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Heavy-ion physics at LHC: Present and future

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Summary. — I will review the main results on heavy ion physics obtained by LHC experiments ALICE, ATLAS and CMS with the 2010 and 2011 Pb-Pb runs and discuss the physics potential for the next few years, including the p-Pb run and the experimental upgrades aimed at exploiting an order of magnitude increase in the machine luminosity.

PACS 25.75.-q – Relativistic heavy-ion collisions.
PACS 25.75.Dw – Particle and resonance production.
PACS 25.75.Ld – Collective flow.

1. – Introduction

The main purpose of heavy-ion physics is to study Quantum Chromo Dynamics (QCD) in the regime of high-energy densities and temperatures. Recent Lattice QCD calculations indicate (see, *e.g.*, [1]) that at low values of the baryo-chemical potential (as appropriate for LHC conditions) a crossover phase transition between hadronic matter and the Quark Gluon Plasma (QGP) should occur at a critical temperature $T_c \approx 150$–$160\,\mathrm{MeV}$, corresponding to a critical energy of $\approx 0.5\,\mathrm{GeV/fm^3}$. While first indications for QGP came from experiments at the CERN SPS, the Relativistic Heavy-Ion Collider (RHIC) program, with a top centre-of-mass energy of 200 GeV per nucleon pair, established the QGP as a medium opaque to hard probes such as high transverse energy jets and as a nearly perfect fluid characterized by a low viscosity to entropy density (η/s) ratio.

The Large Hadron Collider, which started operations with pp collisions at injection energy in late 2009, is currently providing Pb-Pb collisions at a centre-of-mass energy of 2.76 TeV per nucleon pair, *i.e.* 14 times greater than RHIC's top energy. The current scenario describing the evolution of the system formed in high-energy heavy-ion collisions is based on crucial assumptions which need to be validated also in the new energy domain: namely, the assumptions of rapid thermalization in the pre-equilibrium phase (the initial distributions of gluons are far from thermal equilibrium) and of a subsequent hydrodynamic expansion (started at which proper time after the collision?).

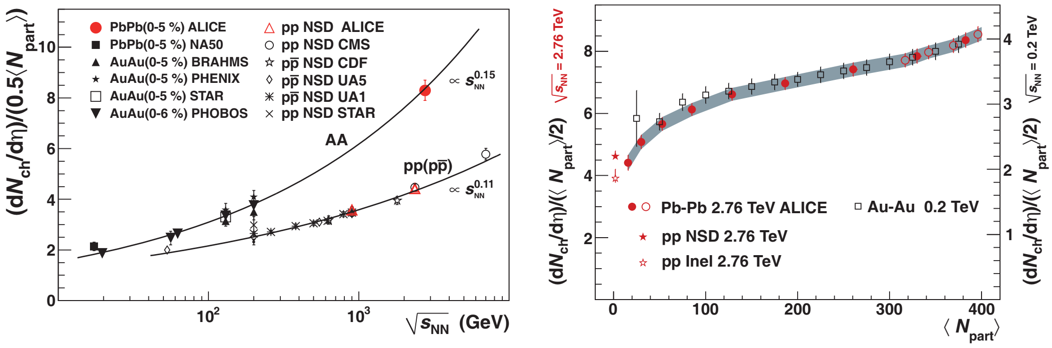

Fig. 1. – Left: Charged-particle rapidity density per participant pair in (anti-)proton-proton and nucleus-nucleus collisions *vs.* $\sqrt{s}$. Right: Centrality dependence of the charged-particle rapidity density per participant pair, in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76\,\text{TeV}$ (vertical scale on the left) and in Au-Au collisions at $\sqrt{s_{NN}} = 0.2\,\text{TeV}$ (vertical scale on the right).

2. – Results from the first Pb-Pb runs

The first Pb-Pb data at the LHC energy of $\sqrt{s_{NN}} = 2.76\,\text{TeV}$ have been collected by the ALICE, ATLAS and CMS experiments in the 2010 and 2011 runs (see also [2] and [3]). A recent review of the main results concerning heavy ions from the three experiments is given in [4].

The charged particle pseudorapidity density in central Pb-Pb collisions at LHC has been measured by the three experiments (see, *e.g.*, [5] and fig. 1, left) and found in excellent agreement (see [4]). Normalizing to the number of participant nucleon pairs this corresponds to a value of $(\mathrm{d}N_{ch}/\mathrm{d}\eta)/(N_{part}/2)$ about 2.1 times the value measured at RHIC in central Au-Au collisions at 0.2 TeV center-of-mass energy, a stronger rise than the one predicted by a $\log(\sqrt{s_{NN}})$ extrapolation from lower energies. The dependence on centrality of charged multiplicity density is very similar (see [6,7]) to the one observed at RHIC, as shown, *e.g.*, in fig. 1, right. The energy density obtained in the most central collisions has been estimated via the Bjorken formula $\epsilon_{Bj} = \frac{1}{\tau\pi R^2}\mathrm{d}E_T/\mathrm{d}\eta$; the product of energy density and formation time, $\epsilon\tau$, is at the LHC about 2.5 larger than the one measured at RHIC. Assuming an upper limit on the formation time of $1\,\text{fm}/c$, an energy density of at least $15\,\text{GeV/fm}^3$ is obtained.

The spatial extent and the temporal duration of the particle-emitting source is extracted from Hanbury-Brown Twiss interferometry of identical bosons (pions in this case) [8]: the HBT radii thus obtained indicate a volume of about $5000\,\text{fm}^3$, which is twice the one observed at RHIC, and a lifetime about 40% longer.

A purely thermal source will emit particles with transverse momentum characterized by one parameter, namely the temperature. If the source is expanding with a common radial flow velocity, transverse-momentum spectra of particles with different masses will be affected in a different way, with pion spectra hardly affected and proton ones most affected. Identified hadron spectra measured at LHC are shown in fig. 2. In the left panel, negatively charged hadron and K^0_s spectra are compared to those measured at RHIC: in general the LHC spectra are harder and the radial flow is larger than at RHIC. In the right panel, positively charged hadron and K^0_s spectra are compared to a viscous hydrodynamical calculation [9], indicating a good agreement for pions and kaons, while the proton yield appears overestimated.

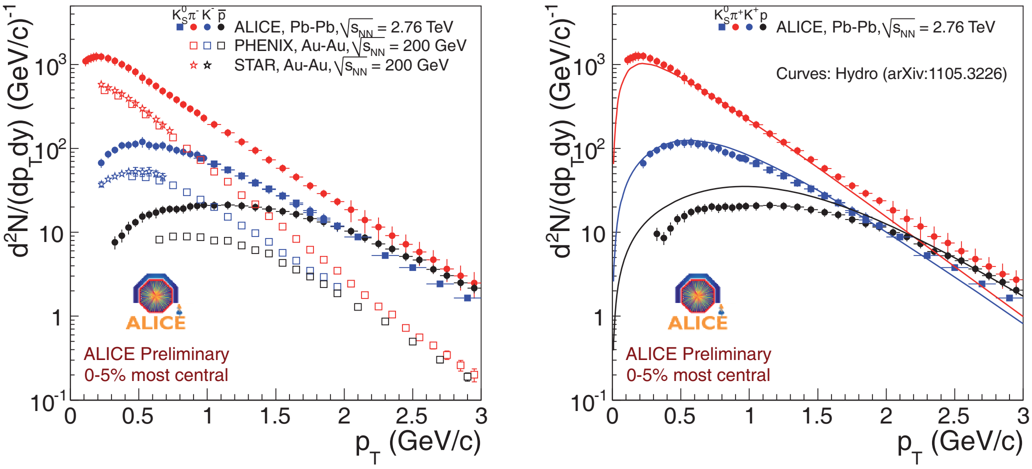

Fig. 2. – Left: Preliminary identified hadron spectra (negatives and K_s^0) in central collisions at LHC (ALICE) compared to RHIC data (PHENIX, STAR). Right: Preliminary identified hadron spectra (negatives and K_s^0) in central collisions at LHC (ALICE) compared to a hydrodynamical calculation [9].

The initial spatial anisotropy of the hot and dense medium formed in a Pb-Pb collision gives rise during the expansion to a momentum space anisotropy which is quantified by a Fourier expansion in the transverse plane. The p_t-integrated elliptic flow coefficient v_2 for charged particles measured (see, *e.g.*, [10]) at LHC is about 30% higher than at RHIC, which is attributed to the harder p_t spectrum at LHC, since the differential flow coefficient $v_2(p_t)$ at LHC is very similar to the RHIC one. More insight is gained by measuring $v_2(p_t)$ for identified hadrons: Figure 3, left, shows preliminary measurements

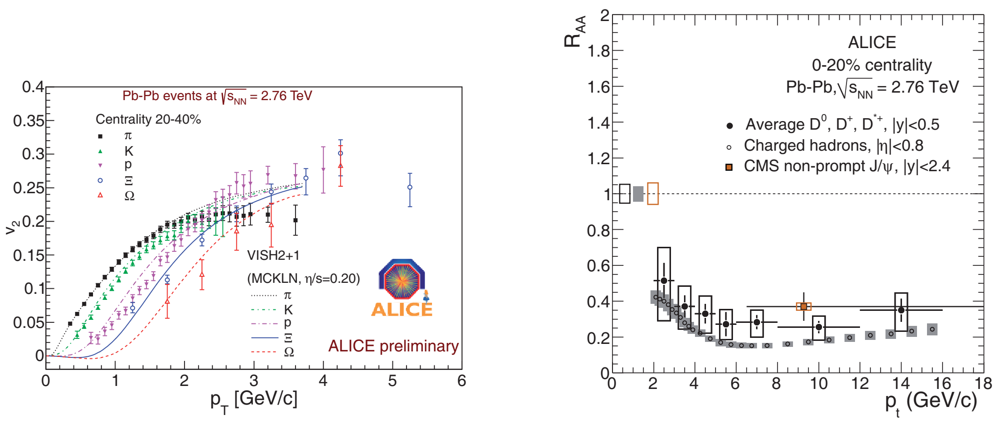

Fig. 3. – Left: Elliptic flow of identified hadrons *vs.* transverse momentum for 20–40% centrality Pb-Pb collisions. Right: Prompt D-meson R_{AA} *vs.* transverse momentum from ALICE compared to charged hadrons form ALICE and non-prompt J/ψ from CMS.

for several identified hadrons including hyperons in 20–40% central Pb-Pb collisions. The mass splitting induced by radial flow is evident, pions being the least affected by radial flow. A comparison with recent hydrodynamical calculation with shear viscosity to entropy density ratio $\eta/s = 0.20$ [9] (in units $\hbar = k_B = 1$) shows good agreement also for hyperons.

A powerful tool to investigate the properties of the medium is energy loss of partons (both radiative and collisional) as a function of the parton color charge, of the parton mass and of the traversed distance in the medium. The experimental observable is the nuclear modification factor $R_{AA} = \frac{1}{T_{AA}}(\mathrm{d}N_{AA}/\mathrm{d}p_t)/(\mathrm{d}N_{pp}/\mathrm{d}p_t)$ (where T_{AA} is the nuclear overlap function, see, *e.g.*, par. 6.6.3.2 of [11]) for hadrons of different flavour. The charged hadron R_{AA} as a function of transverse momentum at LHC (see, *e.g.*, [12,13]) shows a larger suppression than at RHIC, with a minimum attained at ≈ 6–$7\,\mathrm{GeV}/c$; the nuclear modification factor then rises again and levels off at ≈ 30–$40\,\mathrm{GeV}/c$.

ALICE has recently measured the nuclear modification factor of prompt D mesons [14] in central (0–20%) Pb-Pb collisions, see fig. 3, right. For $p_t > 5\,\mathrm{GeV}/c$, a suppression of a factor 3–4 is observed for the three species measured (D^0, D^+ and D^{*+} with the respective antiparticles). Comparing to charged hadrons, which in the measured p_t range are dominated by pions, there is an indication for $R^D_{AA} > R^{charged}_{AA}$, in line with models for the radiative energy loss of partons in the hot and dense medium: gluons (which are the main source of pions) are expected to be more suppressed than light quarks, which in turn are expected to be more suppressed than heavy quarks. The result obtained by CMS [15] on non-prompt J/ψ's from B decays is also shown, indicating a lesser suppression for the heavier b quark.

Jet quenching has been studied extensively at the LHC. For example, ATLAS has measured [16] the asymmetry $A_J = (p_{t1} - p_{t2})/(p_{t1} + p_{t2})$ as a function of centrality, with thresholds of 100 (25) GeV/c, for the transverse momentum of the first (second) jet. The asymmetry grows with centrality, indicating that the second jet loses a great amount of energy in the medium, while remaining back-to-back with the first jet. Similar results have been obtained by CMS [17].

The R_{AA} of J/ψ has been measured by ALICE [18] and by CMS [15] in complementary rapidity and transverse momentum ranges. Comparing LHC results to those obtained by RHIC, one observes at forward rapidity a smaller (factor ≈ 2) and almost centrality-independent suppression at LHC; while at high transverse momenta and central rapidity one finds a larger suppression at LHC. Qualitatively the LHC observations appear to be compatible with a substantial contribution from regeneration to the R_{AA} at low transverse momentum.

Finally, the Υ(1S) suppression has been observed at LHC by CMS [19]: since about 50% of Υ(1S) are decay products of the 2S and 3S states, the observation is compatible with the suppression of the higher states only, at about the same level as observed at RHIC.

3. – Future prospects

The immediate future of the heavy ion program at LHC is the forthcoming p-Pb run at $\sqrt{s_{NN}} = 4.4\,\mathrm{TeV}$. With about 100 M minimum bias interactions collected, ALICE should be able to measure the nuclear modification factor $R_{pPb}(p_t)$ for charged particles up to 50 GeV/c, the same for identified particles (see [20] for a RHIC measurement in d-Au collisions) and for resonances. ALICE will also measure cold nuclear matter effects,

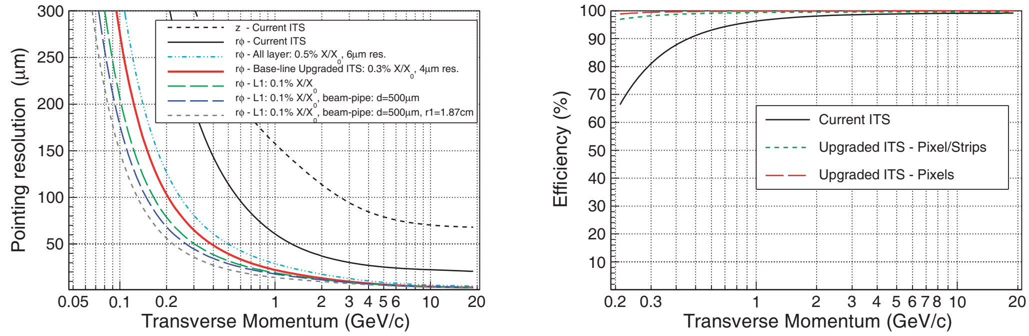

Fig. 4. – Performance of the current and upgraded ALICE ITS. Left: Pointing resolution *vs.* transverse momentum. Right: Efficiency *vs.* transverse momentum.

i.e. shadowing and saturation for gluon PDFs, which are crucial to interpret the results on open charm and charmonium already obtained in Pb-Pb collisions.

Concerning the longer term future, when a ten-fold increase of the integrated luminosity in Pb-Pb is foreseen, ALICE is preparing among other upgrades the barrel detector upgrade [21], aiming at measuring new channels for heavy flavours (*e.g.* $\Lambda_c \to pK^-\pi$ and exclusive beauty decays) and at a better understanding of heavy quark thermalization and energy loss. An example of the improvement achievable in pointing resolution and tracking efficiency with a new design for the Inner Tracking System is shown in fig. 4.

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