Anisotropic flow is recognized as one of the main observables providing information on the early stage of a heavy-ion collision. At RHIC the observed strong collective flow of the bulk matter is considered evidence for an early onset of thermalization, and an ideal hydrodynamical expansion with an equation of state consistent with that obtained from lattice QCD calculations. The large collective flow of the bulk and the inferred large energy loss of the produced jets propagating through the created matter are key signatures for the formation of a Quark Gluon Plasma.

1 Introduction

QCD calculations predict that a sufficient large system heated to a temperature of approximately 170 MeV will undergo a phase transition from normal nuclear matter to a Quark Gluon Plasma (QGP). Heavy-ion collisions are expected to provide the best controlled environment to create and study such a large high temperature system. Experiments at the Relativistic Heavy Ion Collider (RHIC), the first heavy-ion collider, have provided a new era in the study of QCD matter.

2 Azimuthal correlations versus the reaction plane

2.1 Particles with intermediate and high transverse momenta

One of the most promising observables, discovered at RHIC, is the suppression of particles with large transverse momenta. The predicted mechanism for this suppression, the so called jet-quenching, is parton energy loss by induced gluon radiation. The magnitude of the energy loss depends on the parton density (mostly gluons) of the created system and its size.

In non-central heavy-ion collisions the nuclear overlap region in the transverse plane has an almond like shape, see Fig. 1a. In the case of parton energy loss, the particle yield at large transverse momenta due to the spatial anisotropy of the created system will have an azimuthal correlation with respect to the reaction plane (the plane spanned by the beam axis \( z \), and the impact parameter, which is along the \( x \)-axis). As the initial spatial geometry of the collisions is known the azimuthal dependence of the high-\( p_t \) particle yield is a sensitive probe to the details of jet quenching. The particle yield as a function of azimuthal angle can be described by:

\[
E \frac{d^3N}{d^3p} = \frac{1}{2\pi} \frac{d^2N}{p_t dp_t dy} [1 + \sum_{n=1}^{\infty} 2v_n \cos(n\phi)]
\]

The coefficient of the second harmonic of this Fourier decomposition, \( v_2 \), is called elliptic flow.
Figure 1: a) Illustration of the nuclear overlap region in non-central heavy-ion collisions. b) $v_2$ obtained from two, $v_2 \{2\}$, and four particle, $v_2 \{4\}$, cumulant methods versus transverse momentum.

Figure 2: a) The di-hadron azimuthal correlation in and out of the reaction plane b) The di-hadron azimuthal correlation after subtracting the elliptic flow contributions c) $v_2$ at large transverse momenta compared to different energy loss scenarios.

Figure 1b shows the elliptic flow as a function of transverse momenta. The elliptic flow is calculated using the two, $v_2 \{2\}$, and four particle, $v_2 \{4\}$, cumulant methods which give, as shown in Fig. 1b, about 20% difference in magnitude of $v_2$. This is understood because the azimuthal correlation between the particles, used to calculate $v_2$, is not completely caused by their correlation with the reaction plane. Azimuthal correlations from e.g. jets and resonances, would affect the two particle cumulant more than the higher order ones. Fluctuations also affect $v_2 \{2\}$ and $v_2 \{4\}$ but when small in the opposite direction. In our current understanding, the best estimate of the true elliptic flow is between $v_2 \{4\}$ and $(v_2 \{2\} + v_2 \{4\})/2$. The elliptic flow shown has its maximum around 3 GeV/c, and even at 8 GeV/c is still quite substantial. In case of jet quenching the elliptic flow is expected to be non-zero.

The di-hadron azimuthal correlation is expected, due to the spatial anisotropy of the system, to be sensitive to the jet quenching. Figure 2a shows the azimuthal correlations of two charged particles, were the trigger particle is defined as $4 < p_{t, trig} < 6$ GeV/c and the associated particle satisfies $2$ GeV/c < $p_t$ < $p_{t, trig}$. The squares show the di-hadron correlation when the trigger particle is within $\pi/4$ aligned with the reaction plane, the x-axis in Fig. 1a. The stars show the di-hadron correlation when the trigger particle is within $\pi/4$ perpendicular to the reaction plane, the y-axis. The dominant correlation is the opposite oscillation due to the elliptic flow of the trigger and associated particle, which is shown as the dashed lines in Fig. 2a. In Fig. 2,
the di-hadron correlation, in and out of the reaction plane, is shown after the elliptic flow contribution is subtracted[8,10,11]. The near-side jet-like correlation in and out of the reaction-plane is identical within uncertainties and also identical to the correlation observed in proton + proton collisions (solid lines). The away-side correlation is for in and out of the reaction-plane suppressed compared to proton + proton collisions, as expected in the case of jet quenching. It is also suggestive that the correlation out of the reaction plane is suppressed more, which in case of jet quenching is expected due to the different size of the system versus azimuth.

Figure 2c shows the magnitude of the elliptic flow, between 4 and 7 GeV/c, versus the collision centrality. The curves[12] show various attempts, using different energy loss scenarios, to describe the centrality dependence and the magnitude of $v_2$. The large magnitude of the elliptic flow at high-$p_t$ is however difficult to interpret using the energy loss mechanism alone, as illustrated here by the failure of the curves to describe the measurements. The measured $v_2$ is even larger than expected in case of complete quenching[13].

A possible interpretation for the large magnitude of $v_2$ at intermediate $p_t$ comes from the observed mass dependence. Figures[3,14] and[3,15] show the $v_2$ for various particles as a function of $p_t$. At higher transverse momenta the $v_2$ shows a particle dependence, which within uncertainties, can be divided in two groups; baryons and mesons. The proposed mechanism which naturally leads to a baryon/meson scaling is constituent quark coalescence[16]. In this scenario, at intermediate $p_t$, the mesons carry twice the constituent quark $v_2$ (the baryons three times) which implies a constituent quark $v_2$ of about 0.065[18]. In the suppression of particle production a baryon/meson scaling is also observed. In the coalescence/recombination interpretation this follows consistently[17].

### 2.2 Particles with low transverse momentum

The observations at intermediate and high-$p_t$ at RHIC clearly show evidence of strong final state interactions. One of the central questions which remains is if the created system thermalizes, and if this happens early (during the assumed partonic phase) in the collision. One of the first observations at RHIC, Fig. 4, showed a large increase in the integrated elliptic flow from the highest SPS to the highest RHIC energies, approaching the values predicted by ideal hydrodynamical calculations which assumes local thermal equilibrium already after 0.2 fm/c. The collective behavior, one of the key features of a hydrodynamical description, is particularly clear in the mass dependence of the elliptic flow as shown in Fig. 4b. The hydrodynamical model calculations[20] give a good description of the elliptic flow from the light pions to heavier particles like the $\Xi$. 

Figure 3: a) Identified particle $v_2$ from PHENIX[13] b) Identified particle $v_2$ from STAR[15]
Figure 4: a) Integrated elliptic flow values for the highest SPS energy, NA49\cite{10}, and the two highest RHIC energies. b) Elliptic flow as a function of transverse momentum for various particles at low-$p_t$.

3 Conclusions

The observed strong collective flow and the strong suppression of high-$p_t$ hadrons indicates that a dense strongly interacting system is created. The system appears to a good approximation in local thermal equilibrium. The bulk of the system responds as a near-ideal, strongly coupled fluid with an equation of state consistent with lattice QCD calculations. There remain however important fundamental open questions. Perhaps the most important one is the microscopic mechanism underlying the apparent rapid thermalization. High precision measurements of low-$p_t$ multi-strange and charmed hadron spectra and correlations at RHIC and first results from the heavy-ion program at the LHC will provide an important confirmation or perhaps new insights to our current understanding.

References

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