PROCEEDINGS OF SCIENCE

Measurements of $t\bar{t}$ and single top quark production with bosons in ATLAS

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Recent measurements of top quark production in association with an additional boson are presented. The measurements are performed using the full Run 2 proton-proton collision data at a centre-of mass energy of 13 TeV collected with the ATLAS Experiment at the CERN Large Hadron Collider. The results comprise inclusive and differential measurements of top quark pair production with an additional gauge boson, the first observation of the single top quark production with a photon and the first measurements of top quark charge asymmetry in events with a pair of top quarks and a W boson or a photon.

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1. Introduction

Detailed studies of top quark production ($t\bar{t}$) in association with a boson are tests of the electroweak couplings of the top quark to bosons, allow scrutinising accurate theoretical calculations, and can be sensitive to differences between the predictions from various Monte Carlo (MC) simulations. Deviations in the top quark couplings to the bosons from the Standard Model (SM) expectation might hint to the existence of new physics effects that could be probed in the context of e.g. Effective Field Theory interpretations. The measurements presented here are performed using the full data set recorded with the ATLAS detector [1] at the LHC at a centre-of-mass energy of $\sqrt{s}$ = 13 TeV and corresponding to an integrated luminosity of 139 fb^{-1}.

2. $t\bar{t}$ in association with a Z boson

The ATLAS Collaboration measured the inclusive and differential cross sections of $t\bar{t}$ in association with a Z boson ($t\bar{t}Z$) with final states requiring 3 or 4 leptons (e, μ) [2]. Requirements on the total number of jets and b-tagged jets and on the kinematic properties of the leptons are imposed to define the signal region and the control regions to estimate the most relevant background contributions. The inclusive cross section is extracted performing a profile likelihood fit based on the total event yields in each region. It results 0.99 ± 0.05(stat) $\pm$ 0.09(syst) pb, in good agreement with the theoretical prediction [3]. The differential measurements at parton and particle level are presented as a function of kinematic variables of the Z boson and the $t\bar{t}$ system and angular differences between the Z boson and a top quark. An example is shown in Figure 1, left. The data are found to be in good agreement with the predictions.

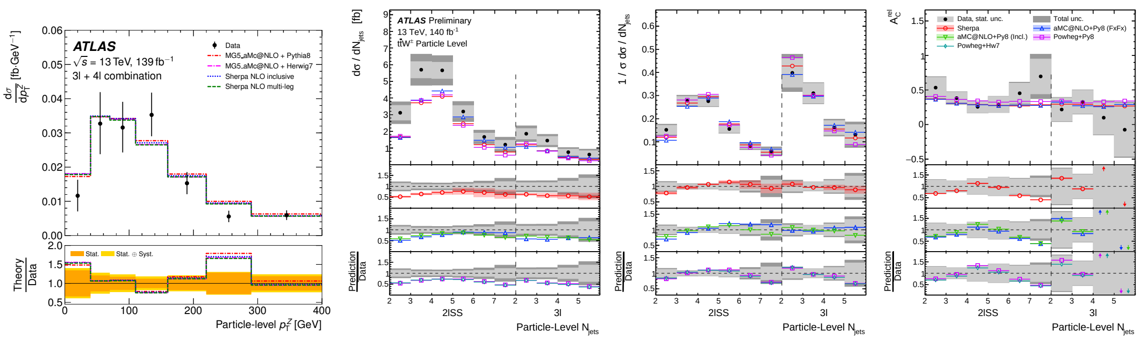

Figure 1: Left: Absolute differential $t\bar{t}Z$ cross sections measured at particle level as a function of the transverse momentum of the Z boson [2]. Right: Absolute and normalised $t\bar{t}W$ cross sections and relative charge asymmetry (A_C^{rel}) as a function of jet multiplicity [4]. The lower part of the plots show the ratio of the predictions to the data.

3. $t\bar{t}$ in association with a W boson

The production of $t\bar{t}$ in association with a W boson ($t\bar{t}W$) offers a very rich phenomenology to scrutinise the SM predictions, from charge-asymmetric production and QCD and EWK corrections, and it is a dominant background for measurements of rare process, such as four top quark production.

The most recent results by the ATLAS Collaboration focus on events with 3 or 2 same-sign leptons (e, μ) [4]. Additionally, requirements on the number of jets, b-tagged jets, lepton charge and flavour are imposed to define signal and control regions to better constrain the main background sources. The main irreducible background events arise from diboson and $t\bar{t}Z$ events, while the reducible backgrounds come mostly from fake/non-prompt leptons from $t\bar{t}$ production and events where the charge of a lepton is misidentified. The inclusive cross section, measured using a simultaneous profile likelihood fit to data in 56 signal and 10 control regions, yields $\sigma_{\text{fid}} = 890 \pm 50(\text{stat}) \pm 70(\text{syst})$ fb consistent within 1.5σ with a NLO calculation [5]. The ratio $t\bar{t}W^+/t\bar{t}W^-$ and the charge asymmetry measurements are in good agreement with the SM predictions. The absolute and normalised differential cross sections are measured using profile likelihood unfolding as functions of observables related to event properties, angular distances between leptons and jets, etc. The shapes are consistent between various MC and data. An example is shown in Figure 1, right.

4. Observation of $tq\gamma$

The observation of single top quark production with a photon was achieved by ATLAS considering final states with one lepton, one photon, one b-tagged jet, one forward jet and missing transverse energy [6]. Events are divided into two signal regions depending on the presence of a forward jet and two additional regions to measure backgrounds with prompt photons, mostly W boson and $t\bar{t}$ in association with a photon ($t\bar{t}\gamma$). Neural networks are employed to further separate separate signal from the background events. The cross section is measured with a profile likelihood fit in a fiducial phase space at parton level with γ radiated from the top quark as well as at particle level. The results are $\sigma_{tq\gamma} \times BR(t \to \ell\nu b) = 688 \pm 23(\text{stat})^{+75}_{-71}(\text{syst})$ fb and $\sigma_{tq\gamma} \times BR(t \to \ell\nu b) + \sigma_{t\to\ell\nu b\gamma q} = 303 \pm 9(\text{stat})^{+33}_{-32}(\text{syst})$ fb, respectively. They are compatible with the SM predictions within 2.1 (2.0) σ at parton (particle) level. This is the first observation of the process with an observed (expected) significance of 9.1 (6.7) standard deviations.

5. Measurement of $t\bar{t}$ charge asymmetry in $t\bar{t}\gamma$ and $t\bar{t}W$ topologies

The $t\bar{t}$ charge asymmetry is diluted at the LHC owing to the large fraction of gluon–gluon-initiated $t\bar{t}$ events, which are symmetric under the exchange of the top quark and antiquark. However, it is enhanced in other topologies where the fraction of quark–antiquark-initiated production is larger, such as in $t\bar{t}\gamma$ and $t\bar{t}W$.

In the case of $t\bar{t}\gamma$ production, the dominant contribution to the asymmetry arises from interference between QED initial- and final-state radiation, yielding a negative asymmetry. The measurement by the ATLAS Collaboration is perfomed selecting single-lepton $t\bar{t}$ events with exactly one isolated photon [7]. Data-driven methods are employed to estimate the background processes with fake objects. A neural network is used to discriminate the $t\bar{t}\gamma$ production from all types of backgrounds and separate events into two regions. The asymmetry is obtained by means of a simultaneous maximum-likelihood unfolding of the rapidity difference of the top and antitop quarks ($|y_t| - |y_{\bar{t}}|$) distributions in the two regions defined by the NN output discriminant. The post-fit distribution in the signal region is shown in Figure 2, left. The measured asymmetry is $-0.003 \pm 0.029 = -0.003 \pm 0.024(\text{stat}) \pm 0.017(\text{syst})$.

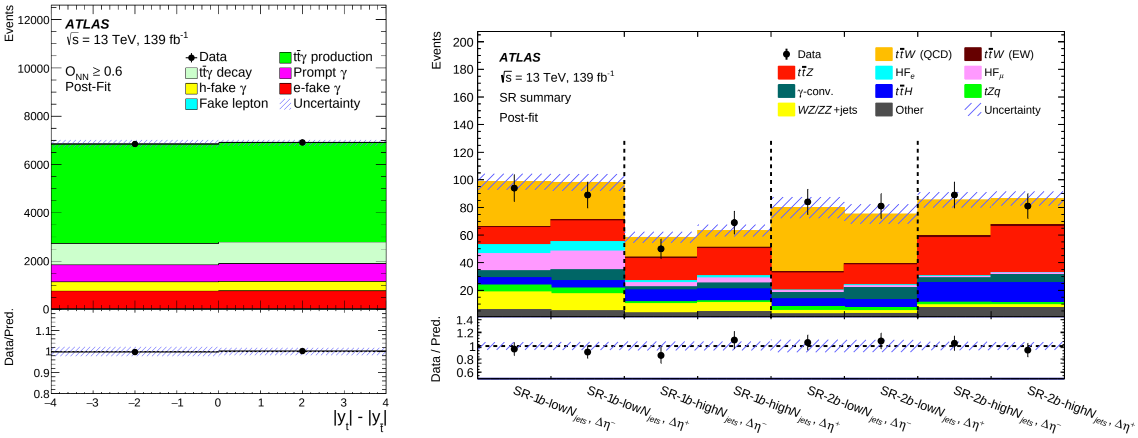

Figure 2: Left: Distribution of $|y_t| - |y_{\bar{t}}|$ after the fit in one of the regions defined by the NN output in the $t\bar{t}\gamma$ charge asymmetry measurement [7]. Right: Comparison between data and the post-fit predictions in the signal regions of the $t\bar{t}W$ charge asymmetry measurement [8]. The error bands include the total uncertainties of the post-fit predictions. The ratio of the data to the total post-fit predictions is shown in the lower panels.

In $t\bar{t}W$ production, dominated by $q\bar{q}$ initial states, the W boson emission polarises the top quarks, resulting in a large negative asymmetry in the decay products. The first search for the leptonic charge asymmetry ($A_C^{\ell\ell}$) with $t\bar{t}W$ events is perfomed in final states with 3 leptons [8]. A boosted decision tree is used to select the correct even lepton from the top quark decay. Requirements on number of jets and b-tagged jets are imposed to define signal and control regions to constrain the main backgrounds ($t\bar{t}Z$, non-prompt leptons), illustrated in Figure 2 (right). A profile likelihood fit of the event yields in each region is used to extract $A_C^{\ell\ell}$. The leptonic asymmetry results $A_C^{\ell} = -0.123 \pm 0.136(\text{stat}) \pm 0.051(\text{syst})$. The results are also measured at particle level in a fiducial phase space close to the selection at reconstruction level using a profile likelihood approach.

The measured charge asymmetries in both topologies are in agreement with the NLO predictions from the MC simulations used in the analyses.

6. Conclusions

Top quark measurements provide relevant information about their production process as described in the SM, as well as sensitivity to possible beyond the SM phenomena. The large data set collected with the ATLAS detector at the LHC so far allowed performing detailed cross section measurements of processes such as $t\bar{t}Z$ and $t\bar{t}W$. Additionally, it allowed reaching the observation of $tq\gamma$ and exploiting $t\bar{t}\gamma$ and $t\bar{t}W$ topologies to measure $t\bar{t}$ production properties.

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