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RHIC AND LHC: PHYSICS PERSPECTIVES *

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Abstract

We discuss some reasons for studying heavy ion collisions at very high energies, and outline the global conditions (initial energy densities, temperatures and baryon densities, freeze-out volumes and lifetimes) to be expected at RHIC and LHC. After surveying the main initial state probes suggested so far, we consider in particular the possibilities of studying high mass dileptons and charmonium/bottomonium production with high energy colliders.

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1. INTRODUCTION

Heavy ion colliders will bring us to higher collision energies than fixed target facilities. But how does that help us in the study of strong interaction thermodynamics? The volume of the initially produced system is determined by the size of the colliding nuclei; we thus cannot get beyond uranium on uranium. The initial density does depend on the collision energy, but all present estimates of the critical value indicate that the CERN SPS should already be sufficient to bring us there. Why do we then want heavy ion colliders, and what can we do with them?

One aim of this talk will be to survey some of the physics reasons that drive us to higher energies. They are of two kinds. There are phenomena that become more pronounced and clear-cut at higher energy: the energy density of the system increases, hence its lifetime becomes longer, its freeze-out volume larger, thermalisation more likely, and so on. And there are things which become possible *only* at high collision energies: the study of the effect of dense matter on the full spectrum of $c\bar{c}$ and $b\bar{b}$ resonances or its effect on jet production, the production of matter of vanishing baryon number density, or the production of an asymptotically free quark gluon plasma.

A further aim of the talk is to see if there are any specific physics questions which are best addressed at one or the other of the two facilities under consideration here. Both are expected to produce extended hot and dense QCD systems hadronizing mainly into mesons. But as we shall see, the capability to study asymmetric collisions (from $p - A$ to $A - A$) should allow RHIC to investigate also the onset of nuclear transparency, while the LHC, with its considerably higher initial energy, should be particularly suited in looking for an asymptotically free quark-gluon plasma of vanishing baryon number density.

In discussing today the physics we expect to explore at RHIC and LHC, we are obviously extrapolating concepts and ideas which seem important now. Their role can easily change in eight or more years, particularly in a field as exploratory as ours. I shall therefore not attempt to be systematic, but rather concentrate on what I find to be most interesting at this time.

2. GLOBAL FEATURES AND CONDITIONS

First of all, we recall that the tremendous increase in incident energy, from 4 GeV c.m.s. energy per nucleon-nucleon collision at the AGS (with Au beams) to 6300 GeV at the LHC (with Pb beams), results in a much smaller variation in the relevant variable for our purposes, the initial energy density ϵ_0 . We can estimate the expected values of ϵ_0 from the multiplicity $(dN/dy)_p$ of hadrons measured per unit central rapidity in $p - p$ and $p - \bar{p}$ collisions. A fit of all data from SPS to Tevatron energies [1] suggests the form

$$(dN/dy)_p \simeq 0.9 \ln[\sqrt{s}/2m_p], \quad (1)$$

where m_p is the proton mass. This can be extrapolated to central $A - A$ collisions

by writing

$$(dN/dy)_A \simeq A^\alpha (dN/dy)_p, \quad (2)$$

where $\alpha \geq 1$ parametrizes the amount of rescattering, with $\alpha = 1$ for a simple superposition of collisions between target and projectile nucleons. In $p - A$ collisions, one finds $\alpha \simeq 1.1$ [2], and we shall use this value for a first estimate of multiplicities in $A - A$ collisions. It is clear, however, that in the collision between two heavy nuclei, there may well be much more rescattering than in $p - A$ interactions. Specific event generators [3–6] in fact give three to four times higher multiplicities, which would lead to a value $\alpha \simeq 4/3$.

Given $(dN/dy)_A$ and an initial interaction volume $V_o = \pi(1.15A^{1/3})^2\tau_o$, with a formation time $\tau_o \simeq 1$ fm, we can assume free flow [7] to get

$$\epsilon_o^{\text{ff}} = m_T (dN/dy)_A / V_o \quad (3)$$

for the initial energy density, or isentropic flow [8] to obtain

$$s_o^{\text{is}} = 3.6 (dN/dy)_A / V_o \quad (4)$$

for the initial entropy density. For an ideal plasma we can relate energy density and entropy density to get

$$\epsilon_o^{\text{is}} \simeq 0.30 [(dN/dy)_A / V_o]^{4/3} \quad (5)$$

for the energy density in the case of isentropic expansion. The ratio of eqs.(5) and (3) gives us (with $m_T \simeq 0.5$ GeV)

$$R_\epsilon \equiv \frac{\epsilon_o^{\text{is}}}{\epsilon_o^{\text{ff}}} \simeq 0.36 [A^{(\alpha-2/3)} \ln(\sqrt{s}/2m_p)]^{1/3} \quad (6)$$

for the ratio of the two different energy density estimates. With $A = 200$ and $\alpha = 1.1$, this becomes

$$R_\epsilon \simeq 0.77 [\ln(\sqrt{s}/m_p)]^{1/3}. \quad (7)$$

The behaviour of $R_\epsilon(\sqrt{s})$ is shown in Figure 1. In the AGS-SPS range, it is near unity, so that here the two estimates give approximately the same result. With increasing $\sqrt{s}$, isentropic expansion begins to give larger values than free flow, since part of the initial energy goes into collective flow, so that eventually flow effects could become apparent even in global variables. To obtain a first estimate of the energy densities to be expected, we shall nevertheless use here the Bjorken form (3), keeping in mind that the isentropic form (5), a larger α (more rescattering) and a larger m_T (minijets) would increase ϵ_o . From eq. (3) we get

$$\epsilon_o = 0.11 A^{\alpha-2/3} \ln(\sqrt{s}/2m_p). \quad (8)$$

The resulting ranges of ϵ_o in $A - A$ collisions at the different facilities are shown in Figure 2, with the lower value in each case corresponding to $A=30$ (e.g. Si, S), the higher to $A=200$ (Au, Pb). We see that from AGS to LHC, the energy density range

is just covered nicely from 0.5 GeV/fm³ (the energy density inside a single nucleon) to almost 10 GeV/fm³; there are no jumps or gaps, the existing and planned facilities complement each other very well. We also see that both colliders really bring a significant increase in the energy density range. It will extend even further, if the higher multiplicities obtained from nuclear event generators with more rescattering are not compensated by longer equilibration times τ_o ; the highest values of ϵ_o are then increased by a factor three to four.

If we assume that the initial state produced in the collision is an ideal plasma of gluons and three flavours of massless quarks, the energy density is given by

$$\epsilon_o = (47.5 \pi^2/30)T_o^4, \quad (9)$$

with T_o for the primordial temperature. In Table 1 we summarize the parameters obtained from our estimates for the heavy ion beams at SPS, RHIC and LHC, including the resulting values of T_o . Even at RHIC and LHC, the initial temperature T_o thus remains below 300 MeV, if we use $\alpha \simeq 1.1$. If we base our estimates on the highest multiplicities obtained by nuclear event generators, retaining $\tau_o \simeq 1$ fm, the temperatures will increase by about 30 %.

Table 1

Parameters and conditions expected for experiments at AGS, SPS, RHIC and LHC.

Machine	Beam – Target	$\sqrt{s}$ [GeV/A]	$(dN/dy)_o$	ϵ_o [GeV/fm ³]	T_o [MeV]
AGS	$^{28}Si - ^{197}Au$	5	70	0.9	150
SPS	$^{32}S - ^{238}U$	20	200	2.4	190
AGS	$^{197}Au - ^{197}Au$	4	230	0.8	150
SPS	$^{208}Pb - ^{208}Pb$	17	700	2.4	190
RHIC	$^{197}Au - ^{197}Au$	200	1400	5.1	230
LHC	$^{208}Pb - ^{208}Pb$	6300	2600	9.0	260

From lattice gauge theory, we get presently about 1 GeV/fm³ as best estimate of the critical value ϵ_c for deconfinement at vanishing baryon number density [9]; it is included in Figure 2. The value of ϵ for which the quark-gluon plasma becomes

asymptotically free is not so easily determined. However, the relation $(\epsilon - 3P)/T^4 = 0$ between energy density and pressure, which is characteristic of an ideal gas, is found to become approximately valid for $T/T_c \gtrsim 1.5 - 2$ [10,11]. This suggests that we can expect an onset of asymptotic freedom at best for $\epsilon \gtrsim 5$ GeV/fm³ in the case of vanishing baryon number density. At finite baryon number density – which, as we shall see shortly, means at least in the AGS-SPS range – there are so far no really reliable results from lattice QCD. Approximative studies [12] agree with the general expectation that for $n_b \neq 0$, ϵ_c may well be lower.

Let us now look at the expected initial baryon number density n_b^0 . When a proton passes through a heavy nucleus, it collides with the target nucleons and is found to lose on the average about 2-2.5 units of rapidity [13]. This result also follows from arguments giving a shift in rapidity δy proportional to the number of collisions ν with target nucleons [14]. Applied to $p - Pb$ interactions, they lead to a $\delta y \simeq 2.5$ for central and $\delta y \simeq 2$ for impact-parameter averaged collisions. The collision of two heavy nuclei may well provide more stopping, however, since now a nucleon from the interior of the projectile can also collide with other stopped projectile nucleons and with secondaries from collisions of these stopped nucleons, not only with the target nucleons themselves [15,16]. Such an enhanced stopping is in fact obtained by recent event generator studies: both the RQMD code [3,4] and the dual parton model [17] give a shift of 3.5 - 4 units of rapidity (see Figs. 3 and 4). The resulting energy dependence of the baryon-free region is shown in Figure 5, and the baryon number distributions themselves are schematically illustrated in Figure 6. We note in particular that for $\delta y \gtrsim 3$, we do not expect a region of vanishing baryon density at RHIC; for $\delta y \gtrsim 4.5$, it would even disappear for the LHC.

To estimate the maximum baryon density obtainable in nuclear collisions, we recall that at the moment of maximum overlap of target and projectile nuclei, there are $2A$ nucleons in an ellipsoid whose thickness in the Lorentz-contracted direction is $2R_A(\sqrt{s}/2m)$, with m for the nucleon mass. Hence the baryon density at this point is $n_b^0/n_o = (2/3)(\sqrt{s}/m)$. The baryons in this ellipsoid can, however, in general not be in global equilibrium; there will be considerable longitudinal expansion. To estimate the density of a system which could be in equilibrium, we restrict ourselves again to a unit rapidity interval around $y = 0$. For the schematic triangular distributions of Figure 6, this means a reduction of n_b^0 by a factor $\{1 - [(Y_{max} - 0.5)/Y_{max}]^2\}$; we assume here that $Y_{max} \geq 0.5$. Once we are beyond the point $Y_{max} = \delta y$, the thickness of the ellipsoid will continue to decrease, but the value of the baryon number distribution at $y = 0$ will start to fall as well (see, e.g., Figure 6 for RHIC with $\delta y = 3.5$). To approximate this, we multiply n_b^0 in the interval $1 \leq (Y_{max}/\delta y) \leq 2$ by the factor $[2 - (Y_{max}/\delta y)]$. We thus arrive at

$$n_b^0/n_o \simeq (2/3)(\sqrt{s}/m)\{1 - [(Y_{max} - 0.5)/Y_{max}]^2\} F(Y_{max}/\delta y) \quad (10)$$

as a rough estimate for the baryon density as function of $\sqrt{s}$; here the function $F(x) = (2 - x)$ is defined to be unity outside the interval $1 \leq x \leq 2$. The resulting behaviour of n_b^0 is shown in Figure 7 for the two cases $\delta y = 2$ and 3.5. We see

that if there is indeed a noticeable enhancement of nuclear stopping beyond that found in $p - A$ collisions, then we should expect matter of maximum baryon number density, with more than ten times standard nuclear density, to be produced around the RHIC energy. This would certainly have impact on our understanding of the space-time picture of the collision, since it is quite contrary to an early onset of nuclear transparency and the resulting one-dimensional longitudinal expansion.

A less geometric way to estimate the expected baryon number density is based directly on the kinematic compression arising by the impact of “later” projectile nucleons hitting the slowed-down earlier ones [15]. It leads to a maximum attainable baryon density

$$n_b^0/n_o \simeq [\delta\gamma - (\delta\gamma^2 - 1)^{1/2}]^{-1}, \quad (11)$$

where $\delta\gamma = \cosh \delta y$. For $\delta y = 3.5$, this gives us $n_b^0/n_o \simeq 33$, compared to the range $7.4 \leq n_b^0/n_o \leq 12$ obtained for $2 \leq \delta y \leq 2.5$.

Although the baryon densities could thus be quite high even up to RHIC energies, so are the resulting values for the entropy per baryon. Using eq.(2), with $\alpha = 4/3$, for the overall number of hadronic secondaries and eq.(14) for the number of baryons per unit rapidity, we get for the ratio of the number of baryons to that of hadrons the behaviour shown in Figure 8. Thus the matter to be expected at RHIC as well as at the LHC will certainly be hot and not baryon-dominated; the dominant secondaries in both cases will be mesons.

This gives us an idea of the energy and baryon number density ranges we can hope to investigate at RHIC and LHC. To study thermodynamics and critical behaviour, we need systems as large and long-lived as possible, and we have to be able to vary the basic thermodynamic variables ϵ_o , n_b^0 and V_o .

The obvious way to vary ϵ_o would be to vary the incident beam energy $\sqrt{s}$. However, since ϵ_o depends on $\sqrt{s}$ only logarithmically, this is not a very effective procedure: reducing the top LHC energy for $Pb - Pb$ collisions by a factor of ten reduces ϵ_o by less than 25 %. Moreover, such changes in beam energy are technically not so easy to carry out [18]. A more effective way is to change A : going from $S - S$ to $Pb - Pb$ collisions increases ϵ_o by more than a factor two. This, however, varies not only ϵ_o , but also the initial volume V_o , which is unimportant only if have reached the thermodynamic limit. How can we check this? Because of nuclear geometry, quite asymmetric collisions, such as $S - Pb$, lead to almost the same average energy density as $Pb - Pb$ collisions, but in a much smaller volume [19]. One way to check if we are approaching the thermodynamic limit thus is through experiments over a range of different projectiles, e.g. $S - Pb$, $Ag - Pb$ and $Pb - Pb$ collisions, at the same beam energy. This is possible at RHIC, but not at the LHC. An alternative way in symmetric collisions is to vary the impact parameter of the collision, by varying the multiplicity or the transverse energy E_T ; this again keeps the energy density approximately constant, but leads to smaller volumes at larger impact parameters [19]. Complementary to these two methods, we can vary ϵ_o at fixed V_o by comparing results from AGS, SPS, RHIC and LHC, although in this comparison n_b^0 is in general not kept constant.

The variation of n_b^o in the different set-ups involves the dependence of nuclear stopping on A and $\sqrt{s}$. At high energies, RHIC remains the only facility for a complete study of stopping from $p - A$ to $B - A$ (with $B \ll A$) to $A - A$ collisions. Such studies at really high energies are crucial, since only they will allow a distinction between the different pictures for the evolution of the collision, and even for $Pb - Pb$ at the SPS, the different presently studied event generators still give quite similar baryon number distributions. The possible range of baryon densities as function of the associated hadron multiplicities, calculated from $S - S$ interactions with $\delta y = 2$ to $Pb - Pb$ interactions with $\delta y = 3.5$, is shown in Figure 9. We have here calculated the multiplicities with $\alpha = 4/3$, in view of the enhanced stopping.

To study the behaviour of bulk matter in QCD, we need large systems; this need is enhanced when we look for critical behaviour, since divergences or discontinuities become pronounced only in the large volume limit. The initial interaction volumes in $A - A$ and $p - p$ collisions are related by

$$V_o^{AA}/V_o^{pp} \simeq (R_A/R_p)^2 \simeq 2 A^{2/3}. \quad (12)$$

This means that in a $Pb - Pb$ collision the interaction volume is about 70 times that of $p - p$. But if the system has a sufficiently high initial density, it can expand considerably and still remain above the confinement point. Thus for $Au - Au$ collisions at RHIC, with an initial energy density of about 5 GeV/fm^3 , we expect at the onset of confinement a volume about 350 times that of a $p - p$ collision; the LHC, with $\epsilon_o \simeq 9 \text{ GeV/fm}^3$ for $Pb - Pb$ collisions, gives more than 630 times the $p - p$ volume. Here again, more rescattering and more stopping would increase the values.

The volume at freeze-out can be determined by requiring that at this point the mean free path λ of a hadron in the system should surpass the dimension of the system, i.e., the hadron “gets through” without interacting [20]. From

$$\lambda = (n_f \sigma)^{-1} = R_f, \quad (13)$$

we get with isentropic expansion and $\sigma \simeq 20 \text{ mb}$

$$R_f^\lambda \simeq 0.69 (dN/dy)_{AA}^{1/2}. \quad (14)$$

Another possibility is to define freeze-out as the point at which the energy density of the system reaches the value of an ideal pion gas [21]. This leads to

$$R_f^\epsilon \simeq 1.24 (dN/dy)_{AA}^{1/3}. \quad (15)$$

Eqs.(14) and (15) state that for increasing $(dN/dy)_{AA}$, ϵ_o increases, resulting in more expansion and hence a larger freeze-out radius – if the initial state indeed consisted of dense matter. The regime of values bounded by eqs. (14) and (15) is shown in Figure 10a; present data lie between these two forms. In the collider region, we thus expect freeze-out volumes in the range from twenty thousand to over a million fm^3 ; this is one reason for hoping that the systems are sufficiently macroscopic to use them in the study of QCD thermodynamics.

We now consider the temporal evolution. The crucial times are sequentially $\tau_o < \tau_c < \tau_h < \tau_f$, with the formation time τ_o , the time τ_c for the onset of confinement, in case of a first order transition followed by the time τ_h , at which the mixed phase is over and the system is fully hadronic, and finally the freeze-out time τ_f . For one-dimensional isentropic longitudinal expansion in the initial dense plasma stage [7], deconfinement begins at time

$$\tau_c = \tau_o (T_o/T_c)^3, \quad (16)$$

in terms of the initial and the critical temperatures. For a strong first order transition (i.e., one with a latent heat given by the difference between the ideal hadron gas and ideal plasma energy densities), we have

$$\tau_h/\tau_c = d_q/d_h \simeq 16. \quad (17)$$

Here $d_q = 47.5$ and $d_h = 3$ are the numbers of degrees of freedom of an ideal quark-gluon plasma with $N_f = 3$ and of an ideal pion gas, respectively. The time between the end of the mixed phase and freeze-out appears difficult to estimate; it is most likely quite short, since the expansion is now probably three-dimensional and the freeze-out temperature is not much different from T_c . The resulting lifetimes τ_c in the plasma and τ_h until the end of the mixed phase are shown in Figure 10b.

We conclude that the lifetime of the plasma phase is really quite marginal for equilibrium (i.e., time-independent) thermodynamics. This is perhaps one of the strongest reasons for insisting on the highest possible $\sqrt{s}$ for large A and as much as possible a selection of events with high E_T or multiplicity.

3. PRIMORDIAL STATE PROBES

We now come to possible tests of the primordial state of matter in high energy nuclear collisions, i.e., we want to study the conditions just after the formation of a thermal system. This problem is particularly difficult, since a system in thermodynamic equilibrium retains no memory of its previous history. What candidates for primordial state probes does that leave us?

We can study signals produced *before* the formation of any thermal system and look for subsequent effects of the medium. The main phenomenon considered in this context is charmonium and bottonium production. The production of $c\bar{c}$ or $b\bar{b}$ pairs is due to hard collisions of partons in the incoming nuclei at a very early time in the interaction, when the system is not yet thermal, and the $c\bar{c}/b\bar{b}$ production process is basically understood in terms of perturbative QCD (gluon fusion). The “perturbatively” produced heavy quark-antiquark pairs must now bind to form charmonium/bottonium states, and the binding will be affected by the presence of a dense medium. A specific case of such an effect is J/ψ suppression by colour screening, predicted to occur in a sufficiently hot quark-gluon plasma [22].

Another proposed probe of similar nature is the study of hard hadronic jets. Such jets arise from the hadronisation of partons which have undergone hard collisions very

early in the interaction; again their formation process is presumably described by perturbative QCD. The subsequent hadronisation pattern, however, could be quite different in a hadronic medium and in a quark-gluon plasma [23] (“jet quenching” and “unquenching”).

We can try to find signals which were produced in the *early thermal* stage of the process and which are not affected by the subsequent hadronisation of the system. The main phenomenon considered here is the emission of dileptons or “direct” photons; these are produced by interactions of the constituents (annihilation, bremsstrahlung) at an early time, and since they interact only electromagnetically, they escape essentially unaffected. In general, thermal dileptons and photons cannot specify the nature of the medium; thus the annihilation spectra of pions and of quarks have the same form $\exp(-M/T)$. They could, however, be used to determine the temperature T_0 of the primordial matter [24], provided we can separate the thermals from other sources of dileptons and photons.

In dense matter, hadronic resonances are predicted to change their characteristics, such as masses, widths or branching ratios [25]. If the decay time of a given resonance into dileptons is sufficiently short, so that it decays while still in the medium, we might be able to observe such resonance modifications. The main candidate here is the ρ , since the ω and ϕ lifetimes are rather long. In a similar vein, if the ρ is produced and decays into pions several times during the lifetime of the medium, then we would expect an enhanced ρ peak in the dilepton spectrum from nuclear collisions [26].

We can look for metastabilities or fluctuations arising directly from the transition. Supercooling (the existence of the system in the plasma phase at temperature below T_c) may lead to a sudden break-up and shock wave formation; these could manifest themselves e.g. in spikes or discontinuities in multiplicity distributions or spectra [27]. Chiral fluctuations could lead to baryon and antibaryon production much enhanced in comparison to what is expected from an equilibrium hadron gas [28]. If freeze-out occurs essentially at the transition point, we could get a system with a large range of scales, leading to intermittent or fractal behaviour [29].

Finally it is possible that a primordial quark-gluon plasma phase could hadronise into new forms of *hadronic* matter. The main candidate here is *strange matter* [30]. Given a system with an equal number of u, d , and s quarks, we could have the formation of “strangelets”, stable or metastable droplets of strange baryonic matter with low overall charge [31]. These could e.g. show up as neutral “supernuclei” of high strangeness and baryon number.

We shall here restrict our discussion of primordial probes to high mass thermal dileptons and to the spectral analysis of $c\bar{c}$ and $b\bar{b}$ resonances, keeping for both cases Drell-Yan production as a reference presumably understood in terms of perturbative QCD. The reason for this restriction is two-fold: one the one hand, these probes have probably been studied in most quantitative detail so far, and on the other hand, the higher energy densities provided by colliders may open up particularly interesting new possibilities for these probes. In Figure 11, we illustrate schematically an idealized form of the expected dilepton spectrum, to indicate the regions we want to consider

here.

The ultimate aim in the study of high mass thermal dileptons is to determine the initial temperature T_0 of the earliest state of matter produced in the collision. Dileptons will be emitted during the entire evolution of the system, at different temperatures, and only the high mass region will be dominated by the smallest coefficient of the mass in the exponential spectrum $\exp -M/T$, i.e., by T_0 . This means that at lower mass, the primordial part will disappear under dileptons from later stages of the evolution ($T > T_0$), in particular also under the tails of ρ , ω and ϕ decays. For sufficiently high masses, however, the pre-thermal Drell-Yan production will dominate, since it falls only as a power in the mass, in contrast to the exponential thermal spectrum. Is there a “window” between these two, in which we can get at the primordial thermal spectrum? The result of recent calculations for thermal dilepton production [32,33] is shown in Figure 12, together with the by now classical “Craigie” fit

$$M^4 (d\sigma/dy dM^2)_{y=0} \simeq 3.75 \times 10^{-5} \exp -15 M/\sqrt{s} \quad (18)$$

for Drell-Yan production in $p - p$ collisions [34]; it is supported quite well by QCD calculations [35]. For minimum bias $A - A$ collisions, we multiply eq. (20) by A^2 . The conclusion drawn from Figure 12 is only partially encouraging. Enhanced rescattering could bring the initial temperature up high enough to observe thermal dileptons in the mass region $1.5 \leq M \leq 2.5$ GeV both at RHIC and LHC, but these are not yet the primordial dileptons. Only for temperatures of around 400 MeV or higher can we perhaps expect to see them in the range $2 \leq M \leq 3.5$ GeV, and such temperatures appear at best just possible for the LHC. With the more conservative temperature estimates, there is little chance to get into the T_0 part of the spectrum at all [36].

An alternative probe for the density and hopefully also for the nature of the primordial medium is given by the analysis of $c\bar{c}$ and $b\bar{b}$ resonances relative to the Drell-Yan continuum [19]. J/ψ suppression, predicted as signal for quark deconfinement [22], was in fact subsequently observed [37]. It is, however, explainable as well in terms of absorption in a dense hadronic medium [38], so that at this time it is not clear if we have a local break-up or a global deconfinement. But we do have a clearly observable and observed effect, so that this probe appears to remain our best bet. What are our chances to measure the relevant spectra at SPS, RHIC and LHC?

The reference measure to check for suppression is Drell-Yan production, and the cross-section for this can be obtained from eq.(18). Estimates of the cross-sections for the production of J/ψ , ψ' and Υ are obtained from this through multiplying by 120, 4 and 30, respectively [34,39]. Note, however, that eq.(18) multiplied by A^2 refers to minimum bias events without any acceptance corrections; correcting for central collisions and acceptances can reduce the effective cross-sections by factors up to order 10^{-2} .

In Table 2 we list the estimates for the monthly minimum bias Drell-Yan production rates for $M = 3.1$ and 9.6 GeV at SPS, RHIC and LHC, obtained from eq.(20) with the quoted luminosities. The dependence of these rates on $\sqrt{s}$ is illustrated in Figure 13. We see that as far as rates are concerned, the J/ψ region should be clearly

accessible at all three facilities. The lower luminosity of the LHC in comparison to the SPS is more than compensated by the increase in cross-section at higher energy. For the RHIC energy and luminosity, this is not the case; however, as a dedicated heavy ion facility, RHIC could be run over longer time periods to provide an equivalent integrated luminosity. The Υ region, on the other hand, is clearly out for the SPS. It comes within reach for the LHC and with extended runs for RHIC, if the quoted luminosities can indeed be reached or exceeded, and if the acceptance is not too much restricted.

Table 2

Drell-Yan cross-sections and monthly production rates expected at SPS, RHIC and LHC for minimum bias $Pb - Pb$ collisions.

Energy	SPS	RHIC	LHC
$\mathcal{L} [\text{cm}^{-2}\text{s}^{-1}]$	10^{28}	10^{26}	10^{27}
$(d\sigma/dMdy)_{y=0}^{M=3.1} [\frac{\text{mb}}{\text{GeV}}]$	2.8×10^{-3}	3.5×10^{-2}	4.3×10^{-2}
$(d\sigma/dMdy)_{y=0}^{M=9.6} [\frac{\text{mb}}{\text{GeV}}]$	3.1×10^{-7}	7.2×10^{-4}	1.4×10^{-3}
$((\text{events/GeV})/\text{month})_{y=0}^{M=3.1}$	7.3×10^4	9.0×10^3	1.1×10^5
$((\text{events/GeV})/\text{month})_{y=0}^{M=9.6}$	8.0×10^0	1.9×10^2	3.7×10^3

It is clear from the above that colliders used for dilepton production suffer severely from luminosity restrictions. As a side remark we note here therefore that if it were possible to run the LHC in fixed target mode with a luminosity comparable to that of the SPS, we would have an excellent dilepton facility. As seen in Figure 13, where we have indicated such a possibility as LHB, its lower energy ($\sqrt{s} = 77 \text{ GeV}$) has little consequence in the J/ψ region, where it would thus give almost a factor 10 higher monthly rates than either SPS or LHC. As we shall shortly see, there are moreover other advantages to carrying out dilepton experiments at not too high an energy. In the Υ region, the (assumed) higher LHB luminosity would make it competitive to the LHC. These advantages only arise, however, when we judge purely from the point of view of dilepton rates. For high initial energy densities as well as for large volumes and lifetimes, we certainly do need the higher energies provided by the colliders.

Finally we want to comment on the P_T dependence of dilepton production. Thermal physics is basically low P_T physics; nevertheless, we can ask if by going to

larger values of P_T , we have a better chance of getting above the Drell-Yan continuum or to the T_o part of the spectrum for smaller dilepton masses. However, the Drell-Yan spectrum decreases less rapidly with P_T than the thermal spectrum [32] and moreover grows at large P_T with increasing $\sqrt{s}$ due to higher order contributions [35]. Hence it will tend to dominate thermal dileptons even more in the large P_T region. The second part of the question – getting to the T_o regime through large $M_T = (P_T^2 + M^2)^{1/2}$ at comparatively small M – is not so easy to answer; it requires a better understanding of when minijets and jets begin to influence the P_T behaviour of dilepton production.

For the spectral analysis of $c\bar{c}$ and $b\bar{b}$ resonance production, the P_T dependence can be of help in separating effects due to initial state parton scattering from those due to deconfinement [19]. To this end, one would have to determine for what values of P_T the suppression ceases. That may be very difficult simply because of the decreasing rates at higher P_T . In addition, however, at high energies the measured J/ψ and ψ' production will be contaminated by J/ψ 's from B decays. Calculations show no effective contamination at energies up to and including RHIC; at the LHC, however, direct J/ψ production both at large P_T as well as at small rapidity $y \leq 2$ will be lost under production through B decay [40]. The latter feature is of considerable interest from the point of view of detector construction: it means that the technically difficult region for low P_T dimuon detection around $y = 0$ is in any case not very desirable, and in the region $y \geq 2$, where the contamination should be negligible, detection also becomes easier.

4. CONCLUSIONS

The advent of RHIC and LHC will vastly extend our range of accessible energy densities ϵ_o in nuclear collisions, bringing us to values at least five to ten times higher than the expected energy density for deconfinement. With AGS, SPS, RHIC and LHC, we will then have facilities covering a range in ϵ_o from the value inside a single nucleon to values for which we can expect the onset of asymptotic freedom.

For such high energy densities, we expect enough rescattering to make thermalisation likely, and we expect volumes and lifetimes to make the application of equilibrium thermodynamics conceivable.

The systems produced at RHIC and LHC will be dominated by meson production, with a net baryon to meson rate of 1/100 or less. However, given an enhancement of nuclear stopping beyond that observed in $p - A$ collisions, RHIC could produce baryon densities ten or more times standard nuclear density and thus test the onset of nuclear transparency and the validity of our picture for the collision evolution. Complementary to this, the LHC is expected to provide energy density variations from 4 to 10 or more GeV/fm³ at vanishing baryon number density.

The accessibility of primordial thermal dileptons remains marginal at RHIC and even at the LHC, where it could become possible only if multiplicities reach the highest presently considered values. Studies of J/ψ production should be feasible at both RHIC and LHC; for the latter, possible contamination from B decay has to be

taken into account. The Υ region, on the other hand, strongly requires maximum luminosity, long runs and large acceptance.

In closing, we should emphasize once more that many considerations presented here are extrapolations into unknown many-body physics. Several event generator studies now give multiplicities exceeding the "standard" estimates by a factor three to four. On one hand this throws doubts on the validity of our picture of the evolution of the collision, with nuclear transparency, large baryon-free regions and one-dimensional expansion. On the other hand, it might mean considerably higher initial energy densities than expected – and this could greatly help in reaching thermal behaviour and deconfinement. It is therefore really crucial to carry out detailed event generator studies, with the different codes "gauged" by a standard set of data, including all available $p - p$ and $p - A$ data up to the highest energies, as well as the available nuclear collision results at lower energies. There may indeed be "more" interaction in nuclear collisions than we have so far assumed; but let us see if it persists when all checks have been carried out.

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Figure 1: The ratio of energy density estimates from free flow and from isentropic expansion, as function of the incident energy.

Figure 2: The estimated energy densities for AGS, SPS, RHIC and LHC as function of the incident energies.

Figure 3: The net baryon number density predicted for RHIC by the RQMD event generator [4].

Figure 4: Preliminary predictions of the net baryon number density at RHIC (a) and at the LHC (b), obtained from an event generator based on the dual parton model [17].

Figure 5: Regions of vanishing baryon number density for $\delta y = 2$ (inner white and light shaded triangles) and $\delta y = 3.5$ (inner white triangle).

Figure 6: Schematic baryon number distributions for SPS, RHIC and LHC, for $\delta y = 2$ (solid line) and $\delta y = 3.5$ (dashed line).

Figure 7: Estimates of the maximum baryon number density as function of the incident energy, for $\delta y = 2$ (a) and 3.5 (b).

Figure 8: Estimated ratio of net baryon to meson density, as function of the incident energy.

Figure 9: Estimates of the expected baryon density range for AGS, SPS, RHIC and LHC, as function of the average multiplicity, with $\delta y = 2$ for $S - S$ and $\delta y = 3.5$ for $Pb - Pb$ or $Au - Au$ collisions.

Figure 10: Expected ratio of freeze-out radius to nuclear radius (a) and of the freeze-out time (b), as function of the incident energy.

Figure 11: The ideal dilepton spectrum.

Figure 12: Thermal dilepton production for primordial temperatures 200 (a), 300 (b), 400 (c) and 500 MeV (d), as function of the dilepton mass, compared to Drell-Yan production for $\sqrt{s} = 17$ (dashed line) and in the RHIC/LHC range (dotted line).

Figure 13: Expected monthly rates for Drell-Yan production in the J/ψ and Υ regions, for minimum bias $Pb - Pb$ collisions at a luminosity of $10^{27} \text{ cm}^{-2} \text{ s}^{-1}$.