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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. In November 2010, ALICE took its first Pb-Pb data at the center-of-mass energy of 2.76 TeV per nucleon pair; reference data in proton-proton collisions at the same energy were collected in 2011. This paper gives an overview of the main physics results obtained with these data. In particular, I will present results on identified charged and strange particle transverse momentum spectra, on anisotropic flow of charged particles, on open heavy flavour and quarkonia production in Pb-Pb collisions, compared to pp collisions. These first Pb-Pb results from ALICE at LHC are broadly consistent with expectations based on lower energy RHIC and SPS data. They indicate that matter created in these collisions, while initially much larger and hotter, still behaves like a very strongly interacting, almost perfect liquid. A brief outlook on the expected results from the second, higher statistics Pb-Pb run of Fall 2011 will be given as well.

PACS 25.75.Ld – Collective flow.
PACS 25.75.Gz – Particle correlations and fluctuations.

1. – The ALICE experiment

The ALICE experiment [1] was designed for the study of the Quark-Gluon Plasma produced in Pb-Pb collisions at the CERN Large Hadron Collider, at a center-of-mass energy which is presently (2010-2011 runs) about 14 times the energy attained previously at the Relativistic Heavy Ion Collider (RHIC). For a general overview of LHC results from Pb-Pb collisions see, *e.g.*, [2]. The experiment is fully described in [1]; results presented in the following are based on the central barrel detectors, namely the Internal Tracking System (ITS), the Time Projection Chamber (TPC) and the Time of Flight system (TOF), as well as on the Muon Spectrometer and on the Electromagnetic Calorimeter (EMCal). In addition, the Zero-Degree Calorimeters (ZDC) and the VZERO scintillator hodoscopes have been used for centrality determination. Two triggers have been used, namely the Minimum Bias (MB) trigger based on signals from the Silicon Pixel Detector

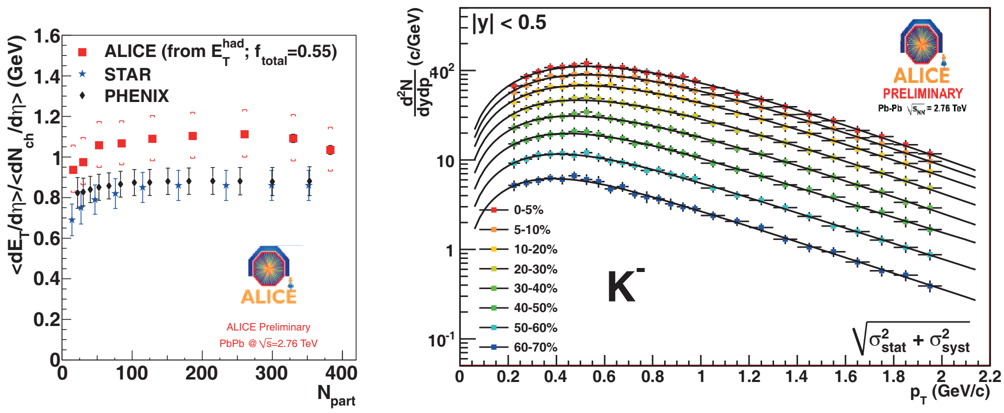

Fig. 1. – Left: transverse energy $\mathrm{d}E_t/\mathrm{d}\eta$ over charged track density $\mathrm{d}N_{ch}/\mathrm{d}\eta$ per participant pair *vs.* number of participants. Right: preliminary transverse momentum spectra of K^- in Pb-Pb collisions of different centralities ranging from 0–5% to 60–70%; lines represent blast-wave fits.

and the VZERO scintillator hodoscopes (see, *e.g.*, [3]), and the MUON trigger given by a muon signal in the trigger chambers of the Muon Spectrometer in coincidence with the MB trigger.

2. – ALICE results from Pb-Pb collisions at 2.76 TeV

Published and preliminary results from Pb-Pb collisions collected in the first Pb-Pb run (Fall 2010) at the LHC energy of 2.76 TeV per nucleon pair are presented in the following. The integrated luminosity in the 2010 run is $2.9\,\mu\mathrm{b}^{-1}$ corresponding to 17.7 million Minimum Bias events. Reference to pp runs at 2.76 and 7 TeV has been made when necessary, in particular to establish the nuclear modification factors described in the following. The higher statistics 2011 Pb-Pb run is briefly described in the final section.

2˙1. *Global event features*. – The main centrality observables used in ALICE are the multiplicity in the VZERO scintillator array and the forward energy in the ZDCs. Using a Glauber fit to the cross-section, centrality classes corresponding to given fractions of the inelastic Pb-Pb cross-section are defined (see, *e.g.*, [4]). For the most central class 0–5%, a charged multiplicity density of 1584 ± 76 at midrapidity has been measured [3]; normalizing to the number of participant nucleon pairs this corresponds to $(\mathrm{d}N_{ch}/\mathrm{d}\eta)/(N_{part}/2) = 8.3 \pm 0.4$, *i.e.* 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 [4] to the one observed at RHIC. The energy density obtained in the most central collisions has been estimated via the Bjorken formula $\epsilon_{Bj} = \frac{1}{\tau\pi R^2}\mathrm{d}E_T/\mathrm{d}\eta$ (see, *e.g.*, fig. 1(left)); 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 $1\,\mathrm{fm}/c$, an energy density of at least $15\,\mathrm{GeV/fm}^3$ is obtained.

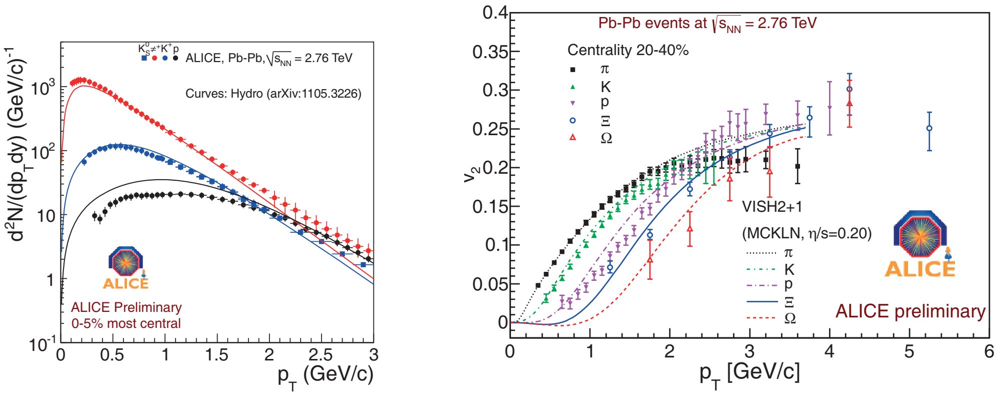

Fig. 2. – Left: Comparison of transverse momentum spectra of positively charged hadrons (and K_s^0) in Pb-Pb central collisions with a hydrodynamical calculation. Right: Elliptic flow coefficient *vs.* p_t for identified hadrons measured in Pb-Pb collisions in the 20–40% centrality class.

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) [5]: the HBT radii thus obtained indicate a volume of about 5000 fm^3, which is twice the one observed at RHIC, and a lifetime about 40% longer.

2·2. *Collective expansion and anisotropic flow.* – Detailed informations on the expansion of the source can be obtained by the transverse momentum spectra and by the azimuthal anisotropy (in particular the elliptic flow coefficient v_2) of identified hadrons. An example of transverse momentum spectra as a function of centrality is given in fig. 1(right). Lines represent blast-wave [6] fits, from which one obtains integrated yields $\mathrm{d}N/\mathrm{d}y$, average p_t and (by performing a simultaneous fit to different hadrons at given centrality) the parameters of the system at kinematic freeze out: temperature T_{fo} and average radial flow velocity β (in units of c). A strong radial flow, $\beta \simeq 0.66$, is observed in the most central collisions, *i.e.* about 10% higher than at RHIC; the estimated T_{fo} is slightly below 100 MeV for the same central collisions. The mean p_t of identified hadrons is correspondingly higher at LHC.

The preliminary p_t spectra of positively charged hadrons (and K_S^0, which extend the p_t range towards higher values) are shown in fig. 2(left) for the most central Pb-Pb collisions. Feed-down from weak decays has been subtracted. Lines represent a recent hydrodynamical calculation [7] which reproduces well the shape and the absolute value of the spectra, with the exception of protons whose yield appears to be overestimated.

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 [8] 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: fig. 2(right) shows preliminary measurements 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.

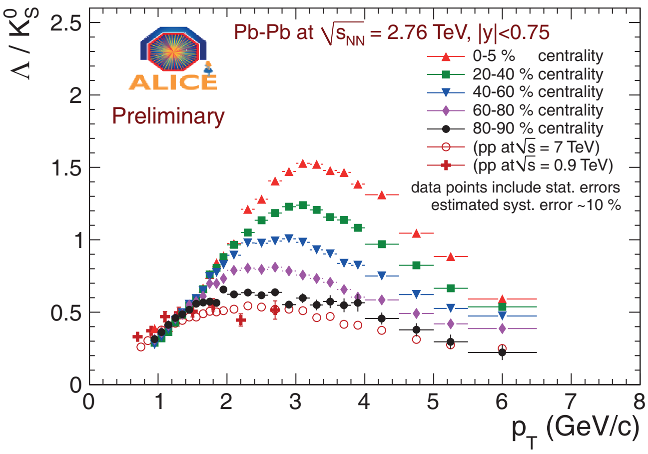

Fig. 3. – Λ/K_s^0 ratio *vs.* p_t for 5 centrality classes in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76\,\text{TeV}$, as well as in pp collisions at 0.9 and 7 TeV.

A comparison with recent hydrodynamical calculation with shear-viscosity–to–entropy-density ratio $\eta/s = 0.20$ [7] (in units $\hbar = k_B = 1$) shows good agreement also for hyperons.

2$\cdot$3. *Strangeness and chemical composition.* – The mid-rapidity yields of identified hadrons provide information on the temperature T_{ch} of the so-called chemical freeze out, after which only elastic interactions occur, which can alter the p_t distributions but not any more the particle ratios. Additional information can be obtained by the p_t dependence of some of the ratios, like, *e.g.*, the strange baryon/meson ratio shown in fig. 3. Strange baryons are more abundant than mesons at higher p_t, and the baryon/meson ratio increases with centrality. The rise with p_t at fixed centrality is consistent with the quark recombination scenario, while the interplay between soft and hard production results in the subsequent decrease with p_t. The maximum value of the ratio is slightly higher at LHC than at RHIC (as measured by the STAR collaboration in central Au-Au collisions at 0.2 TeV, see [9]) and the maximum occurs at higher p_t. The enhancement of this ratio with respect to pp persists up to at least 6 GeV/c.

Another important piece of information comes from the strangeness enhancement, already observed at SPS and RHIC, as obtained from ratios of multi-strange baryon yields in ion-ion and pp interactions. ALICE results on multi-strange baryon production in pp interactions at 7 TeV have been recently released [10]. Figure 4 shows that the enhancement in Pb-Pb collisions (with respect to pp ones) at LHC increases with the number of strange quarks and with centrality, confirming the SPS/RHIC trend; however, the enhancement decreases with increasing center-of-mass energy.

The temperature of chemical freeze out can be extracted combining several particle ratios (including the ones derived from yields of multi-strange baryons), as shown in fig. 5(left) for 0–20% central Pb-Pb collisions at the LHC. The comparison with thermal model [11] calculations indicates a rather low T_{ch} if protons are included, but this appears to be ruled out by the ratios involving multi-strange baryons. If these are included and protons are excluded, a chemical freeze out temperature of 164 MeV (with a chemical

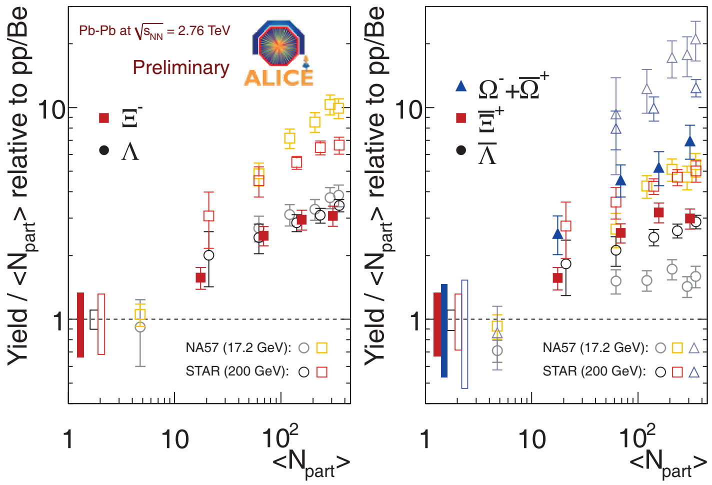

Fig. 4. – Enhancement of multi-strange (anti-)baryon production in Pb-Pb (Au-Au) collisions with respect to *pp* collisions at SPS, RHIC and LHC.

potential $\mu = 1\,\mathrm{MeV}$) is obtained at LHC, which is close both to the one measured at RHIC and to the critical temperature T_c from Lattice QCD calculations.

2·4. *Parton energy loss in the medium.* – The nuclear modification factor $R_{AA} = \frac{1}{T_{AA}}(\mathrm{d}N_{AA}/\mathrm{d}p_t)/(\mathrm{d}N_{pp}/\mathrm{d}p_t)$ of charged hadrons (see, *e.g.*, [12]), heavy flavour mesons [13] and jets is a powerful tool to test the predicted dependence of the parton energy loss in the medium on their color charge and mass. ALICE has observed a larger suppression of charged hadrons with respect to the one measured at RHIC, with the strongest suppression occurring at $p_t \simeq 6$–$7\,\mathrm{GeV}/c$; R_{AA} then increases for $p_t > 10\,\mathrm{GeV}/c$, with hints of flattening above $30\,\mathrm{GeV}/c$, see fig. 5(right).

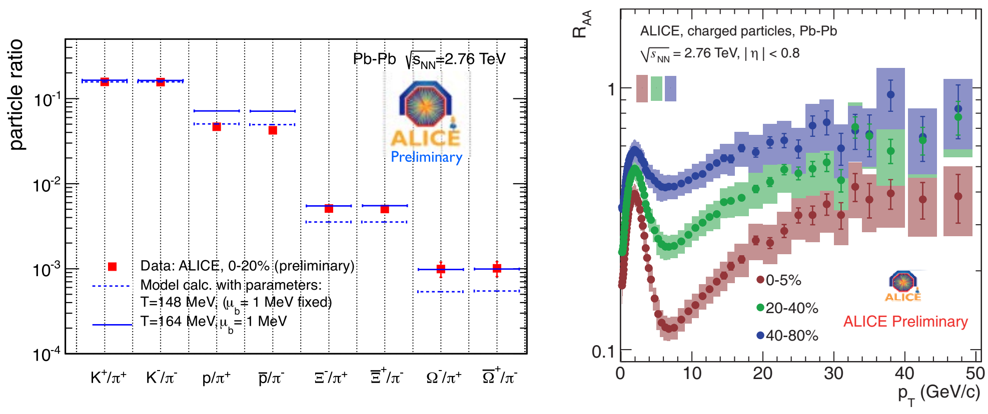

Fig. 5. – Left: Preliminary mid-rapidity particle ratios in 0–20% central Pb-Pb collisions, compared to thermal model calculations. Right: Nuclear modification factor *vs.* p_t for charged hadrons in Pb-Pb collisions, in three centrality classes.

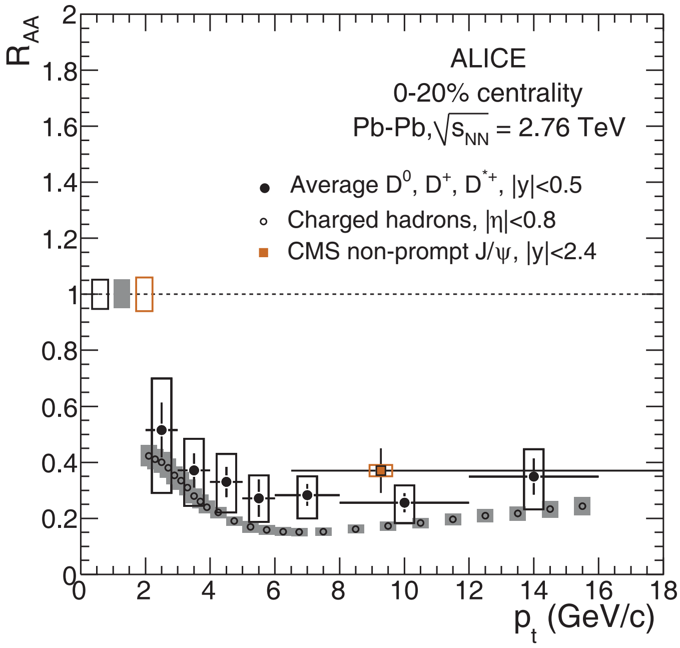

Fig. 6. – D-meson nuclear modification factor (averaged over three species) *vs.* p_t for Pb-Pb collisions, in the 0–20% centrality class. The R_{AA} for charged mesons (dominated by pions) is also shown. The nuclear modification factor for non-prompt J/ψ's at high p_t as obtained by the CMS Collaboration is shown for comparison.

ALICE has recently measured the nuclear modification factor of prompt D mesons [13] in central (0–20%) Pb-Pb collisions, see fig. 6. For $p_t > 5\,\text{GeV}/c$, 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 [14] on non-prompt J/ψ's from B decays is also shown, indicating a lesser suppression for the heavier b quark.

2·5. *Quarkonia dissociation and regeneration in the medium.* – The J/ψ suppression (already observed at SPS and RHIC energies) and its possible regeneration at LHC energies (due to the much greater number of c quarks produced) is perhaps the most important signature for Quark Gluon Plasma formation in heavy-ion collisions. ALICE has recently released the results [15] on the J/ψ nuclear modification factor as a function of p_t down to $p_t = 0$ in the forward rapidity range ($2.5 < y < 4.0$). The nuclear modification factor, integrated over the 0–80% most central collisions, is $0.545 \pm 0.032(\text{stat.}) \pm 0.084(\text{syst.})$ and does not exhibit a significant dependence on the collision centrality. These features appear significantly different from lower energy measurements. More details are given in [15].

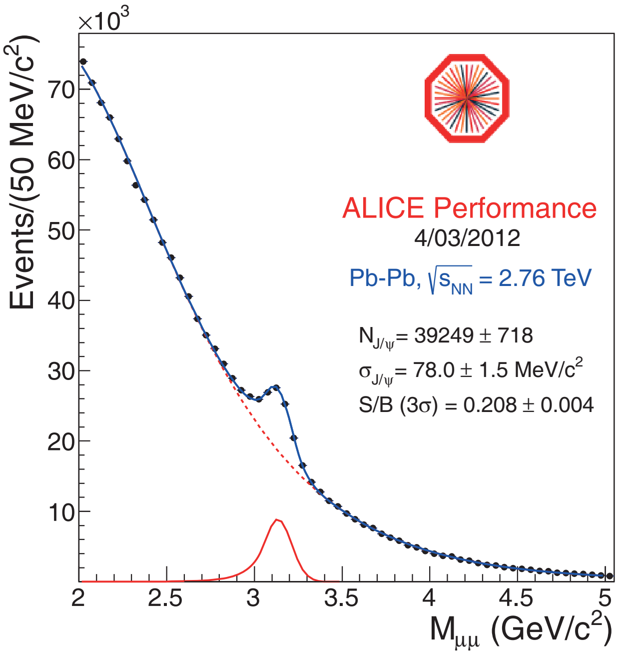

Fig. 7. – J/ψ in the opposite-sign dimuon invariant mass spectra from the 2011 Pb-Pb run.

3. – Conclusions and outlook

The ALICE Collaboration focused in 2011 on the analysis of the first Pb-Pb run at 2.76 TeV of 2010 as well as on the vast amount of pp data collected at 2.76 TeV and 7 TeV in 2010 and early 2011. The main results obtained so far can be summarized as follows: i) a medium with 3 times higher-energy density than RHIC has been observed; ii) a smooth evolution with center-of-mass energy of global events observables has been found, now the Collaboration is looking more differentially into (*e.g.*) higher flow harmonics with identified hadrons and an extended p_t range; iii) a strong suppression of high p_t hadrons with respect to *pp* collisions has been found; iv) the nuclear modification factor R_{AA} of light and heavy quarks is similar; v) the J/ψ at low p_t is less suppressed than at RHIC.

The second Pb-Pb run (Fall 2011) was very successful with an increase of a factor 15 in the collected statistics with respect to the previous year; now the ALICE Collaboration is focusing on analysis of new data (see, *e.g.*, fig. 7, showing the quality of the J/ψ signal collected in the Muon Spectrometer), preparation of the p-Pb run—which in particular will provide a measurement of the cold matter effects relevant for heavy flavours—and on the upgrade programme.

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