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Recent ATLAS measurements of correlations in Pb+Pb and Xe+Xe collisions

Krzysztof W. Woźniak[*a,*]

[a] *Institute of Nuclear Physics, PAS, ul. Radzikowskiego 152, 31-342 Krakow, Poland*

E-mail: krzysztof.wozniak@ifj.edu.pl

ATLAS measurements of flow harmonics, v_{n}, and their fluctuations in Pb+Pb and Xe+Xe collisions at the Large Hadron Collider (LHC), covering a wide range of transverse momenta, pseudorapidity and collision centrality, are presented. The measurements are performed using data from Xe+Xe collisions at 5.44 TeV and Pb+Pb collisions at 5.02 TeV. The flow harmonics are measured using the two-particle correlations, multi-particle cumulants, and scalar product methods. Similar p_{T} and centrality dependence of v_{n}values is observed for both systems. A new universal scaling of harmonics of different orders leading to p_{T} and even centrality independence is described. Measurements of longitudinal flow decorrelations involving two- and four-particle correlations for v_2 and v_3 in Xe+Xe and Pb+Pb collisions are briefly mentioned. Some results for event-by-event correlations between harmonics of different orders, studied with three- and four-particle mixed-harmonic cumulants, are shown. Contributions to these correlations from "centrality fluctuations" are also discussed. Finally the measurement of elliptic and triangular flow of muons from charm and bottom hadron decays in 5.02 TeV Pb+Pb collisions is presented.

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*on behalf of the ATLAS Collaboration
*Speaker

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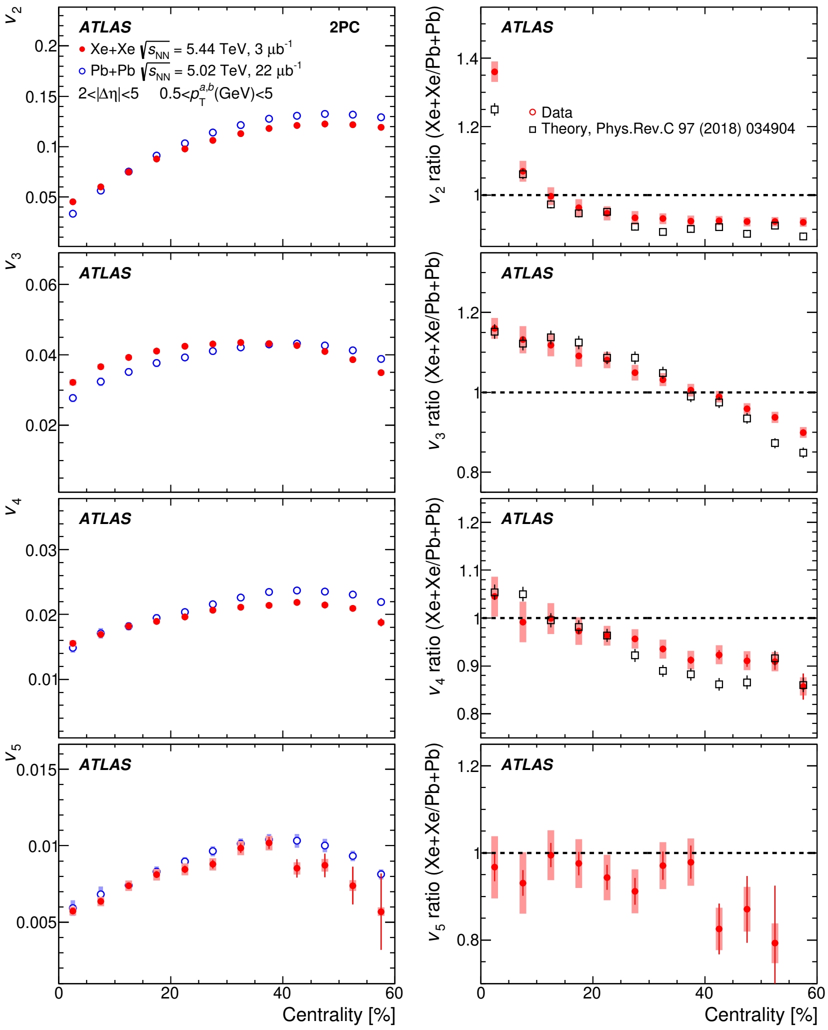

Figure 1: Comparison of flow harmonics in Xe+Xe and Pb+Pb collisions [4].

Collisions of heavy nuclei at very high energies provide favorable conditions for formation of Quark-Gluon Plasma (QGP). This state of matter is characterized by strong interactions between its components, i.e. quarks and gluons, which influence the properties of produced particles. Most energetic partons created in hard scatterings loose their energy while traversing a dense and hot matter which leads to modifications of jet properties, as discussed in Ref. [1]. In the bulk production of particles the interactions in QGP lead to collective effects discussed in this report.

One of main signatures of the QGP formation is the presence of correlations, which reflect the initial geometry of the overlap area of colliding nuclei, which determines the pressure gradients in the matter leading then to anisotropy of the momenta of produced particles. The azimuthal correlations are quantified using parameters of Fourier expansion called flow harmonics. These observables were among the first analysed in the Au+Au collisions at RHIC [2] and in Pb+Pb collisions at the LHC [3]. Since then much more detailed studies of various aspects of such correlations were performed and most recently results for Xe+Xe collisions were obtained [4].

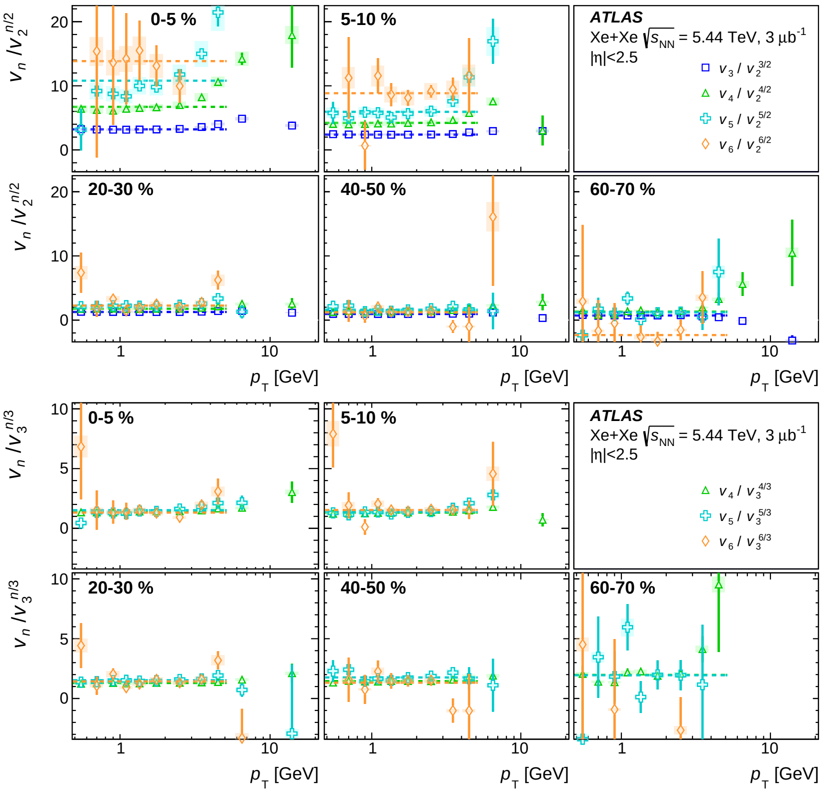

Figure 2: Scaling of flow harmonics of higher order by elliptic flow (upper panels) and triangular flow (lower panels) for selected centrality intervals of Xe+Xe collisions at 5.44 TeV [4].

The results presented here were obtained using the data measured by the ATLAS detector in Pb+Pb collisions at the center-of-mass energy 5.02 TeV and in Xe+Xe collisions at 5.44 TeV. The ATLAS detector comprises several systems including silicon pixel and strip detectors, Transition Radiation Tracker, calorimeters and muon detectors [5]. The first two systems are used in the reconstruction of tracks of charged particles, the calorimeters measure the energy of all particles and are used in determination of the centrality of nucleus-nucleus collisions while the muon detectors allow to reconstruct and identify muons.

The large statistics of Pb+Pb data at 5.02 TeV allows to perform very detailed and precise measurements. The flow harmonics v_n up to n=7 were found to be non-zero [6]. Similar analysis was repeated for Xe+Xe collisions [4]. In this case the data were limited to a single run, thus statistically meaningful results for harmonics v_2 to v_6 were obtained. The shapes of their dependence on p_T and centrality are very similar to those observed for Pb+Pb collisions. A more precise comparison presented in Figure 1 shows however, that in the most central collisions $v_2 - v_4$ harmonics are slightly larger in Xe+Xe collisions than in Pb+Pb collisions while in peripheral collisions they are smaller. This enhancement in central collisions suggests that fluctuations in the initial shape of the overlap of nuclei are larger in collisions of smaller nuclei.

In the Xe+Xe collisions a new scaling of harmonics of different orders was analyzed. Higher order harmonics are divided by elliptic and triangular flow values with an appropriate power to

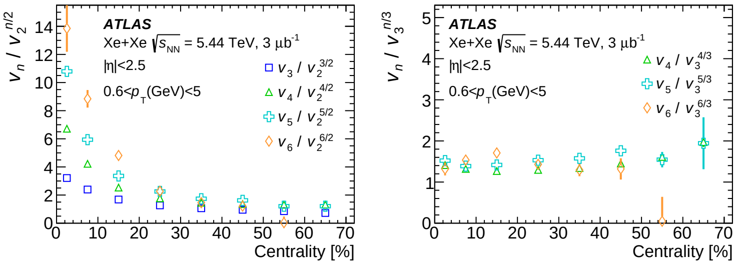

Figure 3: Values of scaled harmonics as a function of centrality of Xe+Xe collisions at 5.44 TeV [4].

obtain $v_n/v_2^{n/2}$ and $v_n/v_3^{n/3}$, respectively. Scaled harmonics, presented in Figure 2, are approximately constant as a function of the transverse momentum. The mean values of scaled harmonics, calculated in the p_T range 0–5 GeV, are shown in Figure 3. The harmonics scaled by v_2 are very large in the most central collisions and then fast decrease in more peripheral collisions. In the case of scaling by v_3 all higher order scaled harmonics are almost the same regardless of p_T and centrality. This means that after measuring v_3 we can predict all higher harmonics, both as a function of p_T and centrality. This may be related to the fact, that v_3 and all higher harmonics are results of fluctuations of the shape of the overlap of colliding nuclei.

Flow harmonics depend not only on event centrality and particle p_T, but they change also with the pseudorapidity of particles. This dependence may manifest as a change of the magnitude of the flow or as a rotation of the event plane (twist). Such effects are studied using multiparticle correlators which are calculated from flow vectors, $\mathbf{q}_n = \sum_j w_j e^{in\phi_j} / \sum_j w_j$, in different psedorapidity intervals [7, 8]. As an example the dependence of correlators $r_{n|n;k}$, defined as:

$$r_{n|n}(\eta) = \frac{\langle \mathbf{q}_n(-\eta)\mathbf{q}_n^*(\eta_{\mathrm{ref}})\rangle}{\langle \mathbf{q}_n(\eta)\mathbf{q}_n^*(\eta_{\mathrm{ref}})\rangle} \tag{1}$$

on pseudorapidity for Xe+Xe collisions is shown in Figure 4 [8]. These correlators decrease with the distance in η approximately linearly. The decrease of $r_{2|2}$ is slightly stronger in most central and in peripheral collisions than for mid-central collisions. The correlators $r_{3|3}$ and $r_{4|4}$ decrease about 2 times faster than $r_{2|2}$, but there is no obvious centrality dependence for them. All correlators have very similar values at two energies of Pb+Pb collisions [7].

The flow fluctuations were studies in ATLAS also on the event-by-event level, using multiparticle cumulants calculated for different centralities and transverse momentum ranges [9]. In Figure 5 several examples of such cumulants are shown (for definitions see Ref. [9]). Negative values of the symmetric cumulant $nsc_{2,3}\{4\}$ indicate anticorrelation between v_2 and v_3 while positive $nsc_{2,4}\{4\}$ and similar centrality dependence of $nac_2\{3\}$ is consistent with non-linear contribution of v_2 to v_4. Different values of these cumulants when calculated using two selections of event classes (based on multiplicity, N_{ch}^{rec}, or transverse energy measured in calorimeters, $\sum E_T$) indicate that centrality fluctuations lead to additional fluctuations of flow harmonics.

The flow harmonics in 5.02 TeV Pb+Pb collisions are measured also for charm and bottom hadrons using muons from their decays [10]. The statistical separation between charm and bottom decays is possible thanks to differences in the distributions of the imbalance between muon momentum measured in the inner detector and the momentum obtained in the muon spectrometer as

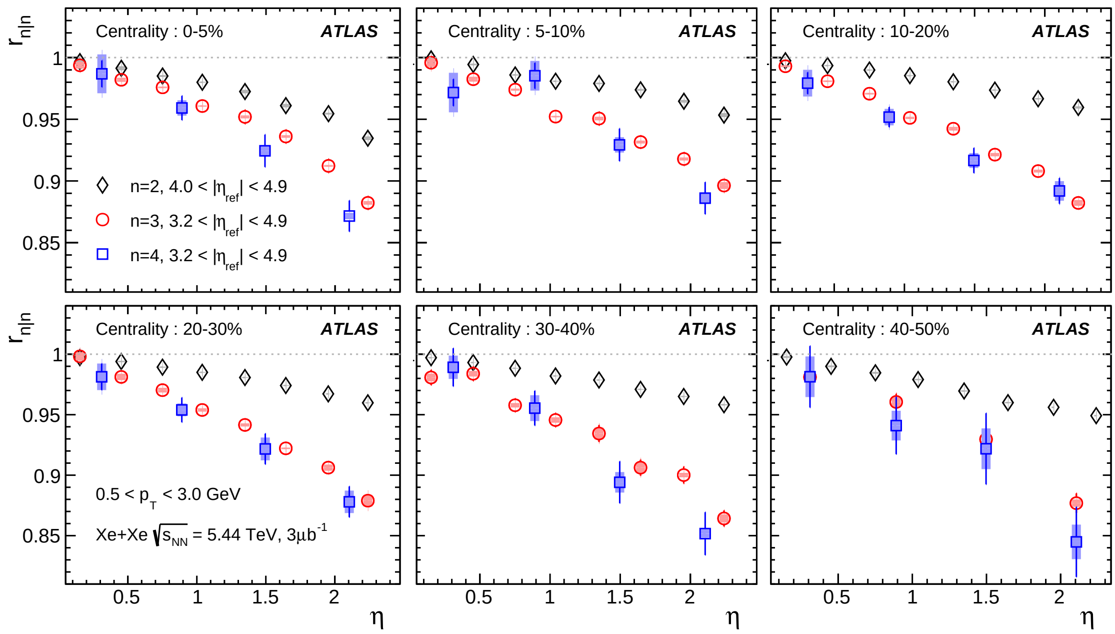

Figure 4: The η dependence of $r_{2|2}$, $r_{3|3}$ and $r_{4|4}$ in Xe+Xe collisions for six centrality intervals [8].

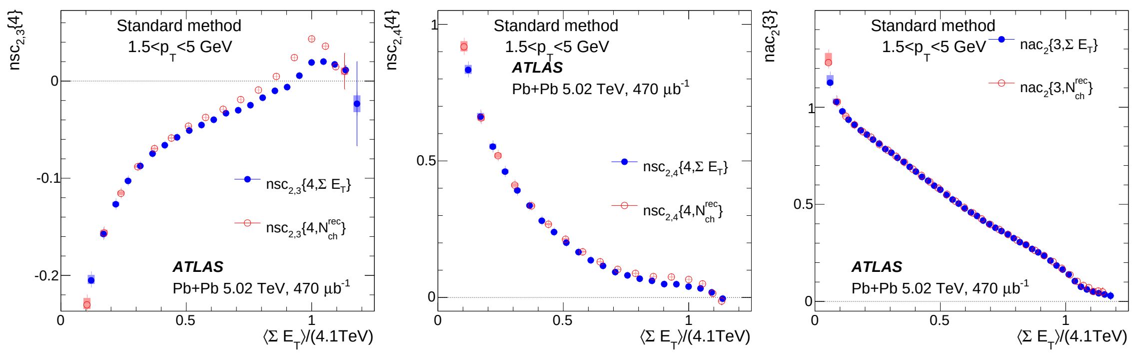

Figure 5: Comparison of $nsc_{2,3}\{4\}$ (left panel), $nsc_{2,4}\{4\}$ (middle panel) and $nac_2\{3\}$ (right panel) obtained using two different selections of event classes based on N_{ch}^{rec} and $\sum E_{\mathrm{T}}$ shown as a function of $\sum E_{\mathrm{T}}$ [9].

well as the distribution of the transverse impact parameter of the muon. The elliptic and triangular flow of charm and bottom hadrons are shown in Figure 6. The v_2 harmonics of bottom hadrons are much lower than those of charm hadrons, especially at lower values of p_{T}. This is also the case for v_3, which for bottom hadrons is very close to zero. The study of p_{T} dependence of charm and bottom hadrons flow may help to understand their creation and interactions in QGP [10].

In summary, the recent studies of correlations in Pb+Pb and Xe+Xe collisions in the ATLAS experiment at the LHC provide many new results. Non-zero flow harmonics are measured up to v_6 (Xe+Xe) and v_7 (Pb+Pb) and a scaling of harmonics of different orders is found. The longitudinal and event-by-event fluctuations of flow harmonics are analyzed. The flow harmonics of charm and bottom hadrons are measured. These results enable better understanding of QGP formation and expansion, and the impact of fluctuations of initial conditions on the observed properties of events.

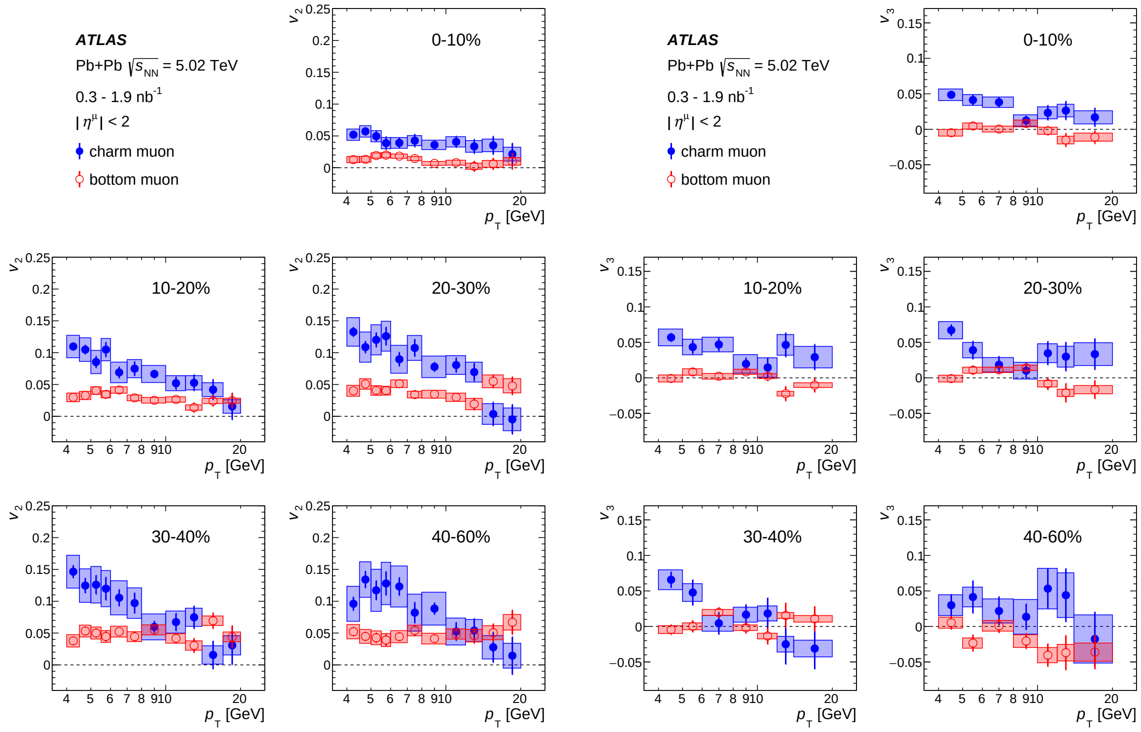

Figure 6: Elliptic (left panels) and triangular (right panels) flow of charm and bottom muons in Pb+Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV [10].

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References

[1] H. Santos (for the ATLAS Collaboration), these proceedings.

[2] STAR Collaboration, Phys. Rev. Lett. **86** (2001) 402; PHOBOS Collaboration, Phys. Rev. Lett. **89** (2002) 222301; PHENIX Collaboration, Phys.Rev.Lett. **91** (2003) 182301.

[3] ATLAS Collaboration, Phys.Lett. B**707** (2012) 330.

[4] ATLAS Collaboration, Phys. Rev. C**101** (2020) 024906.

[5] ATLAS Collaboration, JINST **3** (2008) S08003.

[6] ATLAS Collaboration, Eur. Phys. J. C**78** (2018) 997.

[7] ATLAS Collaboration, Eur. Phys. J. C**78** (2018) 142.

[8] ATLAS Collaboration, arxiv:2001.04201.

[9] ATLAS Collaboration, JHEP **01** (2020) 51.

[10] ATLAS Collaboration, Phys. Lett. B**807** (2020) 135595.