Azimuthal angle two particle correlations have been shown to be a powerful probe for extracting novel features of the interaction between hard scattered partons and the medium produced in Au+Au collisions at RHIC. At intermediate $p_T$, 2–5GeV/$c$, the jets have been shown to be significantly modified in both their particle composition and their angular distribution compared to p+p collisions. Additionally, angular two particle correlations with identified hadrons provide information on the possible role of modified hadronization scenarios such as partonic recombination, which might allow medium modified jet fragmentation by connecting hard scattered partons to low $p_T$ thermal partons.

PHENIX has excellent particle identification capabilities and has developed robust techniques for extracting jet correlations from the large underlying event. We present recent PHENIX results from Au+Au collisions for a variety of $p_T$ and particle type combinations. We also present p+p measurements as a baseline. We show evidence that protons and anti-protons in the $p_T$ region of enhanced baryon and anti-baryon single particle production are produced in close angle pairs of opposite charge and that the strong modifications to the away side shape observed for charged hadron correlations are also present when baryons are correlated.

1. Introduction

One of the most surprising results from the Relativistic Heavy Ion Collider (RHIC) has been the large increase in the $p/\pi^+$ and $\bar{p}/\pi^-$ ratios at intermediate $p_T$, 2–5GeV/$c$ [1]. Studies of $\Phi$ mesons [2] and $\Lambda$ baryons [3] have indicated that the origin of the excess is related to the number of valence quarks rather than particle mass. Baryon and meson differences have also been studied by measuring the elliptic flow, $v_2$, of identified particles which have also been shown to scale with the number of valence quarks [4,5,6]. In this same $p_T$ range in p+p collisions particle production shifts from soft, non-perturbative processes to hard parton-parton scattering followed by jet fragmentation [7]. The valence quark dependence of these effects has inspired a class of models based quark recombination; hadronization is modeled not by fragmentation, but by quarks close together in phase space coming together to form hadrons. In some of these models intermediate $p_T$ hadrons primarily come...
Two particle correlations have been used to determine whether the baryon excess is associated with hard or soft processes and to explore in detail baryon/meson differences at low and intermediate $p_T$. A systematic study of these correlations will allow discrimination between different hadronization scenarios and measurement of the role of hard scattering at intermediate $p_T$. Here we present a selection of the recent PHENIX results from these correlations.

2. Experimental Details

2.1. Two Particle Correlations

Correlations are measured between two classes of particles, triggers and associated particles. The data presented here are from the 2004 Au+Au $\sqrt{s_{NN}}=200$ GeV RHIC run. All particles are charged tracks reconstructed in the PHENIX drift chambers. Particle identification is done via time of flight. The start time is provided by the PHENIX Beam-Beam Counters and the stop time is measured by either the high resolution time of flight or the lead-scintillator electromagnetic calorimeter, which provide $K/p$ separation to $\approx 4.0$ GeV/$c$ and $\approx 2.5$ GeV/$c$, respectively.

The azimuthal angular difference between the trigger and associated particle, $\Delta \phi$, is measured. The non-uniform $\Delta \phi$ acceptance is corrected for with mixed pairs where the two particles are from different events. The associated particle reconstruction efficiency is corrected for by matching the observed single particle spectra to those measured in Ref. Correlations from elliptic flow are removed by using $v_2$ values measured separately. Remaining yield is attributed jet correlations, $J(\Delta \phi)$. Acceptance corrected $\Delta \phi$ distributions are then described by:

$$\frac{1}{N_{trig}} \frac{dN}{d\Delta \phi} = B(1 + 2v_2^{trig}v_2^{assoc} \cos(2\Delta \phi)) + J(\Delta \phi)$$

where $B$ is the combinatorial background level and $v_2^{trig}$ and $v_2^{assoc}$ are $v_2$ values for triggers and associated particles, respectively. $N_{trig}$ is the total number of triggers observed. The determination of $B$ is discussed in Sect. In order to quantify the centrality dependence of the jet correlations $J(\Delta \phi)$ is integrated over $\Delta \phi$ within which particles are expected to be from the fragmentation of the same jet, near-side, or opposing di-jet, away-side. These integrated values are the average conditional yield of associated particles per trigger.

2.2. Combinatoric Background Subtraction Procedures

In two particle correlations a small fraction of the pairs come from the jet-like source which is to be measured. The rest of the pairs come from other sources in the event, pairs where each particle is from a different jet, one particle is from a jet crashed
Jet Correlations with Identified Particles from PHENIX

and the other is not, or where both particles are from soft processes; these pairs are
called the combinatorial background. Unfortunately, the combinatorial background
grows faster than the jet-like signal so extraction of the jet-like signal becomes more
sensitive to the background normalization in central collisions.

PHENIX uses two methods to determine \( B \) in the correlations presented here.
The first, the absolute subtraction method, is described in detail below. This
method has the advantage that it requires no assumption about the shape of the jet
correlations in \( \Delta \phi \). The second method, zero yield at minimum (ZYAM), makes
the assumption that there is a region in \( \Delta \phi \) where there is the jet yield is zero. It
is described in detail elsewhere \(^{11}\).

The absolute subtraction method uses a convolution of the single particle rates
to determine the combinatorial pair rate. The total number of combinatorial pairs
in the event sample, under the assumption that the jet signal is the only source of
correlated pairs, is:

\[
N_{\text{comb}} = \langle n_{\text{trig}} \rangle \langle n_{\text{assoc}} \rangle N_{\text{events}}
\]

where \( \langle n_{\text{trig}} \rangle \) and \( \langle n_{\text{assoc}} \rangle \) are the average number of triggers and partners per event
and \( N_{\text{events}} \) are the total number of events. Normalizing \( N_{\text{comb}} \) by the total number
of triggers as in Eqn. \(^{1}\) gives:

\[
\frac{\langle n_{\text{trig}} \rangle \langle n_{\text{assoc}} \rangle N_{\text{events}}}{N_{\text{triggers}}} = \frac{N_{\text{trig}} \langle n_{\text{assoc}} \rangle}{N_{\text{trig}}} = \langle n_{\text{assoc}} \rangle
\]

Thus, the combinatorial background normalization is simply:

\[
\int_{0}^{\pi} B d\Delta \phi = \langle n_{\text{assoc}} \rangle
\]

\[
B = \frac{\langle n_{\text{assoc}} \rangle}{\pi}
\]

However, the assumption made prior to Eqn. \(^{2}\) is not completely valid, there are
an additional correlations due to fluctuations of the particle multiplicity. The more
central events within a bin have, on average, a higher number of pairs than those
from the lower centrality part of the bin. Thus, the combinatorial background level
is higher because it is biased toward higher multiplicity events. These correlations
increase as the relative width of the trigger and associated particle multiplicity
distributions increase. To minimize these effect the analysis is performed separately in
fine centrality bins, 5\%. This value is near the resolution of the centrality determi-
nation. The final results in wide centrality bins are the average of the fine centrality
binning weighted by the number of triggers in each bin.

The magnitude of the remaining multiplicity correlations is estimated by parameter-
izing \( \langle n_{\text{trig}} \rangle \) and \( \langle n_{\text{assoc}} \rangle \) as a function of a centrality parameter, the number
of participating nucleons \( (N_{\text{part}}) \) or the number of binary collision \( (N_{\text{coll}}) \). Monte
Carlo events are generated with \( N_{\text{part}} \) and \( N_{\text{coll}} \) distributions taken from a Glauber
model \(^{12}\). Trigger and associated particle multiplicities are taken to be distributed
Fig. 1. Yield per trigger on the near, $\Delta\phi < 0.94\text{rad}$ (solid points) and away $\Delta\phi > 2.2\text{rad}$ (hollow points) side for baryon-meson (squares) and meson-meson (circles) correlations as a function of $N_{\text{part}}$. Triggers have $2.5 < p_T < 4.0\text{ GeV/c}$ and associated particles have $1.8 < p_T < 2.5\text{ GeV/c}$. Error bars are statistical errors and the shaded boxes show the systematic errors. There is a 13.6% normalization error which moves all points together.

according to a Poisson distribution with a mean given from the parameterization. These Monte Carlo events contain pairs whose only correlation is due to the $N_{\text{part}}$ ($N_{\text{coll}}$) of the event. The multiplicity correlations are quantified by a parameter, $\xi$, defined as the ratio of the observed pair rate to the combinatorial background level as calculated under the assumption of no multiplicity correlations (Eqn. 2). The systematic error on this procedure comes from varying both the multiplicity parameter between $N_{\text{part}}$ and $N_{\text{coll}}$ and the parameterizations of $\langle n_{\text{trig}} \rangle$ and $\langle n_{\text{assoc}} \rangle$. The combinatorial background level $B$ in Eqn. 6 is increased by a factor of $\xi$. The value of $\xi$ depends on the shape of $\langle n_{\text{trig}} \rangle(N)$ and $\langle n_{\text{assoc}} \rangle(N)$; a strong dependence of the multiplicity on centrality leads to larger values of $\xi$ because there is more of a difference between the central and peripheral edges of the centrality bin. In central, 0-5%, collisions $\xi \approx 1.002$ and in peripheral, 60-65%, collisions $\xi \approx 1.2$.

3. Results and Discussion

3.1. Identified Trigger Correlations

Fig. 1 shows near side meson-meson correlations (filled circles) as a function of the number of participating nucleons, $N_{\text{part}}$. The background has been subtracted by
the absolute subtraction method. The yield per trigger rises linearly with increasing $N_{\text{part}}$. The baryon-meson yield per trigger (filled squares) also rises linearly for $N_{\text{part}} < 250$. In more central collisions the yield per trigger decreases and in the most central collisions is consistent with the peripheral value. The agreement between baryon-meson and meson-meson centrality dependence at $N_{\text{part}} < 250$ is consistent with a picture where both trigger types come primarily from the same source and are associated with an increasing number of associated particles. The difference between the baryon and meson triggers for $N_{\text{part}} > 250$ could indicate baryon production at high centralities is dominated by a different source. However, two particle correlations can only measure the average number of associated particles per trigger, not the fraction of triggers which have associated particles.

This ambiguity can be addressed by measuring away-side, $\Delta \phi > 2.2$rad, yields as a function of trigger particle type. Since the partons that become the near and away side jets are moving away from each other their fragmentation should be independent. Fig. 3 also shows the away side meson yields for baryon and meson triggers (hollow points). No significant difference is seen between the trigger types.

Since baryon number is a conserved quantity, measurement of the charge dependence of correlations between two baryons can be a sensitive probe of differences in
the baryon production mechanism and possibly the jet fragmentation process. Fig. 2 shows $J(\Delta \phi)$ integrated for $\Delta \phi < 0.94$ rad, i.e. the yield of associated particles per trigger as a function of the number of participating nucleons, $N_{\text{part}}$ in the same $p_T$ range as Fig. 1. The $\Delta \phi$ region covers where two correlated particles are expected to come from the fragmentation of the same jet. Again, the background has been subtracted with the absolute subtraction method. Both particles are identified as $p$ or $\bar{p}$ and different sets of points show the different charge combinations with triggers in the $p_T$ region of the baryon excess. The charge inclusive baryon-baryon yield (hollow squares) is flat with $N_{\text{part}}$, except for a smaller yield in the most peripheral collisions. Same sign pairs, $p-p$ and $\bar{p}-\bar{p}$ (triangles), show no yield and opposite sign pairs (filled circles and squares) are consistent with the charge independent yields. No significant difference is seen between $p$ and $\bar{p}$ triggers.

3.2. Associated Particle Ratios

Baryons at all centralities are associated with non-zero jet-like conditional yields, so it is useful to study whether the particle mixture of jet fragments changes with
central collisions, the fraction of baryons in the trigger sample increases with centrality. The combinatorial background has been subtracted with the ZYAM assumption and $J(\Delta\phi)$ has been integrated over $\Delta\phi$ less than the minimum in $J(\Delta\phi)$. Fig. 3 shows the ratio of associated baryons to mesons as a function of $p_{T,assoc}$ for the near-side jet in three centrality classes. At low $p_T$ the ratio is small and there is no significant centrality dependence. At $p_T > 1.5$ GeV/c the ratio increases with increasing centrality.

Triggering on an intermediate $p_T$ particle is expected to bias the near-side jet toward small medium path lengths. If so, the away-side, $\Delta\phi \approx \pi$, typically sees a long medium path length and could be sensitive to medium modifications to the jet fragmentation process, hence we measure the particle composition of the away-side
jet. Fig. 4 shows the ratio of associated baryons to mesons ($\pi^\pm, K^\pm$) with charged hadron triggers, $2.5 < p_T < 4.0$ GeV/$c$, as a function of the associated particle $p_T$ integrated over $\Delta\phi$ from $\pi$ to the minimum of $J(\Delta\phi)$. In peripheral collisions (triangles) the ratio of associated baryons to mesons on the away-side is approximately flat with $p_T$. In central collisions (circles) this ratio increases significantly with the associated particle $p_T$, suggesting that the away-side jet fragmentation is increasingly baryon rich at intermediate $p_T$. At the highest associated particle $p_T$ shown in central collisions the ratio of associated baryons to mesons is consistent with the value observed in the single particles at the same $p_T$ and centrality selections [13].

4. Conclusions

The extraction of jet-like correlations at intermediate $p_T$ is difficult because of the large combinatorial background. PHENIX has developed robust methods to reliably subtract this background. We have described in detail the absolute subtraction method which makes no assumptions about the jet correlation shape.

We have presented some recent results of identified particle jet correlations from PHENIX. In the same $p_T$ range that an excess of baryons has been observed in single particle yields we have observed modification to the jet structure of two particle correlations involving baryons in central collisions. These results suggest that, at least some of, the baryon excess is connected to jet fragmentation in central Au+Au collisions being modified compared to vacuum fragmentation. The yield of associated particles per trigger increases with centrality and the fraction of associated particles per hadron trigger that are baryons increases. These observations, along with the quark number scaling observed in elliptic flow measurements in the same $p_T$ range could indicate that particle production at intermediate $p_T$ is a novel interplay of hard and soft physics. A full understanding of this phenomenology will require models which are able to simultaneously explain single particle yields, elliptic flow and jet correlations.

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