



Characterization of nuclear breakup as a function of hard-scattering kinematics using dijets measured by ATLAS in p +Pb collisions

The ATLAS Collaboration

This Letter analyzes the sensitivity of event geometry estimators to the initial-state kinematics of hard scattering in proton–lead collisions. This analysis uses dijets as a proxy for the parton–parton scattering configuration, correlating it with event geometry estimators, namely the energy deposited in the Zero-Degree Calorimeter and the transverse energy recorded in the Forward Calorimeter in the Pb-going direction. The analysis uses data recorded by the ATLAS detector at the Large Hadron Collider with a nucleon–nucleon center-of-mass energy of 8.16 TeV, corresponding to an integrated luminosity of 56 nb^{-1} . The jets are measured within the pseudorapidity interval $-2.8 < \eta < 4.5$, where positive η values correspond to the direction of the proton beam. Results are presented as a function of the Bjorken- x of the parton originating from the proton, x_p . Both event geometry estimators are found to be dependent on x_p , with the energy deposited in the Zero-Degree Calorimeter about six times less sensitive to x_p compared with the transverse energy deposited in the Forward Calorimeter.

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1 Introduction

The study of hard processes in proton–lead (p +Pb) collisions at the Large Hadron Collider (LHC) [1] has contributed to a richer understanding of nuclear matter effects, both in the hot, dense medium produced in nucleus–nucleus collisions and in the cold nuclear environment [2, 3].

One of the most important cold nuclear matter effects is the modification of the effective partonic structure needed to understand the production rates of hard probes, like jets and heavy vector bosons, in deep inelastic scattering on nuclei and proton–ion (p +A) collisions. The modification of parton distribution functions in the nuclear environment (nPDFs) [4, 5] was studied through measurements across multiple channels by different LHC experiments [6–13].

Hard process rates have also been studied as a function of p +Pb collision centrality, defined using “global” event-level variables, such as forward transverse energy or the number of forward neutrons. Both of these variables are expected to be sensitive to the overall collision geometry, particularly the number of binary collisions (N_{coll}) experienced by the projectile proton [14]. This assumption was validated by ATLAS in a Z boson measurement [7], where the inclusive Z yields were found to be approximately proportional to N_{coll} .

However, such linearity in different centrality selections was *not* observed for jets. ATLAS observed an event activity bias in the first measurement of inclusive jet production in p +Pb collisions at 5.02 TeV [15]. The analysis reported a significant suppression of the jet production normalized to the number of binary collisions in central events compared with peripheral events, with centrality defined using the transverse energy measured in the Forward Calorimeter (FCal) facing the nuclear debris. The suppression was found to be a function of the jet kinematics. More specifically, the central-to-peripheral ratio (R_{CP}) was found to be a function of the jet energy only. Similar observations were made at RHIC by PHENIX [16] and, more recently, by STAR [17]. These results were interpreted as evidence that protons in a configuration containing a parton with a large partonic momentum fraction (Bjorken- x), when interacting with a nuclear target, have a significantly smaller than average cross-section and size [18], a manifestation of color fluctuation (CF) effects [19–21]. CFs in QCD refer to variations in the transverse area occupied by color fields, which become spatially compact when a single parton carries a large fraction of the hadron’s

momentum [22]. By causing the proton to interact with fewer nucleons in the nucleus, the CF effects were found to induce a bias on the event activity and, therefore, on the forward transverse energy used to define the centrality. This bias depends on the kinematics of the jets, suggesting that the initial state could no longer be assumed to be independent of the measured quantities. More recently, ATLAS probed this effect in greater detail by analyzing the centrality dependence of dijet production in p +Pb data collected at 8.16 TeV [23]. By leveraging dijets to reconstruct the event-level initial-state kinematics, this analysis directly showed a correlation between the event activity bias and the Bjorken- x of the proton, x_p , consistent with the CF interpretation proposed in Ref. [18]. The event activity bias in p +Pb is driven by the initial-state kinematics of the hard-scattered parton in the proton, as demonstrated in Ref. [23].

The event activity bias creates non-trivial impediments in the search for signatures of jet quenching effects in small systems, like p +A. Thus, it becomes a topic of great interest to extract the centrality dependence of hard process rates using observables that are less sensitive to these effects [24]. One alternative approach is to select different centrality classes in p +A events based on the number of spectator neutrons measured in the nucleus-going Zero-Degree Calorimeter (ZDC) [25]. The ZDCs have been used as a way to select central events in searches for energy loss signatures, with the measurements in Refs. [26, 27] motivated by the argument that this classification is less biased than the event activity-based selection method.

However, the dynamics of the nuclear breakup in p +Pb collisions are not well understood in many aspects, and are poorly modeled by event generators, especially in the presence of a hard scattering. A measurement of forward neutron production in p +Pb, published by ALICE [28], reported the energy accumulated in the neutron ZDC as a function of the estimated number of binary collisions. The results, self-normalized to the average in minimum bias (MB) events in p +Pb collisions, found the energy in the Pb-going neutron ZDC to monotonically increase with the number of binary collisions, showing a correlation between these two quantities.

Recently, the authors of Ref. [29] argued that CF effects may also be relevant in the nuclear breakup process in ultra-peripheral collisions (UPCs) characterized by a resolved photon exchange. The proposed model links the number of nucleons wounded by interactions with a vector meson with the nuclear breakup dynamics, suggesting that studying forward neutron production can provide a direct handle on the number of binary collisions. Such effects, related to the number of wounded nucleons, can also improve the understanding of ZDC energy measured in e +A collisions at the future Electron-Ion Collider, where it was proposed as a possible centrality tag [30] to map out the impact parameter dependence on nPDFs. A similar model, using a proton instead of a vector meson in the scattering with the nucleus, can be used for the nuclear breakup in p +Pb interactions.

Given the importance of CF effects on centrality-dependent measurements of hard-scattering rates in p +Pb collisions, it is of great interest to study the correlation between the kinematics of the hard-scattered partons, the neutron energy at zero degrees after nuclear breakup, and the forward calorimeter event activity in these events. This inverts the typical approach by directly measuring the quantities used for centrality estimates as a function of jet kinematics, thereby probing the event-activity bias and offering the first direct insight into this behavior.

This Letter presents the first characterization of very forward energy in dijet events in p +Pb collisions at LHC energies, using 56 nb^{-1} of p +Pb data collected by ATLAS during 2016 at a nucleon–nucleon center-of-mass energy ($\sqrt{s_{\text{NN}}}$) of 8.16 TeV. The energy deposited in the ZDC ($E_{\text{ZDC}}^{\text{Pb}}$) and the transverse energy (E_{T}) recorded in the FCal ($\text{FCal} \Sigma E_{\text{T}}^{\text{Pb}}$), both measured on the Pb-going side, are reported as a function of x_p . The normalized $E_{\text{ZDC}}^{\text{Pb}}$ and $\text{FCal} \Sigma E_{\text{T}}^{\text{Pb}}$ distributions and the means of these distributions, $\langle E_{\text{ZDC}}^{\text{Pb}} \rangle$ and $\langle \text{FCal} \Sigma E_{\text{T}}^{\text{Pb}} \rangle$, are analyzed to characterize the evolution of forward energy production in

response to changes in the proton configuration. The correlation between $\text{FCal } \Sigma E_{\text{T}}^{\text{Pb}}$ and $E_{\text{ZDC}}^{\text{Pb}}$ is also investigated to provide insights about the underlying physics linking event activity and nuclear breakup dynamics in p +Pb collisions.

Following Ref. [23], dijets are defined using the two highest transverse momentum¹ jets in a given collision, measured over a wide range of transverse momentum, p_{T} , and center-of-mass (CM) rapidity, y^{CM} , to access a broad x_p phase space. The value of x_p is estimated from the final-state kinematics of the two highest p_{T} jets in each event by using

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

where $p_{\text{T},1}$ ($p_{\text{T},2}$) and y_1^{CM} (y_2^{CM}) denote the transverse momentum and the rapidity of the leading (sub-leading) jet. In simulations, the x_p estimate based on final-state jet kinematics was found to be, on average, 6–8% lower than the true parton-level value in the phase space covered by the analysis. The relative resolution of this estimate, $\sigma_{x_p^{\text{reco}}/x_p^{\text{PYTHIA}}}$, is around 10% for the lowest x_p events, decreasing to 4% with increasing x_p .

In this analysis, x_p is unfolded for experimental effects due to the finite precision of jet reconstruction, and reported at the generator level. $E_{\text{ZDC}}^{\text{Pb}}$ and $\text{FCal } \Sigma E_{\text{T}}^{\text{Pb}}$ are not unfolded for experimental effects, as was done when used for centrality selections in previous analyses [15, 23, 27].

These results present a novel approach to study geometry in proton–nucleus collisions and provide new insights into the role of partonic proton configurations and color fluctuations in the dynamics characterizing these reactions.

2 ATLAS detector

The measurement presented in this Letter is performed using the ATLAS inner detector, calorimeter, ZDC, trigger, and data acquisition systems [25].

The inner detector measures charged particles within the pseudorapidity interval $|\eta| < 2.5$ using a combination of silicon pixel detectors, silicon microstrip detectors (SCT), and a straw-tube transition radiation tracker (TRT), all immersed in a 2 T axial magnetic field. Each of the three detectors is composed of a barrel and two symmetric endcap sections. The pixel detector barrel section is composed of four layers including the insertable B-layer [31, 32], and each endcap consists of three disks placed symmetrically on each side of the interaction region. The SCT barrel section contains four layers of modules with sensors on both sides, and each endcap consists of nine layers of double-sided modules with radial strips. The TRT contains layers of staggered straws interleaved with the transition radiation material. Candidate collision vertices are reconstructed using inner detector tracks. The vertex with the highest track Σp_{T}^2 is defined as the primary vertex.

¹ ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z -axis along the beam pipe. The x -axis points from the IP to the center of the LHC ring, and the y -axis points upwards. Polar coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z -axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$ and is proportional to the rapidity $y = \frac{1}{2} \ln \left(\frac{E+p_z}{E-p_z} \right)$ in the relativistic limit. In the analysis the pseudorapidity sign is determined by the nuclear species, protons travel towards positive rapidities, while ions travel towards negative rapidities. The rapidity in the proton–nucleon center-of-mass frame is shifted by +0.465 units compared with the ATLAS frame. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

The calorimeter system consists of a sampling liquid-argon (LAr) electromagnetic (EM) calorimeter covering $|\eta| < 3.2$, a steel-scintillator sampling hadronic calorimeter covering $|\eta| < 1.7$, LAr hadronic calorimeters covering $1.5 < |\eta| < 3.2$, and two LAr FCals covering $3.2 < |\eta| < 4.9$. The EM calorimeters are segmented longitudinally in shower depth into three layers with an additional presampler layer covering $|\eta| < 1.8$. The hadronic calorimeters have three sampling layers longitudinal in shower depth for $|\eta| < 1.7$ and four sampling layers for $1.5 < |\eta| < 3.2$. During the 2016 p +Pb data taking, a sector of the hadronic endcap calorimeter (HEC), corresponding to $-3.2 < \eta < -1.5$ and $-\pi < \phi < -\pi/2$ was disabled. The FCal is composed of calorimeter towers segmented with fine granularity in $\Delta x \times \Delta y$, corresponding approximately to $\Delta\eta \times \Delta\phi = 0.15 \times 0.15 (0.3 \times 0.3)$ at $\eta = 3.5(4.5)$ [33]. The EM energy scale is used to measure the energy in each tower ($E_{\text{tower}}^{\text{EM}}$). The EM scale properly corrects the energy deposited by photons and electrons, but does not include any compensation to correct for the differences between EM and hadronic showers, as is standard for FCal measurements that are used as geometry estimators in p +Pb [15, 23, 27] and Pb+Pb [34] measurements.

The ATLAS ZDC consists of two detectors located in absorbers ± 140 m from the ATLAS interaction point. Each detector is a sampling calorimeter made up of four modules each with a material budget of 1.14 hadronic interaction lengths. The modules are made of layers of tungsten plates with quartz rods interspersed between them. They measure forward-going neutral particles with $|\eta| > 8.3$, primarily neutrons from nuclear breakup, which carry the original per-nucleon beam energy up to an additional smearing from nuclear Fermi momentum, and very forward neutral particles produced in the interaction.

To have sufficient experimental resolution to reconstruct a single neutron peak while simultaneously measuring calorimeter deposits from 80 or more neutrons from in-time pileup², the ZDC requires a large dynamic range from its front-end electronics. Experimentally, this is accomplished by configuring the ZDC with a dual gain readout system, where a high-gain analog-to-digital converter (ADC) samples with enough granularity to precisely measure relatively smaller energy deposits, while a low-gain module ensures that the ZDC does not saturate in events with sizable contamination from in-time pileup. This dual-gain readout is combined at the reconstruction level to give a single measurement of $E_{\text{ZDC}}^{\text{Pb}}$. In addition, having a reference for each signal allows for a data-driven correction of ADC non-linear behavior, applied at the level of the reconstruction.

ATLAS uses a two-level trigger system. The first-level trigger (Level 1) is hardware-based and implemented with custom electronics. It is followed by the software-based high-level trigger (HLT) [35].

An extensive software suite [36] is used in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

3 Data selection and Monte Carlo simulations

For the 2016 p +Pb run at $\sqrt{s_{\text{NN}}} = 8.16$ TeV, the LHC beam energy configuration was asymmetric between the protons (6.5 TeV), and the Pb nuclei (2.56 TeV/nucleon), resulting in a rapidity shift of the center of mass by 0.465 units toward the p -going direction. The data were collected over two running periods characterized by interchanging species between beam directions. In the first period of the data-taking, when Pb ions circulated clockwise in the LHC, a total integrated luminosity of 56 nb^{-1} was collected. The data analyzed in this Letter are comprised solely of the first data-taking period, referred to as the p +Pb orientation. The second data-taking period is omitted since the presence of a detector from the LHCf

² In-time pileup refer to events containing multiple simultaneous p +Pb collisions.

experiment [37] precludes a precise measurement of the spectator neutron energy. The positive η direction used in the analysis is defined by the proton-going direction.

The data used satisfy detector and data-quality requirements, and contain at least one reconstructed vertex and two reconstructed jets. A set of fully efficient central and forward single-jet triggers [35], characterized by different p_T thresholds, was chosen to provide full p_T coverage over the phase space of this analysis.

Jets are formed from calorimeter towers and are reconstructed using the anti- k_t algorithm [38, 39] with $R = 0.4$, as was done in previous ATLAS jet measurements in p +Pb [23, 27]. This analysis considers events where the two highest p_T jets have reconstructed $p_{T,1} > 40$ GeV, $p_{T,2} > 30$ GeV and $-2.8 < \eta_1, \eta_2 < 4.5$, respectively. The asymmetric η requirement is imposed to avoid jets biasing the centrality determination in the Pb-going FCal. Events with either the leading or the sub-leading jet reconstructed in the acceptance of the disabled HEC region are discarded in both data and Monte Carlo (MC) simulations. To define a rejection criterion for the analysis, the disabled region is increased by an additional 0.4 margin in both pseudorapidity and azimuthal angle, as done in previous jet analyses using these datasets [23, 27, 40]. In this way, jets with constituents affected by the disabled HEC are not considered.

Centrality is defined using FCal ΣE_T^{Pb} [23, 41, 42]. To select only hadronic interactions, the centrality range 0–90% is considered. The contribution of UPC jet production in these events was studied by applying an additional selection based on the rapidity gap [43] and is found to be negligible. In-time pileup events are rejected by requiring that no non-primary vertices have more than six associated tracks. This removes approximately 12% of events from the sample. All these selections are consistent with the p +Pb analysis presented in Ref. [23]

The ZDC ADCs sample their own baseline before every event. This baseline is sensitive to the long tails of preceding p +Pb interactions with significant ZDC activity. By rejecting events with baseline values elevated relative to an acceptable range taken from a dedicated zero pileup sample, events with an out-of-time³ pileup contribution that can affect measurements in the FCal are excluded. This requirement removes approximately 8% of events, after the nominal pileup cut and the centrality selection. This requirement is agnostic to the kinematic properties of the considered event, as it only depends on the process in a previous event.

MC simulations are used to evaluate the performance of the detector and analysis procedure, and to correct the measured distributions for detector effects. The detector response in all MC samples is simulated using GEANT4 [36, 44]. The disabled HEC sector is replicated in the simulation. The p +Pb MC sample makes use of dijet events from 8.16 TeV pp collisions, including the boost in rapidity relative to the lab frame that is in the data, simulated by PYTHIA8 [45] with the A14 set of tuned parameters [46] and the NNPDF2.3_{LO} parton distribution functions [47]. Events from the PYTHIA8 dijet sample are overlaid with events from a dedicated p +Pb data sample collected using MB triggers. The overlay procedure combines the PYTHIA8 and data events during the digitization step of simulation. An event-by-event reweighting procedure is applied to the MC overlay sample, such that the resulting FCal ΣE_T^{Pb} distribution better matches that of the dijet data sample.

³ Out-of-time pileup refers to events preceded by another p +Pb collision where a detector measures signals originating from the preceding event in the sampling window of the current event.

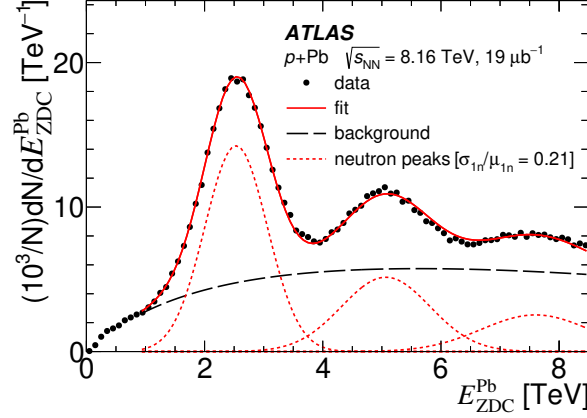


Figure 1: Low energy region of the calibrated ZDC spectrum for events triggered using the proton-going ZDC. The fit result is shown by the solid line. All the fit components are displayed using dashed lines.

4 Analysis

The value of $\text{FCal } \Sigma E_T^{\text{Pb}}$ is defined by a sum over the projection of each $E_{\text{tower}}^{\text{EM}}$ into the transverse plane, for the towers in the pseudorapidity hemisphere facing the Pb ion beam. This definition of $\text{FCal } \Sigma E_T^{\text{Pb}}$ is consistent with the characterization of centrality used in previous ATLAS $p+\text{Pb}$ analyses, for example in Refs. [23, 48].

In a typical $p+\text{Pb}$ event involving a hard scattering, most of the energy deposited into the Pb-going ZDC originates from spectator neutrons evaporating off the struck nucleus. A peaked structure appears in the low-energy region of the ZDC spectrum due to the detector’s response to a small number of neutrons, which can be clearly distinguished. An example of the ZDC energy spectrum and peak fitting result is displayed in Figure 1. The first peak in this structure represents the ZDC response to the energy of a single spectator neutron. The absolute energy response of the ZDC modules is calibrated by a Lagrangian optimization procedure that sets the mean of the single neutron peak equal to the nominal per nucleon beam energy and adjusts calibration factors in each layer to minimize the width of the single neutron peak. The calibration procedure is repeated throughout the run to account for intra-run changes in the detector response. Following calibration, a simultaneous fit is performed to the first three neutron peaks, as well as a background term. Background sources include neutral pions, photons, and beam–beam backgrounds. The functional form of the background term is chosen to facilitate fit convergence in the 1–3 neutron range. On physical grounds this contribution should vanish at zero energy and at large energies. These fits are used to validate the energy scale set by the calibration. The fit procedure is applied on a per-run basis, to account for changes in the detector response during data-taking.

The width of the single neutron peak originates from two separate sources. First, the ZDC is a sampling calorimeter that has a finite experimental resolution. Second, the contribution from nuclear Fermi momentum smears the neutron energy away from the nominal per-nucleon beam energy. The use of a Gaussian distribution to model the calorimeter response to a single neutron is motivated by the assumption that the modification from the convolution of these two sources is roughly symmetric. Below 1 TeV, the detector is primarily observing a mix of low-energy photons and beam backgrounds, with a negligible fraction from single neutrons. The ZDC amplitude reconstruction procedure also requires pulse heights

well above detector noise that limit its precision below 1 TeV. Therefore, below that threshold, the measured energy is treated as zero, i.e., compatible with zero neutrons showering in the ZDC.

A residual pileup subtraction is applied to the $E_{\text{ZDC}}^{\text{Pb}}$ distribution, to remove in-time pileup contributions from interactions that are not rejected by the vertex requirement, and that are characterized by no significant pileup energy deposit in the FCal. This procedure removes approximately 0.19% of the events from the sample.

The jet reconstruction performance for this data sample was scrutinized in detail in a previous analysis, see Ref. [23] for all the relevant details.

To correct for detector effects and bin migration, dijet events are unfolded in x_p using a two-dimensional Bayesian procedure [49], implemented within the RooUnfold package [50]. The value of x_p at particle level is estimated with Eq. 1 using the leading and sub-leading particle-level jets. FCal $\Sigma E_{\text{T}}^{\text{Pb}}$ and $E_{\text{ZDC}}^{\text{Pb}}$ are individually propagated through the unfolding procedure with fully diagonal migration matrices, preserving the event-level correlation between the hard-scattering kinematics and each of the calorimetric energies. An efficiency correction is included in the unfolding to account for reconstructed jets that migrate out of the measurement phase space at the detector-level due to energy resolution effects, as well as to the disabled HEC region.

Each response matrix is reweighted at the event level by the ratio of reconstructed data to reconstructed simulation, as a function of x_p , such that the simulated spectrum better matches the shape of the data. The statistical uncertainties in the resulting FCal $\Sigma E_{\text{T}}^{\text{Pb}}$ and the $E_{\text{ZDC}}^{\text{Pb}}$ distributions, binned as a function of x_p , are evaluated using a bootstrapping method [51].

5 Systematic uncertainties

This measurement unfolds experimental effects in the dijet measurements to access x_p at the particle level. This approach is subject to systematic uncertainties associated with the jet energy scale (JES) and jet energy resolution (JER), the unfolding procedure, and an uncertainty due to a sector of the HEC being disabled for the running period. Measurements of $E_{\text{ZDC}}^{\text{Pb}}$ and $\langle E_{\text{ZDC}}^{\text{Pb}} \rangle$ have additional uncertainties applied to the energy scale of the ZDC. Since the ZDC energies are not unfolded, these uncertainties are evaluated at the reconstructed level. Other sources of systematic uncertainty, such as those related to the removal of the residual pileup in the ZDC, were found to be negligible. For each source of systematic uncertainty, except for the uncertainties in the disabled HEC sector and the ZDC energy scale, the entire analysis is repeated by changing the response matrix according to the systematic variation. The difference between the nominal measurement and that obtained with the systematic variation is taken as the systematic uncertainty.

The treatment of the uncertainties related to the determination of x_p via jets, namely the uncertainties in the JES, JER, and HEC exclusion, is identical to the procedure outlined in Ref. [23]. For brevity, the discussion of these uncertainties is minimized in this Letter. The JES and JER correspond to the mean and variance of the $p_{\text{T}}^{\text{reco}}/p_{\text{T}}^{\text{gen}}$ distributions, where $p_{\text{T}}^{\text{gen}}$ denotes the transverse momentum of the matched generator-level jet in simulation. The HEC exclusion uncertainty evaluates the sensitivity to increasing the exclusion region by 0.1 in both azimuth and pseudorapidity, and repeating the analysis procedure.

The systematic uncertainty in the unfolding procedure is related to the sensitivity to the choice of the prior distribution, i.e., the response matrix reweighting described in Section 4. To determine the sensitivity of

the results to the reweighting procedure, a new set of response matrices was generated without reweighting at the event level, and the full analysis procedure was repeated.

An uncertainty associated with the ZDC energy stability is assigned to quantify the run-by-run variations in the single neutron peak position extracted from fits like the one shown in Figure 1. The residual between the nominal per-nucleon beam energy (2.56 TeV) and the extracted peak position, after allowing for 1σ deviations from the stability, is taken as an uncertainty in the ZDC energy scale. This approach was chosen to avoid overestimating the uncertainties assigned to the ZDC measurements. This residual is intrinsically linked to the finite time-resolution of the calibration procedure described in Section 4. A systematic uncertainty is also assigned to the ZDC non-linear correction mentioned in Section 2. This uncertainty is determined by calculating the difference between $E_{\text{ZDC}}^{\text{Pb}}$ with and without the non-linear correction applied, across the whole spectrum of $E_{\text{ZDC}}^{\text{Pb}}$ values. Akin to the previous ZDC uncertainties, an additional systematic uncertainty is assigned to the stability of this correction and any residual scale variation.

The stability of the FCal in measuring $\text{FCal } \Sigma E_{\text{T}}^{\text{Pb}}$ across the run was scrutinized and the associated uncertainty is found to be negligible compared with other systematic uncertainties assigned.

The variations for each systematic uncertainty were then added in quadrature to produce the total systematic uncertainties in each data point.

The $E_{\text{ZDC}}^{\text{Pb}}$ total systematic uncertainties are dominated by the ZDC energy stability term, which is within 7% for most bins considered. The uncertainty grows towards high $E_{\text{ZDC}}^{\text{Pb}}$ values and at the edges of the x_p measurement range, where it reaches up to 30%.

The total systematic uncertainties in the $\text{FCal } \Sigma E_{\text{T}}^{\text{Pb}}$ distributions in various x_p bins is dominated by contributions from the JES, JER, and unfolding prior components. It is within 10% for most bins, increasing at high and low $\text{FCal } \Sigma E_{\text{T}}^{\text{Pb}}$ values and at the edges of the x_p measurement range, where it gets up to 20%.

The total systematic uncertainties in the distributions of $\langle E_{\text{ZDC}}^{\text{Pb}} \rangle$ and $\langle \text{FCal } \Sigma E_{\text{T}}^{\text{Pb}} \rangle$ are below 2% in all the x_p bins except for the lowest, where it reaches 3%. When ratios are constructed, the JES, JER, HEC, and ZDC uncertainties are treated as fully correlated between measurement interval, while the prior uncertainty is treated as uncorrelated.

6 Results

Normalized distributions of $E_{\text{ZDC}}^{\text{Pb}}$ and $\text{FCal } \Sigma E_{\text{T}}^{\text{Pb}}$ in dijet events are presented in intervals of x_p , estimated by using Eq. 1, chosen to allow a direct comparison with the results of Ref. [23]. The highest and lowest bins are wider to accrue more statistics.

The results for $\text{FCal } \Sigma E_{\text{T}}^{\text{Pb}}$ are displayed in Figure 2. A shift of the FCal distributions towards lower values of $\text{FCal } \Sigma E_{\text{T}}^{\text{Pb}}$ is observed with increasing x_p , as one would expect from the results presented by ATLAS in Ref. [23], where in high- x_p selections a deficit (enhancement) of events with large (small) $\text{FCal } \Sigma E_{\text{T}}^{\text{Pb}}$ was observed via a suppression of the central-to-peripheral ratio, R_{CP} .

To further analyze the event activity bias with increasing values of x_p , Figure 3 shows a comparison of $\text{FCal } \Sigma E_{\text{T}}^{\text{Pb}}$ distributions in well-separated intervals of x_p . The lower panel of Figure 3 shows the ratio of the middle- and high- x_p $\text{FCal } \Sigma E_{\text{T}}^{\text{Pb}}$ distributions to that in low- x_p dijet events. These ratios show that, relative to a lower- x_p selection, higher- x_p events have a $\text{FCal } \Sigma E_{\text{T}}^{\text{Pb}}$ distribution that is significantly different

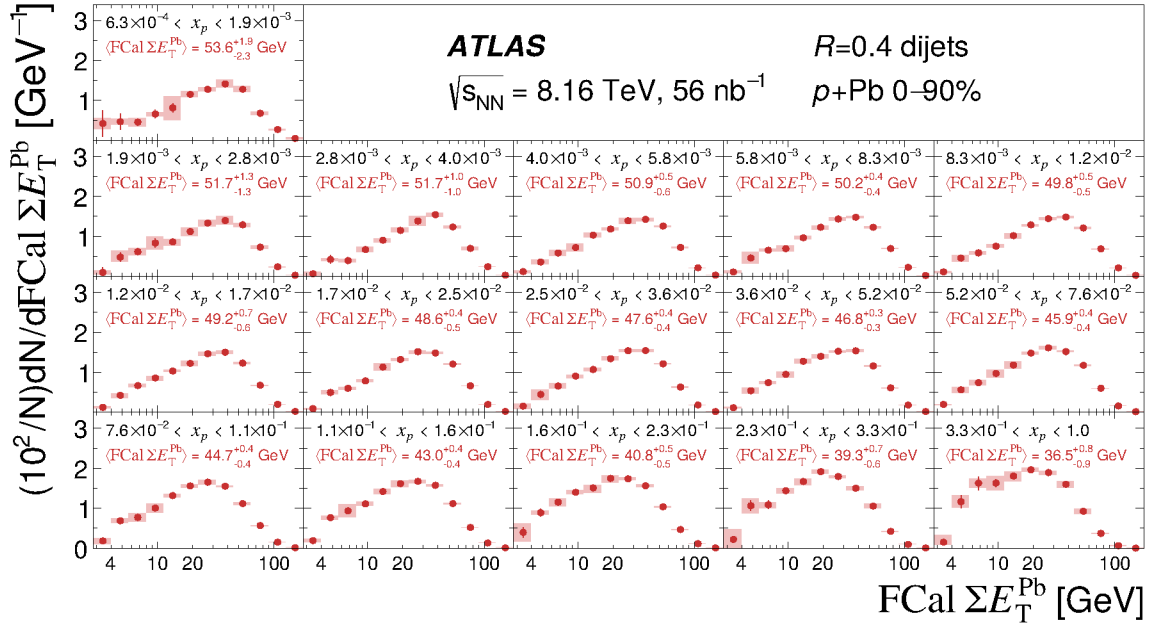


Figure 2: Normalized $\text{FCal } \Sigma E_T^{\text{Pb}}$ spectrum. Each panel represents an x_p selection in dijet events. In each bin of x_p , the $\langle \text{FCal } \Sigma E_T^{\text{Pb}} \rangle$ with uncertainties is displayed in a text inset. Vertical error bars represent the statistical uncertainty, and the shaded areas represent the systematic uncertainty. The width of the shaded area indicates the bin width.

and shifted towards lower energies. This observation represents the first direct confirmation of the event activity bias first observed by ATLAS in jet measurements [15, 23].

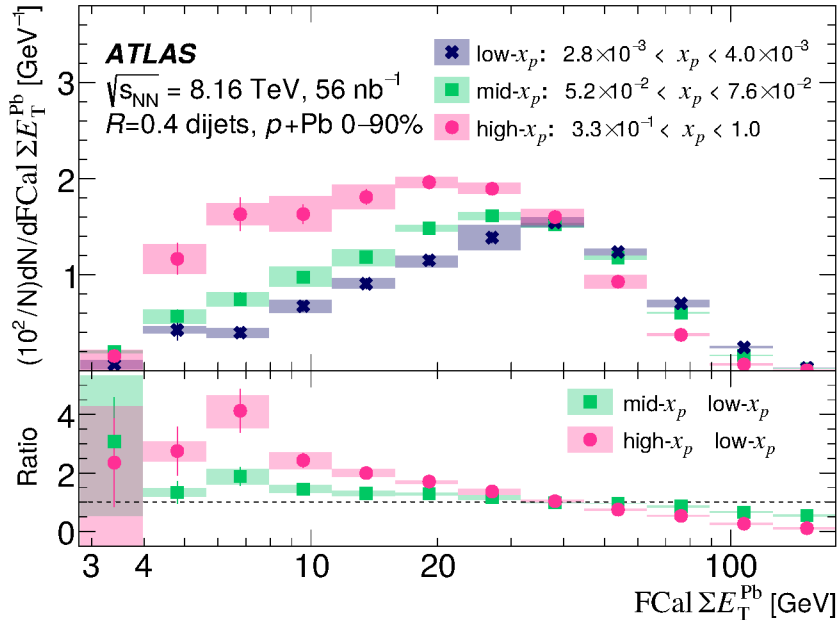


Figure 3: $\text{FCal } \Sigma E_T^{\text{Pb}}$ distributions plotted for low-, middle-, and high- x_p selections. These distributions are normalized to display the change of the $\text{FCal } \Sigma E_T^{\text{Pb}}$ distribution shape with x_p . The bottom panel displays the ratio of the middle- and high- x_p selection over the low- x_p selection. Vertical error bars represent the statistical uncertainty, and the shaded areas represent the systematic uncertainty. The width of the shaded area indicates the bin width.

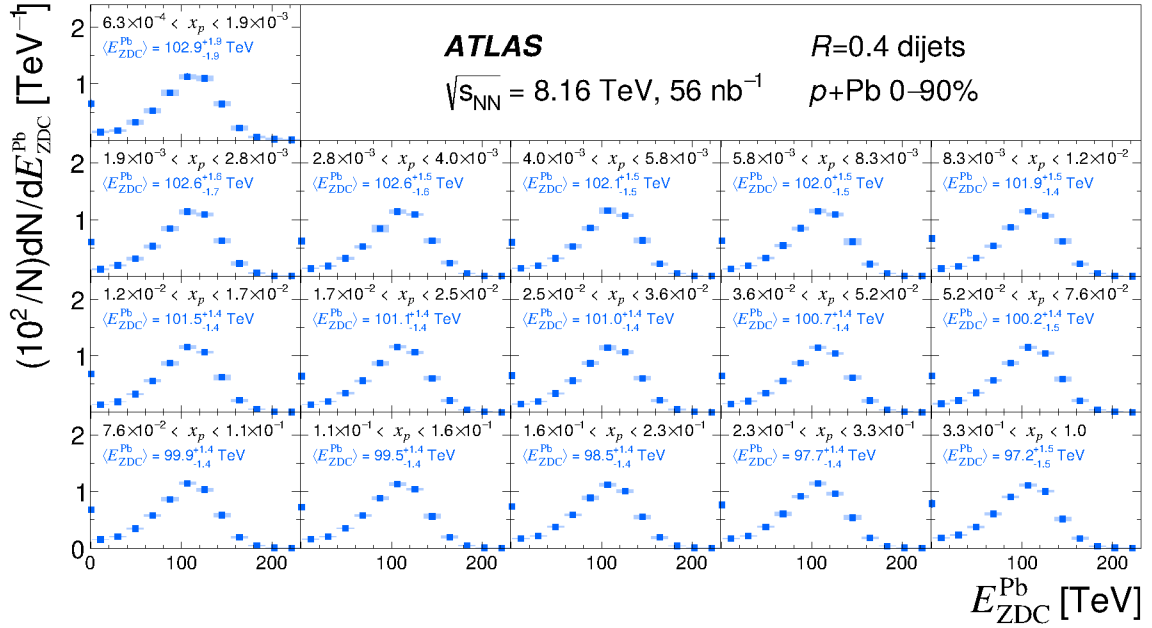


Figure 4: Normalized Pb-going ZDC energy spectrum. Each panel represents an x_p selection in dijet events. In each bin of x_p , the $\langle E_{\text{ZDC}}^{\text{Pb}} \rangle$ with uncertainties is displayed in the text inset. Vertical error bars represent the statistical uncertainty, and the shaded areas represent the systematic uncertainty. The width of the shaded area indicates the bin width.

The distributions of $E_{\text{ZDC}}^{\text{Pb}}$ are presented, in the same fashion as Figure 2, in Figure 4. A shift toward lower values of the mean of the ZDC energy distribution can be observed with increasing x_p , though it is smaller than for the FCal. This change can be seen more clearly by overlaying, once more, well-separated intervals of x_p , this time for $E_{\text{ZDC}}^{\text{Pb}}$, in Figure 5. The lower panel of Figure 5 shows the ratio of the middle- and high- x_p $E_{\text{ZDC}}^{\text{Pb}}$ distributions to that in low- x_p dijet events. The ratio reveals a significant difference between the $E_{\text{ZDC}}^{\text{Pb}}$ distribution in high- x_p and low- x_p events, where the high- x_p distribution has a higher fraction of events with fewer forward neutrons. This conclusion for the ZDC is qualitatively similar to, but substantially weaker than, the event activity bias in the FCal observed in Figure 3.

The first bin in all the $E_{\text{ZDC}}^{\text{Pb}}$ distributions of Figures 4 and 5 is set to 0–1 TeV, to isolate events that are compatible with zero neutrons in the detector. The fraction of events in these bins is smaller than 1%. These distributions are normalized to the bin width, introducing the visual jump between the first bin and the rest of the distribution. Furthermore, in Ref. [52] ALICE observes a small fraction of hadronic Pb+Pb collisions with neutron topologies consistent with zero neutrons in one ZDC side. Extending this to the p+Pb case, one might expect a small fraction of hadronic events to also be characterized by zero breakup neutrons.

These observations of shifting distributions, for both $E_{\text{ZDC}}^{\text{Pb}}$ and $\text{FCal } \Sigma E_{\text{T}}^{\text{Pb}}$, are consistent with a reduction in the number of interactions between the proton projectile and the nucleons in the nucleus with increasing x_p . The relative magnitude of the shift in the distribution of calorimeter energies is significantly larger in the $\text{FCal } \Sigma E_{\text{T}}^{\text{Pb}}$ case compared with the $E_{\text{ZDC}}^{\text{Pb}}$ case.

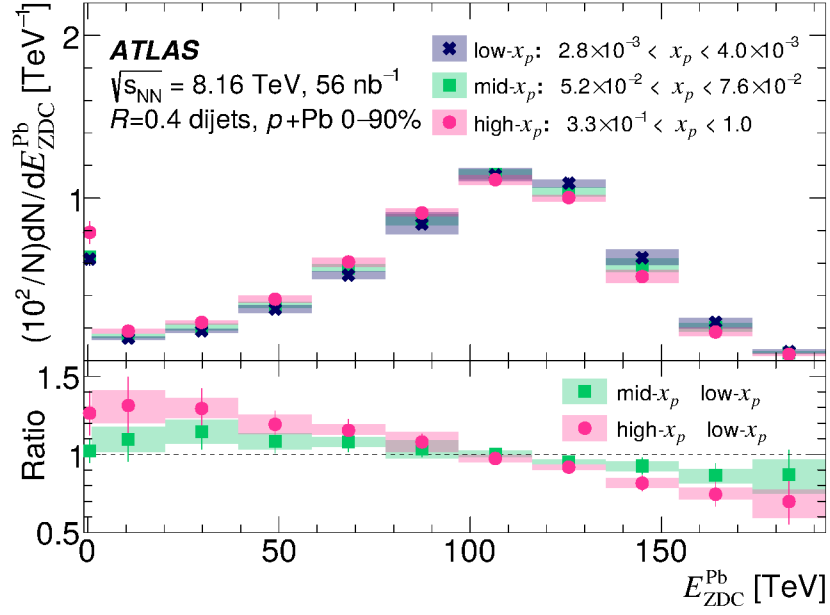


Figure 5: E_{ZDC}^{Pb} distributions plotted for low-, middle-, and high- x_p selections. Each distribution is normalized to display the change of the E_{ZDC}^{Pb} distribution shape with x_p . The bottom panel displays the ratio of the middle- and high- x_p selection over the low- x_p selection. The energy below the ZDC detection threshold (e.g., formally assigned as zero by ZDC reconstruction) is reported in a dedicated bin. Vertical error bars represent the statistical uncertainty, and the shaded areas represent the systematic uncertainty. The width of the shaded area indicates the bin width.

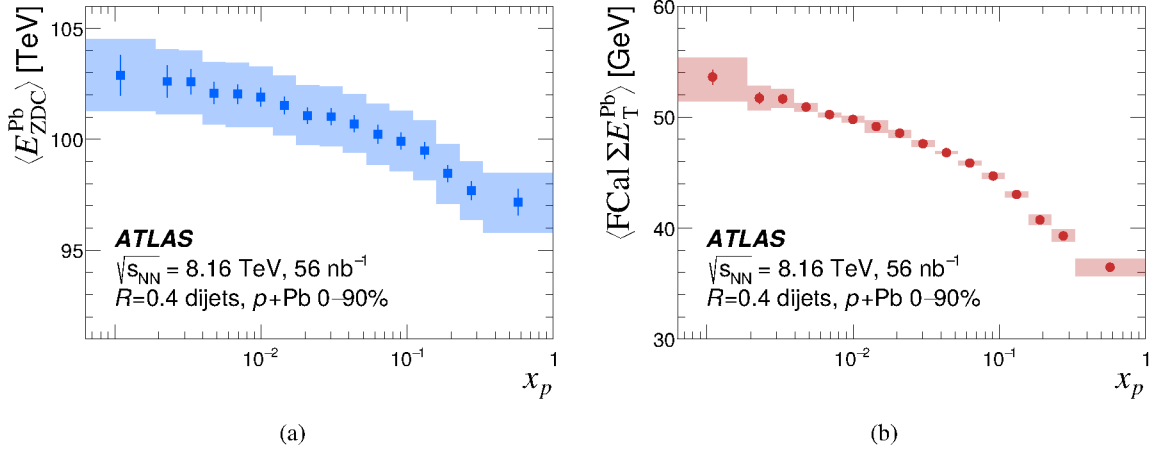


Figure 6: (a) $\langle E_{ZDC}^{\text{Pb}} \rangle$ and (b) $\langle \text{FCal } \Sigma E_T^{\text{Pb}} \rangle$ both as a function of x_p . Vertical error bars represent the statistical uncertainty, and the shaded areas represent the systematic uncertainty. The width of the shaded area indicates the bin width.

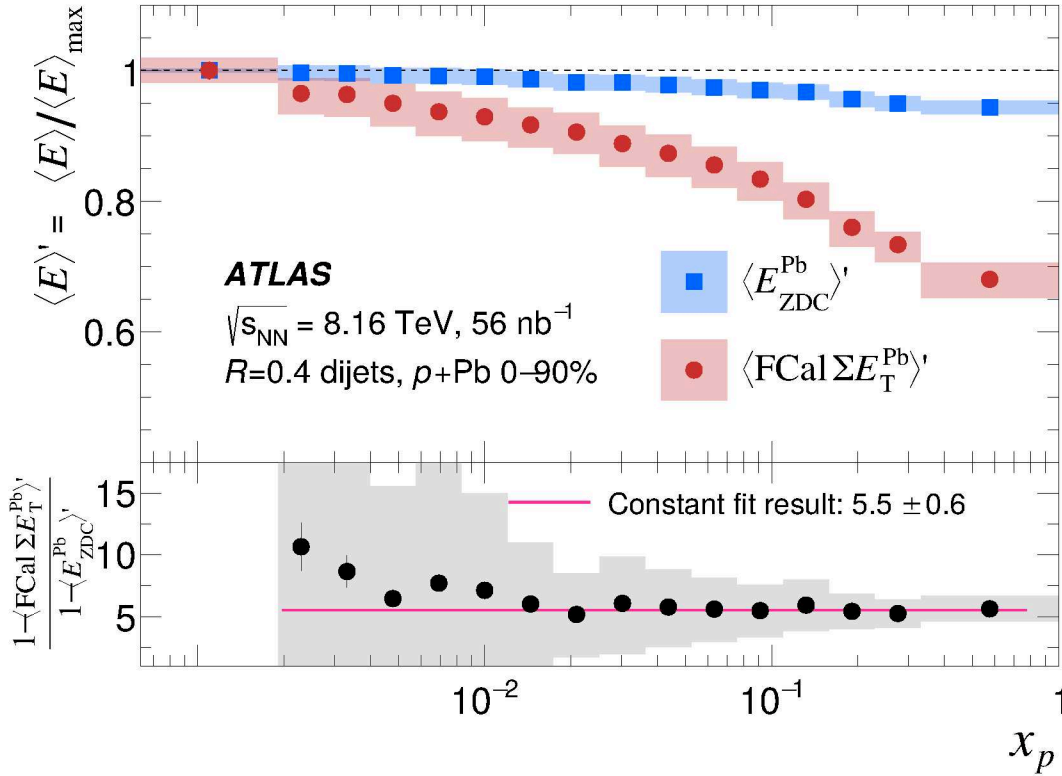


Figure 7: $\langle E_{\text{ZDC}}^{\text{Pb}} \rangle$ as a function of x_p (square) compared with $\langle \text{FCal} \Sigma E_{\text{T}}^{\text{Pb}} \rangle$ as a function of x_p (circle). Both plots are normalized to their maximum value, to display both quantities on the same scale. The bottom panel shows the ratio of the relative change in $\langle \text{FCal} \Sigma E_{\text{T}}^{\text{Pb}} \rangle$ over the relative change in $\langle E_{\text{ZDC}}^{\text{Pb}} \rangle$, fit to a constant function (solid line). Shaded areas represent the systematic uncertainty. The width of the shaded area indicates the bin width. The statistical error on the $\langle E \rangle_{\max}$ is included in the systematic band as it is correlated bin-to-bin in x_p for all bins except for the lowest x_p bin. The vertical error bars represent the uncorrelated statistical uncertainty.

To better understand the correlations between x_p and the energy (transverse energy) detected in the ZDC (FCal), the mean values of the distributions are presented as a function of x_p in Figure 6. Both curves exhibit a decrease as a function of x_p , more pronounced in the region $x_p \gtrsim 0.02$, corresponding to the onset of effects attributed to small proton size configurations in Ref. [23]. The energy accumulated in the Pb-going side of the ZDC decreases by up to $\sim 5\%$ in this region, while a decrease of up to 40% is observed for the FCal. The observed decrease of $\sim 5\%$ in the $\langle E_{\text{ZDC}}^{\text{Pb}} \rangle$ corresponds to, on average, an energy detected in the ZDC corresponding to two fewer beam-energy neutrons. Such a trend is qualitatively compatible with a reduced number of interactions for small proton configurations resulting in a smaller number of breakup neutrons, as suggested in Ref. [29].

Figure 7 shows the comparison between the rates of the x_p -dependent decrease between $E_{\text{ZDC}}^{\text{Pb}}$ and $\text{FCal} \Sigma E_{\text{T}}^{\text{Pb}}$, both normalized to their maximum values. The lower panel shows the ratio of the relative change in $\langle \text{FCal} \Sigma E_{\text{T}}^{\text{Pb}} \rangle$ over the relative change in $\langle E_{\text{ZDC}}^{\text{Pb}} \rangle$ as a function of x_p . The ratio remains approximately constant, as shown by the fit in the Figure. For x_p bins $\lesssim 0.02$, the systematic uncertainty in the ratio becomes large, as even small deviations in $\langle E_{\text{ZDC}}^{\text{Pb}} \rangle$ in this region where $\langle E_{\text{ZDC}}^{\text{Pb}} \rangle$ is close to its maximal value can have a large effect on the ratio denominator. However, the ratio remains consistent with the constant fit within the large systematic uncertainties. This result shows that, in $p+\text{Pb}$ collisions, the energy deposited in the ZDC is about six times less sensitive to the hard process kinematics than the transverse energy at FCal rapidities.

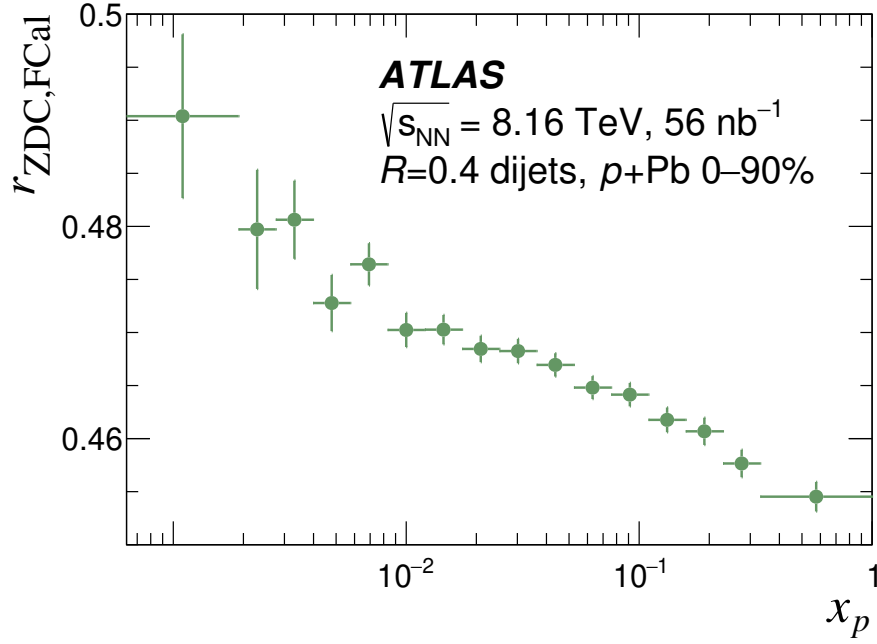


Figure 8: Sample Pearson correlation coefficient ($r_{ZDC,FCal}$) between E_{ZDC}^{Pb} and $FCal \Sigma E_T^{Pb}$, analyzed as a function of x_p . Horizontal error bars represent the bin widths, while vertical error bars represent the standard error associated with $r_{ZDC,FCal}$. The values of x_p are measured at the reconstructed level.

The correlation between the transverse energy produced by the interactions of the participants and the energy deposited by the spectator neutrons in the ZDC in x_p selections, measured at the reconstructed level, is also studied.

The Pearson correlation coefficient ($r_{ZDC,FCal}$) between E_{ZDC}^{Pb} and $FCal \Sigma E_T^{Pb}$, calculated for events in each x_p bin as

$$r_{ZDC,FCal} = \frac{\sum_{i=1}^n [(E_{ZDC}^{Pb})_i - \langle E_{ZDC}^{Pb} \rangle] [(FCal \Sigma E_T^{Pb})_i - \langle FCal \Sigma E_T^{Pb} \rangle]}{\sqrt{\sum_{i=1}^n [(E_{ZDC}^{Pb})_i - \langle E_{ZDC}^{Pb} \rangle]^2} \sqrt{\sum_{i=1}^n [(FCal \Sigma E_T^{Pb})_i - \langle FCal \Sigma E_T^{Pb} \rangle]^2}} \quad (2)$$

is reported in Figure 8. The positive values for $r_{ZDC,FCal}$ indicate that a positive correlation exists between $FCal \Sigma E_T^{Pb}$ and E_{ZDC}^{Pb} across all x_p selections. A small decrease in the Pearson correlation coefficient is observed with increasing x_p . This finding suggests that, in a smaller proton configuration, the forward transverse energy produced by the interactions of the participants is slightly less correlated with the number of spectator neutrons at very forward rapidities.

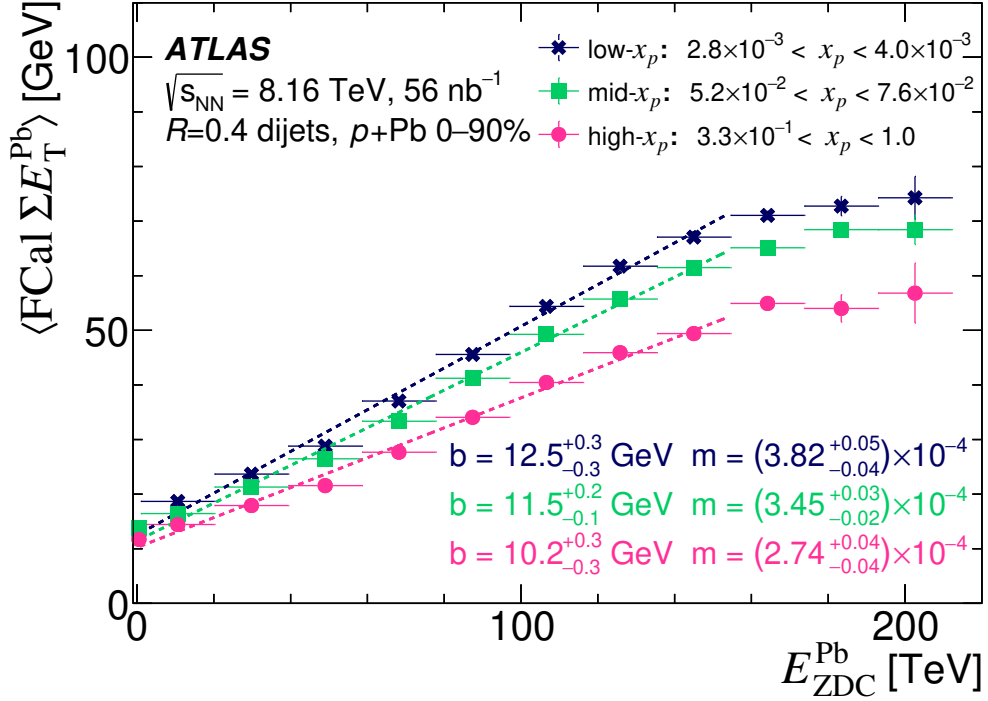


Figure 9: $\langle \text{FCal } \Sigma E_T^{\text{Pb}} \rangle$ plotted as a function of $E_{\text{ZDC}}^{\text{Pb}}$ for three selections of x_p : a low, middle, and high selection. The data in each bin are fit to a linear form ($f(x) = m \cdot x + b$) to approximately describe the correlation between the two energies. Fit parameters (and fit uncertainties) are reported on the figure. The values of x_p are measured at the reconstructed level.

To further study the evolution of the correlation between $\text{FCal } \Sigma E_T^{\text{Pb}}$ and $E_{\text{ZDC}}^{\text{Pb}}$ with x_p , Figure 9 reports $\langle \text{FCal } \Sigma E_T^{\text{Pb}} \rangle$ as a function of $E_{\text{ZDC}}^{\text{Pb}}$ for three different x_p selections. A relationship of $\langle \text{FCal } \Sigma E_T^{\text{Pb}} \rangle$ as a function of $E_{\text{ZDC}}^{\text{Pb}}$ consistent with a linear dependence is observed in the range of 0–150 TeV in $E_{\text{ZDC}}^{\text{Pb}}$ for all the x_p bins. In Figure 9, each distribution is fit to a linear function over that domain to approximately capture the underlying relation between the energies measured in the two calorimeters. The data above 150 TeV, corresponding to ~ 60 neutrons, are not considered in the fit since visible deviations from the linear trend start to appear. This behavior is likely due to fluctuations in the nuclear breakup occurring in events characterized by the highest (most central) event activity (collision geometry). The dependence of the linear fit's slope and intercept on the fit range was studied by systematically varying the upper limit of the fit range to cover ± 1 bin in $E_{\text{ZDC}}^{\text{Pb}}$ relative to the nominal choice of 150 TeV. The slope of the linear correlation between $\langle \text{FCal } \Sigma E_T^{\text{Pb}} \rangle$ and $E_{\text{ZDC}}^{\text{Pb}}$ decreases progressively moving from low to high- x_p values, an observation consistent with the x_p dependence of $r_{\text{ZDC,FCal}}$. Both these quantities are useful metrics for describing how the relationship between $E_{\text{ZDC}}^{\text{Pb}}$ and $\text{FCal } \Sigma E_T^{\text{Pb}}$ changes with x_p . However, a change in the number of neutrons does not directly imply a change in the transverse energy produced by the interactions of the participants at forward rapidity; they change as they both are correlated with the p+Pb collision geometry.

7 Conclusion

This Letter presents the characterization of the dependence of two event geometry estimators, used in the analysis of hard-scatterings in p +Pb collisions, on the initial-state kinematics. The transverse energy deposited in the ATLAS Forward Calorimeter and the forward energy recorded by the Zero-Degree Calorimeter in p +Pb collisions at $\sqrt{s_{NN}}=8.16$ TeV are analyzed as a function of the estimated Bjorken- x of the proton, x_p , accessed through dijet events detected using the ATLAS calorimeter. Both E_{ZDC}^{Pb} and $F\text{Cal} \Sigma E_T^{Pb}$ are shown to be sensitive to x_p , especially in the region $x_p \gtrsim 0.02$, where previous ATLAS results from the same data [23] have shown strong evidence of event activity biases that can be interpreted in terms of color fluctuation effects related to the proton configuration at the moment of the hard-scattering [18]. The average E_{ZDC}^{Pb} shows variations corresponding to two beam-energy neutrons between the high- and low- x_p selections considered in the analysis. Still, compared with the transverse energy in the Pb-going FCal, the energy deposited in the Pb-going ZDC is found to be about six times more robust against variations in the event kinematics for measurements of hard process rate modifications.

Further studies on the correlation between the two geometry estimators as a function of x_p are also reported. This analysis exposes a linear, x_p -dependent, relation between $F\text{Cal} \Sigma E_T^{Pb}$ and E_{ZDC}^{Pb} . These results can be used to advance the simultaneous modeling of event activity and nuclear breakup in p +Pb collisions characterized by the presence of a hard-scattering.

The results presented in this Letter qualitatively support models that connect color fluctuations with neutrons evaporated in the nuclear breakup [29]. Access to the underlying physics linking hard-scatterings and nuclear breakup will also aid the understanding of nuclear evaporation in processes characterized by resolved photon exchange, such as dijet production in UPCs at the LHC and e +A collisions at the future Electron-Ion Collider.

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