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Abstract. Jet quenching in the matter created in high energy nucleus-nucleus collisions provides a tomographic tool to probe the medium properties. Recent experimental results on jet production at the Relativistic Heavy-Ion Collider (RHIC) are reviewed. Jet properties in p+p and d+Au collisions have been measured, establishing the baseline for studying jet modification in heavy-ion collisions. Current progress on detailed studies of high transverse momentum production in Au+Au collisions is discussed, with an emphasis on dihadron correlation measurements.

Jet quenching, first predicted [1], and then observed at RHIC [2], is one of the most significant results of the heavy-ion collider program so far. Attenuation of jets enables tomographic analysis of the created matter using the jet as an effectively external probe of the medium [3]. To gain insight into the detailed mechanisms of the interaction of the fast propagating parton with the medium and, ultimately, to extract the medium properties, jet production and its modification must be studied in a multi-parameter space as a function of p_T, particle species/flavor, centrality, and reaction plane. It is vital to perform the same measurements both in Au+Au and simpler reference systems such as p+p and d+Au, to calibrate the limited set of jet-related observables available in the complex Au+Au environment.

Three different phenomena related to partonic energy loss have been observed for particle production at high p_T in Au+Au collisions at RHIC:

- strong suppression of inclusive hadron spectra in central collisions [2]
- large azimuthal anisotropy in non-central collisions [4]
- disappearance of back-to-back azimuthal correlations in central collisions [5]

Between the last Quark Matter conference [6] and this one, critical high p_T measurements were performed with d+Au collisions [7, 8, 9, 10]. This control experiment distinguished cold and hot nuclear matter effects and the results confirmed that nuclear attenuation observed in central Au+Au collisions is due to final-state interactions of jets in the dense matter formed in heavy-ion collisions. Experimental results on inclusive spectra and azimuthal correlations obtained prior to this conference are reviewed by D. d'Enterria [11] and M. Miller [12]. The quantitative applications of the theory and phenomenology of medium-induced energy loss are summarized by I. Vitev [13].

At this conference, qualitatively new and important results were presented from the first full reconstruction of jets at RHIC. Full jet reconstruction in p+p and d+Au collisions calibrates the dihadron observables used to infer jet properties in Au+Au collisions. New, in-depth, analyses of the older Au+Au dataset were also reported, in particular in the area of dihadron correlations. Whereas measurements of single hadron distributions cover p_T up to 12 GeV/c, hadron-hadron correlation studies are currently statistics limited to rather moderate p_T∼2-6 GeV/c. In this region of transverse momentum, an enhancement of baryon to meson ratios has been observed [14], indicating modifications to the particle production mechanism compared to p+p collisions and pQCD calculations. Nevertheless, some intriguing new results have emerged: direct evidence that back-to-back dijet quenching depends on the azimuthal orientation of the jets relative to the reaction plane; jet-like correlations are shown to exist for trigger mesons, baryons, Λ and K^0; away-side azimuthal distributions associated with a high p_T trigger hadron are suggestive of statistical momentum balance, perhaps indicating equilibration of the medium-induced gluon radiation. Below I will review these and other experimental results presented at this conference.

1. Jet Properties in p+p and d+Au

Results on first full jet reconstruction at RHIC have been presented by STAR [15]. Inclusive jets have been directly measured in p+p and d+Au collisions using calorimetry and charged particle tracking. Full jet reconstruction reduces the uncertainties due to fragmentation of partons into hadrons that are present in di-hadron correlation studies.

Non-perturbative fragmentation processes result in an approximately Gaussian jet cone. The transverse shape of a jet is characterized by $j_T = p_{hadron} \sin\theta$, the hadron momentum component perpendicular to the jet thrust axis. Figure 1 shows that measured j_T distributions in p+p collisions agree well with Pythia which accurately describes jet features at other energies. For jets with $\langle E_T \rangle \sim 11$ GeV, STAR measured $\langle j_T \rangle = 515 \pm 50$ MeV/c. PHENIX [16] performed di-hadron correlation measurements of the near-angle azimuthal ($\Delta\phi$) distributions and extracted $\langle j_T \rangle = 510 \pm 10$ MeV/c which agrees well with the STAR value obtained using full jet reconstruction.

Experiments also reported the measurements of k_T, or the transverse momentum of an individual parton within a nucleon ($k_{T pp}$) or nucleus ($k_{T nucl}$), inferred from the acoplanarity in the dijet production (away-side $\Delta\phi$ distribution). Non-zero values of k_T in hadronic collisions are usually attributed to the intrinsic transverse momentum of the initial state partons due to the finite size of the incoming hadron and to

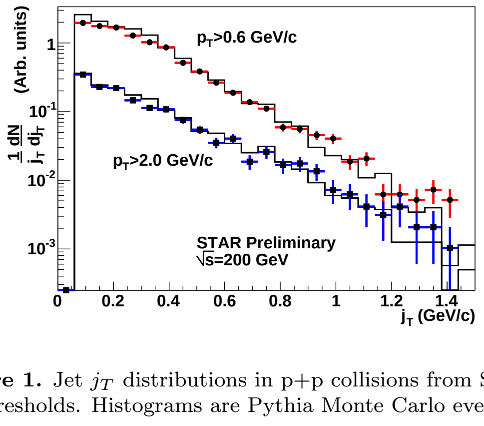

Figure 1. Jet j_T distributions in p+p collisions from STAR [15] for two hadron p_T thresholds. Histograms are Pythia Monte Carlo events.

multiple soft-gluon emission by the partons prior to the hard scattering. Measurements of dimuon, diphoton and dijet production in hadronic collisions have indicated the presence of significant effective k_T [17].

Figure 2 (left) shows the dijet $\Delta\phi$ distribution in p+p and d+Au collisions measured by STAR at $\sqrt{s}$=200 GeV, for jets of energy on the order of $\langle E_T\rangle\sim$ 13 GeV. Larger width of the away-side peak is found in d+Au collisions. Taking ${k_T}^2_{dAu}={k_T}^2_{pp}+{k_T}^2_{nucl}$ indicates a finite value for $k_{T\,nucl}$. PHENIX [16] reported systematic measurements of di-hadron correlations in p+p and d+Au collisions as a function of trigger and associated hadron p_T (Fig. 2, right). $\langle k_T\rangle$ shows a tendency to increase with the larger trigger p_T, with no significant difference in k_T-values measured in p+p and d+Au collisions. STAR quotes the preliminary value of the intrinsic RMS $k_{T\,pp}$=2.3±0.4$\pm^{0.67}_{1.1}$ GeV/c and RMS $k_{T\,nucl}$=2.8±1.2±1.0 GeV/c. The RMS value of the two-dimensional per-parton vector $\mathbf{k}_T$ used by STAR is related to $\langle|k_{Ty}|\rangle$ reported by PHENIX as $\sqrt{\langle k_T^2\rangle}=\sqrt{\pi}\langle|k_{Ty}|\rangle$. Whereas STAR and PHENIX measurements of $k_{T\,pp}$ are consistent with each other and the world data systematics as a function of $\sqrt{s}$, within current statistical and systematic uncertainties it is too early to conclude about possible discrepancies in the measurements of $k_{T\,nucl}$.

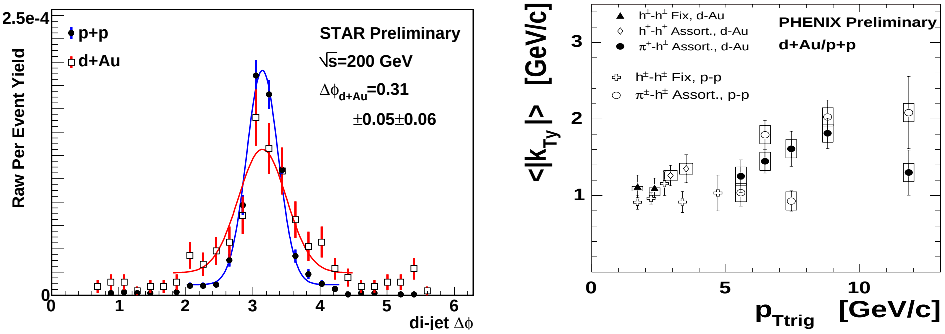

Figure 2. Left: Di-jet $\Delta\phi$ distribution in p+p and d+Au collisions at $\sqrt{s}$=200 GeV from STAR [15]. Right: Variation of $\langle|k_{Ty}|\rangle$ with $p_{T\,trig}$ measured by PHENIX [16].

PHENIX [16] also extracted k_T from the di-hadron azimuthal distributions in Au+Au data for $p_T^{\rm trig}$=2.5-4.0 GeV/c and $p_T^{\rm assoc}$=1.0-2.5 GeV/c. They report a dramatic increase of $\langle k_T\rangle$ with centrality. Interpretation of this result, however, is not straightforward. Strong suppression of away-side jets and large values of elliptic flow measured at RHIC complicate the analysis of di-hadron azimuthal correlations in Au+Au data. Higher statistics and larger p_T-scales are needed to effectively decouple the jet and elliptic flow contributions to the di-hadron distributions.

2. Inclusive Spectra

The p_T-range of single inclusive hadron spectra measured at RHIC has become truly remarkable, reaching p_T=10-15 GeV/c. Since the bulk of the data on inclusive spectra in p+p, d+Au and Au+Au collisions has already been published, I will not review these results. Significant new measurements of hard photons and heavy quarks have been presented at this conference. Direct photon (PHENIX) and open charm (STAR) measurements in d+Au collisions extend up to p_T=11 GeV/c and are reviewed by R. Averbeck [18].

One of the important new results regarding spectra was shown by PHENIX [19]. New data on the nuclear modification factor, the ratio of central and peripheral d+Au spectra normalized by the number of binary collisions, are shown in Fig. 3. It was previously observed that in d+Au collisions, nuclear effects are significant (nuclear modification factor exceeds unity, manifestation of "Cronin" enhancement) in the region of p_T=2-7 GeV/c [8, 9]. The new PHENIX data extend up to p_T=12-15 GeV/c and for p_T>6-8 GeV/c the yields scale with the number of binary collisions, consistent with no significant initial state nuclear effects for high transverse momentum hadrons produced at midrapidity.

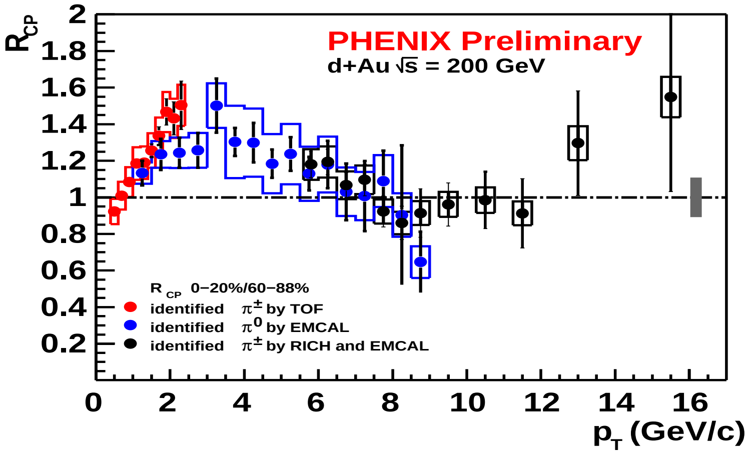

Figure 3. PHENIX data [19] on nuclear modification factor in d+Au collisions at $\sqrt{s}$=200 GeV.

PHENIX also presented detailed centrality dependence of the nuclear modification factor in d+Au and Au+Au collisions for charged hadrons and neutral pions, with the latter extending to 15 GeV/c in Au+Au [19], as well as for $\pi^+ + \pi^-$ and $p + \bar{p}$ [20]. In peripheral collisions the particle yields are consistent with binary scaling for both colliding systems. Going from peripheral to central collisions, progressive enhancement of particle production in d+Au collisions is seen, in contrast to stronger suppression for Au+Au collisions. This strong centrality dependence in d+Au differs, however, from the STAR observations of weak to no centrality dependence of binary-scaled hadron yields [9, 21]. The flavor dependence of the Cronin effect in d+Au collisions is shown to be not large enough to explain the p/π ratio measured in Au+Au collisions. STAR data [22] on Λ, K^0, Ξ and $K^*(892)$ production in Au+Au collisions demonstrate that the difference is due to a baryon/meson effect and seems to be confined to the region of p_T=2-6 GeV/c.

3. Chemistry of a Jet

Identified hadron jet studies in Au+Au collisions may be able to probe the energy loss difference of quarks versus gluons as well as possible modifications in flavor composition and multiplicities in a jet due to coalescence/recombination in the medium. Several aspects of particle production in central Au+Au collisions at RHIC in the p_T-range of 2-6 GeV/c are incompatible with jet fragmentation in simpler systems: large p/π ratio [20], antibaryon to baryon ratio constant with p_T [22], different suppression of proton/pion [20] and lambda/kaon yields [22], and deviation from hydrodynamic mass-ordering in strength of elliptic flow of pions/protons [23] and kaons/lambdas [24]. Models based on coalescence of thermal partons are successful in qualitatively describing the features observed in the data [25].

On the other hand, new data on the relative azimuthal distributions of identified baryons and mesons (PHENIX [26]), Λ and K^0 (STAR [27]) with p_T >2.5 GeV/c and charged particles show finite jet-like correlations. STAR finds that Λ and $\bar{\Lambda}$ correlations with charged hadrons in central Au+Au collisions have different trigger p_T dependences. PHENIX results on the centrality dependence of associated particle yields per identified trigger are shown in Fig. 4. No significant change in yield on the near-side, or decrease expected in a naive coalescence picture, is observed as a function of the number of participants. On the away-side, an overall decrease in the yields is observed similar to back-to-back suppression of charged particles [5]. The data perhaps indicate slightly larger yields on the away side for the baryon triggers. The tendencies shown in the data are quite indecisive at this point; significantly higher p_T probes are required to clarify the observations. It will be interesting to apply asymmetric p_T thresholds for baryons and mesons (with the ratio corresponding to the number of constituent quarks) to test coalescence models. Theoretical progress is also needed to understand whether coalescence/recombination may result in sizable correlations in the azimuthal distributions [25].

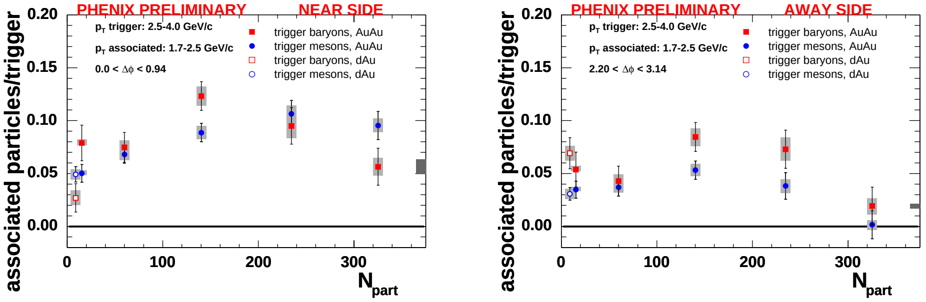

Figure 4. PHENIX data [26] on near (left) and away-side (right) associated particle yields per baryon/meson trigger.

4. Jet Production versus Reaction Plane

Direct evidence of the variation of the strength of back-to-back suppression with azimuthal orientation of the jets relative to the reaction plane was presented by STAR [28]. Di-hadron correlations were measured in non-central Au+Au collisions at $\sqrt{s_{NN}}$= 200 GeV for trigger particles with p_T=4-6 GeV/c sorted in the direction of the reaction plane angle (in-plane) and perpendicular to it (out-of-plane). The trigger particles were paired with associated particles with 2 GeV/$c < p_T < p_T^{\rm trig}$. Figure 5 shows the azimuthal distribution of associated particles in Au+Au (elliptic flow subtracted [29]) compared with p+p reference data. The near-side jet-like correlations measured in Au+Au are similar to those measured in p+p collisions. The back-to-back correlations measured in Au+Au collisions for in-plane trigger particles are suppressed compared to p+p, and even more suppressed for the out-of-plane trigger particles. Such behavior is naturally predicted by jet quenching models, where the energy loss of a parton depends on the distance traveled through the dense medium [30]. Due to energy loss in these models, the high p_T trigger biases the initial production point to be near the surface so the near-side correlations should be similar to those seen in p+p collisions. The away-side correlations are more suppressed when the trigger hadron is emitted perpendicular to the reaction plane. Measurements of the effect as a function of centrality will allow to precisely determine the energy loss dependence on the path length.

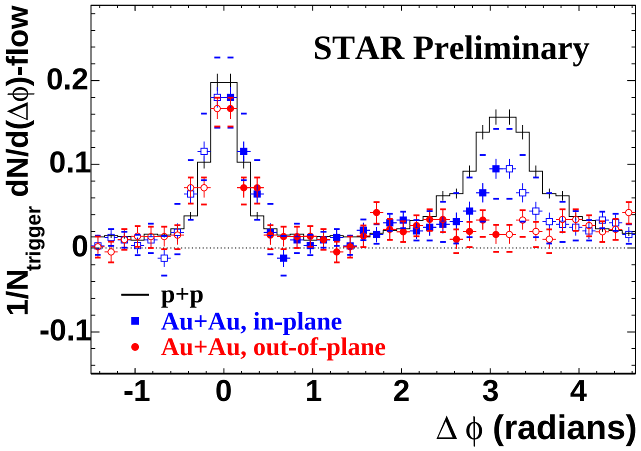

Figure 5. STAR data [28] on azimuthal distributions of associated particles for trigger particles in-plane (squares) and out-of-plane (circles) for Au+Au collisions at centrality 20%-60%, compared with p+p reference data (histogram).

Results on single particle high p_T charged hadron (STAR [28]) and π^0 production (PHENIX [31]) with respect to the reaction plane were also presented. Azimuthal anisotropy, quantified by the second harmonic Fourier coefficient v_2, is found to reach its maximum at $p_T \sim$3 GeV, decreasing very slowly if at all up to $p_T \sim$7-10 GeV/c. STAR performed higher order cumulant analysis for v_2 and compared azimuthal correlations measured in p+p collisions to those in Au+Au. The results confirm strong elliptic flow in mid-central Au+Au collisions at least up to $p_T \sim$ 7 GeV/c, qualitatively consistent with jet quenching. The strength of the v_2 signal remains too large to be explained by quenching alone [32]. Measurements of v_2 that are free of non-flow effects in the p_T-region which is clearly dominated by jets (most likely, $p_T >$ 7 GeV/c) are highly desirable.

5. Reconstruction of the Lost Energy

Measurements of the redistribution of the energy radiated off high energy partons in the medium would provide a very important cross-check of jet quenching and, perhaps, a means to probe the degree of thermalization. First attempt of such studies was presented by STAR [27, 33]. The analysis involves statistical reconstruction of charged hadrons associated with a high p_T trigger particle ($p_T^{\rm trig}$ =4-6 GeV/c) in azimuth and pseudorapidity. The azimuthal distribution of the associated particles with p_T=0.15-4.0 GeV/c with respect to the trigger hadron, after subtraction of the combinatorial background, exhibits jet-like near-angle correlations in p+p and Au+Au collisions (Fig. 6, left). On the away side, the distribution is broad and consistent with a $\cos\Delta\phi$ shape, as expected for statistical momentum balance [35] with no additional dynamical correlations. The dependence of the correlation magnitude on $p_T^{\rm trig}$ for central Au+Au collisions seems to be in agreement with the estimates from momentum conservation, even for $p_T^{\rm trig}$ >6.5 GeV/c [27]. This may signal equilibration of the medium-induced gluon radiation with momentum distributed over many particles.

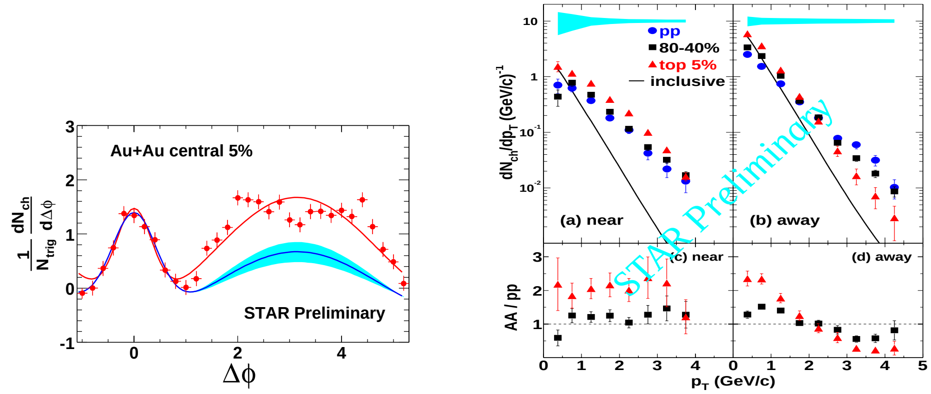

Figure 6. Left: $\Delta\phi$ distribution for 5% central Au+Au collisions measured by STAR [33]. The solid line shows an estimate from the statistical momentum conservation for the away side. Right: STAR data [33] on near-side (a) and away-side (b) p_T distributions of associated charged hadrons for p+p, peripheral and central Au+Au collisions. Lower panels: Ratios of Au+Au to p+p distributions.

The correlation signals were integrated, and charged hadron multiplicities and p_T distributions of associated particles within $|\Delta\phi| < 1.0$ and $|\Delta\eta| < 1.4$ (near-side cone) and $|\Delta\phi| > 1.0$ (away-side cone) of the trigger hadron were studied as a function of centrality in Au+Au collisions and compared to p+p collisions. Figure 6 shows the p_T distributions of associated particles. The away side is observed to be depleted at large p_T and enhanced at low p_T compared to p+p collisions. The broad angular distribution and softening of the spectrum may be consistent with predictions of the softening of the hadron-triggered fragmentation function due to parton energy loss and enhancement of soft hadrons from emitted gluons [34].

6. Conclusions

To summarize, in the last year experiments have gained solid ground on elucidating jet properties at RHIC. Preliminary results on measurements of jet fragmentation in p+p and d+Au collisions provide a baseline for comparison to Au+Au collisions. First direct evidence that back-to-back dijet quenching depends on the azimuthal orientation of the jets relative to the reaction plane has been presented. Future high-statistics measurements of flavor-tagged di-hadron correlations will probe energy loss effects of quark versus gluon jets and test string fragmentation versus recombination. Finding the lost remnants of jets may provide a cross-check of the picture of medium induced final-state energy loss. Statistical reconstruction of jets in Au+Au collisions has shown potential to get an experimental handle on the degree of thermalization at the partonic level. In general, presented data broadly support pQCD-based models of final-state parton energy loss in a dense QCD medium produced in Au+Au collisions at RHIC and put strong experimental constraints on its properties.

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