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New Physics at the Relativistic Heavy Ion Collider

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The Relativistic Heavy Ion Collider (RHIC) has been operating since 2000 and the Large Hadron Collider (LHC) for both proton-proton and heavy ion reactions is set to turn on in the next year. At the XXXIV SLAC Summer Institute in 2006 the focus of talks was on physics at the next energy frontier. In this talk and a second one by R. Snellings [1], we reviewed some of the discoveries made at RHIC to date and connected these discoveries to new physics expected in the future at RHIC and the LHC.

1. Introduction

If we want to study nuclear matter (i.e. partonic matter) at the very highest energy densities and temperatures, it is natural to investigate the highest energy reactions available. This new energy frontier is soon to be at the Large Hadron Collider. In fact, the highest energy densities may even be achieved in LHC proton-proton reactions, instead of lower energy heavy ion reactions. Note that heavy ions at the LHC will have a lower beam momentum due to the smaller Z/A. There is some question about whether even this is true since in proton-proton reactions much of the energy in typical collisions goes into the far forward direction, in contrast to larger stopping power in heavy ion reactions. However, the question of proton-proton reactions for high energy density matter is a good one.

Although a higher energy density may be achieved in proton-proton reactions at the LHC, the partonic re-interaction time scales are shorter due to the smaller size of the collision region (of order 1 fm). Also, it is difficult to select events with different geometries and avoid autocorrelations; a difficulty which has been overcome for collisions of larger nuclei. As we will outline in this proceedings, probes with long paths (> 5 fm) through the medium are a key diagnostic tool and this is unavailable in the smaller size system created in proton-proton reactions. However, we should not rule out proton-proton reactions as interesting to this field, but rather study the similarities and differences with nuclear reactions. Note that Bjorken speculated that “interiors of large fireballs produced in very high energy proton-proton collisions, vacuum states of strong interactions are produced with anomalous chiral order parameters”, which thus led to experiments at Fermilab such as MINIMAX looking for such states [2].

In studying heavy ion reactions at RHIC and the LHC, we are interested in the fundamental properties of nuclear matter at high temperature, often termed a Quark Gluon Plasma. What is the Quark Gluon Plasma? Lattice QCD calculations indicate a rapid increase in the number of degrees of freedom associated with the deconfinement of quarks and gluons from their hadronic chains [3]. The transition point is at a temperature $T \approx 170\ MeV$ and energy density $\epsilon \approx 1\ GeV/fm^3$ for the case of zero net baryon density, as shown in Figure 1. This transition is associated with screening of the long-range confining QCD potential and the restoration of approximate chiral symmetry.

In many calculations the QGP is treated as a free gas of nearly massless quarks and gluons. At high enough temperatures, the average momentum transfer Q^2 in thermal collisions is large enough that the strong coupling constant $\alpha_s << 1$. One then approaches the regime of asymptotic freedom and the plasma should be describable by perturbative QCD, being in the weak coupling limit. Even prior to running at RHIC, it was not clear that this was the correct descriptive regime. In fact, one may expect strong couplings with values of $\alpha_s \approx 0.5$ for temperatures of order $1.5 \times T_c$. Thus, some have recently suggested that the matter created at RHIC is “strongly coupled” and referred to as the sQGP to distinguish it from the free gas scenario (for a discussion of this topic see [4]).

It is important to note that since heavy ion physics is somewhat akin to condensed matter physics in terms of studying medium properties, measuring the energy dependence (excitation function) is very interesting. This is perhaps in contrast with new particle search experiments where pushing to the very highest energy is often (though not always) the most compelling. In the heavy ion case there may be specific interest at temperatures near phase boundaries and in matter at different locations of temperature and net baryon density.

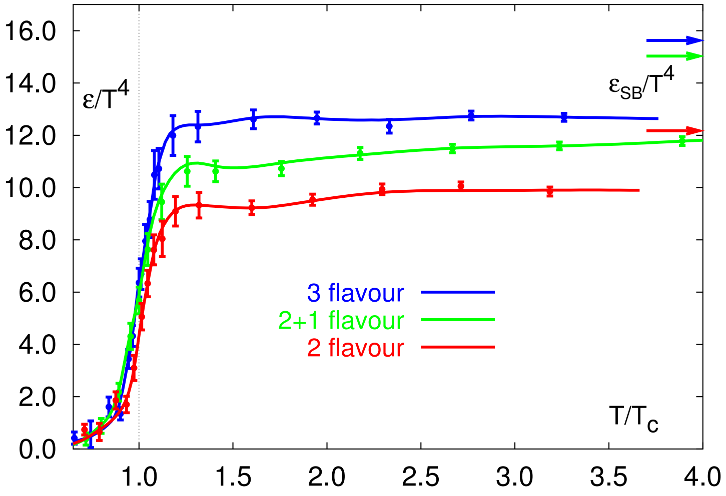

Figure 1: Lattice QCD results for $\epsilon(T)/T^4$ for two and three light flavors of quarks.

2. Early Universe

Many early expectations for observables at RHIC involved a possible first or second order phase transition. If the QGP to hadrons transition in the early universe were a first order QCD phase transition it would lead to a "surprisingly rich cosmological scenario [5]." One speculation was that "although observable consequences would not necessarily survive, it is at least conceivable that the phase transition would concentrate most of the quark excess in dense, invisible quark nuggets [5]." These objects with roughly equal numbers of up, down and strange quarks are referred to as strange quark matter or strangelets, for smaller such objects. Experimental searches in accelerator based detectors to produce the matter and terrestrial experiments to detect such matter have yielded null results to date [6]. Another speculation was that a first order transition would lead to large inhomogeneities in the early universe due to supercooling and bubble formation. This line of investigation was quite active when the dark matter puzzle raised questions about the implied baryon content of the universe from Big Bang Nucleosynthesis (BBN). However, the agreement of the implied baryon density of the universe from BBN and the WMAP cosmic microwave background anisotropy, tells us that there were no large inhomogeneities at this early time. This does not prove, but does support the idea of a QCD continuous transition or smooth cross over rather than a strong first order transition. Recent lattice QCD results for a realistic strange quark mass and net baryon density equal to zero also support this conclusion.

3. Relativistic Heavy Ion Collider Era

The Relativistic Heavy Ion Collider (RHIC) has been operational and producing physics results since 2000. The design energy and luminosity for heavy ions has been achieved and the run-by-run integrated luminosity is still on a strong, faster-than-linear increase. All four dedicated experiments BRAHMS, PHENIX, PHOBOS, and STAR have been taking data. In the laboratory, approximately 10,000 gluons, quarks and anti-quarks from the nuclear wave function are made physical in each head on (termed central) gold-gold reaction. The results are the spectacular event displays that are now on the cover of many standard undergraduate physics textbooks. Detailed summaries of the experimental results as of 2005 are given in a set of published white-papers [7–10].

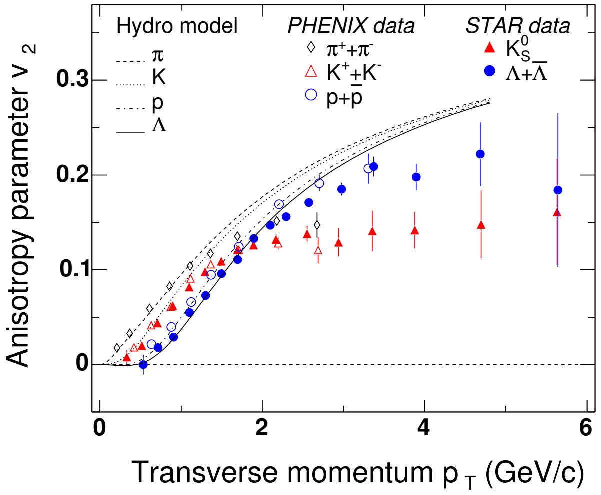

Figure 2: Azimuthal anisotropy (v_2) as a function of p_T from minimum bias gold-gold collisions. Hydrodynamic calculations are shown as dashed lines.

4. Medium Properties

Bjorken described the collision of two protons or heavy nuclei as creating a fireball. So we must first ask what is the size, energy, temperature and global feature set of such a fireball, and even if this descriptor is appropriate. In the collision of two gold nuclei at RHIC some of the initial incoming kinetic energy goes into heating up the newly created medium. Energy deposition is determined by measuring spectator nucleons, and from this the BRAHMS experiment determines that out of 39.4 TeV maximum kinetic energy being brought in for central gold-gold reactions, at least 28 ± 3 TeV is made available for heating the fireball [7]. It should be noted that in a Landau hydrodynamic scenario, this available energy may be even higher. Measurements of the transverse energy production in the collisions indicate that the energy density is well above the transition value expected from lattice QCD at early times $< 2 - 3$ fm/c [8].

How then does the fireball evolve in time after its creation? In non-central collisions, there is a large spatial anisotropy where the nuclear overlap region is "almond" shaped. The degree to which this spatial anisotropy is translated into momentum space is an excellent measure of the pressure and interaction strength among the constituents of the medium. Starting with initial conditions set by the overlap of the two nuclei, hydrodynamic calculations with zero viscosity reasonably describe the experimental data, including the transverse momentum distributions and as shown in Figure 2 the momentum anisotropy (referred to as the v_2 coefficient) [8, 10]. These calculations typically start with an assumed equilibration time of order 0.6 fm/c and an energy density at that time of 20 GeV/fm^3. The agreement of these fluid calculations and the data do not currently allow for constraining the equation of state, in particular since a simultaneous description of momentum, momentum anisotropy and two-particle correlations (HBT) is still a challenge.

A fluid with extremely low viscosity is often referred to as a near-perfect fluid. In fact, motivated by calculations in a gravity dual of a gauge theory (AdS/CFT), it has been postulated that all strongly coupled systems have a lower viscosity bound of $\eta/s < 1/4\pi$ where η is the shear viscosity and s is the entropy density [11]. These calculations are quite interesting as they make connections with string theory and black hole physics in a most puzzling way. The Maldacena duality, know also as the AdS/CFT correspondence, has opened a way to study the strong coupling limit for gauge theories using classical gravity. It is in this framework that the viscosity bound is postulated. Even traditional low temperature super-fluidity does not violate this bound since there always remains a "normal" (non super-fluid) component as shown in Figure 3. A critical goal in the field is to quantitatively determine this ratio for the QGP. As we discuss later, measurements of how heavy quarks (charm and beauty) behave in the medium may give us the best quantitative limits on the degree of "perfection."

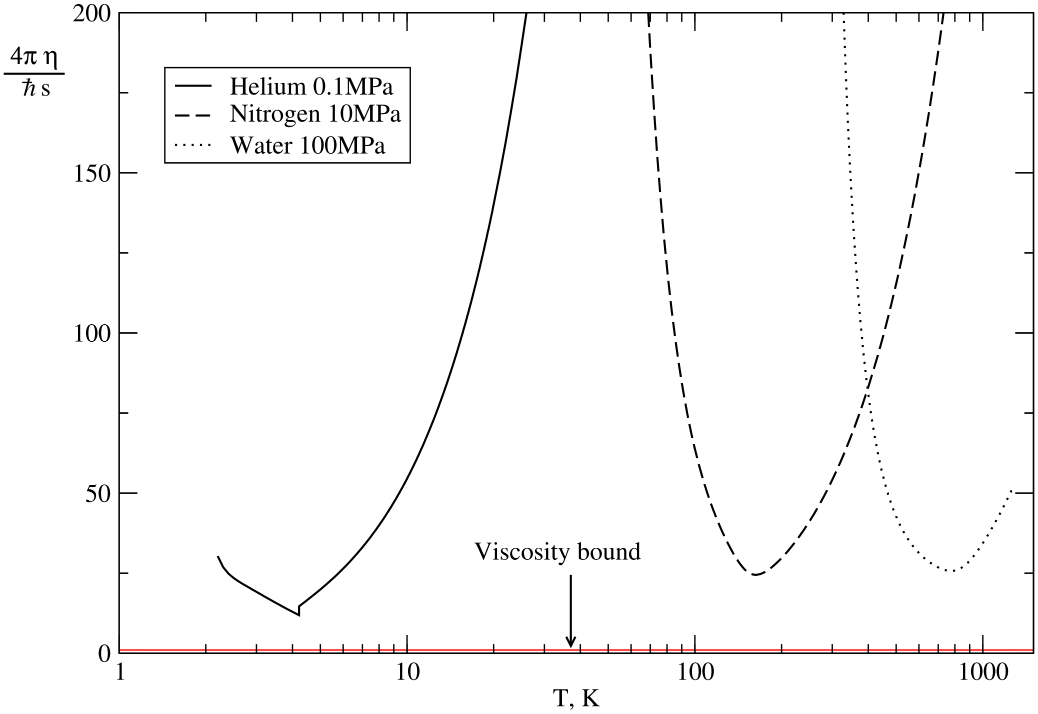

Figure 3: Plotted are the shear viscosity to entropy density ratios (η/s) divided by the conjectured low bound as a function of temperature in Kelvin. Shown are curves for helium, nitrogen and water.

If we see that macroscopically the system is quick thermalized, we can then ask what kind of microscopic interactions might lead to these very rapid equilibration times which then support such low viscosities. Hadronic transport models (RQMD, UrQMD, HSD, etc) with hadron formation times of 1 fm/c fail to describe the data [12]. They significantly under predict the amount of flow, essentially because these long formation times between hadronic interactions preclude having short enough mean free paths for such fast equilibration. Thus, the system does not appear to be a hadron gas, and perhaps this is not surprising given the energy densities achieved in RHIC collisions. Can we describe the system in terms of quarks and gluons that interact with pertubatively calculated scattering rates? Calculations (both analytic and Monte Carlo) utilizing perturbative limits of gluon-gluon interactions lead to long equilibration times > 2.6 fm/c and therefore small momentum anisotropies [13, 14]. Therefore it seems unlikely that the system is a pertrubative QGP. We note that detailed questions about $3 \rightarrow 2$ and higher processes and their contributions are still being studied. Again this should not be overly surprising given that the expected temperatures achieved are only of order $1-2\ T_c \approx 170-340$ MeV, for which α_s over a reasonable distance range is large. An interesting area of recent revival invokes the study of plasma instabilities. This involves the exponential growth of color fields due to instabilities. Color magnetic fields are often quite large and are likely to lead to such exponential growth according to early studies [15]. This may lead to very rapid isotropization. The rapid equilibration is a still a mystery, but with many exciting possible explanations.

5. Probes of the Medium

Now that we understand some global features of the medium, we want to probe it. Sometimes a high energy photon is created in the collision, and it is expected to pass through the plasma without pause since it only interacts electromagnetically giving it a very long mean free path. Sometimes we produce a hard scattered (high energy) quark or gluon. If the plasma has a large enough color charge density, we expect the quark or gluon to lose energy and be swallowed up in the medium. In fact, this is exactly what is observed as shown in Figure 4 [16]. The scaling of direct

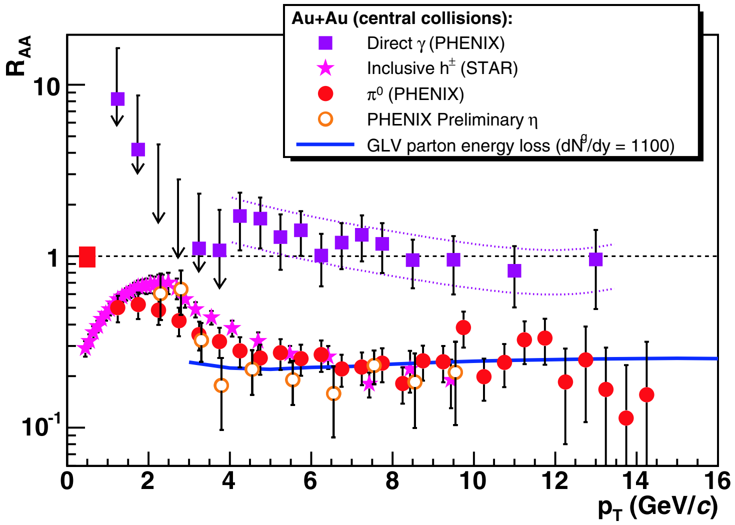

Figure 4: Nuclear modification factor R_{AA} for direct photons and hadrons in central (0-10% of $\sigma_{inel.}^{Au+Au}$) gold-gold collisions at $\sqrt{s_{NN}} = 200$ GeV.

photons shows that we have a well calibrated probe in hard scattering processes. The quarks and gluons resulting in fragmentation hadrons are suppressed by a factor of five, thus mostly disappearing into the medium except consistent with surface emission. In examining multi-particle correlations from jets, one can study this effect of “jet quenching” in more detail. As shown in Figure 5, if one triggers on a high p_T hadron and plots the $\Delta\phi$ distribution of other particles in the same event, one sees a two jet structure in proton-proton reactions (upper left panel). However, in gold-gold central collisions, the opposing jet structure seems to disappear - termed mono-jets [10]. However, if one looks at all hadrons down to low p_T one recovers the energy and momentum of the opposing parton (as one expects from their conservation), but now distributed over a very wide angular range (almost the full hemisphere) and amongst lower p_T particles [10]. As shown in the lower panel, the particle distribution appears to show a two peaked structure [17] which has led to the speculation that this energy is dumped into the medium and represents the response of the medium itself. It has been postulated that this is evidence for a shock wave in the medium, or a wake field in the color of the medium, or perhaps a Cerenkov cone if the medium has a well defined index of refraction. Three-particle and higher correlation studies are underway to help disentangle the evidence for these various proposed medium responses [22].

It is also notable that calculations utilizing AdS/CFT are now being applied to the case of parton probes of the medium. The description is quite interesting, “The external quark trails a string into the five-dimensional bulk, representing color fields sourced by the quark’s fundamental charge and interacting with the thermal medium [18].” Whether this connection yields new insights remains to be seen.

The previous mentioned jet studies are dominated by light quarks and gluons propagating through the medium. The naive assumption is that heavy quarks are too massive to quickly thermalize in medium. However, if interactions are strong enough, the prediction is for a large push of charm from high p_T to lower p_T and for a significant momentum anisotropy v_2 [19–21]. As shown in Figure 6 [17] this is what preliminary results indicate, thus providing what may prove to be the best quantitative information on the shear viscosity. Future measurements via complete D meson reconstruction will be important to pin this down [22].

Not only can we probe the medium with quarks and gluons, we can also utilize created heavy $q\overline{q}$ pairs as probes. We expect a suppression of heavy bound states due to color screening in the QGP. In fact, the experiments observe a suppression of J/ψ states in central gold-gold relative to naive expectations from proton-proton and deuteron-gold reactions[17, 23]. However, the level of suppression is similar to that observed by experiment NA50 in similar reactions [24], but almost an order of magnitude lower colliding energy. If the suppression mechanism were color

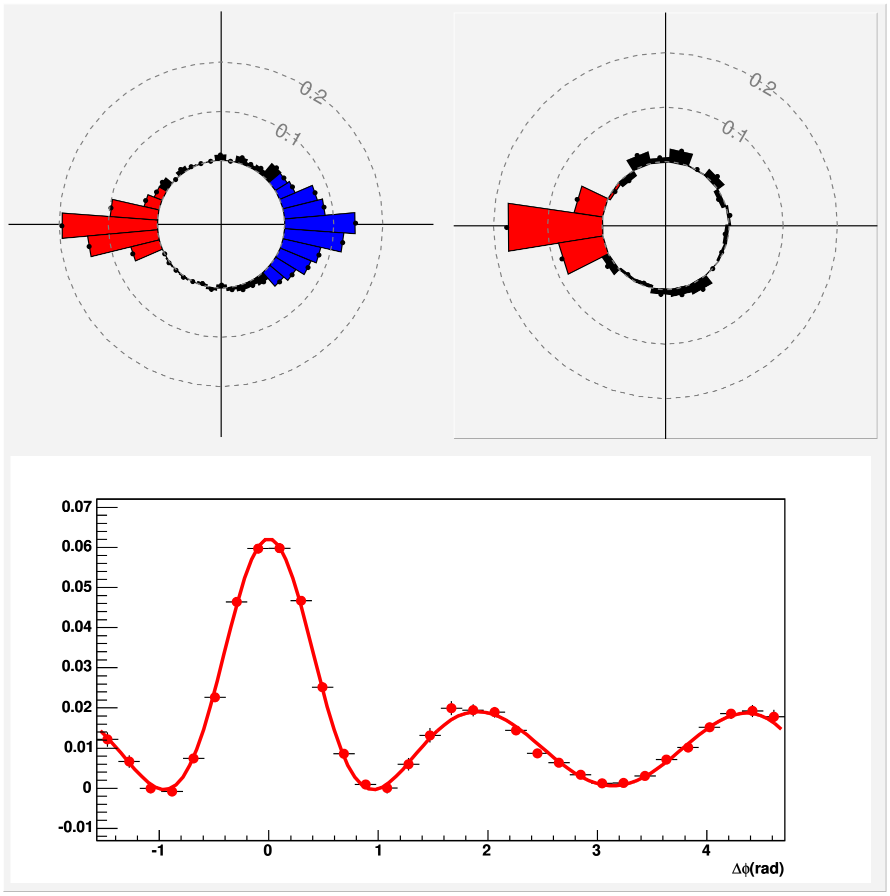

Figure 5: Upper panels results from the STAR experiment are the azimuthal distributions of unidentified hadron pairs for (left) proton-proton reactions and (right) background subtracted central gold-gold reactions. All correlation functions require a trigger particle with $4 < p_T < 6$ GeV/c and associated particles with $p_T > 2$ GeV/c. The lower panel are preliminary results from the PHENIX experiment on the azimuthal distribution in central gold-gold reactions requiring the trigger particle $2.5 < p_T < 4.0$ GeV/c and the associated particles with $2.0 < p_T < 3.0$ GeV/c.

screening or collisions with thermal gluons, the suppression would be significantly greater at RHIC energies. A possible resolution of this puzzle may come from recent lattice QCD results. Some calculations indicate that J/ψ spectral functions persist well above T_c. However, these calculations in the quenched approximation do not appear consistent with conclusions from potential functions derived from the lattice. Thus it is possible the J/ψ largely survive even at RHIC and the observed suppression mechanism is of a different origin or related to decay feed-down from χ_c, ψ' states. It is also possible that at RHIC where 10-20 $c\bar{c}$ pairs are produced in a single central gold-gold reaction, charm recombination may create new J/ψ. These random combination c and $\bar{c}$ coalescence cases should have different kinematics and thus p_T and rapidity distribution measurements of the J/ψ will help confirm or refute this picture.

6. Conclusions

We have successfully created matter at RHIC that is thus far best described as a Quark Gluon Plasma. To be clear, there is no “smoking gun” signature of deconfined quarks and gluons to date but rather a large set of observables that are together allowing us to understand the space-time evolution of the fireball starting from a very high energy density above the transition value. Note that in this proceedings we have only touched on some of the discoveries

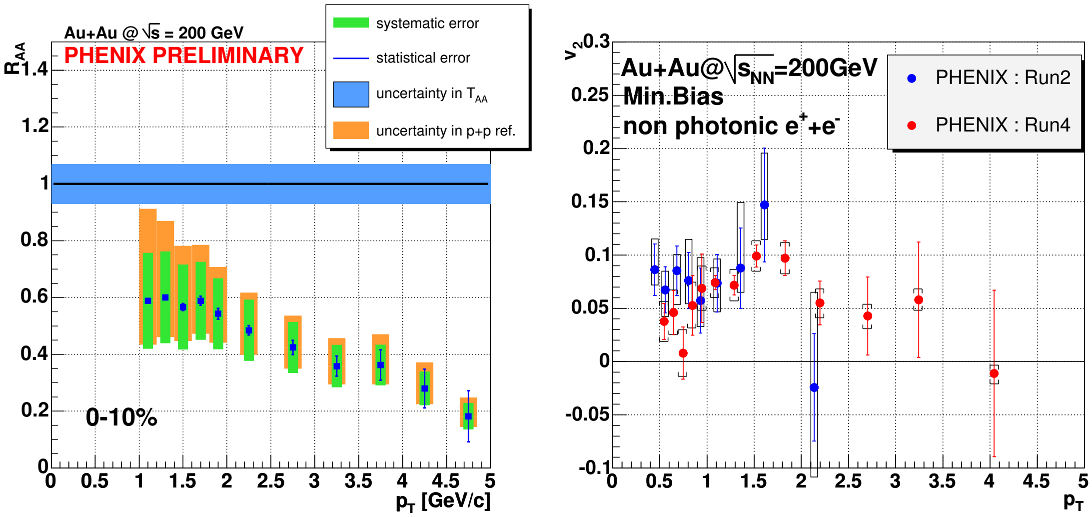

Figure 6: PHENIX Preliminary central 0-10% $Au + Au$ $\sqrt{s_{NN}}$=200 GeV suppression factor R_{AA} for non-photonic electrons (left). PHENIX Run-2 published and Run-4 preliminary v_2 for non-photonic electrons as measured in minimum bias $Au + Au$ 200 GeV reactions (right).

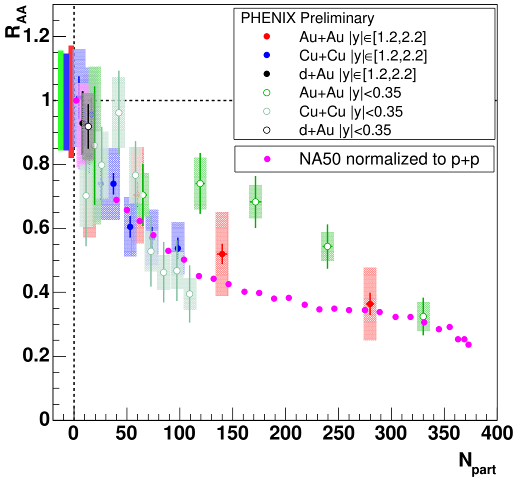

Figure 7: PHENIX preliminary results on J/ψ nuclear modification factor R_{AA} as a function of the number of nuclear participants. Results are shown from gold-gold, copper-copper, and deuteron-gold reactions at forward and mid-rapidity. Also shown are results from the NA50 experiment from lower energy at the CERN-SPS.

at RHIC, and there are abundant additional areas of exploration including anomolous (anti)baryon production, two particle correlations, multi-particle fluctuations, and others. We now have many exciting properties of the matter to understand including the low viscosity, rapid equilibration, novel hadron formation mechanisms, jet quenching and medium reaction, temperature determination, and degrees of freedom. Further exploration and quantification of these properties at RHIC is a future goal coupled with extending these measurements to the new energy frontier at the LHC with the ALICE, ATLAS, and CMS experimental heavy ion programs.

Acknowledgments

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