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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, $\sqrt{s_{NN}} = 2.76$ 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 $\sqrt{s_{\rm NN}} = 17$ 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 ρ-meson, which is interpreted as due to a partial restoration of chiral symmetry in the hot system in which the ρ-meson is created, and by the anomalous suppression (in contrast to the normal suppression due to hadronic interactions) of the J/Ψ, 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 $\sqrt{s_{\rm NN}} = 200$ 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 ($p_{\rm t}$) of identified particles, so as

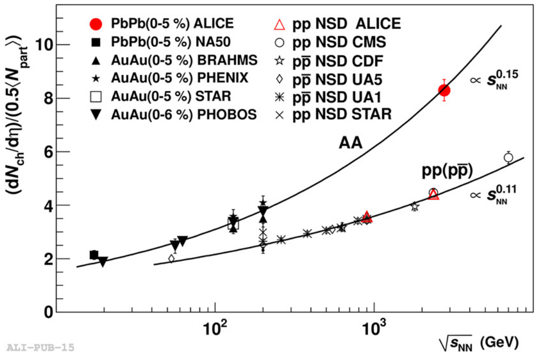

Fig. 1. (Colour online.) Charged-particle pseudorapidity density per participant pair for central nucleus–nucleus and nonsingle diffractive pp, as a function of $\sqrt{s_{NN}}$. The solid lines $\propto s_{NN}^{0.15}$ and $\propto s_{NN}^{0.11}$ are superimposed on the heavy-ion and pp data, respectively.
Figure from Ref. [1].

to provide a comprehensive series of low p_t or soft observables (the formation of soft observables is coupled with the formation of the QGP) that reflect the properties of the QGP. ALICE is also adapted to high-quality measurements of hard probes (the formation of hard probes, with high p_t or high mass, is decoupled from the formation of the QGP), a domain where the ALICE heavy-ion programme at the LHC is complemented by the CMS and ATLAS experiments offering superb calorimetric and muon measurements. The increase in the collision energy at the LHC (ultimately, at $\sqrt{s_{NN}} = 5.5$ TeV, by a factor of 27 compared to the highest RHIC energy) is an additional decisive point in moving forward in the study of the QGP. Collisions of lead nuclei at the LHC create a hot medium at a higher temperature that will stay in the QGP phase for longer, thus amplifying the signals directly related to the QGP. The event multiplicity is increased, providing a more accurate statistical ensemble for multi-particle observables and for event-by event studies. In addition, because the cross-section for the production of hard probes is greatly increased at the LHC with respect to RHIC, the range of measurable rare probes is substantially enlarged.

Consequently, rather than discussing exhaustively the achievements of three years of data taking (ion data have been collected during one month each year, Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV), we highlight a few results, some of which are decisive in confirming the conclusions from RHIC, others that lead to a revision of some RHIC interpretations and lastly, discoveries that were quite unexpected.

3. Hotter, larger, longer lived

The global characterisation of the final hadronic state of the heavy-ion collision defines the first measurements to be performed. They involve the soft particles that are produced dominantly in the collision and carry the information about the bulk dynamics of the colliding system.

Both the multiplicity density in pseudo-rapidity (η, a kinematic parameter related to the polar angle of the particle) space of charged particles ($dN_{ch}/d\eta \approx 1600$) measured by ALICE [1] (Fig. 1) and the transverse energy density ($dE_T/d\eta \approx 2.1$ TeV) measured by CMS [2] constrain the dominant particle-production mechanisms and provide an estimate of the initial energy density per unit volume. This latter quantity is estimated using the Bjorken formula that was established assuming an adiabatic expansion in the longitudinal direction of the overlap region of the colliding ions:

$$\epsilon \sim \frac{dE_T}{d\eta}\frac{1}{\pi R^2 \tau_0} = 3/2\,\langle E\rangle \frac{dN_{ch}}{d\eta}\frac{1}{\pi R^2 \tau_0}$$

where πR^2 is the transverse area of the overlap region, τ_0 the time when thermal equilibrium is established (taken equal to 1 fm/c), $\langle E\rangle$ is the average transverse energy per particle (measured equal to 1 GeV/c), all charged particles are assumed to be pions and the factor 3/2 takes into account the undetected neutral pions. The value of ϵ obtained within these assumptions and for the measured multiplicity and transverse energy density is equal to 15 GeV/fm^3, a value higher by a factor 3 than the highest value obtained at RHIC.

The temperature of the QGP is derived from the measurement of the direct photon spectrum (in contrast to decay photons predominantly emitted in the decay of neutral mesons). Identification of direct photons is however a challenging analysis task because of the overwhelming contribution of the decay photons. ALICE has identified the direct photon contribution as excess to the measured decay photons. At high energy ($E_\gamma > 4$ GeV), the direct photon spectrum exhibits a power-law shape characteristic for photons produced in QCD processes in collisions with large momentum transfer among initial-state partons of the colliding nuclei, and is well calculated by next-to-leading order perturbative QCD. In the low-energy region, the derived spectrum exhibits an exponential thermal-like shape ($\propto e^{(-E_\gamma/T)}$). The slope parameter T is linked to an effective temperature measured to be about 300 MeV, a value 40% higher than the value measured in the same conditions at RHIC. It is an effective temperature averaged over the hydrodynamic time evolution of the system while it

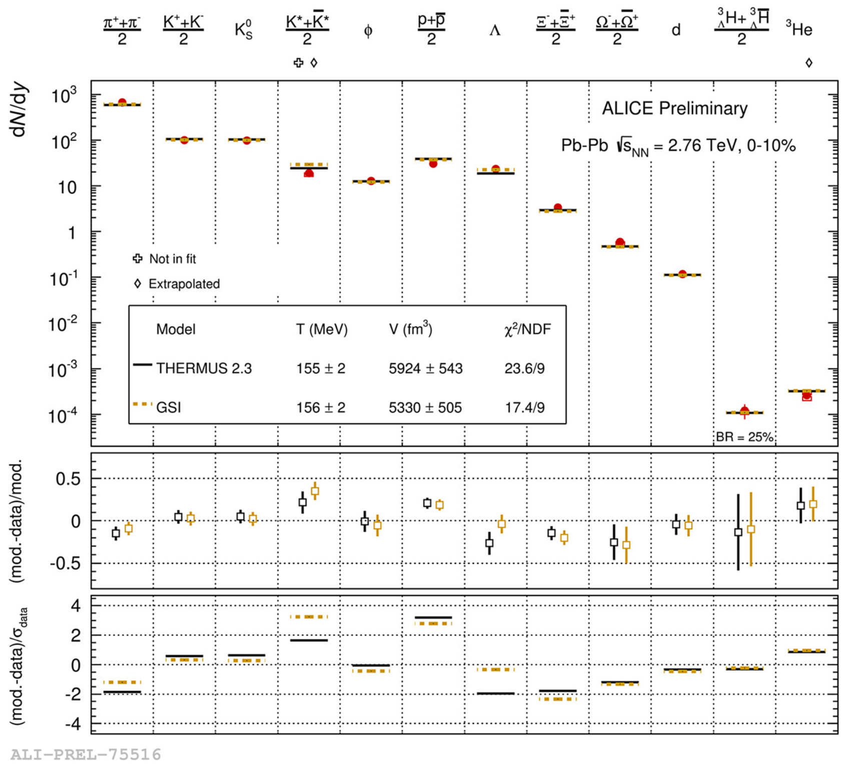

Fig. 2. (Colour online.) Ratio of various particle productions measured in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and compared to the predictions of thermal models.
Figure from Ref. [4].

radiates photons and cools down. The initial temperature of the QGP is therefore higher than this value, but can only be determined in a model-dependent way.

Measuring the size and lifetime of the collision is the next step in following the global properties of the heavy-ion collision. The measurement is based on the technique originally developed by Hanbury Brown and Twiss (HBT) that exploits interference to measure the apparent angular size of distant stars. In heavy-ion collisions, owing to quantum interference effects, two-particle correlations are characterised by an enhancement (depletion) of the correlation between identical bosons (fermions) emitted close to each other in phase space. The interference pattern is related through a Fourier transform to the spatial and temporal distribution of the particle-emitting source. What is actually measured is the space–time distribution of interacting particles at freeze-out, namely the time when strong interactions cease. ALICE has measured the two-pion Bose–Einstein correlations [3]. The deduced freeze-out volume and freeze-out time are significantly larger than those measured at RHIC: at the LHC, the volume (5000 fm^3) increases by a factor of two and the lifetime (10 fm/c) by 30%, in line with the expectation for a hydrodynamically expanding system as the hotter system produced at LHC needs to expand more to cool down to the hadronisation temperature.

This set of measurements is in line with the a priori expectations that the global properties of heavy-ion collisions at the LHC follow a smooth extrapolation of the properties measured at lower collision energies and that heavy-ion collisions at LHC energies create matter at the highest temperature (200,000 times hotter than the centre of the Sun) and energy density (50 times larger than in the core of a neutron star) ever reached in the laboratory, and extends over a larger volume for a longer time than ever before. Matter at the LHC is created under the ideal conditions in which to study quantitatively and with extraordinary precision the properties of QCD matter under extreme conditions.

4. A thermal system

The observation of the collective behaviour of the matter created in heavy-ion collisions and the measurement of its thermodynamic properties constitutes an essential step in the determination of the fundamental properties of QGP.

The chemical composition of the final hadronic state is one of the relevant observables. ALICE has found that in central collisions nearly all kinds of hadrons are produced in the ratios expected from thermal hadronisation models [4] (Fig. 2).

Within such models, particles are created in thermal equilibrium as expressed by a Boltzmann factor depending on the mass m of the particle, the chemical freeze-out temperature and potentials ensuring conservation of quantum numbers such as the baryon number (μ_B) and flavour (quantum number that refers to a species of an elementary particle), in

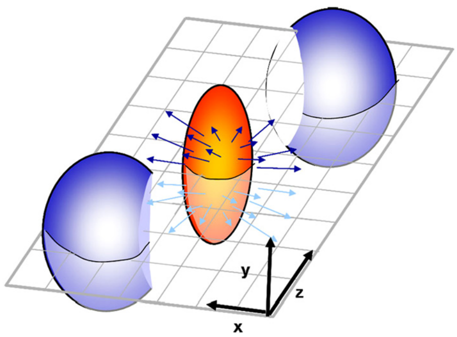

Fig. 3. (Colour online.) Illustration of the geometry of a heavy-ion collision. The reaction plane (x, z) is defined by the momentum axis (z) of the colliding nuclei (blue) and the impact parameter along the x axis. The azimuthal angle of particles emitted from the almond-shaped overlap region (orange) is defined with respect to the reaction plane.

particular, strangeness. An additional factor takes into account the non-conservation of strangeness observed in pp collisions as a suppression of the production of strange particles with respect to the grand canonical thermal formulation.[1] The data from central Pb–Pb collisions are best described with the value of μ_B close to zero (baryon and antibaryon production is balanced). The measured production of strange particles in Pb–Pb collisions is enhanced with respect to pp collisions as a consequence of canonical suppression in pp collisions. This observation is similar to the enhancement already observed at lower collision energies, but it is less pronounced at the LHC due to a reduced canonical suppression. The chemical freeze-out temperature derived from a fit to the data of the thermal model is equal to 154 MeV, a value very close to the phase boundary but lower than the one measured at RHIC (164 MeV). This difference remains unexplained. However, the thermal model greatly over-predicts the proton-to-pion ratio measured at the LHC. A plausible explanation, but not the only one, could be that annihilation processes alter the production rate of protons after chemical freeze-out. These observations strongly support the picture of a final hadron state formed in thermal equilibrium very quickly after hadronisation. What the details are of the mechanism leading to the measured particle ratio at the LHC, and whether it is the same mechanism at work at RHIC, remain under intense debate. One should note that this interpretation of the data requires no assumption about the state of the preceding partonic phase.

The collective motion of the final-state hadrons is imprinted in the particle spectra. The observed evolution of their shape with collision centrality (defined by the value of the impact parameter) and particle mass is in line with the development of a strong radial collective flow (momentum and space variables are correlated) in an expanding fireball. The soft part of the spectra is described by a hydrodynamics-inspired function (the blast-wave function) that encodes the average radial velocity ($\langle\beta_T\rangle$) of the fireball and a kinetic freeze-out temperature (T_K) common to all particle species. A common fit of this function to the spectra of all identified particle measured in central Pb–Pb collisions [5] leads to value of $\langle\beta_T\rangle = 0.65c$, a value 10% larger than the highest value measured at RHIC, and of $T_K = 100$ MeV, a value similar to the one measured a RHIC.

With the studies discussed so far, the LHC confirms the global scenario already established at lower collision energies for a heavy-ion collision in its late hadronic stage: a thermalised system is formed that expands radially like a fireball at 65% of the speed of light and, with some concerns nevertheless, it is characterised quantitatively by a smooth extrapolation from low SPS and RHIC energies to LHC energies. As we shall see later, the success of hydrodynamics in capturing most of the soft observables is a decisive indication that the system is also thermalised in the partonic stage.

5. A perfect liquid

A deeper insight into the dynamics of QGP is gained from more subtle measurements that reveal how the medium created in heavy-ion collisions responds to a perturbation. Empirically, anisotropic flow, which characterises the momentum anisotropy in the final hadronic state, is the observable of choice for such a study. On the theory side, hydrodynamic models describe the transport of a perturbation (the initial geometry anisotropy) by the fluid characterised by its fundamental properties such as the equation of state, viscosity, and in-medium speed of sound. In a non-central collision, the almond-shaped overlap region between the two colliding nuclei generates a density anisotropy and hence a pressure gradient that is the largest along the short axis and that converts into an anisotropy in momentum space (Fig. 3).

The momentum anisotropy survives until the hadronic stage of the collision and is observed as a characteristic pattern in the azimuthal flow of the final-state particles. The pattern is quantified through a Fourier decomposition in terms of the coefficients v_n, where the zero-order coefficient is the isotropic radial flow discussed earlier and the second-order coefficient is the elliptic azimuth-dependent flow. Trends of the v_2 dependence with p_t previously measured at RHIC are confirmed at the LHC. However the p_t-integrated value measured at the LHC is larger, reflecting the larger mean-p_t of

[1] The statistical ensemble is described within the grand canonical formulation, which conserves quantum numbers on average and is applicable for the high-multiplicity AA collisions in contrast to the canonical formulation where quantum numbers are conserved locally and is appropriate for low-multiplicity collisions such as pp and pA collisions.

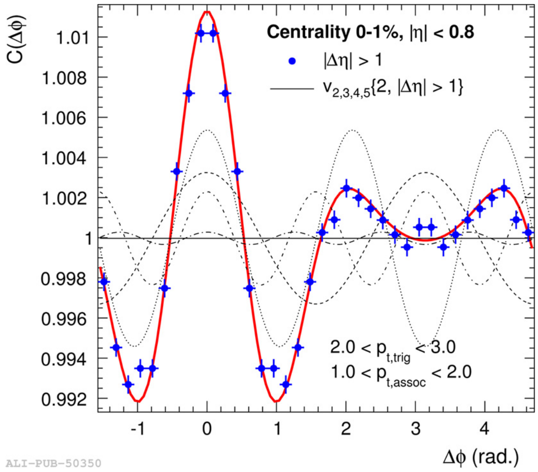

Fig. 4. (Colour online.) The two-particle azimuthal correlation, measured in $0 < \Delta\Phi < \pi$ and shown symmetrised over 2π, between a trigger particle with $2 < p_t < 3$ GeV/c and an associated particle with $1 < p_t < 2$ GeV/c for the 0%–1% centrality class. The solid red line shows the sum of the measured anisotropic flow Fourier coefficients v_2, v_3, v_4, and v_5 (dashed lines).
Figure from Ref. [7].

the soft particles. Comparison of these results with hydrodynamic models indicates that the momentum anisotropy already builds up in the early stage of the collision, shortly after the system has thermalised, and therefore provides a unique probe of the thermodynamic properties of QGP. Another decisive conclusion that can be drawn from the comparison is that the system responds to the initial geometry conditions as an ideal liquid, i.e. a strongly interacting fluid with its mean free path approaching the conjectured quantum limit[2] (quantified through the macroscopic property of the shear-viscosity to entropy-density ratio, $\eta/S \geq \hbar/(k_B 4\pi)$).

The hydrodynamic picture of the QGP dynamics is further constrained by extending the measurement of the momentum anisotropy to identified particles. The interplay of radial flow (radial flow equalises the velocity of particles, not their momentum) with the anisotropic flow components generates a typical mass-ordering in transverse momentum dependence: radial flow shifts the transverse momentum of heavy particles to higher values. Mass ordering has been clearly observed at the LHC in the soft part of the spectrum (typically below 2–3 GeV/c) [6], but differs in some aspects from the pattern observed at RHIC. The scaling of constituent quarks that has been put forward to justify a quark coalescence mechanism, as a new hadronisation mechanism, is not strongly supported by the LHC data.

The analysis of the momentum anisotropy in the final hadronic state has been further refined by extending the Fourier decomposition to odd and higher orders, beyond the second order and up to the eighth order! [7] (Fig. 4). The existence of finite values for these high-order coefficients is associated with the existence of event-by-event fluctuations in the initial geometry of the overlap region between the two colliding nuclei. The fluctuations are consequences of the stochastic nature of nucleon–nucleon collisions, which lead to irregularities in the almond-like shape. These irregularities are then converted into momentum anisotropies of the final-state particles. The measurements (strength, mass, momentum, and centrality dependence) of the different harmonics, all well explained by hydrodynamics calculation, provide stronger constraints on the value of the shear viscosity because they involve shorter wavelength variations and thus larger local pressure gradients. In this way, the precision on the measurement of η/S was largely improved at the LHC as compared to RHIC, the value being now within 2–3 times the quantum limit for perfect liquids.

The QGP created at the LHC looks very much the same as the QGP made at RHIC. It retains the properties of a perfect liquid. This observation is not surprising since in both cases the initial temperature is well above the temperature at which the QGP hadronises and, according to theory, the Stefan–Boltzmann limit for an ideal gas occurs at much higher temperatures. Already, the LHC has shown its strength: the large acceptance of the detectors combined with large particle densities (best suited for measurements of collective effects) was decisive in assessing unambiguously the dynamics of QGP. Particularly remarkable is the discovery of the multi-harmonic decomposition of the momentum anisotropy in the final state that reveals the fine structure of heavy-ion collisions and opens the way towards precision measurements of the fundamental parameters of QGP.

6. An opaque medium

Hard probes, namely probes with high transverse-momentum or mass that are produced in early-stage hard (large momentum transfer) QCD-processes and whose formation is decoupled from the formation of the QGP, are instrumental to

[2] Note that hydrodynamics does not make any hypothesis on the constituent quanta.

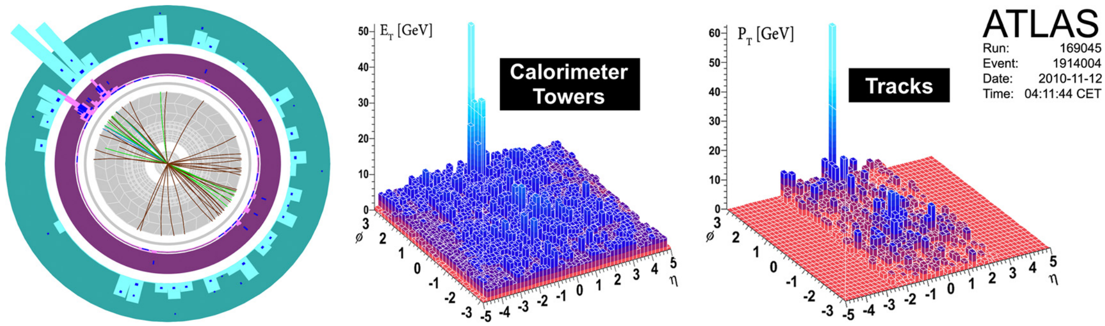

Fig. 5. (Colour online.) Event display of a highly asymmetric dijet event, with one jet with $E_t > 100$ GeV and no evident recoiling jet and with high-energy calorimeter cell deposits distributed over a wide azimuthal region. By selecting low p_t tracks and applying low energy cell thresholds, the recoil can be seen dispersed widely over the azimuth.
Figure from Ref. [10].

deepen further the understanding of the QGP. Thanks to large cross-sections, the LHC excels in making available a large variety of probes that contribute to giving a full and coherent picture of QGP properties.

The suppression of high-p_t hadrons observed first at RHIC is attributed to a mechanism where hard-scattered partons produced early in the collision lose energy while traversing the partonic medium. Partons are empirically identified as a collimated jet of hadrons produced by hadronisation of the partons, hence the name of jet quenching given to this mechanism. Di-hadron correlation measurements show clearly the absence of azimuthal back-to-back correlation in central heavy-ion collisions, suggestive of jet suppression. The effect is quantified by the measurement of the nuclear modification factor $R_{AA}(p_t)$, constructed as the ratio of the hadron spectra measured in AA and pp collisions properly normalised to the number of binary nucleon–nucleon collisions. It was observed to be of the same strength at RHIC and the LHC, but the LHC extended substantially the p_t range over which $R_{AA}(p_t)$ is measured (from 20 GeV/c at RHIC to 100 GeV/c at LHC) [8]. This new measurement has strengthened the jet-quenching interpretation: the energy loss of the parton is described qualitatively and quantitatively by perturbative QCD radiation (gluon) in a strongly interacting medium. However, the measurement is not sensitive enough to quantify precisely the intrinsic properties of the medium and of the strong interaction in the medium. The interpretation in terms of jet quenching was further supported by the observation that gauge bosons (γ and Z), unaffected by the strongly interacting medium, do not indicate a suppression in $R_{AA}(p_t)$ [9].

The actual breakthrough was accomplished through the identification of jets with sufficient energy ($E_{jet} > 100$ GeV) to stick out above the underlying-event background. The observation of a strong imbalance between the transverse energies of azimuthally back-to-back jets, leading to highly asymmetric di-jet events and even mono-jet events in the most central collisions [10] (Fig. 5), is a decisive argument in favour of jet energy loss in the QGP. At the same time, no significant azimuthal de-correlation is observed, suggesting that there is little or no angular scattering of energetic partons during their traversal of the medium.

A first look at details of the energy-loss mechanism has been enabled at the LHC through the study of its dependence on colour charge and mass. The QCD radiative-energy loss, dominant for the most energetic partons, is expected on one hand to be smaller for quarks than for gluons because of the smaller colour coupling-factor of quarks. On the other hand, it is expected to be dependent on the mass of quarks following the suppression of the gluon radiation at small angles from massive quarks. The measured $R_{AA}(p_t)$ for D mesons (mesons containing one charm quark) [11] indicates a suppression as strong as for charged light-flavour hadrons, which are mainly produced in the fragmentation of gluons. Hence this comparison does not support strong colour-charge dependence of the energy loss. The suppression is observed to be weaker for B mesons (mesons containing one bottom anti-quark) than for charged light-flavour hadrons. However, comparison with D mesons not being conclusive, the question on the mass dependence of the energy loss remains open.

Several additional issues regarding the jet-quenching mechanism must be addressed before hard probes can be reliably used to infer basic properties of the QGP. It is already quite well established that the QGP is opaque to the most energetic particles and modifies the partonic shower mainly through soft QCD radiations. The leading parton then fragments with the characteristic pattern of a parton with reduced energy fragmenting in the vacuum. The fate of the radiated energy has not yet been experimentally established. It is likely that the radiated energy is dissipated in the thermal medium out of the empirical jet cone used to reconstruct jets, which would explain why it has so far escaped detection. Another observation, challenging to the theory, is the indication that low-p_t D mesons flow like the soft particles of the bulk [12]. It is tempting to attribute this observation to the thermalisation of the heavy quarks through elastic scattering in the QGP followed by a coalescence mechanism of the heavy quarks with lighter quarks from the QGP.

7. Melting quarkonia

The coalescence mechanism has in fact been invoked earlier to explain the collision-energy-dependent suppression pattern of the J/Ψ meson, the lightest charmonium bound state, that was observed at the SPS and RHIC. Quarkonia states

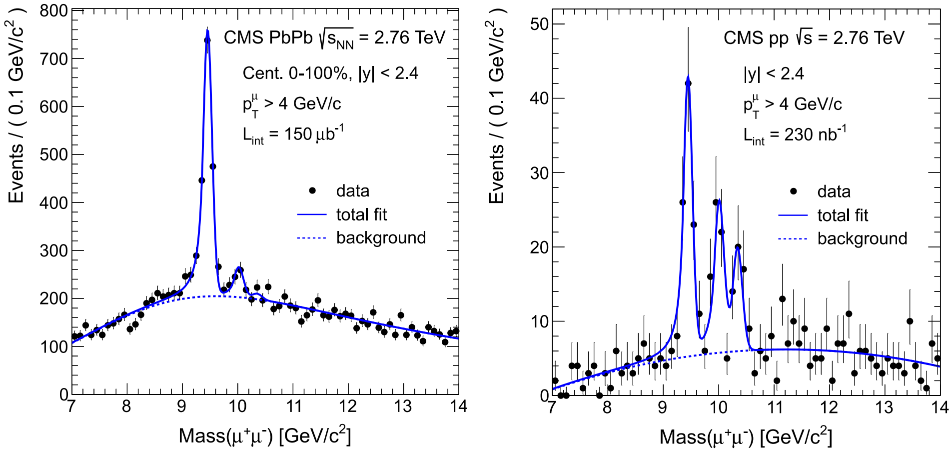

Fig. 6. (Colour online.) Dimuon invariant-mass distributions from the Pb–Pb data at $\sqrt{s_{NN}} = 2.76$ TeV (left) and from the pp data at $\sqrt{s} = 2.76$ TeV (right). The solid (signal + background) and dashed (background-only) lines show the results of the simultaneous fit performed to the pp and Pb–Pb datasets. Figure from Ref. [15].

are hard probes created early in the collisions that are predicted to be dissociated in QGP because the confining potential of heavy quark–antiquark pairs is screened (Debye screening) by quarks and gluons in the QGP. The dissociation depends on the temperature of the medium and occurs sequentially, following the increasing value of their binding energy. In other words, at a fixed temperature the least-bound states dissociate the most easily and hence are suppressed the most.

Following clear suppression of the J/Ψ observed at the SPS and attributed to deconfinement, RHIC surprisingly observed a suppression of the same strength although the temperature of the medium was considerably higher. To reconcile the two observations, the following scenario is suggested. The J/Ψ suppression at the SPS is a result of the deconfinement, at a temperature close to the hadronisation temperature, of the less bound Ψ' charmonium state, whose decay populates 40% of the observed J/Ψ yield. At RHIC, the suppression is balanced by regeneration of J/Ψ where c-quarks and antiquarks created independently in the deconfined medium now combine. This picture is confirmed by the characteristic dependence on p_t (coalescence is the dominant mechanism at low p_t) and rapidity (c-quark density is lowest at forward rapidities) of the suppression pattern measured at the LHC [13]. Many more free c-quarks are created and the coalescence probability is enhanced, resulting in less low-p_t J/Ψ suppression than at lower collision energies. The additional observation that the low-p_t J/Ψ mesons are subject to elliptic flow [14] reinforces this interpretation.

The prediction that the dissociation pattern of quarkonia states depends on their binding energy has been demonstrated with the measured sequential suppression of the bottomonium family [15] (Fig. 6). The $\Upsilon(3S)$ state is found to be significantly more suppressed than the $\Upsilon(2S)$ state, which is more suppressed than the $\Upsilon(1S)$ state, reflecting the decreasing values of their binding energy.

The quarkonia states, which were considered to be probes of choice, have indeed revealed all their richness at the LHC. Their production interpreted in terms of the competing dissociation and coalescence mechanisms provide an unambiguous signal of deconfined matter.

8. A QGP droplet?

The surprise of the first LHC campaign came from proton–lead (p–Pb) collision data. The motivation for collecting these data was dictated by the need to disentangle effects arising from the structure of the initial state (the Pb nucleus) from final-state effects related to the formation of QGP in Pb–Pb collisions. Most of the observations are in line with expectations based on the present knowledge of the partonic structure of the nucleus and of the scaling of particle production through hard processes with the number of binary nucleon–nucleon collisions. The final-state origin of observations such as jet quenching is now unambiguously attributed to final-state effects present only in Pb–Pb collisions.

However, two-particle correlations measured in high-multiplicity events revealed the unexpected: long-range correlations forming a "double-ridge" structure in $\Delta\eta$ (relative pseudo-rapidity) at $\Delta\Phi$ (relative azimuth) equal to 0 and π (back-to-back correlation). The di-jet origin being excluded, the structure is found surprisingly similar to the one observed earlier in heavy-ion collisions where it was attributed to collective flow. The similarity goes even further with the observation of the same p_t-dependence and the same mass-ordering of the elliptic-flow coefficient as observed in Pb–Pb collisions.

Additional similarities were found between p–Pb and Pb–Pb and even pp collisions such as thermal-like final hadronic state, expanding HBT radii, flow and even quarkonia suppression! The question is then whether these observations imply that QGP is also formed in p–Pb collisions. There are alternative explanations. The CGC model succeeds in accounting only for a subset of the observations. More attractive is colour reconnection, a QCD mechanism of final-state interactions between partons from different hard-scattering processes that create effects qualitatively similar to particle–flow correlations.

The formation of QGP in such a tiny system (1–2 fm) remains, however, plausible. Indeed, the determining argument is not the size of the system, but how small is the mean free path of constituent quanta with respect to the system size. Indeed, the vanishing shear viscosity of QGP inferred from Pb–Pb collision data implies a mean free path several times smaller than the p–Pb collision size. Conversely, if the QGP picture in p–Pb collisions does not stand up to further tests, a revision of the interpretation of Pb–Pb collisions at LHC might become necessary.

9. A look into the future

Already during the first years of LHC operation, the experiments have collected data of impressive high quality that allowed consolidating in a short time the conclusions drawn from 10 years of the RHIC programme. The overall scenario of heavy-ion collisions is now on firm ground. The heavy-ion programme is well prepared to proceed further with precision measurements of fundamental parameters of QGP that can be calculated from QCD first principles. The LHC experiments have already begun this study with very promising and even surprising results contributing to the enthusiasm of the scientific community. The increased energy by a factor of two and the increased integrated luminosity by a factor of 100 that LHC will offer from 2015, associated with detectors with improved performances, will be a decisive factor in this quest. In particular, with jet-quenching phenomenology well under control, a unique tool will be at hand for high-resolution tomography measurements of QGP. The LHC programme offers ideal conditions to provide, in a coordinated effort with theory, clear and decisive answers to conceptual questions such as: Is there a phase transition and if so of which order and for which range of parameters? What are the distinctive features of QGP (deconfinement, chiral symmetry…)? Is QGP strongly or weakly coupled? What are the effective constituents of QGP? What are the quantitative properties of QGP (equation of state, shear and bulk viscosity, transport coefficients, electromagnetic response function, colour screening length…)? What are the puzzling results in small systems telling us?

Without doubt, during the next LHC running periods, measurements of the properties of QGP will become of textbook quality as they aim at the goal of the relativistic heavy-ion scientific programme: the discovery and measurement of the properties of highly excited QCD matter, from the hot vacuum to hot and dense baryonic matter.

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