the right-handed (RH) quarks in order to evade the strong bounds from the FCNC processes such as \( K^0 - \bar{K}^0, B_d^{0(\pm)} - \bar{B}_d^{0(\pm)} \) mixings and \( B \rightarrow X_s \gamma, \) etc.. Such a light \( Z' \) should be leptonphobic in order to avoid the strong bounds from the Drell-Yan processes. Therefore the original \( Z' \) model by Jung et al. [10] is chiral, leptophobic and flavor non-universal. One can imagine that \( Z' \) is associated with a new local gauge symmetry \( U(1)' \). Then the original \( Z' \) model has gauge anomalies and is mathematically inconsistent. Also one can not write Yukawa couplings for the up-type quarks if we have only the SM Higgs doublet which has the vanishing \( U(1)' \) charge. Then the top quark would be massless, which is physically unrealistic and unacceptable. Therefore it would be highly nontrivial to construct a realistic gauge theory which satisfies the conditions in the original \( Z' \) model. Let us recall that the original \( Z' \) model was excluded by the same sign top pair productions, because \( Z' \) exchange can contribute to \( uu \rightarrow tt \). The upper bounds on the same-sign top-pair production put strong constraints on this model [11]. However the model with extra \( Z' \) only is not either consistent or realistic because of the reasons described above. The original \( Z' \) model should be extended with new Higgs doublets before one starts working on detailed phenomenology, as described in the next section [12].

**\( U(1)' \) models with flavored multi-Higgs doublets by Ko, Omura and Yu [12]**

In this subsection we review the flavor-dependent chiral \( U(1)' \) model with flavored Higgs doublets that was proposed in Ref. [12]. Our model is an extension of the \( Z' \) model [10] described in the previous section, curing various problems of Ref. [10]. The \( Z' \) boson must be associated with some gauge symmetry if we work in weakly interacting theories, and we consider an extra leptophobic \( U(1)' \) symmetry [12]. And in order to avoid too large FCNCs in the down quark sector, we assigned flavor-dependent \( U(1)' \) charges \( u_i \) (\( i = u, c, t \)) only to the right-handed up-type quarks while the left-handed quarks and right-handed down-type quarks are not charged under \( U(1)' \).

Then, the Lagrangian between \( Z' \) and the SM quarks in the interaction eigenstates is given by

\[
\mathcal{L}_{Z'q\bar{q}} = g' \sum_i u_i Z'_\mu \overline{U}_R \gamma^\mu U_R^i + \text{H.c.},
\]

where \( U_R^i \) is a right-handed up-type quark field in the interaction eigenstates and \( g' \) is the coupling of the \( U(1)' \).

After the electroweak symmetry breaking, we can rotate the quark fields into the mass eigenstates by bi-unitary transformation. The interaction Lagrangian for the \( Z' \) boson in the mass eigenstate is given by

\[
\mathcal{L}_{Z'q\bar{q}} = g' Z'_\mu \left[ (g_{R, u}^u)_{ii} \overline{U}_R \gamma^\mu U_R^i + (g_{R, c}^c)_{ii} \overline{U}_R \gamma^\mu U_R^i + (g_{R, t}^t)_{ii} \overline{U}_R \gamma^\mu U_R^i \right].
\]
The $3 \times 3$ mixing matrix $(g_R^u)_{ij} = (R_u)_{ik} u_k (R_u)_{kj}$ is the product of the $U(1)'$ charge matrix $\text{diag}(u_k=1,2,3)$ and a unitary matrix $R_u$, where the matrix $R_u$ relates the RH up-type quarks in the interaction eigenstates and in the mass eigenstates.

The matrix $R_u$ participates in diagonalizing the up-type quark mass matrix. We note that the components of the mixing angles related to the charm quark have to be small in order to respect constraints from the $D^0-ar{D}^0$ mixing.

If one assigns the $U(1)'$ charge $(u_i) = (0,0,1)$ to the right-handed up-type quarks, one can find the relation $(g_R^u)_{i2}^2 = (g_R^u)_{i3} (g_R^u)_{i3}$. This relation indicates that if the $t$-channel diagram mediated by $Z'$ contributes to the $u\bar{u} \to t\bar{t}$ process, the $s$-channel diagram mediated by $Z'$ should be taken into account, too.

As we discussed in the previous section, it is mandatory to include additional flavored Higgs doublets charged under $U(1)'$ in order to write down proper Yukawa interactions for the SM quarks charged under $U(1)'$ at the renormalizable level. The number of additional Higgs doublets depends on the $U(1)'$ charge assignment to the SM fermions, especially the right-handed up-type quarks. In general, one must add three additional Higgs doublets with $U(1)'$ charges $u_i$ (see Ref. [12] for more discussions). For the charge assignment $(u_i) = (0,0,1)$ we have two Higgs doublets including the SM-like Higgs doublet, while for $(u_i) = (-1,0,1)$ three Higgs doublets are required. The additional $U(1)'$ must be broken in the end, so that we add a $U(1)'$-charged singlet Higgs field $Φ$ to the SM. Both the $U(1)'$-charged Higgs doublet and the singlet $Φ$ can give the masses for the $Z'$ boson and extra fermions if it has a nonzero vacuum expectation value (VEV). After breaking of the electroweak and $U(1)'$ symmetries, one can write down the Yukawa interactions in the mass basis. After all the Yukawa couplings would be proportional to the quark masses responsible for the interactions so that we could ignore the Yukawa couplings which are not related to the top quark.

The number of relevant Yukawa couplings participating in the top-quark pair production depends on the $U(1)'$ charge assignment and mixing angles. The relevant Yukawa couplings for the top-quark pair production can be written as

$$V = Y_{tu}^h \overline{t} t h + Y_{tu}^H \overline{t} t H + i Y_{tu}^a \overline{t} t a + h.c.,$$

where $h$ and $a$ are the lightest neutral scalar and pseudoscalar Higgs bosons, and $H$ is the heavier (second lightest) neutral Higgs boson. We assume that the Yukawa couplings of the other Higgs bosons are suppressed by the mixing angles.

Introducing $U(1)'$ flavored Higgs doublets is very important because they generate nonzero top mass. They also play an important role in top FBA phenomenology. For example the Yukawa couplings of the neutral scalar bosons $h, H, a$ have flavor changing couplings to the up-type quarks because of the flavor non-universal nature of $Z'$ interaction [12]:

$$Y_{tu}^h = \frac{2m_t (g_R^u)_{ut}}{v \sin(2β)} \sin(α - β) \cos α_Φ,$$

$$Y_{tu}^H = \frac{2m_t (g_R^u)_{ut}}{v \sin(2β)} \cos(α - β) \cos α_Φ,$$

$$Y_{tu}^a = \frac{2m_t (g_R^u)_{ut}}{v \sin(2β)}.$$

These Yukawa couplings are not present in the Type-II 2HDM, for example. Our models proposed in Ref. [12] are good examples of non-minimal flavor violating multi-Higgs doublet models, where the non-minimal flavor violation originates from the flavor non-universal chiral couplings of the new gauge boson $Z'$. In our model, the top FBA and the same-sign top-pair productions are generated not only by the $t$-channel $Z'$ exchange, but also by the $t$-channel exchange of neutral Higgs scalars, and the strong constraint on the original $Z'$ model from the same-sign top-pair production can be relaxed by a significant amount when we include all the contributions in the model, as described in the following section.

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1 We note that the relation is not valid for the other charge assignments. For general cases, we introduce a parameter $ξ$ with $(g_R^u)_{i3} = ξ (g_R^u)_{i3}$, where $ξ$ is a free parameter.

2 It is also true that one cannot write nonrenormalizable Yukawa interactions with the SM Higgs doublet only. It is essential to include the Higgs doublets with nonzero $U(1)'$ charges in order that one can write Yukawa couplings for the up-type quarks in this model.

3 This assumption is not compulsory, since all the Higgs bosons might participate in the top-quark pair production in principle. We will keep only a few lightest (pseudo) scalar bosons in order to simplify the numerical analysis.
Phenomenology

In this subsection, we discuss phenomenology of our model described in the previous subsection. If new physics affects the top-quark pair production and could accommodate $A_{FB}^C$ at the Tevatron, it must also be consistent with many other experimental measurements related with the top quark. In our models, both the $Z'$ and Higgs bosons $h$ and $a$ contribute to the top-quark pair production through the $t$-channel exchange in the $u\bar{u} \to t\bar{t}$ process. As we discussed in the previous section, the $Z'$ boson also contributes to the top-quark pair production through the $s$-channel exchange, which was ignored in Ref. [10].

As two extreme cases, one can consider the cases where only the $Z'$ boson or Higgs boson $h$ contributes to the top-quark pair production. Then, our models become close to the simple $Z'$ model of Ref. [10] or the scalar-exchange model of Ref. [13]. Unfortunately, these models cannot be compatible with the present upper bound on the same-sign interference between the contribution from the $Z'$ and those from Higgs bosons $h$ and $a$. In particular, the contribution of the pseudoscalar boson $a$ to the same-sign top-quark pair production is opposite to the other contributions.

In the two Higgs doublet model with the $U(1)'$ assignments to the right-handed up-type quarks, $(u_i) = (0, 0, 1)$, the $s$-channel contribution of the $Z'$ exchange to the partonic process $u\bar{u} \to t\bar{t}$ is as strong as an $t$-channel contribution because of the relation $(g^2_{yFy})_{uut} = (g^2_{yFy})_{utu}$ [12]. In the multi-Higgs doublet models (mHDMs) with other $U(1)'$ charge assignments $(u_i)$’s to the right-handed up-type quarks, the $s$-channel contribution could be small. In general, one can write $(g^2_{yFy})_{uut} = \xi (g^2_{yFy})_{utu}$, where $\xi$ is a function of mixing angles and $0 \leq |\xi| \leq O(1)$. In the case of $m_{Z'} \geq 2m_t$, a resonance around the $Z'$ mass for nonzero $\xi$ would be observed in the $t\bar{t}$ invariant mass distribution. However, such a resonance has not been observed so far in the experiments. This would restrict the $Z'$ mass to be much smaller than $2m_t$ for nonzero $\xi$. For the numeric values for $\sigma^t\bar{t}$, $\sigma^{tt}$, $A_{Y}^C$ and other related data and parameters, I refer to the original paper [14].

(i) $m_{Z'} = 145$ GeV and $\xi = 1$: In this case, the $Z'$ boson can contribute to the top-quark pair production through its $s$-channel and $t$-channel exchanges in the $u\bar{u} \to t\bar{t}$ process. While the Higgs bosons contribute to the top-quark pair production only in the $t$ channel because the diagonal elements of their Yukawa couplings to light quarks are negligible. We scan the following parameter regions: 180 GeV $\leq m_{H,a} \leq 1$ TeV, $0.005 \leq \alpha_t \leq 0.012, 0.5 \leq Y_{tu}^{H,a} \leq 1.5$, and $(g^2_{yFy})_{uut} = (g^2_{yFy})_{utu}$, where $\alpha_t \equiv (g^2_{yFy})_{tut}/(4\pi)$ is defined and $Y_{tu}^{H,a}$ are flavor-off-diagonal Yukawa couplings.

In Fig. 1, we show the scattered plot for $A_{FB}^C$ at the Tevatron and the same-sign top-pair production cross section and $A_{Y}^C$ at the LHC. The green and yellow regions are consistent with $A_{Y}^C$ at ATLAS and CMS in the $1\sigma$ level, respectively. The blue and skyblue regions are consistent with $A_{FB}^C$ in the lepton+jets channel at CDF in the $1\sigma$ and $2\sigma$ levels, respectively. The red points are in agreement with the cross section for the top-quark pair production at the Tevatron in the $1\sigma$ level and the blue points are consistent with both the cross section for the top-quark pair production at the Tevatron in the $1\sigma$ level and the upper bound on the same-sign top-quark pair production at ATLAS. We find that a lot of parameter points can explain all the experimental data. We emphasize that the simple $Z'$ model is excluded by the same-sign top-quark pair production, but in the chiral $U(1)'$ model, this strong bound could be evaded due to the destructive interference between the $Z'$ boson and Higgs bosons. Also the $m_{tt}$ distribution becomes closer to the SM case in the presence of $h$ and $a$ contributions (see Fig. 2). One can realize that it is important to include the Higgs contributions as well as the $Z'$ contributions. All the physical observables are affected by the Higgs contributions.

(ii) $m_h = 125$ GeV and $\xi = 0$: In this case, we discuss the scenario that a light Higgs boson $h$ with $m_h = 125$ GeV, motivated by the recent observation of an SM-Higgs like scalar boson at the LHC [15], also has a nonzero $Y_{hu}^h$. In this case, the $Z'$ boson and Higgs bosons $h, H$, and $a$ contribute to the top-quark pair production. In order to suppress the exotic decay of the top quark into $h$ and $u$, we set the Yukawa coupling of $h$ to be $Y_{hu}^h \leq 0.5$ and masses of $Z', H$, and $a$ are larger than the top-quark mass or approximately equal to the top-quark mass. We scan the following parameter regions: 160 GeV $\leq m_{Z'} \leq 300$ GeV, 180 GeV $\leq m_{H,a} \leq 1$ TeV, $0 \leq \alpha_t \leq 0.025, 0 \leq Y_{tu}^{H,a} \leq 1.5, 0 \leq Y_{hu}^h \leq 0.5$ and $\xi = 0$. The mass region of the $Z'$ boson is taken to avoid the constraint from the $t\bar{t}$ invariant mass distribution at the LHC. If $(g^2_{yFy})_{uut} \simeq 0$ and the $s$-channel contribution of the $Z'$ could be ignored, the mass region of the $Z'$ boson could be enlarged. In Fig. 3, we show the scattered plot for $A_{FB}^C$ at the Tevatron and $A_{Y}^C$ at the LHC for $m_h = 125$ GeV. All the legends on the figure are the same as those in Fig. 1. We find that there exist parameter regions which agree with all the experimental constraints. We emphasize that in some parameter spaces $\sigma^{tt}$ is less than 1 pb.
FIGURE 1. The scattered plots for (a) $A_{FB}^t$ at the Tevatron and $\sigma^{tt}$ at the LHC in unit of pb, and (b) $A_{FB}^t$ at the Tevatron and $A_C^t$ at the LHC for $m_{Z'} = 145$ GeV and $\xi = 1$. In (b), the blue points satisfy the upper bound on the same sign top pair production from ATLAS: $\sigma^{tt} < 4$ pb.

FIGURE 2. The invariant mass distribution of the top-quark pair at the Tevatron in the SM, $Z'$ model, and chiral U(1)$'$ model.

FIGURE 3. The scattered plots for (a) $A_{FB}^t$ at the Tevatron and $\sigma^{tt}$ at the LHC in unit of pb, and (b) $A_{FB}^t$ at the Tevatron and $A_C^t$ at the LHC for $m_h = 125$ GeV and $\xi = 0$, where the contribution of the second lightest Higgs boson $H$ is included.

Summary

The top forward-backward asymmetry at the Tevatron is the only quantity which has deviation from the SM prediction in the top quark sector up to now. A lot of new physics models have been introduced to account for this
deviation. Or it has been analyzed in a model-independent way [16, 17], and some models have already been disfavored by experiments at the LHC. In this section, we investigated the chiral U(1)' model with flavored Higgs doublets and flavor-dependent couplings. Among possible scenarios, we focused on two scenarios, both of which can accommodate with the constraints from the same-sign top-quark pair production and the charge asymmetry at the LHC as well as the top forward-backward asymmetry at the Tevatron.

The chiral U(1)' model has a lot of new particles except for the $Z'$ boson and neutral Higgs bosons. The search for exotic particles may constrain our model severely. For example, our model is strongly constrained by search for the charged Higgs boson in the $b \rightarrow s \gamma$, $B \rightarrow \tau \nu$, and $B \rightarrow D^{(*)}\tau \nu$ decays [18]. In order to escape from such constraints, we must assume a quite heavy charged Higgs boson or it is necessary to study our model more carefully by including all the interactions which have been neglected in this work. More detailed analysis on this issue can be found in Ref. [18].

A NEW RESOLUTION OF HIGGS-MEDIATED FCNC IN 2HDMS WITH LOCAL $U(1)_H$

HIGGS FLAVOR SYMMETRY

Preamble

Adding one more Higgs doublet to the SM is one of the simplest extensions of the SM, leading to the so-called two Higgs doublet model (2HDM). The 2 HDM’s have been studied in various contexts (see, for example, Ref. [19] for a recent review). Generic 2HDM’s suffer from excessive flavor changing neutral current (FCNC) mediated by neutral Higgs boson exchanges. This is due to the fact that the individual Yukawa couplings would not be diagonalized simultaneously when the fermion mass matrices are diagonalized by unitary matrices acting on the left-handed and the right-handed quarks and leptons.

One way to avoid this problem is to impose an ad hoc $Z_2$ discrete symmetry as suggested by Glashow and Weinberg long time ago [20], which is often called Natural Flavor Conservation (NFC):

$$Z_2 : (H_1, H_2) \rightarrow (+H_1, -H_2).$$

The Yukawa sectors can be controlled by assigning suitable $Z_2$ parities to the SM fermions, and the models are often categorized into four types (see Table 1) [21, 22]: However it is well known that this discrete symmetry could generate a domain wall problem when it is spontaneously broken, which is indeed the case in the 2HDM. Therefore the $Z_2$ symmetry is assumed to be broken softly by a dim-2 operator, $H_1^\dagger H_2$ term. Also the origin of such a discrete symmetry is not clear at all.

For long time this Higgs-mediated FCNC problem was solved or evaded by assuming the so-called Natural Flavor Conservation (NFC) criterion proposed by Glashow and Weinberg [20]. In practice, this criterion amounts to assume that the fermions of the same electric charges get their masses from only one type of Higgs doublet. This criterion is easily realized in the two-Higgs doublet model (2HDM) by imposing softly broken $Z_2$ symmetry under which $H_1$ and $H_2$ and the SM chiral fermions are charged differently so that the NFC criterion by Glashow-Weinberg is realized. However the origin of the discrete $Z_2$ symmetry and its soft breaking is not clear at all.

In Ref. [23], we proposed a new resolution of the Higgs mediated FCNC problem in 2HDMs, by implementing the discrete $Z_2$ symmetry to local $U(1)_H$ Higgs flavor symmetry. In the $U(1)_H$ extensions of the usual 2HDMs, it is important to impose the anomaly cancellation in addition to the phenomenologically viable Yukawa interactions, which controls the $U(1)_H$ quantum numbers of the SM fermions as well as new chiral fermions introduced for anomaly cancellation. Therefore the $U(1)_H$ extension of 2HDMs are not really the same as the ordinary 2HDM, even in the limit of infinitely heavy $U(1)_H$ gauge boson. Even if we integrating out the $Z_H$ gauge boson assuming they are very heavy, there could be remaining new chiral fermions which were necessary for the anomaly cancellation. This simple resolution of the Higgs mediated FCNC problem was not proposed before, and it is worthwhile to study its
phenomenology at colliders in more detail [24], at low energy flavor physics as well as in the context of electroweak phase transition and baryogenesis.

**Higgs sector**

Let us assume that \( H_1 \) and \( H_2 \) carry different \( U(1)_H \) charges, \( h_1 \) and \( h_2 \) (with \( h_1 \neq h_2 \) in order to distinguish two of them), with \( g_H \) being the \( U(1)_H \) coupling. The kinetic terms for the \( H_1 \) and \( H_2 \) will involve the \( U(1)_H \) couplings:

\[
D_\mu H_i = D_\mu^{SM} H_i - ig_H h_i Z_{H\mu} H_i
\]

with \( i = 1, 2 \). Then the mass matrix for \( Z \) and \( Z_H \) from the kinetic terms of \( H_1 \) and \( H_2 \) is given by

\[
M^2 = \begin{pmatrix}
g_Z^2 v_1^2 & -g_Z g_H (h_1 v_1^2 + h_2 v_2^2) \\
-g_Z g_H (h_1 v_1^2 + h_2 v_2^2) & g_H^2 (h_1^2 v_1^4 + h_2^2 v_2^4)
\end{pmatrix},
\]

where \( v^2 = v_1^2 + v_2^2 \). Note that the determinant of \( M^2 \) is not zero, as long as \( h_1 \neq h_2 \). If we add an additional \( U(1)_H \) charged singlet scalar \( \Phi \) (its \( U(1)_H \) charge is defined as \( \phi \) with nonzero VEV \( v_\phi \), the (22) component of the (mass)\(^2\) matrix would have an additional piece \( g_H^2 (v_\Phi)^2 \) from the kinetic term of \( \Phi \). The mass mixing must be small to avoid too large deviation of \( \rho \) parameter from the SM prediction. The tree-level deviation within 1\( \sigma \) restricts the mass and coupling of \( Z_H \):

\[
\{h_1(\cos \beta)^2 + h_2(\sin \beta)^2\}^{\frac{g_H^2}{g_Z^2}} \frac{m_Z^2}{m_{Z_H}^2} \lesssim O(10^{-3}),
\]

where \( m_Z^2 = g_Z^2 v^2 \) and \( m_{Z_H}^2 = g_H^2 (v_\Phi^2(\cos \beta)^2 + h_2^2(\sin \beta)^2) + g_H^2 (v_\Phi)^2 \).

The potential of our 2HDM is given by

\[
V(H_1, H_2) = m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 + \frac{\lambda_1}{2} (H_1^\dagger H_1)^2 + \frac{\lambda_2}{2} (H_2^\dagger H_2)^2 + \lambda_3 H_1^\dagger H_1 H_2^\dagger H_2 + \lambda_4 H_1^\dagger H_2 H_2^\dagger H_1.
\]

In terms of the standard notation for the 2HDM potential, our model corresponds to a special case \( m_3^2 = \lambda_5 = 0 \). Note that \( H_1^\dagger H_2 \) or its square are forbidden by \( U(1)_H \) symmetry, since we have imposed \( h_1 \neq h_2 \). If the model were not gauged with the extra \( U(1)_H \), one would encounter the usual problem of a massless pseudoscalar \( A \). In our case, this massless mode is eaten by the \( U(1)_H \) gauge boson, and there is no usual problem with a massless Goldstone boson. Instead the scalar boson spectrum is different from the usual 2HDM, since there would no pseudoscalar \( A \) in our models.

In case we include a singlet scalar \( \Phi \), let us define \( \phi = h_1 - h_2 \), so that \( H_1^\dagger H_2 \Phi \) is gauge invariant. Then there would be additional terms in the scalar potential:

\[
\Delta V = m_3^2 \Phi^\dagger \Phi + \frac{\lambda_5}{2} (\Phi^\dagger \Phi)^2 + (\mu H_1^\dagger H_2 \Phi + H.c.) + \mu_1 H_1^\dagger H_1 \Phi^\dagger \Phi + \mu_2 H_2^\dagger H_2 \Phi^\dagger \Phi,
\]

depending on \( h_1 \) and \( h_2 \) and \( \Phi \). After \( \Phi \) develops a VEV, \( \mu \) terms look like the \( m_3^2 \) term in the conventional notation. And the effective \( \lambda_5 \) term is generated by the \( \Phi \) mediation: \( \lambda_5 \sim (\mu^2/m_\Phi^2) \) well below \( m_\Phi \) scale. In any case there is no dangerous Peccei-Quinn symmetry leading to a massless \( Z^0 \) unlike the usual 2HDM, and no need for soft breaking of \( Z_2 \) symmetry, because of extra \( U(1)_H \) gauge symmetry.

Production and decay modes of the new \( Z_H \) gauge boson will depend on the \( U(1)_H \) charges of the SM fermions, which will differ case by case. In the following, we implement each 2HDM’s with NFC (Type-II,X,Y) to local \( U(1)_H \) gauge theories by assigning suitable \( U(1)_H \) charges to two Higgs doublets \( H_1 \) and \( H_2 \) and the SM fermions, and by adding new chiral fermions for anomaly cancellation.

**Type-I 2HDM**

Let us first start with the simplest case, the Type-I 2HDM, where the SM fermions can get masses only from \( H_1 \) VEV. This is possible, if (with \( h_1 \neq h_2 \))

\[
u - q - h_1 = d - q + h_1 = e - l + h_1 = n - l - h_1 = 0.
\]
There are many ways to assign $U(1)_H$ charges to the SM fermions to achieve this scenario. The phenomenology will depend crucially on the $U(1)_H$ charge assignments of the SM fermions. In general, the models will be anomalous, even if $U(1)_H$ charge assignments are nonchiral, so that one has to achieve anomaly cancellation by adding new chiral fermions to the particle spectrum. For the Type-I case, one can achieve an anomaly-free $U(1)_H$ assignment even without additional chiral fermions: There is one free parameter by which the charge assignments determines the theory, modulo the overall coupling constant $g_H$. It is amusing to observe that there appear an infinite number of new models which is a generalization of the Type-I model into Higgs flavor $U(1)_H$ models without extending the fermion contents at all.

There are four simple and interesting anomaly-free charge assignments without new chiral fermions, however:

- $(u,d) = (0,0)$: In this case, all the SM fermions are $U(1)_H$ singlets. Then $Z_H$ is fermiophobic and Higgsphilic. It would not be easy to find it at colliders because of this nature of $Z_H$, and $h_2 \neq 0$. In this case, $H^{\pm}W^{\mp}Z_H$ couplings from the Higgs kinetic terms would be the main source of production and discovery for $Z_H$. The phenomenology of $Z_H$ will be similar to the leptophobic $Z'$ studied in Ref. [25].
- $(u,d) = (\frac{1}{2}, \frac{1}{2})$: In this case, we have $U(1)_H = U(1)_{B-L}$, and $Z_H$ is the $(B-L)$ gauge boson, which gets mass from the doublet $H_2$ (and also by a singlet $\Phi$, if we include it). Our case is very different from the usual $(B-L)$ model where $U(1)_{B-L}$ is broken only by the SM singlet scalar $\Phi$. Therefore the phenomenology would be very different. However the Yukawa sector is controlled by $U(1)_H$ and a new Higgs doublet $H_2$ with nonzero $U(1)_H$ charge $h_2$.
- $(u,d) = (1,-1)$: In this case, we have $U(1)_H = U(1)_R$. The $Z_H$ couples only to the RH fermions, not to the LH fermions. In this case, the would-be SM Higgs doublet $H_1$ also carries nonzero $U(1)_H$ charge, and Higgs phenomenology of this type of models will be very different from the SM Higgs boson.
- $(u,d) = (\frac{2}{3}, -\frac{1}{3})$: This case corresponds to $U(1)_H = U(1)_Y$, but it is different from the SM, since $h_1 = 1/2 \neq 0$, unlike the SM case where $h_1 = 0$. Higgs phenomenology of this type of models will be very different from the SM Higgs boson.

Other interesting possibilities with vectorlike $U(1)_H$ are to identify $U(1)_H = U(1)_B$ or $U(1)_L$. In these cases, however, the model becomes anomalous, and we have add additional chiral fermions for anomaly cancellation. Again, it is interesting to break $U(1)_B$ or $U(1)_L$ by an $SU(2)_L$ doublet $H_2$ (and possibly by $\Phi$ too).

### Type-II 2HDM

In this subsection, we will implement the Type-II model to a $U(1)_H$ gauge theory. In the Type-II 2HDM, $H_1$ couples to the up-type fermions, while $H_2$ couples to the down-type fermions:

$$V_Y = \sum_i y_{ij}^U Q_{Lj} H_1 U_{Rj} + \sum_i y_{ij}^D Q_{Lj} H_2 D_{Rj} + y_{ij}^E E_{Lj} H_2 E_{Rj} + y_{ij}^N \tilde{T}_H H_1 N_{Rj}.\quad (14)$$

There could be a number of ways to achieve anomaly cancellation. In this talk, I discuss only one possibility, relegating to our original paper for other interesting cases [23]. If we assign $(q,u,d) = (-1/3,2/3,-1/3)$ and $(l,e,n) = (0,0,1)$, the $U(1)_H$-extended Type-II 2HDM corresponds to the leptophobic $Z'$ model in the context of $E_6$ [1], with the following identification of $U(1)_H$ charge in terms of $U(1)$ generators of $E_6$ model:

$$Q_H = I_{3R} - Y_L + \frac{1}{2} Y_R.$$

The extra chiral fields introduced in Ref. [1] cancel the anomaly: and the qualitative predictions made in Ref. [1] will
apply in our case too without any modification. Each generation has one extra vectorlike neutrinos (from $l_L$ and $l_R$ in Table 3) and one LH singlet neutrino ($n_L$), some of which has leptophobic gauge interaction. Therefore baryonic neutrinos are realized in this model.

The Yukawa couplings for SM fermions are given by the Eq. (14), and the mass and mixing terms of the extra fermions will be generalized to

$$V_m = y_{ij}^q m_{li} H_2 l_R^j + y_{ij}^q q_{lR}^j \Phi + y_{ij}^l q_{lR}^j \Phi + y_{ij}^e Q_{lR}^j H_2 q_{Rj} + Y_{ij}^{\tilde{q}} H_2 E_{Rj}$$

$$+ Y_{ij}^{\tilde{q}} H_1 N_{Rj} + Y_{ij}^{D} q_{lR} D_{Rj} \Phi + Y_{ij}^{\tilde{E}} q_{lR} E_{Rj} \Phi + H.c..$$

(15)

Under this charge assignment, corresponding to $E_6$, the mixing terms between the SM fermions and the extra fermions are allowed at tree level, so that their Yukawa coupling must be tuned to avoid the strong constraints from FCNC processes.

One can repeat the same procedures for Type-X and Type-Y, and we refer to the original paper [23] for more detailed discussion on this extension, and I am going to discuss in brief the neutrino physics in the $U(1)_H$ extension of Type-II 2HDM, which is nothing but the leptophobic $E_6$ model discussed by J.L. Rosner sometime ago.

**Neutrino Physics in Type-II with leptophobic $E_6$ fermion contents**

After the spontaneous breaking of $SU(2)_L \times U(1)_Y \times U(1)_H \rightarrow U(1)_{em}$ by nonzero VEV’s

$$\langle H_1 \rangle = (0, v_1/\sqrt{2}), \quad \langle H_2 \rangle = (0, v_2/\sqrt{2}), \quad \langle \Phi \rangle = v_\Phi/\sqrt{2},$$

one can contract the mass matrices for the charged fermions and the neutrinos. In the interaction eigenstate basis, the neutrino mass matrix is given by

$$M_{\text{neutrino}} = \frac{1}{\sqrt{2}} \begin{pmatrix}
0 & 0 & Y_1 v_\Phi & 0 & y^N v_1 \\
0 & 0 & y^I v_\Phi & 0 & Y^N v_1 \\
Y^I v_\Phi & y^I v_\Phi & 0 & y^n v_2 & 0 \\
0 & 0 & y^n v_2 & 0 & 0 \\
y^N v_1 & Y^N v_1 & 0 & 0 & 0
\end{pmatrix}$$

in the basis $(v_L, q_L^c, n_R^c, n_L, n_R^c)$ for each generation. There are a number of new sterile neutrinos in this model, which would result in very rich phenomenology both in particle physics and in cosmology. The detailed analysis of neutrino sector in the Type-II 2HDM with local $U(1)_H$ gauge symmetry with leptophobic $E_6$ matter contents will be presented elsewhere [26].

**Conclusion**

Let me summarize my talk. In this talk, I discussed 2 different types of multi-Higgs doublet models with local $U(1)_H$ Higgs flavor symmetry under which the SM fields could be charged too. One model is for the top FBA with flavor dependent $U(1)_H$ couplings and the other being generalized 2HDMs with flavor universal $U(1)_H$ couplings. The main motivation for extending the Higgs sector with new Higgs doublets with nonzero $U(1)_H$ charges was to write realistic Yukawa interactions for the SM fermions.
The idea of gauging Higgs flavor with $U(1)_H$ gauge symmetry can be applied to the ordinary 2HDMs by implementing the softly broken discrete $Z_2$ symmetry to spontaneously broken local $U(1)_H$ symmetry. By assigning different $U(1)_H$ charges to two Higgs doublets and adjusting the $U(1)_H$ charges of SM fermions properly, one can easily realize the “Natural Flavor Conservation” suggested by Glashow and Weinberg [20]. There are infinitely many ways to assign $U(1)_H$ charges compatible with NFC, unlike the common practice based on discrete $Z_2$ symmetries. Our proposal for Type-II 2HDM has vastly different consequences from the MSSM 2HDM. In the MSSM, the supersymmetric parts of the Higgs potential is Type-II, but eventually becomes Type-III when the loop corrections involving trilinear couplings are included. And Higgs-mediated flavor violation can be enhanced by significant amount, especially for the large $\tan\beta$ region. On the other hand, our models for Type-II are based on $U(1)_H$ gauge symmetry which is spontaneously broken. The Higgs mediated FCNC is not enhanced much even if we include the loop effects, unlike the MSSM. We believe our proposal newly opens a wide window for the 2 HDM’s.

The basic ideas presented in this letter could be readily applied to other cases, for example, to multi-Higgs doublet models in order to control the flavor problem by new gauge symmetries associated with Higgs fields.

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