High-$p_\perp$ charged particles azimuthal correlation in PHENIX

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Abstract

A two-particle azimuthal correlation analysis of the PHENIX data taken at $\sqrt{s_{NN}} = 130$ GeV/c is discussed. A comparison of the magnitude of $v_2(p_\perp)$ extracted from the correlation analysis with those obtained from a reaction plane analysis by the STAR collaboration, indicates surprisingly small non-flow contributions. A similar comparison obtained from the CERES experiment at $\sqrt{s_{NN}} = 17$ GeV/c shows stronger non-flow contributions for a similar $p_\perp$-range which can be attributed to the presence of mini-jets. It is argued that for the $p_\perp$-range below 2-3 GeV/c the RHIC results may be indicative of a novel particle production mechanism related to low-x gluon saturation.

1 Introduction

An increased role of hard scattering physics in heavy ion collisions is expected at RHIC. The presence of partonic back-to-back scattering in p-p collisions at even smaller $\sqrt{s_{NN}}$ was experimentally observed a long time ago [1] and understood in terms of pQCD [2]. In contrast to expectations at the SPS, where the phenomena induced by hard scattering play only a marginal role, the scope of the energy explored at RHIC allows full exploration of the partonic degrees of freedom in heavy ion collisions.

The hard partons are believed to be produced only very early in the collision, so they can provide a sensitive probe for the early evolution of nuclear collisions, where the anticipated quark gluon plasma (QGP) is expected to be produced [3]. The QGP, if formed, is a very dense partonic medium. The high-energy partons propagating through this dense medium are predicted to lose a substantial fraction of their energy [4]. One consequence of this is that the partonic energy loss, measured via suppression of high-$p_\perp$ particle yield, provides the means for measuring the partonic density of the excited matter created in nuclear collisions. Such measurements are believed to be important for the extraction of information about a possible transition to the QGP.

The analysis of the year-1 PHENIX data taken at $\sqrt{s_{NN}}$=130 GeV/c in summer 2000 (details of the PHENIX detector can be found in [5, 6]) brought even more excitement to the heavy ion pQCD community. The ratio of charge particle inclusive yield from central A-A collisions over the yield from p-p collisions scaled by number of binary n-n collisions (the so called "nuclear modification factor" R_{AA}) plotted as a function of $p_\perp$ indicates a clear suppression of particle yield above 1.5-2 GeV/c [7].

This experimental observation was confirmed by the STAR collaboration [8] and the first analysis shows the consistency of observed $p_\perp$ dependence of R_{AA} with jet-quenching [9] and average partonic energy loss of order of $< dE/dx > \approx 0.25$ GeV/fm [10, 12]. Although the interpretation of the observed suppression of high-$p_\perp$ particle yield is still under investigation the phenomenon does appear to be unique. At SPS energies, the observation of a similar jet-quenching has been masked by the "Cronin" effect [13]. That is, early partonic cascade of the high-$p_\perp$ particle yield is actually enhanced by non-pQCD Cronin-type soft multiple scattering and then maybe slightly suppressed by partonic energy loss. Thus, the suppression and partonic energy loss needs to be deduced from reduction of high-$p_\perp$ yield enhancement. Since the Cronin effect is a non-pQCD phenomenon, it is difficult to disentangle the Cronin enhancement and partonic suppression.

This difficulty persists basically also at RHIC, but the magnitude of the Cronin enhancement, predicted by various theory e.g. [14], is smaller because of quantum coherence effects. The data, surprisingly, shows no enhancement. Instead, it exhibits a suppression over the entire $p_\perp$-range, possibly indicating some combined influence of small magnitude for the Cronin enhancement, large high-$p_\perp$ particle suppression or nuclear shadowing [15].

2 High-$p_\perp$ particles azimuthal correlations

Another way of exploring hard scattering in heavy ion collisions is to study the azimuthal correlations between two high-$p_\perp$ particles. Hard scattering is accompanied by the production of two back-to-back parton jets in the center-of-mass frame of the partonic collision. This leads to an enhancement of back-to-back particle yield if hard scattering is present [16]. The correlation in rapidity space is smeared by partonic intrinsic momentum $k_\perp$. The smearing of the back-to-back correlation in azimuthal space is also affected by finite $k_\perp$ (of order of 1 GeV/c) and the fragmentation function, but in a more modest way.

Experimentally the correlation function $C(\Delta\phi)$ is determined as ratio of the

$\Delta\phi$ distribution of "true" particle pairs N_{real} and the distribution for mixed pairs N_{mixed} in which each particle is obtained from a different event.

$$C(\Delta\phi) = \frac{N_{mixed}}{N_{real}} \times \frac{dN_{real}/d\Delta\phi}{dN_{mixed}/d\Delta\phi} \tag{1}$$

In the analysis discussed here we have determined $\Delta\phi$ for all particle pairs in the same event ie. $N(N-1)/2$ pairs, where N is the particle multiplicity in a given event.

At RHIC, at least for $p_\perp \leq 2$ GeV/c, the main source of two-particle correlations is still the soft QCD collective motion associated with hydrodynamic flow [17]. In this case there is no direct correlation between particles. Instead, the particles are all correlated with a reaction plane given by the beam direction and the impact parameter. The azimuthal distribution of produced particles is not any longer isotropic and has a characteristic elliptic shape (we will discuss only this type collective flow, since any other order is not relevant for our analysis). This phenomenon is called "elliptic flow". The associated correlation function is commonly characterized in terms of the Fourier expansion [18]

$$C(\Delta\phi) \propto (1 + 2v_2^2 \cos(2\Delta\phi)). \tag{2}$$

The v_2 coefficient characterizes the strength of the particle correlation with the reaction plane. The correlation function $C(\Delta\phi)$, in case of pure flow events, can be fully described only by use of te $\cos(2\Delta\phi)$ function. The measured correlation function could also contain contributions from resonance decays, or HBT correlations. However, such contributions are typically small and can be effectively suppressed by eg. minimum opening angle cut.

One manifestation of hard scattering events would be a small asymmetry in the otherwise $\cos(2\Delta\phi)$ distribution. The parton fragmentation produces a jet of final state particles in a small cone size giving rise to a near-angle azimuthal correlation - typically of Gaussian shape around 0°. The back-to-back scattered partons produce the far-angle correlations seen as a Gaussian peak distributed around 180°. The width of far-angle Gaussian peak (two jets) should be larger (fragmentation and $k_\perp$ smearing) than the near-angle correlation peak (mono-jets). The number of two-jets events is also smaller (factor 3-5 in case of PHENIX acceptance) than the number of mono-jet events. This is because of limited rapidity acceptance and huge smearing of back-to-back correlations along the beam axis.

Unfortunately the angular width of the hard scattering peaks corresponding to the size of the jet cone is large (20°-30° depending on $p_\perp$) and it is difficult to separate these peaks from the dominant $\cos(2\Delta\phi)$ background. One possible way to overcome this problem is to measure the strength of the anisotropy (v_2) using the standard reaction plane technique and to compare this to the v_2 values derived from two-particle correlation measurement. A larger two-particle correlation v_2 value would then be a signature for the presence of the hard-scattered events.

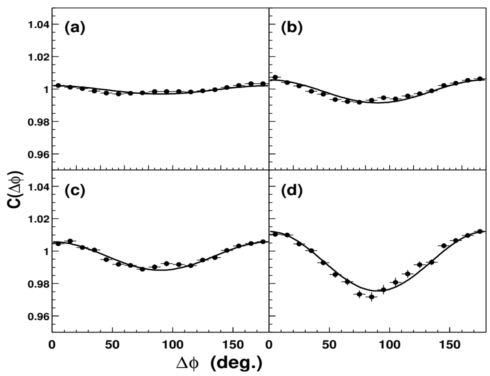

Fig. 1: Two charged particles correlation function (1) for two different centralities (mid-central (a),(c) and fairly peripheral (b),(d)) and two different $p_\perp$-cuts (0.3<$p_\perp$<2.5 (a),(b) and 0.5<$p_\perp$<2.5 (c),(d)).

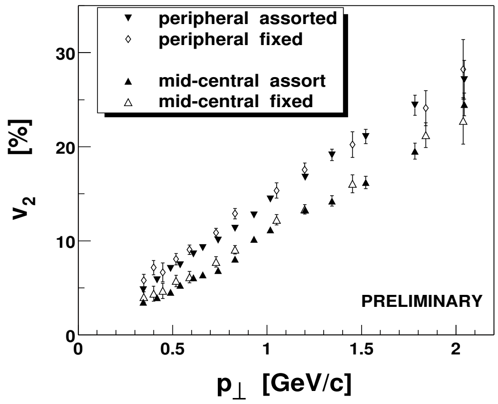

Fig. 2: The differential $v_2(p_\perp)$ values from fixed and assorted method for peripheral events (empty and solid triangles) and for mid-central events (empty diamonds and solid triangles).

A typical example of the two-particle correlation functions obtained for charged particles (1) measured in the PHENIX experiment is shown on Fig. 1. The shape of all four distributions is satisfactorily described by the $\cos(2\Delta\phi)$ function. The correlation is more prominent for more peripheral events and for the higher $p_\perp$-range. No obvious distortions due to the presence of Gaussian-like hard scattering correlations are visible. This allows us to determine the v_2 parameter for various centralities and $p_\perp$-cuts using the prescription (2). The results for 0.3<$p_\perp$<2.0 and two centrality bins are displayed in Fig. 2. We are showing the results from two different techniques used for $v_2(p_\perp)$ determinations:

F Fixed $p_\perp$ method. Particles are correlated only with other particles from particular $p_\perp$-bin.

A Assorted $p_\perp$ method. Particles from $p_\perp$-bin under the consideration are correlated with any other particle from the entire $p_\perp$-range except the considered $p_\perp$-bin. Resulting v_2 is then a product of $v_2(p_\perp)$ and v_2 evaluated using all particles from entire range (see [19]). In case of absence of any non-flow correlations, these two methods should provide the same value of v_2. The advantage of assorted method is, that it uses all particles from entire range for determination of the v_2 in a given $p_\perp$-bin, which significantly improves the statistical errors.

3 What do we learn from two-particles $v_2(p_\perp)$?

An unexpected feature of the data shown on Fig. 2 is that the values of $v_2(p_\perp)$ determined using the assorted and the fixed $p_\perp$ methods, are, within the error bars, the same. Picking the charged particles from the same $p_\perp$-bin one would expect at higher $p_\perp$ a more significant influence of mono or di-jets production. Correlating particles from a given $p_\perp$-bin with all other particles, as done in assorted method, should pick more low-$p_\perp$ flow-like correlations and this method should be less sensitive to the presence of jets in the data.

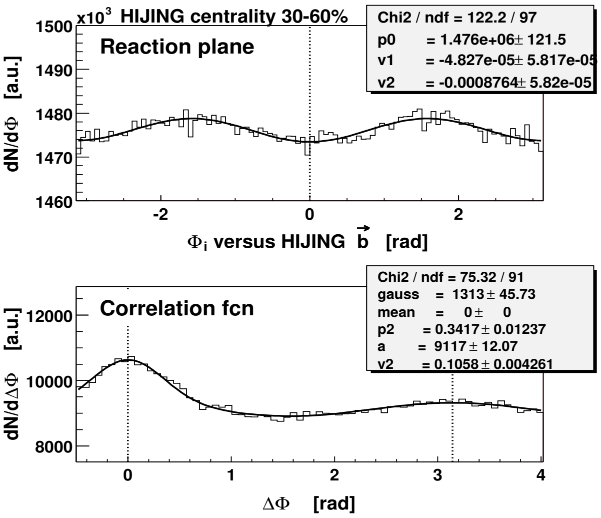

Fig. 3: The angular distributions of all particles from HIJING Monte Carlo event generator. An upper panel show the azimuthal distribution of all particles ($p_\perp > 0.3$ GeV/c) with respect to the HIJING reaction plane. The lower panel shows the two particle correlation function (1) for the same events.

In order the get a rough estimate what is the strength of two-particle correlations predicted by pQCD theory, we can use the HIJING pQCD-based Monte Carlo event generator [20] and calculate the value of v_2 from simulated events. HIJING model gives a reasonable description of the measured $p_\perp$

inclusive spectra in p-p and A-A collisions [11] and a similar calculation was used to determine the parton energy loss [10] deduced from PHENIX Au-Au data. Since this model does not take into account any hadron re-scattering, it does not predict any flow phenomena. But one can use this model to predict the value of v_2 expected if the hard scattering events take place in the A-A collisions.

The results of this calculations are shown on Fig. 3. In the upper panel the azimuthal distribution of all particles ($p_\perp >$ 0.3 GeV/c) generated by HIJING event generator with respect to the HIJING reaction plane is displayed. By fitting the distribution (1) we have extracted $v_2 \approx$ -0.1%. This value is very small, as one should expect, because the model does not simulate the flow phenomena. However, the extracted v_2 is not vanishing and it is negative (out of plane flow). This can be understood via the following. The high energy partons propagating parallel to the impact parameter $\vec{b}$ see less excited matter than those propagating out-of-plane and so they suffer less induced radiation (see [4]). In such a scenario one should see slightly more particles produced out-of-plane (negative v_2). Given the magnitude of the signal this effect is evidently small in this case.

The two-particle correlation v_2 derived from the distribution displayed in the lower panel of Fig 3 is large ($v_2 \approx$10%) and the correlation function can not be satisfactory described by the $\cos(2\Delta\phi)$ function. One can clearly see the presence of a near-angle correlation peak caused by jet fragmentation.

As one can learn from Fig. 3, the two-particles correlation analysis provides larger v_2 than the reaction plane analysis. Correlating particles from higher $p_\perp$-bins the relative fraction of particles emerging from hard scattering should increase with $p_\perp$. On the other hand the reaction plane is determined using all particles down to very low $p_\perp$, so the $v_2(p_\perp)$ is in this case not so strongly affected by presence of jets.

Analysis of the HIJING events suggests, that if jets are produced so copiously as in this model, one should expect significantly larger v_2 derived from two-particle correlation analysis than from the reaction plane analysis.

In Fig. 4 we compare the assorted two-particles $v_2(p_\perp)$ measured in PHENIX with reaction plane analysis carried out by STAR collaboration [21] for one common centrality selection. The solid line represents the calculated $v_2(p_\perp)$ from the particle distribution with respect to the reconstructed reaction plane in HIJING as it would appear in the standard reaction plane analysis (not the same as in Fig. 3, where the particles distribution with respect to the true HIJING reaction plane is plotted). The magnitude of $v_2(p_\perp)$ in reconstructed reaction plane analysis remains small. Upper dashed and dotted lines correspond to $v_2(p_\perp)$ extracted from fixed and assorted two-particle correlation analysis of the same HIJING events, which would appear similar to a substantial hydrodynamic flow.

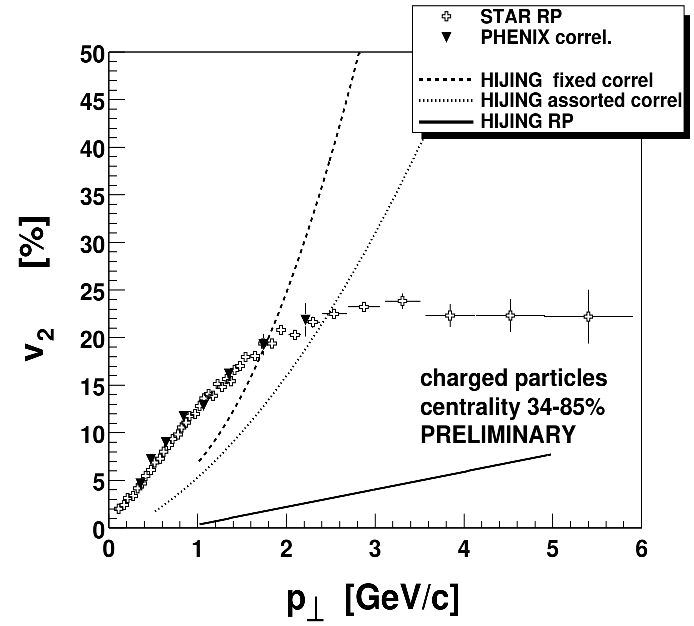

Fig. 4: Differential $v_2(p_\perp)$ derived from PHENIX assorted two-particle correlations (solid triangles) and from STAR reaction plane analysis (empty boxes). The lower dotted line shows the jet-like $v_2(p_\perp)$ from HIJING reaction plane analysis, dashed and solid line correspond to HIJING assorted and fixed correlation technique respectively.

The differences between the dotted, dashed and solid line in Fig. 4 demonstrate different sensitivity of the two-particles and reaction plane $v_2(p_\perp)$ to the presence of jets in the data. But the measured $v_2(p_\perp)$ values from these three different methods (see also Fig. 2) do not differ at all. This clearly indicates a negligible non-flow component in the measured two-particle $v_2(p_\perp)$ in the $p_\perp$-range at least up to 2 GeV/c.

4 Discussion

We have demonstrated the agreement between two different v_2 analysis. Measured values of $v_2(p_\perp)$ from two-particles correlations do not indicate any signature of hard scattering in the $p_\perp$-range up to 2 GeV/c. The same analysis in similar $p_\perp$-range ($1<p_\perp<2.5$ GeV/c) done at SPS [22] shows a significant non-flow component in two particles $v_2(p_\perp)$. One obvious difference between SPS and RHIC is that the particles in the same $p_\perp$-range are at SPS produced from partons with much higher Bjorken x than it is in case of RHIC energy. Particle of $p_\perp$=2 GeV/c carries $2p_\perp/\sqrt{s_{NN}}$ ≈0.25 of total available momentum. Whereas the same particle at RHIC would correspond to $x \approx 0.03$ - factor of 10 less then at SPS. It means at RHIC at least ten times lower x-range of parton structure function is explored. There are various predictions, that at this regime the gluon structure function does not grow any longer with decreasing x, but rather saturates [23]. The partons (mostly gluons) in this saturation region participate in the interaction coherently and form so called "color glass condensate" [24]. The final state particle production may be then dominated by the classical QCD field radiation (mono-jets) and the pQCD picture could be recovered in $p_\perp$-region well above saturation scale ($p_\perp \geq$3-4 GeV/c).

There is still a lot of opened questions which need to be investigated, but the gluon saturation phenomenon seems to be suggestive explanation of observed absence of two-particle correlations in PHENIX data.

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