Jet Structure of Baryon Excess in Au+Au Collisions at \(\sqrt{s_{NN}} = 200 \) GeV

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Two particle correlations between identified meson and baryon trigger particles with $2.5 < p_T < 4.0$ GeV/$c$ and lower $p_T$ charged hadrons have been measured at midrapidity by the PHENIX experiment at RHIC in p+p, d+Au and Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV. The probability of finding a hadron near in azimuthal angle to the trigger particle is almost identical for leading mesons and baryons for non-central Au+Au. The yield for both trigger baryons and mesons is significantly higher in Au+Au than in p+p and d+Au, except for trigger baryons in central collisions. The baryon excess is likely to arise predominantly from hard scattering processes.

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A remarkable feature of relativistic heavy ion collisions is greatly enhanced production of baryons and antibaryons relative to mesons. This enhancement over elementary p+p collisions occurs at transverse momenta ($p_T$) of 2–5 GeV/$c$ [1, 2, 3]. In this range, particle production shifts from soft processes (non-perturbative, low momentum transfer scattering) to hard (high momentum transfer parton-parton scattering). Hard scattering is followed by fragmentation of the scattered partons to jets of hadrons. Baryon and anti-baryon production is suppressed in fragmentation. Phenomenologically, this can be thought of as a large penalty for creating a diquark/anti-diquark pair for baryon formation vs. a quark/anti-quark pair for meson formation.

Since there is no sharp separation of scales between hard and soft processes, it is natural to ask which is responsible for the baryon excess in Au+Au collisions. Hadron formation by recombination of boosted quarks from a collectively expanding source explains the observed baryon/meson ratios [4, 5, 6, 7]. The models include recombination of quarks from a thermal source, but the handling of hard partons varies significantly. Some allow hard parton fragmentation only, with no recombination [3]. Others model the distribution of shower partons in a jet, and allow soft and hard partons to coalesce [8]. These models should produce different hadron-hadron correlations in the recombination region, however quantitative predictions are not available. Baryon production by recombination of purely thermal quarks implies that the baryon excess is of soft origin, not from jet fragmentation. However, the yield of baryons in this momentum range scales approximately with the number of binary nucleon-nucleon collisions [2], which is typical of hard processes. Hadron production via recombination between jet fragments and thermal quarks [8] could preserve jet-like correlations among the final hadrons, presuming that each hadron contains at least one quark arising from a fragmenting hard scattered parton. As baryons contain one quark more than mesons, baryon production may be more strongly enhanced by the availability of additional quarks. Observation of such a mechanism would indicate modification of the jet fragmentation process by the medium produced in Au+Au collisions.

To determine the role of jets in the production of intermediate $p_T$ protons, the PHENIX experiment at RHIC has measured energetic hadronic partners near the baryons. These are the additional fragmentation products from the same jet as the baryon. We present first results on two particle correlations where the trigger particle is an identified meson ($\pi, K$) or baryon ($p, p\bar{p}$) at 2.5 $< p_T < 4.0$ GeV/$c$. Associated particles, i.e. lower $p_T$ charged hadrons, near in azimuthal angle to the trigger are counted. Momentum cuts are chosen to avoid contamination by resonance decays. The centrality and collision system dependence of the associated particle yield per trigger is used to help disentangle thermal quark recombination from jet fragmentation. Trigger particles from recombination of boosted thermal quarks should not have correlated partners beyond the expected correlation from elliptic flow. However, if the source of the baryons is indeed fragmentation of hard scattered partons, the probability of finding a jet-like hadronic partner should be comparable to that observed in p+p collisions. We use p+p collisions without trigger identification to provide a comparison baseline.

Data presented here include collisions at $\sqrt{s_{NN}}$ = 200 GeV of Au+Au (24 million events), d+Au (42 million events) and p+p (23 million events). Charged particles are reconstructed in the central arm of PHENIX using drift chambers, each with an azimuthal coverage of $\pi/2$ and two layers of multi-wire proportional chambers with pad readout (PC1, PC3) [3]. Pattern recognition is based on a combinatorial Hough transform in the track bend plane, with the polar angle determined by PC1 and the collision vertex along the beam direction. Particle momenta are measured with a resolution $\delta p/p = 0.7% \pm 1.0% (GeV/c)$ in Au+Au and $\delta p/p = 0.7% \pm 1.1% (GeV/c)$ in d+Au and p+p. The portion of the east arm spectrometer containing the high resolution Time-Of-Flight(TOF) detector, which covers pseudo-rapidity $|\eta| < 0.35$ and $\phi = \pi/4$ in azimuthal angle is used for trigger particle identification. Beam Counters (BBC) [3] provide the global start; stop signals are from TOF scintillators at a radial distance of 5.06 m. The timing resolution is $\sigma = 120$ ps, which allows a 4$\sigma$ separation of mesons/baryons up to $p_T \approx 4$ GeV/$c$. The Au+Au centrality determination is described in Ref. [10].

Distributions of azimuthal angular difference, $\Delta\phi$, are constructed for trigger-partner pairs. The combinatorial
background is determined by constructing mixed events in two steps: the number of trigger and partner particles is determined by sampling the measured single particle multiplicity distributions in the relevant momentum and centrality ranges. Then the 3-momenta of particles in the mixed event are determined by sampling the measured trigger and partner momentum distributions. To correct for the limited acceptance of the PHENIX spectrometers, the real event $\Delta \phi$ distributions are divided by $\Delta \phi$ distributions from the mixed events, normalized to a constant angular aperture. The shape of this distribution retains effects of the PHENIX azimuthal acceptance, but has no true correlations. The partner yield is then corrected for the reconstruction efficiency, detector aperture and (for Au+Au only) detector occupancy $[11]$. No extrapolation is made to $|\eta| > 0.35$. Since d+Au and Au+Au collisions contain uncorrelated combinatorial background from other particles in the underlying event, the mixed event partner yield per trigger, after the same efficiency correction, is subtracted using the normalization determined by the convolution of the trigger and partner single particle rates.

Because mixing and subtraction is done in finite size centrality bins, the background distribution is biased toward the more central events within a bin, as they produce more particles. Consequently, the subtraction is corrected for the width of the centrality bins used for mixing: 5% in Au+Au and minimum bias in d+Au. The width of trigger and partner number within a centrality bin is determined from the measured centrality dependence of particle multiplicity in the relevant momentum region and particle species $[10, 11, 12, 13]$. This width implies larger fluctuations in the number of partners per trigger in mixed events, so the mixed event partner yields are increased accordingly. This correction modifies the background level by $\approx 0.2\%$ in the most central and $\approx 25\%$ in the most peripheral Au+Au collisions.

Elliptic flow causes an angular correlation in Au+Au unrelated to jet fragmentation, a background to this measurement. The elliptic flow correlation is removed by modulating the azimuthally uniform combinatorial background by $1 + 2v_2^{assoc}v_2^{trig} \cos(\Delta \phi)$, where $v_2^{assoc}$ and $v_2^{trig}$ are the $v_2$ values measured for the partner and trigger $p_T$ ranges, respectively $[14]$ where the reaction plane is measured by the BBC at $3 < \eta < 4$ minimizing the influence of jets in the $v_2$ values. Because the centrality binning in this analysis is finer than in $[14]$, the $p_T$ integrated centrality dependence is used to interpolate $v_2$ for collisions more central than 20%.

Systematic uncertainties in Au+Au and d+Au partner yields arise from uncertainties in the corrections for centrality bin width, systematic and statistical errors on $v_2$ $[14]$ (Au+Au only), uncertainty in the background subtraction due to the event mixing technique, and uncertainty in the detector occupancy correction. The cross-contamination of mesons and protons is less than 5%.

The error on the occupancy correction reaches a maximum of 5% in the most central Au+Au collisions. For most Au+Au bins, the dominant systematic uncertainty on the partner yields is the uncertainty in $v_2$. This produces a systematic error of approximately 0.01 partners per trigger baryon in semi-central and central collisions; for trigger mesons, the corresponding error is somewhat smaller. The event mixing uncertainty is approximately comparable to the $v_2$ uncertainty in these bins. In peripheral Au+Au collisions, the dominant systematic error in the partner yield arises from the centrality bin width corrections and $v_2$ uncertainty. In d+Au collisions, there is no $v_2$, and the partner yield uncertainty is driven by the correction for centrality bias of mixed events. In p+p collisions the systematic error is taken to be the same size as the combinatorial background which is subtracted. The total systematic errors are shown in Figure $2$.

Figure $1$ shows the $\Delta \phi$ distributions with trigger mesons (left) and baryons (right) triggers with $2.5 < p_T < 4.0$ GeV/$c$ and associated charged hadrons with $1.7 < p_T < 2.5$ GeV/$c$ for six centralities in Au+Au collisions. The solid lines indicate the calculated combinatorial background in the event modulated by the measured elliptic flow.

![Figure 1](image_url)
baryons \[10\] which increase 
from thermal quark recombination should have no jet-like 
partner hadrons and would dilute the per-trigger conditional yield. Because this simple estimate does not allow 
for meson production by recombination, which must also 
occur along with baryon production, it represents an upper 
limit to the centrality dependence of the jet partner yield from thermal recombination. The data clearly dis-
agree with both the centrality dependence and the absolute yields of this estimation, indicating that the baryon excess has the same jet-like origin as the mesons, except perhaps in the highest centrality bin.

The bottom panel of Figure 2 shows the conditional yield of partners on the away side. The partner yield in \(2.2 < \Delta \phi < \pi\) rad drops equally for both trigger baryons and mesons going from \(p+p\) and \(d+Au\) to cen-
tral \(Au+Au\), in agreement with the observed disappearance \[17\] and/or broadening \[15\] of the dijet azimuthal correlations. It further supports the conclusion that the baryons originate from the same jet-like mechanism as mesons.

Figure 2 shows the conditional yield per trigger of part-
ner hadrons in \(p+p\), \(d+Au\), and \(Au+Au\) collisions, as a function of the number of participant nucleons. The top panel shows partner yield at small relative angle, from the same jet as the trigger hadron. We observe an in-
crease in partner yields in mid-central \(Au+Au\) compared to the \(d+Au\) and \(p+p\) collisions; this almost doubling of the near side partner yield suggests that the fragmenta-
tion is modified by the medium. In \(Au+Au\) collisions, the near side yield per meson trigger remains constant as a function of centrality, whereas the near-side yield per baryon trigger decreases in the most central collisions as expected if a fraction of the baryons were produced by soft processes such as recombination of thermal quarks. In \(d+Au\) collisions the near-side yields per trigger are the same for meson and baryons triggers, and agree with results from \(p+p\) collisions generated with PYTHIA \[10\].

The dashed line in Figure 2 shows the expected centrality dependence of partners per baryon if all the “extra” baryons \[10\] which increase \(p/\pi\) over that in \(p+p\) col-
lusions were to arise solely from soft processes. Baryons 
around \(\Delta \phi = \pi/2\). However, the non-background associ-
ated partners are observed in the angular range charac-
teristic of jet fragmentation. The near side jet width in \(p+p\) collisions has been measured by PHENIX to be \(\approx 0.25\) rad in a similar \(p_T\) range \[12\].

Figure 2 shows the conditional yield per trigger of part-
ner particles in \(p+p\), \(d+Au\), and \(Au+Au\) collisions, as a function of the number of participant nucleons. The top panel shows partner yield at small relative angle, from the same jet as the trigger hadron. We observe an increase in partner yields in mid-central \(Au+Au\) compared to the \(d+Au\) and \(p+p\) collisions; this almost doubling of the near side partner yield suggests that the fragmentation is modified by the medium. In \(Au+Au\) collisions, the near side yield per meson trigger remains constant as a function of centrality, whereas the near-side yield per baryon trigger decreases in the most central collisions as expected if a fraction of the baryons were produced by soft processes such as recombination of thermal quarks. In \(d+Au\) collisions the near-side yields per trigger are the same for meson and baryons triggers, and agree with results from \(p+p\) collisions generated with PYTHIA \[10\].

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from thermal quark recombination should have no jet-like partner hadrons and would dilute the per-trigger conditional yield. Because this simple estimate does not allow for meson production by recombination, which must also occur along with baryon production, it represents an upper limit to the centrality dependence of the jet partner yield from thermal recombination. The data clearly dis-
agree with both the centrality dependence and the absolute yields of this estimation, indicating that the baryon excess has the same jet-like origin as the mesons, except perhaps in the highest centrality bin.

The bottom panel of Figure 2 shows the conditional yield of partners on the away side. The partner yield in \(2.2 < \Delta \phi < \pi\) rad drops equally for both trigger baryons and mesons going from \(p+p\) and \(d+Au\) to cen-
tral \(Au+Au\), in agreement with the observed disappearance \[17\] and/or broadening \[15\] of the dijet azimuthal correlations. It further supports the conclusion that the baryons originate from the same jet-like mechanism as mesons.

![FIG. 2: Yield per trigger for associated charged hadrons between \(1.7 < p_T < 2.5\) GeV/c for the near- (top) and away-
side (bottom) side jets. The error bars are statistical errors and the grey boxes are systematic errors. There is an additional 
12% error on the overall normalization which moves all points together. The dashed line (top) represents an upper limit of 
the centrality dependence of the near-side partner yield from thermal recombination (see text).](image)

![FIG. 3: \(p_T\) spectra of the near side associated charged hadrons corrected to the full jet yield for meson (left) and 
baryon (right) triggers at \(2.5 < p_T < 4.0\) GeV/c and \(|\eta| < 0.35\) for six centralities in \(Au+Au\), \(d+Au\) and \(p+p\) collisions (non-identified trigger). Errors are statistical only. The curves are exponential fits. Inverse slope values are shown in Figure 4](image)
that jets are symmetric gaussians in both φ and η, and is required for the partner p_T spectra because of the p_T dependence of the jet width. The conditional yields in Figure 2 do not have this additional correction as they are measured in a single p_T bin. The partner spectra in Figure 3 are fitted with exponentials, and the slopes are given in Figure 4 as a function of N_part. The jet partner slopes exceed those of inclusive hadrons in the same p_T range [11], except perhaps in the most central collisions. The partner slopes are consistent between the collision systems and trigger type, indicating a common jet-like source for both baryons and mesons.

We have presented the first study of the jet structure of baryons (p, p̄) and mesons (π, K) at midrapidity in Au+Au collisions at \( \sqrt{s_{NN}} = 200 \) GeV, in the momentum region where baryon production is greatly enhanced in central Au+Au. Three observations indicate that mesons and baryons both arise predominantly from hard processes in all but the most central Au+Au collisions. First, baryons and mesons both have jet-like partner particles. Second, there is no strong change of the slope of the p_T spectra of associated particles from p+p to d+Au to Au+Au collisions, and it is larger than that of inclusive hadrons. Finally, on the away side, the jet partner yield into a 0.94 radian opening angle decreases in central collisions similarly for trigger baryons and mesons. The data are therefore inconsistent with a simple picture of baryon production at intermediate p_T dominated by recombination of only thermal quarks. On the trigger particle side, jets in Au+Au collisions are modified compared to those in p+p. They are richer in leading baryons and show enhanced probability for jet-like partners, except for the most central collisions with trigger baryons.

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