ALICE summary of light flavour results at intermediate and high $p_T$

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Abstract. The ALICE experiment has unique capabilities for particle identification at mid rapidity over a wide range of transverse momenta ($p_T$), making it an ideal tool for comprehensive measurements of hadrons such as charged pions, kaons, and protons as well as $\Lambda$, $K^0_s$ and $\phi$. The transverse momentum distributions and nuclear modification factors, $R_{pPb}$ and $R_{PbPb}$, of these hadrons measured in $p$–$Pb$ and $Pb$–$Pb$ collisions are presented. Baryon-to-meson ratios exhibit a multiplicity-dependent enhancement at intermediate transverse momenta for both $p$–$Pb$ and $Pb$–$Pb$ collisions, while no significant dynamics is observed in the ratios at larger transverse momenta. Finally, measurements of identified particle ratios in association with high-$p_T$ particles as well as within reconstructed jets are presented.

1. Introduction
During LHC Run-1 the ALICE detector has recorded $pp$, $p$–$Pb$, and $Pb$–$Pb$ collisions at different center of mass energies. Heavy-ion collisions at ultra relativistic energies are expected to produce a QCD matter where the quarks and gluons are in a deconfined state. Measurements of the production of hadrons in $Pb$–$Pb$ collisions at intermediate and high $p_T$, relative to $pp$ collisions, provide information about the dynamics of this matter. In the context of light-flavour production, the focus for the $Pb$–$Pb$ results is on parton energy loss — expected to lead to a modification of energetic jets (jet quenching) — and possibly modified fragmentation due to the hot and dense QCD medium.

The excellent tracking and particle identification capabilities of the ALICE experiment, in particular its large time projection chamber, makes it possible to investigate the spectra of baryons and mesons. The results are presented in terms of particle ratios and nuclear modification factors, $R_{AA}$ and $R_{pA}$.

2. $R_{AA}$ and $R_{pA}$ for charged hadrons
The nuclear modification factor is defined as the ratio of the particle yield in $Pb$–$Pb$ to that in $pp$ collisions scaled by the number of binary nucleon-nucleon collisions

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

where $d^2N_{AA}/d\eta dp_T$ is the differential particle yield in $Pb$–$Pb$ collisions, $d^2\sigma_{pp}/d\eta dp_T$ is the invariant cross section for particle production in inelastic $pp$ collisions, and $\langle T_{AA}\rangle$ is the average
nuclear overlap function [1]. In the absence of nuclear modifications $R_{AA}$ is unity for hard processes which are expected to exhibit binary collision scaling.

The nuclear modification factor presented in Fig. 1, shows that the shape of the invariant yield for peripheral Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV is similar to those observed in pp collisions due to the flatness of the $R_{pPb}$, while a strong suppression of charged hadron production at high $p_T$ is observed for central collisions. To establish whether the initial state of the colliding nuclei plays a role in the observed suppression, also the nuclear modification factor in p–Pb for charged particles is shown in the same figure. $R_{pPb}$ is consistent with unity for $p_T > 2$ GeV/$c$, and hence the suppression in Pb–Pb collisions is not due to any initial state effects, but to final nuclear matter effects, such as jet quenching in the hot QCD medium.

![Figure 1](image.png)

**Figure 1.** Nuclear modification factors, $R_{pPb}$ and $R_{pPb}$, of charged particles as a function of transverse momentum for 0-5% central and 70-80% peripheral Pb–Pb at $\sqrt{s_{NN}} = 2.76$ TeV collisions, and central p–Pb at $\sqrt{s_{NN}} = 5.02$ TeV collisions [1].

### 3. $R_{AA}$ and $R_{pA}$ for identified hadrons

When constructing $R_{AA}$ for identified light flavour hadrons, we see in Fig. 2 that, within systematic and statistical uncertainties, they are equally suppressed at $p_T > 10$ GeV/$c$. The large suppression is a sign of considerable energy loss, and the $R_{pA}$ seen in Fig. 3 establishes that this energy loss is predominantly due to the medium and not caused by initial state effects.

For the intermediate $p_T$ range, the protons are less suppressed than the kaons and pions, and a mass ordering is present in the suppression pattern. While the proton and $\phi$ modification factors exhibit rather distinct features, the $\phi/p$ ratio in central Pb–Pb is observed to be approximately constant as a function of $p_T$, as discussed in Sec. 4, indicating that the differences in the $R_{AA}$ can be attributed to different pp spectra shapes.

Looking at identified particles at intermediate $p_T$ in p–Pb collisions instead, we see in Fig. 3 an enhancement of $\Xi$ and p, while K and $\pi$ are consistent with $T_{AA}$-scaled pp values. Furthermore, there is a mass ordering among $\pi$, K, p, $\Xi$, but the $\phi$ does not fit into this pattern.
4. $\Lambda$/K$^0$, p/$\pi$ and K/$\pi$ ratios in Pb–Pb collisions

In Pb–Pb collisions, both $\Lambda$/K$^0$ and p/$\pi$ (Fig. 4 [2], [3]) in central and peripheral collisions are consistent with pp for $p_T > 8$ GeV/$c$, indicating that the processes are dominated by vacuum-like fragmentation.

Looking in the intermediate $p_T$ range for $\Lambda$/K$^0_s$, an enhancement is visible towards more central collisions, see Fig. 4, and a shift of the maximum position towards higher $p_T$ is observed: in the most peripheral collisions (60-80% centrality) there is a maximum of about 0.55 at $p_T \sim$2 GeV/$c$, while the maximum value of the ratio for the most central collisions (0-5% centrality) is about 1.6 at $p_T \sim$3.2 GeV/$c$. This shift is consistent with an increasing radial flow towards more central collisions. The magnitude of these maxima increases by almost a factor of three between most peripheral and most central Pb–Pb collisions. A hydrodynamical model such as VISH2+1 [4] is able to describe the rise at low $p_T$. At higher $p_T$, models with modified fragmentation (EPOS [5], [6]) and coalescence of quarks (Recombination [7]) describe the shape qualitatively well, but overestimate the enhancement [2].
Figure 4. Left: $\Lambda/K^0$ particle ratio as a function of $p_T$ in central (0-5%) and peripheral (60-80%) Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV compared to models in central (0-5%) events [2]. Right: $p/\pi$ and $K/\pi$ ratio as a function of $p_T$ in central (0-5%) Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV compared to pp collisions at $\sqrt{s} = 7$ TeV and models [3].

Figure 4 also shows the $p/\pi$ and $K/\pi$ ratio up to $p_T = 20$ GeV/$c$ for central events, both presenting an enhancement at intermediate $p_T$, with the peak at $p_T = 3$ GeV/$c$. However, the baryon-to-meson ratio $p/\pi$ presents a much more pronounced increase, reaching a value of about 0.9 at $p_T = 3$ GeV/$c$, compared to the two-meson ratio $K/\pi$. As for the $\Lambda/K^0$ case, the ratios are in good agreement with hydrodynamical calculations (Krakow [4]) for $p_T < 2$ GeV/$c$, indicating that the rise of the peak can be described by the mass ordering induced by radial flow. At intermediate $p_T$, around the maxima and up to $p_T \sim 8$ GeV/$c$, the data are qualitatively described by the recombination model by Fries et al. [7], and the EPOS model [5], [6], but these models also overestimate the maximum values.

5. $p/\phi$ in Pb–Pb collisions
To further investigate the main driving parameter in the spectral shape, we study a baryon-to-meson ratio in which the baryon and meson are of similar mass, namely the $p/\phi$ ratio. In Fig. 5 [8] the $p/\phi$ ratio is shown as a function of $p_T$, and it is observed that in central Pb–Pb collisions there is a very small difference in their $p_T$ distributions, i.e. no baryon-meson difference is present. This indicates that the hadron mass determines the spectral shape.

6. Particle ratios in p–Pb collisions
Interestingly, the $\Lambda/K^0_s$ and $p/\pi$ in p–Pb collisions show the same qualitative behavior as in Pb–Pb collisions: a multiplicity dependent baryon-to-meson enhancement at intermediate $p_T \sim 3$ GeV/$c$ is seen in Fig. 6 [9] for two different multiplicity event classes. The results show that p–Pb presents features that are similar to Pb–Pb phenomenology, even though the magnitude of the enhancement in p–Pb is significantly different to the one observed in Pb–Pb. The maximum of the $p/\pi$ ratio reaches 0.8 in central Pb–Pb collisions, but only 0.4 in the highest multiplicity p–Pb events, and the $\Lambda/K^0_s$ maximum in central Pb–Pb is 1.5, while it is 0.8 in corresponding p–Pb collisions. The highest multiplicity bin in p–Pb collisions exhibits ratios of $p/\pi$ and $\Lambda/K^0_s$ which have maxima close to the corresponding ratios in the 60-70% centrality bin in Pb–Pb collisions, but differ somewhat in shape at lower $p_T$ [9].
Figure 5. Ratio $p/\phi$ (scaled with 0.1 for visibility) as a function of $p_T$ up to 5 GeV/c for 0-10% central Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, compared to $\Lambda/K_S$ and $p/\pi$ in the same centrality bin. Figure taken from [8].

Figure 6. $\Lambda/K_S^0$ (left) and $p/\pi$ (right) in $\sqrt{s_{NN}} = 5.02$ TeV p–Pb collisions (left panel) as a function of $p_T$ in one central (0-5%) and one peripheral (60-80%) multiplicity bin. The ratios are compared to results in Pb–Pb collisions (right panels) where central multiplicity bin is 0-5%, and the peripheral multiplicity bin is 80-90%. Figures from [9].

7. The origin of the enhancement

One can investigate whether the origin of this enhancement is due to parton fragmentation (hard) or collective effects (soft) by a two-particle correlation study, where the particles produced in the underlying events, the bulk, are separated from those which are associated with a high-$p_T$ trigger particle, representing a jet-like environment, or the peak region. The peak is defined as a region around $(\Delta \eta, \Delta \phi) = (0, 0)$, and the bulk region around $(\Delta \eta, \Delta \phi) = (\pm 1, 0)$ where one, due to long range (in rapidity) azimuthal correlations, expects the flow structure of the underlying event to be the same as under the peak. To study the jet contribution, the bulk is subtracted from the peak region (in Fig. 7: ”Peak-Bulk”). In Fig. 7 (top) [10], the $p/\pi$ ratios in central
Pb–Pb events are presented for bulk and for peak-bulk event selections, and it is seen that the enhancement is a bulk effect and not present in jet events.

In the p–Pb study, charged particle jets are reconstructed on an event-by-event basis using an anti-\(k_T\) algorithm with resolution parameter \(R = 0.2, 0.3,\) or \(0.4\) and requiring one charged track with \(p_T > 10\) GeV/c. The \(\Lambda\) and \(K^0_s\) yields are measured within the jet cone and corrected for the underlying event before the ratio is taken. When the ratio is compared to the inclusive ratio, the same conclusion as for the \(p/\pi\) ratio can be drawn: that the baryon-to-meson enhancement originates from the bulk, and is not present in the jet structure.

**Figure 7.** Top: \(p/\pi\) ratio as a function of associated particle \(p_T\), in bulk and peak-bulk for 0-10% central Pb–Pb collisions at \(\sqrt{s_{NN}} = 2.76\) TeV, with a leading (trigger) particle \(p_T\) between 5–10 GeV/c [11]. Bottom: \(\Lambda/K^0_s\) ratio in jet with different radii reconstructed with the anti-\(k_T\) method compared to PYTHIA8 and the Pb–Pb inclusive ratio (full black circles) for 0-10% central p–Pb collisions at \(\sqrt{s_{NN}} = 5.02\) TeV.
8. Conclusions
At high $p_T$ we observe a suppression of identified particle production due to parton energy loss. The same suppression is seen for all light quark systems created in Pb–Pb collisions, which suggests that the chemical composition of leading particles from jets in the medium is similar to jets produced in vacuum. No suppression in p–Pb collisions is seen, indicating that the suppression observed in Pb–Pb is a final-state hot-matter effect.

At intermediate $p_T$, the particle ratios show a baryon-to-meson enhancement which in Pb–Pb is understood in the coalescence and/or hydrodynamic flow picture. In p–Pb collisions we see similar features, but less pronounced, as in Pb–Pb. By separating the underlying events from the jet-like structures, we note that the baryon-to-meson enhancement seems to be an effect arising in the underlying events in both Pb–Pb and p–Pb collisions, while the jet-like contributions appear to be unmodified.

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