HEAVY-ION COLLISIONS AT THE LHC

G. Paić

CERN, 1211 Geneva 23, Switzerland

Abstract

An important part of the experimental programme at the Large Hadron Collider to be built at CERN will be devoted to the study of the phase transition to quark-gluon plasma in heavy-ion collisions. One detector, ALICE is devoted to the measurement of most observables characterizing the system formed in the collisions whilst the two p–p experiments, ATLAS and CMS, have capabilities to measure specific signals.

1 Introduction

The Large Hadron Collider (LHC), planned to be operational in 2005 at CERN, will accelerate protons and heavy ions. Different symmetric systems will be accelerated ranging from lead to calcium ions. The possibility to accelerate asymmetric sytems is also envisaged. In the present discussion, we will concentrate on the lead ions. The momentum of the colliding beams will be 2.76 TeV/c per beam with a luminosity of 10^{27}cm^2 s^{-1}. Collisions having lighter nuclei may be of importance for the study of the behaviour of different signals with energy density and other parameters, but the first experiments will be performed with the collisions that ensure the largest energy density.

1.1 Experimental conditions at the LHC

The collision of lead ions at LHC energies will open up a completely new domain of energy densities accompanied by unprecedented kinematic and dynamic conditions, very appropriate for the study of signatures connected to colour deconfinement, or in other words to the creation of quark–gluon plasma (QGP). In addition to the obvious gains that will be obtained by extrapolating from the present results the energy density, size and lifetime of the system, which will be typically an order of magnitude larger than the one currently encountered at SPS energies at CERN ($\sim$ 20 A GeV/c in the centre of mass), the regime at the LHC will allow the QGP to be studied under completely new conditions.

Firstly, the system evolution will be governed by hard/semi-hard parton production [1]. With increasing energy, the semi-hard QCD processes become more and more important due to an increase in the production of semi-hard partons (minijets observed as a rapid rise in the pp total and inelastic cross sections). Furthermore, the $A^{4/3}$ scaling of the semihard production [2] favours the semi-hard production for collisions of large nuclei. The time-scale for the production of semi-hard partons

and transverse energy in the central rapidity region is short, typically of the order of of $\tau_h = \sim 0.1$ fm/c. On the other hand, the soft processes are completed at later stages of the collision, typically $\tau_s = 1/\Lambda_{\rm QCD} \sim 1$fm/$c$. The after-collision system at the LHC will be dominated by gluons both in the parton production and transverse energy production: the initial parton system is about 80% glue. The gluonic system created in the central rapidity will thermalize very fast with very high temperatures of the order of 1 GeV/c. Finally, the net baryon density in the central rapidity region at $\tau \sim 0.1$ fm/c will be small compared to the gluon density, but still not completely negligible.
The completely novel environment at the LHC makes it necessary to build detectors able to cover a large number of potential physics signals in order, not only to detect the QGP, but to understand the behaviour of a deconfined plasma of quarks and gluons and its evolution in time.

1.2 The LHC and heavy-ion operation

CERN has so far approved three experiments for the LHC. Two of them, ATLAS and CMS, are dedicated to proton–proton collisions, whilst ALICE is devoted to the study of heavy-ion (HI) collisions and, for comparison purposes, low-momentum physics in pp collisions. The dedication of the detectors to particular signals is caused by the vast differences in the rate of collisions and the multiplicities of the event expected in pp and HI collisions, respectively. However, in spite of the differences, some signals, in particular dimuon production, maybe also be studied in the pp experiments. Both ATLAS and CMS have capacities to measure a limited number of signals in heavy-ion collisions, but so far only CMS has studied the performance of their detector under these circumstances, so here I shall limit myself to the expected performance of ALICE and CMS in the HI LHC mode.

1.3 The ALICE detector

ALICE (A Large Ion Collider Experiment) will be the only dedicated heavy-ion detector to be operated at the Large Hadron Collider (LHC). It is designed for detecting hadrons, leptons, and photons produced in lead–lead collisions at the LHC, thus covering most of the observables expected to contribute to our understanding of matter at high energy densities, and to the discovery of a possible phase transition to quark–gluon plasma. ALICE has also been designed for the measurement of Ca–Ca and pp collisions (the latter at a lower luminosity than the one used by the dedicated proton–proton detectors). The detector will consist of a central part placed in the 0.2 T field of the LEP L3 magnet, a dimuon detector, a forward multiplicity detector, and a zero degree calorimeter in the forward region outside the L3 magnetic field.

The baseline design of the central part as defined in the Technical Proposal [3] consists of a high-resolution inner tracking system (ITS), a cylindrical TPC, a time-of-flight barrel 3.5 m from the beam, all of them covering the 1.8 units of pseudorapidity around midrapidity over the full azimuth. In addition, there are two detectors of lower coverage ($\sim 5\%$ of the phase space of the central barrel). They are the High Momentum Particle Identification Detector (HMPID) and the Photon Spectrometer (PHOS). The central barrel part is designed to track and identify all emitted particles at the largest rapidity densities envisaged by the theories so far ($dN_{cn}/dY = \sim 8000$) in a large momentum range.

The forward dimuon arm consists of a composite absorber to eliminate the hadrons starting 90 cm from the vertex, a large warm magnetic dipole with a 3 Tm field integral placed outside the L3 magnet, and 10 planes of thin high granularity tracking stations. A second absorber, made of iron, at the end of the spectrometer and four more detector planes are used for muon identification and triggering.

A view of the full detector is shown in Fig. 1.

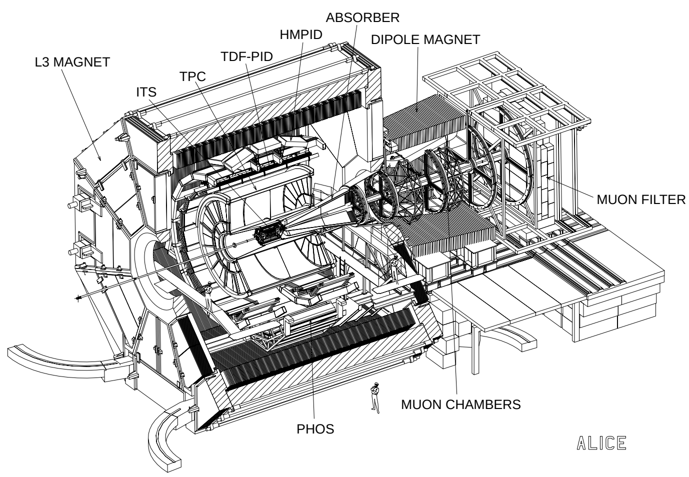

Figure 1: Layout of the ALICE detector. The inner tracking system (ITS), the time projection chamber (TPC), the particle identification barrel (PID), the photon spectrometer (PHOS), and the high momentum particle identification detector (HMPID). The forward muon arm with the absorber, the chambers, and the dipole is visible.

1.4 The CMS detector

The compact Muon Solenoid experiment is constructed around a large solenoid magnet (14 m long and 3 m radius) with a magnetic field of 4 T, guaranteeing a good momentum resolution for high-momentum muons. Specifically, during the heavy-ion operation of the LHC, the CMS detector will be used to detect low-momentum muons in order to study the production of mesons of the Υ family. The measurement of the 2 μ decay channel of the Z also offers the possibilty of studying jet quenching in the quark-gluon plasma looking at the opposite jet energy and/or spatial distribution. In the part relevant to heavy-ion physics the CMS [4] consists of a central tracker consisting of successive layers of high-granularity detectors starting from the inside out with two layers of pixel detectors, four layers of silicon strips, and six layers of microstrip gas chambers; followed by calorimeters for electromagnetic and hadron energy measurements, as well as for the determination of the direction of the particle jets. The muon detector is placed behind the calorimeters and the coil. It consists of four muon stations interleaved with the iron return yoke. The magnetic flux in the iron permits an independent momentum measurement. the muon detector covers up to $|\eta| = 2.4$, the part of the central barrel covering $|\eta| = 1.4$. Muon identification is ensured by the presence of at least 16 λ of material at all angles. The precise muon chambers and fast dedicated detectors provide a trigger with $p_{\rm t}$ thresholds from four up to 100 GeV/c.

A transverse view of a sector of the CMS detector with the trajectory of a muon is shown in Fig. 2.

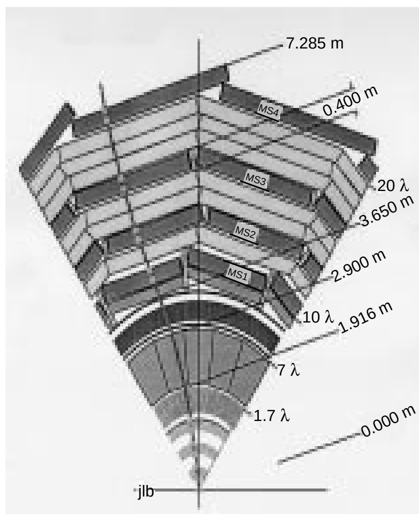

Figure 2: Transverse view of the CMS detector with the trajectory of a muon passing through the detector. MS denotes the muon tracking stations in the iron yoke.

2 Physical observables and signals (early probes)

Two classes of signals are usually considered when speaking of studies of dense matter in heavy-ion collisions: the experimental probes that carry information about the early stages of the system after the collision, and those pertaining to the late evolution of the system.

The photons and lepton pairs provide probes of the interior of the quark–gluon plasma during its hottest and earliest phase, as they are not affected by final-state interactions. However, these observables have small yields and usually rather large background from other (hadronic) sources, and therefore require special care for the detector subsystems.

2.1 Direct photons

The importance of measuring direct photons resides in the fact that in the quark–gluon phase the yield of direct photons having transverse momenta above 2 GeV/c should be clearly superior for a quark–gluon plasma [5]. As photon production by gluon–quark interaction resembles the Compton scattering of a photon off a charged particle, the photon production rate and the photon momentum distribution depend on the momentum distribution of the quarks and gluons at the time of the photon production. This means that the photon spectrum bears witness to the thermodynamic state of the system at a very early stage.

This signal will only be addressed in ALICE by the Photon Spectrometer (PHOS). The spectrometer will cover a surface of ~ 20 m^2 at a radius of 4.6 m. It will have a granularity adapted to the extraction of direct photon contributions from the large background of photons from hadron decays. The ratio of direct to decay photons is expected to be 5–10% or even more. The expected sensitivity of the spectrometer to direct photons is $\sim 5\%$.

2.2 Electron pairs

In ALICE the electrons will be tracked and identified in the same detectors as the hadrons, i.e. the ITS, the TPC, and the TOF array. This means that the momentum range for electrons will be restricted to momenta below 2.5 GeV/c. The main problem is the small number of electrons per event which means that for sufficient statistics, we need large classes of events — typically more than 10^7 events. The present momentum range will allow information to be gathered on the possible effects of dense hadronic matter on the medium modifications of hadronic properties, especially the mass and width of heavy meson resonances.

2.3 Quarkonium suppression

The suppression of J/ψ production [6] in a quark–gluon plasma occurs because a $c\bar{c}$ pair formed by the fusion of two gluons from the colliding nuclei cannot bind inside the quark–gluon plasma. The larger the size of the quarkonium to be formed, the larger the screening effects, so that excited states of quarkonia are more easily 'dissociated' than their ground states. For the light quarkonia and the Υ (2S) the conditions of dissociation should be met at temperatures slightly above those for deconfinement. For the Υ (1S), similar considerations apply, except that the dissociation temperature is higher, ~ 2.5 times the deconfinement temperature. In ALICE the quarkonium suppression will be covered by the dimuon arm that will cover the forward region of ALICE from $\eta = 2$ to $\eta = 4$ [7]. The dimuon arm will have a mass resolution of 1% in order to separate the different resonance states. The correlation with observables measured in the barrel region (e.g. multiplicity, π/K ratio, etc.) will be possible for subsets of events. The suppression of heavy quark resonances is measured by normalizing the observed production cross-sections by a reference signal, such as beauty production in the case of ALICE, which is not suppressed by Debye screening. However, the observation of a suppression is not sufficient in itself to prove the existence of a phase transition; it could also be explained by other processes such as absorption in a dense hadronic medium. As shown in Fig. 3 [7], the distinguishing feature between the melting of the resonances in QGP and other models (such as destruction by comovers) is the energy-density dependence of the survival probability: melting shows a threshold behaviour whereas the comover model predicts a suppression that gradually increases with the energy density. In order to cover a sufficiently large energy-density region to differentiate between the two models, measurements with light- and heavy-ion collisions will be taken. For each ion species the energy density can, in addition, be varied by selecting different impact parameters. As indicated in Fig. 3, we expect to cover the regions 3-6 GeV/fm^3 and 20–60 GeV/fm^3 with light and heavy ions, respectively.

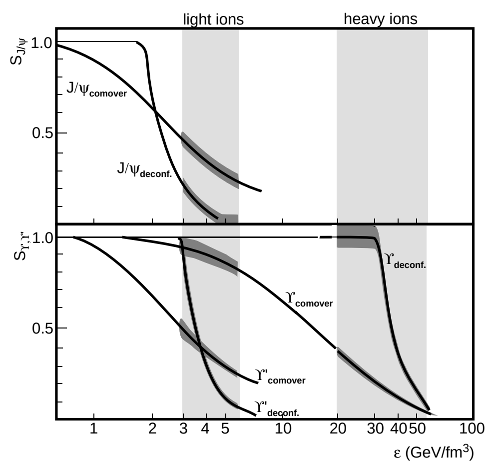

Figure 3: Energy-density dependency of charmonium and bottonium survival probabilities as expected from melting in a deconfined medium and from the comover model. The precision of the measurement with the muon spectrometer after one month of operation at the densities expected with light and heavy ions is shown as 1σ error bands.

In the CMS the quarkonium channel [8] will be studied mainly via the suppression in the Υ family, because of the constraints caused by the necessary momentum cuts and the measurements in the central rapidity region ($|\eta| < 0.9$). The main qualities of the CMS measurement are the very good mass resolution in the Υ peaks ($\sim$ 35 MeV) compared with 70 MeV in ALICE, and the complementarity with ALICE in the rapidity regions studied. In Table 1 the main features of ALICE and CMS for measuring quarkonia using dileptons are given.

Table 1
ALICE and CMS dilepton measuring capacities

Parameter	CMS	ALICE
$\Delta\eta(\Upsilon)$	$-2.4 < \eta < 2.4$	$2.5 < \eta < 4$
$\Delta\eta$ for global variables	Same	Partially same
Mass resolution (MeV)*	40	70–80
Signal/background (Υ)*	1.6	7.1 (over all p_t)
Normalization	Z	$b\bar{b}$
p_t range (Υ)	From 0	From 0
$\Delta\eta(J/\Psi)$	$-2.4 < \eta < 2.4$	$2.5 < \eta < 4$ (dimuons)
		$-0.9 < \eta < 0.9$ (dielectrons)
p_t range (J/Ψ)	High p_t only	From 0
p_t range (Φ)	No	From $p_t > 1.5$ GeV/c (dimuons)
		From 0 (dielectrons)
		Also via the K–K decay channel

* The values quoted for CMS correspond to the barrel region only.

2.4 Open charm detection

Owing to its large mass, charm can be produced only in the early, hotter stages of the collision. The probability of subsequent annihilation is very low, so that essentially all the produced charm ends up in the final state, mostly in the form of open charm hadrons. Open charm is therefore an especially interesting probe of the dynamics of high-energy nucleus–nucleus collisions. Besides production in the initial hard scattering processes, charm could also be produced via parton–parton rescattering in the thermalization phase. An enhancement of charm production is expected, the degree of which will be sensitive to the initial value of the energy density and to the duration of the thermalization phase [9–11]. Predicted values for the ratio of the total to the initial-state production range from about two [10] to about ten [11].

Lower-mass charm hadrons can only decay through weak processes, and travel a measurable distance before decay ($c\tau \simeq 100$ μm). In order be able to identify the secondary vertices with the necessary precision (50 μm) an additional layer of pixel detectors at $r \simeq 4$ cm has been added to the ALICE design compared to the LoI. Simulations carried out for $D^0 \to K^-\pi^+$ and for $D^+ \to K^-\pi^+\pi^-$ charmed mesons predict that for a class of 10^7 events the statistical significance would be $S/\sqrt{B} \simeq 30$ in both cases, provided that the particles are identified. In the absence of kaon identification the significance would deteriorate by a factor 2.6.

3 Physical observables and signals (late probes)

Although less direct than the early probes, the study of hadronic production, occurring after the freeze-out of the system, merits a large effort. The reasons are the following: the signals are usually very strong, and the background contributions are well understood, allowing important parameters to be determined on an event-by-event basis. The event-by-event analysis allows a maximum of information to be extracted concerning the dynamics of high-energy collisions, in contrast with the inclusive analysis where only information on the 'average' collision is obtained.

The statistical accuracy of the measurement of a single-event observable is usually inversely proportional to $\sqrt{N}$, where N is the number of particles (or particle n-tuplets in the correlation analysis) used for the analysis, thus allowing a very precise determination of many properties in a single event.

3.1 Strangeness

There are two major aspects of the so-called 'strangeness signal': the more speculative one is connected with the search for exotic strange matter, which requires the intermediate production of a QGP state. The other, more conventional aspect of strangeness as a QGP signature is an enhanced production of strange hadrons in heavy-ion collisions when compared to nucleon–nucleon or nucleon–nucleus collisions at the same energy [12]. In hadronic reactions the production of strange particles is suppressed compared with the production of hadrons containing only up and down quarks. This suppression increases with the growing strangeness content of the hadrons produced. In a QGP scenario, on the other hand, the production of strange hadrons is expected to be saturated because the strange quark content of the plasma is rapidly equilibrated by $s\bar{s}$ production in interactions of two gluons. The end result will show an enhanced strange particle yield and especially an enhanced yield of multistrange baryons, a signature that cannot be presently explained by a purely hadronic scenario. In ALICE the various aspects of strangeness production are dealt with using the identification of kaons, and the tracking and secondary vertices for hyperons. The main signals envisaged are:

1. K/π ratio

The K/π ratio is indicative of the time-scale for strangeness equilibration — a large ratio being regarded as characteristic of a fast process through gluonic production. The variation of this ratio as a function of the temperature and chemical potential may be very important. The large multiplicities of pions and kaons should allow ratio to be determined this with a good accuracy ($\sim 5\%$) [13].

2. Φ mesons

The identification of kaons in a large momentum interval allows Φ mesons to be identified through their decay into two kaons. The measurement of the yield of the Φ — an $s\bar{s}$ pair — places more stringent constraints on the origin of the flavour composition observed than the π/K ratio. It has also been reported that the production rate may be very sensitive on the quark masses [14, 15]. Also, shifts in the Φ meson mass in a hot hadronic medium have been predicted [16] and possibly observed in Si+Au collisions at the AGS [17]. As the mass of the Φ is so close to two kaon masses, a slight shift in its mass could affect considerably the branching ratio of the decay to the $K\bar{K}$ channel. In ALICE the Φ decay will also be measured in the e^+e^- mode thus opening up the possibility of measuring the ratio of the decay probabilities in the two channels. This ratio is independent of the production cross-sections and may be very sensitive to changes in parton or kaon masses.

3. Hyperons

Hyperons with decay lengths of the order of centimetres will be identified by reconstructing the decay products in the tracking system, and finding secondary vertices near the interaction point. In this way, the following decay chains will be accessed: $K^0 \to \pi^+\pi^-$, $\Lambda \to \pi^- p$, $\Xi^- \to \pi^-\Lambda \to \pi^-\pi^- p$, and $\Omega^- \to K^-\Lambda \to K^-\pi^- p$.

The yields of K^0_s and Λ detected in one event are sufficient for event-by-event characterization. The statistics accumulated for cascades in 10^7 events (corresponding to one month of ALICE operation) will be in the range 10^5 to 10^6, which will allow high statistics in subsamples of 10^5 to 10^6 events.

3.2 Exotica

It has been speculated that droplets of strange matter may be 'distilled' from the initial QGP phase [18] by separating the strange quarks from the antistrange ones. The strange matter droplets thus formed could be stable or metastable objects whose stability, lifetime, and decay modes are strongly parameter-dependent.

The search for strangelets within ALICE will depend on their lifetime and decay modes. In heavy-ion reactions, strangelets and multi hypernuclei (MEMOs — resulting from the coalescence of several strange baryons, without passing through the QGP phase) might be found in the final state. If stable or long-lived, the strangelets will pass through the whole detector and might be detected via dE/dx and/or time of flight, owing to the non-integer value of the charge-to-mass ratio. The sensitivity of the strangelet search is adequate for production probabilities of 10^{-4} per event or more in the central barrel acceptance.

Recently disoriented chiral condensates [19] have been advocated as a potential signal that would manifest itself through anomalous neutral/charged pion ratios. At present ALICE could study this ratio, using the PHOS, in a restricted phase space region. Studies are underway for detectors with larger acceptance that could be devoted to this measurement.

The pp detectors could also tackle this aspect of heavy-ion collisions using the extensive electromagnetic and hadronic calorimetry, but for the time being no detailed consideration has been given to this aspect.

3.3 Jet quenching

From the initial period of the collision only leptons and jets will survive untill the final state and to the detector, but some hadronic probes may also carry information in the early stages. It is typically very difficult to detect low-energy jets with any precision about their energy. Only high-energy jets of >100 GeV/c will be accessible to CMS, either as di-jets or a photon (possibly also a Z boson) on one side) and a jet on the opposite side. This type of measurement is in the domain of the experimental capabilities of the pp experiments at the LHC. It has been proposed [20] that the fact that the protons and antiprotons especially at high momenta are not produced exactly in a symmetric way should be exploited. The antiprotons being more often due to gluonic jets than the protons produced in the region of the structure function where the contribution of valence quarks is important. Hence, measuring the proton and antiproton spectra at high momenta one may observe the effect of jet quenching in a circumvent way, due to the fact that gluonic jets experience more energy loss in the quark–gluon plasma medium. This measurement is possible with ALICE where high-momentum proton identification can be achieved using the HMPID.

Figures 4(a) and 4(b) show the proton and antiproton spectra as obtained from the Hijing event generator for the case without and with quenching.

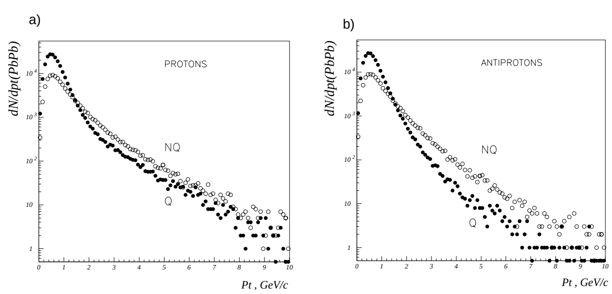

Figure 4: a) Hijing predictions for the momentum distribution of protons without quenching (NQ), and with quenching included(Q); b) Same as Fig. 4(a) for antiprotons.

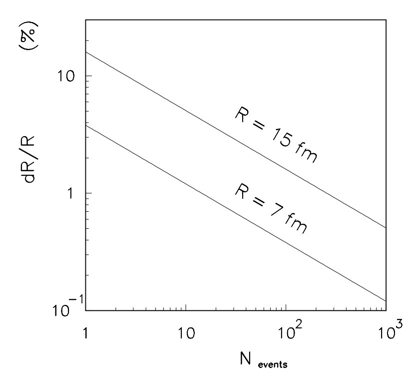

Figure 5: Measurement accuracy for the effective interferometric sizes $R = 7$ fm and $R = 15$ fm as a function of the number of analysed events.

3.4 Correlations

The study of particle correlations is usually of great interest because they carry information about the dynamic evolution of the system such as the proper time of decoupling, the duration of the particle emission for different particle species, and the presence of collective flows. The interferometry measurements are of particular importance because the decoupling time and intensity of transverse flow should be closely related to QGP formation and to the latent heat of the phase transition [21–25]. The entropy density of the system in its QGP state prevents it from hadronizing into a lower entropy density state, unless time is allowed for the system to expand before hadronizing. Large volumes at decoupling would definitely indicate the existence of a phase transition. Correlation studies will be made for the low momenta (< 1.5 GeV/c) using particle identification in the barrel acceptance (ITS, TPC, TOF). The accuracy of the measurement of interferometric sizes as a function of the number of analysed events is shown in Fig. 5. The high multiplicity enables us to study pion correlations in a single event with acceptable accuracy.

The good particle identification and the large acceptance in ALICE will allow correlation studies for identical bosons (kaons and pions), identical fermions (protons, possibly Λ's), and non-identical particles to be carried out.

In addition to the low-momentum correlations, ALICE has optimized the acceptance of the HMPID array in such a way as to allow correlation studies of identified particles at large transverse momenta corresponding to small effective sizes.

4 Conclusions

The present heavy-ion programme at the LHC centred around the ALICE detector, with a complement of information from the CMS detector and possibly ATLAS in the domain of jet quenching and quarkonia suppression, covers in depth most of the experimental parameters relevant for the study of deconfined matter.

References

[1] K.J. Eskola. HEPPH-9610365, Theory Workshop on Relativistic Heavy Ions, Upton, NY, 8–19 July 1996.

[2] J-P. Blaizot and A. Mueller, Nucl. Phys. **B289** (1987) 847.

[3] ALICE Collaboration, Technical Proposal, CERN/LHCC 95–71.

[4] CMS Collaboration, Technical Proposal, CERN/LHCC 94–38.

[5] S. Chakrabarty, et al., Phys. Rev. **D46** (1992) 3802.

[6] T. Matsui and H. Satz, Phys. Lett. **178B** (1986) 416.

[7] ALICE Collaboration, addendum to the ALICE Technical Proposal, CERN/LHCC 96–32.

[8] M. Bedjidian, these proceedings.

[9] E.V. Shuryak, Sov. J. Nucl. Phys. **28** (1978) 408;
Y. Wang et al., Nucl. Phys. **A590** (1995) 539c.

[10] B. Muller and X.-N. Wang, Phys. Rev. Lett. **68** (1992) 2437.

[11] K. Kinder-Geiger, Phys. Rev. **D48** (1993) 4129.

[12] J. Rafelski in *Workshop on Future Relativistic Heavy Ion Experiments,* eds. R. Stock and R. Bock, GSI-Report 81–6 (1981) p. 169.

[13] S. Kiselev et al., ALICE Internal Note/SIM97–08.

[14] R.D. Pisarski and F. Wilczek, Phys. Rev. **D29** (1984) 338.

[15] E.V. Shuryak, Nucl. Phys. **A525** (1991) 3c.

[16] M. Asakawa and C.M. Ko, Nucl. Phys. **A572** (1994) 732.

[17] Y. Wang et al., Nucl. Phys. **A590** (1995) 539c.

[18] C. Greiner, A. Diener, J. Schaffner and H. Stoecker, Nucl. Phys. **A556** (1993) 157c.

[19] F. Wilczek, Nucl. Phys. **A566** (1994) 123c.

[20] X.-N. Wang and M. Gyulassy, Phys. Rev. **D44** (1991) 3501;
X.-N. Wang, private communication and notes at the STAR Physics Workshop, 14–15 January 1995.

[21] S. Pratt et al., Phys. Rev. Lett. **68** (1992) 1109.

[22] S. Pratt, Phys. Rev. Lett. **53** (1984) 1219;
S. Pratt, Phys. Rev. **D33** (1986) 1314.

[23] G. Bertsch, M. Gong and M. Tohyama, Phys. Rev. **C37** (1988) 1896.

[24] A. N. Makhlin and Yu. M. Sinyukov, Yad. Fiz. **46** (1987) 637.

[25] A. N. Makhlin and Yu. M. Sinyukov, Z. Phys. **C39** (1988) 69.