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 \[ \text{\textsuperscript{1, 2}}. \] It is driven by anisotropic pressure gradients built up during the early stage of the collision in the geometrically anisotropic overlap zone \[ \text{\textsuperscript{3}}. \] 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 \[ \text{\textsuperscript{4}}. \] It had been argued \[ \text{\textsuperscript{5}} \] that hydrodynamics was unable to describe elliptic flow data at SPS energies while it accurately describes RHIC data \[ \text{\textsuperscript{6}} \].

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 \[ \text{\textsuperscript{7}}. \] 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 \[ \text{\textsuperscript{i}} \] of elliptic flow for charged particles and for identified pions up to $p_T \approx 3$ GeV/c, and \[ \text{\textsuperscript{ii}} \] of two-pion correlations at $p_T \geq 1.2$ GeV/c. We pursue a statistical analysis \[ \text{\textsuperscript{8}} \] 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 ($\approx 2.5$ GeV/$c^2$) required.

CERES \[ \text{\textsuperscript{9}} \] has acceptance close to mid-rapidity ($2.1 \leq \eta \leq 2.65$) with full azimuthal coverage. Charged particles ($h^+$) 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, $\sigma_{geo}$. We divide the triggered events into six contiguous centrality bins labeled by the percentage of $N_{ch}$ in the range $2 \leq \eta \leq 3$ covered by the SDDs. Numbers of participants, $N_{\text{part}}$, and binary collisions $N_{\text{coll}}$, were calculated from a nuclear overlap model \[ \text{\textsuperscript{10}} \] 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.

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 lower $p_T$ dependence 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 $\sigma_{geo}$ ($\langle N_{ch} \rangle = 190$). 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 [10].

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 $\leq$ $p_T$ $\leq$ 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 $T_f = 120$ 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].
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

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

(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 anisotropy with maxima at $\Delta \phi \approx 0$ and $\pi$ (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 $p_T$.

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. 4(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 [13,20] 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 $(\Delta p_T^2)^{1/2} \approx (p_T) (\sigma_\pi^2 - \sigma_0^2)^{1/2}$. For (5-13)% centrality we obtain $(\Delta p_T^2)^{1/2} = (1.8 \pm 0.4)$ GeV/c. A more accurate

FIG. 2: 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. 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. 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.
treatment \[23\] yields \((2.8 \pm 0.6)\) 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

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

is shown by dashed lines in Fig. 4 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 \(\Delta \phi = 0, \pi\) 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 \(\pi\)) 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 \(\pi\) 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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**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.