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Azimuthal anisotropy in Pb+Pb, Xe+Xe and p+Pb collisions and $v_n - p_{\mathrm{T}}$ correlations in Pb+Pb and p+Pb collisions with the ATLAS experiment

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ATLAS measurements of differential and global Fourier harmonics of charged particles (v_n) in 5.02 TeV Pb+Pb and 5.44 TeV Xe+Xe collisions in a wide range of transverse momenta (up to 60 GeV), pseudorapidity ($|\eta| < 2.5$) and collision centrality (0-80%) are presented. The higher order harmonics, sensitive to fluctuations in the initial state, are measured up to $n = 5$ using the two-particle correlation, cumulant and scalar-product methods. The flow results allow to improve the understanding of initial conditions of nuclear collisions, hydrodynamical behaviour of quark-gluon plasma (QGP) and parton energy loss. The dynamic properties of the QGP can also be studied using a modified Pearson's correlation coefficient, $\rho(v_n, p_{\mathrm{T}})$, that quantifies correlation between the mean transverse momentum and the magnitude of the flow vector. The ρ coefficient is presented for 5.02 TeV Pb+Pb and p+Pb collisions. Azimuthal anisotropy in Pb+Pb collisions is also compared with new measurements in pp and p+Pb collisions.

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1. Flow harmonics in Pb+Pb and Xe+Xe collisions

The ATLAS experiment [1] performed measurements of the flow harmonics in Xe+Xe at $\sqrt{s_{\mathrm{NN}}} = 5.44$ TeV [2]. Several methods like two-particle correlations, scalar-product and multi-particle correlations were used to extract the flow harmonics. The comparison of the differential measurement of $v_n(p_{\mathrm{T}})$ between Xe+Xe and Pb+Pb systems confirmed existence of several nuclear and hydrodynamic effects [3]. By comparing the p_{T}-integrated flow harmonics in Pb+Pb and Xe+Xe collisions, a system-size impact on the observed quantity could be studied. That is, if the flow harmonics scale with centrality then they are of geometric origin, else if the measured flow harmonics are comparable for a given system size, proxied by the number of collision participants N_{part}, the initial state fluctuations are responsible for the observed harmonics. Such a comparison is shown in Figure 1 (top) where v_{2-5} are shown as a function of centrality. A clearly better agreement is observed for the second harmonics between Xe+Xe and Pb+Pb collisions when compared as a function of centrality, supporting the collision geometry as the main factor determining observed large values. For higher order harmonics the scaling is not clear, and therefore, a more sensitive quantity, the four particle cumulant $c_3\{4\}$ is shown as a function of both centrality and N_{part} in Figure 1 (bottom). The Pb+Pb and Xe+Xe data are better aligned when binned as a function of N_{part}, indicating the higher flow harmonics origin from the initial geometry fluctuations that scale with the system size.

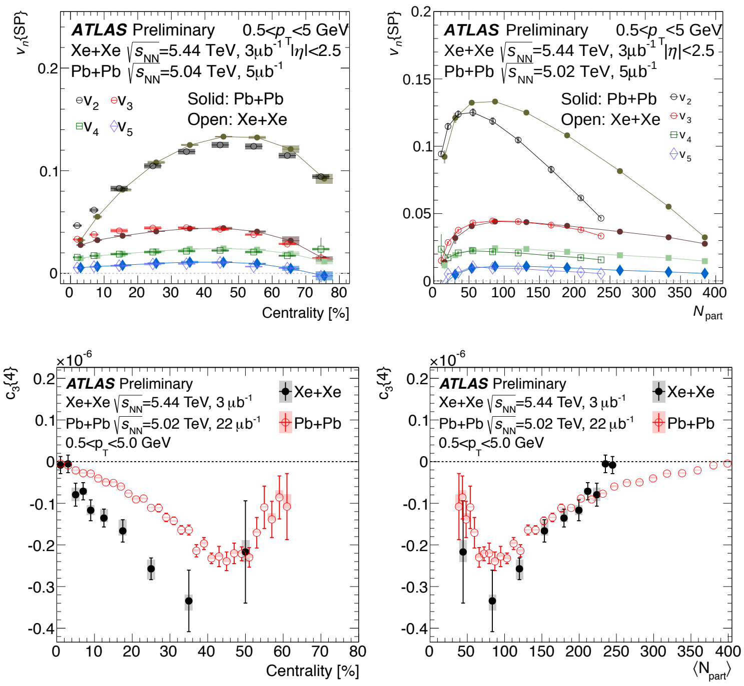

Figure 1: (Top) Comparisons of p_{T} integrated flow harmonics obtained with the scalar-product method for Xe+Xe and Pb+Pb collisions as a function of centrality (left) and number of collision participants (right) [2]. (Bottom) Comparison of four particle cumulants for the third harmonics between Xe+Xe and Pb+Pb collisions as a function of centrality (left) and number of collision participants (right) [2].

2. Flow harmonics - mean transverse momentum correlations

Measuring the correlation of an initial-state quantity (event mean $[p_{\mathrm{T}}]$) with quantity characterising the evolution towards the final state (flow harmonics) allows to shed light on the impact of the former on the QGP evolution. Such a correlation was first reported by the ALICE experiment [4] where the modification of charged particle inclusive spectra was observed for events categorised by a varying strength of azimuthal anisotropy. The events with a larger value of the second flow harmonics v_2 had spectra shifted towards higher values of p_{T}. In the ATLAS measurement [5], a more systematic approach was taken in which a modified Pearsons correlation coefficient ρ is employed [6]. The ρ is independent of the event multiplicity that depends among others on detector performance, thus making the measurement more suitable for comparisons across the experiments and to the theory predictions. The ρ coefficient is defined as

$$\rho = \frac{cov(v_n\{2\}^2, [p_{\mathrm{T}}])}{\sqrt{var(v_n\{2\}^2)_{dyn}}\sqrt{c_k}}. \tag{2.1}$$

where the $[p_{\mathrm{T}}]$ is event mean transverse momenta, v_n is the magnitude of the flow harmonics in an event. The covariance in the numerator, dynamical variance $var(v_n\{2\}^2)_{dyn}$ and the c_k are averages over events as denoted as $\langle\rangle$ and are defined as

$$cov(v_n\{2\}^2, [p_{\mathrm{T}}]) = \left\langle \frac{1}{N}\sum_{k,j} \mathrm{e}^{\mathrm{i}n\phi_k - \mathrm{i}n\phi_j}([p_{\mathrm{T}}] - \langle[p_{\mathrm{T}}]\rangle)\right\rangle \tag{2.2}$$

$$var(v_n\{2\}^2)_{dyn} = v_n\{2\}^4 - v_n\{4\}^4 \tag{2.3}$$

$$c_k = 1/N_{\mathrm{pairs}}\langle\sum_i\sum_{j\neq i}(p_{\mathrm{T},i} - \langle[p_{\mathrm{T}}]\rangle)(p_{\mathrm{T},j} - \langle[p_{\mathrm{T}}]\rangle)\rangle \tag{2.4}$$

where the N_{pairs} is a number of particle pairs and ϕ is particle azimuthal angle. In the analysis precautions were used in order to reduce the non-flow effects by using particles from opposite hemispheres $|\eta| > 0.75$ when calculating quantities related to the flow harmonics and particles in $|\eta| < 0.5$ to obtain quantities related to mean transverse momentum. In addition, to avoid correlations between the multiplicities in forward and central regions the events were categorised using multiplicity in the forward region only. The measurement is performed as a function of a number of participants, N_{part}, in Pb+Pb. Also in Pb+Pb and p+Pb collisions, results are presented as a function of charged particle multiplicity N_{ch} of $0.5 < p_{\mathrm{T}} < 5$ GeV and $|\eta| < 2.5$. For both systems the measurements were performed for collisions at centre-of-mass energy per nucleon pair of 5.02 TeV. The three intervals of p_{T} probe different regions of spectra. The main region in which the correlation is assumed to be well described by hydrodynamic models covers $0.5 < p_{\mathrm{T}} < 2$ GeV. The region including charged particles of p_{T} up to 5 GeV is studied to assert impact of energy loss on the observed correlation. And, finally the low p_{T} limit is increased to 1 GeV in case of Pb+Pb and reduced to 0.3 GeV in case of p+Pb to test sensitivity of the observed correlation to a significantly changed event multiplicity. Figure 2 shows the covariance, dynamical variance for second flow harmonics and the c_k for Pb+Pb collisions. A significant, non-monotonic N_{ch} dependence is observed for covariance and variance. The trend for the latter follows the dependence of the second flow harmonics on centrality that is proxied by the number of charged particles. By

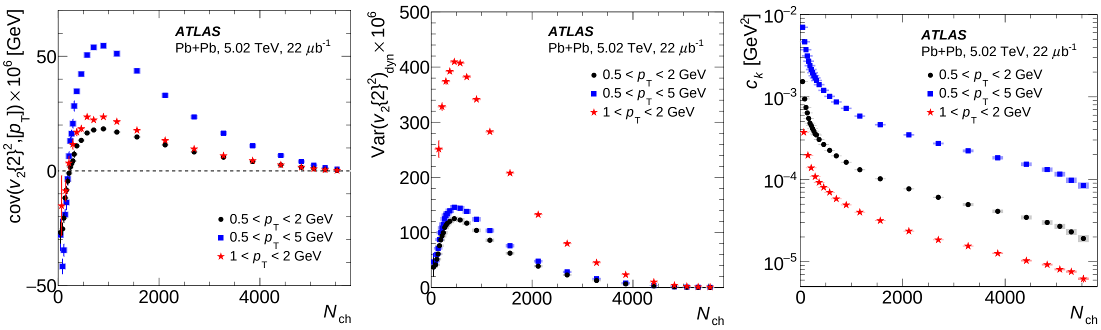

Figure 2: The ingredients of the ρ correlation coefficient for v_2 measured in Pb+Pb data. From left to right are shown covariance, $cov(v_n\{2\}^2, [p_T])$, dynamical variance, $var(v_n\{2\}^2)_{dyn}$, and the c_k as a function of number of charged particles N_{ch} in $|\eta| < 2.5$ and $0.5 < p_T < 5$ GeV [5].

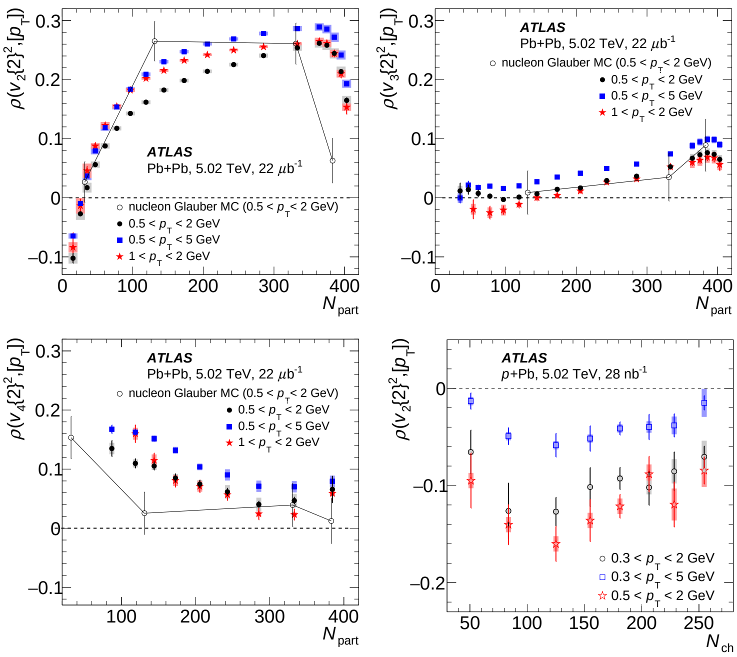

Figure 3: (Top) The modified correlation coefficient ρ as a function of N_{part} for Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for second (left) and third (right) flow harmonics and three p_T intervals as indicated in the legend. (Bottom left) The same coefficient for the fourth harmonics. (Bottom right) The ρ coefficient as a function of charged particle multiplicity N_{ch} in p+Pb collisions [5].

combining these quantities according to Eq.(2.1) the coefficient ρ is obtained. It is shown in Figure 3 for Pb+Pb and p+Pb systems. The correlation for the second harmonics is negative in peripheral Pb+Pb and for high multiplicity p+Pb collisions. It can be interpreted as a result of more compressed initial collision volume. In such a case a higher $[p_T]$ would be observed. At the same time, a small initial collision zone is characterised by a small eccentricity that determines the value of the v_n. When moving towards the more central collisions in case of Pb+Pb data the geometric effect is responsible for the change of the sign of the correlation. A significant magnitude of the correlation signifies a constructive interplay of the initial-stage effects with the system evolution effects up until the very central collisions. In p+Pb data the correlation coefficient is almost constant across the multiplicity range shown. The third harmonics measured in Pb+Pb collisions show a steady rise from lack of any correlation in peripheral events to reach a significant value in the central events. A fall of the correlation for the fourth harmonics as a function of N_{part} is observed. For the Pb+Pb results predictions obtained from hydrodynamical simulations are also shown [6]. Besides the large uncertainties of the model a good quantitative agreement is found supporting the hydrodynamic interpretation of the observed phenomenon.

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