Hard Probes at LHC

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Abstract

This talk gives a theoretical perspective of the physics issues awaiting us when heavy ions will collide in the LHC.

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1 Introduction

The heavy ion physics program at the Large Hadron Collider (LHC) at CERN will commence in about two years from now. It is thus appropriate to ask what we can expect from heavy ion collisions at the LHC, what our physics goals are or should be, and whether the theory community is adequately prepared for the anticipated scientific challenges. In other words, what is our grand strategy for the LHC heavy ion program? I will try to give answers to these questions in my lecture.

It is, first of all, important to recognize that the LHC program will constitute the last step of relativistic heavy ion physics into completely uncharted territory for a long time to come, maybe forever. There is not another accelerator on the planning horizon which could provide higher collision energies, and we have almost (with the exception of $^{238}$U) exhausted the range of accessible nuclear masses. It is also important to keep in mind that the increase of center-of-mass energy from RHIC to LHC is larger, measured on a logarithmic scale, that the step up from SPS to RHIC.

On the other hand, the data taken at RHIC have provided clear evidence that energy densities solidly, maybe even far, in excess of the critical energy density of QCD (about 1 GeV/fm$^3$) have been reached there, implying that the transition from hadronic matter to quark-gluon plasma has been made.
According to common wisdom, higher beam energies will only provide for a hotter quark-gluon plasma, but not something entirely new. This argument has been thrown into doubt in recent years, when experimental evidence from RHIC mounted showing that the produced matter is highly fluid and opaque to probes with open color. If the matter discovered at RHIC is a “strongly coupled” quark-gluon plasma, then maybe the matter that will be produced at LHC energies has a very different structure, more that of a “weakly coupled” gaseous plasma.

It must be noted, however, that lattice gauge calculations do not show evidence for a second transition point above $T_c$, where the structure of QCD matter might change in a qualitative way. The lattice results show the effects of interactions to gradually diminish as the temperature rises, due to the logarithmic weakening of $\alpha_s(T)$, but there is no sign of a dramatic change in thermodynamic quantities or correlation lengths once the transition from hadron gas to quark-gluon plasma is complete. Speculations that the matter produced at LHC will be qualitatively different from that observed at RHIC thus lack a solid theoretical basis.

Taking a conservative attitude, one is led to the expectation that LHC will produce a similar, but hotter type of matter as RHIC. Hard QCD phenomena, which were accessible at RHIC for the first time, will be much more abundant and thus can be more easily studied experimentally. The central question for theorists will, therefore, be whether the theoretical framework that has been developed at RHIC will hold up when the data from LHC experiments come in. The extended kinematic range offered by the LHC will provide for quantitative test of the models and concepts that have successfully described the RHIC data:

- The saturation of initial parton densities reflected in the rapidity distribution of the charged particle multiplicity;
- The almost ideal hydrodynamical evolution of the matter as evidenced in the magnitude of the elliptic flow ($v_2$);
- The scaling of parton energy loss with the path weighted, integrated matter density $\int \rho \tau d\tau$;
- Color screening on subhadronic scales leading to bulk hadronization and hadron formation by valence quark recombination;

The major new probes of matter accessible at LHC energies – $b$-quarks and resolved jets, will permit tests of these theoretical ideas with much improved control on the theoretical predictions (because of the larger momentum scales involved).

If the general picture developed and still being refined at RHIC is found to apply to the LHC data, as well, we will be able to proclaim success. Success,
that is, in having obtained a theoretically firmly grounded understanding of the properties of hot QCD matter – the quark-gluon plasma – and of the space-time evolution of relativistic heavy ion collisions at the highest energies. This would be a major achievement for our field. On the other hand, if the LHC experiments were to bring unforeseen surprises showing, for example, that the matter created at the higher energies is qualitatively different from that formed at RHIC, this would be most exciting, as well. Some would probably find such a scenario more exciting, because it is the tendency of scientists (and funding agencies!) to get easily bored by repeated confirmations of previously made discoveries.

The questions we turn to next are: What do we currently expect nuclear collisions at LHC to look like? Are we ready to make quantitative predictions for LHC data on the basis of our present framework?

2 Expectations for “LH-I-C”

At a maximal nucleon-nucleon center-of-mass energy \( \sqrt{s_{NN}} = 5.5 \text{ TeV} \) for Pb+Pb, compared with \( \sqrt{s_{NN}} = 200 \text{ GeV} \) for RHIC, the LH-I-C (the LHC operated with heavy ions) will have a much larger kinematic range than RHIC (see Fig. 1) \([1,2]\). Jets with \( E_T = 100 \text{ GeV} \) at LH-I-C will probe the same parton structure of the colliding nuclei (measured in terms of Bjorken-\( x \)) as \( 2 \text{ GeV} \) leading hadrons at RHIC. The initial conditions for soft physics at mid-rapidity at LH-I-C will be determined by the parton structure of nuclei in the range \( 10^{-4} < x < 10^{-3} \), as opposed to \( x \approx 10^{-2} \) at RHIC. The far forward and backward regions will provide access to the parton distributions of nuclei down to \( x \approx 10^{-5} \).

Let us begin with the expectations for the environment that will be probed by hard processes in nuclear collisions at the LHC. What kind of matter do we expect these collisions to produce at mid-rapidity? The physical picture of the initial state corresponding to the parton structure of a \(^{208}\text{Pb} \) nucleus at \( x \leq 10^{-3} \) is that of a saturated gluon distribution \([3,4]\). At low scale \( Q^2 \leq Q_s^2 \), small \( x \), and for sufficiently large nuclei \( A \), the gluon density in the nuclear parton distribution becomes so large that nonlinear QCD interactions lead to its saturation. The saturation scale \( Q_s \) at a given \( x \) and transverse position \( b \) is given by the relation \([5]\)

\[
Q_s^2(x, b) \approx \frac{4\pi^2\alpha_s(Q_s^2)N_c}{N_c^2 - 1} xG_N(x, Q_s^2)T_A(b),
\]

where \( G_N \) is the gluon distribution in the nucleon and \( T_A \) is the longitudinally integrated nuclear density profile. The numerical value applicable to the LHC
is not precisely known, $Q_s \approx 2$ GeV/c is a reasonable estimate [6,7,8]. It certainly would be good to obtain a more reliable determination of $Q_s$ for RHIC and use it to extrapolate into the LHC energy range.

When the two nuclei collide, the saturated gluons are scattered on-shell and released [9], creating a state sometimes referred to as the glasma [10], which can be described by semiclassical color fields. As has been shown recently, this form of unequilibrated matter almost immediately equilibrates chemically into a quasi-thermal quark-gluon plasma [11,12]. Using these concepts it is possible to predict the charged particle multiplicity and transverse energy per unit rapidity expected in Pb+Pb collisions at the LHC. Such predictions have been made using schematic saturation models [13,14], as well as in the framework of classical color field dynamics [15]. A third approach uses $k_T$-factorization to calculate the release of gluons from a saturated distribution in the fragmentation region and and extrapolates to mid-rapidity [16]. The predictions obtained in all these approaches agree remarkably well. The predicted charged particle multiplicity at midrapidity for Pb+Pb is $dN_{ch}/dy|_{y=0} \approx 2000 \pm 500$. At an initial time $\tau_i = 1$ GeV$^{-1} = 0.2$ fm/c, this corresponds to an energy density $\varepsilon_i \approx 200$ GeV/fm$^3$, and to 60 GeV/fm$^3$ at $\tau = 0.5$ fm/c. A fully equilibrated quark-gluon plasma at these energy densities would have a temperature of 600 MeV and 450 MeV, respectively.

The higher initial energy density – about a factor 3 above that reached at
RHIC (at the same proper time after the onset of the collision) – together with the much higher range of parton-parton c. m. energies \( \sqrt{s} \) in the initial state, will give the LH-I-C a much larger kinematic range. In particular:

- Jet physics can be probed into the region \( E_T > 100 \text{ GeV} \).
- \( b \) and \( c \) quarks become plentiful hadronic probes of the medium.
- The increased lifetime of the quark-gluon plasma phase, compared to the final hadronic gas phase, reduces the importance of hadronic final-state effects even further for most hard probes, with the possible exception of low-mass lepton pairs.

Two remarks qualifying the last statement are in order. Firstly, the higher initial temperature increases the lifetime of the quark-gluon plasma phase and, owing to an even more rapid transverse expansion of the fireball, helps shorten the final hadronic gas phase. Secondly, the increased transverse expansion velocity, compared with RHIC collisions, will boost hadronic final-state effects to higher transverse momentum. This has implications for the \( p_T \) distributions of low-mass lepton pairs and heavy quarkonium states produced, e. g., by late-time recombination.

3 Hard Probes at LH-I-C

Hard Probes are Standard Model observables that can be predicted perturbatively, with the exception of some infrared sensitive quantities that, either, can be determined from other measurements or by means of reliable lattice simulations, or are the quantities to be probed. Example of hard probes are:

- High-\( p_T \) hadrons.
- High-\( p_T \) di-hadrons (or \( \gamma + \)hadron).
- Single jets.
- \( \gamma \)-jet correlations.
- Heavy quarkonia (\( J/\psi \) and \( \Upsilon \) states).
- High invariant mass lepton pairs.
- High-\( p_T \) photons.
- \( W \) and \( Z \) bosons.

The items in this list marked by an open circle (\( \circ \)) are accessible at both, RHIC and LH-I-C; those marked by a solid bullet (\( \bullet \)) are (probably?) only accessible at the higher LH-I-C energies.

It is important to understand in which range of kinematic parameters a specific probe can be considered as hard in this sense. An example of this issue we have been confronted with at RHIC are single high-\( p_T \) hadrons. We now know
that pions, but not baryons, can be considered as hard probes at transverse momenta above $2 - 3$ GeV/c. For baryons one needs to go to $p_T$ in excess of 6 GeV/c for the perturbatively calculable fragmentation process to dominate over other modes of production. It is unclear at present, where the boundaries of the hard probe domain lie for single hadrons at LH-I-C. We still do not know in which kinematic range charmonium states serve as hard probes of the matter produced at RHIC.

It is equally important to understand how sensitively the extraction of physics from a hard probe depends on a detailed understanding (and sufficiently realistic modeling) of bulk matter properties. An example is the extraction of the jet quenching parameter $\hat{q}$ from single inclusive hadron spectra at RHIC. We have come to understand – and the evening discussions at this conference have greatly contributed to this understanding – that the different values for $\hat{q}$ obtained by different groups (which range over at least one order of magnitude!) are not due to a basic lack of understanding of the fundamental process of parton energy loss, but due to the very much different assumptions made about the evolution of the medium and the procedures used to relate the quenching calculation to the fireball geometry and its evolution. A transport coefficient, like $\hat{q}$, can only be considered to have a physical meaning if a procedure independent determination from the comparison with data is achieved.

Returning to the improved accessibility of hard probes at LH-I-C, it is useful to review some predicted yields [1]:

- Overall charm and bottom production is predicted to increase by a factor 10 and 100, respectively, compared with RHIC.
- About 100 $c$-quark pairs and 5 $b$-quark pairs are predicted to be created in a central Pb+Pb collision at the top LH-I-C energy.
- At design luminosity and top energy, one expects about 20 jets with total $E_T > 100$ GeV per second from Pb+Pb collisions at LH-I-C.
- Under the same conditions, Pb+Pb collisions will yield about one $W$-boson per second and 1 $Z$-boson every three seconds.

At the same time, $dN/dy$ is expected to increase only by a factor 3; $dE_T/dy$ by a factor 5. Thus, hard probes will strongly grow in abundance relative to soft particles.

It is useful to ask whether we are ready to make well founded predictions for hard probes at LH-I-C energies. The ground work for such predictions has been laid by several "yellow book" publications covering nuclear effects on parton distributions functions [17], jets [18], heavy flavors [19], and electromagnetic probes [20]. Quite a bit has been learned in the RHIC physics program about hard probes since then. This experience allows us to address the question for
which probes we currently have a coherent and reasonably complete theoretical framework. Among these are:

- Single high-$p_T$ photons and hadrons.
- Single jets.
- Photon-jet correlations.
- High-invariant mass lepton pairs.

The consistency and completeness of the existing framework is much less clear for di-hadrons at high $p_T$, both, within a single jet and in opposite-side jets, and for intermediate $p_T$ photons. On the other hand, a consistent and comprehensive theoretical framework for heavy quarkonia is still elusive.

4 Case Study: Jets and High-$p_T$ Partons

Instead of an attempt to provide a comprehensive review of the status of all hard probes, which could not be adequately done in this format, it is instructive to consider one example in more detail: high-$p_T$ hadrons. The perturbative QCD framework for this probe is based on the concept of factorization. The differential cross section for inclusive di-hadrons in opposite jets created by a hard parton-parton scattering event of virtuality $Q^2$ is written as

$$
\sum_X \frac{d\sigma_{AA'\to hh'+X}}{dQ^2} = \sum_{p,p'} F_{A\to p}^{(1)} F_{A'\to p'}^{(2)} \otimes \sum_{\bar{p},\bar{p}'} \frac{d\sigma_{pp'\to \bar{p}\bar{p}'}}{dQ^2} \otimes \tilde{D}_{\bar{p}\to h}^{(1)} \tilde{D}_{\bar{p}'\to h'},
$$

where the $\otimes$ symbols indicate convolution over the appropriate kinematic variables. $\tilde{D}_{\bar{p}\to h}(z)$ is the fragmentation function of final-state parton $\bar{p}$ in the presence of the medium, which differs from the vacuum fragmentation function $D(z)$. In the framework of the twist expansion of perturbative QCD, $\tilde{D}(z)$ can be expressed in terms of $D(z)$ and a gluon correlator in the medium traversed by the final-state parton [21,22] or, equivalently, by the energy loss parameter $\hat{q}$ [23]. Details of this formulation and its application to high-$p_T$ hadron production in nuclear collisions can be found in many publications (see e.g. [24] for a review).

What is worth emphasizing here is that this general theoretical framework is not enough. The extraction of the parameter $\hat{q}$ characterizing the stopping power of the medium requires a detailed modeling of the reaction geometry (distribution of scattering vertices, initial density distribution, partonic path lengths, longitudinal and transverse expansion, etc.). It is clear that the value of $\hat{q}$ extracted from the data is correlated with assumptions about the path length $L$ and expansion pattern. As a result of these additional assumptions, the extracted values presently range widely from $\hat{q} = 0.5 - 15 \text{GeV}^2/\text{fm}$. 
It is also important to recognize that the prediction of the nuclear suppression factor $R_{AA}$ for single inclusive hadrons containing heavy quarks has failed. The observed suppression of $D$-mesons in Au+Au collisions at RHIC can barely be described in this pQCD-based framework by considering the additional energy loss due to elastic collisions between the energetic final-state parton and thermal partons in the medium [25], but only if the inevitable feed-down from decaying $B$-mesons is ignored. Similarly, the large contribution to hadron (especially, baryon) production in the intermediate $p_T$ range at RHIC was unexpected and is not describable within the framework of eq. (2).

Keeping these chastening facts in mind, let us consider the predictions of inclusive hadron suppression ($R_{AA}$) at LHC energies. These vary considerably. For example, Vitev et al. predict that $R_{AA}$ in central collisions of heavy nuclei at the LHC rises from about 0.1 at $p_T \sim 10$ GeV/c to about 0.4 for $p_T > 100$ GeV/c [27,26]. On the other hand, Eskola et al. predict a value of $R_{AA} \approx 0.15$ that stays roughly constant over this momentum range [28]. As Loizides has analyzed in some detail, the variation between these predictions arises from the different treatment of the effective path-length distributions for partons with various initial energies. In single inclusive measurements only the most energetic partons can exploit the long paths associated with scattering vertices in the center of the fireball.

What applies to single hadrons does not hold for two-parton coincidences. Because such measurements effectively fix the vertex to be near the surface region on the near (trigger) side, they allow for the exploration of long path lengths of opposite-side partons and thus facilitate a more detailed study of the jet quenching mechanism and determination of the energy loss parameter [30,31] even for moderate $p_T \sim 25$ GeV/c. Other observables that will be exploited at LH-I-C to study the properties of the produced medium are the changes in heavy-to-light meson ratios as a function of $p_T$, which probe the quark mass and color charge dependence of the partonic energy loss [32], and $\gamma$-hadron coincidences, which permit the “tagging” of the $p_T$ of the scattered quark [33].

The much extended kinematic range of parton-parton scattering at LH-I-C, compared with RHIC, will make it possible to study the medium modified fragmentation function $\bar{D}(z)$ rather than just the change in the distribution of leading hadrons. The observation of entire jets, instead of single hadrons, on an event-by-event basis at LH-I-C will facilitate the study of medium induced changes in the jet shape, which are characteristic of the energy loss mechanism [34]. For example, it should be possible to subtract the underlying soft particle distribution with sufficient accuracy to determine $\bar{D}(z)$ for a 150 GeV jet down to $z \sim 0.02$, because only a few of the roughly 300 hadrons contained in the jet cone will have a $p_T > 3$ GeV/c. Finally, the increased transverse flow generated by the higher initial pressure of the medium, combined with the
increased abundance of minijets, will extend the range of quark recombination as the dominant mechanism of hadron formation to larger, maybe even much larger momenta [35,36], at least for baryons.

5 Other Hard Probes

Turning to heavy quarks, there exists a solid theoretical framework in pQCD for the elementary production of heavy quark pairs, owing to the large virtuality scale \( Q^2 = 4m_Q^2 \) involved. Much progress has been made in recent years to develop this framework into the ability to make quantitative predictions (see e. g. [37]). For the more exclusive process of primary quarkonium formation, there exist at least two theoretical frameworks, one grounded in a marriage of perturbative QCD with the nonrelativistic limit of QCD, where color octet quarkonium states need to be included in the factorization [38], the other one invoking a heuristic model for color “evaporation” in the final state [39]. The agreement of the color octet model with data can be improved by using the \( k_T \)-factorization approach [40]. However, some salient predictions of the color octet model (charmonium polarization) have not been confirmed (for a recent review, see e. g. [41]).

The situation becomes even more befuddled when one considers the interaction of heavy quarkonium states with a QCD medium, for which no comprehensive formulation exists at this time. Lattice calculations have recently succeeded in determining the spectral function of a \((c\bar{c})\) pair in various spin-parity channels by means of analytic continuation of the Euclidean correlation function into Minkowski space [42,43,44]. The surprising result is that, in contrast to earlier expectations, the \( J/\psi \) and \( \eta_c \) states survive to temperatures far in excess of \( T_c \), at least until \( 1.5T_c \). This behavior is difficult to reconcile quantitatively with the predictions of potential models [45], which provide such an excellent description of the vacuum properties of charmonium.

There exists presently no consistent treatment of the interactions of heavy quarkonium states with a quark-gluon plasma off equilibrium, which is comparable to the framework developed to describe parton energy loss. If gluons are the dominant source of parton energy loss in the medium, one expects them to also contribute to the dissociation of heavy quarkonium states as these propagate through the medium [46]. The predicted suppression effect at RHIC is quite substantial, and it becomes very large at LH-I-C [19]. On the other hand, charmonium formation may occur within the medium by recombination of independently produced \( c \) and \( \bar{c} \) quarks [47]. In the limit where \( c \)-quarks thermalize in the medium, this will lead to the statistical emission of charmonium at an elevated level dictated by the initial \((c\bar{c})\) production from hard processes [48]. Such a scenario would result in a substantial enhancement
of $J/\psi$ emission at the LH-I-C.

In contrast to phenomena related to heavy quarks, electromagnetic probes of hot and dense matter benefit from a well developed theoretical framework. This is true across a wide range of processes, from initial production by hard QCD processes to thermal radiation of photons and lepton pairs [49], and even for nonequilibrium processes associated with the passage of hard partons through the thermalized medium [50,51]. The importance of using sophisticated models of the space-time evolution is also increasingly recognized. The results from RHIC for real and almost-real photons agree well with the predictions. This suggests that electromagnetic probes of matter are under good theoretical control, and there is little reason to expect that this will be different at LHC energies. Electromagnetic probes also assume an increasingly important role in support of other hard probes. Charmonium and Upsilon states that decay into lepton pairs are a well-known example. The tagging of jet energies by direct photons [52] and the probing of the partonic content of the medium via jet-to-photon conversion [53] are other examples, which will be important probes at LH-I-C.

6 Summary and Outlook

Two years before the start of the LHC heavy ion program, different hard probes of hot QCD matter are in different stages of development. Generally, the theory of electromagnetic probes is well developed and a consistent theoretical framework for quantitative predictions exists. Probes based on the interaction of hard partons or jets with the medium still require an improved and realistic treatment of evolving fireball geometry including collective flow. The inelastic interaction between the jet and the medium also needs additional conceptual clarifications. For example, what is the difference between collisional energy loss, in which the hard parton exchanges a virtual gluon with a thermal parton, and radiative energy loss, when the radiated gluon is eventually absorbed on a thermal parton? This example suggests that the treatment of the energy loss of the leading parton (the jet initiator) must be imbedded into a complete theory of the evolution of the jet inside the medium. The least developed set of hard probes are those associated with heavy quarks, where a comprehensive theoretical framework for the production and propagation of heavy quarkonia in the medium is still missing.

It will be interesting to see whether the matter produced in heavy ion collisions at the LHC is qualitatively different from that produced in collisions at RHIC. One important question in this respect is whether the QCD plasma produced at RHIC is one with inherently strong coupling or a less strongly coupled, but turbulent plasma with anomalous transport coefficients [54]. The former
scenario could entail significantly different behavior of the medium at early times, when the temperature is far above $T_c$; the latter would suggest that matter at LH-I-C looks just like matter at RHIC, only hotter. It remains a challenge to theorists to figure out how hard probes can be used to decide between these two scenarios. Finally, it is worth keeping in mind that there may be new surprises waiting at LH-I-C, just as some key aspects of the RHIC data came as a surprise. In order to prepare for the startup of LH-I-C and to separate true surprises from physics that should have been anticipated on the basis of what we have learned at RHIC, it is important to fill in the mentioned gaps in the theoretical framework of hard probes and to make quantitative predictions for LHC energies based on state-of-the-art evolution models of the matter produced in heavy ion collisions.

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