Search for the Quark Gluon Plasma: A Status Report

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Abstract. This document is the proceedings from an overview talk on the search for the Quark Gluon Plasma (QGP) given at the Particles and Nuclei International Conference (PANIC) in Santa Fe, New Mexico in October 2005. After five years of successful data taking at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory, there is much to report in this field of physics. In this short review, we present a bulleted list of experimental discoveries and conclusions to date on the matter formed in these highest energy nuclear reactions.

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INTRODUCTION

What is the Quark Gluon Plasma? Lattice QCD reveals a rapid increase in the number of degrees of freedom associated with the deconfinement of quarks and gluons from the hadronic chains [1]. The transition point is at a temperature $T \approx 170\ MeV$ and energy density $\varepsilon \approx 1\ GeV/fm^3$ 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.

Is the QGP 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 $1.5 \times T_c$.

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 [2]. The agreement of the implied baryon density of the universe from Big Bang Nucleosynthesis (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 supports 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 also support this conclusion.

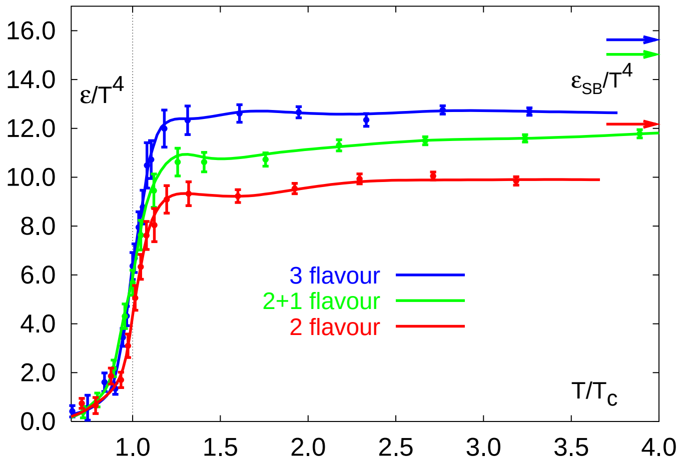

FIGURE 1. Lattice QCD results for $\varepsilon(T)/T^4$ for two and three light flavors of quarks.

RELATIVISTIC HEAVY ION COLLIDER ERA

The Relativistic Heavy Ion Collider (RHIC) was completed in 1999 and had first physics running in the year 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. The polarized proton spin program at RHIC is also now underway with first significant double asymmetry results with implications for gluon polarization shown at this conference [3]. 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 [4, 5, 6, 7].

Global Features of the Medium

When the two gold nuclei collide we want to determine how much of their 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 [4]. It should be noted that in a Landau hydrodynamic scenario, this available energy may be even higher. Additionally 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 [5].

How does the matter behave? In non-central collisions, there is a large spatial anisotropy where the nuclear overlap region is “almond” shaped. The degree to which

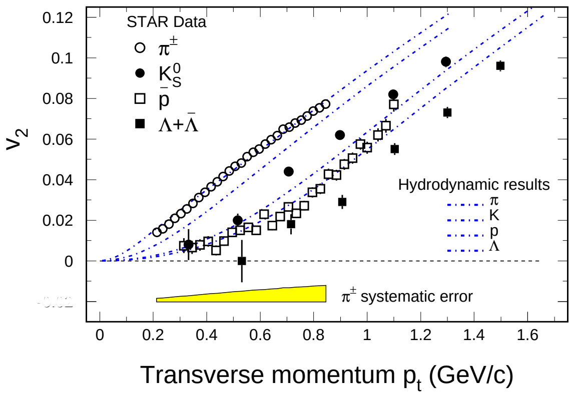

FIGURE 2. Azimuthal anisotropy (v_2) as a function of p_T from minimum bias gold-gold collisions [7]. Hydrodynamic calculations are shown as dashed lines.

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). 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 [8]. Even traditional low temperature super-fluidity does not violate this bound since there always remains a "normal" (non super-fluid) component. A critical goal in the field is to quantitatively determine this ratio for the QGP.

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 [9]. 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. This is perhaps 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

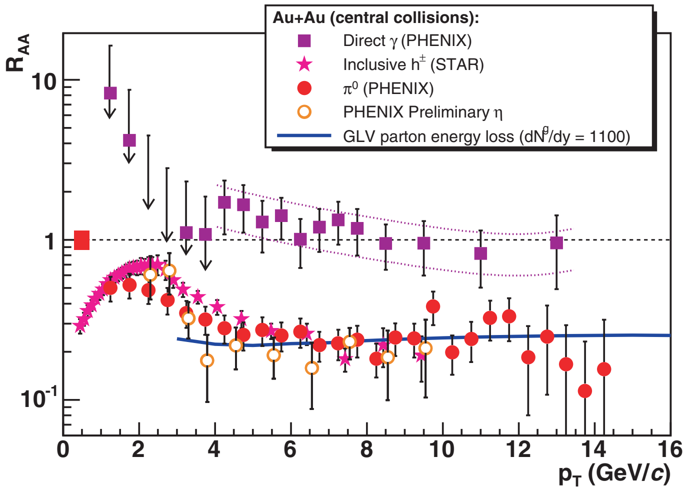

FIGURE 3. Nuclear modification factor R_{AA} for direct photons and hadrons in central (0-10% of $\sigma^{Au+Au}_{inel.}$) gold-gold collisions at $\sqrt{s_{NN}} = 200$ GeV [13].

> 2.6 fm/c and therefore small momentum anisotropies [10, 11] It seems unlikely that the system is a pertrubative QGP. We note that detailed questions about $3 \to 2$ 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 involves 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 [12]. This may lead to very rapid isotropization. Thus, the rapid equilibration is a still a mystery, but with many exciting possible explanations.

Another interesting experimental observation is that even the more massive hadrons exhibit a very similar flow pattern - including the ϕ, Ξ, Ω [7]. These hadrons have reduced inelastic cross sections due to OZI rules and the lack of $\pi - \Omega$ resonances. This has led to the speculation that they acquire their flow at an earlier stage with pre-hadronic degrees of freedom.

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. We expect it to pass through the plasma without pause since it only interacts electromagnetically giving it a very long mean free path. Sometimes we produce a 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 3 [13]. The scaling of direct 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 4, 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 [7]. 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 [7]. As shown in the lower panel, the particle distribution appears to show a two peaked structure [14] 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 [18].

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 [15, 16, 17]. As shown in Figure 5 [14] 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 [18].

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[14, 19]. However, the level of suppression is similar to that observed by experiment NA50 in similar reactions [20], but almost an order of magnitude lower colliding energy. If the suppression mechanism were color 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 $c\overline{c}$ pairs are produced in a single central gold-gold reaction, charm recombination may create new J/ψ. These random combination c and $\overline{c}$ 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.

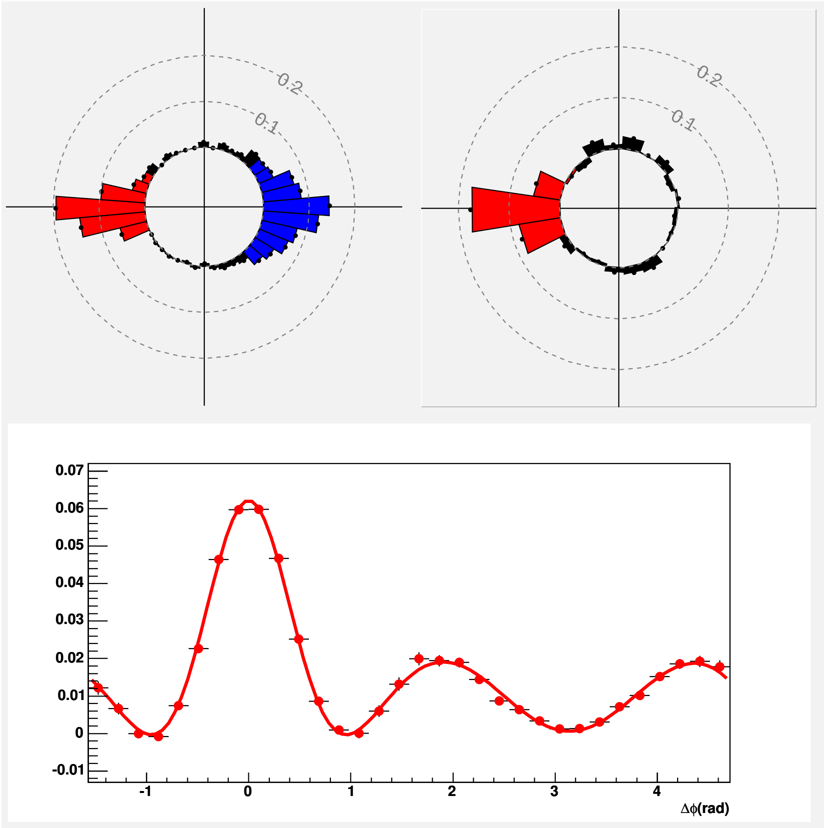

FIGURE 4. Upper panels results from the STAR experiment are the azimuthal distributions of unidentified hadron pairs for (left) proton-proton reactions and (right) background subtracted central gold-gold reactions. All correlation functions require a trigger particle with $4 < p_T < 6$ GeV/c and associated 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.

Radiation

One of the most promising, but difficult, tools for studying the QGP is the measurement of thermal radiation. Traditionally one measures the inclusive yield of photons, then subtracts off the large contributions from decays of $\pi^0, \eta,$ etc. resulting in significant systematic errors at low p_T where the thermal radiation from parton scattering has potentially measurable contributions. A new method for heavy ion reactions of measuring virtual photons ($\gamma \rightarrow e^+e^-$) allows one to subtract away the decay contributions by studying the shape of the invariant mass distribution of the lepton pair. First, preliminary results show an indication of a direct photon yield at low $p_T \approx 1-3$ GeV [14], and in excess of the contribution from NLO pQCD initial hard scattering processes. Experimentalists and theorists are working toward a quantitative extraction and the exciting possibility of a temperature measurement. An alternative method of $\gamma\gamma$ HBT is also being explored [7].

The NA60 experiment at the lower energy fixed target CERN-SPS has recently made

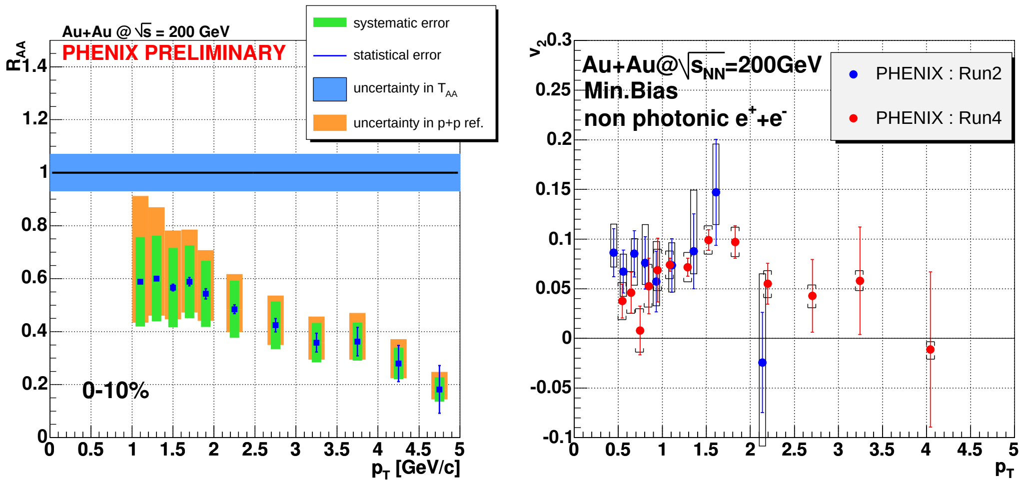

FIGURE 5. PHENIX Preliminary central 0-10% $Au+Au$ $\sqrt{s_{NN}}$=200 GeV suppression factor R_{AA} for non-photonic electrons (left). PHENIX Run-2 published and Run-4 preliminary v_2 for non-photonic electrons as measured in minimum bias $Au+Au$ 200 GeV reactions (right).

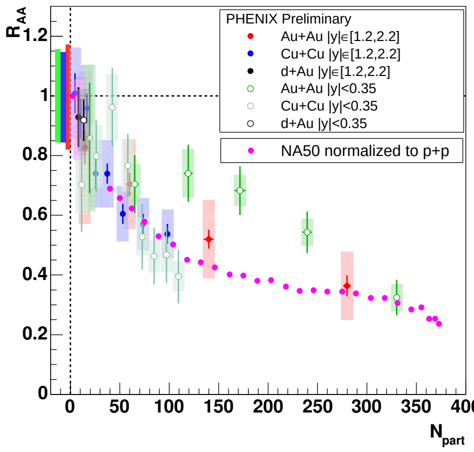

FIGURE 6. PHENIX preliminary results on J/ψ nuclear modification factor R_{AA} as a function of the number of nuclear participants [19]. Results are shown from gold-gold, copper-copper, and deuteron-gold reactions at forward and mid-rapidity. Also shown are results from the NA50 experiment from lower energy at the CERN-SPS [20].

a key measurement of low mass dileptons with very high statistics [21]. These dileptons probe the interactions in the medium at the hot dense early stages. They see indications for significant modification of the ρ spectral functions. This is a key future measurement to be made by the RHIC experiments as well.

CONCLUSIONS

We have successfully created matter at RHIC that is thus far best described as a Quark Gluon Plasma. 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.

In the midst of this exciting progress, significant cuts in basic research in the Department of Energy Office of Science are being proposed and implemented. It is hard for me to imagine a world where we stop asking the big questions or stop trying to answer them. We need to fight for our future. We note that since the PANIC conference a generous private donation of over $10M$ dollars has made operations of RHIC in the next fiscal year possible!

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