Inclusive search for Same-Sign Top Quark Pair Production using di-leptons at $\sqrt{s} = 7$ TeV

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Abstract

Significant evidence of asymmetries in $t\bar{t}$ productions have been recently reported by the Tevatron experiments. This could imply an enhancement of same-sign top pair production via non-universal massive neutral vector boson (Z') at the LHC. This note presents the first inclusive search for same-sign top quark pair production using di-leptons at the LHC. The study is performed using data corresponding to an integrated luminosity of 35 pb^{-1} at $\sqrt{s} = 7$ TeV recorded by CMS in 2010. No excess above the standard model background expectation is observed. Limits at 95% confidence level are set on the propagator mass as a function of Z' couplings to the standard model quarks.

1 Introduction

Recent measurements of the inclusive forward-backward $t\bar{t}$ production asymmetry from the Tevatron experiments show deviations from the standard model (SM) expectations [1, 2, 3]. The largest (3σ) deviation [3] is found to be in the region of high invariant mass with $M_{t\bar{t}} > 450$ GeV. Several attempts have been made to explain this asymmetry [4, 5, 6, 7]. One of the natural modes where such an asymmetry could be induced is via the appearance of Flavor Changing Neutral Currents (FCNC) in the quark sector. Several extenstions of the SM can generate these couplings at tree level [8, 9].

At the LHC, FCNC processes such as $uu \rightarrow tt$ can be produced via the exchange of a Z' boson, and can appear naturally in Techicolor (TC2) models or in general theories with non-universal massive neutral vector bosons. In these models the heavy boson couples strongly to the third generation of quarks, inducing FCNC. An enhancement of same-sign top pair production at the LHC via the exchange of a Z' boson is predicted by a very recent study of the forward-backward asymmetry [4]. This detailed study also provides an explanation of the observed asymmetry at the Tevatron.

This approach requires an interaction of $u - t - Z'$ with:

$$\mathcal{L} = g_W \bar{u}\gamma^{\mu}(f_L P_L + f_R P_R)tZ'_{\mu} + h.c \tag{1}$$

where g_W is the weak coupling strength. The left-handed coupling is set to $f_L = 0$, due to the $B_d - \bar{B}_d$ mixing constraint [10]. The right-handed coupling f_R is chosen to be a free parameter. Fig. 1 shows the t-channel exchange diagrams that can lead to the same-sign tt final state. The initial state involves two $u-$quarks and thus the cross section at the LHC is enhanced due to the large valance quark parton density of the proton. As expected the coupling appears twice in the Feynman diagrams, thus the predicated rate is proportional to f_R^4.

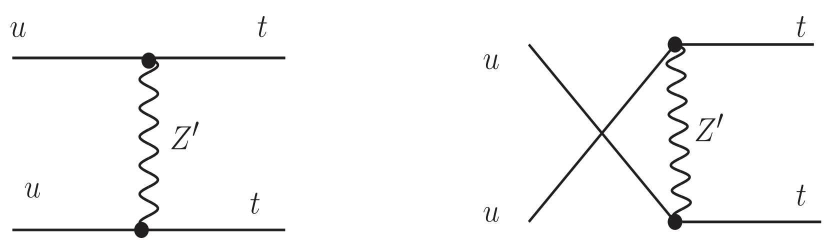

Figure 1: Diagrams for tt pair production induced by Z' exchange in t-channel.

The s-channel production mode, in which the same-sign tt pair is produced in association with a jet is shown in Fig. 2. The invarient mass of the Z' can be recontructed using top quarks decay modes with an additional jet in the final state. As one of the initial parton is gluon initiated, we expect this rate to be lower than the t-channel diagram.

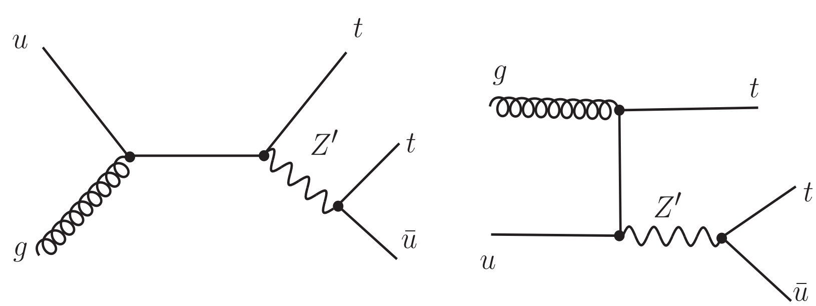

Figure 2: Diagrams for $tt\bar{u}$ production induced by Z' exchange.

We use $\alpha_S f_R^2$ as the proportionality constant for the production cross section. The width of the Z' boson in this case is computed using BRIDGE [12] and verified using MadGraph [11]. The total production cross sections for tt and ttj at the leading-order (LO) are shown as a function of Z' mass in Fig. 3. The signal events are generated using the external model interface in MadGraph/MadEvent [11], with CTEQ6L [13] parton distribution function (PDF). The renormalization and factorization scales are chosen to be at the top mass scale ($m_t = 172.5$ GeV). The cross sections agree well with the published literature [4].

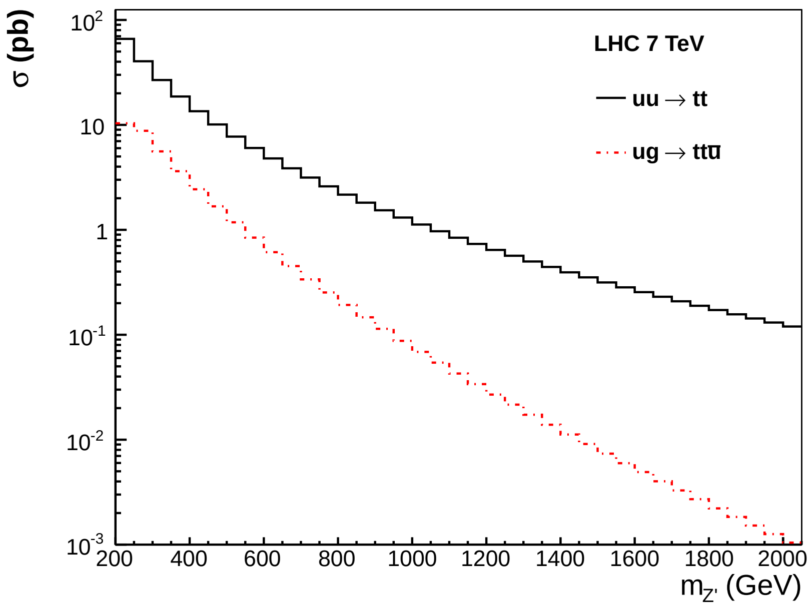

Figure 3: LHC production cross section for tt and ttj diagrams using right-handed coupling, $f_R = 1$. The renormalization and factorization scales are set to the top mass.

In this study we search for same-sign di-leptons originating from tt or ttj pair production as described above. To do this we exploit the approved CMS results on same sign di-leptons documented in [14, 15]. This note is organized as follows: in Section 2 we give an overview of the method and results of Reference [15] and we explain how these can be re-interpreted to set a limit on same-sign top production. In Section 3 we present the the exclusion limit derived as a function of the mass and coupling of the Z' boson. Finally, in Section 4 we summarize the results.

2 Search for Same Sign Top Quark Pair Production

This analysis is based on the approved same-sign di-lepton search documented in AN 2010/247 v6 [14]. In that analysis we searched for events with two isolated same sign leptons, two or more jets, and MET ($\not\!\!E_T$).

This final state is exactly the final state that one would expect from top-top production with both top quarks decaying as $t \to Wb$, $W \to \ell\nu$. In AN 2010/247 we presented event yields and background expectations for several event selections. One of those event selections is very similar to that of the $t\bar{t}$ (opposite sign) dilepton cross-section analysis [18], and thus it is the appropriate selection for a top-top pair search. Briefly, this selection consists of

- Two same sign leptons of $p_T > 20GeV$, $|\eta| < 2.4$
- Two jets of $p_T > 30GeV$, $|\eta| < 2.4$
- $\not\!\!E_T > 20GeV$ ($e\mu$) or $\not\!\!E_T > 30GeV$ (ee or $\mu\mu$)

The results of the search in this kinematical region are summarized in Table 6 of AN 2010/247 v6 [14], which is reproduced below as Table 1. We take the results of Table 1 with one important modification: since we are interested in tt production and not $\overline{tt}$ production, we only consider $\ell^+\ell^+$ events. Thus the BG estimates in Table 1 have to be divided by two. Both observed events in Table 1 have positive leptons. Then, the bottom line yield and bg prediction is: two events observed and 0.9 ± 0.6 expected BG, see Table 2.

2.1 Event Yields

The observed and expected SM event yields in 35 pb^{-1} reproduced from Table 6 of AN 2010/247 v6 [14] are shown in Table 1. The data-driven background prediction is based on a combination of estimating "fake leptons" [19] (FakeRate) and electrons reconstructed with the wrong sign [14] (Charge FlipRate). The probability for muons to be reconstructed with the wrong sign at the relevant momenta is negligible.

Sample	ee	$\mu\mu$	$e\mu$	total
DY	0.00000 ± 0.00000	0.00000 ± 0.00000	0.00000 ± 0.00000	0.00000 ± 0.00000
t$\bar{t}$	0.03700 ± 0.01170	0.04440 ± 0.01282	0.09250 ± 0.01850	0.17391 ± 0.02537
wjets	0.10860 ± 0.10860	0.00000 ± 0.10860	0.00000 ± 0.10860	0.10860 ± 0.18810
tw	0.00079 ± 0.00079	0.00079 ± 0.00079	0.00475 ± 0.00194	0.00634 ± 0.00224
single top t-ch.	0.00138 ± 0.00138	0.00000 ± 0.00138	0.00276 ± 0.00195	0.00415 ± 0.00276
single top s-ch.	0.00000 ± 0.00012	0.00035 ± 0.00020	0.00023 ± 0.00016	0.00058 ± 0.00028
ww	0.00000 ± 0.01219	0.00000 ± 0.01219	0.01219 ± 0.01219	0.01219 ± 0.0211
wz	0.01109 ± 0.00784	0.01109 ± 0.00784	0.07207 ± 0.01999	0.09425 ± 0.02286
zz	0.00000 ± 0.00178	0.00178 ± 0.00178	0.00535 ± 0.00309	0.00713 ± 0.00356
Total MC	0.15886 ± 0.10952	0.05841 ± 0.01515	0.18986 ± 0.03012	0.40713 ± 0.11459
data (35 pb^{-1})	0	0	2	2
fake rate prediction				
single fake	0.47105 ± 0.33308	0.12058 ± 0.12058	1.05798 ± 0.48320	1.64961 ± 0.59914 (8 evts)
double fake	0.00000 ± 0.24180	0.00000 ± 0.02086	0.00000 ± 0.07102	0.00000 ± 0.25288 (0 evts)
fake prediction	0.47105 ± 0.41159	0.12058 ± 0.12237	1.05798 ± 0.48839	1.64961 ± 0.65032
flip rate prediction	0.06 ± 0.01	0	0.02 ± 0.003	0.08 ± 0.01
total data driven prediction	0.54 ± 0.48	0.13 ± 0.14	1.07 ± 0.72	1.74 ± 1.05
total MC driven prediction	0.01 ± 0.01	0.01 ± 0.01	0.08 ± 0.04	0.10 ± 0.05
total bkg prediction	0.55 ± 0.48	0.14 ± 0.14	1.15 ± 0.7	1.8 ± 1.1

Table 1: Data and Monte Carlo yields for the same sign di-leptons with $P_T > 20$ GeV. Uncertainties in the lower three rows also include the systematic uncertanities on the method used.

The event yields have the following characteristics:

- We do not consider rare processes such as $qqW^{\pm}W^{\pm}, WWW, t\bar{t}W$, double parton $W^{\pm}W^{\pm}$, which are negligibly small [14].
- We found small contributions (0.01 events) from conversion of prompt photons in $W/Z\gamma$ using MC and are not considered in order to avoid double counting in the single fake contributions.
- The diboson backgrounds WW, WZ, ZZ are taken from the MC as an additional background estimate. This contribution is tabulated as the total MC driven predicition.
- The prediction from fake rates includes the systematic error of 50%.
- The flip rate prediction also includes an additional systematic error of 50% based on statistics of the same sign events observed in the control region [14].
- The systematic errors are added when propagating the fake/flip rates into total data-driven predictions.
- All MC driven predictions also assume a flat 50% systematic error.

The dominant SM contribution is from $t\bar{t}$ decays. The total estimated background is obtained after the application of Fake and Charge Flip rates to the entire ensemble of SM samples [14]. The data yield is in good agreement with the predication from both MC as well as the data driven predictions.

One of the key components of same-sign top pair search is the fact that the final state includes includes mainly one type of sign. For example, in the t-channel exchange: $uu \to tt \to l^+l^+\mu\nu bb$ only positively charged leptons are involved. The quark quark, $\bar{u}\bar{u}$ scattering is highly suppressed due to the parton luminosities, thus we do not expect any significant contribution from negatively charged leptons. Given that the data driven methods are robust against any given choice of lepton charge [22], we use half of the total background prediction for this search.

The results is summarized in Table 2.

Although the observed events have two positively charged di-leptons, we do not consider this a significant deviation from the prediction.

Same sign di-leptons	Event yield
Total Observed	2
Total Predicted	0.9 ± 0.55

Table 2: Observed and predicted number of events passing the event selection in 35 pb^{-1} of integrated luminosity. The uncertainty also includes systematic errors.

2.2 Systematic Uncertainties

Details of the systematic uncertainties studied are discussed elsewhere [14]. We summarize the most important aspects for the previously described signal in Table 3.

Source	ee	$\mu\mu$	$e\mu$	all
Lepton selection	11.8%	10.6%	10.8%	10.7%
Energy scale	5%	5%	5%	5%
ISR/FSR and PDF	2%	2%	2%	2%
Total without luminosity	12.9%	11.8%	11.9	11.9%
Integrated luminosity	4%	4%	4%	4%
Total	13.6%	12.4%	12.5%	12.5%

Table 3: Summary of systematic uncertainties on the signal selection and expectation. Reported values are fractional, relative to the total cross section.

3 Results

In absence of any significant deviation from the predicted background we set 95% CL. on the number of observed events. Two statistical methods have been used for the upper limit. Both methods assume the uncertainties on signal and background are un-correlated and use a log-normal distribution for error pdfs.

The first method used to compute the upper limit is based on Bayesian statistics [20]. A posterior probability $p(r)$ is used as a function of the signal strength $r = \sigma/\sigma_{SM}$ assuming a uniform prior for r integrating the nuisance parameters associated to the uncertainties. The upper limit at 95% confidence level is then determined by integrating $p(r)$ to determine r', which satisfies $\int_{r'}^{\inf} p(r)dr = 0.05$.

We use the hybrid frequentist-bayesian CLs approach [21] as the second method. Although the two statistical approaches are not equivalent, in this case we get similar results.

- Upper limit at 95% CL. with 12.5% signal systematic error using Bayesian approach = 5.7
- Upper limit at 95% CL. with 12.5% signal systematic error using CLs = 5.6

We use 5.7 events as the upper limit for the rest of this document. This corresponds to a 95% CL. upper limit on the effective cross section for new processes, including the effects of experimental acceptance and efficiency, of 0.3 pb for the same sign di-lepton channel.

Fig. 4 shows the exclusion region at 95% CL. as a function of Z' mass and the right-handed coupling, f_R. LO signal cross sections are used for this study. The limit on t-channel exchange diagrams tt covers a significant region as a function of the Z' mass. In most cases it does not favor large values of the coupling f_R. As expected, when using 35 pb^{-1} of luminosity the limit on ttj production is weak and only excludes up to $m_Z' \sim 510$ GeV for higher values of f_R.

4 Conclusion

In conclusion, the first results on same sign top pair production using di-leptons have been presented. In the proton-proton collision data sample corresponding to an integrated luminosity of 35 pb^{-1} at at $\sqrt{s} = 7$ TeV, no significant deviations from the standard model expectations are observed. Limits on the cross sections for new physics involving tt and ttj pair production via a non-universal massive neutral vector boson (Z') are presented. For the chosen sets of couplings, Z' masses below 2 TeV using t-channel exchange diagrams and below 510 GeV

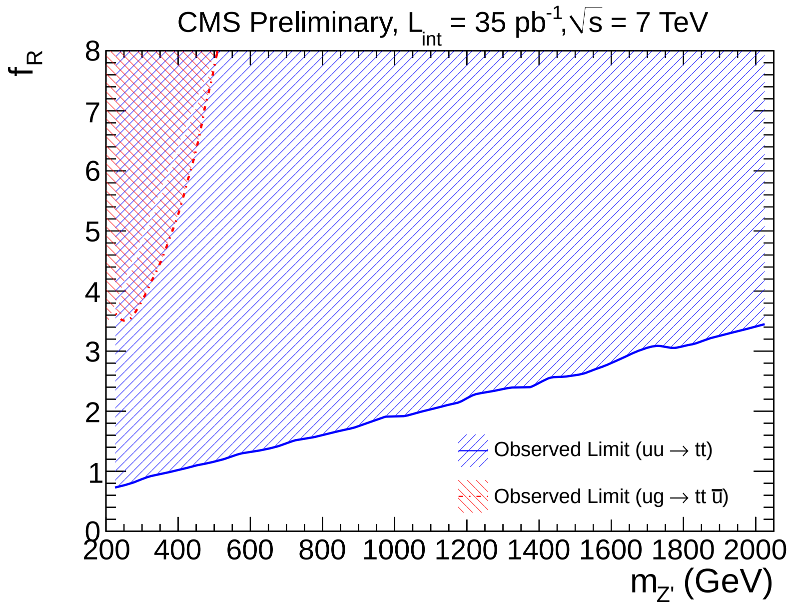

Figure 4: The exclusion region at 95% CL. as a function of Z' mass for various choices of the right-handed coupling, f_R. The solid lines represents regions due to t-channel exchange, where as the dotted line excludes the assumptions on ttj pair production. For the renormalization and factorization scales, μ is set to the top mass.

for ttj production at the LHC are excluded at 95% CL. These results exceed previous limits set by any other experiment.

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