$\mathrm{t\bar{t}} + \mathrm{X}$ PRODUCTION AT ATLAS AND CMS

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Recent measurements of top-quark pair production in association with W-bosons, Z-bosons, photons and b-tagged jets are reported. The measurements are based on ATLAS and CMS analyses of proton−proton collisions at the Large Hadron Collider of 13 TeV center-of-mass energy. Inclusive and differential cross-sections of these rare processes are compared to Standard Model theory predictions. They provide stringent tests of QCD predictions and serve as a probe for new physics beyond the Standard Model.

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1 Introduction

The expected cross-sections of the production of a top-quark pair in association with massive vector bosons, photons or b-tagged jets are about three orders of magnitude smaller than top-quark pair production and constitute rare Standard Model (SM) processes. Inclusive and differential cross-sections are measured by the ATLAS [1] and CMS [2] collaborations at the Large Hadron Collider (LHC) using data taken at 13 TeV center-of-mass energy. The measurements of these rare processes provide tests of QCD predictions and are important backgrounds in the measurement of the associated production of a top-quark pair with the Higgs boson for example, or in searches of physics beyond the SM. The measurements serve as a probe for the presence of new physics like vector-like quarks, strongly coupled Higgs bosons or anomalous couplings of the top quark.

2 $\mathrm{t\bar{t}W}$ and $\mathrm{t\bar{t}Z}$ production at $\sqrt{\mathrm{s}}$ =13 TeV

Simultaneous measurements of the inclusive $t\bar{t}W$ and $t\bar{t}Z$ production cross-sections are performed by ATLAS [3] using 36.1 fb^{-1} of 13 TeV proton−proton collision data taken in 2015 and 2016 and by CMS [4] using 35.9 fb^{-1} of data taken in 2016. CMS recently published a new $t\bar{t}Z$ analysis using 77.5 fb^{-1}, which additionally includes data taken in 2017 [5]. Events where either one or both top quarks decay leptonically are the most sensitive channels and are classified according to the number of leptons, their flavour and charge, and the numbers of jets and b-tagged jets.

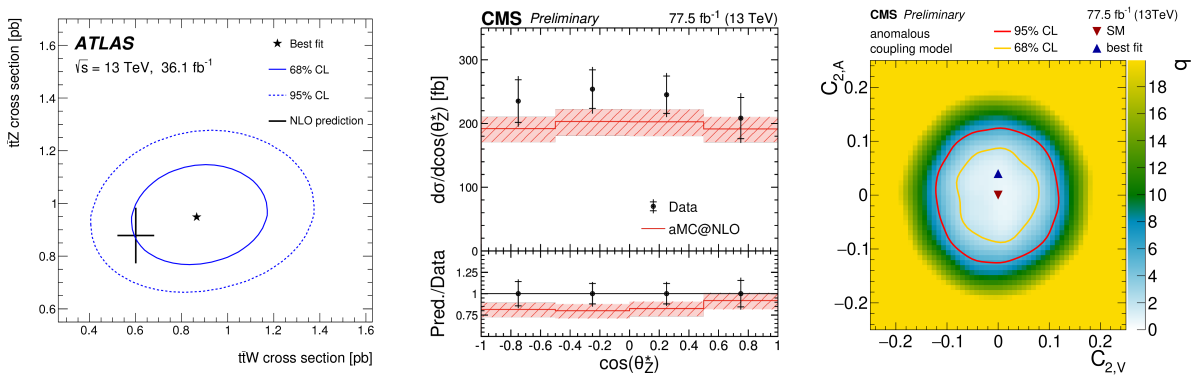

Figure 1 – The left plot shows the ATLAS $t\bar{t}Z$ and $t\bar{t}W$ cross-section measurements [3]. The middle plot shows the CMS absolute $t\bar{t}Z$ cross-section measurement with respect to the $\cos(\theta_Z^*)$ [5]. The right plot shows the CMS log-likelihood scan in the two-dimensional plane of the weak magnetic and electric dipole interaction couplings [5].

In the $t\bar{t}W$ analysis, ATLAS uses the di-lepton same-sign and tri-lepton channels where leptons are required to be isolated in order to reduce background from non-prompt leptons from hadron decays or jets misidentified as leptons. A multivariate discriminant is built to distinguish prompt leptons from leptons arising from heavy-hadron decays inside jets, and another one is created to suppress background from electrons with misidentified charge, which represent an important background in the same-sign di-lepton channel. Control regions are defined to estimate the lepton efficiencies using an orthogonal selection. A total of twelve and four signal regions are used in the di-lepton and tri-lepton channels, respectively, separated by flavour, the sum of charges of the leptons, and the number of b-tagged jets. CMS uses only the di-lepton same-sign channel. A final discriminant is used to categorise events in a total of 20 signal regions depending on the leptons charge, discriminant value and numbers of jets and b-tagged jets.

In the $t\bar{t}Z$ analysis, ATLAS uses three different signal regions in the opposite-sign di-lepton channel, four in the tri-lepton, and another four in the four-lepton channel, categorised by the numbers of jets and b-tagged jets, and separated by lepton flavour. Two control regions are used to determine the normalisation of the WZ+jets and ZZ background. CMS uses four-lepton and tri-lepton opposite-sign same flavour channels, summing up a total of eleven signal regions.

Both ATLAS and CMS measure the $t\bar{t}Z$ and $t\bar{t}W$ production cross-sections simultaneously using a combined fit based on the expected and observed number of events in all control and signal regions. The left plot in Figure 1 shows the ATLAS $t\bar{t}W$ and $t\bar{t}Z$ cross-section measurements, with their precision dominated by systematic uncertainties. They are in good agreement with next-to-leading order (NLO) calculations in QCD. A similar precision is obtained by CMS, with results also compatible with theory.

In addition, CMS measures the $t\bar{t}Z$ absolute and differential cross-sections using 77.5 fb^{-1}. Using an improved lepton selection with respect to the previous analysis, the inclusive cross-section is measured with a 10% precision, representing a 40% uncertainty reduction with respect to the previous result. Absolute differential distributions are also measured with respect to both the transverse momentum of the Z system and the cosine of the angle between the Z and the negatively charged lepton from the Z decay in the Z-rest frame, the latter shown in the middle plot of Figure 1. These are interpreted in models with modified tZ interactions and used to set constraints to anomalous couplings like weak magnetic and electric dipole moments, as shown in the right plot of Figure 1.

3 $\mathrm{t\bar{t}}\gamma$ production at ATLAS at $\sqrt{\mathrm{s}}$ =13 TeV

The measurement of the $\mathrm{t\bar{t}}\gamma$ production cross-section can be used to probe the top to photon electroweak coupling and provide insight on the $t\bar{t}$ spin correlation and charge asymmetry. The

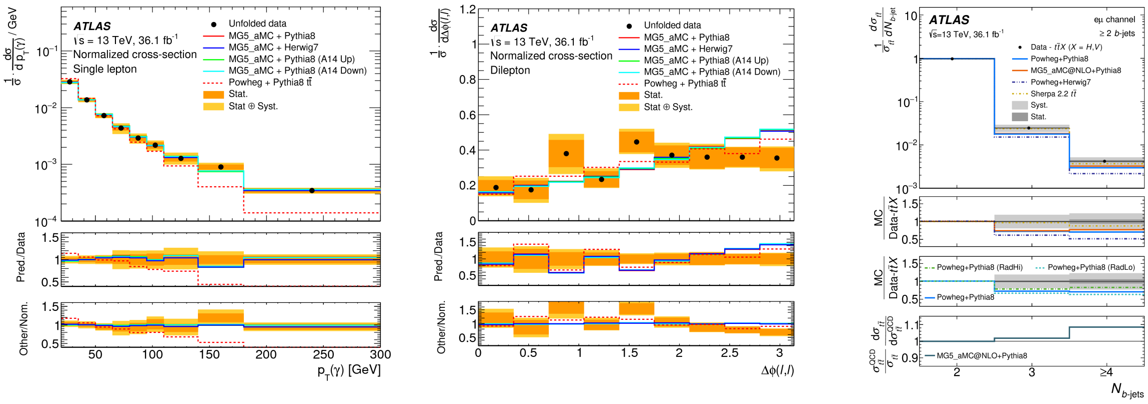

Figure 2 – The left and middle plots show the normalised differential distributions of the transverse momentum of the photon in the single-lepton channel and the azimuthal opening angle between the two leptons measured by ATLAS, respectively [8]. The right plot shows the normalised differential distribution of the b-jet multiplicity measured by ATLAS in the $t\bar{t} + b\bar{b}$ analysis [10].

inclusive and differential fiducial $t\bar{t}\gamma$ production cross-sections were measured by ATLAS [6] and CMS [7] using data taken at 8 TeV center-of-mass energy. A more recent measurement was done by ATLAS using 36.1 fb^{-1} of data taken at 13 TeV [8]. Both the $t\bar{t}$ lepton+jets and di-lepton channels are used. At least one b-tagged jet is required. A neural network trained to distinguish signal from background separately for the single and di-lepton channels is used. The main backgrounds are events with a misidentified lepton, photon or b-jet. A dedicated neural network is trained to discriminate between prompt photons and hadronic-fake photons. This tagger is one of the inputs to the discriminator. Various control regions are used to measure the fake-lepton efficiency and electron-to-photon fake rate. Finally, a profile likelihood fit to an event-level discriminator is performed.

The absolute fiducial cross-section results obtained for the single and di-lepton channels are more precise than the NLO predictions and in good agreement with them. Only the di-lepton measurement is limited by statistics. ATLAS also measures differential cross-section distributions. The kinematic properties of the photon are sensitive to the top to photon coupling, while the di-lepton azimuthal opening angle is sensitive to $t\bar{t}$ spin correlation. For the single-lepton channel, differential distributions of the transverse momentum of the photon, the absolute value of the η coordinate of the photon and the radial distance between the photon and the lepton, are provided. In the di-lepton channel, both the distance in η and azimuthal opening angle between the two leptons are measured in addition to the previous ones. All differential distributions are unfolded to particle level and normalised to unity such that shape discrepancies can be observed. Distributions as predicted by different Monte Carlo (MC) tunes and various parton shower models are compared. All simulations predict very similar shapes and in general describe the data well. The left plot of Figure 2 shows the normalised differential distribution of the transverse momentum of the photon. Data show a harder transverse momentum spectrum than the Pythia 8 prediction. A small deviation from the prediction is observed in the azimuthal opening angle between the two leptons, where the leptons in the prediction are more back-to-back than observed in data, as shown in the middle plot of the same figure.

4 $\mathbf{t\bar{t} + b\bar{b}}$ production at ATLAS and CMS at $\sqrt{s}$ =13 TeV

The measurement of the $t\bar{t}$ production with additional b-tagged jets provide important tests of QCD predictions. State-of-the-art QCD calculations give predictions for the $t\bar{t}$ production cross-section with up to two additional massless partons at NLO in perturbation theory matched to a parton shower, and the QCD production of $t\bar{t}b\bar{b}$ with massive b-quarks is calculated at NLO matched to a parton shower.

CMS published a first analysis using 2.3 fb^{-1} of data at 13 TeV[9]. Only the di-lepton electron-muon channel is included. A two-dimensional b-tagging discriminant for the third versus fourth jets is used in a likelihood function to measure the total cross-section and the ratio of $t\bar{t}+b\bar{b}$ and $t\bar{t}+2$ additional jets irrespective of its type. The results are dominated by systematic uncertainties.

ATLAS recently published results[10] using a total of 36.1 fb^{-1}. The lepton+jets channel is used in addition to the di-lepton electron-muon channel. Templates of b-tagging discriminants categorising the events as $t\bar{t}+b$, $t\bar{t}+c$, $t\bar{t}$+light jet or non-$t\bar{t}$ are built. For the di-lepton channel, a one-dimensional template is built with three bins corresponding to different b-tagging efficiencies for the jet with the third-highest b-tagging discriminant value. For the lepton+jets channel, two-dimensional templates with five bins are built using the discriminant values of the two jets with the third- and fourth-highest b-tagging discriminant values. The fiducial cross-section is extracted using a binned maximum likelihood fit together with data-driven corrections to the predictions of $t\bar{t}+c$ and $t\bar{t}$+light jets. The number of events with more than two b-tagged jets is found to be slightly underestimated. The fiducial cross-sections obtained for the various channels are found a bit higher than the predictions but still compatible.

ATLAS also measures normalised fiducial differential cross-sections as a function of several kinematic variables and compares them with various predictions. The precision of the observables ranges between 10 to 30% at the edge of the phase space. The right plot in Figure 2 shows the differential cross-section as a function of the number of b-tagged jets for data and various MC predictions, including Powheg-Box $t\bar{t}$ at NLO in the matrix element calculation interfaced with Pythia parton shower to predict additional b-jets and Sherpa, modelling zero and one additional-parton process at NLO accuracy and up to four additional partons at leading-order accuracy. Sherpa shows the best agreement with data in most observables.

5 Summary

The measurements of $t\bar{t}$ production in association with vector bosons, photons or additional b-tagged jets provide tests of the SM QCD predictions. The cross-section of the $t\bar{t}$ production in association with a Z boson is measured with a precision of 10% by CMS. Both ATLAS and CMS measure the $t\bar{t}$ production with a W boson with a precision of $\sim$12-14% and are in agreement with theoretical predictions. Various normalised differential cross-sections of $t\bar{t}+\gamma$ production are measured by ATLAS, showing good agreement with NLO predictions. A small deviation from the prediction of the di-lepton azimuthal angle separation distribution is observed in data. The $t\bar{t}+b\bar{b}$ fiducial cross-section is measured by ATLAS and normalised fiducial differential distributions of different kinematic variables are compared to various MC predictions.

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