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

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ATLAS measured the centrality dependence of the dijet yield using 165 nb^{-1} of $p+\mathrm{Pb}$ data collected at $\sqrt{s_{\mathrm{NN}}}=8.16$ TeV in 2016. The event centrality, which reflects the $p+\mathrm{Pb}$ impact parameter, is characterized by the total transverse energy registered in the Pb-going side of the forward calorimeter. The central-to-peripheral ratio of the scaled dijet yields, R_{CP}, is evaluated, and the results are presented as a function of variables that reflect the kinematics of the initial hard parton scattering process. The R_{CP} shows a scaling with the Bjorken x of the parton originating from the proton, x_p, while no such trend is observed as a function of x_{Pb}. This analysis provides unique input to understanding the role of small proton spatial configurations in $p+\mathrm{Pb}$ collisions by covering parton momentum fractions from the valence region down to $x_p\sim 10^{-3}$ and $x_{\mathrm{Pb}}\sim 4\times 10^{-4}$.

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Proton-nucleus ($p+A$) reactions at colliders provide unique opportunities to study the structure of both the proton and the nucleus [1]. By measuring high transverse momentum (p_T) probes generated in $p+A$ collisions over a wide rapidity range, it is possible to investigate modifications of parton distribution functions (PDFs) in the nuclear environment [2–5] from small parton fractional momenta (x) up to the valence quark dominance region. Inclusive jet production rates were measured in $p+\mathrm{Pb}$ collisions at the LHC [6–9] and in $d+\mathrm{Au}$ collisions at RHIC [10]. ALICE also measured the jet production cross sections and nuclear modification of charged jets at 5.02 TeV [6]. None of these results observed a substantial modification of jet rates relative to the geometrical expectation constructed from proton-proton (pp) collisions, i.e., for $p+A$, scaling with the atomic mass number A: $\sigma^{p+A}\simeq A\sigma^{p+p}$. ATLAS [9] and PHENIX [10] analyzed the centrality dependence of the jet production. In this context, centrality is an experimental classification of the collision geometry based on a measurement of the underlying event (UE) activity in a rapidity region entirely separated from the hard-scattering measurement. In $p/d+A$ collisions, centrality is sensitive to the multiple interactions between the projectile and the nucleons in the nucleus, with more central (peripheral) events characterized by a higher (lower) average number of nucleon-nucleon (NN) collisions. Both Refs. [9,10] observed a suppression of the jet yield in central events and an enhancement in peripheral events. ATLAS found the relationship between the suppression and the enhancement to be a function of only the total jet energy. However, the initial hard parton-parton kinematics in each measurement were not fully constrained by the measurement of a single jet. To test for a trivial dependence on the kinematics of an NN collision, ATLAS also performed a measurement of the forward transverse energy in pp collisions [11] and found only a weak correlation between x of the proton beam and the transverse energy in the opposite direction, a trend that is at odds with the $p+\mathrm{Pb}$ results. This implied that the scaling observed in $p+\mathrm{Pb}$ collisions was not a property of the NN collision itself. CMS measured a shift in the Pb beam direction of the mean dijet pseudorapidity as a function of the total forward transverse energy [7], which is dominated by the energy deposited by the Pb debris. The inclusive measurement was observed to be consistent with predictions based on nuclear parton distribution functions (nPDFs), but the relative changes with centrality were found to be much larger than those expected from model predictions using nPDFs [12]. While this result had qualitative similarities to those reported by ATLAS [9], it covered a more limited kinematic range in only a single dijet p_T interval, making it difficult to assess more quantitatively.

These measurements inspired several theoretical works [13–15]. The models proposed in Refs. [13,14] were able to partially reproduce the ATLAS data [9] but were strongly disfavored by the results of Ref. [11]. In Ref. [15], the authors were able to reproduce inclusive jet results at both RHIC [10] and LHC [9] energies using a model based on a

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color fluctuation-related [16] interpretation. The interaction strength of the proton, as well as its transverse size, are treated as dynamic quantities that depend on the instantaneous partonic configuration, considered frozen during the propagation of the proton through the nucleus. Because of QCD color screening, the overall interaction strength of a color-neutral configuration is expected to vary with the transverse area subtended by its color charges [17], which is smaller in hadrons where one parton carries a considerable fraction of the momentum. Therefore, hard $p + \mathrm{Pb}$ scatterings involving configurations of the proton with a large-x parton, typical of the valence quark dominance region, are characterized by a smaller than average size and interaction strength of the projectile. These configurations have a reduced number of soft interactions with the nucleus, resulting in lower underlying event activity and, thus, shifting the event into a more peripheral centrality interval. This can be interpreted as a manifestation of color transparency phenomena [17–20]. Triple differential measurements of the dijet production as a function of centrality would allow for connecting these effects directly to the kinematics of the parton scattering, providing crucial input to advance the understanding of small proton configurations and their relation to the suppression of the overall interaction strength in $p + A$ collisions.

This Letter presents measurements of the centrality dependence of the differential dijet yield in ATLAS $p + \mathrm{Pb}$ data at an NN center-of-mass energy of 8.16 TeV. It uses data collected in 2016 corresponding to an integrated luminosity of 165 nb^{-1}. The LHC was configured with a 6.5 TeV proton beam and a Pb beam with an energy of 2.56 TeV per nucleon. In this measurement, positive (negative) rapidities correspond to the proton-going (Pb-going) direction. The beam configuration resulted in a rapidity shift of the center of mass by +0.465 units in the proton-going direction relative to the laboratory frame.

The measurement presented here was performed using the ATLAS calorimeters, inner detector, trigger, and data acquisition systems [21]. The calorimeter system consists of a sampling liquid-argon (LAr) electromagnetic (EM) calorimeter covering $|\eta| < 3.2$ [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 upward. Cylindrical coordinates (ρ,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 $\eta = -\ln\tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.], a steel-scintillator sampling hadronic calorimeter covering $|\eta| < 1.7$, LAr hadronic calorimeters covering $1.5 < |\eta| < 3.2$, and two LAr forward calorimeters (FCal) 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 in $|\eta| < 1.7$ and four sampling layers in $1.5 < |\eta| < 3.2$, with a slight overlap in η. During the 2016 $p + \mathrm{Pb}$ run, a sector of the hadronic end cap calorimeter (HEC), corresponding to $1.5 < \eta < 3.2$ and $-\pi < \phi < -\pi/2$, was disabled. An extensive software suite [22] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

The dijet yield was measured as a function of

$$p_{T,\mathrm{Avg}} = \frac{p_{T,1} + p_{T,2}}{2}, \qquad y_b = \frac{y_1^{\mathrm{c.m.}} + y_2^{\mathrm{c.m.}}}{2}, \quad \text{and}$$

$$y^* = \frac{|y_1^{\mathrm{c.m.}} - y_2^{\mathrm{c.m.}}|}{2}, \tag{1}$$

where the superscript "c.m." denotes variables translated in the center-of-mass frame of the collision, while the subscripts 1 and 2 refer to the jets with the highest (leading) and second-highest (subleading) p_T in a given event, respectively. $p_{T,\mathrm{Avg}}$ is the average transverse momentum, and y_b and y^* are the boost and the half-rapidity separation of the dijet system, respectively. Note that y^* is directly related to the 2 → 2 scattering angle. These variables can be approximately related to

$$x_p = \frac{p_{T,1} e^{y_1^{\mathrm{c.m.}}} + p_{T,2} e^{y_2^{\mathrm{c.m.}}}}{\sqrt{s_{\mathrm{NN}}}} \simeq \frac{2 p_{T,\mathrm{Avg}}}{\sqrt{s_{\mathrm{NN}}}} e^{y_b} \cosh(y^*) \tag{2}$$

and

$$x_{\mathrm{Pb}} = \frac{p_{T,1} e^{-y_1^{\mathrm{c.m.}}} + p_{T,2} e^{-y_2^{\mathrm{c.m.}}}}{\sqrt{s_{\mathrm{NN}}}} \simeq \frac{2 p_{T,\mathrm{Avg}}}{\sqrt{s_{\mathrm{NN}}}} e^{-y_b} \cosh(y^*), \tag{3}$$

the longitudinal momentum fractions carried by the incident partons in a 2 → 2 QCD scattering in the proton and Pb nucleus, respectively.

Centrality in $p + \mathrm{Pb}$ collisions can be directly related to the number of inelastic collisions between the proton and the nucleons bound in the Pb nucleus. In this analysis, centrality was characterized using the total transverse energy ΣE_T^{Pb}, measured in the FCal in the Pb-going direction [9,23,24], with the resulting distribution being divided into percentiles. A Glauber Monte Carlo (MC) model [25,26] was used to relate ΣE_T^{Pb} to the average value of the nuclear thickness function, T_{AB} [27], in a given centrality class. The reported results were obtained using the 0%–10% (central) and 60%–90% (peripheral) centrality intervals. The resultant $\langle T_{AB} \rangle$ values and associated uncertainties are (0.205 ± 0.013) and $(0.043 \pm 0.009)\ \mathrm{mb}^{-1}$ for central and peripheral collisions, respectively.

Nuclear modification effects are typically characterized by the ratio of the hard scattering rates in the presence and absence of a nuclear environment. In this analysis, the dijet yield was measured in different centrality intervals to construct the central-to-peripheral ratio R_{CP} defined as

$$R_{\mathrm{CP}}(p_{T,\mathrm{Avg}}, y_b, y^*) = \frac{\frac{1}{\langle T_{AB}^{0\%\text{–}10\%}\rangle} \frac{1}{N_{\mathrm{evt}}^{0\%\text{–}10\%}} \frac{d^3 N_{\mathrm{dijet}}^{0\%\text{–}10\%}}{dp_{T,\mathrm{Avg}} dy_b dy^*}}{\frac{1}{\langle T_{AB}^{60\%\text{–}90\%}\rangle} \frac{1}{N_{\mathrm{evt}}^{60\%\text{–}90\%}} \frac{d^3 N_{\mathrm{dijet}}^{60\%\text{–}90\%}}{dp_{T,\mathrm{Avg}} dy_b dy^*}}, \qquad (4)$$

where $N_{\mathrm{evt}}^{0\%\text{–}10\%}$ ($N_{\mathrm{evt}}^{60\%\text{–}90\%}$) and $N_{\mathrm{dijet}}^{0\%\text{–}10\%}$ ($N_{\mathrm{dijet}}^{60\%\text{–}90\%}$) represent the number of sampled minimum-bias and dijet events in central (peripheral) collisions, respectively. The R_{CP} quantifies the deviations in the dijet yield in more central collisions from geometric expectations relative to peripheral collisions, assuming little to no nuclear final state modification in the latter. An R_{CP} of unity implies no centrality-dependent modifications.

The $p+\mathrm{Pb}$ data used in this analysis were required to satisfy detector and data-quality requirements and to contain at least one reconstructed primary vertex and at least two reconstructed jets. A set of central and forward single-jet triggers [28], characterized by different p_T thresholds, were chosen to provide full p_T coverage over a wide pseudorapidity range, corresponding to $-2.8 < \eta < 4.5$. The leading jet was required to have passed the trigger that sampled the largest luminosity and was 99% efficient for the given jet η and p_T. The leading (subleading) jet was further required to have $p_T > 40(30)$ GeV. Events were discarded if either of the jets fell in the acceptance of the disabled HEC region. To define a rejection criterion for the analysis, the disabled region was increased by an additional 0.4 margin in both the pseudorapidity and azimuthal angle. Pileup events were rejected using vertex and track requirements. The exclusion of events in the 90%–100% centrality interval, combined with a rapidity gap requirement [29] in the Pb-going direction, effectively rejected any contribution from ultraperipheral collisions.

Jets used in this measurement were reconstructed using the anti-k_t algorithm [30] as implemented within the FastJet software package [31]. Jets with $R = 0.4$ were formed by clustering four-vectors corresponding to massless calorimeter towers with size $\Delta\eta \times \Delta\phi = 0.1 \times (\pi/32)$. The background energy arising from the UE was subtracted from each tower. An iterative procedure was used to estimate the UE average transverse energy density $\rho(\eta)$ while excluding regions of the detector populated by jets [32]. The UE evaluation was additionally corrected for η-ϕ dependent nonuniformities of the detector.

The performance of the jet reconstruction was evaluated using GEANT4 [33,34] to simulate the detector response and a PYTHIA8 [35] MC sample consisting of dijet events from 8.16 TeV pp collisions, including the boost in rapidity relative to the lab frame that is present in data. The MC sample was generated using PYTHIA8 with the A14 set of tuned parameters [36] and the NNPDF2.3LO parton distribution functions [37]. Events from the dijet sample were overlaid with minimum-bias $p+\mathrm{Pb}$ collisions recorded by ATLAS during the same data-taking period as the analyzed data, ensuring a proper UE description in the MC sample.

To correct for the effects of detector response on the measurement, the dijet yield was unfolded in $p_{T,\mathrm{Avg}}$ using a one-dimensional Bayesian procedure [38], implemented within the RooUnfold package [39]. For each y_b, y^*, and centrality interval, a response matrix was filled using pairs of true and reconstructed jets from the PYTHIA8 overlay MC sample. The statistical uncertainty on the dijet yield was evaluated using a bootstrapping method [40] to generate statistically correlated response matrices.

An efficiency correction was included during the unfolding to account for reconstructed dijets that migrated between y_b and y^* bins or out of the measurement phase space at the detector level due to energy resolution effects. Dijets impacted by the disabled HEC region exclusion were also accounted for with this correction. The size of the efficiency correction on the yields is significant only in the pseudorapidity region corresponding to the disabled HEC, where it reaches approximately a factor of 3. It is on the order of a few percent in the remaining phase space due to migration between y_b and y^* bins and energy resolution effects.

To estimate the systematic uncertainty on the jet energy scale (JES), jet energy resolution (JER), and unfolding procedure, the difference between the nominal result and that obtained by repeating the analysis with modified response matrices was calculated. The JES and JER smearing factors were obtained via *in situ* studies [41], as well as by accounting for reconstruction and calibration differences [32] between this measurement and 13 TeV pp data, where components of the uncertainty were derived. An additional component accounting for MC modeling of the quark and gluon jets is included in the JES uncertainty. The total systematic uncertainty on the dijet yield is dominated by the JES uncertainty, which is approximately 10% in all kinematic intervals. The JER uncertainty is subdominant, reaching up to ∼10% only for the highest y^* values. The uncertainty on the unfolding procedure is related to its sensitivity to the choice of prior, which was reweighted to have better data-MC agreement. To address this, an approach similar to one found in Ref. [9] was used to vary the reweighting, producing modified response matrices. The systematic uncertainty on the unfolding is at the subpercent level for all bins.

The systematic uncertainty associated with the disabled HEC exclusion was evaluated by increasing the fiducial cuts by 0.1 in all directions in azimuth and pseudorapidity and repeating the analysis procedure. The resultant uncertainty was found to be on the order of 1%–2% in the majority of the measurement's phase space.

Correlations in the JES, JER, and HEC uncertainties between central and peripheral bins were accounted for in the propagation of the uncertainties to the R_{CP}. The partial

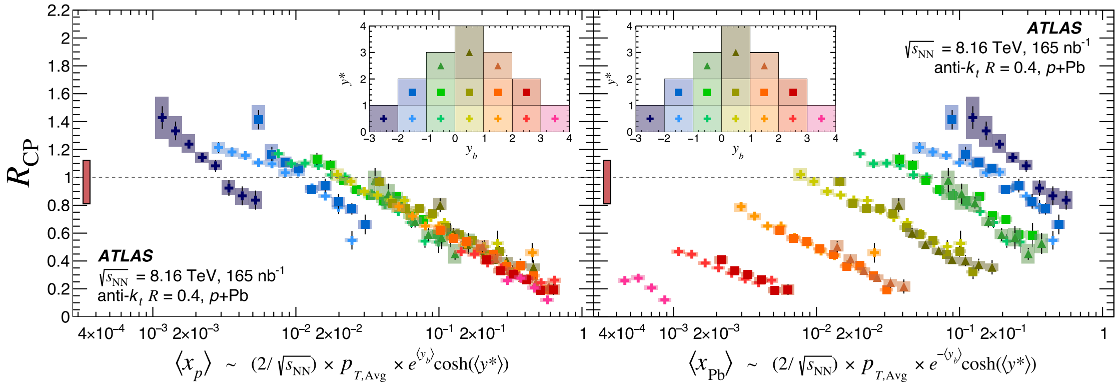

FIG. 1. R_{CP} plotted as a function of approximated x_p (left panel) and x_{Pb} (right panel), constructed using $\langle y_b \rangle$ and $\langle y^* \rangle$. An inset legend is included, showing the $(y_b,\ y^*)$ bins and their corresponding markers. The proton-going direction is defined by $y_b > 0$. Shaded rectangles represent the total systematic uncertainty, while the vertical error bars represent the statistical uncertainty. The solid rectangle on the left side of each panel represents the uncertainty on the T_{AB}.

cancellation of the resulting systematic uncertainties from these sources results in considerably smaller uncertainties on the R_{CP} compared with those on the dijet yield. The normalization uncertainty on the R_{CP} corresponding to the T_{AB} is $+12\%/-19\%$ and is independent of jet p_T and η.

The measured central and peripheral dijet yields are used to construct the R_{CP} as a function of $p_{T,\mathrm{Avg}}$. The R_{CP} values are then plotted against the approximated kinematics of the hard parton scattering, constructed using Eqs. (2) and (3) as $\langle x_p \rangle \sim (2p_{T,\mathrm{Avg}}/\sqrt{s_{NN}})e^{\langle y_b \rangle}\cosh\langle y^* \rangle$ and $\langle x_{Pb} \rangle \sim (2p_{T,\mathrm{Avg}}/\sqrt{s_{NN}}) \times e^{-\langle y_b \rangle}\cosh\langle y^* \rangle$, where $\langle y_b \rangle$ and $\langle y^* \rangle$ are the average values of the dijet boost and half-rapidity separation in each given kinematic bin, respectively. The level of accuracy of this approximation was evaluated via PYTHIA8 MC simulations and found to be accurate within the bin widths used for the measurement.

Figure 1 shows the results as a function of $\langle x_p \rangle$ (left) and $\langle x_{Pb} \rangle$ (right). A distinct x_p scaling of the $R_{CP}(x_p)$ is observed in the valence quark dominance region, characterized by a log-linear decreasing trend. No similar scaling is observed for smaller values of x_p or for any region when expressed as a function of x_{Pb}. Recently, the analysis of forward dijet production in $p+\mathrm{Pb}$ collisions at LHC energies was proposed in order to search for the onset of gluon saturation [42] at low values of x_{Pb}. The saturation scale in the nuclear environment is expected to be enhanced by a factor $A^{1/3}$. The lack of monotonic scaling with decreasing x_{Pb} observed in Fig. 1 suggests that gluon saturation is not the dominant source of the observed effect. These observations can be expected from the color fluctuation-related interpretation discussed at the beginning of this Letter. The measured suppression of the R_{CP} is qualitatively consistent with an x_p-dependent decrease in the interaction strength of proton configurations containing high-x partons, resulting in a modification of the UE activity and, therefore, the centrality. Centrality estimates for events with hard scatterings have been found to be biased by modifications in soft processes, an effect that is typically enhanced with small pseudorapidity separations $\Delta\eta$ between a hard probe and the centrality detector acceptance [23,43,44]. The effect is strongly reduced at large $\Delta\eta$ and is expected to have negligible impact on the R_{CP} x_p scaling reported in Fig. 1.

The x_p scaling observed in Fig. 1 is qualitatively similar to that observed in the 5.02 TeV run 1 inclusive jet analysis [9] as a function of the jet energy. A direct comparison between the results could clarify whether or not they are connected by the same underlying physics. The measurements can be compared by making use of the Feynman scaling variable x_F [45]. Figure 2 shows the dijet results as a function of the approximated x_F computed in each

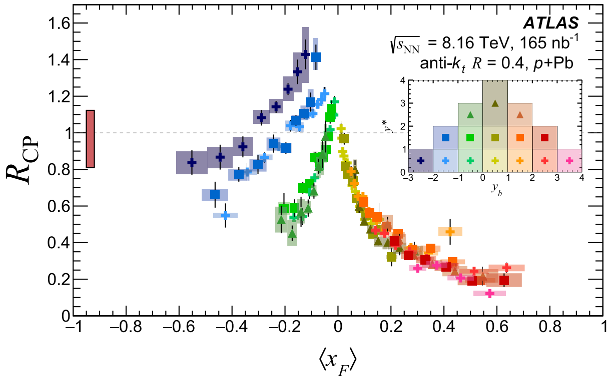

FIG. 2. R_{CP} plotted as a function of approximated x_F, here indicated with $\langle x_F \rangle$ and constructed using $\langle y_b \rangle$ and $\langle y^* \rangle$. An inset legend is included, showing the $(y_b,\ y^*)$ bins and their corresponding markers. The proton-going direction is defined by $y_b > 0$. Shaded rectangles represent the total systematic uncertainty, while the vertical error bars represent the statistical uncertainty. The solid rectangle on the left side of the panel represents the uncertainty on the T_{AB}.

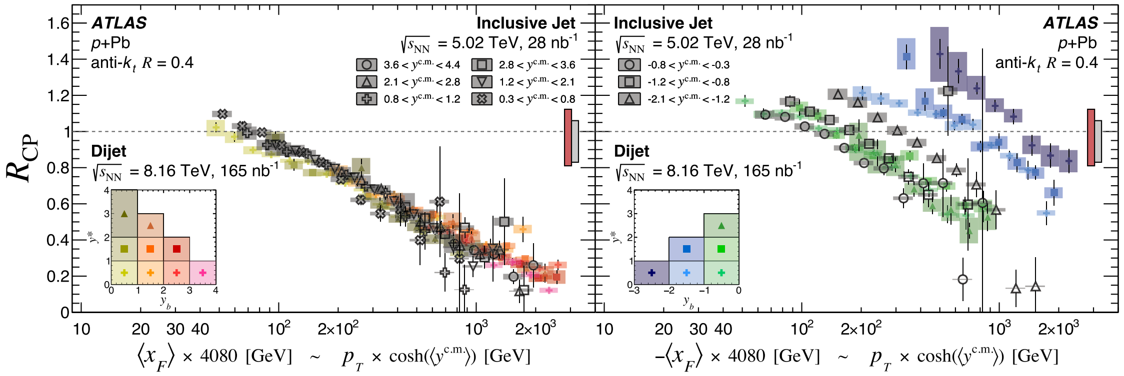

FIG. 3. Dijet R_{CP} results from this Letter compared with inclusive jet R_{CP} at 5.02 TeV measured by ATLAS [9]. The dijet results are denoted by full markers and are reported as a function of $\pm\langle x_F\rangle \times 4080$ GeV, for positive (+, left panel) and negative (−, right panel) y_b ($y^{c.m.}$) results, respectively. An inset legend is included, showing the (y_b, y^*) bins and their corresponding markers. The inclusive jet results are displayed as a function of $p_T \times \cosh(\langle y^{c.m.}\rangle)$ and use open markers. Shaded rectangles represent the total systematic uncertainty, while the vertical error bars represent the statistical uncertainty. The uncertainties on the T_{AB} on the dijet (inclusive jet) results are reported using the left (right) solid rectangle on the right side of each panel. The 5.02 TeV data for $-0.3 < y^{c.m.} < 0.3$ were omitted, since they belong to the transition region between the two panels.

kinematic bin as $\langle x_F\rangle = \langle x_p\rangle - \langle x_{Pb}\rangle$. The mapping of the R_{CP} to $\langle x_F\rangle$ allows for factoring out the beam energy from the results while isolating the dependence of the dijet yield on the parton momentum fractions characterizing the hard scattering. Large positive (negative) values of $\langle x_F\rangle$ are associated to scatterings dominated by the longitudinal momentum of the parton originating from the proton (nucleus). In inclusive jet measurements, x_F can also be constructed as a property of the final state, i.e., $x_F = 2p_z/\sqrt{s_{NN}}$, where p_z is the longitudinal momentum of the measured jet. Assuming the jet mass to be small compared to its transverse momentum and considering $y^{c.m.}$ values large enough that $\sinh y^{c.m.} \simeq \pm\cosh y^{c.m.}$, with the positive (negative) sign corresponding to $y^{c.m.} > 0$ ($y^{c.m.} < 0$):

$$x_F = \frac{2m_T \times \sinh y^{c.m.}}{\sqrt{s_{NN}}} \sim \pm\frac{2p_T \times \cosh y^{c.m.}}{\sqrt{s_{NN}}}. \qquad (5)$$

Therefore, because the results in Ref. [9] were reported as a function of $p_T \times \cosh y^{c.m.}$, a comparison to the results presented in this Letter can be achieved using the relation $\pm x_F\sqrt{s_{NN}}/2 \sim p_T \times \cosh y^{c.m.}$, where the sign of the left-hand side of the equation corresponds to the sign of $y^{c.m.}$. This comparison is shown in Fig. 3. A striking agreement is observed between the results obtained at positive $y^{c.m.}$ and y_b, corresponding to the high-x_p region. This comparison shows 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 as a function of the jet energy is effectively governed by the proton configuration. The agreement between the data progressively worsens when moving toward the negative rapidity region, where the majority of the momentum in the hard scattering is contributed by the parton from the Pb nucleus. These results provide new input to further parametrize color fluctuation effects in $p + A$ collisions. Improvements in the understanding of these effects will also pave the way for future studies of color transparency at the electron-ion collider [46].

These new dijet data can also be used to provide further interpretation of the dijet pseudorapidity measurement as a function of the forward transverse energy carried out by CMS [7]. Analyzing the rapidity dependence of the results in Fig. 1, a more substantial R_{CP} suppression is associated with larger values of y_b, corresponding to higher values of x_p. This observation is directly linked to a shift in the $\langle y_b\rangle$ dependence of the dijet yield measured in central and peripheral events; refer to the Appendix for more details. Thus, these results can be used to recast the observations reported by CMS as a manifestation of the x_p-related scaling reported in this Letter.

In summary, this Letter presents the measurement of the centrality dependence of the dijet yield over a wide range of $p_{T,\mathrm{Avg}}$, y_b, and y^*. The measured R_{CP} is reported in terms of approximated kinematics of the hard parton-parton scattering. In the valence quark dominance region of the proton, a striking x_p scaling of the R_{CP} is observed. Such scaling behavior is not present when the R_{CP} is analyzed as a function of x_{Pb}. By making use of the Feynman variable x_F and a few kinematic considerations, the results are compared with those obtained by ATLAS for the centrality dependence of inclusive jet production at 5.02 TeV [9]. The comparison between the two measurements strongly suggests that the observed $p_T \times \cosh y^{c.m.}$ scaling at 5.02 TeV is driven by the kinematics of the parton originating from the proton. The outcome of this analysis provides new input to explain the systematic shift in the mean $\langle y_b\rangle$ measured by CMS at 5.02 TeV [7]. These results are qualitatively in agreement with the x_p-dependent color fluctuation effects

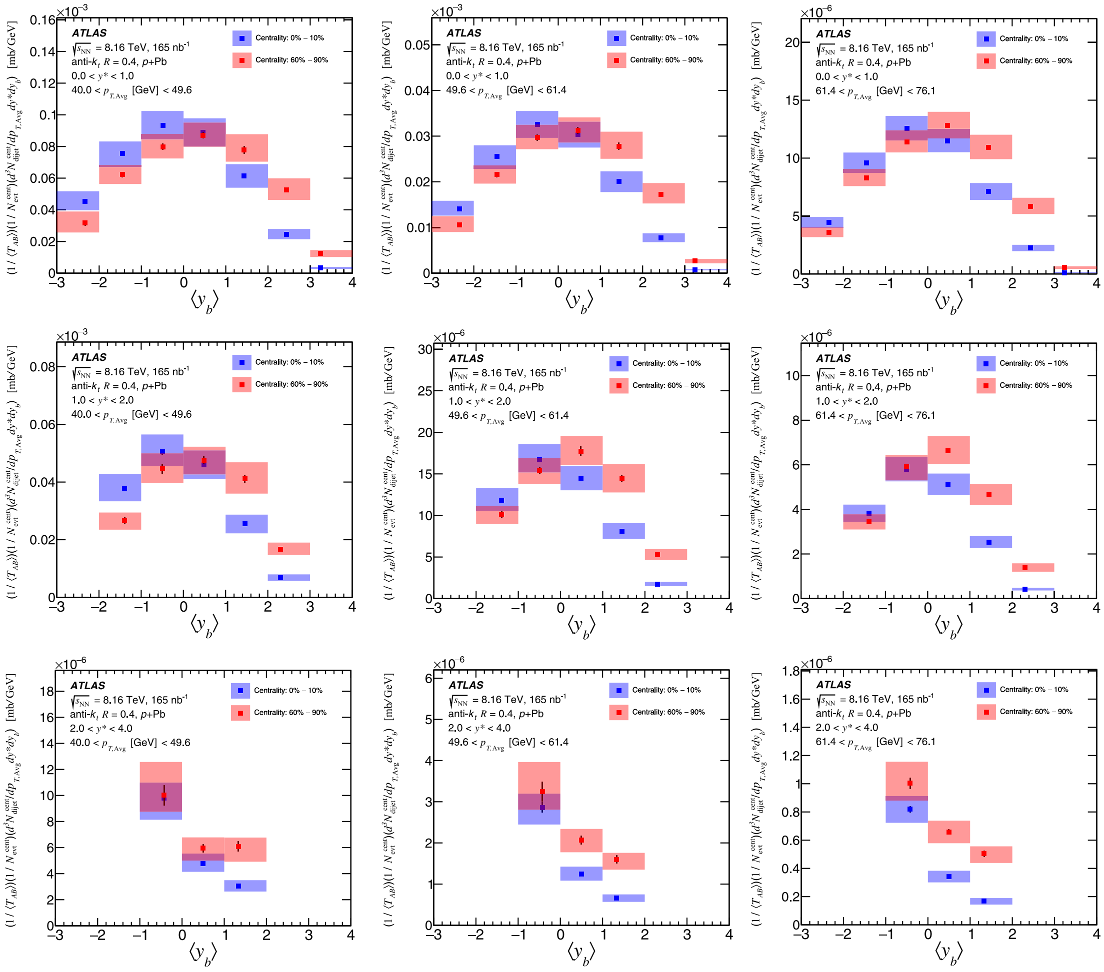

FIG. 4. $\langle T_{AB}\rangle$ normalized per-event dijet yields in 0%–10% (blue) and 60%–90% (red) collisions as a function of $\langle y_b\rangle$ in three representative $p_{T,\mathrm{Avg}}$ bins for $0.0 < y^* < 1.0$ (top row), $1.0 < y^* < 2.0$ (middle row), and $2.0 < y^* < 4.0$ (bottom row). Shaded rectangles represent the total systematic uncertainty, while the vertical error bars represent the statistical uncertainty. The systematic uncertainties for the two distributions are highly correlated.

described in Ref. [15], directly related to small configurations of the proton characterized by a reduced interaction strength. The measurement presented in this Letter represents an essential step forward in the understanding of jet production in $p+\mathrm{Pb}$ collisions in terms of the hard-scattering kinematics.

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Appendix.—The measured triple differential dijet yields can also be used to study the centrality dependence of the $\langle y_b \rangle$ distribution. Figure 4 shows the results as a function of $\langle y_b \rangle$ for central and peripheral intervals in a few representative $p_{T,\mathrm{Avg}}$ and y^* selections. A shift from zero of the two distributions is observed in all the kinematic bins. This deviation is found to be monotonically decreasing as a function of $p_{T,\mathrm{Avg}}$ for peripheral yields in all the y^* ranges. Conversely, central yields show a shift from zero decreasing in magnitude with increasing $p_{T,\mathrm{Avg}}$ only in $0 < y^* < 1$. A moderate increase with $p_{T,\mathrm{Avg}}$ is observed in $1 < y^* < 2$, while in $2 < y^* < 4$ the shift goes from positive (low $p_{T,\mathrm{Avg}}$) to negative (high $p_{T,\mathrm{Avg}}$). These kinematic dependencies are directly reflected in the x_p scaling of the R_{CP} reported in Fig. 1.

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