A Revisit to Top Quark Forward-Backward Asymmetry (Postprint)

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Date: 2017-08-03T00:00:00+00:00

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Full Text

Preamble

IPMU11-0050: A Revisit to Top Quark Forward-Backward Asymmetry

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Abstract

We analyze various models for the top quark forward-backward asymmetry (A_{FB}^t) at the Tevatron, using the latest CDF measurements on different A_{FB}^t observables and the total cross section. The axigluon model in Ref. [5] has difficulties in explaining the large rapidity-dependent asymmetry and mass-dependent asymmetry simultaneously, and the parameter space relevant to A_{FB}^t is ruled out by the latest dijet search at ATLAS. In contrast to Ref. [8], we demonstrate that the large parameter space in this model with a $U(1)_d$ flavor symmetry is not ruled out by flavor physics.

The t-channel flavor-violating Z', W', and diquark models all have parameter regions that satisfy different A_{FB} measurements within 1σ. However, the heavy Z' model, which can be marginally consistent with the total cross section, is severely constrained by the Tevatron direct search for same-sign top quark pairs. The diquark model suffers from too large a total cross section and is difficult to fit the $t\bar{t}$ invariant mass distribution. The electroweak precision constraints on the W' model based on Z'-Z mixing are estimated and the result is rather weak ($m_{Z'} > 450$ GeV). Therefore, the heavy W' model seems to give the best fit for all the measurements. The W' model predicts the $t\bar{t}+j$ signal from tW' production that is 10%-50% of SM $t\bar{t}$ at the 7 TeV LHC. Such a $t+j$ resonance can serve as a direct test of the W' model.

The prompt decay of the top quark before hadronization provides an opportunity to explore its various properties like charge, mass, and spin. Given its large mass, the scale of top quark pair production is greater than $2m_t$ where perturbative QCD plays an important role. Therefore, top quark pair production at hadron colliders can serve as a handle for precision tests of the standard model (SM) gauge interaction, both weak interaction in its decay and the perturbative QCD theory of strong interaction in its production.

From the structure of the SM, the top quark is special. As a colored particle, it is the heaviest known particle which is copiously produced at hadron colliders. Since the top quark acquires its large mass through electroweak symmetry breaking (EWSB), any of its properties deviated from the SM would be an important signal for new physics and potentially indicate the origin of EWSB, which makes searching for new physics in the top quark sector extremely interesting at both Tevatron and LHC.

One important measurement for the top quark in top quark pair production is the top forward-backward asymmetry, which is equivalent to charge asymmetry under CP transformation [1]. For SM production, it involves high-precision calculation of QCD. At $\sqrt{s}$, the $Q\bar{Q}g$ carry an odd power of color charge hence have bremsstrahlung amplitudes $q\bar{q}$ with odd charge conjugation parity in the interference terms among initial state radiation and final state radiation diagrams. There is also interference between the box diagram with the LO diagram that contributes to the charge asymmetry.

The CDF collaboration has recently updated the measurements on the total forward-backward asymmetry in top quark pair production with the semi-leptonic $t\bar{t}$ data with integrated luminosity of 5.3 fb^{-1}. The observed total asymmetry measured in the lab frame and the $t\bar{t}$ rest frame are:

$$A^t_{FB}(p\bar{p}\text{ rest frame}) = 0.150 \pm 0.050(\text{stat}) \pm 0.024(\text{syst})$$
$$A^t_{FB}(t\bar{t}\text{ rest frame}) = 0.158 \pm 0.072(\text{stat}) \pm 0.017(\text{syst})$$

which corresponds to the SM prediction based on the NLO simulation, Monte Carlo for FeMtobarn processes (MCFM), 0.038 ± 0.006 (in lab) and 0.058 ± 0.009 in $t\bar{t}$ rest frame respectively [3]. These measurements have improved the previous results based on 3.2 fb^{-1} of $A^t_{FB}(p\bar{p}) = 0.069\pm0.014$ and $A^t_{FB}(t\bar{t}) = 0.19\pm0.065$ [3]. The top quark forward-backward asymmetry has also been measured in the di-lepton channel as $A_{FB} = 0.42 \pm 0.15(\text{stat}) \pm 0.05(\text{syst})$ in the $t\bar{t}$ rest frame with 5.1 fb^{-1} data [2]. Note that the recent D0 measurement $A^t_{FB} = (8\pm4(\text{stat})\pm1(\text{syst}))\%$ is based on top-pair events that satisfy the experimental acceptance, which is uncorrected for effects from reconstruction or selection and cannot be used to compare with the CDF results [4].

More importantly, with the enlarged data sample, the CDF collaboration has also released two distributional measurements. The most interesting result is the mass-dependent forward-backward asymmetry. The mass-dependent forward-backward asymmetry in the $t\bar{t}$ rest frame in comparison to the QCD correction prediction is:

$$A^t_{FB}(M_{t\bar{t}} > 450\text{ GeV}) = 0.475 \pm 0.088$$

compared to the SM prediction of 0.088 ± 0.013. This 3.5σ deviation may be a strong indication for physics beyond the SM. The second measurement is the rapidity-dependent asymmetry, which is frame-independent, as:

$$A^t_{FB}(|\Delta\eta| > 1.0) = 0.611 \pm 0.123$$
$$A^t_{FB}(|\Delta\eta| < 1.0) = 0.026 \pm 0.018$$

and in comparison to the MCFM SM prediction:

$$A^t_{FB}(|\Delta\eta| > 1.0) = 0.039 \pm 0.010$$
$$A^t_{FB}(|\Delta\eta| < 1.0) = 0.058 \pm 0.006$$

The ratio of the parton-level asymmetries in the two different frames, which differ by longitudinal boost, is $A^t_{FB}(p\bar{p})/A^t_{FB}(t\bar{t}) = 0.95 \pm 0.14$ with the error corrected for the expected correlation across frames in the NLO QCD assumption. Even though the uncertainty is still large, this close-to-1 central value implies that the top events which contribute to the asymmetry mostly lie in the forward-backward direction so the asymmetries are less dependent on longitudinal boosts along the beam direction.

This feature is also shown in the $\Delta\eta$-dependent asymmetry $A^t_{FB}(|\Delta\eta| > 1.0) = 0.611 \pm 0.123$, which shows that the asymmetric events are mostly due to events with larger rapidity difference. On the other hand, the measurement of $t\bar{t}$ cross section $\sigma_{t\bar{t}}$, updated by the 4.6 fb^{-1} CDF result (with $m_t = 172.5$ GeV), is:

$$\sigma^{\text{exp}}_{t\bar{t}} = 7.5^{+0.5}_{-0.7}\ \text{pb}$$

which is in very good agreement with the SM theory prediction of $\sigma^{\text{th}}_{t\bar{t}} = 7.50^{+0.31}_{-0.34}(\text{stat}) \pm 0.15(\text{Z theory})$ pb at NNLO [3].

Therefore, in order for new physics to generate large asymmetry without changing the total $t\bar{t}$ production cross section, the new physics contribution must interfere with the leading SM amplitude. For instance, in order for the production of $u\bar{u}, d\bar{d} \to t\bar{t}$ via s-channel massive Z' to explain the asymmetry, there is no interference between s-channel color singlet exchange $u\bar{u}, d\bar{d} \to Z' \to t\bar{t}$ and QCD $u\bar{u}, d\bar{d} \to t\bar{t}$. The asymmetry events due to Z' will significantly enhance the total cross section $\sigma_{t\bar{t}}$ at the same time, and this causes a strong tension between fitting A^t_{FB} and $\sigma_{t\bar{t}}$. This requirement implies that there are only two categories of candidate models to solve this anomaly:

- First category of models contain s-channel color octet vector boson but with parity violation at both qG and tG vertices [5-8].
- Second category corresponds to the t-channel exchange of light gauge boson with maximal flavor violation that couples initial state u, d quark to the third generation t quark. The large asymmetry can be generated via Rutherford singularity behavior [9-16].

Both categories of models have their realizations in beyond-SM models. Given the updated measurements, especially the new distributional measurements, we discuss the current status of various models. In addition, the models may have other implications that have been or will be constrained by some direct or indirect experiments. One realization of the first category models is the non-universal axigluon model proposed in [5] and it may receive constraints from low-energy neutral meson mixings [8]. However, we show that the flavor bound can be easily evaded by putting a horizontal flavor symmetry $U(1)_d$. In the W_R models [10, 14], since the W_R is charged under SM $U(1)_{\text{em}}$, the neutral component W^3_R would inevitably mix with W^3_L and some extra $U(1)_X$ which induces a Z-Z' mixing. The new ATLAS Dijets [17] search and the Tevatron same-sign dileptons [18] would severely constrain the s-channel axigluon models and the t-channel heavy Z' models. We also study the direct prediction at the Large Hadron Collider (LHC) using the 1σ fitting of all three asymmetry measurements A^t_{FB}(total), $A^t_{FB}(M_{t\bar{t}} > 450$ GeV), $A^t_{FB}(|\Delta\eta| > 1.0)$ with the right total cross section.

The paper is organized as follows. In Section I, we present the 1σ fitting of all three asymmetry measurements for the s-channel color octet model (Section I A), t-channel Z' model (Section I B 1), W' model (Section I B 2), diquark model (Section I B 3) and the corresponding consequences. In Section II, we calculate the production rates for the new particles in various different models at the Tevatron which give the bounds for those models and the LHC signals. In Section III, we consider some indirect bounds for the axigluon from flavor physics (Section III A) and W' model from electroweak precision test (EWPT) (Section III B). Section IV contains our conclusions.

I. UPDATED STATUS OF THE MODELS

In this section, we discuss the updated status of the models based on the latest measurements, especially the new distributional measurements. The simulation in the following discussion is at parton level and leading order. The asymmetry observables are defined at parton level without taking into account possible reconstruction efficiency. The SM contribution to the asymmetries from MCFM simulation have been subtracted from the corresponding measured values. The total cross section is obtained by multiplying a QCD k-factor. Since the latest experimental value is based on $m_t = 172.5$ GeV, for better comparison, we employ the theory calculation at NNLO for $m_t = 172.5$ GeV and the k-factor is 1.3. Last, the differential cross section of $t\bar{t}$ invariant mass is not included as a requirement in the scan since QCD correction [19] and cut efficiency [20] may significantly modify the shape of differential distribution $d\sigma/dM_{t\bar{t}}$.

In the following discussion, we are mostly interested in the region where the three asymmetry measurements can be explained within 1σ.

A. s-channel color octet

The interference term between the color octet vector boson G^a_μ contribution in $q\bar{q}$ annihilation and the SM gluon contribution picks up a term as:

$$\hat{s}(\hat{s} - M_G^2) + M_G^2 A\beta\cos\theta$$

where g_s is the strong coupling, g^A_q is the axial component of the coupling between G^a_μ and light quarks q, and g^A_t is that of the top quark. If the interference contribution is positive ($A > 0$), then $g^A_q g^A_t < 0$ is inevitable [4].

The s-channel models can be realized in various contexts. The first realization is the axigluon models where $SU(3)_c$ color gauge symmetry is only a remnant of $SU(3)_L \times SU(3)_R$ broken by a bi-triplet scalar and another color octet with axial coupling becomes massive. This non-universal gauge interaction potentially causes violation of the GIM mechanism and thus may be constrained from flavor changing neutral current (FCNC) processes such as neutral meson mixings; we discuss its implications in the next section.

However, to achieve the $g_q^A g_t^A < 0$ requirement, the axigluon model has to be non-universal, and one example is the 4-generation model proposed in [5]. Another realization is the models of extra dimension theory where massive color octet Kaluza-Klein (KK) gluons couple to the SM quarks in a chiral form as a result of fermion profiles [21]. The large m_t naturally implies that the top quark and light quarks couple to KK gluons in different ways.

One interesting feature that was discussed in the axigluon model [5] is the mass-dependent asymmetry. Due to the opposite contribution to asymmetry between the interference term and new physics squared term, the asymmetry is positive when the centre-of-mass energy is at intermediate energy but when it is close to the threshold, the asymmetry may become negative. This bending-over in correlation between asymmetry A_{FB}^t and the centre-of-mass energy $M_{t\bar{t}}$ had been shown in the latest CDF measurements, both in the measurement with finite bin sizes of $M_{t\bar{t}}$ and the measurement with below/above $M_{t\bar{t}}$ edge.

We use the axigluon model as one example to illustrate the feature of s-channel models in comparison with the updated measurement. Figure 1 [Figure 1: see original paper] shows the summary of best-fit parameter regions for total asymmetry, mass-dependent asymmetry, rapidity-dependent asymmetry, the total cross section, and the last bin of $d\sigma/dM_{t\bar{t}}$ measurements. Since the total asymmetry has been reduced from the previous fitting in [5], the 1σ region with total asymmetry is enlarged as shown in Fig. 1. However, there is no 1σ region for the mass-dependent asymmetry of $M_{t\bar{t}} > 450$ GeV or the rapidity-dependent asymmetry of $|\Delta\eta| > 1$. Figure 1 shows the 1.5σ parameter space for $A_{FB}^t(|\Delta\eta| > 1)$, $A_{FB}^t(M_{t\bar{t}} > 450 \text{ GeV})$ as well as the total $t\bar{t}$ production rate $\sigma(p\bar{p} \to t\bar{t})$. It is clearly shown that the axigluon model [5] does not consistently generate the large asymmetries in the events of $M_{t\bar{t}} > 450$ GeV and $|\Delta\eta| > 1$ [5].

B. t-channel

As we argued, the ratio of $A_{FB}^t(p\bar{p})/A_{FB}^t(t\bar{t})$ close to one may imply that the top events are mostly in the forward-backward direction so the asymmetries are less dependent on longitudinal boosts along the beam direction. Since the t-channel models naturally predict a large number of events in the forward-backward region, the close-to-one ratio of $A_{FB}^t(p\bar{p})/A_{FB}^t(t\bar{t})$ is a basic feature of t-channel models.

If the asymmetry is due to new physics in the t-channel, the interference contribution between new physics and SM QCD is proportional to $1/(t + m_t^2)$, where $t = -\hat{s}(1 - \beta\cos\theta)/2$ and $1/t$ expansion naturally picks up a $\cos\theta$ dependence. The t-channel physics naturally generates a large asymmetry in the $t\bar{t}$ system. In addition, the maximal asymmetry is generated at the Rutherford singularity where $\theta = 0$ which corresponds to very high centre-of-mass energy. One would then expect a positive correlation between A^t_{FB} and $M_{t\bar{t}}$.

The t-channel Z' model in [9, 12] proposed a color singlet neutral gauge boson with maximal flavor violation between first and third generations, and the new contribution interferes with the SM $u\bar{u} \to t\bar{t}$ amplitude. Similar to the Z' model, instead of neutral current exchange in the t-channel, there is also a proposal using charge current exchange in the t-channel as flavor violation W'. The interference effect is reduced since it' s only the $d\bar{d}$ initial state [10, 14]. Such flavor violation gauge interactions may be realized in horizontal gauge interaction models [13] for neutral current or generalized left-right models [14] for charged current.

A Higgs-like scalar with maximal flavor violation [22] would generate a large negative asymmetry due to helicity-flip in the Yukawa coupling. The spin conservation in the $\theta = 0$ direction requires the top quark to move backward. To resolve this, fermion-number violating diquark scalars with maximal flavor violation were proposed [11, 15, 23]. Diquark scalars can be $\bar{3}$ under $SU(3)_c$ and have fermion-number violating coupling as $tcu\phi$ or $tcd\phi$. Such diquark scalars with flavor violation can also be realized in various BSM contexts, partial unification models, or supersymmetry. For instance, in R-parity violating supersymmetric standard model which contains baryon number violating coupling $\epsilon_{\alpha\beta\gamma}u^c d^c d^c$, the down-type squark $\tilde{d}_i$ can mediate u-channel $d\bar{d} \to t\bar{t}$ that interferes with the QCD $d\bar{d} \to t\bar{t}$ amplitude. All three proposals can in principle predict large positive asymmetry in $t\bar{t}$ production.

In the following paragraphs, we examine the numerics to see whether the models can explain the three asymmetry measurements and the total cross section simultaneously.

1. Z' We first examine the first proposed t-channel model, Z' [9]. To minimize constraints from low energy, the authors proposed a right-handed coupled Z' with large coupling between u and t. The parameter region for 1σ fitting of all three asymmetry measurements as well as the total cross section for light Z' mostly below $t\bar{t}$ threshold is presented in Figure 2 [Figure 2: see original paper]. Due to large destructive interference, the total cross section is always smaller than the measured value. This result is also shown in the NLO calculation of the Z' model [19]. The best-fit points for heavy Z' by requiring 1σ fitting for all three asymmetry measurements are listed in Table I. The corresponding $t\bar{t}$ cross sections are also below the 1σ total cross section, and the best points are towards heavy masses of $\sim$ 700 GeV.

One more complication which has been discussed in [9-11] is that the events in the t-channel exchange tend to be in the high-energy region, which significantly increases the tail of $d\sigma/dM_{t\bar{t}}$, especially the last bin (800 GeV-1.4 TeV) in $d\sigma/dM_{t\bar{t}}$. The QCD correction may change the shape and lower the contribution in the high-energy region [19]. In addition, the t-channel kinematics implies that the top quark events at high energy are mostly in the larger rapidity region while the selection cuts are more efficient for central events. Consequently, the cut efficiency at high invariant mass is quite low [20], which may further decrease the effective total cross section. Polarization of the top quark in the event sample also affects the cut efficiency.

2. W' To resolve the tension between cross section and total asymmetry in the Z' model, the charged current process in the t-channel may give a better fit which has smaller interference effect due to the $d\bar{d}$ initial state. We plot the allowed parameter regions for the t-channel charged current model in [10] in Fig 3 [Figure 3: see original paper]. The 1σ asymmetry region of all three measurements corresponds to a larger total cross section which is outside the 1σ fit of the latest $\sigma_{t\bar{t}}$ measurement. However, various efficiency effects discussed in the last paragraph of the Z' section may significantly reduce the measured cross section.

3. Diquark We use the anti-triplet diquark that couples to $tcu\phi$ to illustrate the feature. Similar to the W' case, there also exist diquark scalars whose couplings are of $tcd\phi$ and these diquark scalars contribute to $d\bar{d} \to t\bar{t}$ instead.

Figure 4 [Figure 4: see original paper] gives the 1σ fitting for the anti-triplet diquark scalar with maximal flavor violation. The 1σ region also exists for the anti-triplet diquark scalar for all the measurements in asymmetries A^t_{FB}. But the corresponding total cross section $\sigma_{t\bar{t}}$ is also larger than the measured value by over 1σ. In addition, the best-fit for cross section and the mass-dependent asymmetry is over 1 TeV, which makes the $d\sigma/dM_{t\bar{t}}$ measurement very difficult to fit as shown in [11]. The latest simulation by [20] also showed that the $t\bar{t}$ events generated by diquark scalar had a higher cut efficiency at high energy; therefore, the anti-triplet diquark fitting is worse than the W'.

II. IMPLICATIONS AT THE TEVATRON AND LHC

After fitting the top forward-backward asymmetries in different kinematical regions, we discuss the other Tevatron bounds for the models and the LHC predictions that can be soon tested in this section.

The Large Hadron Collider (LHC) is a proton-proton collider with centre-of-mass energy of 7 TeV in the first two years of running. Unlike at Tevatron where the axigluon effect only appears as interference, the color octet axigluon of ~ 1 TeV can be directly produced at the LHC and decay into dijet or $t\bar{t}$. With significant decay branching ratio (BR) to $t\bar{t}$, it provides an additional handle to search for it. The study of axigluon at the LHC has been performed by [7]. The ATLAS collaboration has recently released the search for dijet resonance. The latest data has ruled out axigluon masses from 0.6–2.1 TeV by assuming axigluon coupling is only g_s. The axigluon model in [5] has an even larger coupling compared with the ATLAS paper and therefore, the model receives much more severe constraint.

For neutral gauge boson like Z', the flavor-violating vertex of ut will lead to large $uu \to t\bar{t}$ scattering with Z' exchange in the t/u-channel. The same-sign positive top quark pair (tt) becomes particularly interesting at the LHC given its large u-valence quark parton flux [25]. In addition, with large ut coupling, the tZ' associated production is not negligible. Since Z' equally decays into $u\bar{t}$ and $t\bar{u}$, the associated production tZ' or $\bar{t}Z'$ will contribute to $tt+j$, $\overline{tt}+j$, and $t\bar{t}+j$ final states. Again, since the LHC is a proton-proton collider, the $tt+j$ channel dominates the same-sign top production. The $t\bar{t}+j$ channel will appear in the inclusive $t\bar{t}$ search. Since the 1σ parameter space of all the asymmetry constraints corresponds to smaller $t\bar{t}$ pair production, the additional $t\bar{t}+j$ may in principle help to ease the tension at Tevatron. However, if it significantly contributes to $t\bar{t}$, the same amount of same-sign top quark will arise.

Figure 5 [Figure 5: see original paper] (a) gives the $pp \to tt$ production rate at Tevatron and the 7 TeV LHC with the $tt + \overline{tt}$ at Tevatron between 0.7-1 pb for these best-fit points. CDF measured only 3 events for 2 fb^{-1} [18] with acceptance range from 1.5% to 3%. The best-fit points all predict 15-30 same-sign pure leptonic top events before selection cuts but with one b-tagging. Even though these events from t-channel vector boson exchange may suffer from low cut efficiency compared to the t-channel light scalar exchange considered in Ref. [18], the Z' model is strongly constrained by the same-sign top quark scattering. At Tevatron, the same-sign top production due to tZ' associated production is much suppressed due to significant phase space suppression.

The $uu \to tt$ scattering gets significantly enhanced at the proton-proton collider LHC. The production rate can reach 200 pb. Therefore, even at very early running of LHC with about 30 pb^{-1} data and requiring two b-tagged jets, the event number before kinematic cuts is about 70, and the same-sign top quark tt events are expected to be $\mathcal{O}(10)$.

For W' or diquark scalars with flavor violation, since they are electrically charged, they will only contribute to $t\bar{t}$ as at Tevatron. However, since the W' or diquark ϕ has a large dt or ut coupling, the $dg \to tW'$ or $ug \to \bar{t}\phi$ production is significant as shown in [10, 11, 27]. With W' and diquark scalars of typically above top quark threshold, they can decay into t plus one hard jet. The signal is then $t\bar{t}$ plus one hard jet and should appear in the inclusive $t\bar{t}$ searches. The diquark case has already been calculated in our early paper [11].

Figure 6 [Figure 6: see original paper] gives the production of top quark plus W' at hadron colliders. For $M_{W'} < 400$ GeV, the production rate is about 0.1-1 pb at the Tevatron. As we discussed in the previous section, the 1σ fitting parameter space for all the asymmetry constraints corresponds to the larger cross section region. The new contribution to $t\bar{t}+j$ will increase the tension between A^t_{FB} and $\sigma_{t\bar{t}}$. For heavy W' above 400 GeV, due to large phase space suppression, the production rate at Tevatron can then be neglected. However, at the LHC, even with 7 TeV centre-of-mass energy, the production rate is $\mathcal{O}(10\ \mathrm{pb})$. Even though [26] claims that the single top production at Tevatron puts a strong constraint on the $W'b$ coupling, this constraint does not apply to general W' models.

III. INDIRECT CONSTRAINTS FOR MODELS

A. Axigluon with flavor protection

As shown in the previous section, only non-universal axigluon models can provide positive asymmetry. Being a color octet with strong coupling strength, this GIM-violating axigluon will then lead to significant flavor changing neutral current (FCNC) effects:

$$\mathcal{L} = ig_L\bar{q}_i\gamma^\mu(H_q^L)_{ij}P_Lq_jT^aG_\mu^a + ig_R\bar{q}_i\gamma^\mu(H_q^R)_{ij}P_Rq_jT^aG_\mu^a$$

Flavor violation thus can arise from the non-universal gauge couplings due to the rotation between mass eigenstate and gauge eigenstate:

$$u_L = V_{uL}u_L^0, \quad d_L = V_{dL}d_L^0, \quad u_R = V_{uR}u_R^0, \quad d_R = V_{dR}d_R^0$$

The effective coupling in horizontal space is $(V_{uL}^\dagger H_q^L V_{uL})_{ij}$. The rotation from mass eigenstate to gauge eigenstate for up and down type quarks respectively is completely unmeasurable in the weak interaction. The only observable is the mixing in charge current transition which is categorized as the CKM matrix.

To avoid flavor violation in the down sector, one may introduce a $U(1)_d$ symmetry [28] which acts only on the down sector with different eigenvalues for different generations, but V_{dR} does not distinguish the handedness of the quarks. Then the down-quark sector is diagonal with $V_{dR} = 1$ so that there is no FCNC at all in the B_s, B_d, or neutral K system. For simplicity, we take further the rotation matrix of right-handed up-quark sector as $V_{uR} = 1$. Then one can explicitly determine the left-handed up-type quark rotation based on the known CKM matrix using $V_{uL}V_{dL}^\dagger = V_{\mathrm{CKM}}$.

Nowadays the Wolfenstein parametrization [29] is widely used to express the CKM matrix in terms of four parameters (λ, A, ρ, and η). To keep the unitarity of the CKM matrix to all orders of λ, we adopt in the following a definition of Wolfenstein parameters proposed in [30]. Then the effective coupling between up quark and charm quark is $(V_{uL}^\dagger H_q^L V_{uL})_{12} = A^2\lambda^5(i\eta - \rho + 1)$.

Under the assumption of the above rotations, the FCNC operators only arise in left-handed mixing between first and second generation up-type quarks as:

$$(\bar{u}_\alpha\gamma^\mu c_\alpha)(\bar{u}_\beta\gamma_\mu c_\beta) - (\bar{u}_\alpha\gamma^\mu c_\beta)(\bar{u}_\beta\gamma_\mu c_\alpha)$$

where the following decomposition satisfied by the color $SU(3)$ fundamental representation has been implemented:

$$\delta_{\alpha\epsilon}\delta_{\beta\gamma} - \delta_{\alpha\beta}\delta_{\gamma\epsilon} = 2T^a_{\alpha\epsilon}T^a_{\beta\gamma}$$

Under Fierz transformation:

$$(\bar{u}_\alpha\gamma^\mu c_\beta)(\bar{u}_\beta\gamma_\mu c_\alpha) = \frac{1}{2}(\bar{u}_\alpha\gamma^\mu c_\alpha)(\bar{u}_\beta\gamma_\mu c_\beta)$$

the effective $\Delta C = 2$ Hamiltonian can be expressed as:

$$\mathcal{H}^{\text{axigluon}}_{\Delta C=2} = C(\mu)(\bar{u}_\alpha\gamma^\mu c_\alpha)(\bar{u}_\beta\gamma_\mu c_\beta)$$

and the leading order Wilson coefficient at the scale m_G is:

$$C(m_G) = \frac{g_A^2}{4m_G^2}\lambda^{10}(1-\rho+i\eta)^2$$

It means that the D^0-$\bar{D}^0$ mixing in this axigluon model has λ^{10} suppression due to CKM rotation. The RGE running of the above Wilson coefficient is well known:

$$C(\mu_c) = \left[\frac{\alpha_s(m_G)}{\alpha_s(\mu_c)}\right]^{6/23} C(m_G)$$

Notice that the hadronic matrix element of $\Delta C = 2$ operator is:

$$\langle D^0|\mathcal{H}^{\text{axigluon}}_{\Delta C=2}|\bar{D}^0\rangle = \frac{8}{3}f_D^2 m_D^2 B_D(\mu_c)$$

Just like the B^0 parameter $\hat{B}_D$ defined by $\bar{B}^0$ mixing case, one may define the renormalization group invariant:

$$\hat{B}_D \equiv (\alpha_s(\mu_c))^{-6/23}B_D(\mu_c)$$

which should be $\mathcal{O}(1)$. Then the axigluon-induced $\Delta C = 2$ effective operator contributes to the mass difference of the neutral D system as:

$$\Delta m_D = \frac{g_A^2}{4m_G^2}\frac{\alpha_s(m_G)^{6/23}}{8\pi f_D^2 m_D}\hat{B}_D\alpha_s(m_G)A^4\lambda^{10}((1-\rho)^2+\eta^2)$$

The axigluon model can also induce $\Delta C = 1$ effective operators which would in principle affect D^0-$\bar{D}^0$ mixing by:

$$\Delta m_D \sim 2m_D \left|\langle D^0|\mathcal{H}_{\Delta C=1}\mathcal{H}_{\Delta C=1}|D^0\rangle\right|^{1/2}$$

Actually, the experimental observation of comparably large mass and width differences:

$$\frac{\Delta m_D}{\Gamma_D} = 0.98^{+0.24}_{-0.26}\%, \quad \frac{\Delta\Gamma_D}{2\Gamma_D} = (0.83 \pm 0.16)\%$$

strongly implies that they are dominated by the long-distance effects of the SM $\Delta C = 1$ operators. Therefore, the axigluon-induced $\Delta C = 1$ terms could be safely neglected as they should be much smaller than the tree-level SM $\Delta C = 1$ terms.

Taking the Wolfenstein parameters as [32]:

$$A = 0.812, \quad \lambda = 0.2254, \quad \rho = 0.148, \quad \eta = 0.351$$

and $f_D = 207$ MeV [31], we obtain:

$$\left.\frac{\Delta m_D}{\Gamma_D}\right|_{\text{axigluon}} = 0.082\% \left(\frac{1\ \text{TeV}}{m_G}\right)^2$$

which is roughly one order of magnitude smaller than the experimental result.

B. Electroweak constraints on the W' model

In general, the W' must generate its mass through gauge symmetry breaking, then some neutral component in the W' symmetry breaking sector (for instance W_R^3 in $SU(2)_R$ symmetry breaking) would inevitably mix with W_L^3 and some extra $U(1)_X$, which induces a Z-Z' mixing. As a consequence, there is a large Z-Z' mixing which is constrained by electroweak precision tests. In general, the bound from EWPT is subtle since different fermion W/Z boson couplings are modified in different ways which may even depend on models, and a careful global fit is needed. The full results for the W' model to explain the top forward-backward asymmetry will be presented elsewhere. Since the overall modification for fermion Z boson coupling is small (except for some right-handed quarks charged under $SU(2)_R$), we only consider the tree-level Z-Z' mixing as a rough estimation.

For observables that strongly depend on $u_R/d_R/b_R$-Z coupling, such as g_R^2, $Q_W(Cs)$, etc., their deviations from the SM results are still at the same level as Z mass which is transmitted into W boson mass.

We can start to consider a simple $SU(2)_R \times SU(2)_L \times U(1)_X$ model to estimate how large the electroweak constraint is for the Z'-Z mixing. The $SU(2)_R$ is separated from $SU(2)_L$ to avoid the troublesome W-W' mixing. The two Higgs fields h_L and h_R are charged under $SU(2)_L \times U(1)_X$ and $SU(2)_R \times U(1)_X$ respectively, which spontaneously break $SU(2)_L \times SU(2)_R \times U(1)_X$ into the diagonal group $U(1)_{\text{em}}$. In order to raise the Z' mass so we have less constraint from the Z-Z' mixing, we choose h_R to transform as a triplet under $SU(2)_R$ so $m_{Z'} = \sqrt{2} m_{W'}$. The gauge quantum numbers for h_L and h_R are $(0, 1, 1/2)$ and $(1, 2, 0)$ under $SU(2)_R \times SU(2)_L \times U(1)_X$ respectively. For SM fermions, at least the quark doublet $(t, d)_R$ is charged under $SU(2)_R$ and $U(1)_X$ (it is possible to have some extra hidden fermions charged under $SU(2)_R$ and $U(1)_X$ to cancel the gauge anomaly). For the rest of SM fermions, their quantum numbers are the same as the SM ones if one replaces their hypercharge with the $U(1)_X$ charge. The quantum numbers for $(t, d)_R$ and $(u, b)_R$ under $SU(2)_R \times SU(2)_L \times U(1)_X$ are $(1/2, 1, 1/3, 0)$.

The kinetic term for the Higgs fields $\text{Tr}[(D_\mu h_L)^\dagger (D^\mu h_L)] + \text{Tr}[(D_\mu h_R)^\dagger (D^\mu h_R)]$ becomes the mass terms for the massive gauge bosons. The mass matrix of the gauge bosons is:

$$\mathcal{L}_{\text{mass}} = \frac{1}{2}(W_L^3, W_R^3, X) \begin{pmatrix} g_L^2 u^2/4 & -g_L g_R u^2/4 & 0 \\ -g_L g_R u^2/4 & g_R^2 (u^2 + 2v^2)/4 & -g_R g_X v^2 \\ 0 & -g_R g_X v^2 & g_X^2 (2u^2 + v^2) \end{pmatrix} \begin{pmatrix} W_L^3 \\ W_R^3 \\ X \end{pmatrix}$$

We introduce the parameter $\epsilon \equiv u^2/v^2$ which shows that the right-handed symmetry breaking is only a perturbation. This matrix can be diagonalized by means of an orthogonal matrix which we shall call R:

$$\begin{pmatrix} A \\ Z \\ Z' \end{pmatrix} = R^\dagger \begin{pmatrix} W_L^3 \\ W_R^3 \\ X \end{pmatrix}$$

where the mass eigenstates are denoted by A, Z, and Z'. The eigenstate A is massless and identified as the photon. The couplings of our theory are related to the electric charge by:

$$e = g_L \sin\theta_W = g_R \sin\phi \cos\theta_W = g_X \cos\phi \cos\theta_W$$

where θ_W is the weak mixing angle (in the limit $\epsilon \to 0$) and ϕ is an additional mixing angle.

The other two eigenmasses are:

$$m_{Z,Z'}^2 = \frac{g_R^2 v^2}{8 \cos^2\theta_W} \left[1 + \epsilon \sin^4\phi + \frac{g_X^2}{g_R^2}(1 + \epsilon \cos^2\phi) \pm \sqrt{\left(1 + \epsilon \sin^4\phi - \frac{g_X^2}{g_R^2}(1 + \epsilon \cos^2\phi)\right)^2 + 4\frac{g_X^2}{g_R^2}\epsilon^2 \sin^4\phi \cos^4} \right.$$

where we have dropped $\mathcal{O}(\epsilon^2)$ terms. Clearly, Z is identified with the SM Z boson while Z' is referred to as the heavy Z boson.

For small ϵ, the mixing matrix R has the following approximate form:

$$R \approx \begin{pmatrix} \sin\theta_W & \sin\phi\cos\theta_W & \cos\phi\cos\theta_W \\ \cos\phi\cos\theta_W & -\sin\phi\sin\theta_W & \epsilon\cos\phi\sin^4\phi \\ -\sin\phi\cos\theta_W & -\cos\phi\sin\theta_W & 1 \end{pmatrix}$$

from which it is simple to derive the SM fermion couplings. The SM fermion and Higgs couplings to Z and Z' can be written as:

$$\mathcal{L}_{NC} \supset g_R\sin\phi\sin\theta_W T_R^3 + g_X\cos\phi\sin\theta_W Q_X - eQ$$

$$+\epsilon\sin^2\phi\cos^2\phi\left[T_R^3 - \frac{g_X}{g_R}\sin^2\theta_W Q\right]$$

$$+g_L\cos\theta_W T_L^3 - eQ + \epsilon\sin^4\phi Q_X$$

In the limit of large $SU(2)_R$ breaking vev ($\epsilon \gg 1$) and small mixings ($\phi \to 0$), the Higgs current can be approximated as (we drop the $\epsilon\cos^2\phi\sin^3\phi$ term):

$$\mathcal{L}_{Z'(h)} = g_X\sin\phi(h^\dagger D_\mu h) + \text{h.c.} + \mathcal{O}(\epsilon\cot\theta_W\cos\phi\sin^3\phi)T_R^3$$

which induces a dimension-six operator:

$$\mathcal{L}_{\text{eff}} \supset a_h\mathcal{O}_h = \frac{g_R^2}{m_{W'}^2}\sin^4\phi(h^\dagger D_\mu h)^2$$

which coincides with Eq. (29) that $\Delta m^2 \sim \epsilon\sin^4\phi m_Z^2$. We can calculate the corresponding T parameter from the tree-level gauge boson mixing:

$$\hat{T} = \epsilon\sin^4\phi$$

Using the SM model inputs m_Z, G_F (the lifetime of τ), and $\alpha = e^2/4\pi$ as the basic input parameters, we can calculate the allowed parameter space including Higgs radiative corrections according to the most recent results: $S = 0.03\pm0.09$ and $T = 0.07\pm0.08$ (with 87% strong correlation) [31]. The results are presented in Fig. 7 [Figure 7: see original paper]. We can see that for sufficiently heavy Z' and strong coupling g_R (for instance, $g_R = 2$, $m_{Z'} = 900$ GeV which is used in Ref. [20]), it is well above the excluded region.

IV. CONCLUSIONS

We discuss the features of various models for the top quark forward-backward asymmetry anomaly at Tevatron, using the latest CDF measurements on total asymmetry in the lab frame $A_{FB}^{t,\text{lab}}$, the rapidity-dependent asymmetry $A_{FB}^{t}(|\Delta\eta| > 1)$, the mass-dependent asymmetry $A_{FB}^{t}(M_{t\bar{t}} > 450\text{ GeV})$, and the total $t\bar{t}$ production cross section $\sigma_{t\bar{t}}$.

The axigluon model in [5] has difficulty explaining the large rapidity-dependent asymmetry and the mass-dependent asymmetry simultaneously. In addition, the latest dijet search [17] at ATLAS has ruled out the parameter region that is relevant to top A_{FB}^{t}. On the other hand, in contrast to the conclusion in Ref. [8], the model itself does not suffer from flavor constraints from B_d mixing under flavor protection $U(1)_d$, and a careful calculation shows that their contribution to $\bar{D}^0$-D^0 mixing is still one order lower than the current experimental bound.

The t-channel Z' [9], W' [10], and anti-triplet diquark [11] models all have parameter regions that satisfy all three asymmetry measurements within 1σ. However, the corresponding production cross sections predicted by the 1σ asymmetry requirement in the Z' model are always significantly below the 1σ of cross section measurement. The best-fit point of Z' is about 700 GeV with purely right-handed coupling $g_R \approx 1.8$, which corresponds to $\sigma_{t\bar{t}} = 6.9$ pb. However, this best-fit point will generate a large number of same-sign top quark events at Tevatron which is at least five times larger than the SM prediction. We conclude that the Z' model is very difficult to be consistent with all the measurements.

Both W' and anti-triplet diquark models predict cross sections larger than the measurement, but various factors can lower the survival efficiency after cuts in these models to ease the tension between asymmetry and cross section. The best-fit point for anti-triplet diquark lies in a very high mass region, and with better survival efficiency [20], it is difficult to fit the differential cross section $d\sigma/dM_{t\bar{t}}$. A rough estimation for the W' model shows that the bounds from electroweak precision tests are weak due to the heavy Z' and strong coupling g_R. Therefore, we conclude that the best model is the t-channel W' model at the current stage. To test such a model directly, we also use the 1σ asymmetry parameters to compute the production rate of $t\bar{t} + j$ from tW' at 7 TeV LHC, and the production rate is 10%–50% of SM $t\bar{t}$.

Finally, we want to mention that the latest NNLL calculation $\sigma_{t\bar{t}}(m_t = 173.1\text{ GeV}) = 6.30^{+0.31}_{-0.23}$ pb [1] is significantly lower than the experimental results. If the result does not significantly change for $m_t = 172.5$ GeV which is used for Tevatron experiments, then the fits for t-channel W' and anti-triplet diquark would be better while the t-channel Z' would be worse.

ACKNOWLEDGEMENTS

J.S. and K.W. would like to thank Zhejiang Institute for Modern Physics at Zhejiang University and Prof. Mingxing Luo for hospitality after the Tohoku earthquake. We would like to thank Qinghong Cao, Mingxing Luo, Hitoshi Murayama, David Shih, Matt Strassler, Scott Thomas, and Carlos Wagner for useful discussions. We also thank Tim Tait who initiated the electroweak bounds for the W' model from our discussion. The work is partially supported by the World Premier International Research Center Initiative (WPI initiative) MEXT, Japan. J.S. and K.W. are also supported by the Grant-in-Aid for scientific research (Young Scientists (B) 21740169) and (Young Scientists (B) 22740143) from Japan Society for the Promotion of Science (JSPS), respectively. G.Z. is supported in part by the National Science Foundation of China (No. 11075139 and No. 10705024) and the Fundamental Research Funds for the Central Universities.

NOTES ADDED

While this work was being delayed by the huge earthquake in Japan, Ref. [20] appeared, which overlaps with ours in the study of fitting different models on different top forward-backward asymmetries. Our results agree quantitatively with theirs for fitting different top forward-backward asymmetries and the total $t\bar{t}$ cross section. However, we notice that the axigluon model and the heavy Z' model are severely constrained by the dijet search at the LHC (ATLAS) and the same-sign dilepton search at the Tevatron (CDF). Therefore, we conclude that the heavy W' model is the most promising one at present. We also consider the indirect bounds for different models.

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