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Collective dynamics of heavy ion collisions in ATLAS

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An overview of the latest ATLAS measurements of collective behaviour in a variety of collision systems, including 13 TeV *pp*, 5.44 TeV Xe+Xe and 5.02 TeV Pb+Pb collisions is presented. The results shown include measurements of v_{n}-mean p_{T} correlations and longitudinal flow decorrelations in Xe+Xe and Pb+Pb collisions, which carry important information about the initial-state geometry of the Quark-Gluon Plasma; heavy flavour flow harmonics testing the quark energy loss mechanism in QGP; and measurements of the sensitivity of collective behaviour in *pp* collisions to the presence of jets, which provide insight on the role of semi-hard processes in the origin of the flow phenomena in small systems. These results provide stringent tests of the theoretical understanding of the initial state in heavy ion collisions.

Introduction

The main goal of heavy ion collision program of the ATLAS experiment [1] at LHC is to study the properties of the hot and dense QCD matter. It is expected that in these collisions, the energy density of nuclear matter is significantly exceeding the critical value (≈ 1 GeV/fm^3) sufficient for the formation of a new state of matter, the quark-gluon plasma (QGP). The recent ATLAS results [2,3] on azimuthal anizotropy in Pb+Pb, Xe+Xe, p+Pb and *pp* collisions provide significant insight into collective phenomena in large and small systems. The azimuthal anisotropy is described by the harmonics, v_{n}, of the Fourier series of the azimuthal angle distribution of produced particles. The v_{n} values reflect the spatial shape of the interaction area, as well as its deformations in single collisions, the so-called flow fluctuations. Measurements of v_{n} are also important for tuning theoretical models describing QGP.

Flow harmonics decorrelations in Xe+Xe and Pb+Pb collisions

The study of longitudinal flow correlations provides insight into the boost invariance of the initial conditions and space-time evolution of the QGP medium. The correlation is measured between two flow vectors, q_n, separated in pseudorapidity by $\Delta\eta \equiv (\eta - (-\eta)) = 2\eta$, where one flow vector is evaluated at positive η and the other one at negative η. It is quantified by the decorrelation coefficient defined as [4]

$$r_n = \frac{q_n(-\eta)q_n^*(\eta_{ref})}{q_n(\eta)q_n^*(\eta_{ref})}, \tag{1}$$

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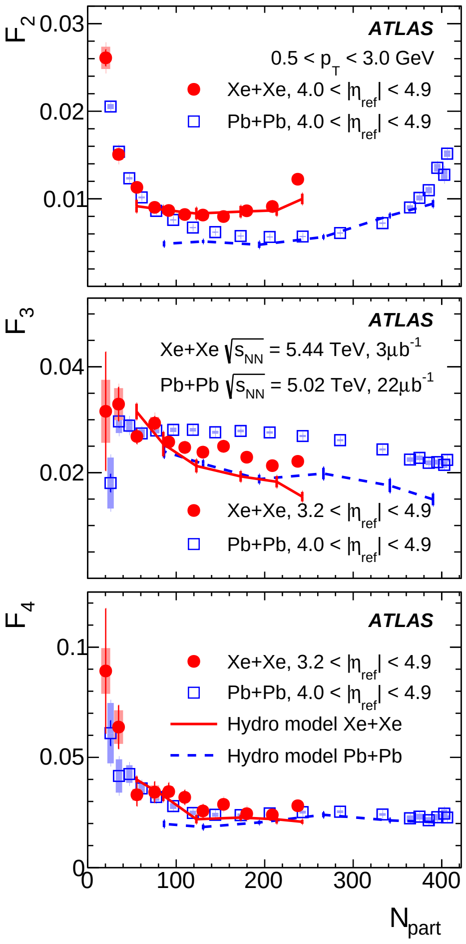

Figure 1. The F_n compared between Xe+Xe and Pb+Pb collisions as a function of N$_{part}$ for n $=$ 2 (top panel), n $=$ 3 (middle panel) and n $=$ 4 (bottom panel). The error bars and shaded boxes on the data represent statistical and systematic uncertainties, respectively [5]. The results from a hydrodynamic model are shown as solid lines (Xe+Xe) and dashed lines (Pb+Pb) with the vertical error bars denoting statistical uncertainty of the model predictions [6, 7].

where $q_n\ (\eta)$ is the flow vector of particles in narrow pseudorapidity intervals covering $|\eta|$ <2.4 and $q_n\ (\eta_{ref})$ is the reference flow vector obtained from the energy deposits in the ATLAS forward calorimeter towers at $|\eta_{ref}| > 4$. The $r_n(\eta) \neq 1$ provides evidence that the correlation between $v_{\rm n}$ harmonics does not factorise into the product of single-particle $v_{\rm n}$ coefficients. ATLAS performed extensive measurements of longitudinal flow correlations for charged particles in Xe+Xe [5] and Pb+Pb [4] collisions at $\sqrt{s_{\rm NN}}$= 5.44 TeV and 5.02 TeV, respectively, indicating significant breaking of the factorization, called longitudinal decorrelation. The magnitude of the factorization breaking is increasing approximately linearly with the growth of the size of the separation in pseudorapidity between the intervals in which the measurement is done. Therefore, the deviation of r_n from unity is parameterized with a linear function, $r_n(\eta) = 1 - 2F_n\eta$. Figure 1 compares the slope parameters F_n

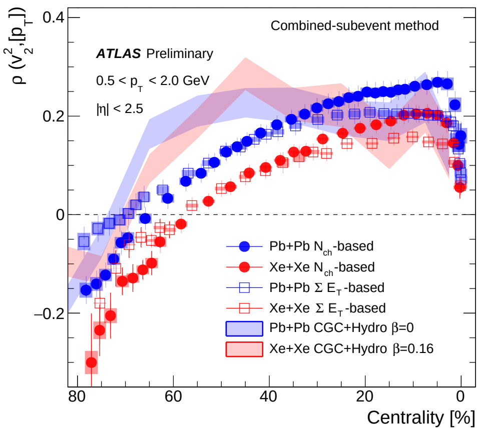

Figure 2. The centrality dependence of $\rho(v_2^2,[p_\mathrm{T}])$ in 5.02 TeV Pb+Pb (blue symbols) and 5.44 TeV Xe+Xe (red symbols) collisions obtained using N_{ch}^{rec}-based event averaging procedure (solid symbols) and $\Sigma E_\mathrm{T}^\mathrm{FCal}$-based event averaging procedure (open symbols) for charged particles in $0.5 < p_\mathrm{T} < 2$ GeV [8]. They are compared with a hydrodynamical model calculation based on Trento initial condition, with the width of the bands representing the statistical uncertainties of the model [9,10]. The error bars and shaded boxes on the data points represent statistical and systematic uncertainties, respectively.

in the Xe+Xe and Pb+Pb collisions as a function of the collision centrality, measured by the number of participating nucleons, N_part. For both systems F_2 shows a strong dependence on $N_\mathrm{part}$while a weaker centrality dependence is seen for F_3 and F_4. The F_4 values agree between the two systems. In the peripheral collisions (for $N_\mathrm{part}< 80$), the F_n for the two systems agree. In the mid-central collisions, F_2 is much larger in Xe+Xe collisions than in Pb+Pb collisions, while an opposite relation is observed for F_3. The data are also compared with predictions from a hydrodynamic model including the longitudinal fluctuations [6, 7]. The model quantitatively describes the behavior of F_2 and F_4 in mid-central collisions, but fails to describe the magnitude of F_3 and the splitting between the two systems.

v_n–mean p_T correlations in Xe+Xe and Pb+Pb collisions

The correlation between magnitudes of flow harmonics and the mean event transverse momentum, $[p_\mathrm{T}]$, is expected to be sensitive to initial conditions in nuclear collisions. The strength of the correlation is measured by means of the modified Pearson's ρ coefficient. It is defined as [11]

$$\rho(v_\mathrm{n}^2,[p_\mathrm{T}])) = \frac{\mathrm{cov}(v_\mathrm{n}\{2\}^2,[p_\mathrm{T}])}{\sqrt{\mathrm{Var}(v_\mathrm{n}\{2\}^2)_\mathrm{dyn}}\sqrt{c_k}}, \tag{2}$$

where in the numerator the covariance between the $v_n\{2\}^2$ and $[p_\mathrm{T}]$ is used. To suppress non-flow effects, the $v_\mathrm{n}\{2\}^2$ values are obtained using two-particle correlations (2PC) of sub-events separated by 1.5 unit in pseudorpidity, $|\eta| > 0.75$, while $[p_{\mathrm{T}}]$ is obtained using charged particles with $|\eta| < 0.5$. The denominator includes the dynamical variance of $v_n\{2\}^2$ [12] and the $[p_{\mathrm{T}}]$ variance calculated by the dynamical p_{T} fluctuation magnitude c_k [13, 14]. The ρ coefficient was obtained for the 5.02 TeV p+Pb, Pb+Pb data samples with an integrated luminosity of 28 nb^{-1} and 22 μb^{-1}, respectively [15]. Recently, ρ was also measured in Xe+Xe collisions at $\sqrt{s_{\mathrm{NN}}}$= 5.44 TeV with integrated luminosity of 3μb^{-1} [8]. Figure 2 shows $\rho(v_2^2, [p_{\mathrm{T}}])$ as a function of the centrality percentile for both Pb+Pb and Xe+Xe collisions for charged particles in $0.5 < p_{\mathrm{T}} < 2$ GeV. In order to check the sensitivity to the event centrality estimator, $\rho(v_2^2, [p_{\mathrm{T}}])$ is shown for the centrality selection based on $\Sigma E_{\mathrm{T}}^{\mathrm{FCal}}$ and the centrality selection based on event multiplicity, N_{ch}^{rec}. Comparing the $\rho(v_2^2, [p_{\mathrm{T}}])$ results obtained with the $\Sigma E_{\mathrm{T}}^{\mathrm{FCal}}$ to those based on N_{ch}^{rec}, it can be seen that in peripheral 50-80% collisions the $\Sigma E_{\mathrm{T}}^{\mathrm{FCal}}$ centrality selections give larger ρ values than those obtained with the N_{ch}^{rec} based selection. An opposite trend is observed for central 0-40% collisions. For mid-central collisions both ρ estimates agree. A weaker correlation is observed in the smaller Xe+Xe system than that in the Pb+Pb collisions over the whole centrality range. A similar strong dependence on centrality is observed for both systems. Theoretical models [9, 10] qualitatively predict the trend as a function of the centrality but cannot describe the data quantitatively.

Heavy flavour flow in 5.02 TeV Pb+Pb and 13 TeV *pp* collisions

To study the effect of quark mass on the radiative and collisional processes of energy loss in QGP the production of heavy flavour particles and their azimuthal anisotropy was studied in the ATLAS experiment. The measurement uses single muon tracks from semi-leptonic decays of charm and bottom hadrons in 13 TeV *pp* [16] and 5.02 TeV Pb+Pb [17] data samples of 150 pb^{-1} and 246 μb^{-1} of integrated luminosities, respectively. In the first stage of the analysis muons from heavy-flavour hadron decays are separated from muons from light-flavour hadron decays using the momentum imbalance between measurement in the inner detector tracking and muon spectrometers. Then, the charm- and bottom-decay muons are separated by using muon track's transverse impact parameter, d_0, distributions. A narrower d_0 distribution is observed for the charm-decay muons than for the bottom-decay muons. As a result, differential yields in 5.02 TeV Pb+Pb collisions and differential cross sections in *pp* collisions for charm- and bottom-decay muons are obtained as a function of the muon transverse momentum from 4 GeV to 30 GeV. These measurements allow obtaining the nuclear modification factor, presented in Figure 3 (top panel) for 0-10% centrality interval. A significant suppression of the charm- and bottom-decay muon yields is observed, with a stronger modification effect for muons from charm hadron decays. The R_{AA} quantifies the average energy loss of heavy quarks in a dense QGP environment. The p_{T} dependence of elliptic flow of charged hadrons in the 10% most central Pb+Pb collisions [18] for charm- and bottom-decays muons is shown in

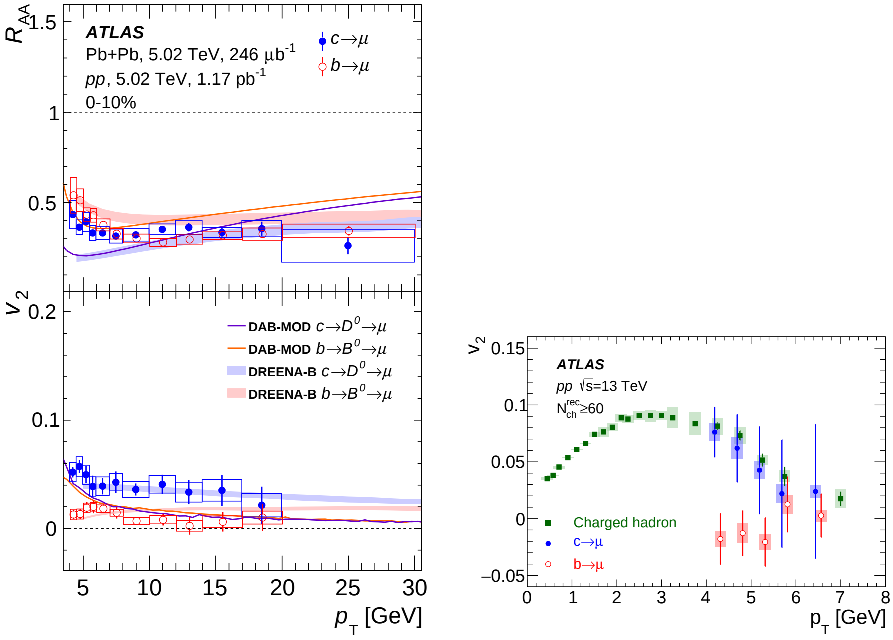

Figure 3. Nuclear modification factor, R_{AA}, (top panel) and elliptic flow, v_2, (bottom-left panel) in 5.02 TeV Pb+Pb collisions for muons from bottom hadron decays and charm hadron decays for 0–10% centrality interval as a function of p_{T}. For comparisons, v_2 of heavy-flavor-decay muons and charged hadrons in 13 TeV *pp* collisions as a function of p_{T} is also shown (right panel) [16–18].

Figure 3 (bottom-left panel). The results indicate substantial modification of the charm- and bottom-decay muon angular distributions, with smaller modifications for the bottom muons as expected theoretically due to their larger mass. For a comparison, Figure 3 (bottom-right panel) shows v_2 of heavy-flavor muons and charged hadrons in 13 TeV *pp* collisions as a function of p_{T} [16]. The bottom-decay muon v_2 is consistent with zero within statistical and systematic uncertainties, while the charm-decay muon v_2 is consistent with that for charged hadrons. These results indicate that bottom quarks, unlike light and charm quarks, do not participate in the collective behaviour in high-multiplicity *pp* collisions.

Sensitivity of flow harmonics to the presence of jets in 13 TeV *pp* collisions

To get insights into the role of hard processes in the formation of azimuthal anisotropy in small systems, a dedicated study involving jet production is performed in a 13 TeV *pp* minimum bias (MB) sample with an integrated luminosity of 64 $\mu\mathrm{b}^{-1}$ [19]. The 2PC method [20] is used to measure flow harmonics with the template matching procedure. To remove particles associated with jets from the 2PC analysis charged-particle tracks within $|\Delta\eta| < 1$ from the jet axis of any jet with $p_{\mathrm{T}}^{\mathrm{jet}} > 10$ GeV are rejected. To study the effect of jets on the flow harmonics measurements, v_{n} coefficients

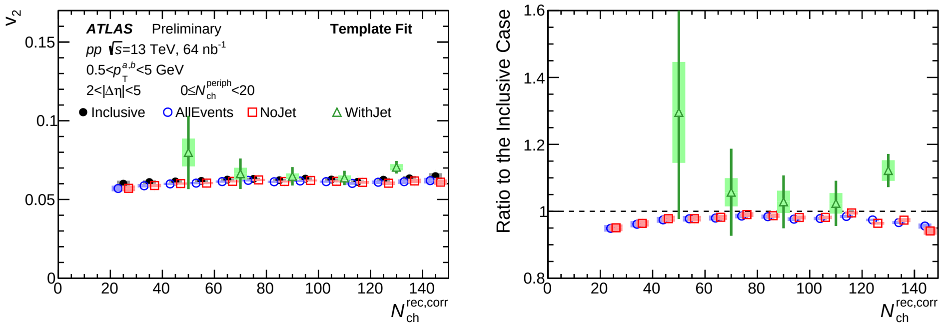

Figure 4. The left panel shows the v_2 as a function of the (efficiency corrected) multiplicity. The data-points for the *Inclusive* sample are drawn at the nominal values while the data-points for the *AllEvents*, *NoJet* and the *WithJet* samples are shifted slightly for clarity. The right panel shows the ratio of the v_2 for the different samples to that in the *Inclusive* sample. For the ratio plots, the correlated uncertainties between the numerator and denominator are removed [19].

are obtained for four event categories selected from the MB sample using particles in 0.5–5 GeV p_{T} range.

- *Inclusive* sample corresponds to the original MB sample, without any jet-particle rejection. The Inclusive v_{n} harmonics are used as a reference.
- *AllEvents* sample represents the original MB sample, but AllEvents v_{n} are calculated by using charged particles tracks not associated with jets.
- *NoJet* sample stands for a sample of events without reconstructed jets.
- *WithJet* sample contains events with at least one reconstructed jet.

Figure 4 compares the multiplicity dependence of the v_2 in these four samples of events. All v_2 values vary only weakly with multiplicity. It is observed that AllEvents v_2 and NoJet v_2 measured using no jet associated tracks, are only marginally smaller (within 2–5%) than the Inclusive v_2. This difference can partially arise from the softening of the p_{T}-spectra when removing particles associated with jets. Another contribution to the observed difference in v_2 can be due to residual changes in the shape of the dijet correlations, that are not accounted for in the template fits. The results for v_2 in the WithJet sample are consistent within large uncertainties with v_2 in the Inclusive sample.

Summary

The selected latest ATLAS results on collectivity in heavy ion collisions were summarised in this report. The measurements provide deeper insight into the role of the impact of initial conditions and into the origin of flow in collisions involving both heavy and light nuclei. The presented measurements can be used to understand the underlying mechanism of QGP dynamics and constrain theoretical models.

Acknowledgments

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