Semi-Hard Scattering Unraveled from Collective Dynamics by Two-Pion Azimuthal Correlations in 158 A GeV/c Pb + Au Collisions

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Elliptic flow and two-particle azimuthal correlations of charged hadrons and high-p_T pions ($p_T > 1$ GeV/c) have been measured close to mid-rapidity in 158A GeV/c Pb+Au collisions by the CERES experiment. Elliptic flow (v_2) rises linearly with p_T to a value of about 10% at 2 GeV/c. Beyond $p_T \approx 1.5$ GeV/c, the slope decreases considerably, possibly indicating a saturation of v_2 at high p_T. Two-pion azimuthal anisotropies for $p_T > 1.2$ GeV/c exceed the elliptic flow values by about 60% in mid-central collisions. These non-flow contributions are attributed to near-side and back-to-back jet-like correlations, the latter exhibiting centrality dependent broadening.

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Late stages of ultra-relativistic heavy-ion collisions are characterized by strong collective transverse expansion. An important signature of collective dynamics in non-central collisions is *elliptic flow* manifesting itself in an azimuthal anisotropy of particle yields with respect to the reaction plane [1, 2]. It is driven by anisotropic pressure gradients built up during the early stage of the collision in the geometrically anisotropic overlap zone [3]. The degree of equilibration achieved during the subsequent evolution might in principle be gauged by comparison to hydrodynamic models which indicate an upper limit of elliptic flow. Its magnitude depends on initial conditions and the equation of state (EoS), but also on system lifetime [4]. It had been argued [5] that hydrodynamics was unable to describe elliptic flow data at SPS energies while it accurately describes RHIC data [6].

Two-particle azimuthal correlations are sensitive to collective flow but might reveal, particularly at large transverse momentum (p_T), also relics of primary scattering in the semi-hard sector which are masked in inclusive p_T spectra at SPS energies by the Cronin effect [7]. It is the purpose of this Letter to demonstrate that collective flow and semihard scattering can be disentangled by measurements of azimuthal anisotropies. We present data (i) of elliptic flow for charged particles and for identified pions up to $p_T \approx 3$ GeV/c, and (ii) of two-pion correlations at $p_T \geq 1.2$ GeV/c. We pursue a statistical analysis [8] which conjectures that the observed anisotropies of non-flow nature are due to dijet-like correlations. An interpretation in terms of resonance decays is unlikely in view of the high invariant mass (≈ 2.5 GeV/c^2) required.

CERES [9] has acceptance close to mid-rapidity ($2.1 \leq \eta \leq 2.65$) with full azimuthal coverage. Charged particles ($h^{\pm}$) are tracked by a doublet of silicon-drift detectors (SDD) before, and a multiwire proportional chamber behind the magnetic field used for momentum determination. Identification of pions with $p > 4.5$ GeV/c is performed by two ring-imaging Cherenkov detectors (RICH). Pion momenta are determined from the ring radii. We analyzed 43 million 158 AGeV/c Pb+Au collisions taken in 1996 at the most central (26±1.5)% of the geometric cross section, σ_{geo}. We divide the triggered events into six contiguous centrality bins labeled by the percentage of σ_{geo} of their upper edges, 26%, 21%, 17%, 13%, 9%, and 5%, respectively. The centrality is determined by charged particle multiplicity $\langle N_{ch} \rangle$ in the range $2 \leq \eta \leq 3$ covered by the SDDs. Numbers of participants, N_{part}, and binary collisions, N_{coll}, were calculated from a nuclear overlap model [10] neglecting fluctuations, resulting in a total inelastic cross section of 6.94 barn.

Conventional elliptic flow analysis is based on the azimuthal particle distribution with respect to the orienta-

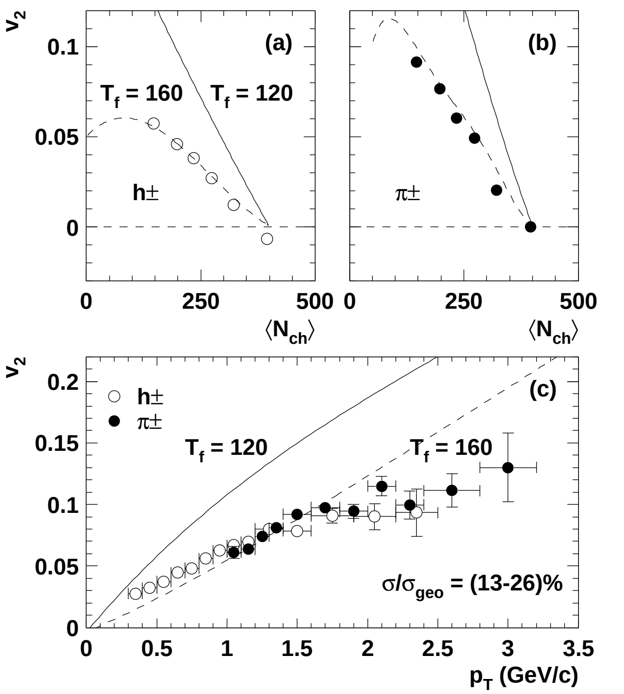

FIG. 1: Centrality dependence of v_2 for (a) $h^{\pm}$, $0.5 < p_T < 2.5$ GeV/c, and (b) $\pi^{\pm}$, $p_T > 1.2$ GeV/c. Statistical errors are within symbols. (c) p_T dependence of v_2, corrected for BEC effects. Here, the centrality corresponds to three leftmost bins in (a),(b) combined. Hydrodynamical calculations with phase transition at T_c= 165 MeV are shown for kinetic freeze-out temperatures of 120 MeV and 160 MeV.

tion Ψ of the reconstructed event plane (EP),

$$\frac{dN}{d(\phi - \Psi)} = A[\ 1 + 2v_2' \cos(2(\phi - \Psi))\ ]. \qquad (1)$$

Measurements of the EP and of the particle anisotropy are obtained from different subsets of the same data sample: the ϕ acceptance is divided into 100 slices and every fourth slice is combined into a subsample. We avoid autocorrelations by using non-adjacent ϕ-slices for v_2' and EP measurements. Non-uniformities in Ψ are removed by standard procedures [11]. Depending on centrality, the r.m.s. of EP resolution is 35-40 degrees. The Fourier coefficient v_2 is obtained after correcting for the EP dispersion, $v_2 = \mathcal{K}\ v_2'$. The correction factor for sample i, $\mathcal{K}_i = \langle \cos(2(\Psi^i - \Psi_R))\rangle^{-1}$, involves the unknown angle Ψ_R of the true reaction plane but can be expressed by the measured sample differences $\Psi^i - \Psi^j$. This spread in $\mathcal{K}$ factors dominates the systematic uncertainties in v_2. Resulting absolute systematic errors vary with centrality between 0.5% and 1.5%.

The flow results are presented in Fig. 1. With centrality, v_2 decreases almost linearly as expected from hydrodynamics. The larger v_2 values for $\pi^{\pm}$ reflect their larger $\langle p_T\rangle \approx 1.45$ GeV/c compared to 0.70 GeV/c for $h^{\pm}$. The p_T dependence of v_2 measured for the first time at the SPS up to 3 GeV/c is shown in Fig. 1(c). The data are averaged over the three most peripheral centrality bins and correspond to (13-26)% of σ_{geo} ($\langle N_{ch}\rangle = 190$). It is seen that v_2 rises about linearly with p_T to a value of about 10% at 2 GeV/c. Beyond $p_T \approx 1.5$ GeV/c, the slope decreases considerably, possibly indicating a saturation of v_2 at high p_T as observed at RHIC [6].

The data in Fig. 1(c) have been corrected for the effects of Bose-Einstein correlations (BEC) [12] with input from [13]. The corrections vary between -15% of v_2 at $p_T = 0.25$ GeV/c and +10% at $p_T > 1$ GeV/c. Since the procedure becomes questionable for central collisions, the data in Figs. 1(a,b) were left uncorrected. We may compare to recent results of NA49 [14] at (12.5-33.5)%. After correcting for different centrality, these are still about 15% larger in the range 1.0≤ p_T ≤1.5 GeV/c.

Results of hydrodynamical calculations [5] using an EoS with a first order phase transition to quark gluon plasma at $T = 165$ MeV and freeze-out at $T_f = 120$ MeV are considerably above the data. If the hydrodynamical evolution is terminated already at $T_f = 160$ MeV [15], good agreement with the elliptic flow data is reached. It should be noted, though, that in this case the p_T spectra of protons are too steep (not shown). Conversely, the T_f= 120 MeV calculation reproduces the spectra. Possible explanations include incomplete thermalization [16]

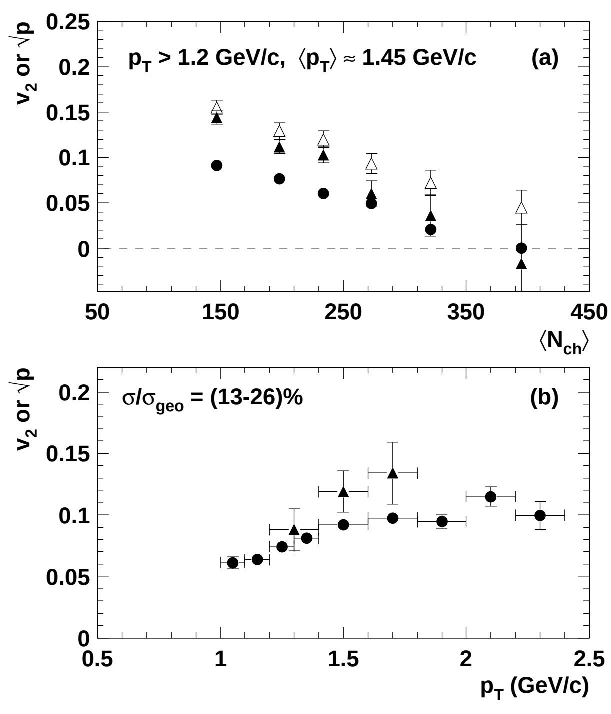

FIG. 2: Anisotropies v_2 from EP method for pions (circles) and $\sqrt{p}$ from two-pion correlations (triangles). (a) Centrality dependence for full azimuth (open triangles) and a range restricted to $|\Delta\phi| \geq 0.6$ rad (closed triangles). (b) p_T dependence of v_2 for the top (13-26)% of σ_{geo}, $\langle N_{ch}\rangle = 190$.

and viscous effects [17].

We turn to the measurement of two-pion angular correlations at $p_T \geq 1.2$ GeV/c which are written in terms of the relative azimuthal angle $\Delta\phi$ as

$$\frac{dN}{d\Delta\phi} = B\ [1 + 2p\cos(2\Delta\phi)]. \quad (2)$$

From the data we determine the second Fourier coefficient p which for pure flow is equal to v_2^2 [11]. The two-pion yield is corrected for single-track reconstruction efficiency which is determined by embedding simulated tracks into real events. This correction varies between 16% and 9%, depending on N_{ch}. At small opening angles, overlapping rings in the RICHes cause a drop in pair reconstruction efficiency. To be less sensitive to a Monte-Carlo (MC) correction, pairs with track separation $\Delta\theta \leq 20$ mrad in polar angle were discarded. This cut reduces the pair efficiency loss by a factor of four while keeping still 60% of statistics. Corrected opening-angle distributions reveal strong a strong anisotropy with maxima at $\Delta\phi \approx 0$ and π (see below). The procedure is supported by the fact that anisotropies remain essentially unchanged after correction whether or not the $\Delta\theta$ cut is applied.

In Fig. 2(a) is shown that the $\sqrt{p}$ values from the two-particle correlation are systematically larger than the v_2 coefficients. It is unlikely that the v_2 values are significantly reduced by a possible bias on EP reconstruction by the high-p_T particles in view of their very small abundance ($\approx 10^{-3}$ of $h^{\pm}$). We have analyzed the full azimuth applying the $\Delta\theta$ cut and MC correction for pair efficiency, and alternatively a range $|\Delta\phi| \geq 0.6$ rad without these remedies. For the first centrality bin ((21-26)%, $\langle N_{ch}\rangle = 147$), the value of $\sqrt{p}$ exceeds v_2 by 70% for full range in azimuth; accounting for BEC effects, this excess is reduced to about 60%. The anisotropy in the restricted $\Delta\phi$ range is similar in magnitude in the first bin as for the full range, but it decreases more strongly with centrality and approaches zero for central collisions (<5%, $\langle N_{ch}\rangle = 395$). The gap between anisotropies from two-pion correlation and conventional flow widens with increasing p_T as can be seen from Fig. 2(b). However, the statistical accuracy is significantly degraded by invoking a two-dimensional window in p_T.

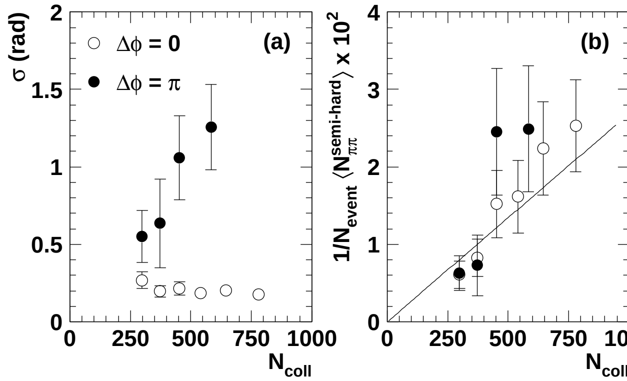

FIG. 4: Centrality dependence of the Gaussian widths of the correlation peaks at $\Delta\phi =\ 0,\ \pi$ (a) and of the areas under the Gaussian peaks, both from fits (b). The most central points for $\Delta\phi =\ \pi$ combine the fourth and fifth centrality bin, (5-13)%. The loss in pair acceptance due to the cut $\Delta\theta \geq 20$ mrad has not been corrected for.

The observed excess is attributed to direct pion-pion correlations, presumably of semi-hard origin, in addition to collective flow. The $\Delta\phi$ distributions shown in Fig. 3(a,b) are well described by two Gaussians at $\Delta\phi = 0,\ \pi$ on top of elliptic flow. Fit parameters are the Gaussian amplitudes and widths and background B, while v_2 is fixed independently by the EP method (v_2^2(EP) replacing p in Eq.(2)). The results in Fig. 4(a) show that the close-angle peak stays narrow at $\sigma_0 = (0.23{\pm}0.03)$ rad, consistent with fragmentation [18]. The back-to-back peak broadens with centrality up to $\sigma_\pi = (1.26{\pm}0.28)$ rad at (5-13)%, from where on it cannot even be discerned from background. Within the statistical errors, the yield contained in both peaks grows linearly with N_{coll} which supports the suggested interpretation of semi-hard scattering. So, the back-to-back component escapes detection in central collisions due to broadening but does not appear to be suppressed in yield.

Partonic rescatterings in medium cause an imbalance in p_T perpendicular to the initial hard scattering plane [19, 20] leading to p_T broadening that is reflected in the width of the back-to-back peak [21]. In contrast, the close-angle peak is not affected since both pions originate from fragmentation of the same parton, and propagating as color singlets experience only little rescattering thereafter. In a small-angle approximation, the p_T broadening is $(\Delta p_T^2)^{1/2} \approx \langle p_T\rangle(\sigma_\pi^2 - \sigma_0^2)^{1/2}$. For (5-13)% centrality we obtain $(\Delta p_T^2)^{1/2} = (1.8{\pm}0.4)$ GeV/c. A more accurate

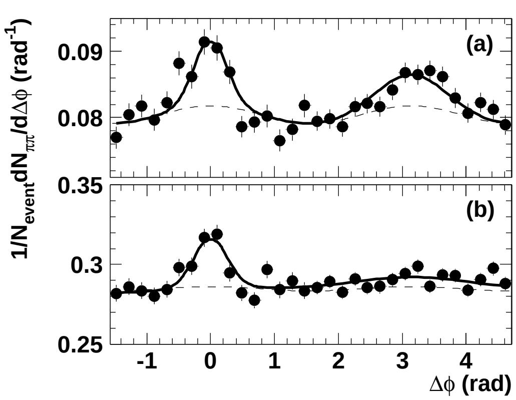

FIG. 3: Two-pion opening angle distributions for $p_T >\ 1.2$ GeV/c (a) for the first centrality bin, (21-26)% and (b) for the fourth, (9-13)%. A cut $\Delta\theta \geq 20$ mrad and corrections for close-pair efficiency losses are applied. Full line shows Gaussian fits to semi-hard components on top of flow-modulated background (dashed line).

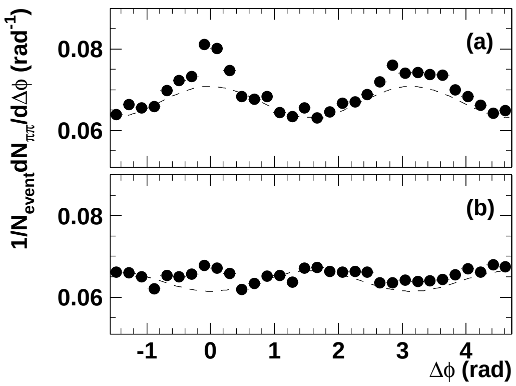

FIG. 5: In-plane (a) and out-of-plane (b) two-pion opening angle distributions. Dashed lines are calculated for pure elliptic flow as measured by the EP method and corrected for BEC. Data are for centrality 13-26%, $p_T \geq 1.2$ GeV/c, a cut on $\Delta\theta \geq 20$ mrad, and are efficiency corrected.

treatment [22] yields (2.8±0.6) GeV/c. Both estimates are similar to values measured in pA collisions [21].

Strong non-flow contributions to the two-particle opening-angle anisotropy are confirmed by distributions in which one of the two pions is detected in the EP ($\pm\pi/4$), or perpendicular to it (again $\pm\pi/4$). The anisotropy, calculated [23] for pure elliptic flow as

$$p_{in/out} = v_2 \cdot \langle \cos(2(\phi - \Psi)) \rangle_{in/out}\,, \qquad (3)$$

is shown by dashed lines in Fig. 5, using the measured $v_2 = 8.5\%$. The angular brackets indicate an average over the respective in-plane and out-of-plane sectors, weighted with the anisotropic yields of Eq.(1), and folded with the measured EP resolution.

In-plane (Fig. 5(a)), elliptic flow and semi-hard pairs both peak at $\Delta\phi$= 0, π where we observe an *excess* over flow. *Out-of-plane* (Fig. 5(b)), the flow pattern is shifted by $\pi/2$, and the semi-hard correlation (always peaking at $\Delta\phi$= 0 and π) fills in the minima of flow. Would the jet-like correlations actually be misidentified elliptic flow, then an increased harmonic amplitude in the out-of-plane correlation would show more *negative* swings at 0 and π than the dashed line in Fig. 5(b), which is not the case.

Summary and discussion.– Differential $v_2(p_T)$ depends on centrality and p_T as expected from hydrodynamical calculations, but we have not been able to reproduce both the magnitude of our v_2 data and the p_T spectra. Above 1.5 GeV/c the slope of measured v_2 flattens while the calculation continues to rise.

The observation of semi-hard two-particle azimuthal correlations embedded in collective flow is novel for SPS energies. The broadening of the back-to-back correlation with increasing centrality suggests that we observe in-medium partonic scattering which affects both parts of a dijet independently. Although the back-to-back correlation broadens in central collisions, there is no sign of its suppression. The absence of broadening of the close-angle correlation supports the view that these pions originate from fragmentation of the same parton. Our results thus exhibit similar features, but also important differences, to recent findings at RHIC [24].

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