Identified Particle Production in p-Pb Collisions
Measured with the ALICE Detector

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Abstract

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 ($p_T$). In this proceeding\textsuperscript{1} recent measurements of $p_T$ spectra for $\pi$, $K$, $K^0_s$, $p$, and $\Lambda$ in p-Pb collisions are presented and compared to results from Pb-Pb and pp. In particular the implications for the question of the existence of radial flow in small systems is discussed.

Keywords: proton nucleus reaction, transverse momentum spectra, light hadrons, LHC, radial flow, collectivity

1. Introduction

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. In central Pb-Pb collisions the spectra of light flavor hadrons, which is the focus here: $\pi$, $K$, $K^0_s$, $p$, and $\Lambda$, have been shown to be successfully described using models relying primarily on the formation of a medium that expands following nearly ideal hydrodynamics and hadronizes according to the statistical thermal model\textsuperscript{[1]}. However, in general the same models have been found to provide a poor description of the measured spectra in peripheral collisions\textsuperscript{[2]}. The failure of the simple combination of hydrodynamics and thermal spectra in peripheral collisions suggests that the spectra there are closer to pp like QCD spectra. This is supportive of the basic idea that a Quark Gluon Plasma (QGP) medium is produced in central collisions,

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but not in peripheral collisions. However, it has recently been discovered at LHC that in p-Pb collisions a double ridge structure reminiscent of azimuthal flow is observed, and a similar structure has been observed reanalyzing the existing RHIC data. To follow up on this observation ALICE has published light flavor hadron spectra as a function of multiplicity in p-Pb. As the data is already published the goal here is only to discuss some aspects of the results.

2. Model Driven Interpretation

Figure 1: The proton-to-pion ratio, \((p + \bar{p})/(\pi^+ + \pi^-)\), as a function of \(p_T\) in pp collisions for p-Pb at \(\sqrt{s_{NN}} = 5.02 \text{ TeV}\) in two multiplicity classes (left) and for Pb-Pb at \(\sqrt{s_{NN}} = 2.76 \text{ TeV}\) in two centrality classes (right). Total systematic uncertainties are shown as open boxes and for p-Pb results the uncorrelated systematic uncertainty is shown by the (small) solid boxes.

Figure 1 shows the essential observation that will be discussed in this proceeding: when the proton-to-pion ratio, \((p + \bar{p})/(\pi^+ + \pi^-)\), in a high multiplicity class is compared to a lower multiplicity class in p-Pb we

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2See G. Roland these proceedings for a much more detailed account of what we have experimentally learned so far on the complicated relation between pp, p-Pb, and Pb-Pb.

3See also R. Venogupolan, A. Sickles, F. Wang, J. Velskova, P. Bozek, and P. Kuijer in these proceedings.

4See also F. Barile in these proceedings.

5A discussion of p-Pb multiplicity and its relation to centrality can be found in the contribution from A. Toia to these proceedings.
observe the same phenomena as for Pb-Pb collisions: a decrease at low \( p_T \) and an increase at high \( p_T \) so that it suggests that the protons have been “pushed” out to higher \( p_T \). Here it is important to stress that for the p-Pb analysis the uncorrelated systematic uncertainty for different multiplicity classes was evaluated and found to be much smaller than the total systematic uncertainty, so the relative multiplicity dependence of the proton-to-pion ratio is known with great precision while the absolute ratio has significant systematic uncertainty.

This behavior is reminiscent of radial flow where the heavier particles are pushed out to higher \( p_T \) by the collective flow velocity boost. Figure 2 shows the measured \( p_T \) spectra for \( \pi, K, p, (p-Pb \text{ and Pb-Pb}) \) and \( K^0_s \) and \( \Lambda \) (p-Pb only) compared to various models that, except for DPMJET (top plot only), all incorporates a hydrodynamic phase. For a detailed discussion we refer to the published references [1, 2, 7] and references therein. One notes that except for peripheral Pb-Pb collisions in general the hydro based models give a good qualitative and in some cases quantitative description of the data. DPMJET which is based on PHOJET extended to nuclear events via Glauber-Gribov theory fails to describe the data suggesting that a hydro-like push is needed to describe the \( p_T \) spectra for high multiplicity p-Pb collisions. It is important to note that in the bottom right plot also the relative trends for \( \pi, K, p \) are different so that it is not just an overall softening or hardening that is missing in the model description.

The main point that the author wishes to point out here is that while the hydro approach fails in peripheral Pb-Pb collisions it works quite successfully for p-Pb – a system of a comparable size. If hydrodynamics is at work in such small systems, as suggested by p-Pb results, then something else, like the understanding of the initial state in nuclear collisions, is needed to explain why it fails for peripheral collisions.

Further studies can be found in the above paper where hydro-inspired blast wave fits are also used to analyze p-Pb and Pb-Pb data [7].

3. Data Driven Interpretation

Figure 3 shows an alternative data driven method of summarizing the results. In the left figure the \( \Lambda/K^0_s \) ratio is shown as a function of the mid-rapidity \( dN_{ch}/d\eta \) in 3 different \( p_T \) bins for all Pb-Pb centrality classes and for all pp and p-Pb multiplicity classes. For each \( p_T \) bin and system, pp, p-Pb, and Pb-Pb, the data points are fitted with a power law function:

\[
\Lambda/K^0_s = A \cdot (dN_{ch}/d\eta)^B
\]

The right figure shows the exponent \( B \) vs \( p_T \) for all 3 systems and it is evident that in fact this exponent, within statistical and systematic uncertainties, is the same for all systems. This is a surprisingly
Figure 2: Light hadron spectra compared to various models for high multiplicity p-Pb (top) and Pb-Pb central (bottom left) and peripheral (bottom right) collisions. All models, except for DPMJET (top plot only), incorporate a hydrodynamic phase, but have various implementation of additional physics in the hadronic phase.
Figure 3: Left: the lambda-to-kaon ratio, $\Lambda/K^0_s$, as a function of the mid-rapidity $dN_{ch}/d\eta$ in three $p_T$ intervals for all measured multiplicity classes (pp and p-Pb) and centrality classes (Pb-Pb). The dashed lines shows power law fits for individual colliding systems. Right: the $p_T$ dependence of the power law exponent from the fits for the 3 systems. As can be seen the relative increase of the ratio with $dN_{ch}/d\eta$ is similar in all cases even out to large $p_T$.

suggestive pattern that similar physics is driving the ratios for all systems and for all sizes (no evidence for an onset in $dN_{ch}/d\eta$).

Is scaling of the particle ratios with the $dN_{ch}/d\eta$ intuitive? It does not appear to be so. In a hydro picture the initial spatial geometry must be very important while in this scaling relation it does not enter. But this might not be all bad, as we just saw in the discussion of figure 2 it is not possible for hydro based models to describe both central and peripheral data, so maybe the $dN_{ch}/d\eta$ scaling is more fundamental.

Another way to vary $dN_{ch}/d\eta$ is by varying the beam energy. Comparing LHC ($\sqrt{s_{NN}} = 2.76$ TeV) and RHIC ($\sqrt{s_{NN}} = 0.2$ TeV) $dN_{ch}/d\eta$ at mid-rapidity it was found that the increase for all centrality classes was approximately a factor 2.1 [8]. So one could expect that if the $dN_{ch}/d\eta$ scaling was fundamental then the evolution from peripheral to central collisions should be the same at both energies. Figure 4 shows a comparison between the $\Lambda/K^0_s$ ratios at LHC and RHIC for central and peripheral events. As can be seen the results for peripheral events are quite similar when the difference in baryon chemical potential, $\mu_B$, at RHIC and LHC is taken into account [9]. However, for central events the “push” in $p_T$ at LHC is significantly larger (as expected from hydro calculations). It would be interesting to extend figure 2 with similar comparisons for RHIC data and the same models. A naive interpretation of the comparison is that it agrees better with the traditional

\[^6\text{In statistical thermal models one would expect } (\Lambda + \bar{\Lambda})/K^0_s \text{ to be approximately independent of baryon chemical potential when } \mu_B \ll T.\]
peripheral/QCD and central/QGP picture.

4. Conclusion and Outlook

Some of the ALICE results for production of $\pi$, $K$, $K^0_s$, $p$, and $\Lambda$ have been presented and discussed. In particular the similarity between the different collision systems, $pp$, $p$-Pb, and Pb-Pb, have been pointed out, where the lack of an onset in system size is surprising and in contrast to ideas of rare fluctuations in small systems. We have also tried to understand how the model predictions relate across system sizes and beam energies to see if a simple model can describe all these systems, and found that this does not seem to be the case.

Another question that is important for the outlook is how the small QCD systems can have collective degrees of freedom. In QCD for light quark systems there is no simple relation between the hadronic states and the quarks, e.g., for the masses, we rather need the scale $\Lambda_{QCD} \approx 200$ MeV. With this scale we can get a rough feeling for the hadronic sizes, $r \sim \hbar c/\Lambda_{QCD}$ and masses. As hadrons are made of 2 or 3 valence quarks we have a good basis to assume that this corresponds to “a unit of QCD matter”. Typically the idea has been that, as in condensed matter physics when grouping atoms

\footnote{See, e.g., the discussion about “fat protons” by B. Mueller in these proceedings}
together, there are emergent features when we group many units of QCD matter together. These emergent features are supposedly the main reasons to study the Quark Gluon Plasma. So by introducing hydrodynamics in small systems the feature becomes QCD like rather than QGP like.

To make progress on the underlying physics one can look for inspiration also in pp models. PYTHIA contains two interesting ingredients.

On one hand it is found that Multi Parton Interactions do not hadronize independently but need a new ingredient where the solution so far has been color reconnection which has recently been shown to give radial flow-like boosts [9]. Color reconnection has no unique implementation and there is an interest in pp physics to explore alternative ideas [10].

On the other hand it is also known that to remove the divergence of the hard cross section at low $p_T$ one needs a scale of order 2 GeV/$c$ rather than $\Lambda_{QCD}$. Interpreted as a length (0.1 fm) it suggests that, e.g., a red charge is “neutralized” by an anti-red charge at this scale [11]. This is perhaps interesting as it suggests that color is organized at a much smaller scale inside the hadrons and could help explain how collective properties can arise in small systems.

With these final words I hope to stress my personal perspective that the high quality data shown at this conference warrant theoretical ideas to be developed for how to falsify the underlying assumptions.

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