ATL-PHYS-PROC-2024-038
28 May 2024

Top-quark physics highlights from the ATLAS experiment

O. Majerský, on behalf of the ATLAS Collaboration
Deutsches Elektronen-Synchrotron DESY, Platanenallee 6,
Zeuthen, Germany

This contribution highlights several recent top physics measurements performed by the ATLAS experiment using Run 2 data. The first observation of the quantum entanglement and the most precise $W \to \mu/e$ lepton-flavour universality test in $t\bar{t}$ events in dilepton channel are presented. In addition, an improved inclusive and the first differential cross-section measurement of $t\bar{t}W$ production is presented.

1 Introduction

The top quark is the heaviest known elementary particle. It decays almost exclusively into a Wb pair, before it can hadronise, thus its decay products allow to probe properties of a *quasi-bare* quark. At the LHC, the top quarks are abundantly produced in $t\bar{t}$ production. The dilepton channel, where both top-quarks decay semi-leptonically, is in particular interesting, because it has very low background contamination. This channel is leveraged in the recent tests of quantum entanglement [1] and lepton flavour universality [2], performed by the ATLAS Collaboration. Finally, the large ATLAS[3] Run 2 dataset allows for both inclusive and differential cross-section measurements of rare processes such as $t\bar{t}W$ production [4].

2 Observation of quantum entanglement in $\mathrm{t\bar{t}}$ production by ATLAS experiment

The dilepton channel of $t\bar{t}$ production is well suited for measuring observables sensitive to top-quark spin correlations, since the leptons from W decays have maximum spin-analysing power. Close to the production threshold, the top-quark pairs at the LHC are produced predominantly in a spin-zero singlet state, which is maximally entangled. The quantum entanglement manifests itself in the spin correlations, and this property is exploited in the recent ATLAS measurement using Run 2 dataset, selecting events with exactly one isolated electron and muon [1].

The measured observable is the *entanglement marker* $D = -3\,\langle\cos\varphi\rangle$, where φ is the angle between the leptons in the rest frames of the individual top quarks and the angled brackets denote the average over an entire dataset. A value of $D < -1/3$ implies that the strength of the spin correlations cannot be explained without entanglement. D is smeared by detector

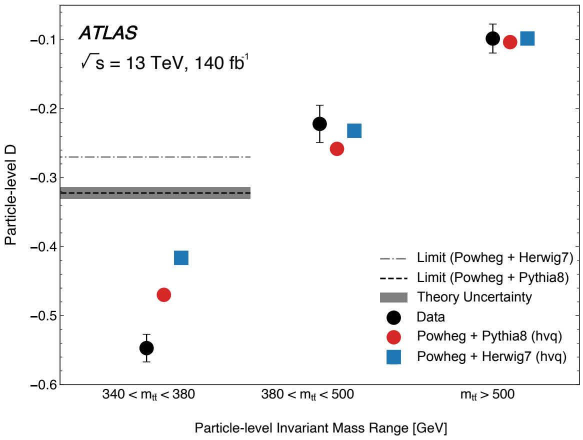

Figure 1 – Comparison of predicted (coloured points) and measured (black points) entanglement marker D after correcting for detector response via the calibration curve, in the signal region ($340 < m_{t\bar{t}} < 380$) and in the validation regions [1]. The entanglement limit corresponding to $D = -1/3$ is shown for two different generator predictions with the grey dashed lines.

resolution and acceptance and background contamination. In order to mitigate these effects, the *calibration curve* approach is used, which is based on deriving the relation between the true value and the reconstructed value of D, using Monte Carlo (MC) simulation with various D predictions.

The value of D measured in data is subsequently corrected using the calibration curve and compared with the predicted limit. Figure 1 shows the predicted and measured value of the corrected D in the signal region, and in two validation regions, where the spin-0 contribution is expected to be suppressed. The corrected measured value of D in the signal region is -0.547 ± 0.002 (stat.) ± 0.021 (syst.), and the uncertainty is dominated by signal modelling uncertainties. Due to the differences in modelling between POWHEG+PYTHIA8 and POWHEG+HERWIG7, the entanglement limit on D has different values, as seen in Figure 1. Nevertheless, for both entanglement limit assumptions, the measured value of D deviates by more than 5σ, providing the first observation of quantum entanglement in a quark pair production at the LHC.

3 Precise test of lepton flavour universality in W-boson decays into muons and electrons

Thanks to the almost exclusive decay of $t \to Wb$, the $t\bar{t}$ production can be used for precise test of lepton flavour universality (LFU). ATLAS has performed a measurement [2] of $R_W^{\mu/e} = BR(W \to \mu\nu)/BR(W \to e\nu)$.

While several sources of systematic uncertainties, such as parton density function and jet uncertainties, cancel out in the ratio, the observable is sensitive to lepton-related systematic uncertainties. Therefore, the actual measured observable is the ratio $R_{WZ}^{\mu/e} = R_W^{\mu/e}/\sqrt{R_Z^{\mu/e}}$, where $R_Z^{\mu/e} = BR(Z \to \mu^+\mu^-)/BR(Z \to e^+e^-)$. The $R_Z^{\mu/e}$ observable maximizes cancellation of lepton-related systematic uncertainties. To obtain the $R_W^{\mu/e}$, the measured $R_{WZ}^{\mu/e}$ is normalised by $\sqrt{R_Z^{\text{LEP+SLD}}}$, where $R_Z^{\text{LEP+SLD}} = 1.0009 \pm 0.0028$ is the most precise measurement of the ratio of Z branching ratios in muon and electron decays by the LEP+SLD Collaborations [2].

The $R_{WZ}^{\mu/e}$ is measured by performing a simultaneous binned likelihood fit using events with

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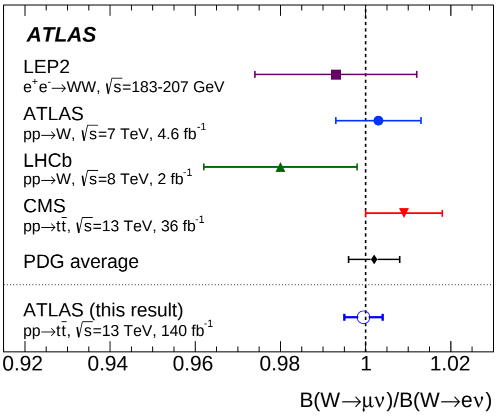

Figure 2 – Comparison of several LFU measurements from the LEP and LHC experiments[2].

opposite-sign ee, $\mu\mu$ or $e\mu$ pair. The fit includes a number of free parameters, including the $R_W^{\mu/e}$, $R_Z^{\mu/e}$, and the inclusive cross-section of $t\bar{t}$ and Z production.

Figure 2 shows the ATLAS measurement compared to previous measurements performed by LEP and LHC experiments and the PDG average. The measured value of $R_W^{\mu/e}$ is 0.9995 ± 0.0045, which is consistent with the assumption of LFU, and is the most precise measurement of $R_W^{\mu/e}$ to date, improving upon the previous PDG world average.

4 Measurement of total and differential cross-sections of the t$\bar{\mathbf{t}}$W production

Recent measurements of $t\bar{t}H$ and $t\bar{t}t\bar{t}$ production have shown consistently higher measured $t\bar{t}W$ cross-section compared to theory predictions[4]. The $t\bar{t}W$ process is difficult to model accurately due to the large impact of higher-order QCD and electroweak corrections. The ATLAS Collaboration has performed its first differential cross-sections measurement with an updated inclusive cross-section measurement of the $t\bar{t}W$ production[4] using the full Run 2 dataset. The measurement uses events with two same-sign ($2\ell SS$) leptons (electrons or muons), and events with three leptons (3ℓ) with total lepton charge ± 1.

The total cross-section is extracted using profile likelihood fit in 2ℓ and 3ℓ categories split by lepton charge, flavour and jet and b-jet multiplicity. Dedicated control regions are included to constrain backgrounds including prompt leptons, such as $t\bar{t}Z$, $t\bar{t}H$, and WZ production, and backgrounds including non-prompt or fake leptons, such as $t\bar{t}$, V+jets and photon material

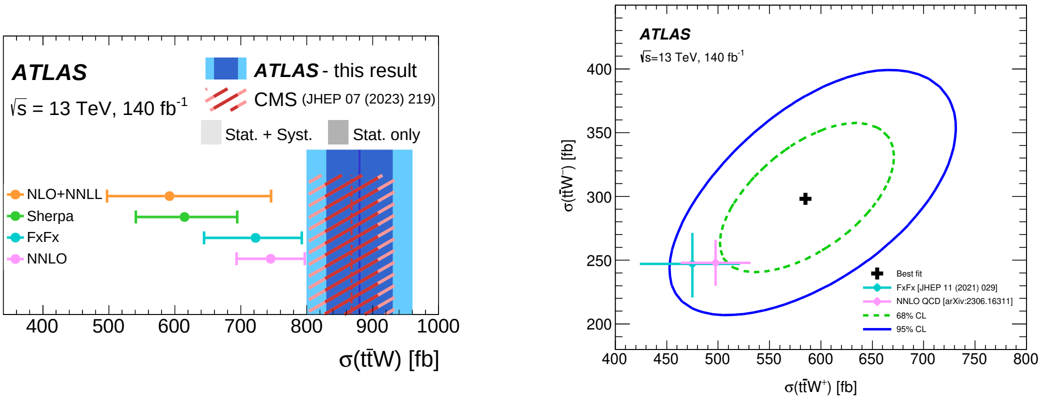

Figure 3 – Comparison of theoretical predictions of $t\bar{t}W$ total cross-section with ATLAS[4] and CMS[5] measurements (left), and the simultaneous measurement of $t\bar{t}W^+$ and $t\bar{t}W^-$ cross-section compared to theory predictions (right).

conversions.

Figure 3 shows the measured total $t\bar{t}W$ cross-sections as well measured cross-sections depending on the W charge, compared with several theoretical predictions. The measured total cross-section is $\sigma_{t\bar{t}W}^{\mathrm{meas.}} = 880 \pm 70$ fb, and its precision is limited by signal and background modelling. The approximate NNLO theoretical prediction of $\sigma_{t\bar{t}W}^{\mathrm{SM}} = 745 \pm 55$ fb agrees with the measurement within 1.4σ, reducing the previously observed tensions with predictions.

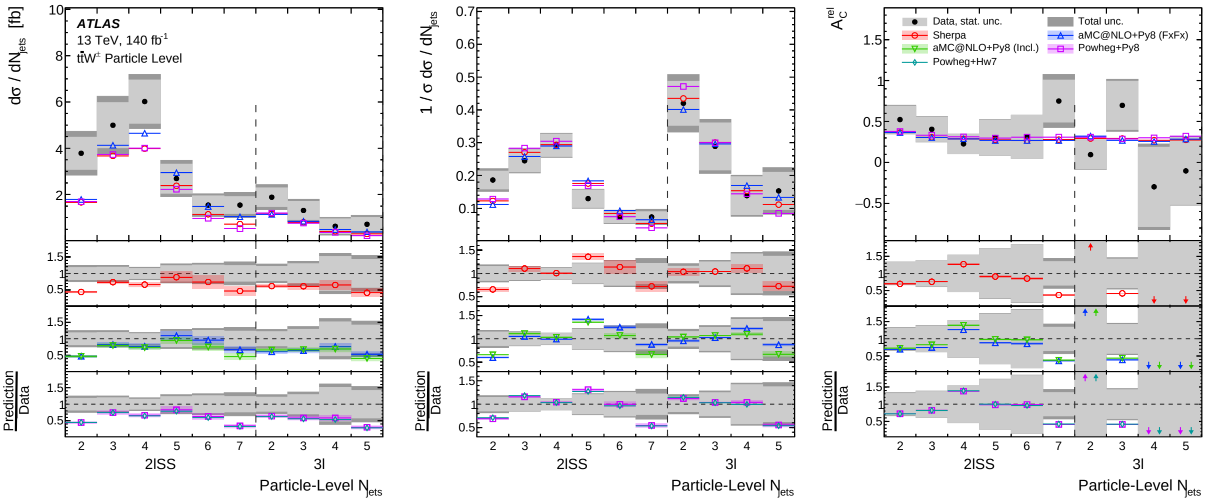

Figure 4 – Comparison of $t\bar{t}W$ MC predictions with measured[4] differential (left), normalised differential (center) cross-section, and relative charge asymmetry $A_C^{\mathrm{rel.}}$ (right).

Finally, the differential cross-sections are extracted using profile-likelihood unfolding in $2\ell SS$ and 3ℓ fiducial regions. Figure 4 shows the unfolded absolute and normalised differential cross-section as a function of the jet multiplicity, and the relative charge asymmetry $A_C^{\mathrm{rel.}} = (\sigma(t\bar{t}W^+) - \sigma(t\bar{t}W^-))/(\sigma(t\bar{t}W^+) + \sigma(t\bar{t}W^-))$. Several NLO MC generator predictions are compared with the data, and similarly as in Figure 3 all of them underestimate the absolute cross-section, while the normalised differential cross-section shows reasonable agreement with the data. In general, the uncertainty on the unfolded data is dominated by statistical uncertainty.

5 Conclusions

The ATLAS experiment has leveraged the top quark and the Run 2 data to test fundamental properties of the Standard Model and quantum mechanics. ATLAS has observed evidence for quantum entanglement in $t\bar{t}$ production, testing this phenomenon in energies previously unprobed. The most precise e/μ lepton flavour universality test was performed, improving upon the previous PDG world combination, showing agreement with the SM assumption of LFU universality. Finally, an updated total and first differential cross-section measurement of the $t\bar{t}W$ production at $\sqrt{s} = 13$ TeV was performed by the ATLAS experiment. The approximate NNLO predictions reduce the previously observed tensions, demonstrating the progress in the challenge of $t\bar{t}W$ production modelling.

References

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