Intermediate and high-p_T physics from STAR

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Abstract

We present results on particle production at intermediate- and high-p_T measured by the STAR experiment at RHIC. In particular, the nuclear modification factors and ratios of particle yields are discussed in order to investigate anomalous baryon production in heavy-ion collisions. Next the azimuthal and pseudo-rapidity correlations of charged hadrons and neutral strange particles (K^0_S, Λ) are presented. In Au+Au collisions, both the near- and away-side correlations are modified with respect to p+p and d+Au collisions. At near side, there is an additional extended correlation in pseudo-rapidity ("the ridge") which is not present in p+p or d+Au collisions. The away-side correlation peak exhibits a strong shape modification at low- and intermediate-p_T resulting in a dip at $\Delta\phi=\pi$. In order to get more insights into the physics origin of this effect, results on three-particle correlations are discussed as well.

1 Nuclear modification factors and baryon/meson ratios

Heavy-ion collisions at ultra-relativistic energies are a unique environment for investigation of nuclear matter under extreme conditions of high temperature and energy density. Studies of particle production in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV at RHIC revealed a strong suppression (by a factor 5) of inclusive p_T distributions of light hadrons in central Au+Au collisions with respect to p+p and d+Au collisions [1, 2] scaled by the number of binary nucleon-nucleon collisions. This suppression, commonly referred to as *jet quenching*, is present out to large transverse momenta ($p_T \approx 20$ GeV/c).

Interestingly, baryons and mesons show a different amount of suppression. While for $p_T > 6$ GeV/c the suppression is within the errors same for baryons and mesons, at intermediate p_T (p_T = 2-6 GeV/c) both strange and non-strange baryons are less suppressed than mesons. This is demonstrated in Figure 1, which shows the nuclear modification factors for charged pions and $p + \bar{p}$ in central relative to peripheral Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV scaled by the relative ratio of binary collisions. This observation also implies that the baryon/meson ratios in heavy-ion collisions are larger than in p+p and d+Au collisions at intermediate p_T [3, 4, 5] as displayed in Figure 2 for p/π^+, p/π^-

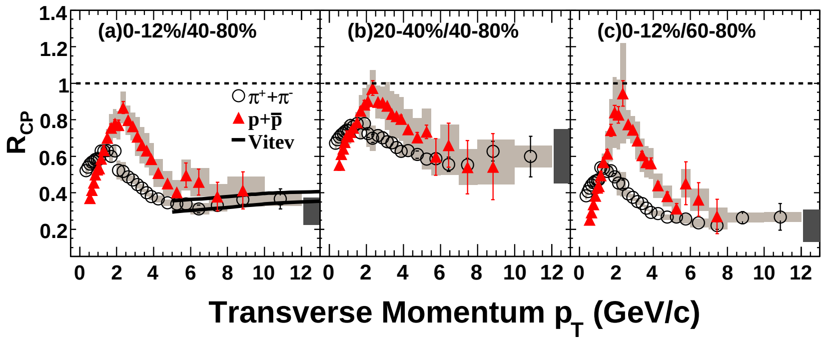

Figure 1: Nuclear modification factors R_{CP} for charged pions and p+$\bar{p}$ in Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV. The shaded boxed represent point-to-point systematic erros. The dark band shows the normalization uncertainty in the number of binary collisions. The solid line is the prediction for charged pions from GLV calculation [6]. The figure is from [3].

and Λ/K^0_S ratios. The measured baryon/meson ratios in both non-strange and strange quark sectors increase with p_T up to about $p_T \approx 3$ GeV/c, where the enhancement of baryon/meson production reaches its maximum value of ≈ 3 relative to p+p collisions. A fall-off of the baryon/meson ratio is observed for $p_T > 3$ GeV/c and both, the strange and non-strange baryon/meson ratios in Au+Au collisions approach the values measured in p+p collisions at $p_T \approx 6$ GeV/c.

These findings suggest that a dominant source of particle production at intermediate p_T is not from jet fragmentation. Parton recombination and coalescence models have been suggested as alternative mechanisms [7, 8, 9, 10, 11]. In these models, competition between recombination and fragmentation results in a shift of the onset of the perturbative regime to higher transverse momenta $p_T \approx$ 4-6 GeV/c. Due to the steeply falling parton transverse momentum spectrum, the fragmentation process is a much less efficient particle production mechanism than recombination. Moreover, the steeply falling parton spectrum favors recombination of three quarks to form a baryon over the recombination of two quarks to form a meson with the same p_T. Such mechanisms then naturally lead to an increased production of baryons relative to mesons which is in qualitative agreement with the data.

2 Azimuthal and pseudo-rapidity correlations

As compared to the nuclear modification factors, studies of the modification of jet structures are expected to provide higher sensitivity to the medium prop-

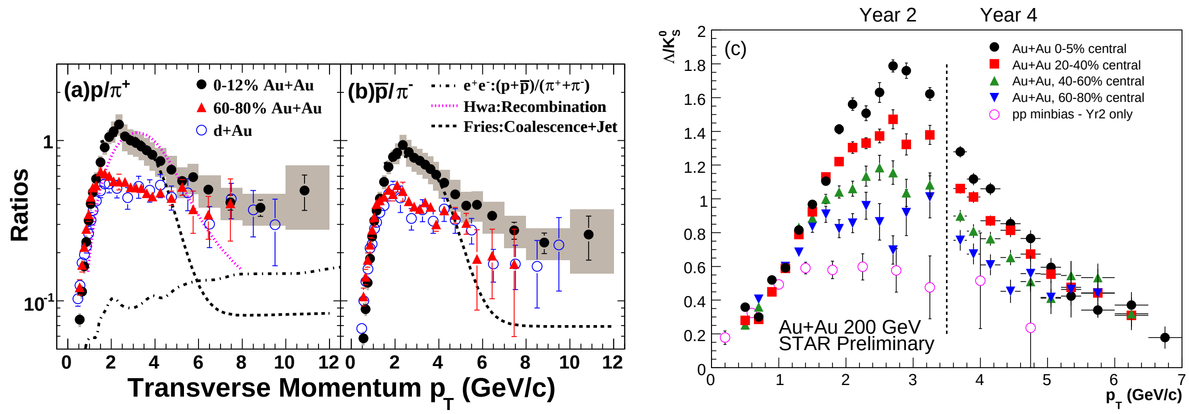

Figure 2: (a) The p/π^+ and (b) $\bar{p}/\pi^-$ ratios in Au+Au and d+Au collisions at $\sqrt{s_{NN}}$= 200 GeV. The shaded boxes represent the systematic uncertainties. The dotted and dashed lines are rcombination model calculations from [7, 11]. The figure is from [3]. (c) The Λ/K^0_S ratio as a function of p_T in p+p and for different centralitites in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV.

erties. Since a direct measurement of jets in heavy-ion collisions at RHIC is difficult due to the large number of produced particles, azimuthal correlations of particles wih large p_T are commonly used to study the jet related processes. Studies of di-hadron azimuthal correlations in central Au+Au collisions resulted in several interesting observations that show striking differences to p+p and d+Au measurements: a) the disappearance of the away-side jet at intermediate p_T consistent with partonic energy loss in medium, b) the increase of the away-side yield of associated particles at low-p_T, c) *Punch through* or the ability of away-side jets, with sufficiently large p_T, to traverse the hot and dense medium, and d) the presence of long range pseudo-rapidity ($\Delta\eta$) correlations on the near side, commonly referred to as *ridge* [13].

In the following sections we discuss recent measurements of azimuthal and pseudo-rapidity correlations in STAR using two- and three-particle correlation techniques, identified particles and different systems in order to obtain more insights into the particle production at RHIC energy.

2.1 Two-particle correlations at near-side: the ridge

One of the remarkable results of the correlation measurements in central Au+Au collisions at RHIC is the observation of an additional long-range pseudo-rapidity correlation on the near-side, *the ridge*, which is absent in p+p and d+Au collisions [12, 13]. This is demonstrated in Figure 3 which shows the di-hadron distribution in $\Delta\eta\times\Delta\phi$ space for charged trigger particles with transverse momentum $3 < p_T^{trig} < 4$ GeV/c and associated charged particles with $p_T^{assoc} > 2$ GeV/c

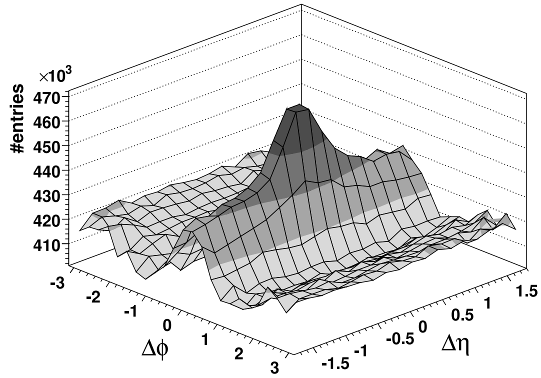

Figure 3: $\Delta\eta \times \Delta\phi$ di-hadron correlation in central (0-12%) Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. The trigger particle has p_T^{trig} = 3-6 GeV/c and p_T^{assoc} >2 GeV/c.

produced in central Au+Au collisions [13]. There is a clear jet-like peak present at small angular separations and it is accompanied by an extended correlation in $\Delta\eta$, the ridge.

Below we study separately the jet and ridge contributions to the near-side yield by analyzing the correlations in two $\Delta\eta$ windows: $|\Delta\eta| < 0.7$ containing both jet and ridge correlations, and $|\Delta\eta| > 0.7$ containing only the ridge contributions, assuming the jet contribution at large $\Delta\eta$ is negligible. As elliptic flow (v_2) is within the STAR acceptance uniform with η, the jet yield is free of systematic uncertainties due to the elliptic flow subtraction. For the ridge yield, these systematic errors are estimated by subtracting the v_2 measured by the event plane method (the lower bound) and by the 4-particle cumulant method (the upper bound). The uncertainties in the elliptic flow subtraction result in about a 30% systematic error on the extracted associated yield. Analysis details can be found in [13, 14]. The yield of associated particles in "jet" and ridge is normalized per number of trigger particles and corrected for the efficiency of associated particles and experimental acceptance including the triangular correction of the $\Delta\eta$ acceptance.

The centrality dependence of ridge and jet yields for charged and strange (Λ, K_s^0) trigger particles associated with charged particles in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV is shown in Figure 4. For all studied trigger particle species, the yield of charged particles associated with the ridge shows a significant increase by a factor of 3-4 going from d+Au to central Au+Au collisions. In contrast, the jet yield is within errors independent of centrality and within errors agrees with that in d+Au collisions.

Next we discuss the p_T distributions of associated particles. It has been shown that the ridge yield persists up to the highest $p_T \approx 6$ GeV/c currently reachable and is approximately independent of p_T^{trig} [13]. A more detailed study

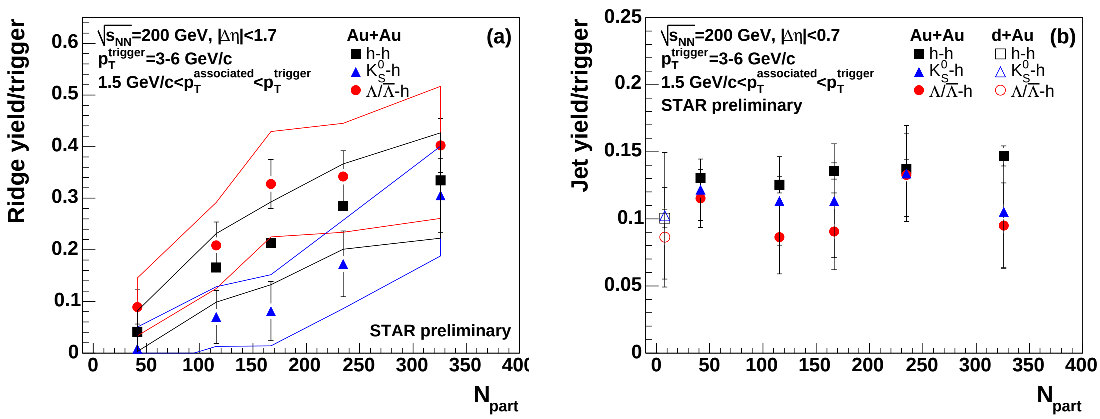

Figure 4: Centrality dependence of the ridge yield (a) and jet yield (b) of associated charged particles for various trigger species in d+Au and Au+Au collisions. The error bands indicate systematic errors on the ridge yield due to the v_2 subtraction.

of the p_T spectra of particles associated with the ridge in different p_T^{trig} windows and its comparison to the p_T spectra of particles produced in the bulk and associated with the jet is presented in Figure 5. The inverse slope extracted from an exponential fit to the spectra is for the ridge-like correlations independent of p_T^{trig} and only by $\approx$ 40-50 MeV larger than that of the inclusive p_T spectrum. The jet-like yield has a significantly harder spectrum, with an inverse slope increasing steeply with p_T^{trig} in line with jet fragmentation.

It is also important to investigate particle composition in the ridge which could help to determine the physics origin of the ridge. Preliminary studies for charged particle triggered correlations with associated strange particles (Λ, K_S^0) in central Au+Au collisions have been carried out [15]. Figure 6 shows the extracted Λ/K_S^0 ratio in the jet and ridge together with the ratio obtained from inclusive p_T spectra. The Λ/K_S^0 for the jet is consistent with the ratio measured in p+p. There is a hint that the Λ/K_S^0 ratio in the ridge is higher than in the jet, however the current statistical errors are large and more data are needed to draw a definite conclusion.

While the existence and properties of the jet-like correlations are similar to those in p+p and d+Au collisions, the origin of the ridge-like component is not yet fully understood. This phenomenon has triggered large interest in the theoretical community and many models attempt to explain the origin of the ridge. Below we briefly discuss some of them.

A model based on the parton recombination in the medium [16, 17], connects the origin of the ridge to the longitudinal expansion of the thermal partons which distributions are enhanced by the energy loss of a hard parton traversing

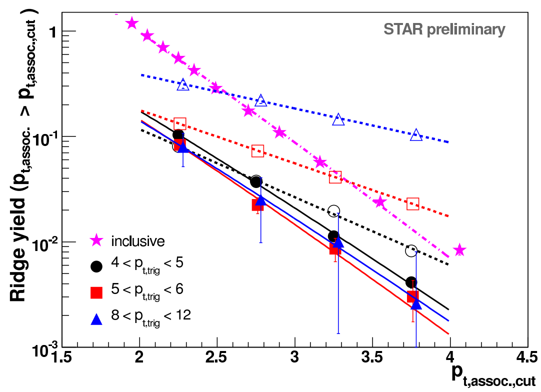

Figure 5: Near-side $p_T^{associated}$ charged hadron spectra for several $p_T^{trigger}$ in central Au+Au collisions for jet-like correlations (dashed) and the ridge (solid)
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the medium. This model predicts an enhanced baryon/meson ratio of particles associated with the ridge following that of particles produced in the bulk. The inverse slope of the particle spectra associated with the ridge should be larger by several tens of MeV with respect to that of particles produced in the bulk, in line with our observations.

In another approach, strong longitudinal collective flow would cause medium-induced broadening of gluon radiation in $\Delta\eta$, leading to a broadening of the jet-structure in $\Delta\eta$ and possibly the formation of a ridge [18].

Yet another model incorporating the longitudinal expansion [19], relates the origin of the ridge to spontaneous formation of extended color fields in the expanding medium due to plasma instabilities. The model predicts ridge at low transverse momenta which should decrease with increasing energy of the associated radiation. The momentum range of the partons contained in the ridge is in the recombination regime and therefore the authors of this model predict that it would reflect itself in the baryon to meson ratio of associated hadrons.

Another suggested mechanism for the origin of the ridge is based on jet quenching combined with strong radial flow [20, 21]. The radial expansion of the system creates strong position-momentum correlations leading to characteristic rapidity, azimuthal and p_T correlations among produced particles.

In the momentum kick model [22], partons in the medium suffer a collision with a propagating jet and acquire in such collision a momentum kick along the jet direction forming a ridge structure.

At this stage more quantitative model predictions as well as further studies of the ridge particle composition, studies at forward rapidities and investigation of 3-particle $\Delta\eta \times \Delta\eta$ correlations are needed to bring more insights into the ridge physics origin.

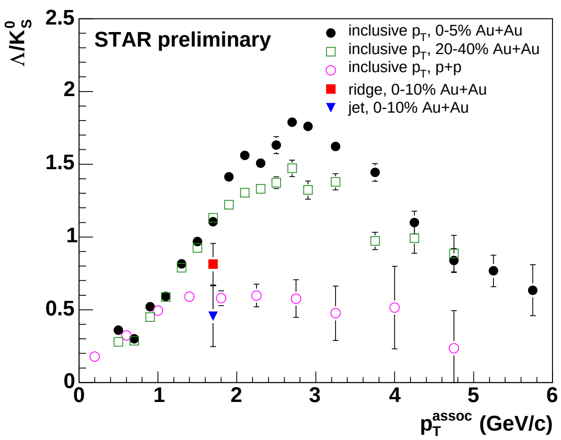

Figure 6: Λ/K_S^0 ratio measured in inclusive p_T distributions, near-side jet and ridge-like correlation peaks in Au+Au collisions together with this ratio obtained from inclusive p_T spectra in p+p collisions.

2.2 Three-particle correlations at intermediate p_T

The observed doubly-peaked structure of two-particle azimuthal correlations around $\Delta\phi \approx \pi$ in Au+Au collisions [23, 24] was suggested as an indication of the Mach cone or wake field [25, 26]. However, the dip might also result from large angle gluon radiation, deflection of jets by radial flow, or Čerenkov gluon radiation [27, 28, 29, 30]. In order to discriminate among various production mechanisms it is therefore necessary to study three-particle correlations. The three-particle correlations presented below are constructed by using three charged particles (1 trigger and 2 associated particles) and calculated in terms of two relative azimuthal angles $\Delta\phi_{ta}$ and $\Delta\varphi_{tb}$, where "t" denotes the trigger particle and the associated particles are labeled "a" and "b". Mach cone emission will lead to peaks at $\Delta\phi_{ta} = \pi \pm \theta_M$, $\Delta\phi_{tb} = \pi \pm \theta_M$, with the Mach angle θ_M determined by the sound velocity in the produced medium. Below we present results of an ongoing experimental search for conical emission in Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV using two different methods: jet-flow background subtraction method and three-particle cumulant method.

The first method is a two component method [31, 32, 33, 34] based on a measurement of three-particle density normalized per trigger particle. It includes explicit subtraction of flow v_2^2, v_4^2, $v_2v_2v_4$ background terms, and carries combinatorial background subtraction using the zero yield at 1 radian (ZYA1) method [35]. The resulting correlations in d+Au and Au+Au collisions are shown in Figure 7. While the three-particle correlations in peripheral Au+Au collisions are qualitatively similar to those in d+Au collisions, in central Au+Au

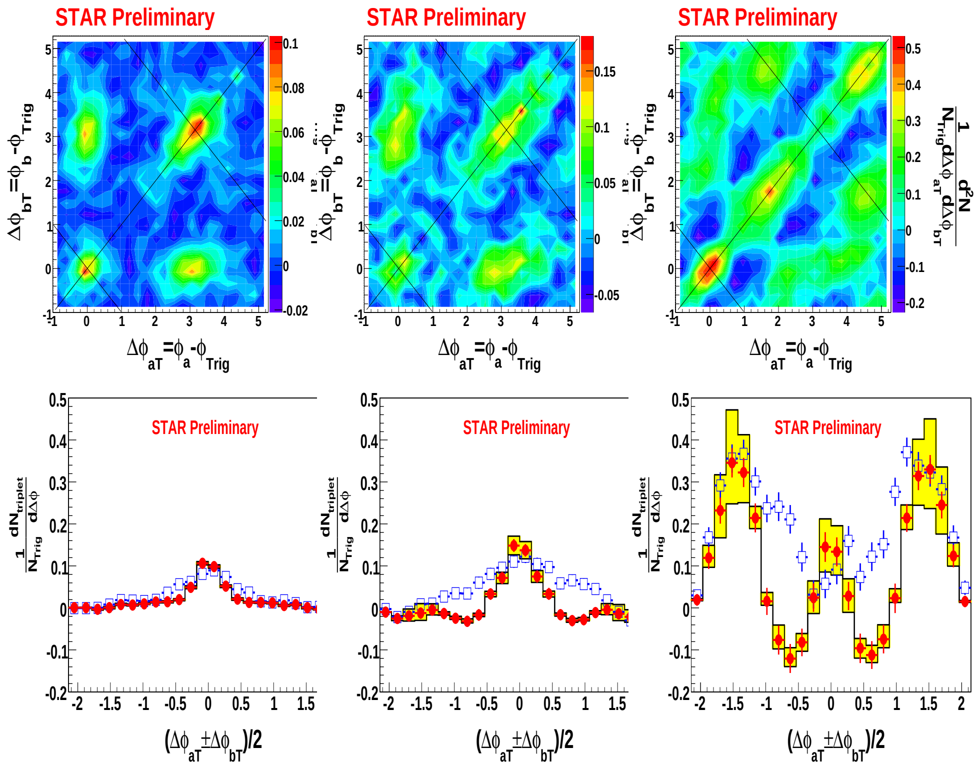

Figure 7: Three-particle correlations obtained in the jet-flow background subtraction method in d+Au (left), 50-80% Au+Au (center), and 0-12% Au+Au collisions (right). The bottom plots show projections along the main (blue) and alternate (red) diagonals together with systematics effects from the background subtraction.

collisions, the shape of the away-side structure is substantially modified: two broad peaks are observed along the main diagonals at angles of $\pi \pm 1.45$ rad and also off diagonal structures at ($\pi \pm 1.45$, $\pi \mp 1.45$) are present. This observation suggests evidence for the conical emission with rather modest sound velocity in the medium at RHIC. We remark that the amplitude of the observed on and off-diagonal structures depends on the jet-flow correlation component, the magnitude of v_2 and v_4 flow and the combinatorial background term normalization. The size of these systematic effects is shown as the yellow histogram band in Figure 7.

Contrary to the previous method, the three-particle cumulant analysis, is a fully model independent method based on measured three-particle densities (i.e. number of triplets/event) from which combinatorial terms are subtracted based on measured two- and one-particle densities. The details can be found in [36, 37, 38]. The evolution of the 3-particle cumulants with centrality in

Au+Au collisions is shown in Figure 8. The data show prominent peaks at (0,0), (π,π), (0,π), and (π,0) present at all centralities and in addition weaker peaks positioned at regular intervals. The latter are strongest in 10-30% centrality class, where v_2 and v_4 flow coefficients are the largest, and can be qualitatively understood as arising from irreducible non-diagonal collective flow contributions of order $v_2 v_2 v_4$ [36]. Parameterizing the measured v_2 and v_4 values yields amplitudes compatible with those observed in the data. While the presence of the near- and away-side peaks can be a result of jet emission alone (with two associated particles either on the near or away-side), they may also result from the interplay of jet correlations with the reaction plane and collective flow.

As for the previous method, we examine the projections of 3-particle cumulants (cf. Figure 8 bottom) to look for an evidence of conical emission. Although the projections exhibit structures consistent with $v_2 v_2 v_4$ terms and no clear evidence for conical emission is observed, it is not excluded that the conical emission is masked by flow terms, or too weak to be visible in this analysis.

We note that the effects of momentum conservation as discussed in [39] for the p_T selection used could influence the conclusions drawn from the experimental observations.

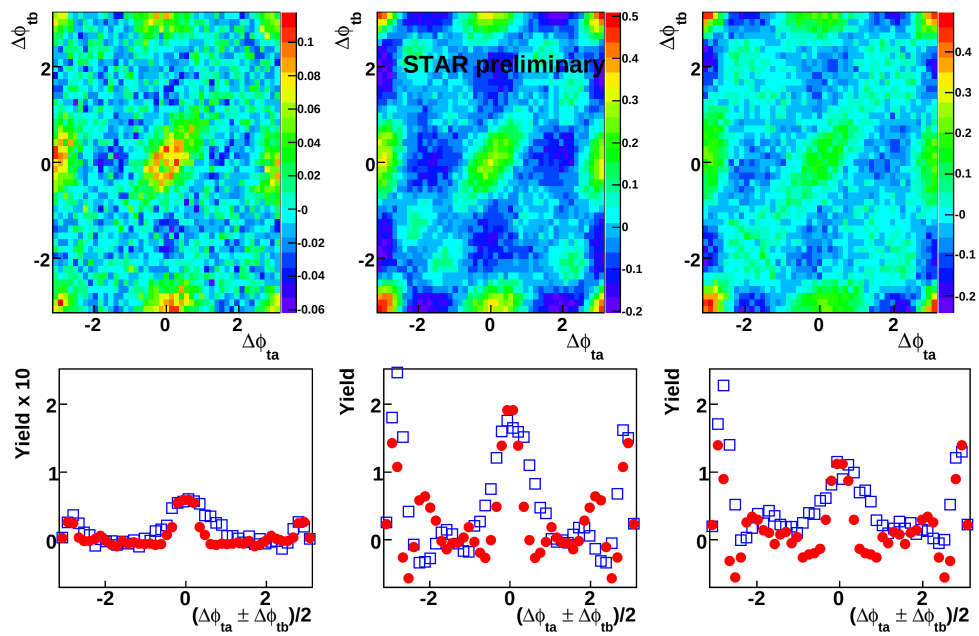

Figure 8: 3-particle cumulants (top row) for 50-80% (scaled x 10) (left), 10-30% (middle) and 0-10% (right) Au+Au collisions together with projections (bottom row) along the main (blue squares) and alternate diagonals (red circles).

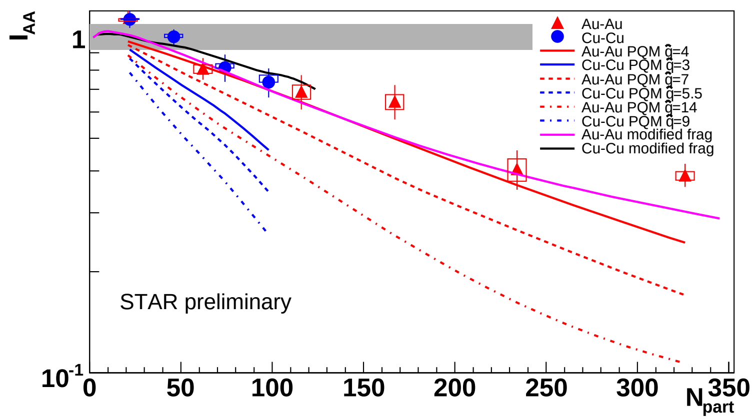

Figure 9: Centrality dependence of the nuclear modification factor (I_{AA}) for the away-side di-hadron correlation peak in Au+Au and Cu+Cu collisions relative to d+Au collisions. The charged hadron trigger particle was selected with $6 < p_T^{trig} < 10$ GeV/c and the associated charged hadron with 3 GeV/$c < p_T^{assoc} < p_T^{trig}$. The red and blue lines (solid, dashed, dotted-dashed) represent calculations from the PQM model for several values of the transport coefficient $\hat{q}$ in Au+Au and Cu+Cu collisions, respectively. The pink and black lines represent the predictions from the modified fragmentation model in Au+Au and Cu+Cu collisions, respectively.

2.3 Di-hadron correlations at high-p_T: path-length dependence of energy loss

In this section we discuss the path length dependence of energy loss by measuring the away-side yield suppression of di-hadrons in Cu+Cu and Au+Au collisions relative to d+Au collisions. Radiative energy loss, which is expected to be dominant for light quarks, is predicted to depend on the square of the path length L traversed by the quark in the medium. Collisional energy loss, on the other hand, is expected to scale linearly with L. Therefore studies in different collision systems, which have for the same number of participating nucleons (N_{part}) different geometry, can be used to test and constrain theoretical predictions.

Figure 9 shows the new STAR results on centrality dependence of the away-side suppression (I_{AA}) in Cu+Cu and Au+Au collisions relative to d+Au collisions [40]. The measurement is done for charged particles with p_T^{trig} =6-10 GeV/c and $p_T^{assoc} > 3$ GeV/c. As expected, the amount of the suppression increases with N_{part}, however no differences between the Cu+Cu and Au+Au collision systems at the same N_{part} are observed. The data are compared to two model calculations. The first one, the Parton Quenching Model (PQM) [41, 42], is based on quenching weights from [43] and the Glauber geometry where the local density scales with the local density of binary collisions. The second model, modified fragmentation model [44, 45], is based on modified fragmentation functions in next-to-leading order QCD calculation and a hard-sphere geometry with local participant density scaling. Both models have been tuned at higher-p_T data from STAR in central Au+Au collisions. The data are in a better agreement with the modified fragmentation model, while the PQM model contradicts the observed N_{part} scaling. It remains to be investigated whether the observed difference in the model predictions is due to the different quenching mechanisms and/or the medium density profiles used.

3 Summary

We have reported recent results on medium modification of inclusive particle production as well as two- and three-particle correlation studies in heavy-ion collisions measured by the STAR experiment at RHIC. The inclusive p_T distributions in central Au+Au collisions show a strong suppression with respect to p+p, d+Au and peripheral Au+Au collisions. The observed suppression is more pronounced for mesons than for baryons and is accompanied by an anomalous enhancement of baryon/meson ratios at intermediate-p_T with respect to p+p and d+Au collisions. These observations suggest that in the intermediate-p_T range, the dominant particle production mechanism is not jet fragmentation and that parton recombination and coalescence play a significant role at RHIC.

The measured correlations reveal a strong contribution from the ridge-like correlations in pseudo-rapidity and in-medium shape modification on the away-side correlation peak with a possible indication of conical emission. The first results on the path length dependence of energy loss from di-hadron correlation studies in two different collision systems, Cu+Cu and Au+Au, have emerged and are in future expected to bring new insights into the partonic energy loss mechanisms.

In the end, we would like to refer the reader to the most recent developments presented a week after the Bormio workshop at the Quark Matter 2008 conference in Mumbai, India (http://www.veccal.ernet.in/qm2008.html). Many new and interesting measurements on particle production at intermediate- and high-p_T at RHIC have been presented there. They include 3-particle pseudo-rapidity correlations, ridge studies at forward rapidities and with respect to the reaction plane, particle ratios in the ridge and in the jet as well as the first γ-hadron correlations in Au+Au collisions.

Acknowledgments

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