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Top Forward-backward asymmetry at the Tevatron vs. Charge asymmetry at the LHC in chiral $U(1)'$ models with flavored Higgs fields

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Abstract. An extra $U(1)'$ model with Z' coupled only to the right-handed (RH) up-type quarks has been one of the popular models for the Tevatron top forward-backward asymmetry (FBA), and has been excluded by the same-sign top-pair productions at the LHC. However, the original Z' model is not physical, since the up-type quarks are massless including the top quark. This disaster can be evaded if the Higgs sector is extended by including new Higgs doublets with nonzero $U(1)'$ charges. We find that some parameter regions could achieve not only the top FBA at the Tevatron, but also the charge asymmetry at the LHC without exceeding the upper limit of the same-sign top-quark pair production at the LHC. The lesson is that it is mandatory to extend the Higgs sector whenever one considers chiral gauge symmetries beyond the SM gauge group. Otherwise some fermions remain massless, and thus it is meaningless to work on phenomenology without the extra Higgs doublets with new chiral gauge charges.

1 Introduction

The top forward-backward asymmetry ($A^t_{\rm FB}$) is one of the most interesting observables because there exists discrepancy between theoretical predictions in the standard model (SM) and experimental results at the Tevatron. The most recent measurement for $A^t_{\rm FB}$ at CDF is $A^t_{\rm FB} = 0.162\pm0.047$ in the letpon+jets channel with a full set of data [1], which is consistent with the previous measurements at CDF and D0 within uncertainties [2]. The SM predictions are between 0.06 and 0.09 [3, 4], so that the deviation is around 2σ.

If the discrepancy in $A^t_{\rm FB}$ is generated by new physics, the new physics model would be tested at the LHC. One of the good measurements is the charge asymmetry A^y_C, which is defined by the difference of numbers of events with the positive and negative $\Delta|y| = |y_t| - |y_{\bar{t}}|$ divided by their sum. The current values for A^y_C are $A^y_C = -0.018 \pm 0.028\pm0.023$ at ATLAS [5] and $A^y_C = 0.004\pm0.010\pm0.012$ at CMS [6], respectively, which are consistent with the SM prediction ~ 0.01 [3]. Another interesting observable at the LHC is the cross section for the same-sign top-quark pair production, σ^{tt}, which is not allowed in the SM. The current upper bound on σ^{tt} is about 17 pb at CMS [7] 2 pb or 4 pb at ATLAS depending on the model [8].[1] Some models which were proposed to account for $A^t_{\rm FB}$ at the Tevatron, predict large A^y_C and/or σ^{tt} so that they are already disfavored by present experiments at the LHC.

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[1] Very recently the CMS Collaboration updated it to be less than 0.39 pb at 95 % C.L.. [9].

2 The original Z' model by Jung *et al.* [10]

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

$$\mathcal{L} = -g_X Z'_\mu \left[\overline{t_R}\gamma^\mu u_R + H.c.\right]. \quad (1)$$

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 FCNS processes such as $K^0-\overline{K^0}$, $B^0_{d(s)}-\overline{B_{d(s)^0}}$ mixings and $B \to X_s\gamma$. And such a light Z' should be leptophobic in order to avoid the strong bounds from the Drell-Yan processes. Therefore the original Z' model 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 not consistent. 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. Therefore it would be highly nontrivial to construct a realistic gauge theory which satisfies the conditions in the original Z' model. Also the original Z' model was excluded by the same sign top pair productions, because Z' exchange can contribute to $uu \to tt$. The upper bounds on the same-sign top-pair production put strong constraints on this model [11]. However the story is not that simple for various reasons described above, and the model should be extended with new Higgs doublets as described in the next section [12].

3 $U(1)'$ models with flavored multi-Higgs doublets by Ko, Omura and Yu [12]

In this section we review the flavor-dependent chiral U(1)′ model with flavored Higgs doublets that were 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 U(1)′ symmetry [12]. The Z' boson better be leptophobic to avoid the stringent constraints from the LEP II and Drell-Yang experiments. Furthermore, it would be very difficult to assign flavor-dependent U(1)′ charges to the down-type quarks and left-handed up-type quarks because it gives rise to dangerous FCNCs. Therefore 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

$$\mathcal{L}_{Z'q\bar{q}} = g' \sum_i u_i Z'_\mu \overline{U^i_R} \gamma^\mu U^i_R, \tag{2}$$

where U^i_R is a right-handed up-type quark field in the interaction eigenstates and g' is the couping 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

$$\begin{aligned}\mathcal{L}_{Z'q\bar{q}} &= g' Z'_\mu \Big[(g^u_R)_{ut} \overline{u_R} \gamma^\mu t_R + (g^u_R)_{ut} \overline{t_R} \gamma^\mu u_R \\ &\quad + (g^u_R)_{uu} \overline{u_R} \gamma^\mu u_R + (g^u_R)_{tt} \overline{t_R} \gamma^\mu t_R \Big]. \end{aligned} \tag{3}$$

The 3×3 mixing matrix $(g^u_R)_{ij} = (R_u)_{ik} u_k (R_u)^\dagger_{kj}$ is the product of the U(1)′ charge matrix 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-$\overline{D^0}$ 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 $(g^u_R)^2_{ut} = (g^u_R)_{uu}(g^u_R)_{tt}$ [2]. 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 [3]. 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 Higgs bosons 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

$$V = Y^h_{tu} \overline{u_L} t_R h + Y^H_{tu} \overline{u_L} t_R H + i Y^a_{tu} \overline{u_L} t_R a + h.c., \tag{4}$$

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 [4].

Introducing $U(1)'$ flavored Higgs doublets is very important because they generates 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]:

$$Y^h_{tu} = \frac{2m_t (g^u_R)_{ut}}{v \sin(2\beta)} \sin(\alpha - \beta) \cos\alpha_\Phi\,, \tag{5}$$

$$Y^H_{tu} = -\frac{2m_t (g^u_R)_{ut}}{v \sin(2\beta)} \cos(\alpha - \beta) \cos\alpha_\Phi\,, \tag{6}$$

$$Y^a_{tu} = \frac{2m_t (g^u_R)_{ut}}{v \sin(2\beta)}\,. \tag{7}$$

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

[2] We note that the relation is not valid for the other charge assignments. For general cases, we introduce a parameter ξ with $(g^u_R)_{uu}(g^u_R)_{tt} = \xi (g^u_R)^2_{ut}$ where ξ is a free parameter.

[3] 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.

[4] 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.

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.

4 Phenomenology

4.1 Generalities and Inputs

In this section, we discuss phenomenology of our model described in the previous section. If new physics affects the top-quark pair production and could accommodate $A^t_{\rm FB}$ 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 top-quark pair production at the LHC in the parameter space which give rise to a moderate $A^t_{\rm FB}$ [12]. In our chiral U(1)$'$ models, the constraint from the same-sign top-quark pair production could be relaxed because of the destructive 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 $(g^u_R)^2_{ut} = (g^u_R)_{uu}(g^u_R)_{tt}$ [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 $(g^u_R)_{uu}(g^u_R)_{tt} = \xi(g^u_R)^2_{ut}$, where ξ is a function of mixing angles and $0 \le |\xi| \le O(1)$. In the case of $m_{Z'} \ge 2m_t$, a resonance around the Z' mass for nonzero ξ 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 ξ.

The cross sections for the top-quark pair production at the Tevatron are $\sigma(t\bar{t}) = (7.5 \pm 0.48)$ pb at CDF [14] and $\sigma(t\bar{t}) = (7.56^{+0.63}_{-0.56})$ pb at D0 [15], respectively. At the LHC, the cross sections for the top-quark pair production are $\sigma(t\bar{t}) = (165.8 \pm 13.3)$ pb at CMS [16] and $\sigma(t\bar{t}) = (177 \pm 11)$ pb at ATLAS [17], respectively. In this work, we require that the cross section for the top-quark pair production is in agreement with the CDF result in the 1σ level, which has the least uncertainty. Another reason to use the Tevatron result for the check of our model is that the top-quark pair production at the Tevatron is more sensitive to new physics in the $u\bar{u} \to t\bar{t}$ process than at the LHC.

In the SM, the top quark dominantly decays into $W+b$. In our models, there are several flavor-changing vertices u_R-t_R-Z', u_R-t_L-h, and u_R-t_L-a. If the Z' or Higgs bosons are lighter than the top quark, it could be dangerous because the branching ratio of the top quark to $W + b$ is significantly altered. We assume that the pseudoscalar Higgs boson a is heavier than the top quark and the branching ratio of the exotic decay of the top quark such as $t \to Z'u, hu$ is less than 5%. We find that the exotic decay mode of the top quark can be suppressed, if we choose $\alpha_x \equiv ((g' g^u_R)_{ut})^2/(4\pi) \lesssim 0.012$ for $m_{Z'} = 145$ GeV and $Y_{tu} \lesssim 0.5$ for $m_h = 125$ GeV.

Furthermore, such large FCNCs could generate the same-sign top-quark pair production through the t-channel diagram in the $uu \to tt$ process, which is forbidden within the SM. The CMS Collaboration announced the upper bound on the cross section for the same-sign top-quark pair production: $\sigma^{tt} < 17$ pb at 95% CL. with a luminosity of 35 pb^{-1} [7], while the limit on the cross sections at ATLAS with a luminosity of 1.04 fb^{-1} are $\sigma^{tt} < 2$ pb at 95% CL. by using an optimized event selection for the Z' model and $\sigma^{tt} < 4$ pb at 95% CL. by using more inclusive selection, respectively [8]. We use the latter limit in this work.

In numerical analysis, we take the top-quark mass to be $m_t = 173$ GeV. For a parton distribution function we use CTEQ6m with the renormalization and the factorization scale equal to $\mu = m_t$. In order to take into account the QCD radiative correction which is unknown as of now for the model under consideration, we use the K factor obtained in the perturbative QCD calculations: namely, $K = 1.3$ for the Tevatron and $K = 1.7$ for the LHC by assuming the same K factor in the new physics model. The center-of-momentum energy $\sqrt{s}$ is 1.96 TeV at the Tevatron and 7 TeV at the LHC, respectively. In the previous works [12], we did not consider the SM NLO contribution to $A^t_{\rm FB}$, but in this work we take into account its contribution to $A^t_{\rm FB}$ by using the approximated formula $A^t_{\rm FB} \simeq A^{t,{\rm SM}}_{\rm FB} + \delta A^t_{\rm FB}/K$, where the first term denotes $A^t_{\rm FB}$ at the SM NLO and the second one corresponds to the contribution from the new physics. We also use the approximated formula $A^y_C \simeq A^{y,{\rm SM}}_C + \delta A^y_C/K$.

4.2 $m_{Z'} = 145$ GeV and $\xi = 1$

In this model, 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 $\le m_{H,a} \le$ 1 TeV, $0.005 \le \alpha_x \le 0.012$, $0.5 \le Y^{H,a}_{tu} \le 1.5$, and $(g^u_R)^2_{tu} =$

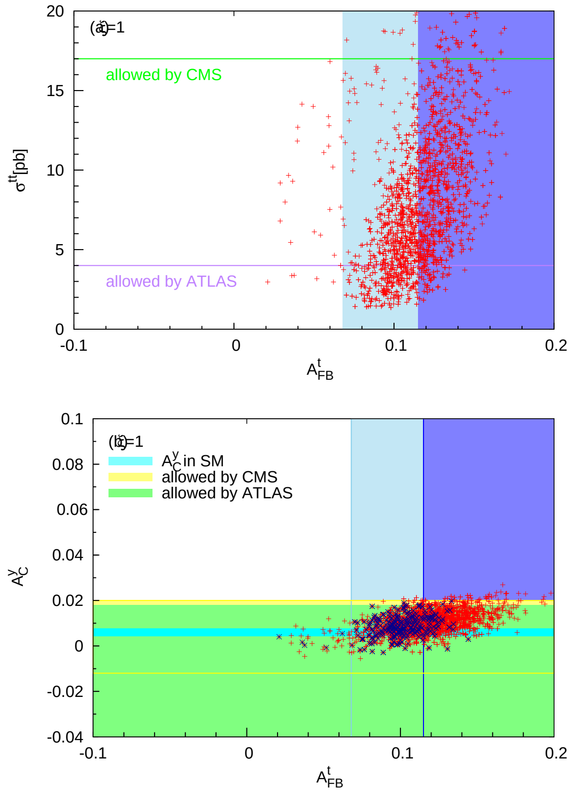

Figure 1. The scattered plots for (a) $A_{\rm FB}^t$ at the Tevatron and σ^{tt} at the LHC in unit of pb, and (b) $A_{\rm FB}^t$ at the Tevatron and A_C^y at the LHC for $m_{Z'} = 145$ GeV and $\xi = 1$. In (b), the blue points satisfy the upper bound on the same sign top pair production from ATLAS: $\sigma^{tt} < 4$ pb.

$(g_R^u)_{uu}(g_R^u)_{tt}$, where $\alpha_x \equiv (g_R^u)_{tu}^2 g'^2/(4\pi)$ is defined and $Y_{tu}^{H,a}$ are flavor-off-diagonal Yukawa couplings.

In Fig. 1, we show the scattered plot for $A_{\rm FB}^t$ at the Tevatron and the same-sign top-pair production cross section and A_C^y at the LHC. The green and yellow regions are consistent with A_C^y at ATLAS and CMS in the 1σ level, respectively. The blue and skyblue regions are consistent with A_{FB}^t in the lepton+jets channel at CDF in the 1σ and 2σ levels, respectively. The red points are in agreement with the cross section for the top-quark pair production at the Tevatron in the 1σ level and the blue points are consistent with both the cross section for the top-quark pair production at the Tevatron in the 1σ 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 $m_{t\bar{t}}$ 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.

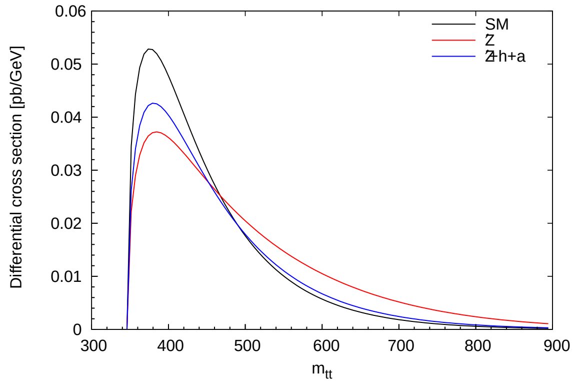

Figure 2. The invariant mass distribution of the top-quark pair at the Tevatron in the SM, Z' model, and chiral U(1)$'$ model.

4.3 $m_h = 125$ GeV and $\xi = 0$

In this subsection, 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 [18], also has a nonzero Y_{tu}^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 $Y_{tu}^h \leq 0.5$ 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, $0 \leq \alpha_x \leq 0.025$, $0 \leq Y_{tu}^{H,a} \leq 1.5$, $0 \leq Y_{tu}^h \leq 0.5$ 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 $(g_R^u)_{uu} \simeq 0$ 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 $A_{\rm FB}^t$ at the Tevatron and A_C^y 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 σ^{tt} is less than 1 pb.

5 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 [19, 20], and some models have already been disfavored by experiments at the LHC. In this work, we investigated the chiral U(1)$'$ model with flavored Higgs doublets and flavor-dependent couplings. Among possible scenarios, we focused on two scenarios in Sec. 4. We found that both scenarios can be accommodated 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.

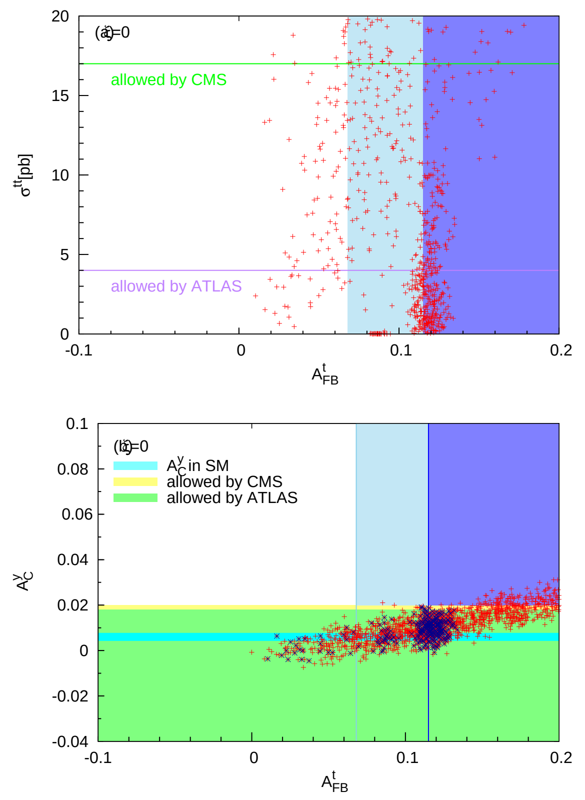

Figure 3. The scattered plots for (a) $A^t_{\rm FB}$ at the Tevatron and σ^{tt} at the LHC in unit of pb, and (b) $A^t_{\rm FB}$ at the Tevatron and A^y_C at the LHC for $m_h = 125$ GeV and $\xi = 0$, where the contribution of the second lightest Higgs boson H is included.

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 $b \to s\gamma$, $B \to \tau\nu$, and $B \to D^{(*)}\tau\nu$ decays [21]. 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. [21].

Acknowledgments

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