JOINT INSTITUTE FOR NUCLEAR RESEARCH

Veksler and Baldin laboratory of High Energy Physics

Final Report of INTEREST program

MPD detector performance study at the NICA collider. Task 1. Study of the MPD phase-space coverage for hadrons and light nuclei in the fixed target mode with different beam-target combinations

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Abstract

This project investigates the MPD phase space for a Xe(A=124) + W collision on a fixed target, using UrQMD as an event generator and MPDRoot as a software framework for simulation. Three types of particles were analyzed: Kaons, Protons and Pions, identifying the intervals of transverse momentum and rapidity with high particle density for each one of them.

Introduction

Main objective

The main objective is to study MPD phase-space coverage for hadrons and light nuclei in the fixed Target Mode. To achieve this goal, it will be necessary to use MPDRoot as a framework for simulation, reconstruction and physical analysis and use UrQMD as an event generator.

MPD

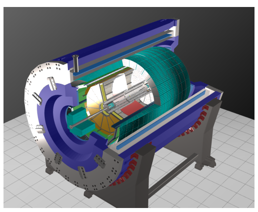


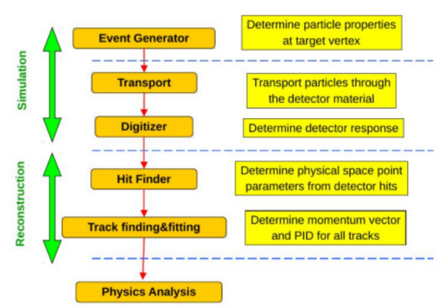
Figure 1: Image of simulated MPD detector

The Multi-Purpose Detector (MPD) is one of the two dedicated heavy-ion collision experiments of the Nuclotron based Ion Collider fAcility (NICA), one of the flagship projects, planned to come into operation at the Joint Institute for Nuclear Research (JINR) in 2022. 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 $\leqslant \sqrt{s_{NN}} \leqslant$ 11 GeV. To achieve its objectives, the MPD relies on cutting-edge technology, including several key detector subsystems. The central barrel components exhibit an approximate cylindrical symmetry within $|\eta| < 1.5$, comprising the Time Projection Chamber (TPC), the Time of Flight Detector (TOF), and the Electromagnetic Calorimeter (ECal). Additionally, the Fast Forward Detector (FFD) within the TPC barrel acts as a wake-up trigger, and the Forward Hadronic Calorimeter (FHCal) near the magnet end-caps helps determine collision centrality and the orientation of the reaction plane for collective flow studies. [1]

MPDRoot

Mpdroot is the off-line software framework for simulation , reconstruction and physics analyses of the simulated or experimental data for MPD experiment. [2]

MPDRoot is based on the Root environment (Data Analysis Framework) and the FairRoot framework, both built on an Object Oriented toolset in C++. Its main function is to facilitate transport through the detector and reconstruction of data, as detailed in the following diagram: [3]



Some of the types of event generators MPDRoot is able to analyze are:

- Ultrarelativistic Quantum Molecular Dynamics (UrQMD)
- Quark-Gluon String Model (QGSM)
- Parton-Hadron-String Dynamics (PHSD)
- Pythia

The simulation of the passage of particles through matter is performed using the Root geometry package together with the simulation packages:

- GEANT 3
- GEANT 4

In this study, UrQMD will be used as an event generator and GEANT 4 to simulate the steps of the particles.

UrQMD

UrQMD (Ultra-relativistic Quantum Molecular Dynamics) is a computer simulation framework used in nuclear and particle physics to study the interactions of high-energy particles, particularly in heavy-ion collisions. It models the dynamics of the collision process from the initial stages of the collision, through the formation and evolution of a hot and dense medium (often referred to as a quark-gluon plasma), to the final stages where particles are emitted. It has a fully integrated Monte Carlo simulation package for Proton+Proton, Proton+nucleus and nucleus+nucleus interactions.

UrQMD employs concepts from quantum mechanics, statistical mechanics, and relativistic dynamics to simulate the complex interactions among quarks, gluons, and hadrons. Researchers use UrQMD to study various phenomena, including the properties of nuclear matter under extreme conditions, the dynamics of particle production in heavy-ion collisions, and the formation of exotic states of matter. [4]

GEANT 4

Geant4 is a toolkit to create simulations of the passage of particles or radiation through matter. Applications built on Geant4 can simulate any setup or detector and radiation source, and record chosen output of physical quantities due to source particles and secondaries interacting with the material of the setup. [5]

Geant4 provides complete functionality for all areas of the simulation of particle transport. It can be used to

- create a model of a geometry with shapes and materials,
- locate points and navigate tracks in that model,
- apply the effects of physics interactions and generate secondary particles,
- record selected information either as tallies or create hits (that are used to generate detector response),
- visualize a setup's geometry and the particle tracks passing through it, and
- interact with an application via an extensible terminal or graphical user interface.

Fixed Target Mode

Fixed-target experiments are those that study the collisions of a highly relativistic particle beam with a target that is stationary in the laboratory. This technique is complementary to collider experiments that study the collisions of particles from two opposed beams. [6]

In fixed target experiments, the energy available for interactions is determined by the energy of the incoming beam. In collider experiments, the collision energy is typically higher because it is determined by the combined energy of both colliding beams. The energy involved in a fixed target experiment is 4 times smaller compared to that in collider with the dual beams of same energy.

The fixed target experiments have a significant advantage for experiments that require higher luminosity (rate of interaction). [7]

The famous Rutherford gold foil experiment, performed between 1908 and 1913, was one of the first fixed-target experiments, in which the alpha particles were targeted at a thin gold foil.

Description of the MPD Experiment

The Beam-Target combination that we are going to study is Xenon (A =124) + Wolfram [Xe(A = 124)+W]. With wolfram being the fixed target.

Approach on the experiment

The steps we must follow to get the space phase of our collision Xenon - Wolfram:

- Produce data set with events at Fixed Target Mode
- Transport through detector and reconstruction
- Get the phase space ditribution −> Rapidity (Y) and Transversal Momentum (p_T)

Produce data set

As we have said before, data generation will be through UrQMD. A total of one million events were generated with the following considerations:

- Collision Xenon-Wolfram
- Kinetic Energy = 2.5Gev
- Impact Parameter b $\in [0, 16]$
- Fixed Target Mode

UrQMD Inputfile

```
pro 124 54          //Proyectile Atomic_mass Atomic_number
tar 184 74          //Target Atomic_mass Atomic_number

nev 200             //Number of Events
imp -16             //Impact Parameter
ene 2.5             //Kinetic Energy
tim 200 200         //Time

cto 27 1            //Target Mode Option

rsd 1270010000      //Random Number
f13
#f14                //Output File
f15
f16
f19
f20

xxx
```

To generate such a number of events, it was necessary to split into several files. A total of 200 events were placed in each input file. So to reach the number of one million events, a total of 5000 files were made. This was made possible by the sed command:

```
for ((INDEX = 0; INDEX < 5000; INDEX++))
do
    sed -e "s/inputfile/inputfile$INDEX/; s/test.f14/test.f14$INDEX/"
        runqmd.bash > runqmd.bash$INDEX
    sed -e "s/1270010000/157401$INDEX" inputfile > inputfile$INDEX
done
```

Transport through detector and reconstruction

After obtaining one million events, they were processed using MPDRoot, using the fixed target mode, according to the following diagram:

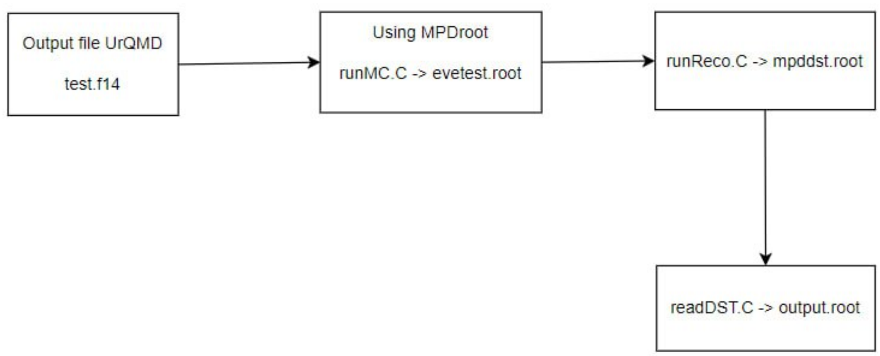


Figure 2: Flowchart of processing UrQMD output files with MPDRoot

Transport and reconstruction considerations were detailed in the runMC. C and runReco.C files, where only the option to activate Fixed Target Mode was modified.

On the runMC.C file was modified:

```
primGen->SetBeam(0.0, 0.0, 1e-6, 1e-6);
primGen->SetTarget(-115.0, 0.0);
primGen->SmearGausVertexZ(kFALSE);
primGen->SmearVertexXY(kFALSE);
```

As before, a total of 5000 runMC.C and runReco.C files were generated to analyze the number of events required.

In a bash file it was used:

```
for ((INDEX = 0; INDEX < 5000; INDEX++))
do
    sed -e "s/test.f14/test.f14$INDEX/; s/evetest/evetest$INDEX/" runMC.C >
        runMC.C$INDEX
    sed -e "s/evetest/evetest$INDEX/; s/mpddst/mpddst$INDEX" runReco.C >
        runReco.C$INDEX
done
```

Within this analysis two considerations were made to work with fragments and nuclei:

1. GEANT 4 10k Steps

2. GEANT 4 500k Steps

The purpose is to determine if there is a significant difference by varying the number of steps selected. This will be discussed in the results.

To reduce the analysis time, we chose a number of 10,000 steps.

Phase space Rapidity (Y) and Transversal Momentum (p_T)

In this section a distinction was made between Kaons, Protons and Pions, distinguishing between Tracks MonteCarlo and Reconstructed, as well as between primary and secondary particles. In addition, cuts were applied in hits > 16.

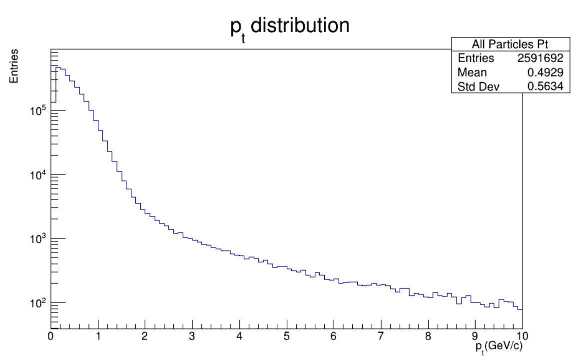
With all these considerations, histograms of Transverse Momentum (p_T), Rapidity (Y) and the phase space between transverse momentum and rapidity were performed.

```
Histograms2D[j][k][m][p] = new TH2F(hist_name, tittle_axis, 100, -4, 4, 100, 0, 10);
    // j -> MC or Reco Tracks
    // k -> Primary or Secondary Particles
    // m -> Kaons, Protons, Pions
    // p -> Pt or rapidity
```

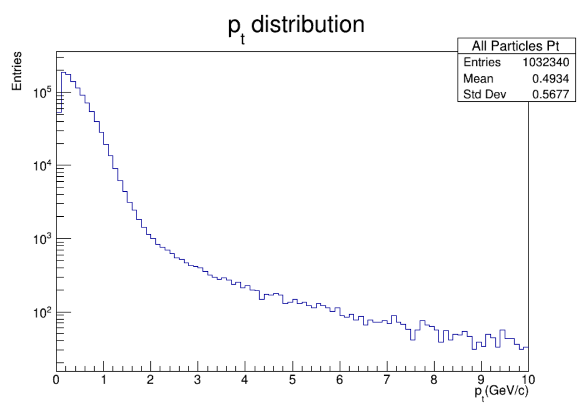
Results

Difference between 10k and 500k Steps

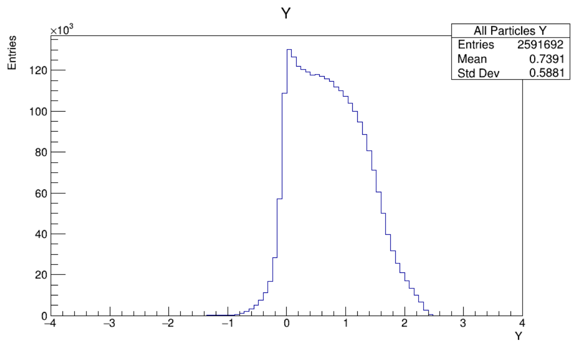
Due to processing constraints, 50,000 events were conducted for 10,000 steps, and 20,000 events for 500,000 steps. Despite this limitation, this dataset should suffice to detect any discernible differences.



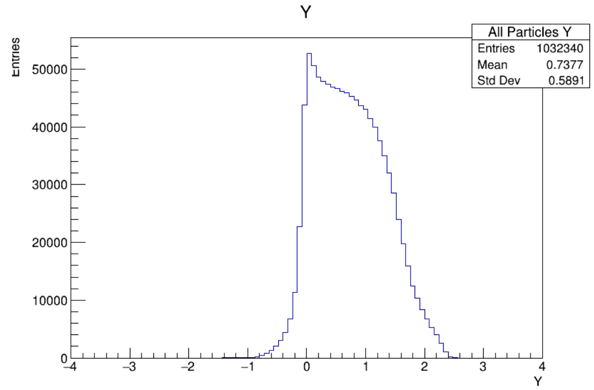
pT Distribution of 10k Steps



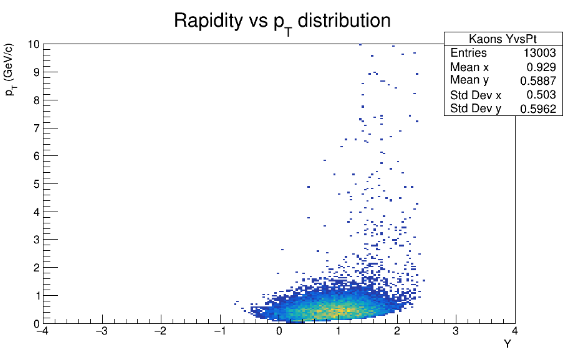
pT Distribution of 500k Steps



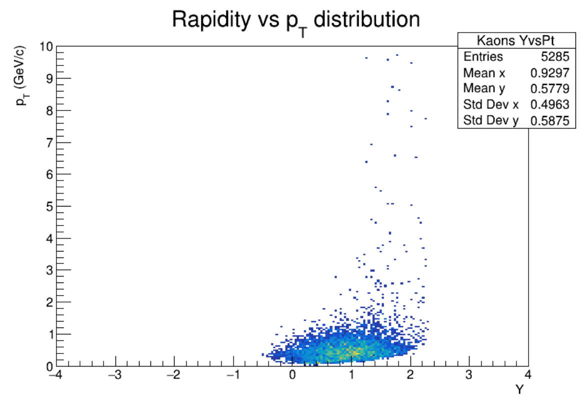
Eta Distribution of 10k Steps



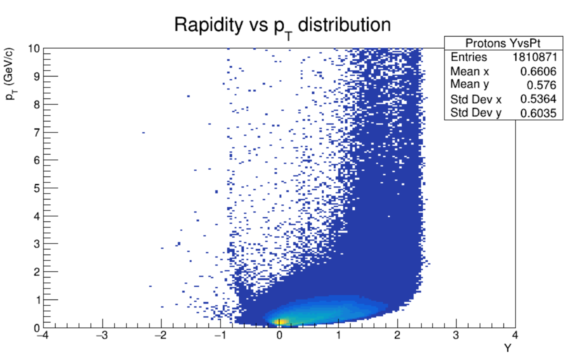
Eta Distribution of 500k Steps



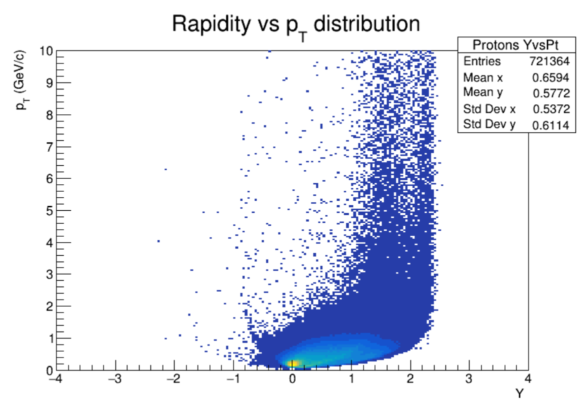
Kaon Rapidity vs Pt Distribution of 10k Steps



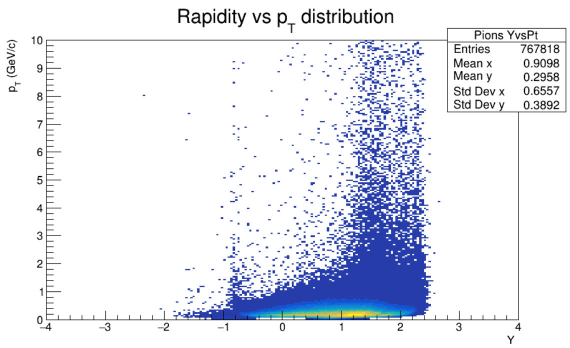
Kaon Rapidity vs Pt Distribution of 500k Steps



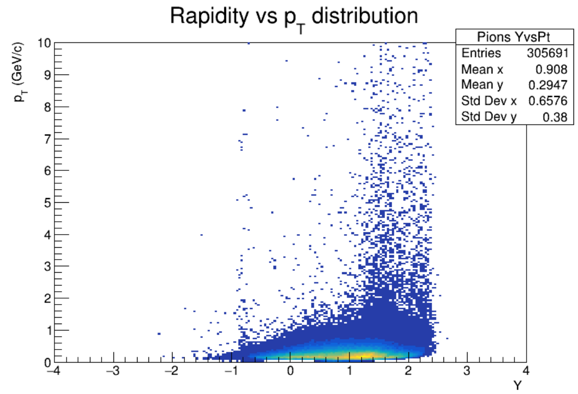
Proton Rapidity vs Pt Distribution of 10k Steps



Proton Rapidity vs Pt Distribution of 500k Steps



Pion Rapidity vs Pt Distribution of 10k Steps



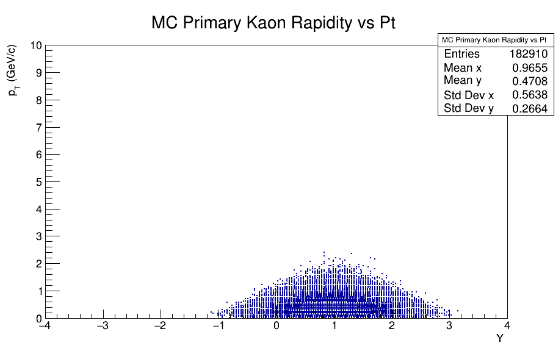
Pion Rapidity vs Pt Distribution of 500k Steps

According to all the histograms, we can notice that the distributions share both the average and the standard deviation, as well as the intervals of higher density. This is true even when the number of entries varies with the number of steps. However, to confidently claim that distributions are the same, a detailed comparison between histograms would be necessary. Unfortunately, owing to time constraints, this task will not be possible in the present report.

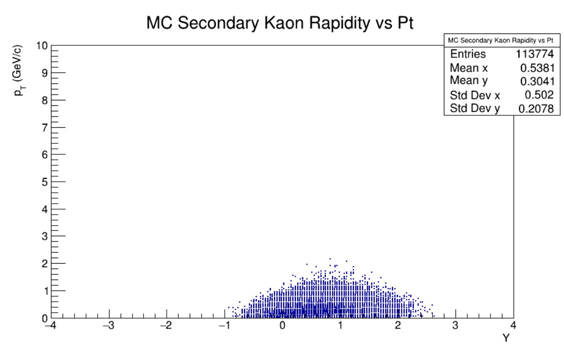
Distributions of Kaons, Protons and Pions

During the processing of events 400 thousand events were corrupted, so this left us with a statistic of 600 thousand events.

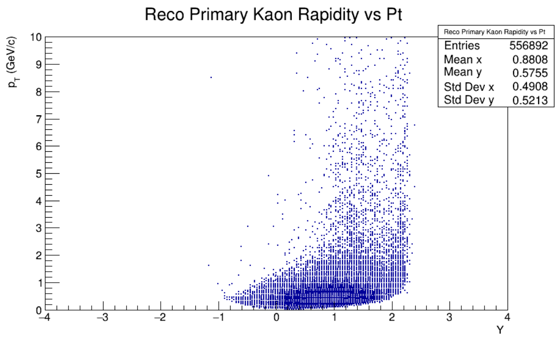
Histograms Kaons



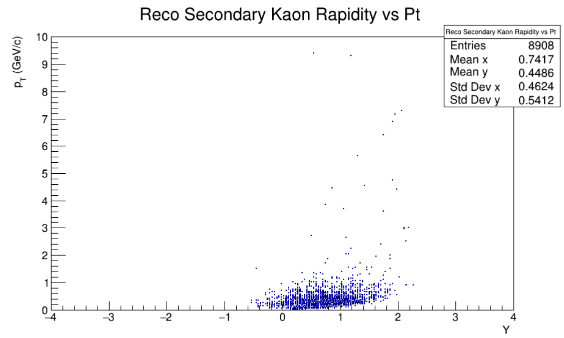
MonteCarlo Track Phase Space for primary particles



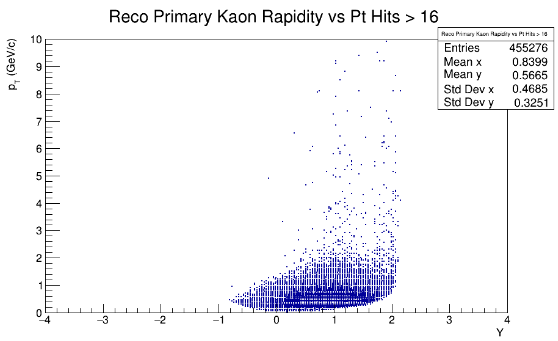
MonteCarlo Track Phase Space for secondary particles



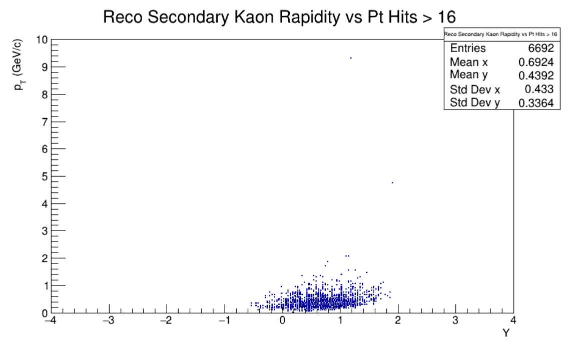
Reconstructed Track Phase Space for primary particles



Reconstructed Track Phase Space for secondary particles



Reconstructed Track Phase Space for primary particles with a cut in hits > 16



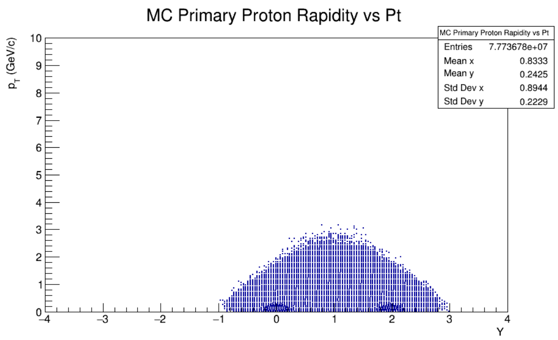
Reconstructed Track Phase Space for secondary particles with a cut in hits > 16

In MonteCarlo histograms, in primary and secondary particles, all the particles are in the intervals of -1 to 3 in rapidity and 0 to 2 in transverse momentum. The large concentration of particulates is found in the intervals of 0 to 2 in rapidity and 0.2 to 1 in transverse momentum for primary particles. For secondary particles the high concentration is in the range of 0 to 1 in rapidity and 0.1 to 0.6 at transverse momentum.

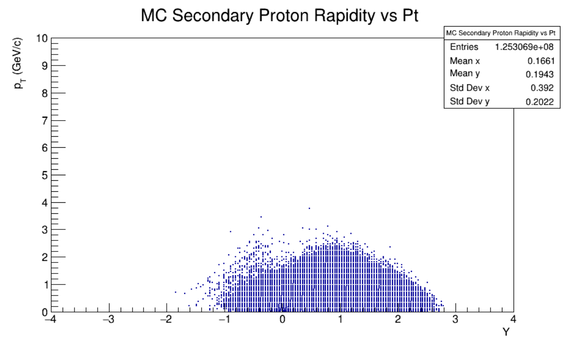
In the reconstructed histograms the primary particles are concentrated in a range of -1 to 2 in rapidity and 0.1 to 10 at transverse momentum, where the high concentration of them is between 0.2 to 1.8 in rapidity and 0.1 to 1 at transverse momentum. The secondary particles are concentrated in a range of 0.5 to 2 in rapidity and 0.1 to 10 in transverse momentum, where the great concentration of them is in 0 to 1.4 in rapidity and 0.1 to 1 in transverse momentum.

Seeing the differences between histograms with Hits > 16 cut, only 81.75% of the particles have hits > 16 for reconstructed primary particles and 75.12% for reconstructed secondary particles, in both cases the cut in hits mostly restricts the particulates with greater transverse momentum.

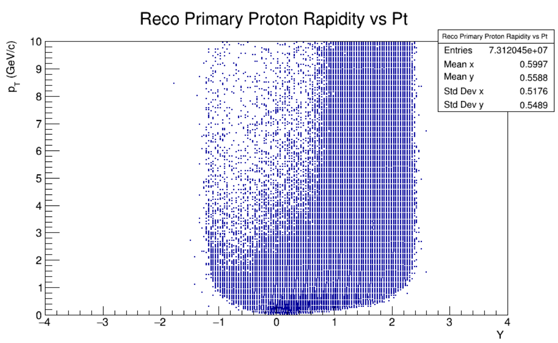
Histograms Protons



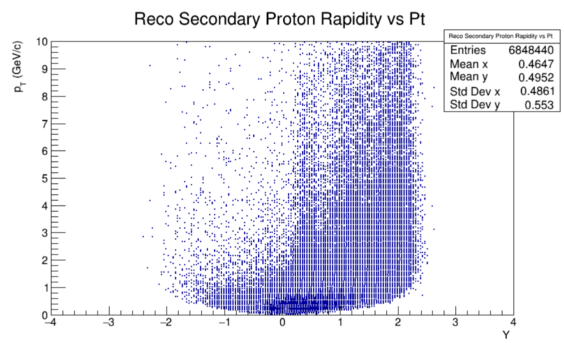
MonteCarlo Track Phase Space for primary particles



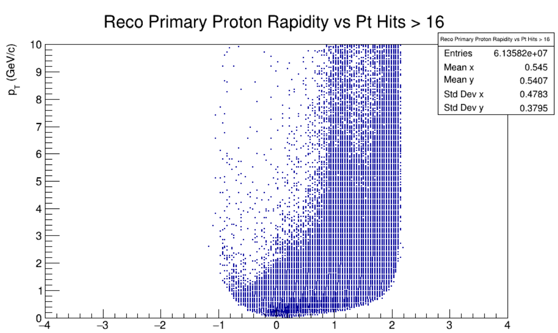
MonteCarlo Track Phase Space for secondary particles



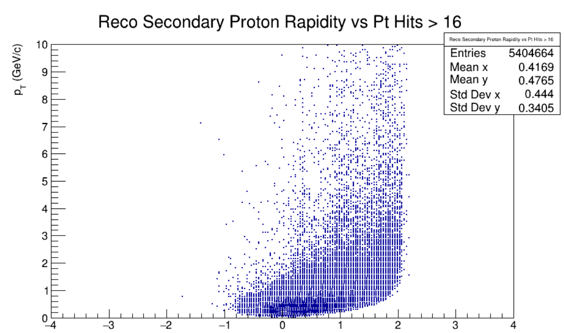
Reconstructed Track Phase Space for primary particles



Reconstructed Track Phase Space for secondary particles



Reconstructed Track Phase Space for primary particles with a cut in hits > 16



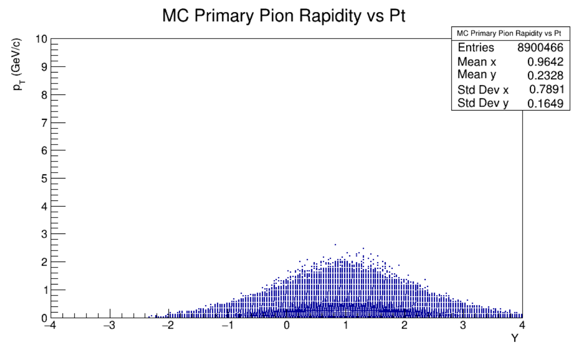
Reconstructed Track Phase Space for secondary particles with a cut in hits > 16

In the Monte Carlo histograms in both cases the particulates are in a range of -1 to 3 in rapidity and 0 to 3 in transversal momentum. In primary particles there are two large concentrations of particles, these concentrations are close to 0 and 2 in rapidity, without exceeding 0.5 at transverse momentum.

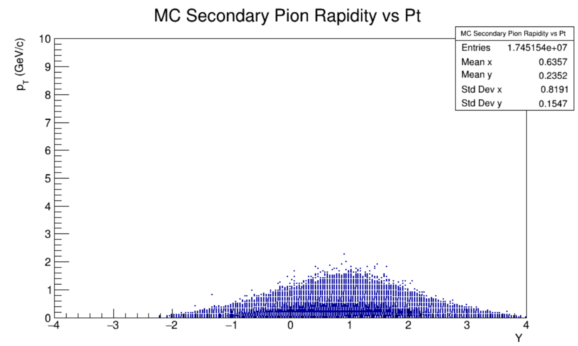
In reconstructed histograms, in both cases the transverse momentum reaches 10 GeV/c. Where for primary particles the highest concentration range is -0.2 to 1 in rapidity and 0.1 to 1 in transversal momentum and for secondary particles the highest concentration range is -0.2 to 1 in rapidity and 0.1 to 0.8 in transverse momentum.

The differences between histograms with Hits > 16 cut, only 83.91% of the particles have hits > 16 for reconstructed primary particles and 78.91% for reconstructed secondary particles, in both cases the cut in hits mostly restricts the particulates with greater transverse momentum.

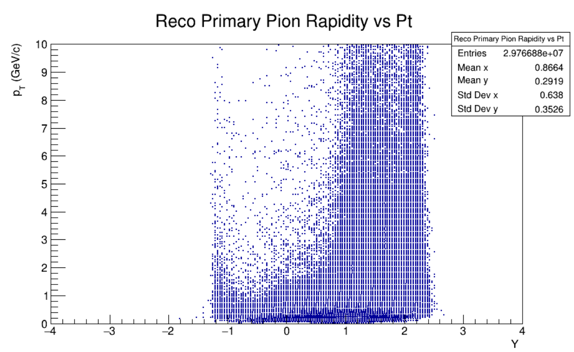
Histograms Pions



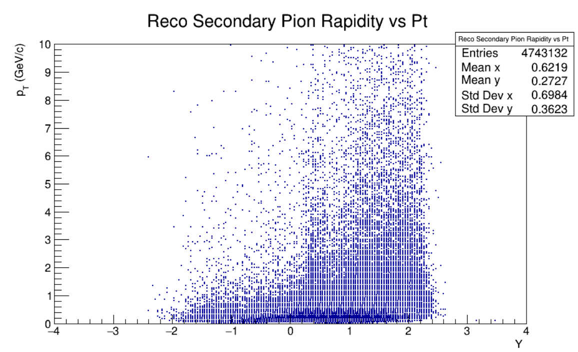
MonteCarlo Track Phase Space for primary particles



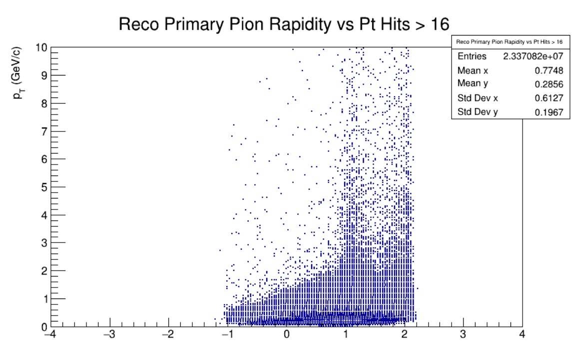
MonteCarlo Track Phase Space for secondary particles



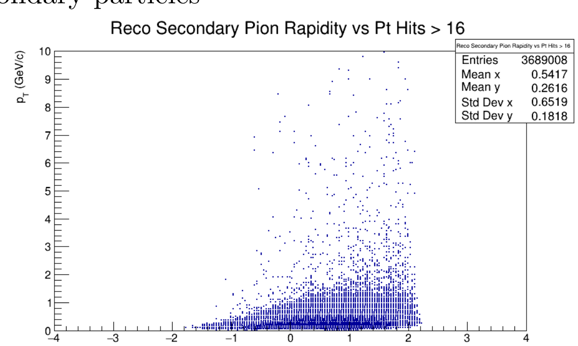
Reconstructed Track Phase Space for primary particles



Reconstructed Track Phase Space for secondary particles



Reconstructed Track Phase Space for primary particles with a cut in hits > 16



Reconstructed Track Phase Space for secondary particles with a cut in hits > 16

In MonteCarlo histograms, the concentration of particulates ranges from -2 to 4 in rapidity and does not exceed 2 GeV/c in transverse momentum. The highest concentration intervals for primary particles range from -1 to 2.8 in rapidity and from 0.1 to 0.6 at transverse momentum for secondary particles from -1 to 2.2 in rapidity and 0.1 to 0.6 at transverse momentum.

In reconstructed the intervals of the particles are -1.4 to 2.4 in rapidity and up to 10GeV/c in transverse momentum, the intervals of higher concentration share them with the Monte-Carlo histograms.

The disparities among histograms with the Hits > 16 cut reveal that only 78.51% of the reconstructed primary particles and 77.77% of the reconstructed secondary particles possess hits > 16. In both scenarios, this cut predominantly limits particles with higher transverse momentum.

Intervals of higher particle density

From all the data we can obtain a table where the intervals of highest concentration of particles for the phase spaces are indicated.

Table of intervals of phase space with higher particle density for MonteCarlo tracks

Histograms	Range Reconstructed pT	Range Reconstructed Y
Primary Kaons	[0.1 , 1]	[0 , 2]
Secondary Kaons	[0.1 , 0.6]	[-0.5 , 1.2]
Primary Protons	[0.1 , 0.4]	[- 0.2 , 0.2]
Primary Protons	[0.1 , 0.4]	[- 1.8 , 2.2]
Secondary Protons	[0.1 , 0.2]	[- 0.1 , 0.1]
Primary Pions	[0.1 , 0.6]	[-1 , 2.6]
Secondary Pions	[0.1 , 0.6]	[-1 , 2]

Table of intervals of phase space with higher particle density for reconstructed tracks

Histograms	Range Reconstructed pT	Range Reconstructed Y
Primary Kaons	[0.1 , 1]	[0.2 , 1.8]
Secondary Kaons	[0.1 , 1]	[0.5 , 1.4]
Primary Protons	[0.1 , 1]	[- 0.2 , 1.4]
Secondary Protons	[0.1 , 0.8]	[- 0.2 , 1.4]
Primary Pions	[0.1 , 0.6]	[-1 , 2.8]
Secondary Pions	[0.1 , 0.6]	[-1 , 2.2]

Conclusion

When comparing both tables, it is observed that the range of highest concentration of particles prevails in both cases. The main difference between the MonteCarlo histograms and the reconstructed ones lies in the transverse momentum intervals, which vary considerably, reaching even 10 GeV/c.

As for the differences between primary and secondary particles, it is noted that primary particles outnumber secondary particles, especially evident in Kaones histograms. On the other hand, the significant differences between histograms with hits cut lie in the reduction of particles with high transverse momentum, which makes the highest density interval in the reconstructed particles more visible. If we apply a stricter hit cut, we could even limit ourselves to the range of higher particle density.

With these results in hand, it is clear that we can conduct studies of many more similar collisions in the future using the same approach and even the same code, which would speed up times and minimize errors. In addition, it is crucial to be more careful when processing and storing the data obtained to avoid complications such as those that arose in this project. Increasing the number of events processed could be beneficial, as it would provide better statistics and allow the detection of possible anomalies that could have gone unnoticed the limited amount of data.

Bibliography

[1] Vahagn Abgaryan, R Acevedo Kado, SV Afanasyev, GN Agakishiev, E Alpatov, G Altsybeev, M Alvarado Hernández, SV Andreeva, TV Andreeva, EV Andronov, et al. Status and initial physics performance studies of the mpd experiment at nica. *The European Physical Journal A*, 58(7):140, 2022.

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[7] fixed. URL https://ed.fnal.gov/painless/htmls/fixed.html.