Probing initial state effects in *p*+Pb collisions via E_T and spectator neutron measurements with the ATLAS detector

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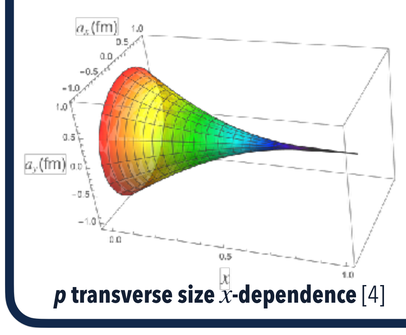
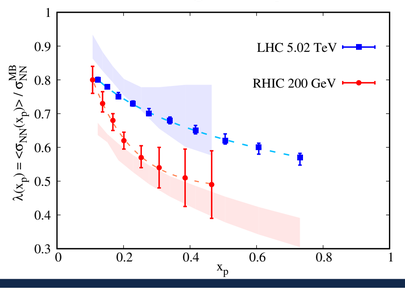
Motivation: is the proton's size fluctuating?

- **Color Transparency** is a fundamental property of QCD, relating the **hard-scattering** kinematics to the **distances between quark-gluon** constituents. **High-*x* → point like** configurations [4].
- Effective **size of interacting hadron** directly connected to **Generalized Patron Distributions** [4].
- **Color fluctuation** models parameterize this *x* dependence in terms of fluctuating cross-sections [3].
- In **p+Pb** collisions, small configurations associated with **less UE activity.**
- **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].

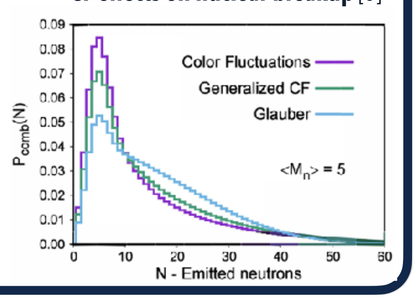


***p* transverse size x-dependence** [4]

Interaction strength x-dependence [3]

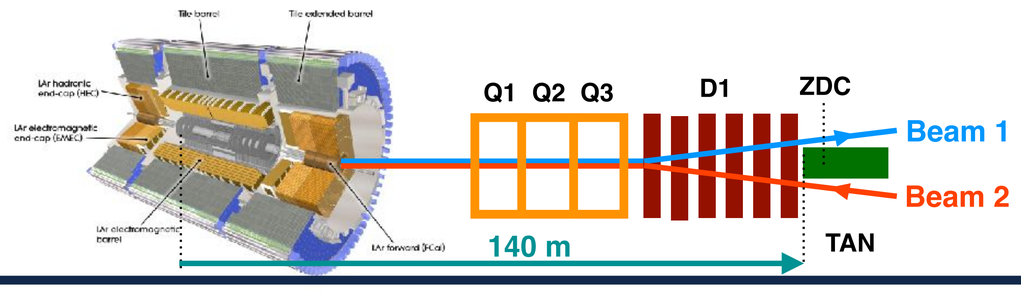


CF effects on nuclear breakup [5]



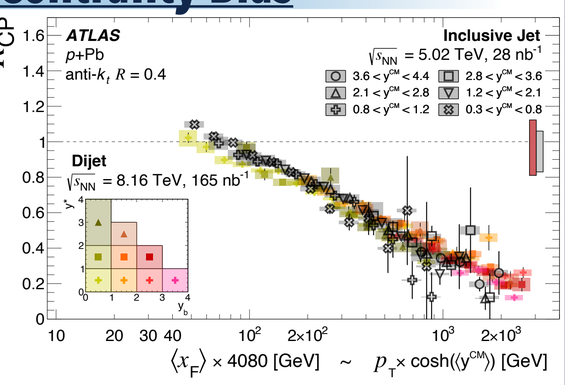
The ATLAS Calorimeter System

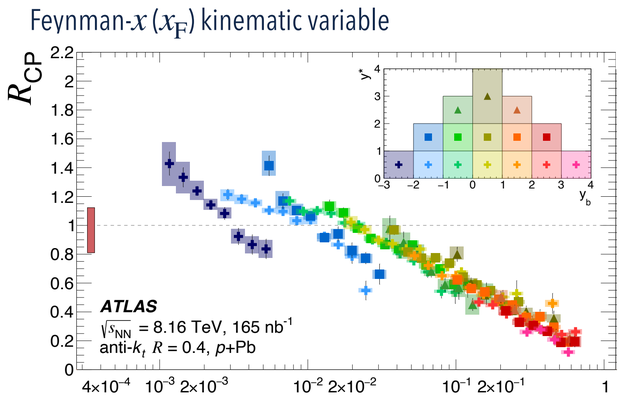
The ATLAS [1] calorimeter system consists of a liquid-argon (LAr) EM calorimeter, a steel sampling hadronic calorimeter, a LAr hadronic end-cap calorimeter, and two LAr forward calorimeters. The system has coverage out to $|\eta| < 4.9$, allowing for jet measurements over a broad range of rapidities. 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 $|\eta| > 8.3$.



Probing CFs indirectly through Centrality Bias

- Both 5.02 TeV (inclusive jets) [2] and 8.16 TeV (dijets) [7] in *p*+Pb measure a central-to-peripheral ratio (R_{CP}), with centrality defined in the Pb-going FCal.
- R_{CP} of (di)jet yields is scaled by geometric factors accounting for the difference in the nuclear thickness between central and peripheral *p*+Pb events
- Both results display strong log linear reduction with Feynman-x (x_F) kinematic variable





- Dijet result [7] gives access to kinematics of the 2→2 partonic scattering, specifically the Bjorken-x of the proton
- Strong **log-linear x_p-scaling** observed when moving toward the **proton's valence dominance region.**

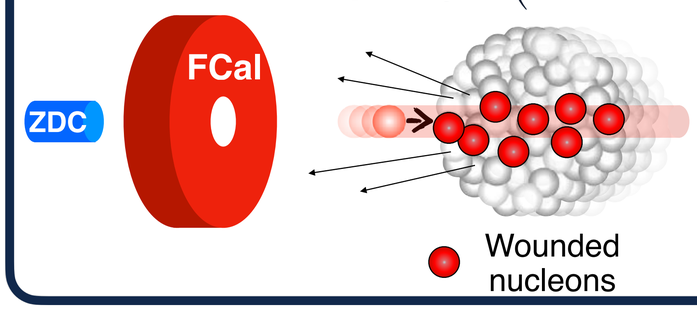
Demonstration that the **physics mechanism** responsible for the R_{CP} suppression **effectively governed by the proton configuration in the initial state**. Supports interpretation in terms of **CFs**, where high-x_p protons are associated with **less binary collisions** and therefore **reduced forward energy flow**.

Details of the Measurement

- Probe hard-scattering dependent effects using dijets to access initial state.
- Measurement uses anti-k_t $R = 0.4$ jets at $\sqrt{s_{NN}} = 8.16$ TeV in 2016 *p*+Pb dataset.

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

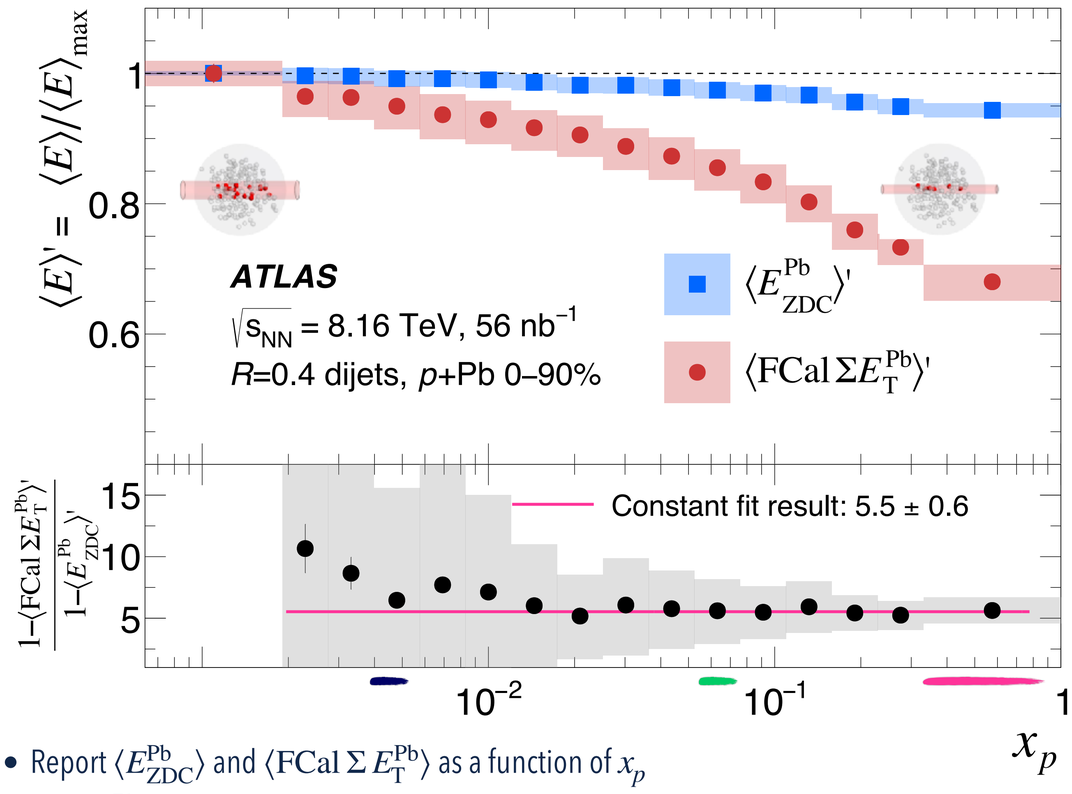
Access Bjorken-x of proton x_p via $x_p = \left(p_{T,1}e^{y_1^{CM}} + p_{T,2}e^{y_2^{CM}}\right) \Big/ \sqrt{s_{NN}}$



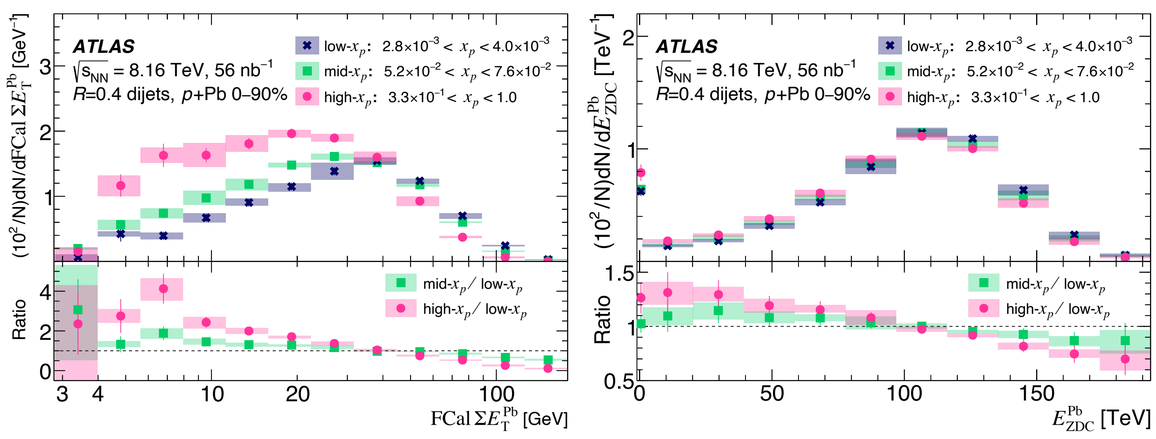
- Measure p+A event geometry estimators (**ZDC** Energy & **Transverse FCal** Energy) on side facing Pb fragments.
- Estimate Bjorken-x of proton at particle level
- Bayesian unfolding in x_p, No unfolding in $E_{ZDC}^{Pb}/\text{FCal}\,\Sigma\,E_T^{Pb}$

Probing CFs with Forward Neutrons & E_T

Study how two different **event geometry estimators** (Pb-going FCal, ΣE_T^{Pb} and Pb-going ZDC Energy, E_{ZDC}^{Pb}) change with the Bjorken-x of the proton, x_p.



- Report $\langle E_{ZDC}^{Pb} \rangle$ and $\langle \text{FCal}\,\Sigma\,E_T^{Pb} \rangle$ as a function of x_p
- The $\langle E_{ZDC}^{Pb} \rangle$ decreases by up to ~**5%** at high-x_p, while up to a **30%** decrease is observed for $\langle \text{FCal}\,\Sigma\,E_T^{Pb} \rangle$.
- 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) $\text{FCal}\,\Sigma\,E_T^{Pb}$ was observed as an x_p-driven decrease in the R_{CP}.
- Ratio of **ΔZDC%** over **ΔFCal%** is **constant** → suggests similar **underlying mechanism**
- Compared to the forward transverse energy, spectator neutrons are **~1/6 as sensitive to the hard scattering kinematics.**

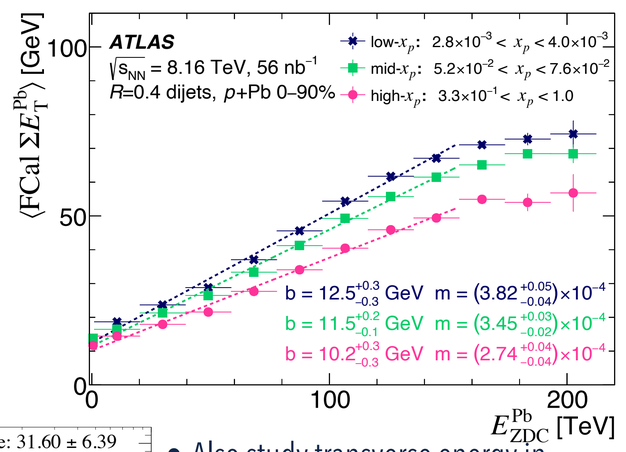


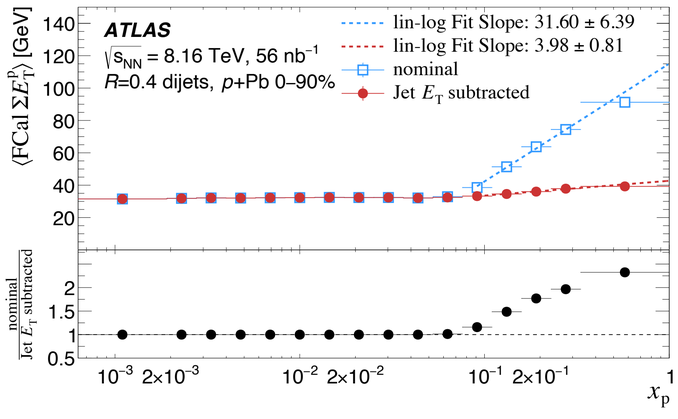
Both ZDC and FCal see **significant shifts toward lower energies** in events with a high-x_p scattering. Effect is more apparent in the FCal.

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.

Additional input into CF-like effects

- Correlations between energies uses x_p at the reconstructed level.
- Report $\langle \text{FCal}\,\Sigma\,E_T^{Pb} \rangle$ as a function of E_{ZDC}^{Pb} for different selections of x_p
- Striking linearity of the $\langle \text{FCal}\,\Sigma\,E_T^{Pb} \rangle - E_{ZDC}^{Pb}$ correlation over the range 0—150 TeV in E_{ZDC}^{Pb}





- Also study transverse energy in proton-going direction
- Once trivial jet contribution is removed, $\langle \text{FCal}\,\Sigma\,E_T^{p} \rangle$ has almost **no dependence** on the hard-scattering kinematics.
- Stronly disfavors "energy conservation" explanation for reduction in $\langle \text{FCal}\,\Sigma\,E_T^{Pb} \rangle$

[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).
[7] ATLAS Collaboration, PRL 132 (2024) 10, 102301

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