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Search for Same-Sign Top-Quark Pair Production at $\sqrt{s} = 7$ TeV and Limits on Flavour Changing Neutral Currents in the Top Sector

The CMS Collaboration*

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Abstract

An inclusive search for same-sign top-quark pair production in pp collisions at $\sqrt{s} =$ 7 TeV is performed using a data sample recorded with the CMS detector in 2010, corresponding to an integrated luminosity of $35\,\mathrm{pb}^{-1}$. This analysis is motivated by recent studies of $\mathrm{p\overline{p}} \to \mathrm{t\overline{t}}$ reporting mass-dependent forward-backward asymmetries larger than expected from the standard model. These asymmetries could be due to Flavor Changing Neutral Currents (FCNC) in the top sector induced by t-channel exchange of a massive neutral vector boson (Z'). Models with such a Z' also predict enhancement of same-sign top-pair production in pp or $\mathrm{p\overline{p}}$ collisions. Limits are set as a function of the Z' mass and its couplings to u and t quarks. These limits disfavour the FCNC interpretation of the Tevatron results.

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The Compact Muon Solenoid (CMS) Collaboration recently published a search for new physics in events with same-sign isolated dileptons, jets, and $\not{E}_T$ [1]. The results of that search are recast in this short Letter to set constraints on the production of same-sign top-quark pairs at the Large Hadron Collider (LHC). This effort is motivated by the recent Tevatron measurements of the forward-backward $t\bar{t}$ asymmetry (A_{FB}) which deviates from the standard model (SM) expectations [2–4]. Many of the attempts put forth [5–24] to explain this asymmetry invoke Flavour Changing Neutral Currents (FCNC) in the top-quark sector [5] mediated by the t-channel exchange of a new massive Z' boson, as shown in Fig. 1. It has also been suggested [18, 21–24] that the anomalous dijet invariant mass distribution recently reported by the CDF collaboration in $p\bar{p} \to W + 2$ jets [25] could be evidence for such a boson.

The same type of interaction would also give rise to same-sign top-quark pair production, as illustrated in Fig. 2. In this case, the initial state involves two u quarks. Because of the large valence quark parton density of the proton, the tt production cross section at the Large Hadron Collider (LHC) could then be large enough to be observable with a modest amount of integrated luminosity. This motivates the search described in this Letter.

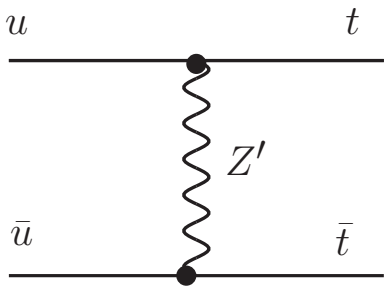

Figure 1: Diagram for $t\bar{t}$ production induced by t-channel Z' exchange, which can generate a forward-backward asymmetry.

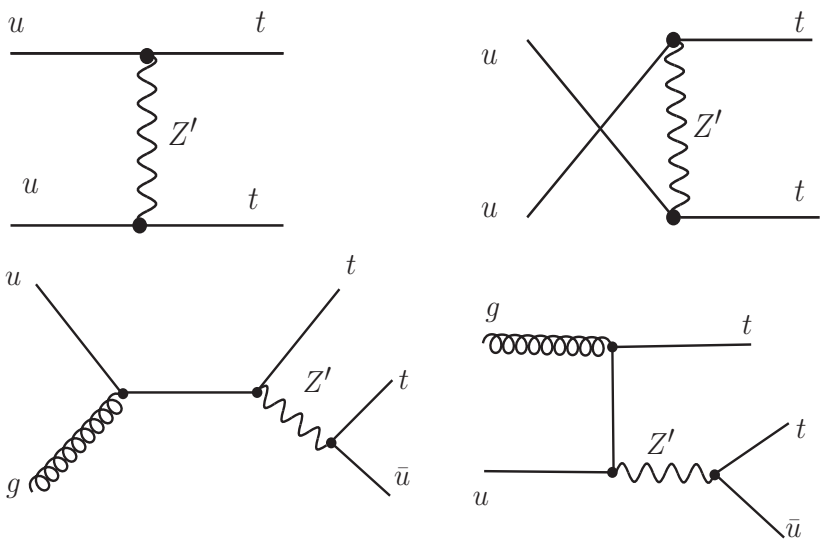

Figure 2: Diagrams for tt and ttj production in the presence of a Z'.

For concreteness, we consider the model of Ref. [9]. The relevant u-t-Z' interaction term in the Lagrangian is

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

where g_W is the weak coupling strength, and P_L and P_R are the left-handed and right-handed projection operators. The left-handed coupling is set to $f_L = 0$, because of the $\mathrm{B_d}$-$\overline{\mathrm{B}}_\mathrm{d}$ mixing constraint [26]. The right-handed coupling f_R and the Z′ mass ($M_{Z'}$) are the free parameters of the model. Within this model there is a narrow range of parameter space consistent with the Tevatron measurements of $\sigma(\mathrm{p\bar{p}} \to \mathrm{t\bar{t}})$ and A_{FB}, which is not excluded by direct searches for same-sign top-quark pairs [9].

We search for pp → tt or pp → ttj using a data sample corresponding to an integrated luminosity of 35 pb^{-1}, collected at a centre-of-mass energy of 7 TeV in 2010 by the CMS experiment [27] at the LHC. We concentrate on the final state where both top quarks decay as t → Wb followed by W → $\ell\nu$, where ℓ = e or μ. Thus, the final state of interest contains two high transverse momentum (p_T) isolated positive leptons (e^+ or μ^+), two or more jets, and missing transverse energy ($\not{E}_T$) from two neutrinos.

The result presented here is based on an already published search for new physics in events with same-sign isolated dileptons, jets, and $\not{E}_T$ [1]. In that search we presented event yields and background expectations for a number of event selections sensitive to different possible new physics contributions. We observed no excess of events for any of the event selections, and we established 95% confidence level (CL) upper limits on non-standard model event yields.

We now reinterpret the results of Ref. [1] in terms of the model of Eq. (1). We start from the "baseline event selection" defined in [1]. Briefly, this selection consisted of two same-sign isolated leptons of $p_T > 10$ GeV, one of which must have $p_T > 20$ GeV, at least two jets of $p_T > 30$ GeV and $\not{E}_T > 20$ (30) GeV for eμ (μμ or ee). Leptons and jets were reconstructed in the pseudorapidity ranges $|\eta| < 2.4$ and $|\eta| < 2.5$, respectively. Three events passed these requirements, with an expected background of 3.4 ± 1.8.

For the purpose of the tt search, the baseline event selection is modified by raising the transverse momentum threshold on the lowest p_T lepton from 10 to 20 GeV, since leptons from t → Wb, W → $\ell\nu$ tend to have high p_T. In addition, we demand that both leptons be positive since we are searching for pp → tt and not pp → $\mathrm{\bar{t}\bar{t}}$. These changes are expected to reduce the background by more than a factor of two.

These requirements select 2 events, while the background expectation is 0.9 ± 0.6 events. The main background contribution is attributed to $\mathrm{t\bar{t}}$ events with one lepton from W decay and one "fake" lepton, i.e. a lepton from heavy flavour decay, an electron from unidentified photon conversion, or a muon from meson decays in flight and other processes. This background is estimated in a data-driven way from studies of the sample of events selected with looser lepton isolation and identification requirements. More details on the event selection and the background estimation can be found in Ref. [1].

As a cross-check, we repeat the analysis with the same kinematic selection, but requiring the two leptons to be negative. No events in the data satisfy these requirements, in agreement with the charge-symmetric background expectation of 0.9 ± 0.6 events.

There is no statistically significant excess of tt candidate events over the background prediction. We thus proceed to set limits on the parameters of the Lagrangian of Eq. (1). The ingredients for this calculation are the observed (2) and expected (0.9 ± 0.6) number of events, the cross section for pp→tt(j) as a function of f_R and $M_{Z'}$, the efficiency of the event selection, the integrated luminosity, and all associated uncertainties.

We used the external model interface in the MADGRAPH [28] event generator to calculate at the leading order (LO) the tt + ttj cross section as a function of f_R and $M_{Z'}$. In this calculation we used the CTEQ6L [29] parton distribution functions (PDFs), fixed the top quark mass M_{top} to be 172.5 GeV, and set the renormalization and factorization scales to be $\mu = M_{\text{top}}$.

MADGRAPH was also used to generate pp→tt and pp→ttj events according to the diagrams of Fig. 2. These events were then processed by PYTHIA [30] for parton showering, followed by the CMS parametrized event simulation, and the same chain of reconstruction and analysis programs used for collision data. The event selection efficiency, including all relevant branching ratios, is (0.95 ± 0.13)%, independent of Z′ mass. Note that the branching ratio for tt→ $\ell\nu$b$\ell\nu$b (ℓ = e, μ) is 4.54% [31], but our selection is also sensitive to leptons from tau decays. The fractional systematic uncertainty on the event selection efficiencies was calculated as in Ref. [1], and its components are summarized in Table 1.

Table 1: Fractional systematic uncertainties on the pp → tt(j) signal selection. ISR/FSR denote initial and final state radiation.

Source	ee	μμ	eμ	all
Lepton selection	11.8%	10.6%	10.8%	10.7%
Energy scale	8%	8%	8%	8%
ISR/FSR and PDF	3%	3%	3%	3%
Total without luminosity	14.6%	13.6%	13.8	13.7%
Integrated luminosity	4%	4%	4%	4%
Total	15%	14%	14%	14%

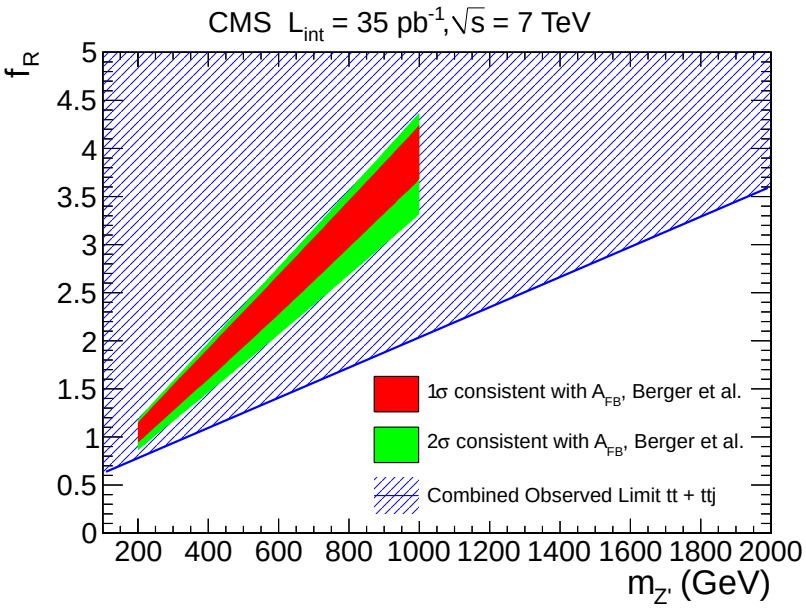

Figure 3: The exclusion region at 95% CL as a function of Z′ mass for various choices of the right-handed coupling f_R in the Lagrangian of Eq. (1). We also show the region of parameter space consistent with the Tevatron measurements of A_{FB} and $\sigma(t\bar{t})$ as inferred in Ref. [9].

We compute the upper limits using a Bayesian method [31]. We assume a flat prior for the signal strength and a log-normal distribution for the nuisance parameters. The 95% CL upper limit on the number of signal events is 5.7 using a 14% uncertainty on the signal efficiency (Table 1). The expected upper limit is $4.4^{+1.4}_{-1.3}$ events. The limit on the cross section is σ(pp →

$\mathrm{tt(j)) < 17.0}$ pb at 95% CL. As a cross-check, we also calculate the upper limit on the number of events using the hybrid frequentist-Bayesian CL_s approach [32]. With this method we find an upper limit of 5.6 events, which demonstrates the insensitivity of our results to the details of the statistical analysis.

Using the LO cross section as computed in MADGRAPH, we turn the limit on the number of events into an exclusion region in the f_R-$M_{Z'}$ plane as shown in Fig. 3. The region of parameter space consistent with the Tevatron A_{FB} [9] is disfavoured by this analysis.

For $M_{Z'} \gg M_{\mathrm{top}}$ the Lagrangian of Eq. (1) is equivalent to $\mathcal{L} = -\frac{1}{2}\frac{C_{RR}}{\Lambda^2}[\overline{\mathrm{u}}_R\gamma^\mu \mathrm{t}_R][\overline{\mathrm{u}}_R\gamma_\mu \mathrm{t}_R] +$ h.c. [33], with $\frac{C_{RR}}{\Lambda^2} = \frac{2g_W^2 f_R^2}{M_{Z'}^2}$. Our limit on f_R, calculated for $M_{Z'} = 2$ TeV, would then correspond to $\frac{C_{RR}}{\Lambda^2} < 2.7\ \mathrm{TeV}^{-2}$ at 95% confidence level. This bound is more stringent than that recently reported by CDF: $\frac{C_{RR}}{\Lambda^2} < 3.7\ \mathrm{TeV}^{-2}$ [34].

In summary, we have established a limit on tt production in pp collisions at $\sqrt{s} = 7$ TeV, based on a search for same-sign dileptons. Our bound can be used to test models of new physics with massive Z' bosons that have been proposed to explain the Tevatron measurements of the $\mathrm{p\overline{p}} \to \mathrm{t\bar{t}}$ forward-backward asymmetry. Our result disfavours this FCNC interpretation.

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