Future Measurements at RHIC

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Abstract

I review the present status of measurements at RHIC and suggest possible upgrades which will be necessary to answer some of the most critical questions in Relativistic Heavy Ion Physics.

1 Introduction

The Relativistic Heavy Ion Collider was completed in 1999 and a host of new experimental results soon appeared. During the past year, the nuclear physics community has undertaken the task of formulating a long range plan to guide funding priorities for the next 10 years. What follows is my view of the future. I have chosen to be rather speculative at times. I will first review what we have learned so far, then pose the questions formulated in the Long Range Plan (LRP), and use these to guide a discussion of the future measurements which should be made.

In addition to the many recent experimental results, theory has been making rapid progress in explaining the phenomena we are seeing at RHIC. This is possible for two reasons. First, powerful theoretical techniques, have been brought to bear on the problem. These are reviewed elsewhere in these proceedings by A. Dimitru[1]. Secondly, RHIC has taken us into a regime in which these theoretical techniques are applicable. It is the convergence of theory and experiment which leads to new understanding. The collection of experimental data alone makes us simple accountants of miscellaneous facts. On the other hand a non-verifiable theory may be elegant, but will not give us an understanding of the world in which we live. I would like to suggest that a sort of standard model is just beginning to emerge in our understanding of the evolution of relativistic heavy ion collisions in the regime we have entered. This picture is not entirely new. The general picture of the phase diagram of QCD has been around for many years. What is new, is that RHIC, now takes us into a regime in which theoretical techniques can now be used to do reasonably reliable calculations, using the model, of experimentally measurable quantities. As such we are beginning to enter into an era of precision measurements in which theoretical predictions of a fundamental nature can be made, and experiments can be done under controlled conditions so that these ideas can be tested.

To do many of these measurements, RHIC will need an increase in luminosity. What is being proposed by the community is an increase by a factor of 40 by the use of electron cooling. In addition, experiments will need to be upgraded, to enhance capabilities and increase sensitivity for rare or hard to measure probes, and to increase the ability of detectors to handle a higher data rate through the use of higher level triggers and expanded DAQ. The details of this will be covered in the next talk by T. Ludlam[2].
2 What Have We Learned?

I will first summarize some of the results from RHIC as they stand now. Much of this material is covered in more depth in separate contributions to this volume. Unless specified, the data is from the first run where the center-of-mass energy was 130 GeV. A small amount of data is now available from run-2 where the center of mass energy was at the canonical value of 200 GeV. Needless to say, the various RHIC collaboration are working hard to produce the results from this latest run.

2.1 Initial Conditions: Energy Density and the Colored Glass Condensate

The first task is to make an experimental estimate of the initial energy density of the system formed in collisions at RHIC to see whether it is high enough to induce a phase transition. Lattice calculations indicate that the phase transition should occur between 150 and 200 MeV corresponding to energy densities between 0.6 and 1.8 GeV/fm$^3$ with the lower estimate being favored by models which include light fermions. Bjorken has given an estimate of the energy density assuming boost invariance:

$$\epsilon = \frac{E}{Volume} = \frac{1}{\pi R^2} \frac{1}{2c\tau_0} \left(\frac{2dE_T}{dy}\right)$$

where $R$ is the radius of the nucleus in question, and $\tau_0$ is the time after the initial collision of thermalization when a temperature can first be defined, typically taken to be between 0.2 and 1 fm/c. As theory has improved it has been recognized that there are at least two relevant time scales for $\tau_0$. The first, as described below is a formation time related to the Colored Glass Condensate. The second, is the actual thermalization time. The PHENIX collaboration has measured $dE_T/dy \sim dE_T/d\eta = 503 \pm 2$ GeV, giving an energy density times thermalization time to be $\epsilon \cdot \tau_0 = 4.6 (GeV/fm^3)(fm/c)$. Conservative estimates give $\tau_0 \sim 1 fm$, whereas estimates from the equilibration of gluons give $\tau_0 \sim 0.2 - 0.3 fm$. This gives an energy density estimate of between 5 and 23 GeV/fm$^3$, an order of magnitude greater than that required for the phase transition as predicted on the lattice.

Recently, McLerran and his colleagues have proposed that the initial conditions in heavy ion conditions could be calculated assuming that the gluon distributions at low $x$ are saturated. The gluon distributions at low-$x$ for protons $\sim 1/x^5$, hence violate unitarity at very low $x$ and saturate. In protons it will occur at about $x \sim 10^{-4}$ depending on the $Q^2$. In a Lorentz contracted nucleus, there is essentially a geometric magnification factor of $A^{1/3}$ making the relevant $x \sim 10^{-2}$. McLerran and his colleagues assumed that since the occupation numbers were high, one could use a classical approximation. This leads to non-perturbative calculations of various experimentally measured quantities, using renormalization group methods which depend on a scale $Q_s$, the saturation momentum given by $Q_s = \alpha_s \frac{2G_A(x,Q^2)}{\pi R^2}$. At RHIC, this is around 1-2 GeV/c. They have dubbed this state, a Colored-Glass-Condensate for reasons I will not explain here.

One of the first calculations to be done using these methods was for the multiplicity distributions as a function of centrality at $\sqrt{s} = 130$ GeV (figure 1a). Admittedly this was a post-diction after the data was available. However, Kharzeev and Levin then predicted...
Figure 1: (a) $dN/d\eta$ distributions as measured by the PHOBOS collaboration and compared with the model of Kharzeev and Nardi for $\sqrt{s}=130$ GeV (b) Theoretical prediction by Kharzeev and Levin for $\sqrt{s}=200$ GeV, where the inset shows the most-central bin as compared with the PHOBOS measurement.

the centrality dependence at the higher energy of $\sqrt{s}=200$ GeV. The prediction, shown in the right panel of the figure does extremely well for the recently published central data from the PHOBOS collaboration. It will be important to observe whether the centrality dependence at the higher energy is borne out. The model gives us an initial energy density of 18 GeV/fm$^3$ in good agreement with the estimate above. This corresponds to a formation time of $\tau_0 \sim \tau_{formation} \sim 1/Q_s \sim 0.1 - 0.2 \text{fm/c}$. Presumably equilibration happens somewhat later. This time corresponds to the time in which the gluons “go on mass shell”, hence this energy density refers not to a thermalized energy density, but rather the maximum energy density reached by the system. Kharzeev, Levin, and Nardi have also made a prediction at $\sqrt{s} = 22$ GeV, but they point out that the model may not work since $\alpha_s$ becomes large. Their central prediction at this energy is that the number of charged particles per participant at mid-rapidity rises slowly by about 20% for central collisions due to the running of the coupling constant $\alpha_s$.

It is worth examining the source of the centrality dependence of the multiplicity in the CGC model. In this model the number of gluons per participant is proportional to the inverse of the strong coupling constant hence, somewhat schematically, $N_{ch} \sim N_{gluons} \sim 1/\alpha_s(Q_s^2)$. The value of $Q_s^2$ rises as a function of centrality since the quantity of interest is the number of gluons per unit area in the target nucleus as seen by a particular projectile. The more the number of gluons, the higher the saturation scale. This is shown in figure 2.
where \( Q_s \) is plotted versus \( N_{\text{part}} \). The corresponding value of \( 1/\alpha_s(Q_s^2) \) is also plotted and compared to the multiplicity per participant as measured by the PHOBOS collaboration. The shapes of the distributions are similar since \( dN/d\eta \) calculated in the CGC model is proportional to \( 1/\alpha_s(Q_s^2) \). This gives rise to the agreement between the theory and the data shown in figure 2a. This result connects the centrality dependence of the multiplicity per participant to the running of the coupling constant. If \( \alpha_s \) did not run, there would be no centrality dependence. It is interesting that a bulk property such as the total multiplicity is intimately connected with a fundamental property of QCD - the running of the coupling constant. The calculation relies on the fact that the number of produced particles is essentially equal to the number of gluons liberated in the initial collision, which in turn is equal (actually a factor of \( 2\ln 2 \approx 1.34 \)) to the number of gluons in the initial virtual saturated state. This then implies that the number of particles may be conserved through the parton to hadron transition - a miraculous fact noted in reference [5]. One can speculate why this is so. An understanding of this may lead to insights into the chiral and deconfinement phase transitions, since the process of partons turning into hadrons includes the generation of the dressed masses of the quarks which comprise hadrons and the confinement of quarks into hadrons. Such a conservation may not hold for other quantities such as the momentum distributions of the final state particles which may be influenced by later stages of the system.

The Colored Glass Condensate model nicely explains one of the seemingly disappointing early results from RHIC. The charged particle multiplicity was found to be lower than naive expectations which sprung from entropy arguments invoking the fact there would be more degrees of freedom in a system of quarks and gluons than in a system of hadrons. In the CGC scenario, the production of entropy is simply choked off by the saturation.

Early results from both the STAR and PHOBOS collaborations indicated that there was a surprisingly strong elliptic flow in non-central collisions (see figure 3). Elliptic flow is an anisotropy which exhibits itself in the momentum distribution of the produced particles. This anisotropy in momentum reflects a space anisotropy of the original, almond shaped collision region. For the space anisotropy to be transferred to the momentum, the system must equilibrated. Since flow is a collective effect, and each particle’s direction is defined by the spacial distribution of all the particles, each particle must “know” the shape of the original distribution. The effect is self quenching. If the time for equilibration is too long, the collision region looses its almond shape, hence the momentum distribution looses its anisotropy. A strong elliptic flow, therefore, implies an early thermalization. The details of this argument were developed in a more rigorous fashion by U. Heintz and his colleagues [8]. One can see in figure 3a, that in mid-central collisions, the data gives a value that is consistent with hydrodynamics which of course assumes thermalization with a zero mean free path. This hydrodynamical model requires a thermalization time of 0.6 fm/c giving an energy density of 20 GeV/fm\(^3\), again consistent with the previous estimate.

It seems fairly certain, then that the initial state formed in Au-Au collisions at RHIC is a strongly interacting system at very high energy density. We can begin to assemble a model (figure 4) of RHIC collisions beginning as a Colored Glass Condensate - essentially a saturated condensate of gluons. This is a virtual state since it is presumably there in all nuclei. What is important in collisions at RHIC, is that the colliding system provides a mechanism for the virtual gluons to become “real” in a formation time which is of order...
0.1-0.2 fm/c. These “real” gluons, then form the initial state which is of interest to us. At this point they are not equilibrated - they have just come into existence at the beginning of the second stage.

The mechanism and timescale of thermalization is probably the most critical question to answer in the short term. If thermalization of gluons occurs then we have the inevitable conclusion that we have created a Quark-Gluon Plasma. The Parton Cascade Model[10] showed the importance of radiative processes in equilibration. Recently, Mueller and his colleagues[13] have shown this by analytical techniques as well. They give an estimate for the equilibration time as $1/Q_s$ multiplied by some power of $\alpha_s$. The Monte-Carlo implementation of the Parton Cascade Model gives an equilibration time of $\sim 0.3$ fm/c, for a total formation time plus thermalization time of about $0.5 -0.6$ fm/c. This is consistent with the value found from the elliptic flow results and hydrodynamic models of 0.6 fm/c, however this agreement should probably not be taken too seriously until more reliable estimates for the thermalization time can be made.

We are left then, at a time of about 0.6 fm/c with a plasma of primarily gluons. Presumably quarks begin to appear as the chemical reactions continue. One of the interesting characteristics of this state is that value of the quark condensate $<q\bar{q}>$ is zero and chiral
Figure 3: (a) The event anisotropy $v_2$ as a function of centrality measured by the total number of charged particles; $n_{ch}/n_{max} \sim 1$ is central. $v_2$ is a measure of the strength of the elliptic flow. (b) $v_2$ as measured as a function of $\sqrt{s}$, showing the large increase from SPS to RHIC.

symmetry is restored. The question of how the condensate actually develops is an interesting one which we know very little about. The equilibrated system, which we can now characterize as a QGP expands and generates flow as it cools. The system proceeds through a mixed phase as it begins to hadronize. This is arguably the most interesting time in the history of the collision - the third and fourth stages in figure 4.

At this point we are faced with host of questions. Is the transition first or second order, or simply a cross over? We do not know the relationship between the deconfinement transition, responsible for the binding of quarks into hadrons, and the chiral transition, responsible for the generation of hadronic mass. Are the transitions at the same value of the temperature? What is the latent heat? Is there an inflation related to the phase transition as is presumably true in the early universe? Are there large scale fluctuations? Answering these questions are the primary goals for the present and future program at RHIC.

2.2 Hadrons-the Later Stages of the Collision

The system continues to cool and expand in the hadronic phase until eventually all the interactions cease and the particles freeze-out. It is these hadrons which we can actually detect. They should reflect the state of the system at hadronic freeze-out. RHIC has made impressive progress in the measurements of these hadronic observables. More complete descriptions are elsewhere in these proceedings. I will only give a brief overview.

Figure 5 shows the plethora of particle ratios that have already been measured. These
Figure 4: A schematic time history of the energy density in RHIC Au-Au collisions. In the first stage the nuclei collide and the low-x virtual gluons become “real”. Thermalization occurs in the second stage and leads to the third stage which is presumably the thermalized Quark-Gluon Plasma. During this stage the system undergoes 3-dimensional expansion and flow can start to develop. This fourth stage is the mixed phase where hadronization occurs. Particles freeze-out soon thereafter at about $\tau \sim 10\text{fm}/c$.

Values are compared to a model assuming chemical equilibrium with three parameters: the freeze-out temperature $T$, the baryo-chemical potential $\mu_B$, and a strangeness saturation parameter, $\gamma_s$. First, one observes that the model works reasonably well and unlike at the SPS, strangeness is saturated, i.e. $\gamma_s = 1$. The fit gives a temperature of 190 MeV and a baryo-chemical potential of 0.04 at chemical freeze-out. This is consistent with a near baryon free system - a fact which can be deduced from the value of $\overline{p}/p$ of 0.6 measured by several of the RHIC collaborations.

We can look at thermal equilibrium as well. Figure 6a shows a fit to the inverse slopes, for central collisions in a model assuming a single freeze-out temperature and radial flow for a variety of center of mass energies from GSI to RHIC. One observes that the temperature appears to saturate at a value of about 130 MeV at the AGS and remains the same at the SPS and RHIC. At RHIC however, the value of $\beta_r \sim 0.5$ is noticeably larger. (I note that
Figure 5: (a) Ratios of various particle yields measured at RHIC as compared to the values in the model assuming chemical equilibration, using a single freeze-out temperature $T$, the baryo-chemical potential $\mu_B$, and a strangeness saturation parameter $\gamma$. The best fit is to $\gamma_s \sim 1$. (b) Freeze-Out values of systems measured at various collision energies on a phase diagram.

the error bars for $\beta_r$ and $T_{th}$ are correlated. If one held $T_{th}$ constant the errors on the flow velocities would be considerably smaller. This can be seen by simply examining the original inverse slopes.) It appears that at RHIC we are observing an increasing radial expansion. A intriguing speculation is that this expansion might be the result of “inflation” caused by the chiral phase transition, similar to that which caused the inflationary phase of the early universe.

One of the questions that one might ask is whether this rapid radial expansion develops in the early gluon phase of the system, during a mixed phase, or later during the hadronic phase before freeze-out. Figure 6b, shows the actual inverse slopes measured for a variety of particles as a function of the mass. The strange-baryons show a tendency to be below the line corresponding to a particular temperature and radial flow velocity. This might indicate that these particles were freezing out somewhat earlier then their lighter counterparts at a time when the flow had not had time to develop fully. A similar trend was seen at the SPS. This interpretation would imply that at least some part of the radial flow developed during a hadronic stage.
2.3 Penetrating Probes

Let us return to the early stages of the collision. Are there probes which can provide information about the state of the system and substantiate the ideas outlined earlier, that is to study the state which may be the QGP? Of course the answer is yes - these are the penetrating probes - leptons, photons, and most notably high $p_T$ particles-presumably the leading particles of jets.

Perhaps the most striking result from the recent data at RHIC comes from the observed suppression of high $p_T$ particles, particularly $\pi^0$'s from the PHENIX collaboration. X.N. Wang and others have pointed out that high $p_T$ jets could be used as probes of the early stages of heavy ion collisions[11]. High $p_T$ partons are the result of hard collisions which happen very early in the collision. Hence as they traverse the fireball, their characteristics can give us information about the system from the earliest times. In particular, the energy loss of these partons should be much greater in a system of deconfined quarks and gluons, since they are directly exposed to the color charges of the medium. Because the jets resulting from these high $p_T$ partons are difficult to isolate from the soft background, it was suggested that leading particles could be used since they typically take about half the energy of the jet. Early calculations simply assumed a constant energy loss per unit length. More detailed QCD calculations[15] indicate the energy loss actually depends on the total path length of
the parton through the fireball. This rather non-intuitive fact is a result of interference effects between the soft gluons radiated from the parton as it looses energy. The energy loss in a QGP can be extremely high - greater than 10 GeV/fm at the highest energy densities presumed to be created in these collisions. However, since the system expands and the lifetime of the high density stage is rather short, the average energy loss of a parton is considerably less.

Before looking at the data, it is worth briefly describing the assumptions used to scale pp collisions to Au-Au collisions. There are two basic scaling methods. The first, and most familiar to heavy ion physicists is scaling with $N_{\text{part}}$, appropriate for are thermal distributions coming from soft processes. Momentum distributions are usually plotted as a function of the transverse mass, $m_T$, a practice coming from the fact that all particles regardless of mass could be described as a universal exponential in $m_T$ for lower energy pp collisions. In heavy ion collisions exponentials tended to describe the shape of the spectra, however the slopes diverge with the heavier particles having larger inverse slopes. This was attributed to the effect of hydrodynamic flow tending to give a higher transverse momentum to heavier particles. These processes reflect the bulk nature of heavy ion collisions. Much of the data from the AGS and SPS scale as a function of the number of participants, $N_{\text{part}}$, which in a central Au-Au collision is $2^9197. A \text{ notable exception to this was the production of strange particles which scaled faster than this, and has been attributed to the enhancement of strangeness in heavy ion collisions. The second scaling method is more appropriate for hard processes - i.e. jet production, and is of course more familiar to those working at high energies. Here spectra can be described as a power law $p_T$. There are no collective effects since one assumes that there is essentially one hard interaction. Particles originate from jet fragmentation. Here the scaling to heavy ion cross sections from pp goes as the number of binary collisions - i.e as the number of hard collisions. A central Au-Au collision has about 1000 binary collisions. Analysis of multiplicity distributions provide evidence for a part of the cross section scaling as the number of binary collisions."

Figure 7 shows the $\pi^0$ $p_T$ distribution together with the expected value from the scaling of the pp cross section with the number of binary collisions for both peripheral collisions and central collisions. As one can see, the the scaling works well for peripheral collisions. In the central collisions, however, the data is over-predicted. Charged particles show a similar behavior, with some complications, as I will describe in a moment. The effect can be highlighted by dividing the data by the scaled pp distribution as in the right panel, shown now both for $\pi^0$s and charged particles. In both cases the result is considerably below one. Also shown is the range of results compiled from data at the SPS. The data from the SPS below $\sim 1.5\text{GeV}$ also lies below one, since the production mechanism for these lower energy particles scales as $N_{\text{part}}$. These are the vast majority of particles. We are concerned with the small number of high $p_T$ particles above $\sim 2\text{GeV}$. (The exact value of “high” $p_T$ is open to question). At the SPS what we see is an enhancement of high $p_T$ particles coming from quark scattering - the well known “Cronin” effect. What is seen at RHIC is quite the opposite. There is a strong suppression above 1.5 GeV for both the charged and neutral particles. Such a suppression may be the first indication of a large energy loss in a QGP.

One may then inquire as to the difference between the charged and neutral spectra. Figure 8 shows the charged spectra for minimum bias events from PHENIX, now using particle ID to the extent possible. One can immediately see the problem. At momenta
above 2 GeV, protons and anti-protons dominate the spectra! How can this happen? This certainly is not characteristic of the distributions of leading particles in jets, where only 10% is a baryon\[17\]. It may be that collective effects such as radial flow are actually pushing the baryons to a higher $p_T$ and we are comparing particles which come from different sources - i.e. jet fragmentation after energy loss for the pions, and low energy protons and anti-protons which have been accelerated due to radial flow effects. At the same time the high $p_T$ partons themselves lose energy and their daughter pions will have a more thermal spectrum then would be characteristic of jet fragmentation. One of the unanticipated implications for the future, is that particle identification at high $p_T$ will be critical to the upgrades considered at RHIC.

Data on leptons and photons will be forthcoming. Already PHENIX has published the first results of electron production giving limits on open charm. This is of particular interest because of the enhancement of intermediate mass dileptons at CERN. However, since charmed quarks themselves pass through the medium just as any other quark, they should loose energy as well and be suppressed; though this effect could be minimized due to a "dead cone" effect\[14\]. Within the next year we should begin to see results on $J/\psi$ production in both the electron and muon channels, low mass vector mesons to the di-electron channel, and perhaps thermal dileptons and direct photons.
3 What Would We Like to Know and what Should We Measure?

If the view espoused here of the high $p_T$ spectra prevails, it will provide vindication of the model described previously and lead to more conclusive results regarding the possible formation of a Quark Gluon Plasma. Perhaps, as I have indicated, it raises more questions than it answers. As a part of the task of putting together the Long Range Plan for Nuclear Physics several meetings were held to consider the future of of the RHIC program. In doing so, the following four major questions were formulated.

- **Evolution of the System:** In relativistic heavy-ion collisions, how do the created systems evolve? Does the matter approach thermal equilibrium? What are the initial temperatures achieved?

- **Deconfinement:** Can signatures of the deconfinement phase transition be located as the hot matter produced in relativistic heavy-ion collisions cools? What is the origin of confinement?

- **Chiral Symmetry Restoration:** What are the properties of the QCD vacuum and what are its connections to the masses of the hadrons? What is the origin of chiral symmetry
breaking?

- **Matter at the Highest Energy Densities**: What are the properties of matter at the highest energy densities? Is the basic idea that this is best described using fundamental quarks and gluons correct?

In what remains of this paper, I would like to take each of these questions in turn and make some suggestions about measurements which might help us answer these questions, and point out what upgrades will be necessary. In any set of such suggestions, there is a danger of compartmentalizing certain results to answering certain questions. In reality our subject is rich with overlapping subjects - measurements meant to answer questions about the later hadronic part of the collision may lead to information about the early stages of the collision.

I will also give more detailed examples of what might be done in three particular measurements - low mass vector mesons, onium suppression, and jet suppression - keeping in mind the statements I have made about precision measurements. I will conclude with a suggested set of priorities for our community.

### 3.1 Evolution of the System

This is perhaps the question for which the suite of detectors at RHIC are most capable of answering, at least for the later hadronic stage of the collision. We already have a basic understanding of much about the final freeze-out phase. It appears that the final state hadrons reflect a both chemical and kinetic thermal distribution. We have first estimates of the kinetic and chemical freeze-out temperatures, chemical potentials, and expansion velocities. There is much left to understand, however, we have the tools in hand to do much of the work. Detectors are well equipped to study HBT, flow and particle yields and spectra.

Thanks to improvements in theory, we may be close to some understanding of the initial stage of the collision as well. Detailed tests of the CGC model will be made in future eA machine proposed to be done at RHIC and in pA collisions with upgraded detectors for looking at collisions involving small x partons.

What is missing is a clear understanding of the stages, after the formation of the CGC particularly related to the thermalization of the initial gluon distribution. Does the strength of the elliptic flow signal really imply that thermalization occurs as early as 0.6 fm? If so, it may be that we already have the answer in hand but it is important to gather more information.

One of the possibilities for examining this stage of the collision is though real and virtual photons from quark-anti-quark annihilation, materializing as electron or muon pairs radiating from the hot, dense QCD matter. While such radiation is emitted at all times during the collision, the reaction dynamics favors emission from the hottest part of the colliding system. Thus, measurement of the distribution of the blackbody thermal radiation will give us information on the initial temperature, and possibly the black body nature of the spectrum. If so, these photons would play the same role for us that the Cosmic Microwave Background Radiation did for our understanding of the early universe. The background to such a signal is formidable since photons and electrons are copiously produced from other
sources such as π⁰ decay. Upgraded detectors designed to reject such backgrounds will be necessary. Systematic analysis, and variation of the initial conditions will be required to solidify the interpretation.

3.2 Deconfinement

As mentioned previously, the suppression of high p_T hadrons from the energy loss of partons as they pass through a deconfined medium is an important signal of deconfinement. This may be enough to establish the effect, however it will be important to be more quantitative. This can be done by making measurements of direct photons produced opposite high transverse momentum hadrons. Since the photon recoils against the quark jet, and since it does not suffer energy loss in the deconfined medium, the photon serves as a indicator of the initial transverse momentum of the jet. This will provide a means to make careful, quantitative measurements of the energy loss. One interesting possibility is to flavor tag the high transverse momentum hadron. A leading K^- with no valence quarks is more likely to come from a gluon jet. This would allow one to measure the difference in the energy loss between gluon and quark jets. Gluon jets are expected to loose energy at twice the rate of quark jets in a deconfined medium. These measurements will require high luminosity because of the low cross sections of such high p_T events. In addition detectors will be required to handle the large luminosities, as well as to identify hadrons to high p_T.

J/ψ suppression is another well-known signature of deconfinement. PHENIX will be able to measure J/ψ production in both the muon and electron channels. STAR will have access to the electron channel within the next several years as their electromagnetic calorimeter is completed providing a second measurement of this signature. One of the critical measurements that must accompany the measurement of the J/ψ is that of open charm production to see whether open charm is enhanced or comes from the “melting” of the J/ψ. To do this, specialized vertex detectors must be added with the position resolution that would allow a measurement of the charm vertex separated from the original event vertex. STAR, PHOBOS and PHENIX have all embarked on R and D programs to construct such an upgrade.

The J/ψ is but one of the vector mesons in the charm family. The excited states of the J/ψ as well as the Υ family will all exhibit some degree of suppression. The suppression of the associated c\bar{c} and b\bar{b} states, can also be observed since they decay to the detectable vector mesons. Each of these states will “melt” at a different temperature (figure 9). In fact the Υ will be used as a control since it should not be suppressed at all at RHIC energies. By varying the temperature of the system though changes in beam energy and species, one can change the pattern of suppression of the various states. Not only would this be a convincing signature of a phase transition, it would give a good measure of the actual energy density.

It appears that the densities are high enough, even in mid-central collisions where the reaction plane can be obtained, that there is a QGP formed albeit with a smaller volume then in very central collisions. This then raises the possibility that one can actually do tomography on the collision region and map out its density profile to some degree in the following manner. One would measure the angle between the reaction plane and the probe of interest, for instance a high pt particle opposite a photon and measure the energy loss as a function of the reaction plane. The path length perpendicular to the reaction plane is
longer than in the direction of the reaction plane because of the almond shape of the collision region in semi-central collisions. As an example of a particularly interesting question that this could address is to see the relationship between energy loss and path length on the one hand and energy density on the other by examining the differences in energy loss as a function of the path length. This would enable one to check the path length squared dependence of the energy loss, mentioned before.

The measurements mentioned in this section would require measuring small cross section processes in many bins of centrality, $p_T$ and reaction plane. This demands an increase in the luminosity as well as large acceptance detectors capable of measuring leptons, photons, high pt particles with particle identification.

3.3 Chiral Symmetry Restoration

Chiral symmetry is broken through the creation of a vacuum scalar condensate that couples to hadrons and provides most of their mass. The challenge for RHIC experiments is to search for evidence of in-medium mass changes of the low mass vector mesons associated with the restoration of chiral symmetry. A direct measurement of the mass of light vector mesons such as the $\rho$, $\omega$, and $\phi$ is possible since they decay rather rapidly within the fireball created at the time of collisions and before hadronization. The decay to di-electrons is particularly interesting since electrons should not be re-scattered in the medium and their invariant mass should reflect the mass of the vector meson in the altered vacuum state. Since some fraction of the vector mesons decay outside the medium (in the case of the $\omega$ some 70-80%), these can be used as a calibration point for the measurement. The fraction exhibiting a shifted mass should change as a function of the transverse momentum and the size of the central fireball. This would be a particularly dramatic signature of the altered

Figure 9: Bottom Plot: Some possible “melting” points for the onium states. Top plot: the corresponding ratio to the unsuppressed values that one would observe experimentally.
vacuum. As in the case of the thermal di-electron signal, a major upgrade will be needed to reject background for detection of the $\rho$, the shortest lived, and hence the broadest of the vector mesons unless it is strongly enhanced which it may well be.

Figure 10: (a) The broadening of the $\omega$ resonance for varying temperatures in the Rapp-Wambach model (b) Simulation of the di-electron signal in the $\rho - \omega$ mass region from high $p_T$ peripheral collisions and low $p_T$ central collisions without Dalitz rejection as explained in the text assuming the Rapp-Wambach model (c) same as figure b for the $\phi$ as explained in the text without Dalitz rejection. Lighter lines indicate the signal in low $p_T$ central collisions, darker lines indicate the signal in high $p_T$ peripheral collisions. (d) same as figure c assuming 90% Dalitz rejection.

The presence of a phase transition as the system cools is also expected to cause fluctuations, which may survive the hadronic phase as fluctuations in particle number and type. Fluctuations and droplet formation are of particular interest, since similar processes may account for much of the large scale structure of the universe and the inhomogeneities observed in the cosmic microwave background. A variety of fluctuations have been proposed as a signature of a phase transition. If the transition is first order, the growth of hadronic droplets and the shrinking of quark-gluon droplets may yield a lumpy final state.
and large fluctuations in particle number. If the transition is a smooth but sufficiently rapid
crossover, domains of misaligned chiral condensate may be formed. If the transition occurs
near a critical point separating first order behavior from crossover behavior, long wave-
length fluctuations imprint unique signatures on the momenta of soft pions. Experiments
will search for such phenomena, and correlate their appearance with other quark-gluon
plasma signatures.

The models of chiral symmetry restoration have followed essentially two approaches. The
first, typified by Rapp and Wambach’s model\cite{19} assumes hadronic degrees of the freedom
as the starting point. The other, typified by Brown-Rho scaling\cite{20}, uses primarily quark
degrees of freedom. Under the hadronic description, the restoration of chiral symmetry
means that the vector (e.g. the $\rho$) and the axial vector (e.g. the $A_1$) will become degenerate
when chiral symmetry is restored. Typically the particle widths increase and the mass does
not go to zero. Brown and Rho however, assumed that all particle masses scale with the
chiral condensate which of course goes to zero when chiral symmetry is restored. These
two views are of course, seemingly contradictory - a situation that is somewhat endemic
to this subject. The two groups have made the conjecture that there is a quark-hadron
duality and that the two approaches will give the same results if one did not have to resort
to perturbation theory, but somehow could calculate the results directly which, of course
is probably not possible, at least not analytically. The only difference between the two
approaches, then is simply the difference between the sets of basis states or “degrees of
freedom” that they choose to use to solve the problem.

Let us suppose that the chiral and deconfinement transition occur at the same place.
Let us also assume that the Rapp Wambach model was correct below the phase transition,
where at least at very low temperature their set of basis states seem reasonable, and Brown
Rho scaling is appropriate above the transition in the sense the the quark masses scale with
the chiral condensate. The Rapp Wambach Model predicts that as we approach the phase
transition from below the vector and axial vector particles widen and become degenerate.
Above the phase transition, the quarks deconfine and presumably the light quark masses
will go to their bare quark masses - essentially zero on the scales which we are considering.
At the phase transition, somehow these pictures must merge. It may be that neither set of
basis states are the correct ones to use near the phase transition. If one was able to find the
correct basis states, one may actually be able to do the calculation in the region of interest.

A similar situation was faced by condensed matter theorists in trying to explain super-
conductivity. Bardeen, Cooper and Schrieffer managed to guess the correct set of basis
states to use - Cooper pairs. Presumably they could have constructed their theory using
electrons as the basis states. The theory would have been just as good but it would have
been hopelessly complicated. Finding the right set of basis states is one of the major steps
to solving such a problem. In the case of QCD, it may be that neither the hadronic nor
the quark basis are the best set of basis states to use near the phase transition. It also may
not be possible to guess the right set of such states with knowledge available to theorists
now. What is needed are experimental results, which then can used as a foundation for
making a reasonably educated guess. Of course we can approach this problem in a brute
force manner using lattice gauge theory on massive computers, however finding the right
degrees of freedom or basis states gives one a much better qualitative understanding of
the phenomena. This is one of the instances in which the interplay between theory and
experiment is the most productive.

The detection of low mass vector mesons, particularly the $\rho$, decaying to di-electrons is a challenging task for similar reasons to the problem of identifying the thermal di-electron signal mentioned previously- the backgrounds are fierce from $\pi^0$ Dalitz decays and photon conversions. A scheme of rejection of Dalitz and conversion pairs must be implemented.

The $\rho$, in addition to being useful for the understanding of chiral symmetry restoration, can also be used as a clock of the mixed and hadronic phases of the collision. Since the lifetime is so short, the $\rho$ decays and is regenerated several times during the collision - for instance from $\pi\pi$ interactions. Since electrons do not interact strongly they can emerge from the collision relatively unhindered. A long mixed and hadronic phase should enhance the $\rho$ to di-electron signal in a matter which yields the lifetime.

In order to study some of these effects, and the need for Dalitz rejection, a simulation was done using as input, the model of Rapp and Wambach which includes the restoration of chiral symmetry and the enhancement of the $\rho$ due to the aforementioned effect. Figure 10a shows the resonance shape of the $\omega$ meson for a variety of temperatures. One can see the slight mass shift, and the broadening of the line shape. A run of $10^9$ central events (about 2 years of running) was assumed. Figure 10b shows the signal for the $\rho$, $\omega$ and $\phi$ assuming the current PHENIX detector which has no Dalitz rejection. The first thing to note is that if the enhancement of the $\rho$ is as strong as the Rapp-Wambach model indicates, the signal will be clearly measurable even with the current configuration of the PHENIX detector without Dalitz rejection. To illustrate the difficulties, however, we turn to the $\phi$ which shifts in a manner similar to the $\omega$. Figure 10c shows a comparison of the signal from low-pt central events where the effect should be the strongest, to the high-pt peripheral events where it should be essentially normal. The statistical error bars are very poor due to the large subtraction which must be performed due to the background. Clearly, one would not be able to deduce any difference. A 90% Dalitz rejection was assumed for figure 10d, and a clear effect of width broadening due to chiral symmetry restoration can be seen.

There are essentially two schemes being considered for Dalitz rejection. One of the methods contemplated is that of a hadron blind detector with large acceptance which has a high probability of detecting both particles of a Dalitz pair. This typically involves a field free region near the vertex so that the low momentum partner is not bent out of the acceptance of the detector. Since the detector is sensitive to electrons which have a relatively low multiplicity, electrons and positrons can be reconstructed and rejected if they are consistent with a Dalitz of conversion pair. Such a scheme could even be implemented on-line. The second involves the use of a vertex detector together with the ability to do good particle identification. Such a detector could measure low momentum electrons since it is so close to the vertex. The background pair could then be rejected in a similar manner to the hadron blind scheme.

3.4 Matter at the Highest Energy Densities

There is a great deal to learn about hadronic interactions at very high energies where we are probing the very low $x$ region of the hadron wave-function. The CGC is critical to understanding these process and an understanding of the gluon densities at these high energies forms the basis for the calculations of the initial conditions in nucleus-nucleus
collisions. Critical experiments to perform will include pA and eA collisions. A future project at the RHIC Collider will be the addition of an electron ring to study eA collisions. In the near future we can begin to use pA collisions. Proton-nucleus collisions are necessary component of the heavy ion program as well, since pA as well as pp collisions serves as a basis for the normalization of AA collisions to provide an understanding of phenomena such as nuclear shadowing. An increase in luminosity is necessary for this task since the same rare signals must be detected.

Signals which can be used to measure the relevant gluon distributions primarily come from gluon fusion processes. These include the production of heavy quarks and W bosons and direct photons. Anti-quark distributions can be probed via Drell Yan. Saturation will affect the rate and the transverse momenta of these probes. Processes which involve very low \(-x\) partons will occur in the very forward portion of the detector and upgrades to lepton, photon and micro-vertex detectors which can cover pseudorapidities as high as \(\eta \sim 5\) are required.

### 3.5 What is Needed?

We are now left with the task of setting the priorities for the future of the RHIC program. One of the important aspects providing enormous strength to the program is a redundancy in the capabilities of the detectors. The different detection and analysis techniques as well as different regions of acceptance can provide a cross check and corroboration of critical signatures lending credibility to the discovery of new phenomena. In particular, STAR is now adding electromagnetic calorimetry over a large acceptance, providing balance to PHENIX’s aggressive electron and muon identification over a somewhat smaller region.

R and D for the detector upgrades has begun. Funding must be provided for this. Upgrades which will be added should and does include a program for Dalitz rejection, high \(p_T\) particle identification, and micro-vertex detection for heavy quark production. Weaknesses of the various detectors are being addressed - for instance in the addition of electromagnetic calorimetry for STAR as just mentioned, and the addition of 4\(\pi\) tracking for the PHENIX detector to enhance jet detection capabilities. STAR already has a good acceptance at very forward rapidities. PHENIX is contemplating the addition of very forward detection of muons and photons as well as a micro-vertex detector in the forward region, though these projects are not as well formulated as some of the others. All detectors must of course enhance their data-acquisition capabilities to enable them to take advantage of the planned luminosity upgrade.

### 4 Conclusions

RHIC provides us with a unique capability to understand QCD interactions, both at high temperatures and in bulk, which was the primary focus of this paper. It will also study pp, pA, and eA collisions in which we can study the quark and gluon distributions themselves as well as the spin of the nucleon in the very rich polarized proton program which I have not mentioned at all.

I remain optimistic about many of the ideas as explained in this paper, particularly the Colored Glass Condensate. However it must be emphasized that it is far too early to
assume that it is a well established theory. Only further experimental evidence can tell us whether it is right or wrong. In fact it may well be that the CGC model turns out to be incorrect, however, the important point is that the future of the RHIC experimental program (and LHC) is very bright. The future of theory in the field is progressing rapidly as well and hand in hand, theory and experiment will work together such that perhaps in the next 5-10 years, our picture of high-temperature QCD will be much more complete giving us an understanding of the nature of the phase transitions and the nature of confinement and hadronic mass—which I remind the reader makes us most of the ordinary matter we see around us.

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