Proc. 24th Winter Workshop on
Nuclear Dynamics (2008) 000–000

24th Winter Workshop
on Nuclear Dynamics
South Padre, Texas, USA
April 5–12, 2008

Understanding Jet Energy Loss with Angular Correlation Studies in PHENIX

J. A. Hanks for the PHENIX Collaboration[1]

[1] Department of Physics, Columbia University,
New York, NY 10027, USA

Abstract. Angular correlation studies provide powerful insight into the energy loss of hard scattered partons as they traverse the partonic medium produced in heavy ion collisions at RHIC. These results are generally compared to jet correlations in p+p collsisions where all correlation strength is attributed to vacuum fragmentation. Strong modification to di-jet correlations has been observed in A+A collisions at RHIC, most notably for the away side jet. Many different effects, including the opacity of the medium, its response to energy deposited by partons as they propagate, and modifications to the parton fragmentation, are involved in producing the final correlation stuctures. Understanding the interplay between these various effects is essential to developing a complete picture of the medium. Measurements of jet correlations involving direct photons provide a unique probe of jet fragmentation effects, as photons are not strongly interacting. Additionally, systematic studies of the away side structure as a function of p_T, as well as attempts to include additional high p_T trigger requirements, can help to distinguish different energy loss mechanisms. We discuss recent PHENIX results from these detailed studies of jet correlations in A+A and p+p collisions.

Keywords: heavy ions, correlations, jets
PACS: 25.75.Gz

1. Introduction

In heavy ion collisions at RHIC we observe a significant modification of jets as a result of their interaction with the medium [1]. We are able to measure such modifications through two particle angular correlations, in which the $\Delta\phi$ between a trigger particle and all associated particles is measured and the large background can be dealt with using statistical subtraction methods [2]. These correlation measurements are performed over a wide range of trigger and associated particle momenta, allowing for a detailed study of how medium modifications depend on both.

The modification of the away-side jet appears in two ways. The first is in the form of a supression of the di-jet at $\Delta\phi = \pi$, which we will refer to as the the "head" region. This suppression can be described well at high p_T in terms of energy loss [3]. The second is in the form of an enhancement away from π, in the "shoulder" region, thought to be due to medium response. There are several models which attempt to explain how this enhancement is produced. One possibility is that the jet propogates faster than the speed of sound in the medium, producing a Mach cone [4]. Another is that the jet is propagating faster than the speed of light in the medium, producing Cherenkov radiation [5]. Finally, the jet propagation may be coupled with the collective flow, causing it to be deflected away from π [6]. These various scenarios can be tested by studying the position of the shoulder peaks as a function of p_T and centrality [3], as well the reaction plane dependence.

Much information can be gained from these di-hadron studies, however there are inherent limitations to how well energy loss can be understood through these measurements, both as a result of the surface bias introduced by the trigger requirement [7], as well as the fact that both the trigger and associated hadrons will experience modification due to the medium. These difficulties can, at least in part, be overcome by measuring correlations of hadrons with direct photons, which do not interact with the medium.

2. Away-side Jet Modification

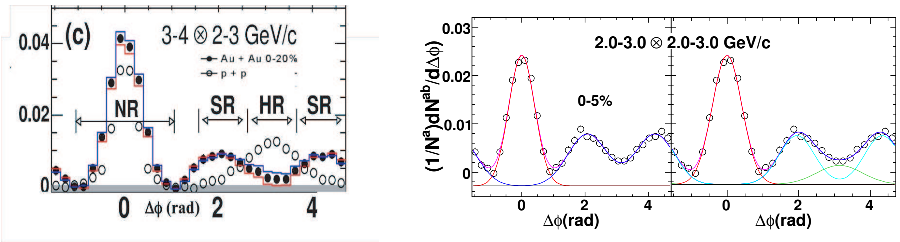
There are several methods in PHENIX for studying the modification of the away-side jet. To understand the interplay between the head and shoulder regions the away-side can be decomposed into three sections: the head region, centered around $\Delta\phi = \pi$ and ranging from $\pi - \pi/6$ to $\pi + \pi/6$; and the two shoulder regions, in the range $\pi/6 < |\Delta\phi - \pi| < \pi/2$. This allows us to study how these various regions evolve. To measure the positions of the shoulder regions there are two fitting procedures that are used. The first uses two gaussians diplaced from π by a distance D, as shown in equation (1).

$$J(\Delta\phi)_{away-side} = A(e^{\frac{(\Delta\phi-\pi+D)^2}{2\sigma^2}} + e^{\frac{(\Delta\phi-\pi-D)^2}{2\sigma^2}}) \tag{1}$$

The second includes a third gaussian, representing the head contribution, which is fixed by the p+p width, and centered at π, as shown in equation (2).

$$J(\Delta\phi)_{away-side} = A(e^{\frac{(\Delta\phi-\pi+D)^2}{2\sigma^2}} + e^{\frac{(\Delta\phi-\pi-D)^2}{2\sigma^2}}) + Be^{\frac{(\Delta\phi-\pi)^2}{2\sigma_{pp}^2}} \tag{2}$$

In these equations J is used to indicate that it is the jet yield being measured. An illustration of both the head/shoulder decomposition and the two fitting methods is shown in figure 1.



(a) **(b)**

Fig. 1. **(a)** Decomposition of away-side into two seperate components, the head and the shoulder. **(b)** Demonstration of the two fits used to determine seperation of two shoulder peaks.

Studying the dependence of the head and shoulder regions on both the trigger and associated p_T reveals that there is an enhancement of the shoulder yield at low associated p_T which persists as we go to higher trigger momentum. This low p_T enhancement gives the shoulder a softer spectral shape, making it appear more bulk-like. We also find that the head is suppressed at intermediate to high associated p_T, for all trigger p_T bins [3]. Using the decomposition of the head and shoulder regions also allows us to compare them directly by looking at the ratio of the integrated yields, R_{HS}, as described by equation (3).

$$R_{HS} = (\int_{head} d\Delta\phi \frac{1}{N_{trig}} \frac{dN}{d\Delta\phi})/(\int_{shoulder} d\Delta\phi \frac{1}{N_{trig}} \frac{dN}{d\Delta\phi}) \tag{3}$$

We find that the shoulder dominates at low partner momentum, up to $p_T \approx$ 4 GeV/c, while as the trigger p_T is increased this ratio becomes consistent with the p+p measurement when the partner p_T is greater than 4 GeV/c [3].

The two fitting methods can be used to extract the D parameter, which is a measure of the separation between the shoulder peaks, and study its dependence on the momentum of either hadron. We find that the peak positions show minimal dependence on either the trigger or partner p_T, as shown in figure 2 [3]. This poses a challenge for models such as Cherenkov radiation which predict a p_T dependence.

It is also possible to use particle ID to measure these types of correlations for baryons and mesons separately to determine how the modification observed depends on species. The results show a similar shape to the away side correlations for both. Additionally, the ratio of baryons to mesons in the away side yields shows a similar centrality dependence to that of the bulk, which is incompatible with vacuum fragmentation [8]. These observations place a tight constraint on models attempting to describe baryons and mesons together, and provides further evidence for the idea that the shoulder region is dominated by medium response.

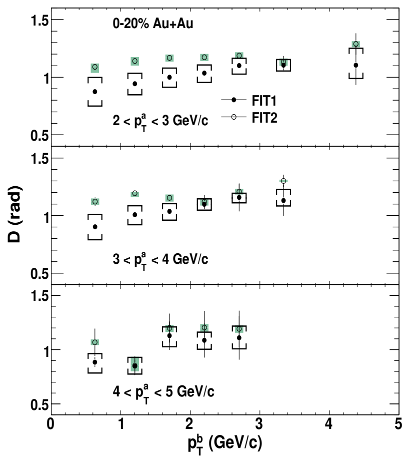


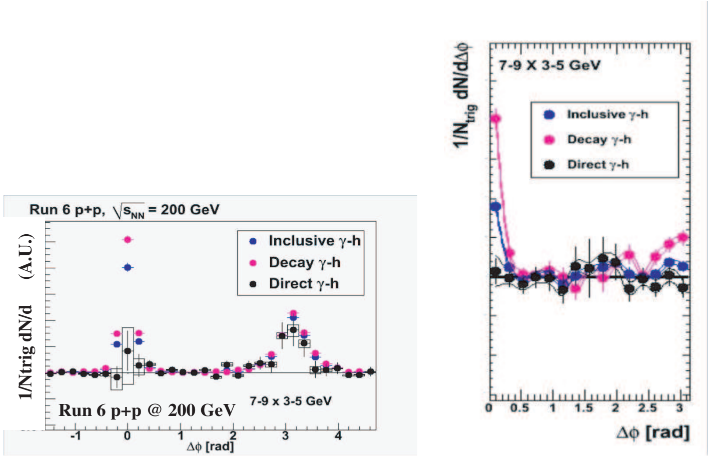
Fig. 2. Shows separation between two shoulder peaks, in the form of the D fit parameter. The fit described by equation (1) is shown in black, the one described by equation (2) is in green.

3. γ-h and h-γ

Correlations between hadrons and photons can go even futher to improve our understanding of the various affects leading to both the energy loss of the jet, as well as the medium response, since the photons remain unmodified. In γ-jet correlations the near-side parton essentially fragments all of its energy into the photon via Compton scattering; the photon then emerges without further interaction. This allows us to measure the initial energy of the recoil jet directly by measuring the photon energy, and therefore to measure the amount of energy loss for the parton in the medium. Additionally, di-jet measurements will be dominated by jets produced near the surface where the energy loss effects are minimal, leading to a geometric bias. The use of a photon trigger removes this bias, allowing for a measurement of the full geometry of the medium through which the jet is propogating.

Figure 3 shows the measured correlation functions both in p+p and Au+Au. In the case of p+p, the near-side yield is consistent with zero, as is expected if the photon carries the full parton energy, and the away-side yield is similar to that for the case of $\pi^0 - h$ correlations. In the case of Au+Au there is a clear suppression relative to the p+p, indicating that this measurement is sensitive to the energy loss of the away-side jet. These preliminary results are encouraging for future more detailed studies of the modification to the away-side via photon-jet correlations.

While the near-side yield in the γ-jet measurement is consistent with zero, there is expected to be some non-zero yield as a result of direct photons produced



(a) (b)

Fig. 3. **(a)** γ-hadron per trigger yields in p+p collisions: inclusive(blue), decay(red), and direct(black). **(b)** γ-hadron per trigger yields in Au+Au collisions: inclusive(blue), decay(red), and direct(black).

as the parton fragments. In addition, the production of fragmentation photons in heavy ion collisions is expected to be modified as a result of the interaction of the jet as it propagates. Direct measurement of this component of the direct photon signal can be attempted through h-γ correlation measurements, as these photons should be correlated with the jet which produces them. A first attempt to perform this measurement in p+p collisions has been made, and figure 4 shows the ratio of the near-side integrated yields for fragmentation photons over inclusive. This measurement is still dominated by large systematics, but a yield of 5-15% is observed at intermediate p_T, and the success of the method is encouraging for future improvements, as well as possible measurements in larger systems.

4. Conclusions

Jet correlations provide a powerful tool for probing energy loss in heavy ion collisions. Studies of two particle correlations over a wide range of p_T, over all centralities, and as a function of reaction plane have all been done at PHENIX. The results provide a description of jet energy-loss and medium response consistent with the idea that medium response dominates at intermediate p_T, and the dependence of this medium response on various parameters such as the trigger and partner p_T's, and reaction plane angle are not inconsistent with models describing jet in-

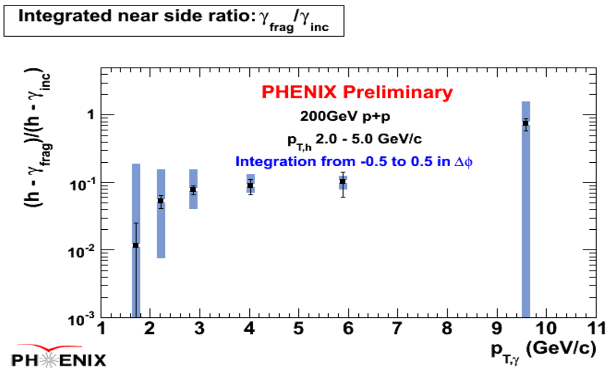


Fig. 4. Shows the ratio of integrated near-side per trigger yield, from -0.5 to 0.5 in $\Delta\phi$ for fragmentation photons relative to inclusive.

duced Mach cones, but pose a challenge for other scenarios such as Cherenkov gluon radiation.

References

1. Adler S. et al, *Phys. Rev. Lett.* **90** (2003) 082302.
2. S. Adler et al, *Phys. Rev. Lett.* **97** (2006) 052301.
3. A. Adare et al, arXiv preprint arXiv:0801.4545 [nucl-ex], submitted to *Phys. Rev. C*.
4. Casalderrey-Solana, Shuryak and Teaney, *Nucl. Phys.* **A774** (2006) 577.
5. Koch, Majumder and Wang, *Phys. Rev. Lett.* **96** (2006) 172302.
6. Armesto, Salgado and Wiedemann, *Phys. Rev.* **C72** (2005) 064910.
7. T. Renk and K. Eskola, *Phys. Rev.* **C75** (2007) 054910.
8. C. Alt et al, arXiv preprint arXiv:0712.3033 [nucl-ex], submited to *Phys. Rev. Lett.*.