I summarize theory at Quark Matter 2002, stressing the continuing inability of a single model to describe all notable features of the data from $\sqrt{s}/A : 55 \rightarrow 200$ GeV.

1. INTRODUCTION

The collisions of large nuclei may give us insight into the nature of QCD at high temperatures and/or densities. In this talk I review the status of theory for heavy ion collisions from Quark Matter 2002. I concentrate on the the results for the largest nuclei, with atomic number $A \approx 200$.

At the SPS at CERN, there are two notable results for $AA$ collisions, for $\sqrt{s}/A : 5 \rightarrow 17$ GeV [1]:

- $J/\Psi$ suppression: the number of $J/\Psi$ pairs is smaller in the most central collisions, versus the extrapolation from peripheral collisions, or from collisions with smaller $A$ [2]. The effect is most striking for the largest nuclei.

- Excess dileptons below the $\rho$: the rate of $e^+e^-$ pairs exceeds that in conventional hadronic models [3], although a broadened $\rho$-meson explains the excess. The effect is more prominent at lower, and not high energies, suggesting a density dependent effect. This also supports interest in going to even lower energies, such as at the proposed GSI collider.

At BNL, RHIC has run at energies of $\sqrt{s}/A = 55$ GeV (briefly), at 130 GeV during Run I, and at 200 GeV during Run II. Results from Run I were first presented at Quark Matter 2001; those from Run II, at this Quark Matter, 2002.

There is one notable change expected change between the SPS and RHIC. At the SPS, the particle multiplicity in $AA$ collisions is a single peak about zero rapidity. By RHIC energies, a Central Plateau was expected to open up, in which physics is (approximately) boost invariant, independent of rapidity. Away from the incident nucleons of the fragmentation region, the Central Plateau is where a system at nonzero temperature, and almost zero quark density, might emerge. Perhaps even deconfined matter, as the Quark-Gluon Plasma.

RHIC experiments find that the Central Plateau is rather narrow. In all, particles are spread out over $\approx \pm 5$ units of rapidity. The multiplicities for identified particles are nearly constant over the central $\approx \pm 1$ unit of rapidity [5,6]. However, the pion’s average

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transverse momentum, $p_t$, is only constant over ±0.5 units of rapidity [6]. But as with other variables, there is much to gain by looking at all rapidities.

Even without (much) electromagnetic data, which proved so interesting at the SPS, so far there are four notable features of the RHIC data:

“High”-$p_t$ suppression: the number of particles with transverse momentum $p_t$ between 2 − 10 GeV is suppressed, relative to that in $pp$, times the number of binary collisions [8][10][11][12]. The overall suppression is by factors of 2 − 4. The suppression is now seen to be approximately constant for these $p_t$ [1]. This is opposite what happens at the SPS, where high $p_t$ particles are not suppressed, but enhanced by factors of 2 − 3, through the Cronin effect.

Elliptic flow: is a measure of momentum anisotropy in non-central collisions. Hydrodynamics predicts elliptic flow is linear in $p_t$ for pions. This is seen up to $p_t \approx 1.5$ GeV, as is the hydrodynamic behavior of protons. For $p_t : 2 \rightarrow 6$ GeV, though, the (total) elliptic flow is flat [13,14], which is not expected from hydrodynamics (or anything else).

HBT radii: pion interferometry gives a measure of the spatial size(s) of the system. Hydrodynamics predicts that a certain ratio of two sizes, $R_{out}/R_{side}$, is greater than one, and increases as $p_t$ does. Instead, experiment finds that $R_{out}/R_{side}$ decreases with increasing $p_t$, and is about one by $p_t \approx 400$ MeV [14,15]. HBT radii indicate that hadronization occurs as a type of “blast” wave [15].

Jet absorption: At these energies, jets are seen in $pp$ collisions, but an angular correlation finds that in $AA$ collisions, the “backward” jet is strongly suppressed [16]. That is, in $AA$ collisions there is stuff there which eats jets.

It is thus an extremely exciting time. For now, experiment is triumphant: especially after the run at $\sqrt{s}/A = 200$ GeV, there is a striking agreement between different experiments for many quantities of interest. The crucial advance has been precise measurements. If quantities are only measured to ±30%, then a lot of theories can hide under the error bars. With errors ±5%, it becomes possible to definitively rule (many) theories out.

The challenge to theorists to synthesize all of these measurements into a consistent framework. Common prejudices held before the RHIC data — such as large increases in multiplicity, and large sizes from a strongly first order transition — are extinct. Certain models can explain some aspects of the RHIC data, but at present, no model can explain everything interesting.

My review of theory at Quark Matter 2002 is organized thematically, emphasizing results of relevance to experiment. Consequently, I will offend by omission, neglecting all work on color superconductivity and other interesting topics.

2. THE BEDROCK: THE LATTICE

Our understanding of QCD at nonzero temperature rests upon numerical simulations on the Lattice [17]. While dynamical quarks must be included in any realistic simulation of QCD, at present the Lattice is not near to the continuum limit with light, dynamical quarks. What it can do, with precision near the continuum limit, is tell us about the pure glue theory. While it is easy to bemoan the lack of nearly continuum data with quarks, it should not obscure this fundamental advance. That we can compute reliably the thermodynamics for non-abelian fields with three colors is no mean feat.
In the pure gauge theory, the deconfining phase transition is rigorously associated with the spontaneous breaking of a global $Z(3)$ symmetry, above a transition temperature $T_c$. Taking the string tension to be $(400 \text{ MeV})^2$, $T_c \approx 270 \text{ MeV}$, within errors which are, at present, $\approx \pm 5\%$. One expects a confined phase of hadrons below $T_c$, and a deconfined Quark-Gluon Plasma above $T_c$. The great surprise from the Lattice is that there is a third region, sandwiched between these two. This happens because the deconfining transition is so weakly first order that there is a nearly critical region about $T_c$. For example, just below $T_c$, the string tension is about one-tenth its value at zero temperature. The nearly critical modes which become light about $T_c$ are electric $Z(3)$ glueballs, or Polyakov loops. Magnetic $Z(3)$ glueballs, or 't Hooft loops, stay heavy.

The Lattice also gives us insight into the transition as the number of colors is varied from three. It is truly second order for two colors, with a critical region whose width, in terms of the reduced temperature $T/T_c$, is wider than for three colors. This leads me to the conjecture that for $N_c$ colors, while the transition is of second order when $N_c < \infty$, its width, in terms of $T/T_c$, shrinks like $1/N_c$ as $N_c \to \infty$. At $N_c = \infty$, then, the transition is of first order.

For three colors, the nearly critical region is within $\approx \pm 10\%$ of $T_c$. A consequence of a narrow critical region is that the potentials for Polyakov loops change very rapidly, within temperatures $\approx \pm 2.5\%$ of $T_c$ [18]. For the rapid expansion rates present in heavy ion collisions, this suggests that even if the system is thermal at $T_c$, its evolution below $T_c$ is far out of equilibrium [18].

A recent advance on the Lattice is to compute spectral functions using the Maximum Entropy Method [19]. The spectral density for the pion has a narrow peak in the confined phase, but is a broad peak in the deconfined phase, at least by $1.5T_c$. In the $\rho$ channel, at $.6T_c$ the peak has moved up a little, and broadened more; the $\rho$ is completely washed out by $1.5T_c$. Spectral functions for heavy quark bound states have also been computed. Notably, the Lattice finds that the $J/\Psi$ remains bound even at $1.5T_c$, although less tightly bound states, such as the $\Psi'$, evaporate below $T_c$. This is in contrast to potential models, which find, due to the decreasing string tension, that all charmonium bound states disassociate below $T_c$ [20].

At present, the Lattice can only simulate dynamical quarks if the pions are too heavy. Estimates are $T_c \approx 175 \text{ MeV}$, with no true phase transition in the thermodynamic limit, but only cross over behavior. It is possible that a first order transition reappears for physical pions, closer to the continuum limit [17]. In principle, the transition can be more strongly first order than in the pure glue theory, since with the addition of three flavors of massless quarks, the ideal gas pressure goes up by a factor of three. (It is useful to compare to the ideal gas pressure, since asymptotic freedom implies that the pressure is ideal at infinite temperature.)

Present simulations with dynamical quarks demonstrate an approximate universality, termed “flavor independence”. This is the observation that as a function of $T/T_c$, the ratio of the true pressure, to the corresponding value in an ideal gas of quarks and gluons, is nearly universal, independent of the number of flavors. This is remarkable, given the large changes in both $T_c$ and in the ideal gas term. This suggests that the thermodynamics of QCD, with three colors and three flavors of dynamical quarks, is dominated by that of the pure glue theory.
Advances have been made with systems at nonzero (quark) chemical potential $\mu$. The Lattice can generate a thermal distribution of quarks, but with standard Monte Carlo techniques, it cannot fill a Fermi sea. However, for a quark with energy $E$, if the temperature $T$ is much greater than $\mu$, then the Fermi-Dirac distribution function at $\mu \neq 0$ is approximately that for $\mu = 0$:

$$\frac{1}{e^{(E-\mu)/T} + 1} \approx \frac{1}{e^{E/T} + 1}$$

(1)

That is, at high temperature it doesn’t matter much whether or not you fill the Fermi sea. Thus the Lattice can compute at $T \gg \mu$: by $\mu \sim 200$ MeV, $T_c$ has only decreased a small amount, to $\sim 160$ MeV [21]. This is well on the way to nuclear matter, which at zero temperature, occurs when $\mu$ exceeds $\approx 313$ MeV. This is a new and strong constraint on effective models of thermal QCD, which often give too large a decrease.

3. STATISTICAL MODELS: A BIG BOOST (VELOCITY)

For the most central collisions at zero rapidity, an amazing summary of the single particle spectra is a thermal fit [22,23,24]. Fits in which chemical freeze-out occurs at the same temperature as kinetic freeze-out are favored, with $T \approx 165$ MeV and $\mu \approx 14$ MeV [25]. Resonance decays describe the excess of low momentum pions in central collisions. What happens for peripheral collisions, which must also have resonance decays, and yet do not have an excess of low momentum pions, is less clear, and usually ignored.

The approximate equality of the temperatures for chemical and kinetic freeze-out is peculiar. Any scattering in a hadronic phase produces chemical freeze-out at a higher temperature than that for kinetic freeze-out [26,27], so the data suggest that both temperatures are really one of hadronization, with little rescattering in a hadronic phase. This is one hint of possible non-equilibrium behavior at RHIC.

The temperature for chemical freeze-out is consistent with data at lower $\sqrt{s}/A$. From energies of $\sqrt{s}/A$ from a few GeV on up, chemical freeze-out occurs along a curve in which the energy per particle is constant, about $\approx 1$ GeV. In the plane of $T$ and $\mu$, even if the hadronization temperature agrees with $T_c$ at $\mu = 0$, it is distinctly lower than $T_c(\mu)$ for $\mu \neq 0$. For example, chemical freeze-out at AGS energies gives about $\mu = 200$ MeV, and a hadronization temperature which is at most $\approx 120$ MeV; from the Lattice, though, at this $\mu$ the corresponding $T_c$ is much higher, $\approx 160$ MeV [21].

To describe the behavior of particles with increasing mass, it is necessary to assume that all hadrons are emitted with respect to a local moving rest frame. At RHIC, the radial velocities of this local rest frame go up to $\approx 2/3$ c; averaged over radius, they are about $\approx 1/2$ c. This can be seen by eye: versus $p_t$, single particle distributions for pions turn up, while those for protons (say) turn down.

The radial dependence of the velocity of the local rest frame is not constrained by the data, and is fit to agree with the observed spectrum. The same is true of hydrodynamical models [14]. This is why they are fits. For example, consider how the single particle spectra change with rapidity, or centrality. While the temperature might be the same, the local flow velocity now depends not just upon the radius, but also upon the rapidity, centrality, etc. It is untenable to consider only zero rapidity, and ignore the rest.
A statistical model implies not only what the chemical composition is, but, as well, the $p_t$-dependence of the single particle spectrum. Of course a thermal distribution should only hold up to some upper scale, perhaps $1 - 2$ GeV. It would be interesting to compute the ratios of moments of transverse momenta:

$$r_n = \frac{|\langle p_t^n \rangle_{exp} - \langle p_t^n \rangle_{th}|}{\langle p_t^n \rangle_{th}}.$$  \hspace{1cm} (2)

Here $exp$ and $th$ denote, respectively, moments computed from experiment, versus a thermal distribution (with some assumed velocity profile). By definition, if the overall number of particles is thermal, $r_0 = 0$. For $n > 1$, $r_n$ is a dimensionless series of pure numbers; the fit is good until $r_n$ is no longer small. This must happen at some large $n$, since eventually fluctuations from hard momentum processes dominate. It would be interesting to determine these ratios from experiment, for all collisions in which a thermal fit works.

4. “IDEAL” HYDRODYNAMICS AND ELLIPTICAL FLOW

A dynamical realization of a thermal fit is a hydrodynamical model. A specific equation of state is assumed, with some initial temperature and velocity profile at some initial time. The system then evolves according to an equation of state, with the parameters chosen to agree with the observed single particle spectra. First order transitions are usually assumed, but this doesn’t matter much, given the rapid expansion characteristic of heavy ion collisions.

A measure of hydrodynamic behavior is given by elliptic flow. For a peripheral collision, in which the two nuclei only partially overlap, an “almond” is formed in the plane perpendicular to the reaction plane. As the system hadronizes, this spatial anistropy turns into a momentum anistropy, with the average momentum larger along the narrow part of the almond then along the long part. This elliptical anistropy has been measured as a function of centrality and $p_t$; overall, the values at RHIC are about twice as large as at the SPS. By geometry, elliptic flow vanishes for zero centrality, as nuclei which completely overlap cannot have any anistropy. Elliptic flow, as measured from two-particle correlations, fails to do this, so that more sophisticated measures, involving correlations between four or more particles, are imperative.

Hydrodynamic models predict that for pions, the elliptic flow depends linearly on the transverse momentum. The local flow velocity also predicts the behavior of elliptic flow for heavier particles, such as protons. Both predictions are borne out by the experimental data, for momenta up to $p_t \approx 1.5$ GeV.

Versus centrality, as measured by the number of participants, hydrodynamics predicts that the elliptic anistropy is linear near zero centrality, which is observed. When the number of participants is half the maximum value, though, hydrodynamics significantly overpredicts the elliptic flow.

Calculations with three dimensional hydrodynamics, giving single particle distributions versus rapidity, have been performed. Even with agreement at zero rapidity, the results from these hydrodynamic calculations are much broader in rapidity than the experimental data.
There are two conundrums about these hydrodynamic fits: first, the initial times required in hydrodynamic calculations are extremely small, $\approx .6 \text{ fm/c}$ [30]. Secondly, they assume ideal hydrodynamics. Even with times expected from saturation (see below), this is a very short time. Further, in QCD viscosity coefficients can be computed from the Boltzman-Altarelli-Parisi equations. At least in weak coupling, the shear viscosity is large (on a natural scale), and cannot be neglected [14,31].

These technicalities should not obscure the fact that elliptic flow demonstrates that heavy ion collisions exhibit significant collective behavior. Further, while fits to single particle spectra with ideal hydrodynamics and short times may well work, this does not exclude the possibility of similar fits with non-ideal hydrodynamics; it is not clear how the times might then change.

As an example, [30] assumes that particles obey a thermal distribution in the transverse direction, but free stream in the longitudinal (or beam) direction. Adjusting the initial conditions to give the right single particle distributions, the resulting elliptical anistropy is too small by a factor of two. As in many other examples, the data sharply limits theory.

Experimentally, it is unremarkable that hydrodynamics fails above $p_t \approx 1.5 \text{ GeV}$. Hydrodynamics should break down at short distances; that it works down to $\approx .13 \text{ fm}$ is actually pretty good. Rather, the surprise is that the elliptic anistropy is approximately constant for $p_t : 2 \to 6 \text{ GeV}$. In QCD, one expects cross sections to peak at some momentum scale on the order of a few GeV, and then to fall off with the powers characteristic of QCD. It is very difficult to imagine how anything flat in $p_t$ could ever emerge.

One possibility is that one is not measuring collective phenomenon at all, but simply some property of two jets, which is misinterpreted as collective flow. [32] used a mini-jet model to obtain an elliptic anistropy which agrees with experiment, the single-particle spectra, though, is wrong. Methods to determine elliptic anistropy using correlations between four or more particles should be insensitive to contamination by jets [28].

5. HBT RADII: A “BLAST” WAVE?

For identical particles, a length scale can be determined by pion interferometry through the Hanbury-Brown-Twiss (HBT) effect [15]. This length scale is related to the surface at which the pions last interacted. Since there is axial symmetry to a heavy ion collision, there are three distances, corresponding to along the beam direction, $R_{\text{long}}$, along the line of sight, $R_{\text{out}}$, and perpendicular to that, $R_{\text{side}}$.

One of the big surprises from RHIC is that the HBT radii did not grow much between $\sqrt{s}/A = 17$ to 200 GeV. The change in $R_{\text{long}}R_{\text{side}}R_{\text{out}}$ is, more or less, the same as the increase in multiplicity, $\approx 50\%$.

This can be taken as direct experimental evidence for the absence of a strongly first order phase transition in QCD, completely independent from the Lattice. If the transition were strongly first order, as it went through $T_c$ the system would supercool and grow in size. Estimates of the sizes of the system before QM’01 ranged up to tens of fermi, which are not seen. Unfortunately, putting a bound on the latent heat of the transition is manifestly a model dependent exercise. Still, it would be an amusing exercise.

The details of the HBT radii, however, have proven to be much more interesting than expected. Before the RHIC data, it was thought that the hadronic firetube from an
AA collision might be like a “burning log”. But instead of smouldering, the RHIC data suggests that the log blows up.

In particular, the results from RHIC appear to contradict any hydrodynamic description \[15,27\]. Versus experiment, hydrodynamics gives values of $R_{\text{long}}$ and $R_{\text{out}}$ which are too large, and a $R_{\text{side}}$ which is too small. Of especial interest is the ratio of $R_{\text{out}}/R_{\text{side}}$: hydrodynamics predicts this ratio should be $\approx 1.5 \to 2$, and which increases with $p_t$. At RHIC, the ratio decreases as $p_t$ goes up, and is about one, $0.85 \geq R_{\text{out}}/R_{\text{side}} \geq 1.15 \ [15]$.

The HBT data can be parametrized as a type of “blast” wave, with a velocity $\approx \frac{3}{4} c \ [15]$. This may indicate a type of “explosive” behavior \[18,33\], a term first used by the experimentalists.

HBT radii can also be used to give a measure of the entropy carried by pions \[15\]. Per degree of freedom, the entropy in peripheral collisions is greater than that in a Bose-Einstein gas, but is less than that for the most central collisions. This may indicate coherence in the initial state.

Partonic models in which the cross section is artificially multiplied by a factor of $\approx 14 \ [34]$ give both $R_{\text{out}}/R_{\text{side}} \approx 1$, at least by $p_t \sim 1.5$ GeV, and a flat elliptical anisotropy. One may view this as evidence that at hadronization, apparently near $T_c$, the partons appear to behave much more strongly than expected from perturbative QCD.

6. “HIGH”-$p_t$ SUPPRESSION

From the first RHIC data, it was clear that the spectra for “high”-$p_t$ particles, meaning above, say, 2 GeV, is qualitatively different in central $AA$ collisions, versus $pp$ collisions at the same energy. Dividing by the number of participants, the number of particles at high-$p_t$ is significantly less in central $AA$ collisions than in $pp$, by overall factors of $2 - 4 \ [8,9,10,11,12]$. This is quantified through the ratio $R_{AA}$, which is the ratio of the number of particles in central $AA$ collisions, divided by that in $pp$, as a function of $p_t$. The suppression begins above $p_t \approx 2$ GeV; above 4 GeV, $R_{AA} \approx 1/3 \to 1/4$ for charged hadrons, and $R_{AA} \approx 1/5 \to 1/6$ for pions \[9\]. A surprise of the Run II data is that for $p_t : 2 \to 9$ GeV, $R_{AA}$ is approximately constant, up to at least 9 GeV \[9\].

This suppression of high-$p_t$ particles is opposite to what is observed at the SPS. There, due to what is known as the Cronin effect, the ratio $R_{AA}$ is greater than one, going up to $\approx 2.5$ by $p_t \approx 3$ GeV. This change in the spectrum must be considered as one of the most dramatic features of the RHIC data.

The usual explanation of high-$p_t$ suppression is due to energy loss \[10,11,12\]. Bjorken originally noted that a fast quark (or gluon) loses energy as it traverses a thermal bath, in just that same way that any charged particle does in matter. Single particle distributions can be explained using parton models \[12\].

Detailed features of the data appear difficult to explain as energy loss, though. Naively, one might expect soft processes to scale as the number of participants, $\sim A$, and hard processes to scale as the number of collisions, $\sim A^{1/3}$. As a hard process, then, one would expect energy loss to scale as $A^{1/3}$. Instead, in peripheral collisions, $R_{AA}$ scales with the number of participants \[35\]. It is possible that the difference of two terms of order $A^{1/3}$ is of order $A$, but that seems unnatural.

Further, the observed constancy of $R_{AA}$ for $p_t : 2 \to 9$ GeV is surprising; perturbative
models of QCD do not give constant behavior. The apparent constancy also reflects changes in particle composition, while pions dominate below $p_t \approx 2$ GeV, unlike $pp$ collisions, there are as many protons as pions above $p_t \approx 2$ GeV. Taking protons as color baryon junctions, in perturbative QCD the pion part of $R_{AA}$ peaks at a smaller $p_t$ than the proton part [36].

In weak coupling, energy loss in QCD is proportional to $\sqrt{E}$, where $E$ is the energy of the jet [10]. If one assumes, simply for the sake of understanding the data, that the energy loss is proportional instead to $E$, with hard particles losing $\approx 7\%$ of their energy per scattering, then a next-to-leading order calculation in QCD gives a good fit to the data [37].

## 7. SATURATION

Another surprise from the first RHIC data was that the multiplicity did not grow as rapidly as predicted, at least on the basis of various cascade models. A natural explanation for this is given by models of saturation [11,38,39,40,11,12].

The application of saturation to AA collisions is, at the most basic level, purely a kinematical effect. Consider a nucleus-nucleus collision, in the rest frame of one of the nuclei. For atomic number $A \approx 200$, in its rest frame the incident nucleus has a diameter no greater than $\approx 2A^{1/3} \approx 15$ fm. By Lorentz contraction, this distance gets shrunk down by a factor which is about $1/(\sqrt{s}/A)$. Eventually, the color charge of the incident nucleus looks not like a nucleus, but just like a very thin pancake, with a big color charge $\sim A^{1/3}$. Assuming that distances on the order of $1/3 \to 1/4$ fm are small on hadronic scales, the incident nucleus looks like a thin pancake when $\sqrt{s}/A : 45 \to 60$ GeV. It is amusing that a simple estimate gives an energy right near where a Central Plateau, in which the particle density is constant with rapidity, first appears.

In details, saturation is a dynamic criterion. It states that at sufficiently small Bjorken-$x$, quark and gluon distribution functions are dominated by gluons, which peak at a characteristic momentum scale, termed the “saturation” momentum, $p_{sat}$. (This gluon dominance is reminiscent of flavor independence for thermodynamics.) For any perturbative approach to work, $p_{sat}$ cannot be less than at least 1 GeV. The above kinematic argument suggests that $p_{sat}^2 \sim A^{1/3}$; thus one can probe smaller $x$ values with large nuclei at RHIC, say, than in $ep$ collisions at HERA.

What is most important about saturation is, again, almost a kinematical effect: it resets the “clock” for heavy ion collisions. In the Bjorken picture which dominated before the RHIC data, one assumed that hadronization occurred at time scales $\approx 1$ fm/c; after all, what other time scale is there? Thus in the Bjorken picture, there seemed as if there was little time for even the largest nuclei, only 7 fm in radius, to thermalize. (Unless, again, there were a strongly first order transition, which is why it was so popular before RHIC.)

With saturation, however, the natural scale of the clock is given by $1/p_{sat}$; for $p_{sat} \approx 1$ GeV, this is already $\approx 2$ fm/c; see, e.g., [11]. That is, saturation makes the hadronic “clock” runs at least five times faster! The possibility of interesting things happening is far more likely.

Saturation is realized in the Color Glass Model [11,38,39]. The gluon fields from the incident nucleus are described as classical color sources, reacting much quicker than the
fields in the target nucleus. Taking a gluon field to scale with the QCD coupling constant $g$ as $A_\mu^g \sim 1/g$, one concludes that the action, and indeed all quantities — such as particle multiplicity, average energy, etc. — scale like $1/g^2$. In an asymptotically free regime, then, all quantities grow like $\sim 1/\alpha_s(p_{sat}) \approx \log(p_{sat})$. This small, logarithmic growth in the multiplicity agrees qualitatively with the RHIC data (although one really needs the increase to LHC energies to make this quantitative).

This picture is only approximate. Even if a gauge field is $\approx 1/g$, the action need not scale like $1/g^2$. In $AA$ collisions, at initial stages there is a screening mass generated along the beam direction, but not transverse, with a mass squared $\sim \alpha_s$ at leading order \[10,11\]. Such a dynamically generated mass scale changes integral powers of $1/\alpha_s \sim \log(p_{sat})$ into fractional powers; see, e.g., \[10,11\].

Modulo these theoretical quibbles, it seems plausible that saturation describes the initial state of $AA$ collisions at high energies. Fits to the particle multiplicity, including the dependence upon centrality and rapidity, agree approximately with the data \[38\]. It is not evident how to turn gluons into hadrons, as sometimes the mysteries of “parton-hadron duality” are invoked. It is surprising that such models work over a wide region of centrality and rapidity, since saturation (valid at small Bjorken-$x$) should not work well in the fragmentation region (which is large Bjorken-$x$). The particle density in such fits has peculiar peak at zero rapidity \[12\]. Experimentally, the fragmentation region appears to be described by a universal limiting form \[35\] (although it is crucial to have data with identified particles, which is presently lacking).

Saturation does not describe other basic features of the data, though. The most serious problem is that the average $p_t$ in saturation is $\langle p_t \rangle \approx 2p_{sat}$; even with $p_{sat}$ as low as 1 GeV, this is an average $p_t \sim 2$ GeV. In contrast, at RHIC $\langle p_t \rangle \approx 550$ MeV. The average energy from saturation will decrease due to inelastic processes and the generation of entropy. Assuming that this fixes the overall constant, one is still at a loss to explain why the average $p_t$ changes by at most 1% between $\sqrt{s}/A = 130$ GeV and 200 GeV, while the multiplicity changes by at least 15% \[6\]. In saturation models, the average $p_t$ grows with multiplicity.

A related problem is the chemical composition. Parton-hadron duality is really gluon-pion duality; but if the average gluon momentum is large, why don’t the hard gluons become kaons? Instead, at RHIC kaons are much less numerous than pions, only about 15% as much.

The elliptic anisotropy can be calculated in a Color Glass \[40\]. As a function of momentum, it is dominated by very soft momentum, peaking at a value of $p_t \approx p_{sat}/4$. This is not seen experimentally.

Of course if saturation describes the initial state, and not the final state, then there is no problem with the above features of the data. Estimates of thermalization in perturbative QCD give numbers $\approx 3$ fm/c \[11,14\]. Further, thermalization occurs not due to elastic processes, but is dominated by inelastic processes \[13\].

It is claimed that the logarithmic growth of the total cross section follows from saturation \[39\]. This is a matter of black and white: if there are massless particles, there is no bound on the total cross section. Thus saturation, which has no mass gap, cannot guarantee a finite total cross section.
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