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Top forward-backward asymmetry in chiral $U(1)'$ models

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Summary. — We construct flavor-dependent chiral $U(1)'$ models with a Z' boson which couples to the right-handed up-type quarks in the standard model (SM). To make the models have realistic renormalizable Yukawa couplings, we introduce new Higgs doublets with nonzero $U(1)'$ charges. Anomaly-free condition can be satisfied by adding extra chiral fermions. We show that these models could analyze the discrepancy between the SM prediction and empirical data in the top forward-backward asymmetry at the Tevatron.

PACS 12.60.-i – Models beyond the standard model.
PACS 14.65.Ha – Top quarks.
PACS 14.80.-j – Other particles (including hypothetical).

During the last three years, the discrepancy between the standard model (SM) prediction and empirical data in the top forward-backward asymmetry (A_{FB}) at the Tevatron has drawn much attention in particle physics. The SM QCD prediction is $0.072^{+0.011}_{-0.007}$ at NLO+NNLL accuracies [1]. While the combined CDF and D0 results are 0.210 ± 0.067 and $0.196 \pm 0.060^{+0.018}_{-0.026}$, respectively, both of which are deviated from the SM prediction by about 2σ [2]. Among a lot of theoretical attempts to resolve the discrepancy [3], the light leptophobic Z' model with large flavor changing couplings to the right-handed (RH) up-type quarks has been paid much attention to [4] because of its large flavor-changing neutral currents. This rather phenomenological model is strongly disfavored by the same-sign top pair production constraint at the LHC [5]. However we point out that this simple Z' model is not a realistic model. The Z' boson should be associated with, for example, chiral $U(1)'$ symmetry [6], whose charge assignment is flavor-dependent. Then, in order to write down proper Yukawa couplings, additional Higgs doublets with nonzero $U(1)'$ charges must be included [7]. This is inevitable when the new gauge group is chiral. In general such a flavor-dependent chiral $U(1)$ symmetry yields gauge anomalies, which can be canceled by introducing extra fermions [7]. After breaking both $U(1)'$ and EW

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symmetries, the Z' and Higgs bosons could contribute to the $t\bar{t}$ pair production with large A_{FB}. Interference between the Z' and Higgs bosons can relieve the strong constraint from the same-sign top pair production. We emphasize that the realistic models with a leptophobic Z' boson which couples to the RH up-type quarks accompany modification of the Higgs sector and its effects must be taken into account together with the Z' boson, in particular, at the LHC. This is true not only in the Z' model, but also in the other models [2] designed to account for A_{FB} at the Tevatron with flavor-dependent couplings.

We assume that only the RH up-type quarks ($U_R^i, i = 1, 2, 3$) are charged under $U(1)'$ with its charge u_i while the left-handed quarks (U_L^i and D_L^i) and the RH down-type quarks (D_R^i) are uncharged. In the mass eigenstates $\hat{U}_R^i$, the interaction Lagrangian for the Z' and $\hat{U}_R^i$ is given by $\mathcal{L} = g' Z'^{\mu} \{(g_R^u)_{ij} \overline{\hat{U}_R^i} \gamma_\mu \hat{U}_R^j\}$, where g' is a gauge coupling of $U(1)'$ and $(g_R^u)_{ij} = (R^u)_{ik} u_k (R^u)^\dagger_{kj}$ with the biunitary matrix $(R^u)_{ij}$ diagonalizing the up-type quark mass matrix [7]. In general $(g_R^u)_{ij}$ could have nonzero off-diagonal elements.

As we have discussed, we have to introduce new Higgs doublets H_i with $U(1)'$ charges $-u_i$ in order to get realistic renormalizable Yukawa couplings. The number of Higgs doublets including the SM Higgs depends on the charge assignment. One can choose the two-Higgs doublet case with $u_i = (0, 0, 1)$, the three-Higgs doublet case with $u_i = (-1, 0, 1)$, or etc. In the mass basis, the Yukawa interactions of lightest neutral scalar Higgs h and pseudoscalar Higgs a can be given by

$$\mathcal{L} = -Y_{ij}^u \overline{\hat{U}_{Li}} \hat{U}_{Rj} h + i Y_{ij}^a \overline{\hat{U}_{Li}} \hat{U}_{Rj} a + \text{h.c.}, \tag{1}$$

where the Yukawa couplings Y_{ij} and Y_{ij}^a are functions of g_R, m_i^u, the mixing angles and vacuum expectation values of the neutral Higgs fields and can have off-diagonal elements [7]. Finally the gauge anomaly can be canceled by introducing an extra generation and two pairs of $SU(2)$ doublets of $SU(3)$ triplets as in ref. [7].

In our model, it could be expected to have large off-diagonal Yukawa couplings $Y_{tu}^{(a)}$ because they are proportional to the top quark mass. The mixing matrix $(g_R^u)_{ij}$ could generally have nonzero off-diagonal elements. We assume that $(g_R)_{13}^u \equiv (g_R^u)_{ut}$ is large, but the other components are well suppressed. Then both the Z' boson and Higgs bosons h and a can contribute to the $t\bar{t}$ production through the $u\bar{u} \to t\bar{t}$ process. The $t\bar{t}$ production rate at the Tevatron and LHC is in good agreement with the SM. We impose that the $t\bar{t}$ cross section at the Tevatron in our model with a K factor $K = 1.3$ is consistent with the measurement (7.5 ± 0.48) pb [8]. In the SM the top quark dominantly decays to the Wb. It might be dangerous that the branching fraction of the top-quark decay to the non-Wb state, which can be generated by the flavor changing neutral currents, is too large. Thus we restrict the branching fraction of the non-SM decay of the top quark to 5%. The flavor changing couplings in the top sector bring on the same-sign top pair production through the $uu \to tt$ process and the single-top production through the $gu \to t + X (X = Z', h, a)$ process. We require the bound $\sigma(pp \to tt) < 17\,\text{pb}$ from the CMS experiment [5], but the single-top production data give no constraints to our model because of difference between final states in experiments [9] and our model. Lastly we consider $A_{FB} = (0.158 \pm 0.075)$ in the lepton+jets channel at CDF [2]. As an illustration of our model we take $m_{Z'} = 145\,\text{GeV}$ $m_h = 180\,\text{GeV}$, $m_a = 300\,\text{GeV}$, and $Y_{tu}^a = 1.1$.

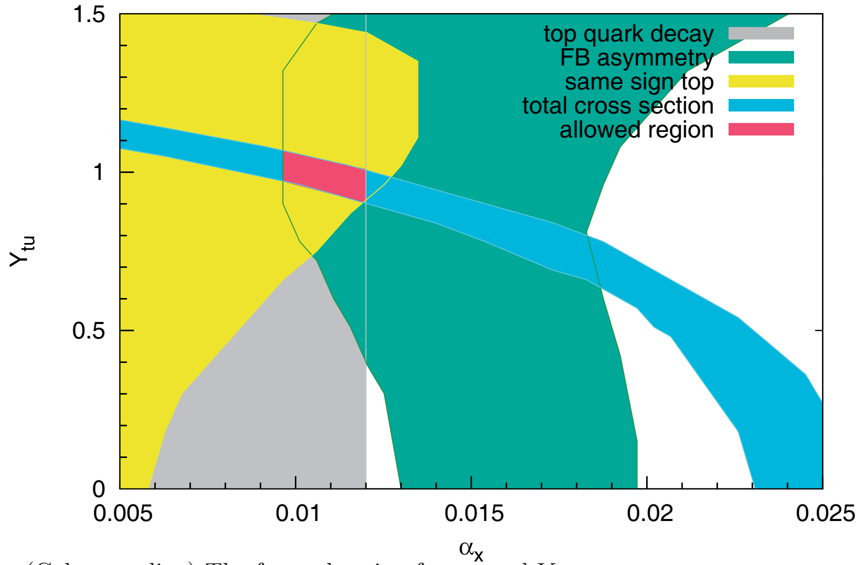

Fig. 1. – (Colour on-line) The favored region for α_x and Y_{tu}.

In fig. 1, we show the allowed region for $\alpha_x \equiv (g' g^u_{Rut})^2/(4\pi)$ and Y_{tu}. The gray, cyan, green, and yellow regions correspond to the regions allowed by constraints from the top quark decay, the $t\bar{t}$ production cross section at the Tevatron, A_{FB} at CDF, and the same-sign top pair production at CMS, respectively. The red region is favored from the empirical data at the Tevatron and LHC. It is remarkable that the strong constraint from the same-sign top pair production can be relieved in our model due to the destructive interference between the Z' boson and Higgs bosons.

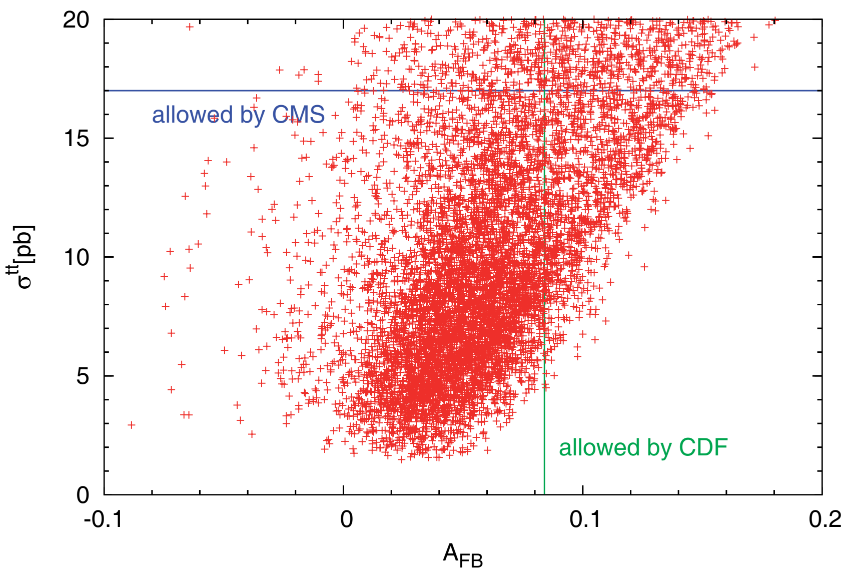

Fig. 2. – The scattered plot for A_{FB} at the Tevatron and σ_{tt} at the LHC in unit of pb.

Now we examine our model by varying the model parameters. In this analysis we fix $m_{Z'} = 145\,\text{GeV}$, but we choose the following parameter regions: $180\,\text{GeV} < m_h$, $m_a < 1\,\text{TeV}$, $0.005 < \alpha_x < 0.025$, and $0.5 < Y_{tu}$, $Y^a_{tu} < 1.5$ with the constraint $|Y_{tu}| < |Y^a_{tu}|$. In fig. 2, we show the scattered plot for A_{FB} at the Tevatron and the cross section σ^{tt} for the same-sign top pair production at the LHC. All the red points in fig. 2 satisfy the $t\bar{t}$ cross section rate at the Tevatron. In fig. 2, the points in the right lower side are allowed by the empirical data. The points in the allowed region have the following bounds: $180\,\text{GeV} < m_h < 250\,\text{GeV}$, $0.005 < \alpha_x < 0.014$, $0.75 < Y_{tu} < 1.3$, and $0.9 < Y^a_{tu} < 1.5$. m_a is not constrained by the data. We note that about 7% A_{FB} from the SM NLO contribution is ignored in this work and it could further enhance A_{FB} at the Tevatron.

In conclusions, we presented $U(1)'$ flavor models with flavor-dependent Z' couplings only to the RH up-type quarks. Additional Higgs doublets with $U(1)'$ charges were introduced in order to to construct realistic models to have renormalizable Yukawa couplings for the up-type quarks. For cancellation of the gauge anomaly we included the extra fermions charged under $U(1)'$. We showed that our model can explain the forward-backward asymmetry measured at the Tevatron and evade the stringent constraint from the same-sign top pair production at the LHC through the destructive interference between the Z' boson and Higgs bosons. We anticipate that our model will be probed in the future experiments.

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