Top Quark Forward-Backward Asymmetry and Same-Sign Top Quark Pairs

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The top quark forward-backward asymmetry measured at the Tevatron collider shows a large deviation from standard model expectations. Among possible interpretations, a non-universal $Z'$ model is of particular interest as it naturally predicts a top quark in the forward region of large rapidity. To reproduce the size of the asymmetry, the couplings of the $Z'$ to standard model quarks must be large, inevitably leading to copious production of same-sign top quark pairs at the energies of the Large Hadron Collider (LHC). We explore the discovery potential for $tt$ and $ttj$ production in early LHC experiments at 7-8 TeV and conclude that if no $tt$ signal is observed with 1 fb$^{-1}$ of integrated luminosity, then a non-universal $Z'$ alone cannot explain the Tevatron forward-backward asymmetry.

In high energy collisions at the Fermilab Tevatron proton-antiproton collider, top quarks are observed to be produced preferentially in the forward hemisphere, where forward is defined by the direction of the incident proton beam. The top quark forward-backward asymmetry $A_{FB}$ shows a deviation of three standard deviations ($3 \sigma$) or more from standard model (SM) expectations in the region of large $t\bar{t}$ invariant mass [1]. A SM asymmetry in rapidity is predicted from higher order QCD contributions [2], but it appears to be too small to fit the data. Furthermore, a reduction of the asymmetry in $pp \to t\bar{t}j$ at next-to-leading order is found in Ref. [3]. Several models of new physics (NP) have been invoked to explain the size of the asymmetry [4, 5]. A model based on the exchange of a non-universal massive neutral vector boson $Z'$ is intriguing because it naturally produces top quarks in the forward region of rapidity via the process $uis \to t\bar{t}$, with a $Z'$ in the $t$-channel [6, 10]. This approach requires a flavor changing neutral current (FCNC) interaction $u\rightarrow t$-$Z'$,

$$\mathcal{L} = g_W \bar{u} \gamma^\mu (f_L P_L + f_R P_R) t Z'_\mu + h.c.,$$  

where $g_W$ denotes the weak coupling strength. The left-handed coupling $f_L$ is highly constrained by $B_d - B_s$ mixing: $f_L < 3.5 \times 10^{-4}$ ($m_{Z'}/100$ GeV) [7]. We choose $f_L = 0$ hereafter.

Figure 1(a) displays the dominant leading-order QCD SM production of a $t\bar{t}$ pair at the Tevatron, while Fig. 1(b) shows $Z'$-induced $t\bar{t}$ pair production. A NP contribution to $A_{FB}$ arises from the absolute square of the NP contribution (Fig. 1(b)) and the interference between the NP and the full set of NLO SM QCD amplitudes. To produce a large enough asymmetry, the coupling $f_R$ must be large if the $Z'$ is heavy [6, 7]. However, it cannot be so large as to result in disagreement with the measured $t\bar{t}$ total cross section and the $t\bar{t}$ invariant mass distribution. In this Letter we derive quantitative bounds on $f_R$ and $m_{Z'}$ from Tevatron measurements of $A_{FB}$ and the $t\bar{t}$ total cross section, and we use these bounds to predict that same-sign $tt$ pair production at the Large Hadron Collider (LHC) should be observed if the $Z'$ explanation is correct.

As illustrated in Fig. 1(c) and (d), a massive $Z'$ exchange inevitably leads to same-sign $tt$ pair production at the LHC [5, 7, 11]. The scattering process involves two valence $u$-quarks in the initial state and is correspondingly enhanced by the large valence quark parton luminosity. We focus on the collider phenomenology of $tt$ pair production in early LHC experiments with 7 TeV center-of-mass (c.m.) energy and 1 fb$^{-1}$ integrated luminosity. In addition to predictions for the rate of same-sign $tt$ pair production at the LHC, we also present a method to search for $Z'$ production in the $tt$ channel and to place bounds on its mass and coupling to quarks.

FIG. 1: Diagrams for (a) $t\bar{t}$ production in the SM, (b) $t\bar{t}$ production induced by $Z'$ exchange, (c,d) $tt$ pair production, and (e,f) $tt\bar{u}$ production.
sign $tt$ pairs, we show that the expected right-handed top quark polarization could be measured. We further consider same-sign $tt$ pair production in association with a jet, as depicted in Fig. 1(e) and (f), from which one can obtain the invariant mass of the $Z'$ from the reconstructed top quarks and the additional jet. Note that there is no resonance in the $tt$ invariant mass spectrum since both top quarks are produced in the $t$-channel.

In Fig. 2(a) we display our inclusive cross sections for $tt$ (solid) and $tt\bar{t}$ (dashed) as a function of the $Z'$ mass ($m_{Z'}$) at the LHC for $f_R = 1$. The signal events are generated with MadGraph/MadEvent \[12\], and the CTEQ6L parton distribution functions \[13\] are used in the calculation. We choose the renormalization and factorization scales to be the top quark mass ($m_t$). The $tt\bar{t}$ rate is smaller because it relies on the gluon-quark luminosity, smaller than the large valence $uu$ luminosity. The much smaller rates for $t\bar{t}$ and $tt\bar{t}$ are not shown; they are suppressed by the $\bar{u}\bar{u}$ parton luminosity in a proton-proton collision.

In order to trigger on same-sign $tt$ events, we demand that both top quarks decay leptonically and we further concentrate on the $\mu^+$ as its charge can be better determined \[14\]. Needless to say, including the electrons would improve the discovery potential. The sample of events of interest to us is defined by $\mu^+\mu^+ b b \not{E}_T$, where the missing transverse momentum $\not{E}_T$ originates from two unobserved neutrinos. Our procedure for simulating the signal and background processes at the parton level, retaining all spin correlations, is similar to that described in Refs. \[15\], \[16\], to which we refer readers for details.

The dominant SM backgrounds are:

\[
pp \rightarrow W^+(\rightarrow \ell^+\nu)W^+(\rightarrow \ell^+\nu)jj, \quad (2)
\]
\[
pp \rightarrow t\bar{t} \rightarrow bW^+(\rightarrow \ell^+\nu)b(\rightarrow \ell^+)W^-(\rightarrow jj), \quad (3)
\]

computed with ALPGEN \[17\]. Other SM backgrounds, e.g., triple gauge boson production ($WWW, ZWW, and WZ\gamma(\sim b\bar{b}b)$), occur at a negligible rate after kinematic cuts. Since muon charge identification is not perfect, we remark that $t\bar{t}$ pair production could also be a background when $\mu^-$ leptons from the antitop quark decay are misidentified as $\mu^+$ leptons. However, this background is negligible \[16\].

At the analysis level, all signal and background events are required to pass the following acceptance cuts:

\[
\begin{align*}
n_j & = 2, \quad n_{\mu^+} = 2, \quad p_T^j \geq 50 \text{ GeV}, \quad |\eta_j| \leq 2.5, \\
p_T^\ell & \geq 50 \text{ GeV}, \quad |\eta_\ell| \leq 2.0, \quad E_T > 20 \text{ GeV}, \\
\Delta R_{jj,\ell,\ell} & > 0.4,
\end{align*}
\]

where the separation $\Delta R$ in the azimuthal angle $(\phi)$-pseudorapidity $(\eta)$ plane between the objects $k$ and $l$ is $\Delta R_{kl} = \sqrt{(\eta_k - \eta_l)^2 + (\phi_k - \phi_l)^2}$. The two jets are further required to be $b$-tagged. We also model detector resolution effects as described in Ref. \[16\].

Table II shows the signal and background cross sections (in fb units) for $tt$ pair production before and after cuts, with $f_R = 1$, for nine values of $m_{Z'}$. The rates for other values of $f_R$ can be obtained from:

\[
\sigma(tt) = \sigma_{f_R=1}(tt) \times f_R^4.
\]

The SM backgrounds are suppressed efficiently such that less than 1 background event survives after cuts with an integrated luminosity of 1 fb$^{-1}$. Based on Poisson statistics, one needs 8 signal events in order to claim a $5\sigma$ discovery significance on top of 1 background event. The discovery potential is plotted in Fig. 2(b) with black-solid ($5\sigma$) and blue-dotted ($3\sigma$) curves.
TABLE I: Signal and background cross sections (fb) for $tt'$ pair production at the LHC (7 TeV) before and after cuts, with $f_R = 1$, for nine values of $m_{Z'}$ (GeV) after the restriction to $2\mu^+$'s and with tagging efficiencies included. The cut acceptances $\epsilon_{cut}$ are also listed.

| $m_{Z'}$ | No cut | With cut | $\epsilon_{cut}$ | No cut | With cut | $\epsilon_{cut}$ | No cut | With cut | $\epsilon_{cut}$ | Background No cut | With cut | $\epsilon_{cut}$ |
|---------|--------|----------|------------------|--------|----------|------------------|--------|----------|------------------|------------------|----------|------------------|
| 200     | 730.6  | 72.0     | 9.9%             | 500    | 82.8     | 15.3            | 800    | 22.7     | 4.7             | 20.9%            |          |                  |
| 300     | 292.5  | 41.0     | 14.0%            | 600    | 51.0     | 9.8             | 900    | 16.1     | 3.4             | 21.2%            |          |                  |
| 400     | 146.4  | 24.3     | 16.6%            | 700    | 33.3     | 6.8             | 1000   | 11.7     | 2.5             | 21.2%            |          |                  |

The forward-backward rapidity asymmetry $A_{FB}$ is defined as

$$A_{FB}^{tot} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{\sigma_{FB}^{SM} - \sigma_{B}^{SM} + \sigma_{NP} - \sigma_{NP}^{B}}{\sigma_{FB}^{SM} + \sigma_{B}^{SM} + \sigma_{NP} + \sigma_{NP}^{B}}$$

$$= \frac{\sigma_{NP}^{F} - \sigma_{NP}^{B}}{\sigma_{NP}^{F} + \sigma_{NP}^{B}} \times \left(1 + \frac{\sigma_{NP}^{SM} - \sigma_{NP}^{B}}{\sigma_{NP}^{SM} - \sigma_{NP}^{B}}\right) \times \frac{\sigma_{tot}^{NP} - \sigma_{tot}^{NP}}{\sigma_{tot}^{F} + \sigma_{tot}^{NP}}$$

where

$$A_{NP}^{FB} = (\sigma_{NP}^{F} - \sigma_{NP}^{B})/(\sigma_{NP}^{F} + \sigma_{NP}^{B}),$$

$$A_{FB}^{SM} = (\sigma_{SM}^{F} - \sigma_{SM}^{B})/(\sigma_{SM}^{F} + \sigma_{SM}^{B}),$$

$$R = (\sigma_{tot}^{NP})/(\sigma_{tot}^{F} + \sigma_{tot}^{NP})$$

are the asymmetries induced by NP in the SM, and $R$ is the fraction of the NP contribution to the total cross section. Here, $\sigma_{FB}$ denotes the $tt$ cross section in the forward (F) and backward (B) rapidity region. The standard model QCD and new physics contributions to the cross sections are denoted by superscripts SM and NP.

The shaded regions in the $f_R$ plane in Fig. 2(b) are derived from requiring consistency with both $A_{FB}$ [1] and the $tt$ production cross section $\sigma(tt)$ [18]:

$$A_{FB} = 0.475 \pm 0.114 \text{ for } m_{tt} \geq 450 \text{ GeV}$$

$$\sigma(tt) = 7.50 \pm 0.48 \text{ pb.}$$

The inner (red) and outer (green) regions correspond to 1$\sigma$ and 2$\sigma$ C.L., respectively. The SM predictions of $A_{FB}(m_{tt} \geq 450 \text{ GeV})$ and $\sigma(tt)$ calculated with $m_t = 172.5 \text{ GeV}$ are 0.088 [1] and 6.9 pb [1], respectively. The lower bound of each band is derived from the $A_{FB}$ measurement while the upper bound is from the $\sigma(tt)$ data. In addition we verify that our computed distribution in $m_{tt}$ is consistent with recent CDF data [20] at the level of $\lesssim 2\sigma$ deviations.

The search for same sign top quark pairs at the Tevatron, $\sigma(tt + tt') \lesssim 0.7 \text{ pb}$ [19], imposes a constraint on $f_R$ and $m_{Z'}$ shown by the black band in Fig. 2(b). Parts of the otherwise allowed 1$\sigma$ and 2$\sigma$ bands are excluded by these data.

The values of $f_R$ indicated by the shaded bands in Fig. 2(b) show that $f_R \gtrsim 1$ for all $m_{Z'}$. They are everywhere above the values needed for 3 standard deviation observation of same sign $tt$ pair production at the LHC.

We conclude that if no $tt$ signal is observed with 1 fb$^{-1}$ of integrated luminosity at the LHC, then a non-universal $Z'$ alone cannot explain the Tevatron forward-backward asymmetry.

If an excess is observed in the $\mu^+\mu^-bb$ plus $E_T$ sample, one must demonstrate consistency with a $uu \rightarrow tt$ origin. Top quark polarization is a good probe of the FCNC $Z'$ because the right-handed $u-t-Z'$ coupling forces the top quarks to be mainly right-handed polarized. Reconstructing the two top quarks and measuring their polarizations would permit validation of the FCNC $Z'$ model. Among the top quark decay products the charged lepton is maximally correlated with the top quark spin. In our signal process the charged lepton from top quark decay exhibits a $1 + \cos \theta$ distribution, where $\theta$ is the helicity angle between the charged lepton momentum in the top quark rest frame and top quark momentum in the c.m. frame of the production process. Following Ref. [15], we use the MT2 method [21] to select the correct $\mu-b$ combinations and to verify whether the final state is consistent with $t \rightarrow Wb$ parentage. Then we make use of the on-shell conditions of the two $W$ bosons and the two top quarks to solve for the neutrino momenta [22, 23]. Once the neutrino momenta are known, the kinematics of the entire final state are fixed and the angular distribution may be constructed.
The reconstructed $\cos\theta$ distribution after cuts is plotted in Fig. 3 and it clearly shows the expected $1 + \cos\theta$ form. The discovery potential of the $t\bar{t}u$ signature is also promising. If a peak can be found in the invariant mass spectrum of a $t$ and a light jet (from the $\bar{u}$ in Fig. 1(e) and (f)), one could confirm the presence of the FCNC $Z'$. The work by E.L.B. and Q.H.C. is supported in part by the U.S. DOE under Contract No. DE-AC02-06CH11357. Q.H.C. is also supported in part by the Argonne National Laboratory and University of Chicago Joint Theory Institute Grant 03921-07-137. C.R.C. is supported by World Premier International Center Initiative (WPI Program), MEXT, Japan. C.S.L. and H.Z. are supported in part by the National Natural Science Foundation of China, under Grants No.11021092 and No.10975004. Q.H.C. thanks Shanghai Jiaotong University for hospitality where part of this work was done. E.L.B. and C.R.C. also thank NCTS in Taiwan for hospitality where part of his work was done. E.L.B. and Q.H.C. also thank MEXT, Japan. C.S.L. and H.Z. are supported in part by the National Natural Science Foundation of China, under Grants No.11021092 and No.10975004. Q.H.C. thanks Shanghai Jiaotong University for hospitality where part of this work was done. E.L.B. and C.R.C. also thank NCTS in Taiwan for hospitality where part of his work was done.

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