DIRECTED AND ELLIPTIC FLOW IN ULTRARELATIVISTIC HEAVY ION COLLISIONS

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Results on elliptic flow in sulfur induced collisions at 200 GeV/c per nucleon in NA38 and in Pb-Pb collisions at 158 GeV/c per nucleon in NA50. Elliptic flow is seen in Pb-Pb collisions but not in S-S or S-Cu collisions. Results are given as a function of the centrality of the collision.

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1. Introduction

The main goal of heavy-ion physics is the study of the equation of state of nuclear matter and the search of a phase transition to a quark gluon plasma (QGP). The suppression of J/ψ production in nucleus-nucleus collisions has been proposed ten years ago as a signal of colour deconfinement [1]. The NA38/NA50 collaboration has measured, at CERN SPS, the charmonium production in its dimuon decay channel for different systems, more precisely in sulfur induced collisions at 200 GeV/A in NA38 and in Pb-Pb collisions at 158 GeV/A in NA50. The evidence for an « anomalous » J/ψ suppression has been pointed out in Pb-Pb collisions [2]. In the search of the QGP, one is led to address the question of whether the matter issuing from these collisions can reach a thermal equilibrium, at least locally. Even if this equilibrium is local, this implies that the matter behaves collectively which would appear as an elliptic flow. In the NA38/NA50 experiment, the electromagnetic calorimeter is used for the neutral E_T flow determination.

2. Experimental setup

The NA38 detector is mainly composed of a dimuon spectrometer which covers the pseudo-rapidity interval $2.8 < \eta < 4.0$, a segmented active target and an electromagnetic calorimeter. The NA50 apparatus is an upgraded version of the NA38 one. A silicon strips multiplicity detector and a zero degree calorimeter have been added. The two calorimeters provide independent estimates of the centrality of the collision. Other detectors allow to define the incoming beam.

The electromagnetic calorimeter measures the transverse neutral energy corresponding to $E_T = E_{\pi^0} \sin(\theta)$ where E_{π^0} stands for the total energy of the produced neutral pions and θ for their polar angle. It is made of scintillating fibers embedded in a lead converter. Its readout is divided into four rings for NA50 (five for NA38) which are azimuthally segmented into six sextants. The neutral transverse energy is measured in the pseudo-rapidity interval $1.1 < \eta < 2.3$ for NA50 (outside the spectrometer acceptance) and $1.7 < \eta < 4.1$ for NA38 (overlapping the spectrometer acceptance). The contamination of charged particles is estimated and corrected by using Monte-Carlo simulations. Its resolution is 7% for central Pb-Pb collisions.

3. Event selection

The standard method to identify an interaction requires a subtarget identification by its associated Cherenkov counter system. Unfortunately, this method is less efficient for peripheral interactions. In order to recover most of the lost peripheral events, the interaction identification for the Pb-Pb 1996 data is based on a contour-cut on the E_T-E_{ZDC} correlation at the 2σ level [2].

4. Directed and elliptic flow at SPS energy

At relativistic energies, individual nucleon-nucleon collisions produce a positive pressure which deflects the projectile and intermediate rapidity fragments away from the target (« bounce-off » and « sidesplash » effects), resulting in a directed flow in the reaction plane. This plane is defined by the impact parameter and the collision axis (Figure 1). At the ultrarelativistic energies achieved at the SPS, most of the available energy remains in the longitudinal direction, so that the bounce of the projectile on the target is tiny.

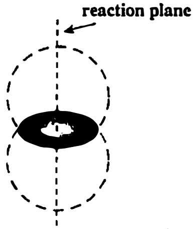

Figure 1 : *A peripheral collision in a transverse plane perpendicular to the beam axis.*

At these energies, the spectators don't influence the expansion of the system because they have left the overlap region before it starts to expand. It has been predicted that if an elliptic flow appears in these conditions, it should be due to collective effects among the produced particles [3]. So it would be a signature of the thermalisation of the produced medium.
In this case, the elliptic flow would develop in the direction of the highest pressure gradient which is the impact parameter direction (in the reaction plane). In central collisions, there is no preferred direction and then no elliptic flow.

5. Analysis method

The flow gives rise to anisotropies in the azimuthal distribution of transverse energy. The determination, event by event, of this distribution provides an information about this effect. For this purpose, we expand the distribution into a finite Fourier serie :

$$\frac{dE_T}{d\varphi} = a_0 + a_1 \cos\varphi + b_1 \sin\varphi + a_2 \cos(2\varphi) + b_2 \sin(2\varphi) + b_3 \sin(3\varphi) \qquad (1)$$

or :

$$\frac{dE_T}{d\varphi} = a_0 + \sqrt{a_1^2 + b_1^2}\cos(\varphi - \varphi_1) + \sqrt{a_2^2 + b_2^2}\cos 2(\varphi - \varphi_2) + b_3 \sin(3\varphi) \qquad (2)$$

The six sextants of the electromagnetic calorimeter provide six transverse energy values $E_{T,k}$ which allow to calculate six Fourier coefficients (a_0, a_1, b_1, a_2, b_2 and b_3) :

$$\begin{aligned} a_0 &= \frac{E_T}{2\pi} \\ a_j &= \frac{j}{6\sin\left(j\frac{\pi}{6}\right)} \sum_{k=1}^{6} E_{T,k} \cos\left(j\frac{(2k-1)\pi}{6}\right) \\ b_j &= \frac{j}{6\sin\left(j\frac{\pi}{6}\right)} \sum_{k=1}^{6} E_{T,k} \sin\left(j\frac{(2k-1)\pi}{6}\right) \end{aligned} \qquad (3)$$

The usual parameters v_1 and v_2 are defined by :

$$\frac{dE_T}{d\varphi} = a_0(1 + 2v_1\cos(\varphi - \varphi_R) + 2v_2\cos 2(\varphi - \varphi_R)) \qquad (4)$$

where φ_R is set for the angle of the reaction plane. v_1 is related to the directed flow and v_2 to the elliptic one.

A comparison of the two last distribution expressions (equations (2) and (4)) allows to calculate directed and elliptic anisotropies from Fourier's coefficients for each event :

$$|v_{1ev}| = \frac{\pi}{E_T}\sqrt{a_1^2 + b_1^2}$$
$$|v_{2ev}| = \frac{\pi}{E_T}\sqrt{a_2^2 + b_2^2} \qquad (5)$$

The measured anisotropies originate from two uncorrelated effects : an anisotropy coming from fluctuations due to the finite multiplicity of the produced particles is added to the relevant one for the flow determination.

The second order (or elliptic) flow is interesting as a signal of a possible thermalisation.

The way to get the flow is to subtract the statistical effects from the elliptic measured anisotropy. It's obvious that this correction can't be done on an event by event basis but only for a set of events of given transverse energy (or multiplicity). For this purpose, the data are divided in transverse energy bins (7 for NA38 and 15 for NA50). For a given E_T (i.e., a given E_T bin) each Fourier's coefficient has a gaussian centered distribution whose sigma can be obtained by a fit. The fluctuations of the third order coefficient, b_3, originate only from the statistical effects. Those of the second order coefficient give in addition an information about the elliptic flow. So, the sigma values of the coefficients a_2 and b_2 bring information about the sum of the statistical effects and of the elliptic flow which add quadratically. Then, the ratio $(\sigma_2/\sigma_3)^2$ can be used to determine if whether or not an elliptic flow is present. An intermediate variable χ is defined as [4] :

$$\chi = \frac{\sqrt{\pi}}{2}\frac{|v_2|}{<|v_{2ev}|>} \qquad (6)$$

where $<|v_{2ev}|>$ is the mean value of the measured elliptic anisotropy, so that :

$$\left(\frac{\sigma_2}{\sigma_3}\right)^2 = C\left(1+\chi^2\right) \propto \frac{\sigma^2_{\text{stat}} + \sigma^2_{\text{elliptic flow}}}{\sigma^2_{\text{stat}}} \qquad (7)$$

where C is a constant.
In central collisions, due to the symmetry, there is no flow and χ equals zero. This allows to determine the value of the constant C and then those of the χ variable for all multiplicities (all E_T bins). Knowing χ and the mean of the measured elliptic anisotropy, we can extract the elliptic flow for each E_T bin :

$$|v_2| = \frac{2}{\sqrt{\pi}}\chi <|v_{2ev}|> \qquad (8)$$

6. Results for Pb-Pb interaction at 158 GeV/c

The transverse energy is proportional to the multiplicity of the produced particles. So the $E_T/E_T(knee)$ ratio is the fraction of the maximum multiplicity and provides a determination of the centrality.
The figure 2.a shows the ratio $(\sigma_2/\sigma_3)^2$ as a function of $E_T/E_T(knee)$ in lead-lead collisions. The value of the C constant is obtained from central collisions. The value of χ is calculated for each E_T bin (figure 2.b). It vanishes for both values zero and one of $E_T/E_T(knee)$ and peaks at mid values.

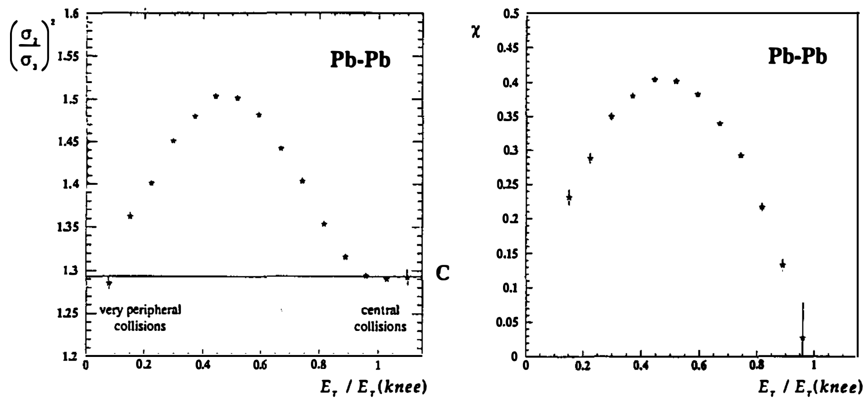

Figure 2.a et 2.b : *Ratio $(\sigma_2/\sigma_3)^2$ (a) and χ variable (b) versus E_T/E_T(knee) in Pb-Pb collisions.*

The figure 3 represents the elliptic flow as a function of E_T/E_T*(knee)*. It peaks at E_T/E_T*(knee)*=0.3 which corresponds to an impact parameter value of about 8 fm. Its maximum value is about 1.75%.

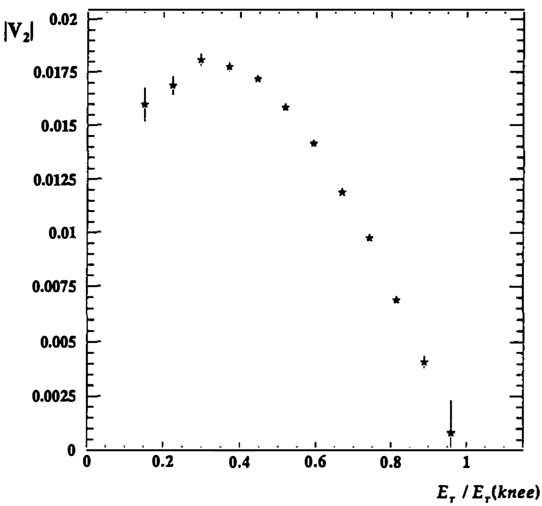

Figure 3 : *The elliptic flow versus E_T/E_T(knee) in Pb-Pb collisions.*

7. Results for S induced interactions at 200 GeV/c

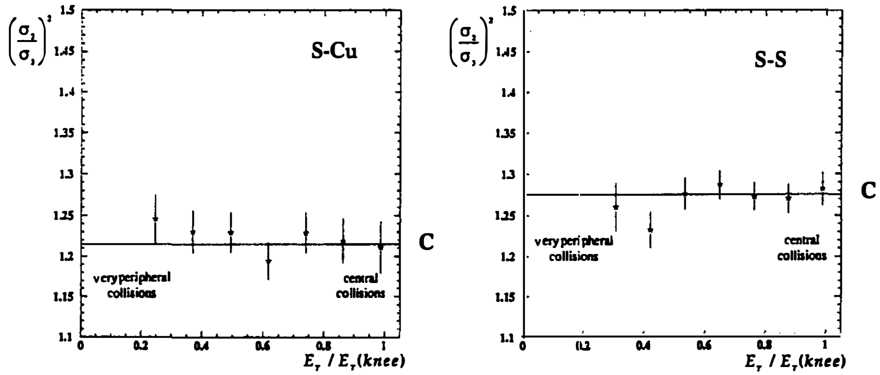

Figure 4.a et 4.b : *Ratios $(\sigma_2/\sigma_3)^2$ versus E_T/E_T(knee) in S-Cu collisions (a) and S-S collisions (b).*

The figures 4.a and 4.b show the ratio $(\sigma_2/\sigma_3)^2$ in sulfur-copper collisions and sulfur-sulfur collisions. These data are compatible with a zero value of the χ variable. There is no elliptic flow in these interactions.

8. Conclusion

Although the electromagnetic calorimeter of the NA38/NA50 experiment is designed to work as a centrality tool, it can be used to determine the azimuthal distribution of the neutral transverse energy for each value of E_T, on an event by event analysis.

An elliptic flow is clearly present in Pb-Pb interactions at 158 GeV/c. Its maximum value is about 1.75% for semi-peripheral collisions. The elliptic flow, as a signature of collective effects, could be a hint of the thermalisation of the matter issuing from these collisions. On the other hand, S-S and S-Cu interactions at 200 GeV/c provide no evidence for the existence of an elliptic flow.

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