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. They could be due to FCNC in the top sectors. These new interactions could imply an enhancement of same-sign top pair production via t-channel exchange of 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 (A_{FB}) from the Tevatron experiments show deviations from the standard model (SM) expectations [1, 2, 3]. Several attempts have been made to explain this asymmetry [4, 5, 6, 7]. One of the most natural ways to induce such an asymmetry would be through Flavor Changing Neutral Currents (FCNC) in the top quark sector. The forward-backward asymmetry in $u\bar{u} \to t\bar{t}$ would then be generated by t-channel exchange of a new massive Z' boson that couples chirally to u and t at the same vertex, as shown in Fig. 1 [4]. The same type of interaction would also give rise to same-sign top pair production, see Fig. 2 and Fig. 3. In this case, the initial state involves two $u-$quarks and thus the cross section at the LHC is enhanced due to the large valence quark parton density of the proton.

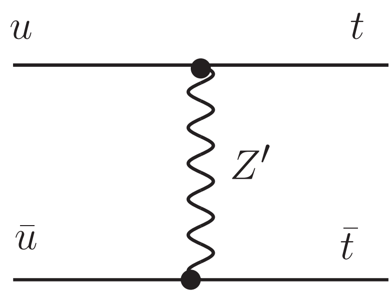

Figure 1: Diagram for $t\bar{t}$ production induced by Z' exchange which can generate a forward-backward asymmetry.

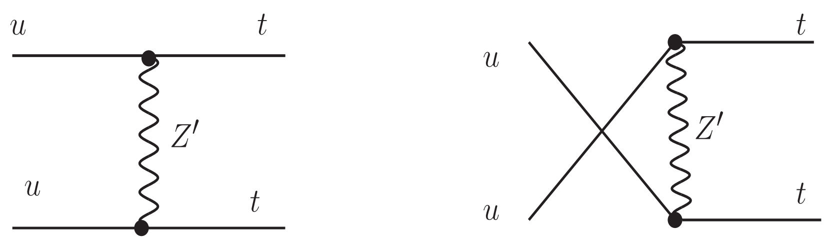

Figure 2: Diagrams for tt pair production induced by Z' exchange in the t-channel.

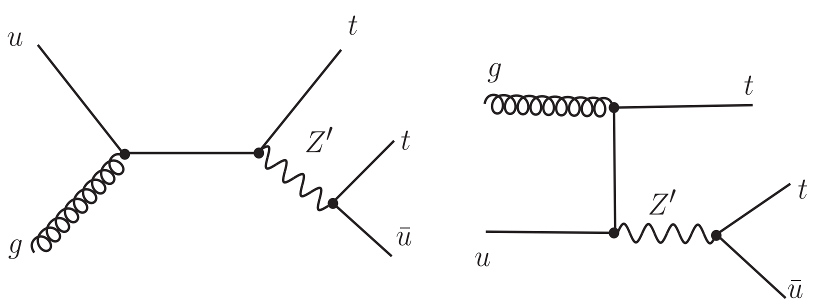

Figure 3: Diagrams for $tt\bar{u}$ production induced by Z' exchange in the s-channel

In this work we consider the model of Reference [4]. The relevant $u - t - Z'$ interaction term in the Lagrangian is:

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

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 and the Z' mass are free parameters in the model. Within this model, there exists a narrow range of parameter space consistent with the TeVatron measurements of $\sigma(p\bar{p} \to t\bar{t})$ and A_{FB}, and not excluded by direct searches for same sign tops, see Fig. 4.

In this study we search for same-sign di-leptons originating from tt or ttj pair production as described above. To

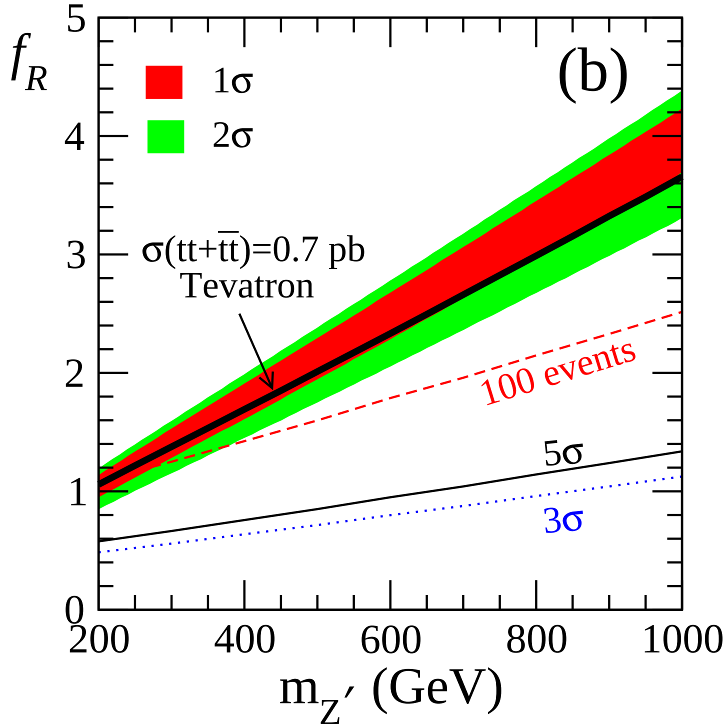

Figure 4: From Reference [4]; the shaded area covers the parameter space consistent with the A_{FB} and $\sigma(t\bar{t})$ from the Tevatron; The line indicated by the arrow shows the Tevatron limit inferred by the authors from same sign top searches at the Tevatron; the remaining lines represent the expectations of Reference [4] for LHC searches in 1 fb^{-1}.

do this we exploit the approved CMS results on same sign di-leptons documented in [14, 15].

This note is organized as follows: the signal Monte Carlo generation is described in Section 2; in Section 3 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 4 we present the the exclusion limit derived as a function of the mass and coupling of the Z' boson. Finally, in Section 5 we summarize the results.

2 Monte Carlo event generation

We used the external model interface in MadGraph [11] to generate $pp \to tt$ and $pp \to ttj$ at LO using the lagrangian of equation 1 with different values of the Z' mass, and with $f_L = 0$, $f_R = 1$. We simulated the model with Z' mass in t- and s-channels ranging from 100 GeV to 2 TeV and between 200 GeV to 2 TeV, respectively. In the s-channel diagram the Z' boson decays to a top and a light flavour quark. In order to be on-shell its mass has to be larger than the top mass. Thus, we have used a lower cutoff of 200 GeV in our simulations.

Different values of f_R are modelled by rescaling the cross-sections for the t-channel (Fig. 2) and s-channel (Fig. 3) by f_R^4 and f_R^2, respectively. We used the 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 width of the Z' boson 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. 5. Our calculated cross sections agree well with the published literature [4].

The events generated by MadGraph are then fed to Pythia for parton showering. They are simulated using the standard CMS fast-simulation program.

3 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] and corresponds to an integrated luminosity of 35 pb^{-1}. In that analysis we searched for events with two isolated same

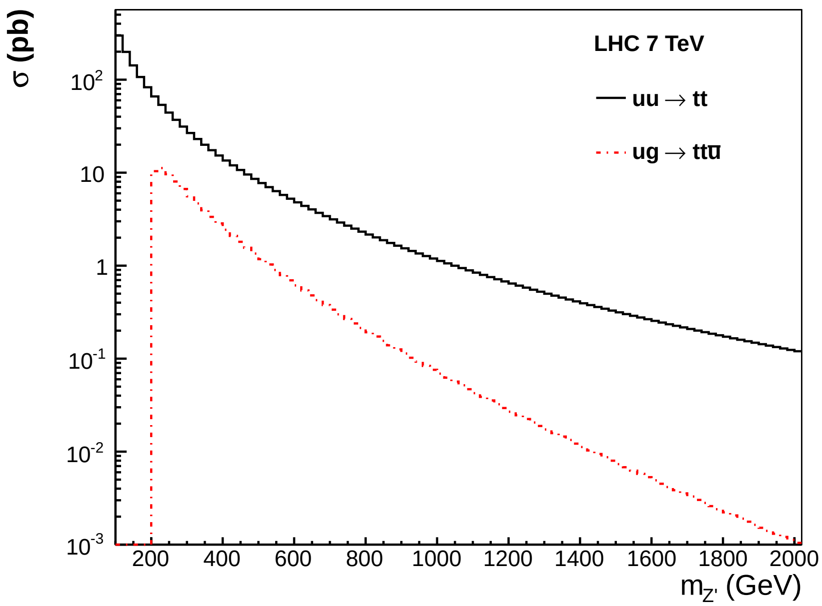

Figure 5: LHC production cross section for tt and ttj diagrams using right-handed coupling, $f_R = 1$. The renormalization and factorization scales are set to the top mass.

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 $t \to Wb$, $W \to \ell\nu$.

3.1 Event Selection

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

More details are to be found in Reference [14].

3.2 Event Yields and Background

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.

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.

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].
- 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.

Sample	$e^{\pm}e^{\pm}$	$\mu^{\pm}\mu^{\pm}$	$e^{\pm}\mu^{\pm}$	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 from Reference [14]. Note that this Table inludes $\ell^+\ell^+$ as well as $\ell^-\ell^-$; Both signal events are $e^+\mu^+$. Uncertainties in the lower three rows also include the systematic uncertainties on the method used.

- 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 dilepton dataset[14]. The data yield is in good agreement with the background prediction.

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. Strictly speaking the W+jets background, which according to MC is about 25% of the total, is not completely charge symmetric. This BG is calculated in a data driven was using the fake rate method. We have repeated the fake rate calculation of Table 1 for positive leptons only; the result is 0.67 $\pm$ 0.34 (stat.) $\pm$ 0.28 (sys.) events, which is consistent with being one half of the estimate for both positive and negative leptons of Table 1 (1.65 events divided by 2 = 0.8).

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, which corresponds to one half the background of Table 2. Thus, we see no statistically significant evidence for $pp \to tt$.

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.

3.3 Systematic Uncertainties on the Acceptance

The methods used to determine the systematic uncertaintare are discussed in Reference [14]. For lepton selections, we take the result from [14]. We have recalculated the systematic uncertainties due to ISR/FSR, PDFs, and jet energy scale appropriate to the $pp \to tt$ process. The results are summarized in Table 3.

Source	ee	$\mu\mu$	$e\mu$	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%

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

4 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 14% signal systematic error using Bayesian approach = 5.7
- Upper limit at 95% CL. with 14% 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. 6 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 $m'_Z \sim 500$ GeV for higher values of f_R.

Fig. 7 shows the combined exclusion region (tt and ttj) at 95% CL. as a function of Z' mass. The combined exclusion is dominated by tt.

5 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. We us these data to set a cross-section limit $\sigma(pp \to tt) < 0.3$ pb at the 95% C.L.. In addition, for a model with a a non-universal massive neutral vector boson (Z'), we exclude a region of the $M(Z') - f_R$ parameter space, where $M(Z')$ is the mass of the Z' and f_R is the strength of the right handed utZ' coupling.

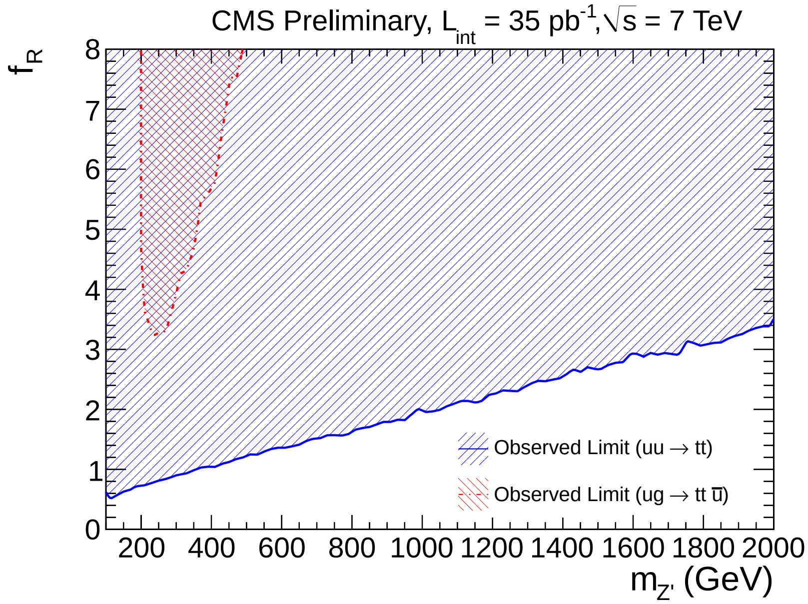

Figure 6: The exclusion region at 95% CL. as a function of Z' mass for various choices of the right-handed coupling, f_R. The solid lines represents regions due to t-channel exchange, where as the dotted line excludes the assumptions on ttj pair production. For the renormalization and factorization scales, μ is set to the top mass.

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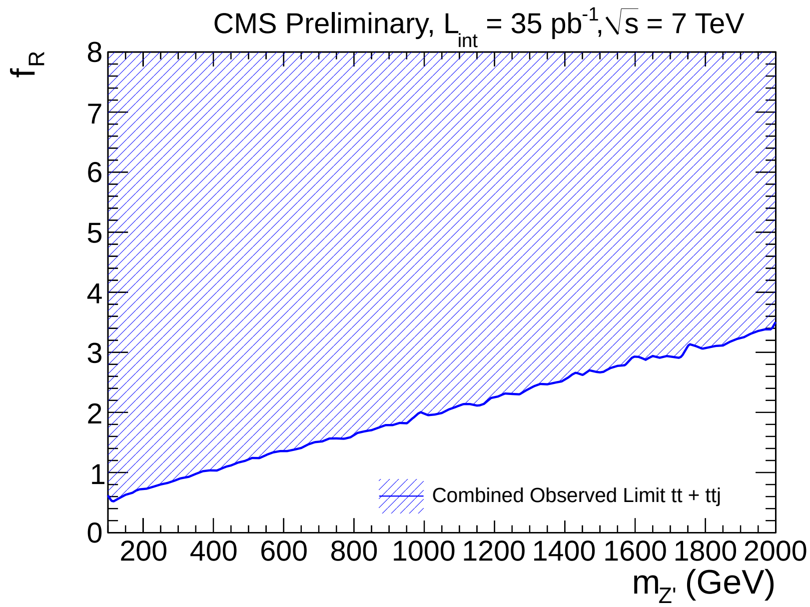

Figure 7: The combined exclusion region at 95% CL. as a function of Z' mass for various choices of the right-handed coupling, f_R. Both t- and s-channel diagrams are added to get the combined exclusion limit on same sign top production at the LHC. For the renormalization and factorization scales, μ is set to the top mass.

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