Jets and high $p_T$ hadrons in dense matter: recent results from STAR

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Abstract. We review recent measurements of high transverse momentum (high $p_T$) hadron production in nuclear collisions by the STAR Collaboration at RHIC. The previously observed suppression in central Au+Au collisions has been extended to much higher $p_T$. New measurements from d+Au collisions are presented which help disentangle the mechanisms responsible for the suppression. Inclusive single hadron spectra are enhanced in d+Au relative to p+p, while two-particle azimuthal distributions are observed to be similar in p+p, d+Au and peripheral Au+Au collisions. The large suppression of inclusive hadron production and absence of the away-side jet-like correlations in central Au+Au collisions are shown to be due to interactions of the jets with the very dense medium produced in these collisions.

1. INTRODUCTION

High energy partons propagating through matter are predicted to lose energy via induced gluon radiation, with the magnitude of the energy loss depending linearly on the color charge density of the matter[1]. This phenomenon may provide a sensitive probe of the medium generated in high energy heavy ion collisions, where a Quark-Gluon Plasma (QGP) is expected to form if sufficiently high energy density is achieved. The high energy partons in such collisions result from the hard scattering of quarks or gluons from the incoming nuclei and are observed experimentally as correlated “jets” of hadrons having large transverse momentum ($p_T$) with respect to the beam direction. The experimental challenge is to measure partonic energy loss (“jet quenching”) in the extremely complex environment of high energy nuclear collisions.

In these talks we discuss recent progress towards the measurement of jet quenching in high energy nuclear collisions by the STAR experiment at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory. At the values of jet $E_T$ accessible at RHIC energies with the currently achieved integrated luminosities, full jet reconstruction with good energy resolution is difficult. We therefore utilize known features of jet fragmentation to study jet quenching, in particular the inclusive spectrum of high $p_T$ (“leading”) hadrons and the angular correlation of pairs of high $p_T$ hadrons. We compare their distributions in centrality-selected Au+Au collisions to those in d+Au and non-singly diffractive (NSD) p+p collisions, all at $\sqrt{s_{NN}}=200$ GeV. Unless otherwise specified, the results reported here are for unidentified charged hadrons, measured in the large cylindrical STAR Time Projection Chamber with a 0.5T solenoidal magnetic field[2]. Related results from STAR are discussed in [3, 4].


2. SUPPRESSION OF INCLUSIVE CHARGED HADRONS

Jets occasionally fragment with a single hadron carrying a large fraction of the total jet energy. The resulting inclusive hadron distributions exhibit power-law ($1/p_T^n$) shapes characteristic of the underlying perturbative QCD (pQCD) processes. Figure 1 shows the event-normalized invariant inclusive charged hadron distributions as a function of $p_T$ for NSD $p+p$ and centrality-selected Au+Au and d+Au collisions\cite{5, 6}. The centrality bins correspond to the indicated percentiles of the total cross section: 0-5% for Au+Au indicates the most central and 60-80% the most peripheral collisions. Power-law shapes are clearly observed in all cases.

Nuclear effects on hadron production in d+Au and Au+Au collisions are measured through comparison to the p+p reference spectrum using the ratio

$$R_{AB}(p_T) = \frac{d^2N/dp_Td\eta}{T_{AB}d^2\sigma_{pp}/dp_Td\eta},$$

where $d^2N/dp_Td\eta$ is the differential yield per event in the nuclear collision $A+B$, $T_{AB}=\langle N_{\text{bin}} \rangle/\sigma_{\text{inel}}$ describes the nuclear geometry, and $d^2\sigma_{pp}/dp_Td\eta$ for p+p inelastic collisions is determined from the p+p measurement. $\langle N_{\text{bin}} \rangle$ is the mean number of binary NN interactions for the given centrality class of $A+B$ collisions. In the absence of nuclear effects such as shadowing, the Cronin effect, or gluon saturation, hard process rates are expected to scale with $\langle N_{\text{bin}} \rangle$, and $R_{AB}(p_T)=1$.

Figure 2 left panel, shows $R_{AB}(p_T)$ for centrality-selected Au+Au relative to p+p collisions. The error bars indicate the statistical and systematic uncertainties of the spectra, while the bands indicate the uncertainty due to the geometrical scaling factor $T_{AB}$. At the highest $p_T$, hadron suppression of approximately a factor 5 is observed for the most central collisions: inclusive hadron production is strongly suppressed at high...
Figure 2. Left: $R_{AB}(p_T)$ (eq. [1]) for Au+Au relative to p+p collisions. Right: $R_{CP}(p_T)$ from Au+Au collisions.

$P_T$ in central Au+Au collisions. For the most peripheral collisions $R_{AB}(p_T)$ is consistent with unity, while intermediate centralities interpolate smoothly between the extremes.

Figure 2 right panel, shows the related quantity $R_{CP}(p_T)$, the $\langle N_{\text{bin}} \rangle$-scaled ratio of particle yields in central relative to peripheral collisions, which also exhibits large suppression of inclusive hadron production in central collisions. Figure 2 also shows the results of three theoretical calculations: two models based on pQCD incorporating shadowing, the Cronin effect and jet quenching in dense matter (pQCD-I[7], pQCD-II[8]), and a model incorporating gluon saturation in the incoming Au nuclei[9]. The pQCD-based calculations contain one free parameter, the energy density for central collisions, which is fit to the data, yielding an initial density 30-50 times that of cold nuclear matter [7, 8]. These calculations then successfully describe the $p_T$ and centrality dependence of the inclusive suppression for $p_T > 5$ GeV/c. The saturation model also describes the suppression and its $p_T$-dependence for the 0-5%/40-60% ratio for $p_T > 5$ GeV/c. These precision STAR data on inclusive charged hadron suppression, covering wide centrality and kinematic range, are well-described by widely differing models which attribute the suppression either to jet quenching in dense matter in the final state or to gluon saturation in the initial state.

In order to elucidate the particle-species dependence of the suppression, Fig. 3 shows $R_{CP}(p_T)$ for $K^0_s$ and $\Lambda+\bar{\Lambda}$ compared to the charged hadron $R_{CP}(p_T)$ already shown in Fig. 2. The mesons scale approximately as the charged hadrons throughout, while the baryons exhibit a pronounced enhancement in the region $2<p_T<4$ GeV/c. The origin of this behavior is at present not understood, though speculations include the Cronin effect and non-perturbative mechanisms such as baryon junctions. At $p_T=5$ GeV/c, all particle species are strongly suppressed by the same amount in central collisions.
FIGURE 3. $R_{CP}(p_T)$ from Au+Au collisions for $K_0^0$ and $\Lambda+\bar{\Lambda}$\cite{10}, and for the charged hadron data also shown in Fig. 2 right panel.

3. CORRELATIONS

The angular correlations of pairs of high-$p_T$ charged particles can be used to study jets in the complex environment of heavy ion collisions\cite{8}. Figure 4 shows the two-particle azimuthal distribution $D(\Delta\phi)$, defined as

$$D(\Delta\phi) \equiv \frac{1}{N_{\text{trigger}}} \frac{1}{\epsilon} \frac{dN}{d(\Delta\phi)}, \quad (2)$$

for peripheral (left panel) and central (right panel) Au+Au collisions and for p+p collisions (both panels). Only particles within $|\eta| < 0.7$ are included in the analysis. $N_{\text{trigger}}$ is the number of particles within $4 < p_T(\text{trig}) < 6$ GeV/c, referred to as trigger particles. The distribution results from the correlation of each trigger particle with all associated particles in the same event having $2 < p_T < p_T(\text{trig})$, where $\epsilon$ is the tracking efficiency of the associated particles. The normalization uncertainties are less than 5%.

In order to compare correlations in Au+Au with p+p, the p+p correlations are scaled up to the same pedestal value at $|\Delta\phi| \sim \pi/2$ as Au+Au and superposed with a $\cos(2\Delta\phi)$ term that characterizes the azimuthal anisotropy in non-central Au+Au collisions (elliptic flow \cite{4}). The magnitude of this additional correlation is measured independently and is given by the second coefficient $v_2$ of a Fourier expansion of the azimuthal distribution relative to the orientation of the reaction plane of the event, for particles having $p_T < 2$ GeV/c \cite{11}. Figure 4 shows that the correlation strength at small relative angle ($\Delta\phi \sim 0$) in peripheral and central Au+Au and at large relative angle ($\Delta\phi \sim \pi$) in peripheral Au+Au are very similar to the scaled correlations in p+p collisions.

The near-side peaks ($\Delta\phi \sim 0$) in all three collision systems are characteristic of jet fragmentation. The away-side peak ($|\Delta\phi| \sim \pi$) from the back-to-back partner jet, apparent in p+p and peripheral Au+Au collisions is strongly suppressed in central Au+Au
Azimuthal correlations for peripheral (left) and central (right) Au+Au collisions compared to the pedestal and flow-scaled correlations in p+p collisions[12].

collisions. These observations, together with the strong suppression of inclusive production and large elliptic flow at high $p_T$ [4], suggest a picture in which jets traversing the bulk of the medium produced in Au+Au collisions are absorbed (strong jet quenching), and the observed jets are biased towards those generated on the surface and heading outwards. However, other explanations, in particular the gluon saturation picture, may also account for some or all of the observed phenomena. Experimentally, these very different scenarios can be discriminated through measurements of d+Au collisions, where initial state effects in the Au nucleus remain but no final state dense medium is generated.

4. D+AU COLLISIONS

pQCD-based models predict an enhancement in the production of high-$p_T$ charged hadrons in d+Au collisions relative to binary-scaled p+p collisions and little change in the back-to-back correlation strength [13, 14], while one version of the saturation model[15] predicts an inclusive suppression in d+Au of about 30% and possibly also suppression of the back-to-back strength due to a mono-jet contribution [16].

Figure 5 shows $R_{AB}(p_T)$ (left) and the pedestal subtracted two-particle azimuthal distributions (right) measured by STAR in minimum bias and central d+Au collisions[6]. $R_{AB}(p_T)$ exceeds unity for $2<p_T<7$ GeV/c, consistent with expectations from the Cronin effect. However, no additional enhancement over p+p is observed for central relative to minimum bias d+Au collisions. In the top right panel, the azimuthal distributions are characterized by a fit to the sum of near-side and back-to-back Gaussian peaks plus a constant. The only significant difference between the p+p and d+Au correlations is the growth in the pedestal value [3]. The lower right panel shows the pedestal-and flow-subtracted azimuthal distribution from central Au+Au collisions along with the pedestal-subtracted distributions from central d+Au and p+p. The near-side peak is similar in all three collision systems, while the away-side peak is suppressed only in central Au+Au collisions.
5. SUMMARY

The strong suppression at high $p_T$ of the inclusive hadron yield and back-to-back correlations in central Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV are not observed in d+Au collisions. The inclusive yield in d+Au collisions is enhanced relative to binary-scaled p+p, consistent with expectations from the Cronin effect, and the back-to-back correlations show little variation relative to p+p. These results demonstrate conclusively that the striking suppression phenomena observed in central Au+Au collisions are due to the interaction of high energy partons or their fragmentation products in the dense medium created in such collisions.

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