ALICE OVERVIEW[*]

Francesco Prino

for the ALICE Collaboration

INFN, Sezione di Torino, Via P. Giuria 1, 10125 Torino, Italy

A general overview of the results obtained by the ALICE experiment from the analysis of the Pb–Pb data sample collected at the end of 2010 during the first heavy-ion run at the LHC is presented.

1. Introduction

In November 2010, Pb nuclei were collided for the first time at the LHC at the centre-of-mass energy $\sqrt{s_{NN}} = 2.76$ 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.

In the next sections, an overview of the ALICE results from the first heavy-ion run at the LHC is presented.

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2. Global event characteristics

The multiplicity of produced particles, quantified by the charged particle density per unit of rapidity $(dN_{ch}/d\eta)$ at mid-rapidity, was measured as a function of the collision centrality [1, 2]. The measurement of the $dN_{ch}/d\eta$ 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 $(dN_{ch}/d\eta)/(N_{part}/2)$ 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_t was estimated by measuring the charged hadronic energy with the tracking system and adding the contribution of neutral particles. The measured E_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$^2 c$) (where τ is the formation time), about a factor 3 larger than the corresponding one at RHIC [4].

The system size is measured from the HBT radii extracted from the study of two-pion correlations [5]. 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 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 [6].

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) [7,8]. 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 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 [7].

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. Rescatterings 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_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 [9]. 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_t-differential elliptic flow, $v_2(p_t)$, measured at the LHC is compatible with that observed at RHIC [9]. The 30% increase in the p_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 $v_2(p_t)$ 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 [10].

The predictions from hydrodynamics, based on the assumption that the QGP shear viscosity over entropy ratio does not change from RHIC to LHC [11], provide a good description of the p_t spectra of pions and kaons in the most central collisions, but disagree with the measured (anti-)proton spectrum, both in shape and yield. This hydrodynamic description reproduces well also the measured $v_2(p_t)$ for the three particle species for semi-peripheral (40–50%) collisions, while for more central (10–20%) reactions it misses the (anti-)protons [10]. An hybrid approach [12] that couples viscous hydrodynamics of the QGP to a microscopic kinetic description of the hadronic phase reproduces significantly better both the $v_2(p_t)$ and the shape of the p_t spectra of (anti-)protons [7,10]. This is an indication for a significant contribution from the extra flow built up in the hadronic phase.

Higher Fourier harmonics in the particle azimuthal distributions were also measured [13]. In particular, odd harmonics, *e.g.* v_3 and v_5, can take non-zero values due to fluctuations in the spatial distribution of the participant nucleons, which cause event-by-event fluctuations of the plane of symmetry Ψ_n relative to the reaction plane. According to hydrodynamics, odd harmonics are particularly sensitive to both the viscosity and the initial conditions of the system. Indeed, the measured triangular flow (v_3) is significantly larger than zero and does not depend strongly on centrality [14]. The presence of higher harmonics provides a natural explanation of the structures observed in the two-particle azimuthal correlations at low p_t, namely the "ridge" at $\Delta\varphi \approx 0$ and large $\Delta\eta$ and the double-bump in the away side ($\Delta\varphi \sim \pi$), already observed at RHIC [15]. These structures in the two-particle correlations were studied in detail by performing a Fourier analysis of the $\Delta\eta - \Delta\varphi$ correlations with large $\Delta\eta$ gap [16]. The data are found to be well described by the first five terms of the Fourier series. At low p_t (*i.e.* $p_t \lesssim 3$–4 GeV/c), the Fourier components extracted from two-particle correlations factorize into single-particle harmonic coefficients which agree with the measured anisotropic flow coefficients. This indicates that the features observed in two-particle correlations at low p_t are consistent with the collective response of the system to the initial state geometrical anisotropy.

4. Particle abundances and strangeness production

The p_t differential distributions and the total yields were measured by ALICE for many hadronic species [7, 17]. 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 [18, 19, 20].

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 ratio 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 [19].

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, can be compared with the predictions of a thermal model based on gran-canonical ensemble with temperature $T_{\rm chem} = 164$ MeV at the chemical freeze-out and bary-

ochemical potential $\mu_B = 1$ MeV [21]. All the measured yields, with the notably exception of protons, are found to agree with the thermal model predictions. The measured proton/pion ratio falls significantly ($\approx 50\%$) below the thermal model expectation [18].

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 [20]. 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 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, $\langle N_{\rm coll} \rangle$. 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 $p_{\rm t}$ 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 $p_t = 50$ GeV/c for various centrality classes [22]. For all collision centralities, the R_{AA} presents a minimum at $p_t \approx 6$–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 $p_t > 30$ 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.

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_S^0 and Λ [23]. At high transverse momenta ($p_t > 6$ GeV/c), the suppression of $\pi^{\pm}$, K_S^0 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_S^0 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_S^0 ratio discussed in Sec. 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 A–A 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 for the 20% more central collisions shows a strong suppression, reaching a factor 4–5 for $p_t > 5$ GeV/c [25]. 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 shows, 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 [27]. 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 flavour decays [28]. A suppression of the muon yield which increases with increasing centrality is observed.

The elliptic flow of D^0 mesons was also measured and shows a hint of non-zero v_2 of charmed hadrons in the range $2 < p_t < 5$ GeV/c [26].

5.3. Quarkonia

Quarkonium states are expected to be suppressed ($R_{AA} < 1$) in the QGP, due to the colour screening of the force which binds the $c\bar{c}$ (or $b\bar{b}$) state. Quarkonium suppression is anticipated to 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. 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 $p_t = 0$ without subtracting the contribution from feed-down from B meson decays. The resulting R_{AA} shows a suppression almost independent of centrality and smaller than that observed by the PHENIX experiment at RHIC in the forward rapidity region [29]. At the LHC, ATLAS and CMS measured J/ψ at mid-rapidity and high p_t (> 6.5 GeV/c) finding a stronger suppression than that observed by ALICE at forward rapidity and low p_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_t and that regeneration mechanisms may play an important role at low p_t. For a deeper understanding, it is crucial to address the initial state effects by measuring J/ψ production in p–A collisions.

6. Summary and conclusions

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 Pb–Pb data sample that will be collected in 2011 as well as from the first p–A collisions foreseen in 2012.

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