Azimuthal correlations and collective effects in a heavy-ion collisions at the LHC energies

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Abstract. Recent highlights from the anisotropic flow and the azimuthal correlation measurements in a heavy-ion collisions at the LHC are presented. Various flow harmonics measured for the charged and identified particles versus transverse momentum, pseudo-rapidity, and the collision centrality are reported. New experimental probes of the local parity violation at the LHC energies using the charge dependent azimuthal correlations are also discussed.

1. Introduction
An azimuthal anisotropic flow which describes collectivity among particles produced in heavy-ion collision is recognized as a key observable used to infer information about the early time evolution of the nuclei interaction. This FAIRNESS 2012 Conference proceedings highlight recent results by the LHC experiments from the anisotropic flow measurements in relativistic heavy-ion collisions at the TeV energy scale. Experimental findings from the search for effects of the local parity violation in strong interaction using the charge dependent azimuthal correlations with respect to the reaction plane at the LHC energies are also discussed.

2. Anisotropic flow fluctuations
It is commonly understood that the even-by-event fluctuations in the initial energy density of a heavy-ion collision plays an important role in the development of the azimuthal asymmetries in the momentum distribution of the produced particles. Since fluctuations are mapped by the interaction among constituents of the expanding medium into the final momentum space asymmetry, the measurements of the anisotropic flow provide a unique experimental information about the properties of the created medium, its evolution, and profile of the initial conditions in a heavy-ion collision. Recently a number of new high statistics experimental results from LHC which help to understand details of flow fluctuations become available. Figure 1(a) shows the results of the multi-particle correlation analysis of the directed $v_1$, elliptic $v_2$, and triangular $v_3$, flow measured for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ GeV by the ALICE Collaboration [1]. Observed non-zero odd flow harmonics represent a significant effect of the initial energy fluctuations especially for the most central collisions where all harmonics become comparable to each other. Agreement between the anisotropic flow estimates with 4, 6, and 8-particle correlations put stringent constraints on the shape of the event-by-even flow distribution.

Differential measurements of the anisotropic flow versus pseudorapidity $\eta$ and transverse momentum $p_T$ provide additional information on the extend of flow fluctuations to forward
Figure 1. Charged particle $v_1$, $v_2$, and $v_3$ measured by ALICE [1, 5] in Pb-Pb collisions at √$s_{NN}$ = 2.76 TeV. (a) Multi-particle estimates of $v_1$, $v_2$, and $v_3$ at midrapidity vs. centrality. (b) Two- and four-particle estimates of $v_2$ vs. pseudorapidity.

Figure 2. (a) Charged particle $v_2$, $v_3$, and $v_4$ measured for Pb-Pb collisions at √$s_{NN}$ = 2.76 TeV by the ATLAS [2], CMS [3], and ALICE [4] Collaborations. (b) Estimate of the relative $v_2$ flow fluctuations as a function of the transverse momentum for different collision centrality classes.

rapidly and higher transverse momenta. Such measurements performed by the ATLAS [2], CMS [3], and ALICE [4] Collaborations are shown in Fig. 1(b) and Fig. 2. The flow estimates obtained with the event plane, two and four-particle measurement techniques [3, 4, 5] suggest that relative flow fluctuations weakly depend on $p_T$ and $\eta$. Figure 2(b) shows that fluctuations extend to higher $p_T$ up to about 8 GeV/c, while Fig. 1(b) indicates a similar amount of relative fluctuations up to $|\eta| \sim 5$.

Further constraints on the effects of the initial energy fluctuations is provided by the measurements of the multi-particle mixed harmonic correlations and the correlation between the different order symmetry planes. Figure 3 shows corresponding results by the ATLAS [6] and ALICE [1] Collaborations in comparison with the expectations from the event-by-event hydrodynamic model calculations using two different profiles of the initial condition [7]. Observed correlations between the two and three planes of symmetry and their qualitative agreement with the hydrodynamic model calculations points on their strong sensitivity to the
Figure 3. (a) 2nd and 4th order event plane correlation vs. the number of participants (centrality) measured by ATLAS [6] for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Results are compared with the event-by-event hydrodynamic model calculations. (b) Three-particle azimuthal correlation proposed in [8] measured by ALICE [1] for the same collision system.

details of the fluctuating initial energy profile. Among other promising developments in the fluctuations studies are the shape measurements of the event-by-event flow distributions (see e.g. [9]), and the measurements of physics observables for event classes selected based on their azimuthal shapes. This new type of study suggested in [10] was successfully applied in the real data analysis by the ALICE Collaboration [11, 12].

3. Elliptic flow of identified particles

Viscous hydrodynamics is considered to be a relevant model to describe a thermalized phase in the time evolution of the system created in a heavy-ion collision. Applicability of the

Figure 4. Identified particle $v_2(p_T)$ measured by ALICE [13] for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Charged pion, kaon, and proton $v_2$ compared to that of (a) $\Xi$ and $\Omega$ and the hydrodynamic model calculations [14], and (b) with $v_2$ of $\phi$-meson, $K_s^0$ and $\Lambda/\bar{\Lambda}$ particles.

hydrodynamic description at the LHC energies can be tested by measuring the particle mass
dependence of the elliptic and triangular flow at small transverse momenta, $p_T < 2 - 3$ GeV/$c$. Figure 4 shows $v_2(p_T)$ of pions and anti-protons in comparison to that of strange ($K^0_s$, $\Lambda$/\bar{\Lambda}) and multi-strange ($\phi$, $\Xi$, and $\Omega$) particles. The main trends of the observed mass splittings of $v_2$ at low transverse momenta is reproduced by viscous hydrodynamic model calculations [14] with a color glass condensate initial condition (see Fig. 4(a)). The flow of heavier particles (proton, $\phi$-meson, $\Xi$ and $\Omega$) is more sensitive to the hadronic rescattering phase and the agreement with data improves when adding this additional phase into the model calculations (see Fig. 2 in [15]). $v_2$ of $\phi$-meson which is shown in Fig. 4(b) follows the mass splitting expected from the hydrodynamics at lower transverse momenta, while its magnitude is close to $v_2$ of other mesons (pions) in the intermediate region of $p_T \sim 3 - 6$ GeV/$c$. Such behavior suggest the constituent quark number ($n_q$) scaling of $v_2$ which is expected for mesons and baryons produced via quark coalescence in a phase of the deconfined quarks and gluons. This scaling may indeed holds at the LHC within 20% at the $p_T/n_q \sim 1.2$ GeV/$c$ (see Figs. (4) and (5) in [13]).

4. Probes of local parity violation in strong interaction

The parity symmetry violation by the strong interactions remains one of the open fundamental questions about the quantum chromodynamics. It is argued [16] that the parity symmetry can be locally violated in a heavy-ion collisions what will result in the experimentally observable separation of charges along the extreme magnetic field generated by the moving ions, the so called chiral magnetic effect (CME). As an experimental probe of the CME it was proposed [17] to use the azimuthal correlations with respect to the collision reaction plane which is perpendicular to the magnetic field generated in the collision. The STAR [18] at RHIC and the ALICE [19] at the LHC observed a clear charge dependence of the two-particle correlation with respect to the reaction plane. The measured observable is parity even and thus is sensitive to effect unrelated to the parity symmetry violation. Recently the ALICE Collaboration extended [20] the measurements with the new set of the mixed harmonic correlators $\langle \cos(\phi_\alpha - (m+1)\phi_\beta + m\Psi_m) \rangle$ (for $m = \pm 2, \pm 4$) and the double harmonic correlator $\langle \cos(2\phi_\alpha + 2\phi_\beta - 4\Psi_4) \rangle$, where $\phi_{\alpha,\beta}$ is the azimuthal angle, $\alpha,\beta$ is the charge of the particle, and $\Psi_m$ is the $m$-th order collision symmetry plane angle. Figure 5(a) shows the correlation difference $\Delta \langle \cos(\phi_\alpha - (m+1)\phi_\beta + m\Psi_m) \rangle$ between the same and the opposite charge combinations. The expected CME contribution

\begin{figure}[h]
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\caption{Charge dependent correlations measured by ALICE [20] for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. (a) The same minus the opposite charge correlations compared to the local charge conservation model [25]. (b) Correlation $\langle \cos(\phi_\alpha - 3\phi_\beta + 2\Psi_4) \rangle$ vs. rapidity separation [20].}
\end{figure}
to the correlator $\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_2) \rangle$ ($m = -2$ in Fig. 5) at the LHC energies is based on the extrapolation of the RHIC results. Depends on the model assumptions, it varies from about 20% [21] up to the full strength [16, 22, 23] of the correlations observed at the LHC if one assumes that magnetic field flux is independent of the collision energy. It is noted [24] that effects of local charge conservation modulated by the anisotropic flow can be responsible for a significant part of the measured correlations. The statement is also supported by model calculations [25] shown in Fig. 5(a). The charge independent part of the correlations can be dominated by effects of flow fluctuations [8], although the differential study of the charge dependent correlation shown in Fig. 5(b) reveals strong dependence on the pair separation in pseudorapidity which is not typical for flow fluctuations. At the moment none of the models is able to reproduce simultaneously the charge dependence and the charge insensitive baseline of the measured correlations.

5. Summary and outlook

The anisotropic flow and the multi-particle azimuthal correlation measurements at the LHC help to clarify the role of the initial energy fluctuations in the multiple particle production in a heavy-ion collision. The particle type and the mass dependence of the anisotropic flow suggest that the system produced in a heavy-ion collision is strongly coupled and evolved via the deconfined phase of quarks and gluons. The new measurements of the mixed harmonic charge dependent azimuthal correlations helps to constrain possible background sources in the search for effects of the parity symmetry violation in the QCD.

Acknowledgements

Supported by the Helmholtz Alliance Program of the Helmholtz Association, contract HA216/EMMI “Extremes of Density and Temperature: Cosmic Matter in the Laboratory”.

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