

## Top quark forward-backward asymmetry and charge asymmetry in left-right twin Higgs model postprint

**Authors:** Wang,L, Wu,L, Yang,JM

**Date:** 2016-12-28T00:00:00+00:00

### Abstract

In order to explain the Tevatron anomaly of the top quark forward-backward asymmetry  $A_{FB}^t$  in the left-right twin Higgs model, we choose to give up the lightest neutral particle of  $\hat{h}$  field as a stable dark matter candidate. Then a new

### Full Text

## Preamble

#### Top Quark Forward-Backward Asymmetry and Charge Asymmetry in the Left-Right Twin Higgs Model

Lei Wang<sup>1</sup>, Lei Wu<sup>2</sup>, Jin Min Yang<sup>2</sup>

<sup>1</sup>State Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China

## Abstract

In order to explain the Tevatron anomaly of the top quark forward-backward asymmetry  $A_{FB}^t$  in the left-right twin Higgs model, we choose to give up the lightest neutral particle of the  $\hat{h}$  field as a stable dark matter candidate. This allows a new Yukawa interaction for  $\hat{h}$  that can be free from the constraint of same-sign top pair production and contribute sizably to  $A_{FB}^t$ . Considering the constraints from the production rates of top quark pairs ( $t\bar{t}$ ), the top decay rates, and the  $t\bar{t}$  invariant mass distribution, we find that this model with such a new Yukawa interaction can explain  $A_{FB}^t$  measured at the Tevatron while satisfying the charge asymmetry  $A_C^t$  measured at the LHC. Moreover, this model predicts a strong correlation between  $A_{FB}^t$  at the Tevatron and  $A_C^t$  at the LHC, i.e.,  $A_C^t$  increases as  $A_{FB}^t$  increases.

PACS numbers: 14.65.Ha, 12.60.Fr, 14.80.Ec, 14.80.Fd

## ## Introduction

The forward-backward asymmetry  $A_{FB}^t$  in top quark pair production has been measured by both experimental groups at the Tevatron. The CDF collaboration measured the asymmetry in the  $\ell+j$  channel and obtained  $A_{FB}^t(\text{CDF}) = 0.158 \pm 0.074$  [1], which is nearly consistent with the D0 result  $A_{FB}^t(\text{D0}) = 0.19 \pm 0.065$  [2]. These results exceed the Standard Model (SM) prediction  $A_{FB}^t(\text{SM}) = 0.009$ , which arises from NLO QCD diagrams [3]. Including the resummation of soft-gluon emission at NNLL, Ref. [4] gives the currently most precise QCD prediction of  $0.072^{+0.011}_{-0.007}$ . The CDF collaboration also reported an abnormally large value of  $A_{FB}^t$  for  $M_{t\bar{t}} > 450$  GeV [1], which, however, is not confirmed by the D0 collaboration [2].

To explain  $A_{FB}^t$ , various attempts have been made, such as via the  $s$ -channel exchange of an axigluon [5] or the  $t$ -channel exchange of  $Z'$ ,  $W'$ , and a scalar [6–12], or through an effective model-independent approach [13, 14]. In this work, we will attempt to explain  $A_{FB}^t$  in the framework of the left-right twin Higgs model (LRTH) [15–17].

In this model, a discrete left-right symmetry ensures the absence of one-loop quadratic divergence of the SM Higgs mass, which emerges as a pseudo-Goldstone boson once a global symmetry is spontaneously broken. The resulting Higgs boson mass is naturally around the electroweak scale when the cutoff scale of the theory is around 5–10 TeV. In the original LRTH, the lightest neutral particle of the  $\hat{h}$  field is stable and thus can be a candidate for a weakly interacting massive particle (WIMP) dark matter [18]. We found that the original LRTH does not contribute sizably to  $A_{FB}^t$ , so we choose to give up the dark matter candidate. This allows a new Yukawa interaction for  $\hat{h}$ , which is found to contribute sizably to  $A_{FB}^t$ .

In our analysis, we will consider the following observables: (1)  $A_{FB}^t$  in the  $t\bar{t}$  rest frame at the Tevatron, which is defined by [10]:

$$A_{FB}^t = A_{FB}^{\text{NP}} \times R + A_{FB}^{\text{SM}} \times (1 - R)$$

where  $A_{FB}^{\text{SM}} = 0.058$  is the asymmetry in the SM, and

$$A_{FB}^{\text{NP}} = \frac{\sigma_{\text{NP}}(\Delta y > 0) - \sigma_{\text{NP}}(\Delta y < 0)}{\sigma_{\text{NP}}(\Delta y > 0) + \sigma_{\text{NP}}(\Delta y < 0)}$$

$$R = \frac{\sigma_{\text{NP}}}{\sigma_{\text{SM}} + \sigma_{\text{NP}}}$$

are the asymmetry induced by new physics and the fraction of the new physics contribution to the total cross section, respectively.  $\Delta y$  is the rapidity difference

between a top and an anti-top. (2) The charge asymmetry of  $t\bar{t}$  production at the LHC, defined by

$$A_C^t = A_C^{\text{NP}} \times R + A_C^{\text{SM}} \times (1 - R)$$

where  $A_C^{\text{SM}} = 0.013$  is the asymmetry in the SM [20], and

$$A_C^{\text{NP}} = \frac{\sigma_{\text{NP}}(|\eta_t| > |\eta_{\bar{t}}|) - \sigma_{\text{NP}}(|\eta_t| < |\eta_{\bar{t}}|)}{\sigma_{\text{NP}}(|\eta_t| > |\eta_{\bar{t}}|) + \sigma_{\text{NP}}(|\eta_t| < |\eta_{\bar{t}}|)}$$

$$R = \frac{\sigma_{\text{NP}}}{\sigma_{\text{SM}} + \sigma_{\text{NP}}}$$

are the asymmetry induced by new physics and the fraction of the new physics contribution to the total cross section, respectively.  $\eta_t$  and  $\eta_{\bar{t}}$  are respectively the pseudo-rapidity of the top and anti-top quark in the laboratory frame. This asymmetry reflects that the top quarks on average are more boosted than the anti-top quarks, which is sensitive to new physics beyond the SM [14, 19]. The CMS collaboration has recently measured this quantity with an integrated luminosity of  $1.09 \text{ fb}^{-1}$  and obtained  $A_C^t = 0.030_{-0.019}^{+0.010}$ , which is consistent with the SM prediction [20]. The uncertainties of the ATLAS measurement of the charge asymmetry are of similar size to the CMS result [21].

- (3) The  $t\bar{t}$  total production cross sections at the Tevatron and LHC. The current cross section measured at the Tevatron is  $\sigma_{\text{exp}} = 7.50 \pm 0.48 \text{ pb}$  for  $m_t = 172.5 \text{ GeV}$  [22], while the SM cross section is  $\sigma_{\text{SM}} = 7.46_{-0.23}^{+0.66} \text{ pb}$  from [24]. The  $t\bar{t}$  total production cross section measured recently at the LHC with center-of-mass energy 7 TeV is  $\sigma_{\text{exp}} = 176 \pm 11.9 \text{ pb}$  from ATLAS [25] and  $\sigma_{\text{exp}} = 168 \pm 11.6 \text{ pb}$  from CMS [26], while the SM cross section is  $\sigma_{\text{SM}} = 165.80_{-8.88}^{+4.44} \text{ pb}$  from [23] and  $\sigma_{\text{SM}} = 157.92_{-6.99}^{+7.79} \text{ pb}$  from [27]. Here, we conservatively require  $0 < \sigma_{\text{NP}}/\sigma_{\text{SM}} < 0.3$  for the Tevatron and  $0 < \sigma_{\text{NP}}/\sigma_{\text{SM}} < 0.25$  for the LHC.
- (4) The top quark can decay into a light quark and a scalar particle if the scalar mass is light enough. The measurement of the total top width is  $\Gamma_t^{\text{exp}} = 1.99_{-0.55}^{+0.69} \text{ GeV}$  [28], which is in agreement with the SM value  $\Gamma_t^{\text{SM}} = 1.3 \text{ GeV}$ , setting a limit on the partial width of any new decay mode.

Finally, we will discuss the constraints from the experimental data on the  $t\bar{t}$  invariant mass distribution and single top quark production.

This work is organized as follows. In Sec. II, we briefly review the left-right twin Higgs model and introduce a new Yukawa interaction for  $\hat{h}$ . In Sec. III, we study the top quark observables mentioned above, focusing on the top quark forward-backward asymmetry at the Tevatron and charge asymmetry at the

LHC under the constraints of the other observables. Finally, we present our conclusion in Sec. IV.

## ## II. LRTH Model with New Yukawa Interaction

The LRTH model [16, 17] has a global symmetry  $U(4) \times U(4)$  with a gauged  $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$  subgroup. The twin symmetry is identified as a left-right symmetry that interchanges  $L$  and  $R$ , which implies that the gauge couplings of  $SU(2)_L$  and  $SU(2)_R$  are identical ( $g_{2L} = g_{2R} = g_2$ ).

A pair of Higgs fields,  $H$  and  $\hat{H}$ , are introduced, which transform as  $(4, 1)$  and  $(1, 4)$  respectively under the global symmetry. They can be written as

$$H = \begin{pmatrix} H_L \\ H_R \end{pmatrix}, \quad \hat{H} = \begin{pmatrix} \hat{H}_L \\ \hat{H}_R \end{pmatrix}$$

where  $H_{L,R}$  and  $\hat{H}_{L,R}$  are two-component objects charged under  $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$  as  $H_L$  and  $\hat{H}_L: (2, 1, 1)$ ;  $H_R$  and  $\hat{H}_R: (1, 2, 1)$ .

The SM-like Higgs doublet  $h = (h^+, h^0)^T$  and the new doublet  $\hat{h} = (\hat{h}^+, \hat{h}^0)^T$  reside in  $H_L$  and  $\hat{H}_L$ , respectively. Each Higgs acquires a non-zero VEV as  $\langle H \rangle = (0, 0, 0, f)^T$ ,  $\langle \hat{H} \rangle = (0, 0, 0, \hat{f})^T$ , which breaks one of the  $U(4)$  symmetries to  $U(3)$  and yields seven Nambu-Goldstone bosons. The gauge symmetry  $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$  is broken down to  $U(1)_{EM}$ , and six of the fourteen Goldstone bosons are respectively eaten by the SM gauge bosons  $W$  and  $Z$ , and additional gauge bosons  $W_H$  and  $Z_H$  with masses of a few TeV. In addition to the SM-like Higgs, we are left with two neutral pseudoscalars  $\phi^0$  and  $\hat{A}$ , one neutral scalar  $\hat{S}$ , and the charged scalars  $\phi^\pm$  and  $\hat{h}^\pm$ . Here  $\hat{S}$  and  $\hat{A}$  come from  $\hat{h}^0 = (\hat{S} + i\hat{A})/\sqrt{2}$ .

The SM quarks and leptons are charged under  $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$  as

$$L_{L\alpha} = \begin{pmatrix} \nu_{L\alpha} \\ e_{L\alpha} \end{pmatrix} : (2, 1, -1), \quad Q_{L\alpha} = \begin{pmatrix} u_{L\alpha} \\ d_{L\alpha} \end{pmatrix} : (2, 1, 1/3)$$

$$L_{R\alpha} = \begin{pmatrix} \nu_{R\alpha} \\ e_{R\alpha} \end{pmatrix} : (1, 2, -1), \quad Q_{R\alpha} = \begin{pmatrix} u_{R\alpha} \\ d_{R\alpha} \end{pmatrix} : (1, 2, 1/3)$$

with  $\alpha$  being the family index.

After the doublet  $h$  residing in  $H_L$  acquires the VEV,  $v \simeq 246$  GeV, the masses of the first two generation quarks and the bottom quark can be obtained from [17]

$$\mathcal{L}_{\text{Yukawa}} = \frac{y_{\alpha\beta}}{2\Lambda} (\bar{Q}_{L\alpha} \tau_2 H_L^*) (H_R^T \tau_2 Q_{R\beta}) + \frac{y'_{\alpha\beta}}{2\Lambda} (\bar{Q}_{L\alpha} H_L) (H_R^\dagger Q_{R\beta}) + \text{h.c.}$$

where  $\tau_2 = i\sigma_2$  ( $\sigma_2$  is the Pauli matrix). The Yukawa interaction of leptons is similar to Eq. (11).

In order to explain the top quark forward-backward asymmetry at the Tevatron, we add the new Yukawa interaction:

$$\mathcal{L}_{\text{new}} = \frac{\kappa_{\alpha\beta}}{2\Lambda} (\bar{Q}_{L\alpha} \tau_2 \hat{H}_L^*) (\hat{H}_R^T \tau_2 Q_{R\beta}) + \frac{\kappa'_{\alpha\beta}}{2\Lambda} (\bar{Q}_{L\alpha} \hat{H}_L) (\hat{H}_R^\dagger Q_{R\beta}) + \text{h.c.}$$

Since the VEV of  $\hat{H}_L$  equals zero, this interaction cannot produce mass terms for SM quarks. With the mass eigenstates and the expressions of  $\hat{H}_L$  and  $\hat{H}_R$  shown in [17], we obtain the following couplings:

$$\mathcal{L}_{\text{int}} = \frac{1}{\Lambda} \left[ (X_u)_{\alpha\beta} \bar{u}_\alpha \hat{h}^0 u_{R\beta} + (X_d)_{\alpha\beta} \bar{d}_\alpha \hat{h}^- u_{R\beta} + (V_{\text{CKM}}^\dagger X_u)_{\alpha\beta} \bar{d}_\alpha \hat{h}^+ d_{R\beta} + (V_{\text{CKM}} X_d)_{\alpha\beta} \bar{u}_\alpha \hat{h}^+ d_{R\beta} \right] + \text{h.c.}$$

To satisfy the constraints from flavor processes and electroweak data, we consider two cases for the mixing matrices  $X_u$  and  $X_d$  (the detailed analysis was given in [11]):

**(i) Case I:**  $(X_u)_{\alpha 1} = \kappa_1 (V_{\text{CKM}})_{\alpha 3}$ ,  $(X_u)_{\alpha 2} = 0$ ,  $(X_u)_{\alpha 3} = 0$  and  $(X_d)_{\alpha\beta} = 0$ . From Eq. (13), we obtain the coupling

$$\mathcal{L}_{\text{int}}^{\text{I}} = y_1 \left[ (V_{\text{CKM}})_{\alpha 3} \hat{h}^0 \bar{u}_\alpha u_R + (V_{\text{CKM}})_{\alpha 3} \hat{h}^- \bar{u}_\alpha b_R \right] + \text{h.c.}$$

with  $y_1 = \kappa_1 \hat{f} / \Lambda$ .

**(ii) Case II:**  $(X_u)_{\alpha\beta} = 0$  and  $(X_d)_{\alpha\beta} = 0$  except for  $(X_d)_{31} = \kappa_2$ . From Eq. (13), we obtain the coupling

$$\mathcal{L}_{\text{int}}^{\text{II}} = y_2 \left[ \hat{h}^0 \bar{b}_L d_R + (V_{\text{CKM}})_{\alpha 3} \hat{h}^+ \bar{u}_\alpha d_R \right] + \text{h.c.}$$

with  $y_2 = \kappa_2 \hat{f} / \Lambda$ .

The cutoff scale  $\Lambda$  is typically taken to be  $4\pi f$  with  $f$  as low as 500 GeV. Sometimes  $\Lambda = 2\pi f$  is also considered [17]. The scale  $\hat{f}$  can be determined from the electroweak symmetry breaking condition. At a rough estimate,  $\hat{f}$  is five times  $f$  or more [17, 29].

For Case I (Case II),  $\hat{S}$  and  $\hat{A}$  from  $\hat{h}^0 = (\hat{S} + i\hat{A})/\sqrt{2}$  ( $\hat{h}^\pm$ ) can contribute to the top quark forward-backward asymmetry at the Tevatron via the  $t$ -channel exchange of such a scalar. This also implies that  $\hat{S}$  or  $\hat{A}$  can no longer be candidates for WIMP dark matter.

The Coleman-Weinberg potential and the soft left-right symmetry breaking terms (the so-called  $\mu$ -term) can give masses for  $\hat{h}^\pm$  and  $\hat{h}^0$  as [17]

$$m_{\hat{S}}^2 = m_{\hat{A}}^2 = m_{\hat{h}^0}^2 = \frac{1}{16\pi^2} \left[ \lambda_1^2 + g_2^2(m_{W}^2) + g_2^2(m_{W_H}^2) + g_1^2(m_{Z_H}^2) \right] \ln \frac{\Lambda^2}{x^2} + \mu^2 \cos x + \hat{\mu}^2$$

$$m_{\hat{h}^\pm}^2 \simeq m_{\hat{h}^0}^2 + \hat{\mu}^2$$

where  $x = \hat{f}/f$  and the last two terms are from the  $\mu$ -term. We neglect the small mass splitting between  $\hat{h}^0$  and  $\hat{h}^\pm$  due to electromagnetic interactions. Note that  $\hat{\mu}^2$  could have either sign, which allows us to vary the masses of  $\hat{h}^0$  and  $\hat{h}^\pm$  as free parameters.

Due to an additional phase factor  $i$  in the Yukawa coupling of  $\hat{A}$ , the contributions of  $\hat{S}$  and  $\hat{A}$  to same-sign top pair production are destructive, and such contributions can even be canceled for degenerate masses of  $\hat{S}$  and  $\hat{A}$ . Thus, the LRTH with this new Yukawa interaction can be free from the strong constraints from  $tt$  production rate reported by the CMS collaboration,  $\sigma(tt) < 17$  pb at 95% C.L. [30].

In fact, we can still introduce a parity in the model under which  $\hat{H}$  is odd while all other fields are even. The non-renormalizable interaction of Eq. (12) is invariant under this parity. This parity can forbid the renormalizable interaction between  $\hat{H}$  and fermions, especially the top quark. The top quark mass can still be obtained from the renormalizable interaction shown in the original LRTH [17].

### ## III. Calculations and Discussions

In our calculations, we take  $m_t = 172.5$  GeV and use the parton distribution function CTEQ6L [31] with renormalization scale and factorization scale  $\mu_R = \mu_F = m_t$ . We assume that the  $K$ -factors are universal, so that QCD correction effects cancel in the ratios  $\sigma_{\text{NP}}/\sigma_{\text{SM}}$  and  $\sigma_{\text{NP}}/(\sigma_{\text{SM}} + \sigma_{\text{NP}})$ , making them the same at LO and NLO.

#### ### A. Case I: $\hat{S}$ and $\hat{A}$

For Case I, the matrix element  $\mathcal{M}$  of the process  $u(p_1)\bar{u}(p_2) \rightarrow t(k_1)\bar{t}(k_2)$ , including SM, new scalar  $\hat{S}$  and  $\hat{A}$  contributions, can be written as in Ref. [12]:

$$|\mathcal{M}|^2 = |\mathcal{M}_{\text{SM}}|^2 + |\mathcal{M}_{\hat{h}^0}|^2 + 2\text{Re}(\mathcal{M}_{\text{SM}}\mathcal{M}_{\hat{h}^0}^*)$$

where

$$|\mathcal{M}_{\hat{h}^0}|^2 = \frac{y^4}{2} \left[ \frac{s^2}{(t - m_{\hat{h}^0}^2)^2} + \frac{t^2 + u^2 + 2sm_t^2}{(t - m_{\hat{h}^0}^2)(u - m_{\hat{h}^0}^2)} \right]$$

with  $s = (p_1 + p_2)^2$ ,  $t = (p_1 - k_1)^2$ ,  $u = (p_1 - k_2)^2$ , and  $y = \sqrt{2}y_1$ .

In Fig. 1 [Figure 1: see original paper], we plot the new physics contributions to  $t\bar{t}$  production rates at the Tevatron and LHC normalized to SM values, and the decay width of  $t \rightarrow u\hat{S}, u\hat{A}$  versus  $m_{\hat{h}_0}$  for Case I. We find that the contributions of  $\hat{S}$  and  $\hat{A}$  to the  $t\bar{t}$  cross section can be positive or negative, depending on the coupling constant  $y_1$  and their masses. Since the  $gg$  process dominates the  $t\bar{t}$  cross section at the LHC and the contributions of  $\hat{S}$  and  $\hat{A}$  are from the  $u\bar{u}$  process, the magnitude of  $\sigma_{\text{NP}}/\sigma_{\text{SM}}$  at the LHC is smaller than that at the Tevatron. The  $t\bar{t}$  cross section measured at the Tevatron gives the strongest constraint on the parameters  $y_1$  and  $m_{\hat{h}_0}$ . For example, the measured value requires  $m_{\hat{h}_0}$  to be larger than 1200 GeV (2000 GeV) in addition to a narrow intermediate region for  $y_1 = 1.0$  (1.6). The  $t\bar{t}$  cross section measured at the LHC and the top quark decay width can hardly provide further constraints.

In Fig. 2 [Figure 2: see original paper], we plot the top quark forward-backward asymmetry  $A_{FB}^t$  at the Tevatron and charge asymmetry  $A_C^t$  at the LHC for Case I. We see that  $A_{FB}^t$  can be enhanced sizably for very low values of  $m_{\hat{h}_0}$ , can exceed 0.1 for larger values, and can be negative in the intermediate region. For the large  $m_{\hat{h}_0}$  region, the left panel of Fig. 1 shows that  $\sigma_{\text{NP}}/\sigma_{\text{SM}}$  is negative, which can play a positive role in enhancing  $A_{FB}^t$  according to its definition shown in Eq. (1) and Eq. (3). The dependence of  $A_C^t$  on  $y_1$  and  $m_{\hat{h}_0}$  is similar to that of  $A_{FB}^t$ , and it remains within the  $1\sigma$  range over large parameter spaces.

In Fig. 3 [Figure 3: see original paper], we scan the parameter space  $100 \text{ GeV} < m_{\hat{h}_0} < 2000 \text{ GeV}$  and plot  $A_{FB}^t$  versus  $A_C^t$  under the constraints of the three observables shown in Fig. 1. We find that  $A_{FB}^t$  and  $A_C^t$  have a direct correlation, and the former always increases as the latter increases. The  $A_{FB}^t$  can be explained to within  $1\sigma$  and reach 0.1 while  $A_C^t$  remains within  $1\sigma$ . For  $A_C^t$  in the range between  $1\sigma$  and  $2\sigma$ ,  $A_{FB}^t$  can reach 0.24. If future more precise measurements at the LHC show that  $A_C^t$  is smaller than 0.0125, the model will lose its ability to produce a large  $A_{FB}^t$  at the Tevatron.

### B. Case II:  $\hat{h}^\pm$

For Case II, the matrix element  $\mathcal{M}$  of the process  $d(p_1)\bar{d}(p_2) \rightarrow t(k_1)\bar{t}(k_2)$ , including SM and  $\hat{h}^+$  contributions, is the same as Eq. (18), but replacing  $m_{\hat{h}_0}$  and  $y_1$  with  $m_{\hat{h}^+}$  and  $y_2$ .

In Fig. 4 [Figure 4: see original paper], we plot the new physics contributions to  $t\bar{t}$  production at the Tevatron and LHC normalized to SM values, and the decay width of  $t \rightarrow d\hat{h}^+$  versus  $m_{\hat{h}^+}$  for Case II. Compared to Case I, the magnitude of  $\sigma_{\text{NP}}/\sigma_{\text{SM}}$  at the Tevatron and LHC for Case II is less sizable due to the smaller parton distribution function of the  $d$  quark. Therefore, a broader region of the parameter space for Case II is allowed by the related experimental data on the top quark. For example,  $m_{\hat{h}^+}$  is required to be larger than 180 GeV (450 GeV) for  $y_2 = 1.0$  (1.6).

In Fig. 5 [Figure 5: see original paper], we plot the top quark forward-backward asymmetry  $A_{FB}^t$  at the Tevatron and charge asymmetry  $A_C^t$  at the LHC for Case II. The  $A_{FB}^t$  can be enhanced sizably for very low values of  $m_{\hat{h}^+}$ , can be negative in the intermediate region, and can be outside the  $1\sigma$  range for large values, which differs from Case I. The  $A_C^t$  can still be within  $1\sigma$  over most of the parameter space.

In Fig. 6 [Figure 6: see original paper], we scan the parameter space  $100 \text{ GeV} < m_{\hat{h}^+} < 1000 \text{ GeV}$  and plot  $A_{FB}^t$  versus  $A_C^t$  under the constraints of the three observables shown in Fig. 4. We find that a relatively large parameter space scanned is allowed by the three experimental data sets on the top quark. The  $A_{FB}^t$  is outside the  $1\sigma$  range when  $A_C^t$  is within  $1\sigma$ , and reaches 0.13 when  $A_C^t$  equals 0.035 (at  $1.5\sigma$ ). The measurement of  $A_{FB}^t$  at the Tevatron is complementary to  $A_C^t$  at the LHC.

### ### C. Other Discussions

The  $t\bar{t}$  invariant mass distribution was measured by CDF, and the results are presented in nine bins of  $M_{t\bar{t}}$  [32], which does not provide a solid constraint on this model since QCD corrections and cut efficiencies may significantly modify the shape of the differential distribution  $d\sigma/dM_{t\bar{t}}$  [7, 8, 33]. However, we further examine the constraints from the invariant mass distribution by requiring the differential cross section in each bin to be within the  $2\sigma$  regions of their experimental values. We scan  $y_1$  ( $y_2$ ) and  $m_{\hat{h}^0}$  ( $m_{\hat{h}^+}$ ) in the region where the total width of the top quark and  $t\bar{t}$  production cross sections at the Tevatron and LHC are in agreement with the corresponding experimental constraints. We plot  $A_{FB}^t$  versus  $A_C^t$  for Case I and Case II in Fig. 7 [Figure 7: see original paper], where  $A_{FB}^t$  is within the  $1\sigma$  range of the experimental value.

From Fig. 7, we find that the constraints from the  $t\bar{t}$  invariant mass distribution can further exclude some values of  $A_{FB}^t$  and  $A_C^t$ . For Case I, our previous conclusions are unchanged. For Case II, some large values of  $A_{FB}^t$  are disfavored by the invariant mass distribution constraints.

The values of  $y_1$  ( $y_2$ ) and  $m_{\hat{h}^0}$  ( $m_{\hat{h}^+}$ ) corresponding to Fig. 7 are shown in Fig. 8 [Figure 8: see original paper]. When  $0.6 < y_1 < 0.75$  ( $0.6 < y_2 < 0.7$ ) and  $100 \text{ GeV} < m_{\hat{h}^0} < 200 \text{ GeV}$  ( $100 \text{ GeV} < m_{\hat{h}^+} < 140 \text{ GeV}$ ),  $A_{FB}^t$  is allowed to be within the  $+1\sigma$  ( $-1\sigma$ ) range for Case I (Case II). In such parameter space, this model can best fit the experimental data of  $A_{FB}^t$ . When  $y_1(y_2) = 0.6$ ,  $\kappa_1(\kappa_2)$  should be around 1.5 for  $\Lambda = 2\pi f$  and 3.0 for  $\Lambda = 4\pi f$  taking  $f = 5f$  (see Eqs. (14) and (15)). Thus, an unnaturally large  $\kappa_1(\kappa_2)$  is not necessary for  $A_{FB}^t$  to be within the  $1\sigma$  range.

For Case I,  $\hat{S}$  ( $\hat{A}$ ) can decay into an up quark and an up-type quark. For Case II,  $\hat{h}^\pm$  can decay into a down quark and an up-type quark. Except for decays into the top quark, other decays are suppressed by the corresponding mixing matrix element. For masses of these scalars much larger than the top quark mass, their total widths can reach half of their masses taking  $y_1 = y_2 = 1$ , respectively.

We find that the value of  $A_{FB}^t$  does not change sizably when varying the width from zero to half the scalar mass, especially when  $A_{FB}^t$  is within the  $+1\sigma$  range for Case I and within the  $1\sigma$  range for Case II. The reason is that the widths of these scalars are very small for such values of  $A_{FB}^t$ , which can be derived from the parameters shown in Fig. 8.

The D0 collaboration has recently measured the single top quark production cross section at the Tevatron by requiring one  $b$ -jet in the final states and obtained  $\sigma(p\bar{p} \rightarrow tqb + X) = 2.90 \pm 0.59$  pb [34], where  $q$  is a light quark. The experimental value is in agreement with the SM  $t$ -channel  $tbq$  result of  $2.26 \pm 0.12$  pb. For Case I and Case II, single top quarks can be produced by the processes  $gu \rightarrow t\hat{S}(\hat{A})$  and  $g\bar{d} \rightarrow t\hat{h}^-$ , respectively. In Fig. 9 [Figure 9: see original paper], we plot  $A_{FB}^t$  versus the cross sections of single top quark associated with scalar production at the Tevatron for Case I and Case II. We find that the cross sections can exceed 1 pb when  $A_{FB}^t$  is larger than 0.15 for Case I and 0.1 for Case II, respectively. However, given that  $\hat{S}$ ,  $\hat{A}$ , and  $\hat{h}^\pm$  cannot decay into a bottom quark, this constraint is not applicable to our model due to the lack of a  $b$ -jet in the final states. A dedicated study is required to establish the applicability of the single top measurements at the Tevatron to our model.

In the LRTH model, there exist additional heavy gauge bosons from the  $SU(2)_R$  symmetric sector, dubbed  $W_H^\pm$  and  $Z_H$ , which can also contribute to the top quark forward-backward asymmetry. In this model, the  $SU(2)_{L,R}$  coupling constants  $g_L$  and  $g_R$  are identical. Experimental limits favor that the quark mixing matrices in the left- and right-handed sectors are the same [17]. For this case, Ref. [9] shows that the value of  $A_{FB}^t$  produced by  $W_H^\pm$  and  $Z_H$  is much smaller than the experimental value. Compared with the contributions of  $\hat{h}^\pm$ ,  $\hat{S}$ , and  $\hat{A}$ , their contributions can be safely ignored.

#### ## IV. Conclusion

In the framework of the left-right twin Higgs model, we introduced a new Yukawa interaction for the doublet  $\hat{h}$ , which means the lightest neutral particle of  $\hat{h}$  can no longer be the dark matter candidate. Such a new Yukawa interaction was found to contribute sizably to the top quark forward-backward asymmetry  $A_{FB}^t$  at the Tevatron. Under the constraints from related experimental data on the top quark, we found that the Tevatron  $A_{FB}^t$  can be explained while the LHC charge asymmetry  $A_C^t$  measurement can also be satisfied.

Although explaining  $A_{FB}^t$  by extending the Higgs sector has been studied in some papers, most of them do not propose a realistic model. By introducing the new Yukawa interaction, we make the LRTH a realistic model that can solve the hierarchy problem in addition to explaining  $A_{FB}^t$ . Furthermore, the degenerate masses of  $\hat{S}$  and  $\hat{A}$  can naturally avoid the strong constraints from same-sign top pair production at the LHC, allowing  $A_{FB}^t$  to reach 0.24.

#### ## Acknowledgments

We thank Manuel Perez-Victoria for helpful comments. This work was supported in part by the National Natural Science Foundation of China (NNSFC) under grant Nos. 11105116, 11005089, 10725526, 10821504, and 10635030, and by the Project of Knowledge Innovation Program (PKIP) of the Chinese Academy of Sciences under grant No. KJCX2.YW.W10.

## ## References

[1] CDF Collaboration, *Phys. Rev. D* 83, 112003 (2011). [2] D0 Collaboration, *Phys. Rev. D* 84, 112005 (2011). [3] J. H. Kuhn and G. Rodrigo, *Phys. Rev. Lett.* 81, 49 (1998); J. H. Kuhn and G. Rodrigo, *Phys. Rev. D* 59, 054017 (1999); M. T. Bowen, S. D. Ellis and D. Rainwater, *Phys. Rev. D* 73, 014008 (2006); O. Antunano, J. H. Kuhn and G. Rodrigo, *Phys. Rev. D* 77, 014003 (2008). [4] V. Ahrens, A. Ferroglia, M. Neubert, B. D. Pecjak, L. L. Yang, *Phys. Rev. D* 84, 074004 (2011). [5] P. Ferrario, G. Rodrigo, *Phys. Rev. D* 80, 051701 (2009); P. Ferrario and G. Rodrigo, *JHEP* 1002, 051 (2010); P. H. Frampton et al., *Phys. Rev. D* 683, 294 (2010); M. V. Martynov, A. D. Smirnov, *Mod. Phys. Lett. A* 25, 2637 (2010); R. S. Chivukula et al., *Phys. Rev. D* 82, 094009 (2010); Y. Bai et al., *JHEP* 1103, 003 (2011); A. Djouadi et al., *Phys. Rev. D* 82, 071702 (2010); K. Kumar et al., *JHEP* 1008, 052 (2010); G. Burdman et al., *Phys. Rev. D* 83, 035012 (2011); E. Alvarez et al., *JHEP* 1105, 070 (2011); C. Delaunay et al., arXiv:1101.2902; M. Bauer et al., *JHEP* 1011, 039 (2010); C. H. Chen et al., *Phys. Lett. B* 694, 393 (2011); R. Foot, *Phys. Rev. D* 83, 114013 (2011); A. Djouadi et al., *Phys. Lett. B* 701, 458 (2011); R. Barcelo et al., arXiv:1105.3333; G. M. Tavares and M. Schmaltz, arXiv:1107.0978; E. Alvarez et al., arXiv:1107.1473; E. Gabrielli, M. Raidal, arXiv:1106.4553; H. Wang et al., arXiv:1107.5769; G. Z. Krnjaic, arXiv:1109.0648; H. Davoudiasl, T. McElmurry, A. Soni, arXiv:1108.1173; E. L. Berger et al., arXiv:1111.3641; X.-P. Wang et al., *Phys. Rev. D* 83, 115010 (2011); J. A. Aguilar-Saavedra, M. Perez-Victoria, *Phys. Lett. B* 705, 228-234 (2011). [6] K. Cheung et al., *Phys. Lett. B* 682, 287 (2009); S. Jung, et al., *Phys. Rev. D* 81, 015004 (2010); V. Barger et al., *Phys. Rev. D* 81, 113009 (2010); I. Dorsner et al., *Phys. Rev. D* 81, 055009 (2010); A. Arhrib, R. Benbrik, C. H. Chen, *Phys. Rev. D* 82, 034034 (2010); G. Rodrigo, P. Ferrario, *Nuovo Cim. C* 33, 04 (2010); J. Cao et al., *Phys. Rev. D* 81, 014016 (2010); *Phys. Rev. D* 83, 034024 (2011); *Phys. Rev. D* 84, 074001 (2011); arXiv:1109.6543; S. Jung, A. Pierce, J. D. Wells, *Phys. Rev. D* 83, 114039 (2011); B. Bhattacharjee et al., *Phys. Rev. D* 83, 091501 (2011); K. M. Patel, P. Sharma, *JHEP* 1104, 085 (2011); M. R. Buckley, et al., *Phys. Rev. D* 83, 115013 (2011); G. Isidori and J. F. Kamenik, *Phys. Lett. B* 700, 145 (2011); E. R. Barreto et al., *Phys. Rev. D* 83, 054006 (2011); A. Rajaraman, Z. E. Surujon, T. M. P. Tait, arXiv:1104.0947; M. I. Gresham et al., arXiv:1107.4364; Y. Cui et al., arXiv:1106.3086; M. Duraisamy, A. Rashed, A. Datta, arXiv:1106.5982; B. Grinstein, et al., arXiv:1108.4027; D. Kahawala, D. Krohn, M. J. Strassler, arXiv:1108.3301; P. Ko, Y. Omura, C. Yu, arXiv:1108.4005; S. K. Gupta, arXiv:1011.4960; E. L. Berger et al., *Phys. Rev. Lett.* 106, 201801 (2011); arXiv:1109.3202; K. Cheung and T. C. Yuan, *Phys. Rev. D* 83, 074006 (2011); Z. Ligeti, G. M. Tavares, M. Schmaltz, *JHEP*

1106, 109 (2011). M. I. Gresham, I. W. Kim, K. M. Zurek, Phys. Rev. D 83, 114027 (2011); J. F. Kamenik, J. Shu, J. Zupan, arXiv:1107.5257; S. Westhoff, arXiv:1108.3341; K. Yan et al., arXiv:1110.6684. [7] J. Shu, K. Wang, G. Zhu, Phys. Rev. D 85, 034008 (2012). [8] B. Xiao, Y.-k. Wang, S.-h. Zhu, Phys. Rev. D 82, 034026 (2010). [9] M. Frank, A. Hayreter, I. Turan, Phys. Rev. D 84, 114007 (2011). [10] Q.-H. Cao et al., Phys. Rev. D 81, 114004 (2010). [11] K. Blum, Y. Hochberg, Y. Nir, JHEP 1110, 124 (2011). [12] J. Shu, T. M. P. Tait, K. Wang, Phys. Rev. D 81, 034012 (2010). [13] D. W. Jung et al., Phys. Lett. B 691, 238 (2010); arXiv:1012.0102; C. Zhang, S. Willenbrock, arXiv:1008.3869; J. A. Aguilar-Saavedra, Nucl. Phys. B 843, 638 (2011); Nucl. Phys. B 812, 181 (2009); C. Degrande et al., arXiv:1010.6304; K. Blum et al., arXiv:1102.3133; C. Delaunay et al., arXiv:1103.2297; C. Degrande et al., arXiv:1104.1798; D. Y. Shao et al., arXiv:1107.4012; J. A. Aguilar-Saavedra, M. Perez-Victoria, Phys. Lett. B 701, 93 (2011); JHEP 1105, 034 (2011). [14] J. A. Aguilar-Saavedra, M. Perez-Victoria, JHEP 1109, 097 (2011). [15] Z. Chacko, H. S. Goh, and R. Harnik, Phys. Rev. Lett. 96, 231802 (2006); R. Barbieri, T. Gregoire, and L. J. Hall, hep-ph/0509242; Z. Chacko, Y. Nomura, M. Papucci, G. Perez, JHEP 01, 126 (2006); R. Foot, R. R. Volkas, Phys. Lett. B 645, 75 (2007); A. Falkowski, S. Pokorski, M. Schmaltz, Phys. Rev. D 74, 035003 (2006); S. Chang, L. J. Hall, N. Weiner, Phys. Rev. D 75, 035009 (2007). [16] Z. Chacko, H. S. Goh, R. Harnik, JHEP 0601, 108 (2006). [17] H. S. Goh, S. Su, Phys. Rev. D 75, 075010 (2007). [18] E. M. Dolle, S. Su, Phys. Rev. D 77, 075013 (2008); L. Wang, J. M. Yang, JHEP 1005, 024 (2010). [19] J. L. Hewett et al., Phys. Rev. D 84, 054005 (2011); J. F. Arguin, M. Freytsis and Z. Ligeti, Phys. Rev. D 84, 071504 (2011). [20] <http://cdsweb.cern.ch/record/1369205/files/TOP-11-014-pas>. [21] <http://cdsweb.cern.ch/record/1372916/files/ATLAS-CONF-2011-106>. [22] T. Aaltonen et al. [CDF Collaboration], CDF note 9913. [23] U. Langenfeld, S. Moch, P. Uwer, Phys. Rev. D 80, 054009 (2009). [24] V. Ahrens, et al., JHEP 1009, 097 (2010). [25] ATLAS Collaboration, arXiv:1110.1027. [26] CMS Collaboration, JHEP 1107, 049 (2011). [27] V. Ahrens et al., JHEP 09, 097 (2010). [28] V. M. Abazov et al. [D0 Collaboration ], Phys. Rev. Lett. 106, 022001 (2011). [29] D.-W. Jung, J. Y. Lee, hep-ph/0701071. [30] CMS Collaboration, JHEP 1108, 005 (2011). [31] J. Pumplin et al., JHEP 0602, 032 (2006). [32] CDF Collaboration, Phys. Rev. Lett. 102, 222003 (2009). [33] M. I. Gresham, I. -W. Kim, K. M. Zurek, Phys. Rev. D 83, 114027 (2011). [34] D0 Collaboration, Phys. Lett. B 705, 313 (2011).

*Note: Figure translations are in progress. See original paper for figures.*

*Source: ChinaXiv — Machine translation. Verify with original.*