Fine structure in the azimuthal transverse momentum correlations at $\sqrt{S_{NN}} = 200$ GeV using the event shape analysis

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Abstract. The experimental results on transverse momentum azimuthal hadron correlations at RHIC have opened a rich field for parton energy loss analysis in heavy-ion collisions. Recently, a considerable amount of work has been devoted to study the shapes of the “away-side” jet which exhibit an interesting and unexpected “double hump” structure not observed in the analogous treatment of $pp$ data. Driven by the possibility that the latter result might just mean that such structure exists already in the case of $pp$ collisions, but that its relative intensity could be small, here we use the Event Shape Analysis to show that it is possible to identify and select well defined event topologies in $pp$ collisions, among which, a double hump structure for the away-side jet emerges. Using two shape parameters, the sphericity in the transverse plane and the recoil to analyze a sample of PYTHIA generated $pp$ collisions at $\sqrt{S_{NN}} = 200$ GeV, we show that this structure corresponds to two jets emitted in the backward hemisphere. Finally, we show that Q-PYTHIA qualitatively reproduces the decrease in the yield of dijet events and the increase of the double hump structure in the away side observed in heavy ion collisions. The implications for the treatment of parton energy loss in heavy-ion collisions are discussed.

PACS. 13.87.-a; 13.87.Fh; 25.75.Bh

1 Introduction

The study of transverse momentum azimuthal correlations (further referred to as azimuthal correlations) of high momentum particles has considerably enhanced our understanding of the parton energy loss mechanism in the dense matter created in the aftermath of a heavy ion collision. The two-particle (dihadron) relative azimuthal angle, $\Delta \phi$, correlation technique provides an alternative approach for accessing the properties of jets. Two classes of hadrons, trigger and partner hadrons, typically from different $p_t$ ranges, are correlated with each other. Jet properties are extracted on a statistical basis from the $\Delta \phi$ distribution built of many events. This approach overcomes problems due to background and limited acceptance and allows the study of jets to be extended to low $p_t$ where soft processes dominate [1].

However after the initial simple explanations to account for the jet shapes the surprise came, namely, that for a given combination of triggering momenta and associated particles, a double hump structure was observed in the away-side associated particle correlations [2] and/or a broadening of the away-side peak [3].

The observation brought about a large number of theoretical explanations with widely different approaches. The existing explanations are based on the assumption that we are indeed facing a difference between the $pp$ and the heavy-ion cases. Among the proposed explanations we can mention: a Mach-like structure (splitting of the away-side peak) [4], gluon Cerenkov-like radiation models [5], the parton cascade model, the Markovian parton-scattering model [6], and the color wake model [7]. One can ask, however, whether the above mentioned characteristics of the away-side peak are already present in $pp$ collisions, only being obscured by the smallness of their intensity.

In the present work we investigate the shape of the away-side correlation peak in collisions at $\sqrt{S_{NN}} = 200$ GeV using an approach based on the Event Shape Analysis (ESA). The questions we want to answer are:

1.- Is it possible to identify and isolate events with topologies that resemble the double hump structure, using ESA in $pp$ collisions?
2.- What is the effect of the event structure on the width of the away peak?
3.- What is the effect of the Q-PYTHIA [8] parton energy loss model on the event shape and away-side correlations?
4.- What are the theoretical implications of the results of the present analysis for parton energy loss consideration?

The work is organized as follows: In Sec. 2 we present the basis for the ESA. In Sec. 3 we show the results obtained for azimuthal correlations for different parts of the event shape phase space.
In Sec. 4 we analyze the effect of the recent Q-PYTHIA generator on the azimuthal correlations. Finally in Sec. 5 we present a theoretical discussion and an outlook of the results as well as the conclusions.

2 Event Shape Analysis

The $e^+ - e^-$ experiments have introduced numerous event shape variables to analyze their data. In hadronic collisions the same approach is not possible due to the fact that the total event shape is dominated by the beam axis. For that reason one defines event shape variables in the plane transverse to the beam. For the sake of the current work we limit ourselves to two parameters, Thrust ($T$) and Recoil ($R$) [9]. $T$ is defined as:

$$T = \frac{\sum_{i} |\vec{q}_{\perp,i} \cdot \vec{n}_{T}|}{\sum_{i} |\vec{q}_{\perp,i}|},$$

where the sum runs over all particles in the final state within the acceptance, $\vec{q}_{\perp,i}$ represent the momentum components transverse to the beam and $\vec{n}_{T}$ is the transverse vector that maximizes the ratio. $T$ (the sphericity in the transverse plane, $1 - T$, closely related to $T$) will be equal to 1 (0) for a jet detected within the acceptance. On the other hand a fully isotropic event will result in a sphericity of 0.5. $R$ is defined as:

$$R = \frac{\sum_{i} |\vec{q}_{\perp,i}|}{\sum_{i} |\vec{q}_{\perp,i}|},$$

where again, the sum runs over all particles in the final state within the acceptance. The necessity for this variable stems from the incomplete acceptance we are faced with in the present application. As defined above, the maximum value of the recoil will be for a jet event where only one jet is detected within the acceptance. In short the Recoil variable takes care of momentum conservation.

3 Results

3.1 The event structure

Figure 1 shows the two-dimensional distribution $R$ vs. $1 - T$ obtained using PYTHIA version 6.4.14 with minimum bias $pp$ collisions at $\sqrt{s_{NN}} = 200$ GeV. In the simulation, we require that all particles be charged primaries and within the pseudorapidity range of $|\eta| \leq 1$. We also require that the events have at least 3 particles with transverse momentum satisfying $|\vec{q}_{\perp,i}| \geq 0.8$ GeV/c.

The distribution shows the following main regions, labeled (A), (B) and (C):

(A) The low $R$ and $1 - T$ region which is known to correspond to dijets.

(B) The high $R$ and low $1 - T$ region which is known to correspond to single jets (with the second jet being out of the acceptance).

(C) The high $1 - T$ region which is known to correspond to the most isotropic events.

We now proceed to analyze the azimuthal distribution obtained from the above three regions which are generated by choosing the highest momentum particle in the event to be at 0 radians. This is shown in Fig. 2, where the near side peaks are well distinguishable for the 3 plots while substantial differences occur in the away-side. For particles in region (A) we find the usual form of the away-side peak. For particles in region (B), as expected, there is no sight of a peak in the away-side. Finally for particles in region (C) we are confronted with a double hump structure. While the behavior of the sample in region (C) should in itself not be unexpected, since it can be associated to a gluon emission with a finite angle, like in the case of the discovery of the gluon [10], it is interesting that this has not been observed in the experiments at RHIC, probably due to the $p_t$ cut that was taken above 2 GeV/c. One notes the very distinct widths of the prominent peaks in the case of taking the whole inclusive data (not shown in the figure) instead of a subsection of back to back jets only.

The main reason for that lies in the fact that the contribution from region (C) can be described as a mere broadening of the away peak when all events are taken and is not readily distinguishable in its own right. Actually, one observes a continuous broadening of the away peak with increasing $1 - T$ values. For the largest value of sphericity the away peak transforms in a double hump structure. We interpret the structure as three jets emitted at 120 degrees.
from each other, as it is illustrated in Fig. 2. In Fig. 3 we show the spectrum for all particles with $p_{t,i} > 0.8$ GeV/c as a function of the sum of the momenta for all particles. We divided the azimuthal correlations in region (C) in three parts: one centered in $\Delta \phi$ around zero, the other two around the two humps at $\Delta \phi \sim 2.1$ radians and $\Delta \phi \sim 4.2$ radians in the away-side correlations (to take into account the hump in the near-side jet and the two humps of the away-side jet, respectively).

For each event, a vector sum of the momenta for the particles in the away-side peaks has been performed. The spectrum thus obtained is compared to the corresponding vector sum of the particle momenta in the near-side peak. The agreement between both spectra is reasonable, pointing to the fact that the three jet assumption is valid [11]. A similar structure in the azimuthal correlations for particles in region (C) of Fig. 1 can be seen even at lower beam energies. The result is not surprising given that the SPS experiments have already reported their analysis on di-hadron correlations in heavy-ion collisions [12].

For these two structures as corresponding to two jets in the away side.

### 4 Azimuthal correlations using the Q-PYTHIA generator

Confronted with the results obtained above we have tried to see what are the predictions of a generator that has been recently released and that takes into account the effects of parton energy loss in the medium simulating the effects to be observed in heavy ion collisions, the Q-PYTHIA generator [8]. This is a Monte Carlo implementation in PYTHIA of medium-induced gluon radiation. Medium effects are introduced through an additive term in the vacuum splitting functions

$$P_{\text{tot}}(z) = P_{\text{vac}}(z) + \Delta P(z, t, q, L, E).$$

where $\Delta P$ is the full splitting probability as given by the medium induced gluon radiation spectrum [8]. All the medium information in $\Delta P$ is encoded in the product $n(\xi) \sigma(r) \sim \frac{1}{2} \bar{q}(\xi) r^2$, where $n$ is the time-dependent density of scattering centers and $\sigma$ is the strength of a single elastic scattering. With this medium-modified splitting function, Q-PYTHIA computes the Sudakov form factor and the evolution equation in the following manner: given a parton coming from a branching point with coordinates $(t_1, x_1)$, where $t_1$ is its virtuality and $x_1$ its energy fraction, the algorithm calculates the coordinates $(t_2, x_2)$ for...
the next branching. The shower begins with a parton that faces the full length of the medium $L$, so the medium effects on the probability of the first branching are evaluated at $L$. The coherence length of the emitted gluon is then computed and its next branching is evaluated at $L - l_{coh}$, where $l_{coh} = 2\omega/k_t^2$ is the gluon formation time and $\omega$ and $k_t$ are the energy and transverse momentum (with respect to the parent parton) of the emitted gluon, respectively. The process is iterated to get the entire energy evolution.

In Figs. 4 and 5 we compare the effect of Q-PYTHIA on the event shape using a sample of events generated with a hard cutoff in $p_t$ of 10 GeV/c and a lower $p_t$ cut on the hadrons of 0.5 GeV/c. The curves obtained correspond to three distinct choices of parameters of Q-PYTHIA: A medium path length of 6 fm with two choices of $\hat{q}$, 1 and 5 GeV$^2$/fm. The interest of the results lays in the behavior of the dependence of the yields in two different parts of the $1 - T$ vs $R$ distribution. While for low values of $R$ and $1 - T$ we observe a decrease of the probability with increasing $\hat{q}$, in the case of high values of $1 - T$ we observe a frank increase of the yield in the away-side correlation with the double hump. These results remind us very much of the double hump structures encountered in the RHIC experiments in collisions of heavy ions. In Fig. 7 we show the projection of the two dimensional plot on the $1 - T$ axis for all values of $R$ less than 0.8. Again the evolution with rising values of $\hat{q}$ is to be noted.

5 Discussion and Conclusions

We have shown that the ESA allows to select events with distinctive features such as a dominant dijet structure and/or multijet structure, by means of the use of two very simple variables: the sphericity $1 - T$ and the recoil $R$. It is important to note that the present analysis allows for the isolation of event classes even in case they are rare. Very significant is the observation of three jet events in $pp$ collisions. To our knowledge the existence of such events, although predicted by theory, have not been identified in the RHIC data. The implementation of Q-PYTHIA shows a very notable evolution of the event shape from dominant dijet structure to a more isotropic geometry, ultimately enhancing significantly event structures with three prongs.

Recall that the radiation of gluons is a well established phenomenon in QCD processes involving fast partons. For instance, in deep inelastic scattering, the observation of events with three jets was one of the smoking guns to confirm QCD as the theory of strong interactions [10]. The distinct signature of a gluon being emitted at a finite angle with respect to its parent parton is the broadening of the $p_t^2$ hadron distribution of the jets beyond their natural spread in momentum given by the uncertainty principle (Fermi motion). In this context, gluon radiation takes place in vacuum and, whereas the emitted gluon spectrum peaks for small gluon energies and emission angles, there is a finite probability for gluon emission at larger angles. This probability can even be computed reliably in perturbation theory when the virtuality of the exchanged photon is large.

In a medium, induced gluon emission is usually understood as an effect whereby medium partons induce small momentum-transfer collisions producing radiation collinear to the direction of the traveling parton. This is
A. Ayala et al: Fine Structure in the azimuthal transverse momentum correlations at $\sqrt{s_{NN}} = 200$ GeV...

Fig. 6. Azimuthal correlations for particles generated by PYTHIA in region (C) with $p_{T}^{\text{hard}} = 10$ GeV/c (solid line), Q-PYTHIA with $\hat{q} = 1$ GeV$^2$/fm and $L = 6$ fm (dashed line) and $\hat{q} = 5$ GeV$^2$/fm and $L = 6$ fm (dotted line), respectively. The chosen bounds for $1-T$ and $R$ are $1-T > 0.25$ and $R < 0.3$.

Fig. 7. $1-T$ spectrum obtained for events with $R < 0.8$ for particles with $p_{T}^{\text{hard}} = 10$ GeV/c (solid line), $p_{T}^{\text{hard}} = 10$ GeV/c and Q-PYTHIA with $\hat{q} = 1$ GeV$^2$/fm and $L = 6$ fm (dashed line) and $\hat{q} = 5$ GeV$^2$/fm and $L = 6$ fm (dotted line).

Thus, the need of a large intrinsic $k_t \simeq 2.68$ GeV, as suggested in Ref. [15] might just reflect an enhanced probability for the emission of gluons with large angles relative to the direction of the away-side parton. We are currently pursuing such possibilities to describe the effect [16].

One may ask whether a comparison of the ESA using Q-PYTHIA and RHIC data can be made, given that this event generator introduces jet quenching only by simulating the emission of radiation and disregarding the background, whereas in a realistic situation of a heavy-ion reaction one knows that jets come along with a large background. In this respect it is important to emphasize that the main goal of this work is to point out to the interesting feature shown by the ESA, namely, the suppression of di-jets and enhancement of three jets in events with large sphericity. It is clear that in a heavy-ion event, one should introduce the appropriate cuts to recover the thrust map in order to get rid of the underlying event. Therefore, in the context of our work, the use of Q-PYTHIA should be taken only as an illustration of a possible effect of jet quenching in a heavy-ion environment.

We have demonstrated the importance of event shape cuts to extract the width of the away peak in azimuthal correlations. In the Monte Carlo $pp$ analysis; we have observed a continuous evolution of the away spectrum starting from a narrow width of the away-side peak to a double hump structure for the most isotropic parts at high $1-T$ values. We have demonstrated the sensitivity of the away peak width to the part of the phase space from where the correlations are extracted.
This study suggests that ESA may allow a more detailed analysis of data. Finally, the predictions of an energy loss afterburner have been shown. Surprisingly this predicts an enhancement of the away double hump correlation structure with respect to PYTHIA, opening thus the possibility to use the amplitude and shape of the away peak to determine $\hat{q}$. The double hump effect observed in heavy ion collisions at RHIC seems to bear some similarity with the shapes observed here in $pp$ collisions. An analysis of data in heavy-ion collisions in a similar way as proposed in this work could shed some additional light on the phenomenon.

Acknowledgments

The authors express their gratitude to Dr. J.P. Revol for suggesting the present investigation and for his judicious comments and to Dr. Leticia Cunqueiro and Dr. Andreas Morsch for valuable discussions on the implementation of Q-PYTHIA. Support for this work has been received in part by DGAPA-UNAM under PAPIIT grants IN116008, IN115808 and IN116508 as well as by the HELEN program.

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