Disappearance of back-to-back high $p_T$ hadron correlations in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

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Azimuthal correlations for large transverse momentum charged hadrons have been measured over a wide pseudo-rapidity range and full azimuth in Au+Au and p+p collisions at $\sqrt{s_{NN}} = 200$ GeV. The small-angle correlations observed in p+p collisions and at all centralities of Au+Au collisions are characteristic of hard-scattering processes already observed in elementary collisions. A strong back-to-back correlation exists for p+p and peripheral Au+Au. In contrast, the back-to-back correlations are reduced considerably in the most central Au+Au collisions, indicating substantial interaction as the hard-scattered partons or their fragmentation products traverse the medium.

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In collisions of heavy nuclei at high energies, a new state of matter consisting of deconfined quarks and gluons at high density is expected [1]. Large transverse momentum partons in the high-density system result from the initial hard scattering of nucleon constituents. After a hard scattering, the parton fragments to create a high energy cluster (jet) of particles. A high momentum parton traversing a dense colored medium is predicted to experience substantial energy loss [2, 3] and may be absorbed. Measurement of the parton fragmentation products after hard-scattering processes in nuclear collisions may reveal effects due to the interaction of high-momentum partons traversing the medium, thereby measuring the gluon density of the medium [4].

High $p_T$ single particle spectra are well described over a broad range of energies [5] in terms of the hadron’s parton distributions, hard parton scattering treated by perturbative QCD, and subsequent fragmentation of the parton. High $p_T$ jet events have also been studied in proton-nucleus interactions [6]. In the absence of effects of the nuclear medium the rate of hard processes should scale linearly with the number of binary nucleon-nucleon collisions. Recent results from RHIC, however, show a suppression of the single particle inclusive spectra of hadrons for $p_T > 2$ GeV/c in central Au+Au collisions, indicating substantial in-medium interactions [7, 8].

In this Letter, we report measurements of two-hadron angular correlations at large transverse momentum for p+p and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. These correlation measurements provide the most direct evidence for production of jets in high energy nucleus-nucleus collisions, and allow for the first time measurements, inaccessible in inclusive spectra, of the fate of back-to-back jets in the dense medium as a function of the size of the overlapping system. The results reveal...
significant interaction of hard-scattered partons (or their fragmentation products) in the medium, with a strong dependence on the geometry and distance of traversal.

The measurements were made using the STAR detector at the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory. The STAR detector is a large acceptance magnetic spectrometer, with a large volume Time Projection Chamber (TPC) inside a 0.5 Tesla solenoidal magnet. The TPC measures the trajectories of charged particles and determines the particle momenta. The TPC has full azimuthal coverage over a pseudo-rapidity range $|\eta| < 1.5$. STAR has excellent position and momentum resolution, and, due to its vertexing capabilities, is able to identify many sources of secondary particles. The p+p analysis uses $\approx$10 million minimum bias p+p events triggered on the coincidence of signals from scintillator annuli spanning the pseudo-rapidity interval $3.5 \leq |\eta| \leq 5.0$. The Au+Au analysis uses $\approx$1.7 million minimum bias Au+Au events and $\approx$1.5 million top 10% central Au+Au events.

Partons fragment into jets of hadrons in a cone around the direction of the original hard-scattered parton. The leading hadron in the jet tends to be most closely aligned with the original parton direction. The large multiplicities in Au+Au collisions make full jet reconstruction impractical. Thus, we utilize two-particle azimuthal correlations of high $p_T$ charged hadrons to identify jets on a statistical basis, with known sources of background correlations subtracted.

Events with at least one large transverse momentum hadron ($4 < p_T^{\text{trig}} < 6$ or $3 < p_T^{\text{trig}} < 4$ GeV/c), defined to be a trigger particle, are used in this analysis. For each of the trigger particles in the event, we increment the number $N(\Delta \phi, \Delta \eta)$ of associated tracks with $2 \text{ GeV/c} < p_T < p_T^{\text{trig}}$ as a function of their azimuthal ($\Delta \phi$) and pseudo-rapidity ($\Delta \eta$) separations from the trigger particle. We then construct an overall azimuthal pair distribution per trigger particle,

$$D(\Delta \phi) \equiv \frac{1}{N_{\text{trigger}}} \int d\Delta \eta N(\Delta \phi, \Delta \eta),$$

(1)

where $N_{\text{trigger}}$ is the observed number of tracks satisfying the trigger requirement. The efficiency $e$ for finding the associated particle is evaluated by embedding simulated tracks in real data. In order to have a high and constant tracking efficiency, the tracks are required to have $|\eta| < 0.7$, which translates to a relative pseudo-rapidity acceptance of $|\Delta \eta| < 1.4$. The single track reconstruction efficiency varies from 77% for the most central Au+Au collisions to 90% for the most peripheral Au+Au collisions and p+p collisions.

Identical analysis procedures are applied to the p+p and Au+Au data. Displayed in Figure 1 are the azimuthal distributions for same-sign and opposite-sign charged pairs from the a) p+p data and b) minimum bias Au+Au data for $4 < p_T^{\text{trig}} < 6$ GeV/c. The data are integrated over the relative pseudo-rapidity range $0 < |\Delta \eta| < 1.4$. Clear correlation peaks are observed near $\Delta \phi \sim 0$ and $\Delta \phi \sim \pi$ in the data. The opposite-sign correlations at small relative azimuth are larger than those of the same-sign particle pairs, while the sign has a negligible effect on the back-to-back correlations.

To isolate the jet-like correlations (localized in $\Delta \phi$, $\Delta \eta$) in central Au+Au collisions, the azimuthal distributions are measured for two regions of relative pseudo-rapidity, $|\Delta \eta| < 0.5$ and $0.5 < |\Delta \eta| < 1.4$. The difference between the small and large relative pseudo-rapidity azimuthal distributions is displayed in Figure 1a, along with single Gaussian fits. Near $\Delta \phi = 0$, the azimuthal distributions from Au+Au and p+p have similar shapes. For the opposite-sign azimuthal distributions, the Gaussian widths are $0.17 \pm 0.01 \text{(stat.)} \pm 0.03 \text{(sys.)}$ radians for p+p data, and $0.20 \pm 0.02 \text{(stat.)} \pm 0.03 \text{(sys.)}$ radians for the central Au+Au data. For the same-sign azimuthal distributions, the Gaussian widths are $0.16 \pm 0.02 \text{(stat.)} \pm 0.03 \text{(sys.)}$ radians for p+p data, and $0.15 \pm 0.03 \text{(stat.)} \pm 0.04 \text{(sys.)}$ radians for the central Au+Au data. The systematic errors reflect the spread of values found for different choices of the $\Delta \phi$ bin width. Within the errors, there are no significant differences between the small-angle correlation widths for p+p and central Au+Au collisions.

The ratios of the opposite-sign to same-sign peak areas are $2.7 \pm 0.9 \text{(stat.)} \pm 0.2 \text{(sys.)}$ for p+p and $2.5 \pm 0.6 \text{(stat.)} \pm 0.2 \text{(sys.)}$ for central Au+Au collisions. In jet fragmentation, there are dynamical charge correlations between the leading and next-to-leading charged hadrons that originate from the formation of $q\bar{q}$ pairs along a string between two partons. This results in a preferential ordering into oppositely-charged adjacent particles along a string during fragmentation. The Hijing event generator, which utilizes the Lund string fragmentation scheme, incorporating these concepts, predicts a ratio of $2.6 \pm 0.7$ for the opposite-sign to same-sign correlation.
strengths. The agreement of this ratio with those measured in the central Au+Au and p+p suggests that the same jet production mechanism is responsible for a majority of the charged hadrons with $p_T > 4$ GeV/c in p+p and central Au+Au collisions.

The decay of resonances would also lead to small-angle azimuthal correlations, but a resonance decay origin is unlikely due to the observed correlation of particles with the same charge sign, the similarity in the measured small-angle azimuthal correlation widths in the Au+Au and p+p interactions, and the strong back-to-back correlations of large $p_T$ particles seen for p+p collisions in Fig. 1b. The latter correlations, indicative of di-jet events [9], are removed from the central Au+Au sample by the subtraction in Fig. 1b. A quantitative analysis of back-to-back jet survival in Au+Au requires the more detailed treatment of background correlations described below.

In addition to correlations due to jets, the two-particle azimuthal distributions in Au+Au exhibit a structure attributable to an anisotropy of single particle production relative to the reaction plane. Previous measurements [17] indicate that, even at large transverse momentum, the particle distributions contain an anisotropy due to elliptic flow that can be characterized by $dN/d(\phi - \Phi_r) \propto 1 + 2v_2 \cos(2\phi - \Phi_r)$, where $\Phi_r$ is the reaction plane angle determined by event by event and $v_2$ is the elliptic flow parameter. This leads to a two particle azimuthal distribution of the form, $dN/d\Delta \phi = B(1 + 2v_2^2 \cos(2\Delta \phi))$. The elliptic flow component of the two-particle azimuthal distribution is measured using several methods [17]. In this paper, $v_2$ is determined using a reaction-plane method.

A simple reference model can be constructed for the two-particle azimuthal distributions of high $p_T$ particles in Au+Au collisions. A number of independent hard scatterings (each similar to one measured in a triggered p+p event) included in an event with correlations due to elliptic flow can be represented by the azimuthal distribution,

$$D_{\text{model}} = D_{pp} + B(1 + 2v_2^2 \cos(2\Delta \phi)).$$

The elliptic flow parameter ($v_2$) is measured independently in the same set of events, and is taken to be constant for $p_T > 2$ GeV/c [17]. The parameter $B$ is then determined by fitting the observed $D_{AuAu}$ in the region $0.75 < |\Delta \phi| < 2.24$ radians, which is largely free of jet contributions in the p+p data.

In Figure 2, the azimuthal distributions for $0 < |\Delta \eta| < 1.4$ in Au+Au collisions at various centralities are compared to Equation 2 using the measured p+p data. The centrality selection is constructed by subdividing the Au+Au minimum bias data sample into subsamples with different charged particle multiplicities within $|\eta| < 0.5$. The parameters $v_2$ and $B$ are determined independently for each centrality bin, and are listed in Table 1. For all centralities, the azimuthal correlation near $\Delta \phi = 0$ is well described by Equation 2. This indicates that the same mechanism (hard parton scattering and fragmentation) is responsible for high transverse momentum particle production in p+p and Au+Au collisions. However, the back-to-back correlations are suppressed in Au+Au collisions compared to the expectation from Equation 2, and the suppression is greater for more central collisions. The most central collisions show no indication of any back-to-back correlations beyond that expected from elliptic flow.

The ratio of the measured Au+Au correlation excess relative to the p+p correlation is:

$$I_{AA}(\Delta \phi_1, \Delta \phi_2) = \frac{\int_{\Delta \phi_1}^{\Delta \phi_2} d(\Delta \phi)[D_{AuAu} - B(1 + 2v_2^2 \cos(2\Delta \phi))]}{\int_{\Delta \phi_1}^{\Delta \phi_2} d(\Delta \phi)D_{pp}}.$$  

The ratio can be plotted as a function of the number of participating nucleons ($N_{part}$), deduced from the centrality bins as described in reference [4]. $I_{AA}$ is measured for both the small-angle ($|\Delta \phi| < 0.75$ radians) and back-to-back ($|\Delta \phi| > 2.24$ radians) regions. The ratio should

| Centrality (%) | $N_{part}$ | $v_2$ | $B$ |
|---------------|-----------|------|-----|
| 60-80         | 20±6        | 0.24±0.04 | 0.065±0.003 |
| 40-60         | 61±10       | 0.22±0.01 | 0.231±0.003 |
| 30-40         | 114±13      | 0.21±0.01 | 0.420±0.005 |
| 20-30         | 165±13      | 0.19±0.01 | 0.633±0.005 |
| 10-20         | 232±11      | 0.15±0.01 | 0.931±0.006 |
| 5-10          | 298±10      | 0.10±0.01 | 1.187±0.008 |
| 0-5           | 352±7       | 0.07±0.01 | 1.442±0.003 |

TABLE I: Centrality, number of participants, $v_2$ ($2 < p_T < 6$ GeV/c), and normalization constant $B$. The errors on $v_2$ and $B$ are statistical only, while the errors on the number of participants are systematic [14].

FIG. 2: Azimuthal distributions (0 < $|\Delta \eta|$ < 1.4, $4 < p_T^{\text{trig}} < 6$ GeV/c) for Au+Au collisions (solid circles) compared to the expected distributions $D_{\text{model}}$ from Equation 2 (open circles). Also shown is the elliptic flow contribution for each centrality (solid curve).
The small-angle correlations with increasing centrality are suppressed compared to the expectation from Equation (3) for small-angle (squares, $|\Delta \phi| < 0.75$ radians) and back-to-back (circles, $|\Delta \phi| > 2.24$ radians) azimuthal regions versus number of participating nucleons for trigger particle intervals $4 < p_{T}^{\text{trig}} < 6$ GeV/c (solid) and $3 < p_{T}^{\text{trig}} < 4$ GeV/c (hollow). The horizontal bars indicate the dominant systematic error (highly correlated among points) due to the uncertainty in $v_2$.

In summary, STAR has measured azimuthal correlations for high $p_T$ charged particles over a large relative pseudo-rapidity range with full azimuthal angle coverage. Comparison of the opposite-sign and same-sign correlation strengths indicates that hard scattering and fragmentation is the predominant source of charged hadrons with $p_T > 4$ GeV/c in central Au+Au collisions. The azimuthal correlations in Au+Au collisions have been treated as the superposition of independently determined elliptic flow and individual hard parton scattering contributions, the latter measured in the STAR p+p data. The most striking feature of the hard-scattering component is an increasing suppression of back-to-back relative to small-angle correlations with increasing centrality. These observations appear consistent with large energy loss in a system that is opaque to the propagation of high-momentum partons or their fragmentation products.

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