Recent ATLAS results on flow measurements in lead-lead and proton-lead collisions

Adam Trzupek on behalf of the ATLAS Collaboration

The H. Niewodniczański Institute of Nuclear Physics Polish Academy of Sciences, ul. Radzikowskiego 152, 31-342 Kraków, Poland

E-mail: `Adam.Trzupek@ifj.edu.pl`

Abstract. Recent measurements from the ATLAS experiment of the azimuthal anisotropy of charged hadron production in the relativistic p+Pb and Pb+Pb collisions at the Large Hadron Collider (LHC) are presented. We report on distributions of event-by-event flow harmonics v_n, $n = 2-4$, for Pb+Pb collisions at energy of $\sqrt{s_{NN}}$=2.76 TeV which provide a direct measure of flow harmonic fluctuations which may be related to fluctuations in the initial geometry of the interaction region. The relative event-by-event elliptic flow fluctuations are compared to the measurement based on the cumulant approach as well as to the model predictions. We also report on measurements of the two-particle correlations in $\Delta\phi$ and $\Delta\eta$ as a function of p_T and the transverse energy (ΣE_T^{Pb}) summed over $3.1 < \eta < 4.9$ in the direction of the Pb beam in $\sqrt{s_{NN}}$ = 5.02 TeV p+Pb collisions. The recoil-corrected $\Delta\phi$-correlation exhibits flow-like modulations for all ΣE_T^{Pb} ranges and particle p_T. To study further the long-range correlations in p+Pb collisions, the elliptic flow has been measured with the cumulant approach and compared to the results from two-particle correlations. The presented p+Pb results exhibit features characteristic for collective anisotropic flow, similar to that observed in Pb+Pb collisions.

1. Introduction

The azimuthal anisotropy of hadron production is a key observable for understanding the properties of the hot and dense medium created in Pb+Pb collisions at the LHC. It is expected that this anisotropy is sensitive to conditions at the very early stage of evolution of the strongly coupled Quark-Gluon Plasma (sQGP) and is related to the spatial configuration of colliding nucleons as well as the energy density fluctuations in the initial overlap region of the two colliding nuclei [1]. The initial spatial asymmetry leads to asymmetric pressure gradients in the QGP, generating a significant azimuthal anisotropy in particle $dN/d\phi$ distributions which is usually described by means of a Fourier series with n^{th} order flow harmonic, $v_n = \langle \cos n(\phi - \Phi_n) \rangle$ where ϕ is the particle azimuthal angle and Φ_n represents the symmetry plane angle. The second order harmonic, called elliptic flow (v_2) characterizes the "elliptical" shape of the initial interaction region, while higher-order flow harmonics (v_3, v_4,...) characterize more complicated configurations.

In ATLAS [2], flow phenomena are explored with charged particles reconstructed in each event within the inner detector consisting of a silicon pixel detector and a semiconductor microstrip tracker (SCT), immersed in a 2 T axial magnetic field and covering a wide pseudorapidity range ($|\eta| <2.5$). The transverse momenta of reconstructed particles are limited by a minimum p_T of 0.5 GeV and 0.3 GeV in case of Pb+Pb and p+Pb collisions, respectively. For measurements,

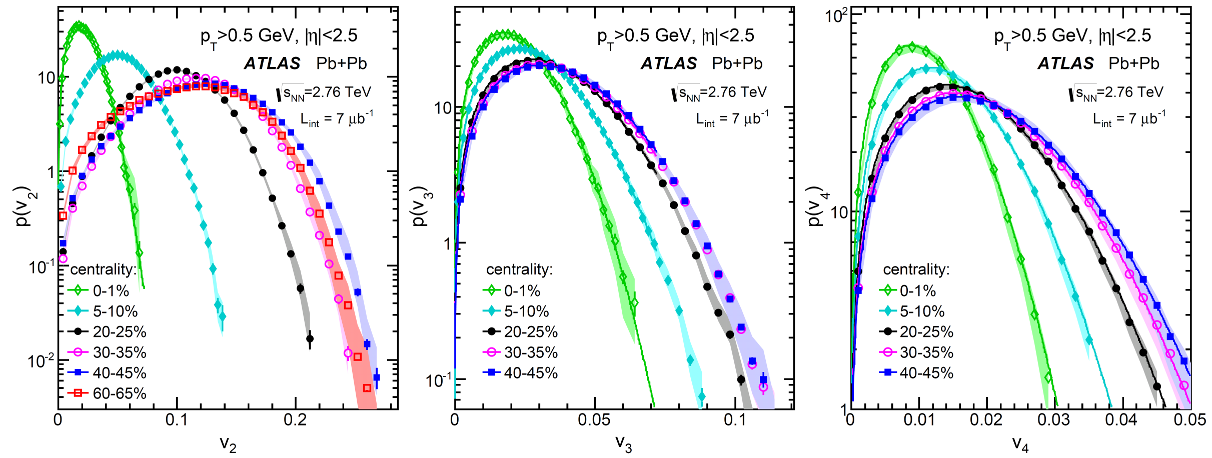

Figure 1. The event-by-event v_n distributions in selected centrality bins for $n = 2$ (left panel), $n = 3$ (middle panel) and $n = 4$ (right panel) [5]. The solid curves represent radial projections of 2D Gaussian functions with the mean rescaled to the measured $\langle v_n \rangle$.

presented in this report, a minimum bias sample of ∼50M Pb+Pb collisions at an energy of $\sqrt{s_{NN}}$=2.76 TeV as well as ∼2M p+Pb collisions at an energy of $\sqrt{s_{NN}}$=5.02 TeV are used.

2. Event-by-event flow harmonic distributions

A detailed analysis of flow harmonics averaged over large Pb+Pb event samples has been recently performed in the ATLAS experiment [3, 4]. Significant values of the higher order harmonics, $v_3 - v_6$, imply presence of large event-by-event flow vector fluctuations. Benefiting from the large acceptance of the ATLAS detector for measurement of charged particles, the distribution of $v_2 - v_4$ measured event-by-event were also recently obtained [5]. In this analysis, the azimuthal distribution of charged particles in each event is expanded into a Fourier series with coefficients corresponding to the single event flow vector components. However, due to finite event multiplicity, indicated by M, the absolute value of the flow vector (corresponding to the true v_n only in the limit $M \to \infty$) is smeared randomly around the true v_n. To correct for this smearing, the Bayesian unfolding procedure was applied [5]. The unfolded distributions represent the distributions of single event true flow harmonics and provide a direct measure of flow harmonic fluctuations. The unfolded distributions of v_2, v_3 and v_4, normalized to unity, are shown in Fig. 1 together with solid lines representing the radial projections of two-dimensional (2D) Gaussian functions with the mean adjusted to $\langle v_n \rangle$ from the data. Figure 1 shows that the distributions of higher order harmonics, v_3 and v_4, are consistent with the 2D Gaussian limit within the full measured centrality range. For the elliptic flow (n=2) the relative fluctuations, $\sigma_{v_2}/\langle v_2 \rangle$, where σ_{v_2} is the standard deviation, are presented in Fig. 2 as a function of centrality for three p_T ranges: $p_T > 0.5$ GeV, 0.5< p_T <1 GeV and p_T >1 GeV. It is observed that elliptic flow fluctuations strongly depend on centrality with the smallest fluctuations found in mid-central collisions ($N_{part} \approx 200$). The largest v_2 fluctuations are observed in the 2% most central collisions which are also consistent with the purely 2D Gaussian fluctuations. The relative fluctuations are nearly the same for $p_T > 1$ GeV and $0.5 < p_T < 1$ GeV.

The magnitude of event-by-event fluctuations of flow harmonics can also be estimated using the two- and four-particle cumulant method [8]. Assuming that non-flow effects and σ_{v_n} are small as compared to $\langle v_n \rangle$, then $\sigma_{v_n}/\langle v_n \rangle \approx \sqrt{(v_n\{2\}^2 - v_n\{4\}^2)/(v_n\{2\}^2 + v_n\{4\}^2)}$. The relative fluctuations from the cumulant method of the elliptic flow are shown in Fig. 3 as a function of p_T in different centrality intervals [9]. For the most central collisions (5-10%), $\sigma_{v_n}/\langle v_n \rangle$ is independent of p_T and for less central collisions increases with p_T. The relative v_2 fluctuations,

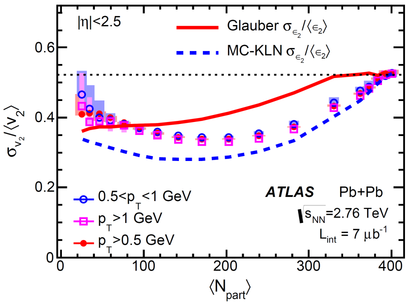

Figure 2. Centrality dependence of σ_{v_2}/v_2 compared to model predictions [6, 7] and 2D Gaussian fluctuations.

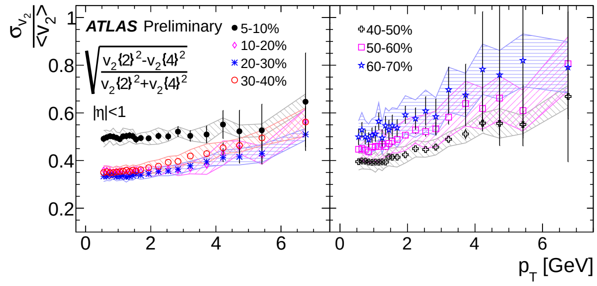

Figure 3. The p_T dependence of the relative elliptic flow fluctuations in seven centrality bins of Pb+Pb collisions from the cumulant method [9].

for $0.5 < p_T \lesssim 2$ GeV, extracted for mid-central collisions (20-30%) are at ~0.35, which is similar to that measured with event-by-event method for a corresponding centrality of N_{part} ≈200, shown in Fig. 2.

3. Azimuthal anisotropy in p+Pb collisions

An important tool to probe the collective phenomena in heavy ion collisions is the two-particle correlation function measured as a function of relative pseudorapidity ($\Delta\eta$) and azimuthal angle ($\Delta\phi$) of particle pairs. Recently, a two-particle correlation (2PC) function was obtained in ATLAS [10] for p+Pb collisions in different centrality intervals measured by the transverse energy ΣE_T^{Pb}. The 2D correlation functions for charged particles in peripheral and central collisions are shown in Fig. 4. For peripheral collisions the correlation function shows a sharp peak centered at ($\Delta\phi$,$\Delta\eta$) = (0, 0) and a broad (in $\Delta\eta$) structure at $\Delta\phi \approx \pi$ (called recoil) both predominantly originating from non-flow effects. In central collisions, in addition to the components observed in peripheral collisions, the correlation function reveals a broad (in $\Delta\eta$) structure at $\Delta\phi \approx 0$ (the "near-side ridge"). The distribution at $\Delta\phi \approx \pi$ is also broadened relative to peripheral collisions, consistent with the presence of a long-range component (the "away-side ridge").

The strength of the long-range component is commonly quantified by the "per-trigger yield", Y($\Delta\phi$), which measures the yield of particle pairs per the yield of trigger particles ($1/N_{trig} dN^{pair}/d\Delta\phi$) [11]. Figure 5 shows the Y($\Delta\phi$) distributions for $2 < |\Delta\eta| < 5$ in peripheral and central collisions as well as their difference (ΔY, solid points) which is symmetric around $\Delta\phi = \pi/2$ and consistent with flow-like modulations. The second order amplitude of these modulations, $v_2\{2PC\}$, depicted in Fig. 6 as a function of p_T is reminiscent of what is

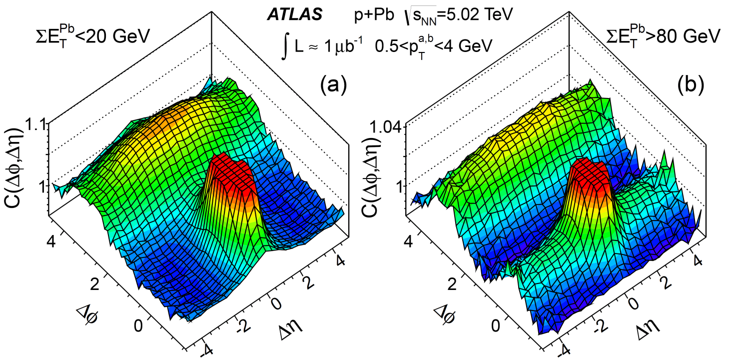

Figure 4. The two-particle correlation function in peripheral (a) and central (b) p+Pb collisions at energy of $\sqrt{s_{NN}}$ = 5.02 TeV [10].

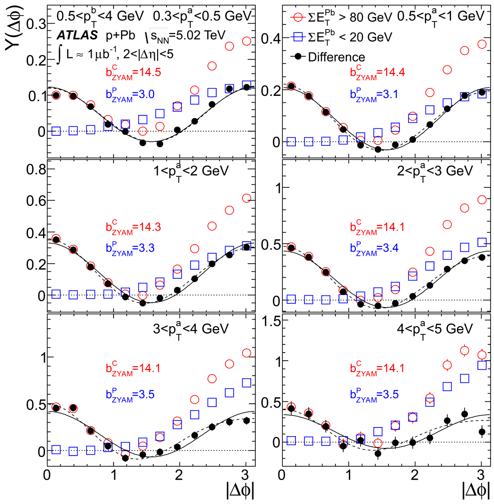

Figure 5. Per-trigger yield (PTY) for particle pairs with $2 < |\Delta\eta| < 5$ in peripheral (squares) and central (open circles) p+Pb collisions in six p_T intervals. Solid points represent the difference [10].

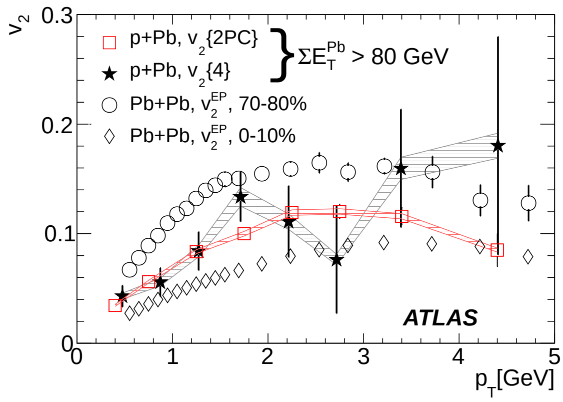

Figure 6. Comparison of the p_T dependence of the v_2 coefficient measured in p+Pb collisions with the four-particle cumulants $v_2\{4\}$ [12], and with the two-particle correlation method $v_2\{2PC\}$ [10] to v_2 obtained with the event-plane method for central and peripheral Pb+Pb collisions [3].

understood to be hydrodynamic flow in Pb+Pb collisions. To further study the collective flow in p+Pb collisions, the elliptic flow harmonics were obtained from cumulant method, $v_2\{4\}$ [12]. Figure 6 shows p_T dependence of $v_2\{4\}$ which is consistent with $v_2\{2PC\}$ and, interestingly, with a magnitude between the values of v_2 obtained with the event-plane method [3] in the most central and most peripheral centrality intervals measured for Pb+Pb collisions.

In summary, ATLAS has presented event-by-event v_2, v_3 and v_4 distributions in a wide centrality range of Pb+Pb collisions at the LHC energy of $\sqrt{s_{NN}} = 2.76$ TeV, which provide a direct insight into fluctuations in the initial geometry of the interaction region. The relative fluctuations of v_2 in the most central Pb+Pb collisions, and v_3 and v_4 within the full, measured centrality range are consistent with radially-projected 2D Gaussian distributions. In mid-central collisions, the relative fluctuations of v_2 are significantly smaller than the Gaussian limit. In $\sqrt{s_{NN}} = 5.02$ TeV p+Pb collisions, the two-particle correlation function clearly shows ridge structures resembling those observed in Pb+Pb collisions and suggesting that collective flow may also be present in p+Pb collisions. The flow interpretation of the p+Pb data is also supported by results from multi-particle azimuthal correlation measurements.

This work was supported by National Science Centre grant number 2011/01/N/ST2/ 04042.

References

[1] Ollitrault J-Y 1992 *Phys. Rev. D* **46** 229.
[2] ATLAS Collaboration 2008 *JINST* **3** S08003.
[3] ATLAS Collaboration 2012 *Phys. Lett.* **B707** 330-348.
[4] ATLAS Collaboration 2012 *Phys. Rev.* **C86** 014907.
[5] ATLAS Collaboration 2013 *JHEP* **11** 183.
[6] Miller M L, Reygers K, Sanders S J and Steinberg P 2007 *Ann. Rev. Nucl. Part. Sci.* **57** 205.
[7] Drescher H J and Nara Y 2007 *Phys. Rev.* **C75** 034905.
[8] Borghini N, Dinh P M, Ollitrault J-Y 2001 *Phys. Rev.* **C63** 054906;*Phys. Rev. C64* 054901.
[9] ATLAS Collaboration 2012 *ATLAS-CONF-2012-117* https://cdsweb.cern.ch/record/1472939.
[10] ATLAS Collaboration 2013 *Phys. Rev. Lett.* **110** 182302.
[11] PHOBOS Collaboration 2010 *Phys. Rev. Lett.* **104** 062301.
[12] ATLAS Collaboration 2013 *Phys. Lett.* **B725** 60.