

# Measurements of $t\bar{t}\gamma$ , $t\bar{t}Z$ , and $t\bar{t}W$ production

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Measurements of the production of top quark pairs in association with electroweak vector bosons from the CMS, ATLAS and CDF collaborations are presented. The CDF collaboration measures the cross section of top pair plus photon production and the ratio of this cross section to the inclusive top pair cross section using  $6 \text{ fb}^{-1}$  of data at  $\sqrt{s} = 1.96 \text{ TeV}$  with the results  $\sigma_{t\bar{t}\gamma} = 0.18 \pm 0.07(\text{stat.}) \pm 0.04(\text{sys.}) \pm 0.01(\text{lumi.}) \text{ pb}$  and  $\sigma_{t\bar{t}\gamma}/\sigma_{t\bar{t}} = 0.024 \pm 0.009$ . The ATLAS collaboration measures the top pair plus photon cross section at  $\sqrt{s} = 7 \text{ TeV}$  using  $1.04 \text{ fb}^{-1}$  of data with the result  $\sigma_{t\bar{t}\gamma} = 2.0 \pm 0.5(\text{stat.}) \pm 0.7(\text{sys.}) \pm 0.08(\text{lumi.})$ . The ATLAS collaboration also sets an upper limit on  $\sigma_{t\bar{t}Z}$  of  $0.71 \text{ pb}$  using  $4.0 \text{ fb}^{-1}$  of data at  $\sqrt{s} = 7 \text{ TeV}$ . The CMS collaboration measures the  $\sigma_{t\bar{t}Z}$  and  $\sigma_{t\bar{t}V(V=W,Z)}$  cross sections using  $5.0 \text{ fb}^{-1}$  of data at  $\sqrt{s} = 7 \text{ TeV}$  with the results  $\sigma_{t\bar{t}V(V=W,Z)} = 0.43^{+0.17}_{-0.15}(\text{stat.})^{+0.09}_{-0.07}(\text{sys.}) \text{ pb}$  and  $\sigma_{t\bar{t}Z} = 0.28^{+0.14}_{-0.11}(\text{stat.})^{+0.06}_{-0.03}(\text{sys.}) \text{ pb}$ .

## 1 Introduction

The top quark was first observed by the CDF and D0 experiments in  $p\bar{p}$  collisions at the Tevatron collider in 1995 [1, 2]. The dominant production mode for the production of top quarks at hadron colliders is the production of top quark pairs via the strong interaction. Much rarer production modes in which the top quark pair is produced in association with an electroweak boson ( $\gamma, Z, W^\pm$ ) are now also within reach due to the large datasets recorded at the Tevatron and LHC colliders. Measurements of these processes allow precise tests of the predictive power of the Standard Model (SM) [3]. Due to its large mass the top quark could play a crucial role in electroweak symmetry breaking. These measurements presented in this note have the potential to allow direct access to the electroweak couplings of the top quark. These processes have similar cross sections and are significant backgrounds to the production of top pairs in association with a Higgs boson. Hence these measurements provide valuable constraints which will improve the precision with which the  $t\bar{t} + H$  process can be measured. In Beyond the Standard Model (BSM) models such as technicolor and models containing strongly coupled Higgs the top quark exhibits altered couplings. As a result these measurements can place constraints on these classes of BSM physics models.

In this note, a suite of measurements of these processes performed by the CDF, ATLAS and CMS experiments are detailed.

## 2 CDF measurements

CDF measures both the cross section of top pair production in association with a photon ( $\sigma_{t\bar{t}\gamma}$ ) and the ratio between  $\sigma_{t\bar{t}\gamma}$  and the inclusive top pair production cross section ( $\sigma_{t\bar{t}\gamma}/\sigma_{t\bar{t}}$ ) [4]. The measurement utilises  $6.0\text{fb}^{-1}$  of integrated luminosity from  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV collected using the CDF II detector. The analysis focuses on the semi-leptonic decay channel by requiring an electron (e) or muon ( $\mu$ ) with  $E_T^{e,\mu} > 20$  GeV, a photon ( $\gamma$ ) with  $E_T^\gamma > 10$  GeV, a jet identified as originating from a b-quark, missing transverse energy  $E_T^{miss} > 20$  GeV, total transverse hadronic energy, ( $H_T$ ) greater than 200 GeV and three or more jets. In order to suppress the backgrounds from photons or leptons that originate from hadronic decay within jets both the lepton and the photon are required to be isolated from other activity in the calorimeter.

After the application of these criteria, the selected event sample is dominated by  $t\bar{t}\gamma$ . Inclusive  $t\bar{t}$  production is selected by applying nearly the same set of criteria with the omission of the photon requirement. These similar selections ensure that systematic uncertainties largely cancel in the measurement of  $\sigma_{t\bar{t}\gamma}/\sigma_{t\bar{t}}$ . The numbers of background events passing these criteria are estimated using simulation. Using these selected events the following results are obtained:  $\sigma_{t\bar{t}\gamma} = 0.18 \pm 0.08$  pb and  $\sigma_{t\bar{t}\gamma}/\sigma_{t\bar{t}} = 0.024 \pm 0.009$ . These results are consistent with the SM prediction.

## 3 ATLAS measurements

### 3.1 $\sigma_{t\bar{t}\gamma}$

ATLAS performs a first measurement of the  $\sigma_{t\bar{t}\gamma}$  in  $pp$  collisions using  $1.04\text{fb}^{-1}$  of data at  $\sqrt{s} = 7$  TeV [5]. This measurement focuses on the single or dilepton decay channels including  $\tau$  leptons. Electron candidates are defined as energy deposits in the electromagnetic calorimeter with an associated, well measured track. All electron candidates are required to have a transverse momentum ( $P_T$ ) greater than 25 GeV and  $|\eta_c| < 2.47$  where  $\eta_c$  is the pseudorapidity of the electromagnetic cluster associated with the electron. Muon candidates are reconstructed from track segments in the different layers of the muon chambers and are matched with tracks found in the inner detector. In this analysis, muon candidates are required to have  $P_T > 25$  GeV and  $|\eta| < 2.5$ . In order to suppress the backgrounds from hadrons mimicking leptons and the semi-leptonic decays of heavy quarks within jets, the lepton candidates are required to be isolated. Since photons can convert into  $e^+e^-$  pairs by interacting with detector material, there are two categories of reconstructed photons. Photons are reconstructed as unconverted photons or are recovered from identified electrons that are more likely to be converted photons. The photon falls into the fiducial region if the  $|\eta|$  of its cluster is smaller than 2.37 and not in the transition region between barrel and end-cap calorimeters. The transverse energy of the photon cluster is required to be larger than 15 GeV. Photons must fulfil a set of tight requirements on shower shapes and hadronic leakage. No isolation criterion is applied, since this information is used to estimate the fraction of photon candidates from misidentified hadrons in the final fit.

The event selection requires the presence of exactly one reconstructed  $\mu$  (e) with  $P_T > 20$  (25) GeV,  $E_T^{miss} > 20$  GeV and  $E_T^{miss} + m_T(W) > 60$  GeV in the muon channel and  $E_T^{miss} > 35$  GeV and  $E_T^{miss} + m_T(W) > 25$  GeV in the electron channel. In addition the events are required to contain at least four jets, one of which has been identified as originating from a b-quark. In order to select photons the following criteria are applied: the event must contain

one well-identified photon with  $E_T > 15$  GeV. In the electron channel the invariant mass of the electron and photon is required to be outside a  $\pm 5$  GeV mass window around the Z peak to reject  $Z \rightarrow e^+e^-$  events.

The cross section is extracted via a template fit to the distribution of the  $p_T^{cone20}$  variable.  $p_T^{cone20}$  is defined as the scalar sum of the transverse momenta of all the tracks in the cone with  $\Delta R < 0.2$  around the photon candidate. Signal photons are generally isolated, fake photons arising from hadrons are typically surrounded by other particles from the fragmentation process. The template for signal photons is obtained from  $Z \rightarrow e^+e^-$  events in data by exploiting the similar  $p_T^{cone20}$  distributions of electrons and signal photons. The template for fake photons arising from hadrons is extracted from a data sample using jet triggers. Backgrounds from top pair events with electrons faking photons are estimated by applying a data-derived scale factor to a simulated sample of top pair events. Other backgrounds from top pair events are estimated from simulation. Backgrounds from  $W + \text{jets} + \gamma$  and multi-jet +  $\gamma$  events are estimated using data-driven methods.

The largest systematic uncertainty on this measurement arises from the estimation of the efficiency of photon identification. Systematic uncertainties from imperfect Monte Carlo modelling are quantified by comparing alternate  $t\bar{t}$  simulations. Uncertainties due to jet energy scale and b-tagging efficiencies are estimated from the methods described in [7, 9]

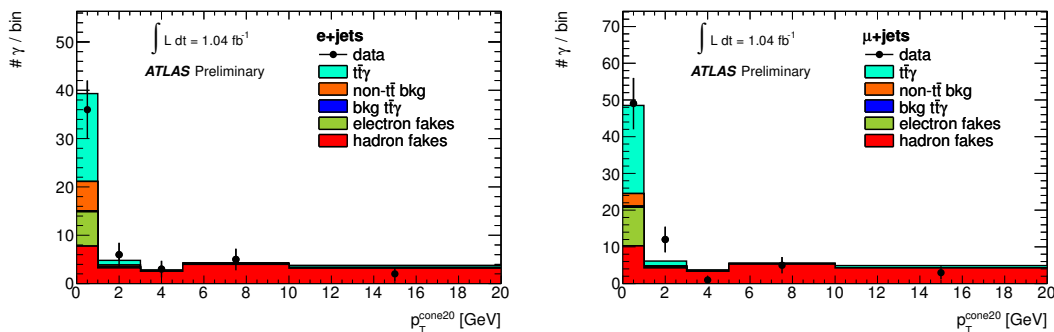


Figure 1: The post-fit distributions for the single electron channel (left) and single muon channel (right). The predicted signal  $t\bar{t}\gamma$  contributions is shown on top of the background contributions.

The fitted  $t\bar{t}\gamma$  contribution is converted into the following results for the cross section times branching ratio (BR):

$$\sigma_{t\bar{t}\gamma} \cdot BR = 2.0 \pm 0.5 \text{ (stat.) } pb \quad (1)$$

which is consistent with the SM prediction.

### 3.2 $\sigma_{t\bar{t}Z}$

ATLAS performs a search for  $t\bar{t}Z$  in production in  $pp$  collisions using  $4.7 \text{ fb}^{-1}$  of data at  $\sqrt{s} = 7$  TeV [6]. The analysis concentrates on final states containing exactly three leptons, in which the Z boson decays to a pair of leptons and one of the W boson from the top decay decays leptonically.

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All electron candidates are required to be isolated and to have  $|\eta_{cluster}| < 2.47$  and  $E_T > 25$  GeV. Muon candidates are required to be isolated and to satisfy  $P_T > 20$  GeV and  $|\eta| < 2.5$ . All jets are required to satisfy  $P_T > 20$  GeV and  $|\eta| < 2.5$ . Events are required to have exactly three leptons, four jets with  $P_T > 30$  GeV and  $E_T^{miss} > 30$  GeV. Additionally, one pair of leptons with opposite-sign charges and same flavour and a dilepton invariant mass consistent with a Z boson is required. In the final signal region, at least one of the jets is required to be b-tagged.

There are a number of SM processes which can produce three real isolated leptons. The dominant process for the signal regions is the production of  $(t\bar{b}Z + \bar{t}bZ + X)$  along with WZ + jets and ZZ + jets. The contributions of these processes to the signal region are estimated using simulation. The background from events containing fewer than three real leptons but at least one fake lepton is estimated using a data-driven technique known as the *matrix-method* that is described in [6].

Systematic uncertainties arising from the mis-modelling of lepton trigger, reconstruction, identification and isolation efficiencies are estimated from data. The lepton momentum scale and resolution is measured similarly. The jet energy scale and b-tagging efficiencies are measured using techniques described in [8, 10, 11]. Systematic uncertainties on individual reconstructed objects are propagated to the  $E_T^{miss}$ . The effect of variations of the renormalisation and factorisation scales is also included. The effect of mis-modelling of initial and final state radiation (ISR/FSR) is studied by varying the amount of (ISR/FSR) in the  $t\bar{t}Z$  simulation. A cross section uncertainty of 50% is applied for the background process WZ + jets. In table 1 the numbers of events expected from simulation and observed in data for the signal region are shown. One event is observed in the data. The expected number of signal events in the signal region is  $0.85 \pm 0.04$  (stat.)  $\pm 0.14$  (syst.). The expected number of background events from SM processes with three real leptons, obtained from simulation, is  $0.28 \pm 0.05$  (stat.)  $\pm 0.14$  (syst.). The expected fake lepton background is  $0.0_{-0.0}^{+1.6}$ .

	SR
$t\bar{t}Z$	$0.85 \pm 0.04$
WZ+jets	$0.06 \pm 0.04$
ZZ+jets	$0.014 \pm 0.014$
$t\bar{t}W$	$0.011 \pm 0.008$
$(\bar{t}bZ + t\bar{b}Z) + X (= jj, l\nu)$	$0.125 \pm 0.013$
WZbbjj	$0.065 \pm 0.016$
MC Total	$1.13 \pm 0.06$
Fake lepton background	$0.0_{-0.0}^{+1.6}$
Observed	1

Table 1: Number of events observed in data and expected from the  $t\bar{t}Z$  signal process and various background for the signal region. The uncertainties shown on the backgrounds estimated using simulation are statistical only.

The results are translated into a 95% credibility upper limit on  $\sigma_{t\bar{t}Z}$  using a Bayesian prescription. A flat prior probability distribution is assumed for the number of signal events and a Poisson likelihood is used. The observed upper limit is 0.71 pb with an expectation of 0.74 pb which is consistent with the SM prediction.

## 4 CMS measurements

CMS performs two complementary analyses to provide the first measurement of the production of a  $t\bar{t}$  pair in association with a vector boson [12]. The analyses utilise  $5.0 \text{ fb}^{-1}$  of  $pp$  collision data at  $\sqrt{s} = 7 \text{ TeV}$ . Muons are measured with the combination of the tracker and the muon system, in the pseudorapidity range  $|\eta| < 2.4$ . Electrons are detected as tracks in the tracker pointing to energy clusters in the electromagnetic calorimeter up to  $|\eta| = 2.5$ . Both muons and electrons are required to be isolated and to have  $P_T$  greater than 20 GeV. Jets are required to have an  $|\eta| < 2.4$  and a  $P_T > 20 \text{ GeV}$ . Jet are identified as originating from b-quarks by a b-tagging algorithm which provides a efficiency for tagging b-jets of approximately 65% and a misidentification 1%.

### 4.1 Trilepton analysis

The trilepton analysis aims to select events from the process  $pp \rightarrow t\bar{t}Z \rightarrow (t \rightarrow bl^\pm\nu)(t \rightarrow bj\bar{j})(Z \rightarrow l^\pm l^\pm)$  (with  $l = e$  or  $\mu$ ). The analysis requires two same-flavour, opposite sign charge leptons with  $P_T > 20 \text{ GeV}$ , where the dilepton system must have an invariant mass between 81 and 101 GeV and  $P_T > 35 \text{ GeV}$ . In addition, a third lepton with  $P_T > 10 \text{ GeV}$  and at least three jets two of which have been b-tagged are required. Finally the scalar sum of all the selected jets ( $H_T$ ) is required to be larger than 120 GeV. Background contributions arise from the Drell-Yan,  $t\bar{t}$  and  $WZ$  processes. Event samples with looser requirements are used to determine the background contributions from the data. The total systematic uncertainty is evaluated by assessing the relative change in signal efficiency and background yield in the simulation when varying relevant sources of systematic uncertainties in the simulation by  $\pm 1 \sigma$ . The dominant uncertainty comes from the background estimate. The cross section is extracted simultaneously from all channels with the result:

$$\sigma_{t\bar{t}Z} = 0.28_{-0.11}^{+0.14}(\text{stat.})_{-0.03}^{+0.06}(\text{sys.}) \text{ pb} \quad (2)$$

This measured cross section is compatible with the NLO prediction of the Standard Model which is  $0.137_{-0.016}^{+0.012} \text{ pb}$ .

### 4.2 Dilepton analysis

The dilepton analysis aims to select events originating from the processes:  $pp \rightarrow t\bar{t}W \rightarrow (t \rightarrow bl^\pm\nu)(t \rightarrow bj\bar{j})(W \rightarrow l^\pm\nu)$  and  $pp \rightarrow t\bar{t}Z \rightarrow (t \rightarrow bl^\pm\nu)(t \rightarrow bj\bar{j})(Z \rightarrow l^\pm l^\mp)$  (with  $l = e$  or  $\mu$ ). The dilepton analysis requires the presence of two same-sign dileptons, one with  $P_T > 55 \text{ GeV}$  and one with  $P_T > 30 \text{ GeV}$  with a dilepton invariant mass greater than 8 GeV, at least three jets with  $P_T > 20 \text{ GeV}$  one of which is b-tagged and  $H_T > 100 \text{ GeV}$ . The main background contributions arise from the non prompt leptons or from mis-reconstruction effects and are estimated using the data. Systematic uncertainties relative to experimental measurements or model uncertainties are evaluated similarly to the trilepton analysis.

In Fig. 2 the event yields separated in lepton flavour channels for the trilepton and dilepton analyses are shown. A total of 16 events are selected in data, compared to an expected background contribution of  $9.2 \pm 2.6$  event. The significance of the observed  $t\bar{t}V$  signal is equivalent to 3.0 standard deviations. A combined cross section is measured simultaneously from the three channels with the result:

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$$\sigma_{t\bar{t}V} = 0.43^{+0.17}_{-0.15}(\text{stat.})^{+0.09}_{-0.07}(\text{sys.}) \text{ pb} \quad (3)$$

This result is compatible with the NLO predictions of the standard model which is  $0.306^{+0.031}_{-0.053}$

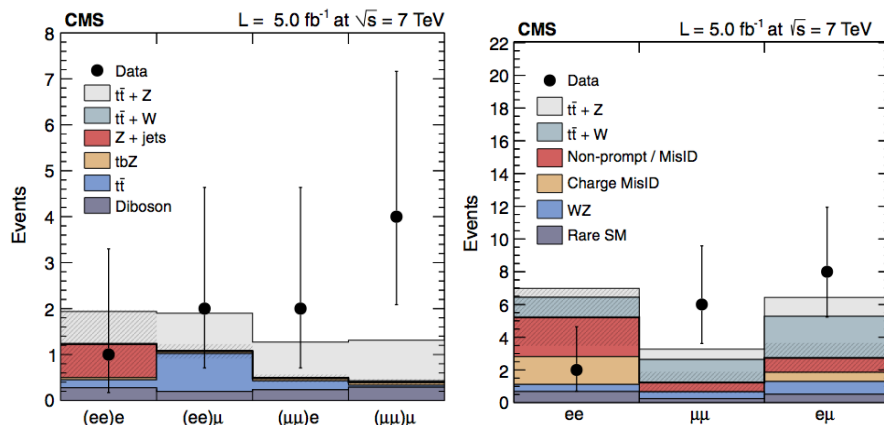


Figure 2: Event yields separated in lepton flavour channels for the trilepton (left) and dilepton channels (right). The expected contributions from signal and background processes are indicated.

## 5 Conclusions

The following measurements of  $t\bar{t} + \gamma$ ,  $t\bar{t} + Z$  and  $t\bar{t} + W$  from the CDF, ATLAS and CMS experiments have been presented. The CDF experiment measured both  $\sigma_{t\bar{t}\gamma}$  and the cross section ratio  $\frac{\sigma_{t\bar{t}\gamma}}{\sigma_{t\bar{t}}}$  at  $\sqrt{s} = 1.96$  TeV. The ATLAS experiment measured the  $\sigma_{t\bar{t}\gamma}$  cross section and sets upper limits on the  $\sigma_{t\bar{t}Z}$  at cross section  $\sqrt{s} = 7$  TeV. The CMS experiment measured  $\sigma_{t\bar{t}Z}$  and the inclusive cross section  $\sigma_{t\bar{t}V}$  where  $V = W, Z$  at  $\sqrt{s} = 7$  TeV. In all cases the results are consistent with the predictions of the SM.

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