PROCEEDINGS OF SCIENCE

A Cornucopia of Experiment at RHIC

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I outline experimental results on heavy ion collisions at the Relativistic Heavy Ion Collider for a non-technical audience. This includes: elliptic flow and nearly ideal hydrodynamics; the suppression of hard particles and the ratio $R_{\rm AA}$; and electromagnetic signals, including dileptons and direct photons. Especially puzzling is why the behavior of heavy (charm) quarks appears to be so similar to that of light quarks.

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1. Introduction

The study of the collisions of heavy nuclei at high energies has a simple motivation: heavy nuclei are big. Either gold or lead nuclei have $A \sim 200$ nucleons, where A is the atomic number. The diameter of such a nucleus is $A^{1/3} \sim 6$ larger than that of a proton; the transverse area, $A^{2/3} \sim 34$ times larger. At high energies, one might hope to study the phase transition(s) possible in QCD, to a deconfined, chirally symmetric state of matter, the Quark Gluon Plasma (QGP). For big nuclei, one might close to a system in thermal equilibrium.

As in other areas of hadronic physics [1], an essential insight was due to Bjorken [2], who suggested that it would be useful going to energies where a plateau in rapidity first emerges. This is the reason why the maximum energy of the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) was chosen to be what it is, as results from the ISR at CERN had shown that in proton-proton (pp) collisions, a central plateau should emerge by then. He also suggested that the study of hard particles, with momentum much larger than the temperature, would be especially useful.

The results from RHIC have demonstrated, far beyond expectation, signs for a novel phase at high energy density [3, 4, 5, 6]. Whatever has been created in the collisions of two nuclei (AA collisions), it is — *experimentally* — very unlike what happens in pp collisions. Indeed, there has been such a profusion of experimental results that one may speak of a "cornucopia" of data, whence my title. In this talk I try to give a brief overview of the experimental situation to date. I generally assume that the reader is familiar with concepts from high energy physics, such as rapidity and the like, but is unfamiliar with the concepts essential for understanding AA collisions, such as the difference between central and peripheral collisions. For reasons of space, I could not discuss many interesting (and still puzzling!) features of the data. I have tried to show the standard plots which have come to define the field since RHIC turned on in 2000.

While I concentrate on results from RHIC, there is continuity of results from the SPS at CERN, to RHIC. This includes those for J/Ψ suppression and the dilepton enhancement at low invariant mass. What is gained by the higher energies at RHIC is that the production of hard particles is much more common. That, and having a dedicated machine and experiments which are able to intensively study the physics.

Results from RHIC will continue with an increase in the luminosity by an order of magnitude, and upgrades to the PHENIX [3] and STAR [4] detectors. In the next year or so there will also be results for heavy ions at the Large Hadron Collider (LHC) at CERN, which will probe a significantly higher regime in energy. As I mention later, the physics for AA collisions at the LHC *might* be very different from that at RHIC.

While I suggest that RHIC is manifestly a triumph for experiment, the theoretical situation is still most unsettled [7], and so I only discuss it in passing. In some ways, the results are analogous to those for high-T_c superconductivity, where experiment also continues to confound theory. I do think that with the intense study possible at RHIC and the LHC, that a common theoretical basis will eventually emerge. In all of this, results from numerical simulations on the lattice form the absolute bedrock upon which our understanding is based [8].

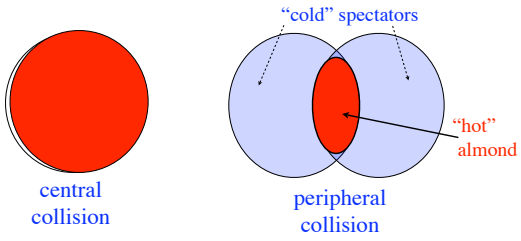

Figure 1: Central versus peripheral collisions for large nuclei.

2. Basics of AA collisions

At RHIC one can study pp, AA, and dA collisions, where the latter are the collisions of deuterons with nuclei. (Deuterons are used instead of protons because the charge/mass ratio is closer to that of a large nucleus.) For pp and AA collisions, the basic variable is the energy per nucleon, $\sqrt{s}/A$. At the AGS at Brookhaven, this goes up to 5 GeV; up to 17 GeV at the SPS at CERN; and from 20 to 200 GeV at RHIC. When I quote results from RHIC, typically I shall quote values from the highest energies, 200 GeV. To date, there do not appear to be dramatic differences in going from the lowest, to the highest energies at RHIC. This will be clarified in the coming years with low energy runs at RHIC down to ~ 5 GeV.

At the highest energies at RHIC there is no nuclear stopping: the incident nucleons go down the beam pipe. Instead of the momentum along the beam, p_z, it is better to use the rapidity, $y = 1/2 \log((E+p_z)/(E-p_z))$, which transforms additively under Lorentz boosts along the beam. Thus one considers the distribution of particles at a given rapidity, y, versus transverse momentum, p_t. Typically I concentrate on results at zero rapidity, $p_z = y = 0$.

The AGS and SPS are fixed target machines; RHIC and LHC are colliders. Fixed target machines allow for much higher luminosities, but it is then difficult to study zero rapidity, since that it somewhere in the forward direction. For colliders, zero rapidity is at 90^o to the beam, facilitating detector construction. The central plateau, being essentially free of the incident baryons, is the most natural place to produce a system at nonzero temperature, and (almost) zero quark chemical potential [2]

At RHIC, the particles are spread out over ± 5 units of rapidity. At zero rapidity there are ~ 900 particles per unit rapidity, versus ~ 600 at the highest energies at the SPS. This sounds like a large number, but in fact, it is not. The total number of particles in a central AA collision should scale like A: $A^{2/3}$ for the area of one nucleus, times $A^{1/3}$ in length as it goes through the other nucleus. Starting with the total number of particles in a pp collision at these energies, and multiplying by A, one finds that, proportionally, there are *only* about 30% more particles produced in AA collisions than a trivial extrapolation from pp. This is a strong constraint on the physics, as it shows that at these energies, there is a *small* amount of entropy generated in AA collisions, relative to pp.

There are two large experiments at RHIC: PHENIX [3] and STAR [4], each with about 400 people; and two smaller ones, BRAHMS [5] and PHOBOS [6], each with about 50. An amusing but specious observation is that the total number of experimentalists working on the associated

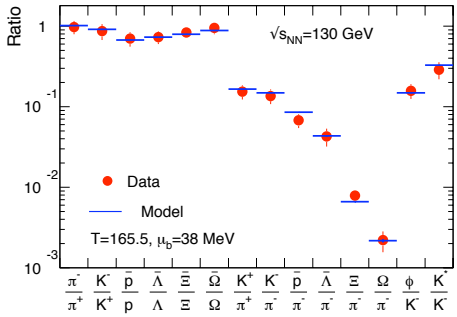

Figure 2: Ratio of particle species, assuming chemical equilibrium.

experiments nearly equals the particle multiplicity (per unit rapidity). This increases slowly, only logarithmically, with energy; the number of theorists grows much slower, perhaps as the log of a log...

At RHIC, STAR [4] and BRAHMS [5] have shown there is a narrow plateau in rapidity, in which the multiplicity, dN/dy, and the average transverse momentum, $\langle p_t \rangle$, of identified particles are both constant over ± 0.5 units of rapidity.

Given the large transverse size of large nuclei, as illustrated in fig. 1 one can distinguish between "central" collisions, where the nuclei overlap completely, and "peripheral" collisions, where they only partially overlap; the direction of the beam is into the page. Experimentalists speak of the number of particpants in a collision: for a central collision with $A \sim 200$, this is ~ 400. The number of participants can be determined down to about ~ 30, especially by using Zero Degree Calorimeters to measure what goes down the beam pipe.

3. Soft particles: elliptic flow and nearly ideal hydrodynamics

Numerical simulations on the lattice indicate that at zero quark chemical potential, there is a crossover to a new regime at $T_c \sim 150 - 200$ MeV [8]. It is natural to think that the most obvious signals for a new state of matter would be from soft particles, whose characteristic transverse momentum is of order T_c.

The first thing one can ask is about total particle multiplicities, integrated over p_t. This is illustrated in fig. 2 [9], which is a fit to over a dozen particle species with only two parameters, a temperature $T_{\rm chemical} \sim 165$ MeV, and a baryon chemical potential, $\mu_{\rm baryon} \sim 38$ MeV. It does not include short lived resonances, such as the Δ, ϕ, K^*, *etc.*, but with a χ^2 per d.o.f. of $4/11$, is an amazingly efficient summary of the data, using a trivial calculation. I remark that this is unlike analogous fits to pp or e^+e^- collisions, where it is necessary to include other parameters which are not standard in textbook thermodynamics. I stress that I do *not* claim that chemical equilibrium has been reached in AA collisions; theoretically, I do not know an unambiguous way of verifying this. Experimentally, though, overall ratios do appear to look like it.

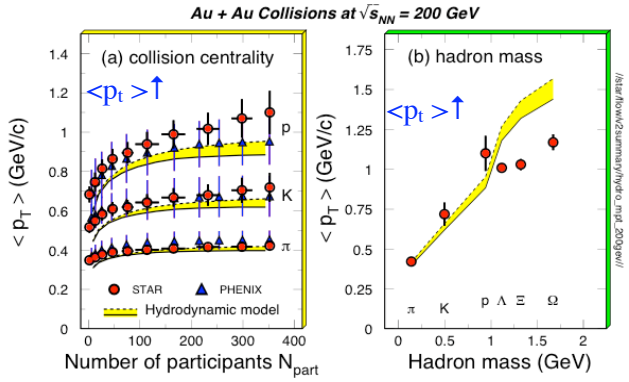

Figure 3: Average transverse momentum, p_t, for different species.

Instead of total multiplicity, integrated over p_t, the next thing one can ask about is the average p_t, versus particle species. This is illustrated in the two figures of fig. 3.

The figure on the left shows the change in the average p_t for pions, kaons, and protons, as one goes from pp (on the left) to the large nuclei in central AA, with $A \sim 200$ (on the right). One sees a large increase in the average p_t for kaons, and especially, protons. This is taken as evidence of radial flow in the collisions of large nuclei: if a particle of mass m flows with a velocity v, its average transverse momentum should scale as $\langle p_t \rangle \sim$ mv. Fits to the spectra indicate that one needs a flow velocity v ~ 0.6c. The effect is more dramatic the heavier the particle is, because light particles, such as pions, already have an average velocity near the speed of light.

What I find striking about this figure, however, is that the average momentum of pions does *not* increase significantly in going from pp to AA collsions, with $A \sim 200$. In a hydrodynamic description, there is no reason for it to, but in the Color Glass model, the saturation momentum $Q_s^2 \sim A^{1/3}$, and so one would expect the average p_t to increase by a factor of $A^{1/6} \sim 2.4$. One could easily imagine having further increases in the average p_t for kaons and protons on top of that, due to radial flow. But this doesn't happen: the average p_t for pions barely budges. While there are successful fits to the particle multiplicity in Color Glass models, the average p_t is then too high by a factor of two. Further, one cannot multiply particles, to decrease the average p_t, without ruining the constraints on the total multiplicity in AA versus pp, mentioned above.

One can then turn to the average p_t of heavier species, shown in the figure on the right hand side of fig. 3; this plot is due originally to Nu Xu. It shows the average p_t for central AA collisions with $A \sim 200$ at the highest energies at RHIC. As seen in the figure on the left hand side, there is a linear increase in the mean p_t between pions, kaons, and protons; for heavier species, though, the Λ, Ξ, and Ω, they all appear to have nearly *constant* $p_t \sim 1.1$ GeV, like that of the proton. These species are all baryons, but it is also found to be true of the ϕ meson.

The usual explanation is that hadrons composed of strange quarks decouple earlier. Even if one assumes that strange particles bunch up into colorless hadrons sooner, though, I would expect that in a graph of $\langle p_t \rangle$ versus mass, that there is one value of the slope of π, K, and p, and another, smaller value, for strange particles. Instead, it appears as if starting with the proton, that it and all heavier hadrons are emitted with essentially *constant* p_t. This is very difficult to understand from

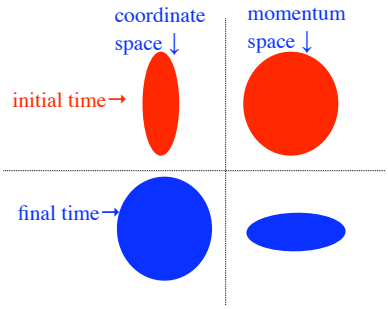

Figure 4: Elliptic flow in a peripheral collision: evolution in both coordinate and momentum space

any hydrodynamic description, where $\langle p_t \rangle \sim$ mv.

A fundamental quantity to measure in heavy ion collisions is that of elliptic flow. To understand this, consider the hot "almond" of the overlap region in a peripheral collision, fig. 1. This is shown also in the upper left hand corner of fig. 4, as a region in coordinate space. The corresponding region in momentum space is shown in the upper right hand corner of fig. 4: it is spherical, because by causality particles can't start out knowing the shape of such a large collision region. As the system evolves, and fields scatter off of one another, in coordinate space the final distribution tends toward one which is spherical; this is shown in the lower left hand corner of fig. 4. At the same time, as the particles scatter, the distribution of particles in momentum space becomes distorted, into an ellipse: particles along the x-axis, where the almond is narrow, move a lot, while those along the y-axis, move less. This is characterized by the quantity

$$\mathrm{v}_2 = \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_x^2 + p_y^2 \rangle} \, . \tag{3.1}$$

This quantity is well defined and so can be measured experimentally. The main problem is determining the reaction plane; *i.e.*, what are the x and y axes. One can also define and measure higher moments, *etc.*

Nuclear physicists who work on collisions at lower energies are well familiar with elliptic flow: then the two nuclei experience a lot of nuclear stopping, form a big blob that lasts a long time, and thus naturally transform the initial anisotropy in coordinate space into one in momentum space.

At high energies, however, the mere existence of elliptic flow tells one that there are significant interactions in AA collisions. The great question about AA collisions at high energies is whether there is *anything* interesting beyond A times a pp collision. Especially in an asymptotically free theory, it is certainly conceivable that the particles, while originally in a almond, just free stream isotropically. In this case, there would be *no* significant v_2 generated.

One way of computing elliptic flow is to use a hydrodynamic description. Given the large particle multiplicities, to zeroth order such a description is reasonable, as hydrodynamics is a simple way of encoding the conservation of energy and momentum in a causal manner. Hydrodynamics requires an equation of state; this one can take, for example, from numerical simulations on the lattice [8]. It is also necessary to specify the transport coefficients of the medium, such as the

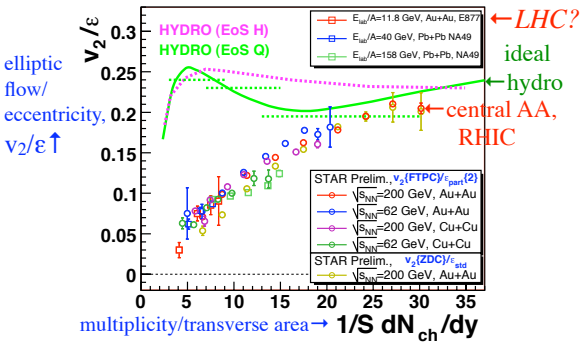

Figure 5: Elliptic flow versus multiplicity

shear and bulk viscosity. For a relativistic medium, there are other transport coefficients, but we concentrate on the shear viscosity, as that appears to be largest and most important.

Shear viscosity is familiar from the non-relativistic example of two parallel plates, in the x and z planes, separated by some distance in y. If one plate is held fixed, and the other is moved with constant velocity along the x-direction, then the shear stress is proportional to the viscosity times the gradient of the velocity in y. That is, the more viscous the fluid, the harder it is to move one plate parallel to the other.

The simplest thing one can do is to compute using *ideal* hydrodynamics, assuming that the shear viscosity vanishes. This is shown in fig. 5, which shows the elliptic flow versus multiplicity in AA collisions. The elliptic flow is divided by the eccentricity, which allows one to compare the collisions of copper nuclei, Cu, with $A \sim 60$, to the largest nuclei, where $A \sim 200$. Plotting versus multiplicity (divided by the transverse area) allows one to plots results from energies at the AGS, SPS, and RHIC. The basic point of this figure is that only for the collisions of the largest nuclei, at the highest energies, that agreement between data and (nearly) ideal hydrodynamics is found. a nearly ideal hydrodynamics agrees with the data. The best fit to the data is obtained with an equation of state that includes a phase transition to a deconfined phase.

Hydrodynamics predicts both single particle distributions (versus p_t) and elliptic flow. It is found that elliptic flow provides a strong constraint on the ratio of the shear viscosity, η, to the entropy density, s [10]:

$$\eta/s \approx 0.1 \pm 0.1(\text{theory}) \pm 0.1(\text{experiment}) \; . \tag{3.2}$$

The experimental errors arise from uncertainty as to the direction of the event plane; there are many sources of error from theory. The value quoted is for η/s, because this enters naturally in hydrodynamics, and is related to an inverse mean free path.

A comparison to various non-relativistic systems is given in fig. 6 [11]. The quantity plotted is again η/s, but for non-relativistic systems, s doesn't change significantly near T_c, unlike for QCD, where it drops dramatically [8]. Taking this ratio does eliminate a trivial dependence on the overall number of the degrees of freedom.

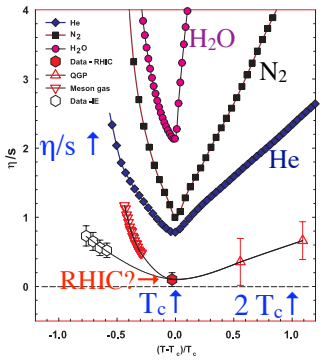

Figure 6: Shear viscosity in various non-relativistic systems

Even given the large error bars in eq. 3.2, this is an *extremely* small value for η/s. (The points from a hadronic gas and the QGP in fig. 6 are theoretical extrapolations.) The value at RHIC is almost an order of magnitude smaller than the smallest value for non-relativistic systems, which is liquid He. Thus RHIC produces "the most perfect fluid on earth".

As a transport coefficient, the shear viscosity vanishes in the limit of weak coupling, as $\eta \sim T^3/\alpha_s^2$, where T is the temperature, and α_s the QCD coupling constant. The fact that η is inversely proportional to a coupling constant sounds peculiar, but it's not. Transport coefficients measure how quickly a system, perturbed from thermal equilibrium, goes back. It takes longer for a weakly coupled system, than a strongly coupled system, because the particles interact less. Technically, it is easiest computing η from a Boltzmann equation. There one finds that η is the ratio of a source term (squared), divided by a collision term: for small α_s, the source term is of order one, and the collision term $\sim \alpha_s^2$. I do not discuss values of η is weak coupling. To date, one cannot reliably compute either η or the entropy near T_c. The situation is not hopeless, though [7, 12, 13, 14, 15].

Since $\eta \sim 1/\alpha_s^2$, a small value for η suggests that the QCD coupling is very large near T_c. This is part of the motivation for what is known as a "strong" QGP [7]. One case where one can compute at infinite coupling is for a theory with $\mathcal{N} = 4$ supersymmetry and an infinite number of colors, where $\eta/s = 1/4\pi$ [13]. This is conjectured to be a universal bound, but string theory provides examples which are $16/25$ smaller, and may be the true bound [14].

As illustrated in fig. 5, the really interesting question is what the elliptic flow will be like at the LHC. Straightforward extrapolations of ideal hydrodynamics can be done, and predict a large increase in v_2 [16]. In this, there appears to be real dichotomy. In a strong QGP [7], if the plasma is strongly coupled near T_c, at RHIC, shouldn't it remain so at the higher temperatures at the LHC? Another example is provided by $\mathcal{N} = 4$ gauge theories: by modifying the theory, they can be adjusted to fit the pressure, as computed from numerical simulations on the lattice for three colors [8], down to T_c [15]. In *all* of these models, however, η/s remains small, $= 1/4\pi$.

In contrast, as shown in fig. 6, non-relativistic models universally show that while the shear viscosity has a minimum at the critical temperature, that it also increases *away* from T_c. The question is really, is the QGP like He, where the increase from T_c to $2T_c$ is only a factor of two, or like H_20, where it is an order of magnitude? A weak coupling analysis of a "semi"-QGP suggests that a large rise in η/s is possible as T increases from T_c [12].

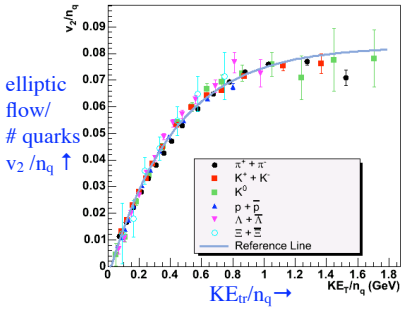

Figure 7: Elliptic flow per quark, versus the transverse energy per quark.

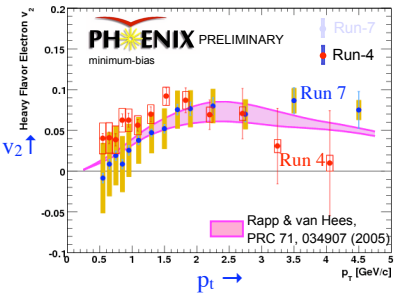

Figure 8: Elliptic flow for charm quarks

Measurements of the elliptic flow at the LHC will tell us from day one of running *AA* collisions. I note that detailed theoretical predictions in non-ideal hydrodynamics need to be carried out, since even if collisions at the LHC start out in a highly viscous regime, at say $\sim 2T_c$, one still cools into a system which has a small viscosity near T_c.

Returning to experiment, in fig. 7 I show a plot of the elliptic flow per quark, versus the transverse energy of a hadron, per quark. By per quark, I simply mean that one divides by two for a meson, and three for a baryon. This shows that at low p_t, there appears to be a universal scaling of elliptic flow for *all* particle species. Dividing by the number of quarks in the hadron is reasonable, but it is astounding that the correct variable to plot against is the kinetic energy (and not, say, the transverse momentum; then one does not find a universal curve). This is typical of the results from RHIC: there are many results which are simply totally unexpected, and hint at some universal mechanism(s), which we do not yet understand.

One can also ask about the elliptic flow of heavy quarks. Here experiment uses single electrons, which arise from the decay of a charm quark, to tag their flow. Now theoretically, one would expect that heavy quarks would *not* flow as easily as light quarks: it should take heavy quarks longer to thermalize, and they should interact in a characteristically different manner. Instead, as shown in fig. 8, the elliptic flow for charm quarks appears to be just as large as that of light quarks!

This is one of the truly astounding results from RHIC. As we shall see again in the next section, heavy quarks appear to interact much more strongly with the "stuff" in central *AA* collisions than we would have expected: *AA* collisions are manifestly not a trivial superposition of *pp* collisions.

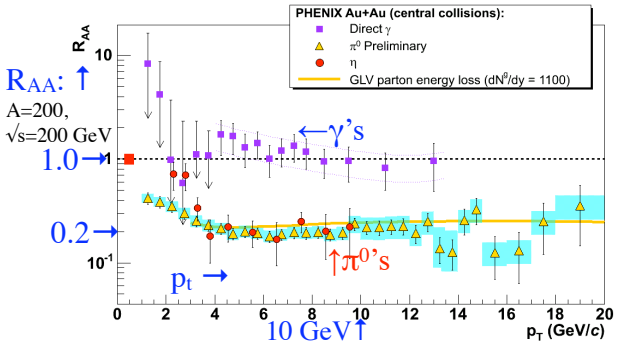

Figure 9: The ratio $R_{\rm AA}$ for photons and pions.

4. Hard particles: suppression and the ratio $R_{\rm AA}$

One of the great experimental surprises of RHIC is that while most of the particles are down at low p_t, the clearest signs for something new in central AA collisions comes from high momentum, $p_t > 2$ GeV. This is typically referred to in the high energy nuclear community as "jets", but is far lower in energy than what most high energy physicists are used to. Consequently, I eschew this term, and just refer to hard particles.

A basic quantity is the ratio $R_{\rm AA}$: this is the ratio of the number of particles in a central AA collision to that in pp, both measured at the *same* p_t (and rapidity):

$$\mathrm{R_{AA}}(p_t) = \frac{\#\text{ particles in central AA}(p_t)}{\mathrm{A}^{4/3}\,\#\text{ particles in pp}(p_t)}. \tag{4.1}$$

The crucial question is how one normalizes. As I discussed above, soft particles scale as A. For hard collisions, the number of binary collisions is A, from the incident nucleus, times $A^{1/3}$ from the width of the target, or $A^{4/3}$. This is only approximate; experimentally, this is modeled by Glauber and Monte Carlo calculations.

However, one doesn't need to understand (or believe) this normalization factor, since one can directly appeal to experiment. The ratio $R_{\rm AA}$ can be measured for any particle species. In fig. 9, I show the plot for photons and neutral pions. Since photons only interact electromagnetically, if the normalization is performed correctly, then $R_{\rm AA}$ should be one. While the error bars are large, $\sim 10\%$, this is true for photons with $p_t > 2$ GeV.

In contrast,one finds that above $p_t \sim 2$ GeV, there are only about 20% of the number of neutral pions expected. (Experimentally, at high p_t it is easiest to pick out neutral pions, by looking for two hard photons with the right invariant mass.) This 20% is a *very* small number. From fig. 1, even in a central collision, there is a contribution from the surface; at least half the hard particles emitted from the surface should escape without interaction. This is another reason why people speak of a strong QGP at RHIC [7].

Indeed, the really surprising thing is that $R_{\rm AA}$ is so *flat* to such a high p_t. It is easy to imagine that effects in a medium would suppress hard particles: they will scatter off of the medium, lose energy, and so emit more soft particles. Theoretically, this is known as energy loss [7]. But at high

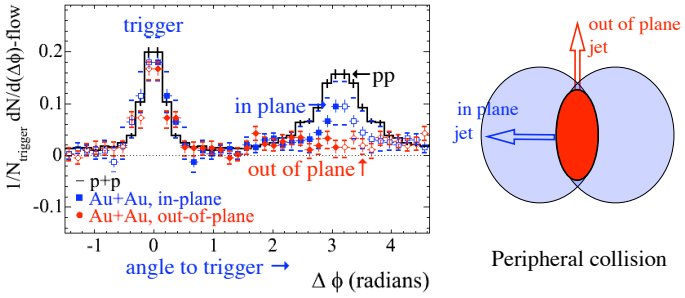

Figure 10: Geometrical suppression of hard particles

enough p_t, scattering off of the medium should go away. Fig. 9 shows that this isn't true for neutral pions with a p_t as high as 20 GeV! Eventually, $R_{\rm AA}$ must go back up to one, or one will question whether it is correctly normalized.

It is reasonable to ask if this suppression is due to some initial state effect in nuclei. Here measurements in dA collisions were crucial: the normalization changes to $2A$, and experimentally one observes not suppression, but enhancement [3, 4, 5, 6], with $\mathrm{R_{dA}} \approx 1.4 \pm 0.1$ at $p_t \sim 3$ GeV. This is due to what is known as the Cronin effect; all that matters for us is that $R_{\rm dA}$ goes in the opposite direction from $R_{\rm AA}$, and so $R_{\rm AA}$ is manifestly a final state effect.

The suppression of hard particles can also be observed on a purely geometrical basis, as shown in fig. 10. Consider a peripheral collision, and trigger on a hard particle, with $p_t : 4 \to 6$ GeV. Then look for a hard particle on the away side, $p_t > 2$ GeV, as a function of the angle to the trigger particle. In pp or dA collisions, this is peaked at 180^o. Now in a peripheral collision, one can look at a hard particle either in the plane of the collision, or out of plane. If the hard particle is in the reaction plane, it goes a small distance through the "hot" almond, and a long ways through the cold nuclear spectators. If out of the plane, it goes a long way through the almond, and little through the spectators. Fig. 10 shows that when the hard particle is in the reaction plane, one does see the away side particle at 180^o; when the hard particle is perpendicular to the reaction plane, one doesn't see the away side particle. That is, the more particles go through the almond, the more the "stuff" there affects their propagation. This is consistent with the small value of $R_{\rm AA}$.

There is interesting structure seen in the angular correlations of the away side particle. Fig. 11 shows results for a trigger particle of $p_t : 2.5 \to 4$ GeV, and an away side particle of $p_t : 2 \to 3$ GeV, integrated over all angles to the reaction plane. There are three curves shown, going from most peripheral to most central. How one defines centrality is in this case secondary. What one can see is that for peripheral collisions, the angular distribution for the away side particle is peaked at 180^o, as in a pp collision. For the most central collisions, the angular distribution at 180^o is suppressed, as seen in fig. 10. What one also sees, however, is an *enhancement* in the distribution of away side particle away from 180^o. This looks very like Cerenkov radiation, or perhaps a Mach cone in a medium [7]. This is really a correlation between three particles, as has been verified by both the PHENIX [3] and STAR [4] collaborations.

Especially with planned upgrades to RHIC, one will also be able to measure correlations between a hard photon and a hard particle. Measuring a hard photon will tell one unambiguously

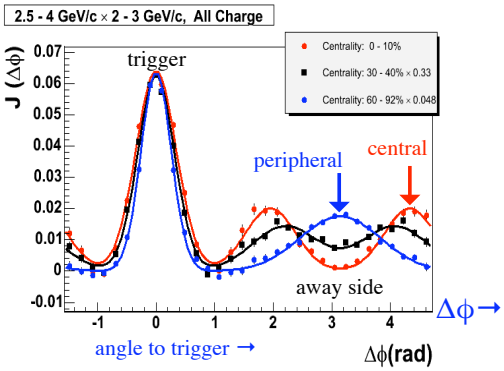

Figure 11: Away side correlations for peripheral to central *AA* collisions.

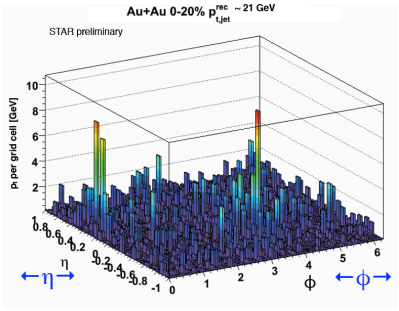

Figure 12: A Lego plot of two jets in central *AA*, $p_t > 20$ GeV.

what the incident energy of the hard particle is, and so one will be able to understand the details of how fast particles are affected by the medium in central *AA* collisions.

All of these figures have triggered on "hard" particles with relatively low p_t. In fig. 12 I show a plot from the STAR collaboration, which is a Lego plot familiar in high energy physics. The trigger is $p_t > 20$ GeV, for the most central *AA* collisions. Even given the high multiplicity of particles at low p_t, if the trigger is sufficiently high, then jets just stick out. At LHC energies, true jets, with transverse momenta of order 50, 100 GeV and higher, will be (relatively) plentiful. This will enable one to really pin down the mechanism which is responsible for $R_{\rm AA}$ and the like.

One can form the ratio $R_{\rm AA}$ for any particle species. In fig. 13 I show the result for charm quarks from the PHENIX collaboration. Here one observes charm by measuring direct electrons. The mass of the charm quark is ~ 1.5 GeV, and the temperature is something like $T_c \sim 200$ MeV [8]. In perturbation theory, the scattering of a heavy quark is very different from that of a light quark: emission of gluon radiation is suppressed in the forward direction ("dead cone" effect). Even without detailed calculation, it would be astonishing if one found that the behavior of a heavy quark were anything like that of a light quark; one expects that heavy quarks are not suppressed as much as light quarks, with so $R_{\rm AA}$ is larger.

This is *not* what experiment shows: fig. 13 shows that for transverse momenta a couple of times the charm quark mass, $p_t \sim 4$ GeV, that $R_{\rm AA} \sim 0.2$, like π^0's! This is a remarkable result,

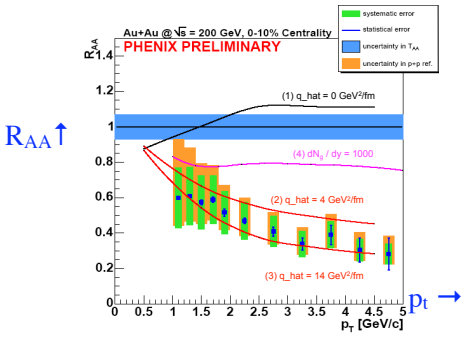

Figure 13: The ratio $R_{\rm AA}$ for charm quarks.

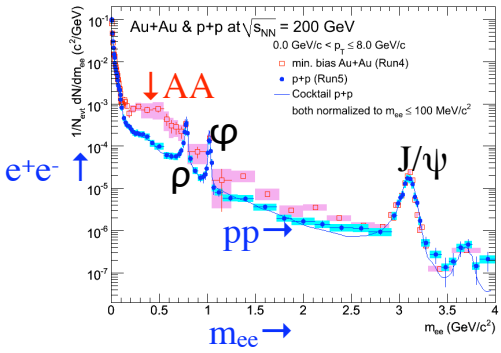

Figure 14: Dilepton spectra for central AA and pp collisions.

and completely unlike any perturbative understanding. Perhaps energy loss is not the whole story.

5. Electromagnetic signals: dileptons and direct photons

Since dileptons only interact weakly with a hadronic medium, they provide essential insight into AA collisions. In fig. 14 I show the dielectron spectra below the J/Ψ, as a function of the invariant mass of the dielectron pair, $m_{\rm ee}$. It is necessary to normalize the spectrum from central AA collisions to that of a "cocktail" from pp collisions.

As seen in collisions at SPS energies, at RHIC energies there is a striking excess in dileptons below the ρ meson. There is a smaller, but still significant excess, above the ρ meson as well. Any excess appears to have disappeared for dileptons above the J/Ψ.

A crucial question is whether the normalization to pp collisions is done correctly. One can show that for the dilepton excess below the ρ meson, for $150 < m_{ee} < 750$ MeV, that the excess first appears when the number of participants is greater than ~ 200, and that it increases as the number of participants increases. This is dramatic evidence that the "stuff" created in central AA collisions is uniquely responsible for the excess at low invariant mass.

In fig. 15 I show the ratio $R_{\rm AA}$ for J/Ψ production in central AA collisions at both RHIC and the SPS. When plotted in this way, one finds that the behavior at these two energies is essentially

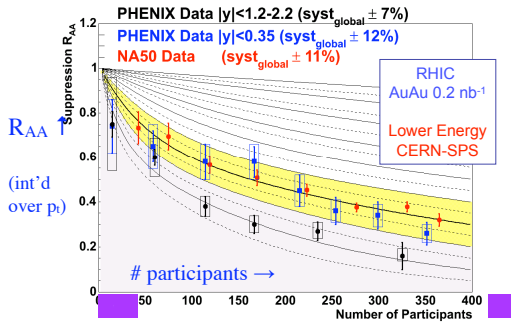

Figure 15: The ratio $R_{\rm AA}$ for J/Ψ's.

identical. This was absolutely unexpected. Various theoretical models had predicted that J/Ψ production might be less at RHIC than the SPS, due to greater scattering in a thermal medium, or greater, due to regeneration. But *no* model predicted exactly the same behavior for $R_{\rm AA}$.

This year, PHENIX has also shown how low mass dielectron pairs can be used to get direct photons from internal conversion [17]. They see a clear excess for photon $p_t : 1 \to 3$ GeV, which they fit to an exponential. This gives a temperature for photon production of $T_{\rm photon} \sim 223$ MeV, with statistical errors of ± 23 MeV and systematic errors of ± 18 MeV. This is a fundamental result, and gives us a lower bound on the temperatures at which the photons were produced.

6. Summary

The results at RHIC have conclusively demonstrated that central AA collisions have produced matter at high energy density which is *very* unlike that produced in pp collisions at the same energy.

There are numerous interesting phenomenon which I didn't have space to cover: the baryon/meson enhancement at intermediate $p_t : 2 \to 6$ GeV; Hanbury-Brown-Twiss interferometry, which shows "explosive" behavior; and the ridge in rapidity. I have emphasized that one of the most mystifying aspects of the data is that the behavior of charm quarks — as seen in their elliptic flow, and the ratio $R_{\rm AA}$ — is essentially identical to that of light quarks. This is very difficult to understand theoretically. This, and the nearly ideal behavior of hydrodynamics, has given rise to the suggestion that the region near T_c is behaving unexpectedly: either a strong [7, 13, 14, 15, 16], or maybe a semi- [12], QGP.

Of course we eagerly await results for AA collisions at the LHC. Collisions at the LHC will produce many more jets, and produce a medium in which the temperatures are significantly (twice?) as high as at RHIC. One might hope that LHC probes a perturbative (or complete [12]) QGP. We will know very soon if LHC produces a nearly ideal fluid, as at RHIC [7, 15], or one which is viscous [12]. The study of bottom quarks will also be very interesting, given the unexpected behavior of charm quarks at RHIC.

I stress, however, that RHIC is uniquely set to intensively study the region about T_c. In the end, I feel no hestitation whatsoever in saying that once RHIC turned on, we entered what is clearly a golden age in high energy nuclear physics, one which is well deserving of the highest possible recognition [1, 2, 3, 4].

References

[1] J. D. Bjorken, *Applications Of The Chiral U(6) X (6) Algebra Of Current Densities*, Phys. Rev. **148**, 1467 (1966); *Asymptotic Sum Rules At Infinite Momentum*, ibid. **179**, 1547 (1969).

[2] J. D. Bjorken, *Highly Relativistic Nucleus-Nucleus Collisions: The Central Rapidity Region*, Phys. Rev. D **27**, 140 (1983).

[3] K. Adcox *et al.*, *Formation of dense partonic matter in relativistic nucleus nucleus collisions at RHIC: Experimental evaluation by the PHENIX collaboration*, Nucl. Phys. A **757**, 184 (2005) [nucl-ex/0410003].

[4] J. Adams *et al.*, *Experimental and theoretical challenges in the search for the quark gluon plasma: The STAR collaboration's critical assessment of the evidence from RHIC collisions*, Nucl. Phys. A **757**, 102 (2005) [nucl-ex/0501009].

[5] I. Arsene *et al.*, *Quark gluon plasma and color glass condensate at RHIC? The perspective from the BRAHMS experiment*, Nucl. Phys. A **757**, 1 (2005) [nucl-ex/0410020].

[6] B. B. Back *et al.*, *The PHOBOS perspective on discoveries at RHIC*, Nucl. Phys. A **757**, 28 (2005) [nucl-ex/0410022].

[7] S. Mrowczynski and M. H. Thoma, *What do electromagnetic plasmas tell us about quark-gluon plasma?*, Ann. Rev. Nucl. Part. Sci. **57**, 61 (2007) [nucl-th/0701002]; B. Muller and J. L. Nagle, *Results from the Relativistic Heavy Ion Collider*, Ann. Rev. Nucl. Part. Sci. **56**, 93 (2006) [nucl-th/0602029]; E. V. Shuryak, *Physics of Strongly coupled Quark-Gluon Plasma*, to appear in Prog. Part. Nucl. Phys. [0807.3033].

[8] Plenary talks at Lattice 2008 by C. DeTar, S. Ejiri, H. Meyer, and M. Teper.

[9] A. Andronic, P. Braun-Munzinger and J. Stachel, *Hadron production in central nucleus nucleus collisions at chemical freeze-out*, Nucl. Phys. A **772**, 167 (2006) [nucl-th/0511071].

[10] M. Luzum and P. Romatschke, *Conformal Relativistic Viscous Hydrodynamics: Applications to RHIC* [0804.4015].

[11] R. A. Lacey *et al.*, *Has the QCD critical point been signaled by observations at RHIC?*, Phys. Rev. Lett. **98**, 092301 (2007) [nucl-ex/0609025].

[12] Y. Hidaka and R. D. Pisarski, *Suppression of the shear viscosity in a "semi" Quark Gluon Plasma* [0803.0453].

[13] D. T. Son and A. O. Starinets, *Viscosity, Black Holes, and Quantum Field Theory*, Ann. Rev. Nucl. Part. Sci. **57**, 95 (2007) [0704.0240].

[14] M. Brigante, H. Liu, R. C. Myers, S. Shenker and S. Yaida, *The Viscosity Bound and Causality Violation*, Phys. Rev. Lett. **100**, 191601 (2008) [0802.3318].

[15] N. Evans and E. Threlfall, *The thermal phase transition in a QCD-like holographic model* [0805.0956]; S. S. Gubser and A. Nellore, *Mimicking the QCD equation of state with a dual black hole* [0804.0434]; U. Gursoy, E. Kiritsis, L. Mazzanti and F. Nitti, *Deconfinement and Gluon Plasma Dynamics in Improved Holographic QCD* [0804.0899].

[16] H. Niemi, K. J. Eskola and P. V. Ruuskanen, *Elliptic flow in nuclear collisions at the Large Hadron Collider* [0806.1116].

[17] A. Adare *et al. Enhanced production of direct photons in Au+Au collisions at* $\sqrt{s_{NN}} = 200$ *GeV.* [0804.4168]