JOINT INSTITUTE FOR NUCLEAR RESEARCH
Veksler and Baldin laboratory of High Energy Physics

FINAL REPORT ON THE START PROGRAMME

Production and Analysis of a mini-DST of the Time of Flight Detector (ToF-400) left side using the BM@N Data

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Abstract

The BM@N (Baryonic Matter at Nuclotron) experiment, located within the NICA complex at the Joint Institute for Nuclear Research (JINR), represents a groundbreaking initiative aimed at investigating the characteristics of dense nuclear matter through nucleus-nucleus collisions against a fixed target, specifically examining Hyperons at the BM@N experiment. This endeavor involves meticulous particle trajectory tracking and Time-Of-Flight (TOF) measurements for precise particle identification. The March 2018 experiment employed Ar and Kr ion beams in conjunction with various fixed targets. Within this project, our primary focus lies in the production and the analysis of a mini-DST of the left side of ToF-400 detector. Accordingly, we will study femtoscopy using the BM@N dataset, with a subsequent comparative analysis against Monte Carlo (MC) simulations, utilizing event generators such as UrQMD, DCM-SMM, and PHSD.

1. Introduction

1.1. NICA Project at JINR

The "Nuclotron-based Ion Collider fAcility" (NICA) would provide unprecedented opportunities to create and investigate QCD matter at densities estimated to exist in the cores of neutron stars. The fixed-target Compressed Baryonic Matter (CBM) experiment at FAIR and the Multi-Purpose Detector (MPD) at the NICA collider will be particularly interested in the exploration of diagnostic probes sensitive to the EOS and degrees of freedom of high-density QCD matter. The current Baryonic Matter @Nuclotron (BM@N) experiment will be improved to explore heavy-ion collisions at beam energies of up to 4A GeV, where the fireball is expected to be compressed to around 4 times saturation density (Report, 2021). Experiments will be carried out in order to determine the mixed phase of baryonic matter and the nature of nucleon/particle spin (Kekelidze et al., 2016).

The following graphic depicts a schematic representation of the NICA-Nuclotron complex as well as the position of the BM@N setup. The light and heavy ion sources, the beam Booster, the Nuclotron accelerator, and the NICA collider are all featured in Fig. 1. (Kapishin, 2017).

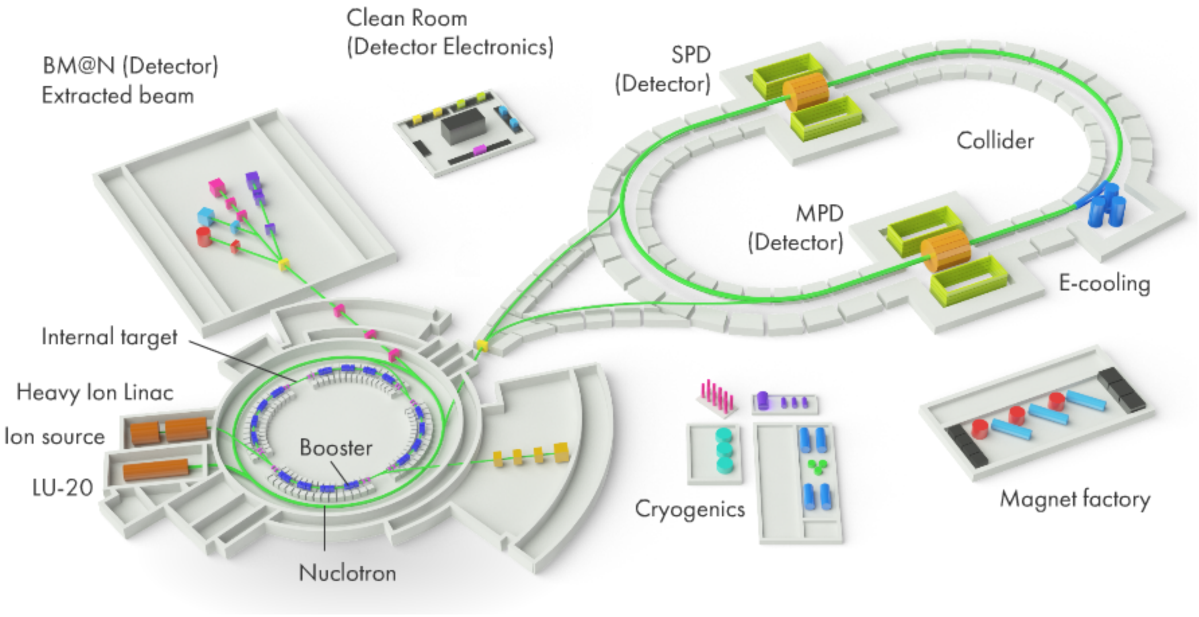


Figure 1: A schematic representation of the NICA complex. *Retrieved from* [NICA Complex]

1.2. BM@N Experiment

One of the most fascinating study topics in current high-energy nuclear physics is the theoretical and experimental examination of the features of strongly interacting matter at high temperatures and densities. Recent discoveries of supermassive neutron stars and neutron star mergers call into question our understanding of high-density QCD matter, such as its equation-of-state (EOS) and microscopic degrees of freedom at high baryon densities. The BM@N experiment seeks to improve our understanding of Quantum Chromodynamics (QCD) matter at densities anticipated to exist in compact star objects. Furthermore, research from this experiment may give information on the role of hyperons in neutron stars. (Project report, 2021).

The BM@N (Baryonic Matter at Nuclotron) experiment is considered the first at the NICA-Nuclotron accelerating complex. The objective of this experiment is to investigate the interactions between relativistic heavy ion beams, with kinetic energy per nucleon ranging from 1 to 4.5 GeV, and stationary targets. Fig. 2 depicts the configuration of the NICA-Nuclotron complex with the BM@N arrangement.

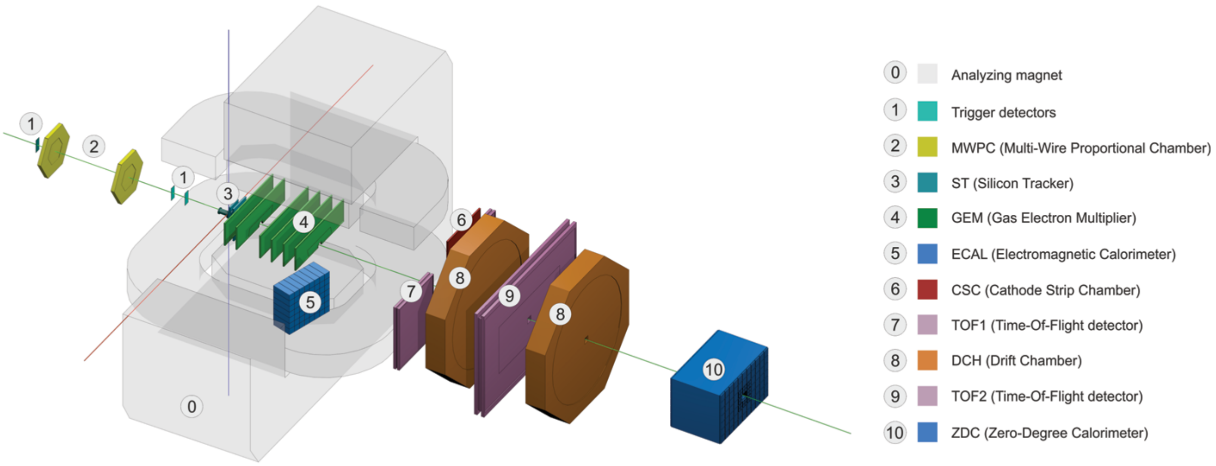


Figure 2: A schematic representation of the BM@N setup in the last run. Retrieved from (Batyuk et al., 2019)

The experiment's inner tracking system consists of the GEM and silicon detectors. It is made up of nine sensitive surfaces, three of which correlate to a silicon detector and the other six to the GEM detector (Batyuk et al.).

This work places special emphasis on Time-of-Flight (ToF) detectors, which ascertain the elapsed time for a charged particle to traverse a predefined distance, typically determined by scintillator plastics. This capability facilitates the particle's identification, as the BM@N experiment primarily relies on these detectors for its particle identification system (Afanasiev et al.)(Alishina et al.).

2. Detectors

2.1. Central Tracker

The central tracker of the BM@N experiment utilizes a dual-coordinate triple Gas Electron Multipliers (GEM). By analyzing the experimental data gathered during the deuteron run, the central tracker was expanded by incorporating forward silicon detector planes in a dual-coordinate configuration. This enhancement was implemented to enhance the accuracy of primary vertex reconstruction. The optimal positions for the GEM and silicon detectors were determined through Monte-Carlo simulations. Fig. 3 illustrates the central tracker setups employed in the most recent runs (Gornaya et al.). The central tracking system is positioned beyond the target area, enclosed within a dipole magnet possessing a bending strength of approximately 2.1Tm and a gap of 1.05 meters between its poles (Afanasiev et al.).

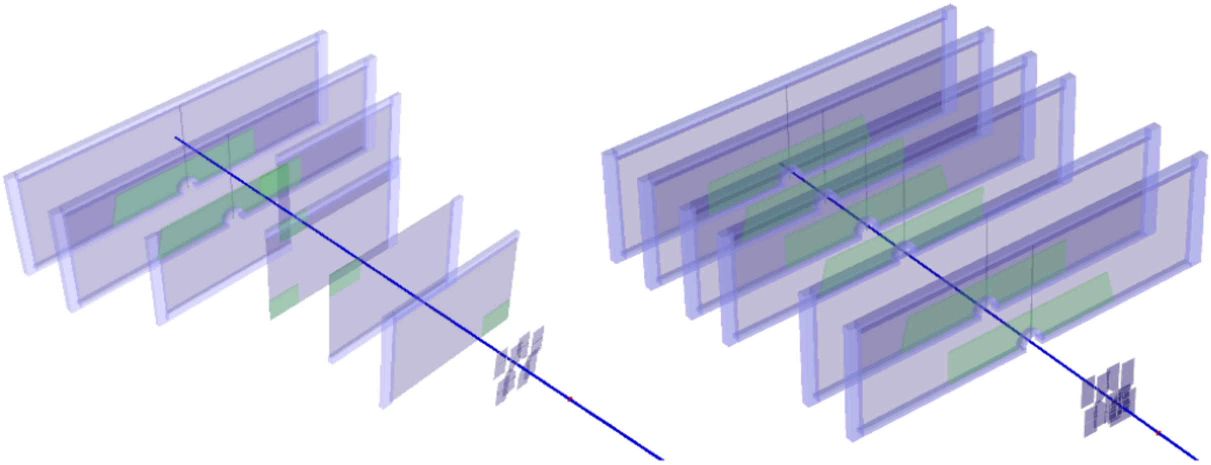


Figure 3: (a) Left: The configuration of the BM@N setup employed during the carbon run. (b) Right: The BM@N setup configuration employed for the Ar/Kr run. Retrieved from (Gornaya et al.).

2.2. ToF-400 mRPC detector

The ToF-400 wall is divided into two symmetrical parts, one on the left and one on the right, aligned with the beam. Each part comprises two gas boxes (modules), each containing 5 mRPCs. These gas boxes are constructed with aluminum frames and covered with aluminum honeycomb to reduce radiation length, although the edges of the gas boxes remain relatively thick. There is ongoing work to develop a new design for the gas boxes (Project report, 2021).

2.3. ToF-700 mRPC detector

The ToF-700 detector, positioned approximately 7 meters away from the target, equips BM@N with the ability to separate pions/kaons up to 3 GeV/c and protons/kaons up to 5 GeV/c. The ToF-700 system comprises 58 glass multigap Timing Resistive Plate Chambers (mRPC).

The dimensions of the wall are 3.2x1.6 m^2, chosen to meet the geometric requirements of the tracking detectors. Impressive time resolution of approximately 60 picoseconds has been achieved, with an efficiency exceeding 97%, and crosstalk signals in adjacent strips are at a few percent level (Project report, 2021).

3. Monte Carlo simulation and Event Generators

Monte Carlo Simulation is a potent computational method in high-energy physics. It models intricate particle interactions and detector responses by generating numerous random events. Researchers use statistical analysis of these simulated events to understand particle behavior, predict experimental results, and enhance detector designs (Peter Lepage).

The Monte Carlo event generators are essential for experimental analysis as they utilize Monte Carlo methods to generate event data. Additionally, they are used for comparing experimental results with theoretical predictions while allowing for future experiment predictions and preparations. In this work we are focused on The Ultra-relativistic quantum molecular dynamics model (UrQMD), Dubna Cascade - Statistical Multifragmentation Model (DCM-SMM), and Parton-Hadron-String-Dynamics model (PHSD) event generators.

3.1. Ultra-relativistic quantum molecular dynamics model - UrQMD

The UrQMD (Ultra-relativistic Quantum Molecular Dynamics) model is a powerful computational framework used in high-energy physics to simulate various collision scenarios, including hadron-hadron, hadron-nucleus, and nucleus-nucleus collisions. It encompasses a wide range of beam energies, from the low MeV per nucleon regime observed in facilities like SIS to the highest energies achievable at the CERN Large Hadron Collider (LHC).

Within the UrQMD model, researchers can explore the interactions and dynamics of 55 different baryon species and 32 different meson species, supplemented by their corresponding antiparticles, providing a comprehensive and versatile tool for investigating the intricate world of particle collisions and the behavior of matter under extreme conditions (Zhang et al.).

3.2. Dubna Cascade - Statistical Multifragmentation Model - DCM-SMM

The DCM-SMM model, a comprehensive transport model, combines the Dubna Cascade Model (DCM), the Quark-Gluon String Model (QGSM), and the Statistical Multifragmentation Model (SMM) to simulate reaction products arising from heavy ion collisions spanning an energy range from hundreds of MeV to hundreds of GeV. This versatile framework incorporates extended coalescence, multifragmentation, hyperfragment production, vorticity in nuclear matter, and Lambda polarization.

Within the DCM-SMM framework, the process of fragment production unfolds in three distinct stages: a dynamic phase leading to the formation of an equilibrated nuclear system, as described by DCM; subsequent disassembly of the system into individual primary fragments, elucidated by SMM; and finally, the de-excitation of these hot primary fragments following evaporation/fission models (Baznat et al.).

3.3. Parton-Hadron-String-Dynamics model - PHSD

The PHSD (Parton-Hadron-String Dynamics) model is a comprehensive framework tailored for studying strongly interacting systems, particularly the evolution of relativistic heavy ion collisions. This model encompasses the entire process, from initial hard scatterings and string formation to the deconfinement phase, and it offers a dynamic portrayal of the hadronization process. Notably, it integrates both partonic elements (quarks and gluons) and hadronic components, thus encompassing the highly interactive quark-gluon plasma (sQGP) and the subsequent interactions throughout the expanding hadronic phase.

Moreover, the PHSD model's versatility is evident in its application to a wide spectrum of collision scenarios, ranging from p+p, p+A, to A+A collisions, covering energies from lower SIS to LHC levels (Bratkovskaya et al.).

4. Femtoscopy

Femtoscopy is a powerful technique for studying the spatial and temporal characteristics of the particle-emitting source in heavy-ion collisions, providing crucial information about the properties of the hot and dense medium formed during the collision process. The study of femtoscopy helps with understanding the properties of the quark-gluon plasma, and the insights gained into collective particle behavior in extreme collision conditions (Lisa et al.).

The suggestion of naming the technique "femtoscopy" comes from that in every instance, the characteristics, intensity, and size of the correlation are responsive to the dimensions of the emitting region. This dimension, which is typically within the range of femtometers (10^{-15} m), can be deduced from the analysis. Correlation functions depend on two three-dimensional momenta, P and q. For high-energy collisions.

The femtoscopic correlation function is empirically formed by taking the ratio of two pair distributions.

$$C(\overline{q}) = A(\overline{q})/B(\overline{q})$$

To create the "signal" A, particles originating from a single event are paired together. The relative momentum distribution, q, for these pairs is accumulated in A, summing up the contributions from all events in the dataset. In contrast, the background distribution B is constructed by selecting one particle from each pair, with each particle originating from a different event (Kisiel).

5. Data and Results

The data provided comes from the BM@N experimental run 7……

The following table contains description of some parameters of interest in the mini-DST data of the Tof-400 left side.

Parameter Symbol	Description
m2	Squared mass of the track
px	X-projection of the track momentum
py	Y-projection of the track momentum
pz	Z-projection of the track momentum
p	Full track momentum
pt	Transverse momentum of the track
nutrpv	Number of tracks in the primary vertex (PV)
ypi	Track rapidity, assuming the track is a pion
nutarg	Target id (1 - C; 2 - Al; 3 - Cu; 4 - Sn; 5 - Pb)

5.1. Production of mini-DST for Tof400

The initiation of the mini-DST project was aimed at simplifying matters for newcomers. The concept behind the mini-DST is to offer an uncomplicated data format and an analysis environment, making it more accessible for beginners.

In order to produce the mini-DST of ToF-400 left panel , the following steps were followed:

- Copy the macro at: /weekly/huhaeva/Alignment_Dx_p/mini_Dst/makeMiniDst.C to my directory /scratch1/heba/
- Copy the bash file pyptAndOtherBins.sh and other files that are required to run the macro
- Make some adjustments to the macro then run the following command: ./pyptAndOtherBins.sh
- The product is a mini-DST for the data of the left panel of the time of flight detector -ToF-400 , which can be found at: /scratch1/heba/Tof400_Data_sigma.root

5.2. Results

5.2.1. mini-DST of ToF-400 results

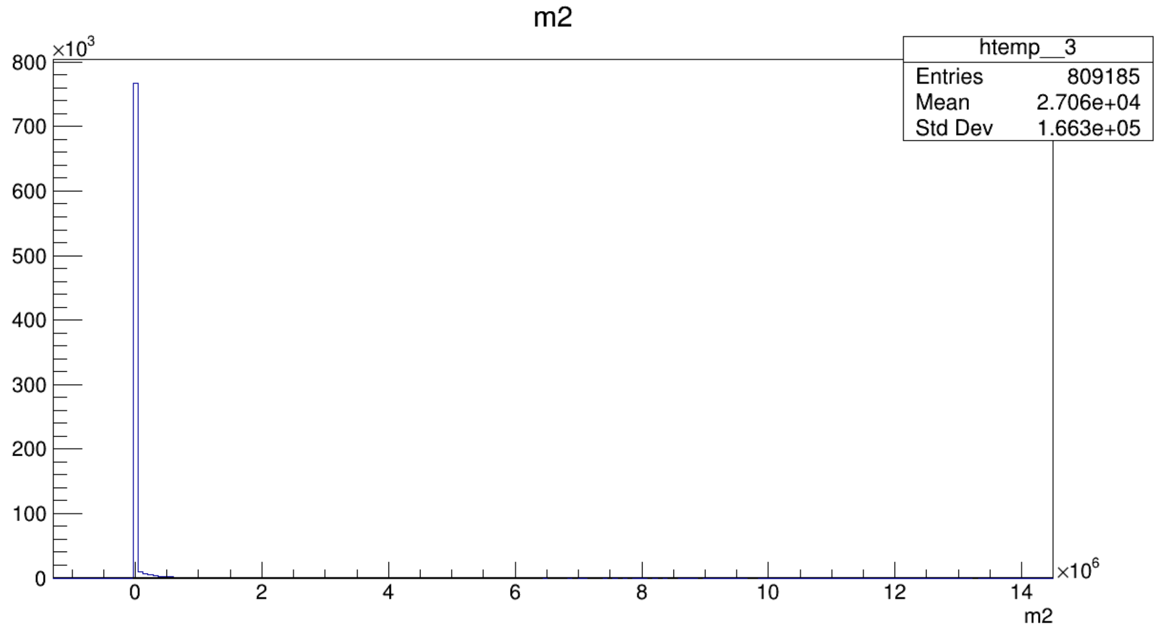


Figure 4: Distribution of squared mass of the tracks in GeV

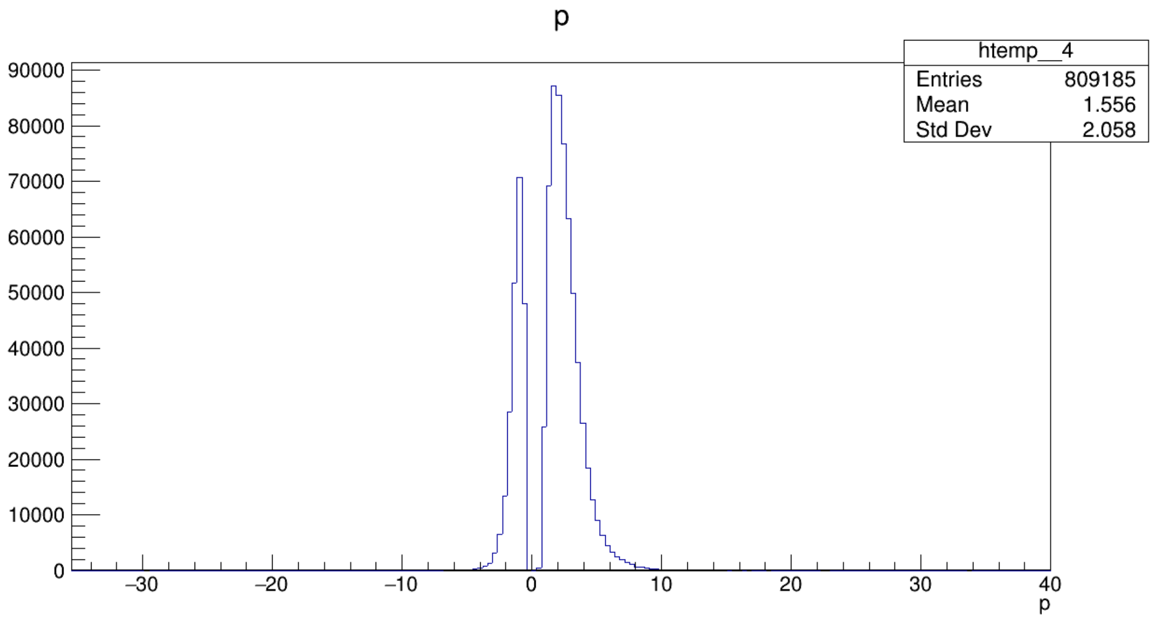


Figure 5: Distribution of Full track momentum in GeV

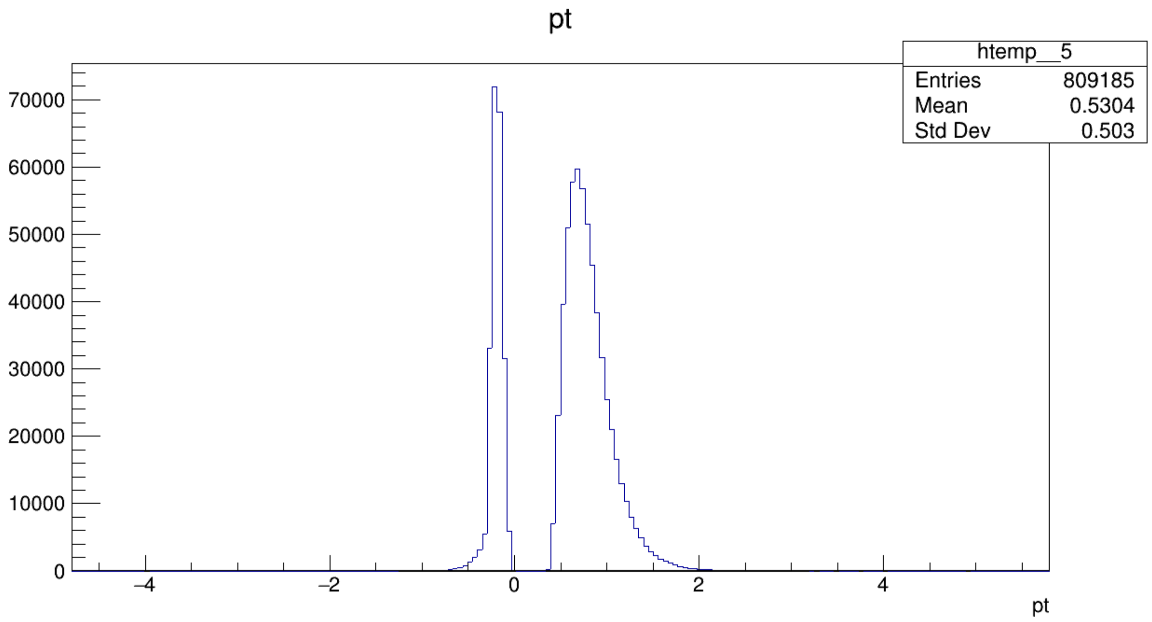


Figure 6: Transverse momentum distribution of the tracks in GeV

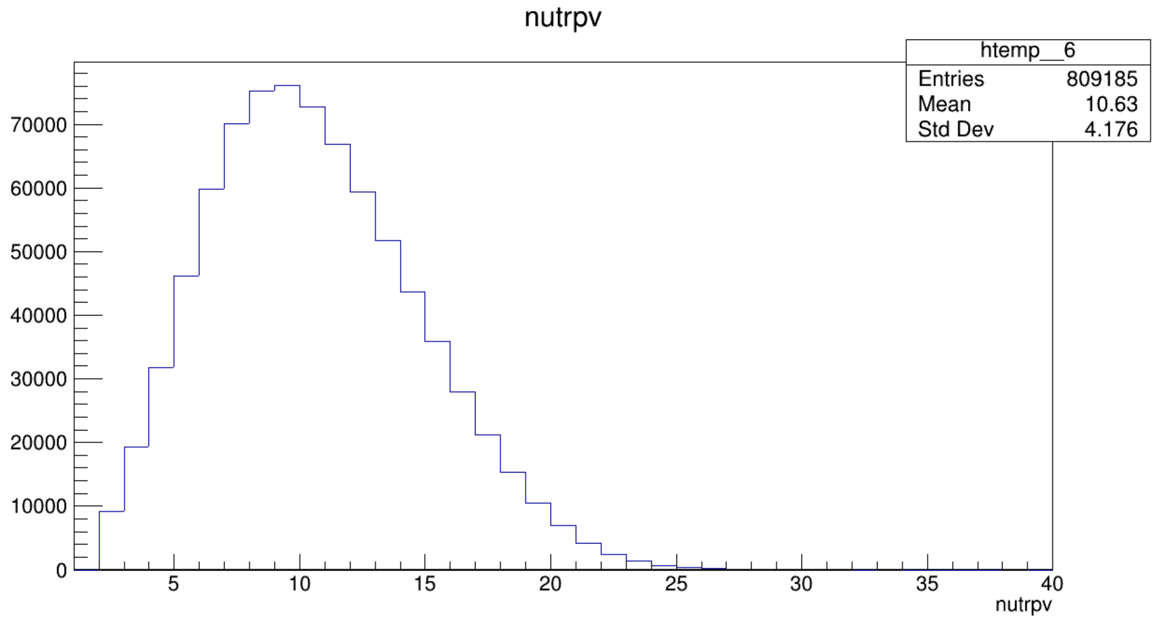


Figure 7: Number of tracks in the primary vertex (PV)

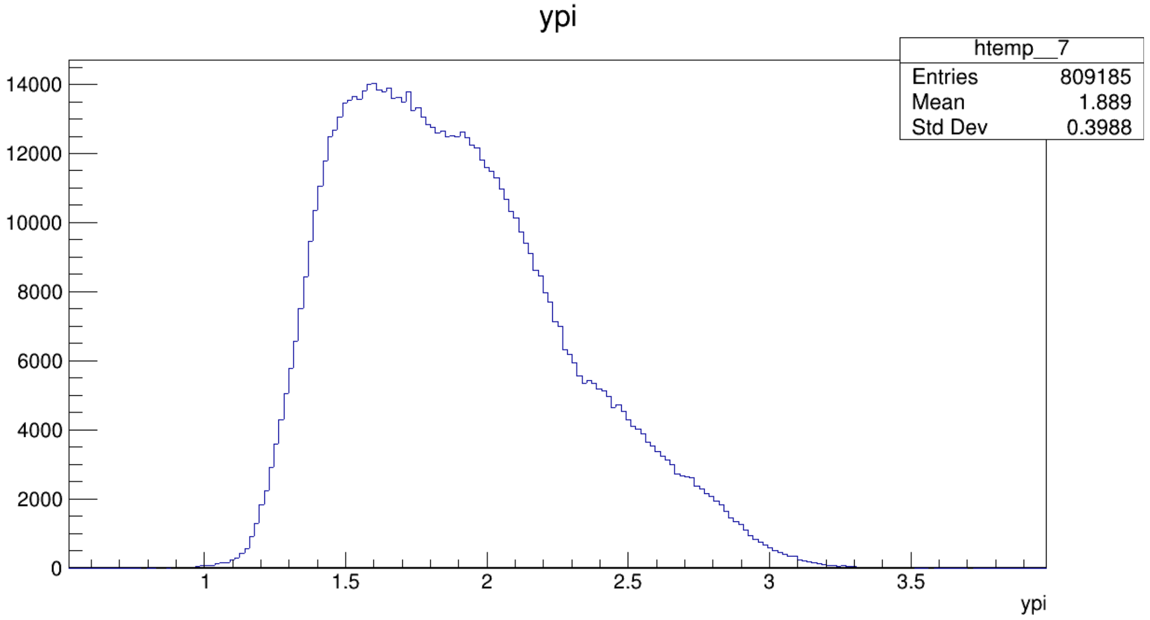
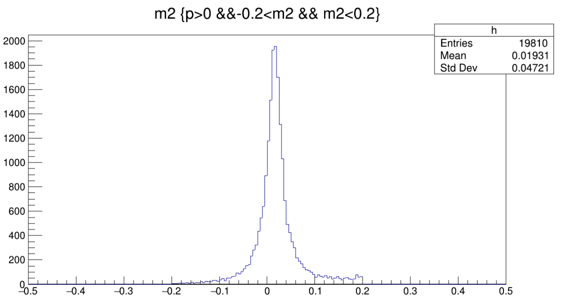


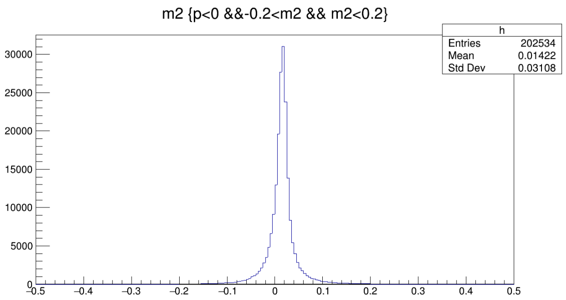
Figure 8: Track rapidity, assuming the track is a pion

5.2.2. mini-DST of ToF-400 results for π^+ and π^-

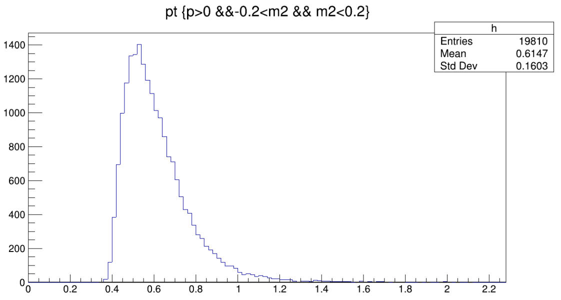
In order to plot for the positive and negative pions only the following cuts were introduced:￼



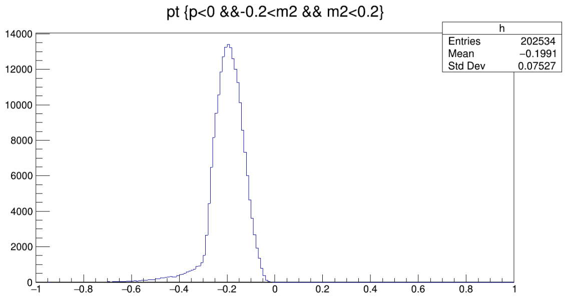
(a) Distribution of squared mass of π^+ tracks in GeV



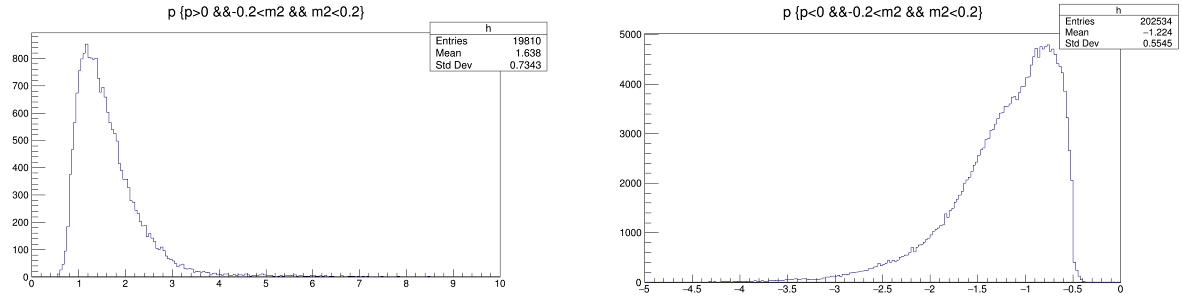
(b) Distribution of squared mass of π^- tracks in GeV



(c) Transverse momentum distribution of π^+ tracks in GeV

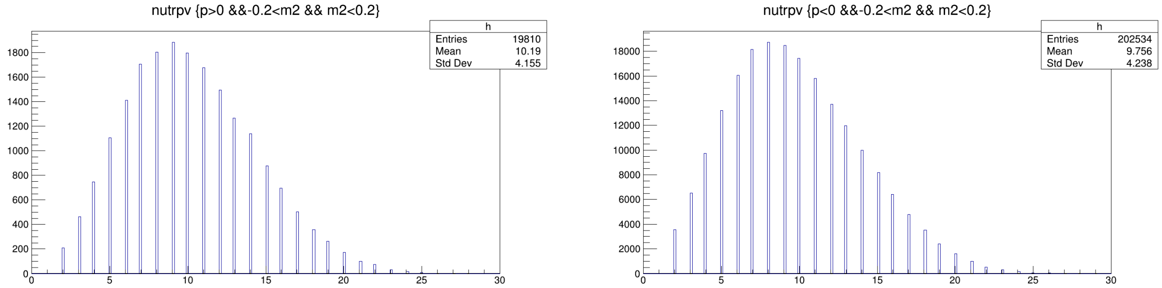


(d) Transverse momentum distribution of π^- tracks in GeV



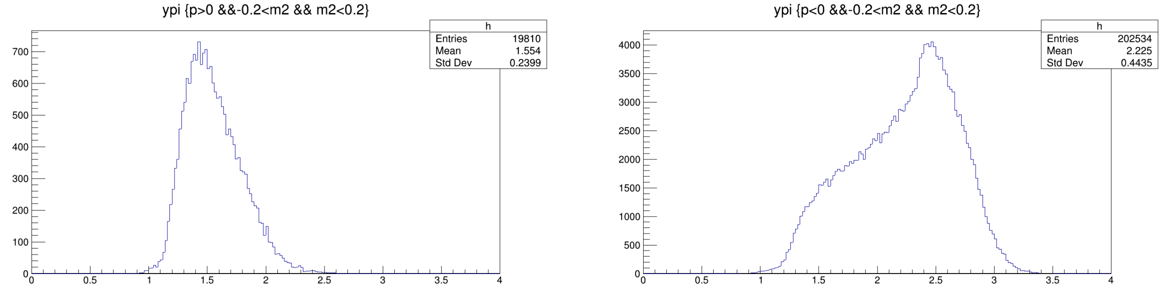
(e) Distribution of π^+ full tracks momentum in GeV

(f) Distribution of π^- full tracks momentum in GeV



(g) Number of π^+ tracks in the primary vertex (PV)

(h) Number of π^- tracks in the primary vertex (PV)



(i) Track rapidity, for positive pions

(j) Track rapidity, for negitive pions

Figure 9: on the left column: The distributions of π^+ data, on the right column:The distributions of π^- data The distributions of π^- data

6. Conclusion

In Conclusion, the NICA complex serves as an example of advanced research and innovation in nuclear physics. The complex's cutting-edge equipment and modular accelerators have enabled ground-breaking experiments such as the BM@N experiment. Within the remarkable complex, the BM@N experiment serves a critical role in resolving the secrets of heavy-ion collisions and nuclear matter under severe circumstances.

One of the key components contributing to the success of BM@N is the Time of Flight (TOF) detectors. These detectors, exemplified by ToF-400 and ToF-700, have demonstrated their ability to provide precise momentum and particle identification, enabling scientists to obtain critical insights into particle interactions within the experimental setup.

A mini-DST of the original DST file of the ToF-400 left side data has been produced. The analysis of the data has shown good results. In our forthcoming research efforts, our main emphasis will be on investigating femtoscopy within the BM@N dataset. We will then proceed to conduct a comparative analysis with Monte Carlo (MC) simulations, utilizing event generators like UrQMD, DCM-SMM, and PHSD for this purpose.

7. Acknowledgments

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8. References

1. The project report “Studies of Baryonic Matter at the Nuclotron (BM@N).” https://bmn.jinr.ru/detector/project/BMN_project.pdf, 2021.
2. Afanasiev, S., et al. “Production of Π+ and K+ Mesons in Argon-nucleus Interactions at 3.2 a GeV.” Journal of High Energy Physics, vol. 2023, no. 7, Springer Science and Business Media LLC, July 2023. Crossref, doi:10.1007/jhep07(2023)174.
3. Alishina, K., et al. “Charged Particle Identification by the Time-of-Flight Method in the BM@N Experiment.” Physics of Particles and Nuclei, vol. 53, no. 2, Pleiades Publishing Ltd, Apr. 2022, pp. 470–75. Crossref, doi:10.1134/s106377962202006x.
4. Baranov, D., et al. “GEM Tracking System of the BM@N Experiment.” *Journal of Instrumentation*, vol. 12, no. 06, IOP Publishing, June 2017, pp. C06041–C06041. *Crossref*, doi:10.1088/1748-0221/12/06/c06041.
5. Batyuk, P., et al. “Event Reconstruction in the BM@N Experiment.” EPJ Web of Conferences, edited by S. Bondarenko et al., vol. 204, EDP Sciences, 2019, p. 07012. Crossref, doi:10.1051/epjconf/201920407012.
6. Baznat, M., et al. “Monte-Carlo Generator of Heavy Ion Collisions DCM-SMM.” Physics of Particles and Nuclei Letters, vol. 17, no. 3, Pleiades Publishing Ltd, May 2020, pp. 303–24. Crossref, doi:10.1134/s1547477120030024.
7. Bratkovskaya, E. L., et al. “PHSD—A Microscopic Transport Approach for Strongly Interacting Systems.” Springer Proceedings in Physics, Springer Singapore, Dec. 2020, pp. 119–36. Crossref, doi:10.1007/978-981-15-9062-7_10.
8. Gornaya, Julia, et al. “Hyperons at the BM@N Experiment: First Results.” EPJ Web of Conferences, edited by S. Bondarenko et al., vol. 204, EDP Sciences, 2019, p. 01006. Crossref, doi:10.1051/epjconf/201920401006.
9. Kapishin, M. N. “The Fixed Target Experiment for Studies of Baryonic Matter at the Nuclotron (BM@N).” Physics of Atomic Nuclei, vol. 80, no. 10, Pleiades Publishing Ltd, Dec. 2017, pp. 1613–19. Crossref, doi:10.1134/s1063778817100027.
10. Kekelidze, V. D., et al. “Three Stages of the NICA Accelerator Complex.” The European Physical Journal A, vol. 52, no. 8, Springer Science and Business Media LLC, Aug. 2016. Crossref, doi:10.1140/epja/i2016-16211-2.

11. Kisiel, Adam. “How to Measure the Size of the Quark-gluon Plasma? And Why Is It Important?” Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics Experiments 2015, edited by Ryszard S. Romaniuk, SPIE, Sept. 2015. Crossref, doi:10.1117/12.2205255.

12. Lisa, Michael Annan, et al. “FEMTOSCOPY IN RELATIVISTIC HEAVY ION COLLISIONS: Two Decades of Progress.” Annual Review of Nuclear and Particle Science, vol. 55, no. 1, Annual Reviews, Dec. 2005, pp. 357–402. Crossref, doi:10.1146/annurev.nucl.55.090704.151533.

13. Peter Lepage, G. “A New Algorithm for Adaptive Multidimensional Integration.” Journal of Computational Physics, vol. 27, no. 2, Elsevier BV, May 1978, pp. 192–203. Crossref, doi:10.1016/0021-9991(78)90004-9.

14. Zhang, Ying-Xun, et al. “Progress of Quantum Molecular Dynamics Model and Its Applications in Heavy Ion Collisions.” Frontiers of Physics, vol. 15, no. 5, Springer Science and Business Media LLC, May 2020. Crossref, doi:10.1007/s11467-020-0961-9.