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Study of Strange Particle Production in Central Pb–Pb Collisions at $\sqrt{S_{NN}} = 2.76$ TeV

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ABSTRACT

We study here the transverse momentum spectra of K_s^0 – mesons, A – hyperons and multi–strange (Ξ^-, Ω^-) particles in the most central *Pb–Pb* collisions at $\sqrt{SNN}$ = 2.76 TeV for the mid rapidity interval |y| < 0.5 by using two different Monte Carlo simulation models: EPOS–1.99 and EPOS–LHC. The validity of simulation codes of these models is checked for *Pb–Pb* collisions at $\sqrt{SNN}$ = 2.76 TeV by comparing the simulation data with ALICE experimental data for the same collisions at $\sqrt{SNN}$ = 2.76 TeV. Strange particles ratio i.e. Λ/K_s^0 and nuclear modification factors for multi–strange particles have been constructed as function of p_T to study these strange particle production and their energy loss mechanism. The simulation models show suppression for the multi–strange particles in the transverse momentum range of 3–7 GeV/c. The outcome agrees with a recent finding by ALICE collaboration where it suggested a possibility that the kinetic freeze–out conditions for strange particles are different from those for non–strange particles.

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Introduction

It is observed in heavy ion collisions experiments at RHIC, SPS and CERN LHC, during the measurements of the transverse momentum (p_T) spectra in *p–p* and *Pb–Pb* collisions, that at high p_T particle production is suppressed in *Pb–Pb* collisions as compared to the particle yields measured in *p–p* collisions [1-9]. Strangeness production measurements are powerful tools for the study of the thermal properties of the deconfined state of Quantum Chromodynamics (QCD) matter during the production of Quark Gluon Plasma (QGP). By comparing the yields of high p_T particles produced in the *Pb–Pb* collisions with the predictions of theoretical models one can obtain some important insight on the fundamental properties of QGP. Bjorken suggested that the observed suppression of charged particle production at high p_T in Pb–Pb collisions is an effect due to the partons energy loss while they propagate through the hot and dense deconfined strongly interacting medium [10, 11].

The modification of high p_T particle production in Pb–Pb collisions is quantified by studying an important observable called nuclear modification factor (NMF) R_{AA} that is defined as

$$R_{\rm AA} = \frac{dN^{\rm AA}/dp_{\rm T}}{< N_{\rm Coll} > dN^{pp}/dp_{\rm T}}$$

Nuclear modification factor (NMF) R_{AA} is a ratio of particle differential yield in *Pb–Pb* collisions to that of *p–p* collisions scaled by the average number of binary nucleon–nucleon collisions $<N_{Coll}>$. The study of R_{AA} imparts important information about the properties of the background medium formed as a result of *p–p* and *Pb–Pb* interactions. If *Pb–Pb* collisions are a simple superposition of elementary nucleon–nucleon collisions R_{AA} is equal to unity it shows absence of nuclear effects. However, if R_{AA} <1, there is a suppression of particles production compared to binary–collisions scaling which takes place due to an effect known as jet quenching of partons [10].

The measurements of R_{AA} for charged particles as a function of p_T at LHC [7–9, 12] have shown that in central *Pb–Pb* collisions at $\sqrt{SNN}$ = 2.76 TeV the particle yields are suppressed by a factor of up to 7 for p_T range of 6–7 GeV/c but the suppression decreases for larger p_T. In 2015 LHC had its first *Pb– Pb* collisions at $\sqrt{SNN}$ = 5.02 TeV and observed nearly same amount of suppression for central *Pb–Pb* collisions within the same p_T range [13]. The results of CMS Collaboration on charged particles for R_{AA} at $\sqrt{SNN}$ = 5.02 TeV TeV have shown a similar amount of suppression in charged particle production for p_T = 6–9 GeV/c in the central *Pb–Pb* collisions [14].

In this work we study the transverse momentum spectra of K_S^0 – mesons, Λ−hyperons and multi– strange particles (Ξ^-, Ω^-) production in the most central Pb–Pb collisions at $\sqrt{S}$ = 2.76 TeV at the mid–rapidity interval (|y| < 0.5) by using Monte Carlo simulation codes including EPOS–LHC and EPOS–1.99. A description of these models is given in the next section. Transverse momentum distributions of strange and multi–strange particles along with the particle ratios and nuclear modification factor as a function of transverse momentum are shown in the results and discussion section. The distributions obtained from the simulation data are also compared with the ALICE experimental data [13]. Last section is based on conclusions.

Method and Models

To study the pT distributions of strange and multi–strange particles produced in the most central Pb– Pb collisions at $\sqrt{SNN}$ = 2.76 TeV and in the rapidity intervals of |y| < |0.5|, we have used two different MC event generators: EPOS–1.99, and EPOS–LHC models [15–17]. EPOS stands for energy conserving quantum mechanical multiple scattering approach, based on partons (parton–ladder), off– shell remnants, and splitting of parton ladders [16]. It is purely constructed on theoretical basis, critically tested and verified over existing hadronic data. EPOS is a model based on parton model including binary parton–parton collisions and each of these collisions produce a separate parton ladder [17]. For the cross–section calculations and particle productions there are energy conservations employed in the EPOS model. However, energy conservation is not considered for cross section calculations in other models [18]. EPOS is a quantum mechanical model which inter–accounts multiple scattering based on partons and strings. It is not only used for cosmic ray physics, but it is also used to simulate data for heavy ion physics experiments such as SPS, LHC and RHIC. EPOS– 1.99 deals mostly with the soft interactions with its emphasis on the high partons densities which are significant for nucleus–nucleus (*AA*) collisions. An upgraded version of EPOS–1.99 is also developed to inter–account LHC energies it is known as EPOS–LHC [19]. This new version of EPOS model can reproduce all minimum bias results for all the particles with transverse momentum up to a few GeV/c. Based on these models we have generated and then analyzed the simulated data.

Results and Discussion

We study the transverse momentum distribution of strange and multi–strange particles produced in the most central *Pb–Pb* collisions at $\sqrt{S_{NN}}$ = 2.76 TeV in the mid rapidity interval (–0.5 < y < 0.5). Transverse momentum distribution of K_S^0 – mesons and Λ – hyperons produced in the most central *Pb– Pb* collisions at $\sqrt{S_{NN}}$ = 2.76 TeV for the simulation codes EPOS–LHC and EPOS–1.99 along with ALICE experimental data are plotted in the Fig.1 and Fig.2 respectively. Next, the transverse momentum distribution of multi–strange particles Ω^- and $\bar{\Omega}^+$ for MC simulation models EPOS–LHC and EPOS–1.99 together with the ALICE data are presented in Fig.3 and Fig.4 respectively. Similarly, Fig.5 and Fig.6 present a transverse momentum distribution of multi–strange particles Ξ^- and $\bar{\Xi}^+$ respectively for central *Pb–Pb* collisions at $\sqrt{S_{NN}}$ = 2.76 TeV using MC simulation models EPOS– 1.99 and EPOS–LHC. ALICE experimental data for the most central Pb–Pb collisions at $\sqrt{S_{NN}}$ = 2.76 TeV is also plotted for comparison. Figure 7 and Fig.8 describe a study of transverse momentum distribution of $\Xi^-+\bar{\Xi}^+$ and $\Omega^-+\bar{\Omega}^+$ respectively, for the most central Pb–Pb collisions at $\sqrt{S_{NN}}$ = 2.76 TeV for MC simulation models EPOS–1.99 and EPOS–LHC together with ALICE data at the same energy. Strange particle yield ratio Λ/K_S^0 as a function of transverse momentum is plotted in Fig.9 for MC simulation models EPOS–1.99 and EPOS–LHC along with ALICE experimental data at the same energy. Nuclear modification factors as a function of transverse momentum are plotted in Fig.10 and Fig.11 for multi–strange particles $\Xi^-+\bar{\Xi}^+$ and $\Omega^-+\bar{\Omega}^+$ respectively, for the most central *Pb–Pb* at $\sqrt{S_{NN}}$ = 2.76 TeV for MC simulation models EPOS–1.99 and EPOS–LHC together with ALICE data. To compare the predictions of the models with the experimental results in all these cases the bottom panels show the ratios of experimental data to MC simulation code.

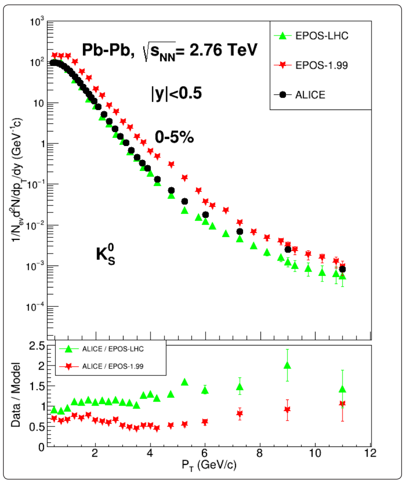

Figure 1: Transverse momentum distribution of K_s^0 –mesons produced in the most central *Pb–Pb* collisions at $\sqrt{S_{NN}}$ = 2.76TeV coming from the MC simulation models EPOS–1.99 and EPOS–LHC. ALICE experimental data for central *Pb–Pb* collisions at $\sqrt{S_{NN}}$ = 2.76TeV are also shown.

From the data in Fig.1 one can see that: EPOS–LHC has problem to describe the experimental data only in the interval of p_T = 4.5–7 GeV/c though EPOS–1.99 predictions are close to experimental data in the pT interval of 7–12 GeV/c. It is necessary to note that in the well–known interval of jet suppression EPOS–LHC underestimates but EPOS–1.99 overestimates it. So, both of models could not explain jet suppression for K_s^0 –mesons explicitly.

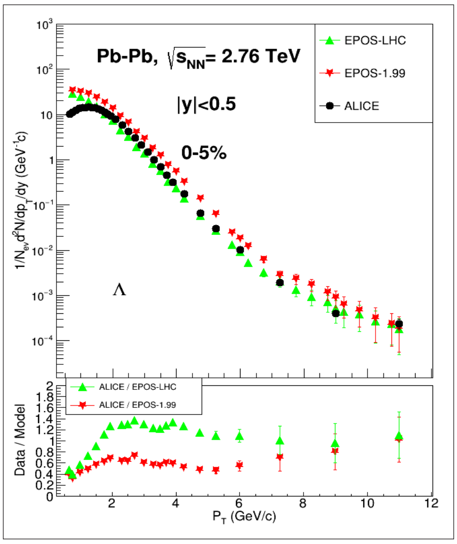

Figure 2: Transverse momentum distribution of Λ– hyperons produced in the most central *Pb–Pb* collisions at $\sqrt{S_{NN}}$ = 2.76TeV coming from the MC simulation models EPOS–1.99, EPOS–LHC. ALICE experimental.

Figure 2 demonstrates that in the case of Λ–hyperons EPOS–LHC has problem to interpret the experimental data in the interval of p_T > 5 GeV/c. However, in the interval of p_T < 2 GeV/c it gives over predictions but in the interval of 2 < p_T < 5 GeV/c it under predicts the data. The EPOS–1.99 predictions are close to experimental data in the p_T range 7–12 GeV/c only. It is again necessary to note in the well–known interval of jet suppression EPOS–LHC under predicts but EPOS–1.99 does over predictions as compared to experimental results.

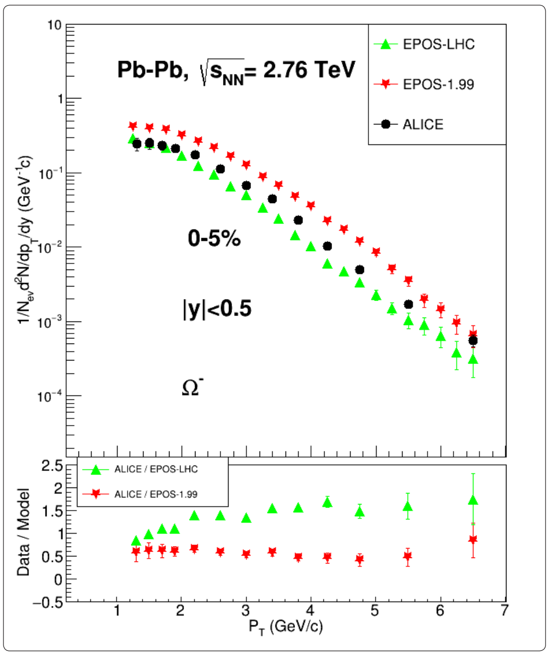

Figure 3: Transverse momentum distribution of Ω^- produced in the most central *Pb–Pb* collisions at $\sqrt{S_{NN}}$ = 2.76TeV coming from the MC simulation models EPOS–1.99 and EPOS–LHC along with ALICE experimental data for *Pb–Pb* collisions at $\sqrt{S_{NN}}$ = 2.76TeV

Figure 3 presents the p_T – distribution of Ω^- particles produced in central *Pb–Pb* collisions at $\sqrt{S_{NN}}$ = 2.76TeV The bottom panel shows the ratios of experimental data to the data obtained from MC simulation code. One can see that EPOS–LHC explains the experimental data at low momenta $1 < p_T < 2$ GeV/c, while it underestimates the yield for $p_T > 2$ GeV/c. EPOS–1.99 estimations for the yield of Ω– particles are higher than the experimental data for the entire p_T range. Both models cannot give quantitative predictions for the well–known interval of jet suppression. Almost the same situation is valid in case of the data for $\bar{\Omega}^+$ plotted in Fig.4.

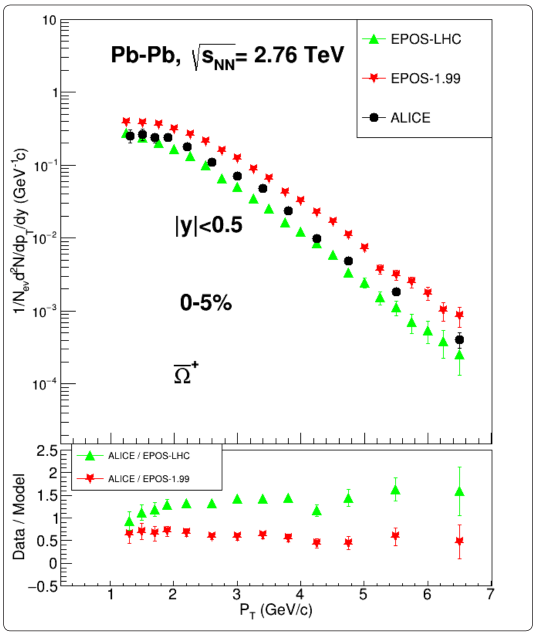

Figure 4: Transverse momentum distribution of $\bar{\Omega}^+$ produced in the most central *Pb–Pb* collisions at $\sqrt{S_{NN}}$ = 2.76TeV coming from the MC simulation models EPOS–1.99, EPOS–LHC and ALICE experimental data.

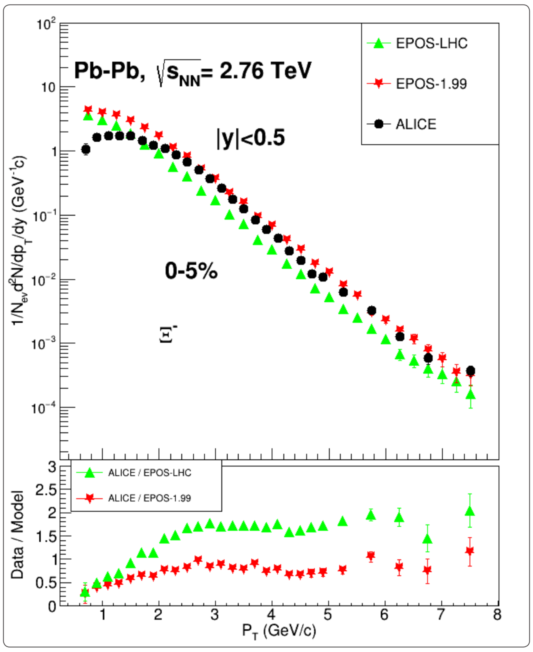

Figure 5: Transverse momentum distribution of Ξ^- produced in the most central *Pb–Pb* collisions at $\sqrt{S_{NN}}$ = 2.76TeV coming from the MC simulation models EPOS–1.99, EPOS–LHC and ALICE experimental data.

One can see from Fig. 5 that the predictions of both the models for the yield of Ξ^- particles are higher than the ALICE experimental data at low transverse momentum (in the interval of $p_T < 1.6$ GeV/c for the EPOS–LHC model and in the interval of p_T<2 GeV/c for the EPOS–1.99). At high p_T regimes EPOS–LHC can give only quantitative predictions though EPOS–1.99 is able to explain quantitatively the behavior of the yield in the high p_T region. The same situation for Ξ^+– hyperons yield comes in Fig.6.

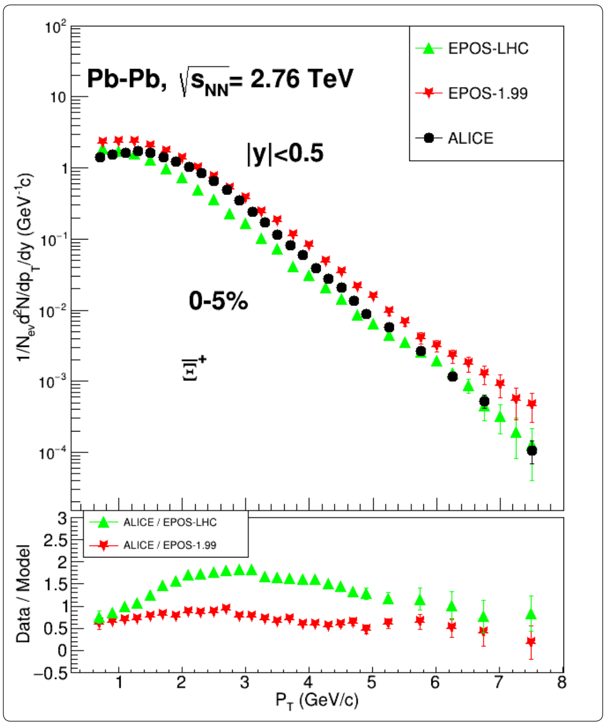

Figure 6: Transverse momentum distribution of Ξ^+ produced in the most central *Pb–Pb* collisions at $\sqrt{S_{NN}}$ = 2.76TeV coming from the MC simulation models EPOS–1.99, EPOS–LHC and ALICE experimental.

One can infer from Fig. 7 that EPOS–LHC model predictions are not consistent for the yield of $\Xi^- + \bar{\Xi}^+$ at low $p_T < 2$ GeV/c, while its predictions are lower than the ones from the experimental data for the region: $2 < p_T < 8$ GeV/c. EPOS–1.99 model calculations overestimate the values at low transverse momentum $p_T < 2$ GeV/c. However, it somewhat coincides with the experimental data for the p_T range: $2 < p_T < 8$ GeV/c.

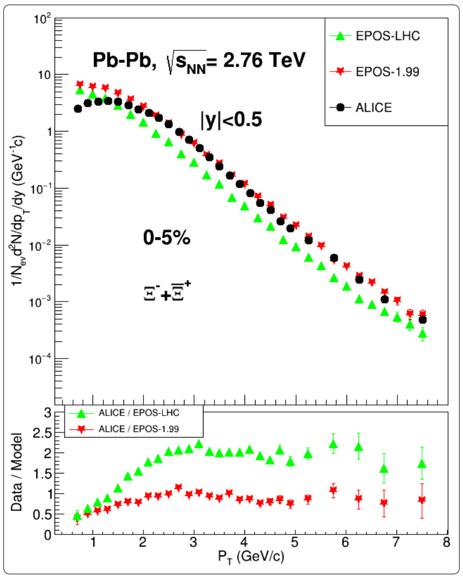

Figure 7: Transverse momentum distribution of $\Xi^- + \bar{\Xi}^+$ produced in the most central Pb–Pb collisions at $\sqrt{S_{NN}}$ = 2.76TeV from the MC simulation models EPOS–1.99, EPOS–LHC and ALICE experimental.

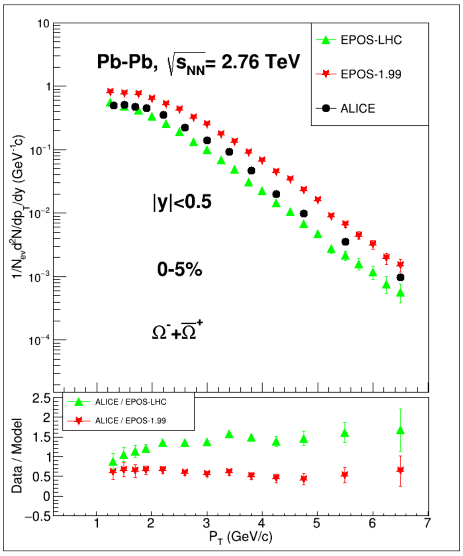

Figure 8: Transverse momentum distribution of $\Omega^- + \bar{\Omega}^+$ produced in the most central *Pb–Pb* collisions at $\sqrt{S_{NN}}$ = 2.76TeV coming from the MC simulation models EPOS–1.99 and EPOS–LHC. ALICE experimental data at $\sqrt{S_{NN}}$ = 2.76TeV are also shown.

Figure 8 describes the transverse momentum distribution of $\Omega^- + \bar{\Omega}^+$ produced in *Pb–Pb* collisions at $\sqrt{S_{NN}}$ = 2.76TeV for afore said simulation models. EPOS–LHC model predictions are in good agreement for $pT < 2$ GeV/c, while its predictions are lower than the experimental data values for the region: $2 < pT < 8$ GeV/c. EPOS–1.99 model calculations are close to the experimental data at low transverse momentum $p_T < 2$ GeV/c, however a deviation can be seen from the experimental data for the p_T range: $2 < p_T < 8$ GeV/c.

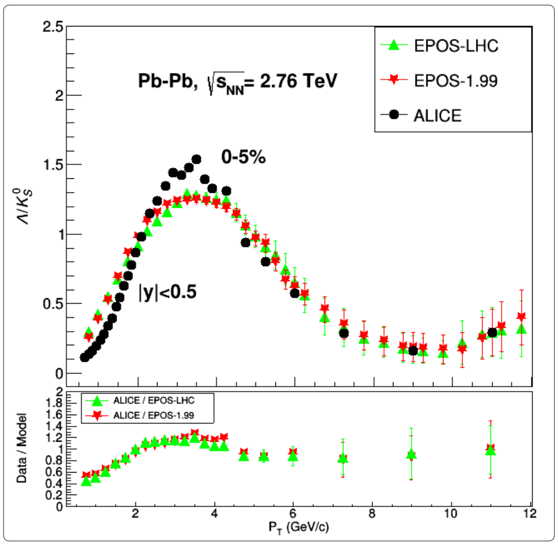

Figure 9: Transverse momentum distribution of Λ/K_s^0 in the most central *Pb–Pb* collisions at $\sqrt{S_{NN}}$ = 2.76TeV coming from the MC simulation models EPOS–1.99 and EPOS–LHC. ALICE experimental data at $\sqrt{S_{NN}}$ = 2.76TeV are also shown.

Figure 9 shows strange particle ratio Λ/K_s^0 as a function of transverse momentum for the most central Pb–Pb collisions at $\sqrt{S_{NN}}$ = 2.76TeV for simulation models EPOS–LHC and EPOS–1.99 model. Their distributions show that predictions of both the models are nearly similar. Both the models overestimate at low $p_T < 2$ GeV/c then slightly underestimate in the interval: $2 < p_T < 4$ GeV/c, consistently explain the experimental data in the region: $4 < p_T < 12$ GeV/c. One can note that in the interval of p_T valid for jet suppression ($2 < p_T < 4$ GeV/c) both models have problem. The situation is, however, during the $\Xi^- + \bar{\Xi}^+$ production as shown in Fig.10. Figure 10 gives nuclear modification factor for multi–strange particles $\Xi^- + \bar{\Xi}^+$ as a function of transverse momentum for the most central *Pb–Pb* collisions at $\sqrt{S_{NN}}$ = 2.76TeV for simulation models EPOS–LHC and EPOS–1.99 model. The distributions show that the predictions of both the models are nearly similar and close to the experimental data for the entire p_T range: $0 < p_T < 8$ GeV/c.

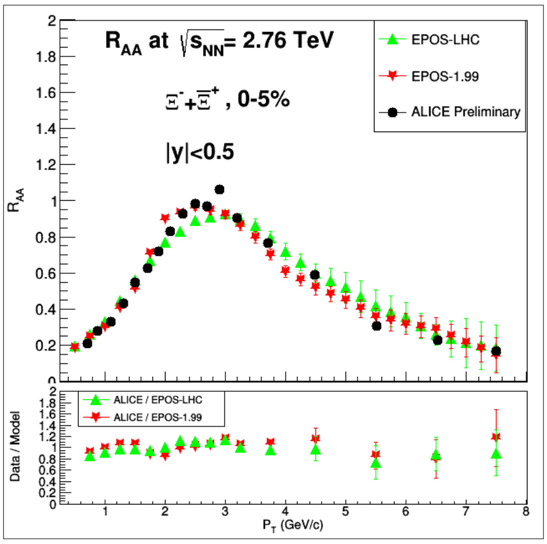

Figure 10: Nuclear Modification factor of multi–strange particles $\Xi^- + \bar{\Xi}^+$ produced in the most central *Pb–Pb* collisions at $\sqrt{S_{NN}}$ = 2.76TeV as a function of transverse momentum for simulation models EPOS and EPOS– LHC. ALICE preliminary data at $\sqrt{S_{NN}}$ = 2.76TeV also shown.

Figure 11 shows the distribution of nuclear modification factor for multi–strange particles $\Omega^- + \bar{\Omega}^+$ as a function of transverse momentum for the most central *Pb–Pb* collisions at $\sqrt{S_{NN}}$ = 2.76TeV using simulation models EPOS–LHC and EPOS–1.99. The distributions show that predictions of both the models are in good agreement with the experimental data at low transverse momentum: $p_T < 3$ GeV/c. However the simulation models underestimate whereas the nuclear modification factor has a decreasing trend i.e., in the interval: $3 < p_T < 7$ GeV/c – the region of jet suppression.

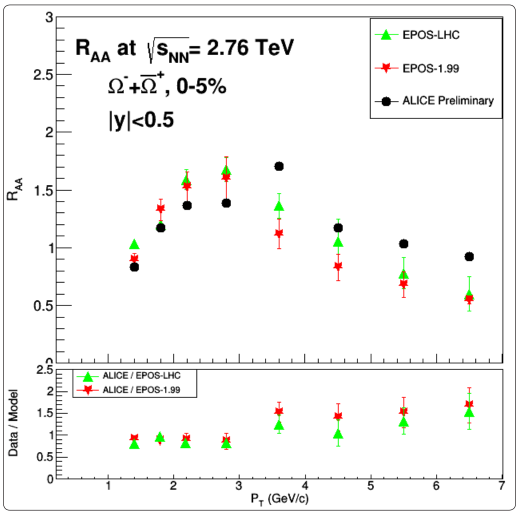

Figure 11: Nuclear Modification factor of multi–strange particles $\Omega^- + \bar{\Omega}^+$ produced in the most central *Pb–Pb* collisions at $\sqrt{S_{NN}}$ = 2.76TeV as a function of transverse momentum for simulation models EPOS and EPOS– LHC. ALICE preliminary data at $\sqrt{S_{NN}}$ = 2.76TeV are also shown.

Conclusions

The transverse momentum spectra of K_s^0 – mesons, Λ– hyperons and multi–strange (Ξ^-, Ω^-) particles have been plotted in the most central Pb–Pb collisions at $\sqrt{S_{NN}}$ = 2.76TeV for the mid rapidity interval |y| < 0.5 by using two different Monte Carlo simulation models: EPOS–1.99 and EPOS–LHC. The validity of simulation codes of these models is tested by comparing the simulation data with the already published ALICE experimental data at this energy. We observe that:

Both models could not explain the behavior of yields in the interval of jet suppression for K_s^0 – mesons, Λ–hyperons, Ω–and $\bar{\Omega}$+ hyperons;

EPOS–LHC is not explaining the behavior of yields in the interval of jet suppression for Ξ^- and $\bar{\Xi}^+$ particles but EPOS–1.99 does give satisfactory predictions for these particles yield in the interval of jet suppression;

Though the EPOS–LHC model cannot describe the behavior of yield for the $\Xi^- + \bar{\Xi}^+$ particles in the high p_T regime, the EPOS–1.99 model data almost coincides with the experimental data in this region of p_T;

Both of models could not explain the behavior of yields for the $\Omega^- + \bar{\Omega}^+$ particles in the high p_T interval;

The behavior of the ratio Λ/K_s^0 as a function of transverse momentum could not be properly reproduced by both models in the jet suppression region ($2 < p_T < 4$ GeV/c);

Both the models can explain the behavior of the nuclear modification factor for multi–strange particles $\Xi^- + \bar{\Xi}^+$ but the models get in problem to describe the behavior of the nuclear modification factor for the $\Omega^- + \bar{\Omega}^+$ particles in the p_T interval 3–7 GeV/c.

Therefore, the overall observations in this work are that the particles with strangeness and multi– strangeness composition are not very well described by both of these models for most of the range of the p_T values under consideration. The results obtained here agree with an earlier observation in Ref. that starting from peripheral collisions when one moves to most central collisions a depletion of strange particles is observed at low $p_T \lesssim 2$ GeV/c, next is their enhancement in intermediate range of $p_T \sim 2 - 7$ GeV/c and then no change is observed for $p_T > 7$ GeV/c [20]. The reasons for the trends in the present study may be similar to those described in Ref. where the authors attributed the problem in intermediate range of p_T to the possibility that the kinetic freeze–out conditions for strange particles are different from those for non–strange particles. Ref. gave a comparison with models at $\sqrt{S_{NN}}$ = 2.76 TeV and reported that the behavior at low transverse momenta is explained by hydrodynamical models while at intermediate range of the momenta it is qualitatively explained by recombination models [20, 21]. However, it was stated in Ref. that EPOS model describes the dependence over the entire transverse momentum range since it incorporates not only radial flow but also the interactions of jets with the medium [20, 22]. Thus we may need to revisit the physics aspects of the Monte Carlo simulation models: EPOS–1.99 and EPOS–LHC and do necessary modifications in their codes for a better coincidence between the experimental and the models data for the most central *Pb-Pb* collisions at $\sqrt{S_{NN}}$ = 2.76 TeV

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References

1. Arsene (2005) Quark–gluon plasma and color glass condensate at RHIC? The perspective from the BRAHMS experiment. Nucl. Phys. A 751: 1-27.
2. BB Back (2005) The PHOBOS perspective on discoveries at RHIC. (PHOBOS Collaboration), Nucl. Phys. A 757: 28-101.
3. J. Adams (2005) Experimental and theoretical challenges in the search for the quark–gluon plasma: The STAR Collaboration's critical assessment of the evidence from RHIC collisions. Nucl. Phys. A 757: 102-183.
4. K. Adcox (2005) Formation of dense partonic matter in relativistic nucleus–nucleus collisions at RHIC: Experimental evaluation by the PHENIX Collaboration, (PHENIX Collaboration), Nucl. Phys. A 757: 184-283 .
5. MM Aggarwal (2002) Transverse mass distributions of neutral pions from 208Pb-induced reactions at 158 • A GeV. (WA98 Collaboration), Eur. Phys. J. C 23: 225-236.
6. D. d'Enterria (2004) Indications of suppressed high p(T) hadron production in nucleus - nucleus collisions at CERN-SPS. Phys. Lett. B 596: 32-43.
7. S. Chatrchyan (2012) Study of high-pT charged particle suppression in PbPb compared to pp collisions at √sNN = 2.76 TeV. (CMS Collaboration), Eur. Phys. J. C 72: 1945.
8. B. Abelev (2013) Centrality dependence of charged particle production at large transverse momentum in Pb–Pb collisions at √sNN = 2.76 TeV, (ALICE Collaboration), Phys. Lett. B 720: 52-62.
9. G. Aad (2015) Measurement of charged-particle spectra

in Pb+Pb collisions at √sNN = 2.76 TeV with the ATLAS detector at the LHC. (ATLAS Collaboration), JHEP 9: 50.
10. J. D. Bjorken (1982) FERMILAB–Pub–82/59–THY, USA.
11. D. d'Enterria and R. Stock, 23 99 (2010).
12. K. Aamodt (2011) Suppression of charged particle production at large transverse momentum in central Pb–Pb collisions at √sNN = 2.76 TeV,. (ALICE Collaboration), Phys. Lett. B 696: 30-39.
13. Z. Yin (2014) Strange and multi-strange particle production in Pb-Pb collisions at with ALICE. (ALICE Collaboration) Intl. J. Mod. Phys.: Conf. Series 29: 1460228 .
14. V. Khachatryan (2017) Charged-particle nuclear modification factors in PbPb and pPb collisions at sNN−−−−√=5.02sNN=5.02 TeV. (CMS Collaboration), JHEP 4: 39.
15. T. Pierog, K Werner (2015) How to Relate Particle Physics and Air Shower Development : The EPOS Model, Proceedings of the 31st ICRC, Łodz.
16. T. Pierog (2015) EPOS LHC: Test of collective hadronization with data measured at the CERN Large Hadron Collider. Phys. Rev. C 92: 034906.
17. K. Werner (2006) Parton ladder splitting and the rapidity dependence of transverse momentum spectra in deuteron-gold collisions at the BNL Relativistic Heavy Ion Collider. Phys. Rev. C 74: 044902.
18. M. Hladik (2001) Self-Consistency Requirement in High-Energy Nuclear Scattering. Phys. Rev. Lett 86: 3506.
19. NN Kalmykov (1994) Russ. Acad. Sci. Phys 58: 1966.
20. M. Šefcík (2018) Strangeness production in Pb-Pb collisions at LHC energies with ALICE. (ALICE Collaboration) EPJ Web of Conferences 171: 13007.
21. R. J. Fries (2004) Recombination models. J. Phys. G 30: S853.
22. K. Werner (2008) The hadronic interaction model EPOS. Nucl. Phys. B 175–176: 81-87.