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Identified charged pion, kaon, and proton production in pp and Pb-Pb collisions at LHC energies measured with ALICE

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ALICE has unique capabilities among the LHC experiments for particle identification (PID) at mid-rapidity ($|\eta| < 0.9$) over a wide range of transverse momentum (p_{T}). For p_{T} from 100 MeV/c up to 3-4 GeV/c (anti)protons, charged pions and kaons can be separated on a track-by-track basis through the measurement of the specific energy loss, dE/dx, and the time of flight. The identification of protons can be extended up to 6 GeV/c by the Cherenkov detector. For $3 < p_{\mathrm{T}} < 20$ GeV/c, statistical PID can be done thanks to the relativistic rise of the dE/dx in the TPC. In this report, the spectra for charged pions, kaons, and (anti)protons from pp (at $\sqrt{s} = 2.76$ and 7 TeV) and Pb-Pb (at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV) collisions will be presented.

The results from pp collisions are important both as a baseline for Pb-Pb measurements and for our understanding of the hadronization process with a focus here on jet fragmentation at high p_{T}. The intermediate p_{T} region is interesting due to the anomalous large peak in the proton to pion ratio that can be an indication for new hadronization processes in Pb-Pb such as recombination.

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The measurement of transverse momentum spectra is of fundamental interest in hadronic collisions as it provides insight into a wide variety of QCD physics. At low transverse momentum, p_{T}, where perturbative QCD is not applicable the spectra have to be modeled using phenomenological approaches. At high p_{T} the production can in principle be described using perturbative QCD, but even for pp collisions this still relies on measured parton distributions and fragmentation functions. In Pb-Pb collisions the measured yield at high p_{T} is sensitive to final state effects, the so-called jet quenching: these hard probes are important tools for studying the medium formed.

When the particles can be identified additional physics phenomena can be studied: quark flavor effects (e.g. strangeness), baryon-meson effects, and mass effects (heavy vs light hadrons). The last effect, in particular, is of interest in Pb-Pb collisions where collective flow effects are large: hadronization in the co-moving frame transverse to the beam axis is boosted in the center-of-mass frame. Recent results from ALICE suggests that even in p-Pb (and pp) similar effects could be present [1].

The main focus in this paper is the intermediate and high p_{T} physics: $p_{\mathrm{T}} > 2$ GeV/c.

1. Experimental method

ALICE is a dedicated heavy-ion experiment with full azimuthal coverage around mid-rapidity ($|\eta| < 0.9$) and a forward muon tracking system. ALICE has unique capabilities among the LHC experiments for particle identification (PID) at mid-rapidity over a wide range of p_{T}. For p_{T} from 100 MeV/c up to 3-4 GeV/c (anti)protons, charged pions and kaons can be separated on a track-by-track basis through the measurement of the specific energy loss, dE/dx, and the time of flight. The identification of protons can be extended up to 6 GeV/c by Cherenkov radiation in a restricted acceptance. For $3 < p_{\mathrm{T}} < 20$ GeV/c, statistical PID is possible thanks to the relativistic rise of the dE/dx. The p_{T} resolution is below 5% at $p_{\mathrm{T}} = 20$ GeV/c.

The analyzes have been documented extensively elsewhere [2, 3], so here the focus is on discussing the results.

2. Results

Figure 1 shows the final identified yields obtained by combining the information from the many different PID detectors. In the following particle ratios and nuclear modification factors based on these spectra are used to extract information about the physics mechanisms.

Figure 2 shows the p_{T} differential particle ratios $(\mathrm{K}^+ + \mathrm{K}^-)/(\pi^+ + \pi^-)$ and $(\mathrm{p} + \bar{\mathrm{p}})/(\pi^+ + \pi^-)$. Spectra from perturbative QCD (pQCD) calculations contain an overall normalization uncertainty (the K-factor) due to higher order corrections, whose effect is canceled out in the particle ratios. What we observe is that the particle ratios are not well described by neither the PYTHIA Perugia 2011 [4] tune or by a pQCD calculation [5]. One observes that for the pQCD calculation [1] the $(\mathrm{p} + \bar{\mathrm{p}})/(\pi^+ + \pi^-)$ vs p_{T} is increasing while in the data it is decreasing for $p_{\mathrm{T}} > 3$ GeV/c. The $(\mathrm{K}^+ + \mathrm{K}^-)/(\pi^+ + \pi^-)$ ratio at high p_{T} appears to be constant at the numerically interesting value

[1] The perturbative part of the calculation yields the partonic production cross sections that are then folded with identified fragmentation functions for quarks and gluons.

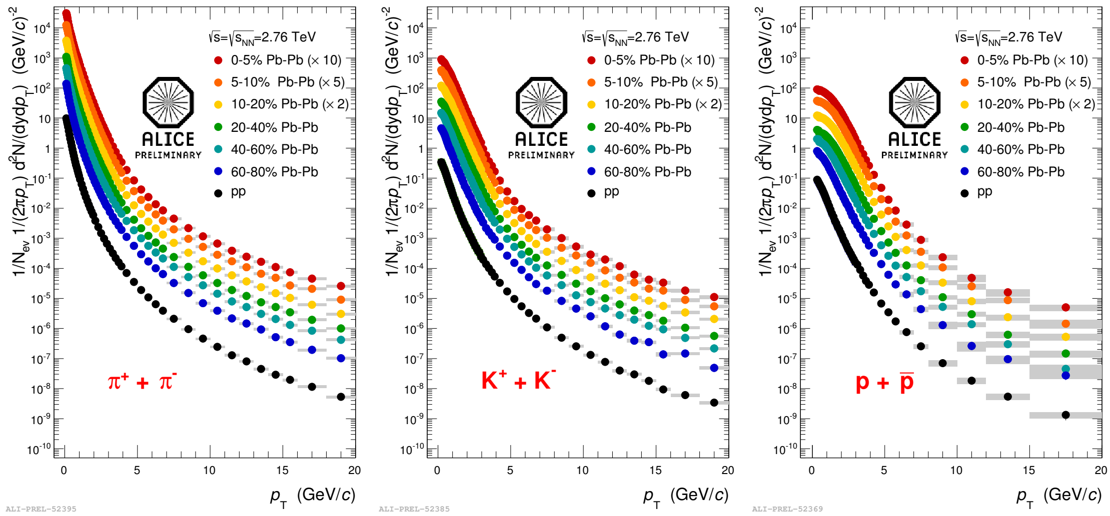

Figure 1: The invariant yield for $\pi^+ + \pi^-$ (left), $\mathrm{K}^+ + \mathrm{K}^-$ (center), and $\mathrm{p} + \bar{\mathrm{p}}$ (right) as a function of p_T for different Pb-Pb centrality classes, $\sqrt{s_\mathrm{NN}} = 2.76$ TeV, and pp at $\sqrt{s} = 2.76$. Statistical errors are indicated by the vertical error bars and systematic uncertainties are shown as gray boxes.

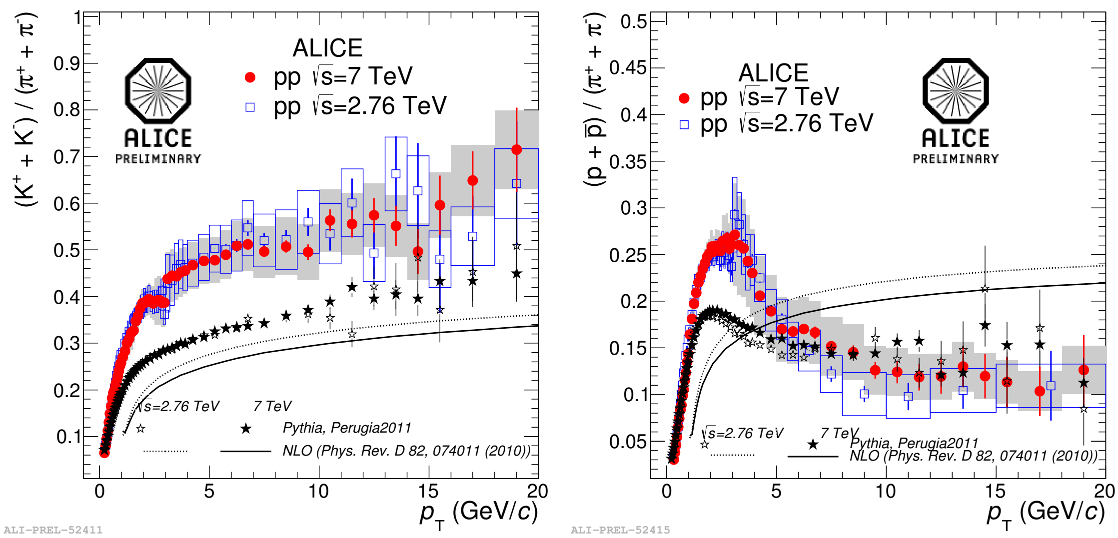

Figure 2: The particle ratios, $(\mathrm{K}^+ + \mathrm{K}^-)/(\pi^+ + \pi^-)$ (left) and $(\mathrm{p} + \bar{\mathrm{p}})/(\pi^+ + \pi^-)$ (right), as a function of p_T in pp collisions at $\sqrt{s} = 2.76$ TeV and $\sqrt{s} = 7$ TeV compared to model calculations. Statistical errors are given by the vertical error bars. Systematic uncertainties (data only) are shown as open blue boxes ($\sqrt{s} = 2.76$ TeV) and gray boxes ($\sqrt{s} = 7$ TeV).

of 1/2, but the disagreement with both calculations suggests that there is no simple interpretation for this limit.

The peak in the $(\mathrm{p}+\bar{\mathrm{p}})/(\pi^{+}+\pi^{-})$ ratio is also observed in the PYTHIA simulation and has recently been traced to an effect of color reconnection [6].

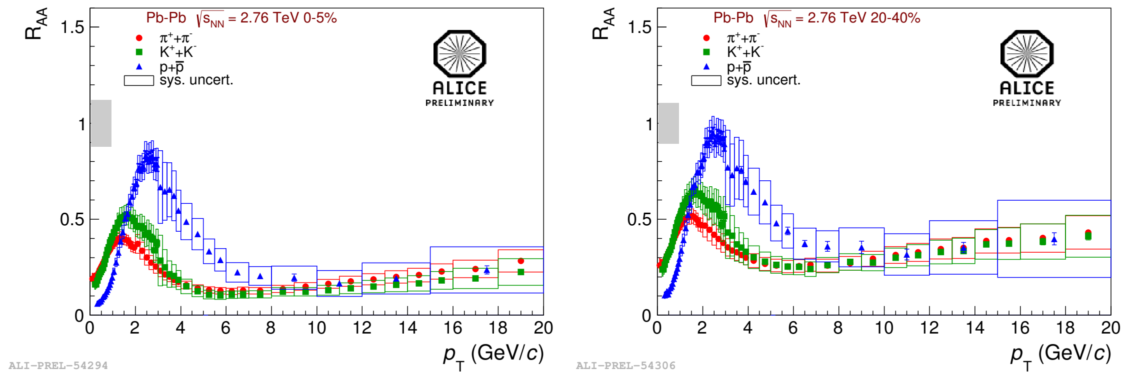

Figure 3: The nuclear modification factor, R_{AA}, for $\pi^{+}+\pi^{-}$, $\mathrm{K}^{+}+\mathrm{K}^{-}$, and $\mathrm{p}+\bar{\mathrm{p}}$ as a function of p_{T} for 0-5 % (left) and 20-40 % (right). Statistical errors are shown by the vertical error bars. Systematic uncertainties are given as colored boxes, and the overall normalization error is indicated by the grey box.

To study final state effects, jet quenching, in Pb-Pb collisions the nuclear modification factor R_{AA} can be computed as:

$$R_{\mathrm{AA}} = \frac{\left(\frac{d^{2}N}{dp_{\mathrm{T}}dy}\right)_{\text{Pb-Pb}}}{\langle T_{\mathrm{AA}}\rangle \left(\frac{d^{2}\sigma_{\mathrm{INEL}}}{dp_{\mathrm{T}}dy}\right)_{\mathrm{pp}}}, \tag{2.1}$$

where $\langle T_{\mathrm{AA}}\rangle$ is the nuclear overlap function obtained from a Glauber calculation for a given centrality class [7]. The total number of binary collisions is $\langle T_{\mathrm{AA}}\rangle\sigma_{\mathrm{pp}}$, and in case there is no nuclear effects one expects binary scaling ($R_{\mathrm{AA}} = 1$) at high p_{T} where pQCD is applicable. We note here that it recently has been shown by ALICE that for p-Pb collisions the nuclear modification factor, R_{pPb}, is consistent with 1 (no modifications) indicating that initial state nuclear effects are small if present [8].

The observed yield of high-p_{T} particles is much smaller than expected from binary scaling because of strong final state interactions with the surrounding dense medium [9]. Experiments at RHIC have shown that this modification is very different for mesons and baryons for $p_{\mathrm{T}} < 8$ GeV/c [10, 11].

The results from RHIC have lead to theoretical speculations on particle specie dependent effects at even higher p_{T}, but as we observe in Figure 3 there is no evidence for large effects at LHC energies, and in fact for $p_{\mathrm{T}} > 8$ GeV/c the suppression is similar. This suggests that the difference for $p_{\mathrm{T}} < 8$ GeV/c is not related to jet quenching and in fact ALICE has shown in a preliminary study that the large difference between baryons and mesons is a bulk effect [12]. For $p_{\mathrm{T}} < 8$ GeV/c particle ratios are a more useful way to study the physics.

Figure 4 (top) shows the $(\mathrm{p}+\bar{\mathrm{p}})/(\pi^{+}+\pi^{-})$ ratio for different centralities. At LHC one observes a similar enhancement of the baryon to meson ratio as at RHIC [11, 13]. In the top right

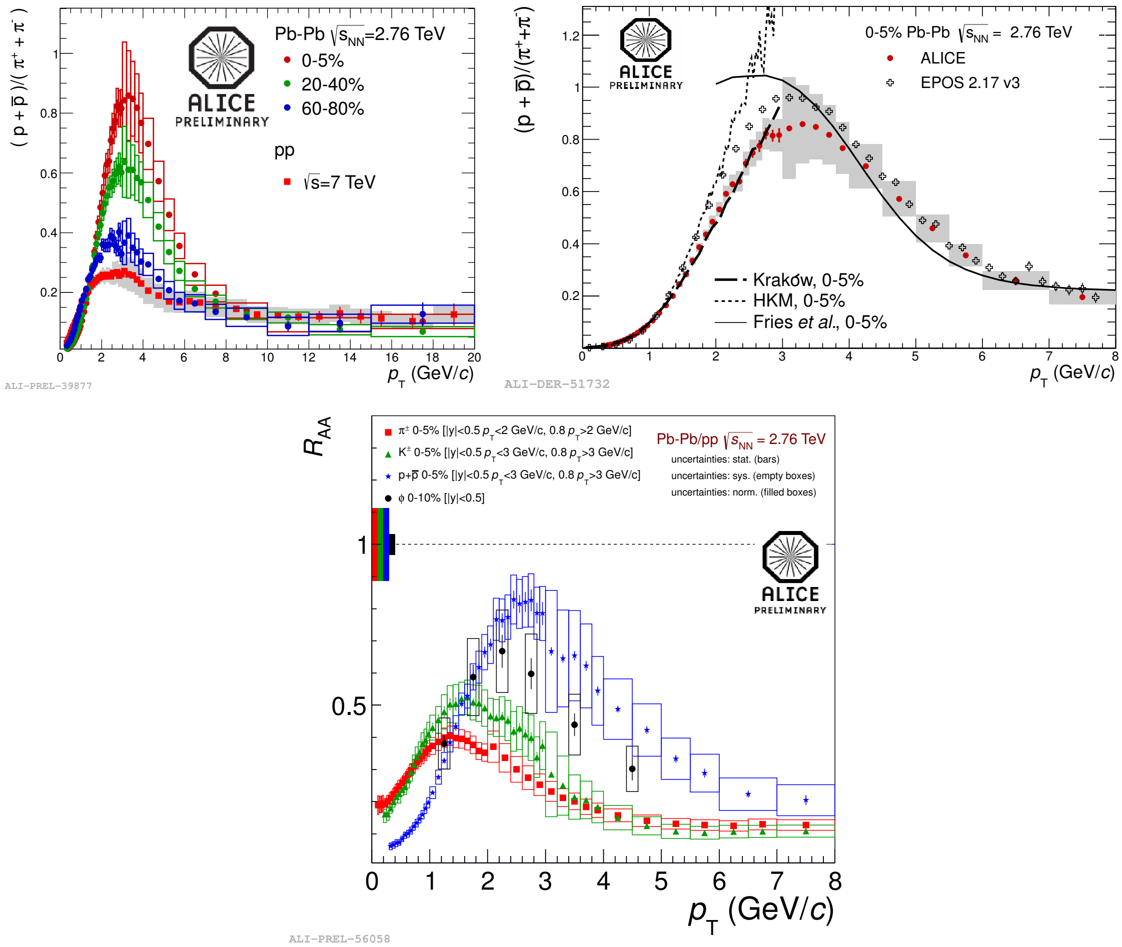

Figure 4: Top: The particle ratio, $(\mathrm{p}+\bar{\mathrm{p}})/(\pi^{+}+\pi^{-})$, as a function of p_{T} for several centralities and pp (left), and compared to models for 0-5 % (right). Bottom: The R_{AA} for $\pi^{+}+\pi^{-}$, $\mathrm{K}^{+}+\mathrm{K}^{-}$, and $\mathrm{p}+\bar{\mathrm{p}}$ for 0-5 %, compared to the R_{AA} for ϕ for 0-10 %.

panel the most central results are compared to two types of model calculations: hydrodynamic models where the particle spectra are determined by the mass of the particle, and recombination schemes where the relevant variable is the number of constituent quarks (baryon/meson effect). The hydrodynamical models, Kraków and HKM, are known to describe well the low p_{T} spectra [14], and hence describe well the rise of the ratio. So the ratio is not anomalous but consistent with a strong hydrodynamic boost. EPOS is a full event generator with a hydrodynamic medium but also includes hard scatterings and a special fluid hadronization scheme for quenched jets to describe the peak [15]. Finally the results are compared to a prediction from the recombination model [16] where it is assumed that lower p_{T} constituent-quark-like degrees of freedom can combine to form mesons (at $2\times p_{\mathrm{T}}$), and baryons (at $3\times p_{\mathrm{T}}$) [2].

In the bottom plot of the figure is shown again the R_{AA}, but compared to results for the ϕ meson which has similar mass as a proton ($\approx$ 1020 MeV/c^2). The systematic errors are quite large

[2]This has been shown to give a particular simple explanation for part of the elliptic flow pattern observed at RHIC, see e.g. [17]

but one qualitatively observes that the ϕ follows the proton below the peak (up to $p_{\mathrm{T}} \sim 2$ GeV/c), suggesting a mass effect, while above the peak it drops faster than the protons leaving room for a baryon effect. The results for the ϕ mesons and for the baryon to meson ratio associated with the jet and the bulk can hopefully help differentiate better between models.

3. Conclusions

The production of identified pions, kaons, and protons at high p_{T} is not well understood in pp and Pb-Pb collisions. The results from ALICE can help to constrain the identified fragmentation functions in pp collisions. The R_{AA} at high p_{T} ($8 < p_{\mathrm{T}} < 20$ GeV/c) seems to indicate that particle species dependent effects are, if present, small. The largest particle specie dependent effects are observed for $p_{\mathrm{T}} < 8$ GeV/c where most of the difference between the results for pp and Pb-Pb collisions below $p_{\mathrm{T}} < 3$ GeV/c can be attributed to the phase in the nuclear collisions where the formed medium expands according to nearly ideal hydrodynamics. In the transition from this soft regime to the hard new hadronization processes, such as recombination, might be needed to explain the data.

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