Studying Jets with Identified Particles at PHENIX

Anne Sickles
Brookhaven National Laboratory, Upton NY 11973
for the PHENIX Collaboration

Abstract
A surprising excess of protons at intermediate $p_T$, 2-5GeV/c, has been observed in Au+Au collisions at RHIC, for which the source is not known. In p+p collisions, particles at this $p_T$ arise from jet fragmentation, however the observed baryon yield in central Au+Au collisions are not compatible with the usual jet fragmentation function. Two particle $\Delta \phi$ correlations are a powerful probe for quantitatively understanding the modifications to jet fragmentation from interactions with the medium. Earlier studies have shown that the excess baryons do have jet-like partners, indicating a hard scattering origin. We present new results from a systematic study of two particle correlations as a function of trigger and partner particle species, charge, $p_T$ and centrality from the high statistics Au+Au dataset. p+p collisions are also analyzed as a reference.

Key words:

PACS:

1. Introduction

A remarkable feature of relativistic heavy ion collisions is the greatly enhanced production of baryons and antibaryons relative to mesons. This enhancement over $p+p$ collisions occurs at intermediate transverse momenta ($p_T$), 2-5GeV/c [1,2]. In this momentum range in $p+p$ collisions particle production shifts from soft, low momentum transfer processes to hard scattering processes dominated by jet production followed by fragmentation. Due to the complicated system in central Au+Au collisions, it is important to determine whether the baryon and antibaryon excess is caused by hard or soft processes. Previous studies have shown that $p$ and $\bar{p}$ between 2.5 and 4.0GeV/c are associated with jet-like partners in a similar manner as mesons at the same $p_T$ [3], indicating a hard scattering origin for the baryon and antibaryon excess.

Models based on hadronization by valence quark recombination have been very successful describing the particle spectra and elliptic flow at intermediate $p_T$ [4,5,6,7]. In the recombination picture quarks close together in phase space come together to form final state hadrons. In this manner hadrons originating from the soft region can dominate in the region $p_T > 2\text{GeV/c}$ which in p+p collisions is generally understood to be hard physics. In general, this mechanism enhances baryon production more than meson production at a given $p_T$ because of the extra $p_T$ in the baryon from the extra valence quark. Previous measurements [3] are incompatible with hadron production at intermediate $p_T$ being dominated by purely soft, uncorrelated, recombination. However, in some models[5,6,8], a fraction of valence quarks are themselves associated with a hard scattering leading to modified jet fragmentation at intermediate $p_T$. The model of Fries et al. [8] is the...
only one to provide calculations in the $p_T$ range of the data in [3]. The calculations shows agreement with the data illustrating the propagation of hard partons through the produced dense matter followed by recombination is a “plausible” mechanism for the origin of the observed correlations [8].

Two particle correlations have been widely used to study jets in heavy ion collisions [9,3,10,11,12] where, due to the high multiplicity and moderate jet, energy direct reconstruction of jets by standard algorithms is not possible. In this approach particles are divided into two classes, triggers and partners. In this work triggers and partners are classified by their $p_T$, particle type and charge. A distribution of the azimuthal angular difference $\Delta \phi$ between trigger partner pairs is constructed. The centrality and particle type dependence of the conditional partner yields per trigger provide information on the the role of jets in hadron production at intermediate $p_T$ and modifications to the fragmentation process due to the presence of the medium in Au+Au collisions.

In Reference [3] correlations of baryons ($p,\bar{p}$) and mesons ($\pi, K$) with charged particles were studied. The results presented here extend that work by studying correlations where both particles are identified. This provides a model independent way to study the effects of the medium on jets and fragmentation at intermediate $p_T$. The $p_T$ range has been chosen so that the trigger particles come from a region where the $p/\pi$ ratio at its maximum and constant, $2.5 < p_T < 4.0\text{GeV} / c$. This is the most direct way to experimentally probe the observed baryon excess.

2. Experimental Setup

Charged particles are reconstructed in the central arms of PHENIX using drift chambers, each with an azimuthal coverage of $\pi/2$ and one layer of multi-wire proportional chamber with pad readout (PC1) [13]. Here triggers have $2.5 < p_T < 4.0\text{GeV} / c$ and partners with $1.7 < p_T < 2.5\text{GeV} / c$. Particle identification via time of flight is done for both types of particles. The PHENIX high resolution time of flight (TOF) gives $K/p$ separation to $\approx 4.0\text{GeV} / c$ and is used for the trigger particle identification. The PHENIX lead-scintillator electromagnetic calorimeter (EMCal) provides $K/p$ separation out to $\approx 2.5\text{GeV} / c$. Partners are identified in either the EMCal or the TOF, which together cover the entire PHENIX azimuthal acceptance. For both triggers and partners a $2\sigma$ match is required between the track projection and the hit in the particle identification detector. The momentum cuts have been chosen to avoid resonance decays which could mimic the jet signal. No correction has been made for protons originating from the feeddown of $\Lambda$ and $\bar{\Lambda}$.

We perform a correction for PHENIX’s non-uniform pair acceptance in $\Delta \phi$. This correction is constructed by measuring the $\Delta \phi$ distribution from trigger-partner pairs where each particle is from a different event. Dividing by this correction removes the effects of the PHENIX acceptance and leaves only the true correlations. The combinatoric background level from the underlying event multiplicity is determined absolutely by the convolution of the trigger and partner single particle rates with an additional correction for centrality correlations [3] which raises the combinatoric background level by $\approx 0.2\%$ in the most central collisions and $\approx 25\%$ in peripheral collisions. A correction for the partner efficiency is applied by matching the observed partner rates to those in [14]. No extrapolation is made for particles beyond the PHENIX $|\eta| < 0.35$ acceptance. Such a correction would be dependent upon an assumption of the shape of the jet profile. The azimuthal correlation from elliptic flow is removed by modulating the combinatoric background level by $1 + 2v_2^{\text{trig}}v_2^{\text{part}} \cos(\Delta \phi)$ where $v_2^{\text{trig}}$ and $v_2^{\text{part}}$ are the $v_2$ values for the trigger and partner, respectively, from [15]. Because the centrality binning in this analysis is finer than in [15] the $p_T$ integrated centrality dependence is used to interpolate $v_2$ for collisions more central than $20\%$.

3. Results

Figure 1 shows the azimuthal angular difference, $\Delta \phi$ between trigger mesons (left panel) and baryons (right panel) with partner mesons in Au+Au collisions for six centralities. The solid lines show the combinatoric background level modulated by the trigger and partner $v_2$ values as described above. The region around $\Delta \phi = \pi/2$ has very limited pair acceptance due to the requirement that the trigger particle be identified in the TOF. For trigger mesons a near side jet peak is visible. For trigger baryons a near side peak is clear for most centralities.

Figure 2 shows that the conditional yield of meson partners per baryon trigger above the combinatoric background for $\Delta \phi < 0.94\text{rad}$. The systematic errors, shown as gray boxes, are primarily from the
PHENIX PRELIMINARY, Au+Au 200GeV, Run4

**MESON TRIGGERS**

- $2.5 < p_T^{\pi} < 2.5$ GeV/c
- $1.7 < p_T^{\pi} < 2.5$ GeV/c

**BARYON TRIGGERS**

- meson partners
- $1.7 < p_T^p < 2.5$ GeV/c

Fig. 1. $\frac{dN}{d\Delta \phi}$ distribution for meson (left) and baryon (right) triggers, $2.5 < p_T < 4.0$ GeV/c, and meson partners, $1.7 < p_T < 2.5$ GeV/c, for six centrality selections in Au+Au. The solid lines show the calculated combinatoric background level modulated by the elliptic flow values. See text for explanation.

Fig. 2. Conditional partner yield per trigger for the same jet, $0 < \Delta \phi < 0.94$ rad, for correlations between baryon, $p, \bar{p}$ (squares), and meson, $\pi, K$ (circles), triggers with meson partners. Triggers have $2.5 < p_T < 4.0$ GeV/c and partners have $1.7 < p_T < 2.5$ GeV/c.

statistical errors on the $v_2$ values used, the systematic error on the $v_2$ due to the reaction plane resolution and the correction for centrality correlations. There is a significant difference in the conditional meson yield between baryon and meson triggers only in the most central collisions. The yield per meson trigger rises slightly with increasing centrality, while the yield per baryon triggers is consistent with the yield per meson trigger until the most central collisions when it is consistent with or less than the yield in peripheral collisions.

Figure 3 shows the number of associated protons or anti-protons per proton or anti-proton trigger, on both the near (top panel) and away side, the regions of near side jet and away side jet fragmentation, respectively as a function of the number of collision participants. The yields are integrated over $\Delta \phi < 0.94$ ($\pi - \Delta \phi < 0.94$) for the near (away) side yields. The main systematic errors are the same as in Figure 2. The opposite sign pairs have a non-zero conditional yield and the same sign pairs have a conditional yield consistent with zero.

### 4. Discussion

There is no significant difference between the baryon and meson triggered conditional yield of meson partners except in the most central collisions in contrast with the excess of protons and antiprotons in the single particles where the yield, in this same
$p_T$ range, scales with the number of binary nucleon-nucleon collisions at all centralities [1] while the mesons are suppressed with increasing centrality. Therefore, the decrease in the conditional yield does not lead to the conclusion that the excess baryon production at intermediate $p_T$ is due to purely soft sources. A comparison of Figures 2 and 3 shows that in the most central collisions such the probability for a baryon triggered jet to contain a meson in the partner $p_T$ range is consistent with the probability it contains an oppositely charged baryon. The calculation in [16], which incorporates soft parton correlations and jet fragmentation, does not show this strong centrality dependence for these correlations.

The lack of centrality dependence in Figure 3 is interesting in light of the fact that the $p/\pi^+$ and $\bar{p}/\pi^-$ ratios in the trigger and partner $p_T$ ranges increase by about a factor of four in central Au+Au collisions relative to $p+p$ collisions. We do not have $p+p$ data for comparison at present, but the conditional yield results are qualitatively consistent with PYTHIA [17] simulations. The lack of centrality dependence to the conditional yield for both the opposite and same sign pairs is consistent with $p$ and $\bar{p}$ production in close angle pairs. While baryon number must be globally conserved, the novel baryon and antibaryon production mechanisms that have been proposed do not necessarily require the “extra” $p$ and $\bar{p}$ appear to conserve baryon number locally in a manner consistent with jet fragmentation, although no theoretical calculations have been done for this observable. It should be noted that the small value of these conditional yield (0.01) does not imply any “missing” baryons. In these conditional yields the partners are measured in a small $p_T$ window and, as noted above, are not corrected for the partner falling outside the PHENIX pseudorapidity acceptance, $|\eta| < 0.35$. Such a correction would be model dependent and would be especially unwise given the interesting STAR data on jet elongation in $\Delta\eta$ [18].

Jet correlations at intermediate $p_T$ are a powerful probe of the medium created in heavy ion collisions at RHIC. In addition to the particle type dependences shown here a strong modification to the away side jet shape has been discovered [11] and elongated correlations in $\Delta\eta$ [18]. Current models are unable to explain all of these interesting phenomena, but, from the data presented here, we know that jet fragmentation on the near side is modified by the medium produced in central Au+Au collisions. The jets are richer in baryon and antibaryon pairs. In the most central collisions baryon triggered jets have significantly fewer meson partners than baryon triggered jets in less central collisions and than meson triggered jets at similar centralities. Clearly, the picture of jets at intermediate $p_T$ originating purely from the surface of the collision region is inconsistent with these data. The same side correlations at intermediate $p_T$ are probing the produced medium in Au+Au collisions and a systematic description of the particle type, centrality and charge dependence of these correlations are crucial to understanding the interactions between hard scattered partons and the medium.

References

[1] S. S. Adler, et al., Phys. Rev. Lett 91 (2003) 172301.
[2] J. Adams, et al., Phys. Rev. Lett. 92 (2004) 052302.
[3] S. S. Adler, et al., Phys. Rev C71 (2005) 051902(R).
[4] R. J. Fries, et al., Phys. Rev. C68 (2003) 044902.
[5] G. V, et al., Phys. Rev. C68 (2003) 034904.
[6] R. Hwa, C. B. Yang, Phys. Rev. C70 (2004) 024904.
[7] R. Hwa, C. B. Yang, Phys. Rev. C70 (2004) 024905.
[8] R. J. Fries, et al., Phys. Rev. Lett 94 (2005) 122301.
[9] C. Adler, et al., Phys. Rev. Lett. 90 (2003) 082302.
[10] C. Adler, et al., Phys. Rev. Lett. 95 (2005) 152301.
[11] S. S. Adler, et al., Phys. Rev. Lett 97 (2006) 052301.
[12] C. Adler, et al., nucl-ex/0604018, submitted to Phys. Rev. Lett.
[13] K. Adcox, et al., NIM A499 (2003) 489–507.
[14] S. S. Adler, et al., Phys. Rev. C69 (2004) 034909.
[15] S. S. Adler, et al., Phys. Rev. Lett. 91 (2003) 182301.
[16] R. J. Fries, Journal of Physics Conference Series 27 (2005) 70–79.
[17] T. Sjostrand, et al., Comp. Phys. Comm. 135 (2001) 238.
[18] J. Putschke, et al., Nucl. Phys. A (these proceedings).