Analysis of Heavy-Ion Collisions using the SMASH Model

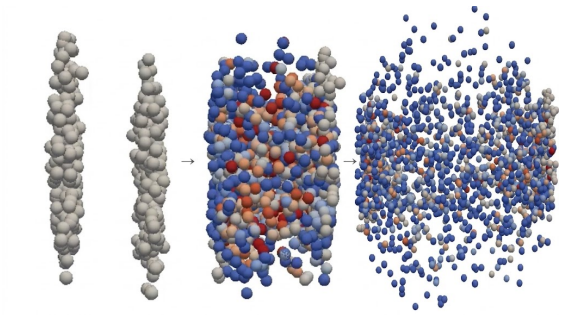
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Abstract

This report presents a femtoscopic correlation analysis of proton-proton pairs in Au+Au collisions at $\sqrt{s_{NN}} = 2.4$ GeV using the SMASH transport model. By applying pure kinematic cuts to isolate the interacting fireball from spectator protons, 1D and 3D correlation functions were constructed across different collision centralities and Equations of State. The results reveal a clear centrality dependence of the emission source size and highlight the necessity of including full Final State Interactions to accurately describe the collision dynamics.



1 Introduction

1.1 SMASH - Simulating Many Accelerated Strongly-interacting Hadrons

1.1.1 What is it?

It is a computational simulation framework used in nuclear and particle physics to model heavy-ion collisions [1]. Fundamentally, SMASH is a microscopic hadronic transport approach that provides a numerical solution to the relativistic Boltzmann equation for non-equilibrium systems.

1.1.2 Why we use it?

The model helps to describe the whole evolution of the dynamic system with kinetic energy between 0.4 and 2.0 GeV per nucleon (typical for the HADES experiment). Using these kinds of tools, physicists are able to much better interpret the experimental data and understand how ordinary hadronic matter behaves under extreme densities. Overall, SMASH allows for the extraction of key observables, including transverse momentum (p_T) spectra, rapidity distributions, collective elliptic flow, and multi-dimensional femtoscopic correlation functions.

1.2 Heavy-Ion Collisions

To understand the fundamental properties of our universe, scientists collide heavy ions in accelerators at relativistic speeds. The primary goal of these experiments is to study strongly interacting matter under extreme conditions of pressure and temperature, allowing us to map the QCD phase diagram and determine the Equation of State (EoS) [2].

Depending on the initial collision energy and the impact parameter (which defines the overlapping region of participating nucleons), the dynamic evolution of the created system goes through several distinct stages:

- **Pre-equilibrium phase:** The initial close-up and penetration of the nuclei, leading to strong interactions between their constituents and maximum compression.
- **Thermalization and Expansion:** The system thermalizes and rapidly expands. At lower collision energies, the system reaches high net-baryon densities and may evolve entirely as a dense hadronic gas without forming a Quark-Gluon Plasma (QGP).
- **Kinetic freeze-out:** Elastic scattering stops, and the final kinematic properties (such as transverse momenta) of the emitted hadrons are firmly established.

It is precisely after the kinetic freeze-out that free hadrons travel to the detectors. By analyzing their final momenta and employing femtoscopic correlation techniques, physicists can accurately reconstruct the spatio-temporal properties of the emission source.

1.3 What is the point of all that?

Neutron stars are some of the densest objects in the universe, created when massive stars collapse after a supernova. Inside their cores, matter is compressed to extreme densities where the strong nuclear force dominates.

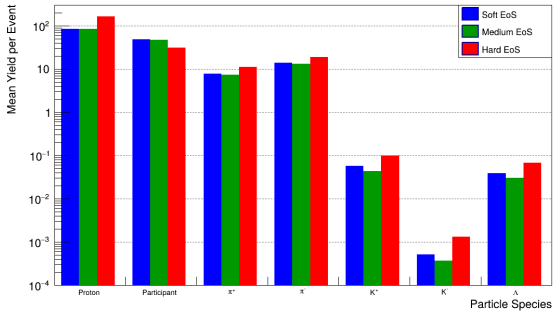


Figure 1: Comparison of mean particle yields per event for soft, medium, and hard Equations of State.

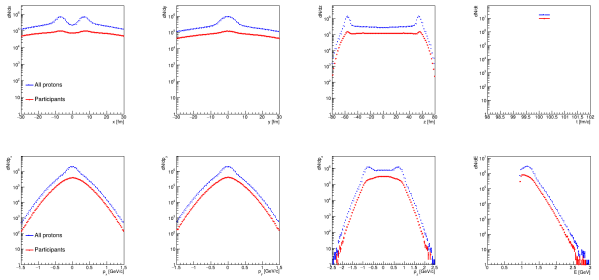


Figure 2: Kinematic distributions comparing all emitted protons with the selected participant protons for the soft Equation of State.

A neutron star's overall properties, like its mass and size, are determined by the Equation of State (EoS) of dense nuclear matter. The extreme conditions inside neutron stars and during their collisions are very similar to those created in low-energy heavy-ion collisions in laboratories [3].

By colliding heavy ions, physicists can recreate and study this highly compressed matter on Earth. Using transport models like SMASH to analyze these collisions helps us understand the nuclear EoS [4]. This perfectly connects microscopic particle physics experiments with the macroscopic astrophysics of stars.

2 Methodology

The topic of my scientific research was the femtoscopic correlation analysis of proton-proton pairs in Au+Au collisions at $\sqrt{s_{NN}} = 2.4$ GeV (1.23 A GeV). Initially, I familiarized myself with the CERN ROOT software and the HAL framework. I began the analysis by calculating the normalized particle yields for three Equations of State (EoS): soft, medium, and hard (Figure 1).

To accurately identify participant protons, specific cuts ($N_{coll} \geq 2$, $t_{last} \geq 1.0$ fm/c) were applied to the SMASH data. As shown for the soft EoS in Figure 2, these cuts successfully remove the high-momentum peaks of non-interacting spectator protons, leaving only the protons that actually collided.

Next, we mapped the kinematic phase space of all emitted protons. Figures 3 and 4 present the invariant relative momentum (q_{inv}) against pseudorapidity (η) and rapidity (y). These two-dimensional distribution highlight the densely populated mid-rapidity region ($y \approx 0$), defining the central core where the interacting fireball is formed.

The transverse momentum (p_T) distribution plotted against laboratory rapidity (y_{LAB}) clearly shows the spectator protons. After applying a kinematic boost to the LAB frame, these non-interacting protons appear as two distinct low-momentum regions at the edges of the distribution.

To filter them out and find the interacting protons, we required each proton to have at least one collision ($N_{coll} > 0$). Figure 6 compares all emitted protons with these selected participants. The condition successfully removes the spectator regions, leaving only the actual participants that form the central fireball at mid-rapidity ($y_{LAB} \approx 0.74$).

This visual separation is crucial for defining the final selection criteria. Because the spectators naturally fall

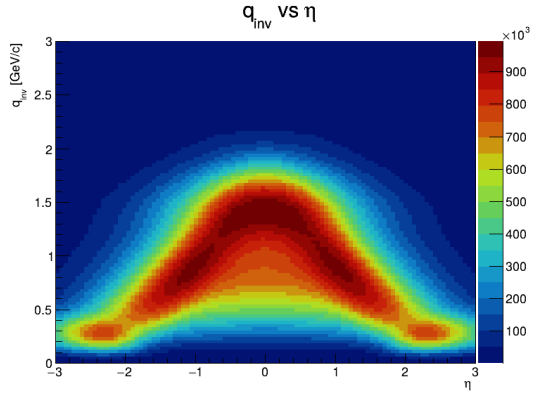


Figure 3: q_{inv} versus pseudorapidity (η) for all protons.

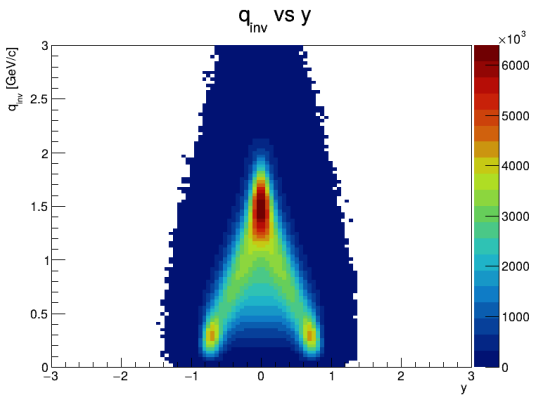


Figure 4: q_{inv} versus rapidity (y) for all protons.

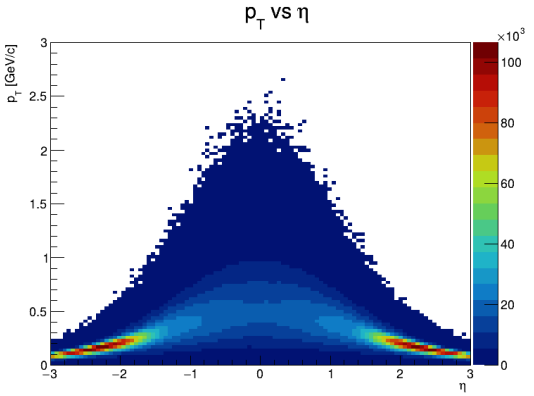


Figure 5: p_T versus pseudorapidity (η) for all protons.

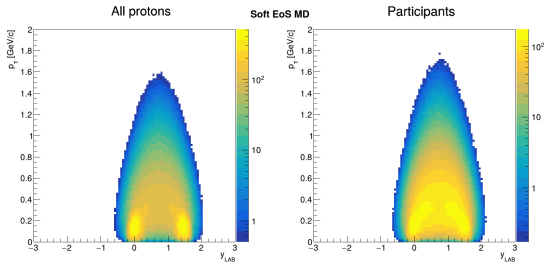


Figure 6: Comparison of p_T vs. laboratory rapidity (y_{LAB}) for all protons and actual participants.

far outside the central rapidity region, we do not need to rely on simulation-specific history flags to isolate the fireball for the final analysis. Instead, we can use pure kinematic cuts.

For the actual femtoscopic correlation functions, the particle kinematics were evaluated in the Center-of-Mass (CM) reference frame, where the fireball is at rest and mid-rapidity is shifted to $y_{CM} = 0$. The clean sample of participant protons was isolated purely by restricting the rapidity to the core region $y_{CM} \in [-0.4, 0.4]$ and the transverse momentum to $p_T \in [0.2, 1.2]$ GeV/c. As demonstrated by the phase space maps, this kinematic window inherently excludes spectator background.

3 Results and discussion

3.1 1D Femtoscopic Correlation Functions

After identifying the participants, we constructed the 1D femtoscopic correlation functions (CF). Figure 7 shows the initial CF for the soft EoS, using cuts on transverse momentum (p_T) and pseudorapidity (η).

For heavy particles like protons, pseudorapidity creates "mustache-like" distributions at low momenta (Figure 5). Therefore, an η-based cut is less accurate for isolating the fireball's core. True rapidity (y) solves this by creating a natural, elliptical shape. Because of this, all subsequent analyses used y instead of η.

Additionally, in the initial η-cut CF, we can observe distinct single peaks. These are residual correlations. Residuals are features in the correlation function that appear for reasons other than the primary physics we want to study (the actual final-state interactions between the particle pair). They act as a background and can be caused by various factors, including particle decays, collective flow, or energy and momentum conservation laws. In our specific case, a major source of this unwanted "garbage" signal is the inclusion of spectator protons (non-interacting protons from the beam or target) when using the less precise η cut. These spectators add false peaks to the true correlation.

Figure 8 shows the refined 1D CFs (using y cuts) across different centralities and Equations of State. These functions include the full Final State Interactions (FSI).

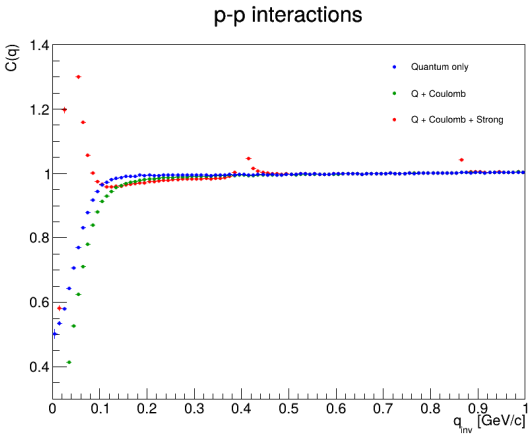


Figure 7: 1D p-p correlation function for the soft EoS using p_T and pseudorapidity (η) cuts.

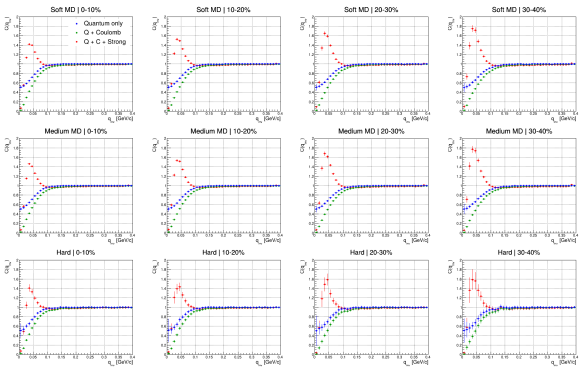


Figure 8: 1D p-p correlation functions across different centralities and all EoS, incorporating QS, Coulomb, and Strong interactions (using y cuts).

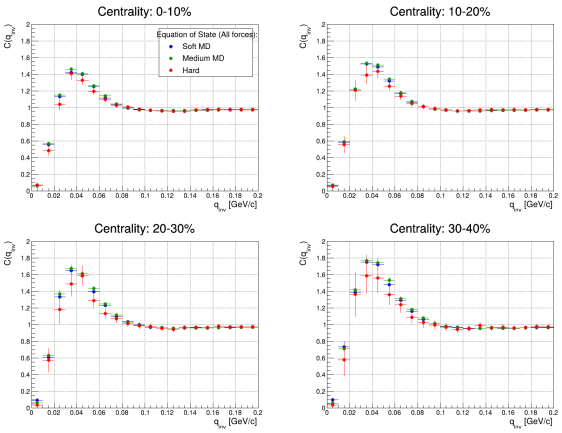


Figure 9: 1D p-p correlation functions for different centralities and Equations of State.

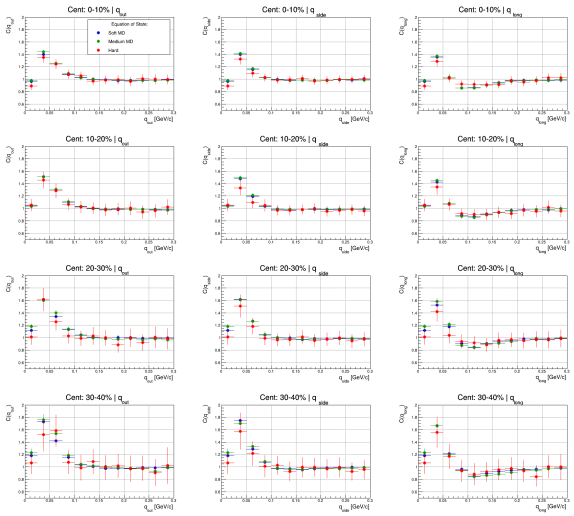


Figure 10: 3D p-p correlation functions (q_{out}, q_{side}, q_{long}) for various centralities and EoS.

For proton-proton pairs, FSI consists of three effects. Quantum Statistics (Fermi-Dirac) and Coulomb repulsion create a dip at zero relative momentum ($q_{inv} \to 0$). Meanwhile, the Strong interaction creates a peak around $q_{inv} \approx 0.02$ GeV/c. By analyzing the height of this strong interaction peak across different centralities, we can accurately measure the spatial size of the emission source.

3.2 Centrality and Equation of State Dependence in 1D and 3D

To better understand the emission source, we looked at both 1D and 3D correlation functions. We tested four centrality classes (0-10%, 10-20%, 20-30%, and 30-40%) and three Equations of State (soft, medium, and hard). All these functions include Quantum Statistics, Coulomb repulsion, and Strong interactions.

Figure 9 shows a clear connection between the correlation function and centrality. When we move from central (0-10%) to more peripheral (30-40%) collisions, the peak from the strong interaction gets higher. In femtoscopy, a higher peak means a smaller emission source. This makes sense geometrically: peripheral collisions have a smaller overlap area between the colliding nuclei, creating a spatially smaller fireball.

To see how the fireball expands in different directions, we used 3D correlation functions with the parameterization q_{out}, q_{side}, q_{long}. Figure 10 shows these 3D results. Just like in the 1D case, the peaks grow in all three directions for more peripheral collisions. Small differences between the EoS models in the out, side, and long directions give us clues about how long the emission lasts and how fast the fireball expands.

Finally, looking at both figures, you can see differences in the error bars. The soft and medium EoS have small error bars because they use a large amount of data (100 simulation files each). The hard EoS has much larger error bars and fluctuations. This is simply because we only had 10 simulation files for the hard EoS. However, even with this limited data, the physical trends related to centrality and fireball size are still clearly visible.

4 Conclusions

This study successfully analyzed proton-proton correlations in Au+Au collisions at $\sqrt{s_{NN}} = 2.4$ GeV using the SMASH model. By applying proper kinematic cuts, we isolated the fireball's core from spectator protons. The 1D and 3D correlation functions showed a clear centrality dependence: peripheral collisions have stronger peaks, meaning the emission source is smaller. We also confirmed that including all Final State Interactions is necessary to accurately describe the fireball.

This study shows that using the SMASH model with proper kinematic cuts is a good way to analyze heavy-ion collisions. However, future work needs much more data, especially for the hard EoS, to reduce statistical errors. With more data, we can accurately measure the exact 3D sizes of the fireball (R_{out}, R_{side}, R_{long}). The final step will be to compare these simulation results with real data from the HADES experiment.

References

[1] SMASH Collaboration, *SMASH - Simulating Many Accelerated Strongly-interacting Hadrons (Official Documentation)*, https://smash-transport.github.io/.

[2] H. P. Zbroszczyk, *Eksperymentalne aspekty badania korelacji femtoskopowych w zderzeniach relatywistycznych ciężkich jonów*, Wydział Fizyki Politechniki Warszawskiej, Warszawa 2018.

[3] Nuclear Physics Institute of the CAS, *Relativistic Heavy Ion Collisions*, https://www.ujf.cas.cz/en/departments/department-of-heavy-ion-physics/research/relativistic-heavy-ion-collisions/.

[4] M. B. Tsang et al., *Constraining neutron-star equation of state using heavy-ion collisions*, Adv. High Energy Phys. 2018 (2018) 7431718, arXiv:1807.06571.