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

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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 ($\Sigma E_T^{Pb}$) 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 $\Sigma E_T^{Pb}$ 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 $\phi$ is the particle azimuthal angle and $\Phi_n$ 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 $\sim 50M$ Pb+Pb collisions at an energy of $\sqrt{s_{NN}}=2.76$ TeV as well as $\sim 2M$ 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 $\sigma_{v_2}$ 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 ($N_{\text{part}} \approx 200$). 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 $\sigma_{v_n}$ 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 $\sigma_{v_2}/v_2$ 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 $\sim 0.35$, which is similar to that measured with event-by-event method for a corresponding centrality of $N_{\text{part}} \approx 200$, 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 $\Sigma E^p_P b$. 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 ($1/N_{\text{trig}} dN_{\text{pair}}/d\Delta \phi$) [11]. Figure 5 shows the $Y(\Delta \phi)$ distributions for $2 < |\Delta \eta| < 5$ in peripheral and central collisions as well as their difference ($\Delta Y$, 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
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.

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