

Results on flow from the ALICE Collaboration

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Abstract

This short overview includes recent results from the ALICE Collaboration on anisotropic flow of charged and identified particles in $\sqrt{s_{NN}} = 2.76$ TeV Pb-Pb collisions. We also discuss charge dependent and event plane dependent azimuthal correlations that are important in tests of the chiral magnetic effect, as well as understanding the dynamics of the system evolution and hadronization process. Lastly, we present ALICE results obtained with a new technique, the event shape engineering, which allows to perform a physical analysis on events with very large or small flow.

1. Introduction

Anisotropic flow was one of the most expected results from heavy-ion program at the LHC. The very first measurements have shown that the anisotropic flow at LHC is large and in rough agreement with expectation from the hydrodynamic model. These results have been intensively discussed at the last Quark Matter conference [1, 2] and have been published [3, 4], but did not reduce the interest in flow results, as new questions have risen up, in particular the ones related to the initial geometry fluctuations. Also, high-energy and high-multiplicity, as well high-statistics data from LHC allow for unprecedented study of event anisotropies at high transverse momenta as well as precision measurements of multiparticle (higher cumulants) correlations. Identified particle flow, for which the ALICE experiment [5] is suited the best among all LHC experiments, is also highly interesting as it provides important information for further understanding of the system evolution (e.g. development of radial flow) as well as hadronization process. Below we discuss new ALICE results related to these questions. The results on elliptic flow of J/ψ , D-mesons, and muons from heavy flavor decays can be found in [6, 7, 8].

In recent years, the charge dependence of the azimuthal correlations, and in particular in correlations with respect to the reaction plane has attracted a lot of attention, first as a measurement sensitive to the Chiral Magnetic Effect (CME) [9], but also due to its sensitivity to the system hadronization and, more generally, to the system evolution till the freeze-out, e.g. charge (quark) production and charge diffusion in the system during its evolution. ALICE Collaboration measurements [10] of the charge dependent correlations are consistent with the (mostly qualitative) expectations from the CME. At the same time the same data would be consistent with the effect of the local charge conservation in combination with the large elliptic flow. ALICE is performing

¹ A list of members of the ALICE Collaboration and acknowledgements can be found at the end of this issue.

measurements which should allow to clarify the picture. Some of those are discussed in these proceedings.

Finally, we review ALICE preliminary results using a new technique, the so-called event shape engineering [11]. This approach allows to select events of a particular shape, either more asymmetric or more “round”, the direction to be very promising in many respects. In this study we address such questions as the role of event shape fluctuations on flow at large transverse momenta. The results are in agreement with results obtained with other methods, in particular comparing 4-particle cumulant results with event plane and 2-particle cumulant measurements.

2. Extending the measurements

Recently, ALICE has submitted the paper [12] extending its anisotropic flow measurements up to $p_T \approx 20$ GeV/c. The nonflow effects in this analysis has been suppressed by using the event plane from the VZERO detectors separated from the TPC by two units of rapidity with an estimate of remaining nonflow included in the systematic error. Along with elliptic flow, ALICE reported results on triangular flow v_3 and fourth harmonic anisotropy measured with respect to both second and fourth order event planes, v_{4/Ψ_2} and v_{4/Ψ_4} . The difference between the two is totally due to fluctuations in the fourth order harmonic flow and as such provides important constraints on the physics and origin of the flow fluctuations. Figure 1 shows the results for the charge particle anisotropies. Results for pions and protons has been also measured (see [12, 13]). Significant nonzero elliptic flow as well as v_3 were found up to the highest transverse momenta. At $p_T > 10$ GeV/c the elliptic flow results are well described by the WHDG model extrapolation to the LHC energies [14] taking into account collision and radiative energy loss in the expanding medium.

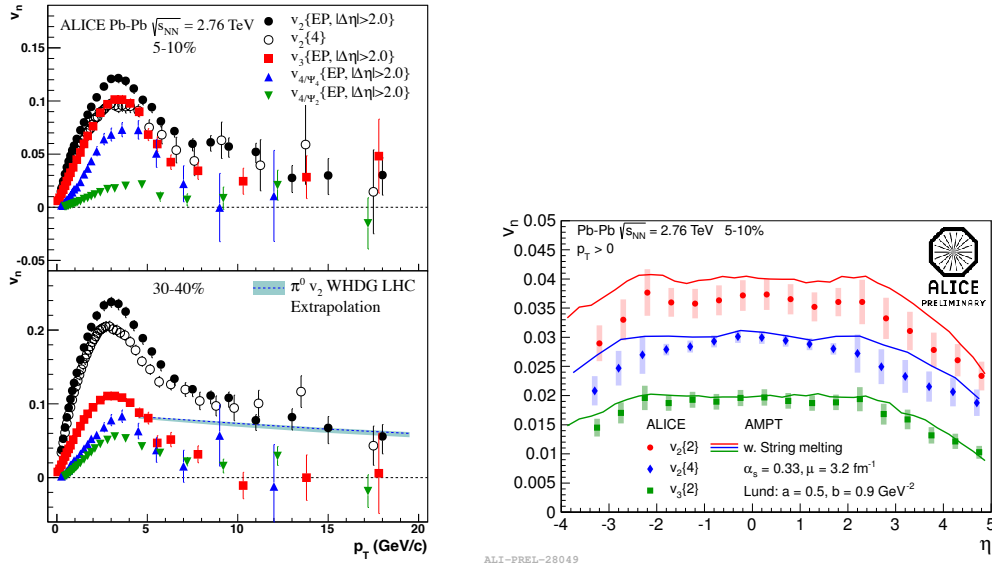


Figure 1: (Left panel) p_T -differential event anisotropies [12]. (Right panel) v_2 and v_3 pseudorapidity dependence.

The analysis of the data from the Forward Multiplicity and the Silicon Pixel Detectors (for details, see [15]) has allowed to extend the measurements of average (no transverse momentum information) anisotropy, v_2 and v_3 up to $\eta = 5$, well above the existed so far measurements. Noteworthy that elliptic flow measurements have been performed with two- as well as four-particle cumulant methods, which allow to study flow fluctuations up to very forward pseudorapidities (see below). Anisotropic flow has been found to be almost independent of pseudorapidity in the region $|\eta| < 2$, see Fig. 1 right panel, and decreasing at larger pseudorapidities. The latter allows to test the limiting fragmentation (longitudinal scaling) picture, the property of the spectra showing the scaling with $\eta - y_{beam}$, the observation made first at lower collision energies. ALICE results agree well with such a scaling. More details of this analysis can be found in [15].

The shape of the p_T -differential anisotropic flow suggests an existence of several regions in the transverse momentum space with distinctly different underlying physics. It is now widely accepted that at $p_T < 1-2$ GeV/c the flow pattern is mostly determined by hydrodynamical flow exhibiting typical “mass splitting” [16]. At large transverse momenta, $p_T > 10$ GeV/c, the anisotropy is believed to be defined by the jet quenching mechanism. One would expect very little particle type dependence in this region, but unfortunately there exists no calculations for that. The intermediate p_T region is less understood. It has been observed that in this region all baryons have similar flow which differs from meson flow approximately in a 3:2 ratio. Such a scaling finds a natural explanation in the quark coalescence picture, the so-called Number of Constituent Quark (NCQ) scaling [17]. The exact boundaries, where this picture is valid, if at all, is not exactly known. As the quark anisotropic flow and hadronization via coalescence means the system being in a deconfined stage, the observation of such a scaling is very important.

Figure 2 presents the ALICE results on identified particle flow, where both, p_T and v_2 are scaled by the number of constituent quarks. Remarkable is the flow of ϕ -meson, which exhibits even smaller v_2 than expected mass dependence at low transverse momenta, but scales very much as other mesons at large p_T . One can judge how well the NCQ scaling holds from the right panel of Fig. 2. In the range $p_T/n_q > 1$ GeV/c the scaling seems to hold at the level of about 10-15%. For a more detailed discussion of the anisotropic flow of identified particles and comparison to hydrodynamic models, see [13].

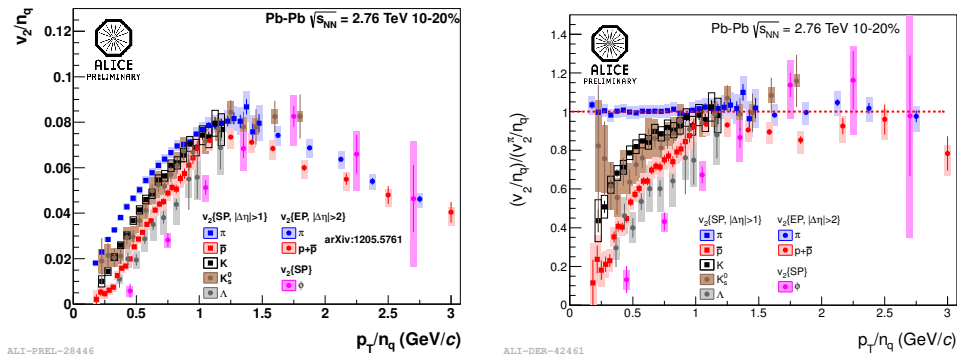


Figure 2: (Left panel) Identified particle elliptic flow scaled with the number of constituent quarks. (Right panel) the same data divided by the polynomial fit to the pion elliptic flow.

3. Understanding flow fluctuations

The anisotropic flow measurements performed by ALICE with both two- and many-particle cumulant methods in wider pseudorapidity regions and at large transverse momenta allow unprecedented tests of the role of flow fluctuations. The flow fluctuations, believed to originate in the fluctuations in the initial geometry, can be estimated from the difference in $v_n\{2\}$ and $v_n\{4\}$ [18]. The results are presented in Fig. 3. Flow fluctuations are found almost independent on pseudorapidity at all centralities and very similar at different transverse momenta up to $p_T \sim 10$ GeV/c. The uncertainties are too large at larger transverse momenta, where the effect of fluctuations might be small. A similar conclusion on p_T extent of flow fluctuations can be drawn from the comparison of v_4 measured with respect to the second and fourth order event planes, which become similar at $p_T > 10$ GeV/c.

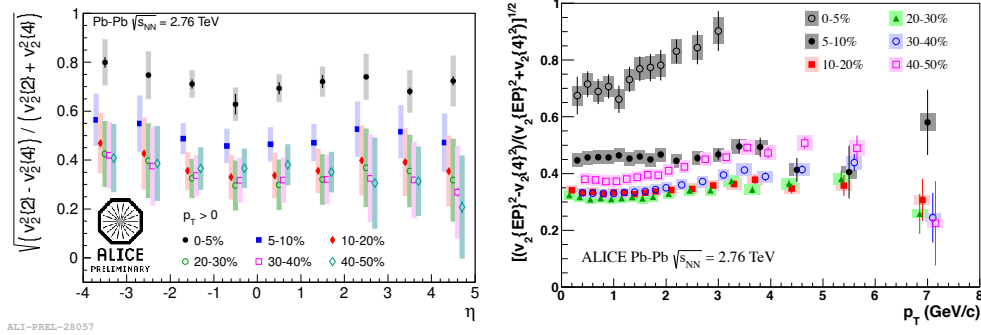


Figure 3: Relative flow fluctuation as a function of transverse momentum (left panel) and pseudorapidity (right panel) for different collision centrality classes.

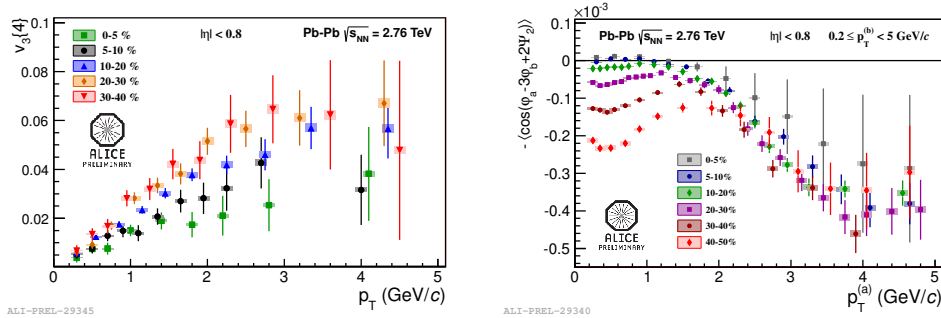


Figure 4: p_T -differential triangular flow from 4-particle cumulant measurement (left panel) and dipole flow from 3-particle cumulants (right panel).

Thanks to the high multiplicity of Pb-Pb collisions at the LHC and to the large recorded sample of events, precise measurements of multiparticle correlations and investigation of the nature of flow fluctuations can be performed in detail. An example is presented in Fig. 4 (left panel) where the differential triangular flow is measured with the 4-particle cumulant method (for the average flow results as a function of centrality, see [19]). Figure 4 (right panel) presents the

results obtained with 3-particle, mixed harmonic correlator as a function of the transverse momentum of first harmonic particle. The correlation between the so-called dipole flow (originating in dipole like density fluctuations), the second harmonic, and the third harmonic event planes has been suggested in [26]. The measurements, though qualitatively similar to theoretical expectations at lower transverse momenta, are quite different from predictions at higher momenta. The origin of a striking similarity in results for different centralities at $p_T > 2$ GeV/c is not clear at the moment. More discussion of the results obtained with many-particle cumulants can be found in [19].

4. Charge dependent correlations and the chiral magnetic effect

Charge dependent correlations, and in particular the charge dependent correlations relative to the different harmonics event planes are of great interest as those could reveal the phenomenon of the charge separation along the magnetic field, usually referred to as the chiral magnetic effect [9]. If observed it would manifest the local parity violation and directly demonstrate the important role of instantons and sphalerons, topologically nontrivial solutions of QCD. The ALICE Collaboration recently measured 2-particle charge dependent correlations relative to the second order reaction plane. The results, see the p_T -average correlations in the left panel of Fig. 5, are qualitatively consistent with expectations from the chiral magnetic effect. These correlations are also found to be remarkably similar in strength to those measured at RHIC.

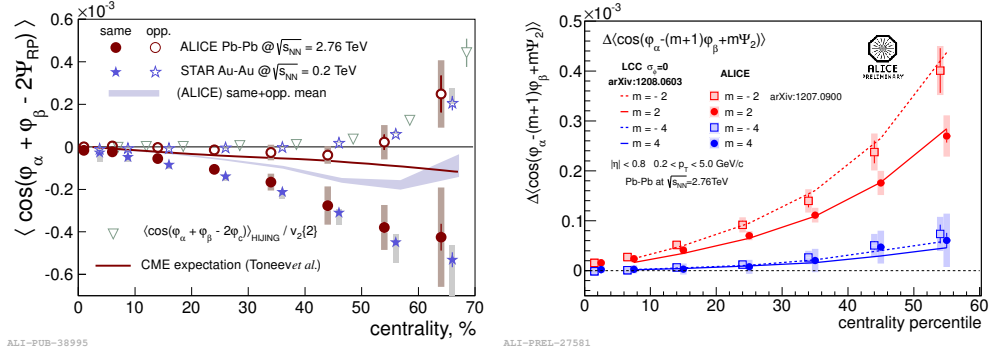


Figure 5: (Left panel) Same- and opposite-sign azimuthal correlations relative to the second order event plane, and (right panel) the charge dependent part of several higher moments of the azimuthal correlations compared to the blast wave model calculations.

It is important to note that the observable used for this measurement is parity even and the results may contain (or even be dominated by) correlations not related to the parity violation. Although at present neither event generator can explain these results, the blast wave model calculations including local charge conservation (at freeze-out) seem to be able to explain most of the charge dependent part of the measured correlations [21]. To investigate the effect of local charge conservation in more detail, the ALICE Collaboration has measured several new correlations, some of which are presented in Fig. 5 along with results of the recent blast wave model simulations [22]. The agreement with the model is very good, indicating that the local charge conservation likely plays an important role in forming such correlations. Note however that the local charge conservation, at least as included in these blast wave simulations affects only opposite charge correlations and has to be combined with some additional mechanism in order to

be consistent with data which exhibits very small opposite charge correlations with almost the entire charge dependent part coming from the same charge correlations.

Further insights in the nature of correlation can be obtained with differential studies, an example of which is shown in Fig. 6. Note a possible change in sign in differential correlations versus $\Delta\eta$. It could indicate that the $\Delta\eta$ correlations reported in [10] for the $\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle$ correlator might not go to zero at large $\Delta\eta$ as originally thought, but only change sign. The measurements at larger $\Delta\eta$ would be very desirable. More details on ALICE measurements of the charge dependent correlation can be found in [23].

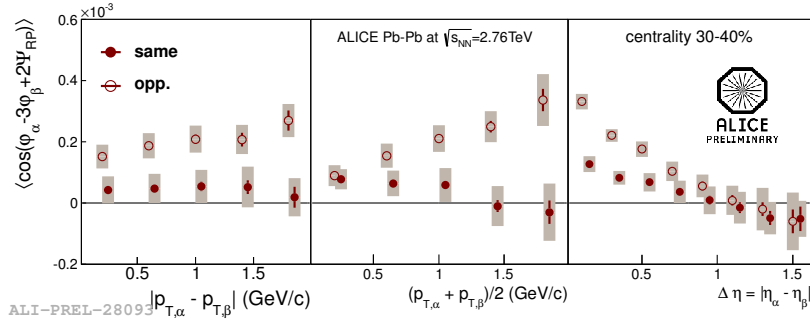


Figure 6: Charge dependent correlator $\langle \cos(\phi_\alpha - 3\phi_\beta + 2\Psi_{RP}) \rangle$ as a function of the two particle momentum difference, momentum sum, and pseudorapidity separation.

Another measurement that can clarify the origin of the charge dependent correlations and the role of the local charge conservation was suggested in [24]: the correlations measured with respect to the fourth harmonic even plane should not contain any contribution from the CME effect but it should include the effect of local charge conservation. The correlations due to the local charge conservation in this case are expected to be somewhat smaller in magnitude as the fourth harmonic flow is not that strong as the elliptic flow. The results of such measurements are presented in Fig. 7 with charge dependent part shown in the right panel. The correlations relative to the fourth harmonic event plane are very weak and suggestive of small contribution from local charge conservation but the detailed blast wave simulation has to be performed to draw more definite conclusion from this measurement.

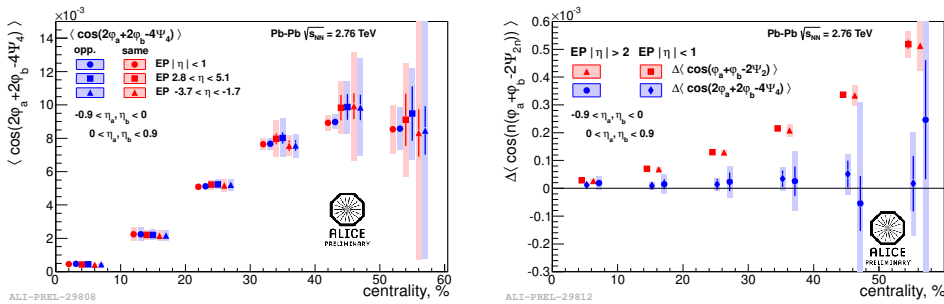


Figure 7: (Left panel) Charge dependent correlations relative to the fourth harmonic event plane as a function of centrality. (Right panel) Comparison of the charge dependent part of the correlations with respect to the second and fourth harmonic event planes.

5. Event shape engineering

During the last few years our understanding of the importance of the initial geometry fluctuations and their role in forming odd harmonic anisotropic flow and all flow fluctuations has significantly improved. The results of measurements and simulations using Monte Carlo Glauber model, suggest that flow fluctuations are very large. This can be used to select events with unusually large or small eccentricities, the technique called the event shape engineering [11]. This technique allows unprecedented studies, for example, of the system with very high density typical of very central collisions, and very large eccentricities as those in peripheral collisions. One should be careful performing the event shape analysis, not to be mistaken with events dominated by nonflow contribution. It was suggested [11] to use event selection (using flow vector magnitude) based on the information from one momentum window (subevent) and perform a physical analysis in a different momentum window (subevent) which is expected to have small correlations via nonflow to the first one.

In ALICE we use an event selection based on the flow vector magnitude measured in one of the VZERO detectors and perform the analysis using the TPC. Those detectors are separated by about two units of pseudorapidity which greatly suppresses nonflow correlations between the two [12]. The results of this event shape engineering analysis are presented in Fig. 8, where the left panel indicates the cuts used to select events with large and small flow (eccentricity) values. The right panel shows the results obtained with the corresponding event selection, in this case the ratio of elliptic flow as a function of transverse momentum in events with large and small flow. Approximately constant ratios indicate that the effect of flow fluctuations on particle production at different transverse momenta is very similar up to $p_T \approx 10$ GeV/c, which is in agreement with earlier conclusions made from comparison of the two- and four-particle cumulant measurements. More details on this measurement can be found in [20]; for the study of p_T spectra modification in events with large or small flow, see [25].

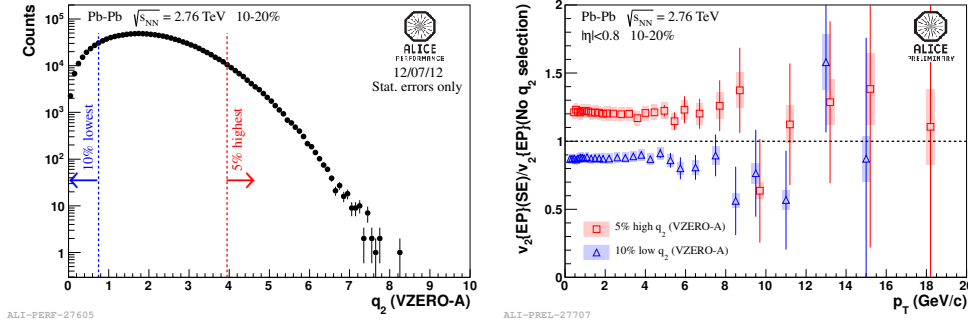


Figure 8: (Left panel) Flow vector magnitude distribution and cuts used to select events with large and small flow. (Right panel) The ratio of flow measured for selected events to that without event shape selection as a function of transverse momentum.

6. Summary

The ALICE Collaboration has significantly extended its flow measurements toward higher transverse momentum and larger pseudorapidity coverage. It presented numerous results on

anisotropic flow up to $p_T \approx 20$ GeV/ c as well as average elliptic and triangular flow in the region $|\eta| < 5$. Based on those measurements we find that the flow fluctuation effect is very similar at all pseudorapidities and up to transverse momenta of about 10 GeV/ c . It was found that the difference between proton and pion elliptic flow extends to about the same transverse momentum, possibly indicating that this might be the region where jet physics starts to completely dominate all features of the particle production. The identified particle flow in the low transverse momentum range is well described by the hydrodynamical model (including hadronic afterburner), while in the intermediate p_T region, often associated with the quark coalescence picture, the NCQ scaling holds at the 10-15% level. Remarkable is the elliptic flow of ϕ -meson which clearly follows the mass splitting in the low transverse momentum region and follows other meson flow at higher transverse momentum. The ALICE Collaboration has presented a suit of charge dependent azimuthal correlations which might significantly clarify their nature, the role of the local charge conservation and possible contribution to these correlations from the chiral magnetic effect. Finally, we have demonstrated that a new promising technique, the event shape engineering, is fully capable of producing new and important results.

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