ELLIPTIC FLOW AND SEMI-HARD SCATTERING AT SPS

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Results on elliptic flow and two-particle correlations in the semi-hard regime are presented.

1 Introduction

The first rounds of experiments at the Relativistic Heavy Ion Collider (RHIC) at BNL have provided us with several clues [1]: the collective expansion following the violent collision of two Au nuclei at $\sqrt{s}$ = 130 and 200 GeV energy per nucleon appears to resemble the outward flow of a perfect fluid. This has been concluded from the fact that the anisotropic, or elliptic, flow measured as the second Fourier coefficient of the particle distribution with respect to the event plane is very large and even reaches up to the predictions of ideal, i.e. *non-viscous*, hydrodynamics. Moreover, elliptic flow, commonly regarded as a property of particles from 'soft' processes, characterized by a scale $\Lambda^2 \ll 1$ GeV^2, persists at large p_T. This seems to be linked to another highlight from RHIC, the suppression of hadron spectra at high p_T (in comparison to the cumulative yield of nucleon-nucleon collisions) together with the disappearance of back-to-back correlations of such hadrons. Both are attributed to *jet quenching* in the Quark Gluon Plasma in which partons after an initial hard encounter loose energy, mostly by gluon radiation. The quenching of large p_T hadrons is believed to be at the origin of anisotropic flow in the semi-hard or hard sector as observed by large azimuthal anisotopies.

We will report here on measurements [2] of inclusive particle p_T spectra, elliptic flow and azimuthal particle correlations up to $p_T \approx 3$ GeV/c in Pb-Au collisions at the CERN Super-Proton Synchrotron (SPS) at $\sqrt{s}$= 17.3 GeV. We shall elaborate on those issues in which SPS physics appears to be at variance with that at RHIC.

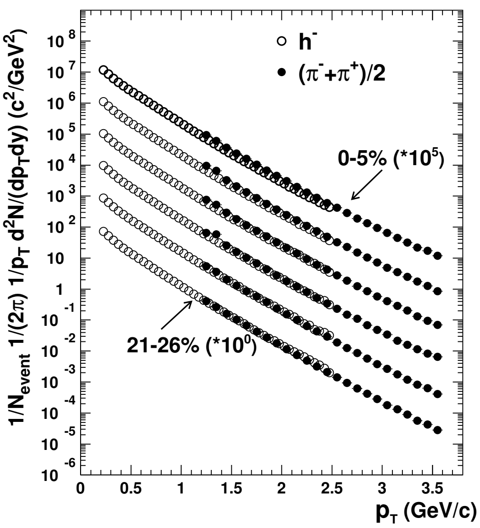

Figure 1: Invariant p_T spectra of inclusive charged hadrons and pions. 158 GeV/c Pb-Au, $2.1 \leq y \leq 2.65$. Different centralities labeled by the percentage of the top inelastic cross section. The lowest, most peripheral spectrum (21-26%, n_{coll}= 293) is at large p_T steeper than the most central spectrum at the top (0-5%, n_{coll}= 774), indicating moderate Cronin enhancement above 2.5 GeV/c, see text.

2 Inclusive spectra

Pions are identified by the double Cherenkov ring imaging spectrometer ($\gamma_{thr} \approx 32$), their momenta measured by the ring radii. Charged hadrons are tracked by a Si-drift telescope and a multi-wire chamber sandwiching the Cherenkov detectors, with magnetic deflection inbetween.

Invariant p_T spectra (Fig.1) of negatively charged hadrons, h^-, and of $\pi^\pm$ are found in close agreement despite entirely different methods used. The concave shape above about 1.5 GeV/c might indicate the power-law characteristics of elementary parton interactions. Inverse slope parameters increase monotonically from 180 to 270 MeV/c between p_T= 0.5 and 2.5 GeV/c, respectively, in close agreement with π° data [3] of WA98.

Reanalyzing the WA98 data using a better p-p reference, d'Enterria[4] finds only weak Cronin enhancement [5] and even some suppression of yields at high-p_T in most central 158 A GeV Pb Pb collisions, in contrast to previous analyses [3,6]. In lack of a suitable p-p reference for $\pi^\pm$, we compare here the most central to the most peripheral spectrum using the ratio

$$R_{CP}(p_T) = \frac{\langle d^2N/dp_T dy\rangle/\langle n_{coll}\rangle(central)}{\langle d^2N/dp_T dy\rangle/\langle n_{coll}\rangle(peripheral)}. \tag{1}$$

For the CERES data of Fig. 1, R_{CP} increases from 0.75 to 1.25 for p_T between 1.3 and 3.5 GeV/c, respectively. So there is very moderate Cronin enhancement at large p_T and no indication of suppression. A possible alternative could be that both effects are present, but nearly cancel.

3 Elliptic flow

The results of the elliptic flow measurement are shown in Fig. 2. The v_2 values have been corrected for the measured resolution in determining the event plane using independent particle samples and for effects of Bose-Einstein correlations of particles close in phase space. Both the decrease with centrality and the linear rise with p_T might be taken to resemble perfect hydrodynamical behaviour. However, the calculations overshoot the data by a large margin, and this deficiency apparently is not easily cured by enforcing early freeze-out at larger T_f= 160 MeV since proton spectra (not shown) are no longer described. It has been suggested that inclusion of viscosity will considerably reduce v_2 [7,8].

The rise of $v_2(p_T)$ gives way to saturation around 2 GeV/c, a feature quite similar to that observed at RHIC [9]. This is the more surprising as v_2 at SPS stays well below the non-viscous hydrodynamical limit. Yet, it is somewhat puzzling that hydrodynamic calculations for v_2 at RHIC figure *below* those for the top SPS energy.

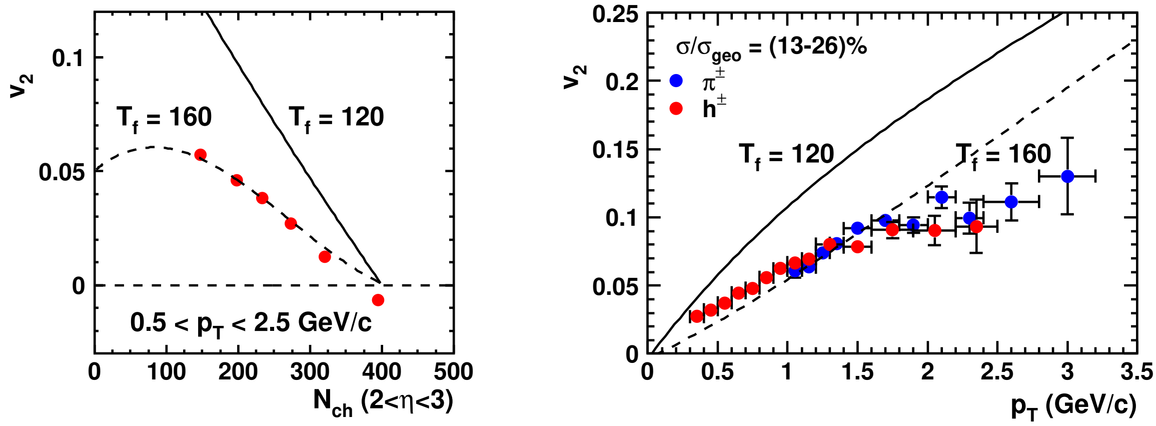

Figure 2: v_2, dependence on centrality (left, for h^-) and transverse momentum (right, for h^- and $\pi^\pm$), compared to ideal hydrodynamical calculations of P. Huovinen using an equation of state with a phase transition at 165 MeV and freeze-out at 120 and 160 MeV.

4 Two-particle correlation in azimuth: collective and partonic

We turn to the opening angle distribution in azimuth (in the plane transverse to the beam), $dN/d\Delta\phi(\Delta\phi)$, between any two high-$p_T$ pions in a given event. The anisotropy is measured by the harmonic coefficient $p = \langle\, cos(2\,\Delta\phi)\,\rangle$. *Direct* correlations cause the anisotropy to exceed the pure-flow magnitude $\sqrt{p} = v_2$. As seen from Fig. 3, the standard v_2 accounts for only about 60% of $\sqrt{p}$, the anisotropy in opening angle, the remaining *non-flow* component is presumably of semi-hard origin. To investigate dijet-like correlations, the measured $\Delta\phi$ distribution (Fig. 3 r.h.s.) is described by two Gaussians centered at $\Delta\phi = 0, \pi$ on top of the measured elliptic flow.

The peaks correspond to average momentum transfers $Q^2 = \ (2\,\langle p_T\rangle)^2 \approx 8.4$ GeV^2, well in the semi-hard regime; the invariant mass of the back-to-back 'object' is above 2 GeV/c^2 which makes resonance decays quite unlikely. Identifying the close-angle peak with parton fragmen-

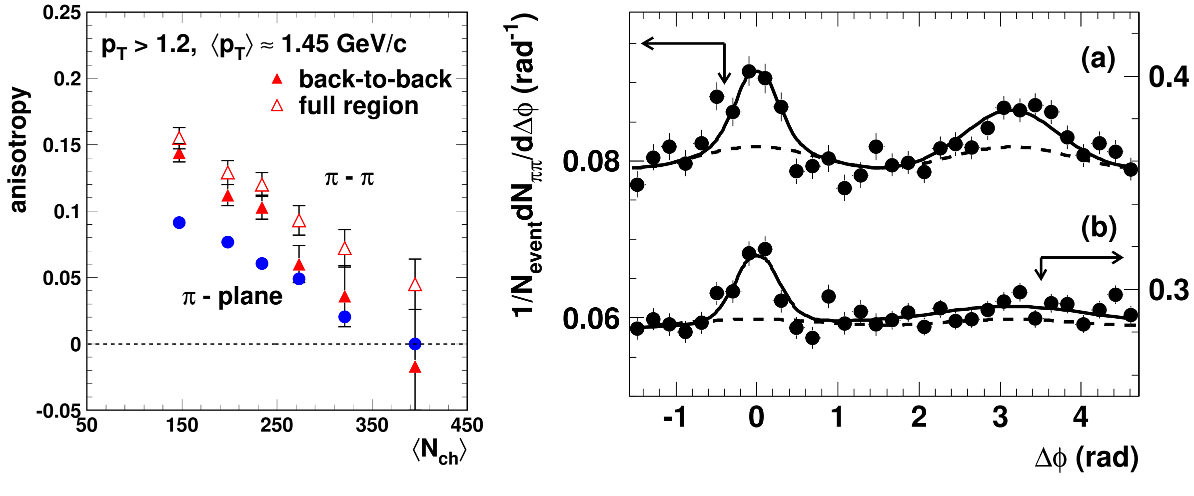

Figure 3: Left: Centrality dependence of anisotropy parameters $\sqrt{p}$ from $\pi\pi$ correlations (triangles) and v_2 from standard flow measurement (circles). Full triangles give anisotropy for a restricted range $\pi/2 \le \Delta\phi \le 3\,\pi/2$. Right: $\Delta\phi$ distribution for pairs of pions of $p_T \ge 1.2$ GeV/c, corrected for detection efficiency. Centrality (a) 21-26%, (b) 9-13%. The $\Delta\phi = 0$ region was protected against distorsions by invoking a minimum track separation $\Delta\theta \ge 20$ mr. The dotted line denotes the independently measured flow contribution, the full line is a fit with two Gaussians fixed at $\Delta\phi = 0$ and π.

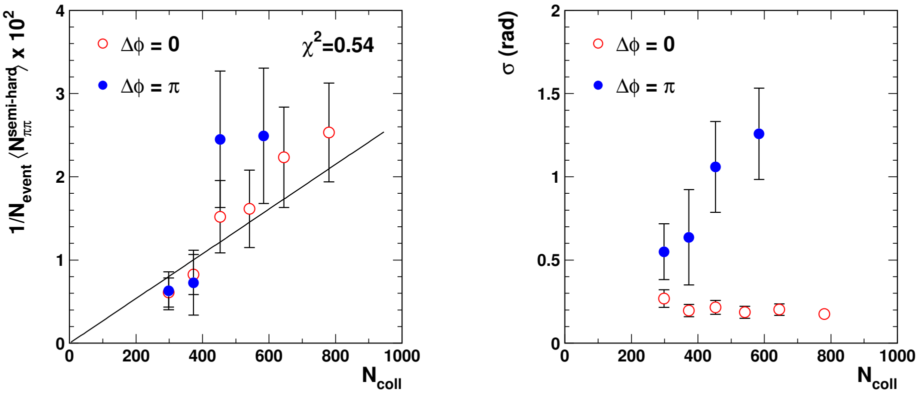

Figure 4: Centrality dependence of semi-hard yields (left) and widths of Gausian peaks (right). The 'back-to-back' component is lost in background for $N_{coll} > 600$. The χ^2 of straight-line fit doubles if plotted *vs* N_{part} instead.

tation, its width σ_0= (0.23±0.03) rad corresponds to an average pion momentum perpendicular to the jet thrust axis of $\langle j_T^2 \rangle^{1/2} = \sqrt{2} \langle p_T \rangle \, \sigma_0$= (472±62) MeV/$c$. This agrees with p-p results from ISR [10] and RHIC [11]. The yields of the 'near-angle' and 'back-to-back' peaks [a] grow linearly with the number of binary collisions, Fig.4; yet, the back-to-back component disappears in more central collisions because its width increases rapidly (see r.h.s. of Fig 3, b).

Of course, the excitement is with the disappearance of the back-to-back component. We derive a k_T broadening of (2.8±0.6) GeV/c for the most-central data point which is significantly enlarged by the nuclear medium compared to p-p [10] and d-Au collisions [11], and quite similar to preliminary results from RHIC [12] for Au-Au. The fact that we see no indication of suppression might be owed to the rather low p_T threshold so that quenched hadrons are still accepted [13]; these and other open questions are currently investigated in more detail [14].

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[a] Symmetric parton-parton scattering within CERES acceptance requires a partonic reference frame moving backward with $p_L \approx 1.5$ GeV/c corresponding to $x_F = -0.2$.