Ways to constrain the away side jet in Au + Au collisions in PHENIX

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Abstract
We discussed methods used by the PHENIX to constrain the flow background in the two particle jet correlation. Both the background level and elliptic flow can be reliably decomposed from the jet contribution. We also studied the non-flow contribution to the reaction plane elliptic flow due to dijets. We found the jet bias is negligible in PHENIX, when the reaction plane is measured at Beam Beam Counter acceptance (3 < |η| < 4).

1. Introduction

Two particle azimuth correlation is a useful tool to study the strongly interacting partonic matter believed to has been created at RHIC Au+Au collisions. The typical correlation function can be decomposed into a jet part $J(\Delta \phi)$ and an underlying event part $\xi$ that is modulated by the elliptic flow [1]:

$$C(\Delta \phi) = J(\Delta \phi) + \xi(1 + 2v_t^2v_a^2 \cos 2\Delta \phi)$$

(1)

In the case that dijet is not modified by the medium, $J(\Delta \phi)$ behaves just like in p+p collisions. The RHIC data has shown a rich modification pattern, which is dependent on the $p_T$ of both particles and can be characterized into four qualitatively distinct regions. 1) A broadening jet shape at the away side and enhancement of the jet multiplicity at both the near and away side at low $p_T$ [2]; 2) A flat or possible volcano-shaped away side jet pairs at intermediate $p_T$ [1]; 3) A seemingly complete disappearance of away side jet or equivalently a flat away side extended to the near side at moderately high $p_T$ [3]; 4) Reappearance of the away side jet peak at very high $p_T$ [4]. Several models were proposed to explain various aspects of the modification pattern, but so far no model can consistently describe all four regions on a quantitative level.

The medium effects on the dijets can be quantified by $I_{AA}$, which is the ratio of the jet yield per trigger in A+A collisions to that in p+p collisions. Since the modification is always on the jet pairs, the following relation holds between the per-trigger yield using the high $p_T$ particles as triggers (type a) and that using low $p_T$ particles as triggers (type b):

$$R_{AA}^a I_{AA}^a = R_{AA}^b I_{AA}^b = \frac{\text{JetPairs}_{AA}}{N_{\text{coll}} \times \text{JetPairs}_{pp}}$$

(2)

where $R_{AA}$ is the single particle suppression factor, $\text{JetPairs}_{AA}$ and $\text{JetPairs}_{pp}$ represent the average number of jet pairs in one A+A collision and one p+p collision, respectively. One would expect $I_{AA}^a = R_{AA}$ for hadron-hadron correlation due to trigger surface bias. In contrast, the medium is transparent to the leading photons in direct photon-jet correlations. One expect that the away side jet behave exactly as the single jet suppression: $I_{AA} = R_{AA}$.

The level of accuracy in extracting the jet signal depends on how well one determines the elliptic flow of both particles, $v_t^2, v_a^2$ and combinatoric background level $\xi$. PHENIX measures the elliptic flow through the reaction plane (RP) method, where the event plane (EP) is determined by the BBC at forward region (3 < |η| < 4). The systematic error on the $v_2$ is dominated by the EP resolution, $\delta v_2^2/v_2^2 = \delta v_a^2/v_a^2 = \epsilon_{\text{reso}}$. $\xi$ represents the ratio of the combi-
natoric background in same event to that in mixed event: \( \langle n_{n} n_{a} \rangle = \xi \langle n_{i} \rangle \langle n_{a} \rangle \). It is typically slightly above 1 due to finite multiplicity fluctuation in a typical centrality bin. The uncertainty on the correlation function can be expressed as:

\[
\delta C = 2 \left( \xi \delta v_{2}^{n} + \xi \delta v_{2}^{a} + \delta \xi v_{2}^{n} \right) \cos 2\Delta \phi + \delta \xi
\]

\[
\approx 2\xi \cos \phi \cos 2\Delta \phi + \delta \xi
\]

Given the typical values of various factors: \( \xi \approx 1 \), \( \delta \xi < 0.1 \), the above formula can be simplified as

\[
\delta C = 4\xi \cos \phi \cos 2\Delta \phi + \delta \xi \quad (4)
\]

2. Constrain Background Level \( \xi \)

PHENIX has previously used two methods in determining the \( \xi \); the absolute normalization (ABN) method [5] and Zero Yield At Minimum (ZYAM) method [1,6]. The ZYAM method assumes there is a point in \( \Delta \phi \) where jet yield is zero, i.e. the background term “kisses” the correlation function. The \( \xi \) value from ZYAM method is a upper limit since the background cannot be higher than the total in Eq.1. The ABN method calculates \( \xi \) directly by assuming a certain relation between multiplicity and centrality.

Here we discuss a third method in constraining \( \xi \), based on the combined information from opposite-sign charged pairs (OSC) and same-sign charged pairs (SSC). Fig.1a shows the azimuthal distributions for OSC and SSC for top 0-5% Au+Au collisions for 2.5 < \( p_{T,\text{trig}} \) < 4 GeV/c and 1 < \( p_{T,\text{asso}} \) < 2 GeV/c. The OSC correlation at the near side is larger than that for SSC, while the charge combination has no effect on the back-to-back correlations. The difference of the jet strength at the near side is a consequence of the charge ordering effect in the jet fragmentation process, which leads to more OSC pairs than SSC pairs. One would not expect any charge correlation between the pair at the \( \Delta \phi \approx \pi \), since they come from different jets. The ZYAM method clearly finds different \( \xi \) values between the two although their true values should be identical. Fig.1b shows the jet signal estimated independently for OSC and SSC using the ZYAM approach. The estimated away side jet yield for OSC and SSC pairs are clearly different due to the difference in \( \xi \) from ZYAM.

In both cases, the ZYAM minimum is at around the same \( \Delta \phi_{0} \approx 0.8 \). The difference at that point indicated different amount of near side jet contribu-

Fig. 1. a),c) The correlation function in 0-5% centrality bin for opposite-sign pairs (open circles) and same-sign charged pairs (closed circles). The lines indicate the background level determined via ZYAM method (a)) and charge-dependent method (c)). b),d) The background subtracted distribution for using ZYAM (b)) and charge-dependent method (d)).

The ABN method calculates different amount of near side jet contribution. Given that the near side jet width are the same between SSC and OSC pairs [7], jet contribution can be written explicitly for the two cases as,

\[
J_{N}^{S} = J_{N}^{S} (\Delta \phi) + J_{A} (\Delta \phi) \quad (5)
\]

\[
J_{N}^{O} = J_{N}^{O} (\Delta \phi) + J_{A} (\Delta \phi) = A_{0} J_{N}^{S} (\Delta \phi) + J_{A} (\Delta \phi)
\]

Define \( \Delta \xi = (A_{0} - 1) J_{N}^{SSC} (\Delta \phi_{0}) \), i.e. the difference in the \( \xi \) value between OSC and SSC pairs, we got

\[
J_{N}^{S} (\Delta \phi_{0}) = \frac{\Delta \xi}{A_{0} - 1} = \frac{J_{N}^{S} (0) / J_{N}^{S} (0) - 1}{J_{N}^{S} (0) / J_{N}^{S} (0) - 1} \quad (6)
\]

\[
J_{N}^{O} (\Delta \phi_{0}) = \Delta \xi \frac{J_{N}^{O} (0) / J_{N}^{O} (0) - 1}{J_{N}^{O} (0) / J_{N}^{O} (0) - 1} \quad (7)
\]

The near side jet contribution at the \( \Delta \phi_{0} \) can be calculated from the near side jet peak value (at \( \Delta \phi = 0 \)), which is given by ZYAM method. Since the jet fraction is large at the peak region, fractional error of the peak values due to uncertain on \( \xi \) from ZYAM is small. We include it in final systematic error. The results of this procedure is shown in Fig.1d. The subtracted distribution are identical on the away side but shifted above 0 as expected.

The charged dependence method is useful when the statistic is good, such that \( \xi \) is well constrained at the ZYAM minimum and \( J_{A} (\Delta \phi_{0}) \) can be reliability estimated. We recognize that there could be contributions from away side jet at ZYAM minimum also, \( J_{A} (\Delta \phi_{0}) \), which is inaccessible in current ap-
The triggers are selected in a limited angular bite of φ. The approach. Thus the ξ value obtained in this method could still be too big. Table 1 summarize the ξ values obtained from the three methods.

3. Constrain $v_2$ from Reaction-Plane Dependent Correlation

Let’s define $\sigma_n = \langle \cos n(\Psi_{EP} - \Psi_{RP}) \rangle$ as EP resolution for nth order harmonics using the elliptic flow RP. According to [8], the pair distribution when the triggers are selected in a limited angular bite of $\phi_\ast \pm \epsilon$ with respect to reaction plane is

$$C_{c,\phi_\ast} = J_{c,\phi_\ast}(\Delta \phi) + \xi (1 + 2v_2^b \frac{b}{a} \cos 2\Delta \phi)$$

$$\begin{cases} a = 1 + 2v_2^c \cos 2\phi_\ast \frac{\sin 2c}{2c} \sigma_2 \\ b = v_2^b + \cos 2\phi_\ast \frac{\sin 2c}{2c} \sigma_2 + v_2^b \cos 4\phi_\ast \frac{\sin 4c}{4c} \sigma_4 \end{cases}$$

Fig. 2a shows the CFs in 0-5% central Au+Au collisions for 6 angular bins in 15° steps. Fig.2b shows the jet yield after subtracting the flow terms calculated according to Eq.8. Although the CFs change dramatically from in plane to out of plane, the calculated flow term tracks the true flow background nicely. Given the small eccentricity in 0-5%, we can safely assume that the jet yield, $J_{c,\phi_\ast}$, does not depend on the trigger direction. In this case, the small difference between the jet functions in Fig.2b can be used to further constrain the $v_2$

4. Non-flow Effects from Jets

Reliable extraction of the jet signal requires accurate determination of $v_2^b$ and $v_2^c$. To this end, contributions from non-flow correlations that lead to azimuth correlations not related to the true RP direction, need to be studied. The non-flow correlations include transverse momentum conservation effects, resonance decays, HBT correlations that are important at low $p_T$ [9,10] and jet correlations that are important at high $p_T$ [11]. The non-flow correlations affect the $v_2$ values either by changing the EP resolution or cause fake $v_2$ by biasing the EP direction towards the now-flow particles. The former is small if the non-flow particle multiplicity is small. The later can be suppressed in PHENIX if the correlations are limited in a narrow $\eta$ window, such as the resonance and intra-jet correlations, thanks to the large $\eta$ separation between BBC and central arm. However, the inter-jet correlations can still bias the BBC reaction plane determination, due to their broad distribution in $\Delta \eta$.

![Fig. 2. a) Correlation function for various 6 trigger direction bin and the trigger integrated bin (the center curve. b) The background subtracted per-trigger yields, the insert figure shows the 6 trigger bins.](image)

![Fig. 3. The effect of the dijet on reaction plane resolution as function of centrality in different rapidity windows. The embedded jet is at mid-rapidity.](image)

We study the biases due to dijet correlations by embedding dijet pairs into background events with realistic flow modulation. The background Au+Au events are simulated with HIJING, which was checked to reproduce the charged hadron multiplicity in $\eta$ from PHOBOS. Elliptic flow is implemented by applying a track by track weight for each HIJING event:

$$w(b, p_T, \eta) = 1 + 2v_2(b, p_T, \eta) \cos 2(\phi - \Psi)$$

where the $\Psi$ is the direction of the impact parameter $b$. The centrality, $p_T$ dependence of the $v_2$ is tuned according to the PHENIX measurement [12]. We
used a common $\eta$ dependence from PHOBOS \cite{13} for all centrality selections. The dijet pairs are generated from PYTHIA event generator, requiring a leading particle above 6 GeV/c at mid-rapidity ($|\eta| < 0.35$). This corresponds to typical energy of $6/\langle z\rangle \approx 10$ GeV/c for the dijets.

The effects of the dijets are evaluated by comparing the event plane before and after the embedding. Since dijet pairs are random with respect to the RP, the EP resolution for combined event is worse as shown in Fig.3. The difference in EP resolution is small except in peripheral bins where the event multiplicity is small. And the difference become negligible in more forward $\eta$ window. On the other hand, dijet tends to pull the event plane towards the dijet direction, resulting in a fake $v_2$ for the leading hadrons as shown in Fig.4, where the relative azimuth distribution between the leading hadrons and EP from either the HIJING event or the combined event are plotted. The dijets are clearly correlated with the EP determined from the combined event, thus have a fake $v_2$.

The size of the fake $v_2$ depends on the rapidity gap between the triggering hadron and the subevent used to determine the event plane. Due to the away side jet swing, one would expect the this bias persists to large $\eta$ region. Fig.5 shows the centrality dependence of fake $v_2$ for various rapidity window. This fake $v_2$ is the raw signal extracted from fit in Fig.4 without divided by EP resolution. The fake $v_2$ decreases as the subevent moves towards large $\eta$. When the subevent is $3 < |\eta| < 4$ (BBC acceptance), the fake $v_2$ becomes almost negligible.

So far, we have assumed normal dijet in our study. RHIC data indicates that there is a broadening of the away side jet and an increase of jet multiplicity at low $p_T$ by about factor of 2 \cite{2,18}. To account for that, we increase the PYTHIA dijet multiplicity by factor of 2 and redo the study of the rapidity depen-

![Fig. 4. The distribution of the leading particle from the dijets relative to the event plane calculated from HIJING only (left) and event plane from the embedded event (right).](image)

![Fig. 5. The fake $v_2$ of the leading particle as function of centrality using the EP determined in four $\eta$ windows. The embedded jet is at mid-rapidity.](image)

![Fig. 6. The EP resolution corrected fake $v_2$ as function of $\eta_{low} < |\eta| < 2.8$ for normal dijet and enhanced dijet.](image)

The $v_2$ measurements can also be affected by the event by event fluctuation of $v_2$ \cite{15,16,13,17}, which is a direct consequence to the event by event fluctuation of the collision geometry. However, since the two particle correlation method is used in this analysis, the event by event fluctuations would also contribute to the $v_2$ correlations. In this sense the $v_2\{2\}$ should be the one to use in Eq.1. Since $v_2\{2\}$ was shown to be consistent with the BBC RP $v_2$ \cite{14} up to 4 GeV/c in $p_T$, it is reasonable to using BBC RP $v_2$ in Eq.1.

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