PROCEEDINGS OF SCIENCE

Associated productions with top ($t + X$, $t\bar{t} + X$ with $X = W, Z, \gamma$, heavy-flavours, $t\bar{t}$) at the LHC

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Latest measurements of top quark pair production in association with electroweak bosons (W, Z or γ) and heavy flavoured jets ($c\bar{c}$, $b\bar{b}$) using data collected by the ATLAS and CMS detector in LHC pp collisions at 13 TeV are presented. Inclusive and differential measurements are included. In addition, a measurement of the very rare four-top-quark production using final states with one or two leptons plus jets and combining with previous results in the multilepton channel is reported.

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1. Introduction

The top quark is the heaviest known elementary particle. Its mass of around 173 GeV [1, 2] makes the top quark unique amongst other quarks as it decays before it can form bound states. In the Standard Model (SM), the top quark decays almost exclusively to a W boson and a b-quark. Top quarks are produced abundantly at the Large Hadron Collider which allows studying top+X processes, i.e. associated production of the top quark with other particles. Top+X processes are one of the rarest SM processes measured at the LHC, with the predicted cross-sections ranging from about 1 pb for the associated production of top-antitop ($t\bar{t}$) with a W boson, down to about 10 fb for the four-top process, at the centre-of-mass energy of 13 TeV. Both the ATLAS [3] and CMS [4] collaborations conduct extensive programs to measure and study top+X processes.

2. $t\bar{t}Z$ and tZq

Associated production of the top quark with a Z boson is an important process that is sensitive to the top-Z coupling, thus it can probe the weak isospin of the top quark. The ATLAS collaboration measures [5] the inclusive cross-section of the $t\bar{t}Z$ process in the three-lepton and tetra-lepton channel in proton–proton collisions at $\sqrt{s}$ = 13 TeV. Events with at least three jets, with at least one b-tagged jet, three or four leptons (electrons or muons) with a Z-mass window compatibility required for the same-flavour leptons, are selected. A profile-likelihood fit is performed in multiple signal regions and background regions to control the dominant ZZ and WZ backgrounds. The measured inclusive cross-section is $\sigma_{t\bar{t}Z} = 0.99 \pm 0.05(\text{stat.}) \pm 0.08(\text{syst.})$ pb, which is in good agreement with the SM prediction of $0.84^{+0.09}_{-0.10}$ pb. Additionally, differential cross-section measurements, unfolded to parton and stable particle level using the Iterative Bayesian Unfolding technique, are provided for various kinematic distributions, e.g. the transverse momentum of the Z boson.

The CMS measurement [6] targets the combined $t\bar{t}Z, tZq$ and tWZ processes. Three and four-lepton final states are probed with the focus on the EFT interpretations. A multi-class neural network (NN) is used to separate the individual signal processes and backgrounds. A dedicated NN is used to construct discriminating variables in the signal regions to enhance the sensitivity to the EFT contributions. A profile-likelihood fit is used to extract the limits on the relevant Wilson coefficients assuming only one coefficient contribution at a time, as well as a fit with all five considered coefficients active simultaneously.

Both ATLAS and CMS collaborations measure [7, 8] the inclusive cross-section of the tZq process targeting the three-lepton final state. Events with at least two jets and three leptons are selected. Both measurements exploit a set of control regions to constrain important backgrounds such as $t\bar{t}Z$, WZ, $Z\gamma$ and $t\bar{t}$. ATLAS uses a NN to separate the signal from the background, while CMS uses Boosted Decision Trees (BDT). A profile-likelihood fit yields $\sigma_{tZq} = 87.9^{+7.5}_{-7.3}(\text{stat.})^{+7.3}_{-6.0}(\text{syst.})$ fb for the ATLAS measurement, and $\sigma_{tZq} = 97 \pm 13(\text{stat.}) \pm 7(\text{syst.})$ fb for the CMS measurement. Both measurements are in a good agreement with each other, as well as in agreement with the SM prediction of $\sigma_{tZq} = 102^{+5}_{-2}$ fb. The CMS collaboration also provides a differential cross-section measurement for events with four or fewer jets, using a multi-class NN to isolate the tZq signal. Likelihood-based unfolding is used to measure the differential-cross sections at the particle and parton levels.

3. $t\bar{t}\gamma$

Associated production of the top quark and a photon is sensitive to the top-photon coupling. ATLAS and CMS measure [9, 10] the cross-section of the $t\bar{t}\gamma$ process inclusively as well as differentially. The CMS measurement targets the single-lepton final state, while ATLAS probes the dilepton channel in the $e\mu$ final state. Due to the different final states, the selection criteria for the events as well as the background composition differ between the measurements. CMS selects events with at least three jets and uses control regions to constrain the non-prompt γ background. ATLAS targets events with at least two jets and uses only a signal region where $t\bar{t}\gamma$ and $tW\gamma$ are considered as the signal. The measured fiducial cross-section from the CMS collaboration is $\sigma^{\text{lepton+jet}}_{t\bar{t}\gamma} = 800 \pm 7(\text{stat.}) \pm 46(\text{syst.})$ fb, and $\sigma^{e\mu}_{t\bar{t}\gamma} = 39 \pm 0.8(\text{stat.})^{+2.6}_{-2.2}(\text{syst.})$ for the ATLAS measurement. The differences in the measured values originate from the different definitions of the fiducial phase space and the branching ratios. The dominant systematic uncertainties arise from the modelling of the signal process and the luminosity uncertainty in the $e\mu$ result, while in the single-lepton measurements the dominant uncertainties originate from mis-reconstructed or non-prompt leptons and photons as well as the signal modelling.

The measured distributions are unfolded to a stable particle level in the CMS measurement and to a parton level in the ATLAS measurement. A dedicated next-to-leading order (NLO) calculation in QCD is compared with the unfolded data and the Monte Carlo (MC) predictions in the ATLAS measurement. Several observables, e.g. the angular distance between the selected photon and the closest parton-level jet, show that the NLO calculation provides a prediction closer to the data compared to the MC generators that have only LO precision in QCD. The CMS collaboration also provides limits on the Wilson coefficients sensitive to the top-photon coupling from a detector-level fit.

Figure 1 shows the summary of the ATLAS and CMS cross-section measurements in the top+X category at the centre-of-mass energy of 13 TeV.

4. $t\bar{t}t\bar{t}$

The production of four top quarks ($t\bar{t}t\bar{t}$) is the heaviest SM final state probed at the LHC. It is also one of the rarest processes with the predicted inclusive cross-section of about 12 fb. ATLAS has recently measured [12] the cross-section of the process in the decay with one charged lepton or two leptons with opposite electric charge (1LOS). The leading order signature of this process is at least eight jets, out of which four are b-jets. The dominant background is the $t\bar{t}$+jets process. Due to many jets expected in the final state, the currently available MC simulation of the $t\bar{t}$+jets processes provide poor prediction in the four tops phase space. Thus, sequential reweighting with five observables is used to correct the predictions of the MC to the observed data. A dedicated BDT is used to separate the signal from the background. A profile-likelihood fit is performed using multiple regions separated by the number of jets, number of b-tagged jets, as well as number of leptons. The fitted cross-section is $\sigma_{t\bar{t}t\bar{t}} = 26^{+17}_{-15}$ fb. The measurement is also combined with the previously measured cross-section [13] from the multiple lepton channel. The combined significance of the measurement is 4.7 standard deviations, and the measured cross-section is 2.2 standard deviations from the SM prediction.

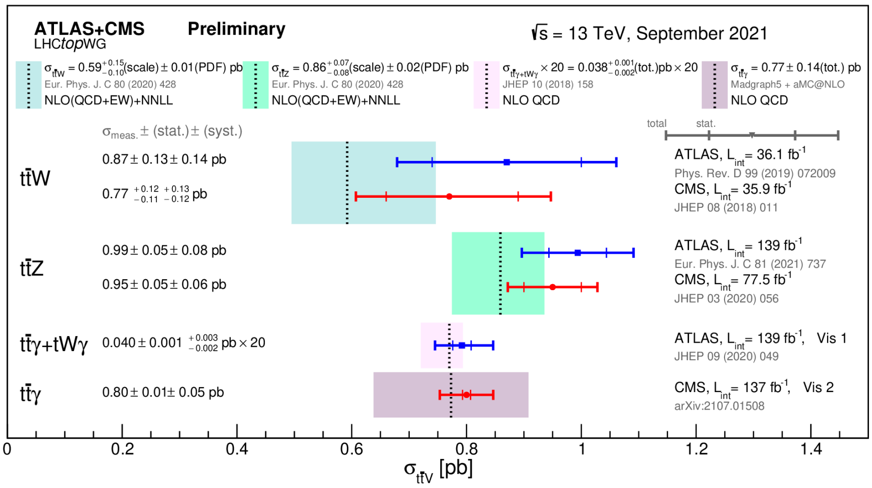

Figure 1: Summary of ATLAS and CMS measurements [11] of $t\bar{t} + X$ ($X = W$, Z or γ) cross-sections at $\sqrt{s} = 13$ TeV. The $t\bar{t} + W$ and $t\bar{t} + Z$ cross-section measurements are compared to the NLO QCD and EW theoretical calculation complemented with NNLL resummation, while the $t\bar{t} + \gamma$ cross-section measurement is compared to the NLO QCD theoretical calculation.

5. $t\bar{t} + c\bar{c}$

The CMS collaboration measures [14] associated production of $t\bar{t}$ with heavy flavour jets, focusing on $c\bar{c}$. The analysis targets the dilepton decay of the $t\bar{t}$ pair. The main challenge of the measurement is to separate the b-jets from c-jets and light-flavour jets. Firstly, a NN is used to identify jets that come from the decay of the $t\bar{t}$ system. The NN is trained to identify the correct permutations of jets matched to the decay products of $t\bar{t}$. Then, a multi-class event-level NN is used to separate the events into five different cases of events based on the flavour of the jets using also the information from the matching-NN. The five-class output of the event-level NN is projected onto two discriminators. Finally, a template fit is performed to extract the absolute cross-section of the various flavours of the additional jets. The fit is repeated to also extract the relative fractions of the cross-sections. The dominant systematic uncertainties of the measurement arise from the fragmentation and hadronisation modelling as well as flavour-tagging. The fitted $t\bar{t}c\bar{c}$ cross-section in the fiducial phase space is $\sigma_{t\bar{t}c\bar{c}} = 0.207 \pm 0.025(\text{stat.}) \pm 0.027(\text{syst.})$ pb and $\sigma_{t\bar{t}c\bar{c}} = 10.1 \pm 1.2(\text{stat.}) \pm 1.3(\text{syst.})$ pb in the full phase space.

6. Summary

Several new results for top+X processes measured by the ATLAS and CMS collaborations are presented. Improved precision for previously measured processes, such as $t\bar{t}Z$ is achieved. New channels and processes are measured e.g. $t\bar{t} + c\bar{c}$. The measurements provide more stringent limits on several Wilson coefficients. More results from the LHC Run 2 as well as from Run 3 are expected from the top+X processes exploiting more sophisticated tools and also focusing on combinations.

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