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Recent results on correlations and fluctuations in pp, p+Pb, Pb+Pb and Xe+Xe collisions from the ATLAS Experiment at the LHC

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The azimuthal anisotropies of particle yields observed in relativistic heavy-ion collisions have been traditionally considered as a strong evidence of the formation of a de-confined quark-gluon plasma produced in these collisions. However multiple recent measurements from the LHC experiments in pp and p+Pb systems show similar features as those observed in Pb+Pb collisions, indicating the possibility of the production of such a de-confined medium also in smaller collision systems. This report presents a comprehensive summary of recent ATLAS measurements in pp and p+Pb collisions as well as in Pb+Pb and Xe+Xe collisions. It includes measurements of two-particle hadron-hadron correlations in $\Delta\phi$ and $\Delta\eta$, with a template fitting procedure used to subtract the dijet contributions. Measurements of multi-particle cumulants using the standard cumulant method as well as a new sub-event cumulant method that suppresses the contribution of non-flow effects are discussed. Studies of longitudinal flow decorrelation and correlations between flow harmonics and mean p_{T} of the event in Pb+Pb collisions are presented to provide deeper insight into details of the geometry of the initial state. First results on flow harmonic measurements from Xe+Xe collisions are also discussed.

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1. Introduction

This proceedings should describe in detail the material presented by the author at the conference. However due to a severe limitation of text length, and still trying to make the text potentially useful for readers, I decided to discuss here only the results of the recent ATLAS [1] measurements in Pb+Pb and Xe+Xe collisions. For the introduction to cumulant methods and the recent ATLAS results on collectivity in small systems, *pp* and *p*+Pb, the reader is referred to my proceedings from the LHCP2018 conference [2] covering exactly the same measurements as discussed in this talk.

2. Longitudinal flow decorrelation in Pb+Pb collisions

It is well established that the quark-gluon plasma (QGP) created in heavy-ion collisions at the LHC is successfully described by relativistic viscous hydrodynamics. Owing to strong event-by-event (EbyE) density fluctuations in the initial state, the space-time evolution of the produced matter also fluctuates event-by-event. These fluctuations lead to correlations of particle multiplicity in momentum space in both the transverse and longitudinal directions with respect to the collision axis. In the recent measurement [4] ATLAS experiment has found that the correlation between the harmonic flow coefficients v_n measured in two separated η intervals does not factorise into the product of single-particle coefficients. This breaking of longitudinal factorisation, or flow decorrelation, is studied using the correlation between the kth-moment of the nth-order flow vectors in two different η intervals, averaged over events in a given centrality interval, $r_{n|n;k}(\eta)$ for $k = 1,2,3$:

$$r_{n|n;k}(\eta) = \frac{\langle \vec{q}_n^{\,k}(-\eta)\vec{q}_n^{\,\star k}(\eta_{\mathrm{ref}})\rangle}{\langle \vec{q}_n^{\,k}(\eta)\vec{q}_n^{\,\star k}(\eta_{\mathrm{ref}})\rangle} = \frac{\langle [\mathrm{v}_n(-\eta)\mathrm{v}_n(\eta_{\mathrm{ref}})]^k \cos kn(\Phi_n(-\eta)-\Phi_n(\eta_{\mathrm{ref}}))\rangle}{\langle [\mathrm{v}_n(\eta)\mathrm{v}_n(\eta_{\mathrm{ref}})]^k \cos kn(\Phi_n(\eta)-\Phi_n(\eta_{\mathrm{ref}}))\rangle}$$

where $\vec{q}_n$ is the per-particle normalised flow vector, and η_{ref} is the reference pseudorapidity common to the numerator and the denominator. The correlator $r_{n|n;k}$ measures the relative difference between kth-moments of flow vectors at different η and $-\eta$. When flow is boost-invariant, $r_{n|n;k}$ will always equal unity. However any difference in the η dependence of the flow magnitude v_n and the event plane angle Φ_n will lead $r_{n|n;k}$ to be smaller than 1. The $r_{n|n;k}$ correlators are measured as a function of η in several event centrality classes in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ and 5.02 TeV [4]. In this proceedings, we only focus on the 1st-moments of elliptic flow, the $k = 1, n = 2$ case. In the measurements the reference pseudorapidity interval is chosen at large pseudorapidity $4 < |\eta_{\mathrm{ref}}| < 4.9$, while the pseudorapidity of $\vec{q}_n(\pm\eta)$ is chosen to be close to mid-rapidity $|\eta| < 2.4$. Such a choice ensures that the correlated particles come from different sub-events, separated by a pseudorapidity gap. In Fig. 1 the measured values of $r_{2|2;1}$ are shown as a function of η, for several centrality classes. The correlator shows a linear decrease with η, except in the most central collisions, where it is more parabolic-like. The decreasing trend is weakest around the $20-30\%$ centrality range, and is more pronounced in both more central and more peripheral collisions. This centrality dependence is the result of a strong centrality dependence of the v_2 associated with the average elliptic geometry [5]. The decreasing trend at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV is slightly stronger than that at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, which is expected as the collision system becomes less boost-invariant at lower collision energy [6]. Although not shown here, in case of correlators $r_{3|3;1}$ and $r_{4|4;1}$ a linear decrease as a function of η is observed, and the rate of decrease is approximately independent of

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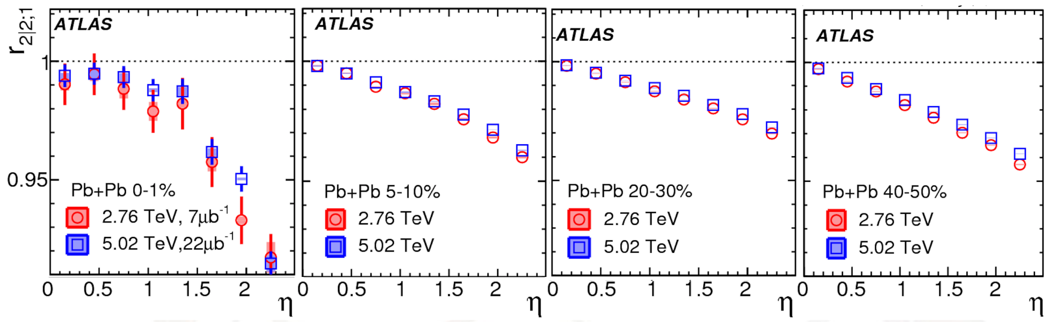

Figure 1: The $r_{2|2;1}(\eta)$ compared between the two collision energies in four centrality intervals. The error bars and shaded boxes are statistical and systematic uncertainties, respectively [4].

centrality [4]. The decreasing trend of $r_{n|n;1}$ for $n = 2,3,4$ indicates significant breakdown of the factorisation of two-particle (2PC) flow harmonics into those between different η ranges. However, the size of the factorisation breakdown depends on the harmonic order n, collision centrality, and collision energy.

3. v_n – mean p_T correlations in Pb+Pb collisions

Better understanding of the relationships between the magnitudes of the flow harmonics and other global event characteristics may provide new insight into the properties of the QGP evolution [7]. The ATLAS experiment has measured correlations between the squares of the n-th order flow harmonics obtained from 2PC, $\mathrm{v}_n\{2\}^2$, and the mean p_T, $[p_\mathrm{T}]$, of the event, in minimum-bias Pb+Pb collisions at $\sqrt{s_\mathrm{NN}} = 5.02$ TeV [8]. As a measure of the correlations a modified Pearson's correlation coefficient ρ is obtained from the standard one R:

$$R = \frac{\mathrm{cov}(\mathrm{v}_n\{2\}^2,[p_\mathrm{T}])}{\sqrt{\mathrm{Var}(\mathrm{v}_n\{2\}^2)}\sqrt{\mathrm{Var}([p_\mathrm{T}])}} \quad\Rightarrow\quad \rho = \frac{\mathrm{cov}(\mathrm{v}_n\{2\}^2,[p_\mathrm{T}])}{\sqrt{\mathrm{Var}(\mathrm{v}_n\{2\}^2)_\mathrm{dyn}}\sqrt{c_k}}$$

where the standard variances have been replaced by their dynamical counterparts [7, 9]:

$$\mathrm{Var}(\mathrm{v}_n\{2\}^2)_\mathrm{dyn} = \mathrm{v}_n\{2\}^4 - \mathrm{v}_n\{4\}^4 = \langle\{4\}_n\rangle - \langle\{2\}_n\rangle^2, \quad c_k = \left\langle \frac{1}{N_\mathrm{pair}} \sum_{i,j\neq i} (p_{\mathrm{T,i}} - \langle[p_\mathrm{T}]\rangle)(p_{\mathrm{T,j}} - \langle[p_\mathrm{T}]\rangle) \right\rangle$$

It was shown in Ref. [7] that the ρ coefficient calculated using realistic, finite multiplicities provides a good estimate of the true value of the correlation coefficient, whereas the R coefficient calculated under the same conditions underestimates the values found in the limit of infinite statistics.

In order to suppress non-flow contributions the analysis was performed using the sub-event method: the flow harmonics v_n were obtained by correlating only tracks between the regions $\eta < -0.75$ and $\eta > 0.75$, whereas $[p_\mathrm{T}]$ was calculated based on tracks from the region $|\eta| < 0.5$. The measured modified Pearson's coefficients $\rho(\mathrm{v}_n\{2\}^2,[p_\mathrm{T}])$ for $n = 2,3,4$ as a function of N_part for four track p_T ranges are shown in Fig. 2. A strong positive correlation $\rho(\mathrm{v}_2\{2\}^2,[p_\mathrm{T}])$ is observed in mid-central and central collisions while negative values are measured for peripheral events. The correlation $\rho(\mathrm{v}_3\{2\}^2,[p_\mathrm{T}])$, is found to be weaker, yet non-zero. The values of $\rho(\mathrm{v}_4\{2\}^2,[p_\mathrm{T}])$ are also positive in the entire centrality range. The centrality dependencies have a non-monotonic behaviour in most central events, suggesting a change in the nature of the source

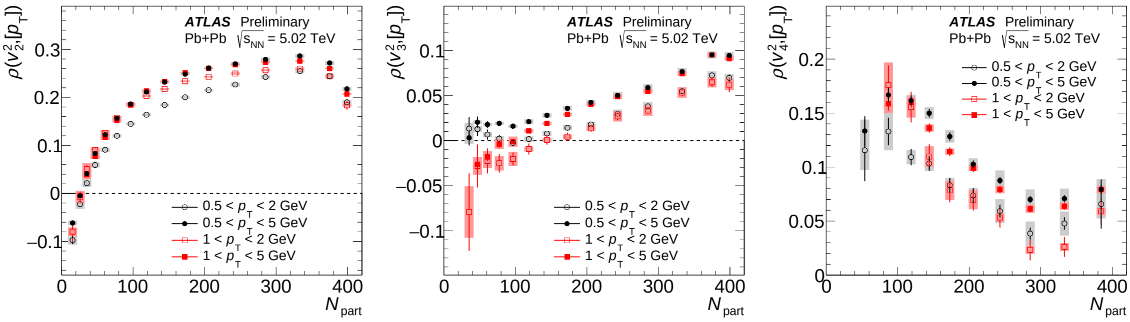

Figure 2: The modified Pearson's coefficient, $\rho(v_n\{2\}^2,[p_T])$, $n = 2,3,4$ (from left to right) as a function of N_{part} in 5.02 TeV Pb+Pb collisions for different p_T intervals. The statistical and systematic uncertainties are shown with vertical lines and shaded boxes, respectively [8].

of the correlations in those events. For each of the three harmonics, the selected charged-particle p_T range influences the value of the coefficients. Measurements with an upper limit of 5 GeV on p_T are more strongly correlated than those with the upper limit of 2 GeV. For the variation of the lower p_T threshold consistent values of $\rho(v_3\{2\}^2,[p_T])$ and $\rho(v_4\{2\}^2,[p_T])$ coefficients are obtained for $N_{part} > 100$ and a difference of only $10-20\%$ is seen for the $\rho(v_2\{2\}^2,[p_T])$ coefficient.

4. Azimuthal anisotropy in Xe+Xe collisions

Since Xe is a smaller nucleus than Pb, Xe+Xe collisions are expected to show larger event-by-event fluctuations in the initial geometry compared to Pb+Pb, leading to larger values of the eccentricities in the initial geometry. On the other hand, a smaller system implies larger viscous effects in the hydrodynamic expansion of the produced QGP fireball [10]. Thus the v_n measurements in Xe+Xe allow the study of the interplay of these two effects. The first measurement of flow harmonics in Xe+Xe collisions at a centre-of-mass energy of $\sqrt{s_{NN}} = 5.44$ TeV by ATLAS are discussed in Ref. [11]. In Fig. 3 the centrality dependence of flow harmonics obtained from the multi-particle cumulant method are shown. The left panel of Fig. 3 shows the centrality dependence of 4- and 6-particle flow harmonics $v_n\{2k\}$, using particles in $0.5 < p_T < 5.0$ GeV. For v_2, different orders of cumulants have similar centrality dependence: largest in mid-central and decreasing towards both central and peripheral. The ordering $v_2\{2PC\} > v_2\{4\} \approx v_2\{6\}$ is observed (see Fig. 3(left, middle), which indicates that v_2 fluctuations are close to Gaussian. For v_3 only the 4-particle cumulant $v_3\{4\}$ is measured, and $v_3\{6\}$ is not shown since its statistical uncertainty is very large. The centrality dependence of v_3 is similar to v_2, and $v_3\{2PC\}$ is two times larger than $v_3\{4\}$ (not shown), indicating strong v_3 flow fluctuations. To quantify the type and strength of flow fluctuations, ratios $v_2\{4\}/v_2\{2PC\}$ and $v_2\{6\}/v_2\{4\}$ are calculated and shown in the middle and right panels of Fig. 3. The results are truncated in ultra-central collisions where statistical uncertainties are too large. For a Gaussian fluctuation model the ratio between $v_2\{4\}$ and $v_2\{2PC\}$ reflects the relative strength of flow fluctuations: a ratio that is close to one suggests that the average geometry dominates, while a ratio close to zero implies that flow fluctuations dominate. The results for $v_2\{4\}/v_2\{2PC\}$ indicate that flow fluctuations are larger in central collisions. Using the same model, the ratio $v_2\{6\}/v_2\{4\}$ is expected to be unity; therefore, the slight deviation from one suggests non-Gaussian fluctuations over a broad centrality range. For the system comparisons, $v_2\{6\}/v_2\{4\}$ in both systems are very close to unity, suggesting the underlying flow fluctuations

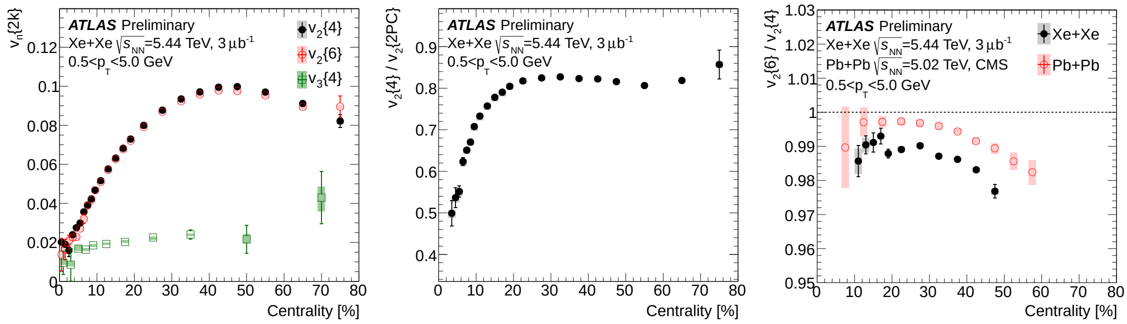

Figure 3: (left) 4- and 6-particle flow harmonics $v_n\{2k\}$ as a function of centrality, with particles in $0.5 < p_T < 5.0$ GeV. (middle) The ratio $v_2\{4\}/v_2\{2PC\}$ as a function of centrality, where $v_2\{2PC\}$ is measured using the 2PC method. (right) The ratio $v_2\{6\}/v_2\{4\}$ from Xe+Xe and compared with Pb+Pb results. The shaded box represents the quadrature sum of statistical and systematic uncertainties [11].

are close to Gaussian. Compared with Pb+Pb, the non-Gaussian component in Xe+Xe is slightly larger in mid-central collisions.

5. Summary

Recently ATLAS has provided several new results on collectivity in small (*pp*, *p*+Pb) and large systems (Pb+Pb, Xe+Xe). Applying new analysis techniques, like sub-event method, it was possible to significantly reduce non-flow contributions and extract flow harmonics reflecting collective effects extending throughout the whole system. Presence of the ridge phenomenon in collisions of small systems has been confirmed. Longitudinal flow correlations have been measured in Pb+Pb collisions for different flow harmonics and also between harmonic flows of different order. Also in Pb+Pb collisions carrelations between flow harmonics and global event characteristic - mean p_T - have been obtained. First measurements of the flow harmonics in the Xe+Xe collisions have been performed, and the results compared to Pb+Pb collisions.

All these new results, available now for *pp*, *p*+Pb, Pb+Pb and Xe+Xe collisions, provide inputs to distinguish between models based on initial-state momentum correlations and models based on final-state hydrodynamics.

References

[1] ATLAS Collaboration, *The ATLAS Experiment at the CERN LHC*, JINST **3** (2008) S08003.

[2] M. Przybycien, *New results on collectivity in small systems with ATLAS*, PoS (LHCP2018) 213.

[3] J. Jia et al., J. Phys. G: Nucl. Part. Phys. 44 (2017) 075106, arXiv: 1701.02183 [nucl-th].

[4] ATLAS Collaboration, Eur. Phys. J. C78 (2018) 142, arXiv: 170902301 [nucl-ex].

[5] P. Huo, J. Jia, S. Mohapatra, Phys. Rev. C 90, 024910 (2014), arXiv: 1311.7091 [nucl-ex].

[6] L.-G. Pang et al., Eur. Phys. J. A 52 (2016) 97, arXiv: 1511.04131 [nucl-th].

[7] P. Bozek, Phys. Rev. C93 (2016) 044908, arXiv: 1601.04513 [nucl-th].

[8] ATLAS Collaboration, ATLAS-CONF-2018-008.

[9] STAR Collaboration, J. Adams et al., Phys. Rev. C72 (2005) 044902, arXiv: nucl-ex/0504031.

[10] G. Giacalone et al., Phys. Rev. C97 (2018) 034904, arXiv: 1711.08499 [nucl-th].

[11] ATLAS Collaboration, ATLAS-CONF-2018-011.