PROCEEDINGS OF SCIENCE

Associated Top Production at the LHC

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Several new and exciting results on the associated top quark production at the LHC are presented. Data collected with the CMS and ATLAS experiments in proton-proton collisions at a centre-of-mass energies of 13 TeV is used and the results are compared to the standard model predictions.

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1. Introduction

At hadron colliders, top quarks are produced predominantly in pairs via the flavor-conserving strong interaction. Alternatively, top quarks can be also produced singly through the electroweak interaction. The large amount of LHC data recorded by the ATLAS [1] and CMS [2] experiments up to date allows probing very rare Standard Model (SM) processes as the associated top quark production processes presented in this document. These processes become fully accessible with Run 2 LHC data at 13 TeV despite their small cross sections and are important background contributions for measurements like $t\bar{t}H$. They are among the most massive signatures produced at the LHC. Finally, these processes receive a significant enhancement in beyond standard models. The following results are presented: top quark pair production in association with a Z boson ($t\bar{t}Z$) [3, 4], with a photon ($t\bar{t}\gamma$) [5, 6] and single top quark production in association with a Z boson (tZq) [7, 8] by CMS and ATLAS, respectively.

2. Top quark pair production in association with a Z boson

The $t\bar{t}Z$ production is the most sensitive process for the coupling of the top quark to the Z boson. Measurements of both the inclusive and differential production cross sections of $t\bar{t}Z$ are presented. The measurements are performed by targeting final states with three or four isolated leptons (electrons or muons). ATLAS uses the full Run 2 dataset with an integrated luminosity of 139 fb^{-1} recorded from 2015 to 2018. The data sample used by CMS corresponds to an integrated luminosity of 77.5 fb^{-1} collected during 2016 and 2017.

The inclusive cross section measured by ATLAS is 0.99 ± 0.05 (stat) ± 0.08 (syst) pb, in agreement with the most precise theoretical predictions. The differential measurements are presented as a function of a number of kinematic variables which probe the kinematics of the $t\bar{t}Z$ system as shown in Fig. 1 (left). Both absolute and normalised differential cross-section measurements are performed at particle and parton levels for specific fiducial volumes and are compared with theoretical predictions at different levels of precision. Overall, good agreement is observed between the unfolded data and the predictions. The production cross section measured by CMS is 0.95 ± 0.05 (stat) ± 0.06 (syst) pb, also in good agreement with SM predictions. Differential cross sections are measured as functions of the angular distribution of the negatively charged lepton from the Z boson decay and the transverse momentum of the Z boson as shown in Fig. 1 (right).

3. Top quark pair production in association with a photon

The production cross section of a top quark pair in association with a photon is measured by ATLAS and CMS based on a data set recorded during the full LHC Run 2. The ATLAS measurements are performed in a fiducial volume defined at parton level. Events with exactly one photon, one electron and one muon of opposite sign, and at least two jets, of which at least one is b-tagged, are selected. The fiducial cross-section is measured to be $39.6^{+2.7}_{-2.3}$ fb. Differential cross-sections as functions of several observables are compared with state-of-the-art Monte Carlo simulations and next-to-leading-order theoretical calculations.

The CMS measurement is performed in events with a well isolated, highly energetic lepton (electron or muon), with at least three jets from the hadronization of quarks and one isolated

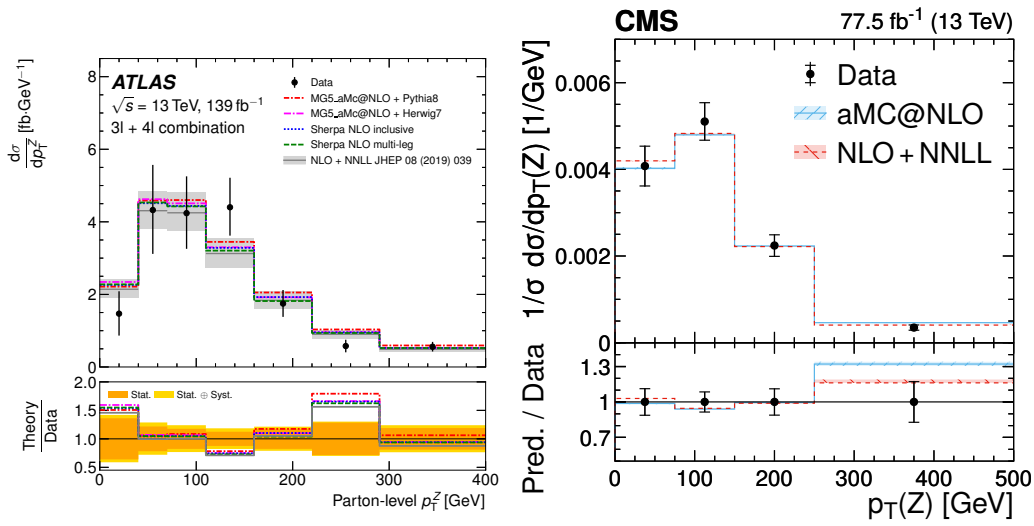

Figure 1: Left: Absolute differential $t\bar{t}Z$ cross sections measured by ATLAS at parton level as a function of the transverse momentum of the reconstructed Z boson [4]. Right: CMS measured differential $t\bar{t}Z$ production cross sections in the full phase space as a function of the transverse momentum of the Z boson. Shown are the normalized cross sections [3]. The data are represented by the points. The inner (outer) vertical lines indicate the statistical (total) uncertainties. The solid histogram shows the prediction from the MadGraph 5_aMC@NLO MC simulation, and the dashed histogram shows the theory prediction at NLO+NNLL accuracy. The hatched bands indicate the theoretical uncertainties in the predictions, as defined in the text. The lower panel displays the ratios of the predictions to the measurement.

photon. The analysis makes use of simultaneous likelihood fits in several signal and control regions to distinguish the $t\bar{t}\gamma$ signal process from various backgrounds. The inclusive cross section for a photon with transverse momentum of $p_T \geq 20$ GeV is measured as 800 ± 46 (syst) ± 7 (stat) fb, in good agreement with the prediction from the SM. These preliminary results are superseded in Ref. [9], submitted to JHEP. The measurement is also carried out differentially in several kinematic observables and interpreted in the framework of the SM effective field theory. All measurements are in agreement with the predictions from the SM.

4. Summary of $t\bar{t}X$ measurements

The ATLAS and CMS measurements of $t\bar{t}X$ (X=W, Z or γ) cross sections at 13 TeV are summarized in Fig. 2. 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. The "Vis 1" and "Vis 2" labels in the figure highlight that the relevant phase space used for the ATLAS and CMS $t\bar{t}\gamma$ measurements are different. The theory prediction and experimental result of the ATLAS measurement $t\bar{t}\gamma$+tW γ process is multiplied by a factor 20 to allow for easy visualization on the same scale. The theory band represents uncertainties due to renormalisation and factorisation scales and parton density functions. Complementary theory predictions for the $t\bar{t}W$ and $t\bar{t}Z$ processes are also available in [11].

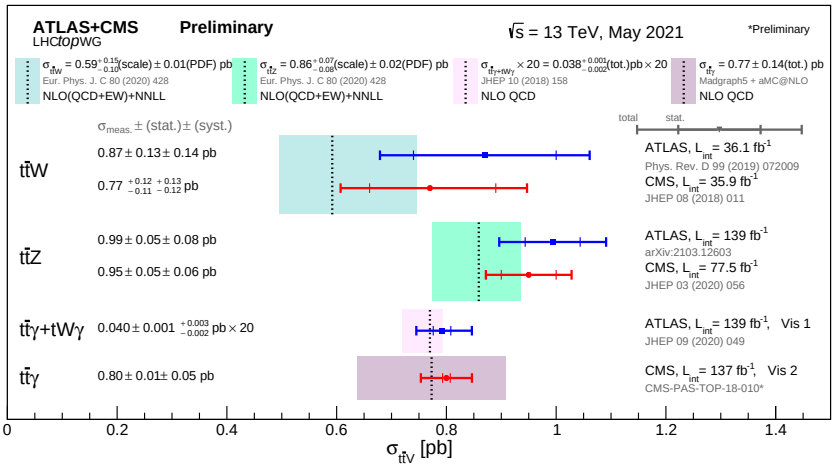

Figure 2: Summary of ATLAS and CMS measurements of $t\bar{t}X$ (X=W, Z or γ) cross sections at 13 TeV [10].

5. Single top quark production in association with a Z boson

Single top quark production in association with a Z boson, where the Z boson decays to a pair of charged leptons, is measured in the trilepton channel by ATLAS and CMS based on a data set recorded during the full LHC Run 2. Events containing three isolated charged leptons (electrons or muons) are selected. The main backgrounds are from $t\bar{t}Z$ and diboson production. ATLAS uses neural networks to improve the background rejection and extract the signal. The measured cross-section including non-resonant dilepton pairs with $m_{l^+l^-} > 30$ GeV is 97 ± 13 (stat) ± 7 (syst) fb, consistent with the SM prediction. CMS measures $87.9^{+7.5}_{-7.3}$ (stat) $^{+7.3}_{-6.0}$ (syst) fb also including non-resonant dilepton pairs.

For the first time, the inclusive tZq cross sections are also measured by CMS separately for top quark and antiquark production, obtaining $62.2^{+5.9}_{-5.7}$ (stat) $^{+4.4}_{-3.7}$ (syst) fb and $26.1^{+4.8}_{-4.6}$ (stat) $^{+3.0}_{-2.8}$ (syst) fb, respectively. The differential tZq cross sections are measured for the first time at parton and particle levels using a binned maximum likelihood-based unfolding. The results are mostly compatible with the SM predictions using both the four- and five-flavor schemes. From the differential distribution of the top quark polarization angle, the top quark spin asymmetry is measured to be $0.58^{+0.15}_{-0.16}$ (stat) ± 0.06 (syst), in agreement with the SM prediction.

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