ALICE-PUB-2001-36
Publication
24 July 2001

Heavy-ion physics at LHC

G. Paic[a]

[a]CERN, EP Division, Geneva

1. INTRODUCTION

Heavy-ion collisions are a part of the complete set of investigations that the Large Hadron Collider (LHC) — to enter into operation in 2006 — wants to explore, namely the connection between phase transitions involving elementary quantum fields, fundamental symmetries of nature and the origin of masses. This programme is distributed over the four planned experiments in the following way.

1. CMS and ATLAS search for particles predicted by the Standard Model resulting from breaking of gauge symmetry of the electroweak force [the Higgs particle(s)] related to the mass generation mechanism of the electroweak gauge bosons. Beyond the Standard Model they will also search for supersymmetric particles which would be manifestations of a broken intrinsic symmetry between fermions and bosons.

2. LHCb performs precision tests of the Standard Model Lagrangian and its CP symmetry violating terms by studying the physics of the heavy b-quark.

3. ALICE [1,2] and CMS [3] study QCD collective phenomena at extreme energy and parton densities. The aim of the heavy-ion physics at LHC is to study equilibrium and non-equilibrium effects in strongly interacting matter at very large energy densities (up to 100 GeV/fm^3), as well as the collective evolution of the created system towards hadronization and freezout. Such studies should give experimental insight into the structure of the QCD phase diagram which predicts that at energy densities of ≈ 0.6 GeV/fm^3 nuclear matter undergoes a phase transition to a deconfined state of quarks and gluons. This transition is connected with the restoration of the chiral symmetry where the quark masses are reduced from their large effective values to their small bare ones. It is interesting to note that this phase transition involving quantum fields occurs at energy densities available in the laboratory and as such is the only one directly accessible.

In the following we will concentrate on the unique physics aspects of the experimental programme on heavy-ion physics at LHC and the main characteristics of the experiments to cover it.

2. SOME BASIC CONSIDERATIONS

2.1. Lattice gauge calculations

Our best handle to explore theoretically the phase transition and some of its characteristics is the lattice gauge theory (LGT). In spite of its limitations (assumption of zero baryon density, static character of the simulations) it is the best existing guideline. In Fig. 1 we show the dependence of the energy density on temperature as currently predicted [4]. The critical energy density as reported by the LGT is $\varepsilon_\mathrm{c} = (6 \pm 2){T_\mathrm{c}}^4$ and the critical temperature is around 170 MeV with an error of about 10%. Although the error may seem small, the fourth power in the exponent entails a considerable error on the predicted energy density!

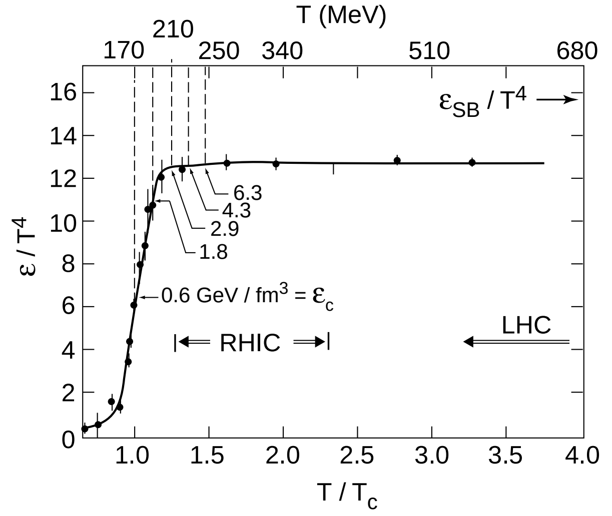

Figure 1. Phase diagram as obtained from lattice gauge calculations.

Experimentally the measurement of the achieved energy density is not straightforward. The expression that links the energy density with the experimental observable is

$$\varepsilon = 3/2(\mathrm{d}N_\mathrm{ch}/\mathrm{d}y)\langle E\rangle/V,$$

where $(\mathrm{d}N_\mathrm{ch}/\mathrm{d}y)$ represents the number of charged particles per unit of rapidity, $\langle E\rangle$ is the average energy carried by the particles, and V is the volume of the system. In its original form derived by Bjorken the volume is chosen to be the transverse area of the colliding nuclei multiplied by 1 fm. The longitudinal length chosen corresponds (taking into account that the nuclei are longitudinally contracted so as to form two colliding 'pancakes') to an estimated time interval for the formation of an equilibrated system. The well-founded assumption that the equilibration times at LHC may be considerably shorter brings an important experimental uncertainty. So the correct procedure for reporting experimental results would be to speak about the energy per unit area rather than per unit volume.

There is another important message from the phase diagram: the right-hand side indicates the energy density limit for a Stefan–Boltzmann gas. The fact that all the lattice gauge calculations miss that limit by a significant amount is usually interpreted as an indication that the system of quarks and gluons above the critical temperature does not behave as a free gas but that residual interactions are still present. This prompts the claim that we are faced with a 'quark–gluon soup' rather than with ideal plasma.

Finally on the upper part of the phase diagram are marked the ranges of temperatures achievable at the Relativistic Heavy Ion Collider (RHIC) in operation at Brookhaven National Laboratory since 2000) and at LHC.

2.2. Parton distributions and the size of the colliding objects

The fast moving hadrons or nuclei represent a system consisting of three valence quarks: sea gluons and quark–antiquark pairs; each of these species has a distinct momentum distribution represented by the parton distribution function.

The partons are confined to a longitudinal scale — $l \sim 1/p \sim 1/(p_0 x)$ where $x = 2p_\mathrm{t}/\sqrt{s}$ by the uncertainty relation. The nucleus itself is Lorentz contracted to a size L given by $L = 2Rm/p$ where m and p are the mass and momentum of nucleons in the nucleus, respectively. In the case when $l > L$ the partons will, depending on their x-value, effectively overlap each other and cover a longitudinal space that is larger than L.

The contribution of the three parton categories to the overall momentum as a function of the x-variable is shown in Fig. 2.

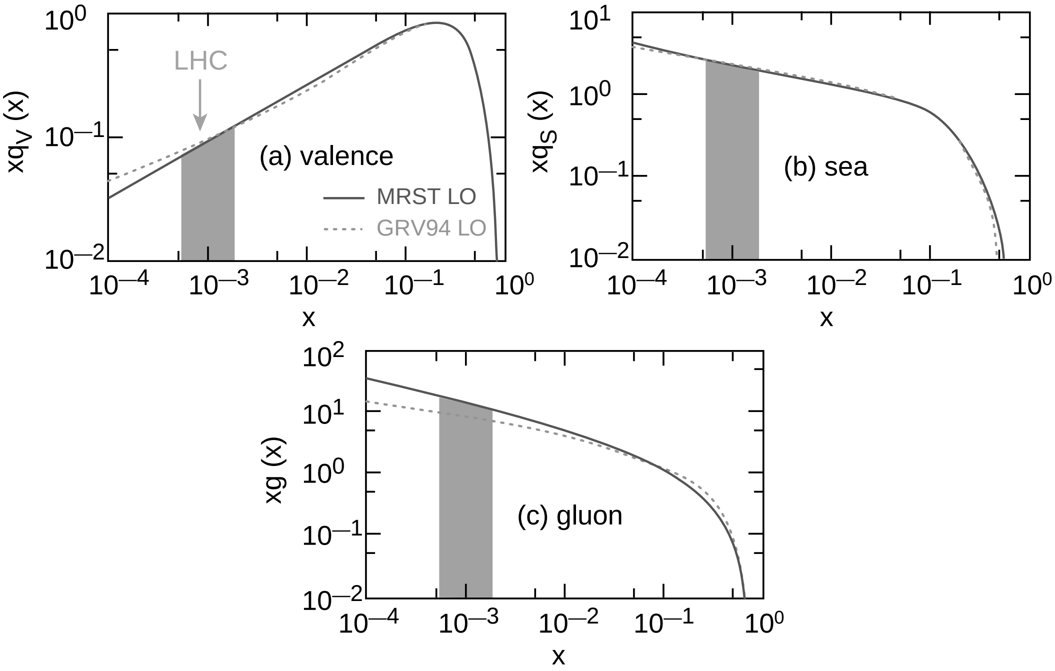

Figure 2. Proton parton distributions at $Q^2 = 4$ GeV^2 for two different parametrizations.

The shaded area shows the range of x-values of the partonic distributions available for investigation at LHC. The range of x-values at RHIC is 20 times larger. One can deduce from Fig. 3 that the partonic densities will be much different at both accelerators.

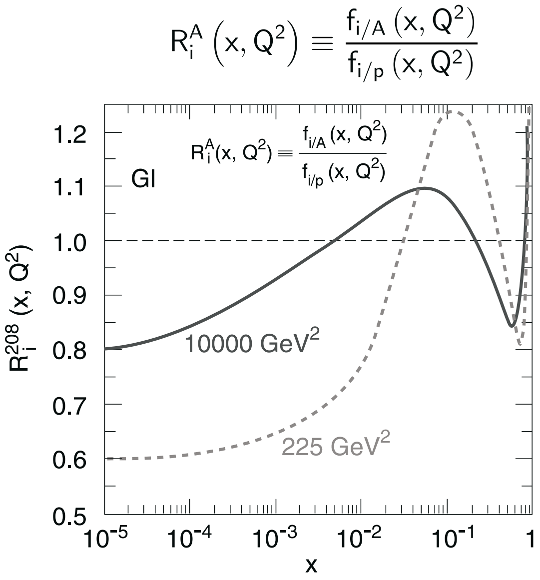

Figure 3. x-dependence of the ratio of the gluon distribution function in a Pb nucleus and in a proton for two different momentum transfers. Adapted from Ref. [5].

2.3. Shadowing phenomena

Another unique aspect of the heavy-ion physics at LHC is the importance of shadowing. It is a well known fact from deep inelastic scattering that the parton distributions in nuclei are modified by multiple interactions along the parton path and by recombination of long-wavelength partons. This effect is very pronounced in the x-value regions at LHC and almost completely absent at RHIC. This feature tells us that the parton distributions also depend on the nucleon content of the nucleus.

3. THE COLLISION – A LABORATORY IN ITSELF

Essentially the collision can be subdivided in space-time into several well identified and distinct phases:

- early pre-equilibrium stage where hard interactions occur;
- thermalization and subsequent expansion of the system of quarks and gluons;
- hadronization;
- freezout.

According to the predictions of LGT and the experimental observations made at SPS (see talk by P. Giubellino) we believe that in the second stage a state of dense matter consisting of quarks and gluons is formed. Our interest is to study the characteristics of this state, its interaction with particles crossing it, its behaviour over time, etc.

In that sense, the initial encounters that yield some very hard collisions giving rise to either energetic jets or to heavy quarks — of which a part will combine into quarkonia

— will give us the probe to test the matter created simultaneously. Comparing similar observables (p_{t} spectra, yields of jets or quarkonia, particle multiplicities, fragmentation functions, etc.) with the same observables measured in pp collisions one may deduce what has happened to the fast initial particles on their way to the hadronic world.

In that sense we can speak about a complete laboratory where the collision prepares both the 'particles' and the 'target' to be analysed. The other aspects of the thermalized system will doubtless — owing to the duration of its existence — also yield interesting results that will not escape experimental scrutiny; however, the possibility of having well-established probes to traverse the quark–gluon system is likely to be the most interesting part.

3.1. The jets and minijets

A large part of the initial interactions will be semi-hard and hard, in contrast with the softer interactions at lower energies. This qualitatively completely new situation is best illustrated by the cross-section dependence of pp scattering on the centre-of-mass energy shown in Fig. 4. From the figure we see that at energies of about 200 GeV (today's energy at RHIC) the proton–proton cross-sections start being dominated by 'minijets'. At LHC the dominance of hard processes is obvious. That a well-understood feature like hard production becomes prominent opens interesting avenues of research. For instance, one may ask about the energy loss the created jets will suffer in the surrounding plasma on their way out into vacuum. The phenomenon is called 'jet quenching' and is the subject of numerous theoretical discussions today. In his paper from 1982 [6] Bjorken writes that 'The high-p_{t} partons may elastically scatter from the quarks and gluons in the plasma thereby degrading its energy and heating the plasma.' Although the theoretical frame has evolved and experimental observation has been inferred from p–A data [7], one may say that the magnitude and more detailed features of the effect in AA collisions will be only understood following experimental data at RHIC and at larger energy at LHC. The experimental observables linked to jet quenching are many: overall multiplicity per event, particle spectra, dijet vs monojet ratio at high E_{t}, azimuthal correlations, rapidity distributions, etc.

3.2. Interplay of nuclear shadowing and jet quenching

The experimental observables will have to cope with a constant and pernicious interplay of effects due to shadowing and those due to jet quenching and/or saturation.

Jet quenching brings with it an increase in the number of particles: The energy loss in the medium manifests itself as a loss of momentum of the leading partons in the jets and a subsequent increase of the low-momentum partons, giving rise to low-momentum hadrons in the end. On the other hand, the shadowing phenomenon suppresses the number of gluons and hence decreases the final multiplicity. Another effect that influences the multiplicity is 'saturation'. Partons may be attributed an elementary transverse area given by $\pi/{p_{\mathrm{sat}}}^2$, where ${p_{\mathrm{sat}}}^2$ corresponds to the saturation momentum. When the sum of these elementary areas becomes larger than the transverse area of the nucleus, namely $\pi {R_{\mathrm{A}}}^2$, the number of partons saturates and is not allowed to grow any further [8,9]. This effect is clearly also a limiting factor for the rise of the multiplicity.

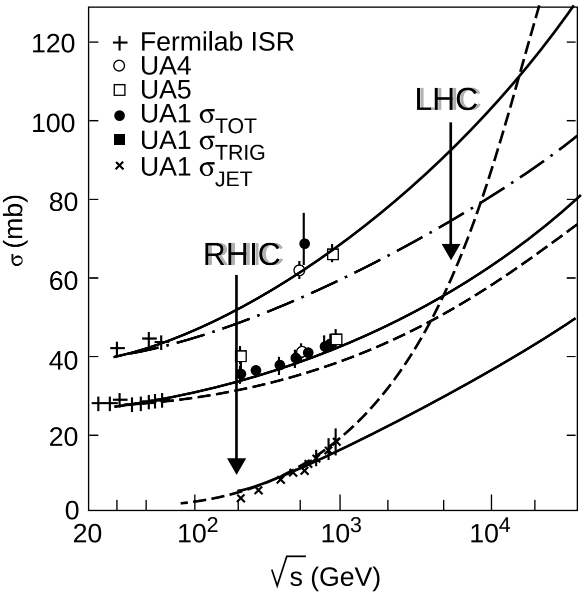

Figure 4. Total, inelastic non-diffractive and minijet cross-sections (full lines) from top to bottom, respectively. The dashed line for minijets represents the input cross-section (which violates unitarity) before unitarity regularization. Dashed-dotted and dashed lines for total and inelastic cross-sections show the behaviour without minijet contribution; from Ref. [10].

3.3. Quarkonia production and Debye screening

Charmonium and bottomium states called quarkonia are produced, like jets, at early times. While J/ψ has been extensively studied at SPS and has been the determining factor to confirm the evidence for the creation of a quark–gluon plasma, $\Upsilon(\mathrm{b\overline{b}})$ will become accessible as a probe of the system — because of its large mass — only at RHIC and LHC. The main parameter that is involved is the measurement of the survival probabilities of the bound quarkonia states. Through the mechanism of colour screening, the Coulomb-like colour charge potential between the two heavy quarks will be 'screened', i.e. modified by the presence of other colour charges in the medium in the following way:

$$V(r) = \frac{\alpha \exp\left[-r/\lambda_{\mathrm{D}}(T)\right]}{r},$$

where r is the distance between the heavy quarks and $\lambda_{\mathrm{D}}(T)$ is the Debye screening length which is a function of the temperature of the system, hence of the energy density. (For an extended account of the screening consult Ref. [11].) In Table 1 we show the radii, binding energies and screening masses for a sample of quarkonia. Measuring the survival probability for the quarkonia coming out of the dense environment should give us information on the temperature reached in the plasma. Figure 5 shows the dependence of the screening potential on the temperature. We see that the LHC range of temperatures (see Fig. 1) should reach the temperature necessary to achieve melting of the Υ.

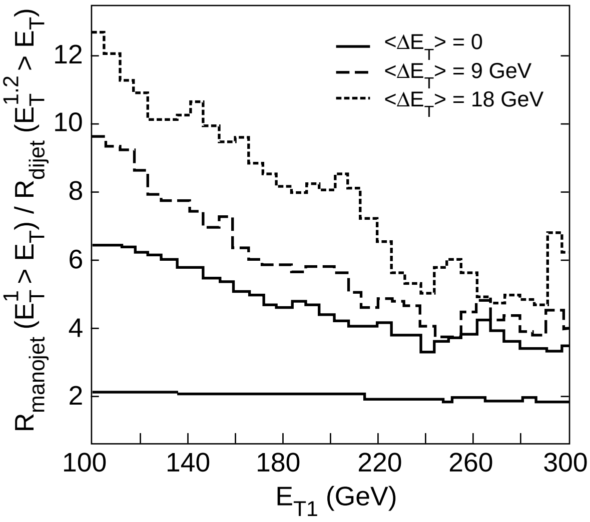

Figure 5. Ratio of monojets to dijets as simulated for the CMS barrel calorimeters as a function of the jet transverse energy [3].

Table 1
Binding energies, radii, and screening masses for a sample of quarkonia.

	J/ψ	ψ'	$\chi_a(1P)$	Υ	ψ'	$\chi_b(1P)$
M [GeV]	3.07	3.698	3.5	9.445	10.004	9.897
r [fm]	0.453	0.875	0.696	0.226	0.509	0.408
μ_D [GeV]	0.699	0.357	0.342	1.565	0.671	0.558

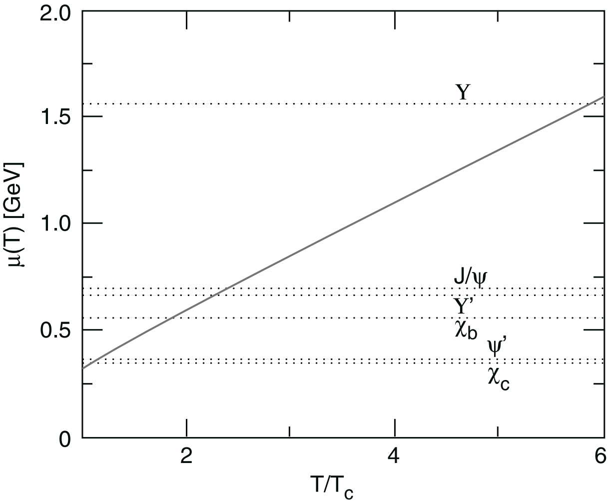

Figure 6. Screening mass as a function of temperature. The curve is taken from Ref. [11] for the high initial temperature limit.

Table 2 presents the expected performances in the CMS and ALICE detectors for the measurement of J/ψ and Υ.

Table 2
Expected performances in the CMS and ALICE detectors for the measurement of J/ψ and Υ.

	ALICE	CMS
J/ψ	$2.5 < \Upsilon < 4$	$\|\eta\| < 1.3$ barrel
		$\|\eta\| < 2.4$ full det.
	all p_t	$p_t > 5$ GeV/c
Υ	$2.5 < \Upsilon < 4$	$\|\eta\| < 1.3$ barrel
		$\|\eta\| < 2.4$ full det.
	all p_t	all p_t

4. EXPERIMENTS AT LHC AND THE OBSERVABLES

As shown above the experimental context in the study of heavy-ion collisions at LHC is fundamentally different from the one we are familiar with at the low-energy machines like AGS and SPS. Already the first results from RHIC demonstrate the importance of well thought out and multiparameter experiments — experiments where the observables are measured in the widest range. The underlying physics predicts features that translate into different trends in the results, as pointed to earlier. Hence the experiments will have to provide sufficient numbers of measured parameters to possibly disentangle the various effects. Concretely we will want to measure

- the identified spectra of particles and compare these with the ones measured in pp and p–A collisions. Measuring the particle ratios as a function of momentum will allow us to get information on the fragmentation function of emerging jets and to compare them with the corresponding values measured in pp collisions. This will require a high quality particle identification — for instance, the ALICE experiment (see below) will use in its set-up all the particle identification methods currently available (dE/dx, time of flight, Cherenkov light, transition radiation, secondary vertex reconstruction, kinematical constraints and calorimeters)! The direct observation of jets is also possible although the identification of jets above 100 GeV transverse energy may be difficult because of the large number of low-energy jets. CMS will approach the jet quenching mainly by measuring the dijet vs monojet ratio.

- the azimuthal anisotropy of various particles with respect to the event plane, which should give us the possibility to understand the dependence of the yields and/or momentum spectra on the geometry of the collision zone. Peripheral collisions will present a very non-symmetric shape with respect to the reaction plane. Therefore one expects a correlation of some observables (jet quenching for instance) with the path length of particles through the medium. (Since the particles from jets are emitted at early times the emission zone for noncentral events keeps a distinct geometrical almond shape and the emission of particles should have different patterns in and out of the event plane. This will require changing the centrality of the collisions, i.e. the impact parameter.

- the behaviour as a function of the initial number of nucleons, calling for the use of beams with different nuclei masses. Currently at least three different systems are considered: Pb–Pb, Sn–Sn, and Ar–Ar. In addition, measurements of the proton–proton collisions and p–A collision are necessary to provide comparison data.

The two experiments planned for heavy-ion physics are ALICE and CMS. The main difference between the two detectors is that ALICE is devoted to the measurement of heavy-ion collisions and as such has been specifically designed to cover most of the observables in an experiment, while CMS has been optimized for hard pp physics — supersymmetric particles, jets and Higgs searches. Therefore with a considerable calorimetry they can cover mainly the jet quenching physics and the quarkonia production [3].

The ALICE experiment (Fig. 7) has been conceived around a powerful tracking provided by six layers of silicon trackers, a time projection chamber and a transition radiation chamber with tracking capabilities (devoted to measurements of quarkonia, and open charm and beauty). The tracking detectors and the accompanying time-of-flight detectors for particle identification have been built in a rapidity acceptance of $|\eta| \leq 0.9$.

This rapidity acceptance has been deemed sufficient to be able to measure the global characteristics of the events on an event-by-event basis. A photon spectrometer for the measurement of the photon energies up to 50 GeV and a high-momentum particle identification (HMPID) cover only partially the central region since their task is inclusive measurements. At higher rapidities we have the muon spectrometer for the measurement of quarkonia, the forward multiplicity detectors, the photon multiplicity detector and the T0 detectors. At very high rapidities ($\eta = 6$) we have the Zero Degree calorimeters and the CASTOR calorimeter for the detection of exotic products (Centauros, Strangelets)

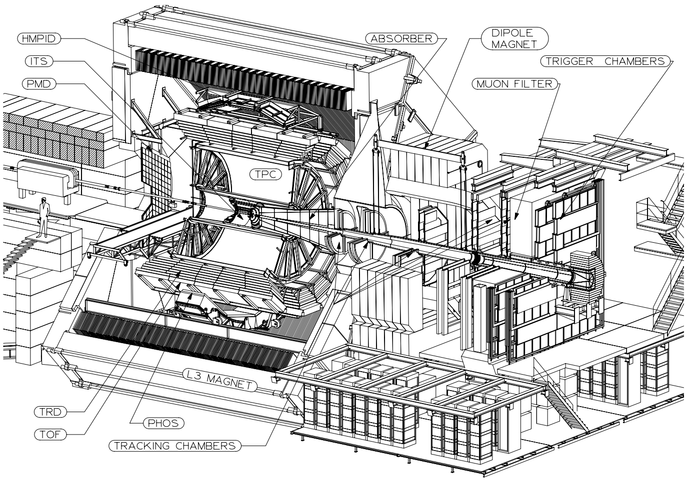

Figure 7. View of the ALICE experiment.

5. CONCLUSION

The heavy-ion beams at LHC will provide the experimentalists and the theoretical community investigating the QCD vacuum state with a tool with qualitatively new features which have been reviewed. In addition, the complete spectrum of currently available oberservables of heavy-ion physics — connected with the thermal expansion and hadronization can also be explored. The detectors ALICE and CMS, with their detecting capabilities and complementarity, are well set to cover this field.

REFERENCES

1. ALICE Collaboration, Technical proposal, CERN/LHC 95–71 (1995).
2. ALICE Collaboration, Addendum to the ALICE technical proposal, CERN/LHC 96–32 (1996).
3. Heavy ion physics programme in CMS, CMS note 2000/060.
4. U. Heinz, hep-ph/0009170; CERN–TH–2000–276.
5. K. Eskola, V.J. Kolhinen, R. Vogt, hep-ph/0104124; JYFL–2001–6.
6. J.D. Bjorken, Energy loss energetic partons in quark–gluon plasma: possible extinction of high pt jets in hadron-hadron collisions, Fermilab-Pub-82/59-THY.
7. M.B. Johnson et al., Phys. Rev. Lett. 86 (2001) 4483.
8. J.P. Blaizot and A.H. Mueller, Nucl. Phys. B 289 (1987) 847.
9. K. Eskola et al., Multiplicities and transverse energies in central AA collisions at RHIC and LHC from pQCD, saturation and hydrodynamics, hep-ph/0104010.
10. A. Capella et al., Phys. Rev. Lett. 58 (1987) 2015.
11. R. Vogt, Phys. Rep. 310 (1999) 197.