PROCEEDINGS OF SCIENCE

Flow and correlations measurements in small and large systems

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Measurements of flow coefficients and correlations between different types of particles are used to characterise the properties of the quark–gluon plasma created in heavy-ion collisions. Moreover, these precise measurements became a key observable in understanding the possible origin of the collective-like behaviour in small collision systems. Recent results of flow and correlations measurements of light and heavy hadrons, in pp, p–Pb, and Pb–Pb collisions are presented.

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1. Introduction

Under the extreme conditions created in heavy-ion collisions, like high temperature and pressure, the quark and gluon degrees of freedom manifest in a deconfined state of matter, quark–gluon plasma (QGP). Multiple effects of the QGP, like collective expansion, strangeness enhancement, jet quenching, or hadron energy loss [1], are measured at the LHC. These provide quantitative description of the QGP properties. Measurements in smaller collision systems, like p–Pb and pp collisions, reveal similarities with heavy–ion collisions. Moreover, a continuous evolution of some observables, which are interpreted as the QGP manifestation in the final state, with multiplicity from small to large collision systems is observed. This points to a possible creation of a small QGP-like system also in small collision systems with large final state multiplicity.

The measurement of the flow coefficients and correlations between different types of particles can help not only to better constrain the QGP properties in heavy-ion collisions, such as the viscosity or the hadronisation time of different particle species, but also to investigate the origin of the collective-like behaviour and its limits in the small collision systems.

2. Results

Balance functions (BFs), which measure the probability that a charged particle produced in the collision will be accompanied by another particle of opposite charge somewhere in the phase space, serve as a tool for studies of particle production mechanisms, transport of balancing charges, and production time [2]. The BFs of unidentified charged particles and pions, measured by the CMS and ALICE Collaborations, respectively, show a similar narrowing for the near-side peak from peripheral to central Pb–Pb collisions. This observation is consistent with radial flow effects and the two-stage quark production scenario [2, 3]. Qualitatively similar narrowing was observed also in p–Pb collisions, suggesting the presence of the radial flow in small collision systems [3].

Many different measurements of anisotropic flow coefficients and their correlations have showed that QGP behaves as an almost perfect fluid with small shear viscosity per one unit of entropy density, η/s. A specific type of transverse momentum differential two-particle correlation function, G_2 (defined in Ref. [4]), has been shown to be sensitive to η/s. The ALICE Collaboration performed a systematic study of the azimuthal and longitudinal width of both, charge dependent and charge independent G_2, as a function of the charged-particle multiplicity in pp, p–Pb, and Pb–Pb collisions. A continuous azimuthal narrowing with multiplicity of both correlators is observed, which is consistent with $\langle p_{\rm T} \rangle$ increase with multiplicity in all collision systems. In Pb–Pb collisions, an around 24% increase of the longitudinal width of the charge independent correlator with multiplicity is observed, consistent with viscous effects of long-lived QGP with small η/s. On the other hand, it undergoes a slight narrowing in pp and a slight broadening in p–Pb collisions in the longitudinal direction, suggesting that these systems may not live long enough for viscous forces to cause the broadening, even in a case that QGP would be formed [4]. Another explanations are explored by the comparisons with various models without QGP-like medium, but none of the considered models is able to give a proper description of the azimuthal and longitudinal widths of both correlators.

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In heavy-ion collisions, the initial spatial anisotropies are translated via interactions during the system evolution into the anisotropies in the final particle distributions in the momentum space. These anisotropies are measured by the coefficients in the Fourier expansion of the distribution of the azimuthal angle of particles with respect to the symmetry plane. The second coefficient, v_2, is called elliptic flow and is caused by the increased pressure in the in-plane direction due to the almond shape of the overlap region of the two colliding nuclei. The coefficients of higher order are rather generated by the fluctuations of the initial state geometry. The medium expansion is affecting mostly the produced soft particles. Nevertheless, the ATLAS Collaboration observed an increase of the elliptic flow coefficient with decreasing centrality from central to semicentral collisions for particles with p_{T} up to 200 GeV/c, while v_3 and v_4 of these particles is compatible with zero [5]. This can be explained by the different path length connected to the overall elliptic geometry, which the high momentum particles need to pass through the QGP. While the distance in the in-plane direction is shorter, the path is longer in the out-of-plane direction. Thus, the hard particles can interact longer with the medium and loose more energy leading to the observed anisotropy. This explanation is supported also by the measurement of flow coefficients of dijets in Pb–Pb collisions performed by the CMS Collaboration, shown in Fig. 1.

Non-zero flow coefficients were observed in many measurements in small systems [10, 11]. The origin is still not clear and in order to investigate the hard fragmentation contribution to v_2 in pp collisions, the ATLAS Collaboration performed a measurement of the elliptic flow coefficient for inclusive, jet, and out-of jet particles [7]. The results are summarised in Fig. 2. It can be observed that while the v_2 of jet particles is compatible with zero, the elliptic flow coefficient for inclusive and out-of-jet particles with p_{T} up to 7 GeV/c is non-zero through a wide range of multiplicities. Moreover, a presence of a high-p_{T} jet in a collision does not affect the magnitude of v_2. These observations suggests that the v_2 in small collision systems is dominated by soft particles and no indication of (path-length) energy loss of hard particles is present in contrary to Pb–Pb collisions.

Previous measurement covers rather pp collisions with high final state multiplicities. In order to identify the minimal size of a collision still showing signs of collectivity, the ALICE Collaboration performed a measurement of the near-side ridge yield visible in long range correlation functions, which is manifestation of the collective flow. The measurement shows non-zero ridge yield down to very low multiplicities. Moreover, from the comparison with the same observable measured in

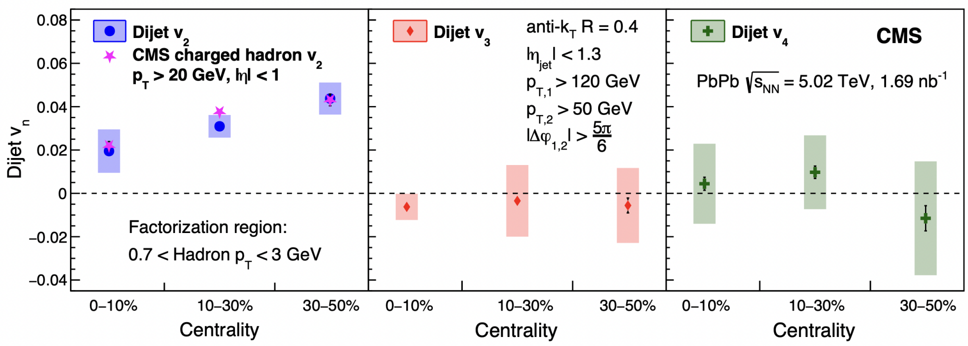

Figure 1: Dijet v_2 (left), v_3 (middle), and v_4 (right) as a function of collision centrality measured in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV [6].

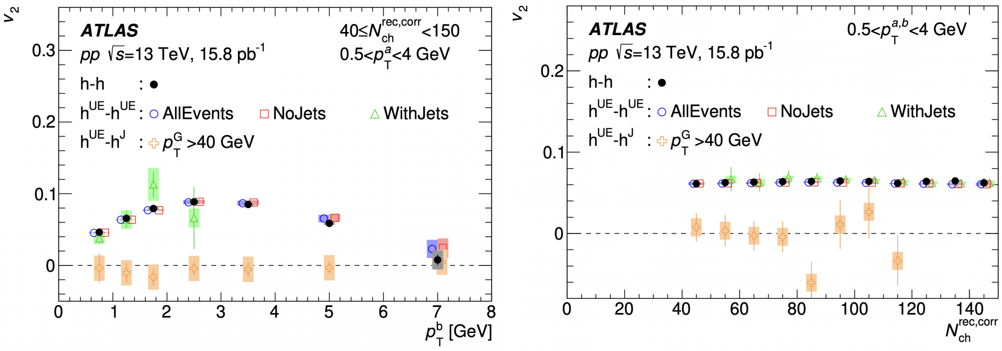

Figure 2: Elliptic flow coefficient measured in pp collisions for jet and underlying event particles as a function of p_{T} (left) and event multiplicity (right) [7].

e^+e^- annihilations at similar multiplicities (Fig. 3), it can be concluded that additional processes must occur in hadronic collisions, as the ridge yield is substantially larger in pp collisions.

3. Conclusion

The correlation and flow measurements continue to bring insights into the understanding of both, small and large, collision systems. In Pb–Pb collisions, the G_2 measurement confirms a creation of a deconfined matter with small η/s while the BFs support the two-stage quark production scenario with a radial expansion in between. Flow coefficient measurements of jets and jet particles show that their elliptic flow coefficient is induced by the path length dependent energy loss while they are not sensitive on the higher order fluctuations. A collective expansion scenario in small systems is supported by the narrowing of the peak width of BF and G_2 correlation functions of low p_{T} hadrons, non-vanishing v_2 which becomes compatible with zero for jet particles, and a significantly higher long-range ridge yield than the one measured in e^+e^- collisions at the same multiplicity. Nevertheless, viscous forces seem not to have enough time to develop and affect the G_2^{CI} longitudinal width in the same manner as in Pb–Pb collisions.

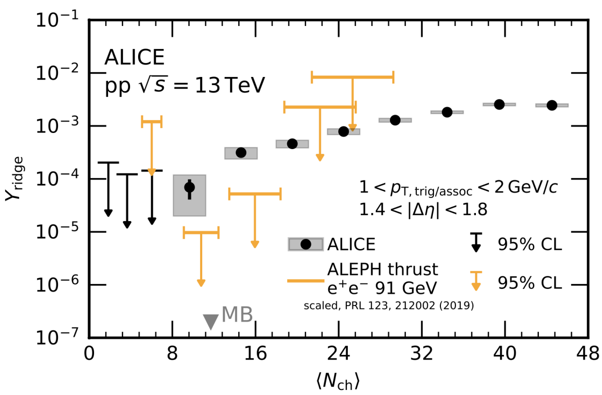

Figure 3: Near-side ridge yield measured in low multiplicity pp collisions at $\sqrt{s}$ = 13 TeV compared with ALEPH e^+e^- results [9].

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