Physics of Ultra-Relativistic Nuclear Collisions with Heavy Beams at LHC Energy

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We discuss current plans for experiments with ultra-relativistic nuclear collisions with heavy beams at LHC energy (\(\sqrt{s} = 5.5\) TeV/nucleon pair). Emphasis will be placed on processes which are unique to the LHC program. They include event-by-event interferometry, complete spectroscopy of the \(\Upsilon\) resonances, and open charm and open beauty measurements.

1. Introduction and Physics Scenario

At LHC energy hard parton-parton collisions will provide the dominant part of the transverse energy produced in a Pb-Pb collision \[1\]. Therefore, the initial stage of such a collision will be manifestly partonic. Because of the very large cross section for gluon-gluon scattering the gluons will reach equilibrium quickly and initial temperatures of about 1 GeV at timescales \(\ll 1\) fm/c will be reached. Typical parameters of such partonic fireballs are collected in Fig. 1. The temporal evolution of such partonic fireballs is depicted in more detail in Fig. 2. For simplicity a first order phase transition was assumed to take place at \(T_c = 170\) MeV but the general picture should be independent of this. In the calculation I have assumed a Bjorken-type longitudinal expansion coupled with a transverse expansion which is small in the parton and mixed phase but significant in the hadronic phase. Entropy is conserved throughout the expansion. Transverse expansion parameters are given in the figure. Because of the very large entropy of \(dS/dy \approx 41000\) created in the collision the life time of the fireball until thermal freeze-out is about 68 fm/c, i.e. comparable to typical low energy nuclear physics time scales \[2\].

Inspection of these figures shows that quark-gluon plasma will indeed be produced over very large space-time volumes at the LHC. Under this scenario we expect exciting and qualitatively new physics results from ultra-relativistic nuclear collisions at the LHC even 6 years after the first collisions at RHIC have been measured. At the LHC there will be two experiments where heavy ion collisions can be studied. The ALICE experiment \[2\] is dedicated to the study of heavy ion collisions and designed such that both hadronic and leptonic observables can be measured. Pb+Pb collisions can also be studied in the CMS experiment \[3\], albeit with focus on high mass di-lepton spectroscopy. Rather than describe these experiments in detail I will concentrate in the following on selected physics

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1 The corresponding quantity for central Pb+Pb collisions at SPS energy is about 1800.
2 This is roughly equal to the oscillation time of the giant dipole resonance in a Pb-nucleus.
### Pb+Pb Collisions at LHC

- $\sqrt{s_{\text{NN}}} = 5.5$ TeV
- $\sqrt{s} = 1150$ TeV = 0.18 mJ
- $N_{\text{mini jets}} \simeq 5000$; $p_t > 2$ GeV/c
- $\epsilon \simeq 1000$ GeV/fm$^3$ ($\epsilon_{\text{Pb}} \simeq 0.15$ GeV/fm$^3$)
- $T \simeq 1$ GeV ($T_c \simeq 0.15$ GeV)
- $dN_{\text{ch}}/dy \simeq 8000$
- $N_{\text{tot}} \simeq 60000$
- $V_{\text{central rapidity slice}}$ at thermal freeze-out:
  - $V = (dN_{\text{tot}}/dy)/n_{\text{freeze-out}}$
  - $V \simeq 12000/0.12$ fm$^3$
  - $V \simeq 1.0 \cdot 10^5$ fm$^3$; $V_{\text{Pb}} = 1500$ fm$^3$
- Lifetime until freeze-out:
  - $\tau_f \simeq 68$ fm/c

Figure 1. Some typical parameters for Pb-Pb collisions at LHC energy

topics which are unique and particular to experiments at LHC energy. Other possible and interesting investigations are described in [2–4].

### 2. Hadronic Observables

A number of interesting physics topics can be investigated by looking at the produced hadrons. They include:

- spectra and production yields of multi-strange baryons.
- event-by-event fluctuations in the hadronic final state.
- azimuthal anisotropies and elliptic flow.
- jet physics via particle spectra at high transverse momentum.
These hadronic measurements are of particular interest at LHC energies since the above mentioned large entropy implies very large rapidity densities for hadrons. Assuming that chemical freeze-out takes place near the phase boundary as has recently been established for hadron yields at AGS energy [6] and SPS energy [7,8] I can use the same thermal model to predict rapidity densities for Pb+Pb collisions at LHC energy. For the thermal model parameters I use a temperature $T=170$ MeV (close to chemical freeze-out at SPS energies, [8]) and a baryon chemical potential $\mu_b = 10$ MeV. Setting $\mu_b$ to zero changes the particle densities very little. To get absolute rapidity densities one has, of course, to specify the freeze-out volume. I take this from the calculation shown in Fig. 2, which implies a fireball volume (for a one unit of rapidity wide slice at mid-rapidity) at chemical freeze-out of $14400$ fm$^3$. A very similar calculation has recently been worked out for RHIC...
energy [3].

In Table 1 we show the corresponding rapidity densities for a number of particle species. The resulting numbers are astonishing indeed. In particular, the high strangeness content of the fireball leads to very large rapidity densities for strange and multi-strange baryons. The sum of all strange baryons approaches 300 per event in one unit of rapidity, and 2000 per event overall! We note that, while the particle ratios are a firm prediction within the thermal model, absolute yields depend on the initial temperature of the (partonic) fireball. Summing up the rapidity density of all charged hadrons (after weak decays) leads then to $dN_{ch}/dy = 7560 \left[ T_i(\text{GeV})/1.05 \right]^3$ since the initial temperature in the present calculation is close to 1.05 GeV (see Fig. 2).

Table 1

Rapidity densities at mid-rapidity for Pb+Pb central collisions as predicted by thermal model calculations [8]. Chemical freeze-out takes place at $T=170$ MeV in a volume of $14400 \text{ fm}^3$. The baryon chemical potential is assumed to be $\mu_b = 10$ MeV. For more details see text.

| particle species | dN/dy for $T=170$ MeV $\mu_b=10$ MeV |
|------------------|--------------------------------------|
| $\pi^- \approx \pi^+$ | 2500 |
| $\pi^0$ | 2800 |
| $\eta$ | 270 |
| $\omega$ | 220 |
| $\phi$ | 57 |
| $K^+ \approx K^- \approx K^0_s$ | 385 |
| p | 250 |
| n | 240 |
| $\bar{p}$ | 220 |
| $\bar{\pi}$ | 210 |
| $p - \bar{p}$ | 30 |
| $\Lambda$ | 126 |
| $\bar{\Lambda}$ | 116 |
| $\Lambda(1405)$ | 7 |
| $\Xi^- \approx \Xi^+$ | 17 |
| $\Omega^- \approx \Omega^+$ | 3 |
| d | 1.0 |
| $\bar{d}$ | 0.9 |

With such hadron yields one can perform a number of exciting investigations, as demonstrated with the list above. For example, Hanbury-Brown/Twiss interferometry

$^3$The coverage of the ALICE central detector is $\pm 0.88$ units of pseudo-rapidity centered at $90^\circ$ to the beams.
measurements for pions and kaons can be performed on an event-by-event basis. Within the above fireball evolution scenario one expects (two-dimensional) transverse radius parameters of the order of 22 fm, i.e. more than a factor of 2 larger than currently measured at SPS energy. The corresponding width in momentum space of the two-particle correlation function will then be of the order of 10 MeV or less, a real challenge for experiments. One should however keep in mind that the large radial flow velocities expected for central Pb-Pb collisions will effectively reduce the "apparent" radii, leading to wider correlation functions if the transverse momentum of the particle pair is not too small. With such measurements one can not only determine the temporal and spatial evolution of the fireball but also search for fluctuations which are expected should the phase transition be of second order. As a "by-product" of such measurements one can also obtain information about the final state interaction of the particles involved. In particular, this may provide the unique possibility to determine the interaction between strange baryons, as well as to search for resonances in these systems. Both programs would be of high interest for the hadron physics community.

3. Quarkonia, Photonic and Leptonic Observables

Many exciting and important investigations will become possible by studying leptonic observables in Pb+Pb collisions at LHC energy. They include:

- complete quarkonium spectroscopy.
- D- and B-meson spectroscopy via semi-leptonic decay channels.
- study of \( \omega \) and \( \phi \)-meson production.
- measurement of the thermal lepton pair continuum at high masses.
- search for anomalous enhancement in the lepton pair continuum at low masses.
- measurement of \( Z_0 \) production.

In addition, the PHOS detector within the ALICE experiment can be used to measure direct photons with the aim to study:

- thermal emission from the quark-gluon plasma and from the mixed phase.
- photon-photon correlations.

In the following I will discuss the new possibilities for quarkonium spectroscopy and D- and B-meson spectroscopy. Another look at leptonic observables within the ALICE forward muon spectrometer can be found in [10].

The long life time of the partonic phase as is visible from Fig. [1] and the high energy density of the partonic fireballs should lead to complete suppression through Debye screening of the color interaction in the deconfined and dense plasma even of tightly bound resonances such as the \( \Upsilon \) mesons. At the LHC one should be able to perform a complete quarkonium spectroscopy (\( J/\psi, \Psi', \Upsilon, \Upsilon', \Upsilon'' \)) to measure the sequential melting of the resonances, on account of their different radii, as a function of the energy density.
Figure 3. Expected dimuon mass spectrum for the ALICE muon arm after a running time of $10^6$ s [3,10]. No plasma suppression is taken into account in this simulation. Note that the $\Upsilon$, because of its small radius of about 0.2 fm, should only "melt" at energy densities above 30 GeV/fm$^3$ corresponding to temperatures $T > 400$ MeV and should therefore not be suppressed at RHIC energies. The variation of the energy density can be achieved either by changing the centrality (impact parameter) or the system size or both. Particularly interesting is the case of the three $\Upsilon$ resonances whose radii vary between 0.2 and 0.8 fm (for comparison, the radius of the $J/\Psi$ meson is about 0.45 fm). The particular interest to study the suppression for the $\Upsilon$ family has been in detail discussed in [11].

At the LHC the $\Upsilon$ resonances can be measured in Pb+Pb collisions in the CMS experiment [5], in the ALICE muon arm [3,10] and in the ALICE central arm using the newly added transition radiation detector [4]. All three detectors will provide a mass resolution of about 100 MeV or better for masses around 10 GeV/c$^2$, sufficient for a good separation of the three resonances. A good impression of the expected quality of the measurement is obtained by looking at Fig. 3. The continuum in this figure is due to combinatorial background of muons from $\pi$ and K decays, from semi-leptonic D-decays and, dominantly,
Figure 4. Distribution of the closest distance $d_0$ to the primary vertex of electron tracks for Pb+Pb collisions at the LHC. The long tails due to electrons from semi-leptonic D- and B-decays are clearly visible. For details see text.

from semi-leptonic B-decays.

The large yields (in the absence of plasma suppression) for $\Upsilon$ states is of course connected to the expected copious production of open charm and open beauty at LHC energies. The measurement of the cross sections for open charm and open beauty production is consequently of paramount importance for understanding the role of color screening in the expected suppression of quarkonium production in Pb+Pb collisions at LHC energy. First, one should note that quarkonium production and open charm or open beauty production are intimately related \[12\]. The heavy quarks are dominantly produced in hard partonic scattering processes (gluon fusion). Some of these heavy quarks will eventually form quarkonia, while the large majority will end up in correlated pairs of D and B mesons. Typical numbers are about 50 $c\bar{c}$ pairs per unit of rapidity compared to 0.5 for $J/\Psi$ mesons in central Pb+Pb collisions. These numbers have been obtained \[4\] using a perturbative QCD approach based on the PYTHIA framework with a K-factor adjusted to reproduce B meson production in pp collisions at the Tevatron and D meson produc-
tion at lower energies. Similar results have been obtained by Gavin et al. [13]. The extrapolation to nucleus-nucleus collisions is done as in [4], i.e. by the total number of nucleon-nucleon collisions. This number is calculated from the nuclear collision geometry at a given impact parameter assuming a Woods-Saxon nuclear density distributions.

One should note that these predictions are still rather uncertain. First, there are indications from the measurements of NA50 at CERN of a possible enhanced open charm production (relative to PYTHIA predictions) already in Pb+Pb collisions at SPS energy [15]. Secondly, the produced heavy quarks may suffer significant energy losses in the hot and dense fireball formed at LHC energies, leading to considerable kinematical rearrangement of the final rapidity and \( p_t \) distributions and, consequently, also to potentially drastic changes in the dilepton invariant mass spectrum from semi-leptonic decays [16,17]. Clearly, a direct measurement of charm and beauty is mandatory for the interpretation of the quarkonium data at LHC energies.

Furthermore, since the quark and the gluon structure functions are likely to be different at LHC energies, one cannot use the Drell-Yan continuum as a convenient normalization for the \( J/\Psi \) measurements. In addition, the Drell-Yan cross section is expected to be completely masked by the open charm continuum. However, a direct measurement of the open charm yield simultaneously with the yield of quarkonia will provide a natural normalization and a gauge against which to quantify the expected suppression of quarkonia.

![Graph](image)

**Figure 5.** Comparison of yields for unsuppressed primary \( J/\Psi \) production and production via B-decay in Pb+Pb collisions at LHC energy. For more details see text.

Such a measurement can be obtained by making use of the transition radiation detector in combination with the inner tracking systems and time projection chamber of ALICE [4]. The idea here is not to fully reconstruct D- and B-mesons but to determine their
yield and $p_t$ spectra via the identification of displaced vertices of electrons and positrons from semi-leptonic decays. Because of the life time on the order of picoseconds the D- and B-mesons typically decay at a distance of a few hundred $\mu$m away from the primary vertex. The quantity $d_0$, the closest distance of a track to the true vertex, is plotted in Fig. 4 for Pb+Pb collisions. The performance of the ALICE inner tracking system leads to a gaussian smearing of less than 100 $\mu$m for tracks with $p_t > 1$ GeV/c. This smearing is visible for the prompt particles (electrons from Dalitz decays of neutral mesons etc.). However, for distances above 200 $\mu$m the $d_0$ distribution is completely dominated by electrons from D- and B-decay: with an appropriate cut one can isolate a nearly pure sample of leptons from heavy meson decay. Many more details about these procedures can be found in [4].

![Figure 6](image)

Figure 6. Reconstruction of J/$\Psi$ mesons from B-decay for Pb+Pb collisions in the ALICE central detector. For details see text and [4].

Although the large open charm and open beauty cross sections make these interesting measurements at least statistically straightforward, they also lead to further potential
problems for the quarkonia measurements. For example, neutral B-mesons have a 1.3% branching ratio to decay into $J/\Psi + X$. The yields for such $J/\Psi$ mesons of course are not plasma-suppressed and are not negligible compared to the primary production of $J/\Psi$ mesons \cite{1}. This is demonstrated in Fig. \cite{2}. Note that for these calculations it was assumed that there is no plasma suppression for the primary $J/\Psi$ mesons. From this figure it is clear that, especially at high $p_t$ secondary $J/\Psi$ production can obscure even moderate plasma suppression of primary $J/\Psi$ mesons.

However, using similar techniques as for the D- and B-mesons one can actually identify directly \cite{4} the secondary $J/\Psi$ mesons in the ALICE central detector and separate them from primary production. Since the necessary vertex cut removes a large amount of combinatorial background, the signal/noise ratio for the identification of secondary $J/\Psi$ mesons is impressive, as demonstrated in Fig. \cite{3}. This technique not only allows a clean separation of primary and secondary production of $J/\Psi$ mesons but also provides a semi-exclusive measurement of the $B_0$ distribution.

Another issue to take into account at LHC energies is the secondary production of $J/\Psi$ mesons from the annihilation of D mesons, i.e. the process $D+\bar{D} \rightarrow J/\Psi + \pi$. Estimates for the yield due to this process have recently been given \cite{18,19} and were discussed at this conference. For presently considered values of the cross section for $D+\bar{D} \rightarrow J/\Psi + \pi$ secondary production could possibly obscure the expected suppression in the plasma. Especially for the $\Psi'$, secondary production could lead to a rather dramatic enhancement \cite{19} with the $\Psi'$ yield even exceeding the $J/\Psi$ yield. It is, therefore, clear that a clean interpretation of $J/\Psi$ production data can only be obtained through a comprehensive measurement of open charm production as is planned with the transition radiation detector in the ALICE experiment.

4. Summary and Outlook
The study of Pb+Pb collisions at LHC energy will provide qualitatively new perspectives for ultra-relativistic heavy ion physics. As the above discussions have shown, even 6 years after the begin of collider experiments at RHIC there will be a rich and unique menu of experiments to be performed on fireballs which are quasi-macroscopic compared to normal nuclear parameters.

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