Testing new physics models by top charge asymmetry and polarization at the LHC

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As a top quark factory, the LHC can test new physics models used to explain the top quark forward-backward asymmetry A^t_{FB} measured at the Tevatron. In this work we perform a comparative study for two such models: the W' model and the color triplet diquark (ϕ) model. Requiring these models to explain A^t_{FB} and also satisfy the top pair production rate measured at the Tevatron, we examine their contributions to the LHC observables such as the polarizations and charge asymmetries in top quark productions and the charge asymmetry in W' (or ϕ) pair production. We find that these observables can be enhanced to their observable levels and current LHC measurement on the top charge asymmetry has already tightly constrained the W' model. We also find that each observable shows different characteristics in different models, which can be utilized to discriminate the models.

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I. INTRODUCTION

So far the top quark properties measured at the Tevatron are in good agreement with the standard model (SM) predictions except the inclusive[1] forward-backward asymmetry A^t_{FB} [1], which, as reported by the CDF collaboration and the D0 collaboration, exceeds the SM prediction by about 2σ [2,3]. Such an anomaly has been widely speculated as a harbinger of new physics and thus stimulated various explanations in extensions of the SM [4–11]. These extensions, albeit in quite different forms, usually have rich top quark phenomenology at colliders. Since the Tevatron is going to be shut down very soon, the task to screen out the right theory is left for the LHC [12].

Although the present top quark dataset at the LHC is moderate, it is already capable of scrutinizing the validity of some extensions. For example, the non-observation of a clear resonance in the $t\bar{t}$ production searched by the ATLAS and CMS Collaborations at $\sqrt{s} = 7$ TeV implies that an axigluon with strong couplings to light quarks should be heavier than 3.2 TeV [13], which makes it less attractive as an explanation of A^t_{FB} [5] (however, as pointed in the last reference in [5], a light axigluon with an enlarged width and reduced couplings to light quarks is still allowed by the current LHC measurements). Meanwhile, since no excess of same-sign top quark events was observed by recent measurements from the LHC and Tevatron [14,15], the light Z' model based on flavor non-universal $U(1)$ symmetry [7] is also disfavored. Among the surviving models two typical ones are the W' model [16] and the diquark (ϕ) model [17], which, as pointed in [18], are preferred by the combined fit of A^t_{FB} and the total $t\bar{t}$ production rate measured at the Tevatron. In this work we focus on these two models and perform a comparative study by considering several observables at the LHC. Our study shows that each of these observables can be enhanced to the observable level and meanwhile exhibits different characteristics in these two models. As a result, the W' model is found to be tightly constrained by the charge asymmetry in $t\bar{t}$ production at the LHC, while the diquark model can be readily explored once more luminosity is accumulated at the LHC.

We will consider the following observables:

(a) Top quark charge asymmetry in $t\bar{t}$ production at the LHC, which is defined by [19]

$$A_C(t\bar{t}) = \frac{\sigma(|\eta_t| > |\eta_{\bar{t}}|) - \sigma(|\eta_t| < |\eta_{\bar{t}}|)}{\sigma(|\eta_t| > |\eta_{\bar{t}}|) + \sigma(|\eta_t| < |\eta_{\bar{t}}|)}, \quad (1)$$

where η_t ($\eta_{\bar{t}}$) is the pseudo-rapidity of the top (antitop) quark in the laboratory frame, and σ denotes cross section. This asymmetry reflects whether the top quarks on average are more boosted than the antitop quarks or not. We note that the CMS Collaboration has recently measured this quantity with an integrated luminosity of 1.09 fb^{-1} and obtained $A_C^{\rm exp}(t\bar{t}) = -0.016 \pm 0.030({\rm stat.})^{+0.010}_{-0.019} \times$ (syst.), which is consistent with its SM prediction $A_C^{\rm SM}(t\bar{t}) = 0.0130(11)$ [19]. A similar result is also reported by the ATLAS Collaboration with larger uncertainties [20]. So this asymmetry can be used to limit new physics models [21,22].

(b) Top quark polarization asymmetry in $t\bar{t}$ production at the LHC, defined by [23]

$$P_t = \frac{(\sigma_{+-} + \sigma_{++}) - (\sigma_{-+} + \sigma_{--})}{\sigma_{+-} + \sigma_{++} + \sigma_{--} + \sigma_{-+}} \quad (2)$$

with the first (second) subscript of σ denoting the helicity of the top (antitop) quark. Unlike light

[1] We do not consider the CDF 3.4σ discrepancy of A^t_{FB} for $m_{t\bar{t}} > 450$ GeV because it is not confirmed by the D0 collaboration.

quarks, top quark decays rapidly before forming any hadronic bound state. So its spin information is preserved by its decay products and can be recovered by their angular distributions. For the $t\bar{t}$ production at the LHC, the top quark is not polarized at the leading order of the SM because the production proceeds mainly through the QCD interaction and the parity-violating electro-weak contribution to the polarization is negligibly small [23], but any addition of new parity-violating interaction of top quark may induce sizable polarization asymmetry [24–26].

(c) Enhancement factor of the $t\bar{t}$ production rate in high invariant mass region of $t\bar{t}$:

$$R_1 = \sigma_{\rm tot}(M_{t\bar{t}} > 1\ {\rm TeV})/\sigma_{\rm SM}(M_{t\bar{t}} > 1\ {\rm TeV}), \quad (3)$$

where $\sigma_{\rm tot}$ incorporates the contributions from the SM and the new physics. In exotic t-channel or u-channel $t\bar{t}$ production, the Rutherford singularity can alter significantly the distribution of the $t\bar{t}$ invariant mass in high energy tail [27], so R_1 may deviate significantly from unity.

(d) Charge asymmetry in the associated production of a single top with a particle X:

$$R_2 = \sigma(tX^-)/\sigma(\bar{t}X^+). \quad (4)$$

This asymmetry can be measured by requiring that the top quark decay semileptonically and X decay hadronically, and looking for the asymmetry between the event numbers with one lepton and one antilepton in the signal, respectively. It was once suggested in searching for single top production in the SM and in limiting new physics models [28,29]. Depending on m_X and the initial partons in $tX^\pm$ production, R_2 may be far larger or smaller than unity.

(e) Charge asymmetry in X^+X^- production defined by

$$A_C(X^+X^-) = \frac{\sigma(|\eta_{X^-}| > |\eta_{X^+}|) - \sigma(|\eta_{X^-}| < |\eta_{X^+}|)}{\sigma(|\eta_{X^-}| > |\eta_{X^+}|) + \sigma(|\eta_{X^-}| < |\eta_{X^+}|)}, \quad (5)$$

Like $A_C(t\bar{t})$, this asymmetry reflects whether X^- or X^+ is more boosted. Given the interactions of the particle X with quarks, this asymmetry is determined by m_X and the energy of the LHC.

This paper is organized as follows. In Sec. II, we briefly describe the features of the W' model and diquark model. Then in Sec. III we discuss some observables in $t\bar{t}$ production, single top production and W' (ϕ) pair production. Finally, we draw our conclusion in Sec. IV.

II. THE W' MODEL AND THE DIQUARK MODEL

Among various explanations of the $A_{\rm FB}^t$ anomaly, the model with a color singlet W' is a promising one [16,18]. This model can be realized in an asymmetric left-right framework [9,30] presented in the Appendix, which is based on the gauge group $SU(2)_L \bigotimes SU(2)_R \bigotimes U'(1)$ and assumes that only the first and third generation right-handed quarks transform nontrivially under the group $SU(2)_R$. The interaction relevant to our calculation is given as

$$\mathcal{L} = -g_R \bar{t}\gamma^\mu P_R d W'^+_\mu + {\rm H.c.}. \quad (6)$$

The $t\bar{t}$ production then gets additional contribution from the t-channel process $d\bar{d} \to t\bar{t}$ via exchanging a W', which may sizably alter $A_{\rm FB}^t$ at the Tevatron. Note that in the framework presented in the Appendix, besides W', the newly predicted neutral and charged Higgs bosons can also contribute to the $t\bar{t}$ production. Since the size of such contribution is model-dependent and may be negligible if these fields are heavy and/or the vev of ϕ_R is much higher than the electro-weak breaking scale [9,30], we in our study do not consider these contributions.

Another model we are considering is the color-triplet diquark model [17], where a new scalar ϕ (called diquark) is assigned with the quantum number ($\bar{\mathbf{3}}$, $\mathbf{1}$, $-4/3$) under the SM gauge group ${\rm SU(3)}_C \times {\rm SU(2)}_L \times {\rm U(1)}_Y$. The relevant Lagrangian is then given by

$$\mathcal{L} = D_\mu \phi^\dagger D^\mu \phi - M_\phi^2 |\phi|^2 + f_{ij} \bar{u}_{i\alpha} P_L u^c_{j\beta} \epsilon^{\alpha\beta\gamma} \phi^\dagger_\gamma + {\rm H.c.}, \quad (7)$$

where the coupling coefficients satisfy $f_{ij} = -f_{ji}$ with i, j being the flavor index, $\epsilon^{\alpha\beta\gamma}$ is the antisymmetric tensor in color space, and $u^c = C\bar{u}^T$ with C being the charge conjugate matrix. In this framework, the discrepancy of $A_{\rm FB}^t$ can be alleviated by the contribution of the u-channel process $u\bar{u} \to t\bar{t}$ mediated by the triplet ϕ. In [31], a comparative study of $A_{\rm FB}^t$ was performed in diquark models where ϕ is assigned in different representations of the $SU(3)$ group, and it was found that the triplet model is better suited to explain the $A_{\rm FB}^t$ anomaly without conflicting with other experimental results. In our analysis, in order to escape constraints from low energy processes such as $D^0 - \bar{D}^0$ mixing, we set f_{ij} to be zero except f_{ut}.

The common feature of the two models comes from the calculation of the $t\bar{t}$ production rate, where the interference of the new contribution with the SM QCD amplitude always partially cancels the pure new contribution. In fact, this cancellation is essential for the models to explain the $A_{\rm FB}^t$ anomaly and at same time keeps other observables consistent with their measured values at the Tevatron. We checked that such cancellation persists in calculating A_C discussed below, and the extent of the cancellation depends on the new particle mass and the collider energy. We also checked that, partially due to the difference in parton distributions for the initial states, $A_{\rm FB}^t$ in the diquark model usually exceeds that in the W' model if $g_R = f_{ut}$ and $m_{W'} = m_\phi$.

III. NUMERICAL RESULTS AND DISCUSSIONS

In this section we present the numerical results for the observables at the LHC with $\sqrt{s} = 7$ TeV. We take the SM parameters as [32]

$$m_t = 172.5\ \text{GeV}, \qquad m_Z = 91.19\ \text{GeV},$$
$$\sin^2\theta_W = 0.2228.\alpha_s(m_t) = 0.1095, \qquad \alpha = 1/128, \tag{8}$$

and use the parton distribution function CTEQ6L1 [33] by setting $\mu_R = \mu_F$ with μ_R and μ_F denoting the renormalization scale and the factorization scale, respectively.

For the constraints from the $t\bar{t}$ production rates, we consider the Tevatron measurements [34], which are so far the most precise results.[2] We require the predictions of the inclusive $A^t_{\rm FB}$ and the total $t\bar{t}$ production rate in each model to lie within 1σ region of their experimental values. As mentioned earlier, we do not consider the discrepancy of the $A^t_{\rm FB}$ in large $t\bar{t}$ invariant mass region reported by the CDF collaboration (about 3.4σ away from its SM prediction for $M_{t\bar{t}} > 450$ GeV [2]) since it is not confirmed by the D0 collaboration [3]. We also do not consider the constraint from the measured $t\bar{t}$ invariant mass distribution at the Tevatron because the shape of such a distribution in high energy tail is sensitive to the cut efficiency of event selection and also to QCD corrections [8,18].

A. Observables in $t\bar{t}$ production

Before presenting our results for $A_C(t\bar{t})$, we point out two features of $A^t_{\rm FB}$. First, because the valence quark in proton always moves in parallel with the proton, $A^t_{\rm FB} > 0$ observed at the Tevatron means that the top quark tends to move along with the valence quark than to move in the opposite direction. Second, $A^t_{\rm FB}$ depends on the collider energy $\sqrt{s}$. We found that as $\sqrt{s}$ increases, $A^t_{\rm FB}$ increases monotonically in the W' model but decreases monotonically in the diquark model. This means that if the two models predict a same $A^t_{\rm FB}$ at the Tevatron, then as $\sqrt{s}$ increases to the LHC energy, the tendency of top quark to move with the valence quark (u or d) in the W' model should be larger than that in the diquark model.

In Fig. 1 we show the correlation between $A^t_{\rm FB}$ at the Tevatron and $A_C(t\bar{t})$ at the LHC in these two models. Such results are obtained by scanning over the two-dimension parameter space of the models and keeping only the samples surviving the Tevatron constraints. We see that $A^t_{\rm FB}$ and $A_C(t\bar{t})$ are of the same sign and with the increase of $A^t_{\rm FB}$ the value of $A_C(t\bar{t})$ increases too. This behavior can be understood by noting the following three points. The first is that in the $t\bar{t}$ rest frame the top and the antitop outgo back to back. So, regardless the underlying dynamics, we always have $|\eta_t| = |\eta_{\bar{t}}|$. The second is that for the t-channel process $d\bar{d} \to t\bar{t}$ or the u-channel process $u\bar{u} \to t\bar{t}$ at pp colliders like the LHC, the $t\bar{t}$ rest frame tends to be boosted along the direction of d or u quark since they are the valence quarks in proton. For a given event, the direction of the valence quarks is definite. Then, if the scattering angle θ_{tq} ($q = u$, d) between the outgoing top quark and the valence quark in $t\bar{t}$ rest frame is less (larger) than $\pi/2$, $|\eta_t|$ defined in the laboratory frame tends to be larger (less) than $|\eta_{\bar{t}}|$. And the last point is if the top quark has equal probability to move along and to move in opposite to the valence quark direction at the LHC (corresponding to $A^t_{\rm FB} = 0$ in $p\bar{p}$ collision), the number of events with $|\eta_t| > |\eta_{\bar{t}}|$ should be same as that with $|\eta_t| < |\eta_{\bar{t}}|$, and hence $A_C(t\bar{t}) = 0$; if the former probability exceeds the latter probability (corresponding a positive $A^t_{\rm FB}$ in $p\bar{p}$ collision), more events with $|\eta_t| > |\eta_{\bar{t}}|$ than with $|\eta_t| < |\eta_{\bar{t}}|$ should be obtained and thus $A_C(t\bar{t})$ is positive. This analysis shows that $A^t_{\rm FB}$ at the Tevatron can be treated as an indicator of $A_C(t\bar{t})$ at the LHC.

Figure 1 also indicates that $A_C(t\bar{t})$ in the W' model is usually several times larger than that in the diquark model for a given value of $A^t_{\rm FB}$. One underlying reason is, as we mentioned before, the probability of the top quark to move along with the valence quark in the W' model exceeds that in the diquark model. Another reason is from the parton distribution of the initial states: at the Tevatron we have $P_{d\bar{d}}{:}P_{u\bar{u}} \simeq 1{:}4$, while at the LHC $P_{d\bar{d}}{:}P_{u\bar{u}} \simeq 1{:}2$. So when both models predict a same $A^t_{\rm FB}$ at the Tevatron, the parton distribution in the W' model is relatively enhanced at the LHC.

Another striking feature of Fig. 1 is that a large portion of the samples in the W' model have been ruled out by the measured value of $A_C(t\bar{t})$ at 2σ level, which implies that the W' model has already been tightly limited by the charge asymmetry. In contrast, in the diquark model the $A_C(t\bar{t})$ value always lie within 2σ range of its experimental central

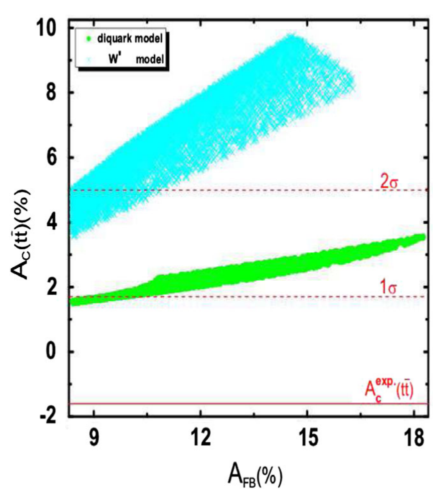

FIG. 1 (color online). The correlation between $A^t_{\rm FB}$ at the Tevatron and $A_C(t\bar{t})$ at the LHC.

[2] The latest LHC measurement [35] has marginally reached the Tevatron precision. If we consider the LHC limits, our results remain unchanged.

value. We checked that the $A_C(t\bar{t})$ value in the diquark model will be further reduced at the LHC as $\sqrt{s}$ is raised to 14 TeV.

In getting Fig. 1, we note that, since the new physics contributions to the $t\bar{t}$ cross section are relatively small, both A_C and A_{FB}^t can be approximated as the SM value plus the new physics effect: $A_C \simeq A_C^{SM} + \delta A_C$ and $A_{FB}^t \simeq A_{FB}^{t\,SM} + \delta A_{FB}^t$. For the values of A_C^{SM} and $A_{FB}^{t\,SM}$, we use their NLO QCD results: $A_C^{SM}(t\bar{t}) = 0.0130$ [19] and $A_{FB}^{t\,SM} = 0.038$ (which is obtained by the MCFM package [2]). In calculating δA_C and δA_{FB}^t, we encounter two kinds of cross sections: the SM cross sections $\sigma_{t\bar{t}}^{SM}$ and the new physics corrections $\delta\sigma_{t\bar{t}}$. We use the tree-level expression of $\delta\sigma_{t\bar{t}}$ due to the absence of its high order QCD correction in literatures, while for the $\sigma_{t\bar{t}}^{SM}$, we use its most precise NNLO result, which is obtained by multiplying its LO prediction by a K factor, i.e. $K \simeq 1.7$ for the LHC [36] and $K \simeq 1.3$ for the Tevatron [37].

In Fig. 2 we show the dependence of $A_C(t\bar{t})$ on the model parameters such as the coupling strength and the new particle mass. Because of the difference in kinematic features of the t and the u channels, the mass ranges favored by A_{FB}^t and $\sigma(t\bar{t})$ are $150\ \text{GeV} < m_{W'} < 700\ \text{GeV}$ and $250\ \text{GeV} < m_\phi < 700\ \text{GeV}$ for the two models, respectively. This figure indicates that for a given new particle mass the coupling coefficient (f_{ut} or g_R) is restricted in a certain region, and as the new particle becomes heavy, the region moves upward. This is because we have required the samples shown in the figure to explain the A_{FB}^t anomaly and at same time to satisfy the $\sigma_{t\bar{t}}$ constraint. This figure also indicates that a heavy new particle along with a strong coupling can predict a large $A_C(t\bar{t})$. We checked this case and found it usually corresponds to a large A_{FB}^t at the Tevatron.

In the left frame of Fig. 3 we show the correlation of the $A_C(t\bar{t})$ with the ratio R_1 defined by Eq. (3). As we mentioned before, for the t-channel or the u-channel $t\bar{t}$ production, the Rutherford singularity tends to push more events to high $M_{t\bar{t}}$ region so that R_1 may be significantly larger than unity. This is reflected in the W' model where R_1 is in the range of 2.0 and 7.7 and in the diquark model where R_1 varies from 1.2 to 2.7. Since the predicted R_1 is in two separated regions, R_1 may be utilized to discriminate the models. We checked the reason for the difference and found that the cancellation between the pure new physics contribution and the interference contribution in the W' model is not as strong as that in the diquark model. We also note that the LHC with higher luminosity is capable of exploring the models with $R_1 > 2$ [27]. So we conclude that the quantity R_1 is complementary to $A_C(t\bar{t})$ in testing the models.

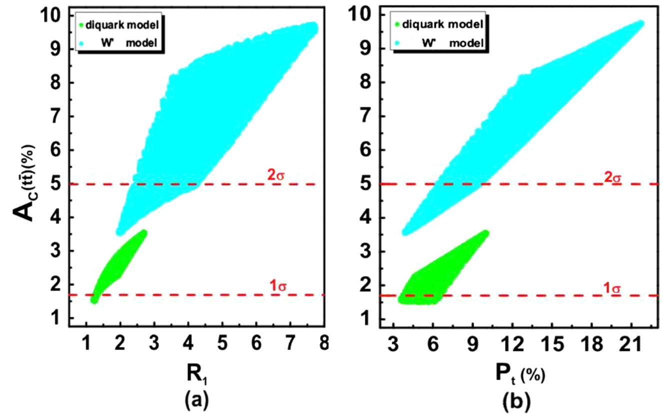

FIG. 3 (color online). The correlations of $A_C(t\bar{t})$ with R_1 and P_t at the LHC, respectively.

Since the new interactions violate parity and hence can lead to top quark polarization asymmetry P_t at the LHC, in the right frame of Fig. 3 we show the correlation of $A_C(t\bar{t})$ with P_t. This figure indicates that the value of P_t increases with the increase of $A_C(t\bar{t})$ with its maximum value reaching 22% and 10% for the two models, respectively. To

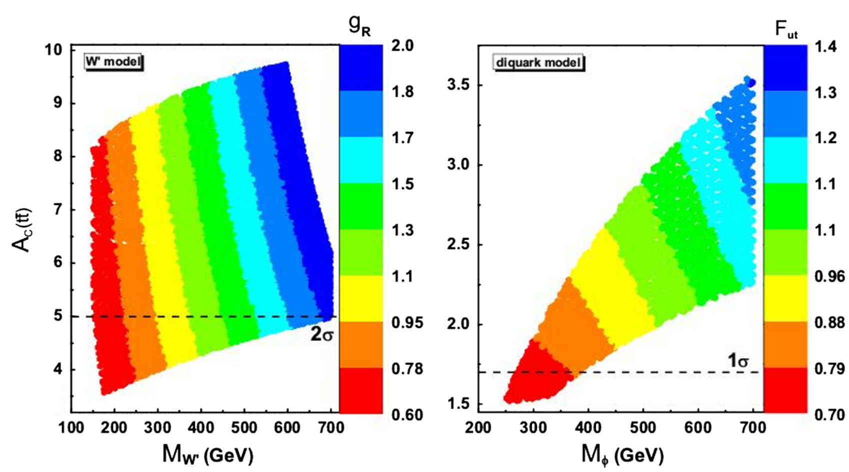

FIG. 2 (color online). The dependence of $A_C(t\bar{t})$ on the model parameters. Samples shown here satisfy the Tevatron measurements at 1σ level described in the text.

roughly estimate the observability of such asymmetry, we calculate the statistical significance N_S defined in [24] for an integrated luminosity of 1 fb^{-1} without considering the cut efficiency and the systematic uncertainties. We find that for nearly all the samples in the models, the predicted P_t can reach its 3σ sensitivity, which is 1.20% for the W' model and 2.15% for the diquark model.

B. Observables in single top production

In the W' (diquark) model, the associated production of single top quark with W' (ϕ) proceeds by the Feynman diagrams shown in Fig. 4. The total production rates (top events plus antitop events) can reach 60 pb and 160 pb for the surviving samples in the two models, respectively.

Because of the electric charge carried by W'^- (ϕ^-), the production rates of the top quark and antitop quark are not equal. Since the initial state is dg ($\bar{u}g$) for the top production and $\bar{d}g$ (ug) for the antitop production, the parton distributions determine $R_2 > 1$ for the W' model and $R_2 < 1$ for the diquark model, where R_2 denotes the charge asymmetry of the associated production defined in Eq. (4). From Fig. 5, we find $3.6 < R_2 < 6.8$ in the W' model while $R_2 < 0.2$ in the diquark model. In our calculation we also find that, although the rate of the tW'^- production decreases monotonically as W' becomes heavy, the ratio R_2 increases. The reason is that the distribution function of the sea quark $\bar{d}$ is more suppressed in high proton momentum fraction region.

In order to further test two models, we investigate the kinematical distributions of the single top productions. As an illustration, we take the best point for each model. The best point is determined by minimizing the χ^2 function defined as

$$\chi^2 = \sum_i \frac{(O_i^{\text{theory}} - O_i^{\text{measured}})^2}{\sigma_i^2}, \quad (9)$$

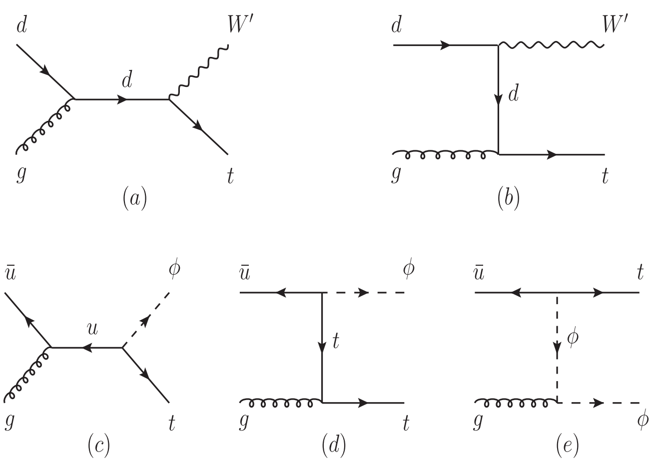

FIG. 4. Feynman diagrams contributing to the single top productions at the LHC.

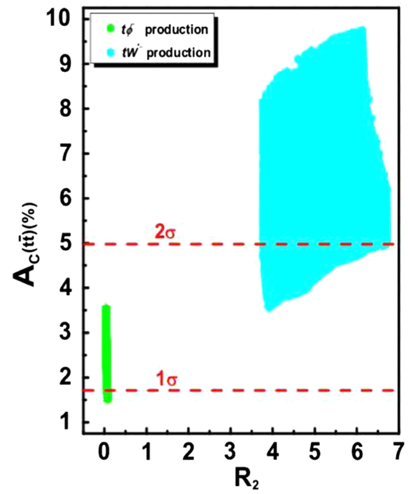

FIG. 5 (color online). The correlations between the $A_C(t\bar{t})$ and R_2 at the LHC.

where the observables O_i are A_{FB}^t and $\sigma(t\bar{t})$ at the Tevatron and $A_C(t\bar{t})$ at the LHC. We add the experimental and the SM errors in quadrature to calculate σ_i. For the W' model the best point is found to be at $g_R = 0.605$ and $m_{W'} = 697.85$ GeV, with $\chi^2/\text{dof} = 4.69/3$; while for diquark model the best point is at $f_{ut} = 0.91$ and $m_\phi = 442.43$ GeV, with $\chi^2/\text{dof} = 1.47/3$. In Table I we present the predictions for the observables at the best points.

In our analysis we assume W'^- and ϕ^- mainly decay as $W'^- \to \bar{t}d$ and $\phi^- \to \bar{t}\bar{u}$ with the antitop quark decaying hadronically so that W' and ϕ can be reconstructed. In this way, the associated productions may be disentangled from the $t\bar{t}$ production [16] which acts as the main background. Using the MadGraph5/MadEvent [38], we study the signal $3j + 2b + l + \not{E}_T$ at the parton level under the basic cuts at the LHC, where $\not{E}_T$ denotes the missing transverse energy.

In Fig. 6 we display the distributions of the total transverse energy H_T and the angle between the b-jet and the light jet coming from $W'(\phi)$, which are all defined in the laboratory frame. The left panel of this figure shows that the most events from tW' have lower H_T than those from $t\phi^-$. The reason is that in the considered case W' is lighter than the diquark state. The right panel shows that the b-jet is inclined to fly along the light jet in the W' model, while to fly in opposite to the light jet in the diquark model. This is because, although the decay products of $W'(\phi)$ are boosted along the direction of $W'(\phi)$, the massive antitop from the $W'(\phi)$ decay may kick its b-jet in certain direction so that the b-jet can deviate from the boost direction. Actually, we find that the b-jet from a left-handed antitop quark (as in the W' model) tends to fly along the direction of the antitop quark [39], which is also the direction of the light jet from the W' decay; while the b-jet from a right-handed antitop quark (as in the case in the diquark model) tends to fly in the opposite direction.

TABLE I. Predictions of the W' model and the diquark model at the best point. X denotes W' or ϕ. New physics contributions to the cross sections at the Tevatron (LHC) are in unit of fb (pb).

	Tevatron		LHC							
	$\Delta\sigma(t\bar{t})$	$A^t_{\rm FB}$	$\Delta\sigma(t\bar{t})$	$A_c(t\bar{t})$	P_t	$A_C(XX)$	R_1	R_2	$\sigma(tX)$	$\sigma(XX)$
W'	107.84	0.054	−0.71	0.011	−0.006	0.05	0.09	6.7	0.26	0.002
diquark	831.20	0.120	0.99	0.021	0.055	−0.69	1.54	0.06	2.5	0.87

For the charge asymmetry in single top production, due to the large jet multiplicities and moderate b-tagging efficiency in the process, the measurement will be somewhat challenging at the LHC. However, we noted that the peak values of H_T(>500 GeV) in both models are much larger than that in the SM ($\sim$ 350 GeV). With higher luminosity and higher kinematic cuts, the measurements of the differential cross sections and the single top charge asymmetries versus H_T will be useful to discover the signals [28]. Moreover, the b-jet angular distribution may serve as a complementary discriminator for the background, since the distribution of $\cos\theta_{bj}$ in the SM is relatively flat in comparison with the signals. The detailed analysis of the backgrounds depends on the full detector simulation which is partially studied in Ref. [40].

C. Observables in $W'^+W'^-$ and $\phi^+\phi^-$ productions

Because of the interactions introduced in Sec. II, the $W'^+W'^-$ production proceeds only by the parton process $d\bar{d} \to W'^+W'^-$ through exchanging a top quark, while the $\phi^+\phi^-$ production may proceed either by $u\bar{u} \to \phi^+\phi^-$ or by $gg \to \phi^+\phi^-$ (via $gg\phi\phi$ and $g\phi\phi$ interactions). We checked our results for the $\phi^+\phi^-$ production and found that the gluon annihilation contribution is usually negligibly small. One main reason is that for the surviving samples presented in Fig. 2, ϕ is usually heavy and thus the gluon distribution in proton is suppressed. We also found that, for given $m_{W'} = m_\phi = m_P$, the $\phi^+\phi^-$ production rate is slightly lower than the $W'^+W'^-$ rate. This is shown in Fig. 7, where one can learn that for $m_P = 250$ GeV, $\sigma(W'^+W'^-)$ may exceed 6 pb while $\sigma(\phi^+\phi^-)$ can only reach 4 pb.

Although the pair production rates are moderate at the LHC with $\sqrt{s} = 7$ TeV, the charge asymmetry A_C can still be sizable because it only reflects the unbalance between the particle and its charge conjugate state in boosting along

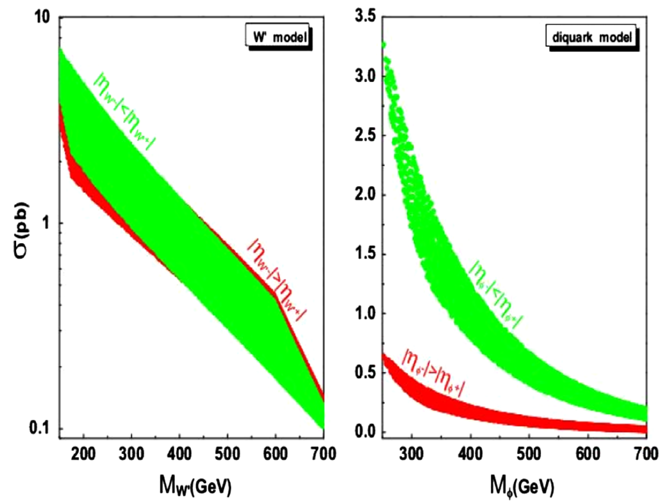

FIG. 7 (color online). Pair production rate at the LHC versus the corresponding particle mass.

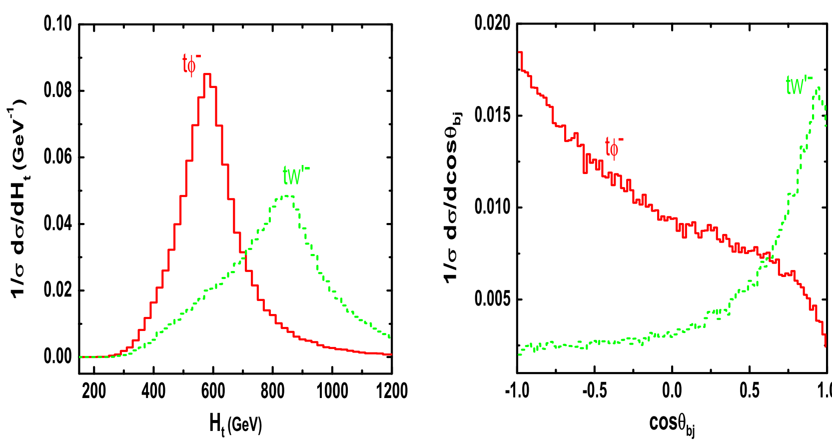

FIG. 6 (color online). The distributions of H_t and $\cos\theta_{bj}$ in the single top productions at the LHC. Here the b-jet and the light jet are required from same new particle.

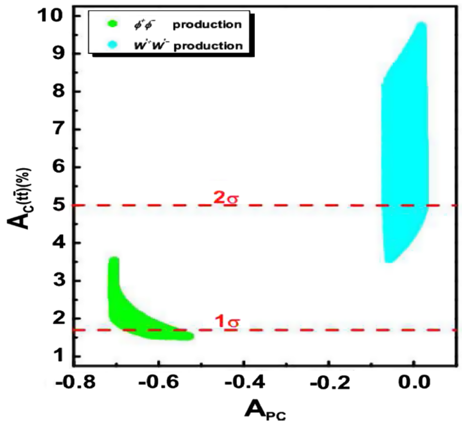

FIG. 8 (color online). The correlation of $A_C(t\bar{t})$ with $A_C(W'^+W'^-)$ and $A_C(\phi^+\phi^-)$ at the LHC, respectively.

the valence quarks. In Fig. 8 we show the charge asymmetry A_C in the two models. This figure indicates that in the W' model the $A_C(W'^+W'^-)$ fluctuates around zero, while in the diquark model $A_C(\phi^+\phi^-)$ varies between -0.5 and -0.8. These results can be understood from Fig. 7, which shows that for $m_{W'} < 408$ GeV the cross section with $|\eta_{W'^-}| < |\eta_{W'^+}|$ is slightly larger than that with $|\eta_{W'^-}| > |\eta_{W'^+}|$, and with the increase of $m_{W'}$ this relation is reversed; while in the diquark model the corresponding former rate is always larger than the latter rate to obtain a significant negative $A_C(\phi^+\phi^-)$.

We note that in the SM the value of A_C for the W^-W^+ production is positive, while in the W' model the value of $A_C(W'^+W'^-)$ is negative for a light W'. The difference comes from the masses of mediators. In the SM, the main contribution to the W^+W^- production is through the t channel by mediating a massless light quark, while in the W' model, it is top quark that mediates the process of the $W'^+W'^-$ production. We checked that if we set m_t to zero, A_C in W' pair production will become positive as $A_C(W^+W^-)$ in the SM. We also note that in the diquark model, even with the constraints from $A_C(t\bar{t})$, the value of $A_C(\phi^+\phi^-)$ can still deviate significantly from zero. We checked that at the LHC with $\sqrt{s} = 14$ TeV the rates for these productions are usually enhanced by about $3 \sim 4$ times, while A_C changes little in both models.

IV. CONCLUSION

In this paper we discussed the potential of the LHC to discriminate the W' model and the diquark model which were used to explain the $A^t_{\rm FB}$ anomaly measured at the Tevatron. With the constraints from the Tevatron, we examine the charge and polarization asymmetries in $t\bar{t}$ production, the charge asymmetries in single top production and $W'(\phi)$ pair production at the LHC with $\sqrt{s} = 7$ TeV. We found that the predictions of these observables may be large enough to reach their detectable levels at the LHC. In particularly, the recent measurement of the charge asymmetry in $t\bar{t}$ production from the LHC has already imposed a strong limit on the W' explanation of the $A^t_{\rm FB}$ anomaly. We also found that each observable in the two models shows different characteristics and a joint analysis of these observables at the LHC can help to discriminate the two models.

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APPENDIX: AN ASYMMETRIC LEFT-RIGHT MODEL WITH A LIGHT W'

The asymmetric left-right model with light W' was proposed in [9,30]. It is based on the gauge group $SU(2)_L \otimes SU(2)_R \otimes U'(1)$ and assumes that only the first and third generation right-handed quarks transform nontrivially under the group $SU(2)_R$ [30]. The symmetry breaking starts with $SU(2)_R \otimes U'(1) \to U(1)_Y$ to obtain the SM hypercharge $Y = 2T^R_3 + Y'$, and subsequently $SU(2)_L \otimes U(1)_Y \to U(1)_{EM}$ to obtain $Q = T^L_3 + Y/2$. For the first breaking, a $SU(2)_R$ triplet Higgs field is introduced so that the neutral gauge bosons Z' of the $SU(2)_R$ group is significantly heavier than the charged boson W' [9,30]. Two distinctive features of the model are exhibited in [30]. One is, after choosing specific rotation matrices to transform right-handed quarks from flavor basis to mass eigenstates, W' may couple to flavors in the combination $(t, d)_R$ with unsuppressed strength, while Z' only has flavor conserving interactions, i.e.

$$\mathcal{L} = g_R \bar{t}\gamma^\mu P_R d W'_\mu + \sum_{q_i=u,t} \{\bar{q}_i\gamma^\mu(g_{Li}P_L + g_{Ri}P_R)q_i\}Z'_\mu + \text{H.c.}. \tag{A1}$$

Such specific choice, as shown in [30], is phenomenologically favored by several anomalies in top physics and B physics observed at the Tevatron. The second feature is, unlike the traditional flavor universal left-right model where the quarks acquire masses by interacting with $SU(2)_L \otimes SU(2)_R$ bi-doublet fields [41], the quark masses are generated in a complex way. For example, the first and third generation right-handed quarks may have Higgs terms like

$$\frac{<\phi_R>f^d_{ij}}{M}\frac{1}{<\phi_R>}\bar{q}'^i_R\phi^\dagger_R H_L q'^j_L + \frac{<\phi_R>f^u_{ij}}{M}$$
$$\times\frac{1}{<\phi_R>}\bar{q}'^i_R\tilde{\phi}^\dagger_R\tilde{H}_L q'^j_L, \quad \text{(A2)}$$

where flavor indices i and j are $i = 1, 3$ and $j = 1, 2, 3$, ϕ_R and H_L are doublet fields under the group $SU(2)_R$ and $SU(2)_L$ respectively with $\tilde{\phi}^a_R = \epsilon_{ab}\phi^{*b}_R$ and $\tilde{H}^a_L = \epsilon_{ab}H^{*b}_L$, and $<\phi_R>$ denotes the vacuum expectation value (vev) of the neutral component of ϕ_R; whereas the second generation right-handed quarks take on the more conventional form

$$f^d_j\bar{q}'^2_R H_L q'^j_L + f^u_j\bar{q}'^2_R\tilde{H}_L q'^j_L. \quad \text{(A3)}$$

Obviously, once the field ϕ_R gets its vev the SM mechanism for mass generation is recovered with the quark Yukawa coupling coefficients Y_{ij} given by $\frac{<\phi_R>f_{ij}}{M}$ for $i = 1, 3$ and f_j for $i = 2$. In addition, as suggested by [30], the five dimension operators in Eq. (A2) may be generated by integrating out heavy $SU(2)_{L,R}$-singlet fermions with mass scale M, which usually carry appropriate hypercharge.

In the W' model, the additional contribution to the $t\bar{t}$ production comes from the t-channel process $q\bar{q} \to t\bar{t}$ via the exchange of W' or neutral/charged component fields of the ϕ_R. Obviously, if the component fields are heavy and/or if $<\phi_R>$ is much larger than the electro-weak breaking scale so that the $\bar{q}q'\phi_R$ interactions are suppressed (see Eq. (A2)), the latter contribution can be safely neglected, which was done in literature [9,30].

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