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Elliptic flow of charged and strange hadrons in PbAu collisions at 158 AGeV/c measured in CERES experiment

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Abstract. Differential elliptic flow of $v_2(p_T)$ for π^-, K_S^0, p and Λ is measured at center-of-mass energy of $\sqrt{s_{NN}}$=17.3 GeV near the mid-rapidity region in rather central PbAu collisions collected by the CERES/NA45 experiment at CERN. The proton $v_2(p_T)$ is extracted from π^+ sample and particle ratios measured by NA49 experiment adapted to CERES conditions. The proton $v_2(p_T)$ data show a downward swing towards low p_T with excursions into negative v_2 values which was not observed earlier. The results are compared with corresponding measurements performed at NA49 and STAR experiments as well as with theoretical predictions from ideal relativistic hydrodynamics. The obtained results for baryons are below hydrodynamic predictions even at the kinetic freeze-out temperature of T_f=160 MeV which needs introducing of a viscous hydrodynamics at the late hadronic phase.

1 Introduction

The elliptic flow v_2 is characterized by the second harmonic coefficient of the azimuthal particle distribution measured with respect to the event plane [1, 2]. The strong interaction between the constituents of the expanding, hot and dense system crated in the collision of two nuclei converts initial spatial anisotropy into the momentum anisotropy. The evolution of the system could be described by relativistic hydrodynamics [3]. This was interpreted as creation of a locally equilibrated system of strongly interacting quarks and gluons known as Quark Gluon Plasma (QGP). The QGP behaves as a nearly perfect liquid with a very small ratio η/s of shear viscosity to entropy density [4, 5].

2 Experiment

A sample of $\approx$30x10^6 rather central PbAu collisions at $\sqrt{s_{NN}}$=17.3 GeV were collected with the CERES/NA45 detector at the CERN SPS. A few mixed trigger selections gave, in average, centrality of $\langle\sigma/\sigma_{geo}\rangle = 5.5\%$. The detector itself is axially symmetric around the beam direction and covers a pseudorapidity range $2.05 < \eta < 2.70$ close to midrapidity ($y_{mid} = 2.91$) with full azimuthal angle. Thus, it is very suited for elliptic flow studies. The radial-drift Time Projection Chamber (TPC) [6] which is operated inside a magnetic field with maximum radial component of 0.5 T provided a precise measurement of the transverse momentum in the range from 50 MeV/c up to above 4 GeV/c. A detailed description of the CERES experiment is given in [7].

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3 Identification and reconstruction of particles and method used

Ability to measure specific-energy loss sampled along the tracks in the TPC is used for partial identification of charged pion candidates [8]. In the two-dimensional scatter plot in Fig. 1, the measured specific energy loss dE/dx is shown as function of particle momentum p for both negative and positive charges. From the measured differential specific energy loss dE/dx in function of particle momentum, pion candidates were selected within $\pm 1.5\sigma$ band (represented with dashed lines) around the nominal Bethe-Bloch formula. In the case of positive charge, over extended range in momentum, pions are mixed with positive kaons and protons. As one can see in Fig. 1, only at very low momenta (below 1.2 GeV/c), protons are clearly identified by dE/dx. We call them directly identified protons.

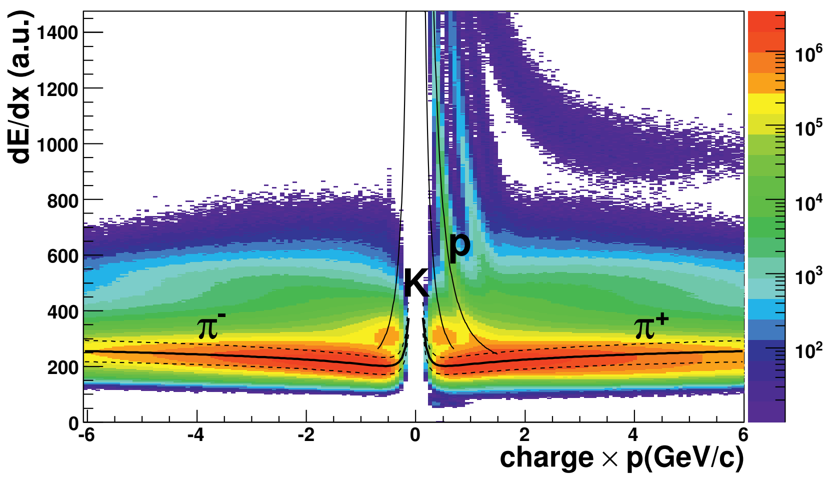

Figure 1. Contour plots of the specific energy loss of charged particles *vs* momentum times charge sign. Full lines show Bethe–Bloch energy loss for pions, kaons and protons. Dashed lines show the applied $\pm$ 1.5σ cut for pion's selection.

The Λ (K^0_S) particles are reconstructed via the decay channel $\Lambda \rightarrow p + \pi^-$ ($K^0_S \rightarrow \pi^+ + \pi^-$). Beside cuts on opening angle and secondary vertex, in order to suppress the contamination of K^0_S (Λ) in the Λ (K^0_S) signal, an Armenteros–Podolanski cut was applied additionaly, admittedly with a considerable loss of signal. More details are given in [8].

The event plane (EP) method is used for the flow analysis itself [2, 9, 10]. The observed anisotropy parameter v_2' is corrected for the finite EP resolution. The EP resolution, $\sqrt{\langle 2cos(2(\Phi_a - \Phi_b))\rangle}$, is calculated using the 2- and 4-subevent method. Here, Φ_a and Φ_b are event plane angles of corresponding subevents a and b. Depending on the centrality, it value goes from $\approx$0.15 to $\approx$0.30. The results are corrected for the quantum HBT effect using the standard procedure described in [11].

4 Results and discussion

In Fig. 2 (left) is shown differential elliptic flow, $v_2(p_T)$, of identified negative pions corrected on K^- mesons admixture as well as on the Bose-Einsten[1] correlation effect. Using the Eq. (1), the

[1] also known as HBT effect

contribution of the negative kaons have been subtracted from the measured elliptic flow of the π^- candidates denoted as "π^-".

$$v_2^{\pi^-} = v_2^{``\pi^-``} + r_{K^-}(v_2^{``\pi^-``} - v_2^{K^-}) \tag{1}$$

Here, r_{K^-} denotes the particle ratio $r_{K^-} = N_{K^-}/N_{\pi^-}$. Based on a similar quark content, as input for $v_2^{K^-}$ we used differential elliptic flow of K_S^0, measured by CERES, which will be presented later. All quantities in Eq. (1) are p_T-dependent. In the same figure is also shown the elliptic flow of π^+ candidates denoted as "π^+". The corresponding v_2 magnitude is smaller with respsect to the one from π^- which indicates that beside presence of a small admixture of K^+ mesons (similarly as in the case of π^-) exists a significant proton admixture in the sample of "π^+" candidates. These distributions,

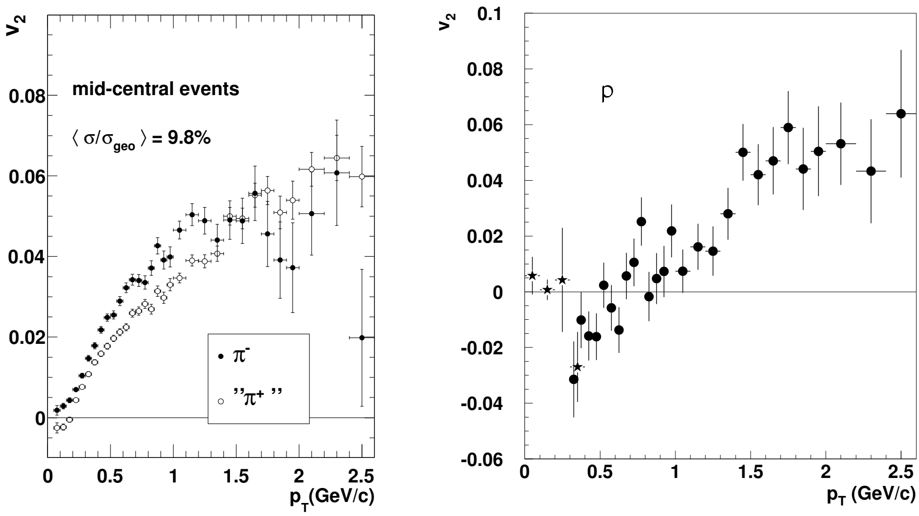

Figure 2. Left: The differential elliptic flow $v_2(p_T)$ of π^+ candidates and identified π^- mesons. Right: The proton elliptic flow $v_2(p_T)$ (closed circles) reconstructed from the flow of π^+ candidates. The first four point (stars) represent the elliptic flow of protons directly identified using the dE/dx.

together with charged particle spectra measured in the CERN NA49 experiment made possible to extract the proton elliptic flow statistically using the following Eq. (2).

$$v_2^{p} = ((1 + r_{K^+} + r_p)v_2^{``\pi^+``} - v_2^{\pi^-} - r_{K^+}(v_2^{K^+}))/r_p \tag{2}$$

Similarly as in the case of Eq. (1), on the r.h.s of Eq. (2) the measured $v_2^{K_S^0}$ is substituted for $v_2^{K^+}$. The particle ratios $r_{K^+} = N_{K^+}/N_{\pi^+}$ and $r_p = N_p/N_{\pi^+}$ specify the contents of K^+ and protons in the "π^+" sample, respectively. In Fig. 2 (right) with closed circles is shown statistically extracted proton elliptic flow, while with stars is shown the elliptic flow from directly identified protons. The first three of these data points, corresponding to directly identified protons, are consistent with zero. The fourth one seems to bridge to the statistically reconstructed points. At low transverse momenta, the proton v_2 magnitude shows an excursion below zero. It takes a minimum near 0.4 GeV/c with $v_2 = -0.0290 \pm 0.0092$ which is 3.2σ below zero. The systematic error near the minimum is about 0.005 and increases up to 0.012 at 2.3 GeV/c.

Elliptic flow of particles with a strange (s) quark, Λ and K_S^0, is measured in a way that these particles are reconstructed differentially in both p_T and in ϕ. The ϕ bins are determined with re-

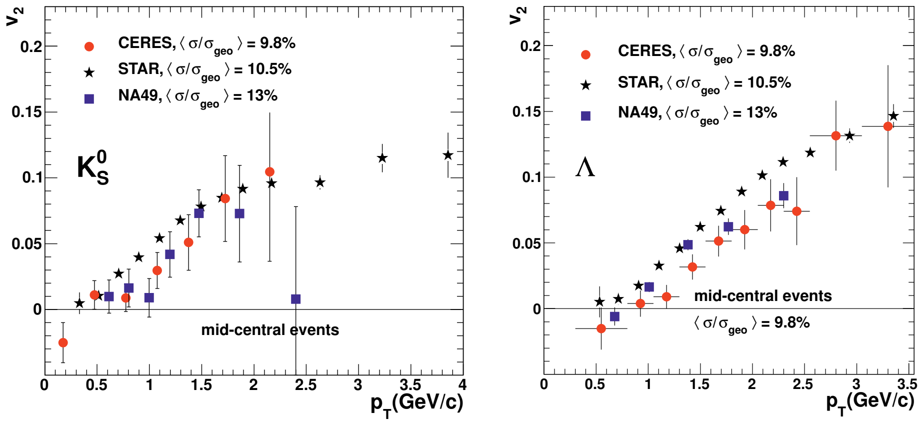

Figure 3. Comparison between the CERES measurements of K_S^0 (left) and Λ (right) elliptic flow to those from the NA49 [12] at SPS and STAR [13] at RHIC. The measurements are performed for similar centralities.

spect to the event plane. In each p_T bin, the obtained distributions $dN_{(\Lambda,K_S^0)}/d\phi$ are then fitted with $c[1+2v_2'cos(2\phi)]$. The v_2 values, corrected for the event plane resolution, are shown in Fig. 3 with red circles. Systematic errors are significantly smaller with respect to the statistical ones. The measurements are performed in mid-central PbAu collisions characterized with $\langle\sigma/\sigma_{geo}\rangle$=9.8%. In the same figure, the obtained results are compared with those from the NA49 experiment (blue squares) extracted from PbPb collisions at the same energy of $\sqrt{s_{NN}}$=17.3 GeV and from the STAR experiment (black stars) at RHIC from AuAu collisions at $\sqrt{s_{NN}}$=200 GeV. One can see a reasonably good agreement between the NA49 and CERES data. In order to compare STAR to CERES results, the former have been rescaled to the centrality used in the CERES experiment. By plotting the STAR v_2 values *vs* centrality for different transverse momenta of Λ and K_S^0 particles, the appropriate scaling factor has been obtained. After rescaling, due to the higher beam energy, the STAR the v_2 values measured at the RHIC are somewhat higher with respect to the ones from the CERES.

The measured elliptic flow values are compared to the results from ideal hydrodynamics calculated by P. Huovinen [14] in 2 + 1 dimensions assuming 1-st order phase transition to QGP at critical temperature of T_c=165 MeV. The calculations were performed for two choices of kinetic freeze-out temperature T_f=120 MeV and T_f=160 MeV.

In Fig. 4 the differential pion elliptic flow is compared with hydrodynamics predictions for the two centrality classes called top- and mid-central collisions. The pion v_2 in the top-central collisions is in a very good agreement with the hydrodynamics results obtained with the 'standard' temperature T_f=120 MeV as it is shown in Fig. 4 (left). In the case of mid-central collisions, Fig. 4 (right), the data up to p_T=1.2 GeV/c suggests position between the two hydro curves and then it saturates. As it is expected, up to p_T=1.2 GeV/c, the pion v_2 stays significantly above the curve which corresponds to T_f=160 MeV. For p_T above 1.2 GeV/c, the data are below hydro curves. These two CERES data sets seem to confirm that departures from ideal hydrodynamics increase with enlarging of impact parameter of the collision. Such behaviour with respect to the ideal hydrodynamics have also been reported from RHIC experiments [13, 15]. It is not known yet whether this indicates incomplete thermalization during primary stages of collision [16, 17], or increasing viscous corrections [18, 19], or a mixture of both.

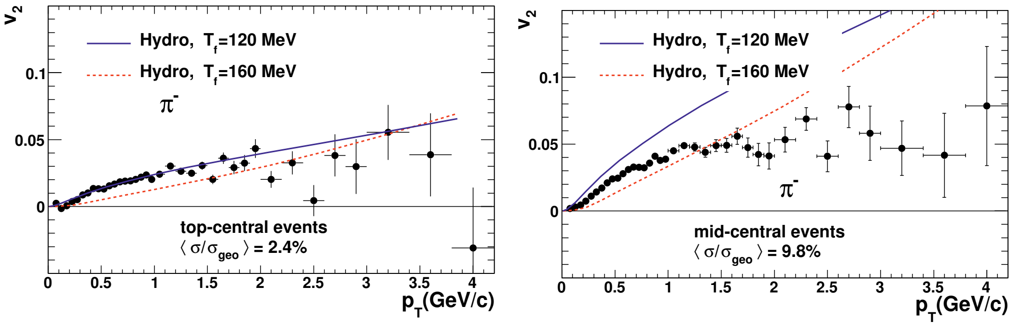

Figure 4. Differential pion v_2 compared to ideal hydrodynamics predictions [14] calculated for two kinetic freeze-out temperatures, $T_f = 120$ MeV (blue solid) and $T_f = 160$ MeV (red dashed). Left: top-central collisions. Right: mid- central collisions. Data are not corrected for K^- admixture.

The comparison between the p_T dependence of the elliptic flow of K^0_S, protons and Λ and ideal hydrodynamics is shown in Fig. 5. While, at p_T<1.1 GeV/c, the $v_2^{K^0_S}$ shows tendency of falling below the hydro curve for T_f=160 MeV (left plot in Fig. 5), it is a fact for baryonic flow (center and right plot in Fig. 5). The majority of proton data points resides below the T_f=160 MeV curve. With decreasing of p_T, hydro curve goes smoothly towards zero while the data continue to fall nearly linearly, crossing the zero around p_T=0.7 GeV/c and reaching minimum of about -0.03 near p_T=0.4 GeV/c. Such early freeze-out would demand an unacceptably large T_f. This observation rather could suggest a suppression mechanism or dissipation which is not included in the ideal hydrodynamics calculation.

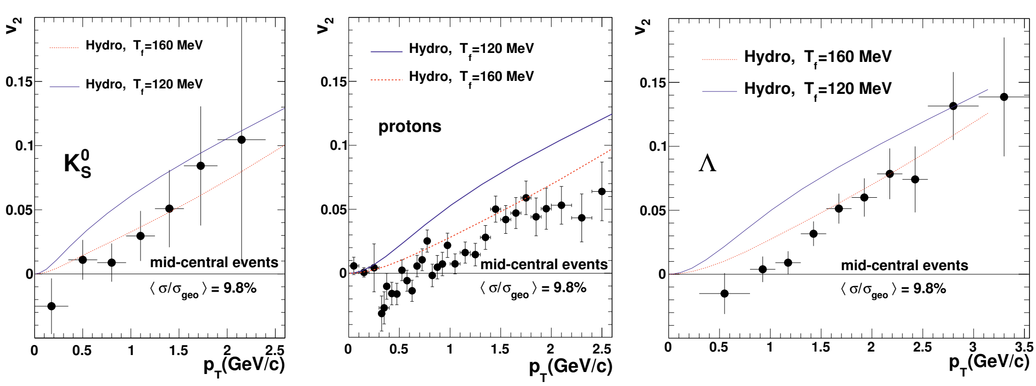

Figure 5. The elliptic flow data of K^0_S (left), protons (middle) and Λ (right) compared to ideal hydrodynamics calculations for $T_f = 120$ MeV (blue solid line) and $T_f = 160$ MeV (red dashed line).

The reduction seen in proton v_2 persist for Λ elliptic flow too (right plot in Fig. 5). The Λ results could be termed 'perfectly in line' with findings for protons. Even an excursion into negative v_2 values as seen for protons would fit into the Λ flow data at very low p_T. The reduction in v_2 with respect to ideal hydrodynamics grow with particle mass. The deviations seen in Λ flow are not stronger than those in proton flow may well be due to the small mass difference: the relative gain from $m(p)$ to $m(\Lambda)$ is only 19%, compared to the steps $m(\pi)$ to $m(K)$ (250%), and $m(K)$ to $m(p)$ (90%); and to limited data precision.

5 Summary

We have presented differential elliptic flow measurements from mid-central PbAu collisions at $\sqrt{s_{NN}}$=17.3 GeV of π^-, K_S^0 and Λ. Additionally, we presented differential elliptic flow of protons directly identified using the dE/dx, as well as elliptic flow of protons reconstructed from impure positive pion sample. The obtained results are compared with those from the NA49 experiment at CERN and from the STAR experiment at RHIC. Also, the results are compared with ideal hydrodynamics predictions. That comparisons show faster decrease of experimental v_2 values towards low p_T, getting stronger for the larger hadron mass. The negative values are reached in proton v_2 which is maybe seen as the most prominent feature of this trend. In general, viscosity in the late hadronic phase suppresses elliptic flow. For protons, the consequences are striking as it could turn their v_2 into negative values. But incomplete thermalization during primary stages of collision could do the same, or a mixture of these two effects.

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References

[1] J-Y. Ollitrault, Phys. Rev. D **46**, 229 (1992)
[2] A.M. Poskanzer and S.A. Voloshin, Phys. Rev. C **58**, 1671 (1998)
[3] P. Huovinen and P.V. Ruuskanen, Ann. Rev. Nucl. Part. Sci. **56**, 163 (2006)
[4] M. Gyulassy and L. McLerran, Nucl. Phys. A **750**, 30 (2005)
[5] T. Hirano, U. Heinz, D. Kharzeev, R. Lacey and Y. Nara, Phys. Lett. B **636** 299 (2006)
[6] D. Adamova, *et al.*, CERES Collaboration, Nucl. Instr. Meth. A **593** 203 (2008)
[7] A. Marín, *et al.*, CERES Collaboration, J. Phys. G **30**, S709 (2004)
[8] D. Adamová *et al.*, CERES Collaboration, Nucl.Phys. A **894**, 41 (2012)
[9] H. Appelshäuser, *et al.*, NA49 Collaboration, Phys. Rev. Lett. **80** 4136 (1998)
[10] G. Agakichiev, *et al.*, CERES Collaboration, Phys. Rev. Lett. **92** 032301 (2004)
[11] P.M. Dinh, N. Borghini, J.-Y. Ollitrault, Phys. Lett. B **477** 51 (2000)
[12] G. Stefanek, *et al.*, NA49 Collaboration, PoS CPD 030 (2006), arXiv:nucl-ex/0611003
[13] M. Oldenburg, *et al.*, STAR Collaboration, J. Phys. G **32** S563 (2006)
[14] P. Huovinen, private communications, 2005
[15] J. Adams *et al.*, STAR Collaboration, Phys. Rev. C **72** 014904 (2005)
[16] U. Heinz and P. Kolb, J. Phys. G **30** S1229 (2004)
[17] T. Hirano, Phys. Rev. C **65** 011901(R) (2002)
[18] D. Teaney, Phys. Rev. C **68** 034913 (2003)
[19] C. Shen and U. Heinz, Phys. Rev. C **83** 044909 (2011)