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Triangular flow of negative pions emitted in PbAu collisions at top SPS energy

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Abstract. The CERES/NA45 experiment measured for the first time triangular flow (v_3) as a function of transverse momentum (p_T) of negative pions emitted around midrapidity in central PbAu collisions at $\sqrt{s_{NN}}$= 17.3 GeV. The v_3, determined within 0.05 < p_T < 2 GeV/c, is corrected for the HBT effects. It is shown that the triangular flow magnitude is smaller by a factor of about 2 than the one measured by the PHENIX experiment at RHIC and the ALICE experiment. Within the analyzed centrality bins, the v_3 does not shows significant centrality dependence. The obtained $v_3(p_T)$ dependence is well described by a viscous hydrodynamic calculation combined with an UrQMD cascade model in the late stages of the collision.

1 Introduction

One of main observables used to study properties of hot and dense systems created in heavy-ion collisions is the single-particle azimuthal anisotropy. In an ideal circle-like geometry of the collisions of two nuclei, the overlapping region has an almond shape which manifests itself in the appearance of the elliptic flow anisotropy [1] driven by strong interactions among constituents of the expanding medium. If the initial-state energy density would be smooth in the transverse plane then only the elliptic flow, v_2, would appears. In a real collision positions of the colliding nucleons fluctuate. As a consequence, beside the event plane derived from the elliptic anisotropy appear event planes of higher-order symmetries and thus also higher-order anisotropies may appear [2]. These higher-order azimuthal anisotropies have been measured at the Relativistic Heavy Ion Collider (RHIC) [3–5] and at the Large Hadron Collider (LHC) [6–8]. The most famous higher-order harmonic, v_3, is called the triangular flow.

Contrary to the elliptic flow which strongly depends on the collision centrality, the triangular flow is nearly independent of centrality. Except for the most central collisions [9], the differential $v_2(p_T)$ at SPS [10–12], although similar in shape to those obtained at the RHIC and LHC experiments, stay below ideal hydrodynamics calculations [13]. This can be explained by insufficient number densities at very early collision stages [14] and strong dissipative effects at the late hadronic stages [15–18].

The negative pions' differential $v_3(p_T)$ measurement from central PbAu collisions at the top SPS energy is presented in this contribution. The results are compared with those from the PHENIX and STAR experiment at RHIC and the ALICE experiment at LHC and also with a hydrodynamics

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calculation coupled with a UrQMD cascade model [19] to describe the late stages. These findings might shed some light on the late stage of collective expansion.

2 Experment and data used

About 30 millions of rather central PbAu collisions at the top SPS energy were collected. CERES detector worked in the magnetic filed of 0.5 T which enable precise measurement of particle momenta with the relative momentum resolution between 2% and 8%. The pseudorapidity[1], η, coverage is close to mid-rapidity (y_{mid} = 2.91). This, together with a full azimuthal, ϕ, coverage well suits for the flow study. In this analysis only negative pions are used. They are identified using the differential energy loss dE/dx along their tracks in the radial-drift Time Projection Chamber (TPC). A mixture of three centrality triggers has been used for data collection in the range 0 – 30% of σ/σ_{geo} with an average centrality of 5.5%. A detailed description of the CERES detector is given in [20].

3 Analysis and results

The third-order harmonic coefficient, v_3, of the azimuthal particle distribution is measured with respect to Ψ_3, the azimuthal angle of the 3rd-order participant event-plane. The angle Ψ_3 is determined as:

$$\Psi_3 = \frac{1}{3} \arctan \frac{\sum_{i=0}^{n} w_i(p_{Ti}) \sin(3\phi_i)}{\sum_{i=0}^{n} w_i(p_{Ti}) \cos(3\phi_i)} \tag{1}$$

The ϕ_i in Eq. (1) denotes the azimuthal angle of the i-th particle out of n used for event-plane reconstruction, and $w_i(p_{Ti}) = p_{Ti}$ are weights used to increase the event-plane resolution. As in [9], the ϕ coordinates are divided into 100 adjacent equal slices spanning the full azimuth. In this way the trivial autocorrelation effect is avoided, and up to some extent the contribution from short-range correlations are removed. The local detector inefficiency are corrected by applying a shifting and flattening procedure to ensure an azimuthally isotropic event-plane distribution in the laboratory system. The azimuthal anisotropy of particle is then measured with respect to the 3rd-order event plane constructed in the above described way. The correction factor, calculated as $(2\langle\cos[3(\Psi_3^{(a)} - \Psi_3^{(b)})]\rangle)^{-1/2}$ from the two nonadjacent sliced subevents, a and b, is used to compensate the observed raw v_3 for finite event-plane resolution. Depending on multiplicity, the value of the correction factor goes from 8 till 11.

As only negative pions are used in the analysis, a spurious triangular flow appears as a consequence of the Hanbury Brown & Twiss effect (HBT) of identical bosons. The HBT effect produces a space-momentum correlation between two identical bosons when $|\vec{p}_2 - \vec{p}_1| \leq \hbar/R$. In the central PbAu collisions R is about 7 fm and thus $\hbar/R \approx$ 30 MeV/c. This is much smaller than the mean pion transverse momentum $\langle p_{\mathrm{T}}\rangle \approx$ 400 MeV/c. The HBT correlation is short range also in azimuth, and it becomes significant only if $|\phi_1 - \phi_2| \leq \hbar/Rp_{\mathrm{T}} \simeq$ 0.1. As identical bosons are used in this analysis, the correlation is positive like flow itself, and therefore the HBT correlations produce a spurious flow.

In order to remove the non-flow HBT contribution, the standard Bertsch-Pratt parametrization and procedure described in [21] has been used. The size of the corrections applied to the raw $v_3(p_T)$ shown in Fig. 1 is large at low p_T, but decreases quickly with an increase of p_T. The systematic uncertainty

[1]Pseudorapidity η is defined as $-ln\tan(\theta/2)$ where θ is the polar angle.

in the determination of the HBT contribution is derived by varying all source parameters by $\pm 1\ \sigma$ together and independently, and then taking the error of the mean of the resulting distribution as the systematic uncertainty for each p_T bin. It has the biggest size (0.4%) just in the p_T region where the HBT effect is largest, and becomes negligible for $p_T > 0.8$ GeV/c. The final, HBT-corrected v_3 increases roughly linearly, starting from zero at transverse momenta close to zero up to 0.04 at p_T around 2 GeV/c.

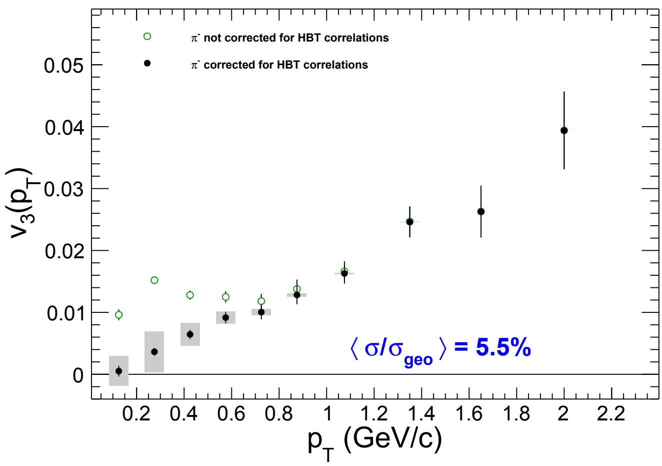

Figure 1. The v_3 as a function of negative pion p_T in PbAu collisions at $\sqrt{s_{NN}}$ =17.3 GeV. Averaged centrality is 5.5%. Open green circles denote v_3 results before, while closed circles those after correcting for the HBT effect. Statistical uncertainties are represented with the error bars, while systematic ones are indicated by gray boxes.

In Fig. 2 are compared CERES v_3 results with those from the PHENIX and ALICE Collaborations at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV and $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV [3, 22], respectively. The PHENIX and ALICE results are limited within the p_T range accessible to CERES and at comparable centrality. The Fig. 2 shows that the $v_3(p_T)$ at RHIC and at LHC energy are nearly equal [23]. In contrast, the $v_3(p_T)$ at the top SPS energy reach only about one half of the corresponding values at LHC energy. The p_T range of the analyzed SPS data is small with respect to that covered by ALICE data [22], and within this restricted p_T range the data suggest a linear $v_3(p_T)$ dependence starting from zero.

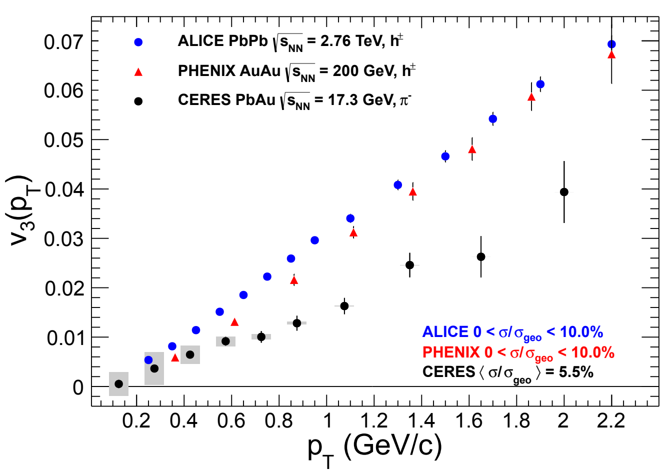

Figure 2. Comparison of negative pions' $v_3(p_T)$ measured at $\sqrt{s_{NN}}$ = 17.3 GeV PbAu collisions (CERES, solid black circles) with those from AuAu collisions at $\sqrt{s_{NN}}$ = 200 GeV (PHENIX, red triangles) and from PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV (ALICE, solid blue circles) at comparable centrality. Statistical uncertainties are represented with the error bars, while systematic uncertainties of the CERES results are indicated by gray boxes.

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The ALICE uses large gaps in η between tracks used to measure v_3. In this way non-flow contributions from jet fragmentation have been effectively suppressed. It is shown in [24] that in very central PbAu collisions at SPS energies the total jet yield is about 0.02 per event which is more than an order of magnitude smaller with respect to the corresponding yield at the LHC energy, while the charged particle $dN/d\eta$ is only 4 times smaller [25]. This is quite fortunate, since, due to the limited η acceptance, was impossible to employ a pseudo-rapidity gap in CERES data.

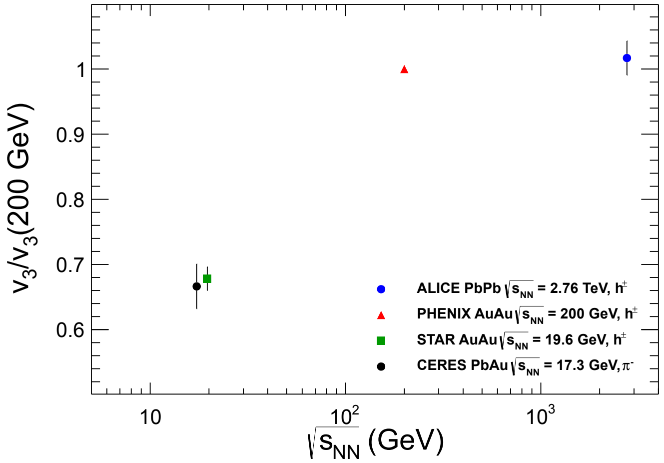

Figure 3. Ratios of the v_3 taken at different collision energies with respect to the v_3 measured in PHENIX AuAu collisions at $\sqrt{s_{NN}}$ = 200 GeV. The v_3 are obtained by integrating the corresponding differential $v_3(p_T)$ over $0.3 < p_T < 2.1$ GeV/c. The data from ALICE, PHENIX and STAR were taken from [22], [3] and [5] respectively.

The p_T-integrated ($p_T > 0.2$ GeV/c) two-particle Fourier coefficients, V_n i.e. the squared v_3 magnitude, as a function of $\sqrt{s_{NN}}$ energy have a shallow minimum between 10 and 20 GeV [5]. The ratio between the STAR $v3$ at 19.6 GeV, which is quite close to the top SPS energy of 17.3 GeV/c, with respect to the v_3 measured at 200 GeV is about 0.63. In Fig. 3 are shown corresponding ratios for 17.3, 19.6, 200 and 2760 GeV/c where in all cases the p_T integration has been done within the range $0.3 < p_T < 2.1$ GeV/c. The v_3 ratio between the top SPS and the top RHIC energy is about 0.66 which is quite close to the one found in [5].

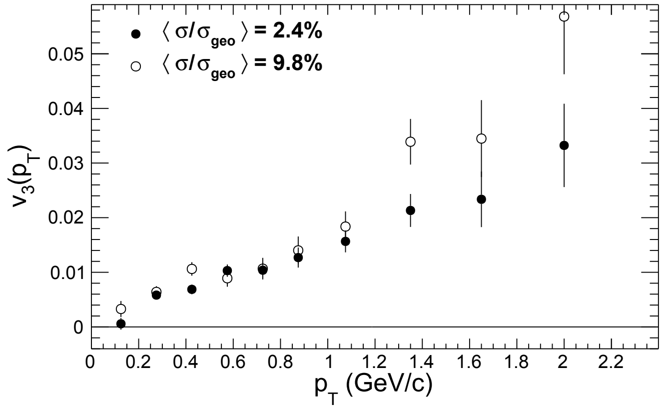

Figure 4. The p_T dependence of the v_3 measured in top-central (closed circles) and mid-central (open circles) PbAu collisions at $\sqrt{s_{NN}}$ = 17.3 GeV.

In difference to the elliptic flow, which reflects the initial anisotropy of the fireball and thus shows a strong centrality dependence (see Fig. 24 in [9]), triangular flow appears entirely from the initial-state fluctuations. In Fig. 4 is shown that the v_3 magnitude is nearly equal for mid-central and top-central collisions, with mean averaged centralities of 2.4% and 9.8%, respectively. A rather weak centrality dependence has also been reported by ALICE [22, 23] where a very slight increase of v_3 with centrality has been observed.

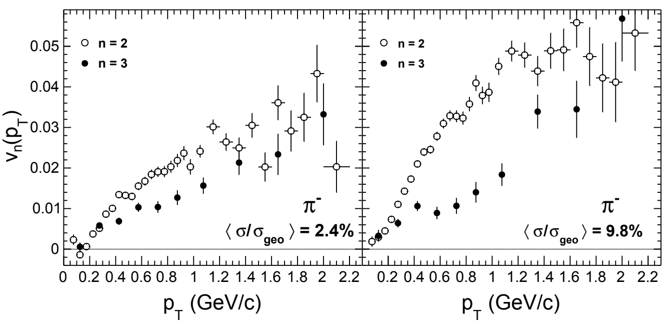

Figure 5. The comparison between the $v_2(p_T)$ (open circles) and $v_3(p_T)$ (closed circles) for top-central (left panel) and mid-central (right panel) PbAu collisions at $\sqrt{s_{NN}}$ = 17.3 GeV.

The difference between the centrality dependence between the elliptic and the triangular flow can be seen also from the corresponding p_T-dependencies which are shown in Fig. 5.

The hybrid models, which combines the relativistic hydrodynamics with transport models, have been used for description of heavy-ion collisions at ultra-relativistic energies. The ideal fluid dynamics is used to describe the evolution of the hot and dense quark-gluon plasma, while hadron transport to describe the late sparse hadron gas. The model calculations [19] shown in this analysis are performed using the vHLLE viscous hydrosolver [26] combined with UrQMD hadron cascade [27]. Within it, kinetic and chemical freeze-outs are described dynamically by the UrQMD hadron cascade without a unique freeze-out temperature. The transition from fluid to cascade part, so called the 'particlization' [19], is set to take place on a constant energy density surface with ϵ = 0.5 GeV/fm^3. But, as the net baryon density is not uniform on such a surface, this density does not correspond to a single temperature. Within the chiral model of the Equation of State (EoS) used in this hydrodynamics description, the value of the switching density ϵ_{sw} corresponds to $T \approx 175$ MeV at $\mu_B = 0$. The rest of parameters used in the model are the two Gaussian radii for the initial distribution of energy, and the starting time for the hydrodynamic phase. Their values, together with the value of the switching density, $\epsilon_{sw} = 0.5$ GeV/fm^3, are based on reproduction of the data in collisions at RHIC energies, and are kept unchanged at the SPS for simplicity. In Ref. [19], the authors of the hybrid model investigated parameter dependence of the model results in the case of 0-5% centrality AuAu collisions at $\sqrt{s_{NN}}$ = 19.6 GeV. It is shown that the model results change less than 10% when the parameters of the model are varied by 10%. Within the model [19] is studied the dependence of the elliptic and triangular flow magnitude on the collision energy.

In Fig. 6, the comparison between the predictions from this hydrosolver+UrQMD model and our $v_3(p_T)$ measurement of negative pions in PbAu collisions at $\sqrt{s_{NN}}$ = 17.3 GeV is shown. The model predictions are calculated for hadrons within $0.2 < p_T < 2.0$ GeV/c and $-1 < \eta < 1$, which is very close to the experimental acceptance. The model calculation is performed within the centrality samples which roughly correspond to the experimental ones. The hybrid model predictions are in a rather good agreement with the experimental results, except in the p_T region between 0.3 and 0.6 GeV/c where the model slightly underpredicts the experimental data.

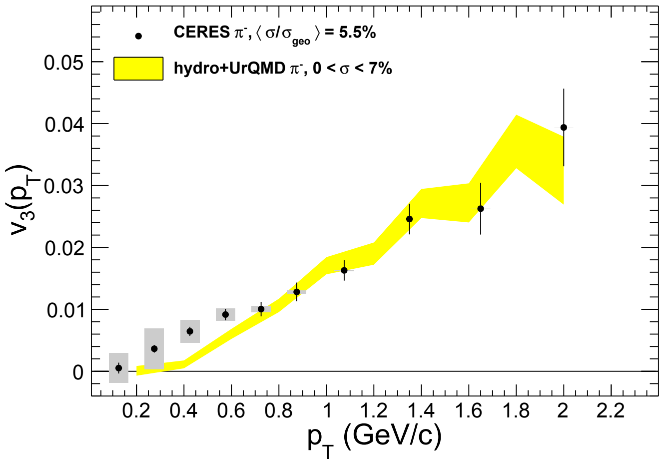

Figure 6. Comparison between the p_T dependence of negative pion v_3 measured in PbAu collisions at $\sqrt{s_{NN}}$ = 17.3 GeV with hydrosolver+UrQMD model predictions. The statistical errors of the model predictions are shown as yellow band. Statistical uncertainties of the experimental results are represented with the error bars, while systematic ones are indicated by gray rectangles.

4 Summary

The triangular flow appears as a hydrodynamic response of the system created in heavy-ion collision to the fluctuation of the positions of the overlapping nucleons at the moment of impact. This is the first differential triangular flow $v_3(p_T)$ measurement at the top SPS energy. The magnitudes of v_3 achieve about one half of the ones measured at the top RHIC and LHC energies. The v_3 measured by CERES at SPS energy of $\sqrt{s_{\rm NN}}$ = 17.3 GeV is similar to the one measured by STAR at RHIC energy of $\sqrt{s_{\rm NN}}$ = 19.6 GeV. The hydrosolver+UrQMD model is able to reproduce the experimental data rather well except in the lowest-p_T region. This comparison could shed some light on the dynamics of the system created in heavy-ion collisions at top SPS energy.

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