STAR QM08 Highlights I:

Characterizing the new state of matter discovered at RHIC: first steps

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1) Introduction

The discovery phase at RHIC has yielded overwhelming evidence for the creation of a new state of matter in central heavy ion collisions— the hottest and densest yet examined in the laboratory. It is highly opaque to colored probes such as quarks and gluons, but not to photons. Elliptic flow measurements suggest the matter behaves as a relativistic quantum liquid with minimal shear viscosity. It produces copious mesons and baryons with yield ratios and flow properties that suggest their formation via the coalescence of partons having the degrees of freedom of valence quarks in a hot thermal bath. These phenomena—not observed prior to the start of the RHIC program—constitute important discoveries which now raise a new challenge: quantitative characterization of the matter's properties. First steps toward this goal were the subject of STAR presentations at Quark Matter 2008. Ultimately the full capability of RHIC II, including increased luminosity and significant detector upgrades, will be required to accomplish **a**) extension of the phenomena discovered with light quarks to hadrons containing charm and bottom, **b**) high efficiency and high luminosity for quarkonia studies and rare probes such as direct γ + jet **c**) precision, differential particle identified correlations and fluctuations, and **d**) acceptance to study the initial-state gluon distribution (i.e. Color-Glass Condensate) in the entrance channel nuclei. Dramatic new developments related to stochastic cooling of RHIC beams put this future within reach years earlier than originally projected. For a complete archive of STAR presentations at Quark Matter 2008, see http://www.star.bnl.gov/STAR/presentations/.

2) Quarkonium dissociation

The dissociation of quarkonia due to color-screening in a Quark-Gluon Plasma (QGP) is a classic signature of de-confinement in relativistic heavy-ion collisions. Results at RHIC thus far are intriguing, showing that the suppression of the J/Ψ as a function of centrality (the number of participants) is similar to that observed at the SPS, even though the energy density reached in collisions at RHIC is significantly higher. Clearly, additional theoretical tests and experimental data in p+p, p+A, and A+A collisions to stress those predictions are needed to advance our understanding. One such theoretical prediction based on string theory application of AdS/CFT suggests that, at high p_T , J/Ψ dissociation results from the presence of a "hot-wind" in a quark-gluon plasma. If true, the effective J/Ψ dissociation temperature is expected to decrease with p_T as 1/sqrt(γ). This conjecture is different from the predictions of more traditional screening models where the suppression due to screening vanishes towards higher p_T. New STAR data reported at Quark Matter 2008 on J/Ψ spectra in p+p and Cu+Cu collisions at $\sqrt{s_{NN}}$ = 200 GeV which address this question are shown in Fig. 1. for $5 < p_T < 14$ GeV/c. The total cross section in minimum-bias Cu+Cu collisions is consistent with that in p+p collisions when scaled by the number of binary nucleon-nucleon collisions in the measured p_T range. The nuclear modification factor (R_{AA}) for $p_T > 5$ GeV/c is measured to be 0.9 ± 0.2 (statistical), challenging existing models which predict suppression at high p_T. In a pQCD based picture, this finding together with the inferred strong suppression of open charm mesons based on the suppression of non-photonic electrons from their semi-leptonic decays in central nucleus-nucleus collisions suggests that the pre-cursor of the J/Ψ in-medium has to be color neutral since, otherwise it would be suppressed by induced gluon radiation similar to the case for open charm mesons. The large signal-to-background ratio of the STAR data at high-p_T allows study, for the first time, of J/Ψ—hadron correlations in p+p collisions to further our understanding of the J/Ψ production mechanism at high-p_T. From STAR data reported at QM08, an absence of charged hadrons accompanying the J/Ψ on the near-side is observed, <u>in contradiction with the strong near-side correlation peak observed in light-quark particle di-hadron correlations</u>. This could signal (i) the contribution from B decays to J/Ψ production in the measured p_T range is small or that (ii) J/Ψ production at high-p_T proceeds dominantly through a color-singlet state.

These results constitute progress toward answering a question fundamental to studies of J/Ψ suppression: the J/Ψ production mechanism and the relative importance of production by fragmentation of gluon and heavy-quarks, decay feed-down, and direct production from color-octet or color-singlet states. Despite intensive work over decades, considerable uncertainty remains concerning the J/Ψ production mechanism and no convincing model exists which satisfactorily explains all the major features of data from elementary collisions. For example, the color-singlet model (CSM) under predicts the J/Ψ spectra measured in pbar-p collisions at $\sqrt{s} = 1.8$ TeV by CDF by an order of magnitude. The color-octet model (COM) proposed to explain the observed yields, fails to explain recent measurements of large spin alignment from the same experiment. In addition, <u>J/Ψ production in e+e- collisions at $\sqrt{s}$ =10 GeV is found to be strongly correlated with the production of open-charm pairs suggesting the yield calculated in leading-order pQCD may not be the dominant contribution.</u> Clearly, additional theoretical work and experimental data are needed.

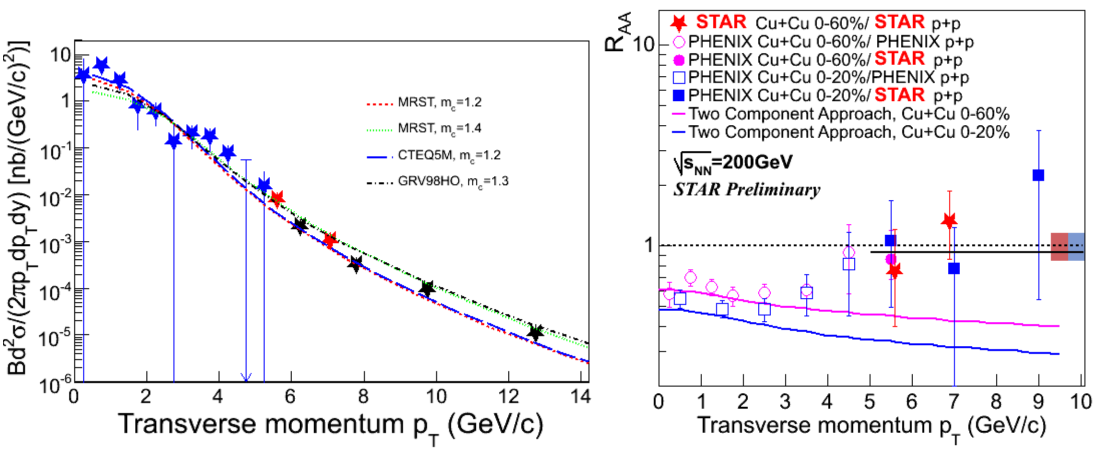

Figure 1 a) The J/Ψ spectrum in p+p collisions at 200 GeV; b) The J/Ψ nuclear modification function vs p_T based on comparison of the spectra in Cu+Cu and p+p scaled by the number of binary collisions

An important step in this direction will be the extension of quarkonia suppression studies to higher mass. At Quark Matter 2008, STAR reported first results on upsilon production at mid-rapidity in Au+Au collisions. Combined with the previous STAR measurement in p+p collisions, these data will yield first results on R_{AA} for the upsilon in the near future.

3) Open heavy-flavor (*D* and *B*) yields and charm related correlations

The study of heavy-flavor production in heavy-ion collisions provides key tests of parton energy-loss models and, thus, yields profound insight into the properties of the produced highly-dense QCD matter. Surprisingly, RHIC measurements in central gold-gold collisions have shown that the high-p_T production of electrons from semi-leptonic decays of mesons containing charm and bottom quarks is suppressed to the same level as observed for light-quark hadrons, which was not expected owing to the dead-cone effect. Energy-loss models describe the observed suppression reasonably well only if the bottom contribution to the non-photonic electrons is very small. Since the measurements are sensitive to the sum of charm and bottom decays, it is of great interest to disentangle the relative contributions experimentally.

At QM08, STAR measurements on heavy-flavor particle correlations in proton-proton collisions have been reported. Heavy-flavor (charm and bottom) events are clearly identified and separated through their characteristic decay topology using azimuthal correlation of non-photonic electrons and reconstructed open charmed mesons, which yield important information about the underlying production mechanism. The specific advantage of this correlation method, in contrast to the conventional heavy-quark measurements, is the possibility to efficiently trigger on heavy-quarks with high transverse momentum using their decay electrons. The results are compared to dedicated simulations from PYTHIA and MC@NLO event generators. The relative bottom contribution to

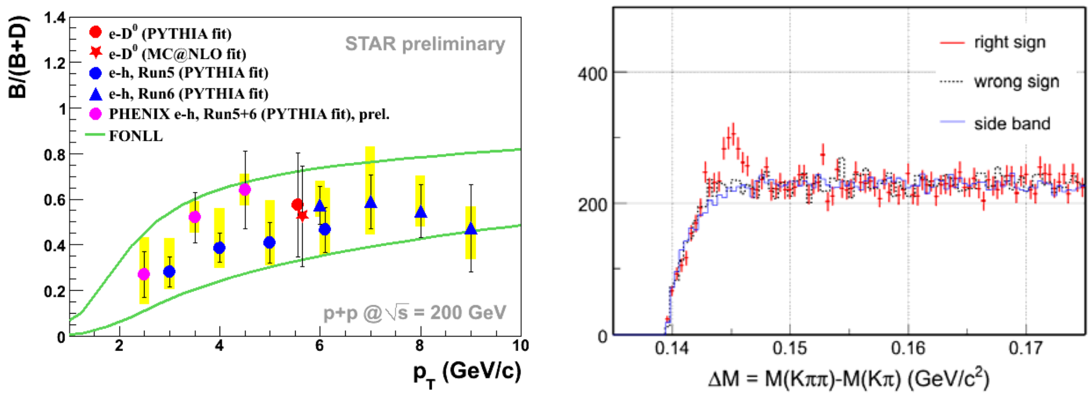

Fig.2 a) Relative bottom contribution to the total non-photonic electron yield in p+p collisions at RHIC derived from e-h and e-D correlations. b) Mass difference between D* and D in the decay of D*→ D+π; Results are from a jet-triggered sample using the barrel electromagnetic calorimeter. With the full-jet reconstruction, the charm (D*) content in a jet was measured on the near and away sides. These results indicate that gluon splitting to c-cbar pairs contributes ~ 5% of the open charm observed at RHIC, consistent with pQCD predictions.

the non-photonic electrons has been extracted. The results are shown in Fig. 2a (red data points), together with the results from electron—hadron correlations highlighted at QM2006 and new e-h correlation data reported by STAR at QM08 which extend the measurement to $p_T \sim 9$ GeV/c. These data provide convincing evidence that bottom contributes significantly to the non-photonic electron yields at high p_T. Combining these results with the R_{AA} observed for non-photonic electrons in central Au+Au collisions, it is inferred that bottom is suppressed significantly at high p_T in contradiction to expectations based on pQCD inspired models of parton energy loss.

An entirely new approach presented by STAR at QM08 involves indentifying the D* content of jets. As seen in Fig 2b, the characteristic peak observed in the invariant mass distribution of D*-D^0 indicates the identification of D* mesons is possible. By utilizing full-jet reconstruction and isolating the near-side of the jet-D* azimuthal angle correlation, the charm (D*) content in a jet was measured. From the correlation strength on the near side it was possible to estimate the amount of open charm production which results from gluon splitting The results indicate that gluon splitting to c-cbar pairs contributes ~ 5% of the open charm production observed at RHIC, consistent with pQCD predictions.

4) v_2/ε and v_2 fluctuation

Results on flow have been among the first of the important RHIC discoveries. From continued research in this area there is now a wealth STAR data on identified particle v_2. As seen in Fig. 3, the new results shown at QM2008 indicate, as observed previously, that at a given collision centrality, the v_2 of baryons and mesons appears to scale with the number of quarks n_q . This is especially evident in the higher transverse kinetic energy region (m_T - mass)/$n_q \geq 0.5$ GeV, where the magnitude of the observed v_2 is also higher indicating stronger collectivity. There is a clear centrality dependence in the eccentricity scaled v_2 which is most prominent in central collisions. Hydrodynamic model predictions are consistent with the experimental data in the low p_T region but over predict the data at higher p_T for all centrality bins measured.

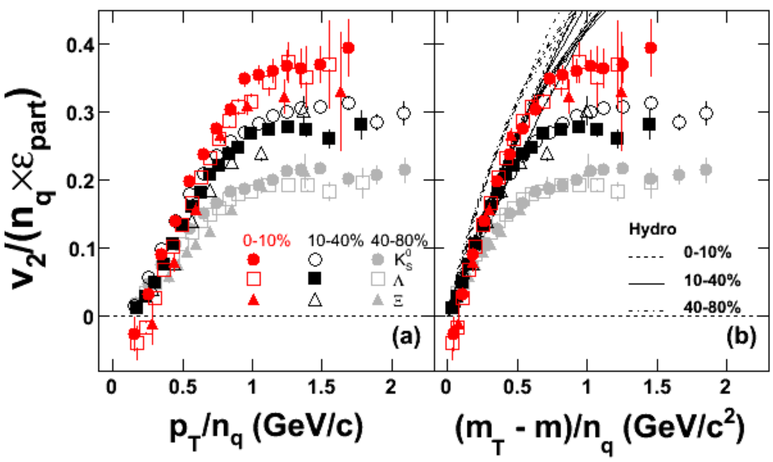

Fig.3 The v_2 scaled by the number of quarks (n_q) and participant eccentricity (ε_{part}) $v_2/(n_q \times \varepsilon_{part})$ of identified particles (K, Λ and Ξ) versus (a) the scaled p_T/n_q and (b) (m_T-mass) /n_q for three collision centrality bins (0-10%, 10-40% and 40-80%). All data are from 200 GeV Au+Au collisions at RHIC. For comparison, hydrodynamic model calculations are shown as lines in (b).

An important result reported at by STAR at QM08 was an in-depth study of v_2 fluctuations which has implications for the initial conditions in the entrance channel nuclei. Using the width of the event-by-event flow vector distribution, STAR placed an upper limit on the width of the v_2 distribution. An absolute value could not be extracted due to the non-flow correlation contributions. The non-flow correlations reflect very interesting physics and can be accessed via two-particle correlation measurements discussed below. The measured upper limit suggests that the flow vector distribution is sensitive to the participant eccentricity and not the standard eccentricity. In addition, since the upper limit and the nucleon participant eccentricity calculation coincide, that model leaves little or no room for other sources of fluctuations and/or correlations. This suggests that alternative models of the initial eccentricity are preferred by the data. These include a calculation using confined constituent quarks instead of nucleons as the participants, and a calculation which assumes a Color-Glass-Condensate initial condition.

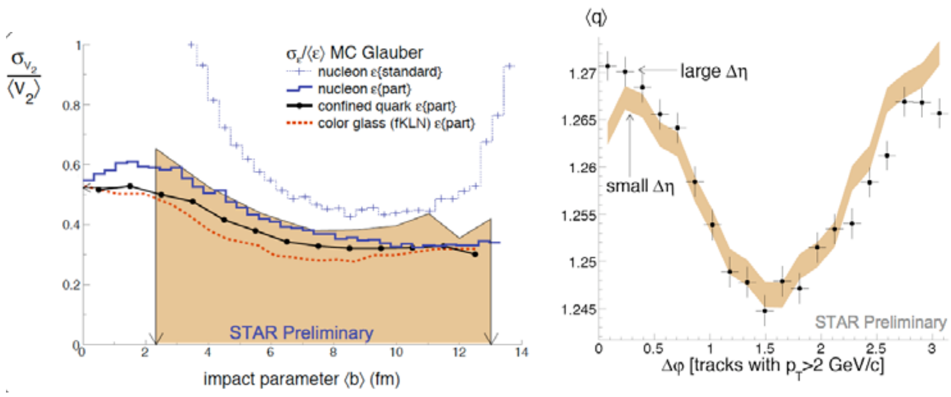

Fig. 4 Upper limit on v_2 fluctuations. The tan band shows the allowed range of the ratio of the width and mean of the v_2 distribution. Several models for initial eccentricity fluctuations are shown. b) ⟨q⟩ for an event vs $\Delta\phi$ of the leading and subleading hadron in the event. Large and small $\Delta\eta$ selections are made on the high p_T pair. Large $\Delta\eta$ is dominated by the ridge while small $\Delta\eta$ contains ridge and jet.

A second important flow observation discussed at QM08 relates to the "ridge". In central Au+Au collisions, the shape of the correlation between two intermediate p_T particles reveals a ridge like structure not seen in p+p collision. On top of this ridge, lies an apparent jet-like peak that is similar to the correlation seen in p+p collisions. It's technically possible to measure the azimuthal anisotropy (characterized by the 2^{nd} Fourier component v_2) of the events that contribute to the "jet" peak, the events that contribute to the "ridge", and the events that contribute to the background. This is done by first measuring the $\Delta\phi$, $\Delta\eta$ correlations for the leading and subleading hadrons in an event. Then the flow vector (q) distribution is measured for the events that yielded entries in the different $\Delta\phi$ and $\Delta\eta$ bins. Fig. 4 (right) shows the mean value of the flow vector as a function $\Delta\phi$ for the leading and subleading hadrons using different selections of $\Delta\eta$. The large $\Delta\eta$ selection is dominated by the ridge and the small $\Delta\phi$ and $\Delta\eta$ contains a contribution from the ridge and the "jet" peak. The initial expectation would be that ⟨q⟩ is independent of $\Delta\phi$ and $\Delta\eta$. What is observed, however, is a non-trivial dependence of ⟨q⟩ on $\Delta\phi$ and $\Delta\eta$. In particular the small $\Delta\phi$, small $\Delta\eta$ region (containing jet+ridge) has a smaller ⟨q⟩ than the small $\Delta\phi$, large $\Delta\eta$ (containing ridge only). This observation implies that events contributing to the jet peak tend to have smaller v_2 values. With this information, it's possible to solve for the v_2 of the events yielding a high p_T pair in the "jet" peak, a high p_T pair in the "ridge", or a high p_T pair in the background. This derivation, however, depends strongly on the assumption that the correlation structure can be divided into three components, a jet peak, a ridge, and a v_2 modulated background. It must also be assumed that there is no correlated yield at the minimum of the correlation function (zero yield at minimum or ZYAM). If these assumptions are invalid, then the results become unphysical and more difficult to interpret.

5) Correlations

Two-particle correlations between a trigger particle and associated particles have been studied intensively at RHIC. Correlations may also be formed using all unique pairs of particles in an event without a trigger particle. The resulting correlations will be sensitive to any process which induces relative momentum correlations between final state particle pairs in the acceptance including, but not limited to minijets (minimum-bias jets with no a-priori p_t cut, dominated by ~1 GeV/c hadrons), elliptic flow, quantum statistics, and resonances. Each of these dynamical processes generates a characteristic correlation structure on relative azimuth and pseudorapidity. As presented at QM08, correlation data from STAR are readily decomposed into a few analytic structures which can be related to the above sources.

An important application of this analysis is to study what happens to the minijet correlation, observed in p+p collisions, in heavy-ion systems as the collision centrality increases. The null hypothesis is that the minijet correlation will increase in amplitude in proportion to the number of binary collisions but otherwise remain unchanged. STAR in fact observes approximate binary scaling in Au+Au collisions from most-peripheral to mid-centrality. However, at about 55% and 40% centralities for the 200 and 62 GeV data respectively, a sharp transition point is observed beyond which the minijet, or same-side (relative $\varphi < \pi/2$) two-dimensional Gaussian correlation structure changes dramatically. The peak amplitude grows rapidly and the relative η width broadens by a factor of 2-3, while the φ width narrows significantly. This correlation structure becomes so large that it is estimated to include 1/3 of all produced particles in central collisions. It is also observed that the same-side peak amplitude, η width, and correlation volume at both energies scale with transverse particle density, estimated as the number of final-sate particles per unit rapidity per unit of initial collision overlap area as shown in Fig 5. Conventional centrality measures such as N_{part} generally compress the peripheral data points. This analysis technique enables unprecedented access to the dynamics of low momentum particles and provides a sensitive probe of the physics affecting the majority of particles produced in heavy ion collisions. Armed with these correlation measurements STAR can provide new information about the collision systems at RHIC, including for example the degree of thermalization in RHIC collisions.

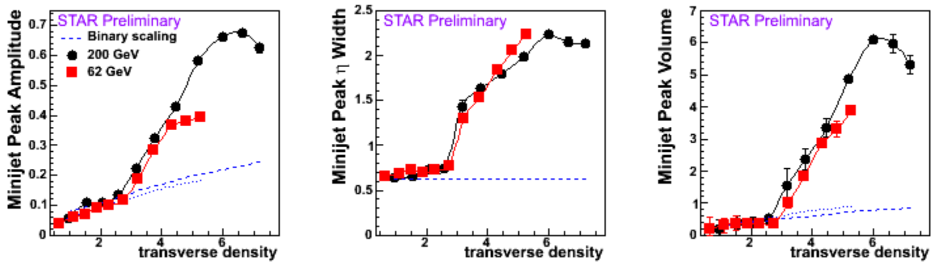

Fig.5 From left to right: amplitude, pseudorapidity width, and volume of the same-side Gaussian correlation component versus transverse particle density. Binary scaling predictions of minijet correlations in proton-proton collisions are indicated by the blue dashed curves.

6) Conclusions

From data presented by STAR at Quark Matter 2008:

1. The p_T range for J/Ψ spectrum in p+p collision has been extended to 14 GeV/c. The R_{AA} (Cu+Cu over p+p) observed for the J/Ψ suggests R_{AA} approaches unity at high p_T, contrary to models which predict significant suppression.
2. New results on e-h and e-D^0 correlations confirm e-h correlation results reported at QM06 and extend the measurement to higher p_T . These results suggest the contribution in the measured p_T range due to non-photonic electrons from bottom semi-leptonic decays is significant. This, combined with the strong suppression of non-photonic electrons observed in A+A collisions, suggests there is significant suppression of bottom at high p_T in contradiction to expectations based on pQCD inspired pictures of parton energy loss. Measurement of the D* content in jets shows ~5% of energetic gluons split to form c-cbar pairs, consistent with pQCD.
3. New results on particle identified v_2 are consistent with number of constituent quark (NCQ) scaling. The value of the v_2 over the eccentricity increases with centrality.
4. The upper limit placed on v_2 fluctuations saturates or exceeds the predicted lower limit on v_2 fluctuations predicted by several models of initial nucleon eccentricity disfavoring them in favor of other models which allow for additional fluctuations.
5. Two-dimensional correlations on relative (η , φ) for $\sqrt{s_{NN}}$ = 62 and 200 GeV Au-Au collisions exhibit a dramatic transition as a function of centrality. The transition point occurs at a common transverse particle density. The correlation structure is large and includes up to 1/3 of the particles produced in central collisions.

7) Outlook

1. STAR and RHIC are on the threshold of new era of quantitative comparison between theory and experiment that will characterize the properties of the remarkable new matter discovered at RHIC.
2. A breakthrough with stochastic cooling puts this future within reach years earlier than originally projected.

3. First steps towards this goal are beginning and entirely new analysis approaches are being developed.
4. A key part of this journey will be the search for the existence and location of a possible critical point in the phase diagram of QCD matter.

A series of upgrades is preparing the STAR detector for RHIC II and will enable:

- 10 times more data acquisition rate (DAQ1000)
- increased particle detection and tracking coverage at forward rapidity with a Forward Meson Spectrometer (FMS) and Forward GEM Tracker (FGT)
- comprehensive particle identification at mid-rapidity utilizing a Time-Of-Flight Barrel) based on multi-gap resistive plate chamber (MRPC TOF) which matches the acceptance of the STAR TPC and Barrel Electro-Magnetic Calorimeter (BEMC)
- topological PID for charm and bottom mesons and baryons utilizing inner tracking close to the beam pipe with the Heavy-Flavor Tracker (HFT) which will provide full kinematic reconstruction of secondary vertices from open heavy-flavor decays.