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

D. Barge, C. Campagnari, P. Kalavase, D. Kovalskyi, V. Krutelyov, J. Ribnik

University of California, Santa Barbara

W. Andrews, G. Cerati, D. Evans, F. Golf, I. MacNeill, S. Padhi, Y. Tu, F. Würthwein, A. Yagil, J. Yoo

University of California, San Diego

L. Bauerdick, I. Bloch, K. Burkett, I. Fisk, Y. Gao, O. Gutsche, B. Hooberman, S. Jindariani

Fermi National Accelerator Laboratory, Batavia, Illinois

Abstract

Significant evidence of asymmetries in $t\bar{t}$ production have been recently reported by the Tevatron experiments. They could be due to FCNC in the top sector. These new interactions could imply an enhancement of same-sign top pair production via the t-channel exchange of a 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 dileptons 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 are set on the propagator mass as a function of Z' couplings to the standard model quarks at the 95% confidence level.

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, as illustrated in 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.

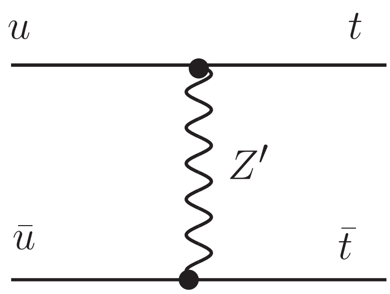

Figure 1: Diagram for $t\bar{t}$ production induced by Z' exchange which can generate a forward-backward asymmetry.

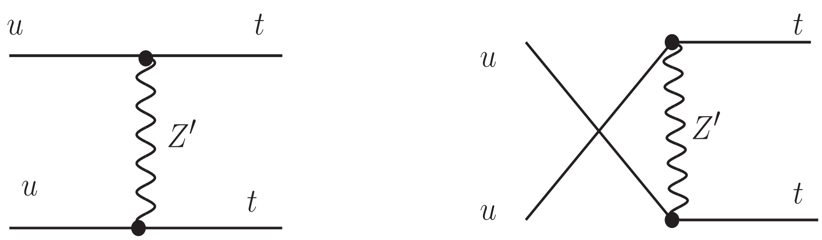

Figure 2: Diagrams for tt pair production induced by Z' exchange in the t-channel.

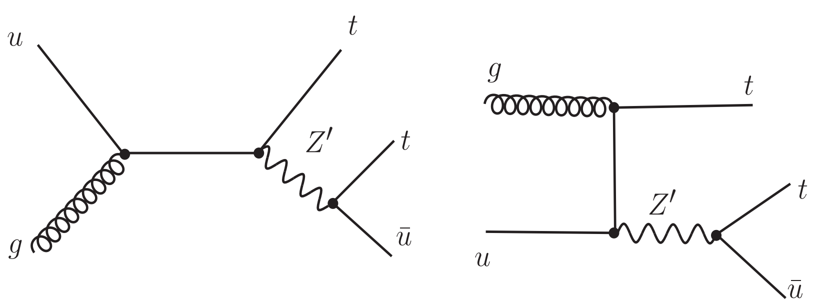

Figure 3: Diagrams for $tt\bar{u}$ production induced by Z' exchange in the s-channel

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 is a narrow range of parameter space consistent with the TeVatron measurements of $\sigma(p\bar{p} \to t\bar{t})$ and A_{FB}, which is not excluded by direct searches for same sign tops. This region is illustrated in Fig. 4.

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

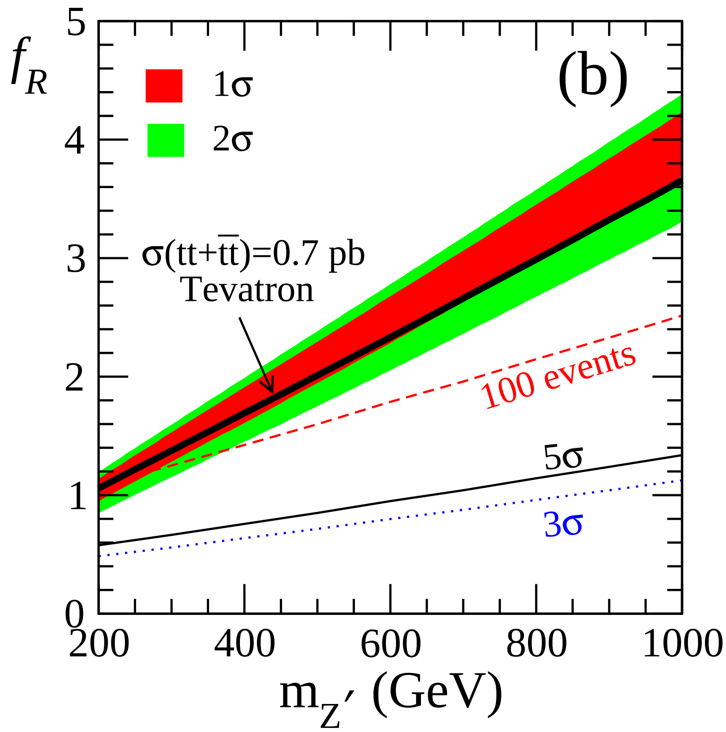

Figure 4: From Reference [4]; the shaded area covers the parameter space consistent with the A_{FB} and $\sigma(t\bar{t})$ from the Tevatron; The line indicated by the arrow shows the Tevatron limit inferred by the authors from same sign top searches at the Tevatron; the remaining lines represent the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

do this we exploit the approved CMS results on same sign dileptons 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 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 $pp \to ttj$ events at LO with the Lagrangian described in Equation 1 with $f_L = 0$, $f_R = 1$. Different values of f_R were 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. The range of Z' masses considered was 100 GeV to 2 TeV in the t-channel and 200 GeV to 2 TeV in the s-channel. The minimum mass cut is higher for the s-channel where the Z' boson decays to a top and a light flavour quark to ensure the on-shell Z' mass is always larger than the top mass. Note that we generated two events with two distinct MadGraph settings for the simulation of top decays: in the first case the decay was handled by Pythia, and in the second case by the `DECAY` package within MadGraph, which does a better job at taking the spin information into account.

We used the CTEQ6L [13] parton distribution function (PDF) and set the renormalization and factorization scales to be at the top mass scale ($m_t = 172.5$ GeV). The width of the Z' boson was calculated using BRIDGE [12] and verified the results with MadGraph [11]. The generated events were fed to Pythia for parton showering. The detector response was taken into account with the standard CMS fast-simulation program.

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].

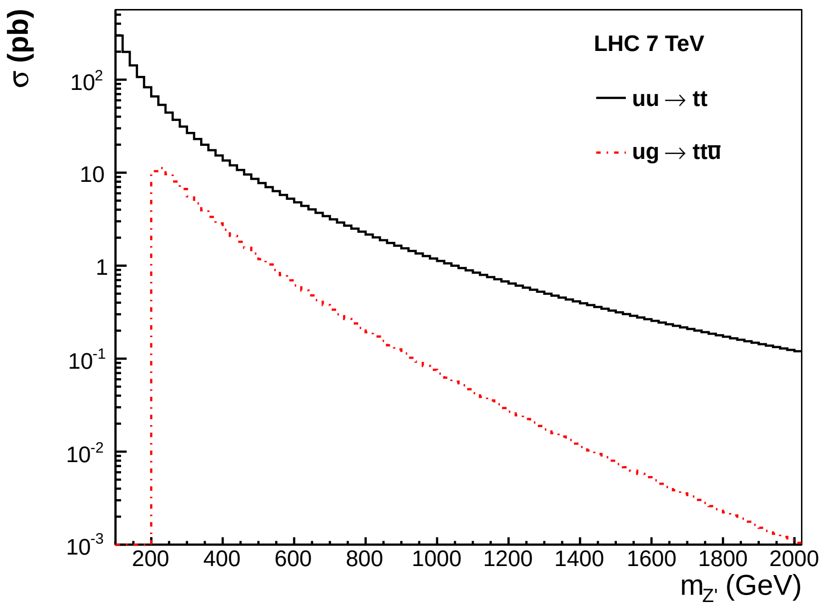

Figure 5: LHC production cross section for tt and ttj diagrams using right-handed coupling, $f_R = 1$. The renormalization and factorization scales are set to the top mass.

3 Search for Same Sign Top Quark Pair Production

This analysis is based on the approved same-sign dilepton 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 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 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 in the relevant momentum range 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].

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 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 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 background 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 background is calculated in a data-driven way using the fake rate method. We have repeated the fake rate calculation of Table 1 for positive leptons only; the result is 0.67 ± 0.34 (stat.) ± 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 background prediction is: two events observed and 0.9 ± 0.6 expected background, which corresponds to one half the background of Table 2. Thus, we see no statistically significant evidence for $pp \to tt$.

3.3 Systematic Uncertainties on the Acceptance

The product of acceptance, efficiency, and branching ratio is determined from simulation. It is found to be $0.95 \pm 0.13\%$, independent of Z' mass (the uncertainty on this quantity is discussed below). This acceptance is calculated using the MadGraph `DECAY` package; when Pythia is used to decay the top quarks, the acceptance is 20% higher, see Fig. 6.

Same sign dileptons	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.

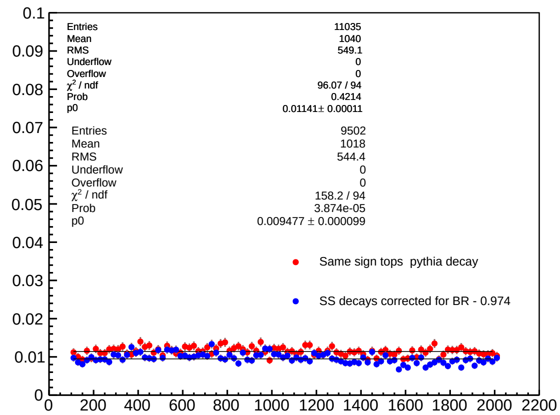

Figure 6: The product of acceptance, efficiency, and branching ratio as determined from MC as a function of Z' mass. The red points correspond to events where the top decays was handled by Pythia; the blue points correspond to events where the top decay was handled by Madgraph, so that spin effects are properly accounted for. In this last case the acceptance was corrected for the fact that the $W \to \ell\nu$ branching ratio in MadGraph is 11.1% instead of 10.8%.

The methods used to determine the systematic uncertainties 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. Note that the expected Bayesian limit is $4.44^{+1.43}_{-1.28}$ events.

This corresponds to a 95% CL. upper limit for $\sigma(pp \to tt)$ of 17.0 pb.

Fig. 7 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 integrated 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. 8 shows the combined exclusion region (tt and ttj) at 95% CL. as a function of Z' mass. The combined exclusion is dominated by tt.

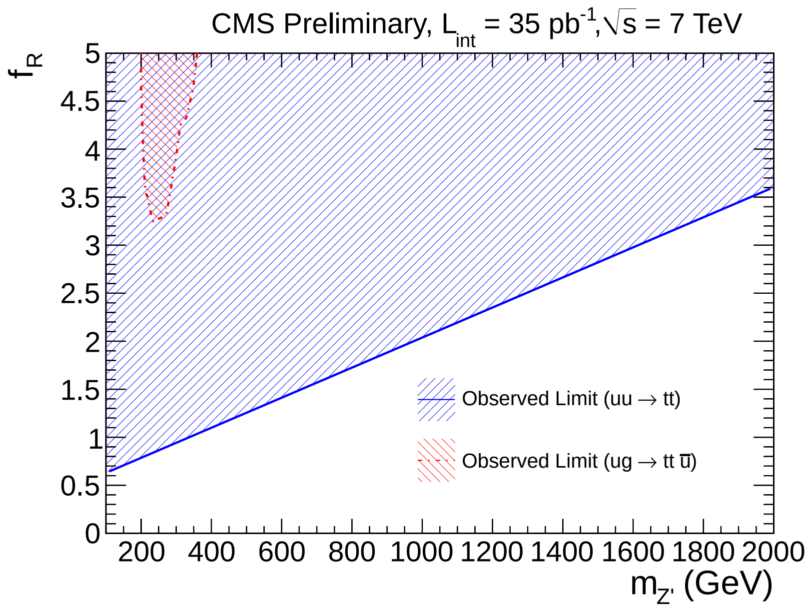

Figure 7: The exclusion region at 95% CL. as a function of Z' mass for various choices of the right-handed coupling, f_R. The solid lines represents regions due to t-channel exchange, where as the dotted line excludes the assumptions on ttj pair production. For the renormalization and factorization scales, μ is set to the top mass.

For $M_{Z'} >> M_{\rm top}$ the Lagrangian of equation 1 is equivalent to $\mathcal{L} = -\frac{1}{2}\frac{C_{RR}}{\Lambda^2}[\bar{u}\gamma^\mu t][\bar{u}\gamma_\mu t] + h.c.$ [**?**], 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 $\frac{C_{RR}}{\Lambda^2} < 2.6$ TeV^{-2} at 95% confidence. This is more stringent than the limit recently reported by CDF: $\frac{C_{RR}}{\Lambda^2} < 3.7$ TeV^{-2} [23].

5 Conclusion

In conclusion, the first results on same sign top pair production using dileptons 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 use these data to set a cross-section limit $\sigma(pp \to tt) < 17.0$ pb at the 95% C.L.. In addition, for a model with 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.

Acknowledgments

We thank Johan Alwall, Ed Berger, Qing-Hong Cao, Chuan-Ren Chen, Chong Sheng Li and Hao Zhang for discussions as well as help in implementation of Z' exchange model in MadGraph/MadEvent.

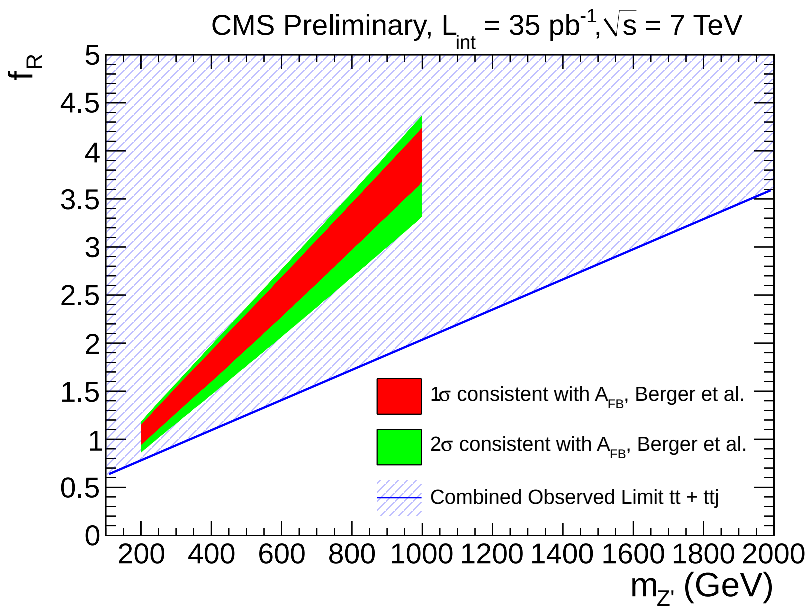

Figure 8: The combined exclusion region at 95% CL. as a function of Z' mass for various choices of the right-handed coupling, f_R. Both t- and s-channel diagrams are added to get the combined exclusion limit on same sign top production at the LHC. For the renormalization and factorization scales, μ is set to the top mass.

References

[1] D0 Collaboration, "First measurement of the forward-backward charge asymmetry in top quark pair production", Phys.Rev.Lett.100:142002, (2008)

[2] CDF Collaboration, "Forward-Backward Asymmetry in Top Quark Production in $p\bar{p}$ Collisions at $sqrts =$ 1.96 TeV", Phys.Rev.Lett.101:202001, (2008)

[3] CDF Collaboration, "Evidence for a Mass Dependent Forward-Backward Asymmetry in Top Quark Pair Production", arXiv:1101.0034, (2011)

[4] Ed.Berger et. al, "Top Quark Forward-Backward Asymmetry and Same-Sign Top Quark Pairs", arXiv:1101.5625, (2011)

[5] M.R. Buckley et. al, "Light Z' Bosons at the Tevatron", arXiv:1103.6035, (2011)

[6] Moira I. Gresham et. al, "On Models of New Physics for the Tevatron Top AFB", arXiv:1103.3501, (2011)

[7] Z.Ligeti et. al, "Explaining the t tbar forward-backward asymmetry without dijet or flavor anomalies", arXiv:1103.2757, (2011)

[8] C.T Hill, Phys. Lett. B345, 483 (1995)

[9] R.S. Chivukula, E.H. Simmons and J. Terning, Phys.Lett.B331,383 (1984); D.J. Muller and S. Nandi, Phys.Lett.B383,345 (1996); E. Malkawi, T. Tait and C.-P. Yuan, Phys.Lett.B385,304 (1996); K. Lane and E.Eichten, Phys.Lett.B433,96 (1998); C.T. Hill, Phys.Rev.D59,075003 (1999); H. Georgi and A.K. Grant, Phys.Rev.D63,015001 (2001).

[10] Q.H. Cao et. al. Phys.Rev.D81, 114004 (2010)

[11] Johan Alwall et. al "MadGraph/MadEvent v4: The New Web Generation", JHEP 0709:028 (2007)

[12] Patrick Meade and Matthew Reece, "BRIDGE: Branching Ratio Inquiry/Decay Generated Events", arXiv:hep-ph/0703031 (2007)

[13] J.Pumplin et. al. JHEP 07:012 (2002)

[14] "Inclusive search for New Physics with Same-Sign Dileptons using early LHC data", CMS AN-2010/247.

[15] CMS Collaboration, "Search for new physics with same-sign dileptons at the LHC", CERN-PH-EP-2011-033.

[16] https://twiki.cern.ch/twiki/bin/viewauth/CMS/StandardModelCrossSections.

[17] T. Sjostrand, S. Mrenna, and P. Skands, "PYTHIA 6.4 Physics and Manual", JHEP 0605:026 (2006).

[18] CMS Collaboration, "First Measurement of the Cross Section for Top-Quark Pair Production in Proton-Proton Collisions at sqrt(s)=7 TeV", Phys.Lett. B695 424-443 (2011).

[19] "Fake Rates for dilepton Analyses", CMS AN-2010/257.

[20] I.Bertram et. al., "A Recipe for the construction of confidence limits", FERMILAB-TM-2104, (2000).

[21] A.L. Read, CERN Report 2000-005 p. 81 (2000).

[22] "Data-driven methods to estimate the electron and muon fake contributions to lepton analyses", CMS AN-2009/041.

[23] "Search for like-sign top quark pair production at CDF with 6.1 fb^{-1}", CDF/PHYS/EXO/PUBLIC/10466, http://www-cdf.fnal.gov/physics/exotic/r2a/20110407.samesigndileptons/sstops.pdf