JOINT INSTITUTE FOR NUCLEAR RESEARCH

Veksler and Baldin Laboratory of High Energy Physics

FINAL REPORT ON THE SUMMER STUDENT PROGRAM

Study of the phase diagram of nuclear matter with identified charged particles at collision energy range $\sqrt{s_{NN}} = 4 - 11\ GeV$

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Abstract

This work presents the results that was obtained during the Summer Student Program at Joint Institute for Nuclear Research (JINR) in the Laboratory of High Energy Physics. We made a brief introduction to the phase transition in hot and dense nuclear matter. In order to investigate properties of a phase transition in such matter an analysis of Monte-Carlo $Au-Au$ collisions with the collision energies $\sqrt{s} = 4, 7, 9, 11$ GeV was made. Investigated data-sets were made for the MPD collaboration and contained a simulation of the gold to gold collisions made with UrQMD MC model and a realistic detector response made by Geant 4 package. The p_T spectra of the identified particles ($K^{\pm}$, $\pi^{\pm}$ and $p, \overline{p}$) were obtained, and the enhanced production of strangeness in collisions of heavy ions was studied by calculating the ratio K^+/π^+. Enhanced strangeness production is one of the major signatures of the phase transition between the hadron state of matter and the quark-gluon plasma (QGP).

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1 Introduction

The currently accepted model of Universe formation is the formation as a result of the Big Bang. In this model, in the time interval $10^{-10} - 10^{-6}$ seconds after the Big Bang, matter existed in a special state of non-confined quarks and gluons, the Quark Gluon Plasma (QGP). The only possibility for reproducing the temperatures and densities of matter that existed at that time is the collision of two heavy atomic nuclei accelerated to very high energies. Experiments constructed to study this phenomenon are carried out at the largest accelerator complexes at different science centres (CERN, BNL, JINR, GSI). One of such experiments which is currently in preparation in the JINR Laboratory of High Energy Physics at NICA complex is MPD experiment.

Collisions of heavy ions at high energies make it possible to study nuclear matter at incredibly high energy densities and temperatures. Different theoretical models can be used to describe state of matter produced, so new experimental data with large statistics are needed to test different theoretical predictions. Quantum Chromodynamics (QCD) is used as the theoretical basis of strong interaction.

Exploring the QCD phase diagram is an important physical goal in programs of heavy-ion collision experiments. The advent of the quark model of hadrons and the development of QCD naturally led to the question whether strongly interacting matter exists in different phases and, if so, of which nature the transitions between these phases are. In particular, it is commonly believed that a gas of hadrons will undergo a transition to a state of quasi-free quarks and gluons, the Quark Gluon Plasma, when its temperature and barionic density exceeds some critical value. These questions have motivated a broad variety of experimental programs of nucleus-nucleus collisions to study the properties of strongly interacting matter at extreme conditions.

2 Theory overview

As we already mentioned, QCD phase diagram is an important item for high-energy heavy-ion collision physics. It is usually plotted in terms of temperature (T) versus baryon chemical potential (μ_B), as it is shown at Figure 1. Assuming that a system created in heavy-ion collisions is thermodynamical, both of these quantities can be varied by changing the collision energy. With this we can access different areas on the phase diagram, by changing parameters of the initial collision. A special experimental program is currently performed at Brookheaven National Laboratory on the Relativistic Heavy Ion Collider (RHIC) scanning phase diagram from the top RHIC energy 200 GeV (lower μ_B) to the lowest possible energy 7.7 GeV (higher μ_B), to look for the signatures of the phase transition [1]. Theory suggests that there is a first order transition from a high energy density and high temperature phase called Quark Gluon Plasma, dominated by partonic degrees of freedom, to a regular nuclear matter phase where the relevant degrees of freedom are hadronic.

For values close to $\mu_B = 0$, experiments at the Large Hadron Collider (LHC) and the Relativistic Heavy Ion Collider (RHIC) have provided evidence of the QGP formation, but exact information about location of the first order phase transition and existence of the critical point at higher μ_B is yet to be experimentally investigated.

It was suggested [2] that a transition to a deconfined state of matter may cause anomalies in the energy dependence of pion and strangeness production in nucleus-nucleus collisions. The idea of this work is to investigate this signature of the phase transition - enhanced strangeness production in heavy ion collisions. The presence of this effect is a necessary condition for the QGP formation. To illustrate this, we consider the dependence of the K/π (proportional to the total strangeness to entropy ratio) on the collision energy $\sqrt{s_{NN}}$, as it reflects the strangeness content in heavy-ion collisions.

Figure 2 shows experimental data from K/π ratios, where it can be seen that while K/π increases with $\sqrt{s_{NN}}$, K^+/π^+ has a peak around 10 GeV, referred to as the horn. One may conclude that a nonmonotonic energy dependence (or a sharp turnover) of the total strangeness to pion ratio appears to be a special property of heavy ion collisions, which is not observed in elementary interactions [3]. Because of this, it is currently being attributed to a phase transition between hadronic matter and QGP.

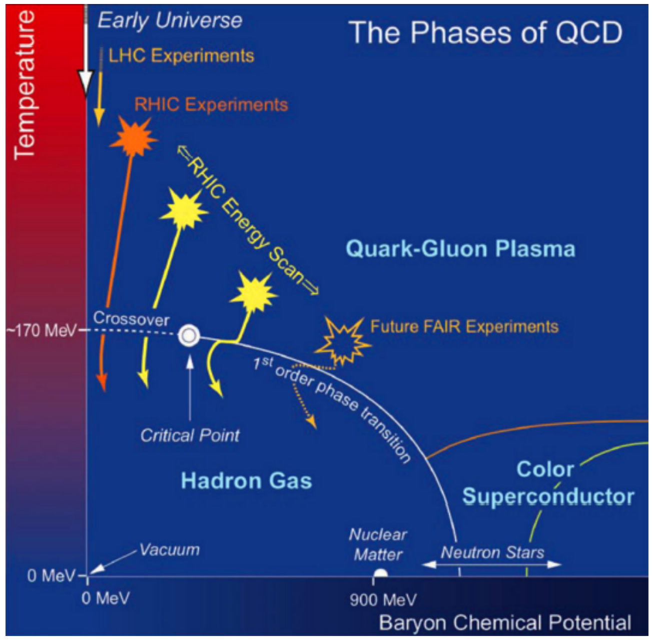


Figure 1: A QCD phase diagram with boundaries that define various states of QCD matter. Figure taken from [2].

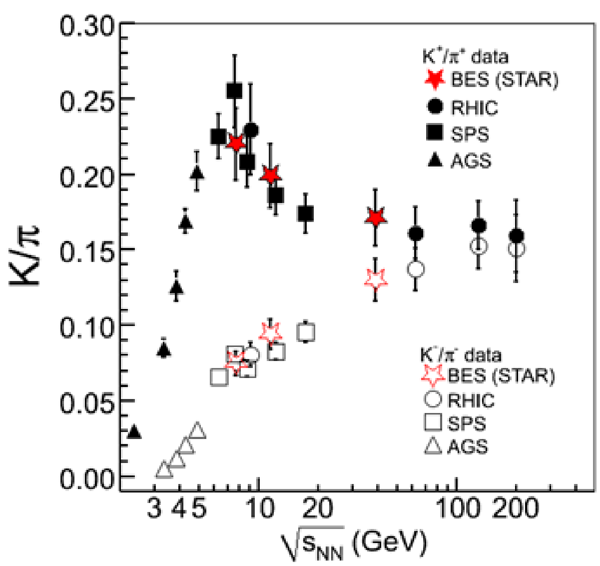


Figure 2: Experimental data for the K/π ratio in central heavy ion collisions. It shows a peak in the K^+/π^+ production, referred to as "the horn" effect.

3 NICA Experiment

NICA (Nuclotron based Ion Collider fAcility) - is a new accelerator complex, which is created on the basis of the Nuclotron accelerator in Joint Institute for Nuclear Research (Dubna, Russia) to study the properties of dense baryonic matter. The NICA complex will provide a wide range of beams: from proton and deuteron, to beams consisting of heavy ions such as gold nuclei [4].

The main goal of the NICA facilities is to search for the mixed phase of quark matter and baryon rich hadronic matter as a consequence of a first order phase transition, bearing strong analogies with a liquid-gas phase instability [5].

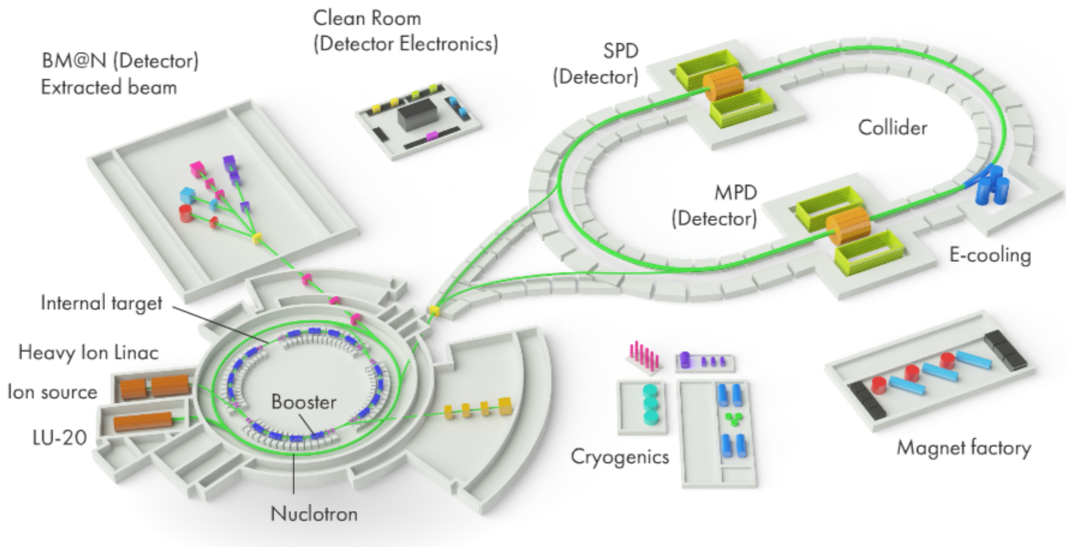


Figure 3: NICA complex scheme.

As the collision energy decreases from the top RHIC energy (200 GeV per nucleon-nucleon pair) to the lowest SPS energy (5 GeV per nucleon-nucleon pair), the maximum energy density created also decreases and there is a certain transition region of the collision energy below which it is no longer possible to access the plasma phase in the course of the collision. Existing data on single-particle spectra and mean multiplicities suggest that this transition occurs within the NICA energy range. Moreover, the energy range of NICA is sufficiently large to encompass both, collisions in which the plasma phase is well developed and collisions in which the matter remains purely hadronic throughout. Thus, NICA is ideally suited for exploring the transition between the familiar hadronic phase and the new plasma phase.

A scheme of NICA facilities is presented on figure 3.

NICA project requires construction of the additional accelerator called "booster" and replacement of the existing heavy ion sources to achieve project parameters. NICA complex will have three major experiments a Multi-Purpose Detector (MPD), a Spin Physics Detector (SPD) both operating in the collider mode and a Baryonic Matter at Nuclotron (BM@N) experiment for fixed-target researches.

3.1 Multi-Purpose Detector (MPD)

The MPD experiment should be competitive to the ones operating at RHIC. It has been designed as a 4π spectrometer capable of detecting of charged hadrons, electrons and photons in heavy-ion collisions in the energy range of the NICA collider [6]. To reach this goal, the detector will comprise a precise 3-D tracking system and a particle identification (PID) system based on the time-of-flight measurements and calorimetry.

The major sub-detectors of the MPD are (see Figure 4):

- a solenoidal superconducting magnet with a magnetic field of 0.5 T (5 m in diameter and 8 m in length);
- a time projection chamber (TPC);
- an inner tracker (IT);
- a time-of-flight (TOF) system;
- an electromagnetic calorimeter (ECAL);

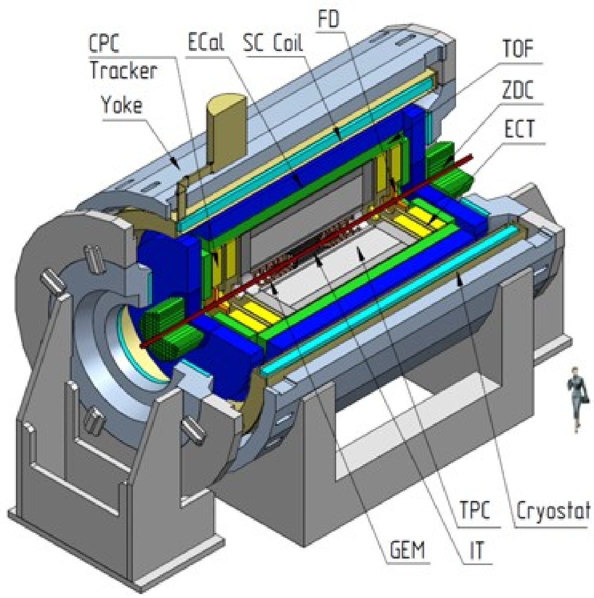


Figure 4: Multi Purpose Detector (MPD) scheme. Picture taken from [6].

- an end cap tracker (ECT) and
- two forward spectrometers based on toroidal magnets (optional).

Three stages are planned for future MPD experiment. Each one of them has a unique set of sub-detectors and will focus on different aspects of phase diagram exploration. The first stage of operation involves magnet, TPC, TOF, ECAL (partially) and IT (partially). It has been shown that the MPD is well optimized for the study of in-medium effects caused by high baryon densities, such as: changing particle properties in the hot and dense medium, event-by-event dynamical fluctuations of strange to non-strange particle ratios, and others [5]. The simulations of the MPD experiment show that a high statistics of studied events could be reached (10^9 minimum bias events and 10^8 central events per week).

3.2 Mpdroot - detector simulation software package

The processes studied with MPD were simulated using the dedicated software framework (MpdRoot). This software is based on the object-oriented framework FairRoot and provides a powerful tool for detector performance studies, development of algorithms for reconstruction and physics analysis of the data [7]. In the applied framework the detector response simulated by a package currently based on the Virtual Monte Carlo concept allows performing simulation using Geant3, Geant4 or Fluka without changing the user code. The same framework is used for simulation and data analysis.

For a realistic simulation of various physics processes an interface for the Monte Carlo event generators for nuclear collisions (UrQMD) was provided.

The view of the MPD detector geometry implemented in the framework is shown on Figure 5.

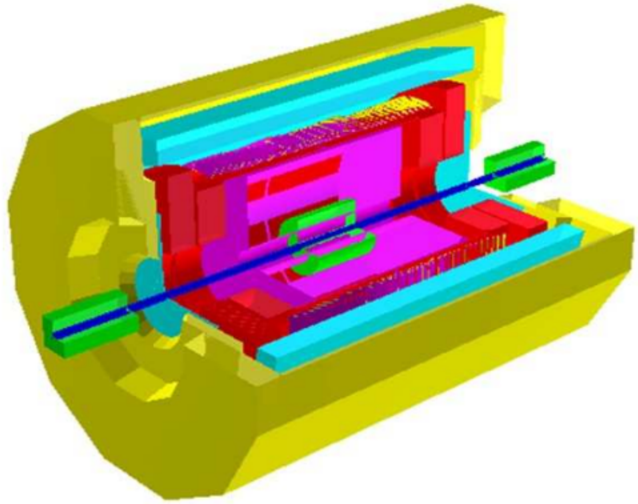


Figure 5: A view of MPD geometry from the simulation package. Picture extracted from [7].

4 UrQMD

Ultra relativistic Quantum Molecular Dynamic model (UrQMD) is a microscopic model used to simulate (ultra)relativistic heavy ion collisions in the energy range from Bevalac and SIS up to AGS, SPS and RHIC [8]. The model describes the phenomenology of hadron interactions at low energies ($\sqrt{s_{NN}} < 5$ Gev) like interactions between hadrons and their resonances. At higher energies ($\sqrt{s_{NN}} > 5$ Gev), the model of excitation of colored strings and their subsequent fragmentation into hadrons is used.

The model is based on the covariant propagation of all hadrons considered at the quasi-particle level in classical trajectories combined with stochastic binary scattering, colored string formation, and resonance decay. This model is using Monte Carlo simulation package for Proton+Proton, Proton+nucleus and nucleus+nucleus interactions. To run this program, the energy in the center-of-mass frame ($\sqrt{s_{NN}}$), the number of events and the freeze-out time are given as inputs for $Au - Au$ collisions.

There is still no single theoretical description that could fully explain the mechanism of hadron-hadron interaction for different collision energies and different kinematic conditions.

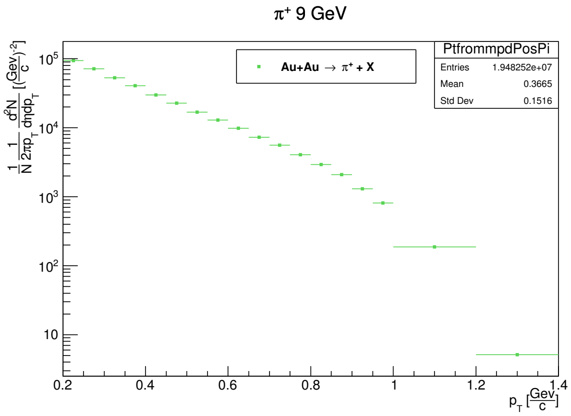
Although the existing simulation models like UrQMD do not incorporate a first-order phase transition, they have been found to reproduce the basic features of heavy-ion reactions in this energy domain. Therefore these computational models can be used to provide a reference with which the measured data may be compared. It is essential that such simulations are made before the detector comes into operation. Furthermore, to make quantitative comparisons possible, a software replica of the detector must be developed so that the simulation results can be corrected for the detector acceptance.

5 Simulation results

Statistics were generated for gold-gold ion collisions for the energies of $\sqrt{s_{NN}} = 4$ GeV, 7 GeV, 9 GeV and 11 GeV with MPD detector geometry made by Geant 4. For each energy, 10^6 events were produced. Further analysis was made as an attempt to reproduce the "horn".

5.1 p_T spectra for different particles

Transverse momentum spectra were calculated at the HybriLIT cluster. We consider the distributions for the particles by the transverse momentum to study the properties of the bulk matter at kinetic freeze-out. The spectra for transverse momentum are presented in Figures , 6, 7, 8 and 9. There are two separated



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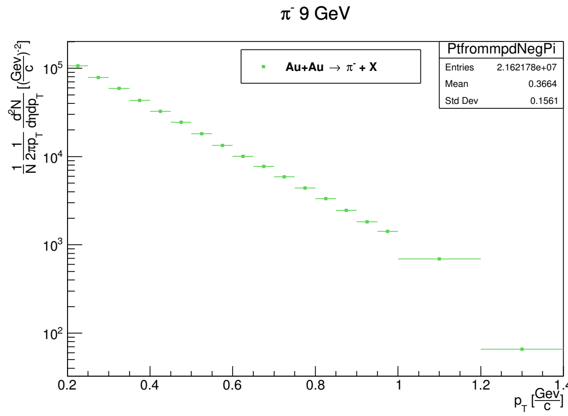

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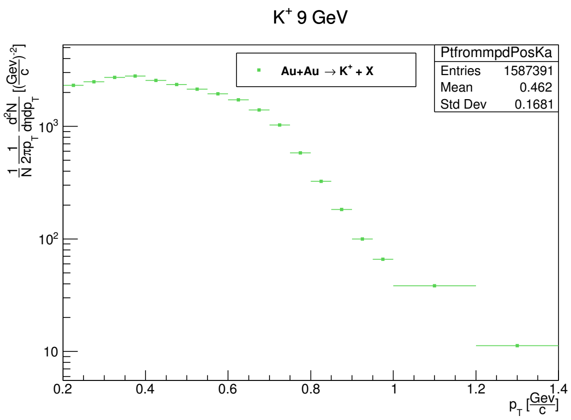

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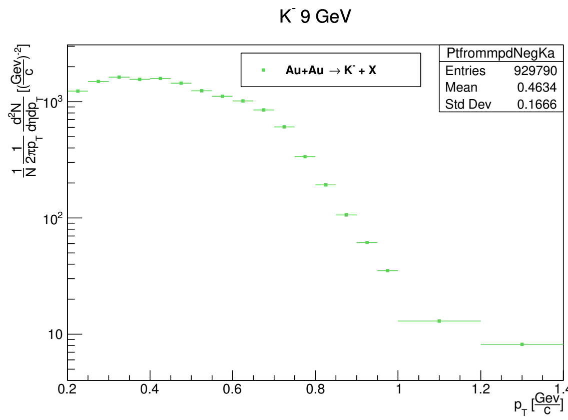

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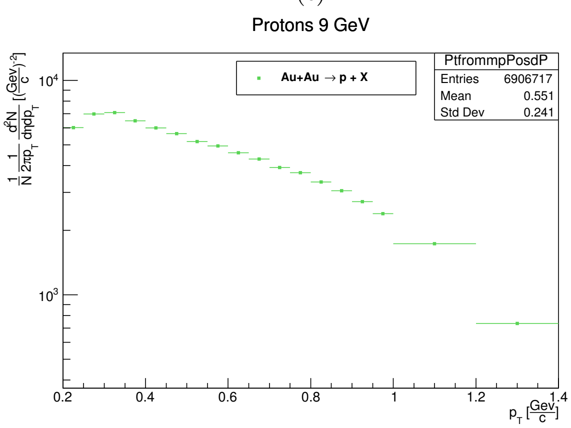

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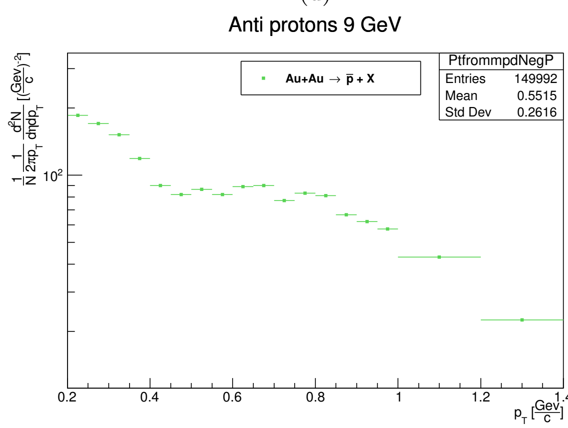
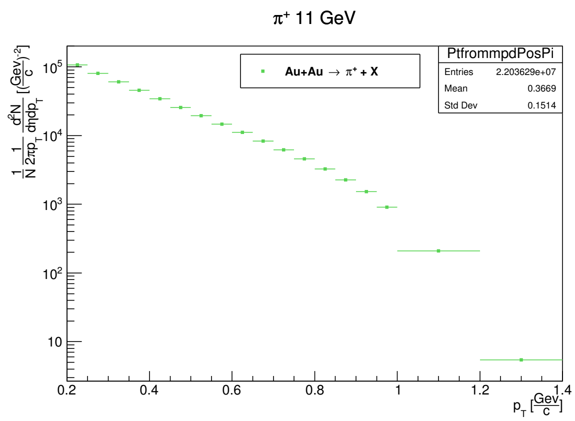


(f)

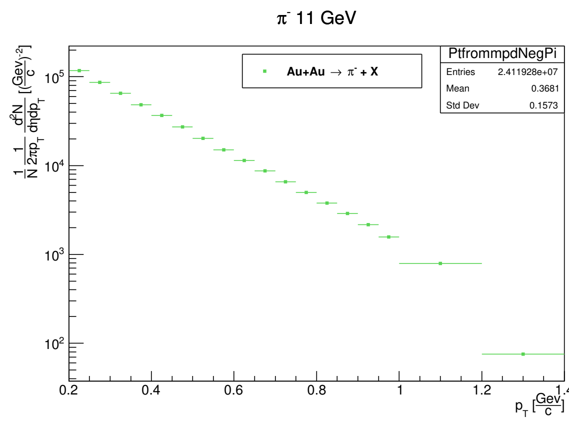
Figure 6: Histograms of particle production as a function of transverse-momentum for the collision energy $\sqrt{s_{NN}} = 9$ GeV with cut for pseudorapidity $|\eta| < 0.5$ and cut for transverse-momentum $0.2 < p_T < 1.4$ for different particles: (a) π^+, (b) π^-, (c) K^+, (d) K^-, (e) p, (f) $\overline{p}$. Normalization was made by number $N = 197 + 197 = 394$, which is the sum of atomic numbers of Au - Au.

groups of histograms: (i) Only for particles with $|\eta| \leq 0.5$; (ii) Only for particles with $|\eta| \leq 0.1$. The histograms for $|\eta| \leq 0.1$ were shown only for pions to illustrate that the dependencies are not much differ. We also used cuts on the p_T value to remove the bins with poor statistics from histograms: $0.2 \leq p_T \leq 1.4$

Gev/c. The results are shown separately for $K^{\pm}$, $\pi^{\pm}$, p and $\overline{p}$. The last two bins on the histograms were made wider than previous because of poor statistics for huge values of transverse momentum.



(a)



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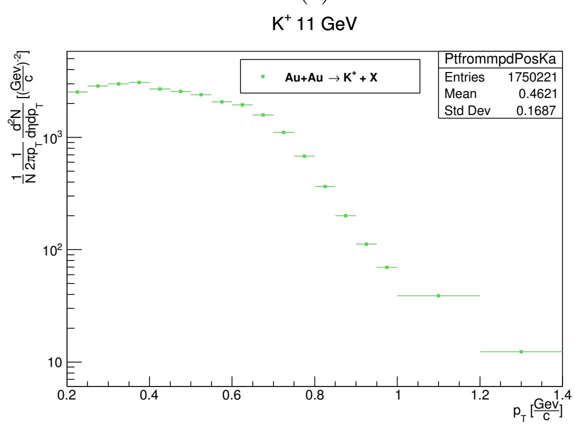

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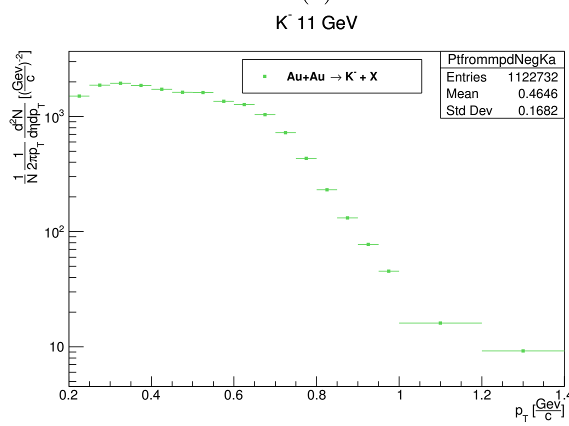

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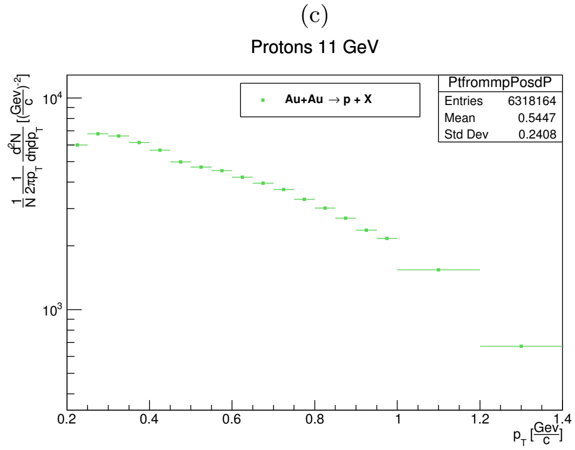

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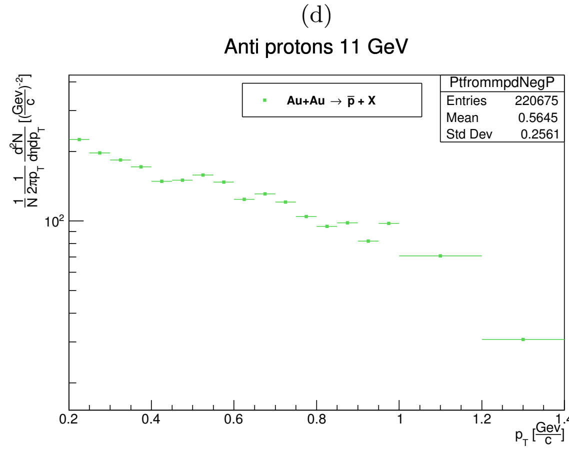
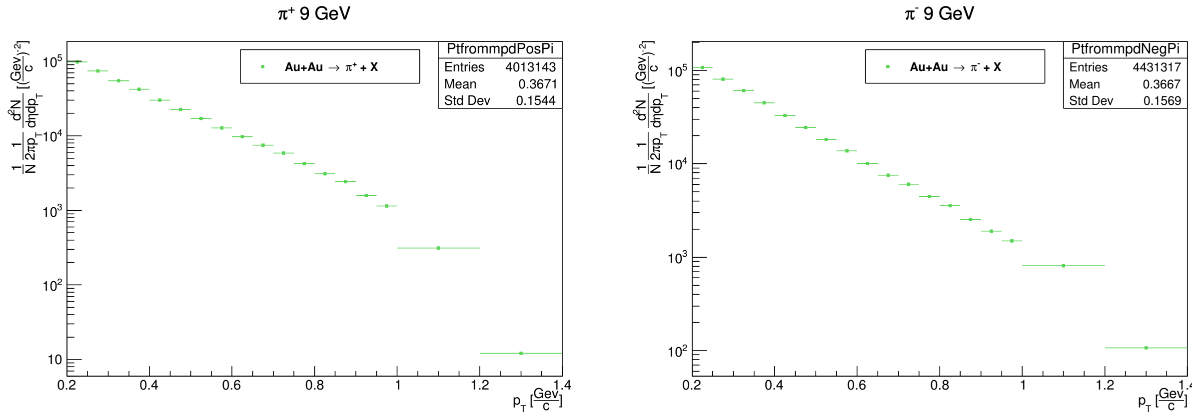


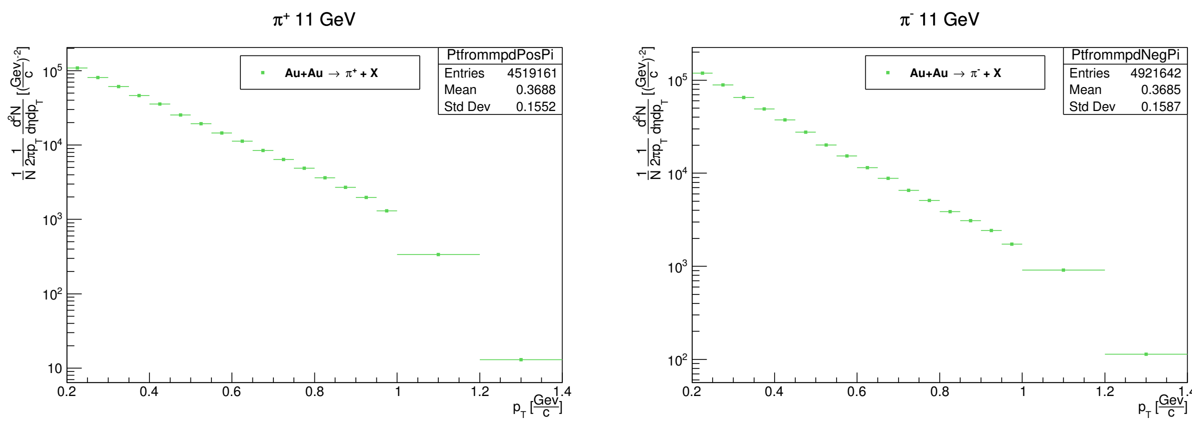
(f)

Figure 7: Histograms of particle production as a function of transverse-momentum for the collision energy $\sqrt{s_{NN}} = 11$ GeV with cut for pseudorapidity $|\eta| < 0.5$ and cut for transverse-momentum $0.2 < p_T < 1.4$ for different particles: (a) π^+, (b) π^-, (c) K^+, (d) K^-, (e) p, (f) $\overline{p}$. Normalization was made by number $N = 197 + 197 = 394$, which is the sum of atomic numbers of Au - Au.



(a) (b)

Figure 8: Histograms of particle production as a function of transverse-momentum for the collision energy $\sqrt{s_{NN}} = 9$ GeV with cut for pseudorapidity $|\eta| < 0.1$ and cut for transverse-momentum $0.2 < p_T < 1.4$ for different particles: (a) π^+, (b) π^-. Normalization was made by number $N = 197 + 197 = 394$, which is the sum of atomic numbers of Au - Au. Histograms shown only for pions because dependencies are really similar as for $|\eta| < 0.5$.



(a) (b)

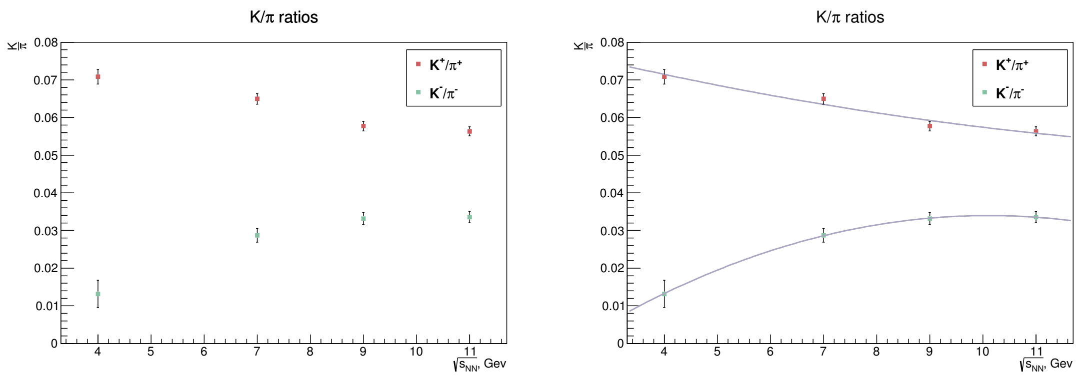
Figure 9: Histograms of particle production as a function of transverse-momentum for the collision energy $\sqrt{s_{NN}} = 11$ GeV with cut for pseudorapidity $|\eta| < 0.1$ and cut for transverse-momentum $0.2 < p_T < 1.4$ for different particles: (a) π^+, (b) π^-. Normalization was made by number $N = 197 + 197 = 394$, which is the sum of atomic numbers of Au - Au. Histograms shown only for pions because dependencies are really similar as for $|\eta| < 0.5$.

5.2 K^+/π^+ and K^-/π^- ratios

The ratios were calculated for all the energies in which statistics were generated. The results for K^+/π^+ and K^-/π^- can be seen in Figures 10 and 11. The graphics are also shown for different pseudorapidity. Further, we fitted the obtained data by the polynomial function $f(x) = p_0 + p_1 \cdot x + p_2 \cdot x^2 + ...$ For $|\eta| < 0.5$ we used the second order polynomial and for $|\eta| < 0.1$ we used second order for the K^+/π^+ and third order for K^-/π^-.

We can observe that K^-/π^- smoothly increase with collision energy, but K^+/π^+ ratio seems to be slowly decreasing. Similar dependence can be seen for both considered cuts for pseudorapidity.

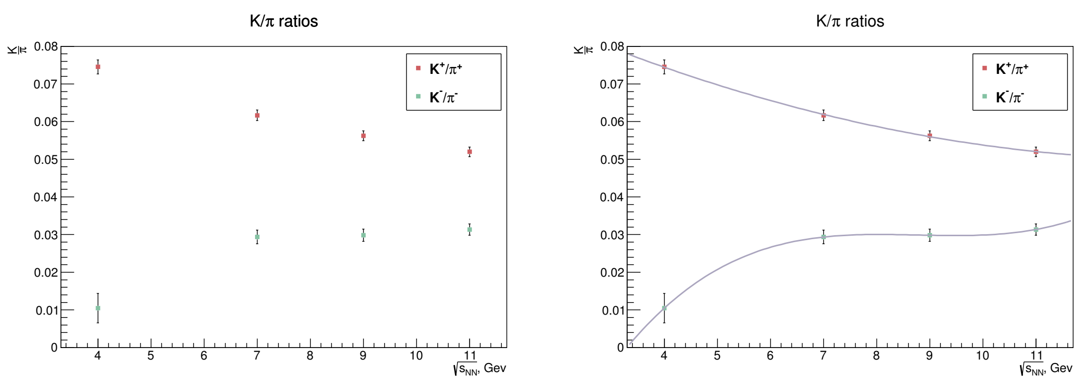
Figure 2 represents the experimental dependence that was expected. In this figure the K^-/π^- ratio in heavy-ion collisions steadily increases with $\sqrt{s_{NN}}$, while K^+/π^+ sharply increases at low energies (”horn”).



(a) (b)

Figure 10: K^+/π^+ and K^-/π^- ratios for pseudorapidity $|\eta| < 0.5$ (a) and fits by polynomial function (b). The parameters of fit 1) K^+/π^+: $\chi^2 = 2.775$; $p_0 = 0.085 \pm 0.008$; $p_1 = -0.0038 \pm 0.0021$; $p_2 = 0.00011 \pm 0.00013$; 2) K^-/π^-: $\chi^2 = 0.008279$; $p_0 = -0.023 \pm 0.013$; $p_1 = 0.011 \pm 0.003$; $p_2 = -0.00055 \pm 0.00019$.

We do not observe such an effect in our results. That's to be expected, because, as was mentioned, UrQMD simulation do not include such physical property as phase transition.



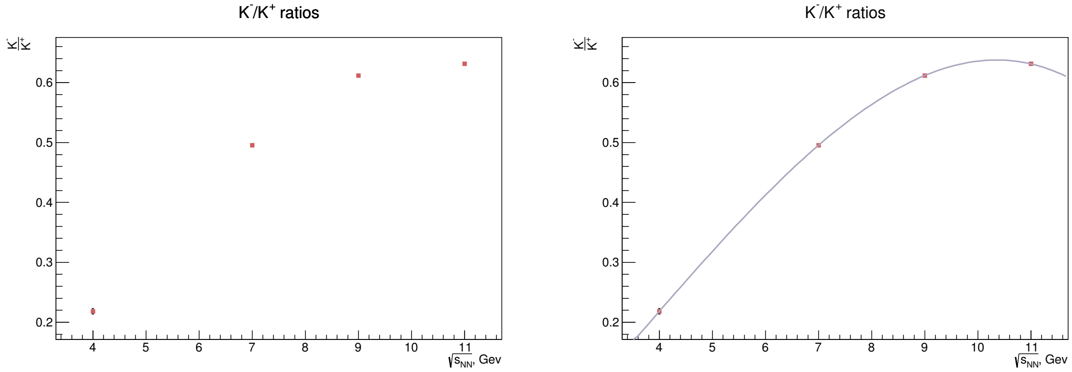
(a) (b)

Figure 11: K^+/π^+ and K^-/π^- ratios for pseudorapidity $|\eta| < 0.1$ (a) and its fit by polynomial function (b). The parameters of fit 1) K^+/π^+: $\chi^2 = 0.07423$; $p_0 = 0.098 \pm 0.007$; $p_1 = -0.00688 \pm 0.00204$; $p_2 = 0.00025 \pm 0.00013$; 2) K^-/π^-: $\chi^2 = 4.6 \cdot 10^{-9}$; $p_0 = -0.09 \pm 0.05$; $p_1 = 0.0439 \pm 0.0205$; $p_2 = -0.005 \pm 0.0028$; $p_3 = 0.00019 \pm 0.00012$.

5.3 K^-/K^+, π^-/π^+ and $\overline{p}/p$ ratios

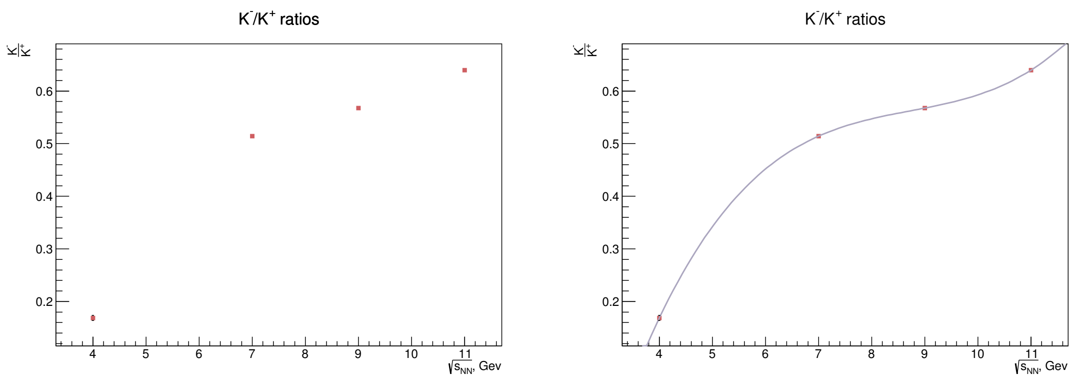
The results for different pseudorapidity can be seen in Figures 12, 13, 14, 15, 16 and 17. We also fitted the data by the polynomial function $f(x) = p_0 + p_1 \cdot x + p_2 \cdot x^2 + ...$ For K^-/K^+ we used the third order. For π^-/π^+ and $|\eta| < 0.5$ we considered fourth order polynomial, for $|\eta| < 0.1$ third order was applied. Speaking of $\overline{p}/p$, the fits were made by second order polynomial.

The Figures 12 and 13 represent that K^-/K^+ ratio quite sharply increases with collision energy. This dependence is in accordance with experimental results [1]. The Figures 14 and 15 demonstrate that π^-/π^+ ratio steadily decrease with $\sqrt{s_{NN}}$. At last, Figures 16 and 17 show that the dependence for $\overline{p}/p$ smoothly increase with collision energy and the similar behaviour can be seen in experimental data from [1], but because of poor statistics for anti-protons, errors for them are too huge and this make our results quite hard to compare.



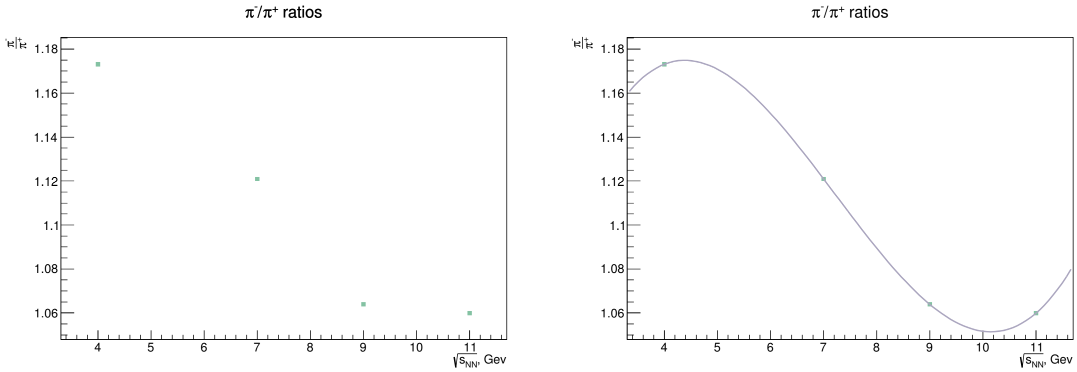
(a) (b)

Figure 12: K^-/K^+ ratios for pseudorapidity $|\eta| < 0.5$ (a) and its fit by polynomial function (b). The parameters of fit: $\chi^2 = 4.921 \cdot 10^{-13}$; $p_0 = -0.16 \pm 0.07$; $p_1 = 0.073 \pm 0.029$; $p_2 = -0.008 \pm 0.004$; $p_3 = -0.00075 \pm 0.00017$.



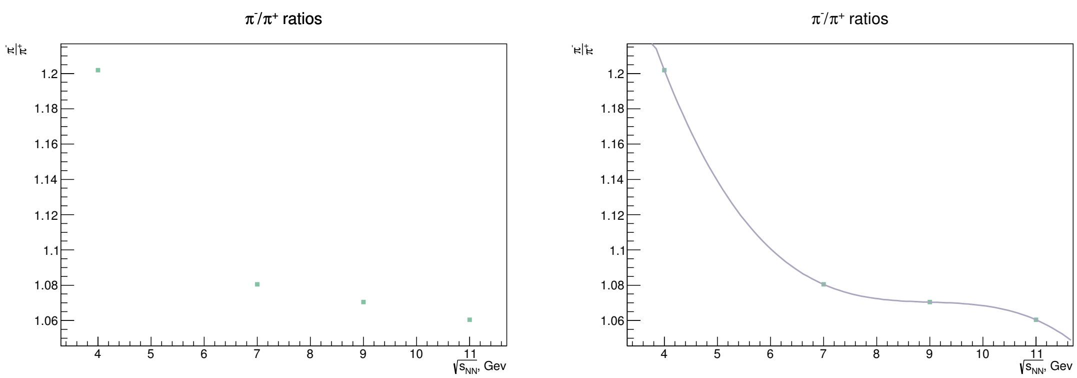
(a) (b)

Figure 13: K^-/K^+ ratios for pseudorapidity $|\eta| < 0.1$ (a) and its fit by polynomial function (b). The parameters of fit: $\chi^2 = 8.925 \cdot 10^{-11}$; $p_0 = -1.51 \pm 0.07$; $p_1 = 0.674 \pm 0.029$; $p_2 = -0.075 \pm 0.004$; $p_3 = -0.00286 \pm 0.00018$.



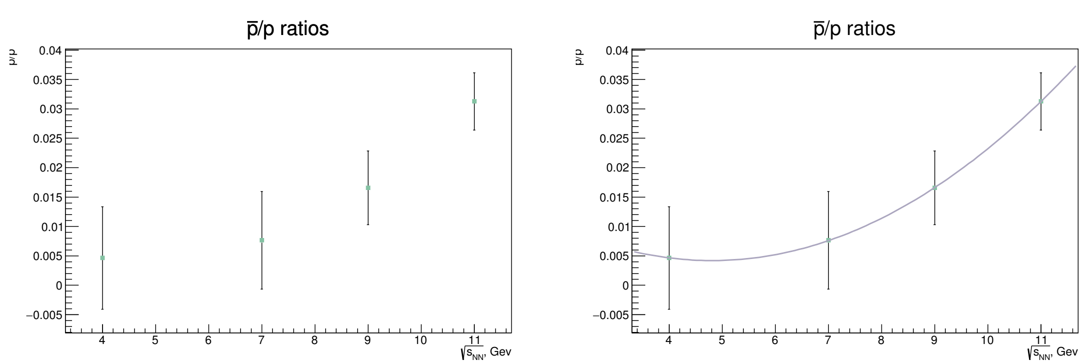
(a) (b)

Figure 14: π^-/π^+ ratios for pseudorapidity $|\eta| < 0.5$ (a) and its fit by polynomial function (b). The parameters of fit: $\chi^2 = 2.939 \cdot 10^{-13}$; $p_0 = 0.8312 \pm 0.0015$; $p_1 = 0.1858 \pm 0.0003$; $p_2 = -0.03131 \pm 0.00004$; $p_3 = -0.001603 \pm 0.000004$; $p_4 = -0.00001088 \pm 0.00000025$.



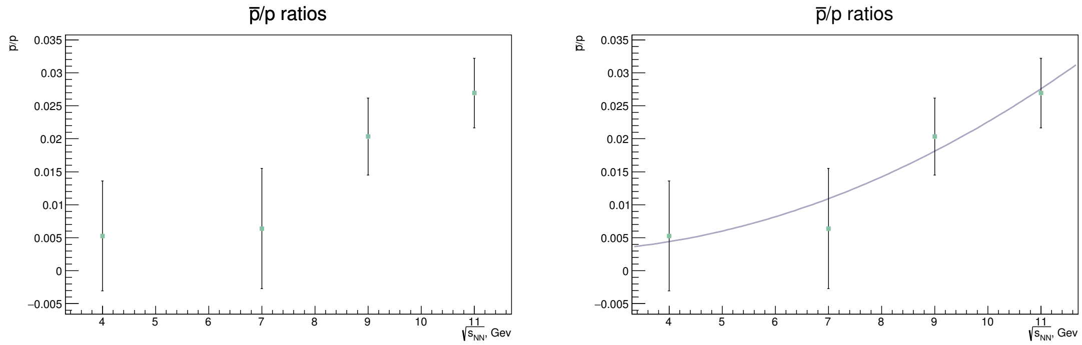
(a) (b)

Figure 15: π^-/π^+ ratios for pseudorapidity $|\eta| < 0.1$ (a) and its fit by polynomial function (b). The parameters of fit: $\chi^2 = 4.172 \cdot 10^{-11}$; $p_0 = 1.817 \pm 0.013$; $p_1 = -0.247 \pm 0.006$; $p_2 = 0.0273 \pm 0.0008$; $p_3 = -0.00101 \pm 0.00003$.



(a) (b)

Figure 16: $\overline{p}/p$ ratios for pseudorapidity $|\eta| < 0.5$ (a) and its fit by polynomial function (b). The parameters of fit: $\chi^2 = 7.629 \cdot 10^{-5}$; $p_0 = 0.02 \pm 0.04$; $p_1 = -0.008 \pm 0.009$; $p_2 = 0.0007 \pm 0.0006$.



(a) (b)

Figure 17: $\overline{p}/p$ ratios for pseudorapidity $|\eta| < 0.1$ (a) and its fit by polynomial function (b). The parameters of fit: $\chi^2 = 0.4197$; $p_0 = 0.004 \pm 0.035$; $p_1 = -0.0009 \pm 0.0097$; $p_2 = 0.0003 \pm 0.0006$.

6 Conclusion

Collisions of heavy ions $Au - Au$ were analyzed at the range of center-of-mass energies $\sqrt{s_{NN}} = 4$, 7, 9 and 11 Gev. The statistics of 10^6 events for each energy was obtained in the UrQMD Monte-Carlo generator. The results of the simulation were compared with the experimental data. The p_T spectra for $\pi^{\pm}, K^{\pm}, p$ and $\overline{p}$ and dependencies of the ratios $K^{\pm}/\pi^{\pm}$, K^-/K^+, π^-/π^+ and $\overline{p}/p$ on the collision energy were obtained. For K^+/π^+ it was not possible to obtain the experimental dependence which can be a strong evidence of a phase transition at such energies, because model that was used to simulate data doesn't consider such physical phenomenon. For K^-/K^+ and π^-/π^+ the dependence is in accordance with the experimental one.

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