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: 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 anisotropies.

We will report here on measurements 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.
2 Inclusive spectra

Pions are identified by the double Cherenkov ring imaging spectrometer ($\gamma_{th} \approx 32$), 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 $\pi^\circ$ data\cite{3} of WA98.

Reanalyzing the WA98 data using a better p-p reference, d’Enterria\cite{4} finds only weak Cronin enhancement\cite{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\cite{6,3}. 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

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

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 $v_2$\cite{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\cite{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.
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 fragmentation, its

![Diagram](image1)

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 an isotropy for a restricted range $\pi/2 \leq \Delta\phi \leq 3\pi/2$. Right: $\Delta\phi$ distribution for pairs of pions of $p_T \geq 1.2$ GeV/$c$, corrected for detection efficiency. Centrality (a) 21-26%, (b) 9-13%. The $\Delta\phi=0$ region was protected against distortions by invoking a minimum track separation $\Delta\theta \geq 20$ 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 $\pi$. 

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.
width $\sigma_0 = (0.23 \pm 0.03) \text{rad}$ corresponds to an average pion momentum perpendicular to the jet thrust axis of $(j_2^2)^{1/2} = \sqrt{2} \langle p_T \rangle \sigma_0 = (472 \pm 62) \text{MeV}/c$. This agrees with p-p results from IS10 and RHIC11. The yields of the 'near-angle' and 'back-to-back' peaks 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 $(2.8 \pm 0.6) \text{GeV}/c$ for the most-central data point which is significantly enlarged by the nuclear medium compared to p-p10 and d-Au collisions11, and quite similar to preliminary results from RHIC12 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 accepted13; these and other open questions are currently investigated in more detail14.

References

1. See Proceedings of 17th Int.Conf.on Ultra-relativistic Nucleus-Nucleus Collisions (Quark Matter 2004, subm. to J.Phys.G
2. G. Agakichiev et al., CERES Collaboration, Phys.Rev.Lett.92, 032301 (2004) and J. Slivova, Doctoral Thesis Charles University, Prague 2003
3. M.M. Aggarwal et al., WA98 Collaboration, Eur.Phys.J.C23, 225 (2002).
4. D. d’Enterria, Phys.Lett.B596, 32 (2004), nucl-ex/0403055 and these Proceedings
5. J.W. Cronin et al., Phys.Rev. D11, 3105 (1975)
6. X.-N. Wang, Phys.Rev.Lett. 81, 2655 (1998)
7. S.A. Bass and A. Dumitru, Phys.Rev. C61, 06409 (2000)
8. D. Teaney, Phys.Rev. C68, 034913 (2003)
9. R. Snellings, STAR Collaboration, these Proceedings
10. A.L.S. Angelis et al., Phys.Lett. 97B, 163 (1980)
11. J. Rak, PHENIX Collaboration, nucl-ex/0403038
12. K. Filimonov, STAR Collaboration, nucl-ex/0403060
13. F. Wang, STAR Collaboration, these Proceedings and private communication
14. G. Agakichiev et al., CERES Collaboration, in preparation

*aSymmetric parton-parton scattering within CERES acceptance requires a partonic reference frame moving backward with $p_L \approx 1.5 \text{GeV}/c$ corresponding to $x_F = -0.2$.}