Chiral $U(1)$ flavor models and flavored Higgs doublets: the top FB asymmetry and the Wjj

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Abstract

We present $U(1)$ flavor models for leptophobic Z' with flavor dependent couplings to the right-handed up-type quarks in the Standard Model, which can accommodate the recent data on the top forward-backward (FB) asymmetry and the dijet resonance associated with a W boson reported by CDF Collaboration. Such flavor-dependent leptophobic charge assignments generally require extra chiral fermions for anomaly cancellation. Also the chiral nature of $U(1)'$ flavor symmetry calls for new $U(1)'$-charged Higgs doublets in order for the SM fermions to have realistic renormalizable Yukawa couplings. The stringent constraints from the top FB asymmetry at the Tevatron and the same sign top pair production at the LHC can be evaded due to contributions of the extra Higgs doublets. We also show that the extension could realize cold dark matter candidates.

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I. INTRODUCTION

The top forward-backward (FB) asymmetry ($A_{\rm FB}^t$) measured at the Tevatron has drawn a lot of attention during the past few years. The most recent updated data from CDF and D0 are [1–3]

$$A_{\rm FB}^t = \begin{cases} 0.158 \pm 0.074 \ \text{(CDF, lepton+jets channel)} \\ 0.42 \pm 0.158 \ \ \text{(CDF, dilepton channel)} \\ 0.19 \pm 0.065 \ \ \text{(D0, lepton+jets channel)} \end{cases} \tag{1}$$

in the $t\bar{t}$ rest frame, whereas the SM prediction [4–7] based on MCFM is 0.058 ± 0.009 [1]. Recent calculations of the top FB asymmetry at the next-next-leading-log (NNLL) do not differ much from the aforementioned SM predictions, and the sizable discrepancy still remains [8].

Motivated by this discrepancy, numerous suggestions have been made on how to explain the observed large top FB asymmetry [9–55]. The models can be categorized into the following: colored spin-1 (axigluon, coloron, Kaluza-Klein gluon, etc.) exchange in the s-channel, light Z' or $W'^{\pm}$ exchange in the t-channel, color antitriplet or sextet in the u-channel, color-singlet scalar exchange in the t-channel, and effective lagrangian approaches. Some models could be tested at the LHC. For example, the original light Z' model [10] is excluded by the recent CMS data on the same sign top pair production [56].

However, most models are phenomenologically motivated by the top FB asymmetry. And the issues related with flavor dependent gauge symmetry, anomaly cancellation and renormalizable Yukawa couplings were not properly addressed. When one considers a complete model including new particles and interactions needed for the top FB asymmetry, there could be additional degrees of freedom that might contribute to the top FB asymmetry. Therefore it may be premature to conclude which model is favored or not. This could be especially the case for models based on a new spin-1 particle.

Independent of the top FB asymmetry, the CDF Collaboration reported an interesting excess on the dijet production associated with a W boson in a dijet mass range between 130 GeV and 160 GeV with an integrated luminosity of 4.3 fb^{-1} [57]. The excess could be interpreted as the production process $p\bar{p} \to WX$ followed by $X \to jj$, where $\sigma(WX) \sim 4$ pb with $m_X \sim 145$ GeV. A possible candidate for X is a light Z' boson [50, 52, 58–62]. Various resolutions without invoking the Z' boson also have been proposed to reconcile the

CDF Wjj excess [49–55, 63–81]. The excess was confirmed by the CDF Collaboration with larger data, but was not confirmed by the D0 Collaboration [82]. It would be remained to be seen if the CDF Wjj excess survives in the future, but it would be desirable to calculate the typical size of $\sigma(Wjj)$ in new physics model under consideration.

Recently, the present authors proposed an extension of the Standard Model (SM) where flavor-dependent $U(1)'$ charges were assigned to the right-handed (RH) up-type quarks [83], and they made the light Z' model of Ref. [10] for the top FB asymmetry complete and realistic by constructing full renormalizable and anomaly free models with flavor dependent charge assignments to the right-handed up-type quarks. In particular, it was shown that the light Z' solution, which is now disfavored by the same sign top pair production constraint by the CMS Collaboration [56], could be revived because there are additional t-channel contributions from the neutral (pseudo) scalar Higgs bosons to the top FB asymmetry and the same sign top pair production. There is destructive interference among Z' and neutral (pseudo) scalar Higgs bosons in the latter observable, making the light Z' scenario with light neutral (pseudo)scalar bosons still a viable solution to the top FB asymmetry. Such models suffer from the constraints from flavor changing neutral currents (FCNC) and the process involving top quarks, so that the charge assignments have to be controlled. In Ref. [83], the authors concentrated on the cases that the nonzero charges are assigned only to the right-handed up-type quarks, and demonstrated that the models provide a possible resolution of the top forward-backward asymmetry [1], the CDF Wjj excess [57], and cold dark matters (CDMs). In this paper, we elaborate on these models considering various $U(1)'$ charge assignments to the SM quarks, and including $U(1)'$ charged Higgs doublets that are to be introduced in order that we can write renormalizable Yukawa couplings for the SM fermions.

Flavor-dependent $U(1)'$ charge assignments would require the extensions of Higgs doublets in order to realize realistic mass matrices with renormalizable Yukawa couplings, if the SM fermions have chiral $U(1)'$ charges. Since the right-handed up-type quarks in the models of Ref. [83] and this paper have flavor dependent couplings whereas other fermions have flavor universal couplings, the SM fermions (at least the right-handed up-type quarks) have chiral $U(1)'$ charges so that we have to introduce $U(1)'$ charged Higgs doublets in order to write the realistic Yukawa couplings for all the SM fermions and generate their masses. As pointed out in Ref. [44, 53], such extra $SU(2)_L$ Higgs doublets may enhance the A_{FB}. In our model,

it turns out that the top FB asymmetry and the same sign top pair production receive contributions not only from the $U(1)'$ gauge boson, Z', but also from neutral scalar Higgs, pseudo-scalar Higgs, and charged Higgs. As we see in the Sec. IV, such Higgs contributions play an important role in achieving the favored region for the top FB asymmetry without conflict with the same sign top pair production, and can accommodate the CDF Wjj signal when the excess is confirmed in the future.

Our models would not be anomaly-free without extra chiral fermions. One simple way to realize anomaly-free theory is adding one extra generation and two SM gauge vector-like fermion pairs. The added fields may also contribute to observed signals and raise new predictions. In fact, FCNC problems will be triggered in some cases, but stable particles, which become CDM candidates, will be guaranteed because of $U(1)'$ symmetry.

On the other hand, such flavor-dependent $U(1)'$ symmetric models may be known as the Froggatt-Nielsen Model (FN) [84], where the Yukawa terms are expressed by the power of a SM gauge singlet, Φ. This model is not renormalizable, but Z' and neutral scalar Higgs fields can contribute to A_{FB}. We also comment on the possibility that it may be compatible with the large $A_{\rm FB}$ to realize the hierarchical structures of Yukawa textures according to the power of Φ like FN, in Sec. II D.

This paper is organized as follows. In Sec. II A and B, we describe the flavor dependent leptophobic $U(1)'$ models, gauge and Yukawa interactions, respectively. In Sec. II C, we discuss the conditions for anomaly cancellation and introduce extra chiral fields for the anomaly cancellation. In Sec. II D, we discuss the FN-type model where Yukawa couplings are expressed by higher-order terms, and then we discuss the explicit models with extra $SU(2)_L$ Higgs doublets charged under $U(1)'$, in Sec. III, based on the argument in Sec. II B: one example is two Higgs doublet model and the other is three Higgs doublet model. In Sec. IV, we discuss phenomenology of each model, and describe the contribution of Z' and Higgs bosons to $A_{\rm FB}$ and the same sign top pair production at the Tevatron and LHC. We also show that the Wjj excess reported by CDF might be interpreted as a leptophobic Z' through $p\bar{p} \to h^{\pm} \to W^{\pm}Z'$ followed by $Z' \to jj$. In Sec. V, we comment on how to achieve stable particles, which are good CDM candidates, in our models, and Sec. VI is devoted to summary. In the appendix, we show the explicit descriptions of Yukawa couplings with Higgs and quarks in the three-Higgs models.

II. $U(1)'$ FLAVOR MODELS WITH $U(1)'$-CHARGED HIGGS DOUBLETS

A. $U(1)'$ Gauge Interactions

In this work, we are interested in explaining the top FB asymmetry in terms of relatively light Z' with mass around 150 GeV. Such a light Z' should be leptophobic in order to evade the stringent bound from Drell-Yan processes from the Tevatron and the LHC. Therefore we start with leptophobic $U(1)'$ gauge models with the following flavor-dependent charge assignments:

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
Q_i	3	2	$1/6$	q_i
D_{Ri}	3	1	$-1/3$	d_i
U_{Ri}	3	1	$2/3$	u_i
L_i	1	2	$-1/2$	0
E_{Ri}	1	1	-1	0
H	1	2	$1/2$	q_h
Φ	1	1	0	q_Φ

with $Q_i^T = (U_{Li}, D_{Li})$, $L_i^T = (\nu_{Li}, E_{Li})$ and $i = 1, 2, 3$ are generation indices. Φ is a SM-gauge singlet with nonzero $U(1)'$ charge which is required to break $U(1)'$ spontaneously and generate nonzero mass for Z'.

Flavor-dependent extra $U(1)'$ models were very popular in order to explain the origin of Yukawa texture in the SM in terms of flavor dependent $U(1)'$ charges of the SM fermions. For example, Froggatt and Nielsen define each fermion charges corresponding to the mass hierarchy, and explain the small Yukawa couplings using the suppression from higher-order terms [84]. This type of models for flavor has serious conflict with the low energy constraints on the highly suppressed FCNC, if the $U(1)'$ gauge boson Z' is as low as ~ 150 GeV. After all, it would be very difficult to accommodate the observed top FB asymmetry in the FN framework, the detailed arguments for which will be given in the later subsection (see Sec. II D).

Let us define the couplings between Z' and the SM quarks in the interaction eigenstates and in the mass (flavor) eigenstates:

$$\mathcal{L}_{Z'f\bar{f}} = g' Z'_\mu \left[q_i \overline{U_L^i} \gamma^\mu U_L^i + q_i \overline{D_L^i} \gamma^\mu D_L^i + u_i \overline{U_R^i} \gamma^\mu U_R^i + d_i \overline{D_R^i} \gamma^\mu D_R^i \right]$$
$$= g' Z'_\mu \left[(g_L^u)_{ij} \overline{\hat{U}_L^i} \gamma^\mu \hat{U}_L^j + (g_L^d)_{ij} \overline{\hat{D}_L^i} \gamma^\mu \hat{D}_L^j + (g_R^u)_{ij} \overline{\hat{U}_R^i} \gamma^\mu \hat{U}_R^j + (g_R^d)_{ij} \overline{\hat{D}_R^i} \gamma^\mu \hat{D}_R^j \right]. \quad (2)$$

Sum over the repeated indices are implicitly understood. The Yukawa matrices and the mass matrices of up- and down-type quarks are related as

$$Y_{ij}^u = (L_u)_{ik}^\dagger m_k^u (R_u)_{kj}, \quad Y_{ij}^d = (L_d)_{ik}^\dagger m_k^d (R_d)_{kj}.$$

Then the $U(1)'$ couplings of up- and down-type quarks are given by $g_{L,R}^u$ and g_{LR}^d:

$$(g_L^u)_{ij} = (L_u)_{ik} q_k (L_u)_{kj}^\dagger, \ (g_L^d)_{ij} = (L_d)_{ik} q_k (L_d)_{kj}^\dagger,$$
$$(g_R^u)_{ij} = (R_u)_{ik} u_k (R_u)_{kj}^\dagger, \ (g_R^d)_{ij} = (R_d)_{ik} d_k (R_d)_{kj}^\dagger. \quad (3)$$

One remark is in order. When one introduces a flavor dependent $U(1)'$ for phenomenologically motivated reasons, it is important to define the $U(1)'$ charges of the SM fermions before electroweak symmetry breaking (EWSB) because the fermion flavor is defined in terms of mass eigenstates only after the EWSB. It would be not reasonable to assume that physical Z' has a nonzero flavor changing interactions in a particular channel in the fermion mass eigenstates. It would be more natural to assume a particular $U(1)'$ assignments in interaction eigenstates. Then this particular charge assignments will be (partly) erased when we go to the mass eigenstates using Eq. (3).

In the left-handed quark sector, a sizable mixing is required to realize CKM matrix. Therefore the flavor changing interactions in the down quark sector, especially $(1,2)$-element, would be problematic if Z' mass is light. As far as we know, the data on $K^0 - \overline{K^0}$, $B_d^0 - \overline{B_d^0}$, $B_s^0 - \overline{B_s^0}$, and $D^0 - \overline{D^0}$ can be accommodated within the SM CKM paradigm very well, so that it might be difficult to assign flavor-dependent charges to, especially, down-type quarks (both D_{Li} and D_{Ri}). This phenomenological constraints can be easily accommodated if we assume that the left-handed up- and down-type quarks and the RH down-type quarks have flavor universal $U(1)'$ charges (including null charge). Then the usual GIM mechanism becomes operative in the down quark sector, and one can easily verify that the flavor changing couplings are allowed only in the RH up-type sector. This would be exactly what we need for explaining the top FB asymmetry in terms of light Z'. The $D^0 - \overline{D^0}$ mixing would be

controlled as described in the Sec. III, and we will focus mainly on $t - u$ mixing which may evade bounds from collider physics. [*] In the subsection II B, we introduce the models with extra $U(1)'$-charged Higgs doublets which realize this scenario evading the stringent constraints from the highly suppressed FCNC.

B.   Renormalizable Yukawa Interactions calls for $U(1)'$-charged Higgs doublets

Here, we introduce renormalizable models which can evade the strong FCNC bounds. We assume that the left-handed up- and down-type quarks and right-handed down-type quarks have universal charge, and only charges of right-handed up-type quarks are flavor-dependent:

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
Q_i	3	2	1/6	q_L
D_{Ri}	3	1	$-1/3$	q_L
U_{Ri}	3	1	2/3	u_i

The above charge assignment realizes

$$(g_L^u)_{ij} = (g_L^d)_{ij} = (g_R^d)_{ij} = q_L \delta_{ij}, \tag{4}$$

which can avoid dangerous tree-level FCNC contributions except for the right-handed up quark sector. The mixing matrix $(g_R^u)_{ij}$ have nonzero off-diagonal elements, so that we could discuss the cases that $(g_R^u)_{ut}$ is large and $(g_R^u)_{uc}$, which contributes to $D^0 - \overline{D^0}$, is suppressed, adopting appropriate Yukawa couplings.

In order to achieve realistic mass matrices and renormalizability in the models with flavor-dependent charge assignments, more than one extra Higgs doublet, charged under $U(1)'$, are required. For example, the assignment satisfying $u_1 = u_2 = q_L$ and $u_2 \neq u_3$ requires at least one extra Higgs doublet field whose $U(1)'$ charge is $(-q_L + u_3)$. In the most generic case $u_1 \neq u_2 \neq u_3 \neq u_1$, three extra Higgs doublets are required for renormalizable Yukawa couplings. If one of u_i is define as $u_i = q_L$, two extra Higgs doublet fields are necessary for realistic Yukawa matrix. In such multi-Higgs models, we have not only neutral scalar Higgs fields, but also pseudoscalar and charged Higgs fields. If their masses are around weak scale, they may also contribute to flavor changing processes through Yukawa couplings. In Sec. III, we

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[*] For example, see Ref. [44, 85, 86] about the FCNC bounds.

investigate 2 explicit models, setting q_L to 0: one is $(u_1, u_2, u_3) = (0, 0, 1)$ assignment which corresponds to 2 Higgs doublet model (2HDM), and the other is $(u_1, u_2, u_3) = (-1, 0, 1)$ assignment which corresponds to 3 Higgs doublet model (3HDM).

C. Conditions for anomaly cancellation

Leptophobic and flavor-dependent $U(1)'$ models generally become anomalous without extra chiral fields. One of the simplest ways to construct anomaly-free theory is adding one extra generation and two SM gauge vector-like pairs as follows:

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
Q'	3	2	1/6	$-(q_1 + q_2 + q_3)$
D'_R	3	1	$-1/3$	$-(d_1 + d_2 + d_3)$
U'_R	3	1	2/3	$-(u_1 + u_2 + u_3)$
L'	1	2	$-1/2$	0
E'	1	1	-1	0
l_{L1}	1	2	$-1/2$	Q_L
l_{R1}	1	2	$-1/2$	Q_R
l_{L2}	1	2	$-1/2$	$-Q_L$
l_{R2}	1	2	$-1/2$	$-Q_R$

One can replace the $SU(2)_L$ doublets (l_{Li}, l_{Ri}) with $SU(3)_c$ triplets.[†]

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
q_{L1}	3	1	$-1/3$	Q_L
q_{R1}	3	1	$-1/3$	Q_R
q_{L2}	3	1	$-1/3$	$-Q_L$
q_{R2}	3	1	$-1/3$	$-Q_R$

$Q_{L,R}$, q_i, d_i and u_i must satisfy the following two equations for the $U(1)'^3$ and $U(1)_Y U(1)'^2$ anomaly cancellation,

$$6 \sum_i q_i^3 - 6 \left(\sum_i q_i \right)^3 - 3 \sum_i d_i^3 + 3 \left(\sum_i d_i \right)^3 - 3 \sum_i u_i^3 + 3 \left(\sum_i u_i \right)^3 = 0, \quad (5)$$

[†] One can also replace them with fields charged or not charged under $SU(3)_c \times SU(2)_L$.

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$$\sum_i q_i^2 + \left(\sum_i q_i\right)^2 + \sum_i d_i^2 + \left(\sum_i d_i\right)^2 - 2\sum_i u_i^2 - 2\left(\sum_i u_i\right)^2 = 2(Q_L^2 - Q_R^2). \quad (6)$$

If one requires rational numbers for all the $U(1)'$ charges, there might be not so many simple solutions of Eq. (5). In the Sec. III, we discuss concrete models satisfying Eq. (5) and Eq. (6).

We also have constraints on the $U(1)'$-charges from the Yukawa couplings which generate masses of the SM fermions and extra fermions. Furthermore, our charge assignment may allow the mixing between the SM fermions and the extra fermions, which causes the FCNC problems. For example, in the case that q_h is set to 0, we have the mixing terms between SM leptons and extra leptons,

$$\lambda_j^l \overline{L'} H E_j + \lambda_i^E \overline{L_i} H E' + h.c. \quad (7)$$

We have to assume that $\lambda_j^{l,E}$ are controlled to avoid the problem. In fact, in the Sec. III B, we consider the case with $q_i = d_i = 0$ and $\sum_i u_i = 0$ where the extra generation is not required and the SM gauge vector-like pairs do not have the mixing.

D. Comments on the FN models

Before the introduction of our explicit models, let us comment on FN-type models. The FN framework [84] based on some $U(1)$ or other flavor symmetries broken at some high energy scale has been a very popular way to understand the flavor structures of Yukawa matrices. One can easily admit that this is probably best motivation for considering flavor dependent gauge symmetry, whether it may be abelian or nonabelian. Froggatt and Nielsen define each fermion charges in order to explain the mass hierarchy and flavor mixings. The small Yukawa couplings are achieved by the suppression from higher-order terms [84].

More explicitly, let us introduce a FN model without extra $SU(2)_L$ Higgs doublets charged under $U(1)'$. Now, the left-handed and RH down-type quarks have flavor-dependent charges for the Yukawa texture. Then Yukawa couplings are given by higher dimensional operators involving some powers of Φ, which is SM gauge singlet with $U(1)'$ charge, q_Φ,

$$y_{ij}^u \left(\frac{\Phi}{M}\right)^{n_{ij}^u} \overline{Q_i} \widetilde{H} U_{Rj} + y_{ij}^d \left(\frac{\Phi}{M}\right)^{n_{ij}^d} \overline{Q_i} H D_{Rj} + h.c., \quad (8)$$

where $\widetilde{H} \equiv i\tau_2 H^*$ and $(n_{ij}^u, n_{ij}^d) = ((q_i - u_j + q_h)/q_\Phi, (q_i - d_j - q_h)/q_\Phi)$. M is the cut-off scale, and $y_{ij}{}^{u,d}$ are coupling constants. After Φ gets the nonzero vacuum expectation value (vev), effective Yukawa couplings, $Y_{ij}^{u,d}$, are induced,

$$Y_{ij}^u = y_{ij}^u \epsilon^{q_i - u_j + q_h}, \ Y_{ij}^d = y_{ij}^d \epsilon^{q_i - d_j - q_h}, \tag{9}$$

where ϵ is defined as $\epsilon \equiv \langle \Phi \rangle / M$ and q_Φ is set to 1. If ϵ is around Cabibbo angle, ~ 0.22, we can expect that the Yukawa texture, which can realize mass hierarchy and small mixing, is appearing effectively, and the degree of the suppression may be described by the power of ϵ, when $y_{ij}^{u,d}$ are set to around 1. For example, assuming that $Y_{ij}^{u,d}$ are close to diagonal, we find that the ratio of masses and mixing are roughly estimated as

$$\frac{m_i^u}{m_j^u} \sim \epsilon^{q_i - q_j - u_i + u_j}, \ \frac{m_i^d}{m_j^d} \sim \epsilon^{q_i - q_j - d_i + d_j}, \ (i < j), \tag{10}$$

and

$$(V_{\text{CKM}})_{ij} \sim \epsilon^{|q_i - q_j|}. \tag{11}$$

The size of each $(L_{u,d})_{ij}$ and $(R_{u,d})_{ij}$ can be also majored by the power of ϵ, and especially L_u and L_d contribute to CKM matrix, V_{CKM}, so that each couplings are estimated as follows: $(g_L^{u,d})_{ij}$ are

$$(g_L^u)_{ij} \sim q_i \delta_{ij} + O((V_{\text{CKM}})_{ij})(q_j - q_i), \tag{12}$$
$$(g_L^d)_{ij} \sim q_i \delta_{ij} + O((V_{\text{CKM}})_{ij})(q_j - q_i),$$

where $(L_{u,d})_{ij}$ are estimated as $(V_{\text{CKM}})_{ij}$, and $(g_R^{u,d})_{ij}$ are

$$(g_R^u)_{ij} \sim u_i \delta_{ij} + (\delta R_u)_{ij}(u_j - u_i), \tag{13}$$
$$(g_R^d)_{ij} \sim d_i \delta_{ij} + (\delta R_d)_{ij}(d_j - d_i).$$

$(\delta R_{u,d})_{ij}$ are the small mixing defined as $(R_{u,d})_{ij} = \delta_{ij} + (\delta R_{u,d})_{ij}$ and they are also estimated according to the mass ratio and CKM matrix,

$$|(R_u)_{ij}| \sim |(R_u)_{ji}| \sim \epsilon^{|u_i - u_j|}, \tag{14}$$
$$|(R_d)_{ij}| \sim |(R_d)_{ji}| \sim \epsilon^{|d_i - d_j|}.$$

We notice that large flavor changing couplings are induced by large CKM elements and small mass hierarchy. For instance, $(L_d)_{12}$, which contributes to $K_0\text{-}\overline{K}_0$ mixing, is estimated as

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$O(\epsilon)$, which is too large, if $(q_1 - q_2)$ is not zero [85]. In order to avoid such too large flavor changing couplings, we have to control the coefficients, $y_{ij}^{u,d}$, and choose appropriate charge assignments. On the other hand, large mixing would be required in (t, u)-element, when we discuss the top forward-backward asymmetry, so that we may have to consider non-trivial charge assignments and $y_{ij}^{u,d}$ dependence for the partially large mixing.[‡]

We can also have Φ-quark-quark couplings induced by Yukawa couplings,

$$Y_{ij}^u n_{ij}^u \left(\frac{\langle H \rangle}{\langle \Phi \rangle} \right) \delta\Phi \overline{U_{Li}} U_{Rj} + Y_{ij}^d n_{ij}^d \left(\frac{\langle H \rangle}{\langle \Phi \rangle} \right) \delta\Phi \overline{D_{Li}} D_{Rj} + h.c., \tag{15}$$

where $\delta\Phi$ is the fluctuation around $\langle \Phi \rangle$. After changing the base, we could find the flavor changing Yukawa couplings because of the charge dependence. If the mixing is small, the rotated $Y_{ij}^u n_{ij}^u$ and $Y_{ij}^d n_{ij}^d$ would be the same order as Y_{ij}^u and Y_{ij}^d, and those terms have the suppression of $\langle H \rangle / \langle \Phi \rangle$. If $\delta\Phi$ is very light, sizable contributions to FCNC could appear, but the Yukawa couplings of $\delta\Phi$ are also suppressed by $Y_{ij}^{u,d}$.

Eventually, it might be difficult to assign flavor-dependent charge according to the realistic Yukawa texture, because of the FCNC constraints and A_{FB}. Especially the flavor-dependent charge assignment to the down-type quarks would generally cause the problem without controlling the coupling constants, y_{ij}^d, because of the sizable mixing for CKM matrix. In the next subsection, we consider models with universal charges in the down-type quarks, which can be expected to evade the strong bounds on B and K mixing, and several Higgs fields charged under $U(1)'$. Φ is also required to make charged and pseudo-scalar Higgs massive. Such $U(1)'$ charged Higgs can contribute to A_{FB}, and we discuss $U(1)'$ gauge boson, (pseudo) scalar, and charged Higgs interactions in the Sec.IV. We will show the case with only gauge boson and neutral scalar Higgs boson, which could be interpreted as the result of this FN-type model [§]. In fact, we will conclude that it is difficult to enhance A_{FB}, and avoid the strong bound from the same sign top production in the FN-type model.

[‡] Eq. (10) and Eq. (14) lead small mixing in (t, u)-element because of the mass hierarchy, m_u/m_t.

[§] In the FN-type model, non-renormalizable operators induce the effective Yukawa coupling like the FN model, but we will discuss the top FB asymmetry supposing that the charge assignment is fixed independent of the Yukawa texture allowing to tune the coupling constants, $y_{ij}^{u,d}$.

III. SIMPLE EXAMPLES WITH FLAVORED MULTI-HIGGS DOUBLETS WITH NONZERO $U(1)'$ CHARGES

In this section, we consider two simple choices of $U(1)'$ charges for the RH up-type quarks,

$$(u_i) = (0, 0, 1) \quad \text{or} \quad (-1, 0, 1).$$

Since the $U(1)'$ is chiral, one has to introduce $U(1)'$-charged Higgs doublets in order to write down the renormalizable Yukawa interactions, as explained in Sec. II B. Here we construct the two-Higgs and three-Higgs doublet models corresponding to the above two charge assignments, and work out the renormalizable Yukawa interactions explicitly. Some of the Yukawa couplings involving the neutral (pseudo) scalar and charged Higgs bosons will be flavor changing in the up-type quark sector, and will be used in Sec. IV for studying the top FB asymmetry, the same sign top pair productions and the Wjj excess at hadron colliders.

A. Two-Higgs doublet model (2HDM) with $(u_i) = (0, 0, 1)$

First, let us consider the model with $(u_1, u_2, u_3) = (0, 0, 1)$ and one extra Higgs doublet H_3 that is charged under $U(1)'$:

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
H	1	2	1/2	0
H_3	1	2	1/2	1
Φ	1	1	0	q_Φ

Φ not only breaks $U(1)'$ spontaneously and generates the Z' mass, but also is required to generate masses of charged and pseudo-scalar Higgs fields for any $U(1)'$ charge assignments. Therefore its $U(1)'$ charge (q_Φ) will be fixed by u_i (see Eq. (27)). Under this assignment, the renormalizable Yukawa couplings are written as follows,

$$V_y = y_{i1}^u \overline{Q_i} \widetilde{H} U_{R1} + y_{i2}^u \overline{Q_i} \widetilde{H} U_{R2} + y_{i3}^u \overline{Q_i} \widetilde{H_3} U_{R3}$$

$$+ y_{ij}^d \overline{Q_i} H D_{Rj} + y_{ij}^e \overline{L_i} H E_{Rj} + h.c.. \tag{16}$$

Two Higgs doublets H_3 and H include two neutral scalar, one pair of charged Higgs and one pseudoscalar Higgs fields. Their vevs are defined as $(\langle H \rangle, \langle H_3 \rangle) = (v \cos\beta/\sqrt{2}, v \sin\beta/\sqrt{2})$.

In the mass basis of SM fermions and the Higgs bosons, the Yukawa couplings of the lightest neutral scalar Higgs boson (denoted by h) with the SM fermions are described by R_u (g_R^u) and their masses, $m_i^{u,d,l}$:

$$V_h = Y_{ij}^u \overline{\hat{U}_{Li}} \hat{U}_{Rj} h + Y_{ij}^d \overline{\hat{D}_{Li}} \hat{D}_{Rj} h + Y_{ij}^e \overline{\hat{E}_{Li}} \hat{E}_{Rj} h + h.c., \tag{17}$$

where $Y_{ij}^{u,d}$ and Y_{ij}^e are defined as

$$Y_{ij}^u = \frac{m_i^u \cos\alpha}{v\cos\beta}\cos\alpha_\Phi \delta_{ij} + \frac{2m_i^u}{v\sin 2\beta}(g_R^u)_{ij}\sin(\alpha-\beta)\cos\alpha_\Phi, \tag{18}$$

$$Y_{ij}^d = \frac{m_i^d \cos\alpha}{v\cos\beta}\cos\alpha_\Phi \delta_{ij}, \tag{19}$$

$$Y_{ij}^e = \frac{m_i^l \cos\alpha}{v\cos\beta}\cos\alpha_\Phi \delta_{ij}, \tag{20}$$

where α is the mixing of 2 neutral scalar Higgs fields, and α_Φ is the mixing between the neutral scalar components of Φ and (H, H_3). Note that $(g_R^u)_{ij} = (g_R^u)_{ji}^* = (R_u)_{i3}(R_u)_{j3}^*$ is satisfied for our choice of $U(1)'$ charges: $(u_i) = (0,0,1)$.

The couplings of charged Higgs and pseudo-scalar Higgs can be written by finding the orthogonal direction of the Goldstone mode. The couplings of charged Higgs boson $h^\pm$ to the SM fermions are described as follows:

$$V_{h^\pm} = -Y_{ij}^{u-} \overline{\hat{D}_{Li}} \hat{U}_{Rj} h^- + Y_{ij}^{d+} \overline{\hat{U}_{Li}} \hat{D}_{Rj} h^+ + h.c., \tag{21}$$

where Y_{ij}^{u-} and Y_{ij}^{d+} are defined as,

$$Y_{ij}^{u-} = \sum_l (V_{\mathrm{CKM}})_{li}^* \left\{ \frac{\sqrt{2}m_l^u \tan\beta}{v}\delta_{lj} - \frac{2\sqrt{2}m_l^u}{v\sin 2\beta}(g_R^u)_{lj} \right\},$$
$$Y_{ij}^{d+} = (V_{\mathrm{CKM}})_{ij}\frac{\sqrt{2}m_j^d \tan\beta}{v}, \tag{22}$$

where V_{CKM} is defined as $(L_u)_{il}(L_d)_{jl}^*$.

The couplings of the pseudo-scalar Higgs, a, are also described as follows:

$$V_a = -iY_{ij}^{au} \overline{\hat{U}_{Li}} \hat{U}_{Rj} a + iY_{ij}^{ad} \overline{\hat{D}_{Li}} \hat{D}_{Rj} a + iY_{ij}^{ae} \overline{\hat{E}_{Li}} \hat{E}_{Rj} a + h.c., \tag{23}$$

where $Y_{ij}^{au,d}$ and Y_{ij}^{ae} are defined as

$$Y_{ij}^{au} = \frac{m_i^u \tan\beta}{v}\delta_{ij} - \frac{2m_i^u}{v\sin 2\beta}(g_R^u)_{ij}, \tag{24}$$

$$Y_{ij}^{ad} = \frac{m_i^d \tan\beta}{v}\delta_{ij}, \tag{25}$$

$$Y_{ij}^{ae} = \frac{m_i^l \tan\beta}{v}\delta_{ij}. \tag{26}$$

In this model, we also have to avoid large (u, c) elements for the bound from $D^0 - \overline{D^0}$ mixing. The small (u, c) gauge coupling, $(g_R^u)_{12}$, would require small $(R_u)_{13}$ or $(R_u)_{23}$. Fortunately, small $(g_R^u)_{12}$ could guarantee small (u, c) elements of Yukawa couplings in this model, and there would be no trouble with $D^0 - \overline{D^0}$ mixing.

Finally, the charged Higgs and pseudo-scalar Higgs must be massive. The origin of the mass terms may be the following terms,

$$\mu H_3^\dagger H (\Phi)^{\frac{1}{q_\Phi}} + h.c., \tag{27}$$

where μ is a coupling constant. If the renormalizability of this term is required, q_Φ should be 1 or 1/2.

We may consider the same set we introduced in Sec. II C to cancel the anomaly: one generation and SM gauge vector-like pairs. However, we may need another extra Higgs doublet for the heavy extra quarks, because $U(1)'$ charges of U_R' and H_3 are -1 and $+1$, and forbid the Yukawa couplings, $\overline{Q_L'} \widetilde{H} U_R'$ and $\overline{Q_L'} \widetilde{H_3} U_R'$. As mentioned in the Ref. [83], we can define all fermions in the extra generation as opposite-chirality fields with the same charge assignment as the third generation. However, such exotic extra generation allows the mass mixing between the SM fermions and extra fermions, like $\overline{D_L'} D_{Ri}$, where D_L' is the extra left-handed down-type quarks, so that we assume that such unfavored mass mixings are sufficiently small enough in order to avoid large FCNC contributions. We could find simpler solutions for for $(0, 0, 1)$ assignment: for example, only one SM gauge vector-like pair, whose $U(1)'$ charges are $(Q_L, Q_R) = (1, 0)$. Even in this case, mass terms between the extra left-handed fermion and SM fermion, which cause FCNC problems, would be allowed by the symmetries.

B. Three-Higgs doublet model (3HDM) with $(u_i) = (-1, 0, 1)$

Next we consider a model with $(u_1, u_2, u_3) = (-1, 0, 1)$, which requires three Higgs doublets. This assignment makes Higgs sector more complicated, but the condition for anomaly cancellation does not require any extra generation, so that we do not need discuss FCNC constraints from, for instance, mixing between the SM leptons and extra leptons. This would be a nice property of this three-Higgs doublet model.

For this $U(1)'$ charge assignment, we need to add two more Higgs doublets H_1 and H_3

that are charged under $U(1)'$ in order to write renormalizable Yukawa couplings and get realistic mass matrices:

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
H_1	1	2	1/2	-1
H_2	1	2	1/2	0
H_3	1	2	1/2	1
Φ	1	1	0	q_Φ

The Yukawa couplings are as follows,

$$V_y = y_{i1}^u \overline{Q_i} \widetilde{H_1} U_{R1} + y_{i2}^u \overline{Q_i} \widetilde{H_2} U_{R2} + y_{i3}^u \overline{Q_i} \widetilde{H_3} U_{R3}$$
$$+ y_{ij}^d \overline{Q_i} H_2 D_{Rj} + y_{ij}^e \overline{L_i} H_2 E_{Rj}. \tag{28}$$

After the EWSB and $U(1)'$ breaking, H_1, H_2 and H_3 will contain three neutral scalar, two pairs of charged scalar and two pseudoscalar Higgs fields. They mix with each other as well as with Φ. Let us express the interaction eigenstates in terms of mass eigenstates:

$$\widetilde{h}_I = O_{IJ}^h h_J,$$
$$\widetilde{h}_n^\pm = O_{nm}^c h_m^\pm,$$
$$\widetilde{a}_n = O_{nm}^a a_m, \tag{29}$$

where $\widetilde{h}_I$, $\widetilde{h}_n^\pm$ and $\widetilde{a}_n$ are scalar, charged and pseudo-scalar Higgs fields in the interaction basis, respectively, with $I, J = 1, 2, 3, \Phi$ and $n, m = 1, 2, 3$, and the fields in the righthand side $h_J, h_m^\pm$ and a_m are in the mass basis, and the Goldstone modes are a_3 and $h_3^\pm$. The mixing matrices O^h, O^c and O^a are 4×4, 3×3 and 3×3 orthogonal matrices, respectively.

In the mass basis of SM fermions and the lightest Higgs, $h \equiv h_1$, the Yukawa couplings, $Y_{ij}^{u,d}$ and Y_{ij}^e, which are defined in the Eq. (17), are described by R_u and m_i^u,

$$Y_{ij}^u = \sum_{k=1}^3 O_{k1}^h \frac{m_i^u}{\sqrt{2}\langle H_k \rangle} (R_u)_{ik} (R_u)_{jk}^*, \tag{30}$$

$$Y_{ij}^d = O_{21}^h \frac{m_i^d}{\sqrt{2}\langle H_2 \rangle} \delta_{ij}, \tag{31}$$

$$Y_{ij}^e = O_{21}^h \frac{m_i^l}{\sqrt{2}\langle H_2 \rangle} \delta_{ij}. \tag{32}$$

The couplings, Y_{ij}^{u-} and Y_{ij}^{d+}, in the Eq. (21) of the lightest charged Higgs boson, $h^{\pm} \equiv h_1^{\pm}$, are also described by

$$Y_{ij}^{u-} = \sum_{k=1}^{3} O_{k1}^c \sum_{l} (V_{\text{CKM}})_{li}^* \frac{m_l^u}{\langle H_k \rangle} (R_u)_{lk} (R_u)_{jk}^*,$$

$$Y_{ij}^{d+} = O_{21}^c (V_{\text{CKM}})_{ij} \frac{m_j^d}{\langle H_2 \rangle}. \tag{33}$$

The couplings of the lightest pseudo-scalar Higgs, $a \equiv a_1$, in the Eq. (23) are also given by

$$Y_{ij}^{au} = \sum_{k=1}^{3} O_{k1}^a \frac{m_i^u}{\sqrt{2} \langle H_k \rangle} (R_u)_{ik} (R_u)_{jk}^*,$$

$$Y_{ij}^{ad} = O_{21}^a \frac{m_i^d}{\sqrt{2} \langle H_2 \rangle} \delta_{ij},$$

$$Y_{ij}^{ae} = O_{21}^a \frac{m_i^l}{\sqrt{2} \langle H_2 \rangle} \delta_{ij}. \tag{34}$$

In this model, we also have to avoid large (u, c) elements for the bound from $D_0 - \overline{D_0}$ mixing. The gauge coupling would require small $(1, 2)$ and $(2, 3)$ mixing in $(R_u)_{ij}$, such as $(R_u)_{12}$ and $(R_u)_{13}$. The Yukawa coupling is not so simple, compared with Sec. III A, but we are sure that the small $(1, 2)$ and $(2, 3)$ mixing could also realize small (u, c) elements in the Yukawa couplings, as we describe in the appendix in detail.

Besides, we do not need the extra generation for anomaly cancellation which caused FCNC from mass mixing for the choice of $(0, 0, 1)$, because of $u_1 + u_2 + u_3 = 0$. Only SM gauge vector-like pairs, such as (q_{LI}, q_{RI}) introduced in Sec. II C, are required, and (Q_L, Q_R) must be defined as $(-1/2, -3/2)$ to cancel $U(1)_Y U(1)'^2$ product. When q_Φ is set to 1, the charged Higgs masses and pseudo-scalar masses can be given by the following terms,

$$\mu_{12} \Phi H_2^\dagger H_1 + \mu_{23} \Phi H_3^\dagger H_2 + h_{13} \Phi^2 H_3^\dagger H_1 + h.c.. \tag{35}$$

If we assume that the mass terms of H_1 and H_3, $m_{H_1}^2 |H_1|^2$ and $m_{H_3}^2 |H_3|^2$, are very large, we can integrate out H_1 and H_3, and we could realize effective one $SU(2)_L$ doublet model which corresponds to the FN-type model,

$$V_y = y_{i2}^u \overline{Q_i} \widetilde{H_2} U_{R2} - y_{i1}^u \left(\frac{\mu_{12} \Phi}{m_{H_1}^2} \right) \overline{Q_i} \widetilde{H_2} U_{R1} - y_{i3}^u \left(\frac{\mu_{23}^* \Phi^\dagger}{m_{H_3}^2} \right) \overline{Q_i} \widetilde{H_2} U_{R3} + \cdots + h.c.. \tag{36}$$

However, in this parameter region, only neutral scalar Higgs boson would contribute to the low-energy physics. In the next section, we will discuss a simple case like the FN-type model

with only neutral scalar Higgs, but we will notice that pseudo-scalar and charged Higgs play an important role to evade the same-sign top bound. In such a case, at least two of Higgs doublets should have masses around weak scale, with nonzero vevs. This would be another way to observe that the FN-type model would not describe the top FB asymmetry and the same sign top pair production properly.

IV. COLLIDER PHENOMENOLOGY

In this section, we discuss phenomenology of our models, especially the top forward-backward asymmetry, the same sign top pair production and the Wjj signal. In the FN-type model, the Higgs contribution would be generically small, because of the small ratio $\langle H \rangle / \langle \Phi \rangle$ and the corresponding Yukawa suppression or assuming that Φ is very heavy. Therefore we can concentrate on the Z' contributions to the processes under consideration that are governed by the gauge couplings. Even if the contribution of the neutral scalar Higgs is dominant, we will find that such scenario is not favored by $A_{\rm FB}$ and the same-sign top pair production, as we see in Sec. IV B 3. In the multi-Higgs doublet models, we have not only neutral scalar Higgs, but also pseudo-scalar and charged Higgs contributions, so that we can improve the result of the FN-type model. In this section, we focus on the 2HDM or 3HDM.

A. Numerical inputs

In the numerical calculation, we take the top quark mass $m_t = 173$ GeV. We use CTEQ6m for a parton distribution function [87]. Both the renormalization and factorization scales are taken to be m_t. We use $K = 1.3$ for the K factor in order to take into account the QCD radiative correction which is unknown as of now. The center-of-momentum (CM) energy $\sqrt{s}$ is taken to be 1.96 TeV at the Tevatron and 7 TeV at the LHC, respectively.

In the 2HDM case with the $U(1)^{'}$ charge assignment $(u_i) = (0, 0, 1)$, one can deduce $|(g_R^u)_{ut}|^2 = (g_R^u)_{uu}(g_R^u)_{tt}$ from Eq. (3). However in the other multi-Higgs models such as 3HDM with different $U(1)^{'}$ charge assignments, this identity would not be valid in general, as can be inferred from Eq. (A2). In the numerical analysis, we assign $|(g_R^u)_{ut}|^2 = (g_R^u)_{uu}(g_R^u)_{tt}$ assuming the 2HDM case. In the multi-Higgs models, this assumption might alter the s-

channel Z' contributions to the $t\bar{t}$ production, but the deviation would be tiny numerically. This is because the contribution to the $t\bar{t}$ production from the diagonal coupling $(g_R^u)_{uu}$ and $(g_R^u)_{tt}$ would be small because the interference terms between the SM QCD contribution at leading-order in α_s and the s-channel diagram mediated by the Z' boson vanish.

There is no strict bound for the mass $m_{Z'}$ of the Z' boson in our models, but it is assumed to be around the EW scale. Since the Z' boson does not couple to the charged lepton and neutrinos by construction, stringent bounds on an extra Z' boson from electroweak (EW) precision tests at LEP II and Drell-Yan processes at the Tevatron and LHC could be avoided. If the Z' boson is heavier than the top quark mass and has diagonal couplings to the SM quarks, its mass could be constrained by dijet production results at hadron colliders. In the relatively low mass region the UA2 experiments give strongest bounds for an s-channel resonance, while the Tevatron experiments strongly constrain its mass in the high mass region of the resonance [77]. Below the region lighter than the top quark the constraint is rather weak.

As discussed before, much attention on the light Z' boson scenarios with the mass around $140 \sim 160$ GeV has been paid, motivated by the recent collider and dark matter experiments. In this work, we consider two cases: $m_{Z'} = 145$ GeV and $m_{Z'} = 160$ GeV. Then the top quark can decay into a Z' boson with an up quark because there is a flavor-changing neutral current in the u_R-t_R-Z' vertex. It could alter significantly the branching ratio of the top quark to Wb. We assume the branching ratio of the top quark to $Z'u$ is less than 5 %. Then the coupling $\alpha_x = (g'(g_R^u)_{ut})^2/(4\pi)$ should be less than 0.012 for $m_{Z'} = 145$ GeV, but it is not constrained in the region $\alpha_x \leq 0.025$ for $m_{Z'} = 160$ GeV.

In the most general case, 4 Higgs doublets are required to write down proper mass terms for the SM fermions. As simpler cases we introduced 2HDM and 3HDM in Secs. III A and III B. Thus at least 3 neutral Higgs bosons and 1 charged Higgs boson pair exist. In this work we assume that only the lightest scalar, pseudo-scalar and charged Higgs bosons are relevant in the $t\bar{t}$ and Wjj production for simplicity. The Yukawa couplings could be proportional to the fermion masses after EW and $U(1)'$ breaking. Thus we assume that the scalar and pseudo-scalar Higgs bosons have large off-diagonal terms $Y_{tu}(\equiv Y_{31}^u)$ and $Y_{tu}^a(\equiv Y_{31}^{au})$ only for the top and up quarks, which may be natural in our model (see Eq.s (18), (24), (A3) and (A6)). The other Higgs bosons are assumed to be sufficiently heavy to have no effects on the $t\bar{t}$ and Wjj production.
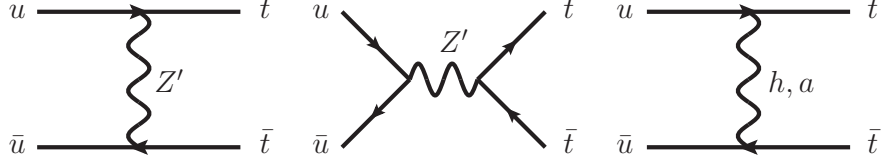
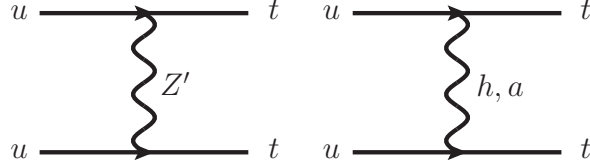FIG. 1. The Feynman diagrams for the $t\bar{t}$ production.

FIG. 2. The Feynman diagrams for the tt production.

In our model, the top quark may decay into a Higgs boson if Higgs boson is lighter than the top quark. If both the Z' and Higgs bosons are lighter than the top quark, the branching fraction of the top quark decay to the non-Wb state could easily be over 10 %, which might be dangerous. In order to avoid this harmful situation, we assume that all the Higgs bosons are heavier than the top quark. In this work, as an illustration of our model, we take $m_h = 180$ GeV, $m_a = 300$ GeV and $m_{h+} = 270$ GeV, respectively. The mass of the scalar Higgs boson looks like conflict with the mass bounds from the recent CMS and ATLAS experiments, which exclude the mass range from 149 GeV to 206 GeV and from 155 GeV and 190 GeV at 95 % C.L., respectively [88, 89]. However in our model the mass bound of the lightest Higgs boson should be weaker, since new decay channels of Higgs boson, such as $h \to t\bar{u}$, $h \to \Phi$+anything etc., will be open.

B. Top physics

1. Empirical data

We show the Feynman diagrams involving new physics contributions to the $t\bar{t}$ production in Fig. 1. The Z' boson contribute to the $t\bar{t}$ production through its t- and s-channel exchange in the parton process $u\bar{u} \to t\bar{t}$, while the h and a bosons contribute only through a t-channel diagram. So far the $t\bar{t}$ pair production cross section is in good agreement with the SM

predictions at the Tevatron and LHC. The empirical cross sections are $\sigma(t\bar{t}) = (7.5 \pm 0.48)$ pb at the Tevatron [90] and $\sigma(t\bar{t}) = (158 \pm 19)$ pb at CMS [91], respectively. In this work we use the Tevatron result in order to check our model, which is more sensitive to the $u\bar{u} \to t\bar{t}$ process.

The top forward-backward asymmetry A_{FB} in the $t\bar{t}$ rest frame is defined by the difference of the top quark numbers in the forward region and in the backward region. The SM prediction at next-to-leading order (NLO) is $A_{\mathrm{FB}} = 0.058 \pm 0.009$ at the Tevatron [1]. The CDF Collaboration reported $A_{\mathrm{FB}}^{\mathrm{lepton+jets}} = (0.158 \pm 0.075)$ in the lepton+jets channel with an integrated luminosity of 5.3 fb^{-1} [1] and $A_{\mathrm{FB}}^{\mathrm{dilepton}} = 0.42 \pm 0.17$ in the dilepton channel [2]. In the dilepton channel the central value of the asymmetry is quite large, but its uncertainty is also large. Both are consistent with each other within 1.5 σ level. A similar deviation in the top forward-backward asymmetry has recently confirmed by the D0 Collaboration with $A_{\mathrm{FB}} = 0.196 \pm 0.065$ in the lepton+jets channel with an integrated luminosity of 5.4 fb^{-1} [3]. For illustration we use the result in the lepton+jets channel at CDF.

In our model the t-channel diagrams play a key role in accommodating all the empirical data. It is known that models with a light Z' boson or a light scalar boson with FCNC are strongly constrained by the same sign top pair production at the LHC [92, 93]. Up to the present the most stringent bound for the same sign top quark pair production is given by the CMS Collaboration: $\sigma(tt) < 17$ pb [56].

2. *Z'-dominant case*

In this section, we consider the case that only the Z' boson contribute to the $t\bar{t}$ production at the Tevatron, assuming that $(g_R^u)_{ut}$, $(g_R^u)_{uu}$, and $(g_R^u)_{tt}$ are dominant over other elements of the coupling matrix $(g_R^u)_{ij}$. This is similar to the simple phenomenological model suggested by Jung, Murayama, Pierce and Wells [10]. One difference is that the s-channel contribution of Z' was ignored in Ref. [10].

Figure 3 represents the allowed region for $m_{Z'}$ and α_x, which is in agreement with each experiment. The cyan band corresponds to the region satisfying the $t\bar{t}$ production cross section at the Tevatron in the 1-σ level, while the green band satisfies the top forward-backward asymmetry at CDF in the 1-σ level, respectively. The yellow region represents the region in which the same sign top pair production at the LHC is less than the upper
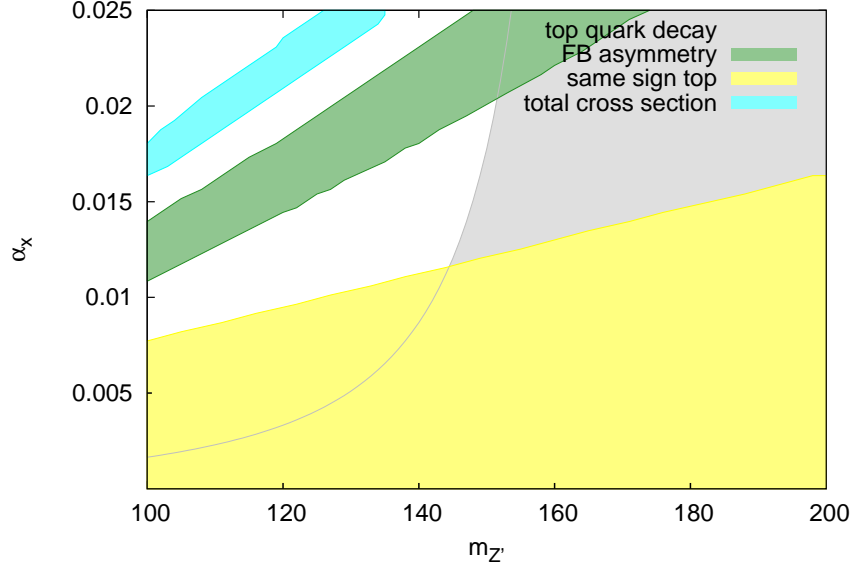
FIG. 3. The favored region for α_x and $m_{Z'}$ in the case where only Z' contributes.

bound at CMS. The branching fraction of the top quark to $Z'u$ is less than 5 % in the gray region. There is no overlapped region from the four constraints we consider. In particular it is quite difficult to evade the strong constraint from the same sign top pair production at the LHC. Figure 3 tells us that the region consistent with Tevatron and LHC could not realize the large $A_{\rm FB}$ which CDF and D0 observe. Thus a simple Z'-exchange model with a large FCNC is excluded.

3. Higgs-dominant case

In this subsection, we discuss top forward-backward asymmetry and the constraints from Tevatron and LHC in the multi-Higgs models. As discussed in the Ref. [44, 53], the Higgs contributions can enhance $A_{\rm FB}$. According to Sec. II B, we have not only Z' contribution but also neutral (pseudo) scalar, and charged Higgs contribution. In this section we consider only the Higgs contribution by assuming that the gauge coupling of the Z' boson is negligible. The scalar and pseudo-scalar Higgs bosons contribute to the $t\bar{t}$ and tt production only through the t-channel diagrams.

If the mixing, especially $(R_u)_{13}$, is large, the (t, u) element of Yukawa coupling for neutral scalar and pseudo-scalar Higgs could be enhanced. Since the Higgs masses are determined by their own vevs, they cannot be arbitrarily heavy, and we could expect them (at least the
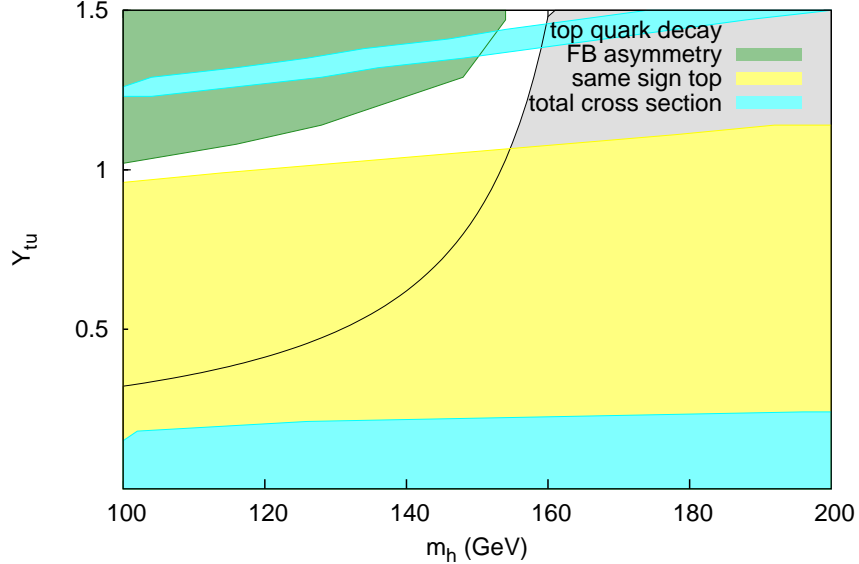
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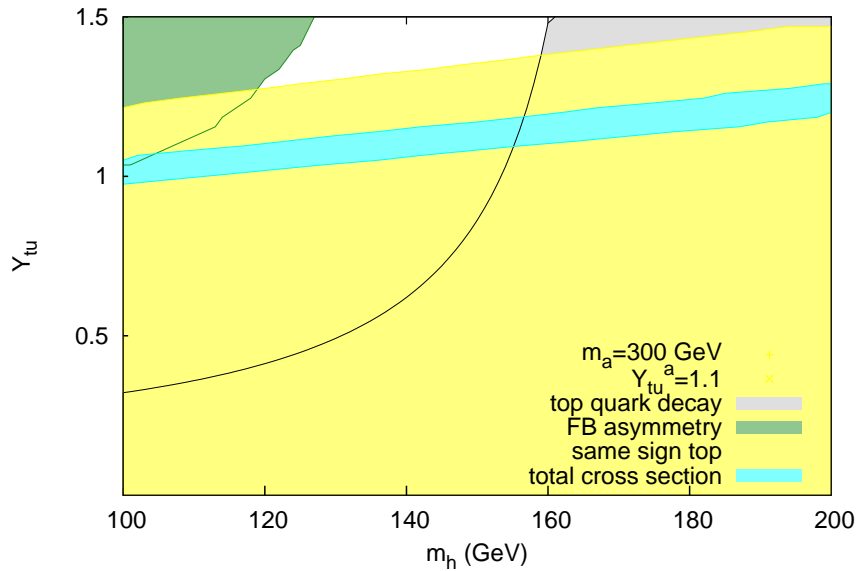FIG. 4. The favored region for Y_{tu} and m_h in the case where only h contributes.

FIG. 5. The favored region for Y_{tu} and m_h in the case where h and a contributes.

lightest one) to contribute to the top physics. h and a bosons can contribute to the same sign top pair production through their t-channel exchanges. In order to avoid the FCNC contribution of Higgs exchanges [44], we adopt the parametrization which we discussed in the subsections III A, III B, and the appendix.

We first consider the case without pseudo-scalar Higgs boson by setting Y_{tu}^a to zero. In
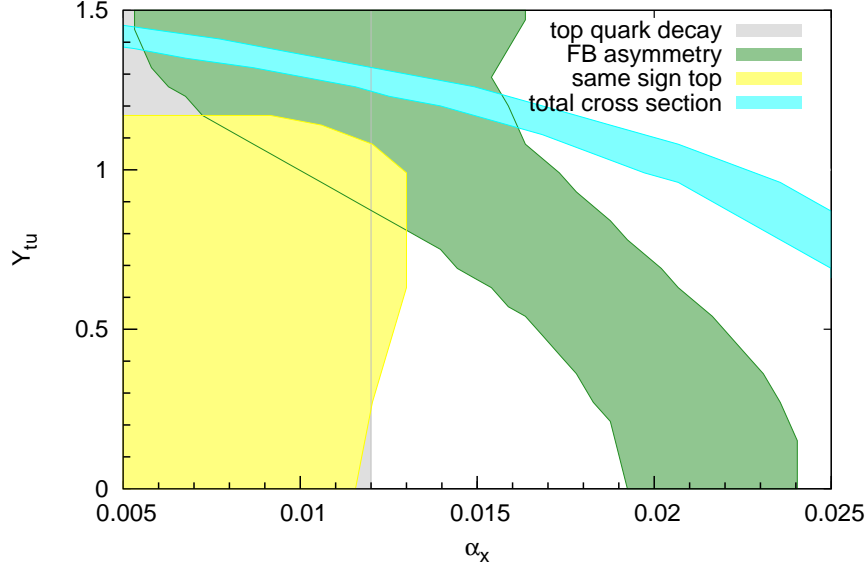
FIG. 6. The favored region for α_x and Y_{tu} for $m_{Z'} = 145$ GeV and $m_h = 180$ GeV.

Fig. 4 we show the each region allowed by the $t\bar{t}$ production (cyan), the same-sign top (yellow), the width of t (gray), and $A_{\rm FB}$ (green), based on the bounds we discussed in the IV B 1. In order to satisfy the bound from the same sign top pair production, Y_{tu} should be less than 1, but it is impossible to get enough enhancement for $A_{\rm FB}$. Thus a simple model with a scalar Higgs boson is excluded.

Next, we consider the case where both h and a contribute to the $t\bar{t}$ and tt production through their t-channel exchanges. For simplicity we assume the Yukawa coupling $Y_{tu}^a = 1.1$ and the mass $m_a = 300$ GeV of the pseudo-scalar Higgs a. We show the allowed region by the $t\bar{t}$ production (cyan), the same-sign top (yellow), the width of t (gray), and $A_{\rm FB}$ (green), respectively, in Fig. 5. In the low mass region $m_h \sim 100$ GeV, there is an overlap region which satisfies constraints from the $t\bar{t}$ production, tt production rates and $A_{\rm FB}$, but the branching fraction of the top quark decay to the Higgs boson becomes quite large. Therefore the model with scalar and pseudo-scalar Higgs bosons is excluded.

4. General case

In this subsection we consider more general case where Z', h and a contributes to the $t\bar{t}$ and tt production. We assume that the Z' boson has only one large off-diagonal element
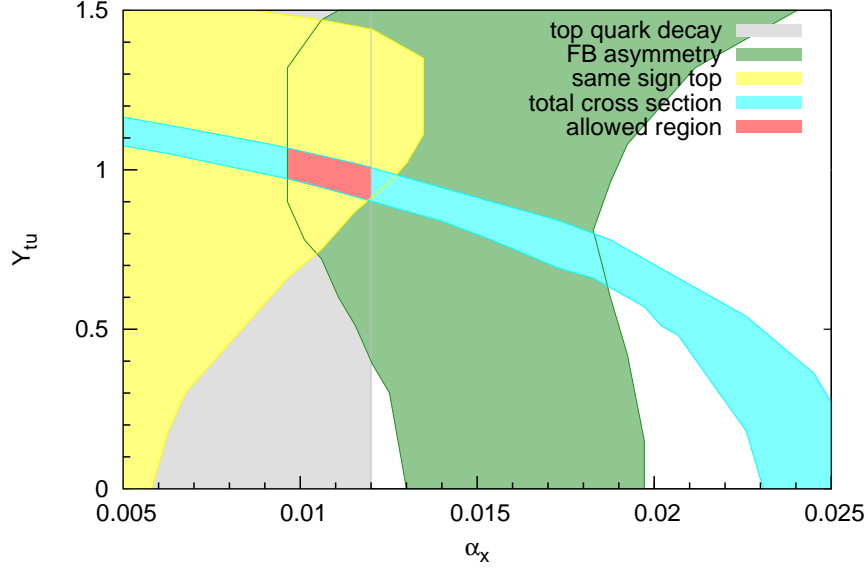
FIG. 7. The favored region for α_x and Y_{tu} at $(m_{Z'}, m_h, m_a) = (145, 180, 300)$ GeV and $Y_{tu}^a = 1.1$.
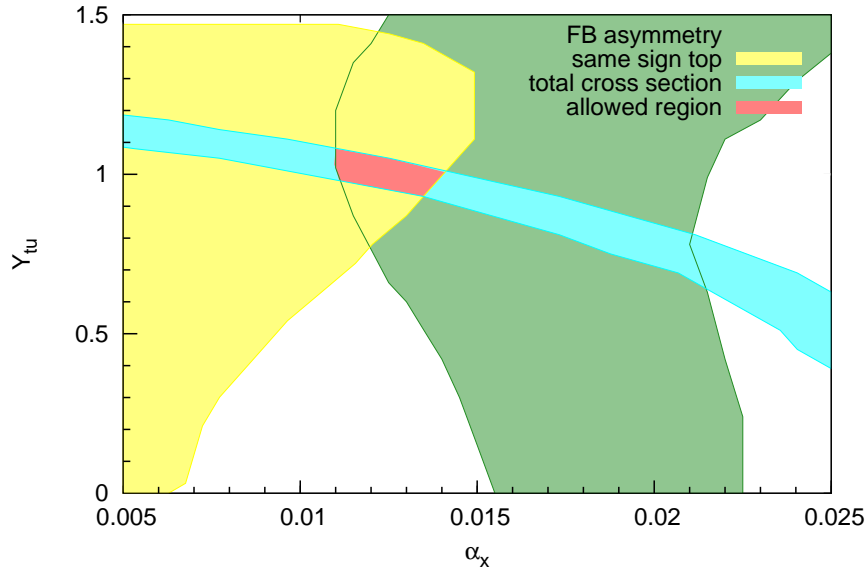

FIG. 8. The favored region for α_x and Y_{tu} at $(m_{Z'}, m_h, m_a) = (160, 180, 300)$ GeV and $Y_{tu}^a = 1.1$.

$(g_R^u)_{ut}$ and two large diagonal elements $(g_R^u)_{uu}$ and $(g_R^u)_{tt}$ as in the previous case[¶]. As we see in the subsections III A and III B, and the appendix, large $(g_R^u)_{ut}$ could enhance the Y_{tu} and Y_{tu}^a elements in 2HDM and 3HDM, as far as H_2 is not a dominant component in the lightest Higgs boson h. On the other hand, small $(g_R^u)_{cc}$, $(g_R^u)_{uc}$, and $(g_R^u)_{ct}$ could realize small (u, c)

[¶] In the 2HDM, $|(g_R^u)_{ut}|^2 = (g_R^u)_{uu}(g_R^u)_{tt}$ is satisfied, and in the 3HDM, $(g_R^u)_{uu}$ and $(g_R^u)_{tt}$ could be smaller than $(g_R^u)_{ut}$, as seen in Eq. A2.

element of the Yukawa couplings for neutral scalar and pseudo-scalar Higgs bosons, which gives the small D^0-$\overline{D^0}$ mixing. If either $\tan\beta$ or $\tan\beta_{1,2}$ are large, Y_{ut} and Y_{ut}^a may be also enhanced. Also the Yukawa coupling for the charged Higgs boson Y_{dt}^{u-} and Y_{bt}^{u-}, which contribute to the B_d-$\overline{B}_d$ mixing at one-loop level, could also be sizable. In order to avoid this situation, we will concentrate on the small $\tan\beta$ region in the following. Then, only the Yukawa couplings for the neutral scalar and the pseudo-scalar bosons, Y_{tu}, Y_{tt}, Y_{tu}^a, and Y_{tt}^a, could be $\sim O(1)$. In the charged Higgs sector, only Y_{bu}^{u-} and Y_{bt}^{u-} are dominant in the small $\tan\beta$ case, which may not contribute significantly to the top physics we are interested in this paper.

First, we consider the case where only Z' and h contribute to the $t\bar{t}$ and tt production by setting Y_{tu}^a to zero. In Fig. 6, we show the each region allowed by the $t\bar{t}$ production (cyan), the same-sign top (yellow), the width of t (gray), and $A_{\rm FB}$ (green) for $m_{Z'} = 145$ GeV and $m_h = 180$ GeV, respectively. As seen in Fig. 6, there is no region which satisfies all the constraints from the collider experiments. In order to be consistent with the upper bound for the same sign top pair production at CMS, the gauge coupling α_x and Yukawa coupling Y_{tu} should be smaller than 0.13 and 1.2, but in that region the $t\bar{t}$ cross section at the Tevatron turns out to underestimate the empirical data. As we mentioned before, the FN-type model could have the neutral scalar Higgs contribution through the mixing between Φ and H, but it is impossible to enhance $A_{\rm FB}$ enough because of the same-sign top bound.

However in the multi-Higgs models, we could have another contribution such as pseudo-scalar Higgs, a. As we see in the Eq. (17) and (23), h and a couplings have opposite signs for the same-sign top pair production, leading to the destructive interference. Therefore we could expect that the interference among a, h, and Z' decrease the tt cross section. For simplicity we assume $Y_{tu}^a = 1.1$ and $m_a = 300$ GeV. Figures 7 and 8 show the allowed regions corresponding to the each experimental bounds in the cases with $m_{Z'} = 145$ GeV and $m_{Z'} = 160$ GeV. We see that the light Z' scenario survives the same sign top pair constraint due to the destructive interference from h and a contributions in the t-channel. The 160 GeV Z' can drastically reduce the branching fraction of $t \to Z'u$, so that the gray region need not be included in the Fig. 8. The red region is consistent with all the experimental results from the Tevatron and LHC up to now. As one can check explicitly using Eq.s (18) and (24), Y_{tu} must be smaller than Y_{tu}^a in the 2HDM. The allowed regions in the Figs. 7 and 8 satisfy this condition. Here we ignore the $\sim 5\%$ asymmetry from the NLO contribution in
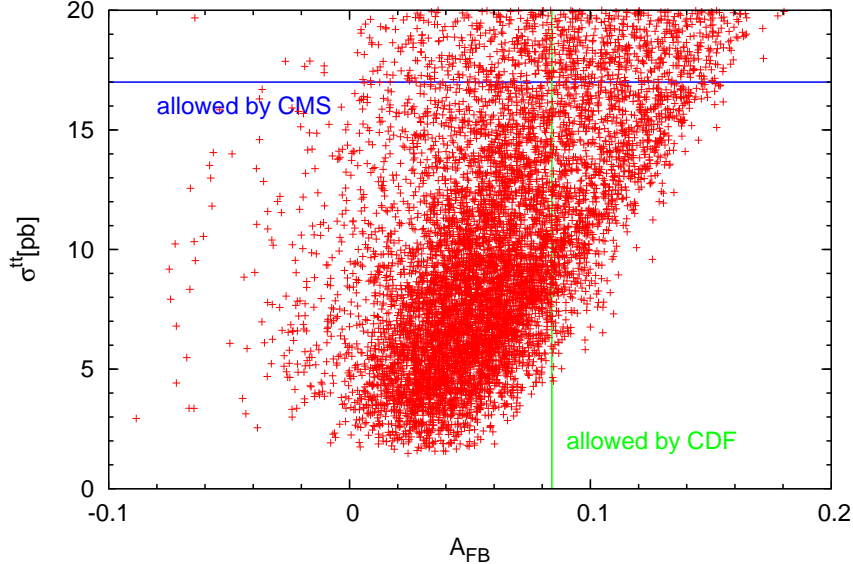
FIG. 9. The scattered plot for the top forward-backward asymmetry at the Tevatron and the same sign top pair production at the LHC in unit of pb for the model parameters which agree with the cross section for the $t\bar{t}$ pair production at the Tevatron.

the SM. Adding this to our predictions will make the $A_{\rm FB}$ larger. $A_{\rm FB}^{\rm New}$ in the allowed region in Figs. 7 and 8 is between 0.084 and 0.12 without the contribution from the SM NLO. If one includes the contribution from the SM NLO effects, $A_{\rm FB}$ could be enhanced to about 14 %.

Now we examine our model by varying the model parameters in order to watch how the allowed region is changed. As we have mentioned earlier, we do not consider the lighter Higgs boson than the top quark mass to avoid the large exotic decay of the top quark. $m_{Z'} = 145$ GeV is fixed in this analysis. For the other parameters, we choose the following ranges: 180 GeV $< m_h, m_a < 1$ TeV, $0.005 < \alpha_x < 0.025$, and $0.5 < Y_{tu}, Y_{tu}^a < 1.5$. We impose the condition $|Y_{tu}| < |Y_{tu}^a|$ which can be induced from Eq.s (18) and (24). In Fig. 9, we show the scattered plot for the top FB asymmetry at the Tevatron and the same sign top pair production at the LHC for the above parameter region. All points in the figure satisfy the top quark pair $(t\bar{t})$ production rate at the Tevatron within 1σ. The right side of the vertical line is consistent with the top FB asymmetry in the lepton+jets channel at CDF, while the lower region of the horizontal line is the allowed region from the same sign top pair production at CMS. Therefore the points in the right-lower side are favored
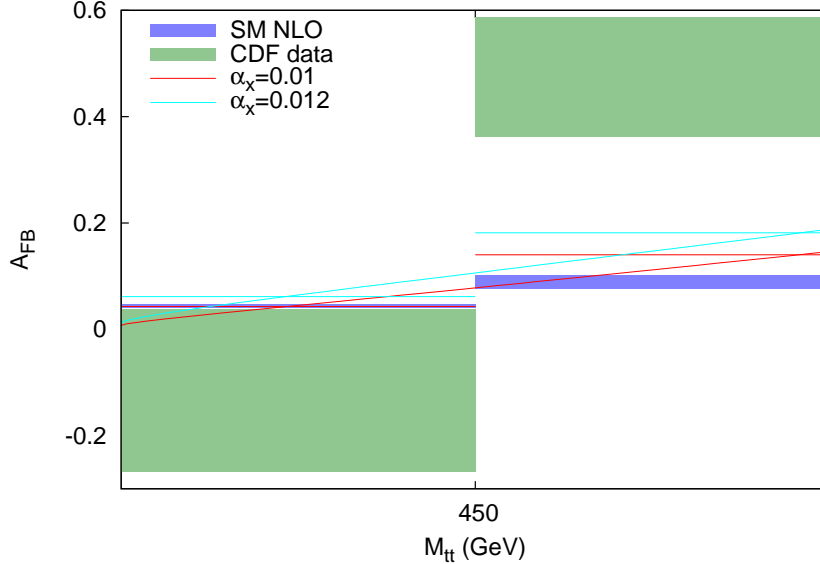
FIG. 10. The top forward-backward asymmetry as a function of the $t\bar{t}$ invariant mass at the Tevatron for $m_{Z'} = 145$ GeV, $m_h = 180$ GeV, $m_a = 300$ GeV and $Y^a_{tu} = 1.1$. The red and cyan lines correspond to $\alpha_x = 0.01$ and $\alpha_x = 0.012$, respectively. The blue bins are the SM prediction from MC@NLO while the green bins are measurements in the lepton+jets channel at CDF.

by the present experiments. The points in the favored region satisfy the following region: 180 GeV $< m_h < 250$ GeV, $0.005 < \alpha_x < 0.014$, $0.75 < Y_{tu} < 1.3$, and $0.9 < Y^a_{tu} < 1.5$ with a constraint $|Y_{tu}| < |Y^a_{tu}|$. The lightest scalar Higgs boson is less than 250 GeV to be accommodated with the data, but the mass m_a of the lightest pseudoscalar Higgs boson is not constrained much by the data. In general the cross section for the same sign top pair production becomes small as the gauge or Yukawa coupling becomes small, but there is no general tendency in the dependence on the Higgs boson masses.

The CDF Collaboration also announced the top forward-backward asymmetry in the lepton+jets channel by dividing the phase space. One of the most interesting results is that $A_{\rm FB}$ in the $t\bar{t}$ invariant mass region larger than 450 GeV is over about 3.4 σ from the SM prediction. In Fig. 10, we depict our results for the invariant mass distribution of $A_{\rm FB}$ for two reference parameter sets: $\alpha_x = 0.01$ (red line or red bin) and $\alpha_x = 0.012$ (cyan line or cyan bin) for $m_{Z'} = 145$ GeV, $m_h = 180$ GeV, $m_a = 300$ GeV, $Y_{tu} = 1$ and $Y^a_{tu} = 1.1$. The green and blue bands correspond to the CDF data in the lepton+jets channel and the SM prediction from MC@NLO, respectively. Our prediction in the large $t\bar{t}$ invariant mass region

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is rather smaller that the CDF data. However if we include the NLO corrections in the SM the prediction would agree with the data within about 2 σ.

C. Dijet resonance

Another interesting observation that might be related with light Z' is the CDF Wjj excess [57]. One possible interpretation of which is $p\bar{p} \to WZ'$ followed by $Z' \to jj$ with $\sigma(WZ') \sim 4$ pb and $m_{Z'} \sim 140$ GeV [58, 59, 61]. This excess however was not confirmed by the D0 Collaboration [82], and more investigation is necessary for understanding this discrepancy. Further data from the LHC for this channel will shed light on this issue.

In our model, Z' and charged Higgs may play an important role in the $p\bar{p} \to Wjj$ process. If charges of $U(1)'$ are assigned to quarks universally, gauge couplings and Yukawa couplings are flavor-blind, but we could have large diagonal elements which would be constrained by the UA2 experiment [94, 95]. The main process would be $u, \bar{d}(d, \bar{u}) \to W^+(W^-), Z'$. As investigated well in Ref.[58, 59, 61], that cross section could be large to explain the data without conflict with the UA2 bound.

In the case that charges of $U(1)'$ are flavor-dependent, we may allow only large off-diagonal elements, such as Y_{tu} and α_x to enhance the $A_{\rm FB}$. In this case, the most important one is the parton process $u\bar{b}(b\bar{u}) \to h^{\pm} \to W^{\pm}Z'$ with a subsequent decay $Z' \to jj$, where $h^{\pm}$ is the lightest charged Higgs boson. The charged Higgs boson has a similar coupling structure to the neutral coupling, so that only the u_R-b_L-h^+ and b_R-u_L-h^- vertices can be as large as that for the u_R-t_L-h. In the 2HDM, the interaction lagrangian for the charged Higgs boson with the W and Z' boson is given by

$$\mathcal{L} = -g' m_W \sin 2\beta h^+ W^{-\mu} Z'_{\mu} + h.c..\tag{37}$$

For $m_{h^{\pm}} = 270$ GeV, we get $\sigma(WZ') \sim 10$ pb $\times \sin^2 2\beta \lesssim 10$ pb at the Tevatron. It would be about 4.5 pb for $\sin 2\beta = 0.7$ which is in the range of the CDF report, but could be substantially smaller if $\sin 2\beta$ becomes smaller. In the 3HDM, $\sin 2\beta$ can be replaced by $\sin 2\beta_2$ for $\xi_1^{\pm}$ (See the appendix).

D. Single top production

The large flavor changing neutral current in the top sector implies a large single top quark production at hadron colliders. For example, there may be large single top production through the $gu \to tZ'$ or th processes in our model. The single top quark production was measured by the D0 Collaboration with $\sigma(p\bar{p} \to tbq + X) = 2.90 \pm 0.59$ pb [96]. The CMS Collaboration also announced the cross section for the single top quark production: $\sigma(p\bar{p} \to tbq + X) = 83.6 \pm 29.8 \pm 3.3$ pb [97]. The experimental results are based on the observation of a top quark with an extra b quark, *i.e.* require tagging two b quarks. However in our model the branching fractions of Z' and h decays to the $bq + X$ state are quite small. Thus our model would not be constrained by the current experiments on the single top production. Eventually our model would be strongly constrained if the cross section in the $p\bar{p}(p) \to t + X$ channel is measured. One possible mode is a jj resonance associate with a single top quark [48].

V. COLD DARK MATTER

As discussed in several papers [98–104], the extension to $U(1)'$ can also provide CDM candidates. As we discuss in the subsection II C, we may require SM gauge vector-like pairs for anomaly condition. Especially, the 3HDM required only (q_{LI}, q_{RI}) for the $U(1)_Y U(1)'^2$ anomaly cancellation. In this section, we comment on the possibility that the required chiral fields give rise to CDM candidates.

First, let us focus on models with $SU(2)_L$ doublet pairs, (l_{Ri}, l_{Li}) instead of $SU(3)_c$ triplets (q_{LI}, q_{RI}), which was introduced in the subsection II C. l_{Ri} and l_{Li} are chiral fields charged under $SU(2)_L \times U(1)_Y$ like the left-handed lepton, so we can expect one component to be charged and the other to be neutral after EW breaking. The Yukawa couplings corresponding to the mass terms are as follows,[**]

$$V_l = y_1^l \Phi^\dagger \overline{l_{R1}} l_{L1} + y_2^l \Phi \overline{l_{R2}} l_{L2}. \tag{38}$$

The charged and neutral fields are degenerate after $U(1)'$ breaking, and then they can be split after EW breaking according to radiative corrections. l_{Li} and l_{Ri} do not have Yukawa

---

[**] When q_Φ is to 1, mass terms of (l_{LI}, l_{RI}) or (q_{LI}, q_{RI}) can be given by this form, because the solution with $Q_L - Q_R = 1$ is always found.

coupling with the SM fermions because of $U(1)'$, so that $U(1)$ global symmetry, which is phase rotation of l_{Li} and l_{Ri}, could be remained, and their stability is guaranteed by the global symmetry. After EWSB, one component is charged and the other is neutral. The light neutral components could be good CDM candidates, as discussed in the Ref. [105]. They are degenerate before EWSB, but especially the charged particles get enough large radiative corrections and then heavier than the neutral. If the mass split is bigger than the electron mass, the charged can decay to the neutral, e, and ν_e through the weak interaction.

The CDM can annihilate to 2 light quarks through Z' and Z boson exchanging, and 2 gauge boson according to the t-channel. If Z' exchanging works to explain CDF anomaly, $g'/m_{Z'}$ is huge like $g'/m_{Z'} \sim 500\text{GeV}$. Our CDM can interact with nuclei through Z' exchanging, so that such large $g'/m_{Z'}$ leads so large direct cross section, $\sigma_{SI} \sim 0.01\text{pb}$. The mass of the CDM is constrained by the search for extra leptons, that is, it must be heavier than 100 GeV, where direct search for dark matters shows negative results. Even if we consider the scenario that Z' interaction is negligible in the direct scattering, for example, in the case that only $(g_R^u)_{ut}$ are large like the 3HDM, Z boson exchanging will work at the higher order. Such heavy CDM scenario is not favored by direct search.

Next, we discuss the case with extra $SU(3)$ triplets, (q_{LI}, q_{RI}).[††] The mass terms are give by Φ like the masses of l_{Li} and l_{Ri}. Those extra colored particles would be stable because of the $U(1)'$ symmetry and $U(1)$ global symmetry corresponding to phase rotation of q_{Li} and q_{Ri}. In order to allow the decay of the extra colored particles, we introduce mixing term between $q_{L1,2}$ and D_{Ri} according to adding X,

$$V_m = \lambda_i X^\dagger \overline{D_{Ri}} q_{L1} + \lambda_i X \overline{D_{Ri}} q_{L2}, \tag{39}$$

where X is SM gauge-singlet scalar with $U(1)'$ charge, Q_L. If X does not get nonzero vev, we can expect X to be stable because of the remnant global symmetry after $U(1)'$ breaking. This type of dark matter has been well investigated in Ref. [101, 103].

It might be possible to consider charge assignments which only require the one extra generation. If the mixing between extra quarks and SM quarks is forbidden by $U(1)'$ charge, we may need extra $SU(2)_L$ doublet scalar which has Yukawa coupling with extra quarks and SM quarks. If the extra Higgs does not get vev, the neutral component could be a CDM candidate [101, 105]. This case also predicts large cross section through Z and Z' bosons.

[††] One can also replace them with fields charged under $SU(3)_c \times SU(2)_L$ with 1/6 $U(1)_Y$ charges in this argument.

VI. SUMMARY

Let us summarize our results. In this paper, we constructed a complete $U(1)'$ model for flavor dependent couplings to the right-handed up-type quarks in the SM, and discussed the top FB asymmetry, the CDF Wjj excess and cold dark matters. We first described the flavor dependent and leptophobic chiral $U(1)'$ models, and introduced new Higgs fields and fermions for the renormalizable Yukawa couplings for the SM fermions and the anomaly cancellation, respectively. Then the couplings of the SM fermions to the new Z' and new flavored Higgs doublets (in terms of the (pseudo) neutral/charged Higgs fields) were derived, and were used for the top FB asymmetry and the CDF Wjj excess as well as the same sign top pair production at the LHC. We found that the interference effects between the Z' and the Higgs bosons generally improves the overall description of the $t\bar{t}$ production cross section at the Tevatron and the top FB asymmetry, their $M_{t\bar{t}}$ distributions, and reduce the production cross section for the same sign top pair at the LHC. Our model for the top FB asymmetry can be tested in the near future at the Tevatron and the LHC by measuring $t \to Z'u$, $h \to t\bar{u} + c.c.$, and the single top production without the b quark in the final states $(p\bar{p}, pp \to tZ')$. Also the spin-spin correlations of $t\bar{t}$ and the longitudinal polarization of (anti)top quark [15, 20] could be useful for testing our models based on the light Z', h and a. It can not be too much emphasized that the (pseudo) scalar Higgs bosons in our models are not added by hand, but should be included in the chiral $U(1)'$ flavor model of Ref. [83]. It is simply inconsistent to do phenomenology without them. And most interestingly, these new Higgs doublets charged under $U(1)'$ not only help the models viable as a solution for the top FB asymmetry, but also can accommodate the CDF Wjj excess for $\sin 2\beta \sim 0.7$ through $p\bar{p} \to h^{\pm} \to W^{\pm}Z'$, which is a kind of bonus when we made a completion of light leptophobic Z' with flavor dependent couplings to the RH up-type quarks. By making the light Z' model for the top FB asymmetry mathematically consistent in terms of anomaly cancellation and physically realistic in terms of renormalizable Yukawa couplings, we found that the models come with new ingredients that could also accommodate other phenomena such as the CDF Wjj excess or the CDM of the universe. There are still constraints we did not touch in this paper, such as ρ parameter. In our models, extra Higgs doublets are charged under $U(1)'$ and induce the mixing between Z and Z'. For example, the tree-level contribution will be written down by the form linear to $\sin \beta$ in 2HDM, so that our parameter choice

must be consistent with the small mixing. We are sure that small $\sin \beta$, ($\lesssim O(10^{-1})$), can realize large (t, u) elements and enough large Wjj excess without exceeding the observed ρ parameter [106].

Finally, we would like to note that our conclusions about extended multi Higgs doublets (with some of them being $U(1)'$ flavored) and the related phenomenology would be generically true for many flavor gauge models with chiral couplings to the SM fermions. Some features obtained in this paper may be specific to our explicit models, depending on the new matter contents we introduce in order that we achieve the gauge anomaly cancellation and also allow the necessary Yukawa couplings. Our strategies can be adopted in any other attempts to construct realistic flavor models for the top FB asymmetry and the CDF Wjj excess as well as $B_s - \overline{B_s}$ mixing in terms of flavor changing Z'. This statement will apply to axigluon models, extra W' model, or flavor $SU(3)$ model for the right-handed up quarks (namely the models with chiral gauge interactions). It would not be enough to include only spin-1 vector bosons in order to discuss the top FB asymmetry or the same sign top pair productions. It is mandatory to construct the entire lagrangian including the realistic renormalizable Yukawa couplings, including new Higgs doublets that are charged under the chiral flavor gauge groups under consideration, in order to discuss the top physics. New Higgs doublets that are charged under chiral gauge symmetry group can modify the top FB asymmetry, the same sign top pair productions and the Wjj. It will remain to be seen if the predictions on the top FB asymmetry, the same sign top pair and related phenomenology depends strongly on the additional Higgs doublets in addition to the original spin-1 gauge bosons (axigluon, Z', W' or $SU(3)$ flavor gauge bosons) effects.

ACKNOWLEDGMENTS

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Appendix A: Explicit description of 3 Higgs doublets model with $(-1, 0, 1)$

We show the explicit descriptions of gauge couplings and Yukawa couplings in the 3HDM of Sec. III B. As we see in the section, the couplings depend on the mixing, $(R_u)_{ij}$, and we have to avoid the FCNC constraint from D^0-$\overline{D}^0$ mixing, so that let us fix R_u matrix as follows,

$$
R_u = \begin{pmatrix} e^{i\delta_1} & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & e^{i\delta_3} \end{pmatrix} \begin{pmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{pmatrix}. \tag{A1}
$$

1. Gauge couplings

In this case, the matrix of gauge coupling, g_R^u, is

$$
g_R^u = \begin{pmatrix} -\cos 2\theta & 0 & -e^{i(\delta_1 - \delta_3)} \sin 2\theta \\ 0 & 0 & 0 \\ -e^{-i(\delta_1 - \delta_3)} \sin 2\theta & 0 & \cos 2\theta \end{pmatrix}, \tag{A2}
$$

and the others satisfy $g_{L,R}^d = g_L^u = 0$. For this choice, there is no $D^0 - \overline{D^0}$ mixing from Z' exchanges.

2. Yukawa couplings for neutral scalar Higgs

Yukawa couplings for SM fermions and lightest neutral scalar Higgs, which are defined in the Eq. (17), are also described according to Eq. (A1),

$$
\left(Y_{ij}^u\right) = \begin{pmatrix} \frac{m_u}{v}\left(\frac{O_{11}^h \cos^2\theta}{\cos\beta_1 \cos\beta_2} + \frac{O_{31}^h \sin^2\theta}{\sin\beta_2}\right) & 0 & \frac{m_u e^{i(\delta_1-\delta_3)}}{2v}\left(\frac{O_{11}^h \sin 2\theta}{\cos\beta_1 \cos\beta_2} - \frac{O_{31}^h \sin 2\theta}{\sin\beta_2}\right) \\ 0 & \frac{m_c}{v}\frac{O_{21}^h}{\sin\beta_1 \cos\beta_2} & 0 \\ \frac{m_t e^{-i(\delta_1-\delta_3)}}{2v}\left(\frac{O_{11}^h \sin 2\theta}{\cos\beta_1 \cos\beta_2} - \frac{O_{31}^h \sin 2\theta}{\sin\beta_2}\right) & 0 & \frac{m_t}{v}\left(\frac{O_{11}^h \sin^2\theta}{\cos\beta_1 \cos\beta_2} + \frac{O_{31}^h \cos^2\theta}{\sin\beta_2}\right) \end{pmatrix},
$$

$$
Y_{ij}^d = \frac{m_i^d O_{21}^h}{v \sin\beta_1 \cos\beta_2}\delta_{ij},
$$

$$
Y_{ij}^e = \frac{m_i^l O_{21}^h}{v \sin\beta_1 \cos\beta_2}\delta_{ij}, \tag{A3}
$$

where $\beta_{1,2}$ are defined as

$$(\langle H_1\rangle, \langle H_2\rangle, \langle H_3\rangle) = \frac{v}{\sqrt{2}}(\cos\beta_1\cos\beta_2, \sin\beta_1\cos\beta_2, \sin\beta_2). \tag{A4}$$

For this choice, there is no $D^0 - \overline{D^0}$ mixing from neutral Higgs exchanges.

3. Yukawa coupling for charged Higgs and pseudo-scalar Higgs

According to the orthogonal directions of Goldstone bosons, we could know the directions of the massive charged and pseudo-scalar Higgs. The direction of Goldstone mode will be $(\cos\beta_1\cos\beta_2, \sin\beta_1\cos\beta_2, \sin\beta_2)$, so that the other massive modes, $\xi_I(q = 1,2)$, will be written as

$$\xi_1 : (\cos\beta_1\sin\beta_2, \sin\beta_1\sin\beta_2, -\cos\beta_2),$$
$$\xi_2 : (\sin\beta_1, -\cos\beta_1, 0). \tag{A5}$$

The Yukawa couplings for the each charged Higgs and each pseudo-scalar Higgs in the Eq. (21) and (23) are

$$\left(\frac{(V_{\text{CKM}})_{il}Y_{lj}^{u1-}}{\sqrt{2}}\right) = \begin{pmatrix} \frac{m_u\tan\beta_2}{v}\left(\cos^2\theta - \frac{\sin^2\theta}{\tan^2\beta_2}\right) & 0 & \frac{m_u\sin2\theta e^{i(\delta_1-\delta_3)}}{v\sin2\beta_2} \\ 0 & \frac{m_c\tan\beta_2}{v} & 0 \\ \frac{m_t\sin2\theta e^{-i(\delta_1-\delta_3)}}{v\sin2\beta_2} & 0 & \frac{m_t\tan\beta_2}{v}\left(\sin^2\theta - \frac{\cos^2\theta}{\tan^2\beta_2}\right) \end{pmatrix},$$
$$Y_{ij}^{d1+} = \frac{\sqrt{2}m_j^d\tan\beta_2}{v}(V_{\text{CKM}})_{ij}, \tag{A6}$$

and for ξ_2 are

$$\left(\frac{(V_{\text{CKM}})_{il}Y_{lj}^{u2-}}{\sqrt{2}}\right) = \begin{pmatrix} \frac{m_u\tan\beta_1}{v\cos\beta_2}\cos^2\theta & 0 & \frac{m_u\tan\beta_1\sin2\theta}{2v\cos\beta_2}e^{i(\delta_1-\delta_3)} \\ 0 & -\frac{m_c}{v\tan\beta_1\cos\beta_2} & 0 \\ \frac{m_t\tan\beta_1\sin2\theta}{2v\cos\beta_2}e^{-i(\delta_1-\delta_3)} & 0 & \frac{m_t\tan\beta_1}{v\cos\beta_2}\sin^2\theta \end{pmatrix},$$
$$Y_{ij}^{d2+} = -\frac{\sqrt{2}m_j^d}{v\tan\beta_1\cos\beta_2}(V_{\text{CKM}})_{ij}. \tag{A7}$$

Y_{ij}^{au} and Y_{ij}^{ad} for each ξ_q are given by $(V_{\text{CKM}})_{il}Y_{lj}^{uq-}/\sqrt{2}$ and $(V_{\text{CKM}})_{il}^{\dagger}Y_{lj}^{dq+}/\sqrt{2}$, and Y_{ij}^{ae} is given by replacing m_j^d in the $(V_{\text{CKM}})_{il}^{\dagger}Y_{lj}^{dq+}/\sqrt{2}$ with m_j^l.

4. $W_\mu^+ \xi_q^- Z'^\mu$ couplings

We can describe the coupling of the charged Higgs with W and Z' bosons. When we set the $U(1)'$ charges of Higgs, (H_1, H_2, H_3), to (q_{H1}, q_{H2}, q_{H3}), the couplings of $\xi_q^\pm$ are

$$-V_{W_\mu^+ \xi_1^- Z'^\mu} = 2m_W g'(q_{H1} \cos^2 \beta_1 + q_{H2} \sin^2 \beta_1 - q_{H3}) \sin \beta_2 \cos \beta_2 (\xi_1^+ W_\mu^- Z'^\mu + \xi_1^- W_\mu^+ Z'^\mu),$$
(A8)

and

$$-V_{W_\mu^+ \xi_2^- Z'^\mu} = 2m_W g'(q_{H1} - q_{H2}) \cos \beta_1 \sin \beta_1 \cos \beta_2 (\xi_2^+ W_\mu^- Z'^\mu + \xi_2^- W_\mu^+ Z'^\mu).$$
(A9)

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