Inclusive search for Same-Sign Top Quark Pair Production using di-leptons 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, 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

Fermi National Accelerator Laboratory, Batavia, Illinois

Abstract

This note presents the first inclusive search for same-sign top quark pair production using di-leptons at the LHC. The study is performed with data corresponding to an integrated luminosity of 35 pb^{-1} at $\sqrt{s} = 7$ TeV recorded by CMS in 2010. Significant evidence of asymmetries in $t\bar{t}$ productions are recently reported by the Tevatron experiments. This has the potential of early enhancements in same-sign top pair productions via non-universal massive neutral vector boson (Z'). 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 [1, 2, 3] from the Tevatron experiments on inclusive forward-backward $t\bar{t}$ production asymmetry shows deviations from the standard model (SM) expectations. 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 were 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 Current (FCNC) effects in the quark sector. Several extenstions of SM can generate these coupling at tree level [8, 9].

At the LHC, processes such as $uu \to tt$ via exchange of a Z' boson can be produced via FCNC 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 with the third generation of quarks which induces FCNC. Very recently a detailed study [4] on forward-backward asymmetry predicts enhancement of same-sign top pair productions at the LHC via the Z' boson. The study also provides explanation of the observed asymmetry at the Tevatron.

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

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

where g_W is the weak coupling strength. The left-handed coupling is set to $f_L = 0$ throughout, due to the $B_d - \bar{B}_d$ mixing constraint [10]. The right-handed coupling f_R is chosen to be a free parameter.

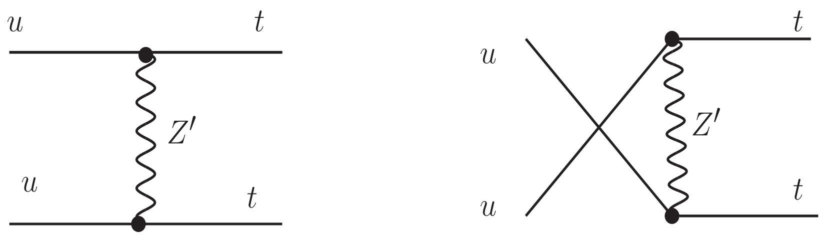

Figure 1: Diagrams for tt pair production induced by Z' exchange in t-channel.

Fig. 1 shows the t-channel exchange diagrams that can lead to same-sign tt final states. The initial state involves two $u-$quarks and thus the cross section at the LHC is enhanced due to large valance quark parton density function (PDF). As expected the coupling appears twice in the Feynman diagrams, thus the predicated rate is proportional to f_R^4.

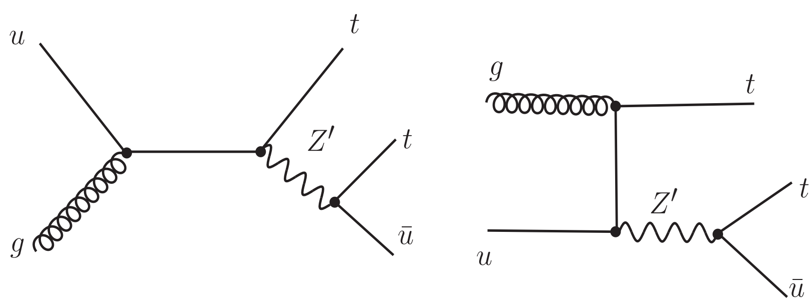

Figure 2: Diagrams for $tt\bar{u}$ production induced by Z' exchange.

Another like sign mode is the tt pair production in association with a jet, as 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. 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 at the leading-order (LO) for tt and ttj as a function of Z' mass are shown 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

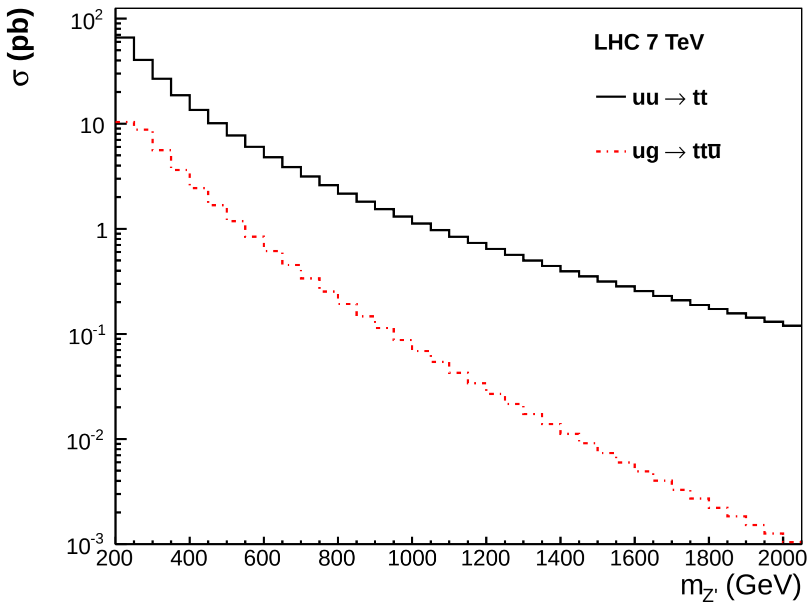

Figure 3: LHC production cross section for tt and ttj diagrams using right-handed coupling, $f_R = 1$. The renormalization and factorization scales are set to the top mass.

the top mass scale ($m_t = 172.5$ GeV). The cross sections agree well with the published literature [4].

In this study we search for same sign di-leptons originating from tt or ttj pair productions. The same sign top production leads to W^+bW^+b final states, where $W^+ \rightarrow l^+\mu$.

The note is organized as follows: in Section 2 we list the data samples used in this analysis; in Section 3 we describe the same sign di-lepton event selection; in Section 4 we discuss the results followed by the exclusion limits in Section 5. Finally, in Section 6 we summarize the results.

The work presented here is based on previously documented studies in [14, 15].

2 Data Samples

The search is performed using the following datasets. The Monte Carlo (MC) cross sections are normalized to the available Next-to-Leading-Order (NLO) or Next-to-Next-Leading-Order (NNLO) cross sections [16].

- Data
  - `EG_Run2010A-Sep17ReReco_v2_RECO`
  - `Electron-PromptReco-v2_RECO`
  - `Mu_Run2010A-Sep17ReReco_v2_RECO`
  - `Mu-PromptReco-v2_RECO`
- Monte Carlo
  - `TTbarJets-madgraph_Spring10-START3X_V26_S09-v1`
  - `WJets-madgraph_Spring10-START3X_V26_S09-v1`
  - For Drell Yan we use a combination of:
    1. `ZJets-madgraph_Spring10-START3X_V26_S09-v1` for di-lepton mass > 50 GeV
    2. `Zee_Spring10-START3X_V26_S09-v1` for di-lepton mass from 20-50 GeV
    3. `Zmumu_Spring10-START3X_V26_S09-v1` for di-lepton mass from 20-50 GeV
    4. `Ztautau_Spring10-START3X_V26_S09-v1` for di-lepton mass from 20-50 GeV
    5. `DYee_M10to20_Spring10-START3X_V26_S09-v1`
    6. `DYmumu_M10to20_Spring10-START3X_V26_S09-v1`

- `WW_Spring10-START3X_V26_S09-v1`
- `WZ_Spring10-START3X_V26_S09-v1`
- `ZZ_Spring10-START3X_V26_S09-v1`
- `SingleTop_tWChannel-madgraph_Spring10-START3X_V26_S09-v1`
- `SingleTop_tChannel-madgraph_Spring10-START3X_V26_S09-v1`
- `SingleTop_sChannel-madgraph_Spring10-START3X_V26_S09-v1`
- `LM0_Spring10-START3X_V26_S09-v1`
- `LM1_Spring10-START3X_V26_S09-v1`
- `PhotonVJets-madgraph_Spring10-START3X_V26_S09-v1`

The analysis is performed using the CMS certified JSON file covering run ranges between 135821 to 149442 for an integrated luminosity of 35 pb^{-1}.

PYTHIA 6.4.22 [17] using MadEvent is used to generate the signal events for various choices of Z' masses. They are simulated using the FastSim model of the CMS detector and finally reconstructed and analyzed using the same software infrastructure as is used to process collision data.

3 Event Selection

The event selection used is not optimized for any specific non-standard model scenario. It is based on small modifications to the baseline di-lepton event selection that we used in our same-sign published study [14, 15]. The only difference is that we now require both leptons to have the transverse momentum $(p_t) > 20$ GeV. A quick summary of the event selection is:

- We require a mixture of unprescaled single and double lepton triggers as mentioned in [14]. The combined trigger efficiency is $\sim 99.9 \pm 0.1\%$ for di-lepton events that pass the event selection.
- At least two isolated same sign leptons (ee, $e\mu$, and $\mu\mu$).
- Leptons must have $P_T > 20$ GeV, $|\eta| < 2.4$.
- We consider L2L3 corrected particle flow Jets with $P_T > 30$ GeV and $|\eta| < 2.4$.
- The scalar sum of the P_T of all jets passing the requirements above should be > 60 GeV.
- At least two jets.
- We remove di-lepton events with invariant mass < 5 GeV.
- Additional Z-Veto:
  - we veto the candidate lepton, if an extra lepton in the event pairs with the candidate lepton to form a Z within the mass range between $76 < m_{\ell\ell}$ (GeV) < 106. This requirement is designed to reject WZ events.
- We require particle flow $\not\!\!E_T > 30(20)$ GeV for $ee, \mu\mu(e\mu)$ events. We find that both tcMET and pfMET lead to similar results.
- We require that all three charge measurements from GSF, CTF and Supercluster Charge algorithms agree. The Supercluster Charge is determined from the relative position of the supercluster with respect to the projected track from the pixel seed.

More details on the selections can be found elsewhere [14, 15].

4 Search for Same Sign Top Quark Pair Production

This section summarizes the results of the search for same sign tt pair production in the di-lepton channel. We use two data-driven methods to estimate background characterized by the presence of two isolated high P_T same sign leptons, $\not\!\!E_T$, and significant hadronic activity. For the purpose of this note we restrict ourselves to the ee, $e\mu$, and $\mu\mu$ final states, *i.e.*, we do not consider τ's, except in the case that the τ decays leptonically.

As we will show in Section 4.1, for this modified baseline selection is similar to the published opposite sign di-lepton pair production cross section paper [18], where the main background is from SM $t\bar{t}$ decays. 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.

4.1 Event Yields

The observed and expected SM event yields in 35 pb^{-1} after applying the event selections described in Section 3 to the datasets described in Section 2 are detailed below. The final event yields also include the systematic uncertanities of the method used.

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 yield has 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. The data yield is in good agreement with the predication from both MC as well as the data driven predictions.

One of the key component of same sign top pair search is the fact that the final state mainly includes only one type of sign. For example, in the t-channel exchange: $uu \rightarrow tt \rightarrow l^{+}l^{+}\mu\nu bb$ only +ve sign leptons are involved. As mentioned earlier, 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 -ve signed 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.

Same sign di-leptons	Event yield
Total Observed	2
Total Predicted	0.9 $\pm$ 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.

Although the observed events have two +ve di-leptons, we do not find this to be a significant deviation from the prediction.

4.2 Systematic Uncertainties

Details of the systematic uncertainties studied are discussed elsewhere [14]. Here we summarize the aspects important for the aforesaid signal.

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.

5 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 errors 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.

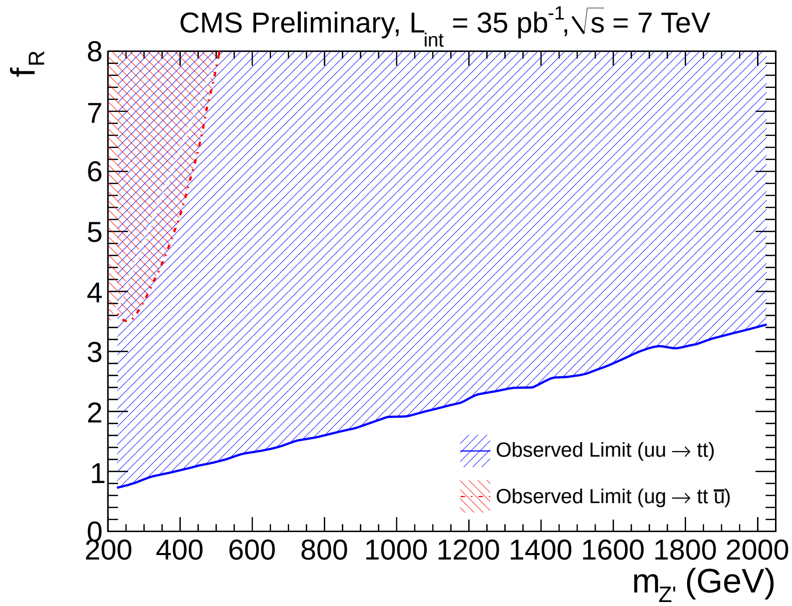

Figure 4: The exclusion region at 95% CL. as a function of Z' mass for various choices of the right-handed coupling, f_R. The solid lines represents regions due to t-channel exchange, where as the dotted line excludes the assumptions on ttj pair production. For the renormalization and factorization scales,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

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

6 Conclusion

In summary, the first results on searches for same sign top pair production using di-leptons have been presented. In the data sample corresponding to an integrated luminosity of 35 pb^{-1}, 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 provided. For the chosen sets of couplings Z' mass below 2 TeV using t-channel exchange diagrams and below 510 GeV for ttj production at the LHC are excluded at 95% CL. These CMS results exceed previous limits set by any other experiment.

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 modes in MadGraph/MadEvent.

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 di-leptons 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.