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

FINAL REPORT ON THE START PROGRAMME

Analysis of particle production in heavy ion collision

Supervisor:
Dr. Alexei Andreevich Aparin

Student:
Maxim Ganin, Russia
Kazan Federal University

Participation period:
March 03 – April 27,
Winter Session 2024

Dubna, 2024

Contents

Abstract

Analysis of the production of particles resulting from the emergence of Au-Au nuclei at various energies is carried out within the framework of the random radiation program at the NICA collider, obtained at the MPD detector. This may be the reason for measuring the bulk properties of the medium resulting from the incorporation of Au ions at high energies. Such an analysis of particle production under different initial conditions can shed light on the mechanisms of quantum chromodynamics and the phase transition in strongly interacting matter from the hadronic state to the quark-gluon plasma. Chemical and kinetic freezing parameters as a function of collision energy and centrality are used to determine a point on the QCD phase diagram.

Mastering technical tools

Over the course of two months of practice, I actively mastered the algorithmic C++ programming language and the ROOT CERN package. Familiarized himself with the basics of the C++ language. I learned how to work with graphs, histograms, and the ROOT Tree object and fitting.

Introduction

The idea of building a fundamental theory of strong interaction - Quantum Chromodynamics (QCD) came simultaneously with the idea that when the temperature increases above a certain critical T ~ 100 MeV or baryon density above ~ 10 nuclear densities, ordinary hadronic matter should transform into a new phase state - gas free quarks and gluons. Moreover, ideas came from different areas. The stability of neutron stars requires a gentler equation than can be obtained from hadronic matter. One was put forward in the works of Ivanenko and Kurdelaidze, where it was predicted that matter in a similar state should be in massive stars for their stability. Itoch then showed the hydrostatic stability of such stars. Baym and Chin later explored the possibility of stars existing as huge bags of free quarks and gluons. On the other hand, the idea of a gas of free quarks and gluons as a form of matter at very high temperatures is naturally obtained from the asymptotic freedom of quarks in QCD.

The task of studying the phase transition in QCD turned out to be very exciting, and over the next decades, a whole line of research was formed in high-level physics, so today the program of every large accelerator or collider capable of accelerating heavy and light ions includes an item on the study of quark-gluon plasma . Interest is drawn to the fact that this is the only way to study in the laboratory the sector of the Standard Model of QCD phase diagram, phase transitions, and thermalization of fundamental fields. And given the very rich dynamic content of the theory, such studies become extremely exciting. The next phase transition in the Standard Model, associated with the restoration of electroweak symmetry, is expected at temperatures of the order of 100 GeV and its experimental study in the laboratory is hardly possible in the near future. The study of QCD turns out to be closely related to fundamental problems in various areas of modern physics:

- **deconfinement and restoration of chiral symmetry:** lattice QCD calculations predict the emergence of a new form of matter at energy densities noticeably higher than $1 \sim \frac{GeV}{fm^3}$, consisting of a large volume of free quarks and gluons with bound masses: Quark-gluon plasma.
- **cosmology of the early Universe:** The quark-hadron phase transition occurred approximately 10 microseconds after the Big Bang and is believed to be the most important event in the universe between the electroweak (SUSY) transition ($\tau \sim 10^{-10}$ c) and nucleosynthesis ($\tau \sim 200$ c). Depending on the order of the perehoa, various cosmological consequences are possible, such as the formation of strangelets and clumps of cold dark matter or the occurrence of baryon fluctuations leading to heterogeneous nucleosynthesis.
- **parton structure and evolution at small x:** HERA data indicate that the hadrons confining high-energy probes are created from a very dense system of low-momentum gluons x = p_{adron}/p_{hadron}. Under

small x restrictions, the exhaustion of an additional large gluon and gluon fusion processes will in the usual account dominate the parton evolution of the hadronic wave function. For large virtualities Q^2 and moderately low x, such evolution is described by linear DGLAP or BFKL equations suitable for the sparse parton regime. At $x \leq 10^{-2}$ and below, depending on the magnitude of the "saturation impulse" Q_s hadrons are more adequately described as dense, saturated systems of partons within the framework of the effective model of colored glass condensate (Color Glass Condensate) with the corresponding nonlinear equations of evolution JIMWLK. Since the increase in gluon density depends on the transverse size of the atom, the saturation effect for ultrarelativistic heavy nuclei ($Q_s^2 \sim A^{1/3}$) is expected to begin earlier than for free nuclei.

- **gauge/string duality:** The theoretical application of the anti-de Sitter/conformal field theory correspondence made it possible to relate problems in strongly interacting gauge theory to problems in weakly interacting dual gravity theory. The application of this approach to a QCD-like theory made it possible to determine the transport properties of quark matter that are accessible to experimental study, such as viscosity, a parameter that determines the amount of energy lost by a fast cartridge, or the diffusion coefficient of a heavy quark - from calculations of the thermodynamics of black holes.
- **astrophysics of compact objects:** At high baryon densities and not too high temperatures, the attractive force between color-antisymmetric quarks can lead to the formation of bound $\langle qq \rangle$ Cooper pairs. Cold dark matter is expected to behave like a colored superconductor with a non-trivial structure of quark pairs due to a combination of different quantum numbers (spin, color, flavor). This regime, which is currently beyond the reach of direct study using accelerators, can arise in the cores of compact stars (neutron, hybrid and other exotic stars).

Phase diagram

Diagram of space-time evolution in collisions of heavy ions, shown in Figure 1, indicates the different phases and the limits of their expansion. Most likely, the QGP is created in time... in the case of sufficient energy density. The deconfinement regime can occur at an energy density exceeding 1 GeV/fm^3. A simple estimate of the energy density:

$$\varepsilon = \frac{1}{\pi R^2 \tau_0} \frac{d\langle E_T \rangle}{d\eta},$$

where R is the effective radius of the interaction region during particle collisions, E_T is the transverse energy, and η is the pseudo-rapidity. Figure 2 shows experimental data on the distribution density per unit pseudo-rapidity at $\eta = 0$ depending on the collision energy. Using these data, it is easy to calculate the energy density, which, as follows from these, reaches the deconfinement value already at energies 4-5 GeV/nucleon in the center of mass system. It is assumed that in the process of collision of relativistic nuclei in a fairly short time, several units, thermodynamic equilibrium of the formed hadronic matter is established. Here QCD can be an effective tool for studying the thermodynamic characteristics of this matter.

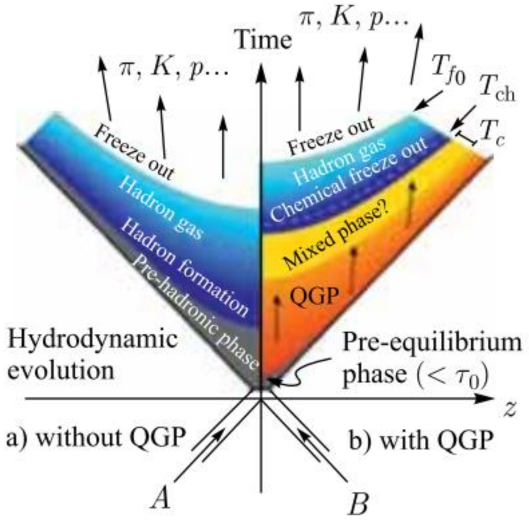


Figure 1. The spatio-temporal picture of the development of the process provides nuclear forces A and B without the formation of CGP

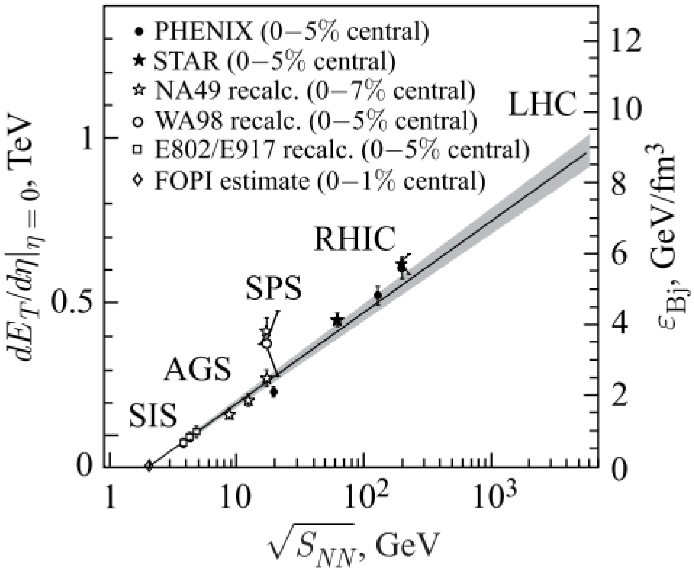


Figure 2. Spatio-temporal picture of the development of the process of collision of nuclei A and B with the formation of QGP. Measured transverse energy per unit of rapidity at η = 0 and the Bjorken energy density of a born matter clump at τ0 = 1 fm/s in central collisions of heavy ions. The extrapolation for the LHC follows a power law as a function of energy.

In QCD thermodynamic equilibrium, matter, as is already known, can be characterized by matter density (or baryochemical potential) and temperature. In Figure 3 shows the phase diagram of strongly interacting matter in terms of these variables.

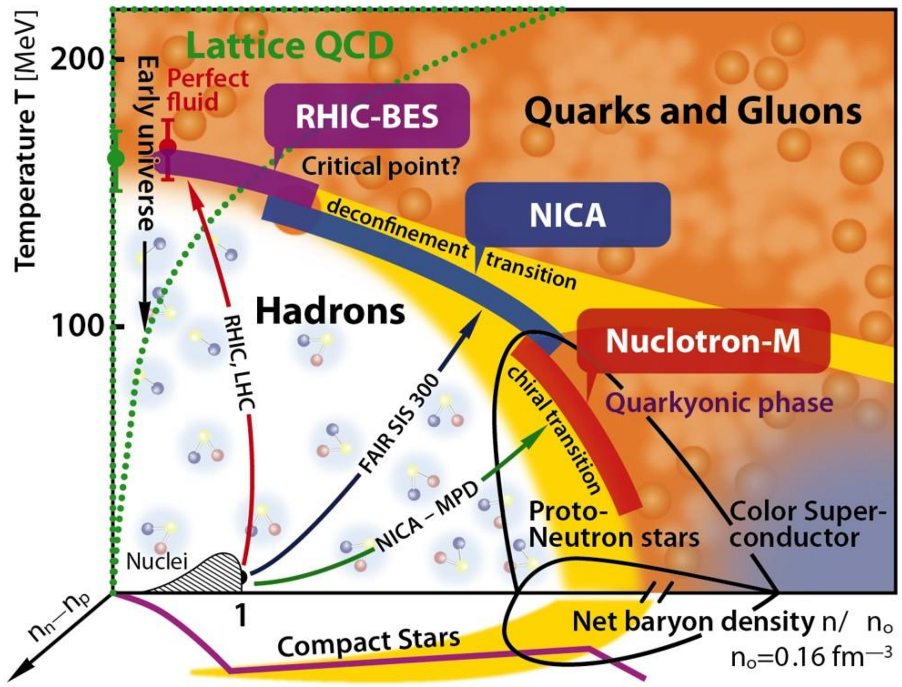


Figure 3. Phase diagram of hadronic matter with transition lines from hadronic gas to quark-gluon plasma and the critical point.

NICA complex and MPD detector

The NICA megascience project and the corresponding MPD (Multi-Purpose detector) are focused on studying heavy ion collisions and studying the properties of quark-gluon plasma and the physics of strong interactions.

NICA complex

The main scientific tasks facing this project:

- The nature and properties of strong interactions between the elementary components of the Standard Model of particle physics - quarks and gluons
- Search for signs of a phase transition between hadronic matter and QGP, search for new states of baryonic matter
- Study of the basic properties of the strong interaction and QGP symmetry

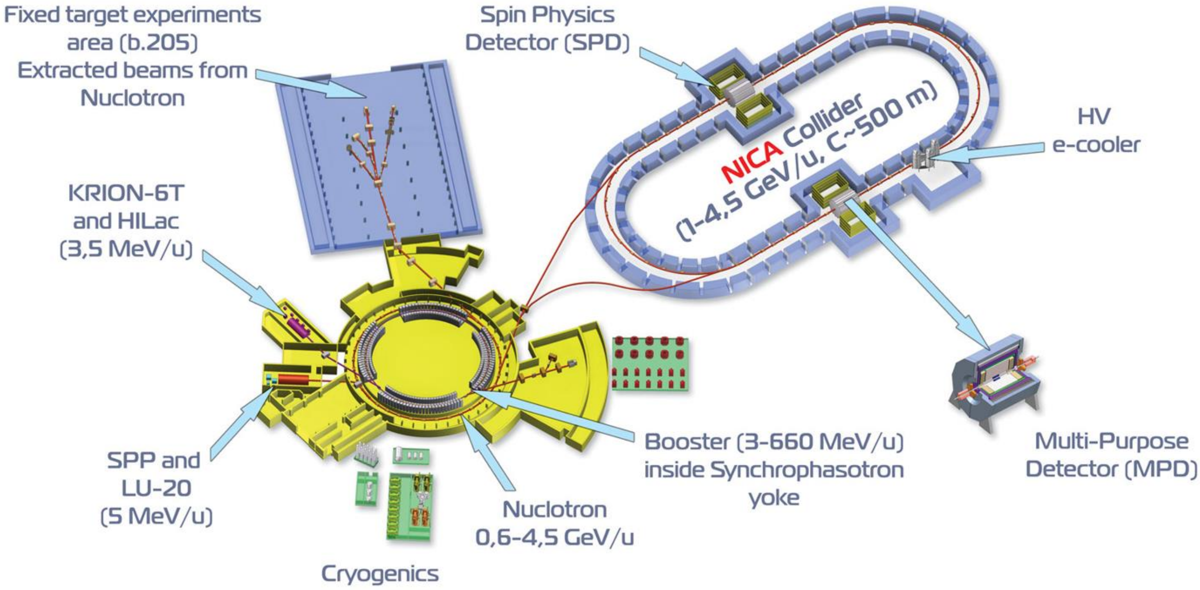


Figure 4.

The NICA complex will provide a wide range of beams: from proton and deuteron beams to beams consisting of tree ions such as gold nuclei. Heavy nuclei have collision energies of up to 4.5 GeV/nucleon, and protons - up to 12.6 GeV.

Physics tasks of the NICA heavy-ion program:

- event-by-event fluctuation in hadron productions (multiplicity, Pt etc.);
- femtoscopic correlation;
- directed and elliptic flows for various hadrons;
- multi-strange hyperon production (including hypernuclei): yield and spectra (the probes of nuclear media phases);
- photon and electron probes

- charge asymmetry

MPD detector

One of the objects of the NICA complex is the MPD detector, which reads the spectra of particles in the 4 Pi survey and registers charged ions, electrons and photons. The device contains such complex systems as an accurate three-dimensional tracking system, a high-performance particle identification system (PID). The total multiplicity of charged particles exceeds 1000 in the most central Au-Au collisions at 11 GeV, and the average transverse momentum of particles formed in particle collisions is below 500 MeV/s. The design of the detector is presented below.

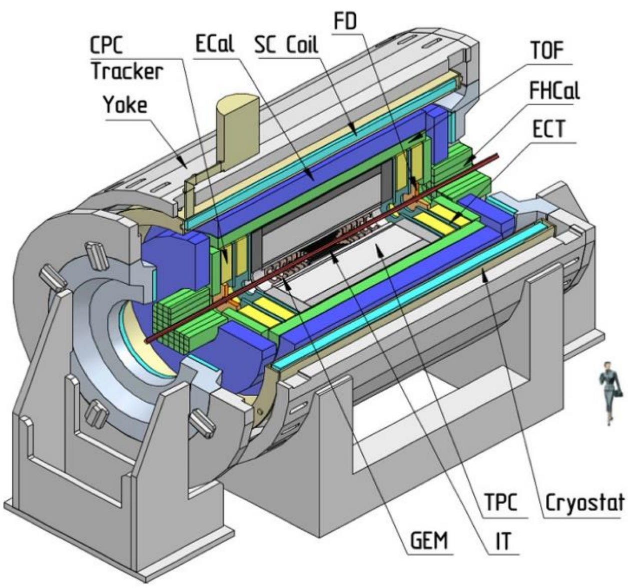


Figure 4.

Data analysis from accelerator NICA

In this work, we obtain and observe such characteristics as position of the event vertex, the energy loss and total momentum analysis of the MPD experiment with the center-of-mass energy of $\sqrt{s_{NN}} = 11$ GeV. As a software environment, the MPD ROOT framework was used. We have a total of 250 original DST files with a total of 115396 Events.

Event Selection

The common point of origin of tracking events is the identification of the first vertices. In order for background events associated with interaction tubes to occur, the radii of the event vertices must be located within smaller limits from the center of the MPD detector. The ring in the dense region, located in the figure below, corresponds to the appearance between the nuclear bundles and the tube bundles.

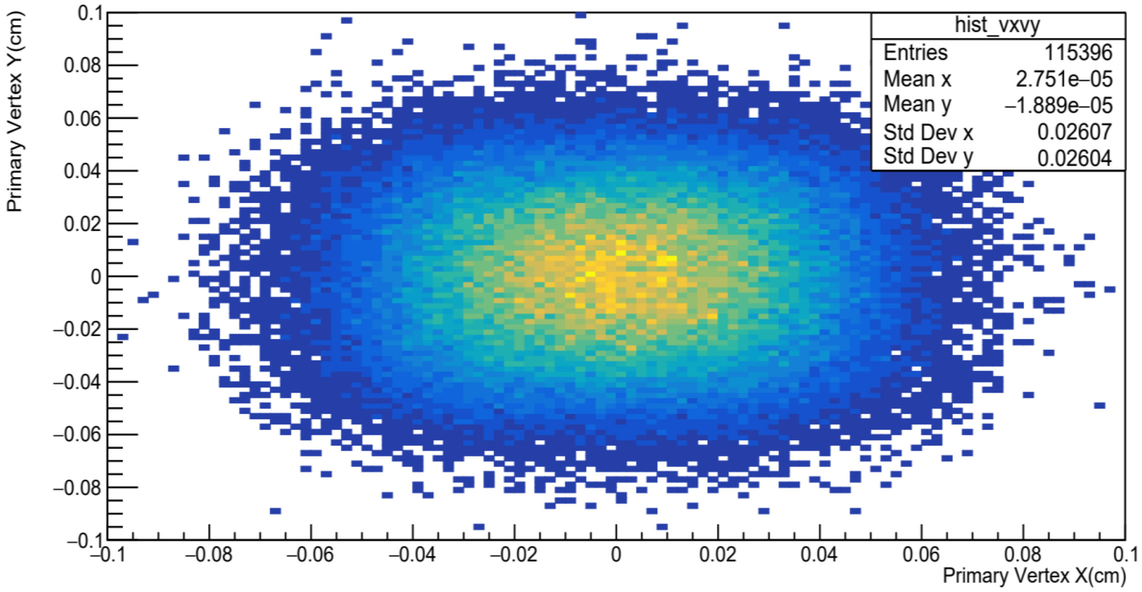


Figure 5. The events involving beam-pipe interactions are rejected by applying a cut of less than 2 cm on the transverse radial position of the event vertex. The results presented here are within rapidity |y | <0.1 and have the same track cuts for all energies.

The distributions of the primary vertex position along the longitudinal (beam) direction (Vz) are shown for Au-Au collisions:

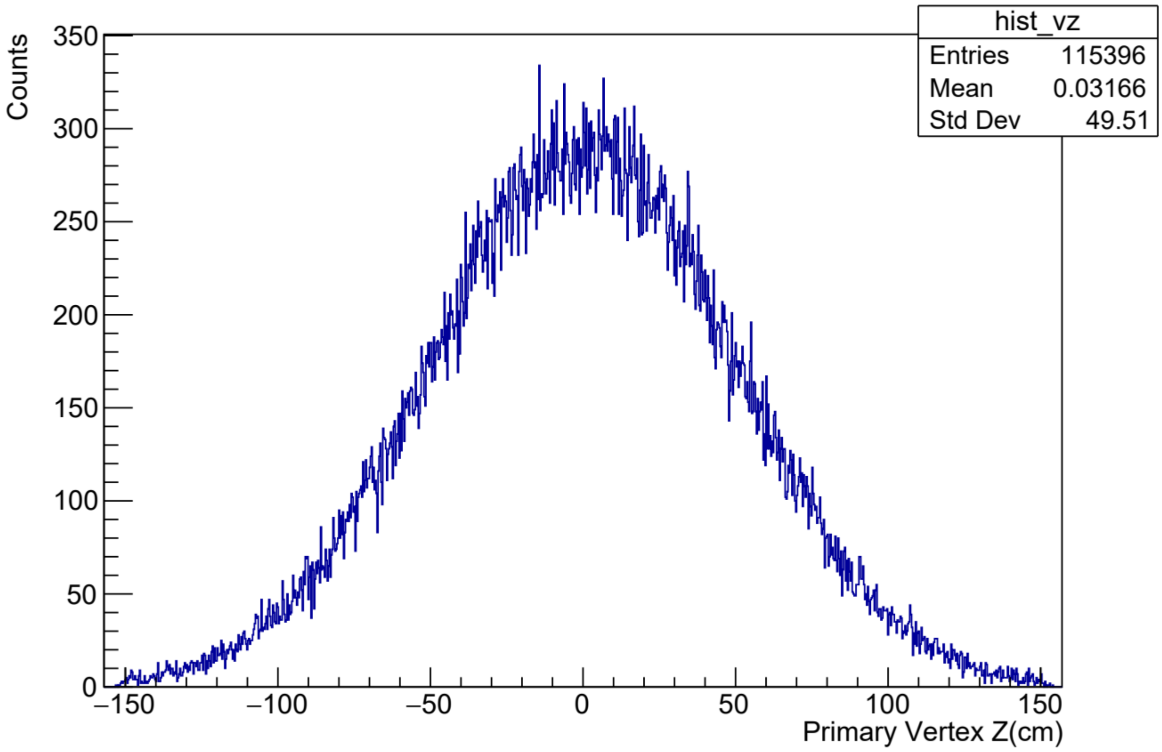


Figure 6

The distribution of z-vertices is relatively not wide.

Also, number of secondary hadrons born in one act of particle interaction turns out to be as follows:

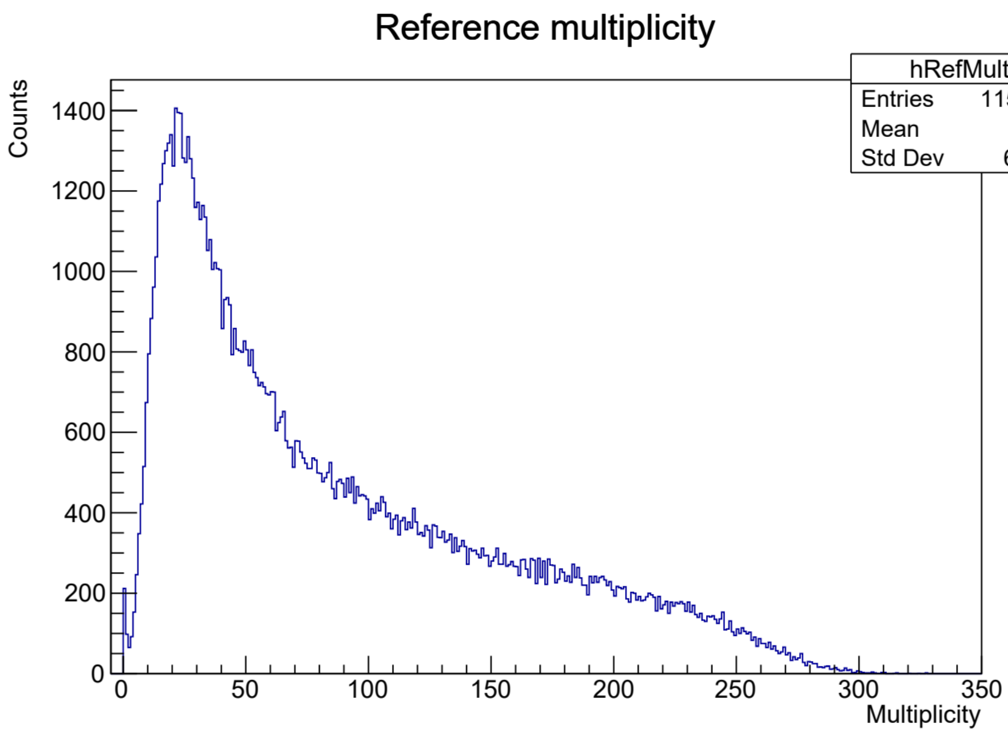


Figure 7. Multiplicity

Particle identification. Energy loss distribution technique.

We can determine the type of particles by looking at the energy loss graph (dE/dx). The following example shows the energies for positive and negative charged pions($\pi^{\pm}$), kaons($K^{\pm}$), protons(p) and antiprotons($\bar{p}$). In the graph below you can identify these particles by the light stripes:

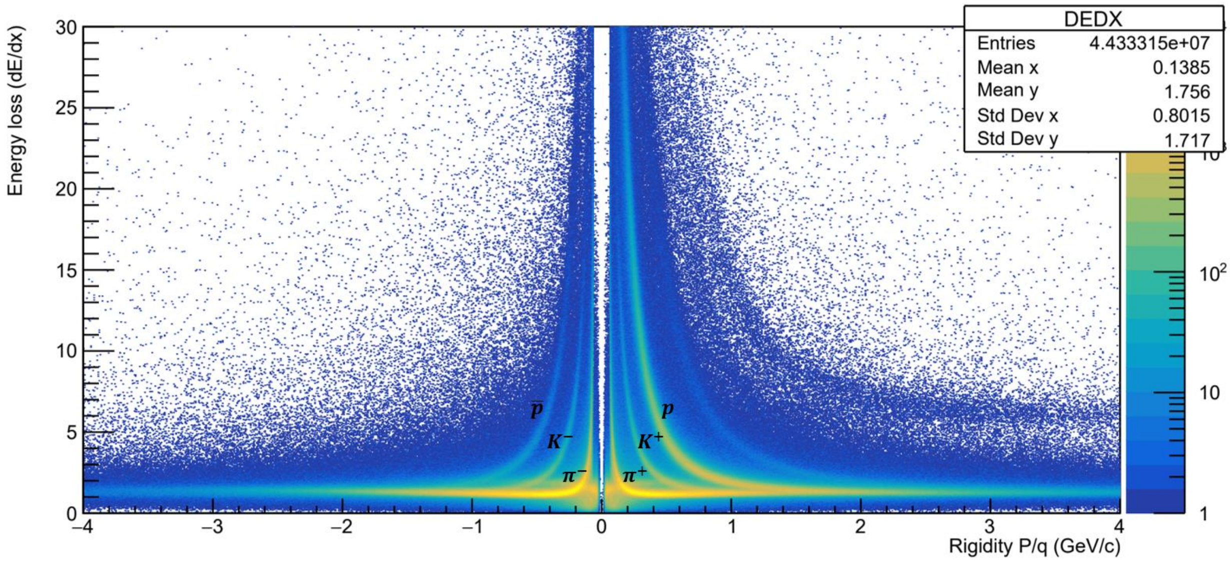
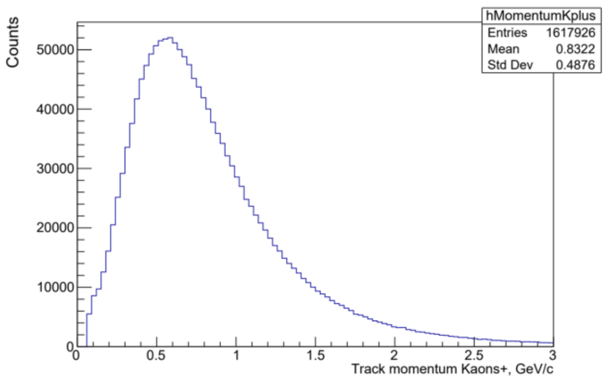


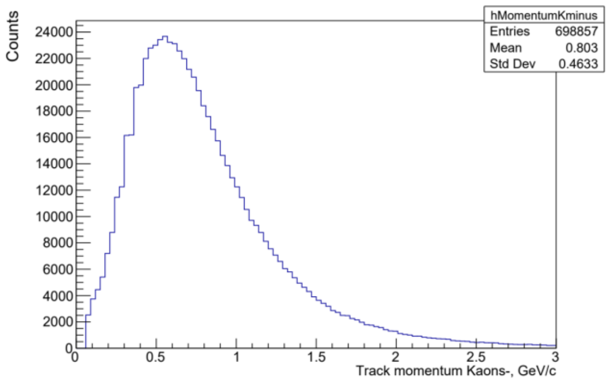
Figure 8. The dE/dx of charged tracks with the rigidity(P/q) for Au-Au at rapidity |y | < 0.1 for all the particles.

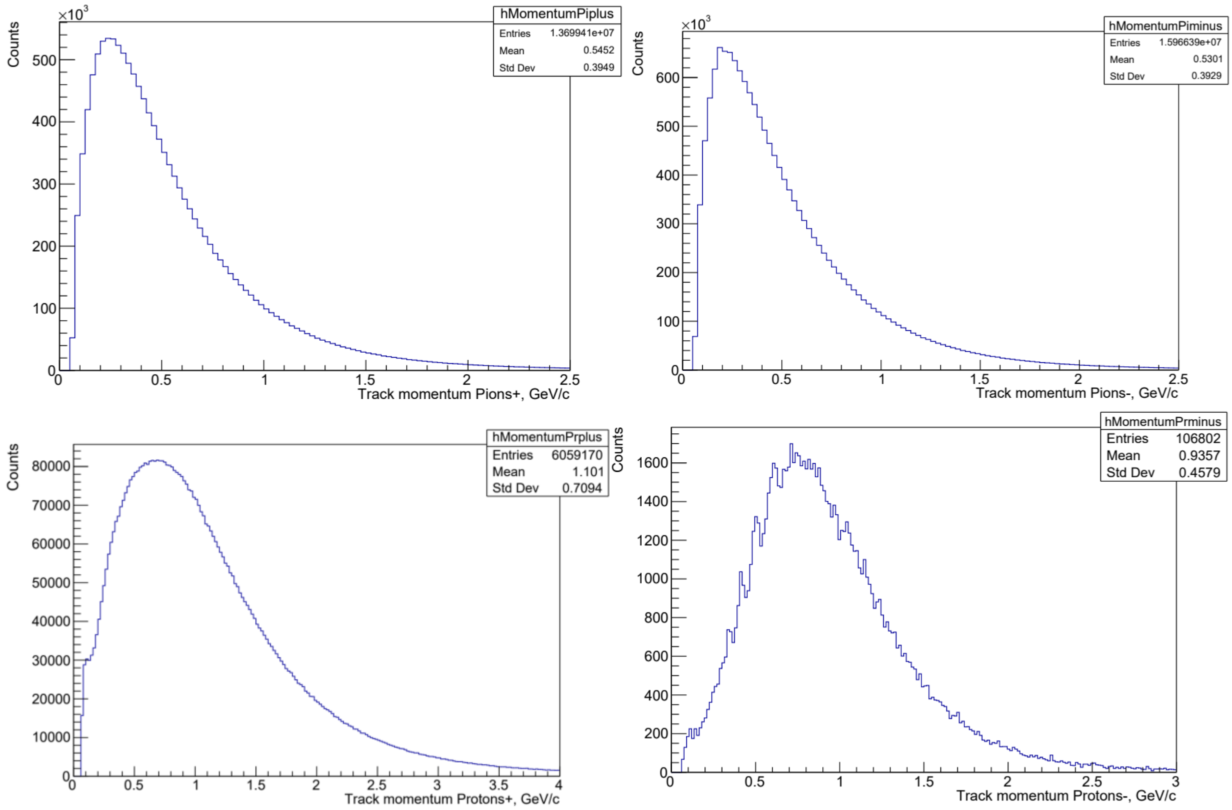
We also use time-of-flight information to identify particles with higher momentum.

Total momentum

Also, we obtained histograms of the distribution tracks of charged points, kaons and protons by particle total momentum and for each + and - particle we obtained the following graphs:






hMomentumPiplus
Entries 1.369941e+07
Mean 0.5452
Std Dev 0.3949
Counts
×10³
Track momentum Pions+, GeV/c
hMomentumPiminus
Entries 1.596639e+07
Mean 0.5301
Std Dev 0.3929
Counts
×10³
Track momentum Pions-, GeV/c
hMomentumPrplus
Entries 6059170
Mean 1.101
Std Dev 0.7094
Counts
Track momentum Protons+, GeV/c
hMomentumPrminus
Entries 106802
Mean 0.9357
Std Dev 0.4579
Counts
Track momentum Protons-, GeV/c

Summary

We reviewed the significance of new research at the new NICA accelerator complex for further study of QCD. Mastered the basic skills and abilities of working with the CERN ROOT package. Using it, we obtained and examined the main characteristics of particle collisions, such as multiplicity histograms, distributions of the primary vertex position along the longitudinal (beam) direction (Vz), histogram of the position of vertex X and vertex Y, and also the total momenta of kaons and pions and protons at the new NICA accelerator complex and the MPD detector, necessary to search for the chemical baryon potential in the phase diagram.

Acknowledgements

I would like to express my gratitude to JINR for providing the opportunity to visit the START program and paying for all the necessary needs for this period and travel. I am also grateful to my mentor Alexey Aparin for his help and organization of my activities during this period. And, of course, I say a special thank you to my partners from VBLHEP Alisher, Sonya, Vin’ and everyone else who helped me master all the tools in solving the problems I needed and helped me compile the programs I needed.

References

1. Kekelidze V. D. Collisions are based on ions: limiting baryon densities // Physics of elementary particles and the atomic nucleus. -2018. – t. 49. - №. 4. – C. 827-851.
2. Adamczyk L. et al. Bulk properties of the medium produced in relativistic heavy-ion collisions from the beam energy scan program //Physical Review C. – 2017. – T. 96. – №. 4. – C. 044904.
3. Students lectures “Collisions of superheavy energy nuclei” given by Pereus’ko D. Y. // Moscow – 2016
4. Aggarwal M. M. et al. An experimental exploration of the QCD phase diagram: the search for the critical point and the onset of de-confinement //arXiv preprint arXiv:1007.2613. – 2010.
5. Adcox K. et al. Formation of dense partonic matter in relativistic nucleus–nucleus collisions at RHIC: experimental evaluation by the PHENIX
6. Adams J. et al. Experimental and theoretical challenges in the search for the quark–gluon plasma: The STAR Collaboration's critical assessment of the evidence from RHIC collisions //Nuclear Physics A. – 2005. – T. 757. – №. 1-2. – C. 102-183.collaboration //Nuclear Physics A. – 2005. – T. 757. – №. 1-2. – C. 184-283.
7. Stephans G. S. F. Exploring the QCD phase diagram with low energy beams at RHIC: critRHIC //Journal of Physics G: Nuclear and Particle Physics. – 2008. – T. 35. – №. 4. – C. 044050.
8. Website: https://nica.jinr.ru/ru/