Jet Characterization at RHIC Energy

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Abstract. Jet quenching is considered to be one of the signatures of the formation of quark gluon plasma. In order to investigate the jet quenching, it is necessary to know the properties of jets produced in relativistic heavy ion collisions. In this calculation, we propose that determination of flow parameters may be used to identify and characterize the jets.

1. Introduction
The quenching of jets in relativistic heavy ion collisions has been proposed to be one of the signatures of the formation of quark gluon plasma [1]-[3]. In order to understand the jet quenching, it is necessary to know the properties of jets. In nucleus-nucleus collisions the experimental identification of jets and determination of their properties is quite difficult task because during the collision process, a large number of hadrons are produced and the particles belonging to a jet, constitute a very small fraction of these. Recently, a method [4] of extracting the properties of the jets present in a heavy ion collision event has been proposed. In this method, a transverse momentum cut has been used to reduce the number of background particles which are used for the analysis. This is based on the azimuthal flow parameters of the particles produced in a single event. This treatment is simple and is able to identify the events having single jet and estimate the number of particles in the jet as well as the jet opening angle reasonably well for different transverse momentum cuts. Basically, the method is successful when the number of jet particles are 5-10% of total number of particles in an event. Using transverse energy cut ensures that low transverse momentum particles, which are abundant and do not belong to jet are removed. At the same time, one has to ensure that the number of background particles are not too small since the fluctuation effects would dominate the flow coefficients and the determination of the properties of the jet will not be accurate.

In the following, the method([4]) is briefly discussed in Sec II. It is applied to the synthetic data as well as simulated data[5] in Section III and summary is presented in Section IV.

2. The Method
The flow coefficients for particles distributed in azimuthal angle $\phi$ are given by

$$v_m = \left\langle \cos(m(\phi - \phi_E)) \right\rangle,$$  \hspace{1cm} (1)

where the angular brackets stand for averaging over all the particles. The flow coefficients $v_m$'s are measured with respect to the reaction plane, defined by azimuthal angle $\phi_E$. Since
the reaction plane is not readily defined in an experiment, it is convenient to compute the flow coefficients using the pairwise correlations of all the particles[4]. It turns out that the computation of pairwise correlated quantities not only removes the uncertainty in the knowledge of the reaction plane but also helps in reducing the statistical fluctuations. In this case the square of the flow coefficients \( v_m^2 \) are given by

\[
v_m^2 = \left\langle \cos(m(\phi_i - \phi_j)) \right\rangle = \frac{\sum_{i,j} \cos(m(\phi_i - \phi_j))}{N^2}.
\]  

(2)

It has been shown in ref([4]) that if the data consists of the number of background particles \( N_b \) distributed uniformly over the azimuthal angle and the number of jet particles \( N_j \) confined within a small azimuthal angle \( \Delta \phi \), the theoretical estimate of the flow coefficients is

\[
v_m^2 = \frac{N_j^2}{N^2} \left[ 1 - m^2 \sigma^2 \right] = \frac{N_j^2}{N^2} \left[ 1 - \frac{\Delta \phi^2 m^2}{12} \right].
\]  

(3)

Here \( \sigma \) is the variance of the azimuthal distribution of the jet particles and the last part in equation above results if the jet particles are uniformly distributed within \( \Delta \phi \).

One can compute the flow coefficients from the data using eq(2) and plot \( v_m^2 \) vs \( m^2 \). A linear fit to the square of the flow coefficients would then yield the number of jet particles and the jet opening angle \( \Delta \phi \). One should note that:

(i) Even in the absence of jet particles, the flow coefficients are nonzero. However, in this case, the number of jet particles computed from the intercept are small and consistent with zero.

(ii) If \( N_j \) is very small in comparison with the total number of particles, the flow coefficients would be small. In that case, the fluctuations dominate and the result is close to the case when there are no jet particles.

(iii) The expression in eq(3) is approximate and valid when \( \Delta \phi^2 m^2 << 12 \). Thus, not many values of \( m \) can be included in the fitting procedure.

(iv) If the data has more than one jet, one does not get a simple expression for flow coefficients. In such a case, the procedure outlined above is not expected to work. However, it has been shown[4] that if the two jets are back-to-back, the flow coefficients for even \( m \) are much larger than those for odd \( m \).

3. The Calculations and Discussions

The background particles in an event are constructed by taking the output from an event generator. For this purpose we have used the generator[5] which uses dynamical hadron string cascade model. For our analysis, we have considered 130 GeV collision of gold nuclei. To these ‘background’ particles, the jet particles are added by hand. We choose different numbers of jet particles and assume that their transverse momenta are larger than 2 GeV. The direction of the jet as well as the azimuthal angle of the jet particles are chosen randomly. We, however assume that the probability of the azimuthal angle of the jet particles is constant over the opening angle \( \Delta \phi \). In the following we shall consider the analysis when the event has only a jet ( no background ) and both jet and background particles are present.

3.1. Jet Only Events

Let us now consider the case where there are no background particles. This is an ideal case where we expect to obtain the best results from our analysis. The results display for the extracted values of number of jet particles \( N_o \) and the opening angle \( \Delta \phi_o \) and compare these with the corresponding input values \( N_g \) and \( \Delta \phi_g \) respectively in Figs. 1 and 2. The calculations are repeated a large number of times with different sets of background particles as well as jet
particles so as to estimate the possible error in the extracted quantities. These results seem to indicate that it may be possible to determine the number of jet particles reasonably well. As for opening angles, we find that the determination may not be very much reliable if the opening angle exceeds 0.75.

![Figure 1](image1.png)  
**Figure 1.** Extracted number of jet particles ($N_o$) vs the corresponding input values ($N_g$).

![Figure 2](image2.png)  
**Figure 2.** Extracted opening angle ($\Delta \phi_o$) vs the corresponding input values ($\Delta \phi_g$).

### 3.2. Events With Jets and Background

We now consider the analysis of events in which a jet is produced in the presence of ‘background’ particles. For this analysis, a large number of events (central collisions) have been considered. The number of particles produced in a central event are large and this may make the determination of jet difficult. It is clear that, for our method to work, the number of background particles should not be very large, so that the jet is not completely swamped by the background particles. One way of controlling the number of background particles is to remove the particles having transverse momentum cutoff larger than 1.5 and 2 GeV, these choices are given in ref[4]. We have therefore analyzed the events by including the background particles having transverse momenta larger than 1.5 and 2 GeV.

![Figure 3](image3.png)  
**Figure 3.** For single jet case, $v_m^2$ vs $m^2$ for the central collisions (N=74 and 28 for $p_t$=1.5 and 2 GeV, respectively).

![Figure 4](image4.png)  
**Figure 4.** For two jets case, $v_m^2$ vs $m^2$ for the central collisions (background particles with two jets and only two jets without background), if the two jets are back-to-back.

Fig. 3 displays a plot of the square of the flow coefficients $v_m$ vs $m^2$ for the two transverse momentum cuts. Here the opening angle is $\pi/6$ and the number of jet particles is 20 for single
jet case. We find that in this figure the extracted values of number of jet particles as well as the opening angle are within 25% of the input values. The plots in Fig. 3 are for the analysis of one particular event. We have repeated the analysis for a large number of such events and these are displayed in Figs. 5 and 6.

**Figure 5.** The extracted numbers of jet particles vs the corresponding input values are shown for $p_t = 1.5$ GeV and $p_t = 2$ GeV, respectively.

**Figure 6.** The extracted opening angles vs the corresponding input values are displayed for $p_t = 1.5$ GeV and $p_t = 2$ GeV, respectively.

The plots in Figs. 5 and 6 show that there is a linear correlation between the particle numbers extracted and the corresponding input numbers when the number of jet particles are larger than 10. Also, the correlation is better for 2 GeV cutoff. The extracted values of the number of jet particles for different input opening angles have similar behavior. Thus, it seems that the extraction of the number of jet particles is quite robust but that of the jet opening angle from the flow analysis is less reliable.

Fig. 4 displays a plot of $v_m$ vs $m^2$ for two jet case, where the opening angle is $\pi/6$, the number of jet particles in each jet is 20 and the angle between the two jets is $\pi$. It clearly shows in this figure that the flow coefficients for odd $m$’s are generally smaller than those of even $m$’s as discussed in ref.[4].

4. Summary

By using flow analysis method we have shown that when the data has a jet with the number of jet particles in excess of 10, the higher flow coefficients are large enough to be measured. In particular, we show that transverse momentum cuts between 1.5 and 2 GeV can be used to enhance the effect of jet particles on the flow coefficients. Further, by analyzing the flow coefficients of different orders, we show that it is possible to extract the information of the number of particles in the jet and jet opening angle.

We have also considered the case when two jets are present. For such a case, we have argued that an important information to be determined in this case is the angle between the two jets. We have shown that it may be possible to estimate this angle between the two jets. This method is useful to apply the RHIC data for the identification of jets.

References

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