

# Identified particle production in pp, p–Pb, and Pb–Pb collisions measured with ALICE at LHC energies.

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**Abstract.** The ALICE detector has excellent Particle IDentification (PID) capabilities in the central barrel ( $|\eta| < 0.9$ ). This allows identified hadron production to be measured over a wide transverse momentum ( $p_T$ ) range, using different sub-detectors and techniques: their specific energy loss ( $dE/dx$ ), the time of flight, the Cherenkov angle or their characteristic weak decay topology. Results on identified particle spectra and production yield ratios at mid-rapidity measured by ALICE in different colliding systems (pp, p–Pb and Pb–Pb) are presented and the similarities among them are discussed. For Pb–Pb collisions the nuclear modification factor as a function of  $p_T$  is shown for different collision centralities.

## 1. Introduction

ALICE is a general-purpose, heavy-ion detector which focuses on QCD, the strong-interaction sector of the Standard Model. It is designed to address the physics of strongly interacting matter and the quark-gluon plasma at extreme values of energy density and temperature in nucleus-nucleus collisions. Detailed description of the ALICE experiment and its detector subsystems can be found in [1], [2] and [3]. The heavy ion collisions produce a system of hot dense matter that expands due to the pressure gradients between the system center and the surrounding vacuum [4]. The system expands collectively and as a consequence it cools down, and undergoes hadronization. The measurement of the identified transverse momentum ( $p_T$ ) spectra provides information about the hadronization processes and the evolution of the created system. In Pb–Pb collisions the low transverse momentum region ( $p_T < 3$  GeV/ $c$ ) provides information about the collective properties of the system like radial flow, where the  $p_T$  spectra have a strong dependence on the mass of the particle. The intermediate momentum region ( $3$  GeV/ $c < p_T < 8$  GeV/ $c$ ) provides information about hadronization mechanisms according to models like quark-recombination [5], where the relevant variable is the number of constituent quarks. In the high momentum region ( $p_T > 8$  GeV/ $c$ ) the effects in the fragmentation due to the medium created can be explored [6].

Information from pp collisions are important not only as a baseline for the Pb–Pb measurements, but also because they give the possibility to improve Monte Carlo generators based on QCD models. The p–Pb information is used to evaluate cold nuclear effects. Recent



ALICE results suggests that p–Pb collisions present effects similar to those observed in Pb–Pb collisions like flow [7].

Previous results on identified particle production in pp, p–Pb and Pb–Pb can be found in [7], [8] and [9]. ALICE results on the nuclear modification factor have been reported in [10].

## 2. Results

Fig. 1 (left) shows the  $p_T$  distributions of charged pions, kaons and protons in pp collisions at  $\sqrt{s} = 2.76$  TeV obtained with the PID information from the Inner Tracking System (ITS), the Time Projection Chamber (TPC), the Time Of Flight detector (TOF) and the High Momentum Particle Identification Detector (HMPID). The combined information from these detectors allow us to measure the spectra within the rapidity window  $|y| < 0.5$  in the  $p_T$  range 0.1 – 20 GeV/ $c$ .

In Pb–Pb collisions the analysis is performed in different centrality classes which are both determined with the amplitude measured in the VZERO detectors and simulations based on the Glauber model [11]. In p–Pb collisions the spectra are reported in multiplicity classes due to the weak correlation between collision geometry and the multiplicity based on the amplitude of the signal of VZEROA detector which is located in the Pb side [7].

The  $p_T$  spectra of pions, kaons and protons measured by ALICE in the most central Pb–Pb collisions (0 – 5 %) are shown in Fig. 1 (right). The  $p_T$  spectra measured by ALICE are flatter than those measured at RHIC energies specially for protons. This indicates a stronger radial flow when increasing the energy. The comparison to models based on hydrodynamics show that VISH 2+1 [12] describes the pion and kaon spectra for  $p_T < 1.5$  GeV/ $c$  qualitatively well, but fails in the description of protons, which can be attributed to a lack of an explicit description of the hadronic phase. HKM [13] inserts a hadronic cascade after the hydrodynamic phase, which further transports them until final decoupling. This improves the description of the protons for  $p_T < 1.0$  GeV/ $c$ . The Kraków [14] model provides a better description of the spectra than the other 2 models. This model uses changes in the effective temperature ( $T_{ch}$ ), consequence of non-equilibrium due to the bulk viscosity. The EPOS [15] model uses breakup of flux tubes which either contribute to the bulk or escape the medium as jets. This model describes qualitatively well the data in a broad  $p_T$  range.

The ratio  $(p + \bar{p})/(\pi^+ + \pi^-) = p/\pi$  is shown in Fig. 2 for two different centralities in Pb–Pb collisions compared to pp collisions. The central events show an enhancement in the intermediate  $p_T$  region (3 – 8 GeV/ $c$ ), compatible with previous observations at RHIC in Au–Au collisions at  $\sqrt{s_{NN}} = 200$  GeV [16], [17]. ALICE has also measured the ratio  $(K^+ + K^-)/(\pi^+ + \pi^-) = K/\pi$  and  $(p/\pi)$  at different pp energies [9] and found no significant energy dependence within the experimental errors.

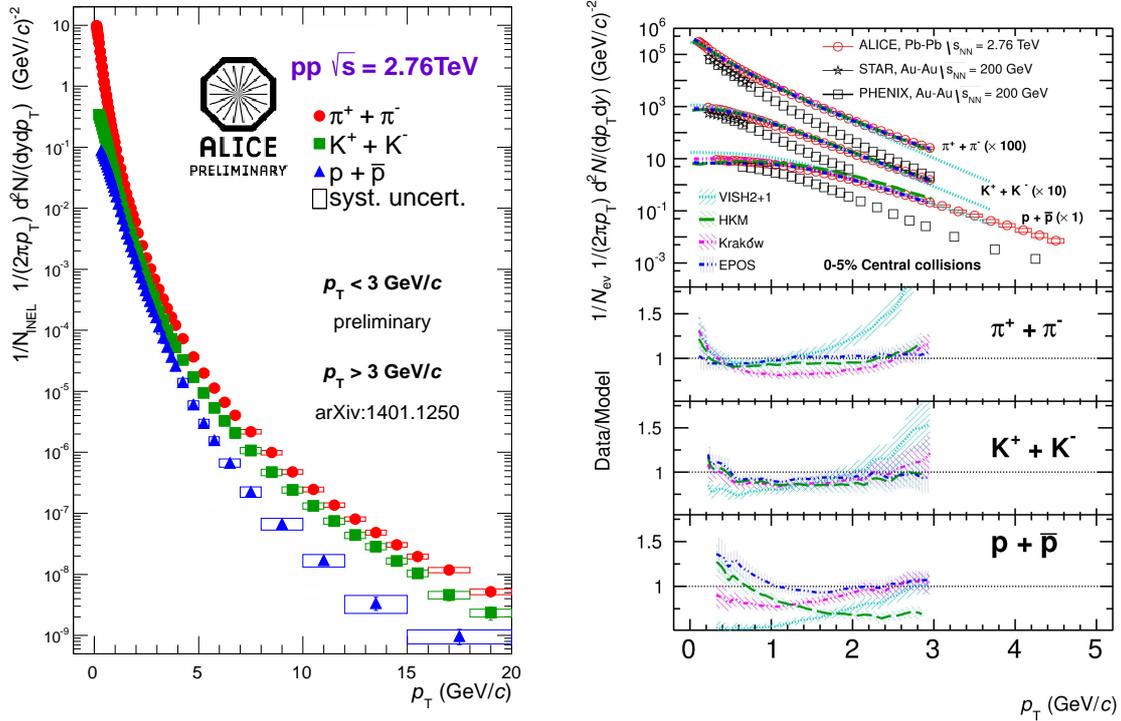
The final state effects in Pb–Pb collisions can be studied by the nuclear modification factor ( $R_{AA}$ ). The  $R_{AA}$  is defined as:

$$R_{AA} = \frac{d^2 N_{ch}^{PbPb}/d\eta dp_T}{\langle N_{coll} \rangle d^2 N_{ch}^{PP}/d\eta dp_T} \quad (1)$$

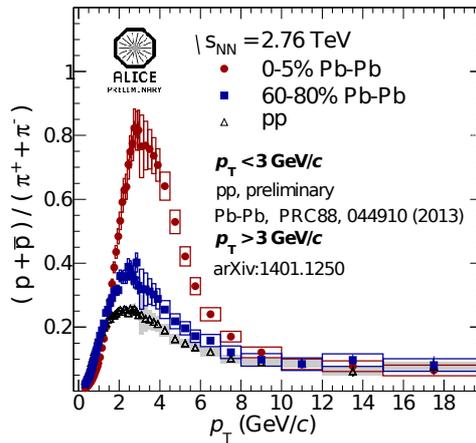
where  $\langle N_{coll} \rangle$  is the number of binary collisions for different centrality classes [11].

Fig. 3 shows that at  $p_T > 8$  GeV/ $c$  the suppression for pions, kaons and protons is the same within systematic uncertainties, for central and peripheral Pb–Pb collisions. This measurement disfavors significant modifications of hadro-chemistry within the hard core of jets [6].

ALICE has shown that in p–Pb collisions, the nuclear modification factor,  $R_{pPb}$ , for charged particles is consistent with one for  $p_T \geq 2$  GeV/ $c$  [18]. This means no suppression is observed in p–Pb collisions unlike in Pb–Pb collisions. This indicates that initial state effects are small. However, the transverse momentum spectra of pions, kaons and protons show similar behavior to that observed in Pb–Pb collisions associated with the collective expansion of a medium.



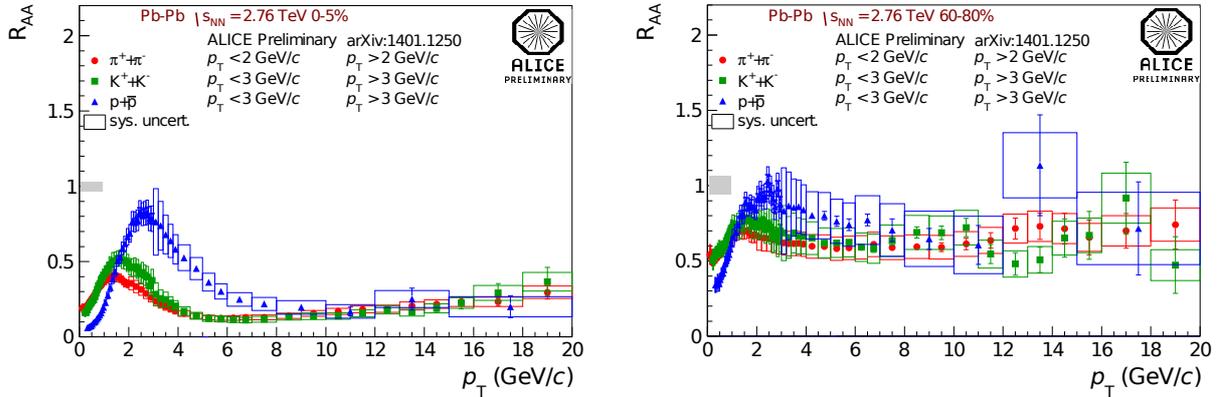
**Figure 1.** Left:  $\pi/K/p$  in pp collisions at  $\sqrt{s} = 2.76$  TeV. Right: Comparison of  $\pi/K/p$  spectra to previous observations in Au–Au collisions at  $\sqrt{s_{NN}} = 200$  GeV and hydro models in Pb–Pb central collisions (0 – 5%).



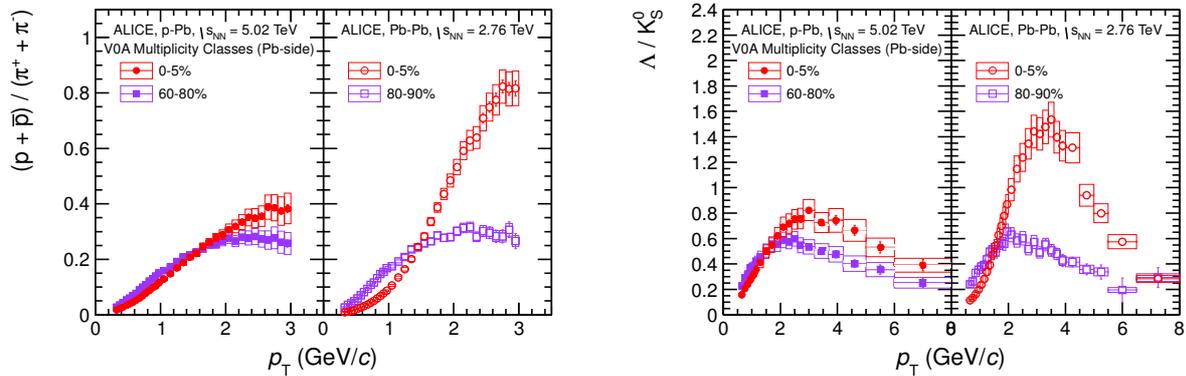
**Figure 2.** Proton to pion ratio measured in pp and Pb–Pb collisions.

The baryon to meson ratios:  $p/\pi$  and  $\Lambda/K_S^0$  for two extreme measured centrality (multiplicity) classes are shown in Fig. 4 for Pb–Pb (p–Pb) collisions. The behavior as a function of  $p_T$  for both systems is similar, showing an enhancement at intermediate  $p_T$  (at  $\approx 3.0$  GeV/c) for high centrality or multiplicity.

The collective expansion can be tested with a blast-wave fit simultaneous to all particles in a



**Figure 3.** Nuclear modification factor for pions, kaons and protons, for central (left) and peripheral collisions.

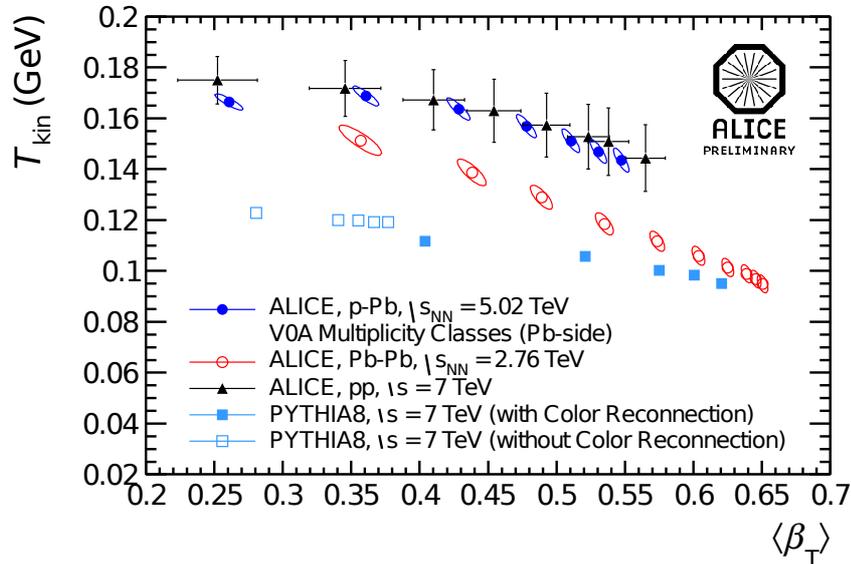


**Figure 4.** Baryon to meson ratio:  $p/\pi$  (left) and  $\Lambda/K_S^0$  (right) as a function of  $p_T$  measured in two multiplicity bins in p–Pb collisions compared to results for two centrality bins in Pb–Pb collisions.

multiplicity bin. This is a traditional way to compare the  $p_T$  distributions and their evolution in different systems. These fits to all particles species provide a kinetic freeze-out temperature  $T_{\text{kin}}$  and the expansion velocity  $\langle\beta_T\rangle$  of the system. Fig. 5 shows the parameters obtained with the blast-wave fit for the 3 different systems: pp, p–Pb and Pb–Pb. The behavior is qualitatively similar in all of them, this observation indicates the presence of radial flow in the 3 systems. On the other hand, the results obtained with simulations based on PYTHIA 8 (tune 4C) [19], which do not include any collective effect, produce a similar pattern, because of a color reconnection mechanism mimicking flow [20].

### 3. Conclusions

ALICE measurements of pion, kaon and proton production as a function of  $p_T$  at several energies for different colliding systems have been presented. ALICE results in pp collisions show no energy dependence on the ratios  $p/\pi$  and  $K/\pi$ . In Pb–Pb collisions the  $p_T$  spectra are qualitatively well reproduced by hydrodynamical models. However one should bear in mind that all the models, even EPOS, fail in the quantitative description of the data in all the  $p_T$  range. The  $R_{AA}$  at high  $p_T$  seems to disfavor particle species (flavor) dependent effects. The baryon to meson ratios in p–Pb collisions exhibit similar enhancement to that observed in Pb–Pb collisions generally



**Figure 5.** Blast-wave fit analysis, compared to Pb–Pb, p–Pb, pp data and MC simulations using PYTHIA8 with and without color reconnection. Charged-particle multiplicity increases from left to right.

related to collective flow. Blast wave fits in Pb–Pb, p–Pb and high multiplicity pp collisions show similar flow signatures, however this is observed also in simulations using PYTHIA 8, which has no hydrodynamics present, but instead has a color reconnection mechanism that mimics radial flow effects [20].

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