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Highlights of the LHC run 1 / Résultats marquants de la première période d'exploitation du GCH

# On the trail of a new state of matter

## *Sur la piste d'un nouvel état de la matière*

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ABSTRACT

Following the results collected in the past 30 years within the heavy-ion scientific program, the progress achieved so far at the CERN LHC during the first data taking period is reviewed.



RÉSUMÉ

S'appuyant sur les résultats obtenus dans le cadre du programme ions lourds ces 30 dernières années, les avancées majeures obtenues auprès du LHC du CERN pendant la première période de prise de données sont passées en revue.



### 1. Introduction

In November 2010, three LHC experiments, ALICE, ATLAS and CMS, recorded the first collisions of lead nuclei at an unprecedented high energy (centre of mass energy per nucleon pair, $\sqrt{s_{\rm NN}} = 2.76$ TeV). This long-awaited event opened a new era in the 30-year old heavy-ion scientific programme with the goal of quantitatively characterising quark–gluon plasma (QGP) and carrying out precision measurements of its elementary properties. QGP is the thermodynamical phase of strongly interacting matter, which according to quantum chromodynamics (QCD), the theory of the strong interaction, exists under extreme conditions of temperature (larger than 160 MeV) and/or energy density (larger than 1 GeV/fm$^3$). In the cosmological Big-Bang model, QGP is thought to be the state of primordial matter that existed during the first tens of microseconds in the evolution of the Universe. QCD predicts that matter undergoes a phase transition from ordinary matter (quarks confined in hadrons) to QGP, where deconfined quarks roam freely over large distances (compared to the confinement size) and where chiral symmetry is restored (the chiral symmetry breaking induces the bulk of hadron masses). The transition is a smooth crossover at sufficiently high collision energies when the net baryon density is low, close to zero, a condition met at the LHC. At high net baryon densities, the transition is thought to be of first order with a yet not well-established critical point. The QGP phase is explored with heavy-ion collisions at ultrarelativistic energies where the required conditions of temperatures and energy densities are reached over a sufficiently large volume (larger than the

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mean free path of constituents) and for a time (few fm/c) much longer than the relevant relaxation times. Beyond the phenomenological aspects related to the exploration of the phase diagram of strongly interacting matter, the heavy-ion scientific programme ultimately aims at establishing how the macroscopic properties of QCD matter emerge from the first principles that constitute the cornerstones of the Standard Model of particle physics.

## 2. SPS and RHIC before LHC

Prior to the start of the LHC, the study of the energy dependence of heavy-ion collisions was indispensable to establish qualitatively the nature of matter at high temperatures. First at the SPS (the Super-Proton Synchrotron at CERN delivered Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 17$ GeV), the combined observations collected by several experiments led in the year 2000 to the conclusion that a new QGP-like state of matter had been created in head-on or central Pb–Pb collisions, featuring characteristics anticipated for a QGP. This conclusion was supported by the enhancement with respect to proton–proton (pp) collisions of the production of strange particles, in particular indicating the formation of a thermalised medium; by the modification of the spectral function of the $\rho$-meson, which is interpreted as due to a partial restoration of chiral symmetry in the hot system in which the $\rho$-meson is created, and by the anomalous suppression (in contrast to the normal suppression due to hadronic interactions) of the $J/\Psi$, which is compatible with the predicted melting in hot, deconfined matter of this bound state of the c quark with its antiquark.

Then, following ten years of data taking at RHIC (the Relativistic Heavy-Ion Collider at Brookhaven, USA, delivered Au–Au collisions at maximum energy $\sqrt{s_{\mathrm{NN}}} = 200$ GeV), the conclusions drawn from the SPS observations were definitively confirmed and knowledge of the properties of QGP was widely extended with a much more precise characterisation. The new state of hot and dense matter was found to behave like a strongly interacting, close to perfect, opaque liquid and it was therefore dubbed the sQGP (s stands for strongly interacting). This conclusion came as a surprise as it was anticipated that, at high temperatures, QGP would be more likely to have the properties of a weakly interacting gas! The initial temperature of the QGP was deduced from the measured direct thermal-photon spectrum (used as input of a calculation of the thermal-photon emission throughout the dynamical evolution of the collision) and was found to be equal to about 300 MeV, a value well above the calculated temperature at which the QGP is predicted to hadronise. The characterisation of QGP as a perfect liquid was derived from the measured collective motion of the final-state hadrons, which, according to a viscous hydrodynamics modelling of the medium's evolution, develops in response to internal pressure gradients. Finally, the medium was found to be quasi-opaque for fast partons (quarks or gluons) travelling through the medium, as a consequence of energy loss via strong interactions (elastic scattering and gluon radiation) of the partons carrying colour charge (the quantum number related to strong interaction in the QCD theory) with the colour-dense medium.

Besides establishing these features that are of great significance and importance to QCD physics, the wealth of data collected at the SPS and RHIC, together with many advances in theory, further established a comprehensive description of the dynamical evolution of a heavy-ion collision at ultrarelativistic energies from the initial impact of the collision to the observation of the final hadronic state in the detectors.

- Initial state: the initial state of the collision is described by the wave function of the nuclei, which is dominated by a large density of sea gluons at small fractional momentum of the constituents and at high virtuality. The dynamics of this system can be modelled from first principles within a classical field theory as is implemented in the colour glass condensate (CGC) model.
- Pre-equilibrium phase: in the collision, gluons are liberated from the dense sea creating a dense non-thermal QCD plasma with highly occupied gauge fields, which is sometimes called the glasma.
- QGP phase: the glasma thermalises rapidly (within less than 1 fm/c) to form a QGP in local thermodynamic equilibrium (the mean free path of constituents is much smaller than any other size involved), the subsequent evolution of which is well modelled in the context of relativistic viscous hydrodynamics.
- Hadronic phase: during its evolution, the system expands and cools down until reaching the temperature of the QGP at which the system hadronises. The chemical composition of the hadronic phase is frozen at a temperature that turns out to be very close to the critical temperature. Elastic scattering further modifies the spectral distribution of the hadrons until kinetic freeze-out, where all interactions cease.

Whereas the thermodynamics of the medium created in the collision modelled by a hydrodynamic evolution of a thermalised system adequately captures many of the measurements, several questions remain open concerning the phases prior to the formation of the QGP. In particular, models describing the initial state of the collision are not yet sufficiently constrained by experiments. The process leading to thermalisation on a very short time scale, as required by the subsequent hydrodynamic evolution, is not understood, and the nature of the degrees of freedom (field quanta, quasiparticles, perturbative particles...) involved in the process is not known.

Having taken on the leading role in heavy-ion physics, the driving motivation behind the heavy-ion programme at the LHC is primarily to perform a quantitative characterisation of the QGP through measurements of an unparallelled degree of accuracy. To reach this goal, the heavy-ion community is relying on a new generation of all-in-one detectors among which ALICE is the one at the LHC dedicated to the heavy-ion programme. The setup and performance of ALICE detectors have been optimised for measurements to very low values of the transverse momentum ($p_{\mathrm{t}}$) of identified particles, so as