Probing initial state effects in nuclear collisions via jet and top-quark measurements with the ATLAS detector

Patrycja Potępa[1,2,*] on behalf of the ATLAS Collaboration

[1]AGH University of Krakow, al. Adama Mickiewicza 30, 30-059 Kraków, Poland
[2]Johannes Gutenberg University Mainz, Saarstr. 21, 55122 Mainz, Germany

Abstract. Proton-lead collisions at the Large Hadron Collider energies offer a unique possibility to investigate initial state effects in nuclear collisions. Thanks to its wide acceptance, ATLAS can measure several probes that can help characterise these effects over a wide kinematic range. By analyzing the centrality dependence of dijet production, it is possible to investigate the suppression of dijet events in central collisions compared to peripheral ones and correlate it to the kinematic of the parton-parton scattering, accessible via the measurement of both jets in the final state. Also, the first measurement of the inclusive cross-section for top-quark pair production in dilepton and lepton+jet decay modes is reported. This process is sensitive to effects at high Bjorken-x values, which are hard to access experimentally using other available probes, and thus provides complementary information on the behavior of nuclear parton densities. In 2016, the ATLAS experiment collected 165 nb^{-1} of proton-lead collisions at a center-of-mass energy of 8.16 TeV per nucleon pair. In this article, new measurements of the centrality dependence of dijet production and the observation of top-quark pair production using this dataset are presented.

1 Introduction

Ultra-relativistic heavy-ion (HI) collisions at the Large Hadron Collider (LHC) provide unique opportunities to study initial-state effects in nuclear collisions. Measuring high transverse momentum (p_{T}) probes produced over a broad kinematic range allows to investigate modifications to parton distribution functions (nPDF) [1]. A wide acceptance of the ATLAS detector [2] offers a possibility to measure several probes, including jets and top quarks.

The presented measurements use proton-lead (p+Pb) data collected with the ATLAS detector during the data-taking period in 2016, corresponding to an integrated luminosity of 165 nb^{-1}. The proton and lead-ion beams had an energy of 6.5 TeV and 2.56 TeV per nucleon, respectively, resulting in a nucleon–nucleon center-of-mass collision energy of 8.16 TeV and a rapidity boost by +0.465 units in the p-going direction relative to the laboratory frame.

*e-mail: patrycja.potepa@cern.ch

2 Centrality dependence of the dijet yield in *p*+Pb collisions

Hard p+Pb scatterings involving configurations of the proton with a large-x parton are characterized by a smaller than average size and interaction strength [3]. Centrality dependence of the dijet yield has been reported by ATLAS in p+Pb collisions [4]. Triple differential per-event dijet yields are extracted as a function of average transverse momentum ($p_{\mathrm{T,Avg}} = (p_{\mathrm{T},1} + p_{\mathrm{T},2})/2$), boost of the dijet system ($y_{\mathrm{b}} = (y_1^{\mathrm{CM}} + y_2^{\mathrm{CM}})/2$) and dijet half rapidity separation ($y^* = |y_1^{\mathrm{CM}} - y_2^{\mathrm{CM}}|/2$). CM stands for variables translated in the center-of-mass frame, while the subscripts 1 and 2 refer to the highest (leading) and second-highest (sub-leading) p_{T} jets in an event, respectively. Positive (negative) rapidities correspond to the p-going (Pb-going) direction. Centrality is characterized using the total transverse energy deposit in the forward calorimeters ($\Sigma E_{\mathrm{T}}^{\mathrm{Pb}}$), measured in the Pb-going direction.

Selected events must satisfy detector and data-quality requirements, and contain at least two reconstructed jets with p_{T} above 40 and 30 GeV. Jets are reconstructed using the anti-k_t algorithm [5] with $R = 0.4$ radius using massless calorimeter towers. Monte Carlo (MC) simulation is used to evaluate jet reconstruction efficiency and perform the unfolding procedure [6]. Dijet events in pp collisions are simulated using Pythia v8 [7] MC generator and overlaid with minimum-bias p+Pb collisions recorded by ATLAS in 2016.

Nuclear modification effects can be characterized by the ratio of the hard scattering rates in the presence and absence of the nuclear environment. The measured dijet yields allow to construct a central-to-peripheral ratio, defined as follows

$$R_{\mathrm{CP}}^{\frac{0-10\%}{60-90\%}}(p_{\mathrm{T,Avg}}, y_{\mathrm{b}}, y^*) = \frac{\frac{1}{\langle T_{\mathrm{AB}}^{0-10\%}\rangle} \frac{1}{N_{\mathrm{evt}}^{0-10\%}} \frac{\mathrm{d}^3 N_{\mathrm{dijet}}^{0-10\%}}{\mathrm{d}p_{\mathrm{T,avg}}\mathrm{d}y_{\mathrm{b}}\mathrm{d}y^*}}{\frac{1}{\langle T_{\mathrm{AB}}^{60-90\%}\rangle} \frac{1}{N_{\mathrm{evt}}^{60-90\%}} \frac{\mathrm{d}^3 N_{\mathrm{dijet}}^{60-90\%}}{\mathrm{d}p_{\mathrm{T,avg}}\mathrm{d}y_{\mathrm{b}}\mathrm{d}y^*}}, \tag{1}$$

where $N_{\mathrm{evt}}^{0-10\%}$ ($N_{\mathrm{evt}}^{60-90\%}$) and $N_{\mathrm{dijet}}^{0-10\%}$ ($N_{\mathrm{dijet}}^{60-90\%}$) denote the number of minimum-bias and dijet events in central (peripheral) collisions, respectively. The average value of the nuclear thickness function in a given centrality class, $\langle T_{\mathrm{AB}}\rangle$, is obtained from the Glauber MC model [8].

Figure 1 shows R_{CP} results as a function of approximated longitudinal momentum fractions $\langle x_p\rangle$ and $\langle x_{\mathrm{Pb}}\rangle$. A distinct x_p-scaling of $R_{\mathrm{CP}}(x_p)$, characterised by a log-linear decreasing trend, is found in the valence quark dominated region. The scaling disappears at smaller x_p values. Separate log-linear trends with increasing suppression are observed for $R_{\mathrm{CP}}(x_{\mathrm{Pb}})$ in each slice in y_{b}. A comparison with inclusive jet R_{CP} at 5.02 TeV measured by ATLAS [9] shows a good agreement in high-x_p region, proving that the observed scaling is governed by similar physics phenomena, most likely related to color fluctuation effects [3].

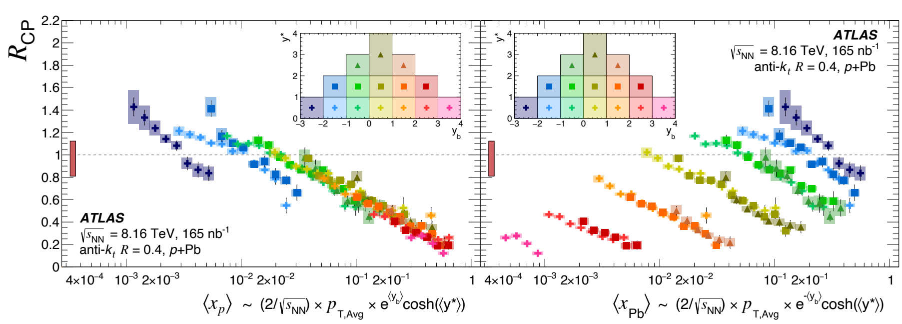


Figure 1: R_{CP} as a function of approximated x_p (left panel) and x_{Pb} (right panel) [4]. Shaded rectangles and vertical error bars represent the systematic and statistical uncertainty, respectively. Solid rectangles on the left-side stand for the uncertainty on the T_{AB}.

3 Observation of $t\bar{t}$ production in lepton+jets and dilepton channels in p+Pb collisions

The top quark provides a novel probe of nPDF in a poorly constrained kinematic region [10]. Top quark-antiquark pair ($t\bar{t}$) production cross section in p+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV has been measured by ATLAS [11]. Top-quark pairs are reconstructed using final states with electrons and muons. Reconstructed electron (muon) candidates must have $p_{\mathrm{T}} > 18$ GeV and $|\eta| < 2.47$ (2.5), and pass 'Medium' identification and isolation criteria. Jets are reconstructed using the anti-k_t algorithm [5] with a radius parameter $R = 0.4$. Jets likely to originate from b-quarks are tagged using the DL1r algorithm [12]. A fake-lepton background contribution is directly estimated from data using the Matrix Method technique [13].

MC simulation samples are used to estimate signal and background contributions, evaluate signal efficiencies, and compare prediction with data. The signal $t\bar{t}$ simulation is produced using the next-to-leading-order event generator Powheg Box v2 [14] interfaced with Pythia v8 [7]. Events from MC samples are embedded into minimum-bias p+Pb collisions.

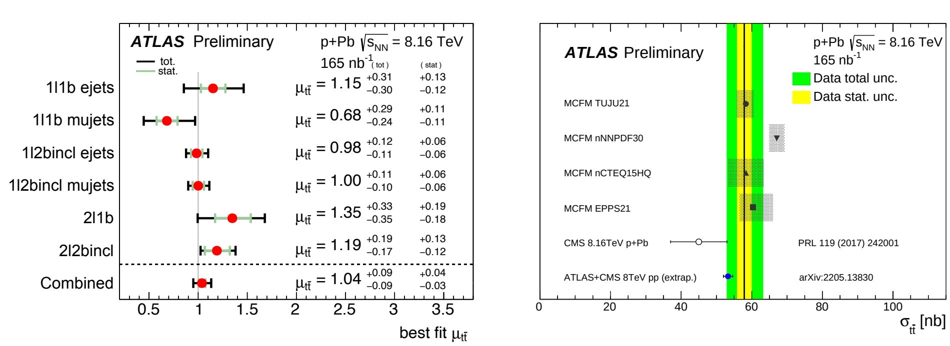
Selected events with exactly one lepton (electron or muon) and at least four jets form the ℓ+jets channel, while the dilepton channel consists of events with exactly two opposite-sign leptons and at least two jets. The ℓ+jets channel is split into four signal regions with one electron or muon and exactly one or at least two b-tagged jets, labelled as $1\ell 1b$ ejets, $1\ell 2b$incl ejets, $1\ell 1b$ mujets and $1\ell 2b$incl mujets. Signal regions in the dilepton channel with exactly one or at least two b-tagged jets are labelled as $2\ell 1b$ and $2\ell 2b$incl, respectively.

The signal strength $\mu_{t\bar{t}}$, which is defined as the ratio of the observed signal yield to the Standard Model expectation, is obtained using a profile-likelihood method [15]. The parameter $\mu_{t\bar{t}}$ is determined by the fit to the $H_{\mathrm{T}}^{\ell\mathrm{jet}}$ data distributions in the six signal regions, where the $H_{\mathrm{T}}^{\ell\mathrm{jet}}$ is the scalar sum of the transverse momenta of the leptons and jets.

The measured inclusive $t\bar{t}$ cross section in the combined ℓ+jets and dilepton channel is

$$\sigma_{t\bar{t}} = 57.9 \pm 2.0\ (\mathrm{stat.})\ ^{+4.9}_{-4.5}\ (\mathrm{syst.})\ \mathrm{nb} = 57.9\ ^{+5.3}_{-4.9}\ (\mathrm{tot.})\ \mathrm{nb}.$$

The total relative uncertainty of 9% is dominated by the systematic contribution. Figure 2a shows $\mu_{t\bar{t}}$ values obtained in each signal region separately and in the combined fit. The highest significance comes from the ℓ+jets channel with at least 2 b-tagged jets. Figure 2b presents a comparison of the obtained $t\bar{t}$ cross section with the CMS result [16], the combined measurement in pp collisions by ATLAS and CMS [17] extrapolated to the center-of-mass energy of 8.16 TeV and scaled by the lead mass number A_{Pb}, and predictions using four nPDF sets [18–21]. A good agreement is found with other measurements and theory calculations.



(a) (b)

Figure 2: Signal strengths with total and statistical uncertainties in different fit regions (a) and comparison between observed and predicted values of $t\bar{t}$ cross section (b) [11].

4 Conclusions

Initial-state effects have been studied in p+Pb collisions at 8.16 TeV recorded by ATLAS in 2016. The total integrated luminosity of 165 nb^{-1} allows to investigate these effects via processes involving jet and top quarks.

The measurement of the centrality dependence of the dijet yield in p+Pb collisions has been reported. The R_{CP} is measured as a function of approximated kinematics of the hard parton-parton scattering. A distinct x_p-scaling of the R_{CP} is found in the valence quark dominance region of the proton. A comparison with inclusive jet R_{CP} at 5.02 TeV measured by ATLAS [9] shows a good agreement in high-x_p region, proving that the observed trend is governed by similar physics phenomenas. Presented results are qualitatively in agreement with the x_p-dependent color fluctuation effects.

The first measurement of $t\bar{t}$ production in p+Pb collisions by ATLAS has been presented. The $t\bar{t}$ production is observed separately in the ℓ+jets and dilepton channels with significance exceeding 5 standard deviations, resulting in the first observation of $t\bar{t}$ production in the dilepton channel in the p+Pb system at the LHC. The total relative uncertainty of 9% makes it the most precise $t\bar{t}$ cross-section measurement in HI collisions to date. With the precision of this measurement, it paves a new way to constrain nPDFs in the high Bjorken-x region.

Acknowledgements

This work was partly supported by the National Science Centre of Poland under the grant number UMO-2020/37/B/ST2/01043 and by PL-Grid Infrastructure.

References

[1] H. Khanpour, S. Atashbar Tehrani, Phys. Rev. D **93**, 014026 (2016)
[2] ATLAS Collaboration, JINST **3**, S08003 (2008)
[3] M. Alvioli, L. Frankfurt, D. Perepelitsa et al., Phys. Rev. D **98**, 071502 (2018)
[4] ATLAS Collaboration (2023), arXiv: 2309.00033
[5] M. Cacciari, G. Salam, G. Soyez, JHEP **04**, 063 (2008)
[6] G. D'Agostini, Nucl. Instrum. Meth. A **362**, 487 (1995)
[7] T. Sjöstrand, S. Mrenna, P. Skands, Comput. Phys. Commun. **178**, 852 (2008)
[8] B. Alver, M. Baker, C. Loizides et al. (2008), arXiv: 0805.4411
[9] ATLAS Collaboration, Phys. Rev. B **748**, 392 (2015)
[10] D. d'Enterria, K. Krajczár, H. Paukkunen, Phys. Rev. B **746**, 64–72 (2015)
[11] ATLAS Collaboration, ATLAS-CONF-2023-063 (2023)
[12] ATLAS Collaboration, Eur. Phys. J. C **79**, 970 (2019)
[13] ATLAS Collaboration (2022), arXiv: 2211.16178
[14] S. Alioli, P. Nason, C. Oleari et al., JHEP **06**, 43 (2010)
[15] G. Cowan, K. Cranmer, E. Gross et al., Eur. Phys. J. C **71**, 1554 (2011)
[16] CMS Collaboration, Phys. Rev. Lett. **119**, 242001 (2017)
[17] ATLAS, CMS Collaborations, JHEP **07**, 213 (2023)
[18] I. Helenius, M. Walt, W. Vogelsang (2022), arXiv: 2207.04654
[19] M. Ubiali (2014), arXiv: 1407.3122
[20] A. Kusina, T. Ježo, D.B. Clark et al., Eur. Phys. J. C **80**, 968 (2020)
[21] K.J. Eskola, P. Paakkinen, H. Paukkunen et al. (2021), arXiv: 2106.13661