STRANGE AND MULTI-STRANGE PARTICLE PRODUCTION IN Pb-Pb COLLISIONS AT $\sqrt{s_{NN}} = 2.76$ TeV WITH ALICE

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We present ALICE results on strange and multi-strange hadron production as a function of centrality in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV at the LHC. Their transverse momentum spectra, yields and particle ratios are compared to the corresponding measurements in pp collisions to address strangeness enhancement and high $p_T$ particle suppression. The results are also compared to measurements at RHIC and SPS energies.

Keywords: strange particles; relativistic heavy-ion collisions.

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1. Introduction

It is generally assumed that collisions of relativistic heavy-ions lead to the formation of a deconfined high temperature and density state of nuclear matter, the quark-gluon plasma. The new phase of matter exists for a short time after the collisions and ultimately hadronizes into final-state particles. Considerable efforts have been put into identifying observables that are sensitive to the properties of the early deconfined stage of the collisions. Strangeness enhancement, one of the first proposed signatures of the deconfined phase \cite{1}, has been commonly considered to be an important probe of the strongly interacting matter created in heavy-ion collisions.

By exploiting the tracking and particle identification capabilities of ALICE, strange ($\Lambda$, $K^0_S$) and multi-strange ($\Xi^-$, $\Omega^-$) particles can be detected via their weak decay topologies and measured over a wide range of transverse momenta. In this report we present the latest ALICE results on strange ($\Lambda$, $K^0_S$) and multi-strange ($\Xi^-$, $\Omega^-$) production in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. In the next section, we present transverse momentum ($p_T$) spectra measured at mid-rapidity ($|y| < 0.5$) as function of centrality. We discuss in the third section the evolution

\cite{1}Some of the results presented at the workshop have, in the meantime, been finalized and these results are used in these proceedings.
of $\Lambda/K^0_S$ ratio as a function of $p_T$, in comparison with the corresponding results in pp collisions at the LHC and in $\sqrt{s_{NN}} = 200$ GeV Au-Au collisions at RHIC. The excitation function of the strangeness enhancement from SPS to LHC energies is discussed in the fourth section. In the fifth section, the nuclear modification factors for multi-strange particles are compared with other identified particles to provide insight into particle production and energy loss mechanisms at play.

### 2. Strange and Multi-strange $p_T$ Spectra in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV

The ALICE experiment, dedicated to study heavy-ion physics at the LHC, has excellent particle identification capability. Strange and multi-strange particles were reconstructed via their weak decay channels: $K^0_S \rightarrow \pi^+\pi^-$, $\Lambda \rightarrow p^+\pi^-$ ($\bar{\Lambda} \rightarrow \bar{p}^+\pi^-$), $\Xi^- \rightarrow \Lambda^+\pi^-$ ($\bar{\Xi}^+ \rightarrow \bar{\Lambda}^+\pi^+$) and $\Omega^- \rightarrow \Lambda^+K^-$. The combinatorial background contribution to the invariant mass distributions of the candidates for all species was reduced by applying cuts selecting specific decay topologies and using information on the specific energy loss in TPC of their decay daughters.

![Graphs showing transverse momentum spectra for $K^0_S$ and $\Lambda$.](image)

Fig. 1. Transverse momentum spectra for $K^0_S$ (top) and $\Lambda$ (bottom) at mid-rapidity for different centrality intervals of Pb-Pb collisions shown in logarithmic (left) and linear (right) scale.

The signal was extracted, for each particle in each $p_T$ interval, by subtracting
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Fig. 2. Transverse momentum spectra for $\Xi^-$ and $\Omega^-$ (a, b) and their anti-particles (c, d) at mid-rapidity in different centrality intervals for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

from the peak population the background, which was estimated by a first or second order polynomial fit. Acceptance and efficiency was estimated via a Monte-Carlo study and applied to correct the signals. The $\Lambda$ yield was further corrected for feed-down contributions from weak decays of $\Xi^-$ and $\Xi^0$ ($\Omega$ contribution being negligible). The $p_T$ spectra of strange and multi-strange particles are shown for different centrality classes in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in Fig. 1 and 2, respectively.

3. $\Lambda/K_S^0$ Ratio

When compared with the peripheral and pp results, $\Lambda/K_S^0$ and $p/\pi$ ratios were observed to be enhanced at intermediate $p_T$ in central heavy-ion collisions at both RHIC\cite{3,4,5} and SPS\cite{6}. These observations suggested that other hadronization mechanisms, such as coalescence, may open up in the deconfined medium created in heavy-ion collisions. Indeed, the so-called “baryon anomaly” could be qualitatively explained if hadrons were formed by recombination of two or three soft quarks\cite{7,8}.

Figure 3 (left) shows the $\Lambda/K_S^0$ ratios as a function of $p_T$ for different centralities in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV\cite{9}. For comparison, also shown in the plot are the ratios measured in pp collisions at $\sqrt{s} = 0.9$ and 7 TeV. The ratio in pp collisions always stays far below 1 and appears to be insensitive to the collision energy.
the ratio in the most peripheral Pb-Pb collisions is compatible with that measured in pp collisions, at intermediate $p_T$ it increases with collision centrality and develops a maximum at $p_T \sim 3$ GeV/$c$ reaching a value of about 1.6 for the 0-5% most central Pb-Pb collisions. However, at $p_T > 7$ GeV/$c$, the $\Lambda/K^0_S$ ratio appears to be independent of collision centrality and very similar to that measured in pp collisions. This suggests that the production of $\Lambda$ and $K^0_S$ at high $p_T$, even in central Pb-Pb collisions, could be dominated by vacuum-like fragmentation of energetic partons.

![Fig. 3](image.png)

A comparison between LHC and RHIC measurements on $\Lambda/K^0_S$ ratios is shown in the right panel of Fig. 3 for the most central (0-5%) and peripheral (60-80%) nucleus-nucleus collisions. Both $\Lambda/K^0_S$ and $\bar{\Lambda}/K^0_S$ are plotted for the STAR measurements in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV considering that the anti-baryon/baryon ratio is about 0.8 instead of $\sim 1$ observed at LHC. As can be seen from the comparison, although the magnitude of the ratio is similar, the position of the maximum seems to shift towards higher $p_T$ as the collision energy increases, suggesting a stronger radial-flow effect at higher collision energy.

Also shown in the right panel of Fig. 3 are theoretical model calculations for the most central collisions. As can be seen, the viscous hydrodynamical model\textsuperscript{10} describes the data well up to $p_T$ about 2 GeV/$c$ but deviates progressively at higher $p_T$. A recombination model calculation\textsuperscript{11} can approximately reproduce the shape, but overestimates the magnitude of the data by about 15%. The EPOS model\textsuperscript{12}, which takes into account the interaction between jets and the hydrodynamical medium, appears to describe the data reasonably well.
4. Strangeness Enhancement

Strangeness enhancement, defined as the enhancement of the relative yield per participant in nucleus-nucleus collisions to that in pp or p-Be collisions, was proposed in the 1980s as a signature of a phase transition to quark-gluon plasma which was expected to take place in relativistic nucleus-nucleus collisions\(^1\). Indeed, the enhancement of strangeness was observed in heavy-ion collisions at the SPS\(^13,\)\(^14,\)\(^15\) and RHIC\(^16\). In particular, the enhancement is more pronounced for multi-strange baryons and decreases as the collision energy increases.

Figure 4 shows the enhancements for multi-strange baryons in Pb-Pb collisions at \(\sqrt{s_{NN}} = 2.76\) TeV, as a function of the mean number of participants \(\langle N_{\text{part}} \rangle\), in comparison with the corresponding measurements by NA57 at SPS\(^13\) and STAR at RHIC\(^16\). The enhancement increases with centrality and with the strangeness content of the particles as observed already at lower energies, but decreases with increasing energy, following the trend observed at lower energies. It is worth mentioning that the production of multi-strange particles in heavy-ion collisions does increase with collision energy from the SPS to the LHC. However, the increase of the multi-strange yields in smaller colliding systems (pBe or pp) used as reference, appears...
to be slightly faster, resulting in the less pronounced enhancement than at lower energies.

5. Nuclear Modification Factor

When an energetic parton traverses the hot dense QCD medium created in relativistic heavy-ion collisions, it suffers large energy loss due to gluon radiation and multiple scatterings. This parton energy loss is expected to lead to a modification of energetic jets (jet quenching), which should be reflected in the $p_T$ spectra of hadrons, originating from the energetic partons produced in initial hard collisions. To quantify the medium modification of the measured hadron yield in nucleus-nucleus (A-A) collisions, it is compared to the expectation from an independent superposition of nucleon-nucleon collisions (binary collision scaling) by introducing the nuclear modification factor:

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dydp_T}{<T_{AA}> d^2\sigma^{NN}/dydp_T},$$

(1)

where $N^{AA}$ is the particle yield in A-A collisions, $d^2\sigma^{NN}/dydp_T$ the cross-section of particle production in pp collisions, and $T_{AA}$ the geometric nuclear overlap function. In the absence of any nuclear modification to the incoherent hard processes, the nuclear modification factor at high $p_T$ is expected to be unity according to the binary collision scaling.

![Graph showing $R_{AA}$ as a function of $p_T$ for multi-strange baryons in most central and most peripheral Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.](image)

Fig. 5. Nuclear modification factor for $\Xi$ and $\Omega$ compared with $\pi$, $K$, $p$ and $\phi$ in most central (left) and the most peripheral Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

Figure 5 shows $R_{AA}$ as a function of $p_T$ for multi-strange baryons in most central and most peripheral Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. For comparison, also
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plotted in the figures are the nuclear modification factors for charged pions, kaons, protons and $\phi$-mesons. At high $p_T$ the $R_{AA}$ for $\Xi$ seems to follow the same trend of the proton, whereas the $R_{AA}$ for $\Omega$ appears not to be suppressed. At intermediate $p_T$ a mass-ordering is clearly observed among the baryons and mesons, respectively.

6. Summary

The results of several studies on strangeness production are presented to investigate the properties of the strongly interacting matter created at the LHC in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. At intermediate $p_T$ $\Lambda$ production relative to $K^0_S$ is strongly enhanced in central Pb-Pb collisions. At high $p_T$ however, $\Lambda/K^0_S$ appears to be similar to pp results, indicating that vacuum-like fragmentation dominates there. The enhancements of multi-strange baryons relative to pp increase both with the centrality and with the strangeness content of the baryon, but decrease with increasing energy, confirming the trend observed at lower energies. The comparison of the nuclear modification factors for multi-strange baryons to lighter particles shows that, while the $R_{AA}$ for $\Xi$ at high $p_T$ seems to follow the same trend as of the proton, the behavior of $\Omega$ is very different from the others.

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