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Measurements of ttbar+X using the ATLAS detector

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The large centre-of-mass energy available at the Large Hadron Collider allows for the copious production of top quark pairs in association with other final state particles at high transverse momentum. The ATLAS experiment has measured several final state observables that are sensitive to additional radiation in top-anti-top quark final states. Results on the top production in association with W and Z bosons at both 8 and 13 TeV are presented along with measurements of the cross section for production with an associated isolated photon at 8 TeV. Analyses probing the top pair production with additional QCD radiation include the multiplicity of jets for various transverse momentum thresholds in the 13 TeV data. These measurements are compared to modern Monte Carlo generators based on NLO QCD matrix element or LO multi-leg matrix elements.

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1. Introduction

The top quark is the heaviest known quark, and the only one with the mass at the electroweak scale. Therefore, its production and decay provide important tests of quantum chromodynamics (QCD) in non-perturbative mode. A deviation from the Standard Model (SM) predictions for the top quark production and decay would be an indication of new physics beyond the standard model. Top quarks are produced in abundance at the Large Hadron Collider (LHC), which offers an excellent opportunity to study in detail their properties.

The results reported in this talk refer to studies of the top-anti-top quark pair production at the LHC in association with other particles. The studies have been performed using the ATLAS detector [1]. The data used in the analyses were recorded by the ATLAS detector in 2011, 2012, and 2015,

2. $t\bar{t}+W/Z$ production

The $t\bar{t}+W/Z$ production has been studied by ATLAS and the $t\bar{t}+W$ $t\bar{t}+Z$ cross-sections recently measured at both 8 TeV and 13 TeV centre-of-mass energy. The 8 TeV analysis [2] has been performed using 20.3 fb^{-1} of integrated luminosity collected by the ATLAS detector in 2012, considers final states with at least two leptons (electrons or muons). Four separate channels were considered: 2LOS (opposite-sign dilepton channel with at least three jets, one or two of which are b-tagged), 2LSS (same-sign dilepton channel targeting the $t\bar{t}W$ events, at least two b-tagged jets were required), 3L (trilepton channel split into Z- and non-Z-subchannels), and 4L (tetralepton channel aiming at $t\bar{t}Z$). The production cross-sections $\sigma_{t\bar{t}W}$ and $\sigma_{t\bar{t}Z}$ were determined simultaneously using a binned likelihood fit over the five control regions constraining the $t\bar{t}$, Z, ZZ, and WZ backgrounds, and the signal regions in the 2LOS, 2LSS, 3L, and 4L channels (Fig. 1, left). The result of the simultaneous fit to the $t\bar{t}W$ and $t\bar{t}Z$ cross-sections along with the 68% and 95% C.L. uncertainty contours is shown in Fig. 1, right. The shaded areas on the plot denote 14% uncertainty resulting from renormalisation and factorisation scale uncertainties as well as PDF uncertainties including α_S variations. The result of the combined fit is

$$\sigma_{t\bar{t}W} = 369^{+86}_{-79}(\text{stat.}) \pm 44(\text{syst.})\text{ fb} = 369^{+100}_{-91}\text{ fb},$$
$$\sigma_{t\bar{t}Z} = 176^{+52}_{-48}(\text{stat.}) \pm 24(\text{syst.})\text{ fb} = 176^{+58}_{-52}\text{ fb}$$

in agreement with NLO QCD theoretical calculations obtained with MADGRAPH5_ANC@NLO.

The measurement of the $t\bar{t}Z$ and $t\bar{t}W$ production was also performed at a centre-of-mass energy of 13 TeV using 3.2 fb^{-1} of data collected by the ATLAS experiment in 2015. This analysis was done in three channels: two same-sign muons, trilepton, and tetralepton. The main reason for choosing the muons for the same-sign channel was that muons have much lower charge misidentification probability compared to electrons. The production cross-sections were extracted using simultaneous fit to the number of events in the signal and background regions. The $t\bar{t}Z$ cross-section was obtained using the trilepton and tetralepton channel, and the $t\bar{t}W$ cross-section was obtained in the trilepton (excluding the Z region) and same-sign dimuon channels. In both cases, the SM cross-section and its predicted uncertainty at NLO in QCD for the other channel ($t\bar{t}W$ and $t\bar{t}Z$, respectively) was assumed. The normalisation corrections for the WZ and ZZ backgrounds

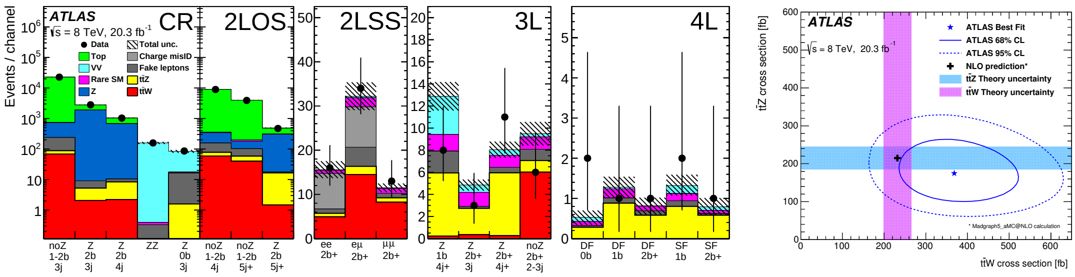

Figure 1: Left (four plots): expected yields after the fit compared to data in the control and signal regions in the $t\bar{t}+W/Z$ (8 TeV) analysis. Right: the result of the simultaneous fit to the $t\bar{t}W$ and $t\bar{t}Z$ cross-sections [2].

with respect to the SM expectations were obtained from the fits and found to be compatible with unity. The measured cross-sections were found to be

$$\sigma_{t\bar{t}W} = 1.38 \pm 0.70(\text{stat.}) \pm 0.33(\text{syst.})\ \text{pb},$$
$$\sigma_{t\bar{t}Z} = 0.92 \pm 0.30(\text{stat.}) \pm 0.11(\text{syst.})\ \text{pb}.$$

3. $t\bar{t}+$jets production

The top-anti-top quark pair production in association with additional jets is sensitive to higher order perturbative QCD effects. The uncertainty in $t\bar{t}+$jets production is a significant source of systematic uncertainties in QCD precision measurements, e.g. top quark mass. This process is also a dominant background in various new physics phenomena searches.

The ATLAS collaboration performed the first direct measurement of jet multiplicity in the $t\bar{t}$ dilepton channel [4]. Previous ATLAS $t\bar{t}+$jets production measurements [5, 6] have been done in the $t\bar{t} \to$ lepton+jets channel, where it is difficult to discriminate between additional jets and jets due to quarks from W hadronic decays. As a result, previous results were reported in terms of overall jet multiplicity. The present analysis selected events with two opposite sign leptons (electrons or muons) and at least two b-tagged jets. The events were categorized in terms of the number of additional jets (excluding the two tagged jets) above certain transverse momentum (p_{T}) threshold (25, 40, 60, and 80 GeV). The results were unfolded to the particle jet level using an iterative Bayesian unfolding [7]. The resulting jet multiplicities were compared to POWHEG+PYTHIA 6, POWHEG+PYTHIA 8, POWHEG+HERWIG++, and AMC@NLO+HERWIG++ Monte Carlo simulations. As an example, Fig. 2 shows the comparison between the measured and predicted number of additional jets in the $t\bar{t} \to ee$ channel for low and high jet p_{T} thresholds. All distributions were found to be consistent with data in all of the measured multiplicities. In fact, for low jet p_{T} there is little difference between the modern generators. However, the POWHEG+PYTHIA 6 predictions are systematically below the data at high multiplicity.

4. $t\bar{t}+$HF production

Measurement of the $t\bar{t}$ production in association with one or more jets containing b- or c-hadrons (referred to as additional heavy flavor (HF) production) is important for a better understanding of QCD. The currently available fixed-order NLO calculations in perturbative QCD

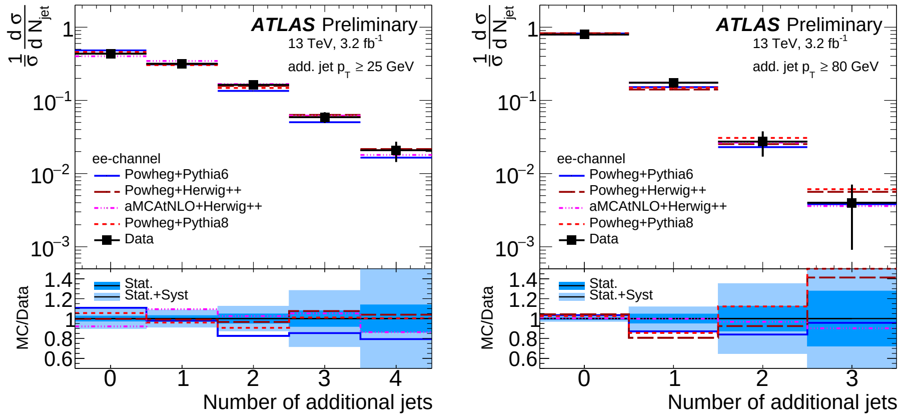

Figure 2: Unfolded jet multiplicity distribution for additional jets with transverse momentum above 25 GeV (left) and 80 GeV (right) in the $t\bar{t} \to ee$ channel compared to various Monte Carlo models [4].

matched to a parton shower have significant uncertainties, so the experimental guidance is desirable. These measurements are even more important as the $t\bar{t}+$HF production constitutes the main irreducible background for the $t\bar{t}H$ production measurements as well as new physics searches including the heavy charged Higgs boson $H^{\pm}$ production in the $t(b)H^{\pm} \to t(b)tb$ channel.

The ATLAS collaboration performed measurement of fiducial cross-section for $t\bar{t}$ production with one or more additional b-jets using 20.3 fb^{-1} of integrated luminosity at the centre-of-mass energy of 8 TeV [8]. Two different methods were used to extract the cross-section. In the cut-based approach, the number of the $t\bar{t}b\bar{b}$ events was obtained by subtracting contributions from various backgrounds according to their theoretical production cross-sections. In this analysis the events with at least four identified b-jets were used. A different approach was based on a template fit to the distribution of multivariate discriminant MV1c used for b-jet identification [9]. While the leading and sub-leading MV1c jets are expected to mostly originate from b-quarks from top quark decays, the third highest MV1c value is sensitive to additional HF production. There were three analyses using this method, performed in the $t\bar{t} \to e\mu$, $t\bar{t} \to$ lepton + jets (where lepton is an electron or muon), and $t\bar{t}b\bar{b} \to$ dileptons channels, respectively. The MV1c templates used in the analyses were defined using Monte Carlo particle jets. For the $t\bar{t} \to e\mu$ analysis, there were three templates: ttb (at least three b-jets), ttc (less than three b-jets and at least one c-jets), and ttl (the rest). For the $t\bar{t} \to$ lepton + jets analysis, the corresponding definitions were similar except that at least five jets were required for the ttb and ttc templates. The $t\bar{t}b\bar{b}$ analysis used four different templates: $ttbb$ (at least four b-jets), $ttbX$ (exactly three b-jets), $ttcX$ (exactly two b-jets and at least one c-jet), and $ttlX$ (the rest). The $t\bar{t} \to e\mu$ analysis is the single one potentially sensitive to the $t\bar{t}+c$ production (the c-flavor in the $t\bar{t} \to$ lepton + jets channel is dominated by hadronic W decays).

The results of the measurements are summarized in Table 1. In all cases the obtained fiducial cross-section is $\sim 30\%$ larger than the one predicted by the POWHEG+PYTHIA 6 simulation. Except for the lepton+jets channel where statistical uncertainty is small, the measurements are equally affected by both lack of statistics and systematic effects. The dominant sources of systematic uncertainties are jet reconstruction, b-tagging efficiency, and effects of Monte Carlo modeling.

Analysis	Measured cross-section [fb]	Predicted cross-section [fb]
σ_{ttb} lepton-plus-jets	950 ± 70 (stat.)$^{+240}_{-190}$ (syst.)	720
σ_{ttb} $e\mu$	50 ± 10 (stat.)$^{+15}_{-10}$ (syst.)	38
σ_{ttb} cut-based	19.3 ± 3.5 (stat.)±5.7 (syst.)	12.3
σ_{ttb} fit-based	13.5 ± 3.3 (stat.)±3.6 (syst.)	12.3

Table 1: Measured $t\bar{t}+$HF cross-sections in the fiducial phase-space regions together with theoretical predictions [8].

5. $t\bar{t}+\gamma$ production

The ATLAS collaboration performed a search for top-anti-top quark pair production in association with a photon using the full 2011 data sample, corresponding to an integrated luminosity of 4.59 fb^{-1} obtained at a centre-of-mass energy of $\sqrt{s}=7$ TeV [10]. This analysis directly probes the $t\bar{t}\gamma$ coupling, which can constrain various models of new physics, including those with composite top-quarks or with excited top-quark production followed by the radiative decay $t^{*}\to t\gamma$.

The analysis was performed in the lepton+jets channel characterized by the presence of exactly one lepton (an electron or muon), at least four jets, of which at least one must be b-tagged, and large missing transverse momentum due to neutrinos escaping detection. The additional photon was required to have transverse energy of at least 20 GeV. The main challenge in the analysis is discrimination between signal photons and neutral hadron decays to final states with photons and hadrons misidentified as photons. This was done using the track-isolation distribution of the photon candidates, defined as the scalar sum of the transverse momenta of tracks around the photon direction. The results of the combined likelihood fit to this distribution to a sum of the signal and background templates are shown in Fig. 3.

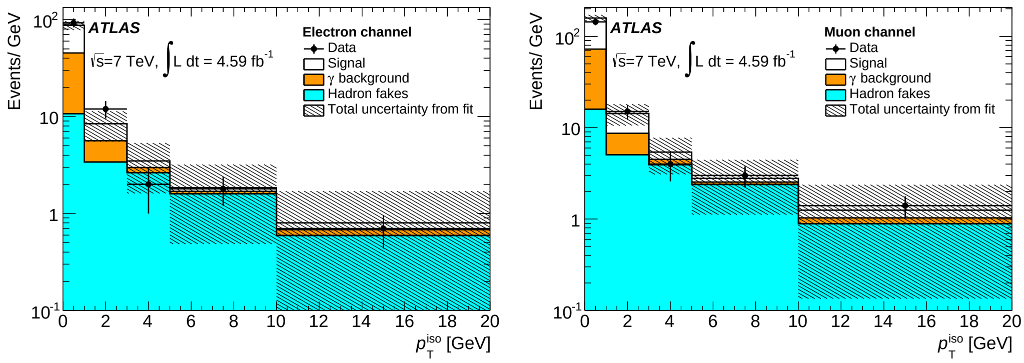

Figure 3: Results of the combined likelihood fit using the track-isolation distributions for the $t\bar{t}\gamma\to e+$jets (left) and $t\bar{t}\gamma\to\mu+$jets (right) channel [10].

The $t\bar{t}\gamma$ signal was observed with a significance of 5.3 σ. The $t\bar{t}\gamma$ production cross-section per lepton flavor, determined in a fiducial kinematic region within the ATLAS acceptance, is measured to be $\sigma^{\rm fid}_{t\bar{t}\gamma}\times{\rm BR}=63\pm8({\rm stat.})^{+17}_{-13}({\rm syst.})\pm1({\rm lumi.})$ fb, to be compared with the theoretical predictions (48 ± 10) fb and (47 ± 10) fb obtained from the WHIZARD and MADGRAPH Monte Carlo generators respectively and then modified by the corresponding NLO/LO factors.

6. Conclusions

Huge available statistics of the top-anti-top quark pair production at the LHC allows detailed studies of the $t\bar{t}+$X production. For the first time, the LHC experiments are capable of studying the top couplings and differential production cross-sections. Recently, the ATLAS collaboration performed several analyses in this area. The measurements presented here include the production of top-anti-top quark pairs in association with W/Z bosons, additional jets, heavy flavor, and photons. In all cases the results are in agreement with the SM predictions. Obtained results help to test the theory predictions and provide solid basis for new physics searches.

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