PROCEEDINGS OF SCIENCE

Observation of associated production of top quarks with the ATLAS experiment

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The large dataset accumulated by the ATLAS detector at a centre of mass energy of $\sqrt{s}$ = 13 GeV provided at the LHC allows the study of rare SM top quark production processes. The observation of associated production of top quarks has provided the first direct measurement of the top quark electroweak couplings with neutral gauge bosons and the first access to the four-top-quark production process. Using the data set collected during Run 2 of the LHC between 2015 and 2018, and amounting to 139 fb^{-1} of proton-proton collisions, the ATLAS experiment has observed ttX production, with X=γ, Z, H and single top quark production with X=γ, Z, W. In this contribution, new differential measurements of the $t\bar{t}Z$ and $t\bar{t}\gamma$ cross-sections are presented, as well as inclusive cross-section measurements of tZq and $tq\gamma$ production. The latter is a brand new result, which corresponds to the first observation of this process. Results are also presented from the search for four-top-quark production, where the combination of several searches in various channels leads to strong (4.7 σ) evidence for the existence of this elusive process.

41st International Conference on High Energy physics - ICHEP2022
6-13 July, 2022
Bologna, Italy

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PoS(ICHEP2022)883

1. Introduction

The top quark is the heaviest known particle in the Standard Model (SM) of elementary particles. Because of its large mass of about 173 GeV, and Yukawa coupling close to unity, the study of its properties is of outstanding interest within the framework of the SM. The associated production of top quarks with vector bosons provides a way to probe the top-boson coupling predictions of the SM throughout the electroweak (EW) sector, thereby giving access to the nature of the top-boson coupling vertices. The SM precisely predicts the structures and strengths of these couplings. They are sensitive to physics beyond the SM (BSM) since several BSM models predict deviations of these couplings from the SM predictions. Here, four cross-section measurements involving the coupling of the top quark to vector bosons, namely tZq, $t\bar{t}Z$, $t\gamma q$ and $t\bar{t}\gamma$, as well as the four top production, $t\bar{t}t\bar{t}$, measured by the ATLAS experiment [1] at the Large Hadron Collider (LHC) using the full Run 2 dataset, representing 139 fb^{-1} of proton-proton collision data measured between 2015 and 2018, are summarised.

2. Top quarks in association with photons

Measuring the production processes of single top quarks, $tq\gamma$, as well as top quark pairs, $t\bar{t}\gamma$, in association with a photon (γ) provides access to the electromagnetic coupling of the top quark to the photon in the SM. ATLAS measured the production of $t\bar{t}$ in association with a photon in the dileptonic final state with an electron and a muon ($e\mu$) [2], thereby studying off-shell effects. The measurement requires one isolated photon with $p_{\text{T}} > 20$ GeV and one electron and one muon. Additionally, at least two anti-k_t jets with a radius parameter of $R = 0.4$, of which at least one must be tagged as a b-jet (at a fixed 85% efficiency) are required. Fiducial inclusive and differential cross-sections of the combined doubly-resonant $t\bar{t}\gamma$ and singly-resonant $Wt\gamma$ process using several observables are measured and compared to a fixed-order theory prediction computed at next-to-leading order (NLO) in QCD, including all off-shell contributions and interference effects. A binned profile likelihood fit to the scalar sum of the transverse momenta of all reconstructed objects in the event, including $E_{\text{T}}^{\text{miss}}$, is performed. The fiducial cross-section is measured to be $\sigma^{\text{fid}}(t\bar{t}\gamma \to e\mu) = 39.6 \pm 0.8(\text{stat.})^{+2.6}_{-2.2}(\text{syst.})$ fb. The measurement is dominated by systematic uncertainties, with the largest arising from the modelling of the $t\bar{t}\gamma$ parton shower. The fiducial cross-section result agrees with the SM prediction of $\sigma^{\text{fid}}_{\text{NLO}} = 38.50^{+0.56}_{-2.18}(\text{scale})^{+1.04}_{-1.18}(\text{PDF})$ fb [3, 4]. While the $t\bar{t}\gamma$ production process was already measured in ATLAS using 36 fb^{-1} of Run 2 data [5] and more precisely using the full Run 2 dataset [2], associated single top production was previously observed only together with Z and W bosons. These processes play a substantial role in the electroweak sector of the SM, e.g. constraining non-resonant contributions of BSM physics.

The inclusive $tq\gamma$ production process was measured, considering leptonic top-quark decays ($t \to l\nu b$) [6]. In this process, photon radiation originates from any charged particle in the initial or final state. The analysis defines two signal regions (SR) and requires the presence of one photon, one electron or muon, one anti-k_t jet with radius parameter $R = 0.4$ tagged at 70 % b-tagging efficiency (tight), no other tagged jets using the 85% operating point (loose) and $E_{\text{T}}^{\text{miss}} > 30$ GeV. One or no forward jet ($2.5 < |\eta| < 4.5$) is also required, depending on the region owing to the t-channel production mechanism of the process. To estimate the contributions from $t\bar{t}\gamma$ and $W\gamma$

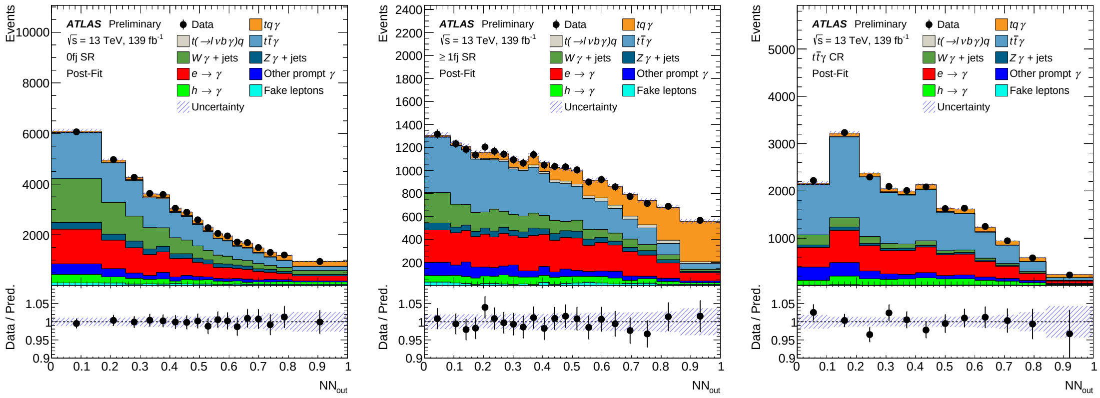

Figure 1: Distributions of the neural network discriminant, NN_{out}, in the central SR (left), the forward SR (center) and the $t\bar{t}\gamma$ CR (right), after the profile likelihood fit [6]. The bottom panel shows the ratio of the observed data to the fitted SM expectation. The uncertainty band includes all systematic uncertainties on the signal and the backgrounds.

processes in the SRs dedicated control regions (CR) are defined. These regions utilise the same selection criteria as the SRs, apart from the b-tagging requirements, and are inclusive in forward jets. While the $t\bar{t}\gamma$ CR requires one additional loose b-jet, the $W\gamma$ CR requires the existence of at least one loose b-jet and no tight b-jets. Dedicated neural networks (NN) are trained based on the signal and background predictions in the SRs to separate the signal from the background. Examples of the output distributions are shown in Figure 1. To extract the signal cross-section, a profile-likelihood fit is performed simultaneously in all SRs and CRs. The observed (expected) significance of the $tq\gamma$ signal is 9.1σ (6.7σ). The measured fiducial parton level cross-section is $\sigma_{tq\gamma} \times \mathcal{B}(t \rightarrow \ell\nu b) = 580 \pm 19(\text{stat.}) \pm 63(\text{syst.})$ fb. The measured fiducial particle level cross-section is $\sigma_{tq\gamma} \times \mathcal{B}(t \rightarrow \ell\nu b) + \sigma_{(t\rightarrow\ell\nu b\gamma)q} = 287 \pm 8(\text{stat.}) \pm 31(\text{syst.})$ fb. The fiducial cross-sections at parton (particle) level agree with the SM prediction in the four-flavour scheme, at NLO in α_S, within 2.5σ (1.9σ). An approximately 40% higher cross-section is observed, consistent with the results of the CMS $tq\gamma$ measurement [7].

3. Top quarks in association with Z bosons

Providing access to the electroweak neutral current coupling, the production processes of top quarks in association with a Z, tZq and $t\bar{t}Z$ are particularly relevant in the SM. Deviations from the SM electroweak prediction of the coupling strength might indicate the existence of new physics within the electroweak sector of the SM, such as new effects in the EW symmetry-breaking mechanism. These scenarios can now be precisely probed at the LHC.
The electroweak production of a single top quark in association with a Z boson, namely tZq, was measured by ATLAS [8] using final states comprising three charged leptons, missing transverse momentum, one jet tagged as a b-jet and an untagged jet at high $|\eta|$. This forward jet arises from the t-channel nature of the production process, and another jet is allowed to include events with additional QCD radiation. The analysis utilises 8 orthogonal signal and control regions based on jet and b-jet multiplicities. Two SRs are enriched in tZq production, additional CRs are used to control

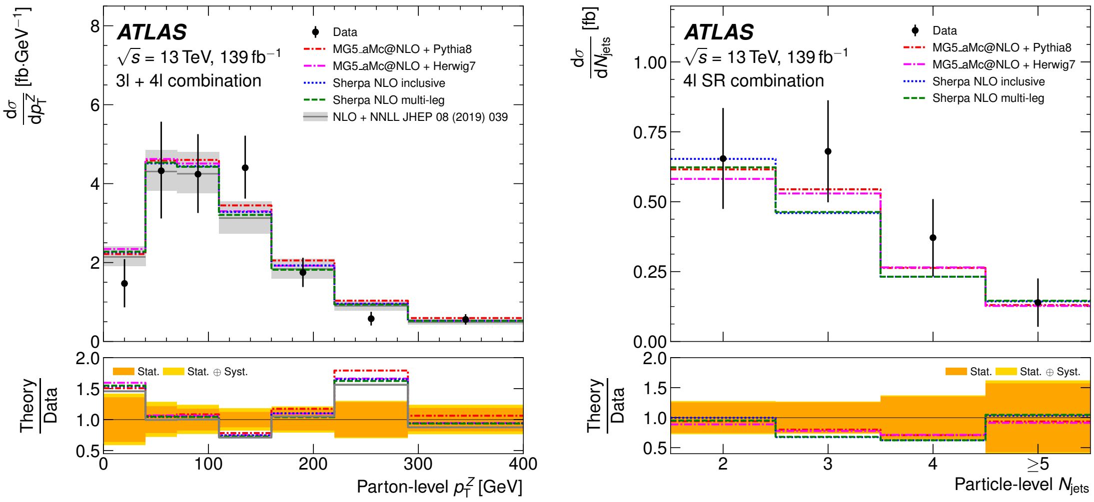

Figure 2: Distributions of the absolute differential $t\bar{t}Z$ cross-section as a function of $p_T(Z)$ at parton-level (left), and jet multiplicity at particle-level (right) [9]. The bottom panel shows the ratio of various theory predictions to the unfolded data. The statistical and total (including all sources of systematic uncertainties) error bands are shown in orange and yellow.

background processes like $t\bar{t}Z$, diboson, and processes with non-prompt leptons. The SRs require the presence of one OSSF lepton pair with an invariant mass, $m_{\ell\ell}$ of $|m_{\ell\ell} - m_Z| < 10$ GeV. In the diboson CRs, a b-jet veto is applied to enhance the contribution of diboson background events. The $t\bar{t}Z$ CR requires tighter b-tagging requirements in the form of an additional b-jet. The $t\bar{t}$ CR is selected by requiring an opposite-sign, different-flavour lepton pair. A three-layer feed-forward neural network (NN), combining several input variables into one discriminant, improves the signal-background discrimination. The tZq cross-section is extracted using a binned maximum-likelihood fit of the signal and control regions. The NN discriminant output are used in the fit in the SRs and $t\bar{t}Z$ CR. The total event yield is used in the $t\bar{t}$ CR. From these CRs, corrections to the normalisation of these background processes are extracted. The tZq cross-section, including $m_{\ell\ell} > 30$ GeV dilepton pairs, is measured to be $\sigma_{tZq} = 97 \pm 13(\text{stat.}) \pm 7(\text{syst.})$ fb. The result agrees with the SM prediction, $\sigma_{tZq}^{\text{SM}} = 102^{+5}_{-2}$fb, calculated at NLO in QCD for $m_{\ell\ell} > 30$ GeV within uncertainties.

The associated production of a top quark pair and a Z boson, $t\bar{t}Z$, was measured in final states with three or four isolated electrons or muons, and at least two anti-k_t jets with radius parameter $R = 0.4$ [9]. Measurements of inclusive and differential $t\bar{t}Z$ cross-sections were performed. As in the tZq analysis, events are required to have at least one opposite-sign-same-flavour (OSSF) lepton pair with an invariant mass, $m_{\ell\ell}$ of $|m_{\ell\ell} - m_Z| < 10$ GeV, where m_Z is the nominal Z boson mass. The lepton pair with an invariant mass closest to m_Z is considered to originate from the Z boson. The inclusive $t\bar{t}Z$ cross-section is measured using two orthogonal trileptonic SRs with varying b-tagging selection criteria. Looser b-tagging selection criteria are used to define the trileptonic differential SRs to increase data statistics. Additionally, four tetraleptonic SRs using varying b-jet multiplicities are split into same-flavour and different-flavour according to the lepton flavour composition of the non-Z lepton pair. While the same-flavour region is enhanced in ZZ

events, the different-flavour region is pure in signal events. Dedicated CRs in the 3ℓ and 4ℓ channels, respectively, control the contributions of WZ and ZZ backgrounds in the SRs. The $t\bar{t}Z$ cross-section and the WZ and ZZ normalisation factors are extracted using a simultaneous profile-likelihood fit to the number of events in the trilepton and tetralepton SR as well as WZ and ZZ CRs. The $t\bar{t}Z$ cross-section, $\sigma_{t\bar{t}Z}$, is measured to be $\sigma_{t\bar{t}Z} = 0.99 \pm 0.05(\text{stat.}) \pm 0.08(\text{syst.})$ pb. The dominating systematic uncertainty is the modelling of the $t\bar{t}Z$ parton shower. The result agrees with the SM prediction $\sigma^{\text{SM}}_{t\bar{t}Z} = 0.84^{+0.09}_{-0.10}$ pb, calculated at NLO in QCD and EW accuracy within uncertainties. Ten observables at particle and parton level are considered for the differential measurement to probe the kinematics of the top quarks and the Z boson and hence the structure of the top-Z coupling. Figure 2 shows examples of the absolute differential $t\bar{t}Z$ cross-section of the transverse momentum of the reconstructed Z boson, p_{T}^{Z}, measured at parton level and the jet multiplicity, N_{jets} at particle level compared with theoretical predictions at NLO and NLO+NNLL precision.

4. Production of four top quarks

Since the top quark has a large coupling to the SM Higgs and large couplings are predicted to hypothetical BSM particles, the $t\bar{t}t\bar{t}$ cross-section is a sensitive probe of the SM and new physics beyond it. Previously ATLAS explored dilepton (2LSS) and trilepton $t\bar{t}t\bar{t}$ final states which led to first evidence for this process with an observed (expected) significance of 4.3σ (2.4σ) [10]. This measurement was recently combined with a new search of 4-top production in the 1L/2LOS final state. The topology of the 1L (2LOS) final states is characterised by four b-jets, and six (four) other jets resulting in signal events with high (b-)jet multiplicities, and 10 (8) jets in total in the 1L (2LOS) channel. The dominating background originates almost exclusively from $t\bar{t}$ events with additional jets. Several CRs are defined based on the lepton and jet multiplicities and different b-tagging requirements to obtain reliable estimates of the $t\bar{t}$ background at high jet and b-jet multiplicities. From these regions with varying signal-to-background ratios and flavour composition of the $t\bar{t}$+jets final states, corrections to the normalisation of $t\bar{t}$ flavour components are extracted, mitigating mismodelling in the SRs. Kinematic mismodelling observed in $t\bar{t}$+jets MC simulation is mitigated by a flavour-based sequential reweighting using relevant jet observables. A boosted decision tree combining several input observables into one output score, maximises the separation between signal and background. The $t\bar{t}t\bar{t}$ cross-section is extracted using a binned profile likelihood fit, which also further adjusts and constrains the different $t\bar{t}$+jets corrections. The combined SM $t\bar{t}t\bar{t}$ cross-section, $\sigma_{t\bar{t}t\bar{t}}$, is measured to be $\sigma_{t\bar{t}t\bar{t}} = 24 \pm 4(\text{stat.})^{+5}_{-4}(\text{syst.})\,\text{fb} = 24^{+7}_{-6}\,\text{fb}$, agreeing within 2σ with the SM prediction of $\sigma^{\text{SM}}_{t\bar{t}t\bar{t}} = 12.0 \pm 2.4\,\text{fb}$ computed at NLO in QCD including NLO components. It corresponds to an observed (expected) significance of 4.7σ (2.6σ) above the background-only hypothesis.

5. Conclusion

With the large Run 2 dataset, top quark production processes with associated Z-bosons and photons were precisely measured by ATLAS at the LHC, allowing for in-depth tests of the electroweak sector of the SM. Many of the analyses presented here are systematically limited, highlighting the need for an improved understanding of theoretical uncertainties such as modelling uncertainties.

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