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Highlights on top-quark physics with the ATLAS experiment at the LHC

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The large top-quark samples collected with the ATLAS experiment at the LHC have yielded measurements of the production cross-section of unprecedented precision and in new kinematic regimes. They have also enabled new measurements of top-quark properties that were previously inaccessible, the observation of many rare top-quark production processes predicted by the Standard Model and boosted searches in the top-quark sector. In this contribution the highlights of the ATLAS top-quark physics program are presented.

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1. Introduction

The heaviest quark in the Standard Model (SM) is the top quark, which decays before hadronisation. This property allows its spin state to be preserved in the distributions of its decay products. Due to its large mass, the top quark is particularly sensitive to potential beyond the Standard Model (BSM) physics at high mass scales. In addition to measuring the properties of the top quark to probe the SM, understanding top-quark behaviour is essential for removing top-quark events that contribute to background processes in other measurements.

The ATLAS experiment at the Large Hadron Collider (LHC), located at the European Organisation for Nuclear Research (CERN) in Switzerland [1], measures top-quark properties. Recent ATLAS results are presented using 13 TeV centre-of-mass energy proton-proton collisions [2–5] and 8.16 TeV proton-lead collisions [6], corresponding to integrated luminosities of 140 fb^{-1} and 165 nb^{-1}, respectively.

2. Same-charge top-quark pair production

Motivated by the potential to observe BSM particle physics processes, a search for top-quark pairs with the same electric charge (same-sign, SS) is performed [2]. At leading order in perturbation theory, the production of SS top-quark pairs is forbidden, and the lowest-order process in the SM has a cross-section that is too small to be detected at the LHC. To search for BSM processes, the model-independent SM Effective Field Theory (SMEFT) framework is utilised, with pointlike four-fermion interactions. Three EFT operators are considered $O_{tu}^{(1)}$, $O_{Qu}^{(1)}$, and $O_{Qu}^{(8)}$, with their corresponding Wilson coefficients (WCs) $c_{tu}^{(1)}$, $c_{Qu}^{(1)}$, and $c_{Qu}^{(8)}$, and the new physics scale set to $\Lambda =$ 1 TeV.

Neural networks are trained to determine signal regions sensitive to the three WCs and to separate signal and background events. Control regions are used to constrain the normalisation of the major background processes. The results of the analysis are in agreement with the SM and place upper limits on the SS top-quark pair production cross-section and the WCs at the 95% confidence level. The observed (expected) upper limit on the SS top-quark pair production cross-section is $\sigma(pp \to tt) < 1.6(2.0)$ fb and the limits on the WCs are $|c_{tu}^{(1)}| < 0.0068(0.0071)$, $|c_{Qu}^{(1)}| < 0.020(0.022)$, and $|c_{Qu}^{(8)}| < 0.041(0.046)$. The limits on the WCs are compared to those from a previous Run 1 analysis, as shown in Figure 1. The results of this analysis represent the strongest constraints on these WCs to date, improving the previous limits by roughly a factor of 10.

3. Top quark pair production in association with heavy flavour jets

The production of top-quark pairs in association with heavy-flavour jets ($t\bar{t}$+HF) is a large, irreducible background to many analyses, such as $t\bar{t}H$ and $H \to b\bar{b}$. These $t\bar{t}$+HF processes are challenging to model due to the scale hierarchy between the $t\bar{t}$ production and the $b\bar{b}$ or $c\bar{c}$ production from gluon emission. Recent results from two ATLAS analyses measuring $t\bar{t}$ + c-jets [3] and $t\bar{t}$ + b-jets cross-sections [4] are presented.

The former analysis uses a custom flavour tagging algorithm, known as the b/c-tagger, to define regions sensitive to $t\bar{t}+ \geq 2c$ and $t\bar{t}$ + $1c$ production [3]. The corresponding fiducial cross-sections are measured, using a profile likelihood fit approach, as $\sigma^{\text{fid}}(t\bar{t}+ \geq 2c) = 1.28^{+0.27}_{-0.24}$ pb

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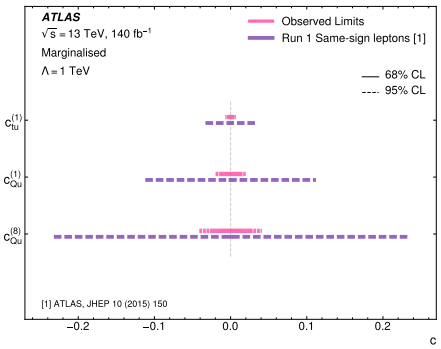

Figure 1: Comparison of the observed WC limits [2] with the cross-section limits obtained by a Run 1 ATLAS analysis, converted to limits on the WCs using the fitted EFT parameterisation [7]. The limits are shown at the 68% and 95% confidence levels, with the Run 1 limits shown only at the 95% confidence level. The SM prediction is indicated by the vertical dashed line.

and $\sigma^{\text{fid}}(t\bar{t} + 1c) = 6.4^{+1.0}_{-0.9}$ pb. Monte Carlo (MC) simulations, with matrix elements calculated at Next-to-Leading-Order (NLO) and interfaced with a parton shower (PS) algorithm (NLO+PS), yield predictions largely consistent with the measured results, but tend to underpredict the observed values, as shown in Figure 2. The dominant uncertainties on the measured cross-sections arise from uncertainties in the $t\bar{t}+ \geq 1c$ signal modelling, calibration of the b/c-tagger and data statistics. A measurement of the cross-section ratios of $t\bar{t}+ \geq 2c$ and $t\bar{t} + 1c$ to the total $t\bar{t}$+jets production was found to be $R^{\text{inc}}_{t\bar{t}+\geq 2c} = (1.23 \pm 0.25)\%$ and $R^{\text{inc}}_{t\bar{t}+1c} = (8.8 \pm 1.3)\%$ in a more inclusive phase space.

The second analysis measured the fiducial and normalised differential cross-section of $t\bar{t} + b$-jets production [4]. The fiducial cross-sections are measured in four phase spaces, defined by the number of b-jets, c-jets and light-jets, with a precision ranging from 8.5% to 16%. The cross-section results are dominated by systematic uncertainties, primarily from b-tagging, jet energy scale and $t\bar{t}$ modelling uncertainties. When compared to theoretical predictions, as shown in Figure 2, the measured fiducial cross-sections have good agreement with the $t\bar{t}b\bar{b}$ matrix element predictions. Differential cross-section measurements are performed with a precision varying from 4% to 20% in the $\geq 3b$ and $\geq 4b$ phase spaces. Most MC predictions provide a good description of the observables, with differences between the predictions generally smaller than the measurement uncertainty and the QCD scale variations in the theory predictions. This highlights the need for improved precision in the theory calculations and refinement in the measurement techniques to better distinguish between models and enhance our understanding of the $t\bar{t} + b$-jets process.

4. Test of lepton flavour universality in W-boson decays into muons and electrons

Lepton Flavour Universality (LFU) is a fundamental axiom of the SM, stating that the couplings of charged leptons to electroweak gauge bosons are independent of the lepton flavour. Recent flavour anomalies in b-hadron decays hint at departures from LFU at the level of a few standard deviations

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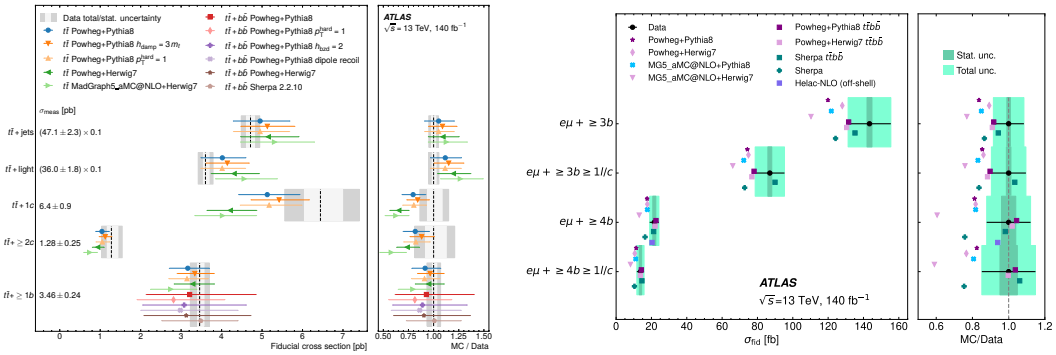

Figure 2: Measured fiducial cross-sections from the $t\bar{t}$ + c-jets ATLAS analysis [3] compared to NLO+PS predictions (left). The $t\bar{t}$+ jets and $t\bar{t}$+ light values are scaled by 0.1 for visualisation purposes. Measured fiducial cross-sections from the $t\bar{t}$ + b-jets ATLAS analysis [4] compared to NLO predictions (right). Both plots display the measured values with total and statistical uncertainties shown as boxes.

[8]. This ATLAS analysis [5] determines the ratio

$$R_{WZ}^{\mu/e} = \frac{R_W^{\mu/e}}{\sqrt{R_Z^{\mu\mu/ee}}} = \frac{\mathcal{B}(W \to \mu\nu_\mu)}{\mathcal{B}(W \to e\nu_e)} \cdot \sqrt{\frac{\mathcal{B}(Z \to ee)}{\mathcal{B}(Z \to \mu\mu)}}, \tag{1}$$

using W-bosons from top-quark decays to calculate $R_W^{\mu/e}$. To reduce lepton identification uncertainties, this ratio is normalised using $Z \to ll$ events. The final result is constructed from the measured parameter of interest $R_{WZ}^{\mu/e}$ and the precise value $R_Z^{\mu\mu/ee} = 1.0009 \pm 0.0028$, obtained from the LEP and SLD experiments [9].

A simultaneous maximum likelihood fit is performed to extract four parameters of interest, $R_{WZ}^{\mu/e}$, $R_Z^{\mu\mu/ee}$, and cross-section values for the $t\bar{t}$ and $Z \to ll$ processes, $\sigma_{t\bar{t}}$ and $\sigma_{Z\to ll}$. These are fit in the various dilepton channels, $e\mu$, $\mu\mu$ and ee, where the latter region is shown in Figure 3. The measured ratio is

$$R_W^{\mu/e} = 0.9995 \pm 0.0022(\text{stat}) \pm 0.0036(\text{syst}) \pm 0.0014(\text{ext}), \tag{2}$$

where the latter uncertainty is from the external measurement of $R_Z^{\mu\mu/ee}$. The result is dominated by systematic uncertainties from the Parton Distribution Functions (PDF), modelling and lepton uncertainties. This measurement is consistent with the SM assumption of LFU and represents the most precise measurement to date, with an uncertainty smaller than the previous world average, as shown in Figure 3.

5. Observation of top-quark pair production in proton-lead collisions

Heavy-ion collisions at the LHC involve both lead-lead (Pb+Pb) and proton-lead (p+Pb) interactions. Top quarks in ultra-relativistic Pb+Pb collisions are considered a valuable probe for studying the properties of the strongly-interacting quark-gluon plasma (QGP). Differences in event yields between Pb+Pb and pp collisions arise from initial state effects, such as differences in PDFs

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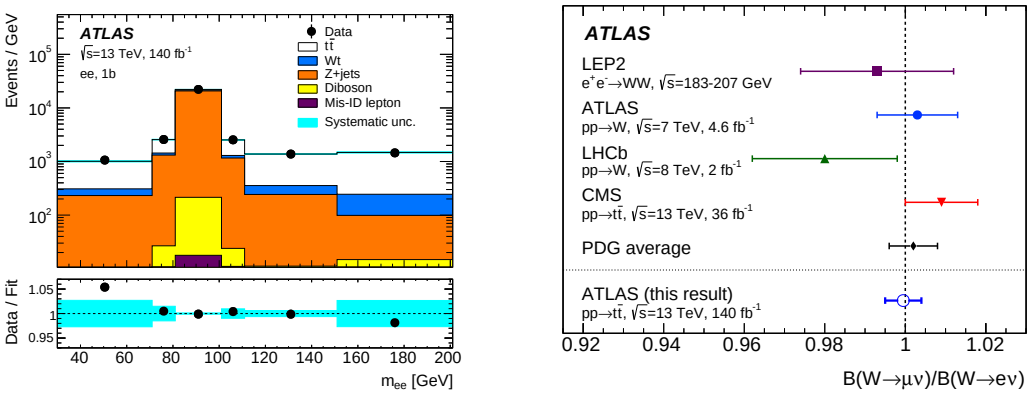

Figure 3: Invariant mass distribution after the fit to the data in the ee channel (left). The measured ratio, $R_W^{\mu/e}$, compared to the PDG average and results from the LEP2 and LHC experiments (right) [5].

between heavy nuclei and free nucleons, and final state effects, such as creation of the QGP. In order to isolate the QGP properties, knowledge of the initial state is essential, and this can be achieved using p+Pb collisions.

This measurement [6] uses a binned profile likelihood fit to extract the cross-section from the scalar sum of the transverse momenta of the leptons and heavy-ion jets, $H_{\mathrm{T}}^{l,j}$. The inclusive cross-section is measured across both dilepton and lepton+jets regions as

$$\sigma_{t\bar{t}} = 58.1 \pm 2.0(\mathrm{stat})^{+4.8}_{-4.4}(\mathrm{syst})\ \mathrm{nb} = 58.1^{+5.2}_{-4.9}(\mathrm{tot})\ \mathrm{nb}. \tag{3}$$

The measurement is limited by systematic uncertainties in the lepton+jets signal region, from the jet energy scale and signal modelling, and by statistical uncertainties in the dilepton channel. The observation of the $t\bar{t}$ process in p+Pb collisions by the ATLAS detector is established, with the background-only hypothesis rejected with a significance exceeding five standard deviations. This result provides the highest precision to date for the $t\bar{t}$ cross-section in nuclear collision

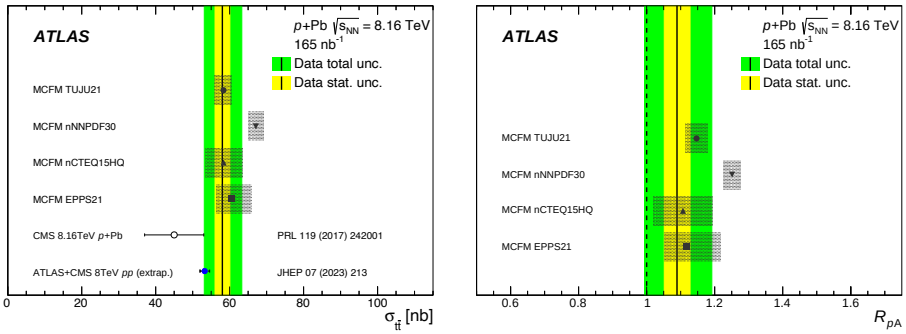

Figure 4: Measured values of $\sigma_{t\bar{t}}$ (left) and $R_{p\mathrm{A}}$ (right) compared to predicted values. The cross-section is compared to an existing CMS measurement and the combined value for $t\bar{t}$ production from pp collisions at the ATLAS and CMS collaborations at $\sqrt{s} = 8\,\mathrm{TeV}$, using the A_{Pb} factor and extrapolated to the centre-of-mass energy of this measurement [6].

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measurements. As shown in Figure 4, this measurement is in good agreement with the SM predictions and is in agreement with the CMS experiment result within 1.4 standard deviations.

In addition, this analysis makes a measurement of the nuclear modification factor for the first time at the LHC. This is defined as

$$R_{p\mathrm{A}} = \frac{\sigma_{t\bar{t}}^{p+\mathrm{Pb}}}{A_{\mathrm{Pb}} \cdot \sigma_{t\bar{t}}^{pp}}, \tag{4}$$

where the $t\bar{t}$ cross-section, $\sigma_{t\bar{t}}^{pp}$, is measured in pp collisions and the mass number of the Pb nucleus, A_{Pb}, is 208. This is measured to be

$$R_{p\mathrm{A}} = 1.090 \pm 0.039(\mathrm{stat})^{+0.094}_{-0.087}(\mathrm{syst}) = 1.090 \pm 0.100(\mathrm{tot}), \tag{5}$$

which is consistent with unity within uncertainties and shows good agreement with predicted values, as shown in Figure 4.

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