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Insights into Au+Au Collision Dynamics at RHIC Using Cosmic Ray Monte Carlo Models

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We present a comparative analysis of the transverse momentum (p_T) spectra of identified hadrons ($\pi^{\pm}$, $K^{\pm}$, and $p/\bar{p}$) produced in Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7 GeV using Monte Carlo event generators EPOSLHC, EPOS4, and Pythia8.3. The simulations are benchmarked against experimental data from the STAR detector across nine centrality classes. EPOS4 and EPOSLHC demonstrate better agreement with data, particularly due to their incorporation of hadronic rescattering and collective flow effects, which are absent in Pythia8.3. In addition, we extract freeze-out parameters using the Tsallis distribution, offering insight into the thermodynamic behavior of the produced system. Our results provide important guidance for improving hadronic interaction models used in cosmic ray air shower simulations.

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1. Introduction

Monte Carlo (MC) event generators are important computational tools used to simulate high-energy particle and nuclear collisions. They generate events that closely resemble real collision outcomes, providing theoretical predictions that help interpret experimental results and explain the underlying physics of strong interactions [1]. These generators incorporate both perturbative and non-perturbative Quantum Chromodynamics (QCD) effects, bridging theoretical models with experimentally observed particle distributions.

Different MC generators have specific strengths and are therefore employed accordingly for different collision systems. For instance, the Pythia8.3 model is predominantly used for hadronic collisions, especially proton-proton (pp) interactions. It performs effectively in modeling perturbative QCD processes. However, in its standard form, it does not account for medium-related effects such as collective flow or hadronic rescattering [2], making it less suitable for simulating heavy-ion collisions. Nevertheless, it can simulate heavy-ion collisions when used in conjunction with the Angantyr model. In contrast, the EPOS family of models, including EPOSLHC and EPOS4, integrates hydrodynamic evolution and hadronic cascade phases [3, 4]. EPOSLHC is specifically optimized for proton-proton collisions at LHC energies, while EPOS4 provides an advanced simulation framework for heavy-ion collisions by incorporating event-by-event hydrodynamics.

Monte Carlo event generators like EPOS and Pythia are widely utilized in astroparticle physics for the simulation of cosmic ray air showers, particularly within frameworks such as CORSIKA and CRMC. The accurate modeling of hadronic interactions at RHIC energies is crucial for reducing uncertainties in extensive air shower simulations, which directly impacts the interpretation of cosmic ray measurements at ground-based observatories [**? ?**]. Validation and tuning of these models using RHIC data ensures a more reliable extrapolation to the much higher energies characteristic of cosmic rays, thereby improving our understanding of primary cosmic ray composition and the physics of particle cascades in the atmosphere.

In the present study, we investigate the p_T spectra of identified hadrons ($\pi^{\pm}$, $K^{\pm}$, and $p/\bar{p}$) produced in Au+Au collisions at a center-of-mass energy of $\sqrt{s_{NN}}$ = 7.7 GeV [7]. We conducted a total of 250,000 simulated events using Pythia8.3, EPOSLHC, and EPOS4, comparing the results with experimental measurements across nine centrality classes. The centrality calibration is performed using the Rivet toolkit, specifically utilizing the "STAR BES CALIB" module [8].

Furthermore, we applied the Tsallis distribution function to the obtained p_T spectra to extract freeze-out parameters, including the effective temperature T and the non-extensivity parameter q. These parameters provide valuable insights into the thermal and dynamical characteristics of the collision system [9–11]. The dependence of these freeze-out parameters on particle species and collision centrality is analyzed to explore potential signatures of collective behavior. This analysis represents a continuation of our previous work on freeze-out dynamics [12–20].

2. Results and Discussion

Figure 1 presents a comprehensive comparison between model predictions and STAR data for $\pi^{\pm}$, $K^{\pm}$, and $p/\bar{p}$ in the most central and peripheral Au+Au collisions. Data points are plotted with distinct markers, and the model results are shown using colored lines for clarity. A ratio

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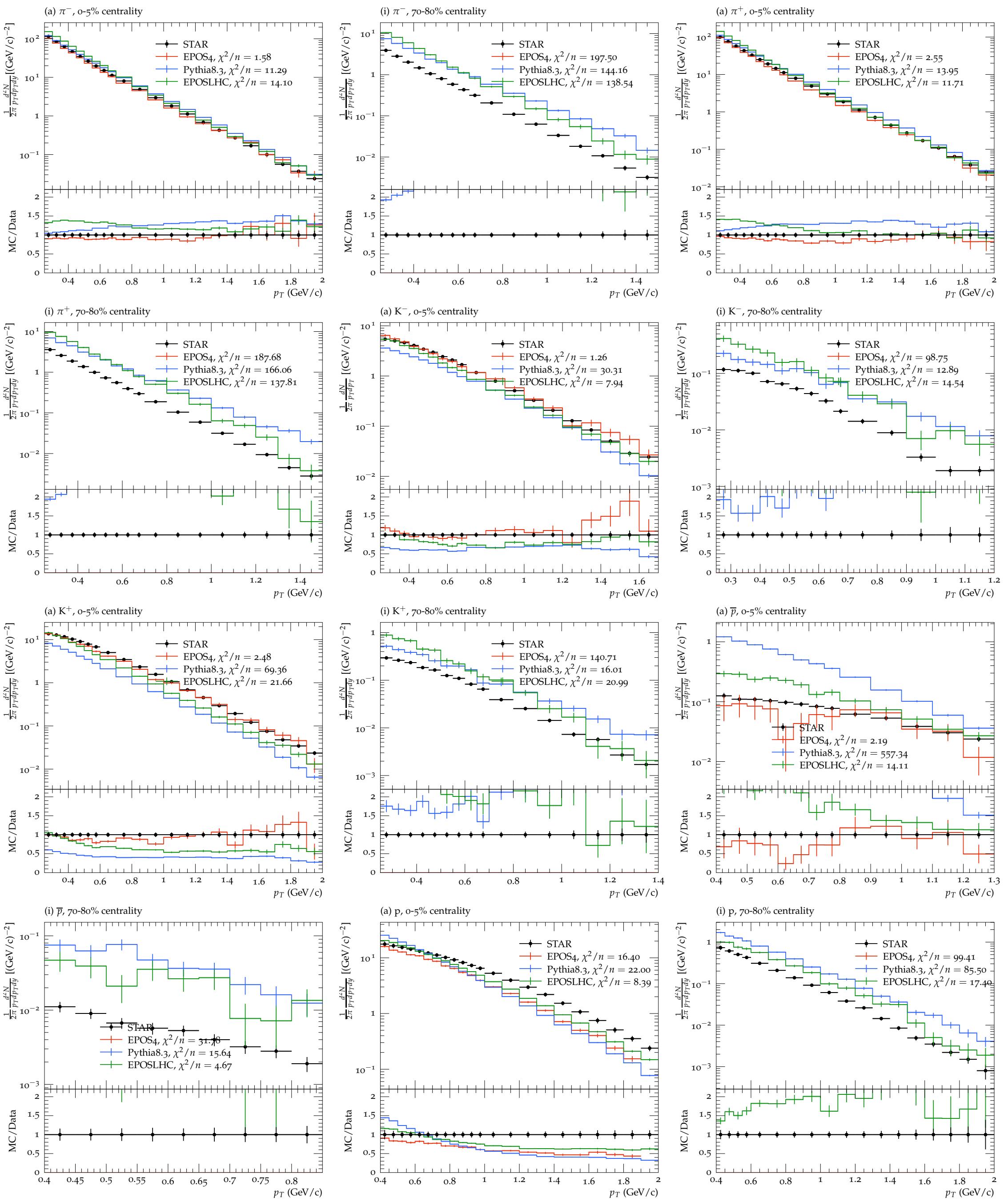

Figure 1: Illustration of the p_T spectra for $\pi^{\pm}$, $K^{\pm}$, and $p/\bar{p}$ in the most central (0–5%) and most peripheral (70–80%) Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7 GeV. Experimental data from STAR [7] are represented by symbols, while colored curves correspond to predictions from EPOS4, EPOSLHC, and Pythia8.3. Each subplot includes a ratio panel showing model-to-data comparisons.

panel beneath each main plot quantifies deviations between the Monte Carlo (MC) predictions and experimental observations.

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Pythia8.3 generally overpredicts pion yields and fails to reproduce the detailed structure of kaon and proton spectra, particularly in central collisions. The lack of medium effects such as collective flow and hadronic rescattering in Pythia limits its applicability in heavy-ion collisions. EPOSLHC, though more tuned for high-energy proton-proton data, performs reasonably at high p_T but underestimates $K^\pm$ and p yields at lower transverse momenta, especially in central bins.

EPOS4 demonstrates the best overall agreement with data. It effectively describes the spectra of $\pi^\pm$, $K^\pm$, and $\bar{p}$ across most centralities, benefiting from its inclusion of hydrodynamic evolution and re-scattering processes. However, discrepancies appear in peripheral bins, where the reduced system volume limits secondary interactions and collective phenomena, leading to underestimation of proton yields at high p_T.

These differences between the models are important because the same hadronic interaction models are also used in cosmic ray air shower simulations. Inaccuracies in describing baryon production or particle spectra can affect how we interpret cosmic ray data. Our results show where the models work well and where they need improvement, which will help make cosmic ray simulations more reliable.

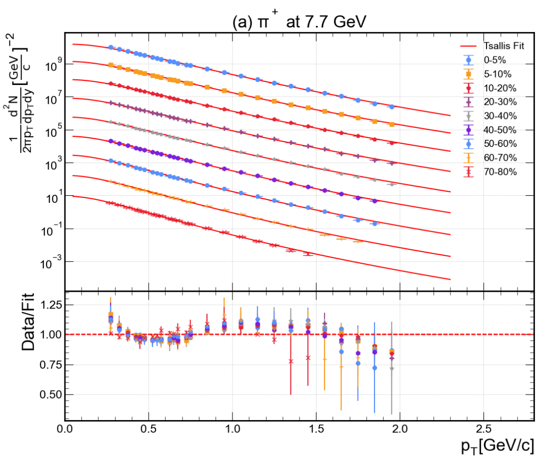

Figure 2: Transverse momentum spectra of π^+ in different centrality intervals of Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7 GeV[7]. Experimental data points are shown with geometric symbols, while the smooth curves represent Tsallis function fits. Each centrality is clearly distinguished by color and/or marker style.

Figure 2 shows Tsallis fits to the π^+ p_T spectra across multiple centrality classes. Geometrical markers represent STAR experimental data, and colored curves denote the fitted Tsallis distribution. The good quality of fits across all centrality bins highlights the model's flexibility in capturing both soft and hard components of the spectra. This approach allows us to extract freeze-out parameters that are sensitive to the medium properties.

Figure 3(a) shows the extracted kinetic freeze-out temperature T as a function of centrality. A clear rise in T with increasing centrality is observed, reflecting higher energy deposition in more central collisions. A mass-dependent ordering of T is evident, with heavier particles (p, $\bar{p}$) showing higher temperatures, consistent with the early kinetic freeze-out of massive hadrons.

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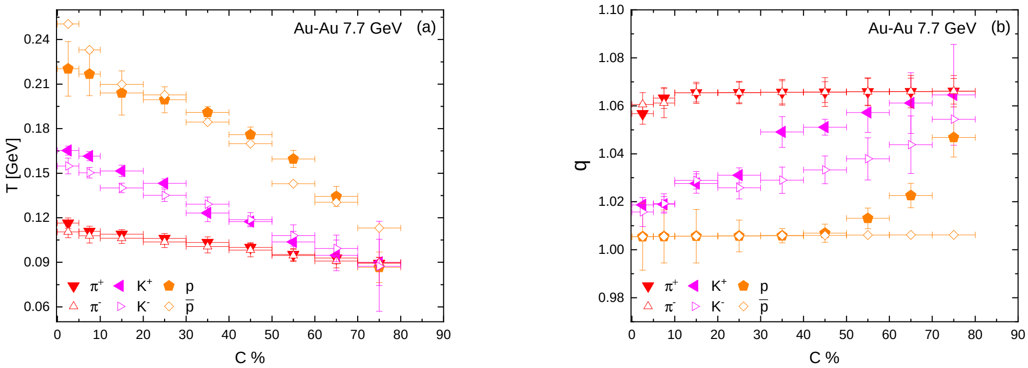

Figure 3: (a) Centrality dependence of the effective temperature T and (b) non-extensive parameter q, extracted from Tsallis fits to the p_T spectra of various hadron species. Data points are shown with species-specific markers. Lines are used to guide the eye.

Figure 3(b) presents the variation of the non-extensive parameter q with centrality. The decreasing trend of q for more central collisions suggests increased thermalization and collective behavior. Furthermore, heavier particles tend to exhibit lower q values than lighter ones, reinforcing the idea that heavier species decouple from the system earlier when it is closer to thermal equilibrium. These findings align with previous studies [9–12] and support the multi-freeze-out scenario in heavy-ion collisions.

3. Conclusion

- We studied p_T spectra of $\pi^{\pm}$, $K^{\pm}$, and $p/\bar{p}$ in Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7 GeV using EPOS4, EPOSLHC, and Pythia8.3.
- EPOS4 and EPOSLHC outperform Pythia8.3 due to their inclusion of collective flow and hadronic re-scattering.
- Pythia8.3 overestimates pion yields and lacks precision for kaons and protons.
- EPOS4 shows the best overall agreement, though it underestimates p spectra in peripheral collisions due to limited re-scattering volume.
- The extracted Tsallis parameters show increasing T and decreasing q with centrality, supporting a thermally equilibrated and collective system in central events.
- This study highlights where hadronic interaction models in CORSIKA and CRMC need to be improved, especially in describing baryon production, so that simulations of cosmic ray showers can be more accurate.

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References

[1] J. M. Campbell et al., “Event generators for high-energy physics experiments,” arXiv:2203.11110 [hep-ph] (2022).

[2] T. Sjöstrand et al., Comput. Phys. Commun. 178, 852 (2008).

[3] S. Porteboeuf et al., arXiv:1006.2967 [hep-ph] (2010).

[4] K. Werner et al., “EPOS4: An event-by-event generator for heavy-ion collisions,” arXiv:2107.12368 (2021).

[5] D. Heck et al., "Extensive Air Shower Simulation with CORSIKA: A User’s Guide, (Version 7.8010)" (2025), https://www.iap.kit.edu/corsika/

[6] Ulrich, R., Pierog, T., & Baus, C. (2021). Cosmic Ray Monte Carlo Package, CRMC (1.8.0). Zenodo. https://doi.org/10.5281/zenodo.4558706

[7] L. Adamczyk et al. (STAR Collaboration), Phys. Rev. C 96, 044904 (2017).

[8] Rivet framework: https://rivet.hepforge.org

[9] Kh. K. Olimov et al., Mod. Phys. Lett. A 35, 2050237 (2020).

[10] G. Biró, G. G. Barnaföldi, and T. S. Biró, J. Phys. G 47, 105002 (2020).

[11] Y. Su et al., Nucl. Sci. Tech. 32, 108 (2021).

[12] S. A. Bass et al., J. Phys. G 25, R1 (1999).

[13] T. Matsui and H. Satz, Phys. Lett. B 178, 416 (1986).

[14] A. Bialas and R. C. Hwa, Phys. Lett. B 253, 436 (1991).

[15] F. M. Liu and S. X. Liu, Phys. Rev. C 89, 034906 (2014).

[16] P. Braun-Munzinger and J. Stachel, Nature 448, 302 (2007).

[17] M. Badshah et al., Symmetry 15, 1554 (2023).

[18] M. Ajaz et al., Symmetry 15, 2063 (2023).

[19] M. Ajaz et al., Chin. Phys. C 48, 053108 (2024).

[20] M. Badshah et al., Chin. Phys. C 48, 104107 (2024).

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