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Top-quark pair production in Pb+Pb collisions in the ATLAS experiment

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Abstract. In relativistic heavy-ion collisions, top quarks are expected to be attractive candidates for probing the quark-gluon plasma as well as to bring unique information about the time evolution of strongly interacting matter. We report the first study of top-quark pair production in lead–lead collisions at the centre-of-mass energy of 5.02 TeV with the ATLAS experiment at the LHC. The dataset was recorded in 2015 and 2018, amounting to an integrated luminosity of 1.9 nb^{-1}. Top-quark pair production cross section is studied in the $e\mu$ channel. The result is compared to theory predictions based on different nuclear PDF sets.

1 Introduction

The top quark is the only elementary particle, along with the Higgs boson, that has yet to be directly observed in lead–lead (Pb+Pb) collisions with a significance exceeding five standard deviations. As the heaviest particle carying colour charge, the top quark is expected to provide novel experimental insights into the quark-gluon plasma (QGP) [1]. In particular, hadronically decaying W bosons from top-quark decays could serve as probes of the time evolution of the QGP [2]. An observation of $t\bar{t}$ production in Pb+Pb collisions represents a critical initial milestone toward enabling more detailed investigations of the QGP.

The full Pb+Pb dataset recorded with the ATLAS detector [3] during the Run 2 campaign allows for the first observation of top-quark pair production with a significance of five standard deviations [4]. The data were obtained in 2015 and 2018 at a nucleon–nucleon centre-of-mass energy of $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, corresponding to the total integrated luminosity of 0.5 nb^{-1} and 1.4 nb^{-1}, respectively. The data were collected under low-pileup conditions with an average number of interactions per bunch crossing of $\langle\mu\rangle = 1.76 \cdot 10^{-3}$ and $\langle\mu\rangle = 2.58 \cdot 10^{-3}$ in 2015 and 2018, respectively.

2 Event selection

Top-quark pairs candidates are reconstructed using events with exactly one electron and one muon. Single-electron and single-muon triggers are employed, with minimum p_{T} requirements of 15 and 8 GeV, respectively [5]. Exactly one primary vertex is required, reconstructed

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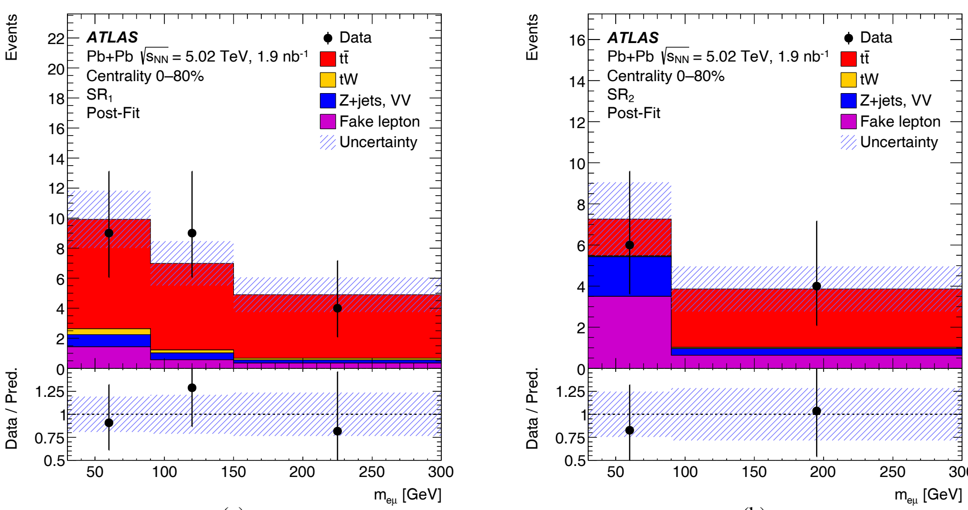
from at least two good-quality charged-particle tracks with $p_T > 0.5$ GeV. Electron (muon) candidates must have $p_T > 18$ (15) GeV and $|\eta| < 2.47$ (2.5), and satisfy 'Loose' identification and isolation criteria [6, 7]. Jets are reconstructed using the anti-k_t algorithm [8] with a radius parameter $R = 0.4$, and are required to have $p_T > 35$ GeV and $|\eta| < 2.5$. The background energy from the underlying event is subtracted on an event-by-event basis. A fake-lepton background contribution is evaluated from data using data-driven techniques.

Events in the electron–muon ($e\mu$) channel of the $t\bar{t}$ decay are studied in the measurement. Only events in the 0–80% centrality interval are used, to avoid contributions from photon-induced processes. Final states containing exactly one oppositely charged $e\mu$ pair are selected. The invariant mass of the $e\mu$ pair, $m_{e\mu}$, has to be above 30 GeV, to minimise the fake-lepton background contribution. At least two jets are required in a given event. Two signal regions (SR_1 and SR_2) are constructed, where events with dilepton transverse momentum $p_T^{e\mu} > 40$ GeV form SR_1, and the remaining events constitute SR_2.

3 Analysis strategy

The signal strength, $\mu_{t\bar{t}}$, is defined as the ratio of the observed $t\bar{t}$ cross section to the Standard Model expectation with no nuclear parton distribution function (nPDF) effects involved. A profile-likelihood method [9] is used to extract $\mu_{t\bar{t}}$ using the $e\mu$ channel of $t\bar{t}$ decays. The value of $\mu_{t\bar{t}}$ is obtained by the simultaneous fit to the $m_{e\mu}$ distributions in the two signal regions. Figure 1 shows a comparison between the $m_{e\mu}$ distributions in data and a sum of predictions in SR_1 and SR_2 after the fit.

Systematic uncertainties affecting the measurement arise from electron, muon, and jet reconstruction, fake-lepton background estimation, the signal and background modelling, and the integrated luminosity. The main sources of systematic uncertainty originate from the modelling of the $t\bar{t}$ process and jet performance. The total relative systematic uncertainty in the measurement amounts to 18%.



(a) (b)

Figure 1. Post-fit distributions of the the $m_{e\mu}$ variable in (a) SR_1 and (d) SR_2, with total uncertainties represented by the hatched area. The bottom panels show ratios of data and a sum of predictions [4].

4 Results

The measured $\mu_{t\bar{t}}$ value is converted into the inclusive $t\bar{t}$ production cross section in Pb+Pb collisions in the 0-100% centrality interval. The measured $t\bar{t}$ cross section in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV is

$$\sigma_{t\bar{t}}^{\mathrm{Pb+Pb}} = 3.6 \,^{+1.0}_{-0.9}\,(\mathrm{stat.}) \,^{+0.8}_{-0.5}\,(\mathrm{syst.})\ \mu\mathrm{b} = 3.6 \,^{+1.2}_{-1.0}\,(\mathrm{tot.})\ \mu\mathrm{b}. \quad (1)$$

The total relative uncertainty amounts to 31% and is dominated by the statistical component of 26%. The observed significance of the measurement is 5.0 standard deviations, leading to the first observation of the $t\bar{t}$ process in Pb+Pb collisions.

Figure 2 shows a comparison of the obtained $t\bar{t}$ cross section with other measurements and theoretical models. Good agreement is found with predictions based on four nPDF sets: TUJU21 [10], nNNPDF3.0 [11], nCTEQ15HQ [12], and EPPS21 [13]. The result is consistent within the total uncertainties with the $t\bar{t}$ cross section reported by CMS [14]. The measurement is also in agreement with the $t\bar{t}$ cross section in pp collisions at $\sqrt{s} = 5.02$ TeV by ATLAS [15], scaled to the Pb+Pb system by the lead mass number squared, A^2_{Pb} ($A_{\mathrm{Pb}} = 208$).

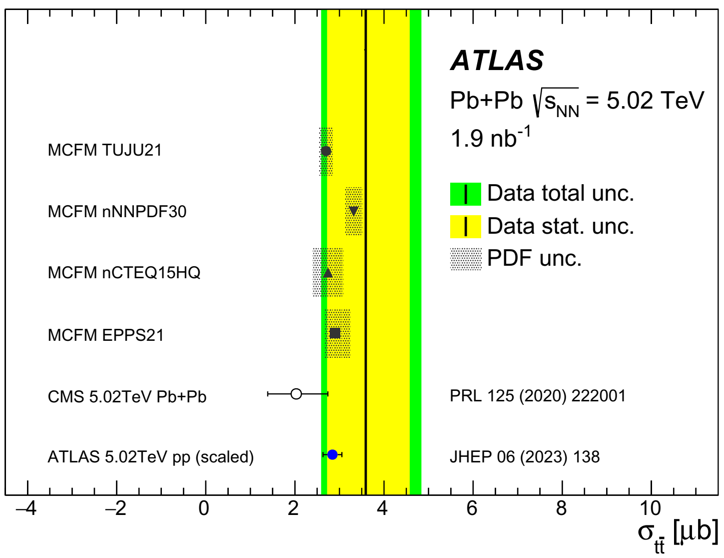


Figure 2. Comparison of the $t\bar{t}$ cross section with the evidence reported by CMS [14] and the scaled measurement in pp collisions by ATLAS [15], along with theoretical predictions based on four nPDF sets [4].

5 Conclusions

The $t\bar{t}$ process is observed in the $e\mu$ channel in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV with the significance of 5.0 standard deviations for the first time. The inclusive $t\bar{t}$ cross section is measured with the total relative uncertainty of 31%, resulting in the most precise measurement of the $t\bar{t}$ process in Pb+Pb collisions to date.

This result paves a new way for further studies of QGP properties at the LHC. The first observation of the $t\bar{t}$ process establishes analysis methods for top-quark production in heavy-ion collisions and opens a possibility of studying the QGP time evolution via hadronically decaying W bosons from top-quark decays.

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