JOINT INSTITUTE FOR NUCLEAR RESEARCH
Veksler and Baldin Laboratory of High Enrgy Physics
(VBLHEP)

FINAL REPORT ON THE START PROGRAMME

Proton Identification and Distribution Analysis in BM@N Using TOF-400

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Contents

Abstract

The BM@N (Baryonic Matter at Nuclotron) experiment, part of the NICA complex at the Joint Institute for Nuclear Research (JINR), is a pioneering project aimed at exploring the properties of dense nuclear matter through nucleus-nucleus collisions using a fixed target. A key focus of the experiment is the study of hyperons and the precision identification of particles through detailed tracking of particle trajectories and Time-Of-Flight (TOF) measurements. In the March 2018 run, Ar and Kr ion beams were directed at various fixed targets. This work concentrates on analyzing proton data obtained from collisions with a lead (Pb) target, specifically utilizing data from the left side of the ToF-400 detector. We will examine a variety of distributions in the BM@N dataset and compare the results with Monte Carlo (MC) simulations generated by event models such as UrQMD, DCM-SMM, and PHSD.

1. Introduction

1.1 NICA Project

The NICA (Nuclotron-based Ion Collider fAcility) experiment at the Joint Institute for Nuclear Research (JINR) in Dubna, Russia, aims to explore the properties of strongly interacting matter under extreme conditions. By colliding heavy ions at high energies, NICA seeks to investigate the phase transition between hadronic matter and quark-gluon plasma, a state of matter believed to have existed shortly after the Big Bang. The facility will enable comprehensive studies of baryonic matter, providing insights into the fundamental forces and interactions that govern nuclear physics. NICA's design includes advanced detector systems, such as the BM@N experiment, to analyze the production mechanisms of baryons in these collisions. This research has profound implications for understanding the behavior of matter in extreme environments, such as neutron stars. Ultimately, NICA aims to contribute significantly to our knowledge of nuclear matter and the early universe, enhancing the theoretical frameworks in high-energy physics. [1,4,5]

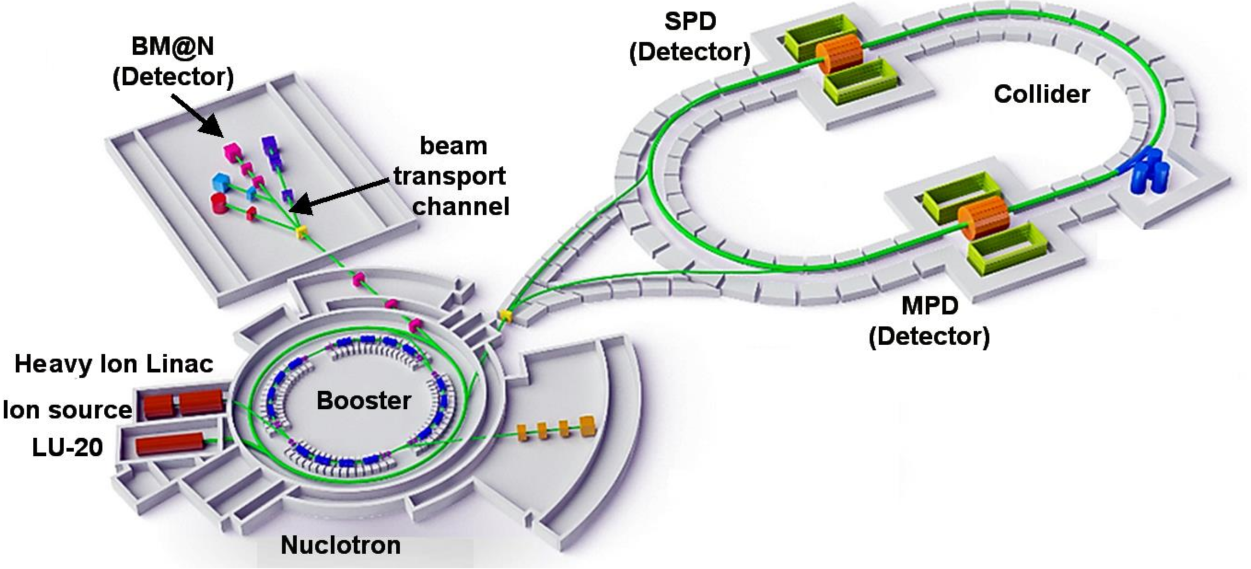

Figure 1NICA Complex.

1.2 BM@N experiment

The BM@N (Baryonic Matter at Nuclotron) experiment is a key initiative within the NICA framework, focused on studying baryonic matter produced in heavy-ion collisions. BM@N aims to explore the production mechanisms and properties of baryons under extreme conditions, enhancing our understanding of nuclear matter. By utilizing advanced detector systems, the experiment analyzes the dynamics of particle interactions, contributing to the investigation of phase transitions between hadronic matter and quark-gluon plasma.

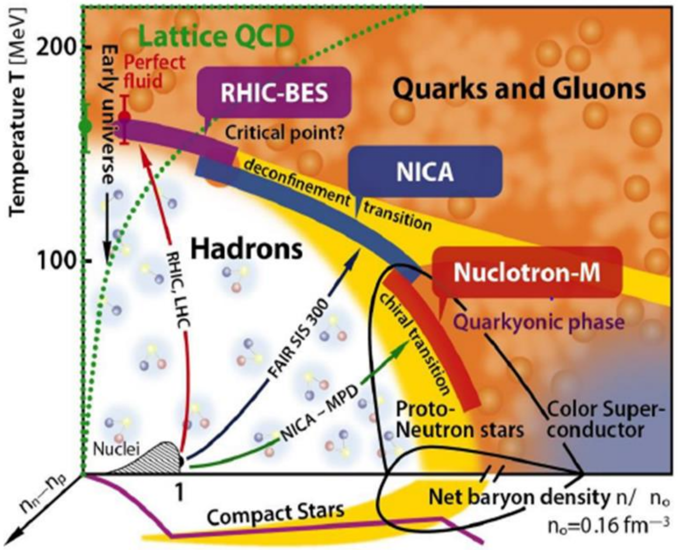

Figure 2 QCD Phase Diagram

The BM@N setup incorporates various detection technologies, including time-of-flight and tracking detectors, to provide high-precision measurements of particle behavior. This research is critical for probing the fundamental aspects of strong interactions and understanding the conditions that lead to baryon formation. Ultimately, BM@N plays a vital role in expanding our knowledge of the universe's early moments and the nature of matter under extreme densities. [2-5]

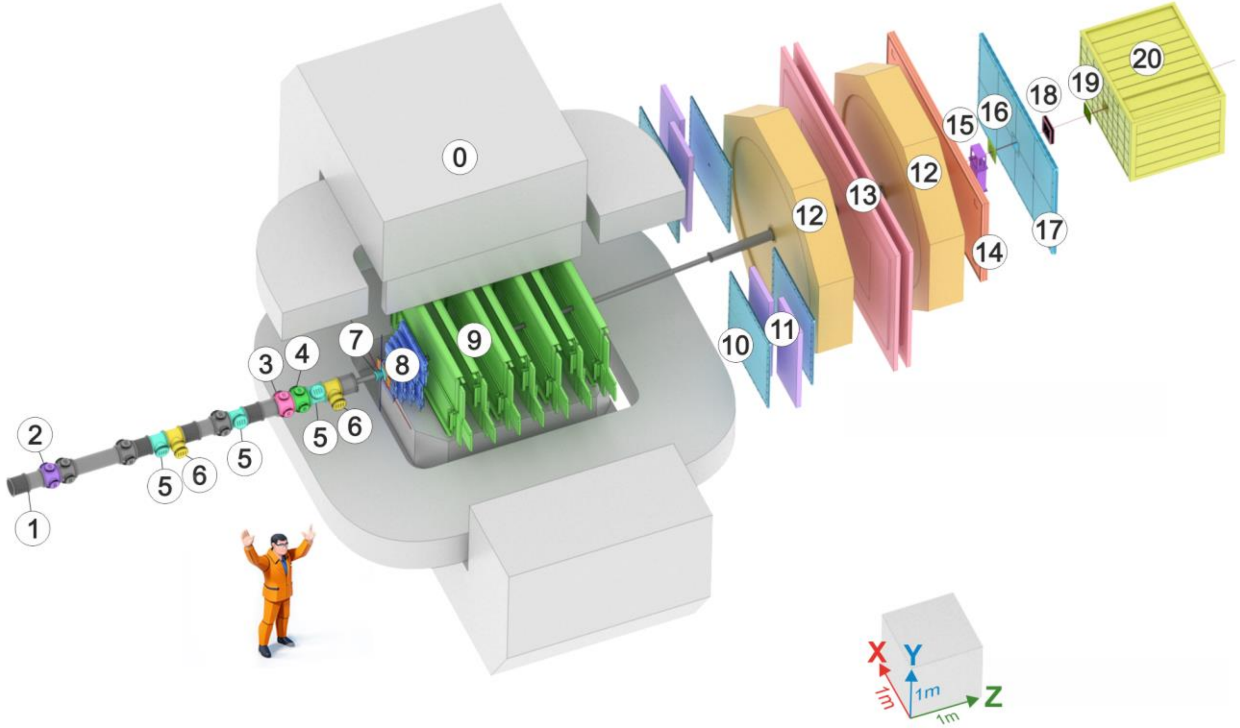

Figure 3. Schematic view of the BM@N setup in the 2023 Xe run. Main components: 0) SP-41 analyzing magnet, 1) vacuum beam pipe, 2) BC1 beam counter, 3) Veto counter (VC), 4) BC2 beam counter, 5) Silicon Beam Tracker (SiBT), 6) Silicon beam profilometers, 7) Barrel Detector (BD) and Target station, 8) Forward Silicon Detector (FSD), 9) Gaseous Electron Multiplier (GEM) detectors, 10) Small cathode strip chambers (Small CSC), 11) TOF400 system, 12) drift chambers (DCH), 13) TOF700 system, 14) Scintillation Wall (ScWall), 15) Fragment Detector (FD), 16) Small GEM detector, 17) Large cathode strip chamber (Large CSC), 18) gas ionization chamber as beam profilometer, 19) Forward Quartz Hodoscope (FQH), 20) Forward Hadron Calorimeter (FHCal).

2. TOF systems

Two time-of-flight systems are used in BM@N for charged particle identification. The first system, TOF400, is placed at about 4 meters from the target and consists of two arms to the left and right of the beam axis. It is focused on identifying particles flying at high polar angles. The time-of-flight distance does not allow effective separation of charged particles near the beam axis. The second wall, TOF700, is located at a distance of about 7 meters from the target, sufficient for an effective separation of particles at small angles. The arrangement of both systems provides continuous geometric acceptance and overlap with the FSD, GEM and Outer Tracker subsystems. The choice of detectors and their parameters was dictated by the following requirements:

- high granularity and rate capability to keep the overall system occupancy below 15 %, while minimizing efficiency degradation due to double hits;
- position resolution better than 1 cm in order to provide effective matching of TOF hits with tracks;
- high combined geometrical and detection efficiency (better than 85 %);
- separation of pions and kaons in the momentum range $0.1 < p < 3$GeV;
- separation of kaons and protons in the momentum range $0.3 < p < 5$GeV.

To achieve necessary performance, a strip-readable Multigap Resistive Plate Chamber (MRPC) detector was chosen for both TOF subsystems. This type of detectors is widely used for time-of-flight measurements. It shows good efficiency, excellent time resolution and the ability to work with particle flux up to tens of kHz/cm^2. [4, 5]

2.1 TOF 400

The ToF-400 (Time-of-Flight 400) detector is a vital component of the BM@N experiment, specifically designed to enhance particle identification in heavy-ion collisions. The detector wall is divided into two symmetrical sections, one on the left and one on the right, aligned with the beam. Each section consists of two gas boxes (modules) containing 5 mRPCs (multi-gap resistive plate chambers) that utilize advanced timing technology for precision measurements. These gas boxes are constructed with aluminum frames and covered with aluminum honeycomb to minimize radiation length, although their edges remain relatively thick. Ongoing development is focused on optimizing the gas box design to further improve performance. The TOF-400 detector operates effectively at lower energy thresholds, capturing a broad spectrum of particle types in high-energy collision environments.

TOF-400 measures the time taken for charged particles to travel a fixed distance, providing critical data for distinguishing between different particle species based on their mass. This high-precision measurement capability is essential for studying particle production, decay, and interactions in the dense environments typical of heavy-ion collisions. The data it provides significantly enhances the understanding of baryonic matter formation and nuclear matter behavior. Integrated with other detectors in the BM@N experiment, TOF-400 contributes to a comprehensive analysis of collision events, helping to cross-reference data and improve the reliability of particle identification. Its role is crucial in achieving the scientific goals of BM@N, advancing the study of nuclear interactions under extreme conditions, and deepening the understanding of particle physics. [4,5]

2.2 TOF 700

The TOF-700 (Time-of-Flight 700) detector is positioned approximately 7 meters away from the target and is an integral part of the BM@N experiment, designed for particle identification at high energies. It consists of 58 glass multigap Timing Resistive Plate Chambers (mRPC) arranged on a wall with dimensions of 3.2x1.6 m², carefully chosen to meet the geometric constraints of the tracking detectors. This detector is capable of separating pions and kaons up to 3 GeV/c, as well as protons and kaons up to 5 GeV/c, making it highly effective in distinguishing particle species in heavy-ion collisions. The TOF-700 achieves impressive time resolution of approximately 60 picoseconds with an efficiency exceeding 97%, while keeping signal crosstalk between adjacent strips to just a few percent, ensuring accurate and reliable data collection.

The TOF-700 operates with high precision, especially in densely populated environments with multiple particles produced in rapid succession during heavy-ion collisions. Its advanced timing systems and readout electronics allow for rapid data acquisition and processing, making it an essential tool for real-time analysis. By measuring the time it takes for particles to travel a set distance, TOF-700 enables researchers to track and identify particles even in challenging high-multiplicity environments. Furthermore, its integration with other BM@N detector systems, such as tracking detectors and calorimeters, enhances the comprehensive analysis of collision events. The data from TOF-700 plays a key role in understanding particle dynamics and the behavior of nuclear matter under extreme conditions, contributing significantly to BM@N's overarching goals of exploring baryonic matter and advancing the study of nuclear physics. [4, 5]

3. Mont-Carlo Generators

Monte Carlo methods are a class of computational algorithms that use random sampling to solve physical and mathematical problems, particularly those involving complex systems with many interacting components. These methods were first developed during the 1940s, primarily driven by the need for simulations in the Manhattan Project. The name "Monte Carlo" was coined by mathematician Stanislaw Ulam, reflecting the randomness inherent in the method, akin to the randomness of outcomes in a casino. Over time, Monte Carlo methods have become indispensable in fields ranging from statistical physics to financial modeling, with a particularly significant role in nuclear physics and high-energy particle physics. [6]

In nuclear physics, Monte Carlo simulations are used to model the stochastic processes that occur during particle collisions, enabling researchers to predict the behavior of particles in high-energy environments, such as those created in particle accelerators. These simulations are crucial for interpreting experimental data, as they allow scientists to compare real-world results with theoretical predictions. Various Monte Carlo models have been developed to handle different aspects of particle physics, each focusing on specific stages of particle interactions, from the initial collision to the final state particles. These models include the Parton-Hadron String Dynamics (PHSD), Dubna Cascade Model (DCM), Statistical Multifragmentation Model (SMM), Quark-Gluon String Model (QGSM), Ultra-relativistic Quantum Molecular Dynamics (UrQMD), and the hybrid DCM-SMM model.

3.1 PHSD (Parton-Hadron String Dynamics)

The PHSD model is a sophisticated tool used to simulate the dynamical evolution of strongly interacting matter, particularly in the context of heavy-ion collisions. Developed as an extension of earlier models, PHSD incorporates both partonic and hadronic phases of matter, allowing it to describe the formation of a quark-gluon plasma and its subsequent hadronization into observable particles. This model is based on a covariant transport approach that includes the dynamics of partons (quarks and gluons), hadrons, and strings, making it particularly well-suited for studying the early stages of heavy-ion collisions. PHSD has been instrumental in advancing our understanding of the QCD (Quantum Chromodynamics) phase transition and the properties of the quark-gluon plasma, providing detailed insights into the non-equilibrium dynamics of nuclear matter under extreme conditions. [7]

3.2 DCM (Dubna Cascade Model)

The Dubna Cascade Model (DCM) was developed at the Joint Institute for Nuclear Research (JINR) in Dubna, Russia, as a tool for simulating the early stages of nuclear collisions. DCM focuses on the cascade of nucleon-nucleon interactions that occur immediately after the initial impact between colliding nuclei. This model treats the interactions of nucleons (protons and neutrons) as a series of binary collisions, leading to the production of secondary particles and the subsequent evolution of the nuclear system. DCM has been widely used to study a variety of nuclear reactions, including those involving light and heavy nuclei, providing valuable insights into the mechanisms of particle production and the role of intranuclear cascades in shaping the outcomes of nuclear collisions. [6]

3.3 SMM (Statistical Multifragmentation Model)

The Statistical Multifragmentation Model (SMM) is designed to describe the disintegration of hot nuclear matter into multiple fragments, a process known as multifragmentation. SMM operates on the premise that at sufficiently high temperatures, a nucleus can break up into several smaller nuclei and individual nucleons. This model treats the breakup process as a statistical phenomenon, where the distribution of fragments is determined by thermodynamic principles, such as temperature and pressure. SMM has been particularly useful in explaining the results of heavy-ion collisions at intermediate energies, where multifragmentation is a dominant reaction mechanism. By providing a statistical framework for analyzing fragment distributions, SMM has helped to deepen our understanding of nuclear phase transitions and the thermodynamic properties of nuclear matter. [6]

3.4 QGSM (Quark-Gluon String Model)

The Quark-Gluon String Model (QGSM) is a Monte Carlo model used to simulate high-energy hadron-hadron and hadron-nucleus collisions. QGSM is based on the concept of quark-gluon strings, which are theoretical objects that represent the color field between interacting quarks and gluons. When hadrons collide at high energies, these strings stretch and eventually break, leading to the production of new hadrons. QGSM models this process by simulating the fragmentation of quark-gluon strings into observable particles, making it a powerful tool for studying the hadronization process and particle production in high-energy collisions. The model has been widely applied to understand the dynamics of particle creation in environments such as those found in high-energy accelerators, contributing significantly to the field of particle physics. [8]

3.5 UrQMD (Ultra-relativistic Quantum Molecular Dynamics)

The Ultra-relativistic Quantum Molecular Dynamics (UrQMD) model is a versatile Monte Carlo generator that combines elements of quantum molecular dynamics with relativistic effects to simulate the behavior of nuclear matter under extreme conditions. UrQMD is designed to handle a wide range of interactions, from nucleon-nucleon collisions to the dynamics of quarks and gluons in high-energy heavy-ion collisions. The model includes a comprehensive set of interactions, including elastic and inelastic scattering, particle decays, and the formation of resonances. UrQMD has been used extensively to study the time evolution of nuclear collisions, providing insights into the formation of dense nuclear matter, the production of hadrons, and the properties of the quark-gluon plasma. Its ability to simulate both the initial collision stages and the subsequent hadronization makes UrQMD a valuable tool in nuclear physics research. [9]

3.6 DCM-SMM

The DCM-SMM model is a hybrid approach that integrates the strengths of the Dubna Cascade Model (DCM) and the Statistical Multifragmentation Model (SMM). This combined model is designed to provide a comprehensive description of nuclear collisions, from the initial cascade of nucleon interactions to the final breakup of the nuclear system into fragments. DCM-SMM allows for a detailed simulation of the entire collision process, capturing both the dynamical evolution of the nuclear matter and the statistical nature of its disintegration. By combining the detailed collision dynamics of DCM with the statistical fragmentation framework of SMM, this model offers a powerful tool for studying nuclear reactions across a wide range of energies. The DCM-SMM model has been particularly useful in analyzing experimental data from heavy-ion collisions, providing a robust framework for interpreting the complex processes that occur in these extreme environments. [6]

3.7 PHQMD (Parton-Hadron Quantum Molecular Dynamics)

PHQMD (Parton-Hadron Quantum Molecular Dynamics) is a hybrid model designed to simulate the dynamical evolution of heavy-ion collisions by integrating both the partonic (quarks and gluons) and hadronic (hadrons and mesons) phases of matter. It combines features from quantum molecular dynamics with partonic interactions, allowing it to describe the early quark-gluon plasma formation and its subsequent hadronization into observable particles. PHQMD tracks fluctuations, correlations, and interactions throughout both phases, making it a valuable tool for studying nuclear matter under extreme conditions. The model provides detailed insights into particle production, flow, and the phase transition between the quark-gluon plasma and hadrons, which are critical in analyzing data from high-energy collision experiments, such as those conducted at NICA and BM@N. [10]

3.8 Summary of Differences

- PHQMD and PHSD focus on both partonic and hadronic phases, making them well-suited for studying high-energy heavy-ion collisions and quark-gluon plasma.
- DCM focuses on the cascade phase, ideal for modeling early nucleon interactions.
- SMM is a statistical model that excels in studying multifragmentation of hot nuclear matter at intermediate energies.
- QGSM specializes in hadron production through string fragmentation in high-energy collisions.
- UrQMD is a versatile model that handles the full dynamical evolution of nuclear collisions across a wide energy range.
- DCM-SMM combines the cascade approach of DCM with the statistical framework of SMM, providing a hybrid model for nuclear collision processes.

4. Methodology & Results

BM@N's experimental run 7 utilized a variety of targets and configurations to analyze particle interactions in heavy-ion collisions. The targets typically used in this experiment include materials like lead (Pb), cesium iodide (CsI), and germanium (Ge), with different thicknesses for each disk target. Specifically, for the 2023 Xe run, the experimental setup involved three disk targets with diameters of 3.2 cm: a 1.75 mm thick CsI target, a 0.85 mm thick CsI target, and a 1.02 mm thick Ge target. These targets were integrated into a pneumatic system that allowed for precise placement and removal within the vacuum chamber, ensuring minimal background noise from structural elements.

This specific run also focused on using beams with varying energies, including Xenon beams at 3.0 AGeV and 3.8 AGeV, aimed at studying high-energy collisions and particle interactions. The magnetic field of the SP-41 analyzing magnet was adjusted for the Xe beams, allowing the experiment to capture detailed momentum measurements of the produced particles and

Parameter Symbol	Description
m2 (Squared mass of the track)	This refers to the square of the mass of the particle associated with the track. It's useful for particle identification, as particles like pions, kaons, and protons have different masses.
px (X-projection of the track momentum)	This represents the component of the particle's momentum along the X-axis in the detector's coordinate system. Momentum is a vector, so it has components along different axes.
py (Y-projection of the track momentum)	Similar to px, this represents the component of the particle's momentum along the Y-axis.
pz (Z-projection of the track momentum)	This is the component of the particle's momentum along the Z-axis, often aligned with the beam direction in particle physics experiments.
p (Full track momentum)	This is the magnitude of the momentum vector, calculated as the square root of the sum of the squares of px, py, and pz. It gives the total momentum of the particle.
pt (Transverse momentum of the track)	The momentum of the particle in the plane perpendicular to the beam direction (typically the XY-plane). It's defined as $pt = \sqrt{px^2 + py^2}$ Transverse momentum is especially important in high-energy physics as it's less affected by the beam's direction.
nutrpv (Number of tracks in the primary vertex (PV))	This represents the total number of tracks originating from the primary vertex (the point where the particle collision occurred). It provides information about the event multiplicity.
nutarg (Target id: 1 - Pb; 2 - Csl; 3 - Ge)	This denotes the type of target material used in the experiment, where the numbers correspond to specific elements: - 1: lead (Pb) - 2: cesium iodide (CsI) - 3: germanium (Ge)

fragments. These runs contributed to a deeper understanding of the behavior of nuclear matter under extreme conditions

The following table contains description of some parameters of interest in the mini-DST data of the Tof-400. [4]

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, the following steps were followed:

Copied the ROOT file Tof400_Data_sigma.root from scratch1/pukhaeva/miniDST to my cluster at mostafan.

- Examined the trees within the ROOT file and visualized the data in tree_tof400, corresponding to all particles.
- Plotted the data for all particles and documented the results.
- Modified a C++ code to extract only proton data by applying specific filters.
- Set the target to lead (Pb) for proton selection.
- Defined the following parameter values for the proton data extraction:
  m^2 low proton = 0.88
  m^2 high proton = 1.1
  zpv low = -3.4
  zpv high = 1.7
  P high = 0.5
  DCAXy = 1
- Analyzed and presented the resulting proton data.

4.1Result for all Particles

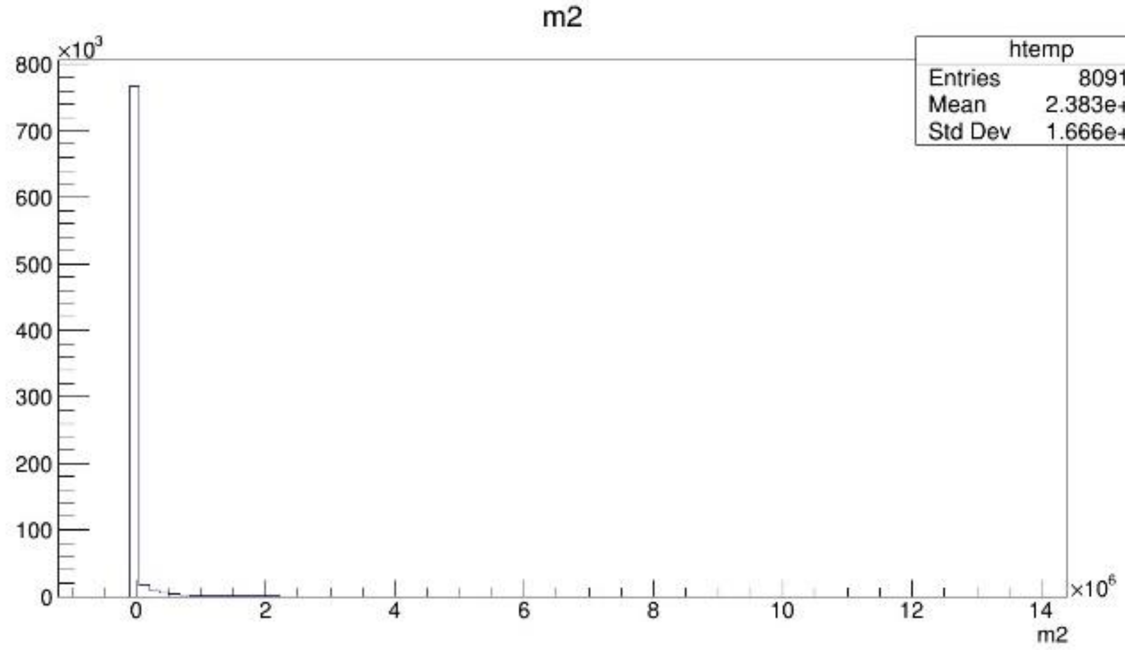

Figure 4: Distribution of squared mass of the tracks in GeV

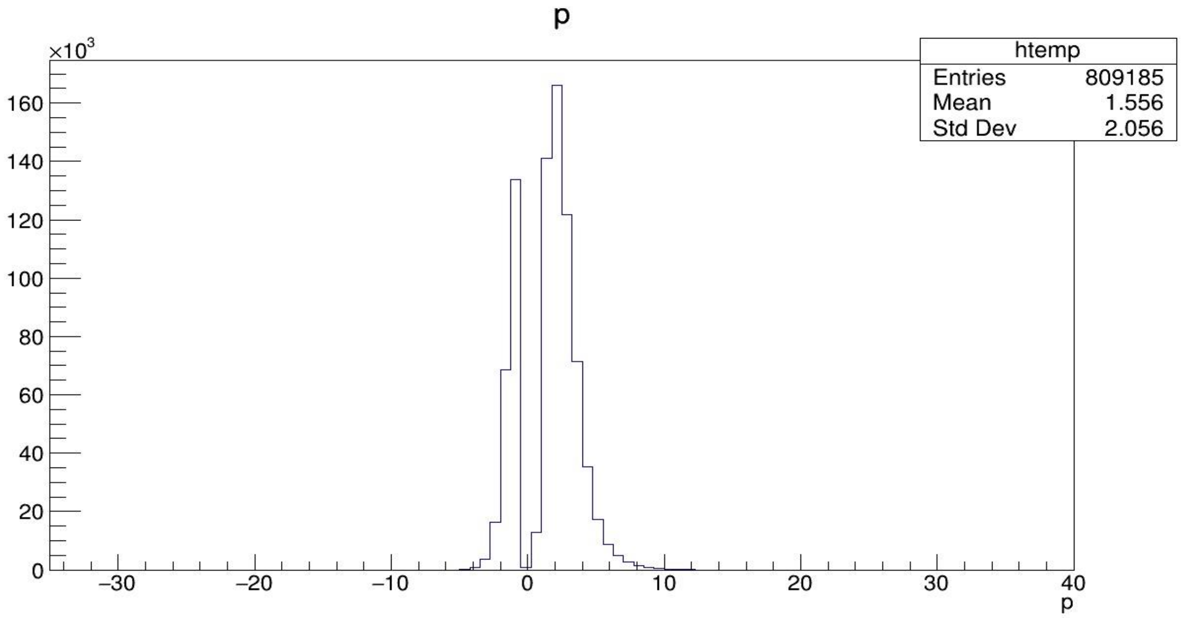

Figure 5: Distribution of Full track momentum in GeV

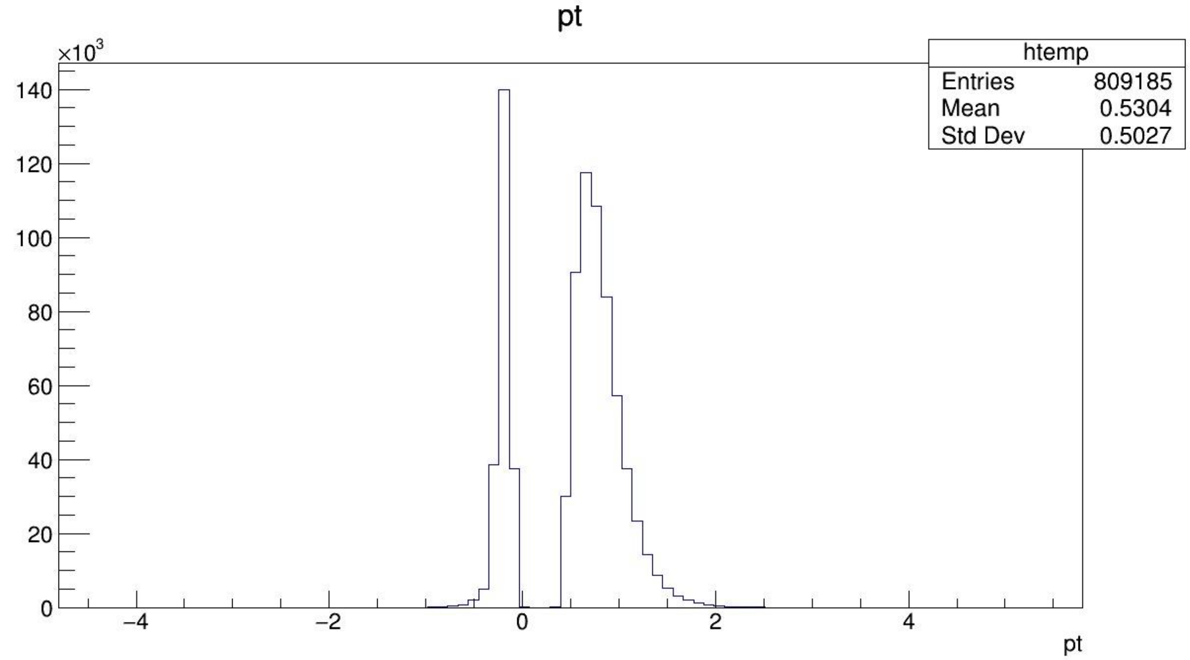

Figure 6: Transverse momentum distribution of the tracks in GeV

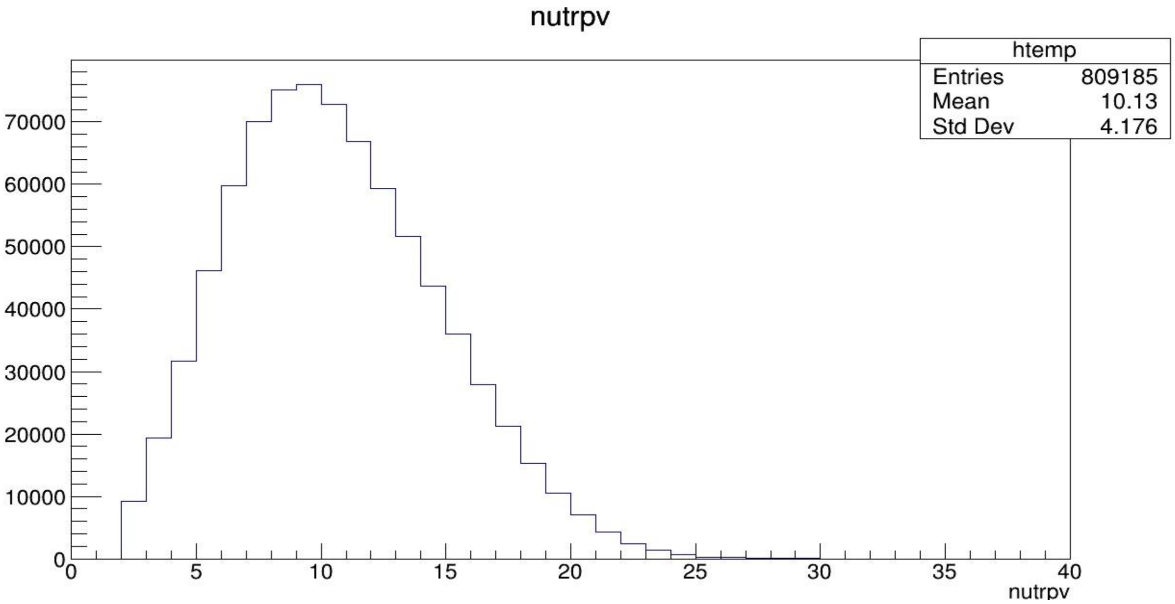

Figure 7: Number of tracks in the primary vertex (PV)

Figures 4 to 7 provide essential insights into the characteristics of all particle tracks detected during the BM@N experiment. Figure 4 illustrates the distribution of squared mass of the tracks, which is crucial for identifying different particle types, as peaks in this distribution can indicate specific particles produced in heavy-ion collisions. Complementing this, Figure 5 presents the distribution of full track momentum, offering valuable information about the kinematic properties of the particles, including their energy and velocity. Figure 6 focuses on the transverse momentum distribution of the tracks, which is important for understanding the dynamics of particle interactions in the collision environment. Finally, Figure 7 shows the number of tracks in the primary vertex (PV), providing insights into the event multiplicity and the complexity of the collision events. By analyzing these distributions of all particle tracks, researchers can gain a comprehensive understanding of the behavior and interactions of particles in high-energy environments, which is critical for advancing nuclear physics research.

4.2 Results for Proton

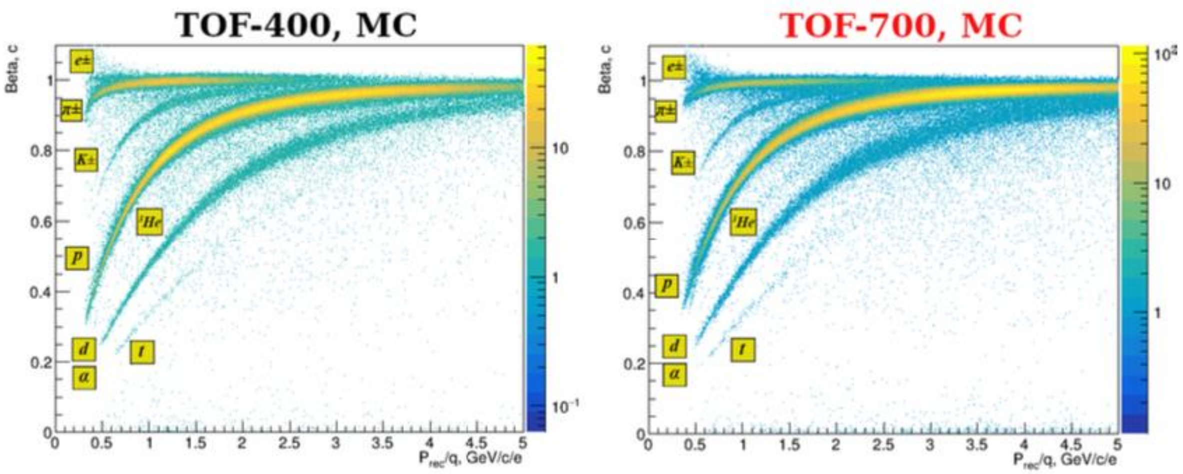

Figure 8 Comparison of TOF-400 and TOF-700 Monte Carlo simulations for particle identification. The Beta vs. momentum plots reveal distinct separation bands for various particles, such as protons, pions, kaons, and deuterons. This data provides insights into the resolution and sensitivity differences between TOF-400 and TOF-700 in detecting and distinguishing between particle types, with TOF-700 showing slightly higher detection intensity at certain momentum ranges.

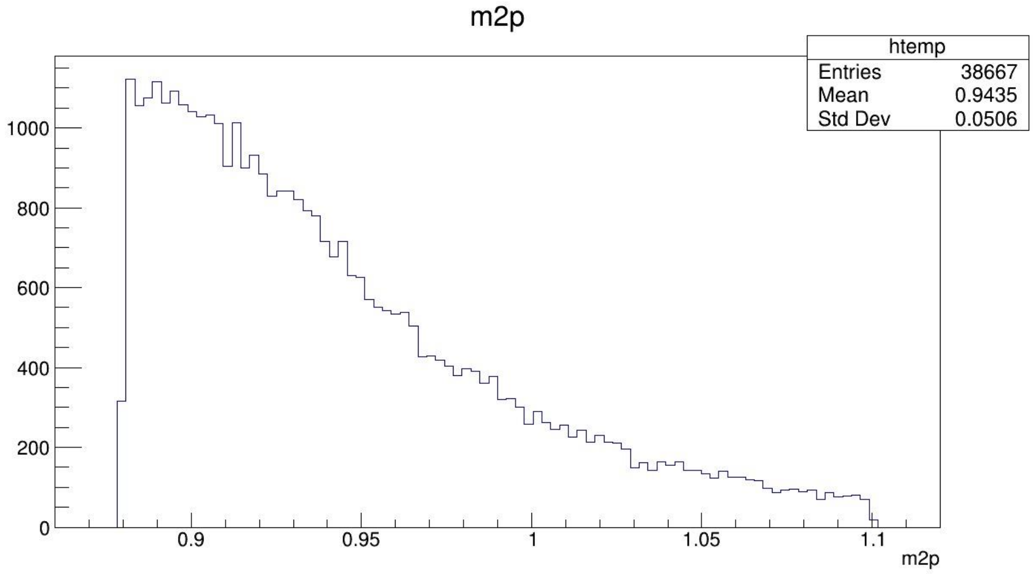

Figure 9 Distribution of squared mass of P tracks in GeV

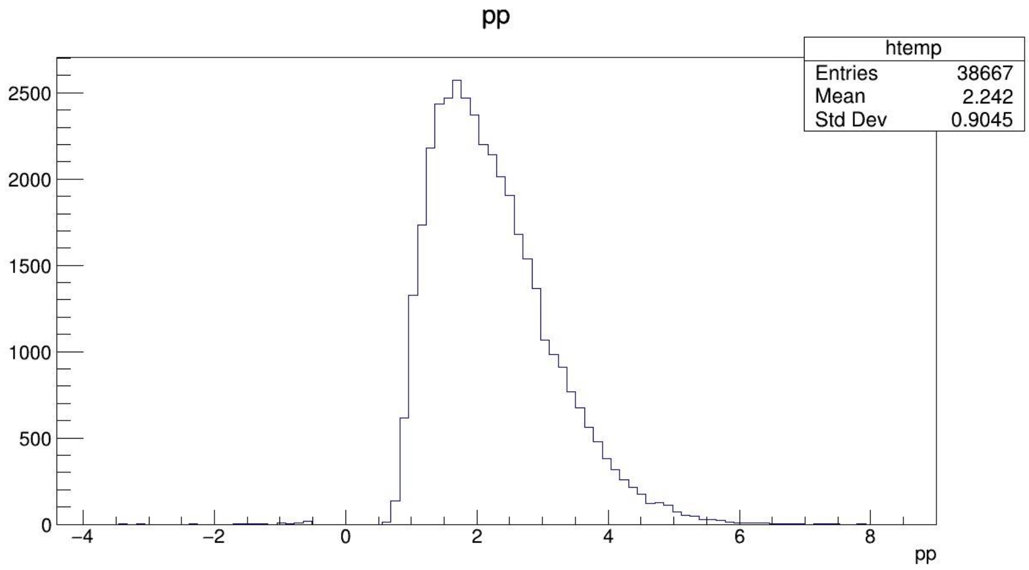

Figure 10 Distribution of P full tracks momentum in GeV

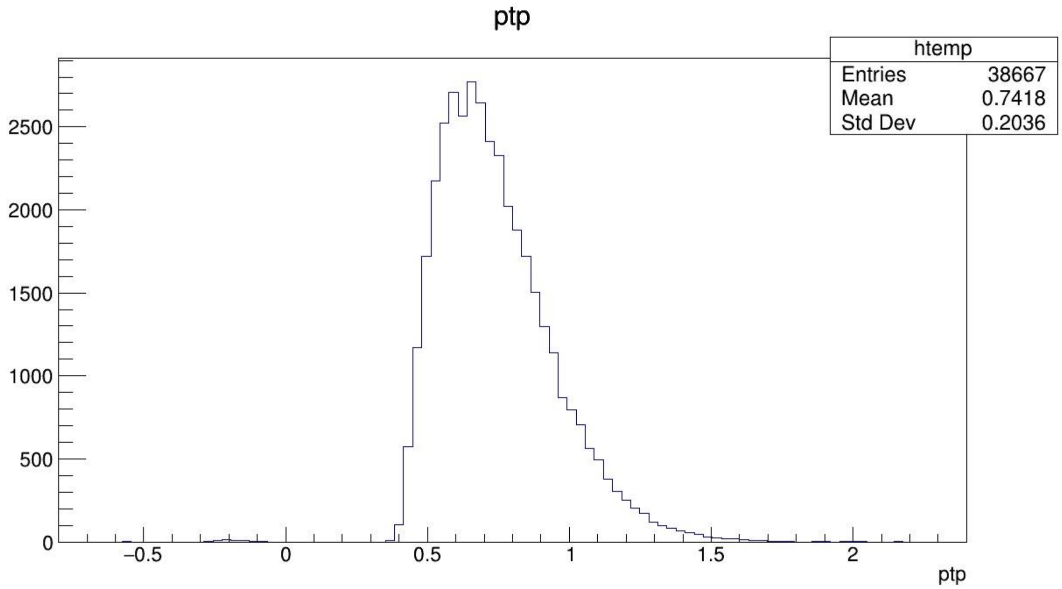

Figure 11 Transverse momentum distribution of P tracks in GeV

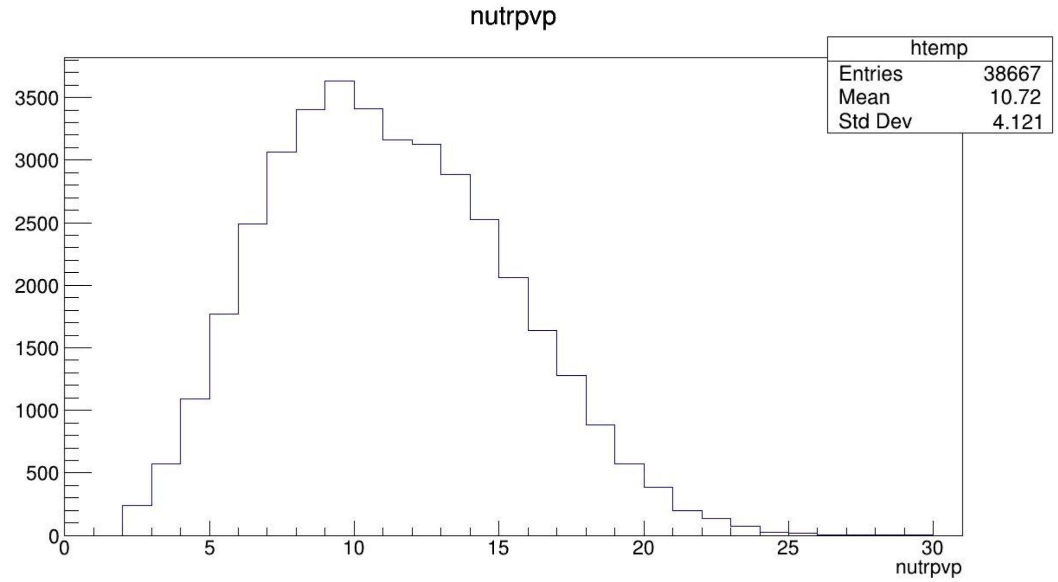

Figure 12 Number of P tracks in the primary vertex (PV)

Figures 9 to 12 offer valuable insights into the properties of proton tracks observed during the BM@N experiment. Figure 8 depicts the distribution of squared mass for proton tracks, which plays a crucial role in verifying proton identification, as specific peaks in this distribution signify the presence of protons among the various particles detected. In conjunction with this, Figure 9 illustrates the distribution of full track momentum for protons, providing essential information about their kinematic characteristics, such as energy and velocity, which are vital for comprehending their behavior in heavy-ion collisions. Figure 10 highlights the transverse momentum distribution of proton tracks, shedding light on the dynamics of proton interactions within the collision environment. Lastly, Figure 11 presents the number of proton tracks in the primary vertex (PV), which is instrumental in evaluating event multiplicity and the complexity of collision events specifically related to protons. By examining these distributions for protons, researchers can enhance their understanding of proton behavior and interactions in high-energy environments, contributing significantly to advancements in nuclear physics research.

Discussion

The results presented in Figures 8 to 11, it is essential to consider the implications of the observed distributions for proton tracks in the context of heavy-ion collisions. The squared mass distribution (Figure 8) reveals distinct peaks that confirm the successful identification of protons amidst a complex background of other particles. This identification is critical, as it allows researchers to isolate proton interactions and study their specific contributions to the overall dynamics of the collision.

The full track momentum distribution (Figure 9) provides insights into the energy and velocity of protons, which are fundamental for understanding their role in the collision process. Analyzing the momentum distribution can help identify patterns related to energy conservation and particle production mechanisms, offering a deeper understanding of the underlying physics governing heavy-ion collisions.

The transverse momentum distribution (Figure 10) is particularly significant, as it reflects the dynamics of proton interactions in the collision environment. A detailed examination of this distribution can reveal information about the collective behavior of protons and their interactions with other particles, which is crucial for understanding the formation of the quark-gluon plasma and other phenomena associated with high-energy nuclear physics.

Finally, the number of proton tracks in the primary vertex (Figure 11) serves as an indicator of event multiplicity, which is essential for assessing the complexity of the collision events. A higher number of proton tracks may suggest more intricate interactions and a richer event structure, which can provide valuable data for theoretical models and simulations.

Overall, the analysis of these distributions not only enhances our understanding of proton behavior in high-energy environments but also contributes to the broader goals of nuclear physics research. Future studies should focus on refining these analyses and integrating them with Monte Carlo simulations to validate experimental findings and further explore the intricate dynamics of particle interactions in heavy-ion collisions. This ongoing research will be vital for advancing our comprehension of nuclear matter under extreme conditions and the fundamental forces at play in the universe.

Conclusion

In conclusion, the analysis of proton data from the BM@N experiment at the NICA complex has provided valuable insights into the behavior of nuclear matter in heavy-ion collisions. By focusing on data from the TOF-400 detector and applying specific criteria for proton identification, we have been able to isolate and study proton interactions with a lead target. The TOF-400 detector has once again demonstrated its critical role in delivering high-precision particle identification, contributing to the broader success of the BM@N experiment in advancing nuclear physics research.

Our analysis of the data from the left side of the TOF-400 detector has yielded promising results, confirming the efficiency of our methodology in extracting relevant proton data. Moving forward, future studies will focus on further refining our analysis techniques and conducting comparative simulations using Monte Carlo event generators such as UrQMD, DCM-SMM, and PHSD. These simulations will provide a deeper understanding of the underlying physics and validate our experimental findings, enhancing our comprehension of particle interactions in high-energy environments.

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