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ALICE results on heavy-ion physics at the LHC

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Summary. — ALICE is a multipurpose detector for high-energy nucleus-nucleus physics at the CERN Large Hadron Collider (LHC). In November 2010, ALICE took its first Pb-Pb data at the centre-of-mass energy of 2.76 TeV per nucleon pair; reference data in proton-proton collisions at the same energy and at 7 TeV were collected in 2010 and 2011. A second, higher statistics Pb-Pb run took place in fall 2011. An overview of the main physics results is presented.

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1. – Introduction

The ALICE detector is very different in both design and purpose from the other experiments at the CERN Large Hadron Collider (LHC). Its main aim is the study of matter under extreme conditions of temperature and pressure, *i.e.* the Quark-Gluon Plasma (QGP), in collisions of heavy ions. With a present energy up to almost 14 times higher than that of RHIC, the previous energy frontier machine for heavy-ion collisions at BNL, we expect a different type of QGP, *e.g.* in terms of initial temperature, lifetime and system volume. Moreover, hard signals like jets and heavy quarks, which serve as probes to study the QGP properties, are abundantly produced at the LHC. ALICE consists of a central barrel part, which measures hadrons, electrons and photons, and a forward spectrometer to measure muons. The central part, which covers polar angles from 45° to 135° over full azimuth, is embedded in the large L3 solenoidal magnet ($B = 0.5\,\mathrm{T}$). It consists of an inner tracking system (ITS) of high-resolution silicon detectors (two layers each of pixel, drift and double-sided strips), a cylindrical TPC, three particle identification arrays of time-of-flight (TOF), Cherenkov (HMPID) and transition radiation (TRD) counters and two single-arm electromagnetic calorimeters (high-resolution PHOS and large acceptance EMCAL). The forward muon arm (2°–9°, $2.5 < \eta < 4$) consists of a complex arrangement of absorbers, a large dipole magnet (3 Tm field integral) and 14 stations of tracking and triggering chambers. Several smaller detectors for triggering and multiplicity measurements (ZDC, PMD, FMD, T0 and VZERO) are located at small angles. The layout of the ALICE detector and its 18 different subsytems are described in detail in [1].

The first LHC heavy-ion campaign at $\sqrt{s_{\rm NN}} = 2.76\,\text{TeV}$ took place in November 2010, which yielded some 30 M inelastic Pb-Pb interactions recorded by ALICE using a minimum bias (MB) trigger. Reference data in proton-proton collisions at the same energy were collected in March 2011; in this short run ALICE could record 70 M MB events and integrate $20\,\text{nb}^{-1}$ of luminosity for rare triggers. During the much longer 2010 pp campaign at $\sqrt{s} = 7\,\text{TeV}$ ALICE, whose primary goal was to collect a sample of MB collisions under clean experimental conditions, recorded some 800 M events with MB triggers, 100 M events with muon trigger and about 20 M high multiplicity events. The selected results presented hereafter are based on these data samples. Important results from ALICE, which have been presented at this Conference (also) in specific talks, are discussed in the correspondig contributions to these proceedings [2-4].

2. – Bulk production

The multiplicity of produced particles provides information on the energy density achieved in the collisions. For central Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 2.76\,\text{TeV}$, about eight charged particles per unit of pseudorapidity per participant pair are produced [5]: about twice as many as at RHIC [6]. The average amount of transverse energy produced per unit of pseudorapidity per participant pair is about 9 GeV (a factor 2.7 larger than at RHIC, the larger multiplicity at the LHC being accompained by an increase in the average transverse momentum of the produced particles), corresponding to an energy density of about $16\,\text{GeV/fm}^3$ (assuming a conservative formation time for the plasma of $1\,\text{fm}/c$). The centrality dependence of the charged particle multiplicity is rather mild, favouring models incorporating some mechanisms (*e.g.* parton saturation) moderating the increase with centrality of the average multiplicity per participant pair. Once the multiplicities are rescaled to account for the difference in the central values, the centrality dependences measured at the LHC and at the RHIC are remarkably similar.

Hanbury Brown-Twiss (HBT) interferometry exploits the quantum interference between identical particles (*e.g.*, charged pions) to evaluate the size of the system at the time of the kinetic decoupling (or "freeze-out"). Compared to the RHIC results, the ALICE experiment finds an increase in the dimensions of the system in all three components [7] (including, finally, also the sideward component). The system expands (collectively) significantly more than measured at the RHIC, with an estimated increase by a factor 2 of the "homogeneity" volume for central collisions

The presence of collective motions arising from the large pressure gradients generated by compressing and heating the nuclear matter is a typical feature of the medium produced in heavy-ion collisions. The radial flow, generated by the collective expansion of the system, is studied by measuring the transverse momentum ($p_{\rm T}$) distributions of identified hadrons (π, K and p) [8]. While pion and kaon $p_{\rm T}$ distributions are in good agreement with hydrodynamic model predictions, the proton spectra are not reproduced by the models, neither in the yield nor in the shape. The radial flow velocity at the kinetic freeze-out is found to be about 10% higher than what observed at top RHIC energy. The average value of the *elliptic flow* coefficient v_2 (the second coefficent in the Fourier expansion of the particle azimuthal distribution) is about 20% larger at LHC than at RHIC for semi-central events (left panel of fig. 1): the behaviour of the system is still very close to that of an ideal liquid, and most of the collective dynamics develops at the partonic stage, as can be inferred from the scaling of v_2 for identified particles with the number of constituent

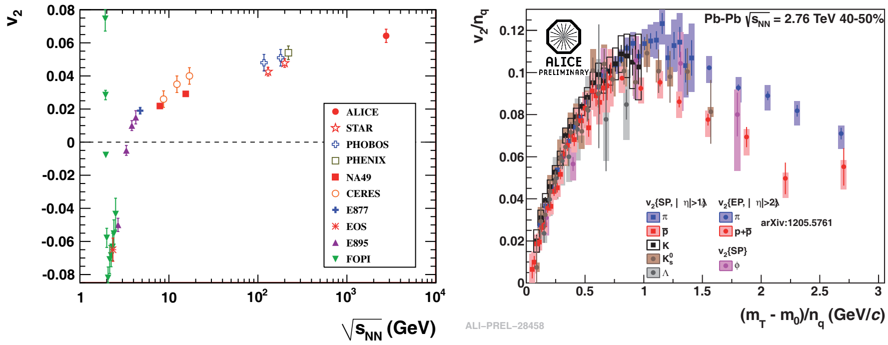

Fig. 1. – Left panel: Integrated elliptic flow coefficient v_2 at 2.76 TeV in Pb-Pb 20–30% centrality class compared with results from lower energies taken at similar centralities [9,10]. Right panel: Elliptic flow coefficient v_2 of identified particle divided by the number of constituent quarks (n_{q}) as a function of $(m_{\mathrm{T}} - m_0)/n_{\mathrm{q}}$, with $m_{\mathrm{T}} = \sqrt{p_{\mathrm{T}}^2 + m_0^2}$.

quarks (right panel of fig. 1). The v_2 coefficient is still significantly different from zero at high transverse momenta, providing important constraints for the energy loss models.

The ratios of particle yields measured for several hadronic species (pions, kaons, protons and hyperons) are sensitive to the thermodynamical conditions at the "chemical freeze-out". Thermal model predictions, based on gran-canonical ensemble with temperature $T_{\mathrm{chem}} = 164\,\mathrm{MeV}$ and baryochemical potential $\mu_{\mathrm{b}} = 1\,\mathrm{MeV}$ [11], describe well all ratios except for those with the proton yield, the measured proton/pion ratio being significantly ($\approx 50\%$) below the thermal model expectation.

3. – Hard probes

One of the most basic measurements that is sensitive to parton energy loss in the hot and dense QCD medium are the charged particle production distributions at high p_{T}. The nuclear modification factor $R_{\mathrm{AA}} = \frac{\mathrm{d}N/\mathrm{d}p_{\mathrm{T}}|_{\mathrm{Pb\text{-}Pb}}}{\langle N_{\mathrm{coll}}\rangle \mathrm{d}N/\mathrm{d}p_{\mathrm{T}}|_{\mathrm{pp}}}$, *i.e.* the ratio between the p_{T}-distributions in Pb-Pb collisions and in pp collisions, scaled with the number of binary collisions, is used to study the energy loss. The nuclear modification factor for charged particles in Pb-Pb collisions is shown in the left panel of fig. 2 for central collisions and compared to RHIC results. In the right panel of fig. 2 the ALICE R_{AA} is shown versus p_{T} with two different centrality selections. The figure clearly shows a significantly larger suppression than at RHIC. The effect is largest for the most central bin 0–5%, where the medium density and the average path length through the medium are the largest. The strongest suppression is seen for $p_{\mathrm{T}} \approx 7\,\mathrm{GeV}/c$, with a gradual rise of R_{AA} towards larger p_{T}. The increase of R_{AA} with p_{T} is qualitatively consistent with the expectation that parton energy loss is only weakly dependent on p_{T}, leading to a reduced relative energy loss at higher p_{T}.

Further insight into the parton energy loss mechanisms can be obtained by measuring the R_{AA} for heavy-flavoured hadrons. Quarks should lose less energy than gluons, due to the smaller colour charge, and, in addition, "massive" quarks are predicted to have a further reduced energy loss with respect to light partons (light-flavour quarks and gluons), due to the "dead cone effect" and other mechanisms [15,16]. Hence a hierarchy is anticipated for R_{AA}, when going from the mostly gluon-originated light-flavour hadrons (*e.g.*, pions) to D and to B mesons: $R_{\mathrm{AA}}^{\pi} < R_{\mathrm{AA}}^{\mathrm{D}} < R_{\mathrm{AA}}^{\mathrm{B}}$. The R_{AA} of prompt D mesons for the 20% most central collisions shows a strong suppression, reaching a factor 4–5 for

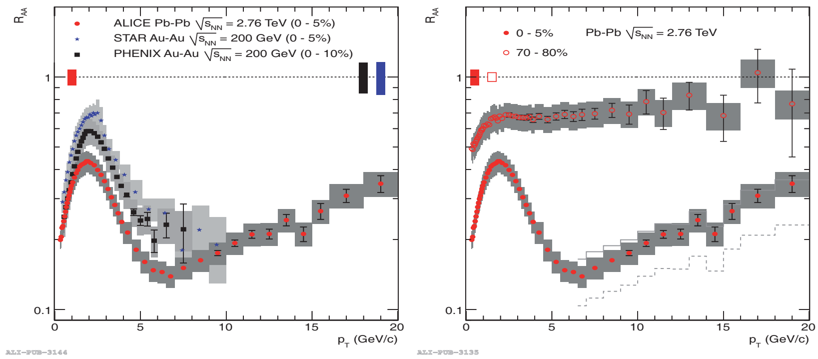

Fig. 2. – $R_{\rm AA}$ of inclusive charged particles at central rapidity as a function of $p_{\rm T}$. Normalization uncertainties are indicated by the bars at $R_{\rm AA} = 1$. Left panel: results for central collisions from ALICE [12] in Pb-Pb interactions at $\sqrt{s_{NN}} = 2.76\,\text{TeV}$ and from PHENIX [13] and STAR [14] in Au-Au interactions at $\sqrt{s_{NN}} = 0.2\,\text{TeV}$. Right panel: ALICE results for central and peripheral collisions [12].

$p_{\rm T} > 5\,\text{GeV}/c$ [2]. With the present statistical and sytematic uncertainties, the ALICE results provide a hint for being $R^{\rm D}_{\rm AA} > R^{\pi}_{\rm AA}$.

Quarkonium states are expected to be suppressed in the QGP, due to the color screening of the force which binds the $c\bar{c}$ (or $b\bar{b}$) state. Quarkonium suppression should occur sequentially according to the binding energy of each meson: strongly bound states (J/ψ and $\Upsilon(1S)$) should melt at higher temperatures with respect to more loosely bound states. At LHC energy, moreover, the more abundant production of charm in the initial state may lead to charmonium regeneration from recombination of c and $\bar{c}$ quarks at the hadronization (phase boundary), resulting in an enhancement in the number of observed J/ψ. The $R_{\rm AA}$ of J/ψ measured at forward rapity is shown as function of the mid-rapidity charged particle density (average number of nucleons that participate to the collision) in the left (right) panel of fig. 3. The nuclear modification factor, integrated over the 0–80% most central collisions, is $0.545 \pm 0.03(\text{stat.}) \pm 0.084(\text{syst.})$ and does not exhibit a significant dependence on the collision centrality. These features appear significantly

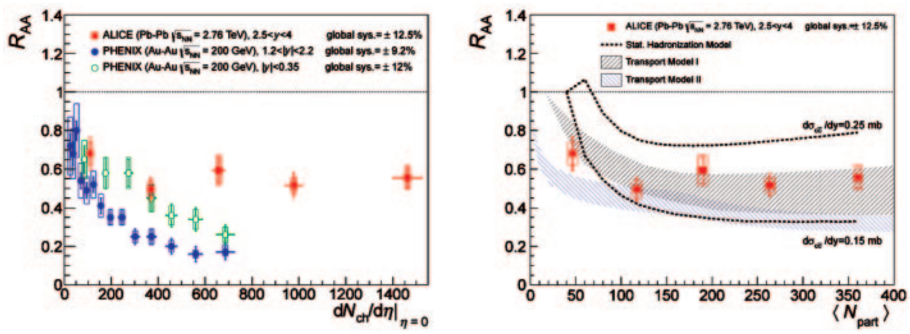

Fig. 3. – Left panel: Inclusive J/ψ $R_{\rm AA}$ as a function of the mid-rapidity charged-particle density measured in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 2.76\,\text{TeV}$ compared to PHENIX results in Au-Au collisions at $\sqrt{s_{\rm NN}} = 200\,\text{GeV}$ at mid-rapidity and forward rapidity [17-19]. Right panel: Inclusive J/ψ $R_{\rm AA}$ measured in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 2.76\,\text{TeV}$ compared to the predictions by Statistical Hadronization Model [20], Transport Model I [21] and II [22].

different from lower energy measurements. Models including J/ψ production from charm quarks in a deconfined partonic phase can describe our data.

4. – Conclusions

With the first Pb-Pb collisions at the LHC, at a $\sqrt{s_{\rm NN}}$ energy of about 14 times higher than that of the RHIC, heavy-ion physics entered into a new energy regime. The studies on the bulk of soft particles produced in the collisions show a smooth evolution from RHIC to LHC: the system created at the LHC, while initially much larger and hotter than at RHIC, still behaves like a very strongly interacting, almost perfect liquid. The first results on the so called "hard probes", such as high-$p_{\rm T}$ hadrons, D mesons and J/ψ, which are much more abundantly produced at LHC, open the era of precision measurements that should allow to impose tight constraints on the properties of the medium created in Pb-Pb collisions at the LHC. Further progress is expected from the analysis of the larger Pb-Pb data sample ($> \times 10$) collected at the end of 2011 as well as from the first p-Pb collisions foreseen in January 2013.

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