First results from RHIC: What are they telling us?

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Abstract. The Relativistic Heavy Ion Collider (RHIC) facility at Brookhaven National Laboratory is the first accelerator specifically constructed for the study of very hot and dense nuclear matter. At sufficiently high temperature, nuclear matter is expected to undergo a phase transition to a quark-gluon plasma. It is the specific goal of the field to study the nature of this plasma and understand the phase transitions between different states. The RHIC accelerator along with four experiments BRAHMS, PHENIX, PHOBOS, and STAR were commissioned last year with first collisions occurring in June 2000. Presented here are the first results from low luminosity beam in Run I. They are a glimpse of the wealth of physics to be extracted from the RHIC program over the next several years.

INTRODUCTION

The long awaited first results from the RHIC facility are now available from all four experiments in the program. Here we review the fundamental physics goals of the field of Relativistic Heavy Ions. We begin with a brief overview of the four experiments and the conditions for Run I at RHIC. Subsequently the early physics results are presented in three sections including understanding the initial conditions, the thermalization of the system, and specific probes of the possible plasma phase. Finally we present an outlook for Run II at RHIC, which is currently underway, and the long term future of the program.

PHYSICS GOALS

The field of Relativistic Heavy Ions has one primary goal. That goal is to understand the behavior of QCD under extreme conditions of high temperature and density. In this limit, non-perturbative QCD may simplify to the extent that it is possible to employ a thermodynamic description of a quark-gluon plasma phase characterized by a screening of the confining potential for partons and the restoration of approximate chiral symmetry. The nature of the QCD vacuum under these conditions is of considerable interest. Calculations in the framework of Lattice QCD indicate that in the low net baryon density limit there may be a phase transition at a temperature of order 150-200 MeV. Currently lattice calculations cannot determine the order of the transition because of theoretical uncertainties associated with the number of light quark flavors included (either two or three if including the strange quark). Thus the order of the transition is currently an experimental question.

Of secondary interest in the field is the implications of the QCD phase transitions on the fields of cosmology and astrophysics. Shortly after the Big Bang the universe is believed to have existed in the quark-gluon plasma phase. As the universe expanded and cooled, the universe went through a hadronization phase transition at a temperature of 150-200 MeV. Witten [1] and others [2] have speculated that a strong first order phase transition in the early universe with associated bubble formation could have led to large inhomogeneities in the baryon density. If the inhomogeneities survived the diffusion process until a temperature of approximately 1 MeV, then they could have observable consequences for Big Bang Nucleosynthesis. There has been continuing work on the modeling of this bubble nucleation and diffusion rates to address this question. It would be a great scientific achievement to determine the order of this transition experimentally from Relativistic Heavy Ion Collisions. In addition, quite recently many theorists have speculated on the nature of dense quark matter, possibly a color superconductor, at the core of neutron stars and other compact objects [3].
It is important to note that particularly at RHIC energies, there are many cross-overs between the physics issues addressed in this field and those in other fields such as: deep inelastic scattering, hadron colliders, TJNAF structure function physics, and condensed matter physics. Hopefully this will broaden the scope of the field and also lead to greater inter-field collaboration.

**RHIC ACCELERATOR AND EXPERIMENTS**

There are four experiments currently implemented for the RHIC heavy ion program, with two additional intersection regions available for future experiments. The two smaller experiments are BRAHMS and PHOBOS, and the two larger experiments are PHENIX and STAR.

The BRAHMS experiment consists of two spectrometer arms that are capable of rotating around a pivot in order to cover a large range of rapidity and transverse momentum. The detectors used include Time-Projection-Chambers (TPC), wire chambers, Cerenkov counters, and a time-of-flight system. Their experimental emphasis is particle identification over a broad rapidity range. They cover nearly the full 12 units of rapidity, well beyond the other experiments’ capabilities. This may allow them to explore the more baryon dense matter at forward and backward rapidities.

The PHOBOS experiment has two main features. The first is nearly $4\pi$ coverage with silicon detectors to measure the total charged particle multiplicity, enable phase space fluctuations analysis, and measure global properties such as elliptic flow. The second part consists of two spectrometer arms, also silicon based, that give good particle identification over a smaller acceptance for measuring two particle correlations and reconstructing the $\phi$ in the $K^+ K^-$ decay channel. They also have partial coverage with a time-of-flight wall to enhance particle identification. PHOBOS emphasizes high data rate and fluctuation analysis capabilities.

The PHENIX experiment is specifically designed to measure electrons, muons, hadrons and photons. The experiment is capable of handling high event rates, up to ten times RHIC design luminosity, in order to sample rare signals such as the $J/\psi$ decaying into muons and electrons, high transverse momentum $\pi^0$’s, direct photons, and others. The detector consists of four spectrometer arms. Two central arms have a small angular coverage around central rapidity and consist of a silicon vertex detector, drift chamber, pixel pad chamber, ring imaging Cerenkov counter, a time-expansion chamber, time-of-flight and an electromagnetic calorimeter. These detectors allow for electron identification over a broad range of momenta in order to measure both low mass and high mass vector mesons. Two forward spectrometers are used for the detection of muons. They employ cathode strip chambers in a magnetic field and interleaved layers of larocci tubes and steel for muon identification and triggering.

The principal detector in the STAR experiment is a large volume Time-Projection-Chamber (TPC). The TPC is augmented with a silicon vertex detector, a small coverage ring imaging Cherenkov (RICH) counter, and an electromagnetic calorimeter. The experiment emphasizes large phase space coverage and particle identification via $dE/dx$, augmented by the limited coverage RICH and a future additional Time-Of-Flight wall. Measurements of strange particles including strange baryons $\Lambda, \Xi, \Omega$ and antibaryons $\bar{\Lambda}, \bar{\Xi}, \bar{\Omega}$, two particle correlations and event-by-event fluctuations are among the many observables accessible to STAR. The large phase space coverage of the experiment allows many critical measurements to be done event-by-event, for example hadron spectra, two particle correlations, and particle ratios.

The design of both the STAR and PHENIX experiments includes a polarized proton program to conduct studies of the spin structure of the proton. Critical to this measurement is the identification of high transverse momentum photons and leptons. The STAR experiment is phasing in an electromagnetic calorimeter that will be crucial for such observations. In particular the RHIC experiments are ideally suited for measuring the gluon contribution of the proton’s spin.

**RUN I**

The RHIC facility is designed to accelerate fully stripped Au ions to a collision center-of-mass energy of 200 GeV per nucleon pair. The design luminosity is $2 \times 10^{26}$ ions/s/cm², which corresponds to approximately 1400 Au + Au minimum bias collisions per second. During Run I at RHIC the maximum energy was 130 GeV per nucleon pair and they achieved 10% of design luminosity by the end of the run. First collisions were achieved in June 2000 and the run continued until the end of August. All four experiments integrated sufficient luminosities to commission the detectors
and produce a variety of initial physics results. It should be noted that the total statistics recorded, for example by the PHENIX experiment, is equivalent to less than one day of sampled collisions at full design luminosity in Run II. Thus the results presented below are just a preliminary look at the physics potential of the RHIC experiments.

**TIME EVOLUTION OF THE COLLISION**

The time evolution of RHIC collisions can be broken down into various stages. The initial stage is that of two Lorentz contracted Au nuclei incident upon each other at ultra-relativistic velocities. This may seem like an uninteresting stage, but there is a great deal of physics in the parton distributions of the nuclei as described by nuclear structure functions. In deep inelastic scattering experiments the parton density increases dramatically at low values of $x$ (momentum fraction carried by the parton relative to the nucleon’s total momentum). Due to the non-Abelian nature of the strong interaction, two gluons can fuse to form a single gluon. Thus, at small enough $x$, the gluon density may in fact saturate. In electron-proton experiments at HERA saturation effects are being investigated at very low $x < 10^{-3}$. However in a nucleus the gluon wavefunction from many different nucleons can overlap and thus saturation may occur at much higher values of $x \approx 10^{-2}$, which happens to be the $x$ scale relevant to collisions at RHIC energies. The RHIC experiments have already begun to address this question. This represents an interesting non-traditional heavy ion physics topic and has large overlap with structure function physics. This has motivated some to propose an electron beam to study $eA$ collisions at RHIC (eRHIC), thereby extending the range of the machine to very low $x$.

The next stage is that of pre-equilibrium. In a time of less than 0.1 fm/c the two nuclei pass through each other and of order 10,000 quarks, antiquarks and gluons collide. Some of these collisions are at large momentum transfer and thus have calculable rates using perturbative QCD. For example, a high transverse momentum quark represents a calculable probe that is generated before any equilibrium is established, but must then traverse the remaining system before fragmenting into a jet cone.

After a period of time of 0.1 to 1.0 fm/c the bath of semi-hard quarks and gluons may equilibrate. It is interested to note that if parton saturation is achieved by the copious production of gluons, the system essentially thermalizes immediately at 0.1 fm/c. What is the nature of the bath of quarks and gluons? Since they are at low relative momentum this can only be reliably calculated in the framework of lattice QCD. Lattice results indicate that a phase transition from confined hadronic matter to a quark-gluon plasma takes place for temperatures in excess of 150 - 200 MeV. In calculations including only two light quark flavors the phase transition appears to be first order, while including the strange quark as a “light quark” changes the transition to second order. A key goal of the field is the determination of the phase transition temperature and the order of the transition.

Since the system has no external constraints it expands and cools off. The analogy of the early universe expanding and cooling after the Big Bang is quite appropriate. If the system has equilibrated then the expansion may be describable via hydrodynamics and an appropriate equation of state. Once the system cools below the critical temperature, the quark and gluons hadronize. The hadrons continue to scatter and interact until eventually all interactions cease (freeze-out), after which particles freely stream away from the collision point. The point at which inelastic collisions cease is referred to as chemical freeze-out, when all particle ratios are frozen. The stage when all elastic collisions cease is referred to as thermal freeze-out, when the momentum distributions of the particles is frozen. Measurements of hadron spectra and correlations give a photograph of the system at the point of thermal freeze-out.

**RESULTS**

Here we divide the early results into three sections detailing: (1) the initial conditions, (2) the thermodynamic properties, and (3) the probes of the plasma state. It should be noted that this is not meant to be a comprehensive review of all results to date, but just a select sample. Many important and interesting results not included below can be found in the recent Quark Matter 2001 conference proceedings [4].

(1) **Initial Conditions**

The first result with a measurement from all four RHIC experiments is the charged particle multiplicity [5, 6, 7, 8]. The four experiments’ results for central (small impact parameter) collisions are in excellent agreement and are shown
in Fig. 1. The multiplicity rises more sharply as a function of center-of-mass energy in heavy ion collisions than in $p+p$ and $p+\bar{p}$ collisions, which is attributed to the increased probability for hard parton scattering in the thick nuclear target seen by each parton.

We expect the charge particle yield to increase for collisions of larger nuclei. However, at low $x$ values, the high density of gluons may in fact saturate due to gluon fusion processes. The contribution to the yield from hard processes should exhibit point-like scaling (scaling with the number of binary collisions) and would thus scale as $A^{4/3}$. However, parton saturation depends upon the nuclear size and would limit the growth of the number of produced partons as $A^{1/3}$. If present, this initial parton saturation would limit the hard process contribution to the total charged particle multiplicity.

Only one nuclear species was accelerated in Run I at RHIC. Thus, rather than changing the mass number $A$ directly we control the collision volume by varying the centrality or the number of participating nucleons for Au+Au collisions. Shown in Fig. 2 are the published results from the PHENIX [6] and PHOBOS [9] experiments for the number of charged particles per participant nucleon pair as a function of the number of participating nucleons. The number of participating nucleons is determined in a slightly different manner by the different experiments. However, the general method is to calibrate the number of spectator nucleons (= $2 \times A$ - participant nucleons) using a measurement of spectator neutrons in a set of zero degree calorimeters that are common to all experiments. By correlating the number of forward neutrons to the number of charged particle produced in the large pseudorapidity region, the event geometry can be understood.

In Fig. 2 one can also see theory comparisons that indicate that a model including parton saturation (EKRT [10]) fails to agree with the more peripheral data. Results from the HIJING model [11] are also shown which does not include parton saturation and thus has a more continuous rise in the particle multiplicity. Since saturation phenomena are only likely to have observable consequences for large collision volumes, it is not possible with present systematics to rule out the saturation picture for the most central collisions.

In order to better test the saturation picture lighter ion, smaller $A$, collisions will be studied in Run II. In addition, heavy flavor (charm and bottom) and Drell-Yan production should be a sensitive probe to the initial parton density. Another proposal is that by varying the collision energy and keeping the nuclear geometry the same you can get a better handle on systematics and test scenarios dependent on the coupling constant and the saturation scale.

In addition to wanting to know the initial parton density, the energy density is of great interest. There are published results estimating the initial thermalized energy density achieved in these collisions. Bjorken originally derived a formula, shown in Eqn. 1, relating the measured transverse energy per unit rapidity to the thermal energy density [12].

$$\varepsilon_B = \frac{1}{\pi R^2 c \tau} \frac{dE_T}{dy}$$  \hspace{1cm} (1)
FIGURE 2. PHENIX and PHOBOS results for $dN_{ch}/d\eta|_{\eta=0}/\sqrt{\langle N_{part}\rangle}$ as a function of $N_{part}$. The hashed and solid bands indicate the systematic errors for the two experimental results. The data point for $p\bar{p}$ with two participants is shown for comparison. Also theoretical predictions from the HIJING and EKRT models are shown.

FIGURE 3. Plotted is the $\pi^-/\pi^+$ and $\bar{p}/p$ ratio as a function of rapidity from the BRAHMS experiment for central collisions.

It should be noted that there is a trivial factor of two error in the original reference that is corrected here. This formulation assumes a boost invariant expanding cylinder of dense nuclear matter and a thermalization time $\tau$. There are two important assumptions in this particular formulation. The first is the boost invariant nature of the collision. There are recent preliminary measurements from STAR and PHOBOS that indicate the distribution of particles is relatively flat over $\pm 2$ units of pseudorapidity. However, shown in Fig. 3 is the measured distribution of $p/p$ from the BRAHMS experiment [13]. This indicates that the system is already changing at rapidity $y \approx 2$, though it is not clear that this is enough to invalidate the energy density formulation. The second question is what is the relevant thermalization time $\tau$.

The PHENIX experiment has published [14] the transverse energy distribution for minimum bias Au+Au collisions. For the 5% most central events, the extracted transverse energy $<dE_T/d\eta>|_{\eta=0} = 503 \pm 2$ GeV. Shown in Fig. 4 is $dE_T/d\eta/(0.5N_p)$ versus the number of participating nucleons. One sees a similar increase in transverse energy as was seen in the charged particle multiplicity yield.

The canonical thermalization time used in most calculations is $\tau = 1$ fm/c, that yields an energy density of
4.6 GeV/fm$^3$, which is 60% larger than measured at the CERN-SPS. In addition, it is believed that the density is substantially higher due to the potentially much shorter thermalization time in the higher parton density environment.

If one achieves gluon saturation the formation time is of order 0.2 fm/c and gives an estimated energy density of 23.0 GeV/fm$^3$. There are even estimates of over 50 GeV/fm$^3$, but they assume a very large drop in the final measured transverse energy due to work done in the longitudinal expansion of the system. All of these estimates are above the energy density corresponding to the phase transition temperature of 150-200 MeV by order 0.6 - 1.8 GeV/fm$^3$.

(2) Thermodynamic Properties

As the system approaches thermal and chemical equilibrium, we need to have an experimental handle on the time scale and degree of thermalization. The earliest and hottest stages of the collision that might be characterized by deconfined matter will emit thermal radiation, real photons $\gamma$ and virtual photons $\gamma^* \rightarrow e^+ e^- \text{ or } \mu^+ \mu^-$. From quark-quark scattering. The resulting photons and leptons escape the collision volume without re-interacting and thus act as a penetrating probe of the early times. This is analogous to measuring neutrinos from the center of the sun. The data sample in Run I is not sufficient for these measurements, so higher luminosity running in Run II is eagerly awaited. However, the ratio of final hadron yields has been measured and gives information on the equilibration condition at the later stage of hadronic chemical freeze-out.

All four experiments have shown particle ratios for $\bar{p}/p \approx 0.6$ and are in excellent agreement with each other. Both STAR and PHOBOS have measured other particle ratios including resonance states such as the $K^*$ by STAR. A collection of ratios (note that many are preliminary results) are shown in Fig. 5. These ratios can be fit to a Grand Canonical Ensemble statistical model and show reasonable agreement with a baryon chemical potential $\mu_B \approx 45 - 55$ MeV and a chemical freeze-out temperature $T \approx 160 - 180$ MeV. An example fit from [15] is shown as solid lines in Fig. 5. It should be noted that the preliminary $K^*$ results are somewhat under predicted. The measurement of other such excited states should really test some of the model assumptions. The freeze-out temperature is not significantly different from that measured at the CERN-SPS, which is not surprising since all systems must cool to approximately the same energy density before particles stop having inelastic scatters.

Some have taken the ability to describe the system by this simple model as an indication of thermalization. However, a similar behaviour is seen in $e^+e^-$ and $pp, \bar{p}p$ collisions with a limiting temperature $T \approx 170$ MeV, though with an additional suppression of strangeness production. There is most likely an important connection between how a small region of vacuum with strong color fields fragments into hadronic states (for example in $pp$ collisions) and how that occurs in a large volume as in heavy ion collisions. This connection needs to be further explored before any firm conclusion about thermalization is made based on hadron ratios.
One of the most exciting early results from RHIC is the measurement of elliptic flow. For non-central collisions, the overlap geometry between the two nuclei is almond shaped. This spatial anisotropy can translate into a momentum anisotropy in the presence of strong re-scattering. One can measure the resulting momentum anisotropy by measuring the second harmonic Fourier coefficient $v_2$ in the azimuthal distribution of particles with respect to the reaction plane. Since the flow is built up from pressure gradients at the earliest stages of the time evolution, it may be sensitive to initial large parton re-scattering in a deconfined phase and to a lesser extent the Equation of State.

The STAR experiment has published [16] results on $v_2$ as a function of collision centrality. Preliminary results from PHOBOS [17] show reasonable agreement, while preliminary results from PHENIX [18] are somewhat larger though with a different transverse momentum selection. The PHOBOS experiment has measured the elliptic flow $v_2$ as a function of pseudorapidity as shown in Fig. 7. Preliminary results from STAR [19] as a function of transverse momentum for minimum bias collisions are shown in Fig. 6. In the left panel, STAR results are shown compared with a hydrodynamic model calculation which shows excellent agreement up to $p_T \approx 1.5$ GeV. This agreement may indicate a large degree of thermalization in the early stages, thus validating the assumption of hydrodynamic expansion. In a specific model calculation [20], they estimate an initial thermal energy density $\varepsilon = 20 \text{ GeV}/f m^3$ at a time $\tau = 0.6 f m/c$. The disagreement between the hydrodynamic calculation at large transverse momentum has been attributed in some
models to the high $p_T$ hadrons being the result of jet fragmentation. Normally jets would be uncorrelated with the reaction plane, but if there is energy loss, as discussed in the next section, the path traveled by the parton in the medium depends on its relative orientation to the reaction plane. In the right panel, the sensitivity of the high $p_T$ elliptic flow to the initial gluon density is shown [21]. These measurements and other preliminary results on flow for different particle species provide further tests to these models.

There are other preliminary results on particle momentum distributions and two particle correlations that indicate large transverse expansion of the system, described as radial flow. Theoreticians are currently working towards a complete description of many of these observables. In particle the preliminary two particle correlation (HBT) results from STAR are a challenge to include into a full hydrodynamic picture and thus represent a critical measurement.

**Hard Process Probes of the Plasma**

An ideal experiment would be to contain the quark-gluon plasma and then send well calibrated probes through it and measure the resulting transparency or opacity of the system. Despite the great challenges heavy ion collisions present, there are such calibrated probes but they must be self-generated in the collision itself. An excellent probe is a parton or quark-antiquark pair. A quark traversing a color confined medium of hadrons sees a relatively transparent system. However, a parton passing through a hot color deconfined medium will lose substantial energy via gluon radiation. In fact, because the radiated gluons can couple to each other, the energy loss is proportional to the square of the path length traversed [22, 23].

The source of these partons is from hard processes producing back-to-back parton jets. In a deconfined medium the parton will lose energy before escaping the system and fragmenting into a jet cone of hadrons. The total energy of the initial parton jet is conserved since eventually the radiated gluons will also hadronize. It is likely that the radiated gluons will have a larger angular dispersion than the normally measured jet cone. Thus one might be able to measure a modification in the apparent jet shape. A more striking signature is that since when the parton fragments into hadrons it has less energy, the fragmentation will result in a much reduced energy for the leading hadron. Thus, a measurement of high transverse momentum hadrons ($\pi^0, \pi^+/−, K^+/−, h^+/−$) is a strong indicator of the opacity of the medium.

The PHENIX experiment has measured the distribution of identified $\pi^0$ for both central and peripheral Au+Au collisions as shown in Fig. 8 [24]. The peripheral results appear to be in good agreement within systematic errors of an extrapolation from $pp$ collisions scaled up by the number of binary collisions expected in this centrality class. However, the central collision results show a significant suppression in the $\pi^0$ yield relative to this point like scaling expected for large momentum transfer parton-parton interactions. If the created fireball in RHIC collisions is transparent to quark jets, then we expect the yield of high $p_T$ hadrons to obey point-like scaling and equal the $pp$ (or equivalently $p\bar{p}$) distribution scaled up by the number of binary $NN$ collisions, or equivalently by the nuclear thickness function $T_{AA}$. 
FIGURE 8. Preliminary PHENIX invariant multiplicity of identified $\pi^0$ as a function of transverse momentum are shown for peripheral and central collisions. Comparison with theoretical calculations with and without parton energy loss are also shown.

This is not what is observed. A more sophisticated calculation [25] yields the same qualitative conclusion.

The STAR experiment has recently submitted for publication [26] the $p_T$ spectra for unidentified negatively charged hadrons in central Au + Au collisions as shown in Fig. 9. Also shown are the equivalent spectra from experiment NA49 at the CERN-SPS at $\sqrt{s} = 17$ GeV and from UA1 in $p\bar{p}$ at $\sqrt{s} = 200$ GeV. The STAR spectra is then divided by the spectra from $p\bar{p}$ scaled by the number of binary collisions, and the result is shown in the lower panel of Fig 9. At low transverse momentum the particle production is dominated by soft interactions which scale with the number of wounded nucleons as indicated by the line at 0.2. The rise from 0.2 as a function of $p_T$ certainly has a large contribution from hydrodynamic flow that will push particles to higher transverse momentum in central Au+Au collisions.

The PHENIX experiment has shown preliminary results extending out further in transverse momentum. Preliminary results for six centrality classes are shown from PHENIX in Fig 10. STAR also has preliminary results for central collisions extending out to $p_T > 5$ GeV that are in reasonable agreement with the PHENIX results. If one takes the ratio of the central spectra to the unidentified spectra in $pp$ collisions scaled up by the number of binary collisions one gets a ratio $R_{AA}$ as shown in Fig 11. It needs to be noted that there is no $pp$ data at $\sqrt{s} = 130$ GeV and thus an extrapolation to that energy is done to calculate $R_{AA}$. This extrapolation is included in the systematic error band, and should be reduced when both experiments measure the spectra in $pp$ in Run II.

There are many important physics points to understand in these results. The ratio appears to stay below one, although that is a marginal conclusion with the present systematic errors. However, this is certainly in qualitative agreement with a parton energy loss scenario, as also seen in the observed suppression in the PHENIX $\pi^0$ spectra. In contrast, the CERN-SPS results show an enhancement that has been attributed to the Cronin effect, or initial state parton scattering that gives a $k_T$ kick to the final transverse momentum distribution. This expected enhancement makes the suppression seen at RHIC all the more striking.

There are a number of open questions that must be considered before drawing any conclusions. The most basic is...
that these $p_T$ values are low relative to where one might have confidence in the applicability of perturbative QCD calculations. In addition, the separation between soft and hard scale physics is blurred in this $p_T$ range, and in fact the CERN-SPS ratio $R_{AA}$ has also been explained in terms of hydrodynamic boosting of the soft physics to higher $p_T$. The preliminary results from PHENIX on the ratios of $\pi/K/p(\bar{p})$ in the middle of this $p_T$ range look more like soft physics than a parton fragmentation function in vacuum. One additional point of concern is that these models of energy loss assume that the parton exits the collision region before finally fragmenting into a jet of forward hadrons. Thus the final hadronization takes place in vacuum. In the $p_T$ range of these early measurements, that conclusion is not so clear. The parton is traveling through the medium with various $k_T$ scatters, and if it hadronizes inside a bath of other particles, the leading hadrons may be slowed down by inelastic collisions with co-moving pions. Lastly, the point-like scaling is known to be violated due to the nuclear shadowing of parton distribution functions. These nuclear modifications are known to reduce the pdf for quarks of order 20% for $x \approx 10^{-2}$; however, the shadowing for gluons is not currently measured. The calculations of [25] have included modeling of this shadowing, but must be viewed with caution at this time. These points need further theoretical investigation. In addition, as will be discussed in the next section, many of these concerns are reduced when the measurements extend to much higher transverse momentum.

**RUN II AT RHIC**

Run II at RHIC is currently starting and the expectation is to have ten weeks of running Au + Au at the full energy $\sqrt{s} = 200$ GeV per nucleon pair at the full design luminosity. This should allow experiments to sample physics from well over one billion AuAu collisions. After these ten weeks, there will be the first polarized proton run, which

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**FIGURE 9.** Invariant multiplicity of unidentified charged hadrons as a function of transverse momentum (top). Ratio of unidentified charge hadrons per calculated binary collision from Au + Au central collisions to those from p + p($p\bar{p}$) collisions extrapolated to $\sqrt{s} = 130$ GeV as a function of transverse momentum (bottom).
FIGURE 10. PHENIX preliminary results for unidentified charged hadron invariant multiplicity as a function of transverse momentum.

FIGURE 11. Ratio of unidentified charge hadrons per calculated binary collision from Au + Au central collisions to those from p + p(γ) collisions (extrapolated to $\sqrt{s} = 130$ GeV) as a function of transverse momentum (GeV). The solid line is the systematic error band on the ratio. The dashed line is the average result from experiments at the lower energy CERN-SPS.

represents the beginning of the RHIC spin program. In addition it provides crucial comparison data sets for the heavy ion program. Beyond this time, the program is not yet determined, but there is active discussion about lighter ion collisions, lower energy running, and possibly deuteron-A collision studies.

In terms of initial conditions, lighter ion running and running at lower energies will be crucial for drawing more firm conclusions about parton saturation and understanding the initial energy density. The thermalization question will be addressed further by the measurement of direct photons and lepton pairs, and chemical freeze-out can be tested with more excited state resonance measurements and multistrange baryons. Two particle correlation measurements have
already been crucial tests of the space-time evolution of the system, and possible measurements as a function of the reaction plane will be an important correlated measurement to elliptic flow.

Probably the area most enhanced by the high luminosity running will be the probes of the plasma. In the Au + Au running, we expect to see hadron spectra about beyond $p_T > 10$ GeV which helps to address many of the current concerns with the preliminary Run I results. In addition, more identified hadrons will be measured at high transverse momentum. Another key observable will be back-to-back correlations at high $p_T$ in order to better calibrated possible parton energy loss scenarios. In addition, a second category of probes via heavy $q\bar{q}$ pairs that form vector mesons such as $J/\psi$, $\psi'$, $Y$ will be measured. Associated measurements of charm and bottom production via single and correlated lepton pairs will be important. All of these measurements are eagerly anticipated.

LOOKING EVEN FURTHER AHEAD

The RHIC program has a long lifetime ahead of it. The first glimpse at the physics from Run I has proven to be very exciting and interesting. There are clearly a number of systematic studies that will be necessary to untangle competing effects and physics. A full energy scan for excitation function measurements, varying the collision geometry and an extensive comparison proton-proton and proton-nucleus program is called for. Understanding the nature of the QCD vacuum at high temperatures is the primary goal for the field, and we are on a good start towards that goal.

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