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Summary on high p_T probes

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Abstract Results on high-p_T probes shown at the Hard Probes 2008 Conference are summarized, with an appreciation of the improvements in precision of the measurements and experimental techniques since the beginning of RHIC operation. Particular attention is given to the latest measurements of the nuclear modification factor of identified particles, photon-hadron correlation measurements, and full jet reconstruction.

1 Introduction

The goal of heavy-ion collisions is to study the medium produced and ultimately quantify the properties of the medium. High transverse momentum (p_T) particles provide particularly good probes of the medium created in heavy-ion collisions because they are created early in the collision and thus are sensitive to the transport properties. Probes of heavy-ion collisions having high transverse momentum became accessible at the Relativistic Heavy Ion Collider (RHIC), due to the large center of mass collision energies (the largest of which has been $\sqrt{s_{NN}} = 200$ GeV). At these high energies, hard production cross sections are large enough for the probes at high p_T to become abundant. The experiments, positioned at intersection points along the RHIC ring, began recording data in 2000.

2 High-p_T spectra

The first measurements of high p_T spectra at RHIC came from Au + Au collisions at $\sqrt{s_{NN}} = 130$ GeV. Already in these data, a factor of 5 suppression relative to binary scaling was observed for the first time [1]. The suppression is quantified with the nuclear modification factor, defined as

$$R_{AA} = \frac{d^2N^{AA}/dp_T d\eta}{\langle N_{binary}\rangle (d^2\sigma^{pp}/dp_T d\eta)/\sigma^{pp}_{inelastic}}, \tag{2.1}$$

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where the numerator is the yield of particles measured in A + A collisions and the denominator is the yield measured in $p + p$ collisions scaled by the mean number of binary collisions in the centrality selection of A + A collisions. In the first measurements from RHIC, the spectra extended to $p_T \sim 4$ GeV/c for identified pions and ∼5 GeV/c for non-identified charged hadrons [1] and had systematic errors of ∼ 30% at the highest measured p_T values. The systematic errors in the measured nuclear modification factor R_{AA} were as large as ∼ 50% due to an additional uncertainty of 35% on the $p + p$ reference spectrum, which was deduced from an interpolation of data taken for other center of mass energies [2].

The most recent measurements of particle production as a function of p_T include many different identified particle species, extend to as high as $p_T \sim 20$ GeV/c, and, in general, have systematic errors of approximately 20%. Figure 2.1 shows the R_{AA} of a compilation of identified particles measured by the PHENIX and STAR experiments [3] for p_T up to 10 GeV/c. This figure highlights not only the wealth of data provided by RHIC, but summarizes some of the key features of particle spectra at high p_T. There seems to be an ordering to the suppression factors in an intermediate p_T range ($2 < p_T < 6$ GeV/c). The η are as suppressed as the pions, the kaons and ϕ are less suppressed than pions, and protons are even enhanced over some range of p_T. Before the measurement of the R_{AA} of the ϕ, it was assumed that there would be a meson/baryon ordering to the amount of suppression, as is observed in the momentum anisotropy v_2 of the particles [5, 6]. However, the ϕ R_{AA} seems to lie between the pions and protons, following the trend of the kaon R_{AA} at lower p_T.

Figure 2.2 shows the nuclear modification factor for mesons compared to that for direct photons (photons not from hadronic decays) up to $p_T \sim 20$ GeV/c [4, 7]. The photons are not suppressed up to $p_T \sim 10$ GeV/c. However, for $p_T > 14$ GeV/c, the photons are suppressed relative to binary scaling. This can be explained theoretically from different effects (perhaps each contributing to the suppression that

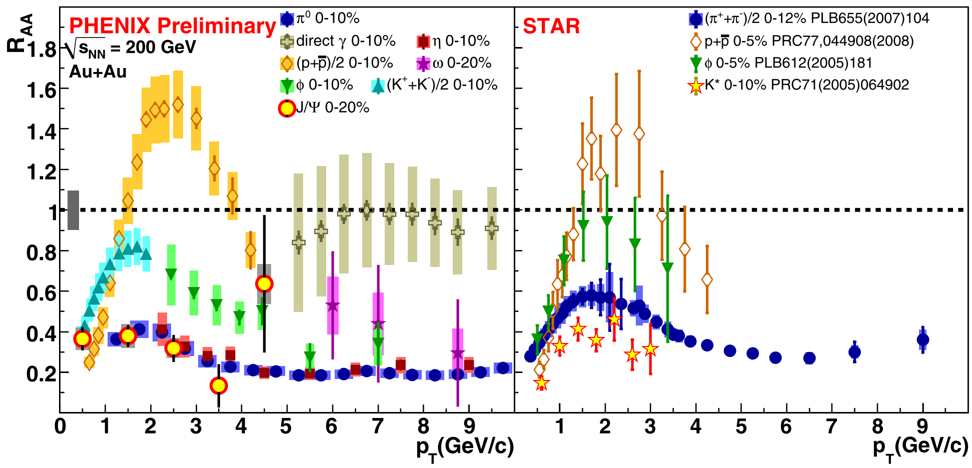

Fig. 2.1 R_{AA} as a function of p_T for identified hadrons, as well as direct photons, for central collisions [3]

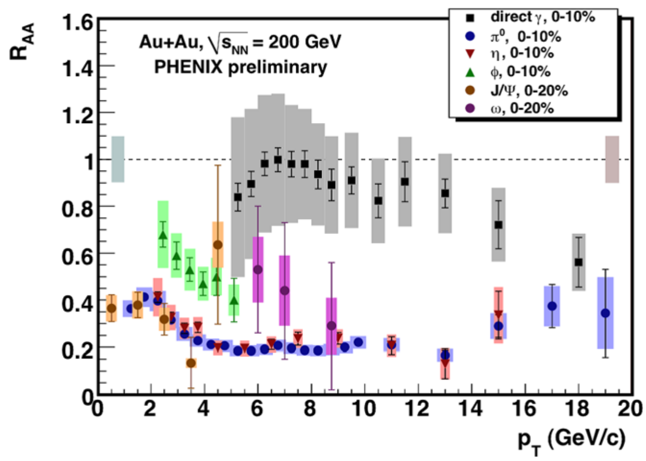

Fig. 2.2 R_{AA} as a function of p_T for direct photons, compared to mesons [4]

is measured) [8]. The recent high-statistics $d+$Au RHIC run should provide an important test of the cold nuclear matter effect (shadowing or gluon saturation).

Theoretical calculations have been largely successful at describing high-p_T spectra of pions and non-identified charged hadrons [9–11]. However, there are several different theoretical approaches that lead to contradicting conclusions about properties of the medium. With different conclusions of the transport coefficient $\hat{q} = \langle k_T^2 \rangle / L$ from different models [12, 13], it is important to understand the different assumptions that lead to these different conclusions. There are ongoing attempts to understand the differences in the energy loss models [13–15].

Despite the successes of these models to describe the suppression observed in the light hadrons, the surprising result of an equally strong suppression of heavy-flavor at high p_T was not predicted by these same models, and could not be described by radiative energy loss alone [16]. The strong elliptic flow measured at RHIC also pointed toward a strongly coupled medium, which led to the question of applicability of perturbative calculations to describe the interactions which lead to energy loss in this medium. Calculations of partonic energy loss in a strong coupling regime, using Ads/CFT to describe the heavy-ion collisions, were also discussed at the conference [17–19].

3 Correlation measurements

The single-particle measurements at high p_T revealed the sizable effect that the medium has on hard-scattered partons. They also revealed new and interesting phenomena relevant at intermediate p_T that could be explained by a recombination production mechanism [20–22], although not all aspects of this idea have yet been fully developed. However, it is difficult to learn about the details of the energy loss mechanism in the medium because the single particles that are measured are those that emerge from the dense medium with significant energy and thus have a strong bias for having been produced close to the surface of the medium. If one wants to go beyond the measure of an overall suppression factor (via R_{AA}), then both sides of a di-jet need to be measured simultaneously. The "near-side" of the di-jet is the side that is triggered on, and is thus again somewhat surface-biased due to the trigger condition of the presence of a high-p_T particle, and the "away-side" jet particles can then reveal the effect of the medium relative to vacuum expectation. Full jet reconstruction has been considered a difficult problem in heavy-ion collisions, where the multiplicities are large (thousands of produced particles). To overcome this technical challenge, RHIC experiments measured azimuthal correlations between two particles to determine jet yields on the near-side and the away-side. Many interesting effects, modifications in the shapes and yields jet-associated correlation function, have been reported. On the near-side, there is a long-range correlation in $\Delta\eta$ [23, 24] (referred to as the "ridge"), while the away-side shows a modification to the Gaussian-like jet shape that has two maxima away from $\Delta\phi = 180°$ [25, 26]. Possible explanations for both the ridge on the near-side [27–32] and the shape modification of particles correlated with the trigger on the away-side for low to intermediate p_T [33–39] have been widely discussed in the literature. With many theoretical ideas that explain the origin of the ridge, what is needed is predictions from these theoretical ideas that can be verified or falsified.

As the luminosity of RHIC increased, the experiments were able to take more data at high p_T, triggering on events with a high-energy cluster in the electromagnetic calorimeter. With larger statistics, correlation measurements extended to higher p_T (both for the trigger particle and the associated particles), where these shape modifications are no longer dominant effects. The ultimate goal for high-p_T probes is to obtain a measure of the modification of the fragmentation function due to the dense medium. In order to make this measurement, it is necessary to have access to the parton's original energy. This is possible via a photon-hadron correlation measurement (γ-jet) [40], where the trigger particle is a high-p_T direct photon, which is not affected by the medium to lowest order, and the hadrons on the away-side measure the medium-modified jet. Figure 3.1 shows the first result of a modified fragmentation function from the jet yields associated with a direct-photon trigger [41]. The yields associated with a direct photon trigger are compared to those associated with a π^0 trigger. The yields for direct photon triggers are smaller, even in peripheral collisions, because the π^0 triggers come from a fragmentation process where the parton possesses a larger p_T than the direct photon that does not come from a fragmentation. In central collisions, there can be additional differences due to a combination of possible effects: energy loss of the π^0 trigger, quark vs. gluon fragmentation, and the amount of the medium that is probed when triggering on an unbiased direct photon. In order to disentangle these effects, the systematic uncertainties on the measurement need to be improved, in addition to including theoretical input for interpretation of the data.

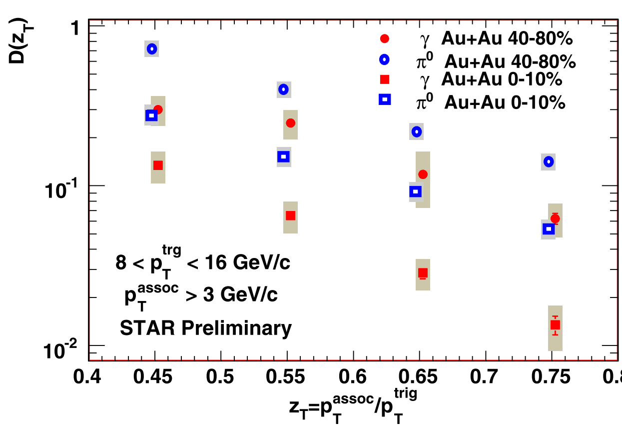

Fig. 3.1 The yields of charged particles associated with a direct-photon trigger with $8 < p_T < 16$ GeV/c, as a function of $z_T = p_{T,assoc}/p_{T,trig}$ for central (0–10%) collisions and peripheral (40–80%) collisions, compared to the yields associated with a π^0 trigger [41]

4 Full jet reconstruction

At this conference, the first ever results from full jet reconstruction in heavy-ion collisions were shown. Theoretical calculations have predicted a modification in the particle-species content in jet fragmentation [42]. Figure 4.1 (left panel) shows the predicted flavor dependence of fragmentation both in $p + p$ collisions and in Au + Au collisions. The fragmentation function is expressed as $dN/d\xi$, where of $\xi = \ln(E_{jet}/p_h)$. The corresponding measurement in $p + p$ collisions is shown in Fig. 4.1 (right panel) for a cone radius of 0.4 [43]. The mass ordering in the peak values of the fragmentation function measurement of kaons and Λ, seems to differ from the calculation of kaons and protons predicted in $p + p$ collisions, emphasizing the importance of having the baseline vacuum measurement before measuring any medium modifications. The effect of the cone radius imposed on the measurement has been studied [43]. Improved precision of these results and the comparison to the theory will serve as important input to constrain the parameters of the calculation.

There has been recent progress on jet reconstruction algorithms to handle the large pile-up expected at the LHC [44]. The improvements have focused on background subtraction, and this has also been relevant for heavy-ion collisions. Figure 4.2 shows the result of applying such algorithms to Au + Au collisions at RHIC [47]. The measurement in central Au + Au collisions agrees with the binary-scaled measurement in $p + p$ collisions for the lowest p_T threshold cut, indicating no modification to the fragmentation function when the full jet is reconstructed. With increasing p_T thresholds, the agreement is not so good; which may be due

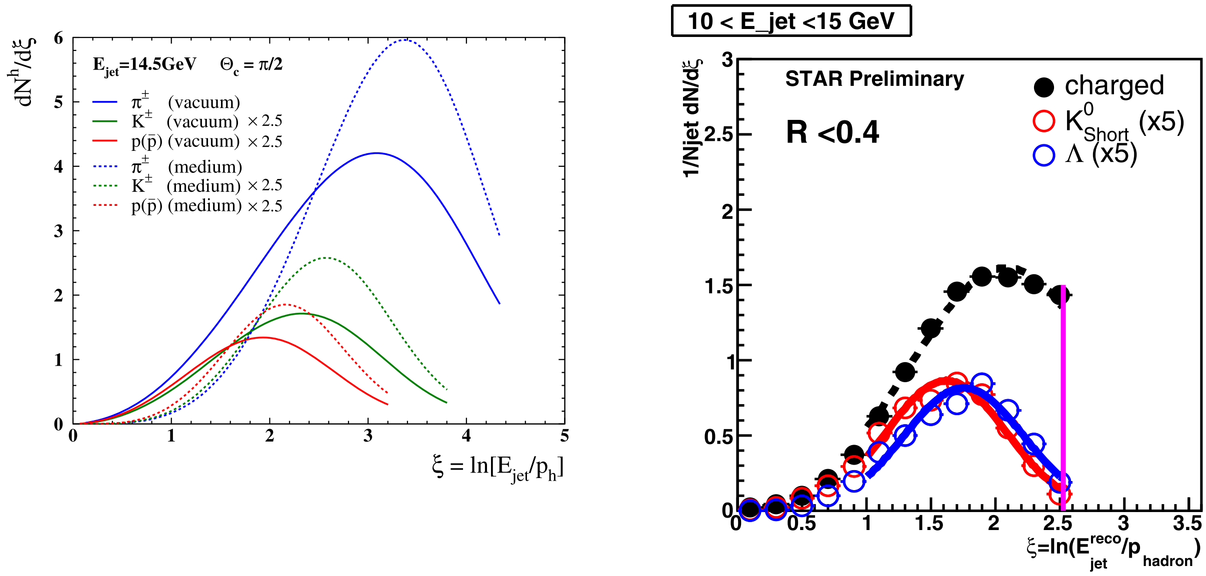

Fig. 4.1 Fragmentation function $dN/d\xi$ as a function ξ from theory (*left panel*) both for vacuum and medium-modified fragmentation, and the measurement in $p+p$ collisions (*right panel*) for different identified particles [43]

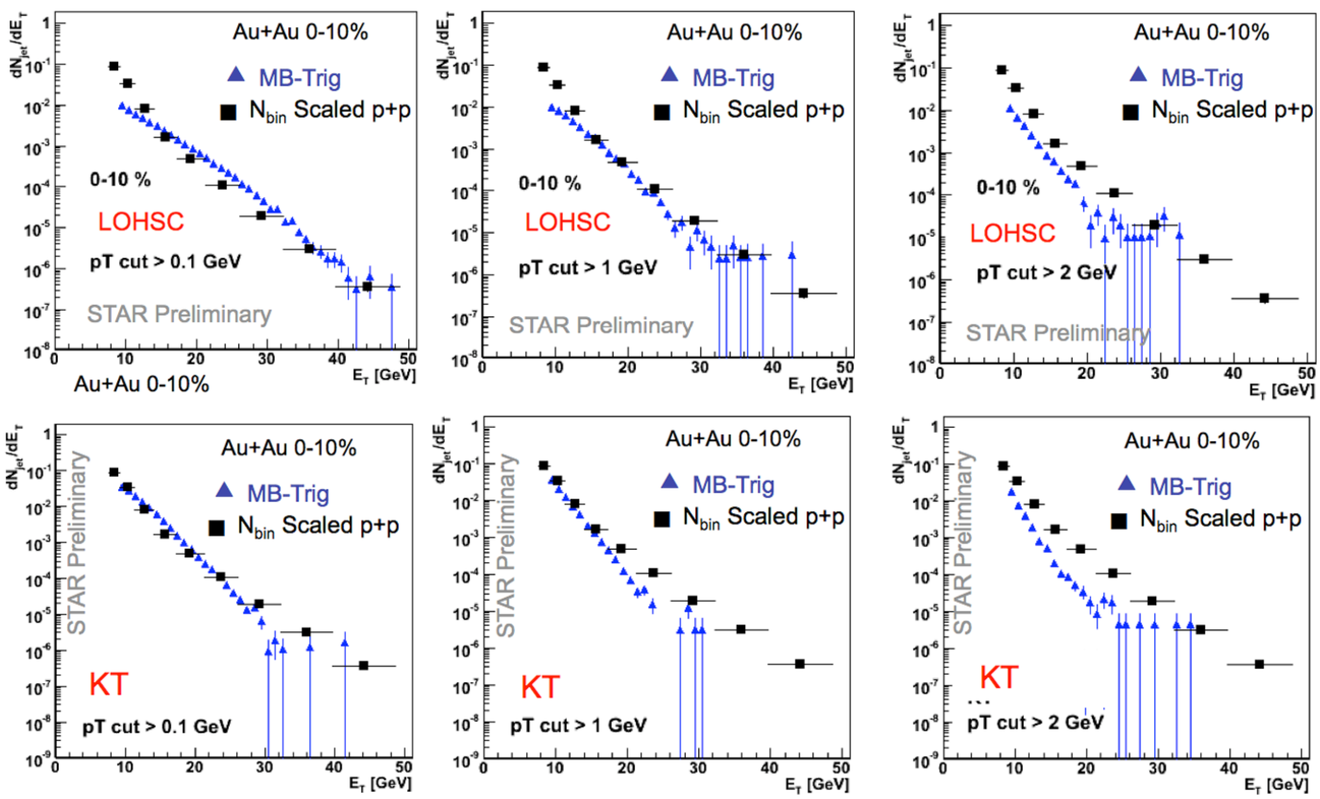

Fig. 4.2 Inclusive jet spectra reconstructed in Au + Au collisions compared to N_{binary}-scaled $p+p$ collisions. The *upper panel* is for results using the Leading-Order High Seed Cone (LOHSC) algorithm, and the *lower panel* for the K_T algorithm [45, 46]. The p_T threshold is increased from left to right [47]

to not fully correcting for the increasing bias. Corrections for the bias from the p_T threshold cut, as well as the jet energy resolution, have been determined by embedding PYTHIA jets into real Au+Au collisions [47, 48]. Further studies of the systematics of this difficult measurement need to be performed before drawing strong conclusions.

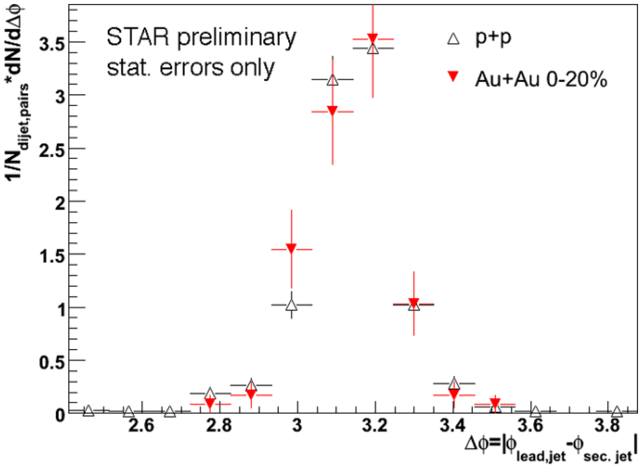

Fig. 4.3 Di-jet $\Delta\phi$ distribution for reconstructed jets with $p_T > 20$ GeV/c measured in central Au + Au collisions compared to $p + p$ collisions [48]

The progress in jet reconstruction in heavy-ion collisions opens up new possibilities in studying jet energy redistribution in the medium and thus understanding properties of the medium such as $\hat{q}$. Figure 4.3 shows the ability of measuring the difference in energy measured on opposite sides of a dijet [48].

5 Conclusions and summary

Many questions remain about our understanding of the medium created at RHIC. In particular, the value of $\hat{q}$ is yet to be determined from the data. Different theoretical calculations have extracted values of $\hat{q}$ from the high-p_T data, but they vary widely. The applicability of perturbative calculations to account for the parton energy loss in the dense, strongly coupled medium has also been questioned. The measurement of the medium-modified fragmentation function, through γ-jet and/or full jet reconstruction, holds the promise of providing answers to these unresolved questions.

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