Subnuclear Physics: Past, Present and Future
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THE LITTLE BANG IN THE LABORATORY: HEAVY IONS @ LHC WITH ALICE

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The LHC has delivered for the first time collisions of Nuclei in November 2010, at an energy of 2.76 TeV per nucleon pair, which represents a jump of more than an order of magnitude over the highest energy nuclear collisions ever studied before. The high energy, the quality of the state-of-the art detectors, and the readiness of the experimental collaborations at the LHC have allowed a rich harvest of important scientific results in a very short time. In this paper a short overview will be given of how the results from the LHC, and in particular from the ALICE experiment, have provided new insight on the properties of matter under extreme conditions of temperature and pressure, analogous to the conditions present in the early phases of the evolution of the Universe.

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1.Why high-energy Heavy-Ion Collisions

Collisions between very high-energy nuclei, normally referred to as Heavy-Ions since they are atoms stripped of their electrons to allow acceleration, produce each a huge number of particles, over ten thousand in a single event at the LHC. A typical event is shown in Fig. 1. The study of such extremely complex events poses a formidable challenge both to the detections systems and to the software and analysis methods to be used to treat and eventually understand the data. So, it is legitimate to ask first of all the question of why experimenters are willing to face such extreme problems, what are the underlying questions which we aim to answer.

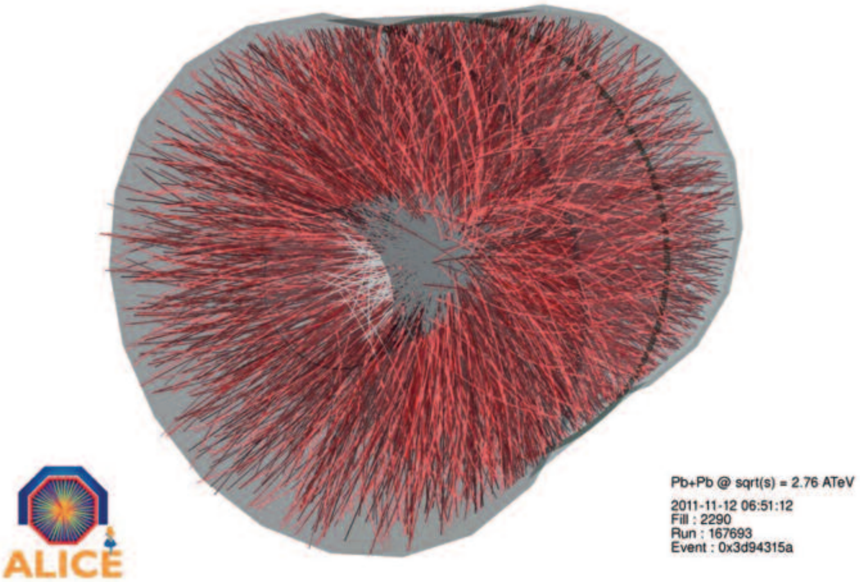

Fig. 1 A collision of two Lead Nuclei as seen by the ALICE detector at the LHC. (CERN-EX-1111290 04)

The strong force, which holds together the nucleons, protons and neutrons, in nuclei and the quarks within the nucleons, is described to great precision by a very successful theory, called Quantum Chromo Dynamics (QCD), in which the quarks possess a color charge and interact exchanging force carriers, the gluons, which are also colored. A fundamental feature of the interaction is the fact that it grows with the distance between the quarks, much like a spring connecting two balls. Therefore, any attempt to isolate a quark are in vain, since the energy stored in the spring will eventually be more than the mass of a quart-antiquark pair: the spring will break generating a pair, and the quarks will not be isolated. This property is called "confinement" and has major consequences. In particular, most of the mass of the hadrons is to be attributed to this feature: more technically, one can say that the mass is acquired dynamically because of the interaction between the quarks, whose Higgs mass would account for just a small fraction, about 1%, of the mass of the light hadrons as shown in Fig. 2. Therefore, since the mass of the matter around us is essentially the mass of the nuclei of the atoms, it can be said that, while the Higgs mechanism is at the base of the masses of the quarks, strong interaction is at the origin of most of the mass of ordinary matter.

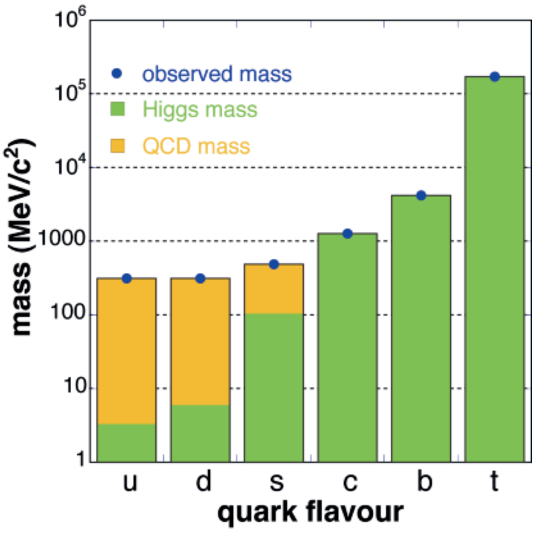

Fig. 2 QCD and Higgs mass components for the light and heay quarks from Ref [1]

The method of colliding high-energy nuclei to heat and compress hadronic matter dates from the early eighties, but the path had been indicated already several years before. It was in 1975 that T.D. Lee pronounced the famous sentence "it would be interesting to explore new phenomena by distributing a high amount of energy or high nuclear density over a relatively large volume", and the idea of deconfinement had been around for some time. Already in 1965 Hagedorn had observed that the mass spectrum of hadronic states led naturally to the concept of a "limiting" or "critical" temperature beyond which the concept of hadron would cease to make sense. In 1973 the development of QCD as the theory describing strong interactions introduced the concept of asymptotic freedom [3][4]: at small distances quarks and gluons would be loosely interacting, or quasi-free.

In 1975, N. Cabibbo and G. Parisi[5] proposed for the first time the existence of a ``different phase of the vacuum in which quarks are not confined", and drew the first schematic diagram of hadronic matter with temperature and baryonic density as axes. Two regions were defined: at low-T and low baryonic density, ordinary hadrons, at high-T, high-μ_B a deconfined state: a new field of research was born! In the same year, J.C. Collins and M.J. Perry[6] developed the idea that matter under extreme density conditions, as in neutron star cores and in the early universe, is made of quarks instead of hadrons, which overlap and lose their identity. Their argument was based on the fact that quarks interact weakly when they are close together, and therefore at high densities could be described as a gas of free massless quarks. Finally, in 1980 E. Shuryak introduced [7] the term quark gluon plasma (QGP) to describe the state of nuclear matter in which quarks are deconfined, stressing the analogy between a classical plasma made by ionized atoms and the state made of colored strongly interacting objects.

In a nucleus-nucleus collision the energy of the incoming projectiles is dissipated in the relatively large volume defined by the overlap region of the two colliding nuclei, thus creating the conditions for a phase transition to deconfined quark matter by heating.

So, by colliding nuclei at high energies we compress and heat a system with a large number of quarks, to form a "bubble" of deconfined strongly-interacting matter, which in a very short time, of the order of 10^{-23}s, expands and cools until ordinary hadrons reconstitute, just as they did in the evolution of primordial Universe, some 10 millionth of a second after the Big Bang.

Over the last three decades, a vigorous experimental program, carried both in Europe and in the United States, has dramatically increased our understanding of nuclear matter under extreme conditions of temperature and density, allowing a real exploration of the phase diagram of strongly interacting matter. Our current understanding is graphically summarized in Fig. 3, with the trajectories allowed by the most important accelerators in operation or under construction: the two colliders LHC (in Europe) and RHIC (in the USA) and the fixed-target high-luminosity facility FAIR under construction in Germany.

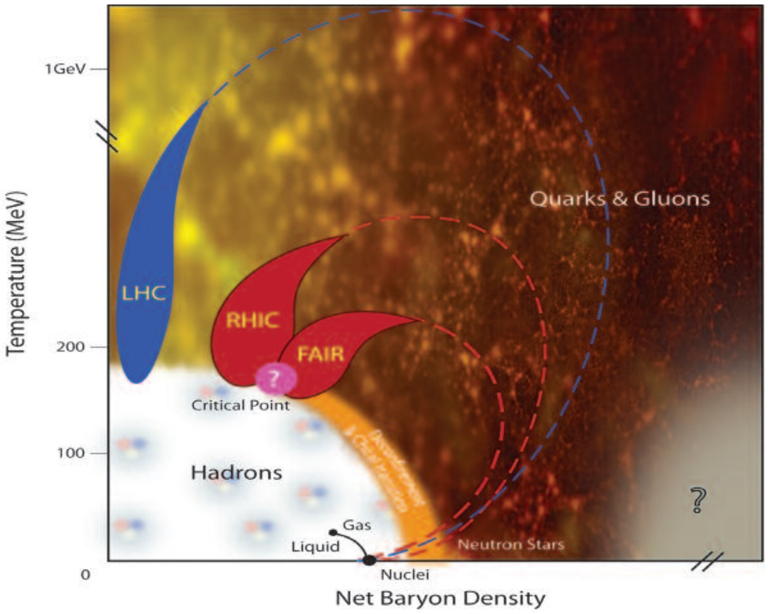

Fig.3 The phase diagram of nuclear matter, from Ref [1]

Together, these programs aim at providing answers to questions such as:

What are the properties of matter at the highest temperatures and densities?

What is the QCD equation of state? How can we test it?

What are the dominant microscopic mechanisms of QCD non-equilibrium dynamics and thermalization?

How does hadronization proceed dynamically? How is it changed in dense QCD matter?

How can the QCD phase diagram be efficiently explored?

Clearly, a comparison of the experimental results with theory is not a trivial task. Since the transition to the deconfined phase is outside the limits of validity of the perturbative QCD, a number of different approaches has been developed to derive the equation of state and the transition temperature. Only at the LHC some aspects of the interactions will be accessible with perturbative methods. Effective lagrangians have been extensively used, and also potential models, and even calculations based on the AdS/CFT correspondence have been providing a fresh look and new insight. Still, the most important and widely used are QCD calculations on a space--time lattice. They generally predict a phase transition to occur, and are able to determine its temperature. Current results indicate a critical temperature around $T_c \sim 170$ MeV, or about 10^{12} K, 100000 times higher than at the center of the Sun, corresponding to a critical energy density of $\varepsilon_c \sim 700$ MeV/fm^3

In the following, I will give a brief overview of the main experimental results obtained so far at the LHC, just little over one year after the very first collision of Lead Nuclei was recorded in the experiments. Three experiments joined in this pioneering work: ALICE [9], a dedicated experiment specifically designed to study nuclear collisions, and both ATLAS [10] and CMS [11], the two general-purpose experiments of the LHC, primarily designed for the study of high-p_T processes in pp collisions. I will focus mostly on the ALICE results.

While I will not describe the experimental apparata, I would like to remind here that ALICE has a very different optimization compared to the other LHC experiments. For the understanding of nuclear collisions it is essential that as many of the produced particle as possible are measured and identified, for the widest possible range of transverse momenta (typically from 0.1 to 100 GeV/*c*) and for all particle types: electrons, muons, photons and hadrons. So, the two guiding principles in the ALICE design have been robust tracking, able to handle the very large number of tracks which characterize Heavy Ion Collisions, and Particle Identification capability. The first is provided by very high granularity tracking detectors providing 3-Dimensional space points (several hundred millions of points) operating in a moderate magnetic field and with very low material. To identify leptons, photons and hadrons, including short-lived particles, such as hyperons, D and B mesons, ALICE features essentially all known techniques: dE/dx, Cherenkov & Transition radiation detectors, Time Of Flight, calorimeters, muon filter and topology (secondary vertices, kinks).

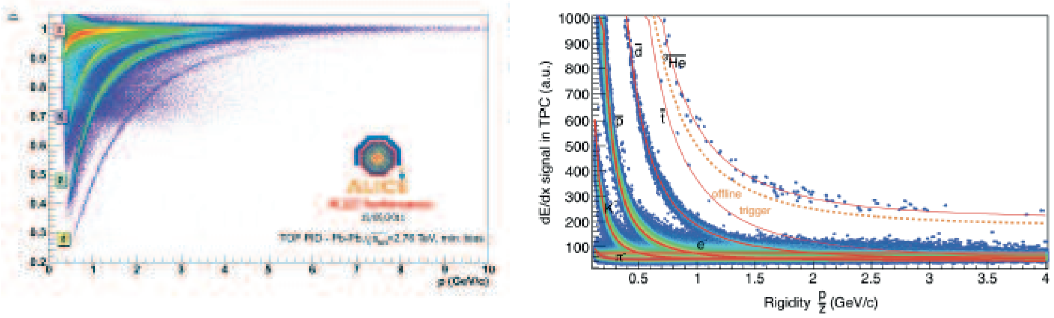

Fig. 4: PID in ALICE with TOF (left panel) and TPC (right panel) from ref.[12]

As an example of the ALICE PID capability, Fig. 4 shows the of the performance of the Time Of Flight (TOF) and of the Time Projection Chamber (TPC)'s energy loss measurement. Both are performing better than originally specified, a remarkable result in detector systems of such complexity observing events with thousands of tracks! The TOF has provided a time resolution below 100 picoseconds, and the TPC an energy loss measurement with a precision better than 6%.

In figure 5 (left panel) the momentum coverage of the various ALICE PID detectors is shown, demonstrating the extent of the coverage achieved. In addition, short-lived particles are identified through their decay topologies: in the right panel of figure 5 the impact parameter resolution expected in ALICE is shown, which is adequate for the measurement of D and B meson decays. K and Λ decays can be efficiently reconstructed for transverse momenta up to more than 10 GeV/*c*. The very fine granularity of the tracking detectors, providing a large number of space points per track, provides high efficiency tracking for charged particles even at the highest particle multiplicities foreseen at the LHC with Pb beams, with a lower limit in momentum lower than 200 MeV/*c*. The very long track length measured allows ALICE to achieve an excellent momentum resolution ($\delta p/p < 5\%$ at 100 GeV/*c*). Several smaller detectors (ZDC, PMD, FMD, T0 and V0) used for global event characterization and triggering are located at small angles. The combination of the central and forward detectors provides coverage for the measurement of charged multiplicity which extends from -3.4 to +5 in pseudorapidity. An Electromagnetic Calorimeter, EMCal, covers about a third of the azimuth and provides improved energy resolution and triggering for jets. A high-resolution crystal photon spectrometer, PHOS, is placed at a very large radial distance from the interaction point (4.6 m). The muon spectrometer covers the forward rapidities, between -2.5 and -4, and features a complex arrangement of absorbers, starting very close to the interaction point (90cm) to minimize muon background from weak hadronic decays, and fourteen planes of tracking and triggering chambers, using 2-D pad readout to handle the high multiplicities.

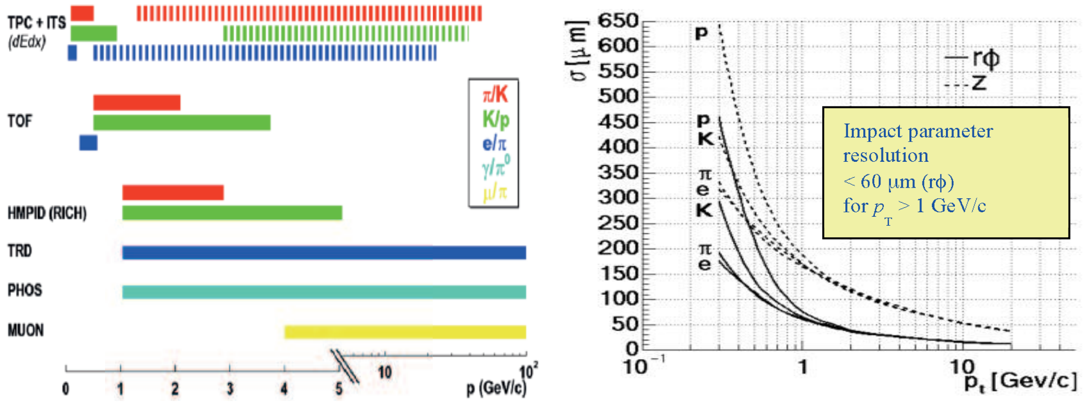

Figure 5: Left: particle identification in ALICE: momentum range and detectors used. Topological identification, not included in this plot, can reach over 10 GeV/*c* for K and Λ. Right: ALICE impact parameter resolution as a function of transverse momentum.

The hardware trigger in ALICE combines the input from detectors with fast trigger capability (T0, V0, ZDC, SPD, TOF, PHOS, EMCal, Muons, ACORDE). It operates at several levels (pretrigger, L0, L1 and L2) to satisfy the individual timing requirements of the different detectors, as the ALICE electronics is in general not pipelined. In addition, a software based High-Level Trigger (HLT) using a farm of up to 1000 multiprocessor PCs performs a preprocessing of the data allowing for a compression of the data volume by a factor of 3.5. It also allows real time data quality monitoring.

2. ALICE results

The first LHC heavy-ion results were already published during the 2010 lead–lead run, lasting for a month. In fact, there were three papers submitted almost simultaneously: the multiplicity measurement [13] and the measurement of v_2 coefficient of the azimuthal anisotropy [14] by ALICE, and by the ATLAS collaboration a paper on jet-energy imbalance [15]; these appeared together in one issue of Phys. Rev. Lett. One of the most spectacular findings at RHIC was that the matter generated in heavy-ion collisions flows like a liquid with very low viscosity, almost at the limit of what is allowed for any material in nature. This tells us that the constituents of this QGP are quite different from freely interacting quarks and gluons, and led to the definition of the matter under study as sQGP, for strongly interacting Quark Gluon Plasma, a liquid very different from the expected gas of quasi-free quarks and gluons. The first LHC azimuthal anisotropy measurement [14] confirms the RHIC results: elliptic flow of particles with the same transverse momenta is almost identical at the two energies. The nearly-perfect fluid has been found to be opaque to even the most energetic partons (quarks and gluons), which appear as jets of particles from the collisions, an effect known as jet quenching. This is an interpretation of the reported strong jet-energy imbalance [15]. However, the physical mechanisms underlying these phenomena are not well understood. Another manifestation of jet quenching manifests is a reduced yield of high-transverse-momentum-particle in central collisions compared to that expected from the measurements in proton–proton reactions. To express such reduction a properly normalized ratio of yields in heavy-ion and in proton–proton interactions – the nuclear modification factor R_{AA} – is used. Since proton-proton collisions are rescaled according to the number of binary collisions, R_{AA} should be well below one at low transverse momentum, where particle production is rather proportional to the number of participant nucleons, and grow toward one for increasing transverse momenta. The suppression pattern observed by ALICE [16] gives factor about 7 (= $1/R_{AA}$) lower charged-particle production in lead–lead collisions at transverse momentum around 6GeV/c, a striking evidence of the energy loss in the extreme density matter.

The size of the pion-emitting source in central lead-ion collisions is deduced from the shape of the Bose-Einstein peak in the two-pion correlation functions [17]. The collective flow makes the size of the system appear smaller with increasing momentum of the pair. This behaviour is clearly visible for the radii measured in the ALICE experiment. The results for measurements of the radius of the pion source in three dimensions indicate a short duration for the emission, hence an “explosive” emission. Time when the emission reaches its maximum is 10–11fm/c, significantly longer than it is at RHIC, see fig. 6 (left side). Moreover, the product of the three components at low pair-momentum, an estimate of the homogeneity volume of the system at decoupling, is twice as large as at RHIC, see fig. 6 (right side).

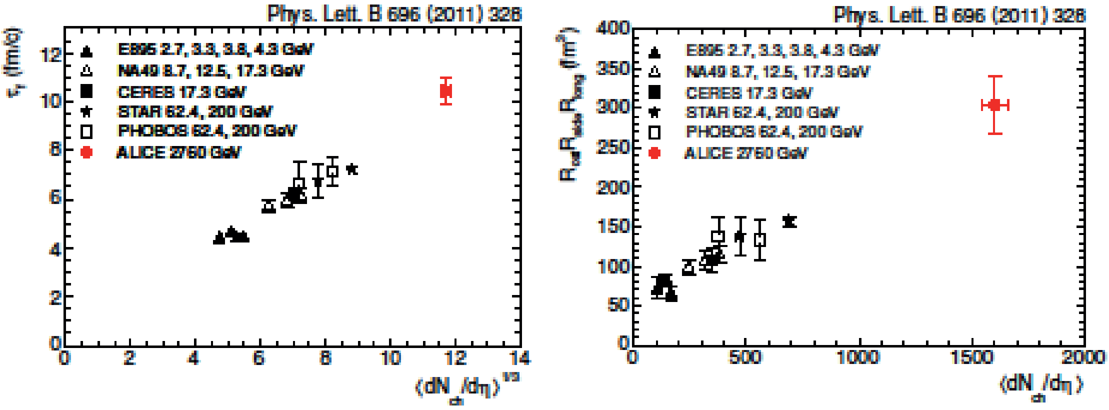

Figure 6. Bose–Einstein pion-interferometry results from different experiments [17]. Estimate of lifetime of emitting source as a function of cube root of particle density (left side). Volume of homogeneity region as a function of particle density (right side).

One of the crucial measurements for the characterization of the fireball produced in heavy-ion collisions are the spectra of identified hadrons, which encode the collective expansion velocity developed in the QGP and in hadronic stages. Moreover, the overall abundances of identified hadrons are believed to be fixed at hadronization, thus they indicate the temperature when chemical composition was established. The measured spectra [18] show an increase of about 10% in the radial-flow velocity when compared to RHIC results. At present, however, the yield ratios observed by ALICE seem to challenge both previous experiments and theory. While the K/π, Ξ/π and Ω/π ratios are compatible with the expectations from the thermal model with a temperature for the “chemical freeze-out” of about 165MeV, as in previous observations, the p/π ratio points to a significantly lower temperature. On the experimental side, there are indications of a similar effect at lower energies, which call for further investigations. On the theoretical side, a number of different possibilities are being investigated, none of them conclusive at the moment.

As mentioned above, the first results on elliptic flow were published [14] during the initial Pb–Pb run. Flow is a fundamental observable since it carries information on the equation of state and the transport properties of matter created in a heavy-ion collision. This observable relates final state anisotropies with features of the initial one, thus allowing study of the medium response and characteristics. The azimuthal anisotropy in particle production is a clear experimental signature of collective flow. It is caused by multiple interactions between the constituents of the created matter and the initial asymmetries in the spatial geometry of a non-central collision. The amount of elliptic flow measured by the v_2 coefficient, integrated over transverse momentum, increases by 30% compared to RHIC energies. However, this increase is entirely a consequence of the growth in transverse momenta. The overall azimuthal distribution of particles emitted in a heavy-ion collision can be described with a Fourier expansion, whose coefficients relate to different aspects of the initial state. ALICE measured also the higher harmonic coefficients of azimuthal distribution [19]; they exhibit much shallower centrality dependence than v_2, and the symmetry planes of v_2 and v_3 coefficients are uncorrelated (see fig. 7, left side). These observations point to fluctuations in the initial geometry as the origin of higher-order azimuthal asymmetries. The flow coefficients can also be studied with a different approach, using two-particle correlations in azimuthal angle [20]. A Fourier decomposition of the correlation function gives squares of different v coefficients, and describes well the structures seen in azimuthal correlations, see fig. 7 (right side), such as the "long-range ridge" (a small angle correlation between particles distanced in longitudinal direction) and the "Mach cone" (a correlation on two sides of back-to-back direction). The collective response to initial spatial anisotropy that causes elliptic flow economically explains these puzzling features, once event-by-event initial-state density fluctuations are considered. The ALICE experiment has analyzed azimuthal asymmetry also separately for different particle species, which constrains models incorporating a realistic initial state and hydrodynamic evolution.

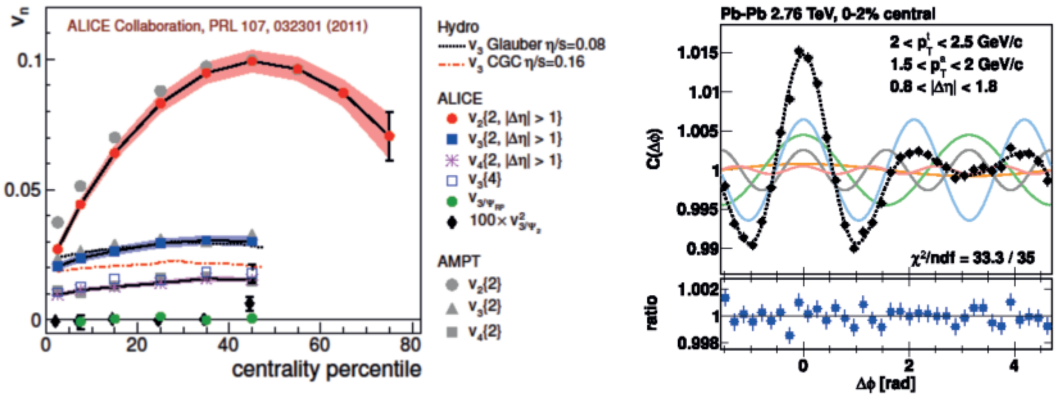

Figure 7. Measurements of azimuthal anisotropy in lead–lead collisions at LHC. Dependence of different v_n coefficients (see legend) on collision centrality [19] (left). Fourier decomposition of two-particle azimuthal correlation function in 2% most central collisions [20] (right).

The two-particle azimuthal correlations at higher transverse momenta measure particle-yield modifications in jet-like structures [21]. When compared to the expectation from proton–proton interactions, the observed yield around high-transverse-momentum particle is slightly higher, while the yield on the opposite side is reduced. This measurement assists the understanding of jet-quenching phenomena. The ALICE collaboration continues to contribute to this topic by studying reconstructed jets, underlying event fluctuations, modifications of jet-fragmentation function, jet-particle composition and providing detailed studies of the dependence of the energy loss on the parton traversing the QGP.

Heavy-flavour particles are recognized to be effective probes of a very dense and hot medium formed in nucleus–nucleus collisions; they are expected to be sensitive to its energy density, through the mechanism of in-medium energy loss. At LHC energies, heavy-flavour particles are copiously produced and thus provide ideal tools for QGP studies. The nuclear modification factor R_{AA} is well established as a sensitive observable for the study of the interaction of hard partons with the medium. Parton energy-loss is caused by the strong interaction, hence the amount of energy loss depends on colour charge of parton. Therefore, quarks are predicted to lose less energy than gluons. In addition, heavy quarks (up to some high momentum), which are slower than light, cannot emit gluons within the so-called "dead-cone" around their trajectory; this effect is expected to reduce the energy loss of heavy quarks with respect to light ones. Thus, a pattern of gradually decreasing suppression (i.e. increasing R_{AA}) should emerge when going from the light-flavour hadrons (e.g. pions), which mainly come from gluons, to the heavier D and B mesons: $R_{\mathrm{AA}}(\pi) < R_{\mathrm{AA}}(\mathrm{D}) < R_{\mathrm{AA}}(\mathrm{B})$. The measurement and comparison of these different probes provides, therefore, a test of the colour-charge and mass dependence of parton energy-loss. The ALICE collaboration has measured the production of the charmed mesons D^0 and D^+, detecting their hadronic decays in lead–lead collisions [22]. In central collisions a large suppression with respect to expectations at large transverse momentum was found, indicating that charm quarks undergo a strong energy loss in the hot and dense state of strongly-interacting matter formed at the LHC. This is the first time that D meson suppression has been measured directly in central nucleus–nucleus collisions. The results show a suppression by a factor 4–5, almost as large as for charged pions, above 5 GeV/*c* (see fig. 8). At lower momenta, there is an indication of smaller suppression for D than for π mesons.

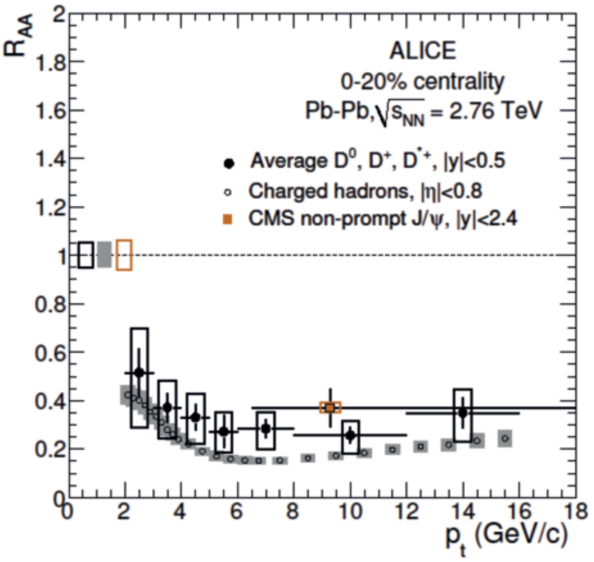

Figure 8. Charmed-meson nuclear modification factor as a function of transverse momentum compared to that of charged hadrons and of non-prompt (mostly from B-decays) J/ψ mesons (as measured by CMS).

Suppression of charmonium production was for a long time considered as one of the main probes for a deconfined medium. At large enough temperatures bound charm–anticharm states are supposed to be dissolved due to Debye screening. However, at LHC energies, new mechanisms of charmonium production in the QGP could occur because of a large number of charm quarks. Around one hundred charm–anticharm pairs are expected to be produced in a central lead–lead collision. Several dynamical transport models predict that charm and anticharm quarks could combine at later stages of the interaction, leading to an enhancement of charmonium production in the most central collisions. ALICE detects charmonium down to very low transverse momentum in two different regions: the central barrel in the dielectron channel and the forward muon arm in the dimuon channel. The detection at low transverse momentum is crucial because the recombination of the charm and anticharm quarks is expected to be the main production mechanism for charmonium below 3GeV/*c*. The different regions allow for the study of QGP with different charm densities. ALICE has studied the nuclear modification factor R_{AA} for J/ψ mesons as a function of collision centrality [23]. The results indicate that the J/ψ nuclear modification factor shows little dependence on centrality (see fig. 9), a trend that is different from that observed at lower energies. For central and mid-central collisions the J/ψ R_{AA} is larger at the LHC than that measured at RHIC. In a complementary study, the CMS collaborations at the LHC have measured a smaller value for the J/ψ nuclear modification factor at transverse momenta above 6.5 GeV/*c*. These observations hint at the recombination of charm and anticharm quarks in the QGP as the main mechanism for J/ψ production in central lead–lead collisions at LHC energies.

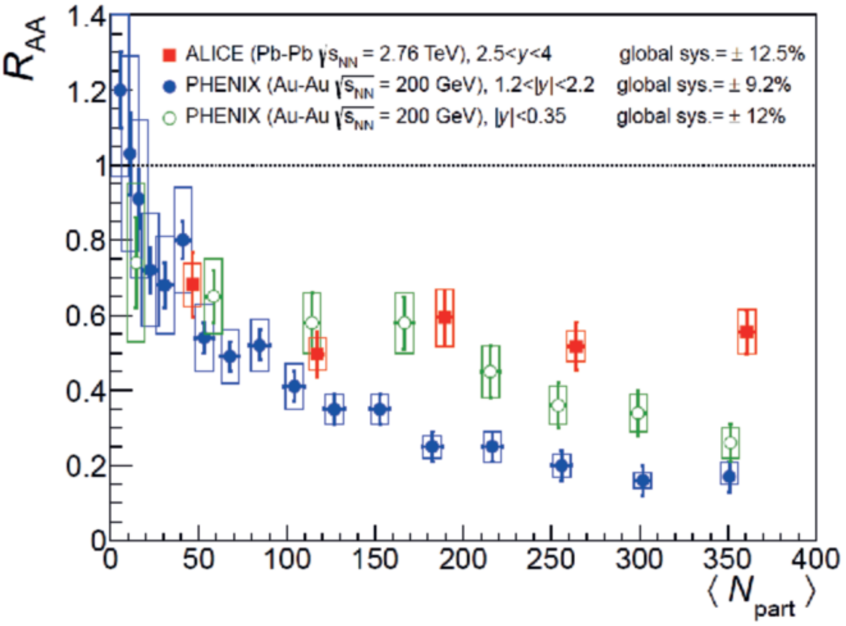

Figure 9. Nuclear modification factor for J/ψ as a function of collision centrality, expressed as number of participants. ALICE data are compared to those from the PHENIX experiment at RHIC.

It is clear from these first results that a coherent picture of the characteristics of the extreme density matter of which our Universe was made of in the first microseconds of its existence. Even more, the tool chosen to study it, heavy-ion collisions at the world's most powerful accelerator, has proven to be the right one, allowing for a continuous improvement of our understanding. The results shown here are but a small subset of the wealth of results obtained so far, and a was a mere hint to the ones coming. It is indeed a very exciting time for the physics of the Quark-Gluon Plasma.

3. The future of ALICE

In 2010 the ALICE detector collected with a minimum-bias trigger about 30 million of lead–lead collisions at centre-of-mass energy of 2.76TeV per nucleon pair. In 2011 there was a short period of proton–proton running at the same energy at the start of the LHC operation, to gather comparison data; these were used for normalization in practically all measurements described above. The rest of the proton running proceeded at (a standard) energy of 7TeV. At the end of the year, the LHC switched again to the heavy-ion mode. This time the instant luminosity grew to above 10^{26}cm^{-2}s^{-1}, and was above the design value for energy 2.76TeV per nucleon pair. ALICE used triggers for different types of lead–lead collisions: central, semi-central, dimuons, photons, jets, ultraperipheral, and others, and collected about 100 million events, inspecting over 0.1nb^{-1} of integrated luminosity.

The coming Heavy-Ion period, due for the beginning of 2013, will be dedicated to proton–lead collisions, to improve the baseline comparison, taking into account modifications of structure functions in nuclei. We expect to collect at least 0.03nb^{-1} of luminosity in the four weeks of pA running. Then the LHC operation will be paused for an upgrade necessary to increase the collision energy. After the restart the ALICE collaboration aims to complete its approved programme, collecting 1nb^{-1} of heavy-ion collisions at the higher collision energy (5.5TeV per nucleon pair in the centre of mass, being the design value). The intention is to achieve a significant part of this agenda before the second long shutdown for the preparation of the LHC luminosity increase, planned for 2018. Under discussion is an ALICE detector upgrade allowing for high-luminosity heavy-ion running after this period. The extended physics program justifying the LHC operation in heavy-ion mode beyond 2020, which would imply collecting over 10nb^{-1} of data, is being prepared.

After having confirmed the main discoveries obtained at RHIC, ALICE has entered an exciting phase of new measurements, allowing a much broader and deeper study of the QGP. At the same time, ALICE is already preparing, on the basis of what has been learnt so far, a next step in more detailed characterization of the extreme state of matter produced at LHC; new, unexpected discoveries may come!

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