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State of the art and perspectives of high-energy heavy-ion physics

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Summary. — Strongly interacting matter at very high temperature and density is expected to exist in a state called the Quark-Gluon Plasma (QGP), in which quark and gluon degrees of freedom are liberated, and with properties very different from the hadronic matter we ordinarily find around us. The only means to study this fundamental state of matter is via the collisions of heavy nuclei in the laboratory. In this work an overview of the most important results on heavy-ion collisions phenomenology and on the study of the QGP properties is presented. Particular emphasis is given to the most recent results obtained at the LHC at CERN at the highest collisions energy reached so far, with a look to the future scenarios.

1. – Introduction

Quantum Chromodynamics (QCD) is the theory of strong interaction that binds together nucleons in the nuclei and quarks within hadrons. QCD predicts (and numerical calculations on the lattice confirm) that nuclear matter undergoes a phase transition to a state of deconfined quarks and gluons, at a critical temperature of about 160 MeV [1], associated to an energy density of about $0.7\,\mathrm{GeV/fm^3}$ [2]. In addition, at about the same temperature, chiral symmetry is expected to be (approximately) restored and quark masses are reduced from their large effective values in hadronic matter to their small bare ones. The strength of the coupling between quarks and gluons depends on their relative momenta. At higher momenta and thus smaller distances the coupling becomes weaker, leading to the so-called asymptotic freedom [3]. Therefore, in a QCD system at very high temperatures the quarks and gluons are expected to become quasi-free so that the bulk properties can be described by an ideal gas Equation of State (EoS). This deconfined dense state of matter is called Quark Gluon Plasma (QGP). Relativistic heavy-ion collisions are a unique tool to study the deconfinement and the EoS of hot QCD matter under controlled conditions [4]. The hot and dense system created in a heavy-ion collision will expand and cool down. Heavy ions are extended objects and the system created in a head-on collision is different from that in a peripheral collision.

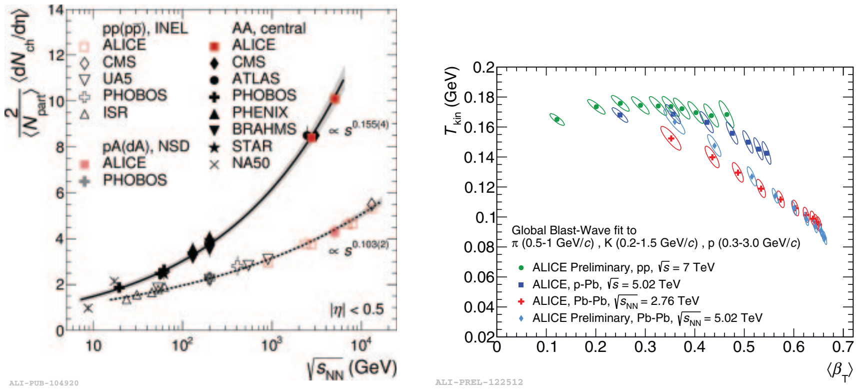

Fig. 1. – Right: [5] values of $(2/\langle N_{\mathrm{part}}\rangle)/\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta\rangle$ for central Pb-Pb and Au-Au collisions as a function of $\sqrt{s_{\mathrm{NN}}}$. Measurements for inelastic pp and p$\bar{\mathrm{p}}$ collisions as a function of $\sqrt{s}$ are also shown along with those from non-single diffractive p-A and d-A collisions. Left: $\langle\beta_{\mathrm{T}}\rangle$-$T_{\mathrm{kin}}$ progression from the Blast-Wave [6] fit to pi, K and p spectra measured in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$, compared to the same in different systems and in Pb-Pb at $\sqrt{s_{\mathrm{NN}}} = 2.76$.

Therefore, collisions are categorized by their centrality. Theoretically, the centrality is defined as the distance between the centers of the two colliding nuclei. The Large Hadron Collider (LHC) provided Pb-Pb collisions at an unprecedented energy of $\sqrt{s_{\mathrm{NN}}} = 2.76$ and $5.02\,\mathrm{TeV}$, during RUN1 and RUN2 periods, respectively. Some of the main probes available in heavy-ion collisions will be shortly described in the next sections, together with some results which are considered to be the highlights of the heavy-ion LHC experimental program so far.

2. – Soft probes

Most of the particles produced in heavy-ion collisions have a momentum lower than $2\,\mathrm{GeV}/c$. Therefore, the study of these "soft" particles and the physical processes involved in their production are of major interest for the comprehension of the QGP properties. They give access to the chemical composition of the system, its size, its temperature, and its dynamics. The number of produced particles (multiplicity) and the transverse energy are important properties of the collisions related to the initial energy density and collision geometry. The left panel of fig. 1 shows the charged hadrons multiplicity for central ion-ion collisions as a function of $\sqrt{s_{\mathrm{NN}}}$. This measurement allows for an estimate of the energy density by means of the Bjorken formula [7] for head-on collisions. The initial energy density at LHC reaches $\approx 15\,\mathrm{GeV}/c$ well above the critical energy density of $\approx 1\,\mathrm{GeV}/c$ obtained from lattice QCD. The transverse momentum distributions of particles produced in heavy-on collisions are described as a combined result of thermal motion and the collective transverse expansion velocity β_{T} at freeze-out, in agreement with a hydrodynamic description [6]. Figure 1 (left) shows the kinetic freeze-out temperature T_{kin} *vs.* the average collective expansion velocity $\langle\beta_{\mathrm{T}}\rangle$ extracted from the Blast-Wave [6] fit to π, K and p spectra measured in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$. For central collisions between equally spherical nuclei, radial flow is the only possible type of transverse flow allowed by symmetry. In non-central collisions between spherical nuclei, the overlap region of the two colliding nuclei is then spatially deformed in the transverse plane. Re-scattering processes among the produced particles transfer this spatial

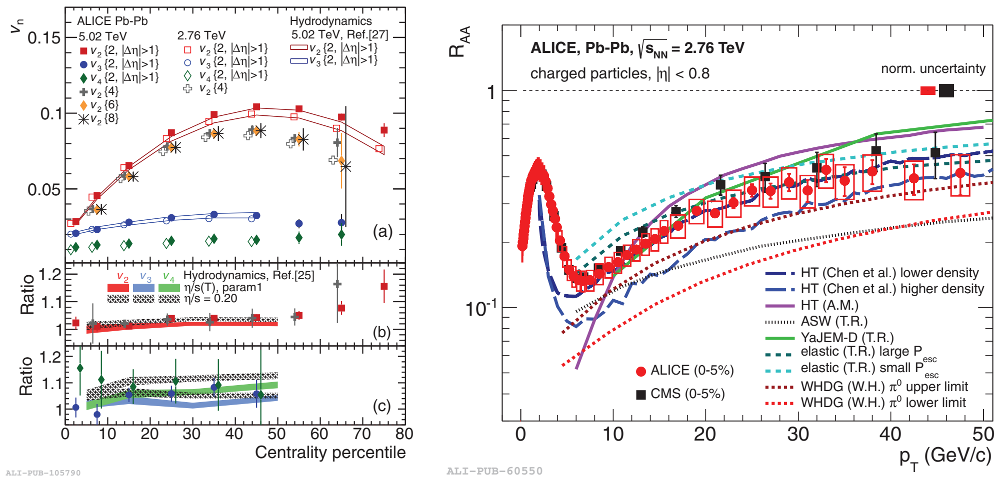

Fig. 2. – Left: anisotropic flow v_n integrated over the p_{T} range 0.2–5.0 GeV/c, as a function of event centrality, for two-particle and multi-particle cumulant methods, measured by ALICE. Measurements for Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ (2.76) TeV are shown by solid (open) markers [8]. Right: [9] nuclear modification factor R_{AA} of charged particles measured by ALICE in the most central Pb-Pb collisions (0–5%) in comparison to results from CMS and model calculations.

deformation onto the momentum space. The momentum anisotropy manifests itself as an azimuthal anisotropy of the measured hadron spectra. One quantifies this anisotropy in terms of the azimuthal Fourier coefficients of the transverse momentum spectrum. At mid-rapidity (for collisions between equal nuclei) the lowest non-vanishing Fourier coefficient is the second-order one, v_2, and it is called elliptic flow. The LHC measurements at 2.76 and 5.02 TeV [8] show that the integrated elliptic flow of charged particles increases by about 30% compared to the elliptic flow measured at RHIC energy of 0.2 TeV. Figure 2 reports the anisotropic flow, v_n, integrated over the p_{T} range 0.2–5.0 GeV/c, as a function of event centrality, for two-particle and multi-particle cumulant methods [8], measured by ALICE. The transfer of the spatial coordinate anisotropy to the momentum space brings information about the viscosity of the fluid, η. The parameter that controls most directly the behavior of the medium is the transport coefficient η/s (the relativistic generalization of the kinematic viscosity). The combination of experimental results and their comparisons to hydrodynamical models, indicates that the QGP produced at LHC behaves like a strongly interacting, almost perfect liquid with a very low value of the shear viscosity to entropy density ratio ($\eta/s \approx 0.20$), close to the theoretical lower bound [10].

3. – Hard probes

The term hard probes indicates particles (hadrons or partons) that are chacterized by a hard scale (mass or momentum) and are therefore produced in the first instants of the nucleus-nucleus collision in hard partonic scatterings, and are affected by the presence of the strongly interacting QGP, which they traverse after their production. Hard probes include: quarkonia (charmonia and bottomonia); heavy quarks, which are detected in the final state as open heavy flavour hadrons or their decay products; high-momentum light quarks and gluons, which are detected in the final state as high-momentum hadrons and jets. The measurement of the modification of the yield and kinematic properties of hard probes is regarded as a rich source of information on their interaction with the QGP and on the QGP properties. The simples observable is the nuclear modification factor R_{AA} of the jet leading particles, defined as the ratio between the measured yields in nucleus-nucleus and pp collisions, normalised to the number of binary nucleon-nucleon collisions, N_{coll}. This quantity is usually studied as a function of p_{T}, and values smaller than 1 at high p_{T} are attributed to energy loss of hard partons. The right panel of fig. 2 shows the R_{AA} of the charged particles in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76\,\mathrm{TeV}$ measured by ALICE and CMS [9]. In a deconfined QGP, quarkonium production is expected to be significantly suppressed with respect to the yield in pp, scaled by N_{coll}, due to a colour screening mechanism that prevents the binding of the q and $\bar{\mathrm{q}}$ pair [11]. However, this suppression scenario is complicated by other mechanisms, related to both hot or cold nuclear matter. On the one hand, by increasing the collision energy ($\sqrt{s_{\mathrm{NN}}}$), the production rates of the q and $\bar{\mathrm{q}}$ quarks increase. As a consequence, at high energies, a new production mechanism sets in, due to the (re)combination, either in the QGP or in the hadronization phase, of the produced $\mathrm{q}\bar{\mathrm{q}}$ pairs [12]. This effect enhances the charmonium yields and it might compensate for the suppression. As shown in [13], at LHC J/ψ is less suppressed than at RHIC. Heavy quarks (charm and beauty) are used to characterize the properties of the hot QGP formed in ultra-relativistic heavy-ion collisions. They are particularly well-suited for these studies, because of the large value of their mass (M) compared to the other scales involved in their production and in interaction processes in the medium. At high momentum (much larger than M), the main goal of heavy-flavour studies is gaining insight into the parton energy loss mechanism [14]. At low momentum (of the order of M), a relevant open question is whether heavy quarks take part in the collective expansion of the QGP and whether they approach thermal equilibrium. Transport calculations are used to study this problem from a theoretical viewpoint [15]. For a more precise QGP characterization it is necessary to study the thermalization and the energy loss of the heavy quarks, so it is important to measure the v_2 of baryons and mesons with heavy quarks, down to very low p_{T}, D mesons at $p_{\mathrm{T}} \approx 0$ and baryon/meson ratio for charm (Λ_c/D) and beauty (Λ_c/B). Such quantities are not measurable with the current experimental apparatus and the LHC RUN1-RUN2 available statistics.

4. – Future scenarios

After the second long shutdown in 2018, the LHC will progressively increase its luminosity with Pb beams eventually reaching an interaction rate of about 50 kHz, *i.e.*, instantaneous luminosities of $\mathcal{L} = 6 \times 10^{27}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, and a collisions energy of $\sqrt{s_{\mathrm{NN}}} = 5.5\,\mathrm{TeV}$. The LHC upgrade will give ALICE, the experiment at the LHC dedicated to the heavy-ion physics, new physics opportunities, *i.e.*, it will study the thermalization of partons in the QGP, with focus on charm and beauty quarks at low p_{T}, measure the low-momentum charmonium (J/ψ) dissociation (and regeneration), study deconfinement and medium temperature, measure the production of thermal photons and low-mass dileptons emitted by QGP to study initial temperature and equation of state of the medium. The ALICE Collaboration is planning to upgrade [16] the current detector by enhancing its low-momentum vertexing and tracking capability, and allowing data taking at substantially higher rates. ALICE will then be in a position to accumulate 10 nb^{-1} of Pb-Pb collisions inspecting about 10^{11} interactions. The planned upgrades include: a new, high-resolution Inner Tracking System (ITS) [17], with a material budget lower than the current one; an upgrade of the Time-Projection Chamber (TPC) with replacement of the readout multi-wire chambers with GEM (Gas Electron Multiplier) detectors and new pipelined readout electronics [18]. This is needed in order to operate the TPC in ungated mode and make its readout dead-time free. An upgrade of the readout electronics of most of the ALICE sub-detectors, an upgrade of the forward trigger detectors and of the trigger system for high rate operation and an upgrade of the online systems and offline data processing software [19] are also foreseen.

5. – Conclusions

Results from LHC RUN1 and RUN2 periods have represented an important step forward in the understanding of the matter created in the nucleus-nucleus collisions at relativistic energies. The energy density of the system created at LHC is well above the critical energy density evaluated by means of QCD lattice calculations. The system created behaves like a strongly interacting, almost perfect liquid with a very low value of the shear viscosity to entropy density ratio. At the LHC, charmonium states are less suppressed than at the lower collisions energy of RHIC, hint of the contribution of a new process, as the $q\bar{q}$ recombination. A better description of QGP needs high-precision measurements of the production of heavy quarks, quarkonia, jet and di-leptons over a large momentum range. ALICE will be upgraded for the LHC RUN3 and RUN4. The tracking performance will be improved both in precision and efficiency, in particular for low-p_{T} particles. The readout rate will reach 50 kHz to collect all the Pb-Pb interactions provided by the LHC.

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