Vol. 36 (2005) *ACTA PHYSICA POLONICA B* No 2

THE FIRST 3 YEARS AT RHIC — AN OVERVIEW*

Richard Seto

University of California, Riverside, CA 92504, USA

(Received November 25, 2004)

This is an overview of the results from the first 3 years of RHIC experiments. RHIC is a collider built to accelerate nuclei to center of mass energies of 200 GeV per nucleon for the study of QCD in bulk systems. The most important result so far is the observation of the suppression of high p_{T} hadrons in central Au–Au collisions followed by the subsequent null experiment where the same suppression was not seen in deuteron–Au collisions. The observed suppression is a final state effect in which a large amount of energy is lost by the fast parton as it penetrates the medium. This observation, together with measurements of the elliptic flow, leads to the conclusion that the energy density reached is at least 10 times that of a normal nucleon. The simplest and most economical explanation of these phenomenon is that the system is a dense, locally thermalized system of unscreened color charges.

PACS numbers: 25.75.Nq, 12.38.Mh

1. Introduction

QCD (Quantum Chromodynamics) is the established theory of the strong interactions which together with the electro-weak force constitute the forces in the Standard Model. These, and perhaps all fundamental theories, picture the vacuum as a complex sea of stuff. It is the interaction of the fundamental constituents of the theories with the vacuum that generates mass and in the case of the strong interaction (QCD) gives rise to the phenomenon of quark confinement. Since the vacuum is a medium, its structure can be altered as the temperature is changed [1]. The most violent of these changes is a phase transition. The various components of the vacuum corresponding to the various forces each went through one or more such transitions at their characteristic temperatures early in the history of the universe. It is very likely that such a phase transition powered the sudden expansion

* Presented at the XXXIV International Symposium on Multiparticle Dynamics, Sonoma County, California, USA, July 26–August 1, 2004.

of the universe known as inflation. Most of the phase transitions studied experimentally — *e.g.* water to ice, Helium-3, magnetic domains — all result from the electromagnetic force. It is natural to ask if we can study a phase transition or transitions resulting from QCD. Such was the task of the Relativistic Heavy Ion Collider (RHIC) which began taking data in 2001. This talk is an overview of what we have learned from the first three major data taking periods. RHIC, located at the Brookhaven National Laboratory, is a large accelerator which can accelerate heavy ions of all species to center of mass energies of 200 GeV. Such violent collisions of large nuclei will leave in its wake, a region of high energy density whose net baryon-density is nearly zero, that is, a high temperature vacuum.

In the past year, the RHIC community, with its four major experiments, STAR, PHENIX, PHOBOS and BRAHMS, has been taking stock of the of its status, in regards to the discoveries made, and the questions yet to be answered [2]. The task was organized around 4 questions:

1. Does the system formed at RHIC reach thermal and chemical equilibrium? If so, what is the initial temperature or energy density? How does the system evolve?

2. Have we seen the signatures of the deconfinement phase transition? If so, what have we learned about the mechanism of confinement?

3. Have we observed the chiral phase transition? What is the relationship between the QCD vacuum and the masses of the hadrons? Or in other words, what is the origin of chiral symmetry breaking?

4. What are the properties of matter at very high energy densities? Is the quark and gluon description the best way to understand the system?

Before describing the experimental data, it is worth reviewing some of the expectations and ideas from theory. Quantitative predictions of QCD at momentum transfers below 1 GeV are difficult, since the coupling constant is large and perturbation theory will not work. Lattice gauge calculations, often done on powerful computers, are used to obtain numerical values for quantities of interest such as the hadron masses spectrum [3]. Such calculations can also be used to predict the critical temperature for the phase transition. QCD has at least two transitions, which are in all likelihood connected. The first is the deconfinement transition, in which the quarks are set free from the confines of their parent hadrons. The second is the chiral transition, the transition responsible for the bulk of the hadronic mass[1]. The two transitions are thought to be at the same temperature. Lattice calculations predict a critical temperature $T_{\rm C}$ of about 170 MeV, giving a critical energy density $\varepsilon_{\rm C} \sim 1\,{\rm GeV/fm^3}$ [4]. In a theory with only gluons and no quarks, the transition is first order. In nature, since the u and d quarks have a small mass, and the strange quark has a somewhat larger mass, the phase transition is predicted to be a cross over. However, since this cross over occurs over a very narrow range of temperatures, the transition is, for all practical purposes, first order, since the temperature cannot be controlled to anywhere near the accuracy needed to tell the difference.

2. Preliminaries

The ideal experiment would be to make a trap for nuclear matter and raise the temperature, as in the center of a star. Unfortunately, there is no containment mechanism which can withstand such forces in the laboratory. Such enormous pressures and temperatures can be produced in high energy collisions from an accelerator. However the duration that the relevant state exists is very short, and evolves with time. Experimentalists must examine the debris of such a collision, whose products come from every stage of the system — both above the transition temperature and below. Some of the products will come from the initial collision before equilibration is reached, and other products will come from reactions taking place significantly after the system has cooled below the transition temperature and will give a background to the interesting products made during the high temperature phase. One of the key ideas is to utilize experimental probes which give information about particular time periods in the evolution of the system. The RHIC experiments become an archaeological expedition, albeit, the timescale is rather short, less then 10^{-21} seconds. But like the archaeologist we must be able to date the relics that we find.

Fig. 1 is a cartoon of the evolution of a heavy ion collision showing the energy density vs time on a log scale. The inset shows the temperature as a function of the time. If one assumes a Stefan–Boltzmann relationship between the energy density and the temperature then one has $\varepsilon_{\rm SB} = N_{\rm DOF}(\pi^2/30)\,T^4$ where the $N_{\rm DOF}$ is the number of degrees of freedom in the system which ranges from 37 to about 47.5 depending on whether the strange quark is taken as massless. Unlike traditional particle physics

[1] The masses of the quarks, at temperatures above the chiral transition are several MeV and can be taken to be nearly zero. In this case, the left- and right-handed sector of quarks are completely separate — hence the name "chiral" symmetry. At low temperature, quarks attain a "dressed" mass due to their interaction with the vacuum and chiral symmetry is broken.

experiments, we are not interested in processes involving only a single scattering. Rather we are interested in the many body processes of the bulk where concepts such as a local temperature and entropy have meaning. The collision proceeds in 5 stages.

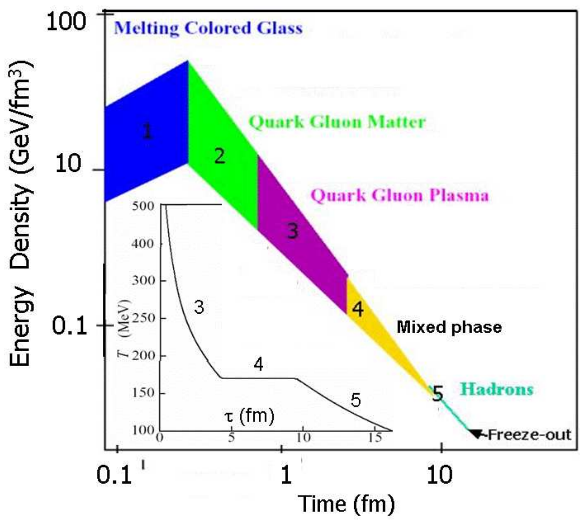

Fig. 1. A schematic of the energy density *vs* time history of the systems studied at RHIC in Au–Au Collisions. The five stages are described in the text. The inset is a temperature *vs* time history for the stages where the temperature is reasonably well defined. Although the figure shows what appears to be a first order transition, the best estimates from lattice calculations tell us that with 2 light quarks, and a moderately heavy strange quark, the transition is a cross over which occurs over a relatively narrow band of temperatures (figure due to Larry McLerran).

1. The initial state — a Colored Glass Condensate — so named because of a model in which the color fields are studied in a classical approximation because of the high occupation numbers. The fields of fast moving particles serve as sources for the slower fields and provide the "frustration" that is typical of a glass. The large Q^2 processes occurring during this stage provide the high p_{T} probes of the system useful for studying later stages of the collision.

2. Quark gluon matter — a pre-equilibrium stage of quarks and gluons lasting about 1 fm leading to a locally equilibrated system. The phenomenon of elliptic flow begins to develop at the end of this stage.

3. The Quark–Gluon Plasma phase. Hard probes leading to the phenomenon of jet suppression are particularly important here, since most of their energy is lost in this phase.

4. The mixed phase, which presumably spans a narrow range in temperature and hadrons form. Even if the transition is strictly a cross over, it is assumed that there is some time during the collision where there is a mixture of quark–gluon plasma and hadrons, while the hadrons are forming. It is also in this phase, together with the QGP phase where chiral symmetry is restored.

5. The hadronic phase where hadrons interact with one another. Radial flow develops and ends in freezeout of the final hadronic products (meaning that all interactions between particles cease) setting the kinetic and chemical freezeout temperatures.

We can divide the processes in a relativistic heavy ion collision into two categories; hard and soft. Hard processes are those with a $p_{\mathrm{T}} > 3\,\mathrm{GeV}$, where perturbative calculations are reasonably accurate. Hard processes can be used as a calibrated probe of the medium since they should scale as the number of initial parton–parton collisions. Shadowing will give a correction to this which must be accounted for by studying proton (or deuteron) nucleus collisions. The modeling of hard processes follows the standard methods of pQCD calculations using structure functions followed by jet fragmentation. These hard processes provide high momentum partons, which loose energy in the medium. This phenomenon, known as jet quenching, is one of the major experimental signatures seen at RHIC.

Models of the soft processes are more complicated since they are non-perturbative. These are the processes which lead to the majority of particle production and hence to the quark–gluon plasma. Non-viscous hydrodynamics, which assumes that the bulk matter is a continuous medium, is often used to model the evolution of the system. Hadronization is done using the so called "Cooper Frye" formalism which simply converts the continuous matter to hadrons conserving charge, momentum and energy in a Lorentz invariant manner. Hydrodynamics requires two external inputs — the initial conditions, and the equation of state. For the latter of these, one can simply assume the EOS of an ideal gas either in the hadronic stage, in which the degrees of freedom are the hadrons, or the QGP stage in which the degrees of freedom are the quarks and gluons. These are often taken as limiting cases and a variety of EOS's are tested. The assumption of zero-viscosity will turn out to be important, as this implies that the medium is actually not an ideal gas, but is rather strongly interacting. In hindsight, that this is true might seem to be obvious as the value of α_{S} at $\sqrt{Q^2} \sim T \sim 300\,\mathrm{MeV}$ is rather large during the QGP phase.

Recently, McLerran [5] and his collaborators have used a classical approximation for the initial stage of the collision, arguing that the occupation numbers at low x, where much of the particle production occurs, are rather high. This model, which they have named the "Colored Glass Condensate", shows the phenomenon of gluon saturation and makes predictions which can be used to calculate the initial conditions in a heavy ion collision which in turn can then be used as input to the hydrodynamical calculations. This calculation relies on the fact that very early in the collision, gluon saturation effects at low x set a value of $Q \sim Q_S$ where α_S can be considered small but the occupation numbers are high. The value of Q_S at RHIC is 1–2 GeV so $\alpha_S^2 \sim 1/10$. The saturation assumed by these authors is present in the initial state before the nuclei collide. This fact will be important in distinguishing these effects, from final state effects such as the formation of a quark–gluon plasma.

A second recent advance has to do with the later stages of the collision — hadronization. Several groups have conjectured that low momentum hadrons in the final state, come primarily from the recombination of partons and not from the fragmentation. While a rigorous calculation can only be done in a range of momenta where masses can be ignored, the general trends predicted by these models seem to explain a variety of experimental observables between about 1 and 4 GeV/c momentum [21].

Fig. 2 shows a schematic of these various models and their connections. The division in the applicability of these models is not absolute. In fact, hydrodynamics which provides the framework for understanding the motion of low and moderate momentum partons will feed into parton recombination models. Parton recombination, which was initially believed to recombine only thermal partons, appear also to incorporate low momentum partons from jet fragmentation as well. For a complete understanding of the exper-

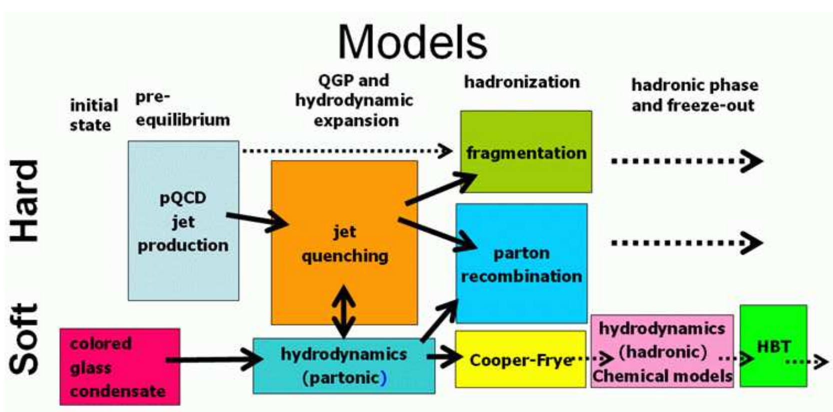

Fig. 2. A diagram of models used for understanding collisions at RHIC. Different approximations are appropriate in each regime depending on the scale of the interaction being modeled, and the degree of thermalization (figure due to S. Bass).

imental data, a rather sophisticated picture, involving all of these models is necessary. This processes is still in its infancy and the cooperation of various types of theorists and experimentalists will be needed to gain a detailed understanding of the dynamics of the heavy ion collision. In the initial stages of this task it is important that we concentrate on whether the overall ideas are correct — even if all the experimental data is not fully reproduced by the models.

One of the important control parameters used by the RHIC experiments, is the impact parameter or centrality of the collision. By convention 0% centrality refers those collisions having the smallest impact parameter, and the term peripheral refers to glancing collisions. The four RHIC experiments all have identical devices (the zero degree calorimeters) which measure the centrality. Soft processes generally scale with the number of participating nucleons in the collisions or $N_{\rm part}$ which is a gross measure of the size and/or energy density of the fireball, whereas the number of hard interactions scale with the number of collisions or $N_{\rm coll}$. Once the impact parameter is determined via measurements of the zero-degree calorimeters, a simple Glauber model is used to determine $N_{\rm part}$ and $N_{\rm coll}$.

3. The initial state — a Colored Glass Condensate

One of the surprising (and for some, disturbing) early observations, was that the multiplicities coming from heavy ion collisions at RHIC energies, was lower than many of the predictions coming from naive pQCD estimates. Kharzeev and his colleagues used the Colored Glass Condensate model to make a prediction of the multiplicity as a function of centrality. They obtained

$$\frac{dN}{dy} \sim \frac{1}{\alpha\,(Q_{\rm S})} N_{\rm part}\,,$$

where $Q_{\rm S}$ is the saturation momentum which is a slow function of $N_{\rm part}$ coming from the fact that the particle density and hence the saturation scale is dependent on the centrality. Fig. 3 shows a comparison of three models with multiplicity data from PHENIX. One can see that the model based on saturation by Kharzeev, Levin and Nardi, (labeled K.L.N.) [6] makes a reasonable accounting for the data at both 200 and 130 GeV center of mass. The paucity of particles compared to naive expectations is attributed to saturation which limits particle production. What is somewhat disconcerting is that the calculation seems to work reasonably at a $\sqrt{s}$=19.6 GeV, where one might not expect the model to be valid. Whether this is cause to doubt the model remains to be seen. In any case one can extract from these models, an energy density in the early stages of the collision of about 18 GeV/fm^3 [6] well above the lattice value of 1 GeV/fm^3 required for the phase transition.

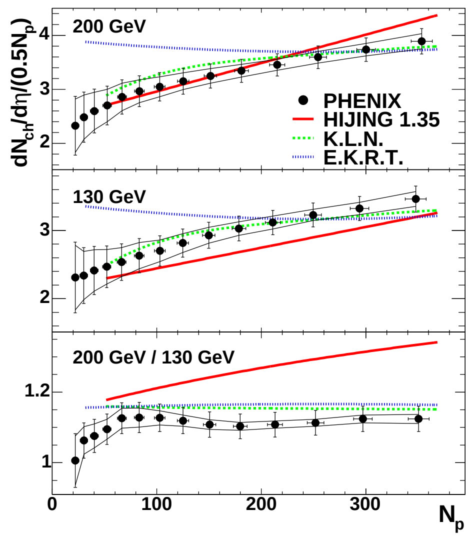

Fig. 3. The charged particle multiplicity per unity pseudorapidity, normalized to N_{part} at 200 GeV and 130 GeV center of mass energy for Au–Au collisions as a function of N_{part}. K.L.N. is the model by Kharzeev, Levin and Nardi [6] based on saturation ideas. E.K.R.T. refers to a model which assumes saturation in the final state [7] and Hijing 1.35 [8] is a model based on pQCD mini-jets.

A second piece of evidence for the CGC relies on the fact that in going to forward rapidities, one begins to sample a lower range in x in the nucleus. The ratio $R_{\mathrm{CP}} = \frac{\mathrm{Yield(central)}/N_{\mathrm{coll}}\mathrm{(Central)}}{\mathrm{Yield(peripheral)}/N_{\mathrm{coll}}\mathrm{(Peripheral)}}$ is a measure of the yield per collision from hard processes coming from central as compared to peripheral collisions, where the peripheral collisions are taken as a baseline. If p–p data is available, it is often used as the baseline as will be done later in the definition of R_{AA}. The BRAHMS experiment, whose strength is the capability to measure very forward rapidities, looked at this ratio in deuteron–nucleus collisions. For a given p_{T}, a lower and lower value of x is sampled as one moves to higher rapidity. Since the gluon structure function increases at low x one would see a stronger suppression as one moves to higher rapidity. Fig. 4 shows just this effect, with the more central collisions showing a larger suppression as one might expect. At midrapidity, above a p_{T} of 2 GeV, one sees an enhancement instead of a suppression. This phenomenon, known as the Cronin effect, comes from initial state multiple scattering of the incoming projectile parton. Even with this enhancement, the saturation effects are strong enough to show an overall suppression at forward rapidities of factor of 2. Theoretical saturation calculations by Kharzeev, Kovchegov and Tuchin show a similar qualitative trend.

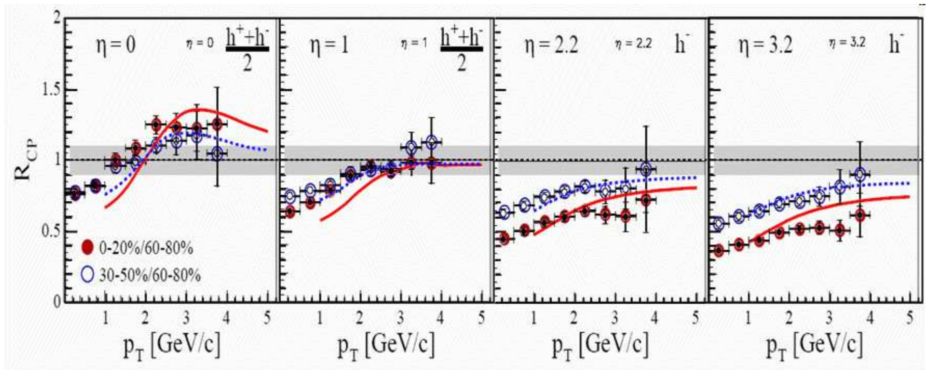

Fig. 4. The ratio R_{CP} for charged hadrons in deuteron–Au collisions for central events and mid-central events in varying bins of pseudorapidity, showing the Cronin enhancement at mid-rapidity and suppression at forward rapidity (Brahms). The fits are to a model by Tuchin *et al.*, [10].

4. Thermalization and elliptic flow

One of the surprising results which was immediately apparent at RHIC was a strong directional anisotropy in momentum known as elliptic flow. Initially the concept may seem foreign to particle physicists, but this is akin to other measurements that have been used in the study of the strong interactions — the "jet shape" variables of thrust, and sphericity. In the case of heavy ion collisions, such behavior involves all particles emerging from the interaction and has nothing to do with jets or hard scattering, but arises from pressure gradients in a spatially anisotropic collision. The anisotropy is strongest in mid-central collisions and disappears for very peripheral or very central collisions. The conversion efficiency from spacial to momentum anisotropy depends on the properties of the medium and hence can be use to understand its properties. In order for efficient conversion, the medium must be strongly coupled. Contrary to what one might presuppose, this implies a zero viscosity and zero mean-free path. Such systems, often called perfect fluids, have been studied in other areas such as atomic physics [11]. One can also calculate the viscosity in particular strongly coupled theories using the AdS5/CFT duality, where one finds that the viscosity zero [12]. In relativistic heavy ion physics, non-dissipative hydrodynamics is used. The quantity of interest is the value of the second Fourier coefficient of the azimuthal momentum anisotropy — the elliptic flow. In simple terms it is the extent to which the shape is elliptical as opposed to spherical. One of the important external inputs to these models is the initial thermalization time at which the pressure gradients begin to be operational. Before this time, the system is assumed to free stream and expand isotropically reducing the spacial anisotropy and thereby the elliptic flow. Using this fact, the value of the elliptic flow when compared to the spacial anisotropy which one obtains from centrality measurements, can give an estimate of the thermalization time. It is found that thermalization times of about 0.6 to 1 fm are required to fit the data. In these models one obtains an energy density of 15–25 GeV/fm^3 [13] similar to the estimate given from the CGC initial conditions.

5. Jet quenching

A long sought signal of high density matter has been the large loss of energy of a fast parton as it penetrates the medium. The energy loss can easily be understood as the radiation of gluons from the fast parton, because of the strong color charges. Since high p_T particles from hard processes scale as $N_{\rm coll}$, one simply compares the p_T spectrum measured in central heavy ion collisions scaled by $N_{\rm coll}$ to a baseline measured in p–p collisions. This effect was dramatically seen at RHIC as shown in Fig. 5 where one can see the rather large (factor of 4–5) suppression for high p_T π^0's as compared to the p–p scaled expectation. One can also see that for peripheral collisions, the scaling works rather well. The $N_{\rm coll}$ scaling of hard processes has been

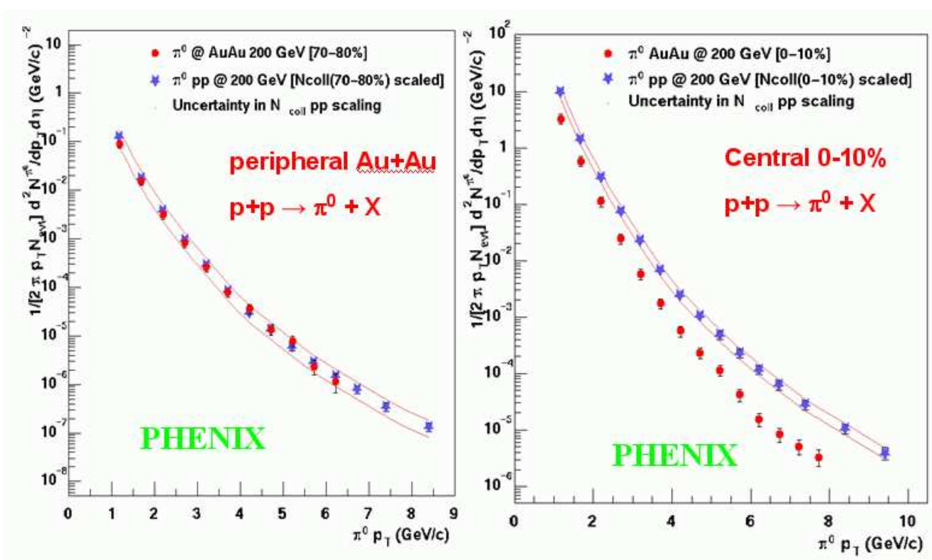

Fig. 5. Left: The p_T spectrum of π^0's normalized to $N_{\rm coll}$ for p–p collisions compared to peripheral Au–Au collisions. Right: The same for central Au–Au collisions, showing that the Au–Au data do not scale — the effect of parton energy loss [15].

double checked using direct photons, which are produced via hard processes but do not loose energy in the medium since they have no color charge[2].

In the third year of data taking, an important "null" experiment was done in which deuteron–gold collisions were studied. It was important to establish that the suppression of high $p_{\rm T}$ particles was the result of final state interactions which would be an indication of the formation of a QGP and not due to some alteration of the initial state such as a CGC. Again, PHENIX looked at mid-rapidity, central collisions. Fig. 6 shows the quantity R_{AA} for π^0's similar to $R_{\rm CP}$ described above, but using p–p collision data in the denominator. One sees for central Au–Au collisions, a factor of 4–5 suppression at high $p_{\rm T}$, whereas for deuteron–gold collisions the ratio is about unity. There is a slight indication of a Cronin type enhancement in the d–Au collisions.

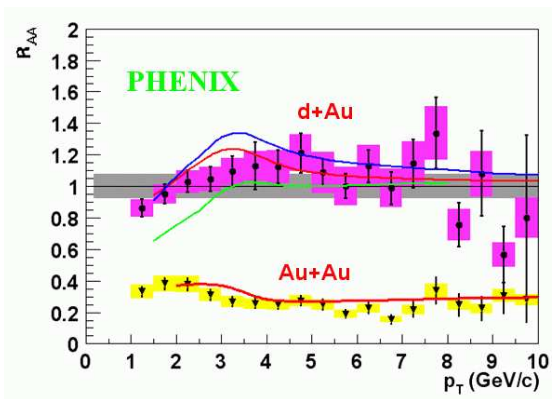

Fig. 6. The ratio R_{AA} as explained in the text for d–Au collisions and central Au–Au collisions. One can see the clear suppression below unity for central Au–Au data, and a lack of suppression in the d–Au data [15–17].

At this point, it was clear to RHIC experimentalists, that we were observing a final state phenomena whose most probable explanation was the loss of energy due the passage of partons through a dense partonic medium. Calculations done by Vitev and Gyulassy [17] reproduced the data reasonably well and gave an energy density of 15 GeV/fm^3 early in the history of the expanding fireball, with an initial gluon density of about $\frac{dN_{\rm gluon}}{dy} \sim 1100$. Reasonable hadronic calculations are unable to reproduce such a large energy loss [18].

[2] It also appears that single electrons coming primarily from charm (after the Dalitz and photon-conversion contributions have been subtracted) follow this scaling as well. Heavy quarks are thought not to loose energy due to a dead cone effect that limits the radiation because of kinematics.

One can then further study the loss of energy by looking at opposite side jets, since one of the hard partons would traverse a larger distance in the dense medium. This was done by triggering on a high $p_{\rm T}$ particle and looking at the opposite side in the collision. In peripheral collisions (or in p–p collisions) the opposite side jet signal should be rather strong, whereas in central Au–Au collisions, the opposite side jet would be considerably broadened with a large multiplicity of soft particles resulting from the energy loss of the outgoing parton. The typical $p_{\rm T}$ of particles from collisions assuming a thermal distribution would be well below 1.5 GeV. Fig. 7 shows a correlation plot in azimuthal angle. An initial trigger particle was chosen with

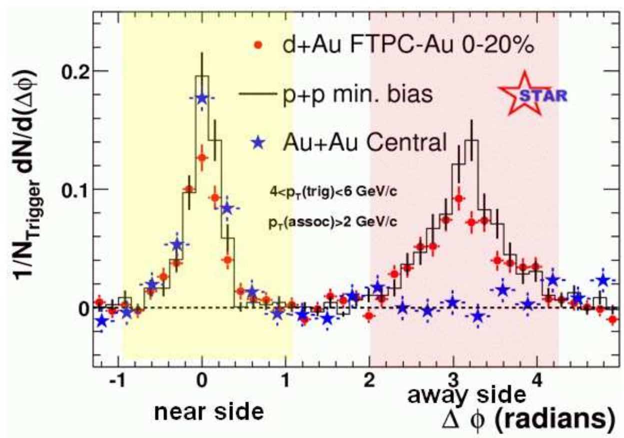

Fig. 7. Particles correlated with a high $p_{\rm T}$ trigger particle showing the jet-like structure. For p–p and d–Au collisions, one can see the recoil jet clearly. For central Au–Au collisions — the recoil jet disappears [19].

the requirement that the $p_{\rm T}$ be between 4 and 6 GeV. The angle between all particles with $p_{\rm T}$ above 2 GeV/c and the trigger particle are then plotted. For p–p and d–Au collisions, one sees a clear two "jet" structure. In contrast, while the same side jet appears clearly in central Au–Au collisions, the away side jet disappears. The simplest explanation is that the hard processes occur near one surface. One of the jets escapes with very little energy loss while the other jet is almost completely quenched. The particles associated with the away side jet can be identified if the correlation is extended down to very low $p_{\rm T}$ (0.15 GeV) since momentum must be conserved. These particles are very soft, higher in multiplicity and broader in angle; in short they approach a thermalized distribution, as one might expect, if the phenomenon is really due to the energy loss of partons in a colored plasma.

6. Hadronization

All of the processes discussed so far are amongst quarks and gluons. However, we see hadrons in our detectors and not quarks and gluons. The process of hadronization is one of the most interesting aspects of the study of QCD at RHIC, since this involves chiral symmetry breaking, or the generation of hadronic mass, and confinement.

One of the curious puzzles that faced the experiments was the large proton to pion ratio at moderate p_{T}'s between 2 and 5 GeV. Critical to this measurement was the particle identification capabilities of the PHENIX experiment. Fig. 8 shows the (anti)proton to pion ratio. For central events the ratio is about 1.0 for protons and 0.8 for anti-protons. For peripheral events the values are similar to that from p–p collisions and jets [20]. The data extends to about 4.5 GeV where PHENIX's time of flight is no longer able to uniquely identify protons. In order to check if this behavior extends to higher momentum, the charged hadron to neutral pion ratio was measured. The charged hadron is a mixture of charged pions which one can assume is about twice the neutral pion yield, (anti)protons, and kaons. Above 5 GeV this ratio returns to a nominal value of about 1.5 consistent with p–p collisions, so the effect is confined to a p_{T} range between 2 and 5 GeV. Such a large production of baryons at moderate p_{T} contradicts our current understanding of fragmentation in the vacuum where only about 20% of the particles are baryons. This led theorists to assume that there was some mechanism for hadronization which depended on the density. They assumed that hadrons were forming from a recombination of quarks already present in the medium [21]. Such a mechanism would enhance baryons at high p_{T}. If

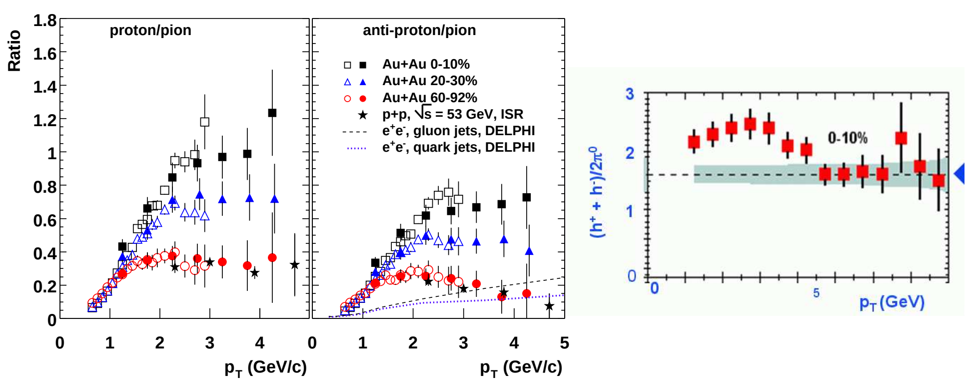

Fig. 8. Left: (Anti)proton to π^0 ratio for different centrality classes for Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Error bars represent the quadratic sum of statistical and systematic errors (PHENIX). Right: charged hadron to $2\pi^0$ ratio showing the return to the nominal value above 5 GeV/c (PHENIX).

one assumes that there is a ball of thermal partons expanding from internal pressure, the joining of 3 quarks (baryons) would create a hadron with a p_{T}, 3/2 that of a hadron created from 2 quarks (mesons). Since the spectrum is falling steeply, this would lead to a large enhancement of baryons.

One can test this idea another way. Elliptic flow (v_2) develops early in the collision when the degrees of freedom are presumably quarks and gluons. If recombination is at work, then the elliptic flow of identified particles, scaled by the number of constituent quarks should reflect the underlying elliptic flow of partons. Fig. 9 shows the v_2 of a variety of particles *vs* p_{T}. After rescaling with n, the number of valence quarks, all hadrons fall on the same line above $p_{\mathrm{T}}/n \sim 1\,\mathrm{GeV}$. In fact the idea works down to very low p_{T} for all particles aside from the pions. One of the causes of this discrepancy is that many of the low p_{T} pions are actually from the subsequent decays of resonances such as Δ and ρ. More complex models which actually include such effects bear this out [22].

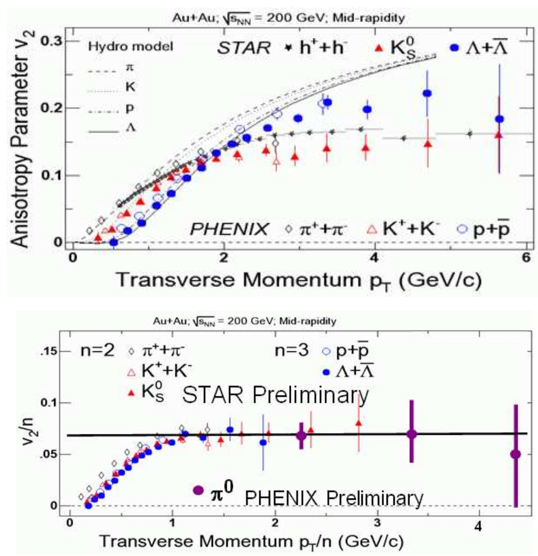

Fig. 9. Top: v_2 for various particles as a function of p_{T}. Bottom: v_2 *versus* p_{T} both scaled by n, the number of valence quarks, showing that above 1 GeV, all fall on the same line.

A question now arises. Is recombination from thermal quarks or do fragmentation quarks from hard collisions also participate? If recombination is from purely thermal quarks, then hadrons formed from recombination should show no jet-like correlations. Fig. 10 shows the centrality dependence of the associated charged hadron yield for particles between $1.7 < p_{\mathrm{T}} < 2.5$ GeV/c above a combinatorial background for trigger baryons and trigger mesons in the p_{T} range 2.5–4.0 GeV/c in a 54° cone around the trigger particle [23].

Both mesons and baryons, which presumably are made via recombination in the momentum range in question, have associated particles, meaning that they have some jet-like qualities to them. This appears to mean that by some mechanism, hard scattered partons, hadronize by picking up partners from the thermal bath. The radiated gluons (which are primarily collinear with the fast quark) retain some of their directionality. For baryons in central collisions, the effect appears to be reduced, hinting that the formation of baryons in the most central collisions is primarily from thermalized quarks.

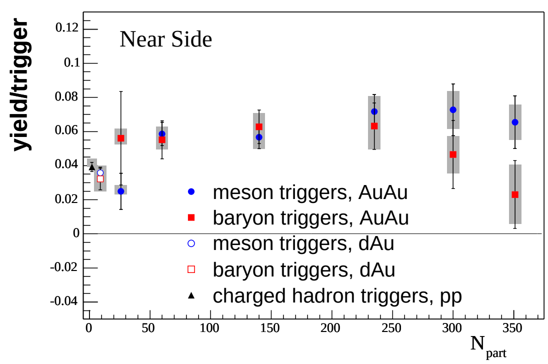

Fig. 10. Yield of particles withing a cone around high p_T trigger particle as a function of centrality as described in the text (PHENIX).

The rather simple picture of recombination as means of hadronization, while appealing, leaves some open questions. First, the quark degrees of freedom have a place in this picture, but where are the gluons? In this picture, it is as if the quarks already have their dressed constituent masses before recombining. How did this happen? Where is chiral symmetry broken? There is also a seeming reduction of entropy inherent to the mechanism. Where does it go? By its very nature this picture is a schematic cartoon for non-perturbative physics. Mueller and his colleagues [21] among others have tried to put it on a more theoretically sound footing, however, this requires assumptions (*e.g.* ignoring the masses of the hadrons) which limits the direct applicability of the theory to $p_T > 2\,\text{GeV}$ or so.

7. Conclusion

The first three years of data taking at RHIC have yielded a wealth of information. There is strong evidence that: (1) the system has reached a very high energy density, greater than 10 times that of an ordinary nucleon; (2) the system thermalizes rapidly; (3) the system behaves as a liquid of near zero viscosity, indicating that it is very strongly interacting; (4) the system is very opaque indicating that the cross sections are extremely large, much larger than is typical of hadronic cross sections. The simplest explanation of these phenomena is that RHIC has formed a thermalized system of quarks and gluons. It may be that the degrees of freedom are more complicated. Indeed recombination ideas may indicate that the degrees of freedom may change as the system passes through the phase transition.

Operationally, both experimentalists and theorists at RHIC no longer think of the degrees of freedom as ordinary hadrons, but rather as a near thermalized system of quarks and gluons, a Quark–Gluon Plasma. The challenge now is that of characterizing the system that is created. We still have very little experimental understanding of the chiral symmetry and deconfinement transitions. One of the most direct probes of the mass is the dilepton decay of light mesons (ρ, ω, and ϕ). These resonances have short lifetimes. The invariant mass of electrons whose source is the decay of resonances inside the high temperature fireball, should reflect the mass of the resonance in a high temperature vacuum. In addition, we have only begun to probe the charm sector. A high statistics run including the J/ψ has been completed and analysis is now beginning which may yield more insights into the mechanism of confinement. Direct photon–quark pairs can be used as a calibrated probe to make more quantitative measurements of energy loss. Probes such as HBT correlations have yet to be understood. All of these probes are being pursued, and will be needed to understand the fundamental connection between the QCD vacuum, the masses of the hadrons, and the chiral and deconfinement phase transitions.

REFERENCES

[1] T.D. Lee, *Rev. Mod. Phys.* **47**, 267 (1975); T.D. Lee, *Trans. N.Y. Acad. Sci. Ser. 2* **40**, 0111 (1980); T.D. Lee, G.C. Wick, *Phys. Rev.* **D9**, 2291 (1974).

[2] White papers, to be submitted to *Nucl. Phys.* **A**; PHENIX Collaboration, K. Adcox *et al.*, `nucl-ex/0410003`; B.B. Back *et al.* (PHOBOS Collaboration), `nucl-ex/0410022`; I. Arsene *et al.* (BRAHMS collaboration), `nucl-ex/0410020`; STAR white paper is forthcoming.

[3] S. Aoki *et al.* (CP-PACS Collaboration), *Phys. Rev. Lett.* **84**, 238 (2000).

[4] F. Karsch, *Lect. Notes Phys.* **583**, 209 (2002). F. Karsch *et al.*, *Nucl. Phys.* **A715**, 701 (2003).

[5] L.V. Gribov, E.M. Levin, M.G. Ryskin, *Phys. Rep.* **100**, 1 (1983); A.H. Mueller, Jian-wei Qiu, *Nucl. Phys.* **B268**, 427 (1986); L.D. McLerran, R. Venugopalan, *Phys. Rev.* **D49**, 2233, 3352 (1994); **D50**, 2225 (1994); E. Iancu, A. Leonidov, L.D. McLerran, *Nucl. Phys.* **A692**, 583 (2001); E. Iancu, L. McLerran, *Phys. Lett.* **B510**, 145 (2001).

[6] D. Kharzeev, E. Levin, *Phys. Lett.* **B523**, 79 (2001); D. Kharzeev, E. Levin, L. McLerran, *Phys. Lett.* **B561**, 93 (2003b); D. Kharzeev, M. Nardi, *Phys. Lett.* **B507**, 121 (2001).

[7] K. Ozawa *et al.*, *Phys. Rev. Lett.* **86**, 5019 (2001); K.J. Eskola, K. Kajantie, P.V. Ruuskanen, K. Tuominen, *Nucl. Phys.* **B570**, 379 (2000); K.J. Eskola, P.V. Ruuskanen, S.S. Rasanen, K. Tuominen, *Nucl. Phys.* **A696**, 715 (2001).

[8] V. Topor Pop *et al.*, *Phys. Rev.* **C68**, 054902 (2003).

[9] K. Ozawa *et al.*, *Phys. Rev. Lett.* **86**, 5019 (2001); I. Arsene *et al.*, (BRAHMS Collaboration), submitted to *Phys. Rev. Lett.*, nucl-ex/0403005.

[10] D. Kharzeev, Y.V. Kovchegov, K. Tuchin, *Phys. Rev.* **D68**, 094013 (2003a).

[11] K.M. O'Hara, S.L. Hemmer, M.E. Gehm, S.R. Granade, J.E. Thomas, *Science* **298**, 2179 (2002) shows a nice example with a picture.

[12] G. Policastro, D.T. Son, A.O. Starinets, *J. High Energy Phys.* **0209**, 043 (2002).

[13] D. Teaney, J. Lauret, E.V. Shuryak, nucl-th/0110037; P. Huovinen, P.F. Kolb, U.W. Heinz, P.V. Ruuskanen, S.A. Voloshin, *Phys. Lett.* **B503**, 58 (2001) [hep-ph/0101136]; P.F. Kolb, U. Heinz, nucl-th/0305084; U.W. Heinz, P.F. Kolb, hep-ph/0204061.

[14] K. Adcox *et al.* (PHENIX Collaboration), *Phys. Rev. Lett.* **87**, 052301 (2001).

[15] S.S. Adler *et al.* (PHENIX Collaboration), *Phys. Rev. Lett.* **91**, 072301 (2003) [nucl-ex/0304022]; S.S. Adler *et al.* (PHENIX Collaboration), *Phys. Rev. Lett.* **91**, 241803 (2003), hep-ex/0304038.

[16] S.S. Adler *et al.* (PHENIX Collaboration), *Phys. Rev. Lett.* **91**, 072303 (2003).

[17] I. Vitev, M. Gyulassy, *Phys. Rev. Lett.* **89**, 252301 (2002); I. Vitev, *Phys. Lett.* **B562**, 36 (2003); X.N. Wang, *Phys. Lett.* **B565**, 116 (2003); A. Accardi, M. Gyulassy, *Phys. Lett.* **B586**, 244 (2004) [nucl-th/0308029]; P. Levai, G. Papp, G.G. Barnafoldi, G. Fai, nucl-th/0306019.

[18] W. Cassing, K. Gallmeister, C. Greiner, *Nucl. Phys.* **A735**, 277 (2004), [hep-ph/0311358].

[19] STAR Collaboration, *Phys. Rev. Lett.* **91**, 072304 (2003).

[20] S.S. Adler *et al.* (PHENIX Collaboration), *Phys. Rev. Lett.* **91**, 172301 (2003).

[21] R.J. Fries, B. Muller, C. Nonaka, S.A. Bass, *Phys. Rev. Lett.* **90**, 202303 (2003) [nucl-th/0301087]; R.J. Fries, B. Muller, C. Nonaka, S.A. Bass, *Phys. Rev.* **C68**, 044902 (2003) [nucl-th/0306027]; R.C. Hwa, C.B. Yang, *Phys. Rev.* **C70**, 024905 (2004) [nucl-th/0401001]; R.C. Hwa, C.B. Yang, *Phys. Rev.* **C67**, 034902 (2003) [nucl-th/0211010].

[22] V. Greco, C.M. Ko, P. Levai, *Phys. Rev. Lett.* **90**, 202302 (2003), nucl-th/0301093.

[23] PHENIX Collaboration, S.S. Adler, *et al.*, nucl-ex/0408007, to be submitted to *Phys. Rev. Lett.*