ALICE results from Run-1 and Run-2 and perspectives for Run-3 and Run-4

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1. Introduction

The ALICE detector at the LHC [1, 2] has been conceived specifically to study heavy-ion physics, with a precise tracking of the very high-multiplicity events expected in such collisions and with a powerful particle identification based on different techniques, applicable in a wide momentum range. These features are complementary to the other LHC experiments more focused on hard physics in pp collisions.

The detector (Fig. 1) consists of a central region with tracking and PID detectors embedded in a solenoid with magnetic field B=0.5 T, and a forward arm for muon measurements down to pseudorapidity \( \eta \approx 4 \). ALICE collected Pb–Pb, pp and p–Pb collisions during LHC Run-1 and Run-2 as reported in Tab. 1.

Differently from hadrons, heavy ions are much more extended objects and therefore the characteristics of a collision depend strongly on the relative distance in the transverse plane between the two colliding nuclei. Usually a nucleus–nucleus collision can be seen as an overlap of independent nucleon–nucleon collisions: the number of such collisions depends on the impact parameter which is the distance between the centers of the two colliding nuclei in the plane orthogonal to the beam direction. However such a parameter is not a direct observable in heavy-ion collisions and an experimental definition is usually based on the multiplicity of charged particles, on the transverse energy at midrapidity or on the energy measured in the forward rapidity region. In particular, measurements in ALICE are mostly based on the amplitude of the V0-scintillator signal [3], whose distribution is fitted using a Glauber model [4] to define the centrality classes. Indeed events are grouped into different classes (centralities) which represent the fraction, in percent, of minimum bias collisions starting from those with small impact parameter (centrality \( \sim 0\% \)) to the most peripheral events (\( \sim 100\% \)). The Glauber model also allows us to correlate the centrality with some basic parameters of the collision: the number of participating nucleons (\( N_{\text{part}} \)) and the number of binary collisions (\( N_{\text{coll}} \)).
Table 1. ALICE data taking periods. The nominal magnetic field was $B = 0.5$ T except for Xe–Xe system and few pp data samples at $\sqrt{s} = 13$ TeV in 2015-2017.

<table>
<thead>
<tr>
<th>Year</th>
<th>Systems</th>
<th>$\sqrt{s_{NN/pN}}$ (TeV)</th>
<th>Integrated Luminosity ( nb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run-1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2009-2010</td>
<td>pp</td>
<td>0.9</td>
<td>$\sim 0.15$</td>
</tr>
<tr>
<td>2011</td>
<td>pp</td>
<td>2.76</td>
<td>$\sim 1.1$</td>
</tr>
<tr>
<td>2010-2011</td>
<td>pp</td>
<td>7</td>
<td>$\sim 4800$</td>
</tr>
<tr>
<td>2012</td>
<td>pp</td>
<td>8</td>
<td>$\sim 9700$</td>
</tr>
<tr>
<td>2013</td>
<td>p–Pb</td>
<td>5.02</td>
<td>$\sim 30$</td>
</tr>
<tr>
<td>2010-2011</td>
<td>Pb–Pb</td>
<td>2.76</td>
<td>$\sim 0.1$</td>
</tr>
<tr>
<td>Run-2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2015</td>
<td>pp</td>
<td>5.02</td>
<td>$\sim 100$</td>
</tr>
<tr>
<td>2015-2016</td>
<td>pp</td>
<td>13</td>
<td>$\sim 14000$</td>
</tr>
<tr>
<td>2016</td>
<td>p–Pb</td>
<td>5.02</td>
<td>$\sim 3$</td>
</tr>
<tr>
<td>2016</td>
<td>p–Pb</td>
<td>8.16</td>
<td>$\sim 20$</td>
</tr>
<tr>
<td>2016</td>
<td>Pb–p</td>
<td>8.16</td>
<td>$\sim 20$</td>
</tr>
<tr>
<td>2015</td>
<td>Pb–Pb</td>
<td>5.02</td>
<td>$\sim 0.4$</td>
</tr>
<tr>
<td>2017</td>
<td>Xe–Xe (B=0.2 T)</td>
<td>5.44</td>
<td>to be estimated</td>
</tr>
</tbody>
</table>

The evolution of the system produced in ion-ion collisions can be schematically described as following: the Lorentz-contracted colliding nuclei produce, in a time $\leq 1$ fm/c, a hot system of quarks and gluons interacting inelastically, which later thermalizes into a deconfined phase lasting of the order of a few fm/c and containing all allowed SU(3)$_{\text{color}}$ states. The system then expands and cools down until particles with zero color are formed and a chemical freezeout temperature is reached. At this moment the particle composition is fixed. Further expansion and
cooling brings the system to a kinematic freezout temperature when no more elastic collisions are possible and the kinematic properties of the particles are defined. While electroweak interacting particles (photons, Z, W, . . . ) pass the medium unchanged, partons are strongly affected by the dense/hot matter. For this reason hadron production at very high transverse momentum ($p_T$) is a very effective observable to explore energy loss via QCD interactions in a highly dense medium.

In the next sections a selection of ALICE results is presented (a more detailed review can be found in [5]).

2. Soft probes

Soft probes (low $p_T$ observables) are sensitive to the full evolution of the medium produced in ultra-relativistic heavy-ion collisions and therefore are very important in characterizing the properties of the QGP (Quark Gluon Plasma) in terms of mechanisms for hadron production, statistical/thermal features and collective phenomena developed in such a regime.

2.1. HBT correlations

The fireball spatial extent at decoupling is accessible via interferometry, a technique which exploits the Bose-Einstein enhancement of identical bosons close in phase space. In nuclear physics the strength of such a correlation for identical bosons is sensitive to different geometrical parameters (radii) of the emitting source. The size of the medium at freeze-out can be characterized by the correlators along the three axes providing the corresponding radii $R_{\text{out}}$ and $R_{\text{side}}$ (the size in the transverse plane) and $R_{\text{long}}$ (the size along the longitudinal direction). The estimate of the fireball volume relies on the product of the three radii. In Fig. 2 the volume of the system is reported for different center-of-mass energies as a function of the average charged-track multiplicity density, $\langle dN_{\text{ch}}/d\eta \rangle$. The ALICE results give a source volume at the LHC energies $V \sim 300\,\text{fm}^3$, a factor 2 larger than the volume measured at RHIC, while the corresponding lifetime is estimated to be $\tau \sim 10\,\text{fm}/c$, a 20% longer than that measured at RHIC.

![Figure 2. Volume of the fireball vs. charged-track multiplicity density from two-pion HBT correlation: ALICE results compared to lower energy experiments.](image-url)
2.2. Hadron production

Other observables in the soft sector (mass, meson/baryon ratio, ...) are based on the outstanding capabilities of ALICE for particle identification. Many features of the system produced in heavy-ion collisions are strongly dependent on the different particle properties, and consequently the ALICE detector was optimized to identify hadrons in a very wide $p_T$ range, from very low $p_T$ ($\sim 150$ MeV/$c$) to $p_T$ as large as few tens of GeV/$c$.

Hadron production was measured at the LHC in central and peripheral Pb–Pb collisions [7, 8]. The $p_T$ dependence of pion, kaon and proton spectra was found to be much harder than at RHIC, as predicted by models based on the hydrodynamic expansion of the produced medium (Fig. 3, left). The centrality dependence of the $p/\pi$ ratio production shows the role of the particle masses in such expansion. In the most central events, protons appear to be pushed to higher momenta under a higher pressure gradient (Fig. 3, right): this is a typical feature of a hydrodynamical mechanism in the presence of a collective motion.

![Figure 3](image.png)

**Figure 3.** Left: $p_T$ spectra of particles for summed charged states at 0-5% centrality, compared to hydrodynamical models and results from RHIC. Right: Proton over pion ratio as a function of $p_T$ at different centralities. Both figures are taken from [8].

In addition, the enhancement in baryon production with respect to mesons named “baryon anomaly” [9, 10], is pronounced also in the strangeness sector, as for the $\Lambda/K$ ratio [11] (Fig. 4). This effect, strongly centrality dependent, may indicate not only an increase of radial flow but also a change in the production mechanism, with hadron production by hadronization being coupled to quark recombination. Production via recombination is expected to play an important role at intermediate $p_T$, when partons start to be closer in phase space due to an increase of their density. To distinguish effects related to the mass or to the quark content a comparison between protons and $\phi$-mesons is very useful. The flatness of the $\phi/p$ ratio reported in Fig. 4 may indicate that the production of hadrons for $p_T < 2$ MeV/$c$ is driven by their mass.

In general, strangeness production is expected to be favored in Pb–Pb collisions as observed at AGS [12], SPS [13, 14] and RHIC [15] if a deconfined phase is created. Multistrange production is a good observable to quantify it: in ALICE this measurement [16] was performed following the same prescription adopted by previous experiments (Fig. 5). At the LHC energies an enhancement of the $\Xi$ and $\Omega$ production was found when moving from pp to Pb–Pb collision systems, similarly as observed at lower energies. The predictions for $\Xi/\pi$ and $\Omega/\pi$ at the LHC from the thermal models are also shown; they are based on a grand canonical approach, described in [17] (full line, with a chemical freeze-out temperature parameter $T = 164$ MeV) and [18] (dashed line, with $T = 170$ MeV).

More recently, ALICE measured the production of strange baryons also for p–Pb in different multiplicity classes (Fig. 6) [19]. The plateau in the multistrange-over-pion ratio for high
2.3. Anisotropic flow

ALICE studied in details the anisotropy in momentum space of produced particles. If the matter is strongly interacting, initial anisotropies in coordinate space, coming either from the geometry of the collision or from fluctuations, convert into an anisotropic momentum distribution. An illustration of the anisotropy development in a strongly interacting medium is reported in Fig. 7.

In order to reconstruct this anisotropy the particle distribution can be decomposed, event by event, into a series of Gaussian distributions in momentum space. This decomposition allows one to study the flow coefficients which characterize the anisotropy of the produced particles. The flow coefficients, denoted by \( v_n \), are defined as the Fourier coefficients of the particle angular distribution in momentum space. For a given event, the particle distribution can be written as:

\[
\phi(\theta, p_T) = \sum_{n=0}^{\infty} v_n(\eta) \exp(i n \theta) f(p_T)
\]

where \( \theta \) is the polar angle, \( p_T \) is the transverse momentum, \( f(p_T) \) is the particle distribution in transverse momentum space, and \( v_n(\eta) \) is the flow coefficient at rapidity \( \eta \).

The first non-zero flow coefficient is \( v_2 \), which is related to the second Fourier coefficient of the angular distribution and measures the eccentricity of the event shape. Higher flow coefficients, such as \( v_3 \), \( v_4 \), etc., measure more complex anisotropies and constitute an increasingly stringent test of initial conditions or medium evolution. The study of these coefficients provides insights into the collective flow dynamics and the interaction mechanisms in the medium.
Figure 6. $\Xi$ and $\Omega$ over $\pi$ ratios vs. charged track multiplicity density in pp, p–Pb and Pb–Pb collisions [19].

Figure 7. Due to an initial spatial anisotropy of the region where nucleons interact, different pressure gradients may develop along the in-plane and out-of-plane directions in a strongly interacting medium. Therefore, despite of an isotropic momentum distribution of the initial states, the momenta of the final products are anisotropically distributed. The different scenarios, with (right) and without (left) the assumption of a strongly interacting matter, are shown.

In order to clarify the role of radial expansion in the development of $v_2$ (elliptic flow), the measurement has to be performed separately for each identified particle [20]. For instance, at low transverse momenta the $\phi$-meson elliptic flow is similar to that of the (anti)proton: this can be explained as a similar effect of radial flow on particles with similar mass. At intermediate transverse momenta, $p_T > 2.5$ GeV/c, the hydrodynamic regime does not provide a good description. In such a regime other processes, like quark recombination, may play a more important role leading to a different behavior depending on the quark content (meson/baryon...
splitting). In particular, the $\phi$ meson “stays” with other mesons above 3 GeV/$c$ accordingly to the prediction of coalescence/recombination models.

### 3. Hard probes

Hard probes have been investigated deeply in the previous energy regimes [22]. It is generally accepted that, before hadronization, partons lose energy in the medium via gluonstrahlung or in multiple collisions [23, 24, 25]. This process is called “quenching”, was predicted by QCD [26] and was discovered at RHIC [27].

Several observables have been proposed to probe the hard-parton interactions with the medium. One of the most direct ones used to characterize the energy-loss mechanism is the nuclear modification factor $R_{AA}$, which quantifies the change in particle $p_T$ distributions from $pp$ to Pb–Pb systems:

$$R_{AA}(p_T) = \frac{d^2N_{AA}}{d\eta dp_T} \langle T_{AA} \rangle \frac{d\sigma_{pp}}{d\eta dp_T},$$

where $T_{AA}$ is the nuclear-overlap function derived with a Glauber calculation [4], which accounts for the average number of binary collisions occurring in AA systems for a given centrality selection. If heavy-ion interactions are just a mere overlap of $N_{\text{coll}}$ binary nucleon–nucleon collisions, then $R_{AA}$ is expected to be one.

As shown in Fig. 9, hadrons are strongly suppressed, while pure electroweak probes are compatible with unity.

#### 3.1. Charmed probes

Charm and beauty quarks are produced in the early stage of the collision. Their production in pp collisions at the LHC is a tool to test pQCD calculations in a new energy domain. As for charged particles the nuclear modification factor was computed in several centrality selections [29]. The results are reported in Fig. 10: the suppression for charm mesons is very clear, indicating a strong interaction with the hot medium produced. The strength of $R_{AA}$ suppression is almost as large as that observed for charged particles, which are mainly light-flavor hadrons, with a possible indication of a slightly higher value for open-charm states in the lower $p_T$ region.

As for hadrons and jets, the same measurement was performed in p–Pb collisions for centrally produced D mesons [30]. Within the errors, the data do not show any sign of suppression, compatible with the absence of cold-nuclear effects and the genuine suppression in Pb–Pb collisions due to the interaction of the heavy quarks with the medium produced.
Figure 9. Nuclear modification factor $R_{AA}$ of hadrons measured by ALICE in p–Pb and Pb–Pb collisions [28].

Figure 10. Average $R_{AA}$ for prompt $D^0$, $D^+$ and $D^{*+}$ in p–Pb and Pb–Pb 0–10%(30–50%) versus $p_T$.

According to the color-screening model [31], the measurement of the in-medium dissociation probability of the different quarkonium states is expected to provide an estimate of the initial
temperature of the system.

Several models attempt to reproduce the RHIC data by adding to the direct $J/\Psi$ production a regeneration component from deconfined charm quarks in the medium. This charmonium regeneration is stronger at the LHC where the high-energy density of the medium and the large number of $c\bar{c}$ pairs produced in central Pb–Pb collisions favor this extra production.

The nuclear modification factor for inclusive $J/\Psi$ production is reported in Fig. 11 [32, 33, 34].

![Figure 11](image)

**Figure 11.** Inclusive $J/\Psi$ $R_{AA}$ [33, 34] as a function of the number of participating nucleons as measured in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, compared to PHENIX results [35, 36] in Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV at forward rapidity.

The ALICE measurement is compared to PHENIX results [35, 36] (Fig. 11). Focusing on central collisions, at forward rapidity ALICE results are larger by a factor 3 than the PHENIX ones. This is consistent with a larger $J/\Psi$ regeneration at the LHC.

### 3.2. Collectivity of charm quarks

If the charm quark shares the collective motion of the medium with the light quarks it should be visible looking at observables strongly correlated with the bulk properties. For this reason it is very interesting to look for non-zero correlation in the anisotropic coefficients (flow). ALICE measured $v_2$ for D mesons in semi-central collisions. D mesons $v_2$ is positive in the range $2 < p_T < 6$ GeV/$c$ with $5.7\sigma$ significance [37] and comparable in magnitude to that of light flavor hadrons, as shown in Fig. 12-left.

For semi-central collisions, indications of a non-zero $J/\Psi$ $v_2$ is also observed in the intermediate $p_T$ range, as shown in Fig. 12-right [38].

Both results seem in agreement with the global picture in which a significant fraction ($\sim 30\%$ according to the models reported in the figure) of the observed $J/\Psi$ yield is coming from recombination of charm quarks in the deconfined phase.

### 4. (Anti)nuclei and Hypernuclei production

Ultra-relativistic ion collisions create suitable conditions for producing light (anti)nuclei, because a high-energy density is reached over a large volume. In relativistic heavy-ion collisions, nuclei and corresponding antinuclei are produced with nearly identical rates. In Fig. 13-left the production rate for nuclei and antinuclei is reported. When increasing the atomic number the
Figure 12. Left: Average of $D^0$, $D^+$ and $D^+$ $v_2$ as a function of $p_T$ [37], compared to charged particle $v_2$ [21] in non central (30-50%) Pb–Pb collisions. Right: Inclusive $J/\Psi$ $v_2(p_T)$ for non central (20-60%) Pb–Pb collisions [38]. Calculations from two transport models are also shown.

Production is suppressed nearly exponentially according to the expectation both from thermal and coalescence models [39]. In the coalescence picture the production rate for a nucleus with atomic number $A$ depends on the baryon density (nuclei are formed by coalescence of baryons) and it may be approximated by the formula:

$$E_A \frac{dN_A}{dp_A^3} = B_A \left( E_p \frac{dN_p}{dp_p^3} \right)^A,$$

(3)

where $E$ and $p$ are, respectively, the energy and momentum of particles, $A(p)$ refer to nucleus (proton) and $B_A$ is the coalescence parameter, namely the phase-space volume allowed for coalescence. It is worth to note that Eq. 3 is an approximation because it assumes that the volume of the source is constant and then re-assorbed in the $B_A$ parameter. ALICE measured the $B_A$ parameter in different collision systems (accordingly to Eq. 3) and the results are reported in Fig. 13-right. As it can be noted, when increasing the multiplicity of the system the coalescence parameter decreases. This could be ascribed to the increasing volume of the source emitting the nuclei which is not taken into account in this approximation.

In any case, such a measurement is really important for astroparticle experiments to estimate the possibility to create antinuclei by coalescence of antibaryons. In particular the AMS experiment [41] can benefit from the ALICE measurement of $B_3$ [42] to reduce the uncertainties of the background contamination when looking at the primary $^3$He detection.

In addition to the study of (anti)nuclei ALICE is also able to reconstruct the daughter particles emitted in hypernuclei decay. $^3\Lambda \rightarrow ^3$He $+ \pi^-$ (and charge conjugated, branching ratio $\sim 25\%$) is an efficient channel to detect hypernuclei. In Fig. 14-left a clear peak in the invariant mass distribution for the channel considered is visible. By reconstructing the secondary vertices of the decays ALICE measured the lifetime of this state with the best precision reached so far (Fig. 14-right).

Such measurements allow us to understand better the baryon-baryon interactions in the strangeness sector and to study the structure of multistrange systems.

5. The ALICE upgrade for Run-3 and Run-4

The LHC machine will provide in the next years Pb–Pb collisions with increasing luminosity. The current schedule is reported below:
Figure 13. Left: $dN/dy$ for protons ($A=1$) up to $^4\text{He}$ ($A=4$) and the corresponding anti-particles in central (0-10%) Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [39]. Right: $B_A$ parameter in different collision systems as a function of charged particle multiplicity [40].

Figure 14. Left: $^3\text{He} + \pi$ invariant mass distribution in Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV. Right: Hypertriton lifetime.

- Run-2 (ongoing up to 2018) collecting a luminosity in Pb–Pb of 1 nb$^{-1}$;
- Run-3 (2021-2023) expecting a luminosity in Pb–Pb of 6 nb$^{-1}$;
- Run-4 (2026-2029) expecting a luminosity in Pb–Pb of 7 nb$^{-1}$.

In order to benefit from the increasing statistics ALICE is going to upgrade several detector systems during the Long Shutdown 2 (2019-2020). One of the major changes is the upgrade to faster detectors and continuous readout to increase the acquisition rate of the events [43]. In this respect the major improvement concerns the time-projection chamber which will be upgraded with a GEM technology [44]. On parallel the online and offline systems will be completely renewed [45] to allow us to manage the new features of the DAQ model. One of the main goals in Run-3 and Run-4 is the high-precision measurement of charm and beauty quark properties in the medium. This will be achieved by improving the capability of the secondary-vertex reconstruction after the ITS upgrade [46] and the installation of the Muon Forward Tracker.
To extend the study of the thermal properties of the medium using thermal photons and low-mass dileptons emitted by the QGP, some dedicated runs will be taken at a lower magnetic field (B=0.2 T). This specific configuration was already validated during Run-2 with Xe–Xe collisions, but a large data sample with such a condition will be reached only at Run-3.

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