RELATIVISTIC HEAVY ION PHYSICS IN THE NEW MILLENNIUM

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The field of relativistic heavy ion physics has seen significant advancement in the new millennium toward a greater understanding of QCD at high temperatures with the commissioning and operation of the Relativistic Heavy Ion Collider (RHIC) starting in 2000. Here we review progress in the field as presented in a set of lectures at the Lake Louise Winter Institute on Fundamental Interactions in February 2004.

1. Introduction

These proceedings are an overview from a set of lectures on the subject of relativistic heavy ion physics as given at the Lake Louise Winter Institute on Fundamental Interactions in February 2004. These proceedings are meant to highlight progress and open questions in the field, and are no where near a comprehensive review of the field as a whole. We begin with a discussion of the goals of the field and a definition of the quark-gluon plasma. We discuss the role of the quark-gluon plasma in the early universe and in relativistic heavy ion reactions. We discuss in detail recent heavy ion experimental results including initial state physics, bulk particle production, collective motion, and partonic probes of the medium. We then summarize with an outlook toward the future.

A number of interesting new results in this field of physics were presented at the International Conference on Quark Matter in January 2004. All of the conference talks are posted on the web at

- http://www.lbl.gov/nsd/qm2004/program.html

This generated multiple articles in the popular press including three in the New York Times all in the same week.[1]

- "Newly Found State of Matter Could Yield Insights Into Basic Laws of Nature"
- "Tests Suggest Scientists Have Found Big Bang Goo"
- "Like Particles, 2 Houses of Physics Collide"

The New York Times articles, though certainly simplifying the physics, do reflect the excitement of the physicists involved, but also the complexity of the system being discovered and the incomplete picture we currently have.

2. Why Are We Here?

The purpose of the field of relativistic heavy ion physics is to observe and understand the nature of Quantum Chromodynamics (QCD) under extreme and novel conditions. QCD as our theory of the strong interaction is full of both fascinating complexity and sometimes also amazing simplicity? It is successful at predicting many experimental observables with great precision, and yet unable to be used to directly calculate the basic characteristics of hadrons. Our inability to study in isolation the nature of the fundamental particles of the theory (quarks and gluons) presents many challenges to furthering our knowledge. What about QCD matter under extreme conditions of high temperature or high density? Can we understand characteristics of the matter that dominated the very earliest stages of the universe? Can we observe characteristics of hot and dense nuclear matter in the laboratory with relativistic heavy ion collisions? Can these observations give us insight about the transition from partons bound in hadrons to a deconfined system of quarks and gluons? These are the questions for which we seek answers.

3. Quantum Chromodynamics

Most of us believe that QCD is the correct quantum field theory for strong interactions. We believe this because of the successful calculation and experimental verification of, among other things, high energy jet yields and the evolution of the partonic structure of the proton as calculated via DGLAP evolution.[2] Figure 1 shows transverse energy jet spectra from CDF in Run II at the Tevatron compared quite favorably with an NLO pQCD calculation.[3]

These examples are next-to-leading order perturbative QCD calculations that are applicable at large Q^2. However, one cannot use the same calculation technique to determine the absolute partonic structure of hadrons, only their evolution in Q^2. Figure 2 shows the strong coupling α_s as a

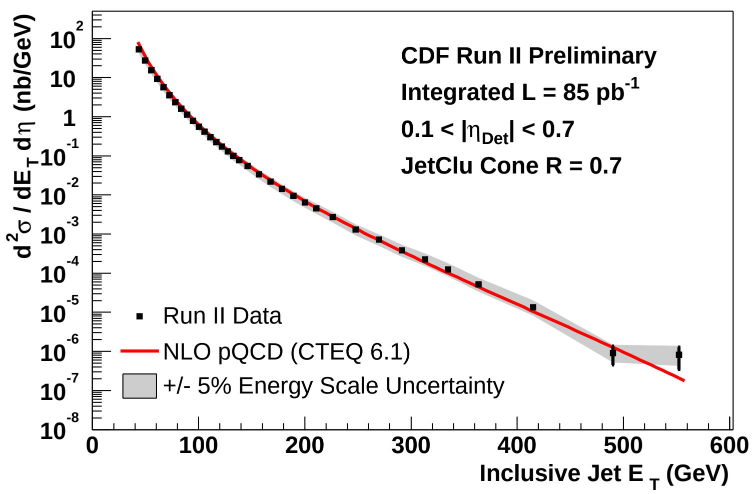

Figure 1. CDF Run II Preliminary Inclusive Jet Yield versus transverse energy compared with an NLO pQCD calculation using CTEQ6.1 Parton Distribution Functions.

function of Q. At large Q, α_s is small and the perturbative expansion is convergent, while at low Q this is no longer the case. So what about the non-perturbative world around us? Using numerical techniques of lattice QCD one can calculate the various hadron masses and obtains agreement at around the 10% level (with the possible exception of the Goldstone boson pions), as shown in Figure 3.[4]

If we want to ask questions about the nature of partonic matter at high energy densities, we are often forced to rely on lattice QCD calculations. However, it should be noted that at truly high temperatures (far above what we can achieve with RHIC or at the future LHC), the average Q^2 for the individual parton-parton scattering can be quite large. This "perturbative" plasma would have only "weakly" interacting quarks and gluons as their interactions would be dominated by the region where α_s is small. However, at temperatures and energy densities more realistic to our experiments ($T \approx 100 - 500\ MeV$), perturbative calculations are sure to break down.

4. Quark-Gluon Plasma

Lattice QCD predicts a phase transition to a quark-gluon plasma at a temperature of approximately $T \approx 170\ MeV \approx 10^{12}$ Kelvin, as shown in

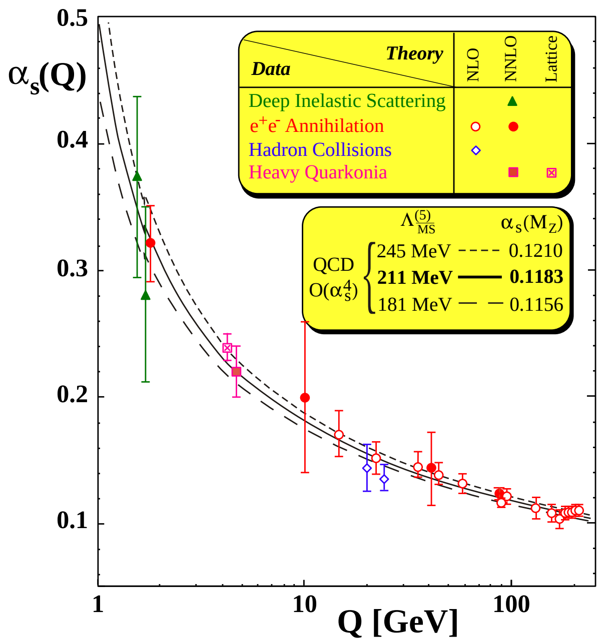

Figure 2. The strong coupling α_s as a function of Q in GeV as measured in various channels.

Figure 4.[5] This transition temperature corresponds to an energy density $\epsilon \approx 1\ GeV/fm^3$, an order of magnitude larger than normal nuclear matter density. Calculations indicate a significant change in behavior of the system over a small change in temperature including restoration of approximate chiral symmetry. Energy densities above the transition value correspond to many hadrons per cubic fermi. Hadrons cannot exist as in vacuum at this density. There is no way for a parton to know which hadron wavefunction it belongs to at this density.

The exact order of this phase transition is not known. In a pure gauge theory (only gluons) the transition appears to be first order. However, inclusion of two light quarks (up and down) or three light quarks (adding the strange) can change the transition between 1st order, 2nd order and a smooth crossover. These calculations are at zero net baryon density and the nature of the transition and the medium itself may significantly change as one changes the net baryon density of the medium.

In the case of massless non-interacting particles, one has a simple relation between the energy density ϵ and the temperature T depending on the

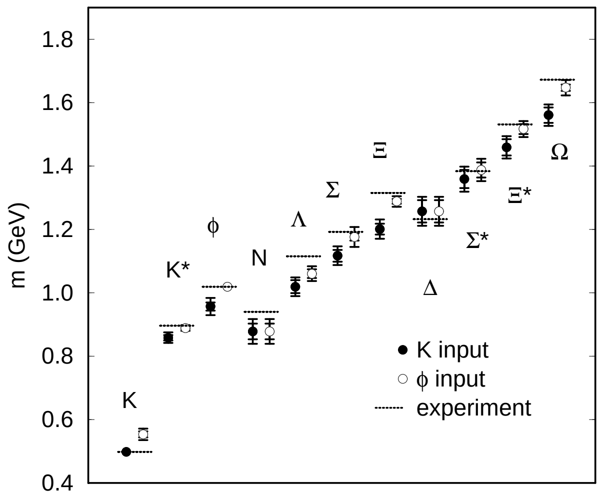

Figure 3. Hadronic masses calculated via lattice QCD compared with the experimentally determined spectra.

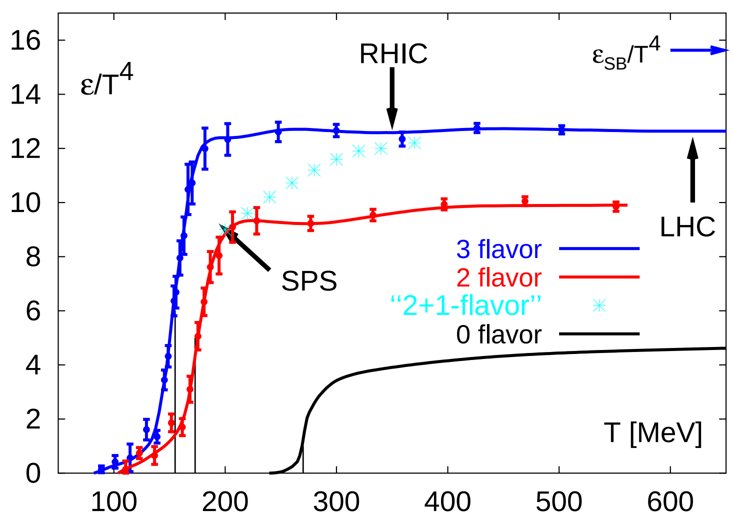

Figure 4. Lattice QCD results for the energy density / T^4 as a function of the temperature (MeV). Note the arrow on the right side indicating the level for the Stefan-Boltzmann limiting case.

number of degrees of freedom in the system g.

$$\epsilon = g\frac{\pi^2}{30}T^4 \tag{1}$$

In the case of temperatures of order $T \approx 100 - 500\ MeV$, in a hadron gas there are three degrees of freedom for the three Goldstone boson pions. However, in a quark-gluon plasma there are over 30 degrees of freedom from the light quarks and gluons.

It is interesting to note that the lattice results indicate a system that is still significantly different from the Stefan-Boltzmann limit. However, many people state that the lattice is "not so far from the non-interacting gas limit", and thus expect a "weakly" interacting gas of quarks and gluons. Walter Greiner states that "in order to allow for simple calculations the QGP is usually described as a free gas consisting of quarks and gluons. This is theoretically not well founded at $T \approx T_c$."[6] The quasi-particles in the plasma may be phonons or plasmons rather than quarks and gluons. The plasmons would arise because near the transition temperature the effective coupling α_s could be large and a dynamical mass $m_g \approx T_c$ could be generated by gluons.

How high a temperature is needed not just to form a quark-gluon plasma, but to approach this "weakly" interacting plasma? A calculation of the pressure of hot matter within perturbative QCD is shown in Figure 5.[7] The pressure result oscillates significantly as one considers contributions of different orders. These oscillations are an indication that the expansion is not yielding reliable results. However at temperatures approaching 1000 times T_C, they appear to be converging toward the Stefan-Boltzmann limit (asymptotically free partons). It is interesting that in considering the highest order term, the results are still non-convergent though one seems to approach the lattice calculated pressure. Due to the high parton occupation, the perturbative expansion is never completely convergent as one gets in single parton-parton scattering.

A schematic version of a phase diagram of nuclear matter is shown in Figure 6.[8] This figure shows a transition to a color superconducting phase of matter at large density and low temperature. In this phase one has partons forming Cooper pairs. At high temperature and low density, the latest lattice results with a realistic strange quark mass indicate, though not definitively, that the transition is a smooth crossover. Thus, there may be a tricritical point in the phase diagram connecting a first order transition at high density to this crossover.

Where can we study nuclear matter under such extreme conditions

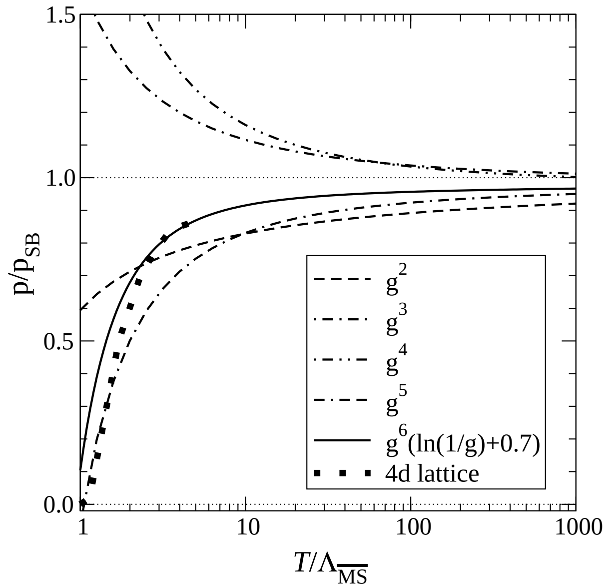

Figure 5. Perturbative QCD results for the pressure as a function of temperature at various orders normalized to the Stefan-Boltzmann value p_{SB}.

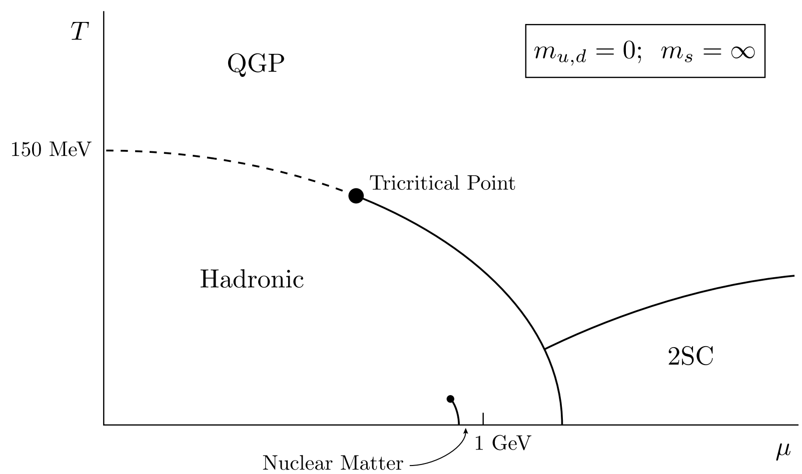

Figure 6. Theoretical phase diagram of nuclear matter, not yet confirmed by experiment.

where we might hope to have advancement in QCD theory and experimental access? The early universe shortly after the big bang is a system

where one almost certainly started out with a "perturbative" plasma which cooled into something we might try to describe on the lattice, and then transitioned into hadrons. Neutron stars are a system with very high net baryon density (of order ten times that of normal nuclear matter), but very low temperature and thus might be relevant for studying the color superconducting phase. And then there is the relativistic heavy ion program where we can control the system in the laboratory.

5. Transitions of the Early Universe

In our current understanding of the history of the universe, shortly after the big bang, the universe went through an enormous expansion during an inflationary period. Post-inflation, the radiation dominated universe gave way to a universe filled with quark-gluon plasma. Six microseconds after the big bang, the universe cooled below a temperature of approximately 200 MeV and the quark-gluon plasma had all the quarks and gluons confined into hadrons. One second later, at a temperature of order 2 MeV, the hadrons (protons and neutrons) formed light nuclei in a process referred to as big bang nucleosynthesis (BBN). Then 300,000 years later, electrons and nuclei (mostly protons) formed atoms, at which point the universe became relatively transparent for photons. Photons at this point largely decoupled from the universe and are the cosmic microwave background we observe today.

We are particularly interested in the transition from a bath of quarks and gluons (quark-gluon plasma) to a system of hadrons (for example protons and neutrons) where the quarks and gluons (partons) are bound.

In a seminal paper, Ed Witten wrote in 1984 that "a first-order QCD phase transition that occurred in the early universe would lead to a surprisingly rich cosmological scenario," and "although observable consequences would not necessarily survive, it is at least conceivable that the phase transition would concentrate most of the quark excess in dense, invisible quark nuggets."[9] These quark nuggets could be in the form of strange quark matter (SQM), composed of roughly equal numbers of up, down and strange quarks. Bubbles of supercooled quark-gluon plasma could have formed strange quark matter nuggets with baryon number ($A >> 1000$).

Strange quark matter could even be more stable than Fe^{55} and thus be the true ground state of nuclear matter. Iron would then decay into SQM, but with a lifetime longer than the age of the universe since it would be a 55th order weak decay. If SQM were not just metastable, but completely

stable, it could be a source of baryonic dark matter. Despite the heavier neutral current mass of the strange quark (relative to up and down), the new flavor quantum number may allow for a lower total energy if the Fermi energy levels for up and down quarks are occupied. Twenty years after Witten's paper many searches for strange quark matter have been made in terrestrial matter, nuclear reactions, and in relativistic heavy ion collisions. All have yielded null results to date.[10,11]

Also, if the plasma-to-hadrons transition were a strong first order phase transition, bubble formation in the mixed phase could have resulted in a very inhomogeneous early universe. Big bang nucleosynthesis calculations assume a homogeneous universe. This line of investigation was quite active when the dark matter issue raised questions about the implied baryon content of the universe as derived from big bang nucleosynthesis. An important question is whether inhomogeneities from bubbles in the mixed phase would survive diffusion as the universe cooled down to 2 MeV when BBN occurred? Are the bubbles too small and close together such that diffusion erases the inhomogeneities before nucleosynthesis?

In 2001, the Boomerang Experiment reported that "The value deduced from the second harmonic in the acoustic oscillations for $\Omega_B = 0.042 \pm 0.008$ (cosmic baryon mass density) is in very good agreement with the value one gets by applying the theoretical details of primordial big bang nucleosynthesis to the observations of cosmic abundances of deuterium."[12] Does this observation rule out a first order phase transition in QCD? This confirmation of BBN does not rule out a first order phase transition in QCD because of the diffusion issue, but places some model dependent limit on the level of supercooling and bubble formation in the transition.

The universe at 300,000 years old is extremely homogeneous, isotropic to one part in 100,000. The WMAP experimental results now provide an amazing advance in our precision knowledge of the early universe, though still little constraint on the quark-gluon plasma phase. Unfortunately nothing decoupled at the QCD transition for us to still measure today, like the photons 300,000 years later when atoms were formed. Thus, the study of extreme QCD in this regime must turn to accelerators rather than the sky.

6. Relativistic Heavy Ion Collider

The Relativistic Heavy Ion Collider (RHIC) facility is located at Brookhaven National Laboratory in Upton, New York, USA. The facility was first commissioned and brought on-line in 2000. Heavy ion reactions

have been studied over the last three decades at ever increasing energy. At the lowest energies, the reactions exchange protons and neutrons and one can study issues of nuclear structure. At intermediate energies, the nuclei are largely broken apart and one has a cascading of nucleons and excitation of hadronic resonances. At the Brookhaven AGS and CERN SPS fixed target programs, one hoped to create the quark-gluon plasma state, albeit with higher net baryon density and lower temperature than at RHIC. Most of this presentation focuses on the recent RHIC results, but it should always be kept in mind how these results connect and build upon lower energy results. Certainly as the Large Hadron Collider (LHC) heavy ion program begins in 2007, the connections between RHIC and LHC will be a critical tool for understanding QCD matter.

The first gold-gold collisions at RHIC were observed by all experiments in June 2000 at $\sqrt{s}_{NN} = 130\ GeV$. There was immediately some "interesting" press coverage about possible disaster scenarios if RHIC created a black hole. As a simple exercise, the Schwarzschild radius for all the energy deposited in a RHIC collision would be 10^{-49} meters, which is much smaller than the Planck length! In comparison, the compression in the reaction and subsequent expansion is never expected to have a system smaller than 10^{-16} meters. If we ignore the conflict of quantum mechanics and general relativity at the Planck scale, we find the black hole, even if somehow there is over three orders of magnitude more compression than expected, would evaporate by Hawking radiation in 10^{-83} seconds.

RHIC has been quite successful in its commissioning of the heavy ion program and in 2004 (the fourth running year of the collider), the design energy $\sqrt{s_{NN}} = 200\ GeV$ and design luminosity for gold-gold collisions was achieved, and more importantly, successfully run over many months of data collection. As we stated at the conference "RHIC is kicking butt!"

7. Experiments

There are four dedicated experiments in the RHIC program for heavy ion studies. The two large scale experiments are STAR and PHENIX. The STAR experiment focuses on hadronic observables over a very large acceptance. Their detector consists of a solenoid magnetic field and a large coverage time-projection chamber (TPC). The TPC is the primary tracking device and is augmented by an inner silicon detector, ring-imaging Cerenkov detector, electromagnetic calorimeter and time-of-flight system. The PHENIX experiment focuses on electromagnetic probes of the medium.

The detector is comprised of four separate spectrometers. Two at 90 degrees with tracking detectors, ring imaging Cerenkov counter, and electromagnetic calorimetry all used to identify photons, electrons and hadrons. Two spectrometers at forward angles are designed to track muon primarily for reconstruction of quarkonia states.

The two smaller experiments are BRAHMS and PHOBOS. BRAHMS has two rotating spectrometer arms with excellent hadron particle identification detectors. Their spectrometers cover the broadest range of rapidity for identified hadrons. PHOBOS characterizes the reactions over nearly 4π with silicon detectors. Additionally they have a central spectrometer to measure charged hadrons in many silicon layers, augmented with a time-of-flight scintillator system.

8. Initial State Physics

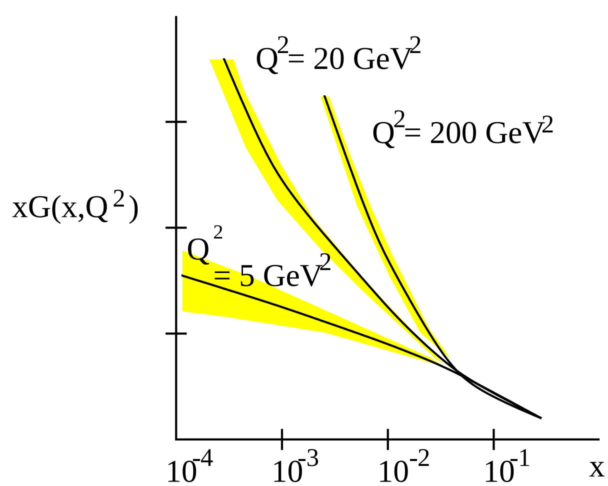

Figure 7. Gluon Structure $xG(x, Q^2)$ as a function of x for three values of Q^2.

In this section we review the relevant physics of the initial state, before the two nuclei collide and immediately afterwords. Deep inelastic scattering (DIS) experiments at HERA have revealed an amazing complexity of the partonic structure of the proton. At short wavelength (large values of Q^2) there is an enormous growth of low x gluons in the proton's structure. Note that x is the fraction of the proton's momentum carried by the parton. In

fact, at high Q^2 the proton is almost completely dominated by this sea of gluons as shown in Figure 7.[13]

When we collide heavy gold ions at RHIC, we essentially ignore the nuclear shell structure for nucleons since the kinetic energy of the reaction easily overwhelms the nuclear binding energy. Since the energy is quite large, one can think of the collision as being between two walls of gluons. In that sense, some people have referred to RHIC as a gluon collider. The nuclei are merely containers for transporting these gluons to the collision point.

In the collision, of order 10,000 gluons, quarks and anti-quarks (mostly gluons) are freed from their virtual excitation in the nuclear wavefunction and made physical in the laboratory. What is the nature of this ensemble of partons? One thing for certain is that it represents a major technology and detector challenge to measure and characterize these reactions. The RHIC experiments and community have successfully met this challenge and the detectors have all worked remarkably well in this high particle density environment.

8.1. *Particle Multiplicity*

In collisions of electrons and positrons (e^+e^-), the annihilation can yield back to back outgoing quark and anti-quark partners. Due to the confining nature of QCD, these partons fragment into hadrons, collectively referred to as jets. One can ask the question of how this hadronization process results in a certain multiplicity of hadrons and the energy distribution among these hadrons. At reasonably high energy one can calculate perturbatively the evolution of radiated gluons by this quark and anti-quark. If one then assumes parton-hadron duality (one scale factor), one can predict the collision energy dependence of the hadron multiplicity. Calculations by Mueller and others reveal an excellent agreement with the experimental data from $\sqrt{s}$ of 10 to 200 GeV.[14]

In proton-proton and proton-antiproton reactions, the hadron multiplicity is noticeably lower than in e^+e^- reactions at the same $\sqrt{s}$. One can understand this qualitatively since much of the available energy in proton-proton reactions is carried in longitudinal motion, often referred to as incomplete stopping or the leading particle effect. In fact, if one scales the $\sqrt{s}$ down to account for the energy in the forward direction, one sees reasonable agreement between the e^+e^- and proton-proton reactions.[15] This is a surprising scaling observation since in the e^+e^- case one can calculate the

the multiplicity perturbatively, but in proton-proton reactions one cannot since their is not a set of simple diagrams and gluon radiations.

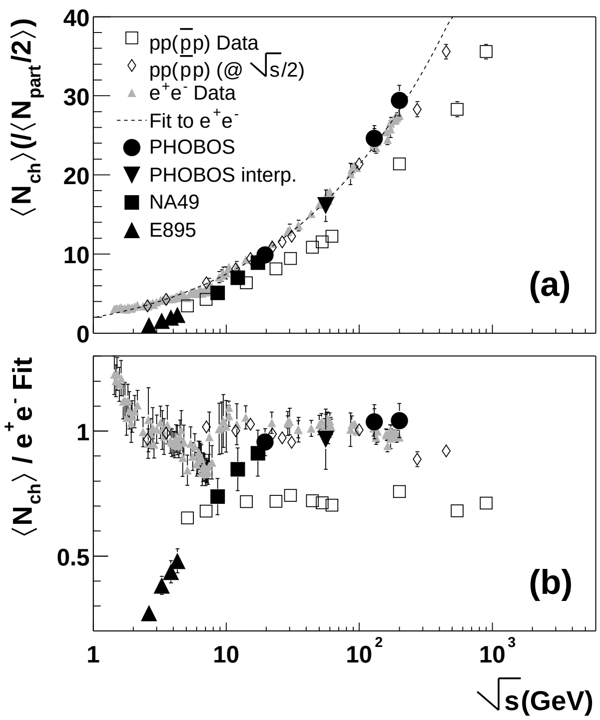

Figure 8. Charged particle multiplicity per participant pair as a function of $\sqrt{s}$ for proton-(anti)proton and heavy ion gold-gold data. Also shown are the e^+e^- data and a best line fit.

The PHOBOS experiment has checked this scaling now including heavy ion reactions.[16] As shown in Figure 8, one observes a reasonable similarity in the energy dependence. What does this mean? It is difficult to reconcile since if the only thing that mattered was the total energy deposition per unit volume, perhaps this scaling is expected. However, it is claimed that e^+e^- does not follow a statistical distribution, but rather the perturbative gluon radiation distribution. This is an active discussion, but for example the large difference in multiplicity between gluon and quark jets implies that not all energy is equally available for charged particle production.

These global observations are puzzling. One might ask if e^+e^- reactions

are then the same as gold-gold. The clear answer is no, but it may be that the mechanism for deciding how energy is distributed between particle multiplicity and kinetic energy per particle reflects some simple underlying physics.

8.2. *Proton and Nuclear Parton Structure*

One theoretical framework to attempt to understand the multiplicity of particles, is by viewing particle production as freeing virtual partons from the incoming nuclear wavefunction. As stated previously, the proton and nucleus are dominated by low x gluons when viewed at high Q^2. One of the great successes of QCD is the agreement of NLO DGLAP evolution over a broad range of Q^2.[2] However, the DGLAP fits have many free parameters (18-30) and the form of the parameterization is not given by theory. In fact, for Q^2 of order 1 GeV^2, the gluon density is going negative. This is physically allowed but may still be a hint of a breakdown in DGLAP. One problem in interpreting this data is that for the HERA experiments the lowest x values probed are always at the lowest Q^2, where the breakdown of NLO DGLAP may not be surprising. The current HERA running may not resolve these issues since machine changes limit the coverage at the lowest x values. Future electron-ion collider (eRHIC) or future running at HERA may be needed.

One explanation for the breakdown of DGLAP is given in the context of gluon saturation models. In deep inelastic scattering (DIS) the physics is often described in the target rest frame. One can imagine the photon as fluctuating into a quark and antiquark pair (color dipole). As one evolves to higher Q^2 the color dipole radiates additional gluons until one approaches the unitary limit of the cross section. It has been shown that this is the equivalent to a very different description in the probe rest frame. Now imagine a probe striking a very Lorentz contracted proton or nucleus. The wavefunction of low x gluons will overlap and the self-coupling gluons fuse. This then saturates the density of gluons in the initial state. Venugopalan, McLerran and collaborators show that in this limit, factorization breaks down and one can describe the proton or nucleus in terms of classical gluon fields as solutions of the Yang-Mills equation.[13] These solutions are often referred to as the color glass condensate (CGC). Note that while one could potentially make a physical system in this saturation regime, in the nuclear wavefunction the CGC is like a Fock state of the wavefunction, and so not the same as a state of matter like the quark-gluon plasma.

It is now well established experimentally that the nucleon structure functions are modified in nuclei. There are various modifications including suppression of partons at high x (EMC effect), possible enhancement of partons at intermediate $x \approx 10^{-1}$ (anti-shadowing), and large suppression of partons at low $x \approx 10^{-2}$ and below (shadowing and possibly saturation). In the low x regime, one can think of the gluons from all the nucleons in the nucleus in a longitudinal slice as overlapping and thus enhancing the gluon recombination (more saturation).

$$xg(x_{eff}, Q^2) = A^{1/3} xg(x, Q^2) \tag{2}$$

Thus, it may be true that at low $Q^2 \approx 1 GeV^2$ an x value of 10^{-7} in the proton might be the equivalent of 10^{-2} in a nucleus. This remains to be tested.

These saturation models have been applied to RHIC data and predict the total charged particle multiplicity distributions with a free parameter for the saturation scale Q_{sat} for gold nuclei. It is not directly calculable the relation between the saturation scale in the proton measured at HERA and for a gold nucleus measured at RHIC. Kharzeev and collaborators find quite good agreement with the growth of charged particle multiplicity with reaction impact parameter, and also the angular distribution of charged particles.[17] They assume that the saturation scale drives all the physics and then invoke parton-hadron duality with a scale factor to compare with experimental results. This agreement is intriguing, but not yet compelling. A key question is whether this universal behavior of QCD in the saturation limit is the driving physics at HERA and RHIC and whether the details to relate the calculations to final state hadronic observables are well constrained. Comparison with the transverse energy production is another important check.[18]

One major issue is that at RHIC particle production is dominantly from low Q^2 processes where one cannot compare the saturation picture to a firm QCD prediction without saturation. In addition, there are expected to be medium effects that can mask the physics. In Run III at RHIC there was a study of deuteron-gold reactions where one expects almost no medium effects. It should be noted that this running is nearly equivalent to proton-gold reactions, but with the matched rigidity of the two beams, the accelerator was able to achieve collisions without having to move the intersection DX magnets. If one looks at forward rapidity, one is effectively

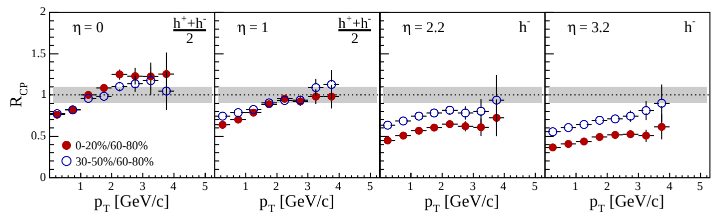

Figure 9. BRAHMS experimental results on charged hadron production in deuteron-gold reactions for different pseudo-rapidities as a function of transverse momentum. The ratio of yields in central to peripheral reactions scaled by the nuclear thickness ratio is shown.

probing lower x partons in the gold nucleus.

$$x \approx \frac{M}{\sqrt{s}} \times e^{-y} \tag{3}$$

Data from the BRAHMS experiment indicates a significant suppression of hadrons at moderate p_T as one measures at more forward rapidity, as shown in Figure 9.[19] This may be an indication of nuclear shadowing as described via saturation, though more quantitative comparisons must be made. Also, this intermediate p_T is not free from soft physics contributions which may complicate the interpretation. Additionally, the PHENIX experiment has shown similar data but also at backward rapidity, thus sampling high x partons in the gold nucleus. This may shed light on anti-shadowing, and perhaps help disentangle the soft and hard physics contributions.

9. Collective Motion

After the initial set of partons are freed from the nuclear wavefunction, either via the color glass condensate or otherwise, they have the possibility to interact with each other. Alternatively if they behave as a non-interacting ideal gas, they may simply exit and individually hadronize eventually leaving signals in our detectors. This would simply appear as a superposition of proton-proton reactions.

We have an excellent experimental handle on the coupling of the partons in the system, through what is referred to as elliptic flow. In non-central gold-gold reactions, the created system is almond shaped with very different density gradients along the impact parameter direction and perpendicular to it. This large spatial anisotropy can be translated into a momentum space anisotropy if there is a large pressure (microscopically, a lot of rescattering). Experiments can measure the azimuthal angle distribution of

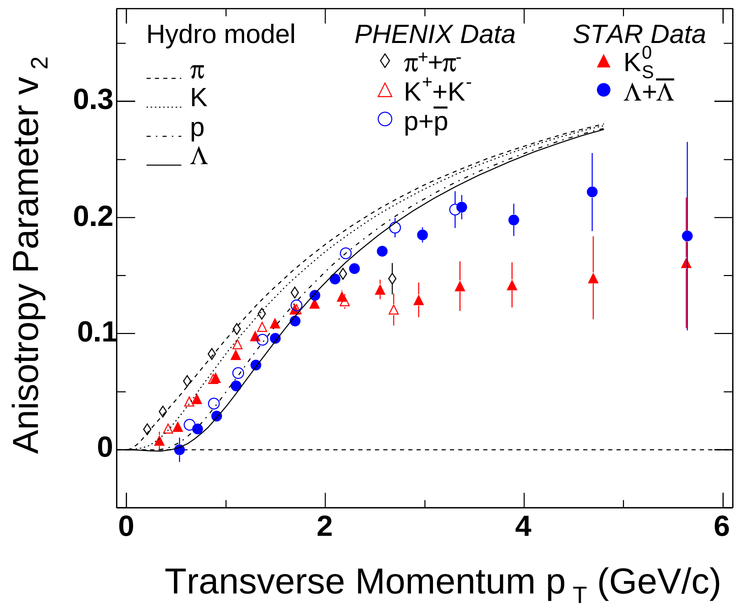

Figure 10. Anisotropy parameter v_2 as a function of p_T for various hadron species. Also shown are results from a hydrodynamic model calculation.

particles and make a Fourier decomposition. The second component v_2 is referred to as the elliptic flow.

As shown in Figure 10 there is a large v_2 that is increasing with transverse momentum for all hadronic species measured.[20,21] Even the multi-strange baryons as measured by the STAR experiment appear to have large collective behavior. PHENIX has shown preliminary data that give a slight hint that the charm mesons may follow a similar flow pattern, though more data needs to be analyzed to confirm such a result.[22,23]

If one assumes that there is enough re-scattering to achieve local equilibration, and we assume some initial conditions for the density, one can make use of hydrodynamic calculations. One can use simple equations of motion which are solvable using an equation of state, that is derived from lattice QCD. There is good agreement between the experimental data at mid-rapidity for identified hadron transverse momentum spectra and also the v_2 at low transverse momentum $p_T < 2\ GeV$. It is notable that the hydrodynamic description fails above this p_T which may not be surprising

as there must be a finite scattering limit. It is also extremely important to note that the energy density and starting time for the calculations is of order $\epsilon \approx 20\ GeV/fm^3$ and $t \approx 1 fm/c$.[24,25]

The success of the hydrodynamic calculations with zero additional viscosity (which would result from finite mean free paths) has led many to conclude that the system must be "strongly" coupled (i.e. lots of re-scattering). Molnar and collaborators have made a parton cascade calculation including only the perturbatively calculable part of the scattering cross section.[26] Effectively this is a calculation of a "perturbative" "weakly" interacting plasma of quarks and gluons. One can think of the partons as having asymptotic freedom within the medium. Most likely this is not applicable to RHIC collisions since α_s is still large for average parton-parton scatterings, but is an important benchmark. They find they under-predict the v_2 for hadrons leading many to conclude that we have formed a "strongly" coupled system, in contrast to the calculations "weakly" coupled perturbative system, which is perhaps not so surprising. It should be noted that there is a question of how to map from the partonic v_2 in the calculation to the hadronic v_2 that is measured. This issue needs clarification since a parton coalescence mechanism (as discussed later) may significantly enhance the resulting hadron v_2.

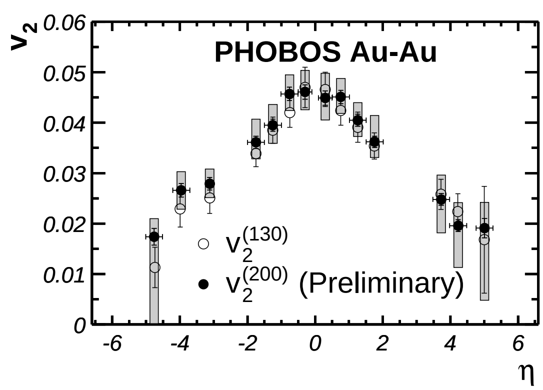

Figure 11. PHOBOS measured v_2 for charged particles as a function of pseudo-rapidity in gold-gold reactions at two energies.

The hydrodynamic models have trouble describing the longitudinal motion, where it is observed that v_2 falls quite quickly in moving to forward

and background rapidity, as shown in Figure 11.[27] Many of the models assume boost-invariance, as in the Bjorken expansion scenario, which is not supported by the BRAHMS rapidity distribution of pions. Some have argued that this is due to dissipative effects. One must be careful to not simply assume lack of full equilibration wherever the models do not agree with data. Also, the lifetime for the system implied by the two particle correlation (Hanbury-Brown Twiss) are essentially the same as at lower energies. Perhaps this is a complex influence of late stage resonance gas and re-scattering, but this HBT puzzle needs to be resolved before one might draw more detailed conclusions about the equation of state.

Agreement with hydrodynamic calculations is a strong indicator of thermalization of the system. However, so far no calculation is able to in detail understand the dynamics of how such fast thermalization, less than $1 - 2\ fm/c$, is possible. One complication in interpreting the v_2 result is the balance between the equation of state and degree of thermalization. One can imagine that as one increases the pressure of the system toward the Stefan-Boltzmann limit, the collective motion v_2 should increase. However, as the pressure is increasing, the interactions are actually decreasing in strength. Thus, as one has a more weakly coupled system, the time for equilibration (when one can apply the pressure) is getting longer. Since the system lifetime is quite short, of order $10\ fm/c$, it might be that the v_2 would start to decrease. In fact, if one went to a non-interacting gas limit, despite very large pressure in equilibrium, the system would never approach equilibration and thus have no v_2. A non-interacting gas cannot generate elliptic flow. Thus, even though a quark-gluon plasma will never truly be non-interacting, there is a competition between equilibration and pressure. Interesting comparisons of v_2 with lower energy data may help shed light on this question.

Also, the data appear to favor an equation of state with a soft-point corresponding to a large latent heat in a phase transition as predicted via lattice QCD. However, any strong conclusion needs a more systematic check on the uniqueness of the initial conditions, thermalization time, level of equilibration and equation of state.

10. Probes of the Medium

Normally we would characterize an electromagnetic plasma by sending a well calibrated probe through the medium and observing its interactions. Is the plasma transparent or opaque to our probe? In nuclear and particle

physics there is no feasible mechanism to aim a probe to intersect at the space and time where the particle collision occurs. Therefore all our probes of the medium must be internally generated.

A unique feature at RHIC over lower energy experiments is that there is an appreciable rate of hard (high Q^2) parton-parton scattering embedded in proton-proton and gold-gold reactions. These hard scatterings can be calculated within perturbative QCD, and are thus calibrated. For example, in proton-proton reactions one can determine the yield of high transverse momentum neutral pions by assuming co-linear factorization, universality of parameterized structure functions and fragmentation functions, and pQCD determined parton-parton scattering cross sections.

$$\frac{d\sigma_{pp}^{\pi^0}}{dyd^2p_T} = K \sum_{abcd} \int dx_a dx_b f_a(x_a, Q^2) f_b(x_b, Q^2) \frac{d\sigma}{dt}(ab \to cd) \frac{D^0_{h/c}}{\pi z_c} \quad (4)$$

One finds that these calculations agree with the PHENIX neutral pions measured at 90 degrees from $p_T \approx 2 - 13\ GeV$, at the level $\pm 50\%$.[28] This agreement is at the level of the uncertainties due to the scale chosen for the perturbative expansion and variations in gluon fragmentation function parameterizations.

It should be noted that pQCD is well tested and calculationally under control compared to non-perturbative physics. However, there are some important disagreements. For example beauty production differs form NLO pQCD by a factor of 2-3 (though slightly reduced in recent years)[29] and direct photons differ from NLO pQCD at lower energies and moderate p_T.[30] At RHIC at the lowest p_T for the neutral pions ($p_T \approx 2 - 4\ GeV$) one may really not expect pQCD to be accurate since the coupling α_s at this Q^2 is not so small and the NLO calculation may miss important contributions to the scattering.

10.1. *Experimental Observations*

One can extend these calculations to nuclear reactions by including the scaling by the nuclear thickness function. If the parton scatterings are point-like, then they should simply scale with the nuclear thickness. Modifications from this scaling may indicate nuclear modifications in the initial state parton distribution functions or modifications in the final state fragmentation (medium effects).

What about in heavy ion reactions? PHENIX measurements of neutral pions in peripheral (large impact parameter events) agree very well from

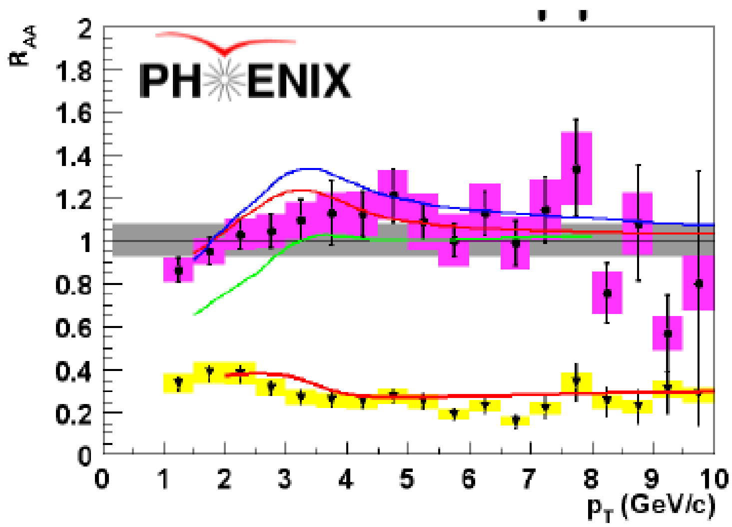

Figure 12. PHENIX data on R_{AA}, the ratio of neutral pion yields in AA reactions relative to pp reactions scaled by the nuclear thickness, shown as the lower triangles. The upper data points are R_{dA} comparing yields in deuteron-gold reactions to proton-proton.

$p_T \approx 2 - 8\ GeV$ with the proton-proton result including the calculated nuclear thickness scaling. However, for central gold-gold reactions (small impact parameter) the heavy ion data is suppressed by a factor of 4-5 relative to expectations as shown in Figure 12.[31] There are four possible explanations for this large scaling violation.

(1) One is that the initial density of partons in the incoming nuclear wavefunction is suppressed. This so called initial-state effect could be the result of nuclear shadowing or saturation where the number of partons in the PDF is reduced. The expected level of nuclear shadowing does not explain such a large suppression, but there are more extreme shadowing proposals where the gluon density saturates as described in color glass condensate models.

One prediction of a large initial-state suppression is that some suppression should remain if one studies these high p_T processes in proton-gold or deuteron-gold reactions. The gold nucleus would still have a suppressed low x partonic content. However, control experiment deuteron-gold data from all four RHIC experiments shows no such suppression for hadrons at 90 degrees to the reaction, as shown with PHENIX data in Figure 12.

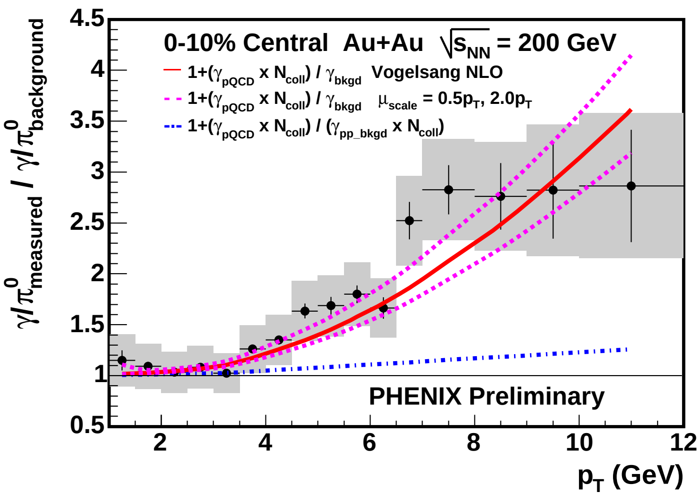

Figure 13. PHENIX preliminary direct photon results in central gold-gold reactions. The data is plotted as a ratio of photons to neutral pions for data compared to simulation (including no direct photons). The observed excess is consistent with NLO pQCD expectations for direct photons scaled by the nuclear thickness, but with neutral pions suppressed as previously measured by PHENIX.

Another key check of initial-state effects is the observation of direct photons (gluon-Compton produced). In the direct photon case, the co-linear factorization equation still applies except the photon does not interact in the medium and has no fragmentation. Thus it is mostly sensitive to the initial PDF's and the gluon-quark scattering cross section. PHENIX has measured all photons and then subtracted off photons from π^0 and η decays. The remaining direct photon yield is quite consistent with NLO pQCD calculations scaled by the nuclear thickness function as shown in Figure 13.[32] Additionally, preliminary results from the PHENIX experiment show that the total charm quark cross section appears to scale with the nuclear thickness.[22] Since charm is dominantly produced in initial hard reactions and then conserved through the medium evolution, it is quite sensitive to any modification to the incoming nuclear flux of gluons.

Note that the deuteron-gold results and direct photon and charm results do not rule out any initial state effect (of the order 20-30%); however, they do rule out an initial-state effect as being the dominant contributor to the suppression seen in gold-gold reactions.

(2) Two is that the hard scattered partons interact in the medium which modifies the energy distribution of resulting hadrons. Partons will multiple scatter with other color charged objects in medium and thus will lose energy via induced gluon radiation (bremsstrahlung). As the leading parton and all the additional radiated gluons must eventually hadronize, the experimental observable is a softening of the fragmentation function. Most calculations of the angular distribution of the final hadrons indicate that the jet distribution will be somewhat broader since the radiated gluons can have of a wider angular distribution.

(3) Three is that the pQCD calculated hard scattering cross section is incorrect. This possibility seems quite unlikely given the agreement of the NLO pQCD calculation with the proton-proton data. In addition, above $p_T > 10\ GeV$ there should be no remaining soft contribution to the neutral pions.

(4) Four is that there is a complete breakdown of co-linear factorization and universality. This is a possibility not often discussed that one should keep in mind. In this dense color environment there may be much more complex couplings that violate the factorization altogether.

Here we will focus more on the second scenario of medium induced modification. Calculations using perturbative QCD give quite good agreement with experimental data and imply a gluon density of order $dN_g/dy = 1100$ for central gold-gold reactions.[33,34] These calculations require some additional input on initial state multiple scattering, shadowing and re-absorption of gluons to completely describe the data. It is critical to note that the energy density implied by these calculations is of the same order as the energy density needed to drive the hydrodynamic calculations into agreement with the experimental v_2 data.

An excellent test of this theory is in doing the same calculation for heavy quarks. At intermediate p_T the light quarks are moved at almost the speed of light, but heavy quarks have a much lower velocity. Thus there is an expected suppression of radiation in a forward cone called the "dead-cone" effect. This means that heavy quarks should not be as effected by induced gluon radiation. Data from the PHENIX experiment appears to support this "lack of suppression" but more statistics at higher p_T are needed.[22] An additional idea is to look for three jet events in the LHC heavy ion program with ATLAS and CMS.[35] Since at least one jet must be a gluon, it will have a larger color coupling to the medium and lose substantially more energy.

It will be extremely useful to have some theoretical systematic errors

applied to these calculations. Originally it was thought that in the presently available RHIC range $p_T < 15~GeV$, a reliable quantitative prediction of quenching cannot be made due to the soft singularity that causes instability of the pQCD description. In one formalism for these calculations[33], they assume that no gluon modes propagate below the plasma frequency. This provides a natural scale for the infrared cutoff. However, this would also then be true for the 0th order radiation and the normal fragmentation process would be also be modified. There have been attempts to include this for heavy charm and beauty quarks, but not for light quarks.[36]

The above calculations assume that the interaction with the medium is purely partonic. Certainly at high p_T simple formation time considerations make it unlikely that hadrons are formed in medium. One interesting piece of experimental data comes from deep inelastic scattering on nuclei by the HERMES experiment. They measure electrons (positrons) exchanging a photon with a quark in a nucleus. By the deflection of the lepton one knows the energy given to the struck quark. The quark then propagates through the remainder of the nucleus and can have interactions in this “cold” or normal nuclear medium. They observe a large suppression of high z fragmentation hadrons. They observe that larger nuclei show larger suppression as shown in Figure 14.

The data have been interpreted in the same manner as heavy ion reactions, i.e. parton multiple scattering and induced radiation softening the fragmentation function.[38] It should be noted that if the parton is of sufficient energy (short enough wavelength), then it probes the individual partons inside of the nucleon constituents of the nucleus. Thus this energy loss is not sensitive to whether the partons are deconfined as one might expect in a heavy ion created media or confined, as one knows is the case for a normal nucleus.

There is an alternative interpretation of the HERMES data in which the hadrons are formed in medium and high z fragments are suppressed by hadronic interactions with the nucleus. The observation of a large hadron species dependence of the suppression is a challenge to the partonic energy loss picture. One important question is whether the time scale for the parton to come on-shell and hadronize is the same in these reactions as at RHIC.

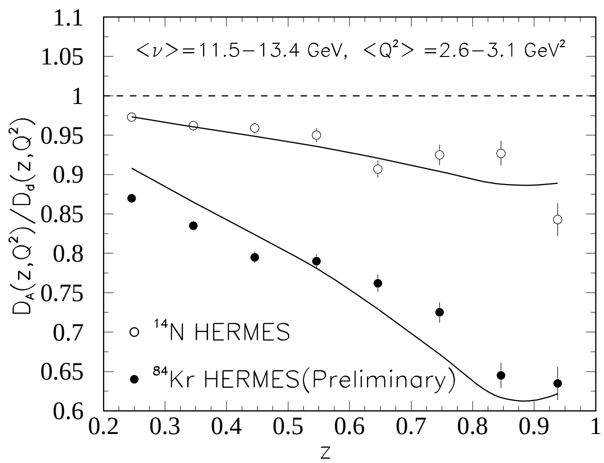

Figure 14. HERMES data comparing the relative fragmentation probability D(z) in DIS reactions on different thickness nuclear targets..

10.2. *Jet Observations*

Jet correlations are an important test in determining what type of final state medium effect may be at play. At RHIC, the detectors are not designed for complete jet energy reconstruction with large coverage electromagnetic and hadronic calorimetery (as in CDF, D0, ATLAS, CMS). In part this is from budget considerations, in addition to the fact that the soft particle backgrounds at RHIC dominate jets within a typical jet cone size for jets less than 40 GeV.

However, the experiments can characterize jets and verify that high p_T hadrons are the result of parton-parton scattering. STAR and PHENIX measure the azimuthal angular distribution of all particles relative to a high p_T trigger particle. One observes a clear "near-angle" peak from other fragmentation products of the jet and an "away-angle" peak from fragmentation of the partner scattered parton. The away side peak is broader due to acceptance limitations in the longitudinal direction (rapidity) and energy imbalance of the two jets from final state radiation.

In proton-proton reactions, this back-to-back angular correlations is shown in Figure 15.[39] In central gold-gold reactions, the away-side jet correlated hadrons disappear. As seen in Figure 15, the near side distribution is of similar strength to that in proton-proton, but the away side correlation is completely gone. Note that this analysis has trigger particles from $4-6\ GeV$ and only includes associated particles with $p_T > 2\ GeV$. Conser-

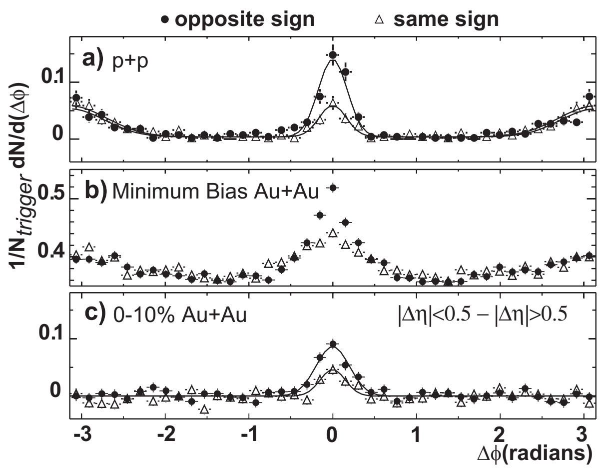

Figure 15. Azimuthal distributions of same-sign and opposite sign pairs for a) p+p b) minimum bias Au+Au and c) background subtracted central Au+Au collisions. All correlation functions require a trigger particle with $4 < p_T^{trig} < 6\ GeV/c$ and associated particles with $2 < p_T < p_T^{trig}\ GeV$.

vation of energy and momentum says that the away side jet cannot really disappear. Where has the energy gone? One schematic way to think about the back-to-back jets is that if the medium somehow suppresses jet products, then a high p_T trigger particle biases the "near-angle" jet to have come from the surface of the medium (thus less medium suppression). If the "near-angle" is biased toward a short path through the medium, then the "away-angle" is biased toward a long path through the medium. Perhaps partons lose energy in medium, and thus the fragmentation products are all below $p_T = 2\ GeV$. Perhaps some type of multiple scattering causes a broadening of the angular distribution that appears to remove the correlations. My particular favorite idea is that we might form black holes at RHIC, which though evaporating quickly via Hawking radiation, might absorb the jet. Though this is not a sound physics idea, it definitely gets lab management's attention.

The answer to this question of the missing energy was partially given at the Quark Matter 2004 conference. PHENIX showed preliminary results with a lower p_T threshold that reveal a substantial broadening of the "away-angle" jet as one compares proton-proton, peripheral gold-gold and central gold-gold reactions.[41] The broadening is more than a factor of two. The STAR experiment showed preliminary results that with greater

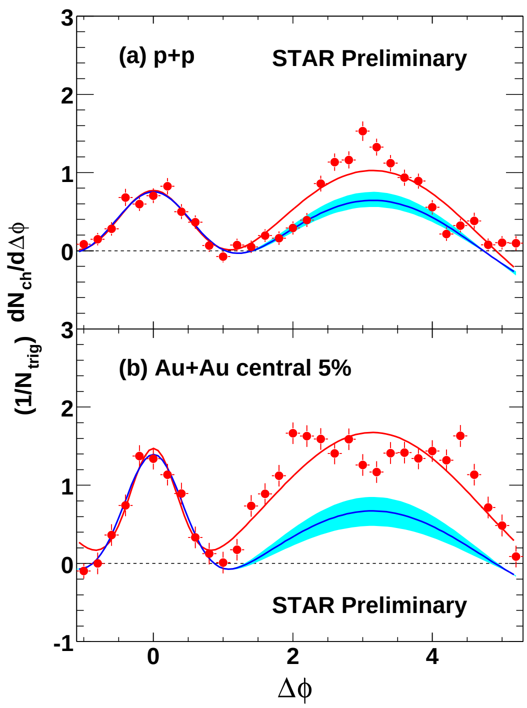

Figure 16. Preliminary results from the STAR experiment on azimuthal distributions of hadrons in proton-proton and gold-gold reactions. The threshold for inclusion of hadrons in the correlation distribution is $p_T > 200\ MeV$.

statistics and reducing the p_T cut on the correlated hadrons all the way down to 200 MeV, they then see the "away-angle" correlation.[40] Though the distribution does not appear jet-like, it answers the question of what happened to the energy of momentum. One exciting observation is that the broadened, energy reduced jet fragmentation products end up with a momentum of order 500 MeV. This is not so different from the $< p_T >$ of the bulk medium. Thus, one might speculate that the jet energy has been completely thermalized in medium if it has a long enough path through the medium.

11. Hadronization

Another unique observation at RHIC is the particle ratios at intermediate $p_T \approx 2-5\ GeV$. The jet correlation measures indicate that this momentum

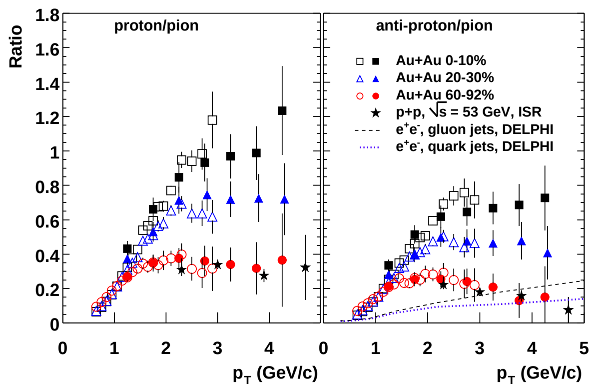

Figure 17. PHENIX ratio of (anti) protons to pions as a function of p_T for various centralities.

range has large contributions from jet fragmentation; however PHENIX and STAR observe a large enhancement of the (anti) baryon to meson ratio in this transverse momentum range, as shown in Figure 17.[42] This antibaryon and baryons excess is very different from the jet fragmentation expectation where the ratio of baryons to mesons is always less than one. The parton energy loss picture predicts that the hadrons are still produced from jet fragmentation. A recent proposal is that these intermediate baryons and mesons have a large contribution from valence quark recombination or coalescence rather than fragmentation.[43] Since to form a baryon one needs three co-moving quarks instead of two for a meson, there is an additional p_T push. These models must be confronted with more data on jet correlations for the mesons and baryons and detailed multi-strange baryons data. One must also distinguish checks on recombination as a hadron forming mechanism and the underlying distribution of partons that contribute to this recombination.

12. Conclusions

The relativistic heavy ion program has passed the first key test. The nuclear physics community is capable of constructing and running world class "high-energy" type experiments and re-constructing the physics from the 10,000 particle debris. The second phase has arrived. Observations have been made of a very dense gluonic medium with strong pressure built up. The gluon density is above the predicted phase transition level and behaving with characteristics of a fluid. The third phase is next: heavy quarko-

nia measurements to test color deconfinement, low mass vector mesons for parton correlations in the plasma, and future comparisons with the Large Hadron Collider heavy ion program.

We have determined experimentally that a volume of matter is created the size of a gold nucleus that is equilibrated with an initial energy density of order ten times nuclear matter density. If you combine this with the lattice results, you reach the obvious conclusion that we have created a quark-gluon plasma. However, we do not yet have, in my opinion, compelling experimental evidence of some of the expected unique plasma properties predicted by QCD. Thus, we know that we have created the quark-gluon plasma, but at present do not have enough information to declare a discovery - which necessitates conclusive evidence of some unique plasma features. This is what the future holds.

13. Acknowledgments

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This proceedings is dedicated to my daughter Madeleine Rose Nagle, and the memory of my father John David Nagle.

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