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Recent results from the ALICE experiment in pp and PbPb collisions

Enrico SCOMPARIN for the ALICE Collaboration*
INFN Torino (Italy)
E-mail: scomparin@to.infn.it

ALICE is the dedicated heavy-ion experiment at the CERN LHC. At the end of 2010 Pb-Pb collisions were studied for the first time, at a center of mass energy per nucleon-nucleon collision $\sqrt{s_{\rm NN}} = 2.76$ TeV. In this contribution the main results obtained in this run are reviewed, together with highlights from the LHC pp run at $\sqrt{s} = 7$ TeV. Finally, prospects for future measurements are briefly summarized.

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*Speaker.

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1. Introduction

In November 2010 Pb nuclei were collided for the first time at the LHC at the centre-of-mass energy $\sqrt{s_{\rm NN}} = 2.76$ TeV, about 14 times higher than the highest energy achieved at RHIC. Three experiments (ALICE, ATLAS and CMS) collected data during the 5 weeks of running with Pb ions. The integrated luminosity delivered by the LHC was 10 μb^{-1}.

The study of Pb–Pb collisions in the new energy regime attained at the LHC is aimed at gaining deeper insight on the properties of nuclear matter at extreme conditions of temperature and energy density, where Lattice QCD predicts the matter to be in a Quark Gluon Plasma (QGP) state. Experimental measurements at the LHC are a key benchmark for models that reproduce the features observed at lower collision energy. Furthermore, results from the LHC are expected to address some of the issues that are not completely understood from the SPS and RHIC experiments (e.g. the J/ψ suppression). Finally, since the cross-section for QCD scatterings with high virtuality increases steeply with $\sqrt{s}$, hard partons are abundantly produced at the LHC, thus enabling high precision measurements for the experimental observables related to high momentum and heavy flavoured particles.

Furthermore, ALICE collects proton-proton data, at a luminosity up to $\sim 10^{30}$ cm^{-2}s^{-1}, i.e. lower than that of the other LHC experiments. These data are an essential reference for the study of Pb–Pb collisions. In addition, soft QCD issues and some selected hard processes ($D-$meson production, quarkonia) can be investigated.

In the next sections, an overview of the ALICE results from the first heavy-ion run at the LHC is presented, together with some highlights of the pp physics accessible to the experiment.

2. Global event characteristics

The multiplicity of produced particles, quantified by the charged particle density per unit of rapidity (dN_{ch}/dη) at mid-rapidity, was measured as a function of the collision centrality [1, 2]. The measurement of the dN_{ch}/dη provides insight into the density of gluons in the initial stages and on the mechanisms of particle production. The multiplicity in the 5% most central collisions at the LHC is larger by a factor 2.2 with respect to central collisions at top RHIC energy. The increase of multiplicity with centre-of-mass energy is steeper than the $\log\sqrt{s}$ trend observed at lower energies. The centrality dependence of (dN_{ch}/dη)/($N_{\rm part}$/2) (see Fig. 1) has a similar shape to that observed at RHIC and is reasonably reproduced both by models based on gluon saturation in the initial state and by two-component Monte Carlo models [2].

The produced transverse energy $E_{\rm t}$ was estimated by measuring the charged hadronic energy with the tracking system and adding the contribution of neutral particles. The measured $E_{\rm t}$ per pseudorapidity unit can be used to estimate the energy density with the Bjorken formula [3]. For the 5% most central collisions at the LHC, the resulting value is $\varepsilon_{Bj}\tau \approx 15$ GeV/(fm^2c) (where τ is the formation time), about a factor 3 larger than the corresponding one at RHIC.

The system size is measured from the HBT radii extracted from the study of two-pion correlations [4]. For central collisions, the homogeneity volume is found to be larger by a factor two with respect to the one observed in central collisions at the top RHIC energy. The decoupling time for mid-rapidity pions exceeds 10 fm/c and it is 40% larger than at RHIC. The HBT radii were also

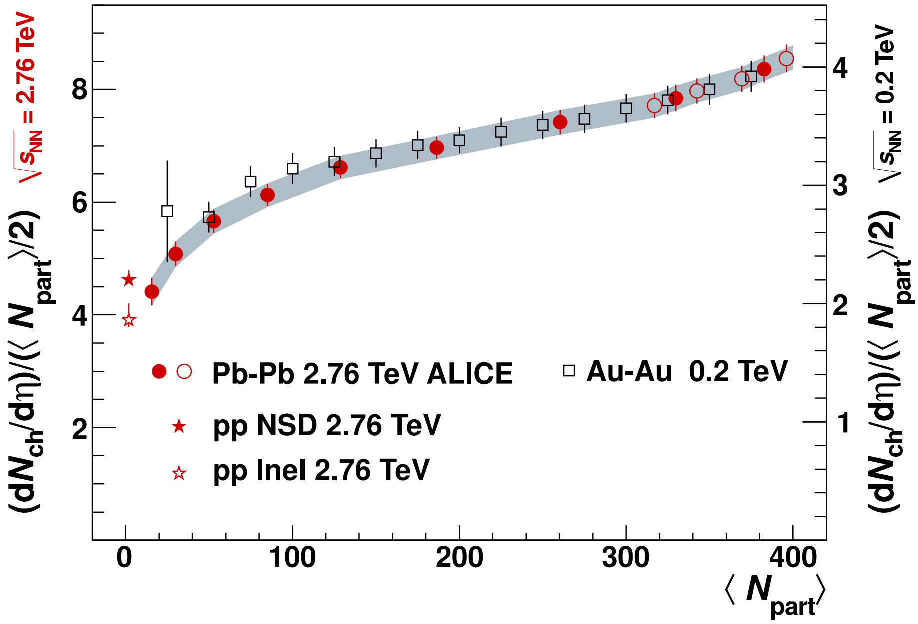

Figure 1: Dependence of $dN_{ch}/d\eta$ on the number of participants for Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and Au–Au collisions at $\sqrt{s_{NN}} = 0.2$ TeV (RHIC average). The scale for the lower-energy data is shown on the right-hand side and differs from the scale for the higher-energy data on the left-hand side by a factor of 2.1. For the Pb–Pb data, uncorrelated uncertainties are indicated by the error bars, while correlated uncertainties are shown as the grey band. Statistical errors are negligible. The open circles show the values obtained for centrality classes obtained by dividing the 0–10% most central collisions into four, rather than two classes. From Ref. [2].

extracted as a function of the event multiplicity and compared with results at lower $\sqrt{s}$. R_{long} is found to follow the linear trend with $dN_{ch}/d\eta^{1/3}$ observed at lower energies. R_{side} has a slightly different slope as a function of multiplicity resulting to be at the lower edge of the uncertainty of the trend from lower $\sqrt{s}$, while R_{out} is clearly below the trend set by lower energies. This slower increase of R_{out} with centre-of-mass energy can be explained in the framework of hydrodynamic models [5].

3. Collective motions

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 fireball, is studied by measuring the transverse momentum (p_t) spectra of identified hadrons (π, K and p) [6]. The spectra reconstructed at the LHC are seen to be harder (i.e. characterized by a less steep distribution and a larger $\langle p_t \rangle$) than those measured at RHIC at $\sqrt{s_{NN}}$=200 GeV. This is a first indication for a stronger radial flow at the LHC. The radial flow velocity at the thermal freeze-out, is estimated via a blast-wave fit to the π, K and p spectra (see Fig. 2) and, for the most central collisions at the LHC, it is found to be about 10% higher than what observed in central collisions at top RHIC energy [6].

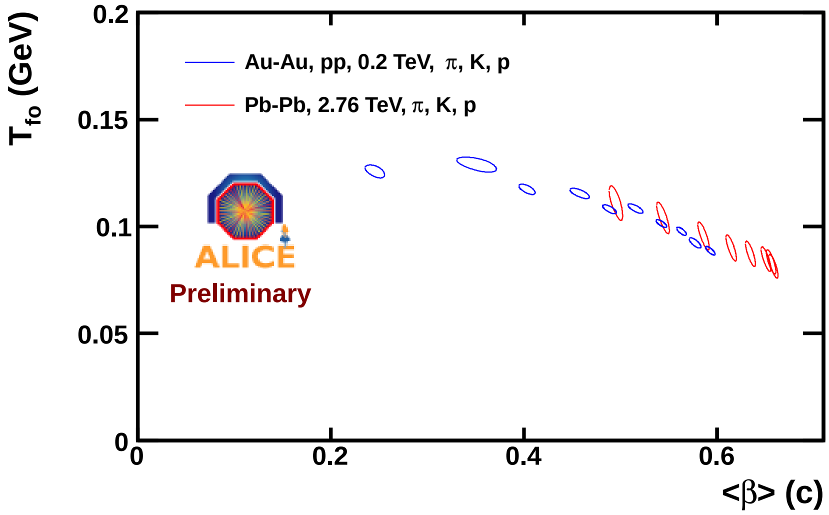

Figure 2: Blast wave fit results. The radial flow velocity β and the freeze-out temperature T are shown for various centrality bins and compared to RHIC results. From Ref. [6].

The collective behaviour of the fireball is also studied from the anisotropic flow patterns in the transverse plane that originate from the anisotropy in the spatial distribution of the nucleons participating in the collision. Re-scatterings among the produced particles convert this initial geometrical anisotropy into an observable momentum anisotropy. Anisotropic flow is characterized by the Fourier coefficients $v_n = \langle \cos[n(\varphi - \Psi_n)] \rangle$, where n is the order of the harmonic, φ is the azimuthal angle of the particle and Ψ_n is the angle of the initial state spatial plane of symmetry. The dominant harmonic is the elliptic flow, v_2, which is sensitive to the properties of the system (equation of state, thermalization time, viscosity) in the various stages of its evolution. The $p_{\rm t}$ integrated elliptic flow of charged particles at the LHC is found to increase by about 30% from the highest RHIC energy of $\sqrt{s} = 200$ GeV [7]. The large value of elliptic flow indicates that the hot and dense matter created in heavy-ion collisions at LHC energies behaves like a strongly interacting fluid with exceptionally low viscosity, as already observed at RHIC. The $p_{\rm t}$-differential elliptic flow, $v_2(p_{\rm t})$, measured at the LHC (see Fig. 3) is compatible with that observed at RHIC [7]. The 30% increase in the $p_{\rm t}$ integrated elliptic flow is therefore due to the increased average transverse momentum of the produced particles as a consequence of the stronger radial flow. The larger radial flow leads also to a more pronounced dependence of v_2 on the particle mass. The mass splitting among $v_2(p_{\rm t})$ of identified pions, kaons and protons at the LHC is actually found to be slightly but significantly larger than that observed at lower collision energies.

4. Particle abundances and strangeness production

The $p_{\rm t}$ differential distributions and the total yields were measured by ALICE for many hadronic species [6, 8]. Charged pions, kaons, protons are identified via their dE/dx and time-of-flight. K^0_S mesons, Λ, Ξ and Ω hyperons are reconstructed from their decay topologies.

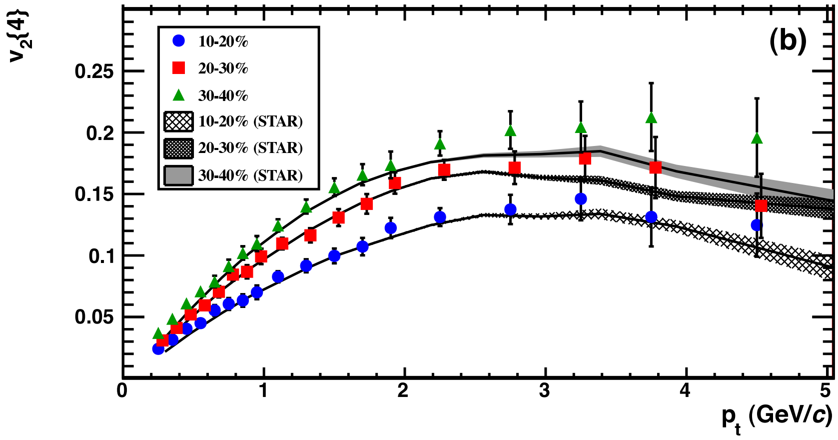

Figure 3: The The p_t-differential elliptic flow $v_2(p_t)$ (obtained with the 4-particle cumulant method), for three centrality bins as a function of transverse momentum, compared with lower energy results obtained by STAR. From Ref. [7].

The baryon/meson ratio, which is sensitive to the hadronization mechanism and in particular to quark recombination at the phase boundary, is studied in the strangeness sector via the ratio Λ/K^0_S as a function of p_t in different centrality intervals. The Λ/K^0_S in peripheral (80-90%) collisions stays below 0.7 and is quite similar to what observed in p–p. With increasing centrality the baryon/meson ratio increases developing a maximum at $p_t \approx 3$ GeV$/c$ and it reaches a value $\Lambda/K^0_S \approx 1.5$ for the 5% most central events. With respect to what observed at lower energies, the baryon enhancement results larger at the LHC and the position in p_t of the maximum of the Λ/K^0_S is slightly shifted towards higher transverse momenta.

The yields of pions, kaons, protons, Ξ and Ω are extracted by integrating the measured p_t spectra after fitting them with a blast-wave function. The particle abundances normalized to that of charged pions, are compared in Fig. 4 with the predictions of a thermal model based on gran-canonical ensemble with temperature $T_{chem} = 164$ MeV at the chemical freeze-out and baryochemical potential $\mu_b = 1$ MeV [9]. All the measured yields, with the notably exception of protons, are found to agree with the thermal model predictions. Contrary to what happens at lower energy, the measured proton/pion ratio falls significantly ($\approx 50\%$) below the thermal model expectation. The origin of such a discrepancy is presently not understood.

The production of multi-strange baryons in Pb–Pb collisions was also compared with that measured in p–p collisions. This was done using the ratio between the yield of Ξ and Ω hyperons in Pb–Pb and p–p after normalizing to the number of participant nucleons. An enhancement of the production of Ξ and Ω in heavy-ion collisions with respect to p–p is observed also at LHC energies. The enhancement is lower than that observed at SPS and RHIC energies, confirming its decreasing trend with increasing $\sqrt{s}$. This is a consequence of the smaller effect of canonical suppression for strangeness production in p–p reactions at higher collision energies.

5. Characterization of the medium with hard probes

Particles with large transverse momentum and/or mass, which are produced in large-virtuality

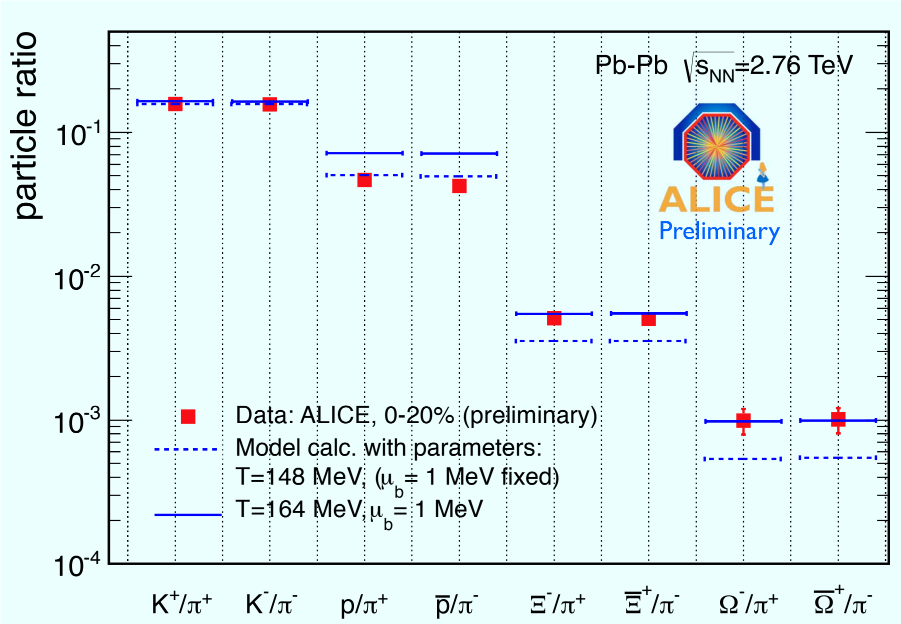

Figure 4: Comparison of identified particle ratios with thermal model [9] predictions. From Ref. [6].

parton scatterings in the early stages of the collision, are powerful tools to probe the medium created in heavy-ion collisions. Their production in nuclear collisions is expected to scale with the number of nucleon–nucleon collisions occurring in the nucleus–nucleus collision (binary scaling). The experimental observable used to verify the binary scaling is the nuclear modification factor, R_{AA}, defined as the ratio between the yields measured in heavy-ion and p–p collisions after normalizing the A–A yield to the average number of nucleon-nucleon collisions for the considered centrality class, $\langle N_{\mathrm{coll}} \rangle$. It is anticipated that the medium created in the collision affects the abundances and spectra of the originally produced hard probes, resulting in a break-down of the binary scaling and in a value of R_{AA} different from 1. It has however to be considered that other effects related to the presence of nuclei in the initial state (e.g. nuclear modifications of the PDFs, Cronin enhancement) can break the expected binary scaling.

5.1 High momentum particle suppression

Partons are expected to lose energy while traversing the strongly interacting medium, via gluon radiation and elastic collisions with the partonic constituents. The measurement of the single-particle nuclear modification factor as a function of p_{t} is the simplest observable sensitive to the energy lost by hard partons produced at the initial stage of the collision. The amount of energy lost is sensitive to the medium properties (density) and depends also on the path-length of the parton in the deconfined matter as well as on the properties of the parton probing the medium.

The R_{AA} of unidentified charged particles has been measured by ALICE up to $p_{\mathrm{t}} = 50$ GeV$/c$ for various centrality classes [10]. For all collision centralities, the R_{AA}, shown in Fig. 5, presents a minimum at $p_{\mathrm{t}} \approx 6-7$ GeV$/c$ and then increases slowly up to about 30 GeV$/c$. A hint of flattening of the nuclear modification factor is observed for $p_{\mathrm{t}} > 30$ GeV$/c$. The amount of suppression increases with increasing centrality. For the 5% most central collisions, the R_{AA} measured at the LHC is smaller than that at RHIC, suggesting a larger energy loss and indicating that the density of the medium created in the collision increases with the increase of $\sqrt{s}$. It should also be considered that the fraction of hadrons originating from gluon jets increases with increasing centre-of-mass energy and, in radiative energy loss models, this is expected to give rise to a lower R_{AA} because gluons lose more energy than quarks while traversing the QGP.

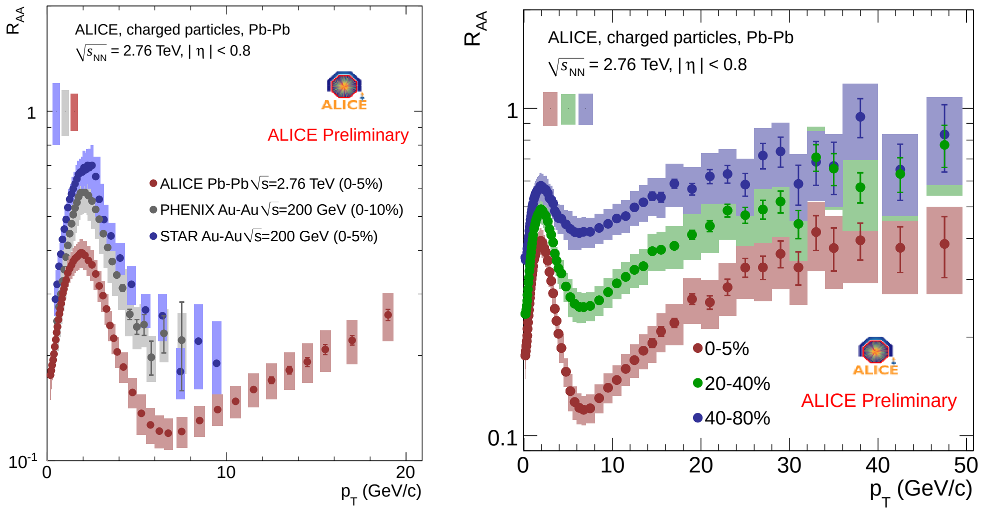

Figure 5: The nuclear modification factor R_{AA} for unidentified charged particles measured by ALICE, compared with RHIC results (left) and shown as a function of centrality (right). From Ref. [10].

The R_{AA} was also measured for identified hadrons: $\pi^{\pm}$ in the range of dE/dx relativistic rise ($3 < p_t < 20$ GeV$/c$), π^0 reconstructed via conversions of the decay photons, K^0_S and Λ [11]. At high transverse momenta ($p_t > 6$ GeV$/c$), the suppression of $\pi^{\pm}$, K^0_S and Λ is found to be compatible with that of unidentified charged hadrons. At lower transverse momenta, the charged and neutral pions result to be slightly more suppressed (= lower R_{AA}) than charged hadrons and the R_{AA} of Λ is significantly larger than that of K^0_S and charged hadrons. This is a consequence of the baryon enhancement observed in heavy-ion collisions at intermediate momenta, that was also seen in the Λ/K^0_S ratio discussed in section 4. In particular, the Λ nuclear modification factor measured at the LHC is lower than the one observed at RHIC. This is due to the fact that the different physical mechanisms that contribute to the R_{AA} of Λ baryons, namely the baryon enhancement in AA collisions, the canonical suppression in the p–p reference and the in-medium energy loss, are quantitatively different at the two energies.

5.2 Open heavy flavours

Further insight into the energy loss mechanisms can be obtained by measuring the R_{AA} for heavy-flavoured hadrons. Radiative energy loss models predict that quarks lose less energy than gluons (that have a larger colour charge) and that the amount of radiated energy decreases with increasing quark mass. Hence, a hierarchy in the values of the nuclear modification factor is anticipated: the R_{AA} of B mesons should be larger than that of D mesons that should in turn be larger than that of light-flavour hadrons (e.g. pions), which mostly originate from gluon fragmentation.

ALICE measured open charm and open beauty with three different techniques: exclusive reconstruction of D^0, D^+ and D^{*+} hadronic decays at mid-rapidity, single electrons after subtraction of a cocktail of background sources at mid-rapidity, and single muons at forward rapidity. The R_{AA} of prompt D mesons is shown in Fig. 6. For the 20% more central collisions a strong suppression is observed, reaching a factor 4-5 for $p_t > 5$ GeV/c [12]. At high p_t the suppression is similar to the one observed for charged pions, while at low p_t there seems to be an indication for $R_{AA}(D) > R_{AA}(\pi^\pm)$. The measurement of cocktail-subtracted electrons show, for the 10% most central events, a suppression by a factor 1.2-5 in the p_t range between 3.5 and 6 GeV/c, where charm and beauty decays dominate [13]. For both D mesons and electrons, the suppression is seen to increase with increasing centrality. At forward rapidity, the ratio of central-to-peripheral yield (R_{CP}) was measured for muons with $p_t > 6$ GeV/c where the background contamination is negligible with respect to muons from heavy flavor decays [14]. A suppression of the muon yield which increases with increasing centrality is observed.

The elliptic flow of D^0 mesons was also measured and show a hint of non-zero v_2 of charmed hadrons in the range $2 < p_t < 5$ GeV/c [15].

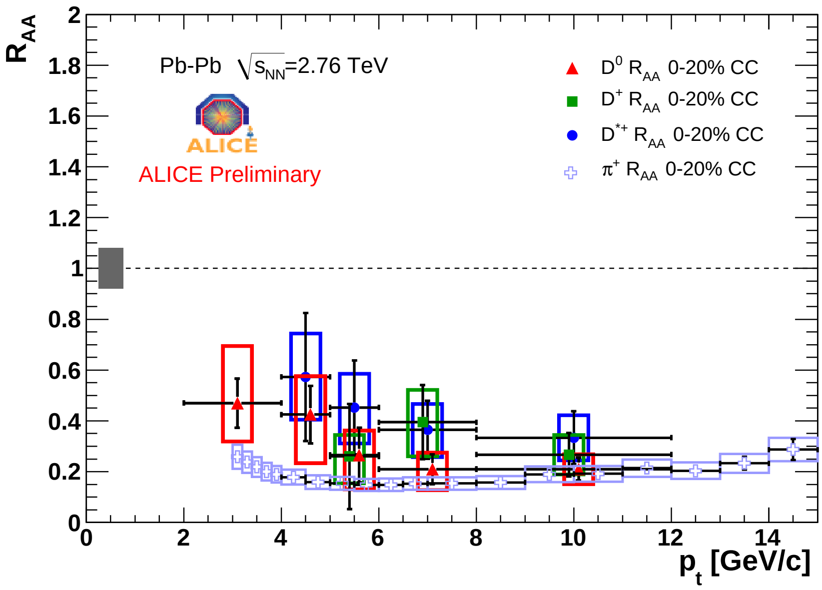

Figure 6: The nuclear modification factor R_{AA} for D-mesons as a function of p_t, for central Pb–Pb events. The results are compared with the suppression obtained for a light hadron (π^+). From Ref. [12].

5.3 Quarkonia

Quarkonium states are expected to be suppressed ($R_{AA} < 1$) in the QGP, due to the color screening of the force which binds the $c\bar{c}$ (or $b\bar{b}$) state and to other mechanisms such as gluon-induced dissociation. Quarkonium suppression is anticipated to occur sequentially according to the binding energy of each meson: strongly bound states (J/ψ and Υ(1S)) should melt at higher temperatures with respect to more loosely bound states. For collisions at high $\sqrt{s}$, it is also predicted that the more abundant production of charm in the initial state would lead to charmonium regeneration from recombination of c and $\bar{c}$ quarks at the hadronization, resulting in an enhancement in the number of observed J/ψ.

ALICE measured the J/ψ nuclear modification factor as a function of collision centrality at forward rapidity. J/ψ mesons are measured down to $p_{\rm t} = 0$ without subtracting the contribution from feed-down from B meson decays. The resulting $R_{\rm AA}$, shown in Fig. 7, shows a suppression almost independent of centrality and smaller than that observed by the PHENIX experiment at RHIC in the forward rapidity region [16]. At the LHC, ATLAS and CMS measured J/ψ at mid-rapidity and high $p_{\rm t}$ ($>$ 6.5 GeV/c) finding a stronger suppression than that observed by ALICE at forward rapidity and low $p_{\rm t}$, and also stronger than that measured at RHIC at central rapidity. Overall, the LHC results on J/ψ nuclear modification factor suggest that the J/ψ suppression depends on $p_{\rm t}$ and that regeneration mechanisms may play an important role at low $p_{\rm t}$. For a deeper understanding, it is crucial to address the initial state effects by measuring J/ψ production in p–A collisions.

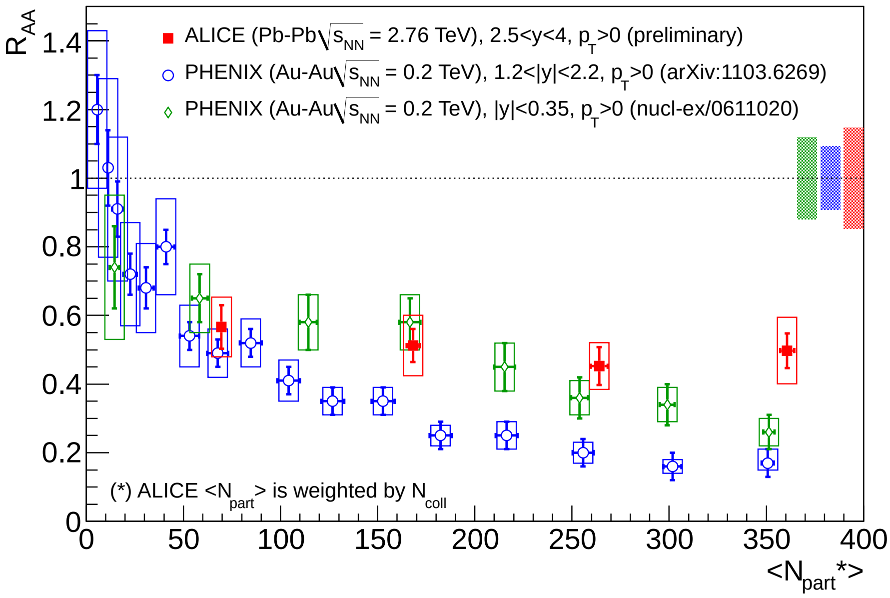

Figure 7: Inclusive J/ψ $R_{\rm AA}$ in $2.5 < y < 4$ in PbPb collisions. The result is compared to PHENIX results in $1.2 < |y| < 2.2$ and $|y| < 0.35$. For ALICE results, the $\langle N_{\rm part}\rangle$ values are weighted by the number of nucleon-nucleon collisions to account for the large centrality bin size. From Ref. [16].

6. Highlights from p–p studies: the J/ψ polarization

As discussed in the Introduction, ALICE can also study genuine p–p physics issues. A remarkable example is given by the study of the charged particle multiplicity in p–p collision, where the ALICE result at $\sqrt{s} = 900$ GeV has represented the first physics results published after the start-up of the LHC [17].

Another very interesting study carried out by ALICE is the polarization of the inclusive J/ψ produced in p–p collisions at $\sqrt{s} = 7$ TeV. The polarization λ_θ of quarkonium states, when studying their dilepton decay, is obtained from the polar angle distribution of the decay products, as

$dN/d\cos\theta \propto (1+\lambda_\theta \cos^2\theta)$. It is a crucial observable for the understanding of the production mechanisms in QCD-inspired models. In particular, Non-Relativistic QCD (NRQCD), the first theoretical approach to satifactorily reproduce the transverse momentum distribution for J/ψ production at Tevatron, predicted a transverse ($\lambda_\theta > 0$) polarization of J/ψ in contrast with the observation of a slightly longitudinal polarization [18]. This puzzling observation can now be tested at the much higher LHC energies, and ALICE (see Fig. 8) has recently measured, in the transverse momentum region $0 < p_{\rm T} < 8$ GeV/c, λ_θ values consistent with zero, i.e. no polarization [19]. First NRQCD theoretical calculations for LHC energy are now appearing [20] and the agreement with the ALICE result is promising, showing that a final validation of this QCD-inspired theoretical approach is within reach.

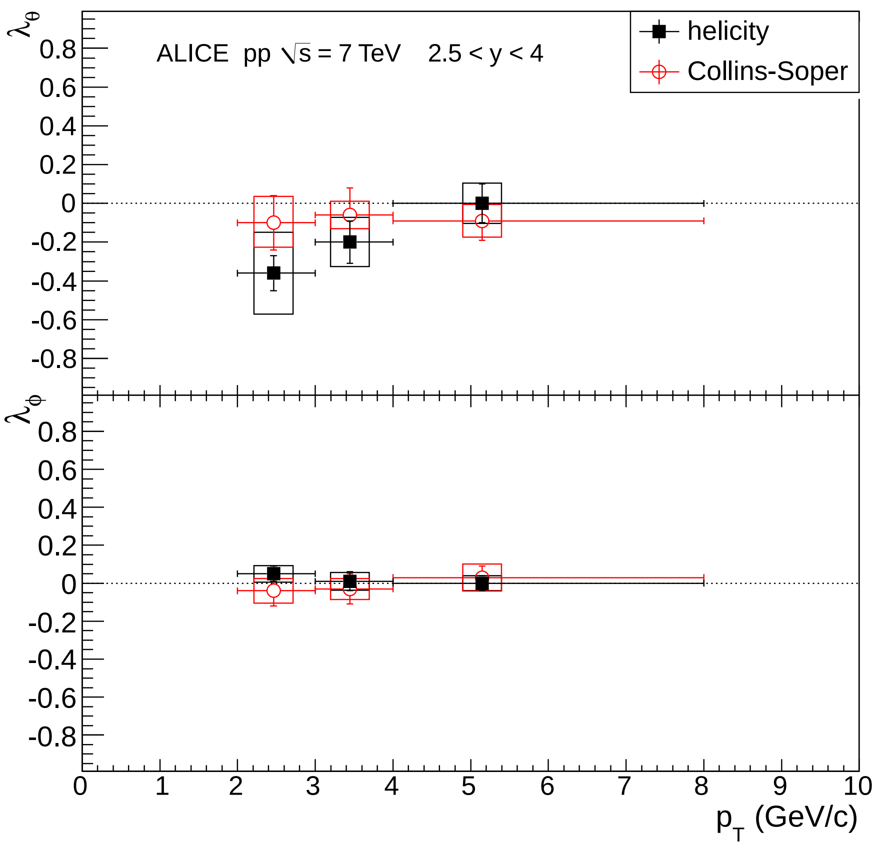

Figure 8: The polarization parameters λ_θ and λ_ϕ (the last one not discussed in the text) as a function of $p_{\rm t}$ for inclusive J/ψ, measured in the helicity (closed squares) and Collins-Soper (open circles) frames, the two most commonly used reference frames for polarization measurements (see [19] for details). The error bars represent statistical errors, while systematic uncertainties are shown as boxes. From Ref. [19].

7. Conclusions and prospects

The first Pb–Pb run at the LHC enabled the study of heavy-ion physics in a new energy regime, about 14 times higher than that attained at RHIC. The studies on the bulk of soft particles produced in the collision demonstrate that the fireball formed in heavy-ion collisions at the LHC reaches higher temperatures and energy densities, lives longer, and expands faster reaching a larger size at the freeze-out as compared to lower energies. With the first heavy-ion run, we also started to exploit the abundance of high p_t and large mass probes which allows high precision measurements in the hard physics sector.

Further progress is expected from the analysis of the larger (by more than one order of magnitude) Pb–Pb data sample that has been collected at the end of 2011. In particular, the study of the nuclear modification factor for hard probes, such as open charm and quarkonia, will be carried out with fine binnings in centrality, transverse momentum and rapidity.

Finally, p–A collisions in the LHC are foreseen at the end of 2012 and will be extremely important to study cold nuclear matter effects on the various observables described in this paper.

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