Quark Matter 2006: High-p_T and jets

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Abstract. An overview of new experimental results on high-p_T particle production and jets in heavy ion collisions from the Quark Matter 2006 conference is presented.

In these proceedings, I will summarise new results on high-p_T particle production and jet-like correlations from Quark Matter 2006. The large statistic data sample collected at RHIC in p+p, Cu+Cu and Au+Au provides access to increasingly high p_T and allows to explore the intermediate p_T regime in more detail. At the highest p_T, we explore our understanding of the 'perturbative limit' where hadron production and energy loss calculations are relatively well controlled. Measurements in this regime are compared to theory to extract characteristics of in-medium fragmentation and ultimately to determine the energy density of the medium generated in heavy ion collisions. At intermediate p_T, a number of surprising effects has been observed, such as the large baryon/meson ratio [1–3] and strong modifications of triggered di-hadron correlations [4, 5]. An intriguing new result in this area is the observation of correlated particle production associated with jets at large rapidity separation $\Delta\eta$. Also of special interest are jet-like correlations of identified particles, because these may shed light on the origin of the baryon/meson enhancement at intermediate p_T.

It should be noted that this field is also developing at SPS: at the previous Quark Matter and also in this meeting, a number of new analyses were presented of nuclear modification factors for hadron production ranging up to $p_T = 4 - 5$ GeV. New results exist from NA49 [6], NA57 [7] and WA98 [8]. So far, it seems that at SPS energies the Cronin effect plays a large role, also due to the intrinsically limited p_T-reach at low $\sqrt{s_{NN}}$.

1. R_{AA} and the medium density

The suppression of high-p_T particle production compared to a properly scaled p+p reference was the first indication of significant parton energy loss at RHIC. At this year's conference, a detailed quantitative confrontation of various models with the measured nuclear modification factor R_{AA} of π^0, reaching out to $p_T = 20$ GeV, was presented [9]. The left panel of Fig. 1 shows the data and curves from the PQM model [10], using different values of the medium density, expressed as the time-averaged the transport

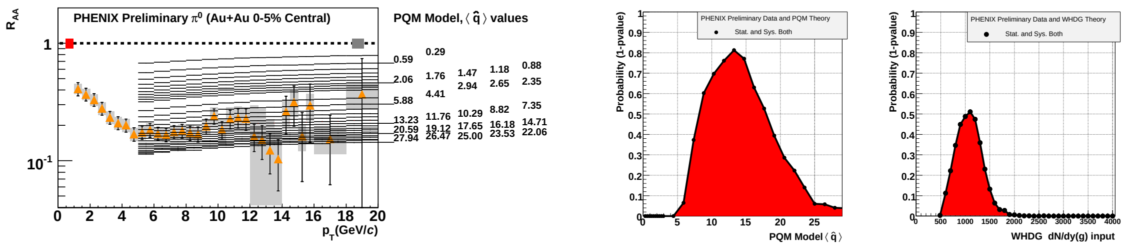

Figure 1. Left panel: Measurements of the nuclear modification factor R_{AA} for π^0 from PHENIX compared to PQM model calculations with different medium densities. Middle and right panels: likelihood distribution for data given the medium density, using the PQM model (middle) and the GLV formalism (right).

coefficient $\hat{q}$. For every value of the medium density, a likelihood value was calculated using the statistical and systematic uncertainties on the data. The resulting likelihood distribution is shown in the middle panel. The right panel shows a similar curve based on the GLV formalism [11]. The extracted limits on the medium density, for 90% probability, are $6 < \langle\hat{q}\rangle < 24$ GeV^2/fm and $600 < dN_g/dy < 1600$ respectively. The model calculations underlying these predictions are becoming more realistic, using Woods-Saxon based medium density profiles and fluctuations of the energy lost by gluon radiation. Such effects may impact the value of R_{AA}, because the energy loss can be large and the kinematic range at RHIC is limited. It is exciting to see that high-p_T physics at RHIC is entering the quantitative era.

In order to fully constrain the dynamics, more differential measurements, such as di-hadron correlations, path length dependent measures (elliptic flow v_2 or R_{AA} as a function of the angle with the reaction plane) and γ-jet measurements should be confronted with energy loss calculations. This will provide more insight in for example the probability distribution for energy loss, which is different in the multiple-soft scattering (BDMPS) and the few-hard scatterings (GLV) limits [12], and which is not well constrained by R_{AA} alone [13].

2. Di-hadron correlations at intermediate and high p_T

Fig. 2 presents an overview of associated yields with intermediate and high-p_T trigger hadrons [14]. The left panel shows the near side yields ($|\Delta\phi| < 0.9$) and the right panel shows the away side yields ($|\Delta\phi| > 0.9$). The results are presented as a function of $z_T = p_{T,assoc}/p_{T,trig}$. The associated yields in d+Au collisions show an approximate scaling in this variable, with the spectra becoming slightly steeper with increasing $p_{T,trig}$. In Au+Au collisions, on the other hand, a marked increase of the yield with decreasing $p_{T,trig}$ is observed on both the near and away sides.

On the near side, the yields in Au+Au collisions are similar to d+Au only for the highest $p_{T,trig}$ ($6 < p_{T,trig} < 10$ GeV), with a small enhancement at the lowest z_T. For the lower $p_{T,trig}$, enhancements up to a factor four are seen in Au+Au collisions. This

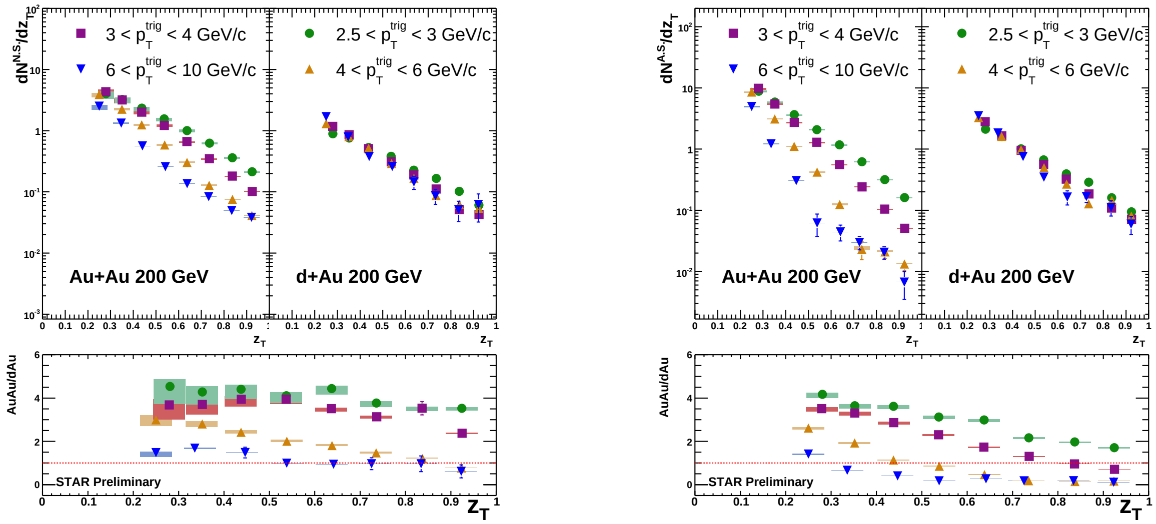

Figure 2. Correlated yields on the near side ($|\Delta\phi| < 0.9$, left panels) and away side ($|\Delta\phi| > 0.9$, right panels) as a function of $z_T = p_{T,assoc}/p_{T,trig}$, for several ranges of $p_{T,trig}$. Results from 0-12% central Au+Au and d+Au collisions are shown and the ratio Au+Au/d+Au is presented in the lower panels. The shaded bands show the uncertainty due to elliptic flow of the background.

enhancement is further discussed in the next section.

On the away side a similar evolution is seen, but with the away-side yields in Au+Au being suppressed by a factor 4-5 below the d+Au yields at high p_T. The suppression at high $p_{T,trig}$ is consistent with expectations from energy loss calculations using medium densities similar to those used for the calculations that describe $R_{AA}(p_T)$ [10, 15]. Due to the counterbalancing biases from the trigger and associated hadron p_T, di-hadron measurement are more sensitive to the medium density profile than inclusive measurements [15]. At lower $p_{T,trig}$, the away-side yields in Au+Au collisions show an enhancement rather than a suppression. The evolution from suppression to enhancement is a function of both $p_{T,trig}$ and $p_{T,assoc}$.

Qualitatively, the observed changes in the correlated yields can be induced by parton energy loss. For a given trigger hadron p_T, a reduction of the transverse momentum of the leading charged hadron due to energy loss in Au+Au events could lead to a higher initial jet energy being selected than in d+Au events. The larger jet-energy would then lead to an enhanced correlated yield in Au+Au. It is also possible that the increased yield is due to a jet-induced response of the medium.

It should also be noted that the strongest modifications of the correlated yields are seen at the lower p_T, where the baryon/meson ratio is also found to be enhanced compared to expectations from vacuum fragmentation [1–3]. A natural question therefore is whether the modifications in the correlated yields and the increased baryon/meson ratio have a common origin.

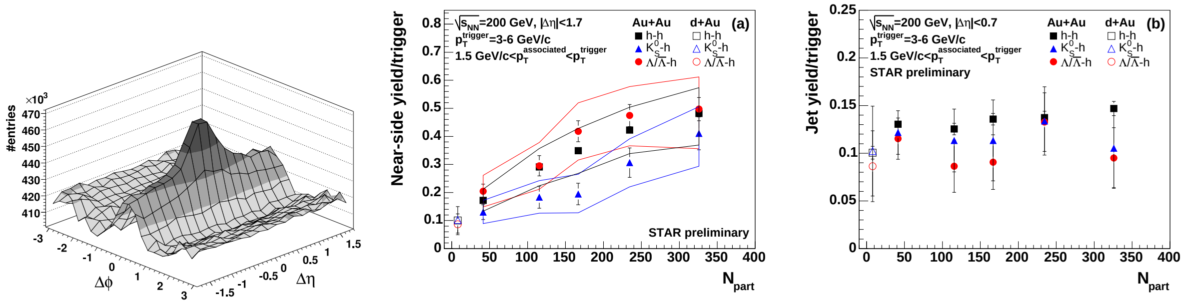

Figure 3. Near-side correlated yield as a function of centrality for different trigger species. Left panel: Associated yield in full acceptance. Right panel: Jet yield from subtraction of the yield at large $\Delta\eta$ from the yield at small $\Delta\eta$.

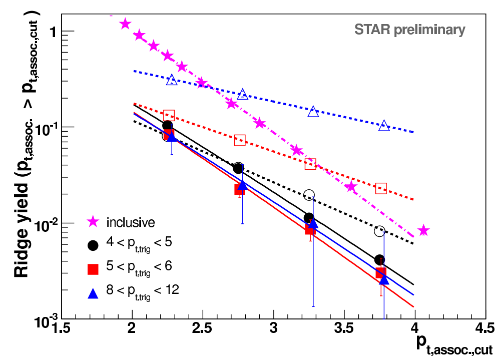

Figure 4. Near-side associated hadron spectra for several $p_{T,trig}$ in central Au+Au collisions. The associated yields are separated in a peak around $\Delta\eta = 0$ (jet-like contribution, dashed lines) and a $\Delta\eta$-independent contribution (the ridge, full lines).

2.1. Near side shape: the ridge

A striking phenomenon in near-side jet-fragmentation was reported at this conference: the increase in associated yield on the near side, which is seen in Fig. 2, is found to have a large contribution at larger $\Delta\eta$. The left Fig. 3 shows the distribution in $\Delta\eta$ and $\Delta\phi$ of associated charged particles with $p_{T,assoc} > 2$ GeV with a trigger particle $3 < p_{T,trig} < 4$ GeV [16, 17]. There is a clear elongation visible of the associated yield on the near side. In fact, it seems that there are two components to the near-side fragmentation: a central peak around $(\Delta\eta, \Delta\phi) = (0, 0)$ and a component that is elongated in $\Delta\eta$, termed 'the ridge' by STAR [16].

The size of the 'ridge'-effect is further illustrated in the middle and right panels of Fig. 2. The middle panel shows how the total yield on the near side increases with centrality due to the ridge effect. The right panel shows the centrality dependence of the near-side yield in the jet-like peak, which is obtained by subtracting the yield measured at larger $\Delta\eta$ from the yield at small $\Delta\eta$. The jet-like yield is independent of centrality.

The analysis was performed for unidentified charged hadrons as well as with leading identified K^0 and Λ. Both the jet and ridge yields are similar for all trigger species, given the current rather large statistical and systematic uncertainties. A similar effect is seen in analyses of charged hadrons [18] and identified particles [19] by PHENIX, but the effect is not as pronounced due to the smaller η-acceptance.

Fig. 4 shows how the jet and ridge yields evolve with $p_{T,assoc}$ and $p_{T,trig}$. The jet

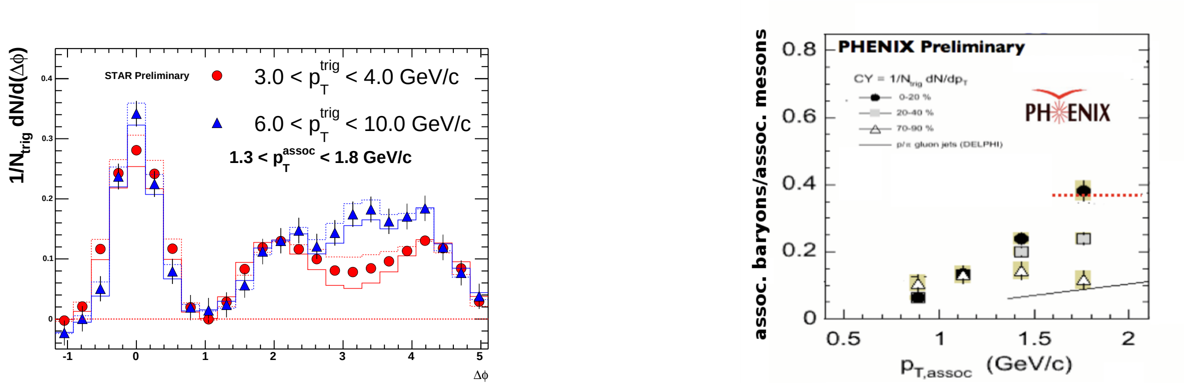

Figure 5. Away-side properties at intermediate p_T. Left panel: Azimuthal distributions of hadrons with $1.3 < p_T < 1.8$ GeV associated with trigger hadrons in two different p_T-ranges, from 0-12% central Au+Au collisions. Right panel: associated baryon/meson ratio on the away-side for charged trigger hadrons with $2.5 < p_T < 4.0$ GeV, for three different centralities in Au+Au collisions.

component shows a clear increase with $p_{T,trig}$, and a flattening of the $p_{T,assoc}$ spectrum as expected from jet fragmentation. In fact, it turns out that the z_T-dependence of the yields in the jet-component are very similar to measurements in d+Au collisions [16]. The ridge-yield falls off more steeply with $p_{T,assoc}$, similar to the p_T-spectra from inclusive charged particles. The ridge-yield is independent of $p_{T,trig}$, and remains significant out to the highest measured $p_{T,trig}$.

It seems that the near-side jet-like peak is dominated by fragmentation dynamics, while the ridge contains softer particles, either from gluon radiation coupling to longitudinal flow or from the flowing medium itself [20–24].

2.2. Away side shapes at low p_T: enhancement and broadening

The away-side correlation shapes at low to intermediate p_T are also found to be strongly modified in Au+Au collisions compared to p+p or d+Au reference data. This is illustrated in Fig. 5, which shows azimuthal distributions of hadrons with $1.3 < p_T < 1.8$ GeV associated with trigger hadrons in two different p_T ranges from central 0-12% Au+Au collisions [14]. For lower $p_{T,trig}$ ($3 < p_{T,trig} < 4$ GeV) a depletion of the yield at $\Delta\phi = \pi$ is seen, leading to a doubly-peaked structure. New data presented at this conference show that for higher $p_{T,trig}$ ($6 < p_{T,trig} < 10$ GeV, triangles in Fig. 5), there is no pronounced depletion. Clearly, the shape and magnitude of the away-side associated yield evolve with $p_{T,trig}$ and $p_{T,assoc}$, indicating the interplay of multiple processes which dominate the dynamics in different kinematical regimes.

Detailed studies of the away-side structure at low and intermediate p_T using three-particle correlations are being pursued by STAR and PHENIX at RHIC and CERES at SPS [18, 25–27]. The aim of these studies is to distinguish between scenarios involving conical emission [28] and large acoplanarity, but other mechanisms that give rise to correlation structure, most notably the effect of momentum conservation [29], should

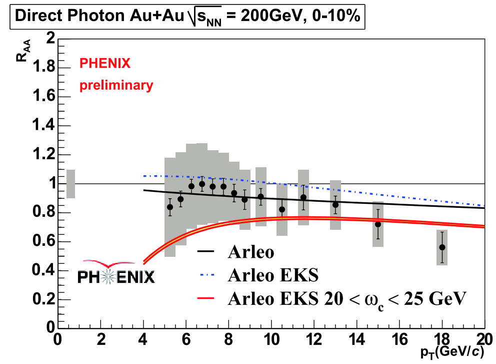

Figure 6. Nuclear modification factor R_{AA} for direct photons in 0-10% central Au+Au collisions, using new run-5 p+p result as a reference. The curves show various calculations of direct photon production, taking into account isospin effects and energy loss in the hot and dense medium.

also be considered.

Explorations of jet structure with identified hadrons in the intermediate p_T regime may also shed light on the baryon/meson enhancement. The right panel of Fig. 5 shows the asssociated baryon/meson ratio on the away side for intermediate-p_T trigger hadrons ($2.5 < p_{T,trig} < 4.0$ GeV) [19]. For central collisions, the baryon/meson ratio increases with $p_{T,assoc}$ and reaches the value observed for inclusive charged particles [2]. It would be interesting to see similar measurements with trigger hadrons with $p_T \gtrsim 7$ GeV, where the baryon/meson ratio reaches the value expected from jet fragmentation.

3. Non-interacting probes: photons

The increasing statistics being collected at RHIC for both heavy ion and p+p events also leads to improved sensitivity for the rarest probes, such as direct photons. Fig. 6 shows the nuclear modification factor for direct photons as measured by PHENIX, now using new p+p results from RHIC run-5 [30]. The curves show a number of different expectations for R_{AA} [31]. A small suppression is expected from isospin effects in the Au nucleus. A larger effect is expected due to the suppression of fragmentation photons by energy loss of quark jets in the medium (curves labeled $20 < \omega_c < 25$ GeV). The data indicate that there may be a small suppression at high p_T, but there is no indication of the expected in-medium suppression at lower p_T, albeit with large uncertainties. It has also been suggested that quark-photon conversions in the medium could lead to an enhancement of direct photon production at intermediate p_T [32]. There is no evidence for such an enhancement in the data.

3.1. γ-hadron correlations

High-p_T γ-jet production promises to be a sensitive probe of parton energy loss, because it provides a sample of jets with calibrated energy. This makes it possible to probe the probability distribution of energy loss and thus the medium density profile, which is very difficult with di-hadron measurements at RHIC [13]. Fig. 7 shows first results on γ-jet measurements in p+p and Au+Au collisions from this conference. The left panel shows the result from STAR in p+p collisions [33], which agrees with HIJING expectations.

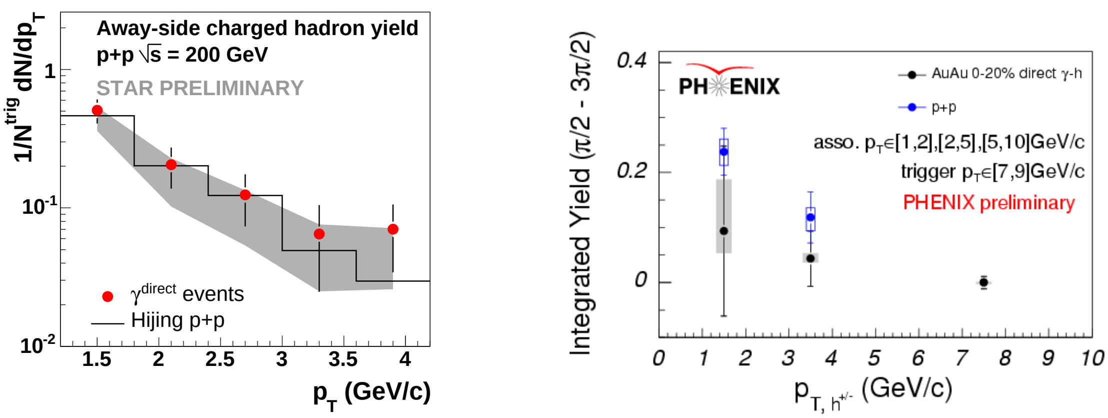

Figure 7. Away-side charged hadron spectra from events with a direct-photon trigger. Left panel: STAR results from p+p events with $8.5 < E_{T,trig} < 10.5$ GeV. Right panel: PHENIX results in p+p and Au+Au with $7 < E_{T,trig} < 9$ GeV.

The right panel shows results from PHENIX for p+p and Au+Au collisions [34]. The Au+Au results are consistently lower than the p+p results, as expected from parton energy loss. At present, the statistical and systematic uncertainties are still large. Both collaborations are aiming to improve the precision of the Au+Au measurement with an upcoming large statistics Au+Au run.

4. Conclusion and Outlook

New results from high-statistics analyses at RHIC as presented at this conference explore in-medium energy loss in detail. Measurements at intermediate p_T show that there are large contributions to particle production from phenomena that are not obviously related to vacuum jet fragmentation, such as the near-side ridge and the strongly broadened and enhanced away-side structure. Di-hadron correlation measurements with identified particles are also being explored, and show for example an increased baryon/meson ratio on the away side for intermediate p_T trigger hadrons. So far, no clear connection between the effects seen in correlation yields and the enhanced baryon/meson ratio for inclusive particles has been established, but this may happen in the near future, as more detailed measurements with identified hadrons become available.

At higher p_T, particle production follows the expectations of vacuum fragmentation more closely. With increasingly detailed treatments of energy loss in model calculations, we are approaching a quantitative description of the energy loss process and constraints on the medium density profile. To constrain the theory further, comparisons should be made with as much of the existing measurements as possible, including nuclear modification factors, azimuthal asymmetries and di-hadron fragmentation. In addition, centrality and system size dependence measurements should be used to determine path length dependence and energy density profiles.

γ-jet events provide a unique probe of parton energy loss because the photon and the jet have balancing transverse momenta, thus presenting a calibrated differential measure of energy loss. This type of measurement is now actively being pursued at RHIC, with first results from p+p collisions presented in this meeting. A next long Au+Au run at RHIC will probably provide quantitative insight in parton energy loss in γ-jet events.

In the near future, first LHC data will give a tremendous boost to the research with penetrating probes. The kinematic range for measurements at LHC is well into the regime where parton energies are larger than the typical energy loss, and this will allow much more differential measurements. I am looking forward to future results from LHC and from RHIC runs at higher luminosities which will explore in-medium energy loss models and the medium density in heavy ion collisions in quantitative detail.

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