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


# FINAL REPORT ON THE START PROGRAMME

Study of quality assurance (QA)


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# Abstract

The main goal of this report is to study of quality assurance (QA) analysis. For our analysis, we are going to consider information from two parts of the MPD detector: TPC and TOF.

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# I. Introduction

The Multi-Purpose Detector (MPD) is under construction at the Joint Institute for Nuclear Research (JINR) in Dubna, as part of the Nuclotron-based Ion Collider fAcility (NICA) Accelerator Complex. The MPD Collaboration aims to study the phase diagram of QCD matter at maximum baryonic density, determine the nature of the phase transition between the deconfined and hadronic matter and search for the critical point. The combination of significant luminosity at NICA, collider geometry of the experiment and collision energies $\sqrt{S_{NN}}$ spanning the range of 4 to 11 GeV, where the transition from baryon to meson dominated matter is expected will allow MPD to provide unique insight into these questions. The status of the assembly of the detector in MPD Hall, as well as the progress in the production of MPD subdetectors will be reported on [1].


Figure1. The schematic view of the NICA complex [1].

## 1.1 Main Objective

The main aim from this project is to learn basic knowledge of C++ programming language and ROOT software framework and use it to process the data, which are taken from Monte Carlo simulation of the MPD detector at NICA.

The TPC is the time projection chamber, it measures the space points of a particle's path as well as the ionization of the gas. The combination of a particle's trajectory and the value of the magnetic field give an opportunity to evaluate the momentum and rigidity of a particle, which, in turn, leads to the discovery of a particle's charge.

TOF is the time-of-flight detector that allows us to find the velocity of a particle. With this knowledge, it is possible to identify a particle's mass.

### 1.2 Foundation of ROOT

ROOT is a software framework for data analysis and Input/Output: a powerful tool to cope with the demanding tasks typical of state of the art scientific data analysis. It provides all the functionality needed for big data processing, statistical analysis, visualization and storage. Among its prominent features is an advanced graphical user interface, ideal for interactive analysis, an interpreter for the C++ programming language, for rapid and efficient prototyping and a persistency mechanism for C++ objects, used also to write every year petabytes of data recorded by the Large Hadron Collider experiments. This introductory guide illustrates the main features of ROOT which are relevant for the typical problems of data analysis: input and plotting of data from measurements and fitting of analytical functions. Daily, thousands of physicists use ROOT applications to analyze their data or for modeling [2].

### 1.3 Multi-Purpose Detector (MPD)

The main physics experiment at NICA is the MPD, which will be operating at the collider. In 2018 an international scientific collaboration of MPD has been established. Currently, it is composed of 42 institutes from 12 countries, as well as JINR as a host institution. The collaboration will be operating the MPD apparatus, which is shown schematically in Fig. 2. Its designated position is the MPD Hall, which is located at the northern straight section of the NICA collider. Since 2020 the building has been available for MPD activities. Its main scientific purpose is to search for novel phenomena in the baryon-rich region of the QCD phase diagram by means of colliding heavy nuclei in the energy range of 4 GeV< $\sqrt{S_{NN}}$ <11GeV. A wealth of results, obtained by colliding heavy ions at different beam energies, has been gathered by experiments at SIS, AGS, SPS, RHIC and the LHC facilities. The new experimental program at the NICA-MPD will fill a niche in the energy scale, which is not yet fully explored, and the results will bring about a deeper insight into hadron dynamics and multiparticle production in the high baryon density domain.

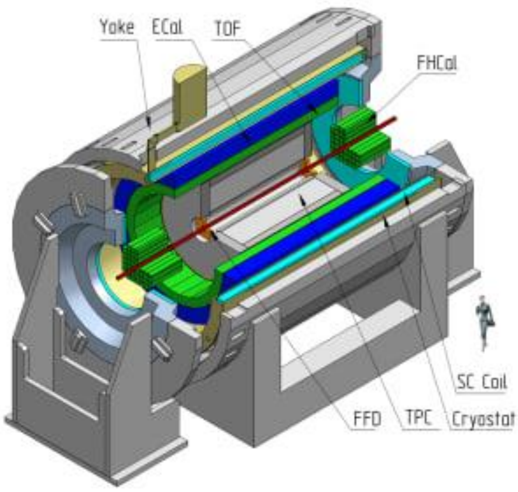


Figure 2. Multi-Purpose Detector [3].

The "central barrel" components have an approximate cylindrical symmetry within $|\eta|<1.5$. The beam line is surrounded by the large volume Time Projection Chamber (TPC) which is enclosed by the TOF barrel. The TPC is the main tracker, and in conjunction with the TOF they will provide precise momentum measurements and particle identification [3].

**1.4 Time Projection Chamber (TPC)**

The TPC is the main tracking detector of the MPD central barrel. It is designed to perform three-dimensional precise tracking of charged particles and momentum measurements for transverse momentum $p_t$> 50 MeV/c. The track reconstruction is based on the drift time and R-$\varphi$ cylindrical coordinate measurement of the primary ionization clusters created by a charged particle crossing the TPC. Charged particles traversing this volume ionize the gas mixture of 90% Ar+10% $CH_4$ along helix-shaped trajectories. The efficient tracking at pseudorapidities up to $|\eta| \leq 1.5$. Two-track resolution of about 1 cm. Hadron and lepton identification by dE/dx measurements made with a resolution better than 8% [4].

Momentum measurements in combination with dE/dx travelled by a particle measurement, dE/dx are used for flow analysis of identified particles. dE/dx traveled by a particle through a specific material is described by the Bethe-Bloch formula [5]:

$$\frac{dE}{dx} = \frac{4\pi}{m_e c^2}\frac{nz^2}{\beta^2}\left(\frac{e^2}{4\pi\varepsilon_0}\right)^2\left[\ln\left(\frac{2m_e c^2\beta^2}{I(1-\beta^2)}\right) - \beta^2\right] \quad (1)$$

where $\beta$ equals $v/c$, v is velocity of the particle, c is the speed of light, E is the energy of the particle, x is the distance travelled by the particle $m_e$ , $m_e$ is the rest mass of the electron, n is the electron density of the target, z is the particle charge, e is the charge of the electron, $\varepsilon_0$ is the vacuum permittivity and I the mean excitation potential of the target. The TPC is calibrated in order to describe dE/dx travelled with a parameterization of the Bethe-Bloch formula. By combining total momentum $\frac{dE}{dx}$ and $p_{tot}$ over primary total momentum measurements the particles can be identified (see Fig. 11).

### 1.5 Time-Of-Flight (TOF)

The Time-Of-Flight principle is based on measuring the time it takes for a wave to travel from a source (a time-of-flight sensor) to an object and back. The TOF system is intended to perform particle identification for momentum up to 2 GeV/c. The “central barrel” components have an approximate cylindrical symmetry within $|\eta|<1.5$. The beam line is surrounded by the large volume Time Projection Chamber which is enclosed by the TOF barrel. The TPC is the main tracker, and in conjunction with the TOF they will provide precise momentum measurements and particle identification. The Electromagnetic Calorimeter (ECal) is placed in between the TOF and the MPD magnet. It will be used for detection of electromagnetic showers, and will play the central role in photon and electron measurements. The MPD superconducting solenoid magnet is designed to provide a highly homogeneous magnetic field of up to 0.57 T (with a default operational setting of 0.5 T), uniform along the beam direction, to ensure appropriate transverse momentum resolution for reconstructed particles within the range of momentum of 0-3 GeV/c. As the average transverse momentum of the particles produced in a collision at NICA energies is below 500 MeV/c, the detector was designed to have a very low material budget. In the forward direction, the Fast Forward Detector (FFD) is located still within the TPC barrel. It will play the role of a wake-up trigger.

Below in Fig. 10.1 and 10.2 give information about distribution of $m^2$ and $p_t$ with positive and negative charges. In this analysis particle tracks are reconstructed using global tracks, which are tracks reconstructed using both TPC and TOF signals. Particles are also identified by using only the TPCs signal. TOF measure the particle velocity β relative to the speed of light in vacuum, $\beta = {}^{v}/_{c}$ which allowing the mass square $m^2$ of the particle to be determined:

$$m^2 = p^2({}^{1}/_{\beta^2} - 1) \tag{2}$$

stop time - start time = τ (time of flight) is associated with reconstructed tracks in the TPC by track extrapolation to the TOF. The TPC provides the momentum p, and total length $L$, so we can calculate inverse velocity [6].

$$\frac{1}{\beta} = \frac{c\tau}{L} \tag{3}$$

where c is speed of light. From the relativistic particle momentum, we obtain

$$p = m\beta\gamma => p^2 = \beta^2(m^2 + p^2) \tag{4}$$

where $m$ is particle mass.

## II. Analysis of the data

In this work we focus on Bi (83/209) + Bi (83/209) collisions at $\sqrt{S_{NN}}$ = 9.2 GeV and impact parameter from 0 up to 12 fm within PHQMD model. Total number of events was used around one half million.

### 2.1 Event

For the analysis, selection of events in the center of the TPC is required, to avoid events that haven't occurred in the center of the TPC. Events required to have a $|V_z| < 150$ cm, where $V_z$ is the z-coordinate of the primary vertex position which is measured by the TPC. Tails of the histogram for primary vertex in z-direction do not contain enough counts and therefore they are not added into analysis. The primary vertex position of an event in the radial direction $|V_r| < 0.1$ (cm).

The loss of formed particles on the edges of the detector is not the only problem that the position of the primary vertex introduces. In the transverse direction, if the primary vertex gets closer to the beam pipe, the collision of nuclei may be disrupted by one of the nuclei interacting with the beam pipe's material.

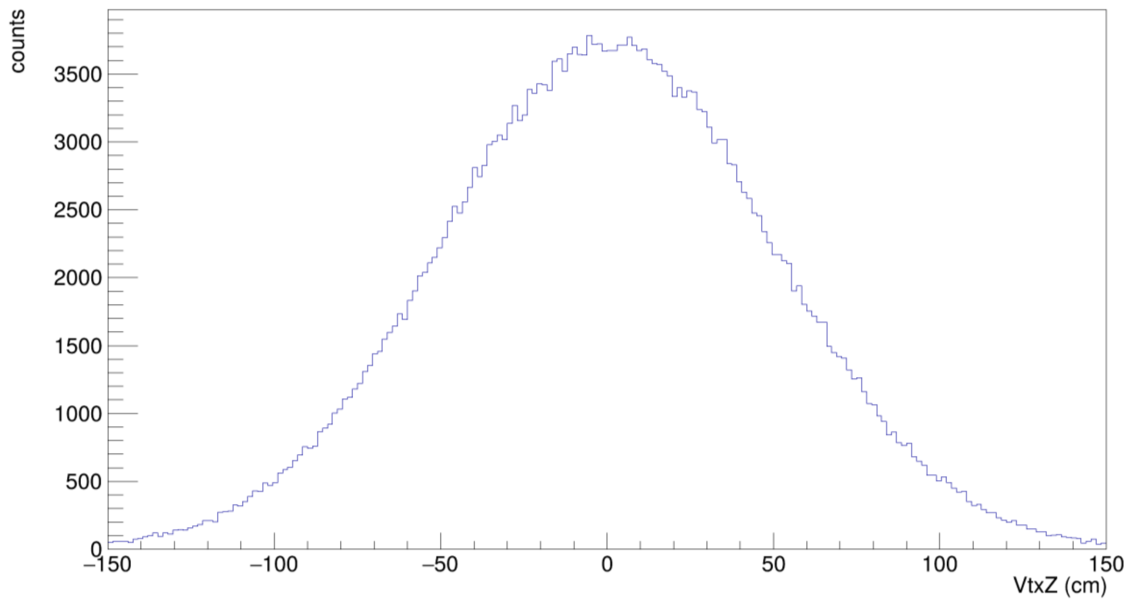


Figure 3. The primary vertex of z-coordinate.

In Fig.3 shows the position of the primary vertex z. In the Cartesian coordinate system, there are x, y, and z coordinates of the vertex. The z-coordinate is a longitudinal component that is responsible for the position of the primary vertex along the beam pipe of the MPD detector.

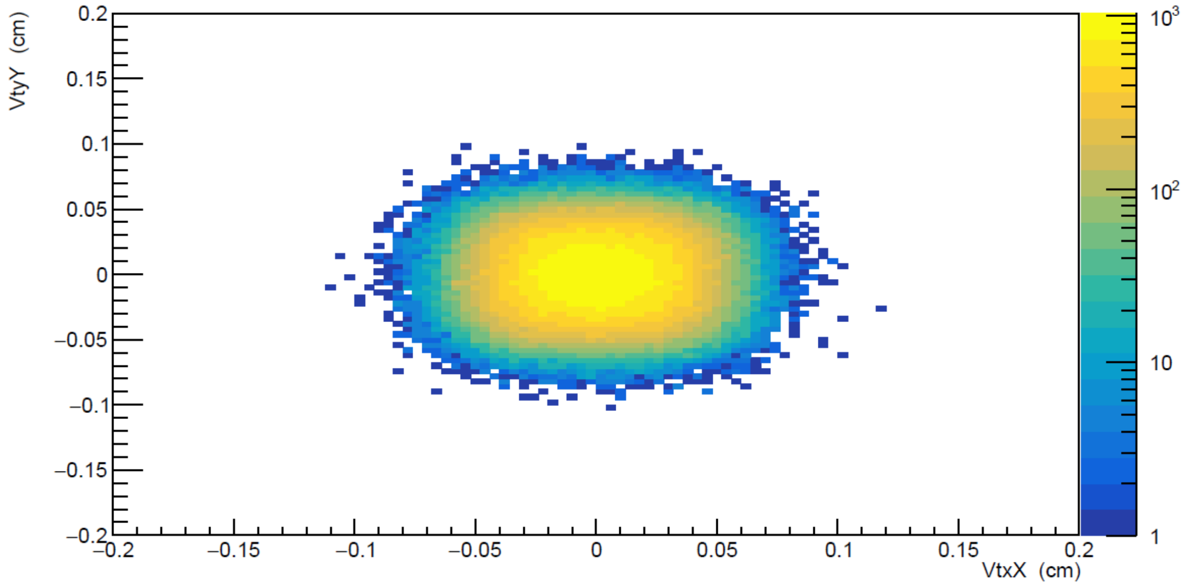


Figure 4. Primary vertex in xy-plane $V_r$.

The Fig .4 shows a 2D histogram representing the distribution of primary vertices in the XY-plane, specifically in $V_{tx}X$ and $V_{ty}Y$ centimeters. The color gradient indicates the density of events, with yellow representing areas of higher density and blue representing areas of lower density. The concentration of points around the center indicates the typical region where primary vertices are reconstructed in this experiment.

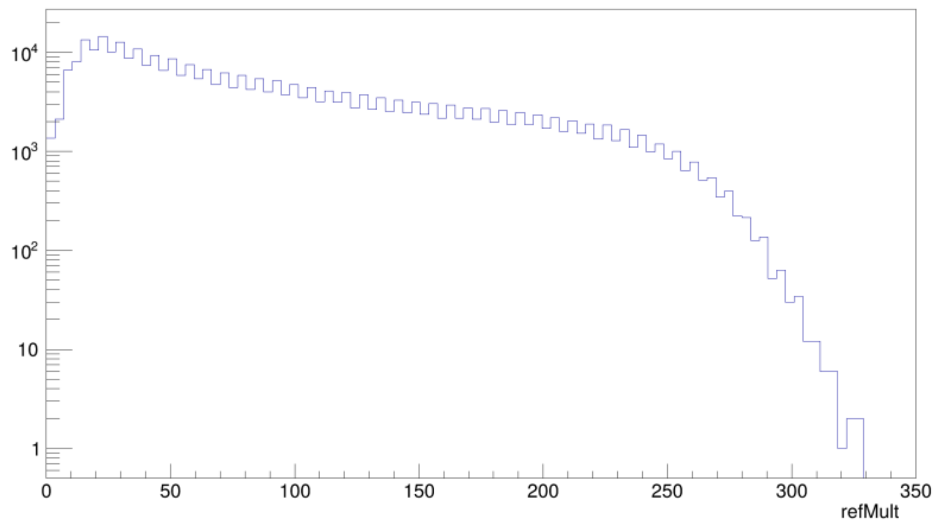


Figure 5. Reference multiplicity.

Reference multiplicity is connected to the event's centrality which describes the initial overlap region of the colliding nuclei. According to Fig.5 the distribution shows a peak at lower multiplicities, with a gradual decline as multiplicity increases. The x-axis represents the reference multiplicity, which is a measure of the number of tracks detected in event. The y-axis, on a logarithmic scale, represents the frequency of events corresponding to each multiplicity value.

**2.2 Track**

After selecting events, desired particles should be selected. As described in 2.1part particle identification is done in the TPC and TOF detectors. To make sure, that measured particles fall into detector acceptance, only tracks with pseudorapidity $|\eta| < 1.5$ were accepted. Resulting tracks are denoted as global tracks and determine the vertex primary position. These tracks are called primary tracks.

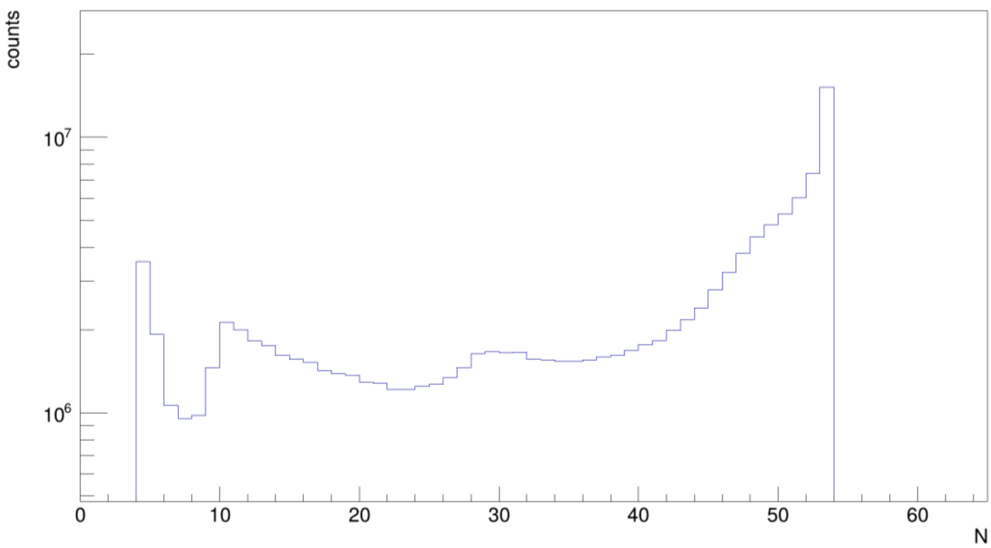


Figure 6. Number of hits produced by a particle's track.

In Fig.6 displays a histogram that represents the distribution of the number of hits produced by a particle's track. The x-axis indicates the number of hits, while the y-axis shows the count of occurrences, on a logarithmic scale.

Pseudorapidity is found, using the following formula:

$$\eta = \frac{1}{2} ln \left( \frac{|\vec{p}|+p_L}{|\vec{p}|-p_L|} \right) \tag{5}$$

where $|\vec{p}|$ total momentum of the global track , $p_L$ transverse momentum of the global track.

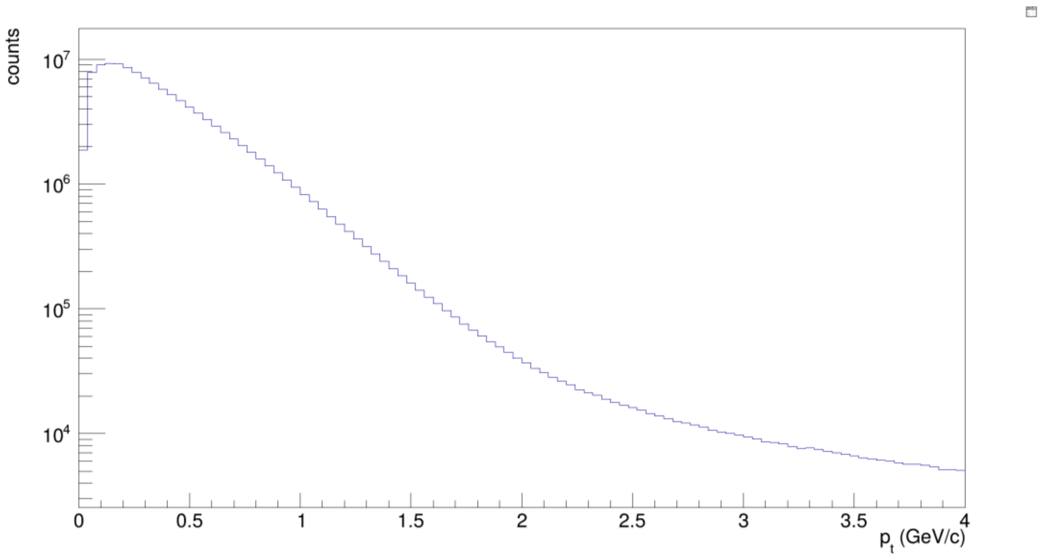


Figure 7.1. Distribution pseudorapidity of a particle.

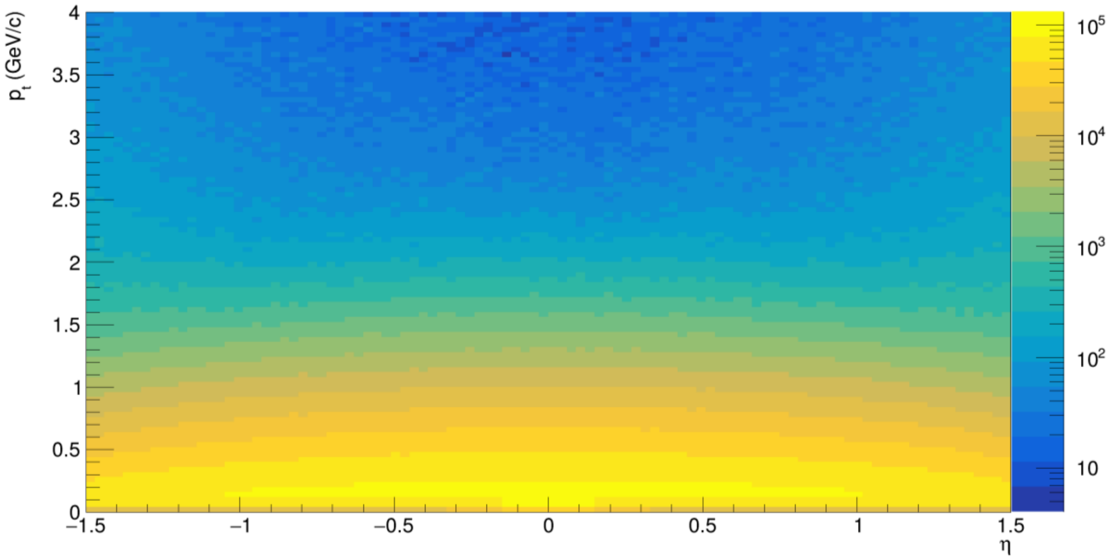


Figure 7.2 Distribution pseudorapidity of a particle.

In Fig.7.1 shows a one-dimensional distribution of particles over $p_t$, where $p_t$ track primary transverse momentum, while in Fig.7.2 two-dimensional distribution of particles over η and $p_t$.

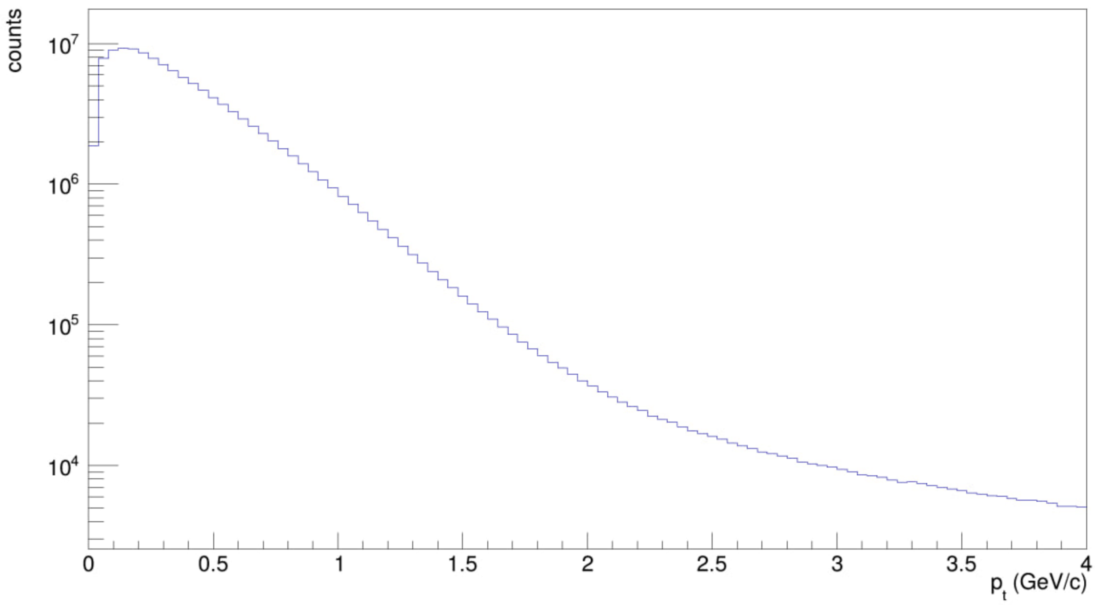


Figure 8.1. Track primary transverse momentum.

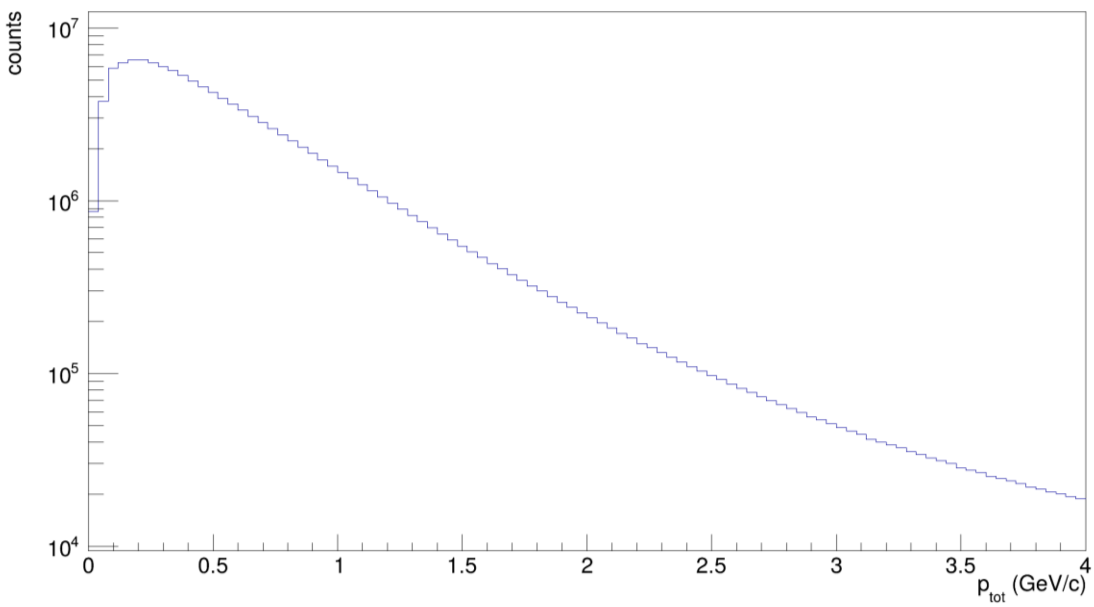


Figure 8.2. Track primary total momentum.

In Fig 8.1 and 8.2 show momentum of particle in track primary transverse and track primary total momentum.

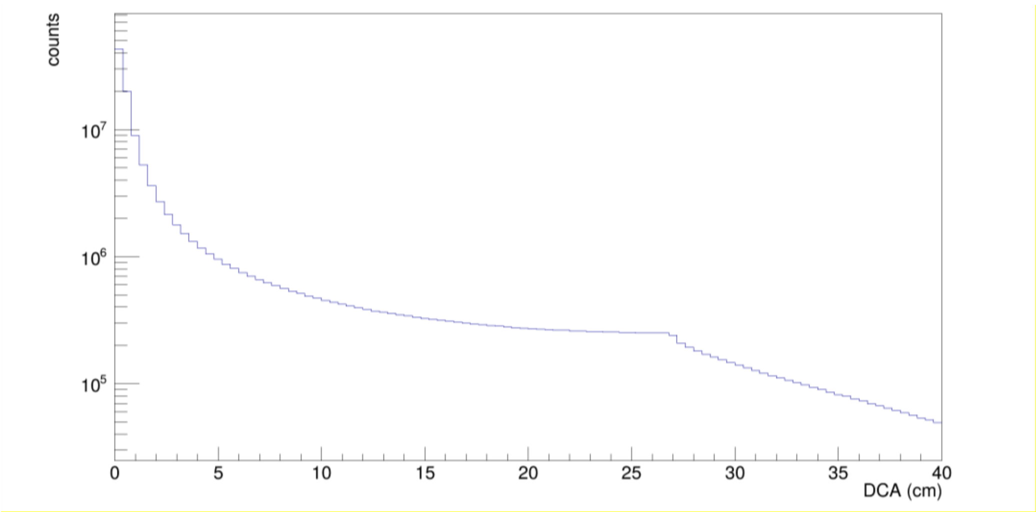


Figure 9. DCA distribution.

In Fig. 9 DCA (Distance of Closest Approach) is the shortest distance between two particles' trajectories in space the trajectories of charged particles are reconstructed using various detector layers. The DCA is calculated to determine how close a particle's trajectory comes to a specific point, such as the origin of the detector or another particle's trajectory.

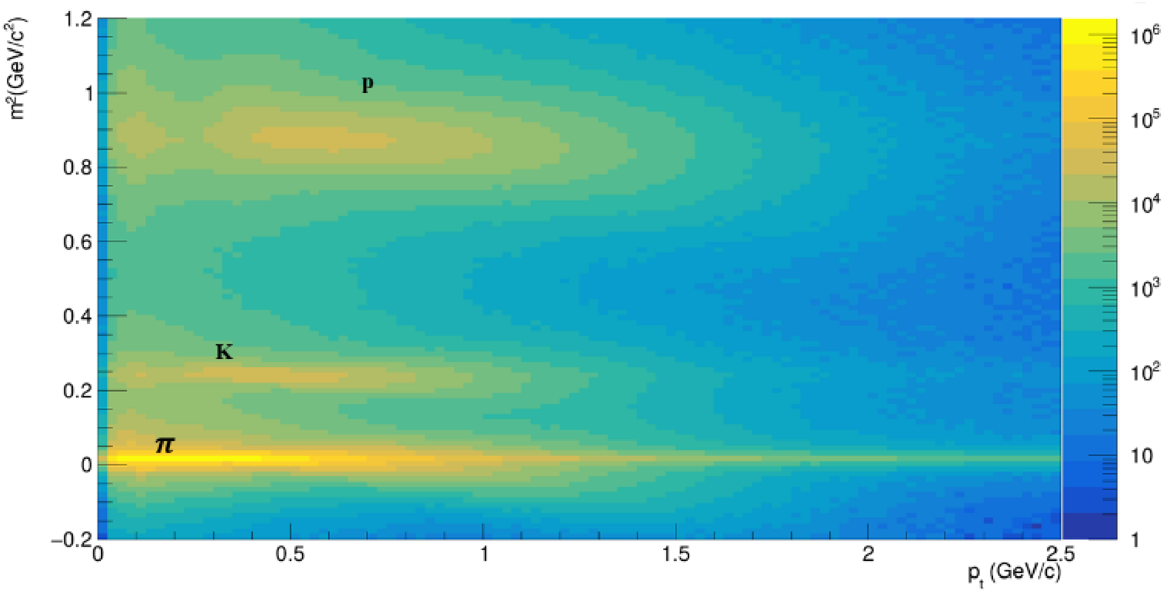


Figure 10.1. Distribution of $m^2$ a function of $p_t$ for $\pi^+$, $K^+$, and p.

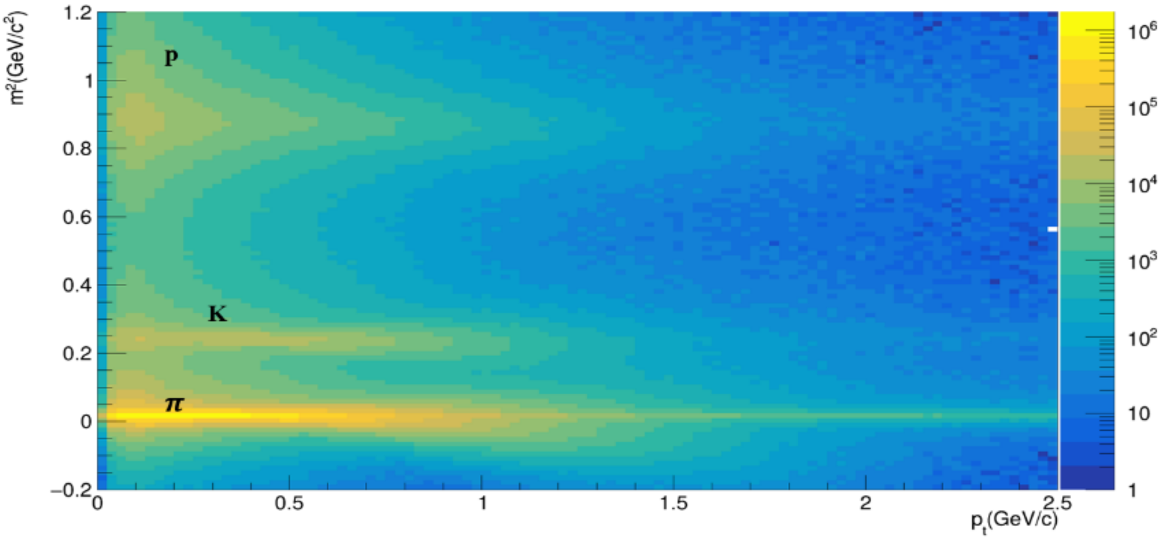


Figure 10.2. Distribution of $m^2$ a function of $p_t$ , for $\pi^-$ , $K^-$ and $\bar{p}$ .

In Fig.10.1 and Fig.10.2 show the distribution of squared mass $m^2$ as a function of transverse momentum $p_t$ for different types of particles .A histogram Fig.10.1 positive charges particles identified, while in Fig.10.2 particles with negative charges. These plots are often used to distinguish different particles based on their mass and momentum, especially in experiments involving particle collisions. The specific curves allow for the identification of particles like $\pi$, K, p, and d.

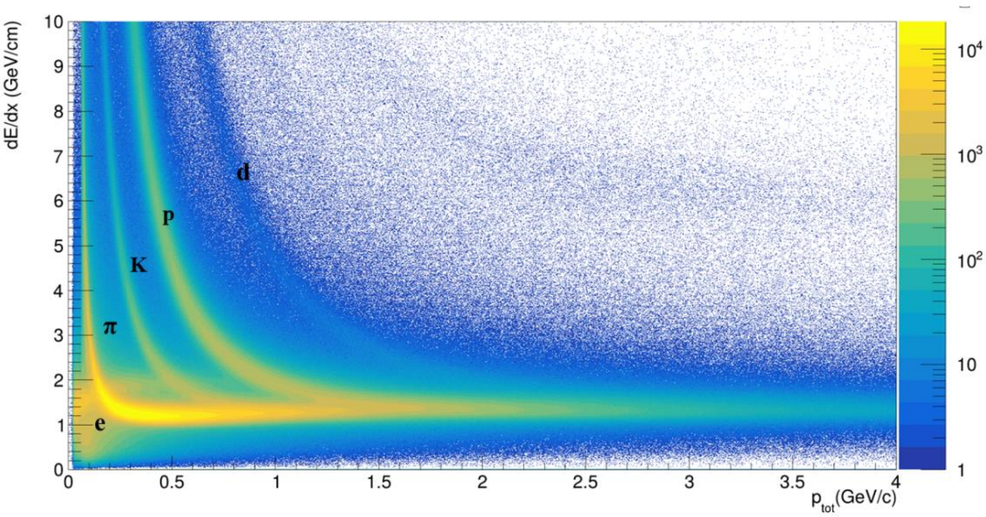


Figure 11. Distribution of ionization loss energy for e, $\pi$, K, p and d are identified.

Fig.11 shows a distribution of ionization energy loss (dE/dx) versus momentum ($p_{tot}$) for different particles (electrons, pions, kaons, protons and deuterons).

This type of plot is typically used in particle detectors, such as the MPD (Multi-Purpose Detector), to identify particles based on their specific energy loss as they pass through a medium. Each particle type follows a distinct curve in the plane, allowing for particle identification.

The color scale on the right indicates the number of detected events, with a higher count shown in warmer colors (yellow) and lower counts in cooler colors (blue).

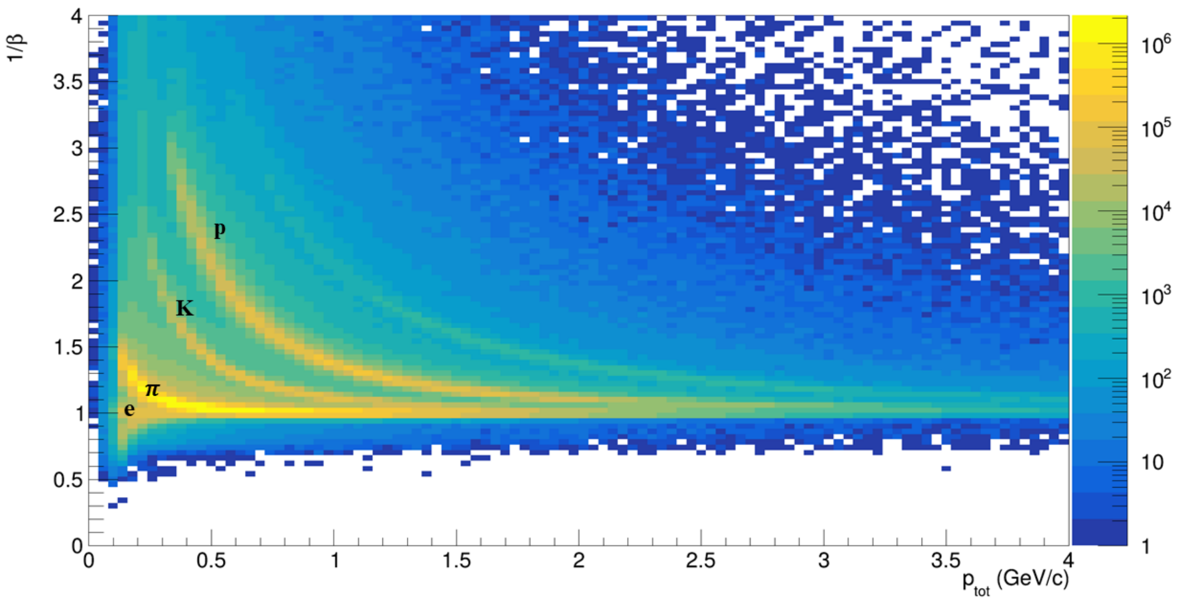


Figure 12.1 The TOF $1/\beta$ versus total momentum $p_{tot}$ of tracks.

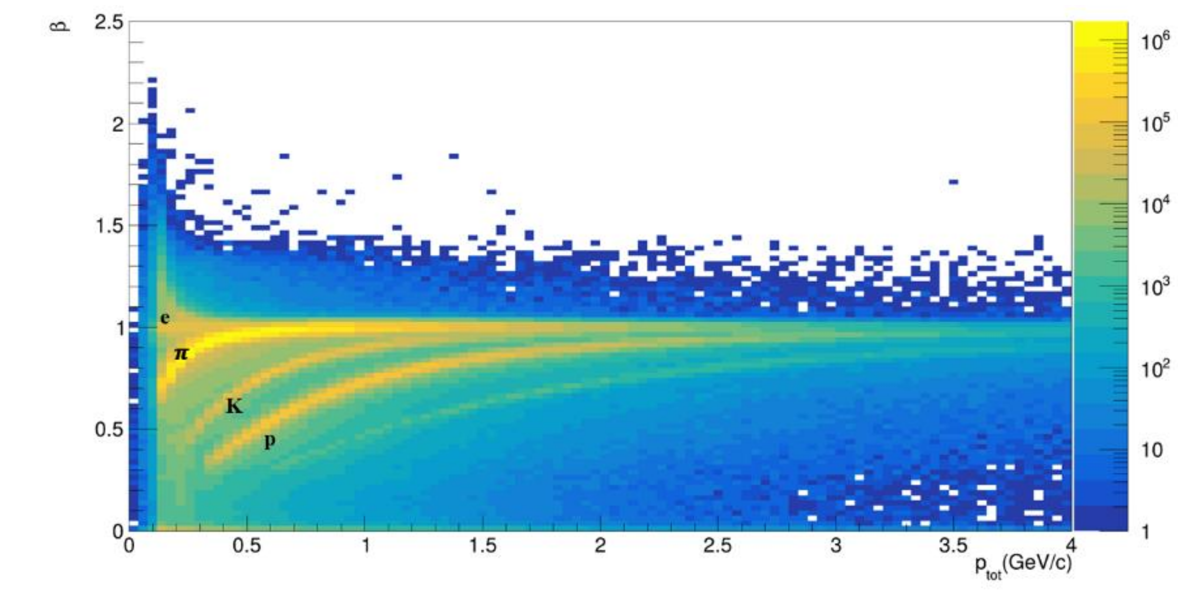


Figure 12.2 The TOF $\beta$ versus total momentum $p_{tot}$ of tracks.

Fig.12.1 is a histogram of the dependence of $1/\beta$ on the total momentum $p_{tot}$.and Fig.12.2 is a histogram of the dependence of $\beta$ on $p_{tot}$. The graph also shows the distribution of different particles as a function of their total velocity. These figures allow distinguishing between particle types based on their velocities and total momentum.

# Acknowledgement

I would like to thank the University Center of JINR for giving me such an incredible opportunity to participate in the Summer Student Program and to broaden my horizon on Networking, Computing and Computational Physics. Special thanks to Elena Karpova for helping resolve any arising problems and answering to my all questions.

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It is a pleasure to have had the opportunity to work with them and I look forward to counting on their support in the future.

# Reference


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