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Heavy-ion physics at the LHC

C. Oppedisano
INFN, Sezione di Torino - Torino, Italy

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Summary. — A color-deconfined state of strongly interacting matter is expected to be formed in high-energy collisions of heavy nuclei. Lattice Quantum Chromodynamics (QCD) calculations predicts that, under the conditions of high-energy density and temperature reached in these collisions, a phase transition to a Quark-Gluon Plasma (QGP) occurs. The main aim of the heavy-ion experimental programme at the LHC collider is to characterize and study the medium formed in such collisions. In this paper several observables and measurements performed by the LHC experiments studying heavy-ion collisions will be addressed, compared to results at lower energy and discussed.

PACS `25.75.-q` – Relativistic heavy-ion collisions.
PACS `12.38.Mh` – Quark-gluon plasma.
PACS `47.70.-n` – Reactive and radiative flows.
PACS `14.40.Pq` – Heavy quarkonia.

1. – Introduction

Ultra-relativistic heavy-ion collisions are the experimental tool used to assess the properties of QCD matter at extreme energy density and temperature. Lattice QCD predicts that, for energy density of the order of $1\,\mathrm{GeV/fm^3}$ and temperature around $170\,\mathrm{MeV}$, a phase transition from hadronic matter to a state of deconfined partonic constituents, the Quark-Gluon Plasma (QGP), occurs. The inverse transition, from partonic to hadronic matter, occurred in the early universe $\sim 10\,\mu\mathrm{s}$ after the Big Bang. The Large Hadron Collider (LHC) at CERN provides an experimental insight to this regime at the highest temperature and energy densities currently available, coupled with a low baryonic density environment. These conditions are similar to the ones of the early universe. The main aim of the current heavy-ion experimental research is the study of the transition and the characterization of the formed medium. The RHIC experimental programme at Brookhaven has established in the last decade that the hot medium formed in Au-Au collisions at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ behaves as a perfect liquid [1,2]. At the LHC three experiments study heavy-ion collisions: ALICE (A Large Ion Collider

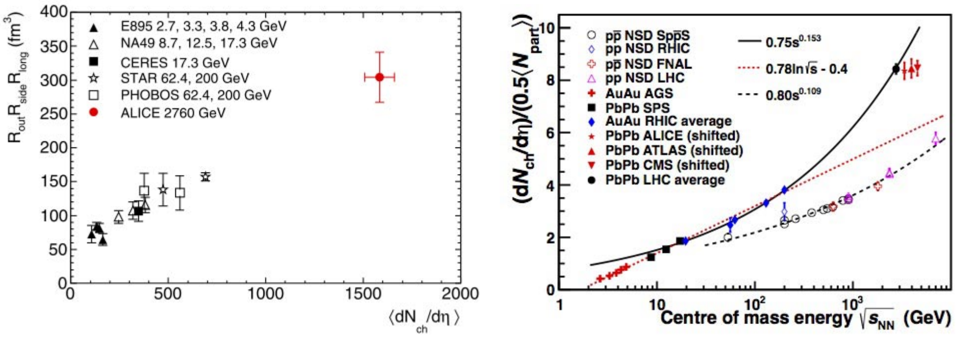

Fig. 1. – Left: Freeze-out volume ($k_T = 0.3\,\mathrm{GeV}/c$). Right: charged particle pseudorapidity density per colliding nucleon pair *versus* center-of-mass energy for p-p and A-A collisions (results from the 3 LHC experiments, shifted for comparison purposes, are in good agreement).

Experiment) that has been specifically designed for this purpose, ATLAS (A Toroidal LHC ApparatuS) and CMS (Compact Muon Solenoid). In the following the properties of the medium formed in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$ will be presented, going through some of the many results from the LHC experiments.

2. – Global event observables

Global event observables are of fundamental importance in characterizing the properties of the strongly interacting medium created in heavy-ion collisions. They allow in fact the characterization of the collisions by describing the initial state and the following dynamical evolution. In nucleus-nucleus collisions it is common to define the centrality of the collision, usually defined through the impact parameter b, the distance between the centers of the colliding nuclei in the plane transverse to their incoming directions. The centrality is directly related to the geometry of the collisions, namely to the number of participating nucleons (N_{part}) and to the number of binary collisions (N_{coll}). The observables are then usually studied as a function of centrality: the more central the collision, the higher the energy density. The highly compressed strongly interacting system created in the collisions is expected to undergo longitudinal and transverse expansion. Experimentally, the expansion rate and the spatial extent of the fireball at decoupling time are accessible via measurements based on interferometry techniques [3]. ALICE [4] measured, in central collisions, a freeze-out volume of $300\,\mathrm{fm}^3$ (2 times the value measured at RHIC energy, see fig. 1, left) and a lifetime between the collisions and the freeze-out of $\sim 10\,\mathrm{fm}/c$ (about 20% higher than at RHIC). Extrapolating the temperature from direct photon spectra, ALICE finds an initial temperature $T = (304 \pm 51)\,\mathrm{MeV}$. These measurements indicate that the fireball formed in nuclear collisions at the LHC is hotter, lives longer and expands to a larger size at freeze-out as compared to lower energies. The charged particle multiplicity produced in the collisions is linked to the initial energy density and it can provide constraints on the particle production mechanisms, allowing the discrimination of the soft ($\sim N_{part}$) from the hard ($\sim N_{coll}$) regime [5]. Particle production at LHC energy is no longer compatible with a logarithmic dependence as a function of $\sqrt{s}$ as it was true for the data up to top RHIC energy, but follows a power law [6] (see fig. 1, right).

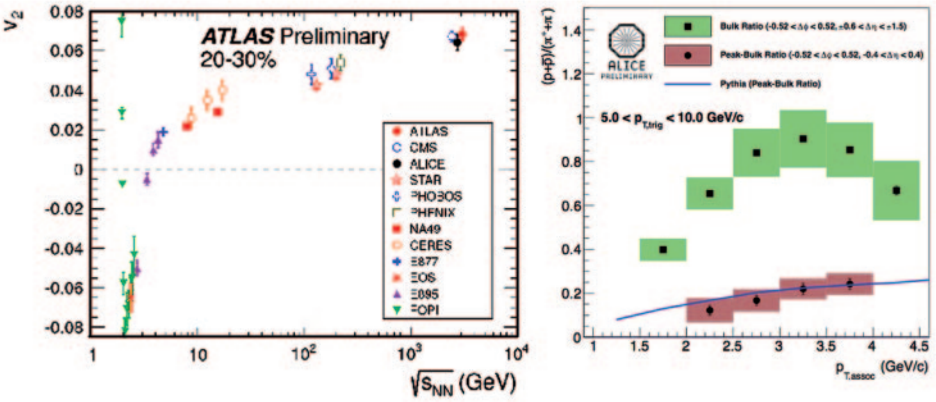

Fig. 2. – Left: elliptic flow v_2 *versus* center-of-mass energy [12]. Right: baryon over meson ratio *versus* p_T of associated particles for bulk and jet-like (peak-bulk) contributions.

3. – Bulk particle production

The bulk matter created in high-energy nuclear reactions can be quantitatively described in terms of hydro-dynamic models. The initial hot and dense partonic matter rapidly expands and cools down, ultimately undergoing a transition to a hadron gas phase. Particle momentum distributions reflect the conditions later in the evolution, at the "kinetic freeze-out" from the hadron gas phase, when elastic interactions cease [7]. The collective expansion is driven by internal pressure gradients and quantified by the average transverse velocity, $\langle \beta_T \rangle$ [8]. Low-p_T spectra of identified particle measured by ALICE [9] are in good agreement with hydrodynamic models. The spectra are harder than at RHIC, indicating a stronger radial flow at LHC with a radial flow velocity $\langle \beta \rangle \sim 0.65$ and a kinetic freeze-out temperature $T_K \sim 95\,\text{MeV}$ [9].

4. – Anisotropy and correlations

For non central collisions the geometric overlap region is anisotropic. This initial spatial asymmetry is converted via multiple collisions into an anisotropic momentum distribution of the produced particles. The azimuthal anisotropy is usually characterized by the Fourier coefficients [10,11]: $v_n = \langle \cos[n(\phi - \psi_n)] \rangle$ where ϕ is the azimuthal angle of the particle, ψ_n is the angle of the initial state spatial plane of symmetry, and n is the order of the harmonic. The second Fourier coefficient v_2 is called elliptic flow and provides a measurement of the strength of collectivity. The large elliptic flow observed at LHC provides evidence for strongly interacting matter which appears to behave like a perfect fluid. A moderate increase of v_2 relative to RHIC is observed (see fig. 2, left).

Angular correlations between unidentified charged trigger and associated particles are studied to further characterize the properties of the medium. At intermediate p_T, jet-like correlations dominate over collective effect. The"peak" and the "bulk" region can be selected by integrating the obtained distribution respectively around $\Delta\phi \sim 0$ and $\Delta\phi \sim \pi$(1). The jet-like yield can be obtained by subtracting the bulk contribution from the peak. In fig. 2 (right) the baryon to meson ratio as a function of the associated

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(1) $\Delta\phi = (\phi_{TRIG} - \phi_{ASSOC})$, $\Delta\eta = (\eta_{TRIG} - \eta_{ASSOC})$.

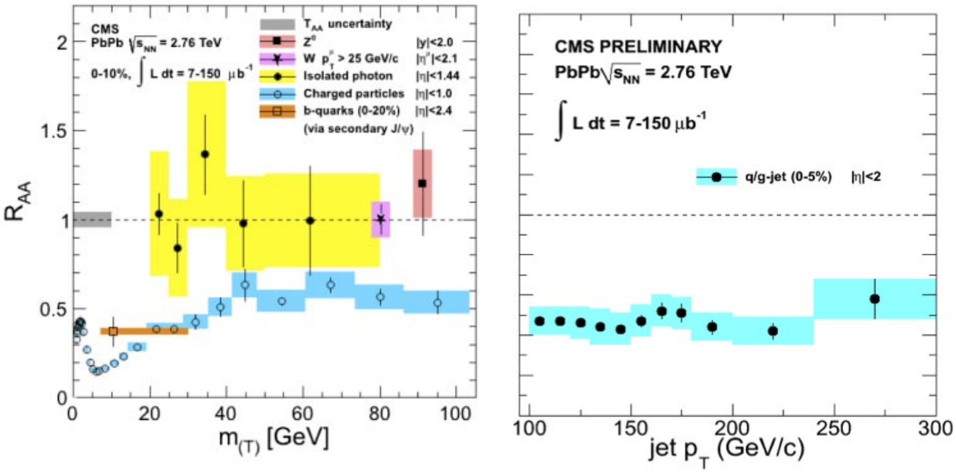

Fig. 3. – Left: R_{AA} for hadrons, photons and W, Z bosons. Right: jet R_{AA}.

particle p_T is reported for the bulk (in green) and for the jet-like (peak-bulk) (in red) contributions. While the jet-like particle production is consistent with fragmentation occurring in the vacuum, the bulk production shows a baryon over meson enhancement. The hadronization process can in fact occur either by the fragmentation of a single parton or by the recombination of 2 (3) partons for mesons (baryons), the latter leading to a baryon over meson p_T enhancement.

5. – Jet quenching

High-p_T particles are originated from hard parton scatterings and are therefore characterized by early formation time. They interact with the strongly coupled medium and are an ideal tool to probe the medium formed in the collisions. The observables that are usually studied are the nuclear modification factor, defined as the ratio of particle production measured in nucleus-nucleus to the proton-proton spectrum scaled by the average number of binary collisions, $R_{AA} = \frac{\mathrm{d}^2N^{AA}/\mathrm{d}p_T\mathrm{d}\eta}{\langle N_{coll}\rangle \mathrm{d}^2N^{pp}/\mathrm{d}p_T\mathrm{d}\eta}$, and the dijet energy asymmetry, $A_J = \frac{E_{T1}-E_{T2}}{E_{T1}-E_{T2}}$. In fig. 3 the R_{AA} is shown as a function of the transverse mass for different particles and for jets [13]. Photons, W and Z^0 bosons are in agreement with the p-p result scaled by N_{coll}, as expected for electromagnetic probes. Charged hadrons and jets are strongly suppressed, supporting the in medium parton energy loss. A large dijet energy asymmetry has been observed in central collisions relative to p-p collisions [14] [15]. The energy lost by jets in the medium can be quantified using a calibrated probe that is not affected by the traversed dense strongly interacting matter. ATLAS and CMS studied jets tagged with photons [16]. The fraction of photons with a jet partner is strongly reduced with increasing centrality and about 15% of the jet energy is lost for most central events.

6. – Heavy-flavor production

Heavy-flavor hadrons, containing charm and beauty, probe the conditions of the medium formed in nucleus-nucleus collisions. Hard partons, are produced during the initial stage of the collision in high-virtuality scattering processes. They interact with

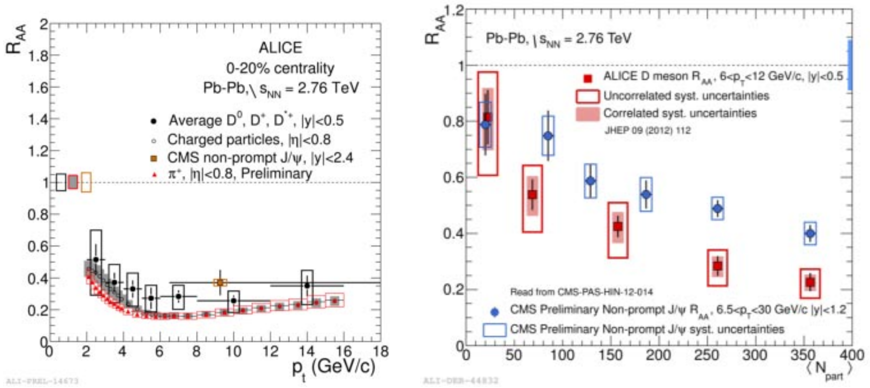

Fig. 4. – Left: average R_{AA} of D mesons compared to charged particle nuclear modification factors. Right: B and D meson R_{AA}^B as a function of centrality.

the medium, and are expected to be sensitive to its energy density, through the mechanism of parton energy loss. The energy loss is expected to occur mainly via inelastic (medium-induced gluon radiation, or radiative energy loss) processes. Quarks have a smaller color coupling factor with respect to gluons, therefore the energy loss for quarks is smaller than for gluons. In addition, the "dead-cone effect" should reduce the small-angle gluon radiation for heavy quarks, further attenuating the effect of the medium. In conclusion, a larger suppression (smaller energy loss) is expected for heavy quarks: $R_{AA}^{\pi} < R_{AA}^{D} < R_{AA}^{B}$. ALICE measured a strong suppression in central collisions for D mesons (D^+, D^*, D^{*+}) [17]. The suppression is close to that observed for charged particles and almost as large as the one measured for pions, with a possible indication, not fully significant with the present level of experimental uncertainties, of $R_{AA}^{\pi} < R_{AA}^{D}$ (see fig. 4, left). D meson nuclear modification factor has also been compared to the R_{AA} for non-prompt J/ψ mesons (from B decays) measured by CMS [18]. The B meson suppression is weaker, but also this comparison is not yet conclusive and would require more differential and precise measurements of the transverse momentum dependence (see fig. 4, right).

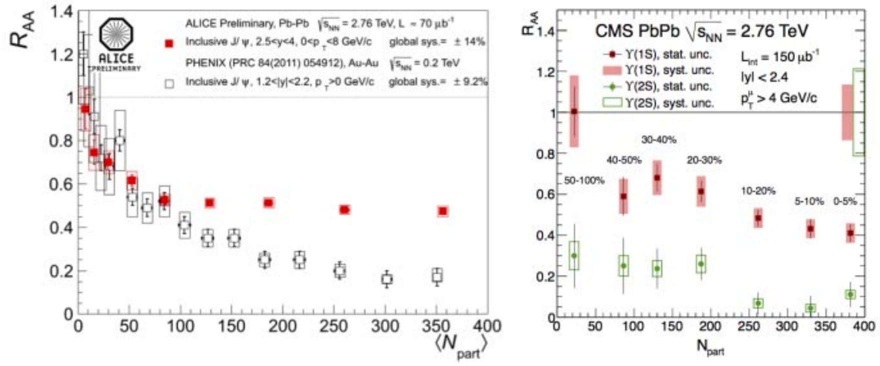

Fig. 5. – Left: J/ψ R_{AA} as a function of N_{part} compared to RHIC results. Right: sequential suppressions of the Υ family as a function of centrality.

7. – Quarkonium production

The dissociation of $c\bar{c}$ bound pairs by color screening was proposed as one of the signatures of the deconfined medium [19]. The in-medium dissociation of the different quarkonium states has been addressed as a tool to provide an estimate of the initial temperature of the system. In fact, dissociation of bound states is expected to occur sequentially, reflecting the increasing values of the binding energies. More recent models [20, 21] propose a regeneration component from deconfined charm quarks in the medium. At LHC a suppression of J/ψ and Υ mesons for central collisions has been observed, looking at different channels (e^+e^-, $\mu^+\mu^-$) and in different rapidity and kinematical ranges. The suppression is smaller than the one measured at RHIC and SPS energies (see fig. 5, left). ALICE studied the J/ψ suppression down to $p_T = 0$, finding a larger suppression at higher p_T [22]. Models including a large fraction of J/ψ produced from recombination can describe the data. CMS measured the production of the bottomonium family relative to p-p collisions, reporting a sequential suppression of $\Upsilon(ns)$ states [23], as can be seen in fig. 5 (left).

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