PROCEEDINGS OF SCIENCE

Measurement of top-quark properties with the ATLAS detector at the LHC

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Due to the large mass, top quarks decay before top-flavoured hadrons can be formed. This feature yields experimental access to the top quark polarisation and production asymmetries. The large top quark sample at the Large Hadron Collider (LHC) enables measurements of other properties, such as the W-boson branching ratios and helicity, and fragmentation functions of the bottom quarks. In this contribution, recent measurements of top-quark properties within the ATLAS Experiment are presented, including in particular, a first analysis of the energy asymmetry in $t\bar{t}$ production, the first analysis of charge asymmetry in $t\bar{t}+\gamma$ production and a measurement of top-quark polarisation in single-top quark production.

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

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PoS(ICHEP2022)886

1. Introduction

The large mass of the top quark, which is close to the electroweak symmetry breaking scale, indicates that this particle could play a special role in the Standard Model (SM), as well as in beyond the Standard Model (BSM) theories. Moreover, the top quark has a very short lifetime ($\tau = 0.5 \times 10^{-25}$ s) and decays before hadronisation ($\tau_{\text{had}} \sim 10^{-24}$ s) or spin de-correlation take place ($\tau_{\text{spin dec.}} \sim 10^{-21}$ s). Therefore several properties of the top quark may be measured precisely from its decay products.

Due to the large top-pair production ($t\bar{t}$) cross section for 13 TeV proton-proton (pp) collisions, the Large Hadron Collider (LHC) experiments collect an unprecedented number of top-quark events. The copious amount of detected events allows for high precision measurements in order to probe predictions of quantum chromodynamics (QCD), which provides the largest contribution to $t\bar{t}$ production.

This article focuses on three recent results in the top-quark sector by the ATLAS [1] Collaboration, using proton-proton (pp) collisions at LHC:

- the inclusive and differential measurements of the energy asymmetry (A_E) in $t\bar{t}j$ events at 13 TeV;
- the inclusive measurement of the charge asymmetry (A_C) in $t\bar{t} + \gamma$ events at 13 TeV;
- the first complete study of the top-quark polarisation using single-top t-channel events at 13 TeV.

2. Measurement of the energy asymmetry in $t\bar{t}j$ production at 13 TeV with the ATLAS experiment

In QCD, the charge asymmetry in $t\bar{t}$ production first occurs at next-to-leading order (NLO); in $t\bar{t}j$ production it is induced at tree level due to the presence of the additional jet. Contributions from new particles can lead to significant modifications of the asymmetry compared to the SM prediction. By construction, the energy asymmetry is sensitive to the charge asymmetry in a different phase-space region than the rapidity asymmetry. In combination, the two asymmetries are therefore powerful probes of physics beyond the Standard Model in the Standard Model Effective Field Theory framework (SMEFT).

The energy asymmetry is measured with the 13 TeV proton-proton collision data collected by the ATLAS experiment during Run 2 in 2015-2018 of the LHC [2]. The energy asymmetry observable (A_E) quantifies the energy imbalance (ΔE) between top and antitop quarks as a function of the jet scattering angle θ_j with respect to the beam axis:

$$A_E(\theta_j) = \frac{\sigma^{\text{opt}}(\theta_j|\Delta E > 0) - \sigma^{\text{opt}}(\theta_j|\Delta E < 0)}{\sigma^{\text{opt}}(\theta_j|\Delta E > 0) + \sigma^{\text{opt}}(\theta_j|\Delta E < 0)} \tag{1}$$

with the optimised cross section $\sigma^{\text{opt}}(\theta_j) = \sigma(\theta_j|y_{t\bar{t}j} > 0) + \sigma(\pi - \theta_j|y_{t\bar{t}j} < 0)$, $\theta_j \in [0, \pi]$, where $\sigma(\theta_j)$ is the differential cross section as a function of θ_j, and $y_{t\bar{t}j}$ is the rapidity of the $t\bar{t}j$ system.

The energy asymmetry is measured in the semileptonic decay channel, and the hadronically decaying top quark must have transverse momentum above 350 GeV. The results are corrected for detector effects to particle level in three bins of θ_j. The measurement agrees with the SM prediction at NLO accuracy in QCD in all three bins, as shown in Figure 1(a). In the bin with the largest expected asymmetry, where the jet is emitted perpendicular to the beam, the energy asymmetry is measured to be -0.043 ± 0.020, in agreement with the SM prediction of -0.037 ± 0.003. Interpreting this result in the SMEFT framework, it is shown that the energy asymmetry is sensitive to the top-quark chirality in four-quark operators and is therefore a valuable new observable in global SMEFT fits (Figures 1(b) and (c)).

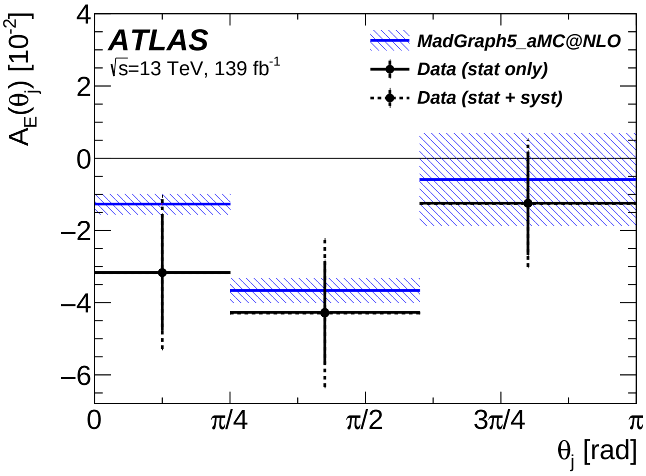
3. Measurement of the charge asymmetry in top quark pair production in association with a photon with the ATLAS experiment

The $t\bar{t}$ charge asymmetry (A_C) 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. Thus, it is enhanced in other topologies, where the fraction of quark-antiquark initiated production is larger, such as the associated production of a $t\bar{t}$ with a photon ($t\bar{t}\gamma$), and the overall asymmetry is expected to have a negative value according to the SM predictions. These sources of asymmetry are only present in the $t\bar{t}\gamma$ events where the photon is radiated from the initial state partons or the top quarks (referred to as $t\bar{t}\gamma$ production in the following), while it is diluted in the $t\bar{t}\gamma$ events where the photon arises from any of the charged decay products of the $t\bar{t}$ system ($t\bar{t}\gamma$ decay in the following). Therefore, only the $t\bar{t}\gamma$ production process is considered as signal in this analysis.

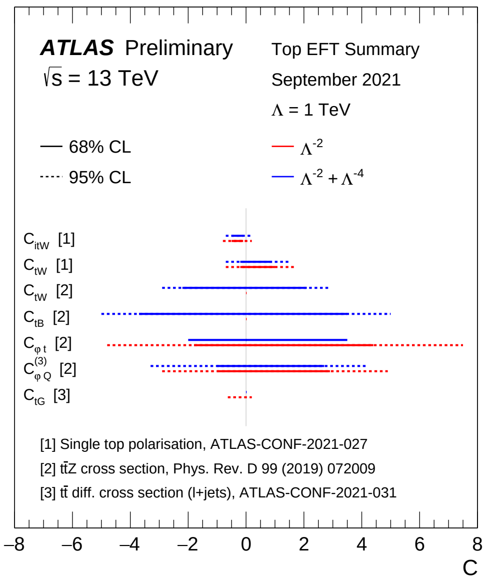
The measurement is performed in the single-lepton $t\bar{t}$ decay channel using proton-proton collision data collected with the ATLAS detector at the LHC at a centre-of-mass-energy of 13 TeV during the years 2015-2018, corresponding to an integrated luminosity of 139 fb^{-1} [4]. In order to extract the asymmetry, the top quarks are reconstructed using a kinematic likelihood fit. The separation between signal and background processes is enhanced using a Neural Network (NN) approach. The output distribution of the NN is used to define two regions, one enriched in background events and one in signal events. The charge asymmetry is obtained from the distribution of the difference of the absolute rapidities of the top quark and antiquark using a profile likelihood unfolding approach. It is measured to be $A_C = -0.006 \pm 0.030$ in agreement with the SM expectation.

4. Measurement of the polarisation of single-top quarks and antiquarks produced in the t-channel at $\sqrt{s} = 13$ TeV and bounds on the tWb dipole operator from the ATLAS experiment

The QCD $pp \to t\bar{t}$ process produces unpolarised top quarks because of parity conservation in QCD, while single-top-quark production yields a large sample of highly polarised top quarks and top antiquarks. In the t-channel at LO, as a consequence of the vector minus axial-vector (V-A) form of the tWb vertex, single-top quarks are produced with their spin completely aligned along the direction of the down-type quark. For single top quarks produced by the dominant subprocess, this direction is the spectator-quark direction, while for the subdominant subprocess it is the direction of the incoming down-type antiquark. For single top-antiquark production, the spin aligns in the direction opposite to that of the incoming down-type quark in the dominant subprocess, and opposite



(a)



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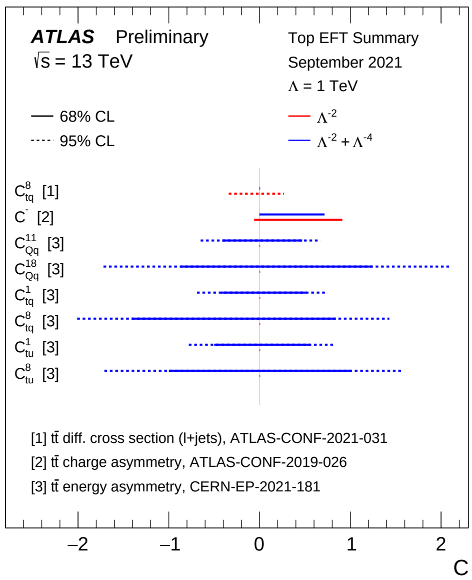

(c)

Figure 1: (a) Data measurements (black points with errors) and predictions (blue lines) of the energy asymmetry in three bins of θ_j [2]. (b and c) Summary of constraints on four-fermion SMEFT operators from top-quark measurements at the ATLAS experiment. The bounds on the Wilson coefficients of SMEFT are reported at the 68% CL (solid) and/or 95% CL (dashed) depending on the availability in the corresponding measurement. The bounds are reported without (red) and/or with (blue) taking into account the quadratic term of the SMEFT operator, depending on the availability in the corresponding measurement. Limits on each individual operator are derived fixing the rest to the SM value. The vertical bar represents the SM prediction [3].

to that of the spectator antiquark in the subdominant process. Thus, the degree of polarisation for a sample of single-top-quark or single-top-antiquark events depends on the mix of dominant and subdominant production processes and the relative alignment between the beam line and spectator-quark directions, averaged over the sample selected. In all cases, the direction is relative to the rest frame of the top quark or antiquark.

The analysis performs a simultaneous measurement of the three components of the top-quark and top-antiquark polarisation vectors in t-channel single-top-quark production [5]. It is based on data from proton-proton collisions at a centre-of-mass energy of 13 TeV corresponding to an integrated luminosity of 139 fb^{-1}, collected with the ATLAS detector at the LHC. Selected events contain exactly one isolated electron or muon, large missing transverse momentum and exactly two jets, one being b-tagged. Stringent selection requirements are applied to discriminate t-channel single-top-quark events from the background contributions.

The top-quark and top-antiquark polarisation vectors are measured simoultaneously from the distributions of the direction cosines of the charged-lepton momentum in the top-quark rest frame. Each component of the polarisation vector is thereby measured without any assumption about the other two components. In addition, normalised differential cross-sections corrected to a fiducial region at particle level are determined as a function of the charged-lepton angles for top-quark and top-antiquark events separately and inclusively. They can be combined with other experimental inputs to derive bounds on complex Wilson coefficients in the EFT framework.

The three components of the polarisation vector for the selected top-quark event sample are measured to be $P_{x'} = 0.01 \pm 0.18$, $P_{y'} = -0.029 \pm 0.027$, $P_{z'} = 0.91 \pm 0.10$ and for the top-antiquark event sample they are $P_{x'} = -0.02 \pm 0.20$, $P_{y'} = -0.007 \pm 0.051$, $P_{z'} = 0.79 \pm 0.16$. They are all in very good agreement with the SM predictions at next-to-next-to-leading order (NNLO) accuracy, as shown in Figure 2(a). The normalised differential cross-sections are in agreement with SM predictions, as shown in Figure 2(b). The derived boundaries on the complex Wilson coefficient of the dimension-six O_{tW} operator are $C_{tW} \in [-0.9, 1.4]$ and $C_{itW} \in [-0.8, 0.2]$, both at 95% confidence level; they are also compatible with the SM, as shown in Figure 2(c).

References

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[3] ATLAS Collaboration, "Top EFT summary plots December 2021", ATL-PHYS-PUB-2021-043.

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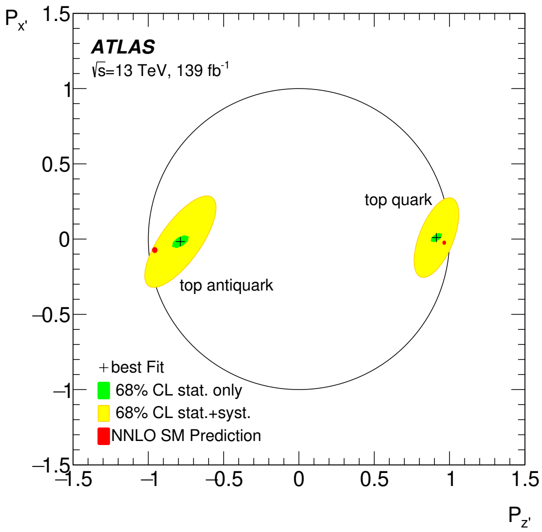
[5] ATLAS Collaboration, "Measurement of the polarisation of single top quarks and antiquarks produced in the t-channel at $\sqrt{s}$ = 13 TeV and bounds on the tWb dipole operator from the ATLAS experiment", arXiv:2202.11382 [hep-ex], accepted by JHEP.



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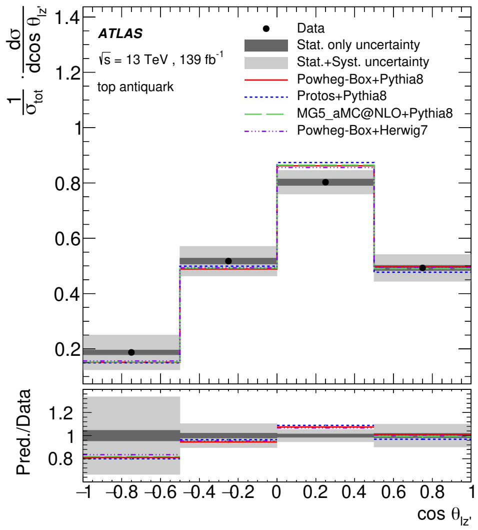

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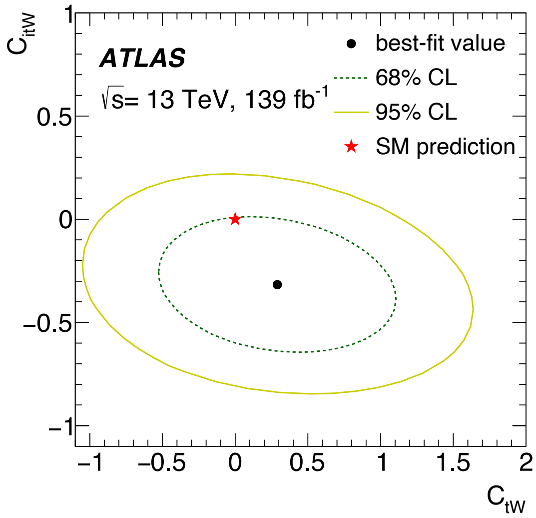

(c)

Figure 2: (a) Summary of the observed best-fit polarisation measurements ($P_{z'}$, $P_{x'}$) with their statistical-only (green) and statistical+systematic (yellow) contours at 68% CL. (b) Particle-level normalised differential cross-sections as a function of $\cos\theta_{z'}$, along with various SM MC predictions of the t-channel signal for top antiquarks. The data, shown as the black points with statistical uncertainties, are compared with predictions (lines). The uncertainty bands include both the statistical and systematic uncertainties. (c) The observed best-fit value (dot) for the Wilson coefficients C_{tW} and C_{itW} with the uncertainty contours at 68% CL (dashed) and 95% CL (solid). The red star indicates the SM prediction [5].