PROCEEDINGS OF SCIENCE

Measurement of collective dynamics in pp, Xe+Xe, and Pb+Pb collisions with the ATLAS detector

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This report discusses ATLAS measurements of collective, flow phenomena in a variety of collision systems, including pp collisions at 13 TeV, Xe+Xe collisions at 5.44 TeV, and Pb+Pb collisions at 5.02 TeV. These include measurements of $v_n - [p_\mathrm{T}]$ correlations in Xe+Xe and Pb+Pb, which carry important information about the initial-state geometry of the Quark-Gluon Plasma and can potentially shed light on: any quadrupole deformation in the Xe nucleus; measurements of flow decorrelations differential in rapidity, which probe the longitudinal structure of the colliding system; and measurements of the sensitivity of collective behavior in pp collisions to the presence of jets, which seek to distinguish the role that semi-hard processes play in the origin of these phenomena in small systems. These measurements furthermore provide stringent tests of the theoretical understanding of the initial state in heavy-ion collisions.

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1. Introduction

The long-range final-state correlation measurements in heavy-ion collisions were one of the landmark results leading to the discovery of quark-gluon-plasma (QGP). In this state quarks and gluons are deconfined and form a state that can be described well as very low viscosity liquid. Among various measurements the one performed most commonly is the study of long-range azimuthal correlations between final-state particles. Their presence reflects both the asymmetries in the initial stage of the collision but also carry information on the system evolution in the QGP phase. Similar in magnitude and characteristics, correlations were observed also in collisions of smaller nuclei and even in pp collisions. An ongoing effort in the field is to understand those effects by measuring nontrivial correlations, by looking at various collision systems, and by exploring the correlation of rare probes.

This proceeding contains a brief discussion of two results on azimuthal correlations measured in pp, Xe+Xe, and Pb+Pb for charged hadrons measured by the ATLAS experiment [1].

2. Measurement of $v_n - [p_{\mathrm{T}}]$ correlations in Xe+Xe and Pb+Pb collisions

The extent of the initial state is correlated with the mean transverse momentum of the particles in the event, $[p_{\mathrm{T}}]$ [2]. Similarly the initial eccentricity translates to the azimuthal asymmetry in the final state. Both the initial-state radii and eccentricity are correlated, thus a correlation is expected between the final-state observables. In simulations it was also found that the observed correlations are insensitive to the parameters of hydrodynamical QGP simulations and therefore are very valuable for studying of initial-state conditions.

The quantitative measurement technique was proposed in Ref. [3] and was executed by ATLAS for Pb+Pb and p+Pb systems [4]. The same measurement for Xe+Xe was performed once such collision data became available [5]. The measurement in Xe+Xe collisions allows for studying system size differences and also provides insight into Xe-nuclei deformations.

The correlation coefficient ρ is obtained as

$$\rho_n = \frac{cov(v_n\{2\}, [p_{\mathrm{T}}])}{\sqrt{c_k}\sqrt{var(v_n\{2\})_{\mathrm{dyn}}}}, \tag{1}$$

where $v_n\{2\}$ is n-th flow harmonic obtained using two-particle correlations, $[p_{\mathrm{T}}]$ is mean momentum of particles in the event, c_k is variance of the $[p_{\mathrm{T}}]$ and the $var(v_n\{2\})_{\mathrm{dyn}}$ is variance of the $v_n\{2\}$ modified to compensate for finite multiplicity of particles in the event. For the Xe data, ATLAS has extended the initial approach in which the $[p_{\mathrm{T}}]$ and flow related quantities were measured in sub-events separated by rapidity gap. In order to improve on statistical precision of measurements in peripheral collisions, other combinations of sub-events, partially or fully overlapping were also measured. In these proceedings however, only the standard results based on the three sub-event method are presented. The results for harmonics 2, 3, and 4 are shown in Figure 1. Qualitatively similar behavior is observed for 2nd harmonic, however the correlation is weaker across a wide centrality range for Xe+Xe as compared to Pb+Pb. In both cases the correlation is stronger with centrality up to about 5% percentile where it then drops. Correlation for 3rd and 4th harmonics exhibit similar trends indicating the existence of similar correlations in the initial stage in both systems.

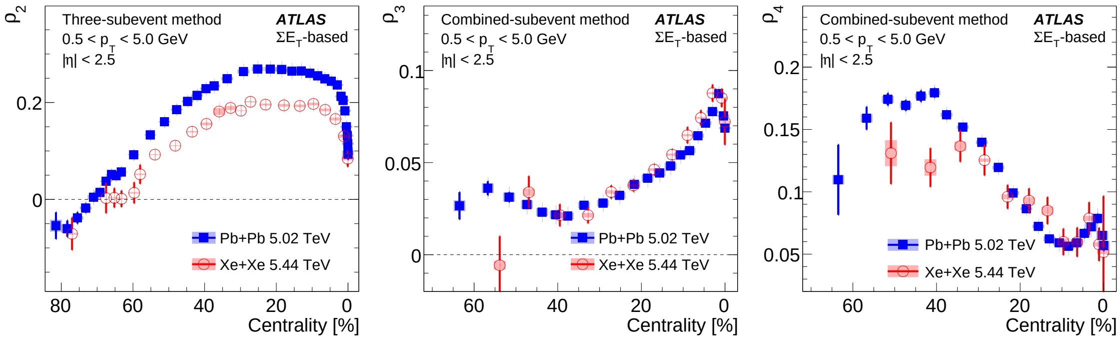

Figure 1: Comparison of correlation coefficient ρ for 2nd, 3rd, and 4th harmonics (correspondingly from left to right) as a function of centrality between Pb+Pb and Xe+Xe collisions [5].

The values of ρ_2 obtained for the most central collisions are shown in Figure 2, compared to the Trento [6] model. Several simulations with varied Xe nucleus deformation parameters are compared to the data that favours a particular one. It is also evident from the plot where the ratio of $\rho_2^{\mathrm{Xe+Xe}}/\rho_2^{Pb+Pb}$ is shown. Sensitivity of the ρ correlation measurement to such an effect makes it a good tool for nuclear shape tomography that is not accessible otherwise. In particular this measurement is the first evidence of triaxial ^{229}Xe deformation.

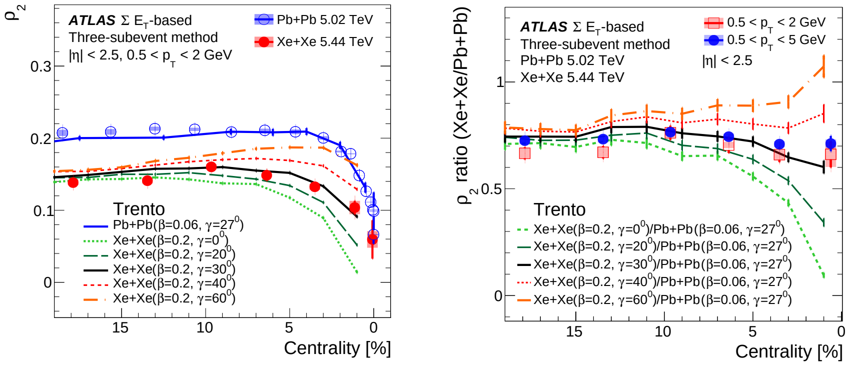

Figure 2: (left) Comparison of the ρ_2 as a function of centrality for central collisions obtained from data and the one obtained from a set of Trento simulations for Pb+Pb and Xe+Xe collisions [5]. (right) The ratio of the ρ_2 in Xe+Xe over Pb+Pb in the same centrality intervals compared to the set of Trento simulations [5].

3. Measurement of v_n decorrelation in small collision systems

The success of extending the concept of the QGP and its hydrodynamic description to small collision systems [7] calls for further studies in this direction. An important input to the modeling is a precise description of the initial conditions. This is typically approached with Glauber MC from which an initial transverse energy density profile is obtained. In more complete models, e.g. in Ref. [8], the longitudinal profile is also obtained and subjected to the hydrodynamic QGP evolution. The longitudinal modelling typically involves Lund-type strings with the longitudinal span that qualitatively allow longitudinal asymmetry. That is, if strings are longer in η than

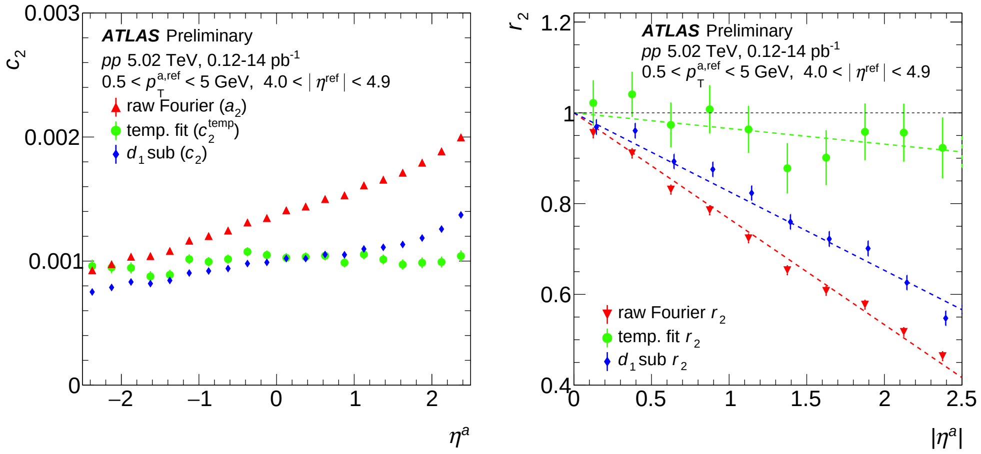

Figure 3: (left) The uncorrected decorrelation coefficient c_2 as a function of rapidity difference between the reference sub-event and a region of interest, η_a [9]. (right) Decorrelation slope parameter r_2 as a function of rapidity distance between sub-events [9].

accessible experimentally, no decorrelation can be measured. In particular, a difference of this kind is expected for longitudinal decorrelations measured in pp and Xe+Xe collisions. In the latter case, a strong decorrelation signal is expected where in the former flow harmonics are not expected to change along η.

The ATLAS experiment has measured decorrelation signals in pp collisions at 5.02 and 13 TeV and compared to Xe+Xe collisions at 5.44 TeV [9]. The observables quantify a change of the flow harmonics v_n measured using two-particle correlations with small and large rapidity gaps. In the small systems, the measurement is difficult due to the contribution of short-range non-flow correlations that mimic the decorrelation signal, as is shown in Figure 3. The three sets of points show raw and gradually corrected quantities. The trend is similar, yet the magnitude of the change is significantly smaller after the correction. The ratio of small to large gap correlation signal

$$r_n(\eta_a) = \frac{c_n(-|\eta_a|)}{c_n(|\eta_a|)}, \tag{2}$$

where $|\eta_a|$ is a difference between the rapidity gaps, is also shown in the figure. Several non-flow correction methods were devised. The so-called d_1 method, relying on an assumption that the first Fourier moment is solely due to the non-flow and that the non-flow effects impact similarly the second moment, is considered the most robust. An evolution of the decorrelation with the amount of activity in event quantified by the count of charged particles, $N_{\mathrm{ch}}^{\mathrm{rec}}$, is shown in Figure 4. The F_n is the slope parameter of $r_n(|\eta_a|)$. The variation with rapidity of the first moment, r_1, has a significant and constant slope. It is largely independent of multiplicity as expected by non-flow effects. The F_2 drops significantly with a number of particles per event. The corrected quantities (d_1 sub F_2 and crtd. temp. F_2 [9]) indicate weaker dependence. The d_1 method indicates significant decorrelation that is smallest in events with small multiplicity.

The decorrelation evolution with multiplicity for Xe+Xe collisions is shown in Figure 4. Similarly, F_1 is significantly larger than F_2 and mostly independent of centrality. The evolution of F_2 with multiplicity is consistent with that observed in earlier measurements [10]. Interestingly, the

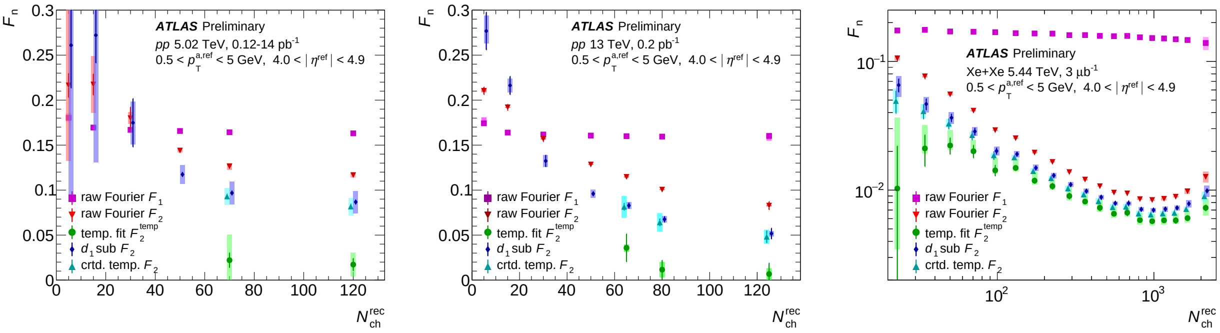

Figure 4: The decorrelation slope parameter F_2 as a function of charge-particle multiplicity for pp (left and centre) at two collision energies and Xe+Xe (right) [9].

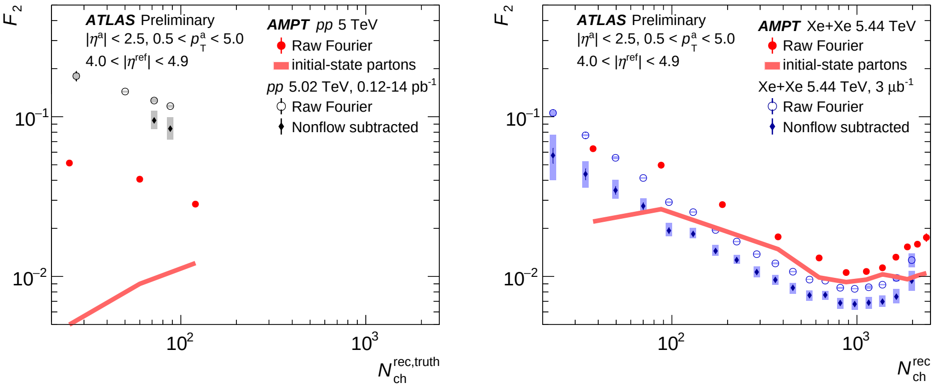

Figure 5: Comparison of the decorrelation slope parameters F_2 as a function of charge-particle multiplicity for pp (left) and Xe+Xe (right) systems with the AMPT calculations (initial-state partons and final-state particles) [9].

same non-flow subtraction techniques as used for pp collisions were applied here and a relevant difference between corrected and uncorrected decorrelation is seen. The F_2 changes significantly with multiplicity with the highest values for less central events and reaches minimum at about 20% percentile of centrality to rise towards most central collisions.

Comparisons of F_2 to the AMPT model [11] are shown in Figure 5. Two sets of calculations are investigated, one using initial-parton properties and another more comparable to the experimental results using final-state particles. A good qualitative modelling of Xe+Xe collisions, both at the level of initial partons and final-state particles is observed. In contrast, the modelling of the pp collisions (at 5 TeV) does not describe the data well.

4. Summary

Recent results on azimuthal correlations in pp, Xe+Xe, and Pb+Pb collisions were reported. The correlation between average particle momentum in the event and the flow harmonics was found to be qualitatively similar in Xe+Xe and Pb+Pb systems. The quantitative comparison points to a very well known difference in the azimuthal asymmetry between two nuclei of different sizes.

Detailed comparisons to models, especially the ratio of ρ_2 of Xe+Xe over Pb+Pb in very central collisions indicated the sensitivity to fine details of the initial state. In particular it allowed to obtain first experimental constraints on ^{129}Xe nuclei deformation moments and prove experimentally its triaxial shape.

The decorrelation analysis was performed for pp and Xe+Xe collisions. The measurement proved to be non-trivial due to impact of non-flow on the standard template method. A significant decorrelation was confirmed for Xe+Xe collisions. Similarly, the decorrelation signal was observed and significant for the pp system. Actual values of the decorrelation slope F_2 depend somewhat on the method selected, however, the method based on the fewest assumptions indicates non-zero F_2 values along a wide multiplicity range. The AMPT modelling is satisfactory for Xe+Xe collisions but fails to reproduce the pp data.

Acknowledgements

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