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Semihard scattering unraveled from collective flow at the SPS

The CERES/NA45 Collaboration

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Abstract. A study of elliptic flow and two-particle azimuthal correlations of charged particles ($0.5 < p_{\mathrm{T}} < 2.5$ GeV/c) and high-p_{T} pions ($1.2 < p_{\mathrm{T}} < 3.5$ GeV/c) in Pb+Au collisions at 158A GeV/c, close to midrapidity, is presented. Elliptic flow (v_2) rises linearly with p_{T} to a value of about 10% at 2 GeV/c. Beyond $p_{\mathrm{T}} \approx 1.5$ GeV/c, the slope decreases and possibly indicates a v_2 saturation at high p_{T}. Two-pion azimuthal anisotropies for $p_{\mathrm{T}} > 1.2$ GeV/c exceed the v_2 values by about 60% in semicentral collisions. This non-flow component is attributed to near-side and away-side jetlike correlations. While the near-side peak remains constant with centrality 0.23±0.03 rad, as expected for fragmentation, the away-side peak experiences broadening and disappears in central collisions.

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1 Introduction

Properties of nuclear matter under extreme conditions created in high-energy heavy-ion collisions have now been studied for about two decades. The systematic measurements performed over a wide range of collision energies ($\sqrt{s}$ = 8–200 GeV) show that the evolution of a heavy-ion collision is dominated by collective effects commonly referred to as *flow*. In a non-central collision, the collective expansion is driven by anisotropic pressure gradients built up during the early stage of the collision, due to the geometrically anisotropic overlap zone of the colliding nuclei. An important signature of this collective expansion is *elliptic flow* [1], which quantifies the magnitude of the azimuthal anisotropy of emitted particles with respect to the reaction plane. At sufficiently large transverse momenta ($p_{\mathrm{T}} > 2$ GeV/c) hard processes are expected to contribute significantly to particle production. Since an event-by-event reconstruction of jets in the high multiplicity enviroment of an A+A collision is very difficult, two-particle azimuthal correlations at high-p_{T} are commonly used to disentangle the hard processes from flow [2]. Particles originating from hard processes will create a double-peak structure in their azimuthal distributions typical for jetlike events on top of the elliptic flow pattern.

We report about elliptic flow and two-pion azimuthal correlations at moderately large $p_{\mathrm{T}} > 1.2$ GeV/c to trace primeval partonic scattering and the onset of thermalization in the medium at the top SPS energy ($\sqrt{s} = 17$ GeV). The results are discussed keeping in mind the p_{T} broadening and jet quenching observed at RHIC ($\sqrt{s} = 200$ GeV). More details can be found in [3–6].

2 Experimental setup and data sample

The data presented in this paper were measured by the CERES experiment in 1996 before the spectrometer was upgraded by a time projection chamber [7]. The spectrometer covers a pseudo-rapidity range $2.1 < \eta < 2.65$, near mid-rapidity, and has full azimuthal acceptance, which is

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Table 1. Definition of the centrality classes

Class	$\langle N_{\mathrm{ch}}\rangle$	$\sigma/\sigma_{\mathrm{geo}}(\%)$	b (fm)	$\langle N_{\mathrm{part}}\rangle$	$\langle N_{\mathrm{coll}}\rangle$
1	147	21 – 26	6.8 – 7.5	159	293
2	198	17 – 21	6.0 – 6.8	189	368
3	234	13 – 17	5.3 – 6.0	222	453
4	273	9 – 13	4.4 – 5.3	255	542
5	321	5 – 9	3.4 – 4.4	289	639
6	395	< 5	< 3.4	336	774

important for studies of azimuthal distributions. Charged particles are reconstructed on a statistical basis combining information from two radial silicon drift detectors (SDD), placed closely behind the segmented Au target, and a multi-wire proportional chamber, behind a magnetic field used for momentum determination. The currents in two superconducting solenoidal coils producing the magnetic field have an opposite sign and result in a sharply located azimuthal kick directly proportional to momentum, leaving the polar angle of a particle track unchanged to the first order. Charged pions are identified and distinguished from electrons by smaller ring radii in two ring-imaging Cherenkov detectors (RICH). The RICH detectors are filled with CH_4 which has a high Cherenkov threshold, $\gamma_{th} \simeq 32$. Consequently pions produce Cherenkov light only if their momentum is above 4.5 GeV/c, offering a natural selection of high-p_{T} pions. Pion momenta are determined from the ring radius measurement due to its higher precision in comparison to the deflection in the magnetic field [3].

We have analyzed $41 \cdot 10^6$ Pb+Au collisions taken at $\sqrt{s} = 17$ GeV. The measured data correspond to the most central 26.0±1.5% of the geometric cross section σ_{geo}. The centrality was determined offline using the number of charged particles, N_{ch}, measured by the SDD's in the pseudo-rapidity range $2 < \eta < 3$. The data sample was divided into six centrality classes, as summarized in Table 1. Each class is characterized by $\langle N_{\mathrm{ch}}\rangle$, the fraction of geometrical cross section $\sigma/\sigma_{\mathrm{geo}}$, the impact parameter b, the number of participants $\langle N_{\mathrm{part}}\rangle$, and the number of binary collisions $\langle N_{\mathrm{coll}}\rangle$, obtained from a Glauber calculation neglecting fluctuations [8].

3 Collective elliptic flow

First we discuss results on elliptic flow, which will serve later as a basis for the azimuthal correlations at large p_{T}. The strength of elliptic flow is quantified by the second Fourier coefficient v_2 [9] of azimuthal particle distributions with respect to the reaction plane Ψ_R

$$\frac{dN}{d(\phi - \Psi_R)} = A(1 + \sum_{n=1}^{\infty} 2\, v_n \cos(n(\phi - \Psi_R))). \quad (1)$$

The orientation of the reaction plane is *a priori* unknown and has to be estimated. Consequently the measured v_2 values have to be corrected for the finite resolution of this estimated event plane. Measurements of the event plane were obtained from charged particle tracks measured by the SDD's using a subevent method. Non-uniformities in the event plane distribution were removed by standard procedures [3,9]. Depending on centrality, the event plane resolution is 35–40 degrees.

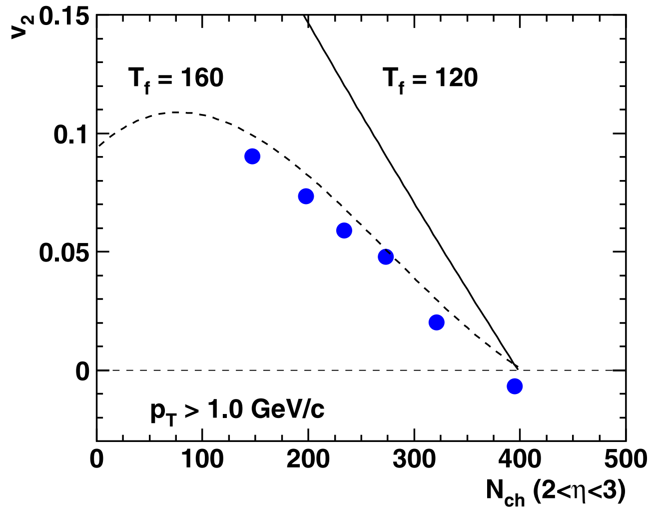

Fig. 1. Centrality dependence of v_2 for charged pions. Hydrodynamical calculations with a phase transition at T_c = 165 MeV are shown for kinetic freeze-out temperature T_f = 120 MeV (solid line) and T_f = 160 MeV (dashed line)

The centrality dependence of the elliptic flow of pions with $p_{\mathrm{T}} > 1$ GeV/c, corrected for the event plane dispersion, is shown in Fig. 1. We observe that v_2 decreases approximately linearly with N_{ch} and vanishes in the most central collisions, where no asymmetry in the overlap zone is present. The quoted errors are statistical only. The absolute systematic errors on v_2 vary between 0.5% in semicentral and 1.5% in central collisions. The transverse momentum dependence of v_2 is presented in Fig. 2. Here, we have added v_2 measurements for charged particles as charged pions compose 85% of the total yield and thus we cover the p_{T} region below that for which pions are identified by the RICH detectors. The data in Fig. 2 are averaged over the first three centrality classes corresponding to 13–26% of σ_{geo} and corrected for Bose-Einstein correlations [10] with input from [11]. This correction varies between −15% of v_2 at $p_{\mathrm{T}} = 0.25$ GeV/c and 10% for $p_{\mathrm{T}} > 1$ GeV/c [3]. We remark that the centrality dependence of v_2 (Fig. 1) was left uncorrected because the correction procedure becomes questionable for central collisions. We observe a linear rise of v_2 with transverse momentum up to $p_{\mathrm{T}} = 1.5$ GeV/c, when the slope decreases, possibly indicating a saturation of v_2 at large p_{T}, similar to observations at RHIC [12].

It is very interesting to compare the measured v_2 values to expectations from ideal (*non-viscous*) hydrodynamics. The authors of [13] use an equation of state with a first order transition to a quark gluon plasma at $T_c = 165$ MeV and two different kinetic freeze-out temper-

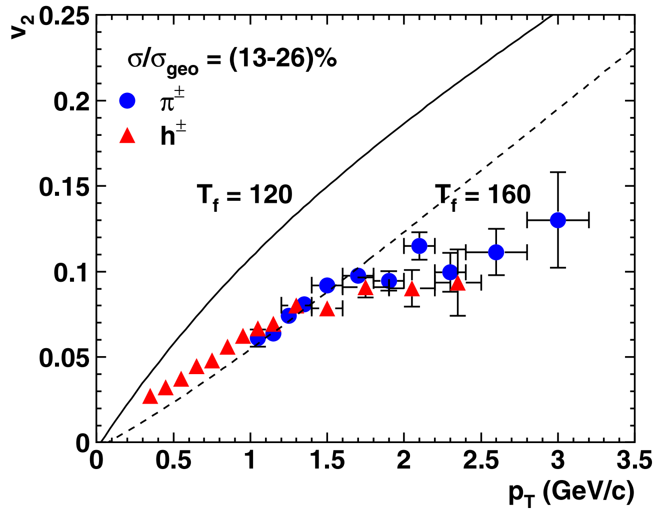

Fig. 2. p_T dependence of v_2 for charged pions and hadrons. The lines have the same meaning as in the previous figure

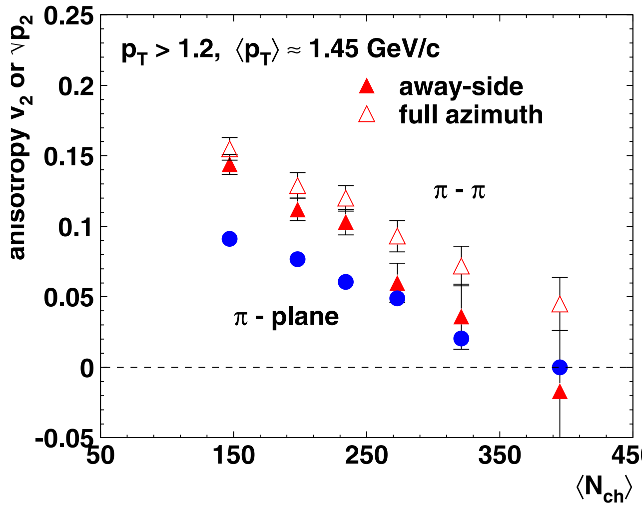

Fig. 3. Centrality dependence of pion elliptic anisotropy for pions ($p_T > 1.2$ GeV/c) obtained from the event plane method (v_2, circles) and from two-pion azimuthal correlations ($\sqrt{p_2}$, triangles), as obtained from the full azimuth (open triangles) and from the away-side region (full triangles).

atures, $T_f = 120$ and 160 MeV. As can be seen from Fig. 1 and Fig. 2, the data favor the higher freeze-out temperature $T_f = 160$ MeV. However, the lower freeze-out temperature $T_f = 120$ MeV is necessary to describe the inclusive p_T spectra of protons at the SPS energy. While our $v_2(p_T)$ data are rather similar to those at RHIC, albeit about 30% smaller at comparable p_T [14], a solid discrepancy might emerge only with the presented comparison to *ideal* hydrodynamical calculations, which predict larger values of v_2 at the SPS than at RHIC. Possible explanations might be either incomplete thermalization or a necessity to include viscosity in the calculations [15].

4 Azimuthal correlations at high-p_T

We turn to the measurement of azimuthal correlations between pions identified in the RICH detectors. In analogy to correlations of particles with the reaction plane [cf. (1)], we can describe the pair-wise distribution as

$$\frac{dN_{\text{pairs}}}{d(\Delta\phi)} = B(1 + \sum_{n=1}^{\infty} 2\, p_n \cos(n\Delta\phi)) \quad , \qquad (2)$$

where $\Delta\phi$ is the azimuthal angle difference between two tracks. As can be easily shown, for pure flow $p_n = v_n^2$ [9]. The measured correlation function was corrected for the pion reconstruction efficiency. For $p_T > 1.2$ GeV/c pions, the correction factor varies between 6 to 11 depending on centrality [3]. The systematic error of the efficiency correction is 15%. In addition, there is a significant drop in pair reconstruction efficiency at $\Delta\phi \approx 0$, due to a finite two-ring resolution of the RICHes. To be less sensitive to the Monte-Carlo correction, we discarded pairs with track separation $\Delta\theta \leq 20$ mrad in polar angle. Although this cut is not sufficient to fully avoid the region of inefficiency [3,6], it reduces the pair efficiency loss at $\Delta\phi \approx 0$ by a factor of 4 while keeping 60% of the statistics. The correction procedure is supported by the fact that the extracted anisotropies agree within one standard deviation whether or not the $\Delta\theta$ cut is applied. The systematic error of the pair reconstruction efficiency is 20%.

We compare the elliptic anisotropy obtained from azimuthal correlations, $\sqrt{p_2}$, and from the event plane method, v_2. Figure 3 shows the centrality dependence of the elliptic anisotropy obtained with both methods. We can see that $\sqrt{p_2}$ (from two-particle correlations) systematically exceeds v_2 (from the event plane method) and remains finite even in the most central collisions. The observed excess is largest in the most peripheral bin, where it reaches a value of 70%. Accounting for Bose-Einstein correlations, this value is reduced to approximately 60%. A more detailed study shows that $\sqrt{p_2}$ from two-particle correlations calculated only in the away-side region (*'back-to-back'*) behaves differently. While in the first centrality bin the anisotropy in the away-side region coincides within the errors with that in the full range, it decreases more strongly with centrality and approaches zero for central collisions. The transverse momentum dependence of v_2 from both methods is compared in Fig. 4. The gap between v_2 from azimuthal correlations and event plane method increases with p_T. However, the statistical significance of this measurement is degraded by invoking a double-differential window in p_T.

We attribute the observed excess to direct $\pi\pi$ correlations which are presumably semihard in origin. A study of the two-particle correlations with respect to the event plane [3,4,6] supports the non-flow origin of the observed excess. An interpretation of the away-side excess in terms of resonance decays is unlikely, in view of the high invariant mass (≈ 2.5 GeV/c^2) required. A possible contribution

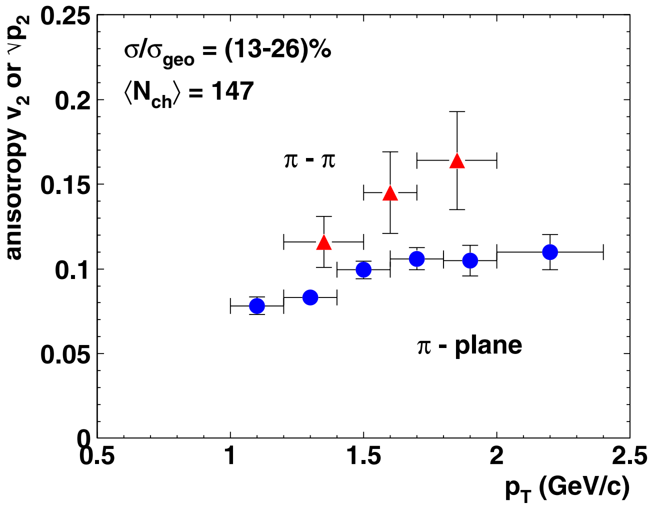

Fig. 4. Transverse momentum dependence of pion elliptic anisotropy in semicentral collisions from the event plane method (v_2, circles) and from azimuthal correlations ($\sqrt{p_2}$, triangles)

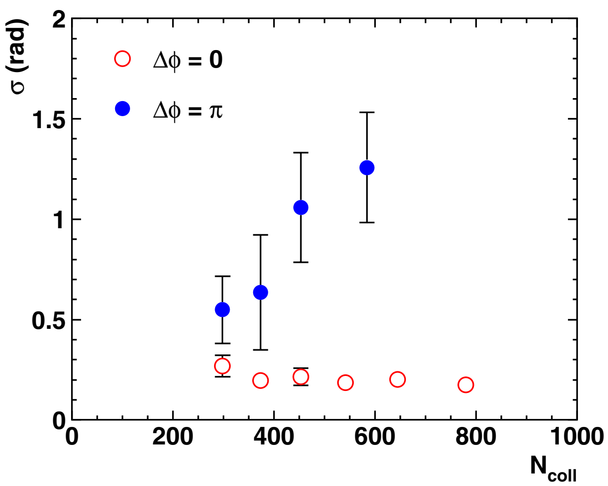

Fig. 5. Centrality dependence of the Gaussian widths of the correlation peaks at $\Delta\phi = 0$ (open circles) and $\Delta\phi = \pi$ (full circles). The most central point for $\Delta\phi = \pi$ is averaged over centrality classes 4 and 5

from resonance decays to the near-side excess cannot be excluded and it is currently under investigation.

We have fit the correlation functions with two Gaussians fixed at $\Delta\phi = 0, \pi$ on top of an elliptic flow modulated background, where the elliptic flow was taken from the event plane method. Fit parameters are the Gaussian amplitudes and widths, and the background B. We have estimated a systematic error of 15% due to uncertainties in the background term. Below, we discuss only the properties of the Gaussian widths of the correlation peaks. The properties of the pion pair yield were studied in [3,4]. We have found that, within statistical errors, the $\pi\pi$ yield grows linearly with N_{coll} [4], which supports the interpretation of a semihard origin of the high-p_{T} correlations.

Figure 5 shows the centrality behavior of the Gaussian widths for both correlation peaks. The near-side peak remains narrow at $\sigma_0 = 0.23 \pm 0.03$ rad, averaged over the measured centrality range, which is consistent with fragmentation [16]. The corresponding average momentum perpendicular to the transverse momentum of the parton is $\langle |j_{Ty}| \rangle = 190 \pm 25$ MeV/c; $\langle j_T \rangle = \pi/2 \langle |j_{Ty}| \rangle = 300 \pm 40$ MeV/c [17]. This value is somewhat smaller than ISR [18] and RHIC [17] measurements. The away-side peak, however, shows a different behavior. Its width increases with centrality from about 0.5 rad for the first centrality bin up to $\sigma_\pi = 1.26 \pm 0.28$ rad at 5–13% of the most central σ_{geo} from where on it cannot be distinguished from background. The last measured point corresponds to $\langle |k_{Ty}| \rangle = 1.6 \pm 0.3$ GeV/c ($\sqrt{\langle k_T^2 \rangle} = \sqrt{\pi} \langle |k_{Ty}| \rangle = 2.8 \pm 0.6$ GeV/c), which agrees well with measurements in central Au+Au collisions at RHIC [17].

Moreover, it is very interesting to study the properties of the Gaussian width of the correlation peaks as a function of p_{T}. Since this study requires a lot of statistics, we have constructed the correlation function in a slightly different way. We have imposed several p_{T}-cuts only on one of the pions in the pair (*trigger*) going from 1.2 to 1.8 GeV/c, while keeping the second pion in the pair (*associated*) within 1.2 GeV/$c < p_{\mathrm{T}} < p_{\mathrm{T}}$(trigger). Figure 6 shows the Gaussian width dependence on p_{T}(trigger) for the away-side peak. The data are averaged over the first two centrality bins, 17–26%, where the away-side peak can be distinguished from the elliptic flow background. Although the statistical errors for this measurement are rather large, there seems to be an indication of a narrowing of the away-side peak with the p_{T} of the trigger particle, as expected for semihard processes. A similar study for the near-side peak is not possible due to large systematic uncertainties from the Monte-Carlo correction at $\Delta\phi = 0$ as a function of p_{T}.

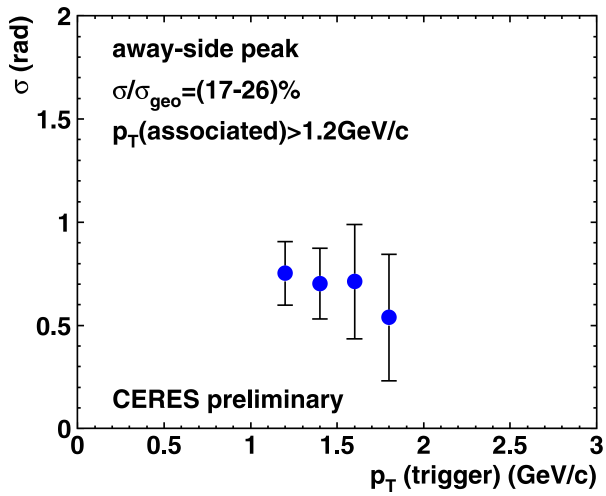

Fig. 6. Dependence of the Gaussian width of the away-side correlation peak ($\Delta\phi = \pi$) on the p_{T} of the trigger pion. The data are averaged over the first two centrality bins. The associated pions have p_{T}(associated)> 1.2 GeV/c

5 Summary

We discussed some properties of the semihard azimuthal correlations of pions at moderately high p_{T} embedded in the elliptic flow at top SPS energy. The near-side peak remains narrow at all measured centralities, which is consistent with fragmentation. Meanwhile, the away-side peak broadens and disappears in the background in the most central collisions. Our findings thus exhibit similar features, but also differences, to observations at top RHIC energies [12,14,19]. The elliptic flow at the SPS behaves differently than at RHIC. Although the $v_2(p_{\mathrm{T}})$ dependence indicates the possibility of saturation at high p_{T}, which is clearly observed at RHIC, the v_2 values are well below the expectations from ideal hydrodynamics, in contrast to RHIC. Observations at RHIC show [19] that the properties of the away-side peak in central Au+Au collisions depend on the studied p_{T} range. At RHIC energy, the away-side peak is suppressed and disappears for associated particles with $p_{\mathrm{T}} > 2$ GeV/c and the depleted energy reappears in the low p_{T} particles ($p_{\mathrm{T}} > 0.15$ GeV/c). In our studied range ($p_{\mathrm{T}} > 1.2$ GeV/c) at SPS energy, the away-side peak broadens with centrality without a sign of suppression.

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