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

Final Report of INTEREST program

Study of bulk properties of the medium produced in heavy ion collisions at MPD

Study of the Bi+Bi collisions for the MPD/NICA

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Participation Period

November 2-nd - December 11-th

Dubna, 2020
Wave 2

Abstract

In this report, we present the analysis of identified charged particles ($\pi^{\pm}$, $K^{\pm}$, p, p^{-}) formation at midrapidity region of $|\eta| < 0.5$ in Bi-Bi ion collisions at energies $\sqrt{S_{NN}}$ = 7.7, 9, 9.46 GeV. The particle momentum spectra for charged hadrons is measured using data from statistical Monte-Carlo generator: Ultrarelativistic Quantum Molecular Dynamics (UrQMD) for the Multi-Purpose Detector (MPD) of the NICA project. We measure the particle identification efficiency and validate various track level cuts for lowering the uncertainties. The analysis of particle multiplicity dependence on the collision energy and centrality dependence of the spectra was performed for investigated particle species. Finally, we analyze ratio of strange to non-strange particles dependence on the collision energy.

Introduction: The QCD phase diagram

One of the major goals in high energy nuclear collisions is to determine the conditions behind the phase transition between hadronic matter and the Quark Gluon Plasma (QGP) state. Nucleus is a bound state of protons and neutrons which are called nucleons. Nucleons are formed by colored quarks and gluons which interact strongly and are confined by the strong interaction. This means that particles with color charge, such as the quarks, can't be observed in free state. This is the reason why the study of internal structure of hadronic matter is so complicated. [1]

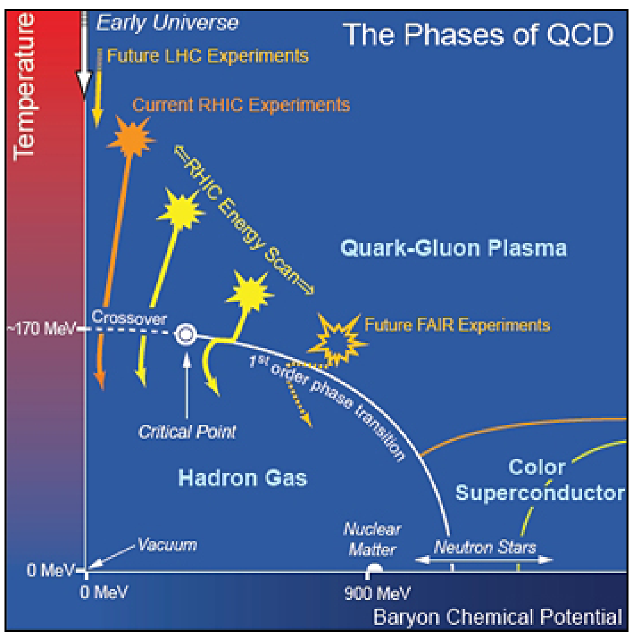


Figure 1: Conjectured version of the QCD phase diagram with μ_B on the horizontal axis and Temperature T (in energy units) on vertical axis. Figure taken from [2].

QGP state of matter could be found at temperatures and densities that existed shortly after the

Big Bang, at very high temperature and/or density. QGP has been created in several laboratories at different conditions. The most accessible way to characterize the phase diagram is in the terms of temperature (T) and baryon chemical potential (μ_B), as shown in figure 1. For values close to $\mu_B = 0$, experiments from the Large Hadron Collider (LHC) and the Relativistic Heavy Ion Collider (RHIC) have provided evidence of the QGP formation, but exact parameters of the first order phase transition location and existence of the critical point at higher μ_B is yet to be found. There are several methods used in the search for the critical point and for the first order phase transition related to different experimental characteristics of the QGP formation.

Several observations at the top energies RHIC [2] have been associated with the existence of a phase transition with partonic degrees of freedom in the early stages of heavy-ion collisions. Such observables are the suppression of high transverse momentum, hadron production in Au+Au collisions relative to scaled p+p collisions, large elliptic flow (v_2) for hadrons with light as well as heavier strange valence quarks, and differences between baryon and meson v_2 at intermediate p_T range in Au+Au collisions.

Signatures of the phase transition

Calculations from lattice QCD [7] suggest that for a medium created in collisions with zero or low μ_B there is a smooth cross-over transition, while for large values of μ_B, the transition is first order. The point in the (T, μ_B) plane where the first order phase transition ends, is the QCD critical point [8] as shown in 1. The search of the critical point and phase boundary in the QCD phase diagram is currently a focus of different experimental and theoretical nuclear physics researches.

The idea is to vary the collision energy, in order to scan the phase diagram from the top energies, like at RHIC, to the lowest possible energy, like at the NICA and FAIR complexes to look for the signatures of the QCD phase boundary and the QCD critical point. In order to do so we study the established signatures of the QGP formation as function of beam energy. The turn-off of these signatures at a particular energy would suggest that a partonic medium is no longer formed at that energy. Near the critical point, there would be enhanced fluctuations in multiplicity distributions of conserved quantities: net-charge, net-baryon number, and net-strangeness [9]. These observables would suggest the existence of a critical point if they were to show large fluctuations or divergence from a baseline in a limited collision energy region [2].

The study of bulk properties such as dN/dy, $< pT >$, particle ratios, and freeze-out properties can show an insight of the particle production mechanisms, also this studies may help to reveal the evolution and the behavior of the system formed in heavy-ion collisions as a function of collision energy. [2]

The MPD/NICA project

The Nuclotron-based Ion Collider FAcility (NICA) is a new accelerator complex at the Joint Institute for Nuclear Research (JINR) in Dubna, Russia. Its goal is to study the properties of dense baryonic matter. The most important problems in this area are: the nature and properties of strong interaction between elementary constituents of the Standard Model of particle physics – quarks and gluons. The search for signs of the phase transition between hadronic matter and QGP; search for new phases of baryonic matter, study of basic properties of the strong interaction in vacuum and QCD symmetries. [10]

NICA will provide variety of beam species ranged from protons and polarized deuterons to very massive gold ions. Heavy ions will be accelerated up to kinetic energy of $\sqrt{s_{NN}} = 11$ GeV and protons – up to $\sqrt{s_{NN}} = 27$ GeV. The heart of the NICA complex is the upgraded accelerator "Nuclotron" (that has been working at JINR since 1992). The two interaction points are prepared at the NICA collider ring: one for heavy-ion studies with the MPD detector and the other for polarized beams for the SPD experiment [1]. Other experimental facility will operate on extracted beams on the fixed target experiments. NICA will have three main experiments:

1. The Baryonic Matter at Nuclotron (BMN)
2. The Spin Physics Detector (SPD)
3. The MultiPurpose Detector (MPD)

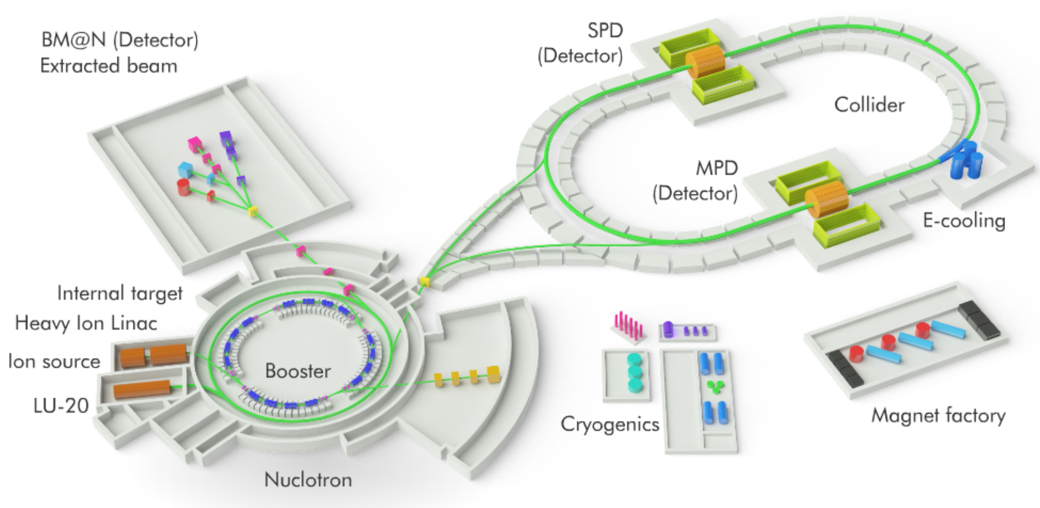


Figure 2: A scheme of NICA complex. It is shown the three experiments and the rest of the components. Image taken from [1]

The expected date of putting the NICA collider for commissioning is the end of 2022. At the same time the MultiPurpose Detector (MPD) has been designed to operate at NICA. Components of MPD are currently in production. The assembly of different detector subsystems on-site has already started. In late 2021 the detector setup will start the commissioning on cosmic data, to be ready for data taking on first beams from NICA.

The Multipurpose Detector

The MPD apparatus has been designed as a 4π spectrometer capable of detecting charged hadrons, electrons and photons using heavy-ion collisions at high luminosity in the energy range of the NICA collider. To reach this goal, the detector will comprise a precise 3-D tracking system and a high-performance particle identification (PID) system based on the charged tracks energy loss information from Time Projection Chamber and time-of-flight measurements.

The basic design parameters has been determined by physics processes in nuclear collisions at NICA and by several technical constrains guided by a trade-off of efficient tracking and PID against a reasonable material budget. At the design luminosity, the event rate in the MPD interaction region is about 6 kHz; the total charged particle multiplicity exceeds 1000 in the most central Au+Au collisions at $\sqrt{S_{NN}} = 11$ GeV. As most of the produced particles has transverse momentum less than 0.5 GeV/c, the detector design requires a very low material budget. The general layout of the MPD apparatus is shown in figure 3. The whole detector setup includes Central Detector (CD) covering ± 2 units in pseudorapidity (η) [1] and two forward spectrometers FS-A and FS-B.

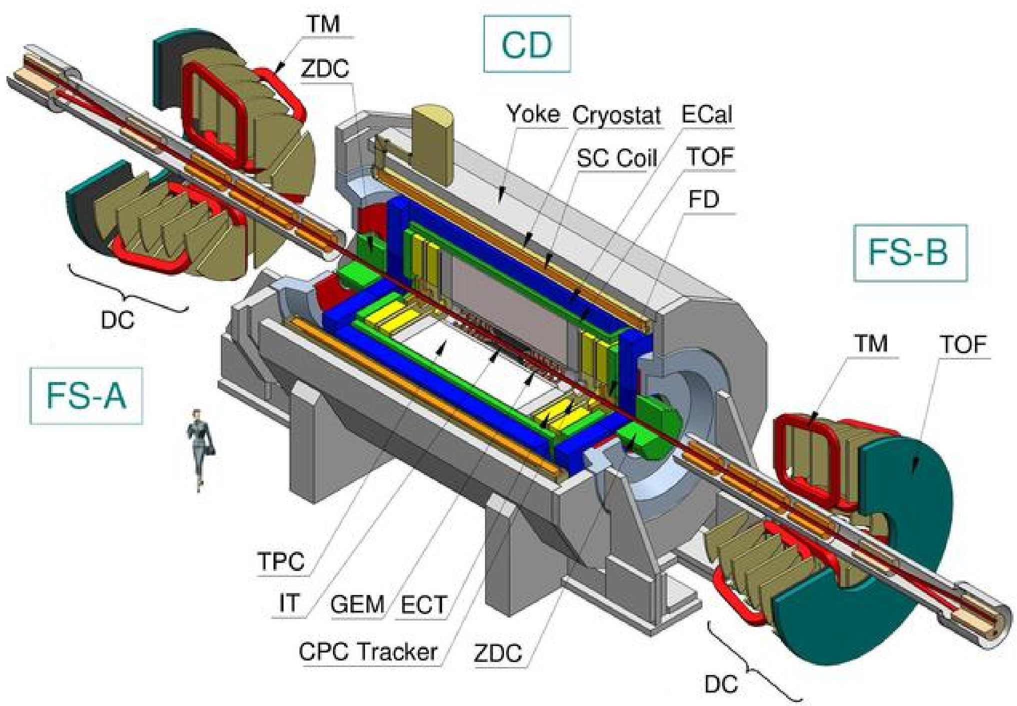


Figure 3: General view of the MPD detector

Monte-Carlo Generator: UrQMD

The Monte-Carlo event generator: Ultra-relativistic Quantum Molecular Dynamic (UrQMD) [3] is a microscopic Monte Carlo model based on the use of phase space to describe nuclear reactions. It describes the low-energy hadron interaction ($\sqrt{s_{NN}} < 5GeV$) as the interaction between hadrons and the hadron interaction at high energies ($\sqrt{s_{NN}} > 5GeV$) as the excitation of colored strings followed by their splitting into hadrons.

The model is based on covariant propagation of all hadrons considered at the quasi-particle level in classical trajectories in combination with stochastic binary scattering, color string formation, and resonance decay. This model is used to simulate the interactions of proton-proton, proton-nucleus and nucleus-nucleus.

Project Goals

- To analyze Bi-Bi collisions at energies of $\sqrt{s_{NN}} = 7,\ 9,\ 9.46$ GeV; from statistical data using UrQMD Monte-Carlo generator for the MPD detector.
- Plot the particle outputs as function of the transverse momentum for the identified hadrons: kaons, pions, protons.
- Analyze the behavior of strange particles in the collision of heavy ions by calculation the ratio K^+/π^+.
- The main goal is to study one of the signatures of the phase transition between the hadron state of matter and the state of quark-gluon plasma (QGP).

Scope of work

The NICA complex will start operations in late 2022, for technical run the Multipurpose Detector will start colliding Bi+Bi ions complementary to Au+Au ion collisions, we aim to contribute to the studies of bulk properties of this system for incoming run of MPD/NICA.

Method

For the analysis we used the Monte-Carlo official data from the MPD collaboration which are located at the NICA LHEP computing cluster [11]. Using the available data of UrQMD at the center-of-mass energy range: $\sqrt{S_{NN}} = 7.7,\ 9,\ 9.46$ GeV for Bi+Bi collisions and statistics of 10^6 events for each energy.

The particle production were plotted as a function of the transverse momentum for the identified particles (kaons, pions and protons) for different collision energies. The following conditions were imposed on the spectra:

- TPC NofHits > 20;
- $|\eta| < 0.5$;
- $0.1 < p_T < 2.5$ GeV.

Here is a brief description of the Monte-Carlo generations used in this analysis:

Events 7.7 GeV

The production is based on UrQMD, with particular settings at the input file: 500 min. bias Bi+Bi 7.7 GeV events per run. This production relays on GEANT4 to simulate the detector response and use UrQMD as an event generator for the colliding system. For the reconstruction phase, it was used a particular reconstruction file with the recommended TOF time resolution and turned off EmcHitCreation (see [5]).

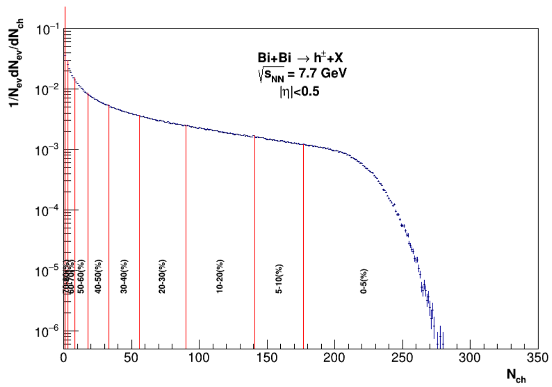
Events 9 GeV The production is based on UrQMD Monte-Carlo input with min. bias events. Simulations in mpdroot were set to ”standard” default settings (see [4]).

Events 9.46 GeV This data set is based on UrQMD event generator set up to generate minbias Bi+Bi collisions. This Monte-Carlo production was originally requested for a Geant4 based general-purpose project, which included simulation of the MPD-ECAL (v.3 geometry) and had enhanced (x20) probabilities for light vector meson decays to $e^+e^- + X$ channels, since original branching for such decays is 10^-4 -10^-5, the enhancement does not affect the simulation of hadrons [6]. The original MpdDecay config file was replaced with the one included in [6].

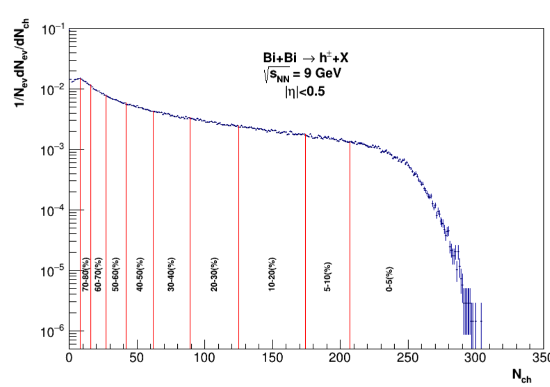
Results

Multiplicity of particles in collisions

In figures 4a, 4b we show the multiplicity of charged particles for 7.7 and 9 GeV with centrality classes. The centrality of interacting nucleon pairs determines the overlap region of colliding nuclei and is related to the collision impact parameter.



(a) Multiplicity distribution for 7.7 GeV



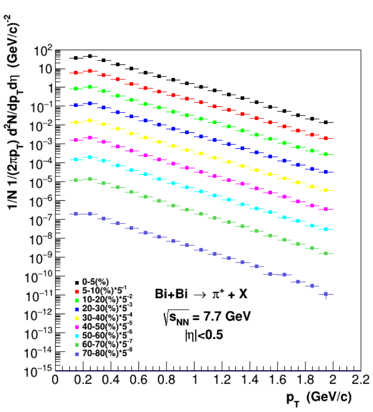
(b) Multiplicity distribution: 9 GeV

Figure 4: Multiplicity distribution in centrality ranges for 7.7 GeV

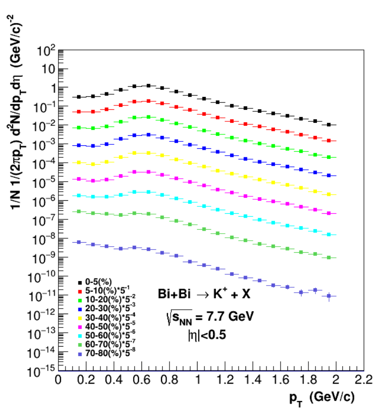
Transverse momentum p_T for different centrality classes

Results for 7.7 GeV

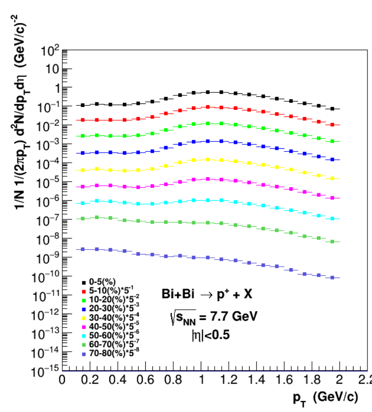
In figure 5 presented particle spectra dependence on transverse momentum calculated for different centrality classes, the spectra for centralities other than 0–5% are scaled for visibility. The results of protons differ greatly from those of pions and kaons, in figure 5c we see a different slope, for positive charged protons the plot is almost uniform.



(a) π^+



(b) K^+

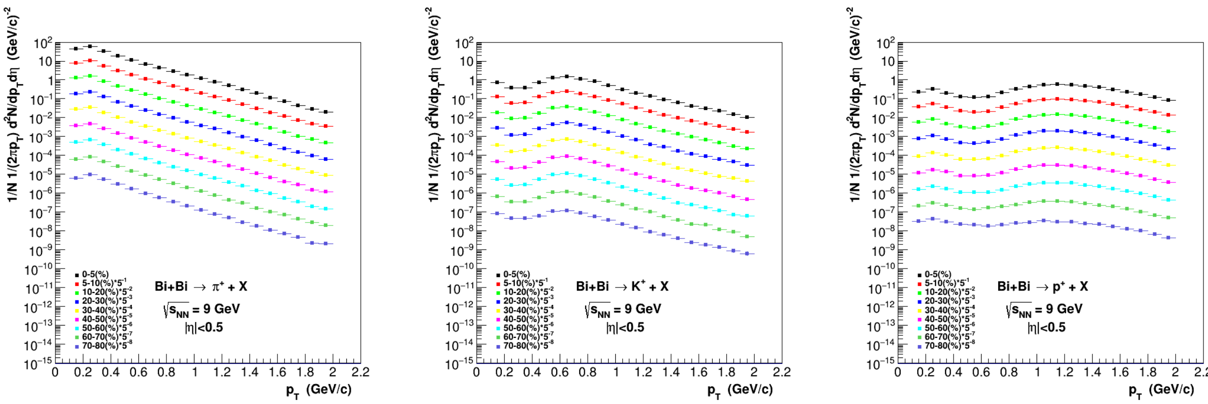


(c) p^+

Figure 5: Transverse momentum p_T output for different centrality classes. For positively charged particles.

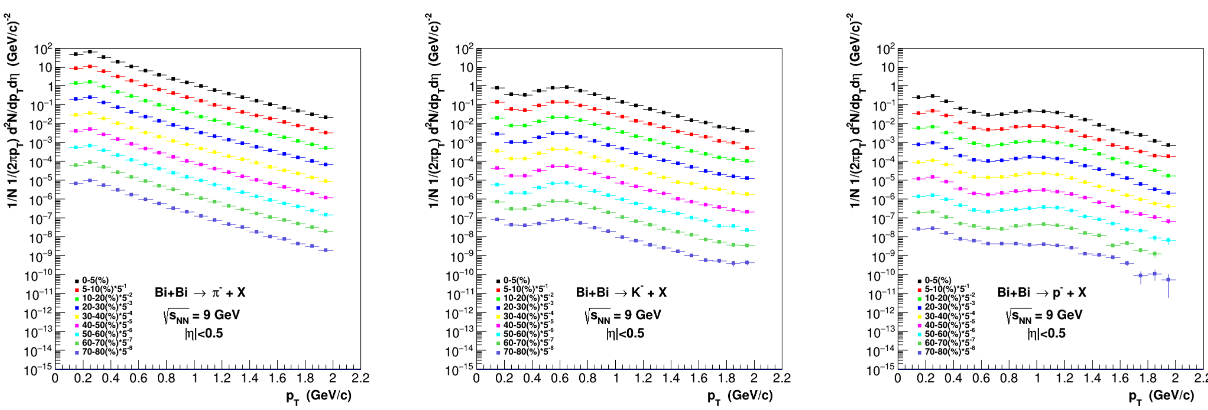
Results for 9 GeV

The main difference in this results with the previous one is the change of shape and tendency of the p_T distribution in the centrality class of $70\% - 80\%$ which are noticeably out of expected shape and below expected value for energies of 7.7 GeV. This remark does not happen in 9 GeV results as shown in the corresponding plots, and neither in the results for 9.46 GeV.



(a) π^+ **(b)** K^+ **(c)** p^+

Figure 6: Transverse momentum p_T output for different centrality classes. For positively charged particles.



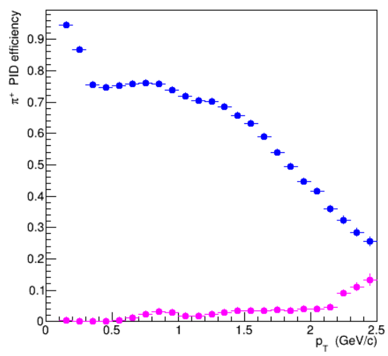
(a) π^- **(b)** K^- **(c)** p^-

Figure 7: Transverse momentum p_T output for different centrality classes. For negatively charged particles.

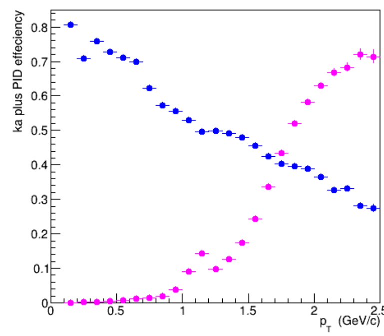
Efficiency calculations

Results for 7.7 GeV

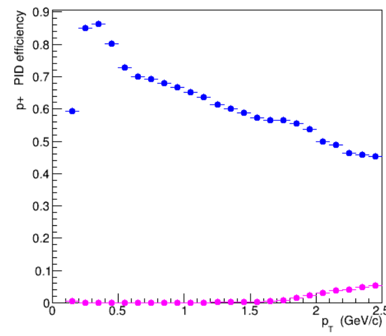
In the next figures we show the PID total efficiency calculated (plots in blue), and the ratio of incorrectly defined particles to all defined ones (plots in magenta). While the efficiency refers to the particles detected by the TPC and TOF over the ones generated by the Monte-Carlo, the contamination ratio refers to the particles that were not correctly defined over all the particles, meaning that if the efficiency is low, there will be an increase in the ratio in magenta. The possibility of the two plots crossing exists, however for pions this does not happen. For both, positive charged pions and negative charged pions the efficiency behavior decreases with the transverse momentum p_T and the ratio of defined particles stays below 20%. The results obtained are considered reasonable.



(a) π^+

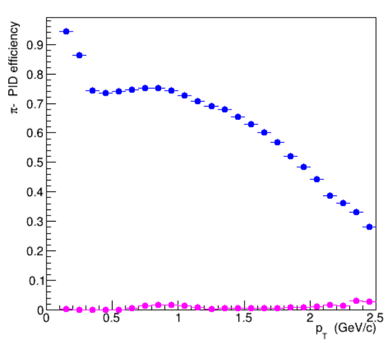


(b) K^+

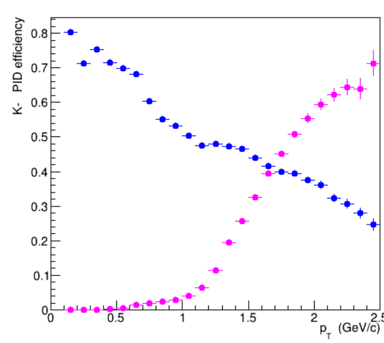


(c) p^+

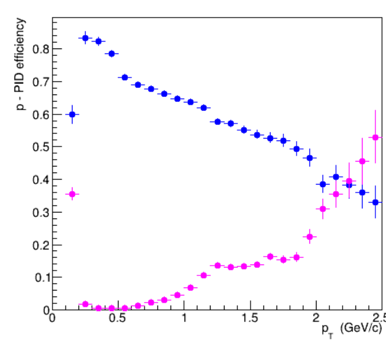
Figure 8: Efficiency plots for positive particles.



(a) π^-



(b) K^-

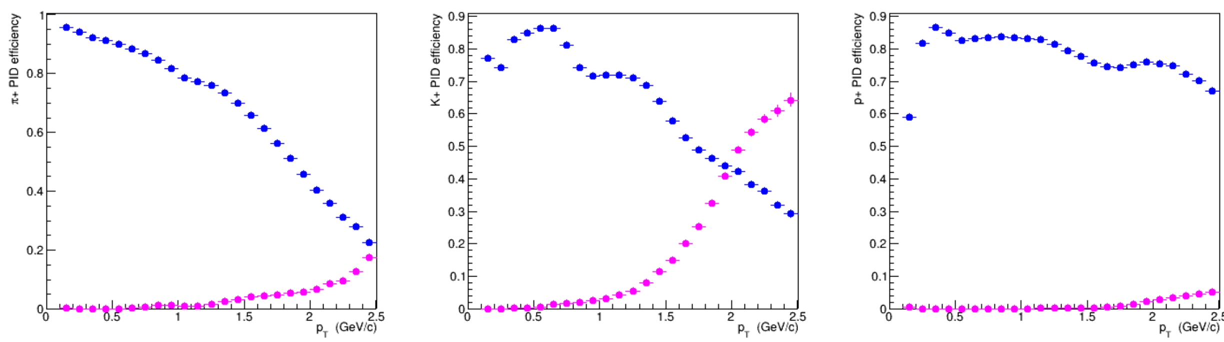


(c) p^-

Figure 9: Efficiency plots for negative particles.

Results for 9 GeV

For kaons we see the mentioned cross of plots occurring at. Kaons efficiency decreases with p_t but ratio increases a lot, at first sight this might mean that TPC may have some problems defining kaons produced at the collisions. For positive charged protons the total PID efficiency is above 70% and the ratio of incorrectly defined particles to all particles never grows over the 10%, for negative charged protons the efficiency decreases and shows a error bars and the ratio increases with p_T.



(a) π^+ **(b)** K^+ **(c)** p^+

Figure 10: Efficiency plots for positive particles.

Results for 9.46 GeV

The results obtained are reasonable even compared to those of [12]. However, we did notice strange behavior in the 9.4 and 7.7 GeV results, the graphs appear to be scaled and the first two points on the blue efficiency graphs seem out of place. Until the time of this report, this observation is attributed to the version of the PID code used. However, the reconstruction code used in the mpdroot software for this dataset (as stated above) for 7.7 and 9.46 GeV was customized for purposes of other projects, for the 9 GeV dataset the original configuration was used for reconstruction, this fact may also lead to a possible reason for the behavior of these plots.

Conclusions

- We have analyzed UrQMD Monte-Carlo data of Bi+Bi collisions in the center of mass energy range of $\sqrt{S_{NN}} = 7.7,\ 9,\ 9.4$ GeV.
- Particle spectra were plotted as a function of transverse momentum p_T for pions, kaons and protons.
- For complete analysis, it is necessary to analyze more data at different center-of-mass energies to include the whole range of NICA complex collision energies.

- With further efforts this results can be compared with Au+Au ion collisions results obtained by other members of this group (see [12])

Acknowledgments

I would like to express my gratitude to my supervisor for this opportunity and support that I received during the 6 weeks of the project. And I would also like to thank the Organizing Committee of the INTEREST program for allowing me to be part of this experience.

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