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Recent ATLAS results relevant for PDFs at low and high x, saturation in both *pp* and HI collisions[***]

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These proceedings summarise the results of three major studies of nuclear parton distribution functions (nPDFs) from high-energy collisions at the CERN LHC. The first study examines top quark pair production in p+Pb collisions, investigating nPDF modifications at high Bjorken x. The second study analyses the centrality dependence of dijet yields in p+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV}$, revealing scaling behaviour with Bjorken x. The final study presents photon-nuclear production of dijets in ultraperipheral Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$, providing insights into low-x gluon distributions. Collectively, these results enhance the understanding of nPDFs and lay a foundation for future investigations into photonuclear interactions and gluon saturation phenomena.

1. Introduction

The study of nPDFs is crucial for understanding the internal structure of nuclei and their interactions at high energies. Ultraperipheral collisions (UPCs) and proton-nucleus (p+A) collisions provide unique environments to probe these functions through photon-induced processes and high-energy parton interactions. These proceedings consolidate the results of three major studies carried out at the ATLAS detector, investigating different aspects of nPDFs under different collision conditions.

2. ATLAS detector

The ATLAS detector at the LHC is a versatile, general-purpose instrument designed to study a broad range of physics phenomena. With nearly full 4π coverage, the detector comprises several key subsystems, including

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the Inner Detector (ID), electromagnetic and hadronic calorimeters, and a muon spectrometer [1]. The detector's calorimeter system provides comprehensive coverage for jet measurements, while the inner detector enables precise tracking of charged particles. ATLAS provides extensive pseudorapidity coverage, with $|\eta|$ up to 4.9, and features high-precision electromagnetic and hadronic calorimeters, which are essential for the accurate reconstruction of jet kinematics. This design allows the ATLAS detector to perform a wide range of measurements, making it an essential tool for studying LHC particle collisions.

3. Observation of top-quark pair production in p+Pb collisions in the ATLAS experiment

The observation of top-quark pair production in proton-lead (p+Pb) collisions provides a new probe to study nPDFs and their modification in nuclear matter. These studies provide insight into parton dynamics at high Bjorken-x and high Q^2, which are crucial for understanding gluon distributions in nuclei. In addition, due to their large mass, top quarks serve as valuable probes of the quark-gluon plasma (QGP) in ultra-relativistic heavy ion collisions [2].

3.1. Event selection and signal and background modelling

The data, collected in 2016, correspond to an integrated luminosity of 165 nb^{-1} from p+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV. Electrons and muons with high transverse momentum ($p_{\mathrm{T}} > 18$ GeV) were selected for the analysis. Two primary channels were considered: the lepton+jets channel, which includes one high-p_{T} lepton and at least four jets (with one b-tagged), and the dilepton channel, which consists of two opposite-sign leptons, at least two jets, and at least one b-tagged jet. The Lepton+jets channel is further divided into $1\ell 1b$ and $1\ell 2b$ regions for e+jets and μ+jets, while the Dilepton channel is categorized into $2\ell 1b$ and $2\ell 2b$ regions. Backgrounds from fake and non-prompt leptons are estimated using a data-driven matrix method [3].

Signal modelling was performed using Monte Carlo samples generated with POWHEG BOX v2, interfaced with PYTHIA for parton-shower modelling. Systematic uncertainties were evaluated with HERWIG 7.2, while backgrounds from W+jets, Z+jets, single top, and diboson processes were modelled with SHERPA v2.2.10. Nuclear effects on the $t\bar{t}$ cross-section in proton-lead collisions, including anti-shadowing and the EMC effect, have been included using NNLO QCD calculations with nPDF sets such as EPPS21 and nNNPDF30.

3.2. Results

The top quark pair production cross-section was measured in both the lepton+jets and the dilepton channels. The inclusive cross-section for $t\bar{t}$ production was found to be $\sigma_{t\bar{t}} = 58.1 \pm 2.0\,(\text{stat.})^{+4.8}_{-4.4}\,(\text{stat.})\,\text{nb}$.

The nuclear modification factor, $R_{p\text{A}}$, quantifies deviations from binary collision scaling in p+A collisions. A value of $R_{p\text{A}} = 1$ indicates no nuclear modification, while deviations from unity indicate nuclear effects such as shadowing, saturation or energy loss. This factor was first measured at the LHC for the production of $t\bar{t}$: $R_{p\text{A}} = 1.090 \pm 0.039\,(\text{stat.})^{+0.094}_{-0.087}\,(\text{stat.})$.

This result is in agreement with theoretical predictions and indicates a slight enhancement of $t\bar{t}$ production in proton-lead collisions compared to proton-proton collisions. The measured $\mu_{t\bar{t}}$ value, which represents the signal strength (ratio of observed to expected cross-section), is 1.04 ± 0.09 for the combined analysis of all channels; the results of the individual channels are shown in Figure 1.

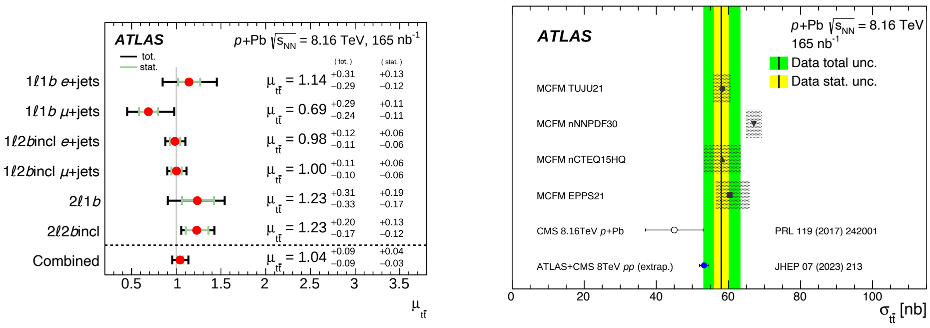

Fig. 1. (a) Signal strength values in different channels, and (b) comparison of theoretical predictions using different nPDF sets with the measured cross-section [2].

The results were also compared with previous measurements by the CMS collaboration, which observed $t\bar{t}$ production in p+Pb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV with lower precision [4].

4. Measurement of the Centrality Dependence of the Dijet Yield in p+Pb Collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV with the ATLAS Detector

High transverse momentum processes, such as dijet production, are sensitive to nuclear modifications in parton distribution functions (nPDFs), especially within high-density nuclear environments. This study [5] investigates the centrality dependence of dijet yields in p+Pb collisions, where centrality, which reflects the collision impact parameter, is experimentally determined using the total transverse energy in the Pb-going forward calorimeter. Previous studies [6, 7] have shown that nuclear modifications vary with Bjorken-x, suggesting significant implications for gluon distributions at small x in nuclei.

4.1. Event selection and signal and background modelling

The data used for this study were collected by the ATLAS detector at the LHC in 2016, corresponding to an integrated luminosity of 165 nb^{-1}. Dijet events were selected using reconstructed jets from the anti-k_t algorithm with a radius parameter $R = 0.4$. Jets passing specified p_{T} and η thresholds were selected, with leading and subleading jets required to meet $p_{\mathrm{T}} > 40$ GeV and $p_{\mathrm{T}} > 30$ GeV, respectively.

Centrality classes were defined based on transverse energy in the forward calorimeter (Pb-going direction), allowing classification into central (0%-10%) and peripheral (60%-90%) collisions. This categorisation provided a means to explore nuclear modification effects across collision geometries.

Dijet events were characterised by p_{T}, rapidity boost (y_{b}), and rapidity separation (y^*) in the center-of-mass frame. Centrality-dependent yields were calculated using a Glauber Monte Carlo model to account for nuclear overlap.

Monte Carlo (MC) samples for dijet production were generated using PYTHIA 8, with event-by-event fluctuations in the underlying event (UE) modelled by overlaying minimum-bias p+Pb collisions. A one-dimensional Bayesian unfolding method [8] was applied to correct detector resolution effects and efficiency losses, especially in specific rapidity regions.

4.2. Results

The central-to-peripheral ratio R_{CP} is defined as:

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

where $\langle T_{AB}\rangle$ is the nuclear thickness function. The R_{CP} values showed suppression dependent on x_{p}, especially prominent in the high-x_{p} region dominated by valence quark contributions. No significant scaling relative to x_{Pb} was observed, suggesting minimal gluon saturation effects within the studied kinematic range.

Figure 2 presents R_{CP} as a function of Bjorken-x_{p}, demonstrating a decreasing trend with increasing x_{p}, which aligns with theoretical models incorporating colour fluctuation effects. These results agree with previous findings [7] and support models linking large-x partons with reduced colour screening.

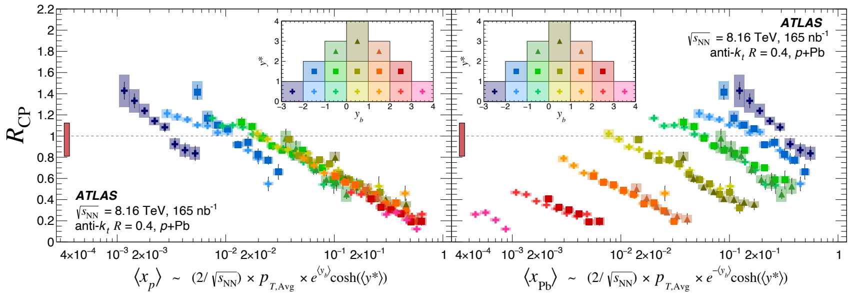

Fig. 2. $R_{\rm CP}$ as a function of approximated $x_{\rm p}$ (left panel) and $x_{\rm Pb}$ (right panel). Shaded rectangles and vertical error bars represent the systematic and statistical uncertainties, respectively. Solid rectangles on the left side indicate the uncertainty on the T_{AB}.

5. Photo-nuclear Jet Production in Ultra-peripheral Pb+Pb Collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV with the ATLAS Detector

The study of high-energy UPCs with a heavy nucleus, such as Pb+Pb, provides a powerful probe of nPDFs through the interaction of quasi-real photons with partons in the opposing nucleus. These γ+A processes are sensitive to gluon distributions at low x, where nuclear shadowing effects are significant. In contrast to proton-lead (p+Pb) collisions, UPCs provide a cleaner environment for the isolation of photon-induced processes, as the photon-emitting nucleus remains intact without hadronic breakup. This work [9] builds on previous measurements in p+Pb collisions [10] and aims to provide new insights into photonuclear interactions at unprecedented energy scales.

5.1. Event selection and signal and background modelling

The data for this analysis were recorded by the ATLAS detector during the 2018 Pb+Pb collision run at the LHC, corresponding to an integrated luminosity of 1.72 nb^{-1}.

Photo-nuclear events are identified by selecting interactions with a 0nXn signature in the Zero Degree Calorimeters (ZDC), ensuring no neutrons in the photon-going direction and at least one neutron in the opposite direction. This criterion reduces contamination from hadronic processes, isolating γ+A interactions. Additional event selections are applied based on rapidity gap requirements and minimum transverse energy ($\sum E_{\mathrm{T}}$) threshold to further confirm the ultra-peripheral nature of the collision. MC samples of γ+A interactions are generated using PYTHIA 8 with nCTEQ15 nPDFs and the A14 tune, modelling both direct and resolved contributions. The detector response is simulated using GEANT 4. The MC sample includes various jet configurations to cover the kinematic range of interest in H_T, x_A, and z_γ.

The differential cross-sections for dijet production are measured as functions of H_T, the nuclear parton momentum fraction x_A, and the photon parton momentum fraction z_γ. These variables are defined as:

$$H_T = \sum_i p_{T,i}, \quad x_A = \frac{M_{jj}}{\sqrt{s_{\mathrm{NN}}}} e^{-y_{jj}}, \quad z_\gamma = \frac{M_{jj}}{\sqrt{s_{\mathrm{NN}}}} e^{y_{jj}} \tag{2}$$

where M_{jj} and y_{jj} represent the invariant mass and rapidity of the jet system, respectively.

5.2. Results

This analysis provides valuable insights into nuclear parton dynamics and modification effects. Cross-sections are systematically studied as functions of key kinematic variables—x_A, H_T, and z_γ—to investigate parton distribution functions (PDFs) and their behaviour in a nuclear environment. The results reveal significant nuclear modification effects, including shadowing at low x_A, which directly impacts gluon distributions and enhances the understanding of parton behaviour within nuclear media.

These findings are compared with theoretical models, including PYTHIA with nCTEQ15 PDFs and nuclear photon flux calculations, to assess their accuracy in describing high-energy photonuclear interactions. In-situ comparisons are used to reduce the uncertainties associated with JES and JER, while the stability of the unfolding method is verified through pseudo-experiments. The uncertainty associated with luminosity is tightly constrained at 2.0%, ensuring the reliability of the measurements. Additionally, statistical uncertainties are carefully examined to evaluate their impact on the precision of differential cross-sections, further reinforcing the robustness of the results.

This study's high-precision measurements reveal cross-section trends, showing scaling behaviour with z_γ and low-x suppression consistent with nuclear shadowing and reduced parton densities. These results provide a critical benchmark for theoretical models and enhance our understanding of low-x parton dynamics, aiding global PDF fits in nuclear and particle physics.

6. Conclusion

The studies presented here provide significant advances in the understanding of nPDFs at both high and low Bjorken x. Top-quark pair production in p+Pb collisions provides new insights into high-x modifications, while centrality-dependent dijet yields explore nuclear effects across collision geometries, highlighting suppression at high x. In addition, photon-nuclear dijet production in ultra-peripheral Pb+Pb collisions sheds light on low x gluon behaviour, demonstrating the impact of nuclear shadowing. Taken together, these results from the ATLAS experiment provide valuable insights that inform nPDF models and deepen the study of gluon saturation and nuclear effects in high-energy collisions.

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