Stepping outside the neighborhood of $T_c$ at LHC

Urs Achim Wiedemann

Physics Department, Theory Unit, CERN, CH-1211 Genève 23, Switzerland

Abstract

"As you are well aware, many in the RHIC community are interested in the LHC heavy-ion program, but have several questions: What can we learn at the LHC that is qualitatively new? Are collisions at LHC similar to RHIC ones, just with a somewhat hotter/denser initial state? If not, why not? These questions are asked in good faith, and this talk is an opportunity to answer them directly to much of the RHIC community."

With these words, the organizers of Quark Matter 2009 in Knoxville invited me to discuss the physics opportunities for heavy ion collisions at the LHC without recalling the standard arguments, which are mainly based on the extended kinematic reach of the machine. In response, I emphasize here that lattice QCD indicates characteristic qualitative differences between thermal physics in the neighborhood of the critical temperature ($T_c < T < 400 - 500$ MeV) and thermal physics at higher temperatures ($T > 400 - 500$ MeV), for which the relevant energy densities will be solely attainable at the LHC.

1. From AGS to SPS, from SPS to RHIC, from RHIC to LHC

In the study of nucleus-nucleus collisions, an order of magnitude increase in center of mass energy has always been accompanied by major discoveries. The move of heavy ion experiments in the late 1980s from the Brookhaven Alternative Gradient Synchrotron to the CERN SPS illustrates this as clearly as the move a decade later from the CERN SPS to experiments at the relativistic heavy ion collider RHIC. In both cases, the increased kinematic reach gave access to qualitatively novel characteristics of the collision system, such as the discovery of $J/\Psi$-suppression at the CERN SPS, or the discovery of leading hadron suppression ("jet quenching") at RHIC. Also, in both cases, observations made already at the lower center of mass energy could be characterized in much more detail and reached a more mature understanding at higher center of mass energy. For instance, hadronic abundances close to thermal equilibrium had been measured already at the AGS, but our current understanding of hadrochemistry in terms of a grand canonical description was firmly established only at the CERN SPS, where two-parameter fits of thermal models accounted for the abundances of a large number of hadronic resonances, including rare multi-strange baryon yields which showed up to a factor 20 enhancement. Another example is elliptic flow, which had been measured in great detail at the CERN SPS. But it was only the gentle but continuous increase of the elliptic flow signal with center of mass energy, and its particle species dependence at transverse momenta inaccessible at the CERN SPS, which gave strong support to the current hydrodynamic interpretation of elliptic flow at RHIC. Furthermore, the move to a higher center of mass energy and the accompanying increase in precision and/or kinematic reach repeatedly initiated novel developments in theory. For instance, our current understanding of signatures of chiral symmetry restoration and thermal modifications of vector...
mesons has been largely developed and refined by the interplay of theory and experiment at the CERN SPS. The same can be said about HBT two-particle correlations or the global picture of expansion dynamics in the context of the SPS, or the theory of jet quenching and of saturation in the context of RHIC.

These developments are likely to be continued at the LHC. Discoveries arise as a consequence of (logarithmic) increases in kinematic reach and/or substantial improvement of instrumentation or precision. Understanding arises from a tight interplay between theory and experiment on the newly accessible measurements. For the LHC heavy ion program, the most foreseeable advances due to kinematic reach and instrumentation have been reiterated repeatedly in plenary talks. For instance, a factor $\sim 30$ increase in center of mass energy from RHIC to LHC will make many rare hard probes for the first time measurable and it will provide abundant samples of jets up to $E_T \approx 200$ GeV. The increased kinematic reach will also add qualitatively novel insight to many soft characteristics of heavy ion collisions: For instance, the abundance of charmed and beauty hadrons will provide novel tests for our understanding of the hadrochemical composition in heavy ion collision. Extending the measurements of elliptic flow to systems with denser initial conditions has the potential of falsifying or refining our current interpretation in terms of fluid dynamic evolution. Also, a factor $\approx 30$ increase in center of mass energy tests particle production at unprecedented low Bjornen-\textit{x}, where saturation phenomena may leave characteristic traces. Beyond these and other foreseeable physics opportunities, there is the exciting thought that a factor 30 jump into the unexpected is always a unique chance for finding the unexpected.

The novel physics opportunities, alluded to sketchily in the above paragraphs, could be discussed in much more detail by extrapolating the established (SPS and RHIC) phenomenology to the higher LHC center of mass energy, and discussing the resulting expectations in the light of the established experimental capabilities. However, the organizers discouraged me from reiterating once more these standard arguments. They rather encouraged me to reflect on the question of whether there are first principle calculations in quantum field theory, which could support the idea that the matter produced in heavy ion collisions at the LHC is qualitatively different from the matter produced at RHIC. In the following, I would like to recall some results from lattice QCD, which may support a positive answer.

![Figure 1: (color online) Lattice data for finite temperature 2+1 flavor QCD with physical strange quark mass and almost physical light quark mass. Left hand side: Temperature dependence of energy density $\epsilon$ and three times the pressure in units of $T^4$. Right hand side: The trace anomaly $(\epsilon - 3p)/T^4$. Data are for lattices with different temporal extent $N_\tau$ and for different actions. Figure taken from Ref. [1].](image-url)
2. QCD thermodynamics outside the neighborhood of $T_c$

Most generally, heavy ion physics aims at understanding how collective phenomena and macroscopic properties of matter emerge from the fundamental interactions of the non-abelian quantum field theory QCD. Heavy ion physics addresses this question at the highest energies and densities attainable in the laboratory, where partons are expected to be the relevant physical degrees of freedom, and where thus the connection of collective phenomena to the QCD lagrangian is most direct. Arguably the most striking collective phenomenon predicted from first principle calculations in QCD is the occurrence of the QCD phase transition to a deconfined state with restored chiral symmetry. This phase transition is seen clearly for instance in the ratio $\epsilon/T^4$ of energy density over temperature to the fourth power, which shows a rapid, almost step-function increase ("rapid cross over") at the critical temperature, indicative of a sudden change of the number of physical degrees of freedom, see the left hand side of Fig. 1.

A priori, it is unclear to what extent the systems created in heavy ion collisions are sufficiently close to (local) thermal equilibrium, and to what extent other confounding effects in their dynamical evolution are sufficiently unimportant to provide detailed tests of the QCD lattice equation of state. Part of this question remains to be decided in an interplay between experiment and theory. Based on Bjorken’s pocket formula, however, one may estimate the initial energy density attainable in heavy ion collisions. Typical numbers for the initial temperature attained in heavy ion collisions lie in the range of

$$200 < T_{\text{initial}}^{\text{SPS}} < 300 \text{ MeV},$$
$$300 < T_{\text{initial}}^{\text{RHIC}} < 500 \text{ MeV},$$
$$500 < T_{\text{initial}}^{\text{LHC}} < 1000 \text{ MeV}.$$  

These numbers come with significant uncertainties [2], in particular since Bjorken’s estimate is proportional to the (collision energy dependent) time $\tau_i$, at which the system is assumed to reach kinetic equilibrium. Taken at face value, however, the equilibration temperatures estimated above suggest that the CERN SPS experimental program was the first to gain access to the QCD high temperature phase, while RHIC was the first machine to create systems which spend a significant time of their dynamical evolution in this high temperature phase. Following this logic, the LHC will be the first machine to create initial conditions with energy densities, which lie far away from the neighborhood of the phase transition. Given that the ratio $\epsilon/T^4$ is apparently featureless above $T_c$, one may then rightly ask whether heavy ion collisions at the LHC "may be similar to RHIC ones, just with a somewhat hotter/denser initial state". However, while the figure of $\epsilon/T^4$ is arguably an iconographic representation of the QCD phase transition, its featurelessness above $T_c$ is not shared by many other thermodynamic quantities.

One thermodynamic quantity, which is not featureless above $T_c$, is the so-called interaction measure or trace anomaly $(\epsilon - 3p)/T^4$. It vanishes asymptotically for $T \gg T_c$, but it shows a characteristic and quantitatively important peak in the region close to but above $T_c$, see right hand side of Fig. 1. In view of the estimated initial temperatures given above, one may argue that the RHIC machine seems to have access only to the part of the high energy phase, where the interaction measure is sizeable. In contrast, LHC will be the first machine to test the high temperature phase in the region of almost vanishing interaction measure, where the equation of state approaches that of a free gas $\epsilon \approx 3p$ and where the system shows approximate conformal invariance. We now turn to arguments, which support the view that properties of the medium change qualitatively for $T > 400 – 500$ MeV and that a different set of techniques may be ap-
Applicable for the description of the QCD high temperature phase far outside the neighborhood of \( T_c \).

### 2.1. The Polyakov loop

For pure Yang-Mills theory without quarks, the trace of the Wilson line of the gauge field along the cyclic imaginary time direction

\[
\text{Tr} L(\vec{x}) = \text{Tr} \left\{ \mathcal{P} \exp \left[ i \int_0^\beta d\tau A_0(\tau, \vec{x}) \right] \right\}
\]

is a good order parameter for deconfinement. This so-called Polyakov loop can be interpreted in terms of a static quark free energy,

\[
\langle \text{Tr} L(\vec{x}) \rangle = \exp \left[ -\beta \Delta F_q(\vec{x}) \right].
\]

The Polyakov loop needs to be renormalized in order to eliminate self-energy contributions to \( \Delta F_q \). At low temperature, quarks are confined; as a consequence, the static quark free energy tends to infinity, and the thermal expectation value of the renormalized Polyakov loop \( L_{\text{ren}} \) vanishes. At high temperature, the system is deconfined, the static quark free energy becomes negligible, and \( \langle \text{Tr} L(\vec{x}) \rangle \) approaches unity. These features are clearly seen in the lattice data of Fig. 2.

Figure 2: (color online) The renormalized Polyakov loop \( L_{\text{ren}} \) of 2+1 flavor QCD for different lattice actions and lattices of different temporal extent. Figure taken from Ref. [1].

Pure SU(3) Yang-Mills theory has an exact \( Z(3) \) center symmetry in its confined phase, which gets spontaneously broken at the deconfinement transition. The Polyakov loop transforms under this exact \( Z(3) \) symmetry, \( \text{Tr} L(\vec{x}) \rightarrow z \text{Tr} L(\vec{x}), \ z \in Z(3) \). The corresponding symmetry transformation has to do with the boundary conditions of the allowed gauge transformations in the temporal direction, and its effects can be directly seen in the minima structure of the effective potential of the Wilson line [3]. In the deconfined phase, the potential has three minima, located at \( \text{Tr} L = \exp [2\pi i k/3], \ k = 0, 1, 2 \). All three minima are physically equivalent and the system arbitrarily chooses one. For temperatures below \( T_c \), the \( Z(3) \) symmetry is restored. Figure 3 shows lattice results which illustrate this clearly.

Adding quarks to SU(3) Yang-Mills theory breaks the center symmetry explicitly. The three minima in the effective potential of the Wilson line are not degenerate any more, but the minimum
at $\text{Tr}L = 1$ is favored over the complex minima at $\exp[2\pi i/3]$ and $\exp[4\pi i/3]$. The latter correspond to metastable configurations. However, even with dynamical quarks, the qualitative aspects regarding fluctuations between different minima are similar to the pure gauge theory. As a consequence, the qualitative change of breaking the $Z(3)$ symmetry by adding quarks leads only to very mild numerical changes of the thermal expectation value $\langle \text{Tr}L(\vec{x}) \rangle$ (see e.g. Fig. 2 of Ref. [4]). These observations support the view that even in the presence of quarks the Polyakov loop can still serve as an indicator of the transition to the QCD high temperature phase.

2.2. The Polyakov loop in the range $T_c < T < 3T_c$ and above

We consider now in more detail the physics, which determines the shape of $\langle \text{Tr}L(\vec{x}) \rangle$. At temperatures above $4 - 5T_c$, the system resides in one of the three $Z(3)$ minima and the renormalized Polyakov loop takes the asymptotic value of unity. Lowering the temperature, one observes a qualitative change that starts to set in around $2 - 3T_c$, see Fig. 2. The physics reason is that fluctuations between the minima get more important, and thus the expectation value of the Polyakov loop gets smaller since it averages over these minima. Finally, as one lowers the temperature to the critical one, the system is tunneling constantly between the different minima and it resides in different ones in different spatial regions. As a consequence, the expectation value of the Polyakov loop vanishes.

In short, what drives this transition are fluctuations between different minima, and these lead well above $T_c$ to a qualitative change in the characteristics of the QCD high temperature phase. We emphasize that this qualitative change occurs in a kinematic range of temperature, in which the QCD coupling constant varies only mildly. This illustrates that the mild logarithmic scale dependence of the strong coupling constant above $T_c$ does not imply that major thermodynamic characteristics of QCD show a negligible evolution for temperatures above $T_c$. Rather, what matters for the temperature dependence of the Polyakov loop is not the temperature dependence of the coupling constant $\alpha_s(T)$, but rather the importance of fluctuations whose dynamical relevance changes dramatically with the distance to the QCD phase transition.

To sum up, the Polyakov loop illustrates that there is a qualitative change in the physics of the quark gluon plasma between a broad transition region $T_c < T < 3T_c$ and temperatures higher
than $3 T_c$. According to our simple estimates, the higher energies at which the renormalized Polyakov loop reaches its high-temperature limit $\langle \text{Tr} L(\vec{x}) \rangle \rightarrow 1$ will be accessible at the LHC but could not be explored yet at RHIC.

2.3. The return of quasi-particle models?

As discussed above, the $Z(3)$ center symmetry plays a crucial role in the region $T_c < T < 3 T_c$, but not for higher temperatures. Remarkably, in almost all quasiparticle models [6, 7], such as those based on high-temperature dimensional reduction, one ends up explicitly breaking the center symmetry. These techniques rely on expanding around a minimum field configuration, which resides in one of the $Z(3)$ minima (For recent work aimed at circumventing this ansatz and working with a $Z(3)$ symmetric effective theory, see Refs. [8, 9]). In general, since quasi-particle models expand around a single minimum without accounting for the other (almost) degenerate minima, such models cannot be expected to account reliably for bulk thermodynamic quantities in a temperature range which is dominated by the fluctuations between different $Z(3)$ minima.

This field-theoretic observation is in line with the general statement that strong coupling techniques are needed to describe thermodynamic properties in the temperature range accessible at RHIC.

For temperatures above $3 T_c$, this argument does not hold any more: a compelling reason for why weak coupling techniques are inapplicable is gone. This does not imply automatically that weak coupling techniques are applicable, but several observations indicate indeed that they may become applicable for $T > 3 T_c$, while they clearly fail at lower temperatures. For instance, it is a generic feature of weakly coupled quasi-particle models that the difference $\epsilon - 3 p$ is proportional to $T^{-4}$. In contrast to this weak coupling expectation, lattice data indicate a quadratic dependence on $T$ in the range $T_c < T < 3 T_c$ [10]. For temperatures above $3 T_c$, however, the trace anomaly vanishes approximately, and this behavior is compatible with a weakly coupled quasi-particle model.

These observations may suggest that the "strong coupling paradigm", which has been developed in the context of RHIC phenomenology, may not extend to the entire thermodynamical range accessible at the LHC. In other words: that the strong coupling constant changes only logarithmically on the scale between RHIC and LHC initial temperatures should not be construed as implying the inapplicability of weak coupling techniques. There are field theoretic arguments, which indicate that weak coupling techniques can account for thermodynamic properties above $3 T_c$ if not applied to the physics of elementary partonic quanta but to effective thermal degrees of freedom. The kinematic reach of LHC opens the window for a novel conceptual debate about how to view hot and dense matter far away from the neighborhood of $T_c$.

3. Summary

We have used Bjorken estimates for the initial temperature to relate lattice simulations of finite temperature field theory to the experimental conditions in heavy ion collisions. This supported arguments that RHIC has explored an intermediate temperature range up to $T \approx 400 - 500 \text{ MeV}$, in which the value of the Polyakov loop deviates significantly from unity and where the interaction measure $(\epsilon - 3 p)/T^4$ indicates strong deviations from the equation of state of an ideal gas. These features are characteristically different from those of the genuine high temperature phase of QCD, which sets in only for temperatures above $400 - 500 \text{ MeV}$, and which is thus only accessible by experiments at the LHC. At face value, these lattice data hence suggest
that the matter produced in heavy ion collisions at the LHC may be characteristically different from the matter produced at RHIC.

In particular, the field theoretic motivation of quasi-particle models relies on expanding around minimum field configurations, which reside in one of the $Z(3)$ minima. As a consequence, such quasi-particle models are unlikely to capture the bulk properties of thermal QCD in a temperature range up to 400 - 500 MeV, which is dominated by fluctuations between the $Z(3)$ minima. On the other hand, both the approximate validity of an ideal equation of state for $T > 400 – 500$ MeV, and the value of the Polyakov loop in this temperature range supports the idea that a weak coupling description of the medium in terms of some effective physical degrees of freedom becomes applicable. In other words, the question of whether a perturbative description of the medium produced at LHC is applicable may not depend so much on the value of the strong coupling constant, which changes only logarithmically. It may rather depend on the availability of a stable minimum field configuration, on top of which a perturbative expansion in effective degrees of freedom can be based. Since the value of the Polyakov loop changes dramatically from the RHIC to the LHC energy range, lattice QCD strongly supports the view that such a stable minimum field configuration exists only for temperatures reachable at the LHC, while lower temperatures are dominated by fluctuations between different metastable minima.

Relating first principle calculations of lattice QCD to the phenomenology of heavy ion collisions is known to involve significant uncertainties. In particular, it relies on controlling possibly confounding factors. These arise for instance from non-equilibrium physics. Within a thermalized evolution, they can also arise from the known strong collective dynamics, which turns essentially all medium effects into averages over different periods of the expansion (and, a fortiori, into averages over different temperatures). Heavy ion collisions at the LHC will be initialized at much higher energy densities than those at RHIC, but they will live through the entire range of energy density explored at RHIC. The above qualitative arguments allow us to state that there are arguments from 1st principle calculations in lattice QCD, which indicate that the matter produced at the LHC should not be assumed to be solely somewhat hotter or denser than that produced at RHIC. Rather, the analysis of data at the LHC may require a critical assessment of the fundamental question of whether bulk thermodynamic quantities at the LHC are best described by strong coupling techniques.

Acknowledgments

In developing the above arguments, I have profited substantially from discussions with A. Vuorinen and exchanges with A. Kurkela.

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