Probing initial state effects in nuclear collisions via dijet and spectator neutron measurements with the ATLAS detector

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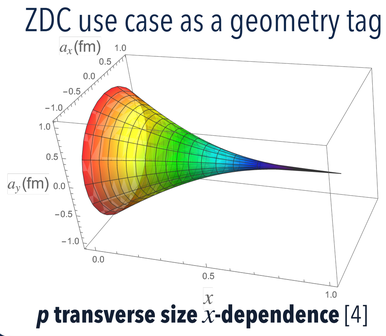
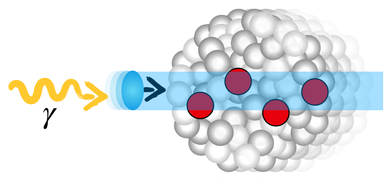
Motivation: is the proton's size fluctuating?

- p containing high-x partons are associated with small configurations, characterized by reduced interaction strength and less UE activity. This is a manifestation of color fluctuations (CFs) [3].
- Nuclear breakup in p+A collisions at LHC energies is still poorly understood.
- Recent increase in interest in how CF effects influence nuclear breakup in resolved UPC [5]. Constrain ZDC use case as a geometry tag in e+A collisions at EIC [6].

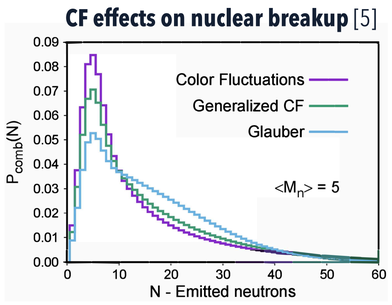


p transverse size x-dependence [4]



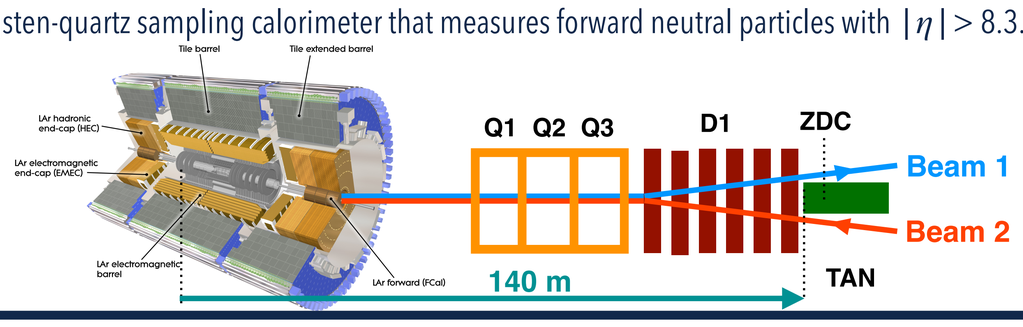
Resolved γ in UPC

CF effects on nuclear breakup [5]

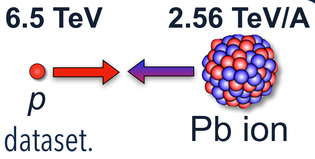


The ATLAS Calorimeter System

The ATLAS [1] calorimeter system consists of a liquid-argon (LAr) EM calorimeter, a steel sampling hadronic calorimeter, a LAr hadronic end-cap calorimeter, and two LAr forward calorimeters. The system has coverage out to $|\eta| < 4.9$, allowing for jet measurements over a broad range of rapidities. The LAr forward calorimeters (FCal) provide coverage from $3.2 < |\eta| < 4.9$. The ATLAS Zero Degree Calorimeter (ZDC) consists of two detectors located in absorbers ±140 m from the interaction point. Each detector is a tungsten-quartz sampling calorimeter that measures forward neutral particles with $|\eta| > 8.3$.



Details of the Measurements



- Probe hard-scattering dependent effects using dijets to access initial state.
- Measurements use anti-k_t $R = 0.4$ jets at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV in 2016 p+Pb dataset.
- Centrality intervals are defined by the total transverse energy in the Pb-going FCal, $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}}$.

$$p_{\mathrm{T},1} > 40\ \mathrm{GeV}, \quad p_{\mathrm{T},2} > 30\ \mathrm{GeV}, \quad \text{and} \quad -2.8 < \eta < 4.5$$

Dijet R_{cp} Measurement

- 1D bayesian unfolding in $p_{\mathrm{T,Avg}}$ + efficiency correction for any residual y_{b} or y^* migration.

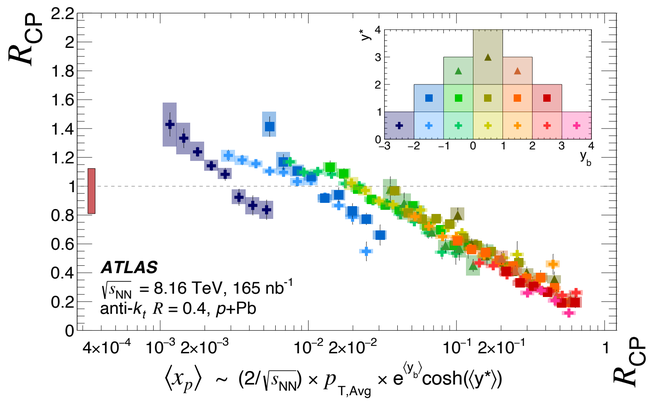
$$p_{\mathrm{T,Avg}} = \frac{p_{\mathrm{T},1} + p_{\mathrm{T},2}}{2}, \quad y_{\mathrm{b}} = \frac{y_1^{\mathrm{CM}} + y_2^{\mathrm{CM}}}{2}, \quad y^* = \frac{|y_1^{\mathrm{CM}} - y_2^{\mathrm{CM}}|}{2}$$

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

Forward Neutrons & E_T Measurement

- Measure p+A event geometry estimators (**ZDC** Energy & Transverse FCal Energy) on side facing Pb fragments. $E_{\mathrm{ZDC}}^{\mathrm{Pb}}$ $\mathrm{FCal}\,\Sigma\,E_{\mathrm{T}}^{\mathrm{Pb}}$
- **Directly** estimate Bjorken-x of the proton at hadron level
- Bayesian unfolding in x_p, No unfolding in $E_{\mathrm{ZDC}}^{\mathrm{Pb}}/\mathrm{FCal}\,\Sigma\,E_{\mathrm{T}}^{\mathrm{Pb}}$

Probing CFs through a Central-to-Peripheral Ratio, R_{CP}

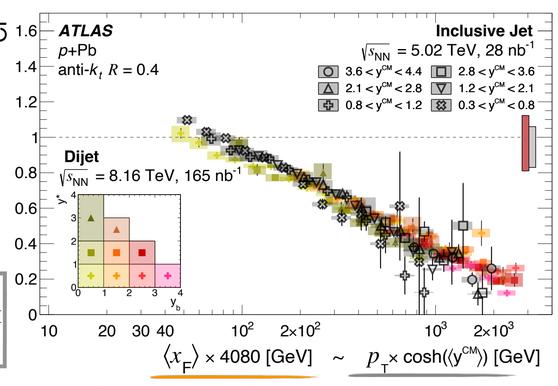


- Access x_p via $x_p \simeq \frac{2p_{\mathrm{T,Avg}}}{\sqrt{s_{\mathrm{NN}}}} e^{y_b}\cosh(y^*)$
- Strong **log-linear x_p-scaling** observed when moving toward the **proton's valence dominance region.** This trend breaks down when approaching low-x_p(↔ high x_{Pb}).
- Direct link to 5.02 TeV inclusive jet results [2] achievable thanks to Feynman-x (x_{F}) variable

$$x_p - x_{\mathrm{Pb}} = x_{\mathrm{F}} = \frac{2p_z}{\sqrt{s_{\mathrm{NN}}}} \sim \pm 2\frac{p_{\mathrm{T}} \times \cosh y^{\mathrm{CM}}}{\sqrt{s_{\mathrm{NN}}}}$$

Initial state definition | Final state definition

$$\pm\frac{\sqrt{s_{\mathrm{NN}}}}{2} \times x_{\mathrm{F}} \sim p_{\mathrm{T}} \times \cosh y^{\mathrm{CM}}$$

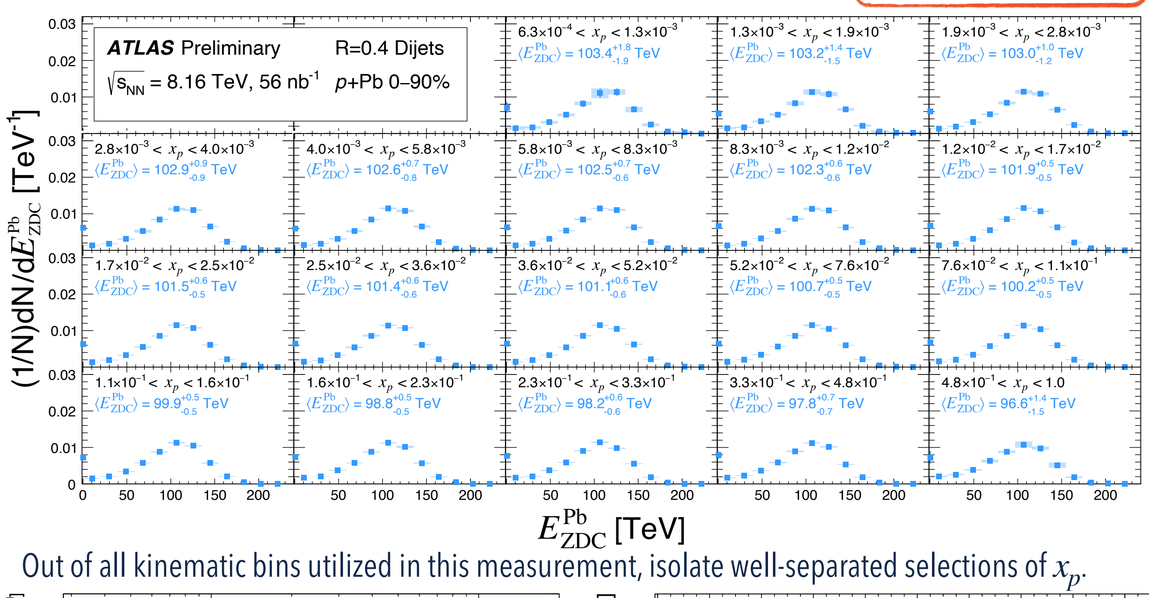


Demonstration that the **physics mechanism responsible for the R_{CP} suppression** in this kinematic region is the **same** in the two analyses, and the **scaling behavior** observed at 5.02 TeV with the jet energy is **effectively governed by the proton configuration in the initial state**.

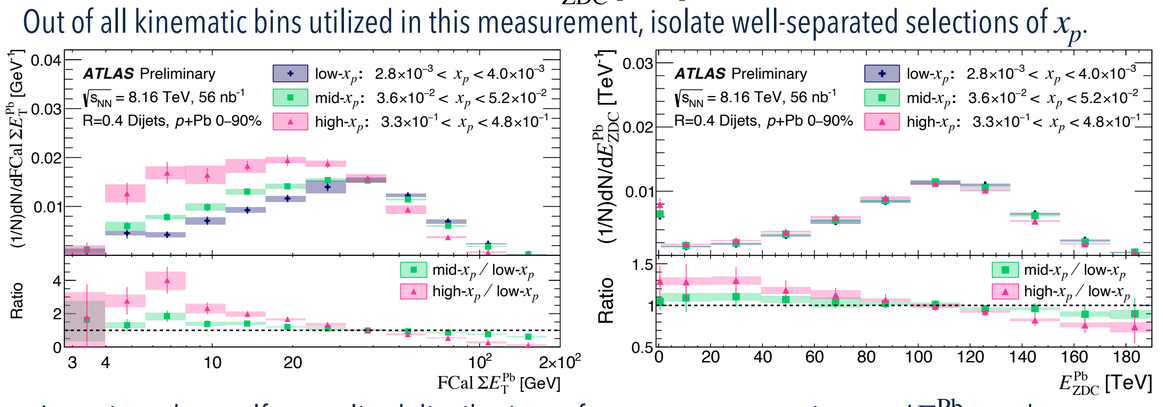
Probing CFs with Forward Neutrons & E_T

Self Normalized $E_{\mathrm{ZDC}}^{\mathrm{Pb}}$ distributions as a function of **hadron-level** x_p.

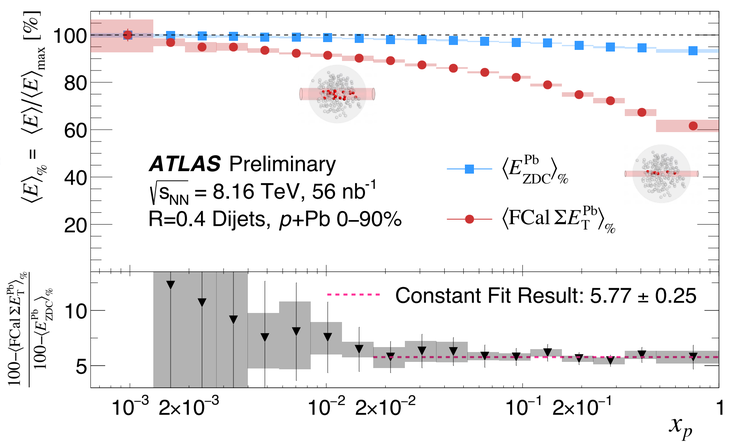
$$x_p = \frac{p_{\mathrm{T},1}e^{y_1^{\mathrm{CM}}} + p_{\mathrm{T},2}e^{y_2^{\mathrm{CM}}}}{\sqrt{s_{\mathrm{NN}}}}$$



Out of all kinematic bins utilized in this measurement, isolate well-separated selections of x_p.



- Investigate how self normalized distributions of event geometry estimators ($E_{\mathrm{ZDC}}^{\mathrm{Pb}}$ and $\mathrm{FCal}\,\Sigma\,E_{\mathrm{T}}^{\mathrm{Pb}}$) vary with respect to x_p.
- Behavior in FCal consistent with event activity bias interpretation of previous dijet measurement, where in high-x_p selections an excess (deficit) of events with small (large) $\mathrm{FCal}\,\Sigma\,E_{\mathrm{T}}^{\mathrm{Pb}}$ was observed as an x_p-driven decrease in the R_{CP}
- ZDC also sees shift towards lower $E_{\mathrm{ZDC}}^{\mathrm{Pb}}$ in high-x_p selections, but is less sensitive than FCal.
- Report $\langle E_{\mathrm{ZDC}}^{\mathrm{Pb}}\rangle$ and $\langle \mathrm{FCal}\,\Sigma\,E_{\mathrm{T}}^{\mathrm{Pb}}\rangle$ as a function of x_p.
- The $\langle E_{\mathrm{ZDC}}^{\mathrm{Pb}}\rangle$ decreases by up to ~5% at high-x_p, while up to a 40% decrease is observed for $\langle \mathrm{FCal}\,\Sigma\,E_{\mathrm{T}}^{\mathrm{Pb}}\rangle$.
- Ratio of **relative change in FCal** over **relative change in ZDC** is **constant** → suggests similar **underlying mechanism**



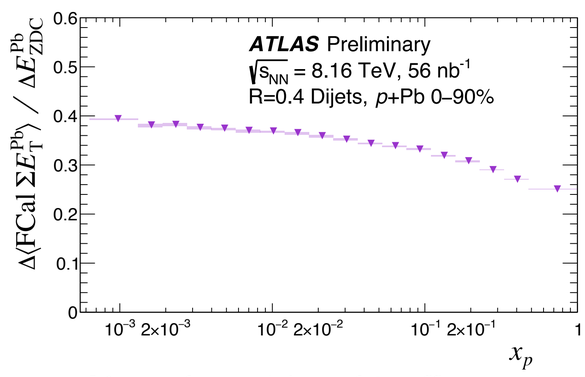
Compared to the forward transverse energy, spectator neutrons are **~1/6 as sensitive to the hard scattering kinematics.**

Reports the **first measurement** of ***p*+Pb nuclear breakup** correlated with **proton configurations in the initial state** at LHC energies, advancing the study of ***p*+A** physics.

Correlations Between Forward Neutrons & E_T

Correlations between $E_{\mathrm{ZDC}}^{\mathrm{Pb}}$ and $\mathrm{FCal}\,\Sigma\,E_{\mathrm{T}}^{\mathrm{Pb}}$ use x_p at the **reconstructed** level.

- Report $\langle \mathrm{FCal}\,\Sigma\,E_{\mathrm{T}}^{\mathrm{Pb}}\rangle$ as a function of $E_{\mathrm{ZDC}}^{\mathrm{Pb}}$ for different selections of x_p
- Striking linearity of the $\langle \mathrm{FCal}\,\Sigma\,E_{\mathrm{T}}^{\mathrm{Pb}}\rangle - E_{\mathrm{ZDC}}^{\mathrm{Pb}}$ correlation over the range 0—155 TeV in $E_{\mathrm{ZDC}}^{\mathrm{Pb}}$
- Parameterize this change by fitting to a linear function



- Evolution of linear fit slope, representing the 'per neutron FCal energy' for each x_p bin
- **Consistent x_p-driven reduction** of the 'per neutron FCal energy' is observed in the same x_p-range characterized by the log-linear R_{CP} suppression

Novel input for modeling of **CF effects** and nuclear breakup in ***p*+A collisions.**

Quantifies how **canonical p+A event geometry estimators** depend on the **hard-scattering kinematics** and can be **biased by CF-like effects.**

[1] ATLAS Collaboration, JINST 3 (2008) S08003.
[2] ATLAS Collaboration, PLB 748 (2015) 392–413.
[3] Alvioli et al., PRD 98, 071502(R) (2018).
[4] Brodsky et al., Physics 2022, 4, 633–646
[5] Alvioli et al., PRC 110, 025205 (2024).
[6] Zheng et al., Eur. Phys. J. A 50, 189 (2014).

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