Top quark forward-backward asymmetry and W' bosons

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The top quark forward-backward asymmetry measured at the Fermilab Tevatron collider deviates from the standard model prediction. A W' boson model is described, where the coupling W'-t-d is fixed by the $t\bar{t}$ forward-backward asymmetry and total cross section at the Tevatron. We show that such a W' boson would be produced in association with a top quark at the CERN Large Hadron Collider (LHC), thus inducing additional $t\bar{t}+j$ events. We use measurements of $t\bar{t}+n$-jet production from the LHC to constrain the allowed W'-t-d couplings as a function of W' boson mass. We find that this W' model is constrained at the 95% confidence level using $0.7\ \mathrm{fb}^{1}$ of data from the LHC, and could be fully excluded with $5\ \mathrm{fb}^{1}$ of data.

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I. INTRODUCTION

Measurements of the forward-backward asymmetry in $t\bar{t}$ production (A^t_{FB}) by the CDF [1] and D0 [2] Collaborations have garnered great interest, as the experimental results appear to disagree with standard model predictions [3] at the 95% confidence level. Many models have been proposed to explain this anomaly as physics from beyond the standard model. Some models envision new s-channel processes [4] like axigluons, or other exotic scenarios [5]. Other models invoke new particles, such as W' bosons [6–11] or Z' bosons [12–14] that enter via virtual t-channel exchange. There are also model-independent ideas about the $t\bar{t}$ asymmetry [15–17].

A new vector boson with a large flavor-changing coupling between the first and the third generation could induce a large enough $t\bar{t}$ charge asymmetry to explain the anomaly through a t-channel exchange. Neutral vector bosons (Z') are already constrained by early Large Hadron Collider (LHC) data, as they would produce too many same-sign top quark pair events at the LHC [13,18]. Hence, we focus in this paper on whether charged vector currents (W' bosons) are a viable explanation once faced with measurements from the LHC.

Standard model-like W' bosons are highly constrained by direct measurements into final states with leptons at LHC ($m_{W'} > 2.15$ TeV [19]) or with top quarks at the Fermilab Tevatron ($m_{W'} > 890$ GeV [20,21]). To avoid any chance of direct lepton production bounds, or flavor physics constraints [22], we focus on right-handed W' bosons. To avoid direct constraints from single-top-quark production, we consider a nonstandard W' which couples to one first and one third generation right-handed quark. The relevant interaction Lagrangian for this model [6–11] may be written as

$$\mathcal{L} = \frac{g}{\sqrt{2}} V'_{td} \bar{d} \gamma^{\mu} P_R t W'_{\mu} + H.c., \tag{1}$$

where g is the standard model $SU(2)_L SU(2)L$ gauge interaction coupling constant. One could allow these W' bosons to couple strange quarks to top quarks. However, the strange quark parton density is not large enough to meaningfully contribute to the $t\bar{t}$ charge asymmetry. Hence, we follow Refs. [6–11] and consider only the coupling in Eq. (1) above.

While we can avoid direct production limits for W' bosons, in this paper we demonstrate that early $t\bar{t}+j$ data from the CERN Large Hadron Collider already severely constrains these models. Hence, W' bosons are not expected to be a viable solution to the $t\bar{t}$ forward-backward asymmetry anomaly. We organize the rest of this paper as follows: In Sec. 1 we describe the analytic and numerical contribution of W' bosons to the $t\bar{t}$ forward-backward asymmetry, and derive the parameters consistent with the Tevatron anomaly. In Sec. III we examine the contribution of W' bosons to $t\bar{t}+j$ measurements, set a 95% confidence level (C.L.) limit on the allowed W' mass and coupling V'_{td}, and exclude the parameters required to explain the Tevatron anomaly. We summarize our results in Sec. IV.

II. W' MODEL AND $t\bar{t}$ ASYMMETRY

The W' contribution to the $t\bar{t}$ production process $d_{p_1,\lambda_1,c_1} + \bar{d}_{p_2,\lambda_2,c_2} \to t_{p_3,\lambda_3,c_3} + \bar{t}_{p_4,\lambda_4,c_4}$ (where p_i, λ_i, and c_i are the four momentum, helicity, and color factor of the ith particle, respectively), can be factorized into nonzero partonic level helicity amplitudes as

$$\frac{g^2 V'^2_{td} \hat{s} \delta_{c_1c_3}\delta_{c_2c_4}}{8(\hat{t} - m^2_{W'})} \mathcal{M}(\lambda_1, \lambda_2, \lambda_3, \lambda_4). \tag{2}$$

We have [23]

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$$\mathcal{M}(+,-,+,+) = -\sqrt{1-\beta^2}(2+r_{W'}^2)\sin\theta, \quad (3)$$

$$\mathcal{M}(+,-,+,-) = -[2(1+\beta)+(1-\beta)r_{W'}^2] \times (1+\cos\theta), \quad (4)$$

$$\mathcal{M}(+,-,-,+) = [2(1-\beta)+(1+\beta)r_{W'}^2] \times (1-\cos\theta), \quad (5)$$

$$\mathcal{M}(+,-,-,-) = \sqrt{1-\beta^2}(2+r_{W'}^2)\sin\theta, \quad (6)$$

where $\hat{s}=(p_1+p_2)^2$, $\hat{t}=(p_1-p_3)^2=-\frac{1}{2}\hat{s}(1-\beta\cos\theta)$, $\beta=\sqrt{1-4m_t^2/\hat{s}}$, $r_{W'}=m_t/m_{W'}$ and θ is the angle between p_1 and p_3 in the $t\bar{t}$ center of momentum frame. The corresponding standard model (SM) helicity amplitudes are [23]

$$\mathcal{M}(+,-,+,+) = -g_s^2 t^a_{c_2c_1} t^a_{c_3c_4}\sqrt{1-\beta^2}\sin\theta, \quad (7)$$

$$\mathcal{M}(+,-,+,-) = -g_s^2 t^a_{c_2c_1} t^a_{c_3c_4}(1+\cos\theta), \quad (8)$$

$$\mathcal{M}(+,-,-,+) = g_s^2 t^a_{c_2c_1} t^a_{c_3c_4}(1-\cos\theta), \quad (9)$$

$$\mathcal{M}(+,-,-,-) = g_s^2 t^a_{c_2c_1} t^a_{c_3c_4}\sqrt{1-\beta^2}\sin\theta. \quad (10)$$

The interference term σ_{INT} between the SM amplitude and the new physics amplitude is negative. This property is useful in explaining the Tevatron anomaly, because the interference term will largely cancel the contribution to the $t\bar{t}$ inclusive cross section from the new physics term. As such, a V'_{td} can be found that gives a large additional contribution to the forward-backward asymmetry A^t_{FB}.

The total cross section of $t\bar{t}$ production at Tevatron is 7.5 ± 0.48 pb [24]. The leading-order (LO) cross section obtained from MADEVENT 5 [25] is 5.63 pb using CTEQ6L1 parton distribution functions (PDFs) [26]. The next-to-leading-order (NLO) $t\bar{t}$ total cross section from MCFM 6.0 [27] is 6.9 pb using CTEQ6.6M PDFs (where the renormalization scale and factorization scales are chosen to be $\mu_r=\mu_f=172.5$ GeV) [26]. In order to address how new physics modifies the standard model results, we rewrite the total SM cross section as

$$\sigma_{SM}^{NLO} = \sigma_{SM}^{NLO(F)} + \sigma_{SM}^{NLO(B)} = \sigma_{SM}^{LO} + \Delta\sigma_{SM}. \quad (11)$$

The addition of W' bosons will modify the $t\bar{t}$ cross section already at leading order, and lead to a "new physics" cross section $\sigma_{NP}=\sigma_{SM}^{LO}+\sigma_{INT}+\sigma_{NEW}$. We include the NLO QCD correction in the SM part by considering $\sigma_{NP}^{Tot} \equiv \sigma_{NP}-\sigma_{SM}^{LO}+\sigma_{SM}^{NLO}$. The quantity of interest, A^t_{FB}, is calculated using

$$\begin{aligned} A^t_{FB} &= \frac{\sigma^{(F)}-\sigma^{(B)}}{\sigma^{(F)}+\sigma^{(B)}} \\ &= \frac{\sigma_{NP}^{(F)}-\sigma_{SM}^{LO(F)}+\sigma_{SM}^{NLO(F)}}{\sigma_{NP}-\sigma_{SM}^{LO}+\sigma_{SM}^{NLO}} - \frac{\sigma_{NP}^{(B)}-\sigma_{SM}^{LO(B)}+\sigma_{SM}^{NLO(B)}}{\sigma_{NP}-\sigma_{SM}^{LO}+\sigma_{SM}^{NLO}} \\ &= \frac{\sigma_{NP}^{(F)}+\sigma_{SM}^{NLO(F)}-(\sigma_{NP}^{(B)}+\sigma_{SM}^{NLO(B)})}{\sigma_{NP}-\sigma_{SM}^{LO}+\sigma_{SM}^{NLO}} \\ &= \frac{(\sigma_{NP}^{(F)}-\sigma_{NP}^{(B)})+(\sigma_{SM}^{NLO(F)}-\sigma_{SM}^{NLO(B)})}{\sigma_{NP}-\sigma_{SM}^{LO}+\sigma_{SM}^{NLO}} \\ &= \frac{A_{FB}^{NP}\times\sigma_{NP}+A_{FB}^{SM}\times\sigma_{SM}^{NLO}}{\sigma_{NP}^{Tot}}, \end{aligned} \quad (12)$$

where $A_{FB}^{SM}=5.0\%$ [2], and $\sigma_{NP}^{(F)}-\sigma_{NP}^{(B)}$ is obtained from events generated using MADEVENT 5. The NLO QCD correction to the W' model can be found in Ref. [10], however, that work found it to be numerically small (at most a few percent), and so we do not include it in this work.

In order to establish the relevant parameters of the W' model, we scan the region [200 GeV, 1000 GeV] $\times$ [0.1, 10.0] in the parameter space ($m_{W'}$, V'_{td}) using a generic W' model file [28] in MADEVENT 5 with CTEQ6L1 PDFs and a floating scale scheme. The W' width is given by [29]

$$\Gamma_{W'} = \frac{g^2|V'_{td}|^2 m_{W'}}{16\pi}(1-r_{W'}^2)(1+\frac{r_{W'}^2}{2}). \quad (13)$$

The width is narrow, and is checked using BRIDGE [30]. The $t\bar{t}$ asymmetry is compared with the unfolded result from D0 [2]. The unfolded result is obtained with the assumption that the modified event distribution is the same as in the standard model. This is not exactly correct for our new physics model, but the difference is found to be small.[1] Neglecting the nontrivial correlation between σ_{NP}^{Tot} and A^t_{FB}, for simplicity, we do a combined fit to both variables. The 1σ (2σ) regions of allowed parameter space are defined by

$$\frac{(\sigma_{t\bar{t}}-\sigma_{t\bar{t}}^{\rm obs})^2}{\delta\sigma_{t\bar{t}}^2} + \frac{(A_{FB}-A_{FB}^{\rm obs})^2}{\delta A_{FB}^2} \le 1(4), \quad (14)$$

and shown in Fig. 1. These regions are consistent with the full NLO results of Ref. [10].

III. CONSTRAINTS FROM THE LHC

While s-channel production of a W' boson is explicitly turned off in this model, the W' boson could be produced in association with a top quark at the LHC. The final state will

[1] We confirm the claims of Ref. [10] that the change in acceptance between the standard model and W' model is small.

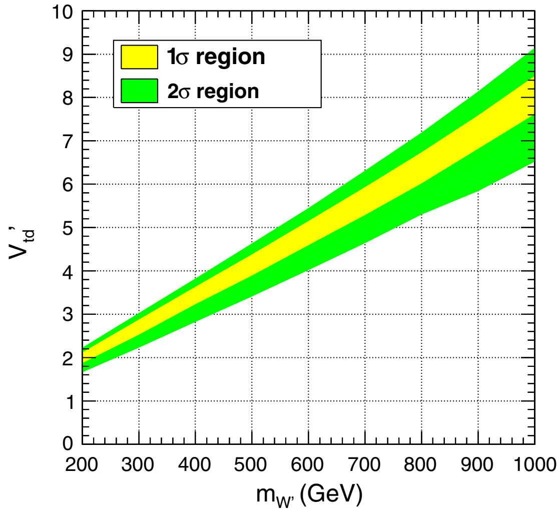

FIG. 1 (color online). Region of W' coupling V'_{td} vs W' mass consistent with Tevatron measurements of the $t\bar{t}$ asymmetry.

be $t\bar{t} + j$ (see Fig. 2). This signal can easily be checked at the LHC [7,11,16]. Both the ATLAS [31–33] and CMS [34] collaborations have published results of the inclusive and $t\bar{t} + n$-jet cross section measurements.

The strongest constraint on our model comes from the dilepton decay mode of top quark pair production measured by ATLAS [31] using an integrated luminosity of $0.70\,\mathrm{fb}^1$. The topology of the final state is an opposite-sign dilepton pair with three jets and large missing transverse energy $\not{E}_T$. We simulate detector effects by smearing jets and leptons with an energy resolution parametrized by $\frac{\delta E}{E} = \frac{a}{\sqrt{E}} \oplus b$; where $a = 0.5$, $b = 0.03$ for jets [35], $a = 0.1$, $b = 0.02$ for electrons [35,36], and $a = 0.04$, $b = 0$ for muons [37]. We calculate the missing transverse energy $\not{E}_T$ after smearing from the imbalance of the reconstructed jets and leptons. To compare with the ATLAS $t\bar{t} + j$ analysis, we add cuts on the smeared events as follows:

(i) Electrons: $p_{Te} > 25$ GeV, $|\eta_e| < 1.37$ or $1.52 < |\eta_e| < 2.47$;
(ii) Muons: $p_{T\mu} > 20$ GeV, $|\eta_\mu| < 2.5$;
(iii) Jets: $p_{Tj} > 25$ GeV, $|\eta_j| < 2.5$;
(iv) $\Delta R_{jj} > 0.4$, $\Delta R_{ej} > 0.4$, $\Delta R_{\mu j} > 0.4$, $\Delta R_{\mu\mu} > 0.3$, $\Delta R_{e\mu} > 0.2$, $\Delta R_{ee} > 0.2$;
(v) and the invariant mass of the charged leptons $m_{ll} > 15$ GeV.

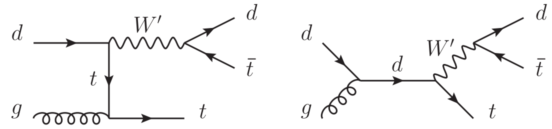

FIG. 2. The Feynman diagrams of $t\bar{t} + j$ production in this W' model.

After acceptance cuts, different cuts are added to ee and $\mu\mu$, or $e\mu$ events.

(i) For ee and $\mu\mu$ events, the missing transverse energy $\not{E}_T > 60$ GeV, and m_{ll} must differ by at least 10 GeV from the Z^0-boson mass.
(ii) For $e\mu$ events, the scalar sum of the transverse momenta of jets and leptons $H_T > 130$ GeV.

We compare our result with the ATLAS data shown in Fig. 1(a) of Ref. [31]. There will be a contribution from higher-order corrections to tW' + jets if some of the partonic jets are merged by the jet reconstruction algorithm. The tW' process could also be detected in events with more than three jets due to initial state radiation and final state radiation. To mimic these effects on acceptance, we rescale our calculation by comparing our SM $t\bar{t} + j$ results from MADEVENT 5 (with cuts and smearing) to the theoretical prediction (after cuts) used in Ref. [31]. All of the new physics results are rescaled by this same factor and then compared with the data. We note that the observed event number by ATLAS is a little larger than the SM prediction, which slightly weakens the constraint we extract from the data.

In Fig. 3 we show the allowed parameter space consistent with the Tevatron forward-backward asymmetry anomaly, and the independent 2σ bound on V'_{td} we extract from the fit to ATLAS data. We see that already with the first $0.7\,\mathrm{fb}^1$ fb − 1 data, the 1σ region of parameter space consistent with the Tevatron A^t_{FB} is completely excluded at greater than a 95% C.L. Below 600 GeV the 2σ region of parameter space is also excluded at 95% C.L.

In the process we are examining, $\sigma(pp \to tW' \to t\bar{t}d) \propto V'^2_{td}$, the cross section significance $S/\sqrt{B}$ scales like $\sqrt{N}$,

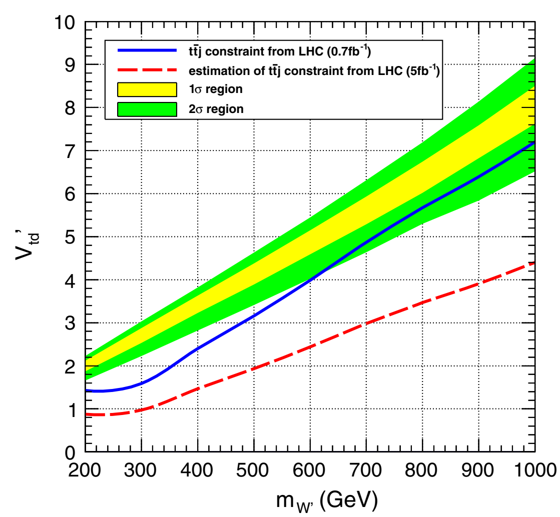

FIG. 3 (color online). Constraint from the LHC $t\bar{t} + j$ search on the W'boson. The parameter space above the solid blue line is excluded by the ATLAS data with $0.7\,\mathrm{fb}^{-1}$ of integrated luminosity at a 2σ level. We also show the expected exclusion curve (the dashed red line) with $5\,\mathrm{fb}^{-1}$ of integrated luminosity.

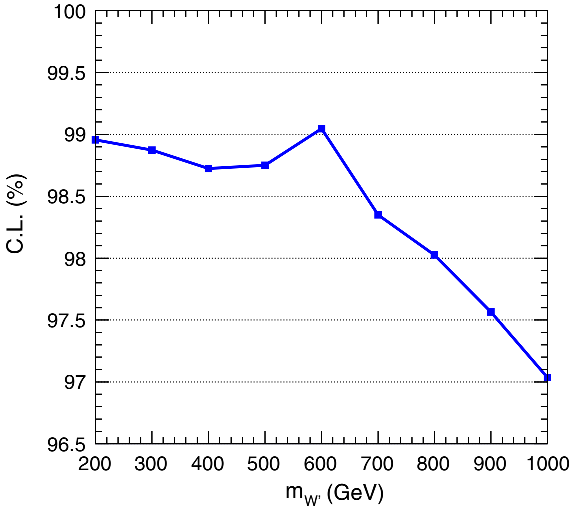

FIG. 4 (color online). Exclusion level (in percent) of the W' model from a simultaneous fit of three experimental observables.

where N is the event number. Hence, the bound on V'_{td} will decrease $\propto \mathcal{L}^{-1/4}$ when the integrated luminosity $\mathcal{L}$ increases. We use this scaling to estimate the bound on V'_{td} that can be reached with the existing $5\,\text{fb}^1$ of integrated luminosity, and show this bound in Fig. 3 (the dashed red line). With $5\,\text{fb}^1$ data, a W' model with coupling constant V'_{td} large enough to explain the Tevatron top quark forward-backward asymmetry anomaly can be unambiguously excluded.

In addition to considering the independent limit on W' production from LHC data, we also consider the limit obtained by a combined fit to the $t\bar{t}$ total cross section at the Tevatron, A^t_{FB}, and $t\bar{t}+j$ from the LHC. Since there are two free parameters $(m_{W'}, V'_{td})$, we have

$$\chi^2/\text{d.o.f.} = \frac{1}{3-2}\left[\frac{(\sigma_{t\bar{t}} - \sigma^{\text{Tev}}_{t\bar{t}})^2}{\delta\sigma^2_{t\bar{t}}} + \frac{(A_{FB} - A^{\text{Tev}}_{FB})^2}{\delta A^2_{FB}} + \frac{(\sigma_{t\bar{t}j} - \sigma^{\text{LHC}}_{t\bar{t}j})^2}{\delta\sigma^2_{t\bar{t}j}}\right] \tag{15}$$

for the right-handed W' model. The confidence region is calculated from the χ^2 cumulative distribution with one degree of freedom. The result is shown in Fig. 4. A simultaneous fit excludes a right-handed W' model at more than a 97% C.L. While A^t_{FB} provides tension with the standard model at the Tevatron, a simultaneous fit for all three measurements is only excluded at the 92% C.L. In other words, the standard model agrees better with data than the attempted W' boson fix.

IV. CONCLUSIONS

We study a right-handed W' model which has been suggested as an explanation of the Tevatron $t\bar{t}$ forward-backward asymmetry anomaly in the context of recent measurements from the Large Hadron Collider. Measurements of inclusive $t\bar{t}$ production constrain this W' model, because a W' boson would induce extra $t\bar{t}+j$ events. We find that the values of the W' mass and coupling V'_{td} required to fit both $\sigma_{t\bar{t}}$ and A^t_{FB} at Tevatron at the 2σ level, are excluded at 95% C.L. by measurements of $t\bar{t}j$ with $0.7\,\text{fb}^1$ of data by the ATLAS Collaboration. If the full $5\,\text{fb}^1$ data set is analyzed, the measurement of $t\bar{t}j$ alone will push this limit to more than 3σ. We also show that a simultaneous fit to three measurements excludes W' bosons as an explanation for the Tevatron $t\bar{t}$ forward-backward asymmetry at a 97% C.L.

In addition to the measurements considered here, we point out the D0 Collaboration measures the charge asymmetry of the charged leptons (A^l_{FB}) from top quark decay in $t\bar{t}$ events [2]. Because of angular correlations between the top quark and the charged lepton from its decay, it has been shown that there is a correlation between A^t_{FB} and A^l_{FB} [23] that suggests a light right-handed W' boson is preferred by the data. The limits we obtain from the LHC with $0.7\,\text{fb}^1$ of data are even stronger for light W' bosons (nearly 99% C.L. exclusion) than for heavier W' bosons. Adding A^l_{FB} information from D0 would further disfavor this W' boson model.

We conclude by noticing that even though the W' boson only couples to the right-handed top and down quarks, there are still constraints from flavor physics. The constraint from $B \to \pi K$ is strong, and the right-handed W' model here may also be constrained by the branching ratio of rare B decays at the 2σ level [9]. However, due to a relatively large theoretical uncertainty for the B decays (even for the standard model prediction [38]), the direct production limit we present from collider physics is needed to exclude this right-handed W' model.

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