

EXPERIMENTAL OVERVIEW OF SMALL-SYSTEM RESULTS WITH THE ATLAS DETECTOR*

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The ATLAS small-system program began in 2012 with the first p +Pb collisions delivered by the LHC. Measurements across several collision systems and energies show that small systems exhibit collective phenomena similar to those observed in large collision systems. In contrast, hard-probe measurements in p +Pb collisions show no significant modification consistent with jet quenching, and observed centrality dependencies are largely explained by initial-state effects and event-activity biases.

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1. Introduction

Theoretical studies proposed ultra-relativistic heavy-ion collisions as a means to reach energy densities sufficient for the formation of a deconfined medium of quarks and gluons, the quark–gluon plasma (QGP) [1]. Evidence for QGP formation was established in collisions of large nuclei, such as Pb+Pb at the SPS and Au+Au at RHIC. This conclusion was supported by a broad set of measurements, including suppression of high- p_T hadrons [2], strong collective flow [3], quarkonium suppression [4], and in-medium modification of light vector mesons [5].

While pp collisions serve as a vacuum baseline for the QGP-related modifications observed in heavy-ion collisions, LHC experiments including ATLAS [6] observed collective phenomena similar to those known from large heavy-ion collisions in high-multiplicity pp [7–9] as well as p +Pb collisions [8–11]. Possible final-state effects in p +Pb have been investigated using jets [12], charged hadrons [13], quarkonia [14], and top-quark pair production [15].

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In 2025, ATLAS recorded pilot data for $p+O$, $O+O$, and $Ne+Ne$ collisions. The results of these intermediate-sized collision systems are discussed in [16].

2. Hard probes and initial-state effects

ATLAS measurements in $p+Pb$ collisions demonstrate that soft particle production scales with the number of nucleons participating in the collision N_{part} [17], while hard processes scale with the number of binary nucleon–nucleon collisions N_{coll} [18]. The observed scaling reflects the same collision geometry, since in $p+Pb$ collisions the two quantities are closely related by $N_{\text{coll}} = N_{\text{part}} - 1$. The scaling observed is only approximate, as seen in Fig. 1. Deviations from the Glauber model [19], a geometric model describing nuclear collisions as a set of independent nucleon–nucleon interactions and providing estimates of N_{coll} and N_{part} , can arise because the effective proton–nucleon interaction cross section can fluctuate on an event-by-event basis [20]. In Glauber–Gribov extensions of the Glauber model, fluctuations in the cross section are allowed. The relative variance of the interaction strength is characterized by ω_σ . Accounting for the color fluctuations improves the description of the observed scaling behavior in $p+Pb$ collisions.

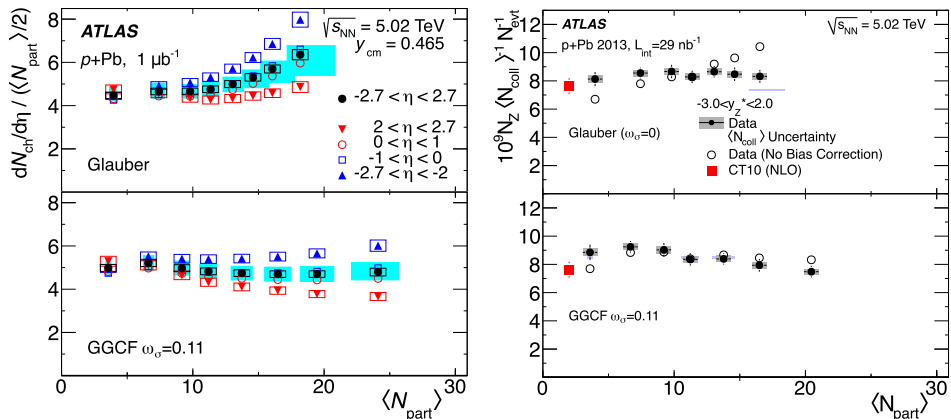


Fig. 1. Left: Charged-particle multiplicity as a function of the number of participants N_{part} [17]. Right: Z yield as a function of the number of nucleon–nucleon collisions N_{coll} [18]. The measurements are compared with Glauber-model predictions with and without color-fluctuation corrections characterized by the parameter ω_σ .

In contrast to $Pb+Pb$ collisions, where many nucleon–nucleon interactions occur, and fluctuations of the interaction strength average out, $p+Pb$ collisions involve a single proton interacting with the nucleus. Event-by-event fluctuations of the proton configuration can therefore modify the effective proton–nucleon interaction cross section and, consequently, the num-

ber of participating nucleons in the collision. As a result, the event activity used for centrality association is correlated with the hardness of the process. Hard probes such as jets therefore provide a direct way to investigate the interplay between hard scattering and event activity in p +Pb collisions.

ATLAS investigated the magnitude of final-state effects using hard probes in p +Pb collisions. Jet quenching was studied by measuring the nuclear modification factor $R_{p\text{Pb}}$ of inclusive jets [12]. When averaged over centrality, $R_{p\text{Pb}}(p_T, \eta)$ was found to be consistent with unity. However, when performed differentially in jet rapidity and centrality class, $R_{p\text{Pb}}(p_T)$ exhibited a non-trivial dependence. Such behavior pointed toward a correlation between hard scattering and event activity, known as the event activity bias. To investigate this effect, dijet production in p +Pb collisions [21] was measured. The kinematics of dijet events allow the momentum fractions of the incoming partons, x_p and x_{Pb} , to be probed through the dijet rapidity variables

$$y_b = \frac{y_1 + y_2}{2} \quad \text{and} \quad y^* = \frac{|y_1 - y_2|}{2}.$$

The central-to-peripheral ratio of the scaled dijet yields R_{CP} was studied as a function of these quantities, where dijet events were categorized according to $\{y^*, y_b\}$. As shown in Fig. 2, the centrality dependence of dijet production scales with the proton momentum fraction x_p , while no similar scaling is observed with x_{Pb} .

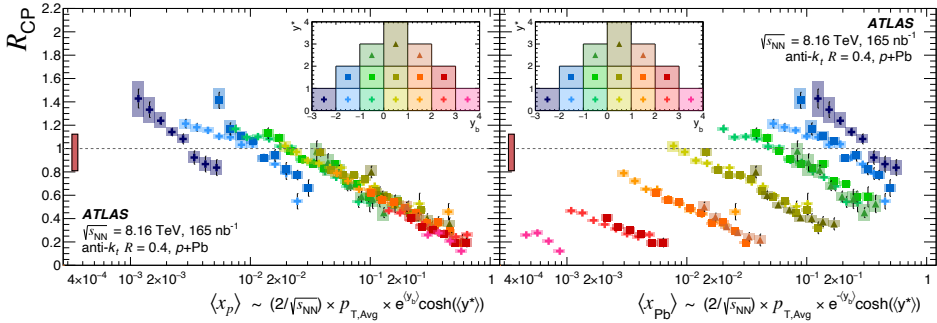


Fig. 2. Central-to-peripheral ratio of the scaled dijet yields R_{CP} in p +Pb collisions shown as a function of the proton momentum fraction x_p (left) and the Pb momentum fraction x_{Pb} (right) [21].

Thus, the R_{CP} suppression is found to be effectively governed by the proton configuration rather than by nuclear effects in the Pb nucleus. This interpretation is further supported in Ref. [21], where consistent R_{CP} scaling was observed for both inclusive jet and dijet measurements when studied as

a function of the Feynman variable x_F [22], defined as the fraction of the maximum possible momentum in the center-of-mass frame carried by the longitudinal momentum of the produced object.

Since the event activity estimator itself may be correlated with the hard scattering, alternative estimators of the collision geometry were studied. In particular, the energy deposited in the Zero Degree Calorimeter (ZDC), sensitive to spectator neutrons, was investigated [23]. Unlike the forward calorimeter energy $\sum E_T^{\text{Pb}}$, which reflects the particle production in the event, the ZDC signal originates from the breakup of the Pb nucleus and thus should be less directly correlated with the hard scattering. Using dijet kinematics to probe x_p , the ZDC-based estimator was found to be about six times less sensitive to x_p than $\sum E_T^{\text{Pb}}$, as displayed in Fig. 3. However, the dynamics of nuclear breakup in $p+\text{Pb}$ collisions are not well constrained by current models, particularly in the presence of hard scattering, which limits the use of the ZDC signal as a robust centrality estimator.

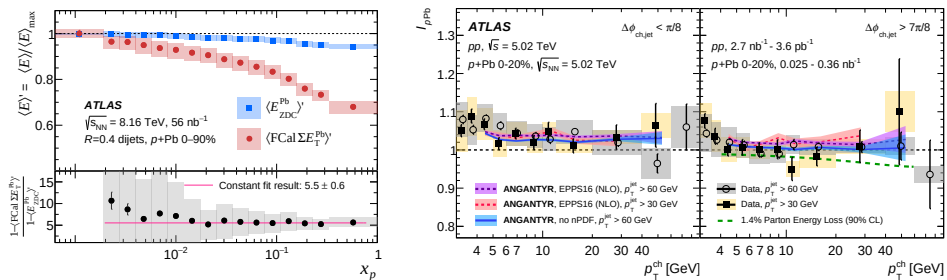


Fig. 3. Left: Dependence of the ZDC energy $E_{\text{ZDC}}^{\text{Pb}}$ and forward calorimeter energy $\sum E_T^{\text{Pb}}$ on the proton momentum fraction x_p in dijet events [23]. Right: Per-trigger yield modification factor $I_{p\text{Pb}}$ for charged particles correlated with a high- p_T jet in near-side and away-side regions [13].

To further constrain final-state effects in $p+\text{Pb}$, jet–hadron correlations are studied [13]. Charged particles are correlated with a high- p_T jet, and the per-trigger associated yield is compared between $p+\text{Pb}$ and pp collisions. The per-trigger yield modification factor $I_{p\text{Pb}}$ is studied in two regions. The near-side region ($|\Delta\phi_{\text{ch,jet}}| < \pi/8$) is sensitive to modifications of jet fragmentation in the medium. The away-side region ($|\Delta\phi_{\text{ch,jet}}| > 7\pi/8$) is sensitive to energy redistribution caused by parton energy loss. The near-side modification factor is well reproduced by an Angantyr simulation performed without final-state effects or jet quenching. In addition, the away-side modification factor is consistent with unity within uncertainties. Together, these observations indicate no significant modification of either jet fragmentation or the recoil-jet structure in $p+\text{Pb}$ collisions, placing strong constraints on possible jet-quenching effects in small systems.

Complementary information about the final-state effects in $p+\text{Pb}$ is provided by measurements performed with other hard probes. Nuclear modification factors have been measured for charged hadrons [24], quarkonia [14], and top-quark pairs [15]. All of these measurements are consistent with unity within uncertainties, indicating no strong final-state suppression comparable to the jet quenching observed in heavy-ion collisions with large nuclei such as $\text{Pb}+\text{Pb}$ [25]. Within the experimental uncertainties, the quarkonium measurements still leave room for moderate modifications of the production rates [14], as shown in the left panel of Fig. 4. Additional insight into quarkonium production is obtained from correlations with the underlying-event activity. The right panel of Fig. 4 shows the charged-particle multiplicity accompanying different $\Upsilon(nS)$ states in pp collisions [26]. Excited Υ states are associated with smaller charged-particle multiplicities than the ground state, a feature not reproduced by current Monte Carlo generators. The observed correlation between quarkonium production and the underlying-event activity indicates that the production of excited Υ states is linked to the event environment. Such a correlation contrasts with the approximate m_T -scaling observed for light hadrons [27], further emphasizing that quarkonium production follows mechanisms distinct from those governing light-hadron production.

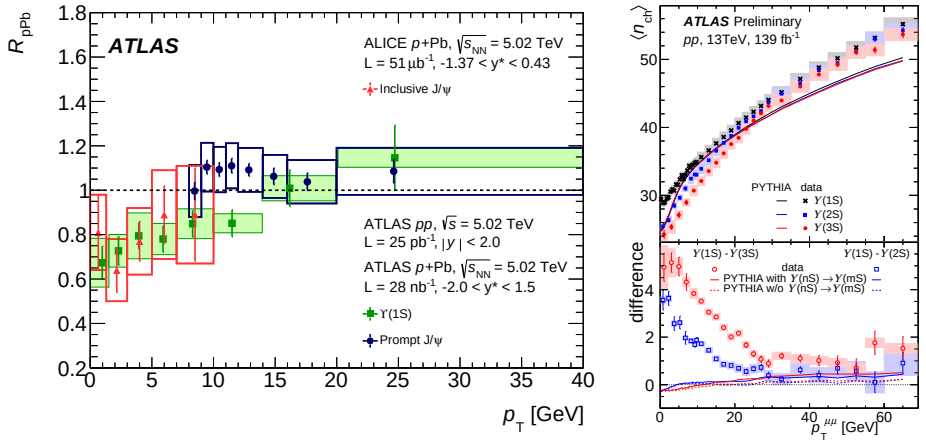


Fig. 4. Left: Nuclear modification factor of quarkonium states measured in small collision systems [14]. Right: Charged-particle multiplicity associated with different $\Upsilon(nS)$ states in pp collisions [26].

3. Collectivity

Collective phenomena reminiscent of those observed in heavy-ion collisions were discovered in small systems. Two-particle correlations are studied as functions of the angular differences $\Delta\phi$ and $\Delta\eta$ between particle pairs.

A long-range structure in $\Delta\eta$ around $\Delta\phi = 0$, known as the ridge, previously observed in heavy-ion collisions [28], was observed in high-multiplicity p +Pb collisions [10] in a pilot run, and later studied in detail with larger datasets and deployment of high-multiplicity triggers [11]. Both measurements used the zero-yield-at-minimum (ZYAM) assumption, which identifies the minimum of the $\Delta\phi$ distribution as a region with negligible correlated yield and subtracts the corresponding pedestal. Later, the template-fit method was introduced, describing the high-multiplicity correlation function as a superposition of the low-multiplicity correlation and a modulated component associated with collective behavior [7]. The ridge structure observed in pp collisions is shown in the left panel of Fig. 5.

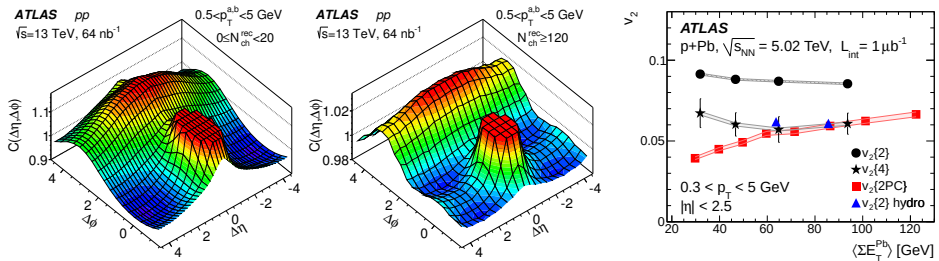


Fig. 5. Left: Long-range two-particle correlation function observed in high-multiplicity pp collisions, showing the ridge structure [7]. Right: Elliptic flow coefficient v_2 measured with various methods illustrating the suppression of non-flow contributions [29].

The azimuthal structure of the long-range correlations can be characterized by Fourier coefficients v_n , with the second harmonic v_2 providing the dominant contribution to the ridge structure. However, two-particle correlations may contain contributions from non-flow effects. To suppress such contributions, flow coefficients were measured using multi-particle cumulants [29]. Higher-order particle correlations reduce the influence of non-flow effects and provide a more robust probe of collective behavior. The right panel of Fig. 5 compares v_2 obtained from two-particle and four-particle cumulants. The four-particle cumulant suppresses non-flow contributions and yields a smaller value of v_2 , which shows a better agreement with both the v_2 obtained from two-particle correlations and the hydrodynamical model prediction. Subsequent ATLAS studies of v_n coefficients were conducted. In p +Pb collisions, $v_n(p_T)$ are measured for $n = \{1, 2, 3, 4, 5\}$ [29] and in pp collisions, $v_2(p_T)$ is measured for various $\sqrt{s}$ and multiplicities [7]. Results presented in Ref. [8] study higher-order c_2 involving correlations among up to eight particles in p +Pb, as well as performing qualitative studies of pp , p +Pb, and Pb+Pb cumulants. In the same publication, $c_2\{4\}$ is found to

be positive and event-selection-dependent in pp , indicating the presence of significant jet-induced non-flow contributions. To further suppress such contributions, the subevent cumulant method divides the event into separate pseudorapidity regions and constructs cumulants from particles belonging to different subevents [9]. The two- and three-subevent methods significantly reduce jet-induced correlations. As shown in Fig. 6, this approach leads to more negative values of $c_2\{4\}$, corresponding to a positive v_2 signal in both pp and $p+Pb$ collisions even at moderate multiplicities.

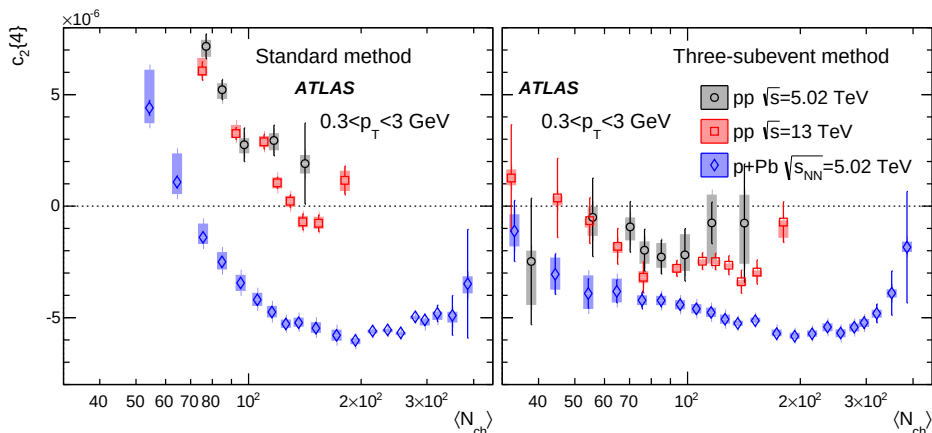


Fig. 6. Four-particle cumulant $c_2\{4\}$ measured in pp and $p+Pb$ collisions using the standard method (left) and the three-subevent method (right), demonstrating the suppression of jet-induced non-flow correlations [9].

4. Conclusion

The small-system program performed with the ATLAS experiment at the LHC has revealed a rich phenomenology in pp and $p+Pb$ collisions. Hard-probe measurements indicate no significant medium-induced modification of the spectra, while the soft sector exhibits collective behavior reminiscent of heavy-ion collisions. Understanding these results required improved analysis techniques, including controlling initial-state effects and event-activity biases in the hard sector, and suppressing non-flow correlations in the soft sector.

Future measurements with intermediate-sized systems such as O+O and Ne+Ne may provide further insight into the unification of the description of collision systems from small to large.

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REFERENCES

- [1] J.D. Bjorken, *Phys. Rev. D* **27**, 140 (1983).
- [2] PHENIX Collaboration (K. Adcox *et al.*), *Phys. Rev. Lett.* **88**, 022301 (2002).
- [3] STAR Collaboration (K.H. Ackermann *et al.*), *Phys. Rev. Lett.* **86**, 402 (2001).
- [4] NA50 Collaboration (M.C. Abreu *et al.*), *Phys. Lett. B* **477**, 28 (2000).
- [5] NA60 Collaboration (R. Arnaldi *et al.*), *Eur. Phys. J. C* **61**, 711 (2009).
- [6] ATLAS Collaboration (G. Aad *et al.*), *J. Instrum.* **3**, S08003 (2008).
- [7] ATLAS Collaboration (G. Aad *et al.*), *Phys. Rev. Lett.* **116**, 172301 (2016).
- [8] ATLAS Collaboration (M. Aaboud *et al.*), *Eur. Phys. J. C* **77**, 428 (2017).
- [9] ATLAS Collaboration (M. Aaboud *et al.*), *Phys. Rev. C* **97**, 024904 (2018).
- [10] ATLAS Collaboration (G. Aad *et al.*), *Phys. Rev. Lett.* **110**, 182302 (2013).
- [11] ATLAS Collaboration (G. Aad *et al.*), *Phys. Rev. C* **90**, 044906 (2014).
- [12] ATLAS Collaboration (G. Aad *et al.*), *Phys. Lett. B* **748**, 392 (2015).
- [13] ATLAS Collaboration (G. Aad *et al.*), *Phys. Rev. Lett.* **131**, 072301 (2023).
- [14] ATLAS Collaboration (M. Aaboud *et al.*), *Eur. Phys. J. C* **78**, 171 (2018).
- [15] ATLAS Collaboration (G. Aad *et al.*), *J. High Energy Phys.* **2024**, 101 (2024).
- [16] P. Vana, *Acta Phys. Pol. B Proc. Suppl.* **19**, 5-A9 (2026), this issue.
- [17] ATLAS Collaboration (G. Aad *et al.*), *Eur. Phys. J. C* **76**, 199 (2016).
- [18] ATLAS Collaboration (G. Aad *et al.*), *Phys. Rev. C* **92**, 044915 (2015).
- [19] M.L. Miller, K. Reygers, S.J. Sanders, P. Steinberg, *Annu. Rev. Nucl. Part. Sci.* **57**, 205 (2007).
- [20] M. Alvioli, M. Strikman, *Phys. Lett. B* **722**, 347 (2013).
- [21] ATLAS Collaboration (G. Aad *et al.*), *Phys. Rev. Lett.* **132**, 102301 (2024).
- [22] R.P. Feynman, *Phys. Rev. Lett.* **23**, 1415 (1969).
- [23] ATLAS Collaboration (G. Aad *et al.*), *Phys. Lett. B* **877**, 140440 (2026).
- [24] ATLAS Collaboration (G. Aad *et al.*), *J. High Energy Phys.* **2023**, 074 (2023).
- [25] ATLAS Collaboration (M. Aaboud *et al.*), *Phys. Lett. B* **790**, 108 (2019).
- [26] ATLAS Collaboration, «Correlation of Υ meson production with the underlying event in pp collisions measured by the ATLAS experiment», *ATLAS-CONF-2022-023*.
- [27] PHENIX Collaboration (A. Adare *et al.*), *Phys. Rev. D* **83**, 052004 (2011).
- [28] ATLAS Collaboration (G. Aad *et al.*), *Phys. Rev. C* **86**, 014907 (2012).
- [29] ATLAS Collaboration (G. Aad *et al.*), *Phys. Lett. B* **725**, 60 (2013).