Overview of results from ALICE at the CERN LHC

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Abstract. ALICE, a general-purpose heavy-ion detector at the CERN Large Hadron Collider, has collected data from pp, p–Pb and Pb–Pb collisions. The results show intriguing properties of the produced matter in Pb–Pb collisions at \( \sqrt{s_{NN}} = 2.76 \, \text{TeV} \) demonstrating that the created system is larger, hotter and denser compared to the one created in heavy-ion collisions at lower energies and it still behaves like an almost perfect, strongly interacting liquid. The high energy and luminosity at LHC open up the possibility to explore high-\( p_T \) and high-mass observables as probes of the medium at the new energy regime.

1. Introduction
QCD calculations on the Lattice predict that, at certain critical conditions of energy density and temperature, normal nuclear matter undergoes a phase transition to a deconfined state of quarks and gluons known as Quark-Gluon Plasma (QGP), where chiral symmetry is also restored \([1, 2]\). Experimentally, ultra-relativistic heavy-ion collisions make it possible to reach and exceed the critical energy density (with latest estimates being close to 0.5 GeV/fm\(^3\) \([1]\)) thus allowing to study, in the laboratory, strongly interacting matter under extreme conditions and the details of the QCD phase transition. After intense theoretical and experimental research at SPS and RHIC the first experimental results from the LHC heavy-ion program \([3, 4]\) confirmed the RHIC observations \([5]\) and provided additional evidence of the existence of this new state of matter at the new energy regime \([6]\). Hence, the focus now turns towards the detailed characterization of the properties of the QGP \([7]\).

ALICE, designed as a multi-purpose detector \([8]\), measures a multitude of observables characterizing the different stages of the collision with the aim to deduce the properties of the created system in terms of its equation of state and transport properties \([9]\). A short overview of ALICE experimental results, mainly from the analysis of Pb–Pb collisions at \( \sqrt{s_{NN}} = 2.76 \, \text{TeV} \), is presented.

2. Bulk properties
The properties of the bulk matter created in heavy-ion collisions and its dynamic evolution is studied by measuring the characteristics of the majority of particles with momenta below a few GeV/c. They include multiplicity distributions, which can be related to the initial energy density, yields and momentum spectra of identified particles, which are determined by the conditions at and shortly after hadronisation, and particle correlations, which measure the space-time evolution of the source and its collective transport properties.
Figure 1. (Left) Charged particle pseudorapidity density, \(dN_{\text{ch}}/d\eta\), per participant as a function of \(\sqrt{s_{\text{NN}}}\) for nucleus–nucleus, proton–nucleus and proton–proton collisions. (Right) Charged particle pseudorapidity density, \(dN_{\text{ch}}/d\eta_{\text{lab}}\), in NSD p–Pb collisions at \(\sqrt{s_{\text{NN}}} = 5.02\) TeV compared to theoretical predictions.

**Multiplicity** Particle production at low-\(p_T\) is a non-perturbative process and cannot be calculated based on first principles (QCD). The first measurements of particle multiplicities at LHC were eagerly awaited to constrain model predictions which varied widely even after the RHIC data became available. Within days after the first ion collisions a charged particle pseudorapidity density of \(dN_{\text{ch}}/d\eta \approx 1600\) was published by ALICE for the 5% most central Pb–Pb collisions in the central pseudorapidity \(|\eta| < 0.5\) [10]. Compared to the RHIC measurement of \(dN_{\text{ch}}/d\eta \approx 690\) for the 5% most central Au–Au collisions at \(\sqrt{s_{\text{NN}}} = 200\) GeV/c [11] shows an increase of \(\approx 2.3\).

Figure 1–left presents the charged particle pseudorapidity density per participant measured in pp, p–Pb and Pb–Pb collisions by the LHC experiments [12, 13, 14] compared to nucleon–nucleon and nucleus-nucleus data at lower energies. The energy dependence of \(dN_{\text{ch}}/d\eta\) shows that particle production in Pb–Pb at LHC is no longer compatible with a logarithmic dependence with \(\sqrt{s_{\text{NN}}}\), as it was true for the data up to the top RHIC energy [15], but follows a power law with an exponent of 0.15. The proton–nucleus and proton–proton data show a less steep dependence on energy than the Pb–Pb data and they can both be described by a power law with slightly different exponents of 0.10 and 0.11, respectively.

To shed light into the different production mechanisms p–Pb studies are of particular interest because of their potential to disentangle final-state effects characteristic of the formation of hot QCD matter, from initial-state effects already present in cold nuclear matter. Figure 1–right shows the \(dN_{\text{ch}}/d\eta_{\text{lab}}\), measured by ALICE, in Non-Single Diffractive (NSD) p–Pb collisions at \(\sqrt{s_{\text{NN}}} = 5.02\) TeV [16]. The forward–backward asymmetry between the proton and lead hemisphere is clearly visible. The measurement is compared to particle production models [17, 18, 19, 20, 21] that describe similar measurements in other collision systems; see for details [16]. Most models which include shadowing [21] or saturation [17, 20], approximately get the right value of \(dN_{\text{ch}}/d\eta_{\text{lab}}\). HIJING 2.1 [21], where the gluon shadowing parameter \(s_g = 0.28\) was tuned to describe the RHIC data [22, 15], describes the pseudorapidity distribution quite well.

**Energy density** The measured \(dN_{\text{ch}}/d\eta\) can be related to the initial energy density of the created system using the formula proposed by Bjorken [23]. The energy density reached in central Pb–Pb collisions of about \(\epsilon = 15\) GeV/fm\(^3\) [24] is almost three times higher than the one reported at RHIC [5] and well above the critical energy density required for the predicted phase transition.
Initial temperature  The relative increase of energy density from RHIC to LHC implies an initial temperature at LHC of ≈ 300 MeV for central Pb–Pb collisions. This is confirmed by the measurement of direct thermal photons which are emitted at the very initial stage of the collision. Figure 2–left shows the $p_T$ spectrum of direct photons measured by ALICE using the measurement of $\gamma$ conversions for the 40% most central Pb–Pb collisions [25]. At $p_T > 4$ GeV/c the spectrum is well reproduced by the NLO pQCD prediction for pp collisions, scaled by the number of binary collisions. However, below 2 GeV/c there is an excess attributed to thermal photons. An exponential fit in the $p_T$ range 0.8–2.2 GeV/c yields an inverse slope parameter $T = (304 \pm 51)$ MeV, where the quoted error includes both the statistical and systematic uncertainties. The LHC value is about 40% higher than that measured in a similar analysis by PHENIX [26].

Source size and lifetime  The space-time evolution of the expanding system has been studied using identical pion interferometry techniques (known as Hanbury-Brown-Twiss correlations [27]) in 5% central Pb–Pb collisions showing that the freeze-out volume (the size of matter when strong interactions cease) is 5000 fm$^3$, two times larger than the one measured at RHIC, and its total lifetime (the time between collisions and freeze-out) is 10 fm/c, 30% larger than at RHIC. The extracted volume, plotted as a function of charged particle multiplicity, together with the world data, shows a linear monotonic increase, seen in Fig. 2–right, where the freeze-out volume is given as the product of a geometrical factor and the HBT-radii (called $R_{\text{long}}, R_{\text{side}}, R_{\text{out}}$) [28]. Extrapolation to zero $dN_{\text{ch}}/d\eta$ shows that the source size coincides with the initial volume of a Pb nucleus ($\approx 800$ fm$^3$) and the source lifetime, not shown here, vanishes [6].

In general, and as expected, the system created in central Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV at LHC is characterized by higher energy density and temperature, bigger volume at freeze-out and longer life-time, than the one created at the highest RHIC energies in Au–Au collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV. Further details of its properties are reflected at the spectra and correlations of different particle species.

2.1. Identified particle spectra and yields  The energies available at the LHC open up the possibility for detailed measurements at an extended $p_T$ range. In ALICE $p_T$ spectra of identified particles, shown in Fig. 3, were measured
Transverse momentum ($p_T$) spectra of identified particles in Pb–Pb and pp collisions up to 20 GeV/$c$ using different particle identification techniques.

by various techniques, and for the first time up to $p_T = 20$ GeV/$c$ for $\pi$, K and p including the TPC $dE/dx$ measurements at the relativistic rise above 5 GeV/$c$ [29]. Measurements at RHIC have shown that at low $p_T < 2$ GeV/$c$, the dynamics of bulk matter can be described by Relativistic Hydrodynamical Models (RHM), at high $p_T > 8$ GeV/$c$, the spectra reflect the interaction of partons from hard scatterings with the medium while at intermediate $p_T$, the interplay of soft and hard processes is reflected.

Even at LHC energies about 95% of particles are produced with $p_T$ below $\approx 1.5$ GeV/$c$ reflecting the dynamics of the expanding system which shows collective behaviour that can be described in terms of hydrodynamics [30].

Transverse momentum spectra at low-$p_T$. In particular, the $p_T$ distributions at low-$p_T$ reflect the conditions at kinetic freeze–out, where particle momenta are fixed. Details on the ALICE measurements of low-$p_T$ spectra of identified charged hadrons ($\pi$, K and p) are presented in this conference [31]. The spectra, measured in the $p_T$ range $0.1 < p_T < 4.5$ GeV/$c$ at mid–rapidity ($|y| < 0.5$), for the 5% most central Pb–Pb collisions [32], are harder than the ones measured in central Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV at RHIC [33, 34] reflecting the stronger radial flow at LHC. A blast–wave fit of the spectra [35] yields the values of the kinetic freeze–out temperature $T_{\text{kin}} = 96 \pm 10$ MeV, similar to the one at RHIC, and of the collective radial flow velocity $\langle \beta_T \rangle = 0.65 \pm 0.02$, 10% higher than the one at RHIC. The ALICE data compared to hydrodynamical calculations [36, 37, 38] show better agreement when interactions during the hadronic phase are taken into account.

Particle yields and thermal models. The conditions at chemical freeze–out, where particle abundances are fixed, are characterized by the chemical freeze–out temperature ($T_{ch}$) and baryochemical potential ($\mu_B$) and are determined from measured particle yields via thermal model calculations. The ALICE measurements for the 20% most central Pb–Pb collisions, presented in this conference [31], are compared to a thermal model prediction [39] with chemical freeze-out temperature $T_{ch} = 164$ MeV and baryochemical potential $\mu_B = 1$ MeV, very similar to the prediction of $T_{ch} = 170$ MeV given in [40]. The measured yields of p and $\Lambda$'s are significantly
lower than those predicted by the model calculations and the ones measured at RHIC. When adjusting $T_{ch}$ to describe the data, a much lower temperature $T_{ch} = 152$ MeV is obtained and the fit does not reproduce the data well ($\chi^2 = 39.6$ per 9 d.o.f.) [41]. A possible explanation for these deviations from the thermal model predictions may be interactions in the hadronic phase. In particular, large cross sections for baryon–antibaryon annihilation can be the origin of the lower yields of some baryons [42, 43]. This is also supported by ALICE femtoscopic measurements of $p\bar{p}$ and $\Lambda \bar{\Lambda}$ correlations [44, 45].

2.2. Azimuthal anisotropies

Measurements of azimuthal particle anisotropies probe collective phenomena characteristic of a bulk system such as the one expected to be created in heavy–ion collisions [46]. In non-central collisions, pressure gradients, developed in the overlap region of the two colliding nuclei, transform, through interactions between the produced particles, the initial spatial anisotropy into an observed momentum anisotropy, leading to an anisotropic particle distribution $\frac{dN}{d\phi}$. This anisotropy is usually quantified via a Fourier expansion of the azimuthal distribution of particles [47], $\phi$, with the Fourier (or flow) coefficients $v_n$ dependent on $p_T$ and given by:

$$v_n = \langle \cos [n(\phi - \Psi_n)] \rangle,$$

where $n$ is the order of the flow harmonic, $\phi$ the azimuthal angle of the particle and $\Psi_n$ the azimuthal angle of the initial state spatial plane of symmetry of harmonic $n$. The second Fourier coefficient, $v_2$, is called elliptic flow with $\Psi_2 \approx \Psi_{RP}$ where $\Psi_{RP}$ is the reaction-plane angle, defined by the beam direction and the impact parameter plane. It has been extensively studied as it was first suggested in [48] as a measure of collective phenomena of bulk matter. It was contrasted to thermal motion, a superposition of independent pp collisions, where particle momenta are not correlated relative to the reaction plane.

Higher order odd harmonics had usually been neglected because they were expected to be zero due to symmetry reasons. However, the statistical nature of individual nucleon–nucleon collisions can lead to highly irregular shapes of the reaction zone and the corresponding initial energy and pressure distributions [49, 50] resulting in event-by-event fluctuations of the elliptic flow direction and magnitude and other $v_n$ coefficients. Different experimental methods are used to measure the symmetry plane angles and the different $v_n$ coefficients, via two- and multi-particle correlations [51, 52, 53] each one of them being sensitive to different effects, thus allowing a comprehensive study of non-flow contributions and fluctuations.

Properties of the medium and hydrodynamic models The first ALICE measurements [3] confirmed hydrodynamic predictions and indicated that the system created in Pb–Pb collisions at LHC still behaves as a strongly interacting almost perfect liquid with minimal shear viscosity to entropy ratio, $\eta/s$, like the one at RHIC [54, 55, 56, 57, 58]. Additional constrains on $\eta/s$ were obtained studying $v_2$ as a function of centrality and $p_T$ for different particle species as well as from measurements of $v_3$. Comparison with models yields $\eta/s$ in the range $1–2.5 \times 1/4\pi$ (with $\hbar = k_B = 1$) [46], very close to the lower bound conjectured by AdS/CFT for a good relativistic quantum fluid [59], where the uncertainty in the determination of $\eta/s$ comes mainly from the definition of the initial conditions. Recent results [46] show that IP-Glasma initial conditions [60] and average values for $\eta/s$ of 0.2 for Pb–Pb collisions at the LHC and 0.12 for Au–Au collisions at top RHIC energies, provide a good description of all currently available data.

$v_n$ measurements in extended pseudorapidity ALICE extended the azimuthal anisotropy measurements both in pseudorapidity and $p_T$ [61, 62]. At mid-rapidity five harmonics were measured while $v_2$ and $v_3$ were measured up to $\eta = 5$. Figure 4–left shows the pseudorapidity dependence of $v_2$ and $v_3$ up to $\eta = 5$ for very central (0–5%) and peripheral (50–60%) collisions. The anisotropic flow is almost independent of pseudorapidity for $|\eta| < 2$ and decreases at
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Figure 4. (Left) $v_2$ and $v_3$ pseudorapidity dependence for very central (0–5%) and peripheral (60–80)% Pb–Pb collisions. (Right) $v_2$ longitudinal scaling over two orders of magnitude in collision energy.

Larger rapidities. The integrated $v_2$ increases by 20–30% at mid-rapidity and about 30% at forward rapidity relative to RHIC, at the higher limit of predictions, but still in agreement with hydrodynamic model calculations. $v_3$ shows a weak centrality dependence with similar magnitude for the very central and peripheral collisions. For the 5% most central collisions $v_2$ exhibits a similar trend and magnitude as $v_3$. These measurements indicate that $v_2$ is driven by geometry while $v_3$ is driven by initial state fluctuations, which are also generating a non-zero $v_2$ for the very central collisions. The elliptic flow measurements in the extended pseudorapidity range were performed with two- as well as four-particle cumulant methods allowing to study flow fluctuations up to very forward pseudorapidities [61].

Extending the measurement to $\eta = 5$ allows testing the limiting fragmentation picture first observed at RHIC; namely, $v_2$ was found to be independent of collision energy when studied in the rest frame of one of the colliding nuclei. The ALICE $v_2$ measurement, shown in Fig. 4–right, together with the RHIC data, confirms that this longitudinal scaling holds from the lowest RHIC energy $\sqrt{s_{NN}} = 19.6$ GeV up to the TeV regime at LHC $\sqrt{s_{NN}} = 2.76$ TeV [63].

$v_n$ measurements in extended $p_T$ ALICE also extended the measurement of the charged particle anisotropies ($v_2$, $v_3$ and $v_4$) up to $p_T \approx 20$ GeV/c as shown in Fig. 5 [62]. The fourth order harmonic anisotropy was measured with respect to the second and fourth order event planes, $v_4(\Psi_2)$ and $v_4(\Psi_4)$. The difference between the two is totally due to fluctuations in the fourth order harmonic flow and as such provides important constraints on the physics and origin of the flow fluctuations. Significant non-zero $v_2$ and $v_3$ were found up to the highest measured transverse momenta. At $p_T > 10$ GeV/c the elliptic flow results are well described by a model [64] which takes into account collision and radiative energy loss in an expanding medium.

In general, the shape of the $p_T$-differential anisotropic flow suggests the existence of several regions in the transverse-momentum space with distinctly different underlying physics processes. It is now widely accepted that at $p_T < 1–2$ GeV/c the flow pattern is mostly determined by hydrodynamical flow exhibiting a typical "mass splitting" [65]. At higher momenta, $p_T > 10$ GeV/c, the anisotropy seems to be defined by the energy loss and one would expect little particle type dependence in this region. The intermediate $p_T$ region is less understood.

$v_2$ of identified particles Hydrodynamic model calculations predict a characteristic dependence of $v_2$ on the particle mass at low values of transverse momentum ($p_T < 2$ GeV/c) induced by the collective radial expansion of the system, which being cumulative throughout the whole collision,
Figure 5. $p_T$-differential event anisotropies, $v_2$, $v_3$, $v_4$ measured for different centrality classes of Pb–Pb collisions up to $p_T \approx 20$ GeV/c.

Figure 6. (Left) The $p_T$-differential $v_2$ for different particle species. (Right) The dependence of $v_2/n_q$ on the scaled kinetic energy. In both plots, the 10–20% centrality bin is shown.

has a significant contribution from the partonic phase. However, the hadronic rescattering that follows might mask the information of the early stage. Hence, particles with small hadronic cross section could be more accurate probes of the early stage of the collision.

Figure 6–left shows the $p_T$-differential $v_2$ for different particle species ($\pi$, K, $K^0_S$, $\bar{p}$, $\Lambda$, $\phi$) measured in the 10–20% centrality range. At $p_T \leq 2$ GeV/c, a clear mass ordering is seen attributed to collective radial flow that shifts heavier particles to higher $p_T$. Remarkable is the flow of the $\phi$-meson which has a mass similar to the one of the proton. While at low-$p_T$ the $v_2$ of $\phi$ is similar to the one of the protons, at high-$p_T$ follows the trend of mesons. The measurements are compared to hydrodynamical calculations [36] using $\eta/s = 0.2$ and the Color Glass Condensate (CGC) initial conditions, shown by the solid curves. The model reproduces the $p_T$ dependence of $v_2$ for $\pi$ and K up to $p_T \approx 2$ GeV/c but overestimates $v_2$ for heavier particles. However, including a hadronic phase improves the agreement with the data.
Quark number scaling

At RHIC it was observed that all baryons exhibit similar flow which differs from the flow of mesons, approximately by a factor 3:2 [66]. These findings led to the interpretation that hadron formation is dominated by quark coalescence at the end of the partonic evolution [67]. ALICE studied quark scaling at different centrality ranges and different representations. Figure 6–right shows the $v_2$ of identified particles in the same centrality range, 10–20%, scaled by the number of constituent quarks, $n_q$ ($n_q = 2$ and 3 for mesons and baryons, respectively), as a function of the transverse kinetic energy, $K E_T = (m_t - m_0)$, scaled by $n_q$, and divided by the polynomial fit to the pion elliptic flow. In this representation quark scaling is broken below 1 GeV while at higher $p_T$ holds at the level of 20%.

3. Hard processes and medium induced effects

The high energy and luminosity at LHC lead to large cross sections and production rates for hard processes, i.e. those involving high-momenta or high-mass scales. Such probes, originating from hard parton scatterings with large momentum transfer at the initial stage of the collision, are calculable with pQCD in elementary collisions and can be used to probe the created medium as they are expected to interact with it prior to hadronisation.

In particular, the energy of the partons is reduced through collisional energy loss and medium-induced gluon radiation. Based on QCD, it is predicted that gluons lose a larger amount of energy than quarks because of the dependence of the energy loss on the colour coupling factor [68]. In addition, the in-medium effects are expected to be further reduced for heavy quarks due to a reduced small angle gluon radiation known as the “dead–cone effect” [69].

On the other hand, the “J/Ψ suppression” was one of the first “QGP signatures” [70] and a pattern of “sequential melting” of quarkonia bound states was predicted to signal deconfinement due to colour screening [71, 72]. However, at LHC, due to the abundant production of c and b quarks a recombination effect may be expected during the collision history [73, 74, 75] or at hadronization [76].

Hence, the details of the production and propagation of high-$p_T$ and high-mass probes are studied to explore the mechanisms of parton-energy loss and deconfinement in the medium. Experimentally, several techniques are used to investigate suppression effects. One can compare the relative production of single particles or fully reconstructed jets in nuclear collisions to expectations from superposition of independent nucleon–nucleon collisions or study angular particle correlations. The suppression is usually quantified by the nuclear modification factor, $R_{AA}$, which is the ratio of yields in A–A collisions to the pp cross section scaled by the number of binary collisions,

$$R_{AA} = \frac{(1/N_{\text{ext}}^{AA})d^2N_{ch}^{AA}/dp_Td\eta}{\langle N_{\text{coll}} \rangle (1/N_{\text{ext}}^{pp})d^2N_{ch}^{pp}/dp_Td\eta},$$

(2)

where the number of binary nucleon–nucleon collisions $\langle N_{\text{coll}} \rangle$, is given by the product of the nuclear overlap function $T_{AA}$ calculated from the Glauber model [77], and the inelastic NN cross–section $\sigma_{\text{inel}}^{NN}$. In the absence of nuclear effects $R_{AA}$ is unity by construction.

3.1. High–$p_T$ particles and jets

Charged particles $R_{AA}$ in Pb–Pb collisions A large suppression of high-$p_T$ hadrons was first observed at RHIC [5], in the 5% most central Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV relative to pp, whereas particles that do not interact strongly, e.g. photons, are not modified. The reported suppression is a factor of 5 at $p_T = 5–6$ GeV/c and independent of $p_T$ up to 20 GeV/c. At LHC, the suppression is confirmed, the accessible $p_T$ range is significantly extended, and the measurements include particles, such as Z, W and isolated photons, which show no modification [78, 79, 80].
Figure 7. (Left) The nuclear modification factor $R_{AA}$ for the 5% most central Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, compared to CMS data and model calculations. (Right) The nuclear modification factor $R_{p\bar{p}}$ for p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV compared to $R_{p\bar{p},Pb}$ for the 5% most central and 70–80% peripheral Pb–Pb collisions.

Figure 7–left shows the charged particles $R_{AA}$ for the 5% most central Pb–Pb collisions [81]. The ALICE results (full circles), measured at mid-rapidity, are in good agreement with the CMS measurement [82] (full squares) within the uncertainties. At $p_T \approx 2$ GeV/$c$ a pronounced maximum is observed which is interpreted as another manifestation of collective radial flow [6]. At higher $p_T$, $R_{AA}$ exhibits a minimum, reaching $\approx 0.13$ at $p_T = 5–7$ GeV/$c$, a slightly lower value than the one at RHIC, where $R_{AA} \approx 0.2$. Above 7 GeV/$c$, $R_{AA}$ increases to $\approx 0.4$ at $p_T > 30$ GeV/$c$ and remains flat up to more than 100 GeV/$c$ (as measured by CMS [82]). The measurements are compared to model calculations that used RHIC data to calibrate the medium density and implement different energy-loss mechanisms [83]. Several of them can reproduce qualitatively the increase of $R_{AA}$ with increasing $p_T$. This rise can be understood as a decrease of the parton fractional energy loss with increasing $p_T$, reflecting the weak energy dependence of pQCD radiative energy loss on parton energy.

The ALICE $R_{AA}$ measurement for $\pi$, $K$ and $p$, presented in this conference [31], show that while at low $p_T$ a hierarchy of suppression is observed, reflecting strong radial flow, at $p_T$ above $\approx 8–10$ GeV/$c$, the suppression seems to be the same for the different particle species indicating that the effect of the medium is the same for all light-flavoured quarks.

**Charged particles $R_{AA}$ in p–Pb collisions** As a control experiment to clarify initial state effects the data from the p–Pb pilot run at $\sqrt{s_{NN}} = 5.02$ TeV are used [84] and the nuclear modification factor is compared to Pb–Pb results as shown in Fig. 7–right. The charged particles $p_T$ distribution is measured around mid-rapidity in the $p_T$ range $0.5 < p_T < 20$ GeV/$c$. The $R_{p\bar{p}}$, shows a suppression of charged particle production in p–Pb collisions for $p_T < 2$ GeV/$c$ followed by a rise to $R_{p\bar{p}} \approx 1.1$ for $p_T \approx 4$ GeV/$c$ and is consistent with unity for $p_T > 6$ GeV/$c$. The observed trends qualitatively resemble the $R_{dAu}$ at RHIC although, the enhancement shown by ALICE data is less than that observed at RHIC. At low-$p_T$ the suppression might be related to parton shadowing or saturation while the rise at $p_T \approx 4$ GeV/$c$ is interpreted as originating from multiple scattering in the initial phase of the collision and is known as Cronin effect.

The $R_{p\bar{p}}$ is compared to the Pb–Pb central (0–5%) and peripheral (70–80%) collisions. Exhibiting a rather good $N_{part}$ scaling for $p_T > 5$ GeV/$c$ the p–Pb data demonstrate that the strong suppression of hadron production at high $p_T$ observed in central Pb–Pb collisions at LHC is a fingerprint of the hot quark-gluon matter created in Pb–Pb collisions.
Reconstructed jets $R_{AA}$ Similarly, the properties of the medium are reflected in the modification of fully reconstructed jets. The ALICE measurement of the jet nuclear modification factor $R_{AA}^{Pythia}$, shown in Fig. 8–left, are based on charged particles reconstructed with the TPC and the ITS [85] while the reference jet spectrum was extracted from Pythia and verified with a small sample of pp data at the same energy. The measurement covers the low-$p_T$ region, down to $p_T \approx 30$ GeV/c and extends up to $p_T \approx 110$ GeV/c. The suppression pattern is similar to the one observed for single particles. The jets $R_{AA}^{Pythia}$ exhibits a strong suppression for central events and is gradually increasing for more peripheral collisions.

Particle composition in jet-like structures To study the jet hadronchemistry and the effects of the interplay of soft and hard processes the particle composition in jet-like structures is investigated studying the $p/\pi$ ratio [86, 44]. Jet-like structures are selected via particle correlations in $\Delta\eta$ (difference in pseudorapidity) and $\Delta\phi$ (difference in azimuthal angle) relative to a trigger particle (with $p_T$ in the 5–10 GeV/c range). The $p/\pi$ ratio is defined in the following areas. (a) "bulk": a region far from the trigger particle (b) "peak": particles close in $\Delta\eta$–$\Delta\phi$ to the trigger particle (c) "jet" ("peak"–"bulk"): the region obtained subtracting "peak-bulk" after correcting the "peak" $p/\pi$ ratio for the contribution of the underlying event.

Figure 8–right shows the ratio of the $p/\pi$ spectra in the two angular regions, "bulk" and "jet" ("peak–bulk") as a function of $p_T$. It is found that in the "near-side" of the "jet" region, the $p/\pi$ ratio is consistent with the expectation from pp estimated by Pythia while in the "bulk" region it is compatible with the one obtained for non-triggered events of same centrality (in the $p_T$ range 1.5–4.5 GeV/c where the analysis was performed) i.e. the ratio increases by factor 3–4 compared to pp. This suggests that there is no significant medium-induced modification of jet particle ratios and that the enhancement of the $p/\pi$ ratio observed in Pb–Pb minimum bias events is a result of bulk processes and not jet fragmentation. The detailed understanding of the influence of the medium on jet fragmentation requires further studies.
3.2. Heavy flavour

The abundant production of c and b quarks at LHC (about 100 pairs in a central collision) makes possible highly differential measurements which can probe the details of the underlying physics processes such as deconfinement, energy loss, thermalisation and hadronisation mechanisms. After the first observations of heavy-quark energy loss and collective flow at RHIC [87] ALICE performs a comprehensive study of quarkonia production in nuclear and elementary collisions with emphasis on their dependence on different kinematic variables, measuring them in various decay channels and a wide kinematic range, as detailed in this conference [88] and [89, 90, 91].

Deconfinement and quarkonium suppression Figure 9–left shows the $R_{AA}$ for inclusive $J/\Psi$ as a function of the mean number of participants [92]. The ALICE measurement (full squares) was performed via the $\mu^+\mu^-$ channel at forward rapidity ($2.5 < y < 4$), and covers low-$p_T$ down to $p_T=0$. It shows little centrality dependence, and gives a centrality integrated $R_{AA}^{0%-80%} = 0.545 \pm 0.032$ (stat.) $\pm 0.083$ (syst.). The ALICE $R_{AA}$ is compared with the RHIC measurements at forward (filled points) and central (open points) rapidity [93]. For central collisions, the ALICE data show less suppression than at RHIC at forward rapidity. The difference becomes smaller but still remains significant comparing the ALICE data to the RHIC mid-rapidity data [92]. The ALICE measurements at mid-rapidity show similar trends. For details of the analysis at mid-rapidity see [92, 94] and at forward rapidity [95, 96]. Further differential measurements, as presented in Fig. 9–right, show that a smaller suppression is observed at low-$p_T$ ($p_T < 2$ GeV/c) than at high-$p_T$ ($5 < p_T < 8$ GeV/c) especially in more central collisions.

Such results are qualitatively in agreement with recombination scenarios, where regeneration effects are expected to be important at low $p_T$ and mid-rapidity for central collisions; further details on the measurements and comparisons with models are detailed in this conference [88].

D-mesons $R_{AA}$ and suppression hierarchy Based on the QCD predictions on energy loss, see section 3.1, pions, mostly originating from gluons should be more suppressed than charmed particles and those than particles containing beauty, leading to a hierarchy of suppressions with $R_{AA}^{D^0} > R_{AA}^{D^+} > R_{AA}^{D^{*+}}$. Figure 10–left presents the $R_{AA}$ for prompt D-mesons calculated as the average of the relevant factors for $D^0$, $D^+$ and $D^{*+}$ mesons [97] for the 20% most central Pb–Pb collisions measured at mid-rapidity [98, 99]. A suppression factor of 3–4 is observed corresponding to a minimum of $R_{AA} \approx 0.25$ at $p_T=5–6$ GeV/c.
The nuclear modification factor, $R_{AA}$, for the average D–meson for the 20% central Pb–Pb collisions compared to charged particles and non–prompt J/Ψ from CMS [101]. (Right) The $R_{AA}$ of $D_s$ compared to the one of $D^0$, $D^+$ and $D^{*+}$ for the 0–7.5% centrality range.

To test the predicted hierarchy of suppression, the results are compared to the $R_{AA}$ of charged particles measured also at mid-rapidity, and found to be very similar. At $p_T < 8 \text{ GeV}/c$ the average $R_{AA}$ for prompt D-mesons is slightly higher than the charged-particle $R_{AA}$ (however, still within the systematic uncertainties) showing a weak indication that $R_{AA}^{D} > R_{AA}^{\text{charged}}$. At higher $p_T$ the D-mesons $R_{AA}$ is similar to the one of charged particles (mostly light hadrons) [100], also supported by higher statistics measurements up to $p_T \approx 36 \text{ GeV}/c$ [98, 99]. The ALICE results are compared to the CMS measurements [101] for non–prompt J/Ψ mesons with $p_T > 6.5 \text{ GeV}/c$, mostly originating from B decays, where a weaker suppression is seen suggesting that $R_{AA}^B > R_{AA}^{D_s}$ [102]. While, within the current statistical errors, the measurements indicate that the $R_{AA}$ of non-prompt J/Ψ is larger than that of prompt D-mesons, and the later larger than the one of light hadrons, the current precision of the measurements prevents to conclude with respect to the expected colour charge and mass hierarchy of parton energy loss [90].

Comparisons of the heavy-flavour suppression factor $R_{AA}$ in the most central class to NLO MNR calculations with EPS09 shadowing parametrizations [90] show that the heavy flavour suppression cannot be explained with only nuclear shadowing at $p_T > 4 \text{ GeV}/c$. Detailed studies based on the p–Pb data at 5.02 TeV will clarify the issues of the initial state effects.

$D_s$ $R_{AA}$ and hadronisation mechanism The ALICE measurements of D-mesons are complemented with the first measurement of $D_s$ in heavy-ion collisions [103], of particular interest since it contains $c$ and $s$ quarks and can probe details of the hadronisation mechanism. Figure 10–right shows that in the 8–12 $\text{ GeV}/c$ $p_T$ range the $D_s$ $R_{AA}$ is compatible with that of non-strange charmed mesons exhibiting a suppression factor 4–5 above $8 \text{ GeV}/c$. At lower $p_T$ the $D_s$ $R_{AA}$ seems to increase relative to the one of the $D^0$. However, the current uncertainties preclude any conclusion on the predicted enhancement of $D_s$ mesons relative to non-strange D-mesons [104].

$v_2$ of D-mesons and $J/Ψ$ Further insight on the properties of the medium can be obtained investigating azimuthal anisotropies of heavy-flavoured hadrons. If heavy quarks interact strongly with the medium, heavy-flavoured hadrons should inherit the medium azimuthal anisotropy. Measurements of heavy-flavoured particles $v_2$ at low-$p_T$ can provide information on the degree of thermalisation while at high-$p_T$ on the path-length dependence of energy loss.
Figure 11–right presents the first measurement of J/Ψ v2 at LHC [105]. The pT–differential v2 of inclusive J/Ψ measured at forward rapidities for the 20–60% centrality range shows a non–zero v2 value suggesting that charm quarks may follow the collective behaviour of the bulk system. A similar measurement for prompt D–mesons at mid-rapidity, for the 30–50% centrality range, in the pT range 2 < pT < 6 GeV/c, show a finite v2 value with a significance of 3σ compatible within errors with that of the light hardons [90]. The measurement of the D0 RAA in- and out-of plane azimuthal regions for the 30–50% centrality class, shown in Fig. 11–right [106], indicates larger suppression in the out-of-plane azimuthal region as expected due to the longer path length. Comparisons with models show that at low-pT, both v2 and energy loss could explain the results while at high-pT energy loss seems to be the most probable scenario. A challenge for theory is the simultaneous description of the RAA and v2 and a consistent description of energy loss for light and heavy quarks [88]. In summary, the measurements of v2 and RAA are sensitive to the medium transport properties. However, more precise measurements covering low-pT are required to resolve the contributions of different underlying mechanisms.

4. Summary

ALICE, with unique capabilities on tracking and particle identification, delivered a comprehensive set of results characterising the different stages of Pb–Pb collisions. The created system shows the expected features extrapolating from RHIC thus confirming hydrodynamic and thermal models in the new energy regime. Precision measurements are advancing providing detailed information on its initial conditions and transport properties. The analysis of the p–Pb pilot run already demonstrates that the observed features in the Pb–Pb collisions are not a cold matter effect but the fingerprint of the created quark-gluon plasma.

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