Probing the properties of dense partonic matter at RHIC

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The experimental highlights from PHENIX are summarized from the point of view of probing the properties of dense partonic matter produced at RHIC.

1. Introduction

The first three years of RHIC results have been summarized by the four RHIC experiments in their White Papers[1–4], which were published during this conference. It is appropriate to start the summary and the focus of the results of PHENIX in this Quark Matter 2005 conference from the conclusions of the white paper. In the last paragraph of the PHENIX white paper we wrote[1]:

> *In conclusion, there is compelling experimental evidence that heavy-ion collisions at RHIC produce a state of matter characterized by very high energy densities, ...*
> *... additional incisive experimental measurements combined with continued refinement of the theoretical description is needed to achieve a complete understanding of the state of matter created at RHIC.*

The questions we want to address in this summary are:

- *What additional incisive experimental measurement do we now have?*
- *What additional information on the properties of the matter can be derived from the new data?*

2. Highlights of new PHENIX data

We have observed that the matter is very opaque and dense. It is so dense that even a 20 GeV/c pion is stopped. In figure 1 we show our preliminary data for the nuclear modification factor, R_{AA}, of π^0 in central Au+Au collisions in the p_T range up to 20 GeV/c[5]. The suppression is very strong, and it is flat at $R_{AA} \simeq 0.2$ up to 20 GeV/c. There is no hint that it returns to unity. The figure also shows that the suppression of π^0's and η's is very similar, which supports the conclusion that the suppression occurs at the parton level, not the hadron level. This strong suppression of mesons is in stark contrast to the behavior of direct photons[6], also shown in the figure. The direct photons

*for the full list of PHENIX authors and acknowledgements, see Appendix "Collaboration" of this volume.

follow binary scaling (i.e. $R_{AA} \simeq 1$). This is strong evidence that the suppression is not an inital state effect, but a final state effect caused by the high density medium created in the collision. The curve in the plot shows a theoretical prediction[7] using the GLV parton energy loss model. The model assumes an inital parton density $dN/dy = 1100$, which corresponds to an energy density of approximately 15 GeV/fm^3. The data show that the suppression is somewhat stronger than the prediction, suggesting that the matter density may be even higher than these estimates.

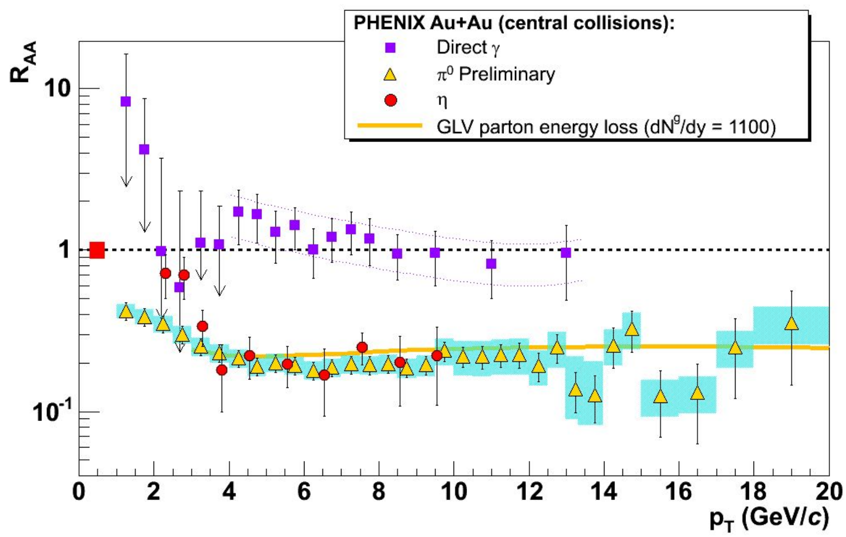

Figure 1. Nuclear modification factor, R_{AA} of π^0 (triangles), η (circles), and direct photon (squares).

We have observed that the matter is so dense that even heavy quarks are stopped. The data shown in figure 2 are the nuclear modification factors, R_{AA}, of single electrons from heavy flavor decay. The data show that heavy quarks, mainly charm in this p_T region, suffer substantial energy loss in the matter, which results in strongly suppressed single electron spectra. The suppression is very strong, almost as strong as that of light flavor mesons (π^0 and η).

These data provide strong constraints on and challenges to the energy loss models. The curves in the figure are theoretical predictions[8,9]. The theory curves of [8] are for charm quarks only, while that of [9] includes the effect of beauty, which is predicted to have smaller energy loss in the medium. If the effect of beauty is removed, the predictions of the two approaches are quite similar. The strong suppression shown in the data requires a large transport coefficient (as large as $\hat{q} = 14$ GeV^2/fm), or correspondingly a very high initial parton density (as high as $dN/dy = 3500$). Such a high parton density may be consistent with the strong suppression observed in π^0, but it is a challenge to the theories since it is not compatible with the observed final state particle multiplicity. In addition, the data may require a strong energy loss of beauty in the medium. This leads to a recent suggestion that the main energy loss mechanism is not gluon radiation, but elastic scattering[10,11].

This matter is so strongly coupled that even heavy quarks flow. Figure 3 shows our preliminary data of the elliptic flow strength, v_2, of single electrons from heavy quark decay[12]. The data clearly demonstrates that the v_2 of single electrons is non-zero, and that therefore the parent D meson have non-zero elliptic flow. This confirms our earlier results[13]. In order to get some idea of how strong the D meson v_2 is, we compare the data with the calculated single electron v_2 from the D meson decay. Here we use a simple *ansatz* that the $v_2(p_T)$ of the D mesons has the same shape as that of pion, but its strength is scaled. The comparison shows that our data can be reproduced rather well if the D meson v_2 is approximately 60% that of pion. Thus the charmed mesons flow, but not as strongly as light mesons. We also see that the flow strength drops in higher p_T, above 2.5 GeV/c. This is the p_T region where the contribution from beauty decays becomes significant. Is the drop due to the B meson contribution? This is an open question which has to be addressed in future. In the figure, we compare the theoretical predictions of [14] with our data. The data at low p_T favors the models that include flow for the charm quarks. In turn, charm quark flow would indicate high parton density and strong coupling in the matter. The strength of the flow can be reproduced either by resonance-like states[10] or a large cross section of c-quarks ($\sigma \simeq 10$ mb)[15] in the dense medium. If these models are correct, the charm flow data can be taken as evidence for strongly coupled QGP. It is not a weakly coupled gas.

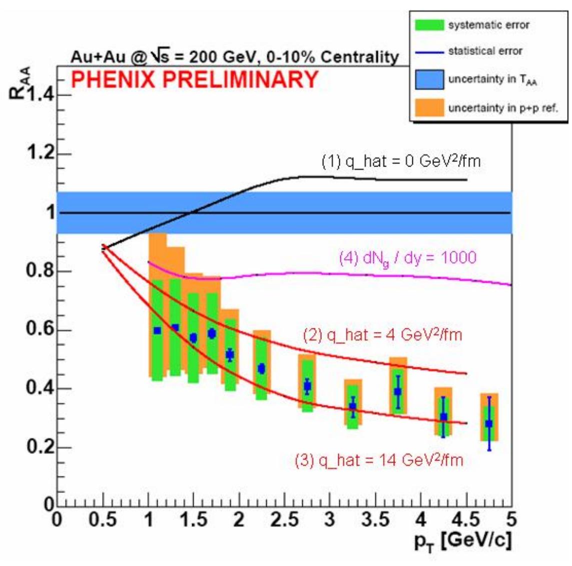

Figure 2. The nuclear modification factors R_{AA} of single electrons from heavy quark decay. The theory predictions ((1)-(3) from [8] and (4) from [9]) are also shown.

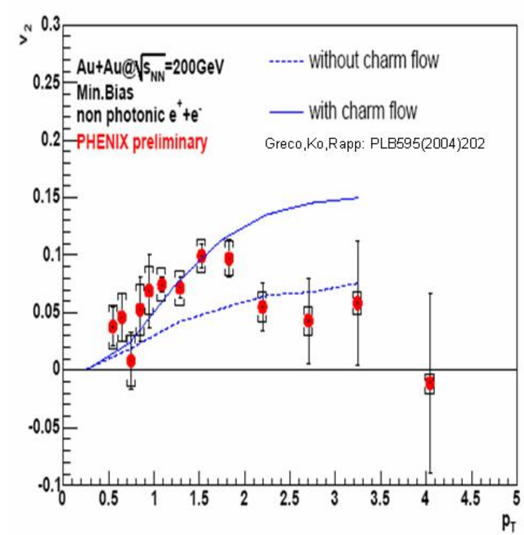

Figure 3. The elliptic flow strength v_2 of single electrons from heavy quark decay. The curves on the figure are charm coalescence model predictions[14] with (solid) and without (dashed) charm quark flow.

We now have the first promising result of direct photon measurements at intermediate p_T ($1 < p_T < 5$ GeV/c) from the analysis of low mass, high p_T electron pairs[16]. In figure 4, we show our preliminary direct photon results. The measurement is done through low mass electron pair analysis, but it is converted to the real photon invariant yield assuming $\gamma_{direct}/\gamma_{incl.} = \gamma^*_{direct}/\gamma^*_{incl.}$. Are these thermal photons? The rate is above a pQCD calculation[17] scaled by T_{AB}. The pQCD calculation agrees with our direct photon measurements in $p+p$ very well in $p_T > 5$ GeV/c. However, we need reference measurements in $p+p$ and d+Au to draw definite conclusions. The same analysis method can be used in $p+p$ to test the validity of pQCD in this low p_T region, and in d+Au to examine cold nuclear matter effects such as Cronin effect. If the yield is due to thermal radiation, the data can provide the first direct measurement of the initial temperature of the matter through comparison between the data and theoretical calculations. Comparison with a model prediction[18] yields the value of 500 to 600 MeV for T_{max}, where T_{max} is the maximum temperature at the center of the fireball. Averaging over the entire volume leads to smaller values of 300 to 400 MeV. These values are, of course, only meaningful if and only if these photons are indeed thermal photons, but nevertheless these results are quite intriguing.

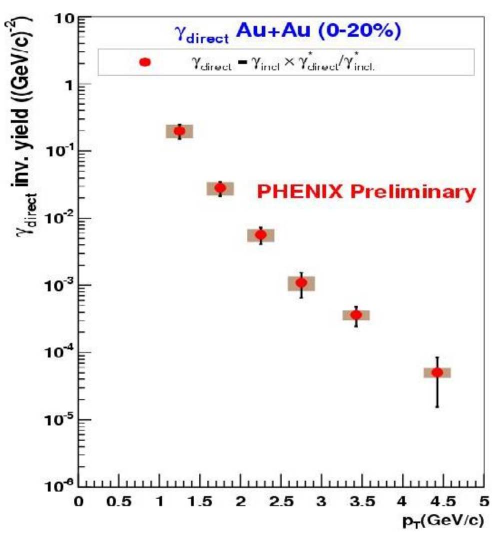

Figure 4. The transverse momentum spectrum of intermediate p_T direct photons from central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

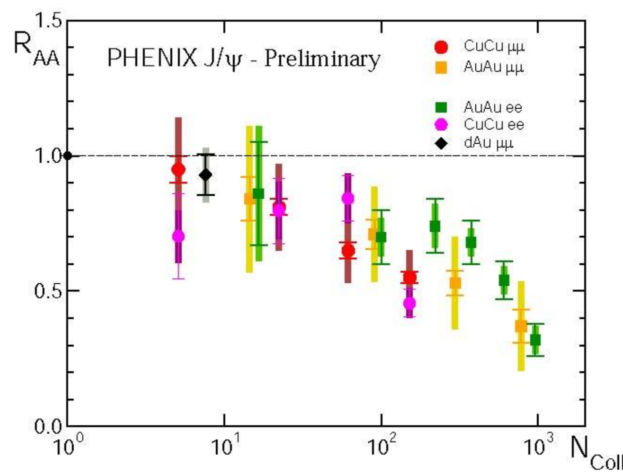

Figure 5. The nuclear modification factors R_{AA} of J/ψ in d+Au, Cu+Cu, and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

We now have very comprehensive data of J/ψ production at RHIC energies, from p+p to d+Au to Cu+Cu to Au+Au; both in central rapidity ($|y| < 0.35$) in the e^+e^- channel and in forward rapidity ($1.2 < |y| < 2.4$) in the $\mu^+\mu^-$ channel[19]. The nuclear modification factors, R_{AA}, of J/ψ at RHIC energies are presented in figure 5. The data show that, in the most central collision, J/ψ's are clearly suppressed beyond the cold nuclear effect. The preliminary data are consistent with predictions of the models with the suppression plus re-generation through charm recombination/coalescense[20]. Do the data really show suppression plus re-generation? One way to test the re-generation model is to measure the v_2 of J/ψ.

We have observed that the shape of the jets is modified by the matter. Figure 6 shows our preliminary data of jet shape analysis[21]. The data show that the shape of the away-side jets changes with the centrality. The reason for the modification of the jet

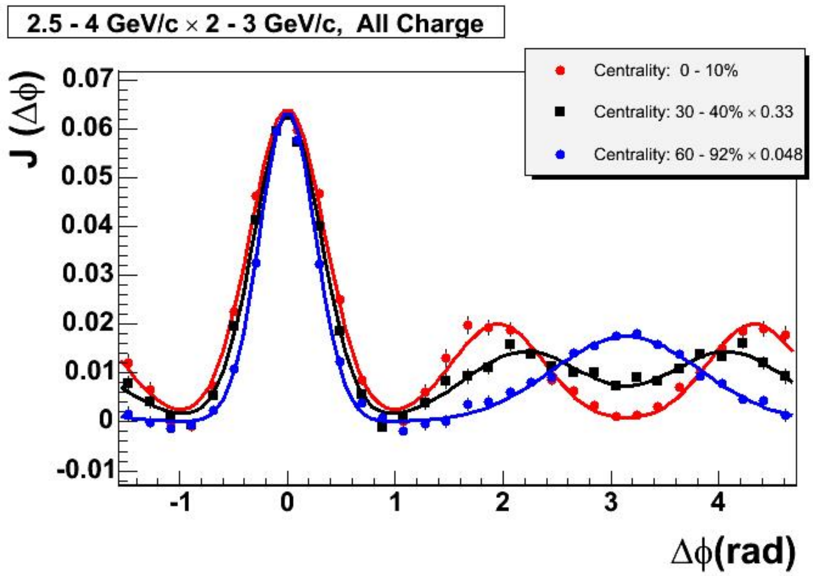

Figure 6. Jet modification in Au+Au collisions with different centralities.

shape is not well understood. It could be exotic effect like Mach cone[22], or Cerenkov-like radiation[23], or something that is more conventional. If this is due to Mach cone or Cerenkov-like radiation, the jet shape measurements will open up new possibilities to measure the properties of the matter. Can the properties such as the velocity of sound or color di-electric constant be measured from the shapes? The data show great potential for the di-jet tomography as a powerful tool to probe the properties of the matter.

3. Summary and Conclusions

We are now moving from the initial discovery phase of dense partonic matter to the next phase of probing the properties of the matter created at RHIC. The penetrating probes such as high p_T particles, heavy quarks, direct photons, J/ψ's, and jet tomography are very powerful tools to study the properties of the medium, as summarized symbolically in figure 7. The new PHENIX preliminary data show that the matter is so dense and opaque that even 20 GeV/c pions and heavy quarks are stopped; it is so strongly coupled that even charm quarks flow; it might be so hot that it copiously produce thermal radiation; it may melt but regenerate J/ψ; and it modifies jets. Close cooperation between theory and experiment is needed to quantitatively determine the properties of the medium. We look forward to working with the theory community to extract the properties of the matter.

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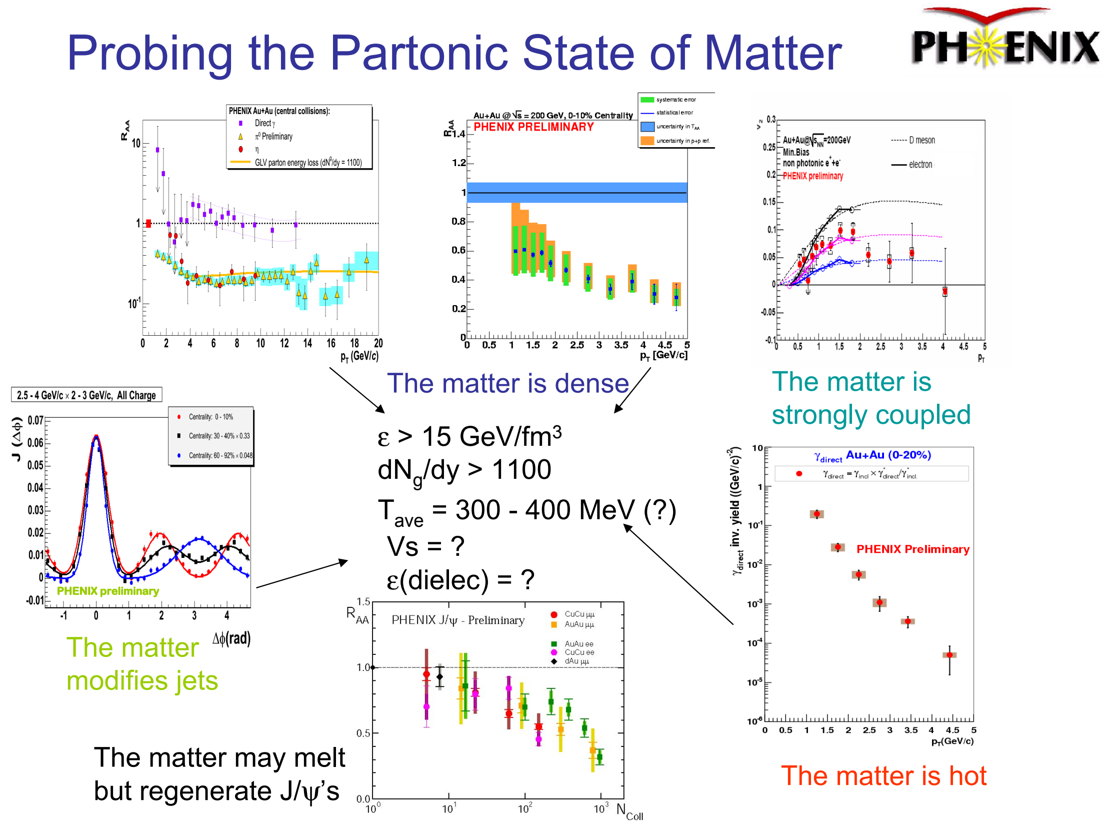

Figure 7. Probing the partonic state of matter created at RHIC from many observables.

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