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

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(Received 7 February 2011; published 17 May 2011)

The top quark forward-backward asymmetry measured at the Tevatron collider shows a large deviation from standard model expectations. Among possible interpretations, a nonuniversal 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 nonuniversal Z' alone cannot explain the Tevatron forward-backward asymmetry.

DOI: 10.1103/PhysRevLett.106.201801 PACS numbers: 13.85.Rm, 14.65.Ha, 14.70.Pw

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 3 standard deviations (3σ) 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 $p\bar{p} \to t\bar{t}j$ 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 [4–9]. A model based on the exchange of a nonuniversal massive neutral vector boson Z' is intriguing because it naturally produces top quarks in the forward region of rapidity via the process $u\bar{u} \to t\bar{t}$, with a Z' in the t channel [5–10]. This approach requires a flavor changing neutral current (FCNC) interaction u-t-Z',

$$\mathcal{L} = g_W \bar{u}\gamma^\mu (f_L P_L + f_R P_R) t Z'_\mu + \text{H.c.}, \quad (1)$$

where g_W denotes the weak coupling strength. The left-handed coupling f_L is highly constrained by B_d-$\bar{B}_d$ mixing: $f_L < 3.5 \times 10^{-4}$ $(m_{Z'}/100\text{ GeV})$ [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 [5,7]. 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 Figs. 1(c) and 1(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 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 1(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 $tt\bar{u}$ (dashed) as a function of the Z' mass ($m_{Z'}$) 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 $tt\bar{u}$ rate is smaller because it relies on the gluon-quark luminosity, smaller than the large valence uu luminosity. The much smaller rates for $\bar{t}\bar{t}$ and $\bar{t}\bar{t}u$ 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

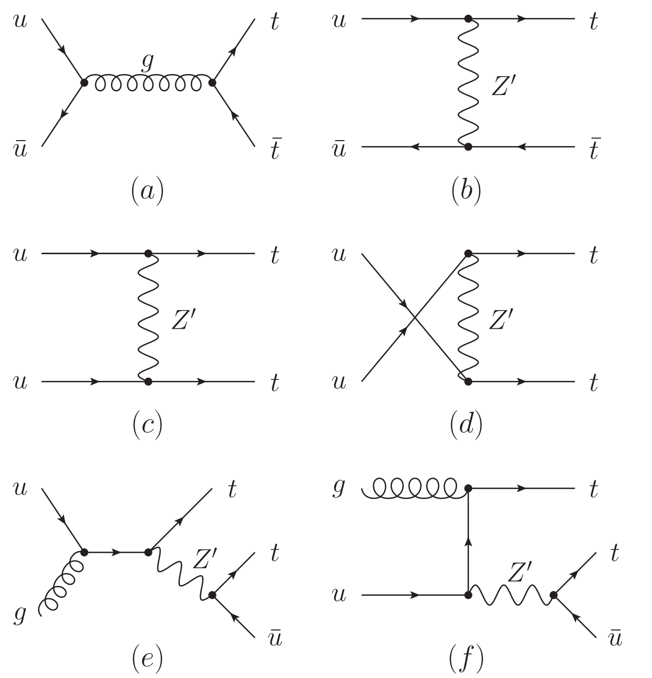

FIG. 1. Diagrams for (a) $t\bar{t}$ production in the SM, (b) $t\bar{t}$ production induced by Z' exchange, (c),(d) tt pair production, and (e),(f) $tt\bar{u}$ production.

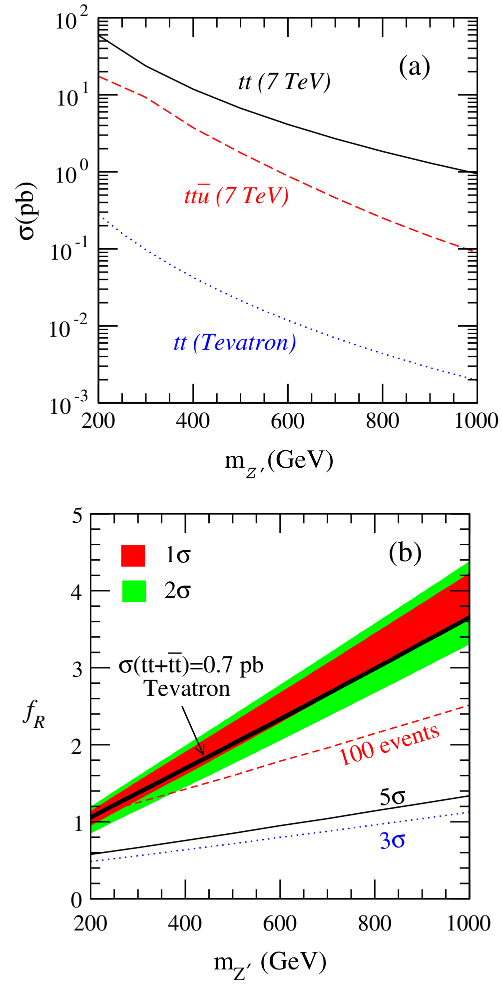

FIG. 2 (color online). (a) Inclusive production cross sections for tt and ttj induced by Z' exchange, with $f_R = 1$, at the LHC (7 TeV) and Tevatron. (b) The shaded bands in the plane of $m_{Z'}$ and f_R are determined from our fit to A_{FB} and $\sigma(t\bar{t})$; the inner (outer) band corresponds to 1σ (2σ) C.L. Lines are drawn for 5σ and 3σ discovery of tt at the 7 TeV with an integrated luminosity of 1 fb^{-1}, after all cuts are imposed, as specified in the text. A dashed line shows the expectation for 100 signal events. The Tevatron limit on f_R from direct search for same-sign top quark pairs is presented.

concentrate on the μ^+ 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 $\mu^+\mu^+ bb\not{E}_T$, 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

$$pp \to W^+(\to \ell^+\nu)W^+(\to \ell^+\nu)jj, \tag{2}$$

$$pp \to t\bar{t} \to bW^+(\to \ell^+\nu)\bar{b}(\to \ell^+)W^-(\to jj), \tag{3}$$

computed with ALPGEN [17]. Other SM backgrounds, e.g., triple gauge boson production (WWW, ZWW, and $WZg(\to b\bar{b})$), 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 μ^- leptons from the antitop quark decay are misidentified as μ^+ leptons. However, this background is negligible [16].

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

$$n_j = 2, \quad n_{\mu^+} = 2, \quad p_T^j \geq 50 \text{ GeV}, \quad |\eta_j| \leq 2.5, \quad p_T^\ell \geq 50 \text{ GeV}, \quad |\eta_\ell| \leq 2.0, \quad \not{E}_T > 20 \text{ GeV}, \quad \Delta R_{jj,j\ell,\ell\ell} > 0.4, \tag{4}$$

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

Table I 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

$$\sigma(tt) = \sigma_{f_R=1}(tt) f_R^4. \tag{5}$$

The SM backgrounds are suppressed efficiently such that less than 1 background event survives after cuts with an

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 $\epsilon_{\rm cut}$ are also listed.

$m_{Z'}$	No cut	With cut	$\epsilon_{\rm cut}$	$m_{Z'}$	No cut	With cut	$\epsilon_{\rm cut}$	$m_{Z'}$	No cut	With cut	$\epsilon_{\rm cut}$	Background	No cut	With cut	$\epsilon_{\rm cut}$
200	730.6	72.0	9.9%	500	82.8	15.3	18.5%	800	22.7	4.7	20.9%	$t\bar{t}$	1205.2	0.4	0.03%
300	292.5	41.0	14.0%	600	51.0	9.8	19.3%	900	16.1	3.4	21.2%	$WWjj$	115.8	0.2	0.16%
400	146.4	24.3	16.6%	700	33.3	6.8	20.4%	1000	11.7	2.5	21.2%	WWW/Z	0.4	0.01	2.5%

integrated luminosity of 1 fb^{-1}. Based on Poisson statistics, one needs 8 signal events in order to claim a 5σ discovery significance on top of 1 background event. The discovery potential is plotted in Fig. 2(b) with black-solid (5σ) and blue-dotted (3σ) curves.

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

$$\begin{aligned} A_{FB}^{\rm tot} &= \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{\sigma_F^{\rm SM} - \sigma_B^{\rm SM} + \sigma_F^{\rm NP} - \sigma_B^{\rm NP}}{\sigma_F^{\rm SM} + \sigma_B^{\rm SM} + \sigma_F^{\rm NP} + \sigma_B^{\rm NP}} \\ &= \frac{\sigma_F^{\rm NP} - \sigma_B^{\rm NP}}{\sigma_F^{\rm NP} + \sigma_B^{\rm NP}}\left(1 + \frac{\sigma_F^{\rm SM} - \sigma_B^{\rm SM}}{\sigma_F^{\rm NP} - \sigma_B^{\rm NP}}\right)\frac{\sigma_{\rm tot}^{\rm NP}}{\sigma_{\rm tot}^{\rm SM} + \sigma_{\rm tot}^{\rm NP}} \\ &= A_{FB}^{\rm NP} R + A_{FB}^{\rm SM}(1 - R), \end{aligned} \tag{6}$$

where

$$\begin{aligned} A_{FB}^{\rm NP} &\equiv (\sigma_F^{\rm NP} - \sigma_B^{\rm NP})/(\sigma_F^{\rm NP} + \sigma_B^{\rm NP}), \\ A_{FB}^{\rm SM} &\equiv (\sigma_F^{\rm SM} - \sigma_B^{\rm SM})/(\sigma_F^{\rm SM} + \sigma_B^{\rm SM}) \\ R &\equiv (\sigma_{\rm tot}^{\rm NP})/(\sigma_{\rm tot}^{\rm SM} + \sigma_{\rm tot}^{\rm NP}) \end{aligned} \tag{7}$$

are the asymmetries induced by NP and in the SM, and R is the fraction of the NP contribution to the total cross section. Here, $\sigma_{F(B)}$ denotes the $t\bar{t}$ 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 $t\bar{t}$ production cross section $\sigma(t\bar{t})$ [18]:

$$\begin{aligned} A_{FB} &= 0.475 \pm 0.114 \quad \text{for } m_{t\bar{t}} \geq 450 \text{ GeV} \\ \sigma(t\bar{t}) &= 7.50 \pm 0.48 \text{ pb}. \end{aligned} \tag{8}$$

The inner (red) and outer (green) regions correspond to 1σ and 2σ C.L., respectively. The SM predictions of $A_{FB}(m_{t\bar{t}} \geq 450\text{ GeV})$ and $\sigma(t\bar{t})$ calculated with $m_t = 172.5$ GeV are 0.088 [1] and 6.9 pb [7], respectively. The lower bound of each band is derived from the A_{FB} measurement while the upper bound is from the $\sigma(t\bar{t})$ data. In addition, we verify that our computed distribution in $m_{t\bar{t}}$ is consistent with recent CDF data [19] at the level of $\lesssim 2\sigma$ deviations.

The search for same-sign top quark pairs at the Tevatron, $\sigma(tt + \bar{t}\bar{t}) \lesssim 0.7$ pb [20], imposes a constraint on f_R and $m_{Z'}$ shown by the black band in Fig. 2(b). Parts of the otherwise allowed 1σ and 2σ 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 5 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 nonuniversal 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 $uu \to tt$ 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 θ 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 μ-b combinations and to verify whether the final state is consistent with $t \to Wb$ parentage. Then we make use of the on-shell

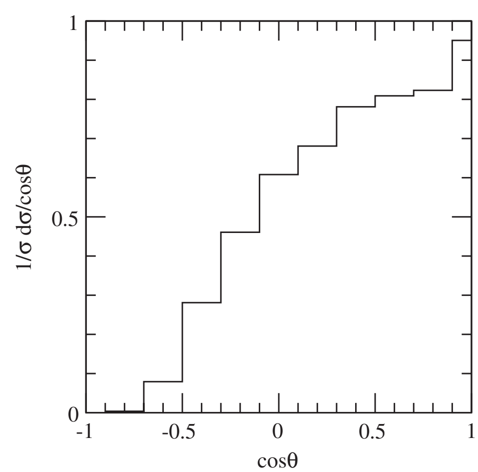

FIG. 3. Normalized distribution of the angle of the charged lepton relative to the top quark in the c.m. frame in the tt pair production after cuts and efficiencies are included for $m_{Z'} = 800$ GeV and $f_R = 1$.

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 $tt\bar{u}$ 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 1(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 this work was done.

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