Soft Probes of the Quark-Gluon Plasma in ATLAS

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Measurements of low-p_{T} (< 5 GeV) particles in Pb+Pb collisions at the LHC provide valuable insight in the production and evolution of the quark-gluon plasma. In particular, measurements of the elliptic and higher order flow harmonics imprinted on the azimuthal angle distributions of low-p_T particles directly probe the strongly-coupled dynamics of the quark gluon plasma and test hydrodynamic model descriptions of its evolution. The large acceptance ATLAS detector makes it possible to measure flow event-by-event and to determine the correlations between different event planes and different flow harmonics.

In collisions of lead nuclei from two beams accelerated in the Large Hadron Collider (LHC) to the energy in the centre-of-mass of $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV a very high energy density is achieved in a relatively large volume. This leads to creation of a dense, strongly interacting matter - the Quark-Gluon Plasma (QGP). Such matter undergoes first an expansion and then a hadronization leading to particles observed in detectors. While the properties of most energetic partons (observed as jets) are affected mostly by the initial conditions of QGP, the production of particles with lower momenta is also sensitive to the later evolution of QGP. Detailed studies of various correlations between low-p_{T} particles were performed by the ATLAS experiment. In these analyses information from several parts of the ATLAS detector [1] was used. In the Inner Detector covering over 5 pseudorapidity units ($|\eta| < 2.5$) tracks of charged particles are reconstructed. The calorimeters register energy of hadrons, electrons and photons in the $|\eta| < 4.9$ range. The signal registered in the $3.1 < |\eta| < 4.9$ range (i.e. from Forward Calorimeters) is used as a measure of the centrality of Pb+Pb collisions.

In heavy-ion collisions, with an exception of the most central ones, the area of the overlap of nuclei has an elongated shape. The asymmetry of the QGP volume leads in hydrodynamical models to different pressure gradients and then to the azimuthal asymmetry of particle emission (flow). The asymmetry is studied using the Fourier expansion:

$$\frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}\phi} \sim 1 + 2\sum_{n=1}^{\infty} v_n(p_{\mathrm{T}}, \eta)\cos(n(\phi - \Phi_n)),$$

where azimuthal angles ϕ and Φ_n of the charged particles and the reaction planes, respectively, are used.

The second Fourier harmonic, v_2, called elliptic flow, represents the magnitude of correlations connected with the elongated shape of the overlap of the nuclei. In the LHC experiments it is usually measured using particles with $p_{\mathrm{T}} > p_{\mathrm{T,min}}$, with $p_{\mathrm{T,min}} = 0.3 - 0.5$ GeV, with a model dependent extrapolation to $p_{\mathrm{T}} \approx 0$. No extrapolation is needed in ATLAS if *tracklets*, defined as two hits registered in the innermost pixel detector, compatible with the primary vertex position, are used to reconstruct particles with p_{T} down to 0.07 GeV. In Fig. 1 the dependence of the

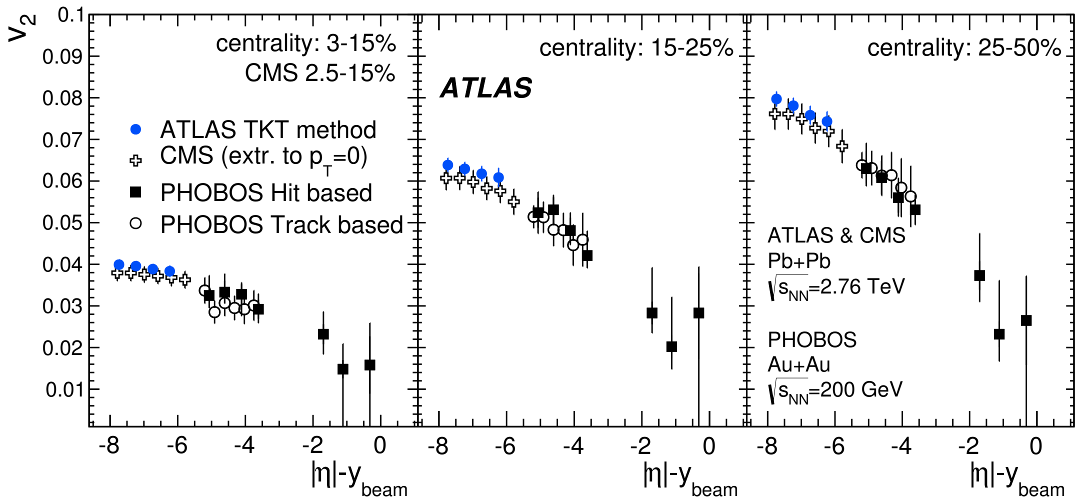

Figure 1: Integrated elliptic flow, v_2, presented as a function of $|\eta| - y_{beam}$ for three centrality intervals obtained by the ATLAS [2] and CMS [3] experiments for Pb+Pb collisions at $\sqrt{s_{\rm NN}} =$ 2.76 TeV and by the PHOBOS experiment [4] for Au+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV.

integrated elliptic flow, v_2, on pseudorapidity, shifted by the rapidity of the beam, $y_{\rm beam}$, is presented. This shift corresponds to the Lorentz transformation of rapidity to the rest frame of one of the colliding nuclei. After such transformation the PHOBOS experiment observed an extended longitudinal scaling of v_2 at energies $\sqrt{s_{\rm NN}} = 19.6 - 200$ GeV [4]. The data points from ATLAS follow the trend seen by PHOBOS, unfortunately, the acceptance of the ATLAS detector is too small, to obtain any overlap with PHOBOS,

Flow harmonics can be also measured without determination of the event plane angle, Φ_n, using two-particle or many-particle correlations. If flow is the only source of the two-particle correlations, flow harmonics can be calculated as $v_n\{2\} = \sqrt{\langle\cos(n(\phi_a - \phi_b))\rangle}$. For $2k$-particle correlations ($k > 1$) especially useful are *cumulants*, which measure genuine $2k$-particle correlations. A comparison of flow harmonics obtained by ATLAS using the event plane method, $v_n\{\rm EP\}$, two-particle correlations, $v_n\{2\}$, four-particle cumulants, $v_n\{4\}$, and mean values of $p(v_n)$ distributions from event-by-event measurements, $v_n\{\rm EbyE\}$ is shown in Fig. 2 [5]. For all measured harmonics we observe $v_n\{2\} > v_n\{\rm EP\} > v_n\{\rm EbyE\} > v_n\{4\}$ relation. $v_n\{2\}$ are the largest beacuse of the non-flow contributions from short range correlations (for example resonance decays), suppressed in all other methods. The differences between $v_n\{\rm EP\}$, $v_n\{\rm EbyE\}$ and $v_n\{4\}$ are mainly due to flow fluctuations affecting each of them in a different way. In addition to four-particle cumulants, also six- and eight-particle cumulants are used by ATLAS to measure $v_2\{6\}$ and $v_2\{8\}$, respectively. They are very similar to $v_2\{4\}$, which means that already by using the four-particle cumulants non-flow contributions are efficiently suppressed [5].

Another comparison of the data and models of heavy-ion collisions is possible in a study of correlations between two or more event plane angles, Φ_n, measured in different η intervals for different harmonics [6]. The correlators are defined as $\langle\cos(c_1\Phi_1 + 2c_2\Phi_2 + ... + lc_l\Phi_l)\rangle$ with the constants c_n fulfilling the constraint $c_1 + 2c_2 + ... + lc_l = 0$. In Fig. 3 eight correlators with two event planes measured by ATLAS are presented [6]. Usually the correlations are positive, especially for $4(\Phi_2 - \Phi_4)$, $6(\Phi_2 - \Phi_6)$ and $6(\Phi_3 - \Phi_6)$, but for one of three plane correlations, $2\Phi_2 - \Phi_3 + 4\Phi_4$, it is negative [6]. The values and centrality dependence of correlators from the data and predicted by Glauber model are distinctly different. However, a good qualitative agreement with the data is seen for predictions from the AMPT model [7], which starting from the same initial state as the Glauber model in addition simulates final-state dynamics.

The correlations between magnitudes of flow harmonics measured by ATLAS [8] are presented in Figs. 4 and 5. The data points were obtained in narrow bins of flow vector, q_2 (defined in Ref. [8]), and centrality. The flow vector characterises the asymmetry of the particle production and is directly related to the shape of the initial volume of the QGP, while the centrality reflects its size mostly. For v_2 measured in different p_{T} intervals, linear correlations within fixed centrality are observed (Fig. 4) and only the slope of the linear fit changes with centrality. This suggests presence of viscous effects which are controlled by the overall system size and not its shape. Negative, approximately linear correlations between v_3 and v_2 are observed (Fig. 5 left), similar to anti-correlations between corresponding eccentricities calculated from the positions of participating nucleons. However, the correlations between v_4 and v_2 (Fig. 5 right) are non-linear and thus are not completely eccentricity driven [8].

Detailed studies of several aspects of flow phenomena in ATLAS provide a better understanding of the QGP initial state and evolution. In the flow harmonics calculated from multi-particle cumulants non-flow contributions are suppressed. Effects of final-state dynamics have large impact on correlations between event plane angles. The analysis of correlations between elliptic flow and other flow harmonics reveals viscous effects, anti-correlation of v_3 versus v_2 and non-linear terms in v_4 and v_5 dependence on v_2.

Acknowledgments:

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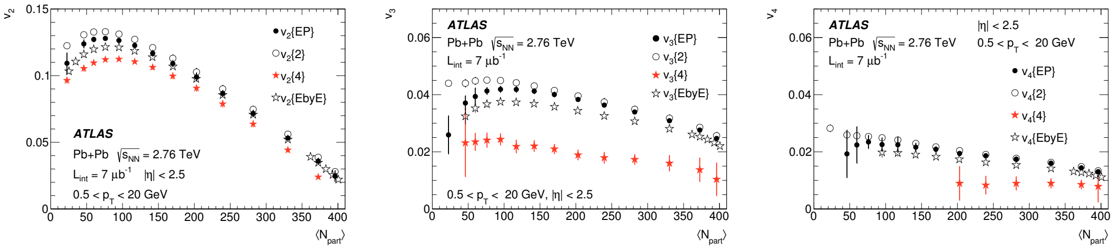

Figure 2: N_{part} dependence of flow harmonics: v_2 (left), v_3 (middle) and v_4 (right) obtained using several different methods [5].

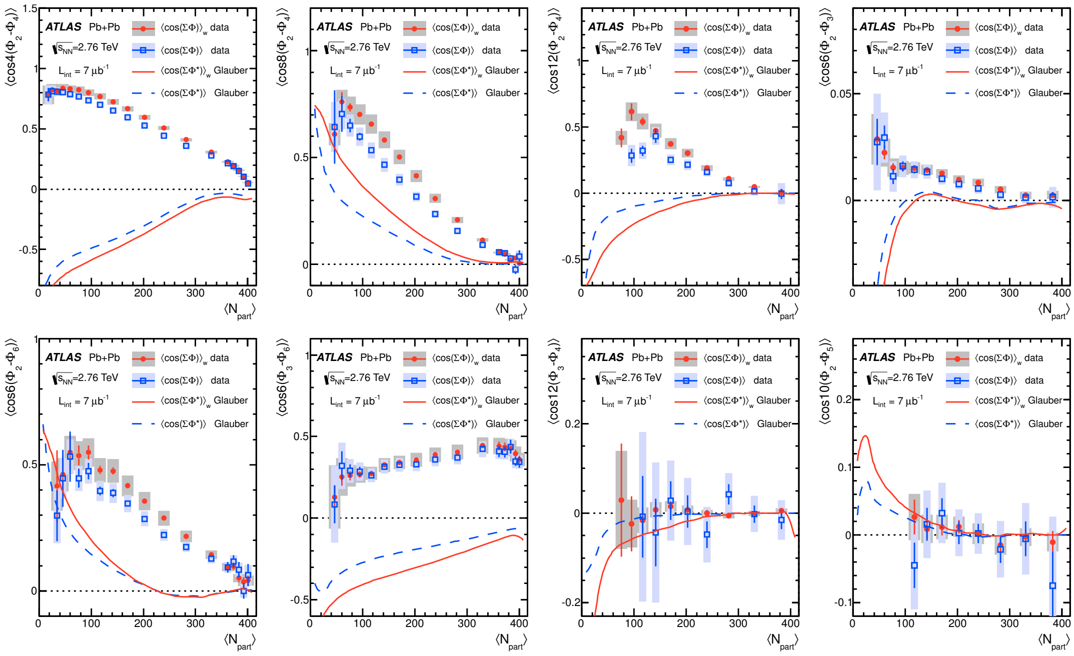

Figure 3: Centrality dependence of two-plane correlators (points) compared with correlations among participant-plane angles expected from the Glauber model (lines) [6].

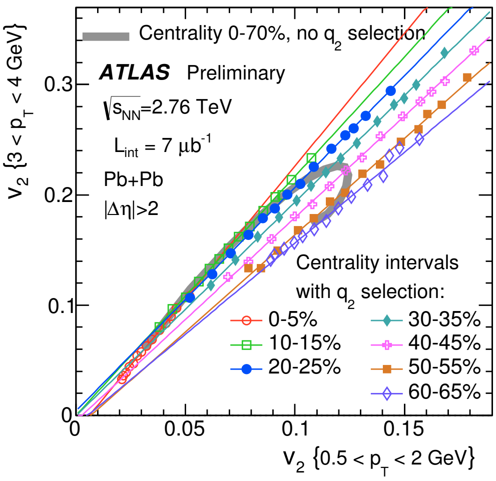

Figure 4: The correlation between values of v_2 measured in 3-4 GeV p_T range and in 0.5-2 GeV p_T range for several centrality and q_2 intervals, overlaid with the centrality dependence without q_2 selection (grey band) [8]. Linear fits to the data points in each centrality are shown as straight lines.

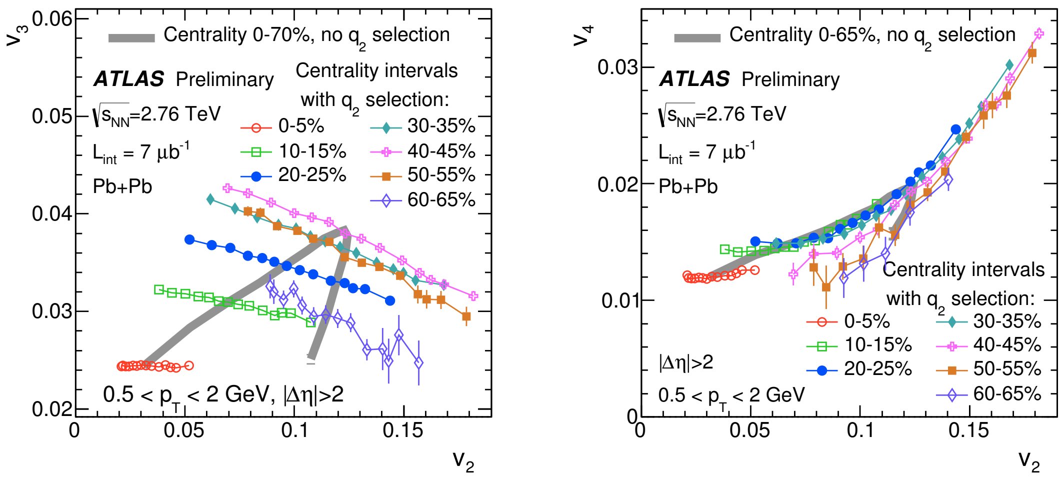

Figure 5: The correlation (left) between v_3 and v_2 and (right) between v_3 and v_2, all measured in 0.5-2 GeV p_T range [8]. Several different centrality selections (denoted by different symbols and colours) and q_2 intervals are used and overlaid with the centrality dependence without q_2 selection (grey band).