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

FINAL REPORT ON THE SUMMER STUDENT PROGRAM
Research of the possibility of hypertriton recovery in the BM@N experiment

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Abstract

The BM@N (Baryonic Matter at the Nuclotron) is an experiment at the NICA (Nuclotron-based Ion Collider fAcility) accelerator complex. During the experiment, collisions of flying particles with the target occur. In this case, new particles, such as hypertritons, can be born. When processing the experimental data, it is possible to extract information about the presence of a hypertriton among particle tracks. It is also possible to simulate the birth of a particle beam with the presence of hypertritons. The reconstruction of these data is close to the data of a real experiment. Thus, a study was made of identifying hypertriton tracks among the data.

Contents

Introduction

It is difficult to imagine modern physics without particle accelerators, which make it possible to reproduce a high-energy particle beam colliding with a target made of various materials. One of these is the Nuclotron. It allows you to explore baryonic matter, to explore the birth of hypernuclei. The study of these phenomena allows us to discover the laws of the structure of our world.

1.1 BM@N experiment

The accelerator complex NICA (Nuclotron-based Ion Collider fAcility) is being developed in Dubna on the basis of the Joint Institute for Nuclear Research. It is needed to study the properties of dense baryonic matter, to reconstruct the quark-gluon plasma. One of the components of the complex is the BM@N experiment (Baryonic Matter at Nuclotron). The JINR Nuclotron will provide high-energy heavy ion beams. This will make it possible to carry out work on the formation of strange matter in the course of collisions of heavy ions. Heavy ion collisions at high energies provide a unique opportunity to study the nuclear matter under extreme density and temperature. These extreme conditions are well suited to the investigation of the compressibility of the nuclear matter, in particular, the stiffness of the nuclear equation-of-state (EOS) [1].

The detector system includes STS detectors. These are several layers of silicon sensors that record information about flying particles. They are located perpendicular to the path of the particles, one behind the other. Analysis of the information obtained from these detectors makes it possible to reconstruct particle tracks. The system also includes TOF

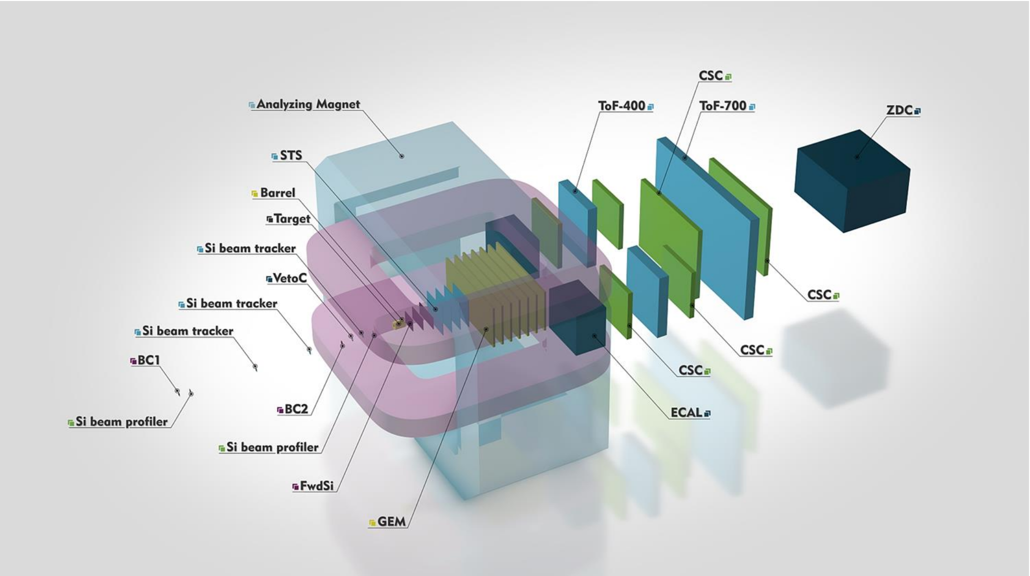

Figure 1.1: The scheme of the BM@N detectors [1]

detectors, TOF 400 and TOF 700. They are located 400 and 700 centimeters from the target. They help to accurately register the time of flight of a particle to the detector, and also determine well the ratio of momentum and particle mass. TOF700 is perpendicular to the particle path, and TOF400 is somewhat around, registering deviating particles.

1.2 Hypertritons

A hypernuclei is a nucleus which contains at least one hyperon (a baryon carrying the strangeness quantum number) in addition to the normal protons and neutrons. Hypernuclei containing the lightest hyperon, the Lambda, live long enough to have sharp nuclear energy levels. Hypernuclei are bound nuclear systems of non-strange and strange baryons. The most studied are Λ-hypernuclei, where a nucleon of the nucleus is replaced by a Λ hyperon, and they are indicated with the usual notation of the nuclei ${}^{A}_{\Lambda}Z$ where A is the mass number and Z the number of proton.
The hypertriton ${}^{3}_{\Lambda}H$ is the lightest Λ-hypernucleus. It is a loosely bound

baryonic system composed by one proton, one neutron and one Λ. It is also the weakest bound strange few-body hadronic system, since the Λ separation energy is only [2]:

$$B_\Lambda = 0.13 \pm 0.05 MeV$$

It was discovered at the beginning of the hypernuclear physics by analising the events produced in the interaction of K^- both in flight and at rest with the nuclei of the sensitive layers of the visualizing detectors used in those years. Several Λ-hypernuclei, including the ${}^3_\Lambda H$, have been found since the beginning of the hypernuclear physics.
These are the possible decay channels of ${}^3_\Lambda H$ [2]:

$${}^3_\Lambda H \to \pi^- + {}^3He$$

$${}^3_\Lambda H \to \pi^0 + {}^3H$$

$${}^3_\Lambda H \to \pi^- + d + p$$

$${}^3_\Lambda H \to \pi^0 + d + n$$

$${}^3_\Lambda H \to \pi^- + p + p + n$$

$${}^3_\Lambda H \to \pi^0 + p + n + n$$

In this study, we will consider only one decay channel, into ${}^3He$ and π^-.

Simulation and reconstruction of experimental data

In order to simulate the events occurring in a real experiment, the Bmnroot software package (simulation and analysis framework for the BM@N experiment) is used. It provides a powerful tool for detector performance studies, event simulation, and development of algorithms for reconstruction and physics analysis of data of the fixed target events registered by the BM@N facility.

1.3 Simulation

In order to simulate the tracks of particles colliding with a target, it is necessary to transfer a data file to the program. These data were previously obtained in a real experiment. It is also necessary to specify the type of generator to use.
To simulate real events, the DCMSMM generator is used. This is a monte-carlo generator of heavy ion collisions, based on Dubna Cascade Model (DCM-QGSM) and Statistical Multifragmentation Model (SMM) [3]. The model aimed to generate particle—nucleus and nucleus—nucleus collisions at a wide range of energy was created to provide the computer simulation support to new experimental facilities BMN and MPD at the accelerator complex NICA. It can simulate the production of both light particles and nuclear fragments and hyperfragments on the event

by event basis.
The problem is that hypertritons are born extremely rarely, which means that even for a small number of them, a lot of events will have to be simulated. The solution is to artificially add hypertritons to each event. This does not correspond to reality, but it allows us to have a sufficient number of hypertritons among the data, which facilitates analysis. We use the MpdHypYPtGenerator generator to add hypertritons to the events. You can set the probability of the birth of hypertritons and their number. We added strictly one hypertriton to each event. At the output, we get a .root file with a tree with various information about the simulated particle tracks.

1.4 Reconstruction

This file is passed as input to the reconstruction algorithm. According to available data, it recreates the pattern of particle tracks in the form in which it is obtained in a real experiment on detectors. Reconstruction algorithms are not perfect, so it is not always possible to reliably state that these data reflect the real pattern of particle tracks. Reconstruction errors occur, tracks can change their appearance significantly. This complicates data analysis, since the resulting tracks can create the illusion of good results or dependencies, or smear the desired dependencies.

Hypertriton modelling

1.5 Hypertritons only. Simulation

First, there is a desire to understand exactly how the simulated hypertritons behave. To do this, a simulation was launched in which only a hypertriton was born in each event, without other particles. We need to consider exactly those events in which the decay into ^3He and π^- occurred. MCTracks in the simulation contain information about their PDG code, for a hypertriton it is 1010010030 [4], as well as the ID of their parent particle. This allows us to trace the decay products of the hypertriton, and consider only those where there are particles we need. Out of 30,000 events, we received 7377 events containing the desired decay. That is, the probability of this decay path is about 25%. We can calculate the value of the invariant mass for this pair, get the reference value – 2.992 at fig.1.2.

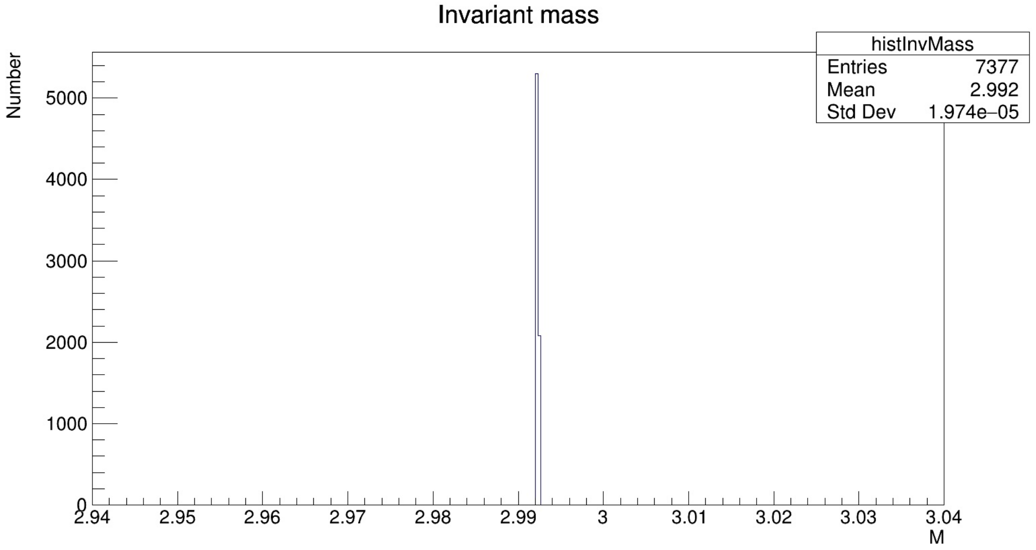

Figure 1.2: Distribution of invariant mass for ${}^{3}_{\Lambda}H$

Plotting various graphs gives information about what values the particles can take in the simulation, which then allows you to more effectively filter out unsuitable tracks in events. But the complexity is caused by the uniform distribution of some values, the values are rather blurred. For example, the total momentum of helium-3 at fig.1.3

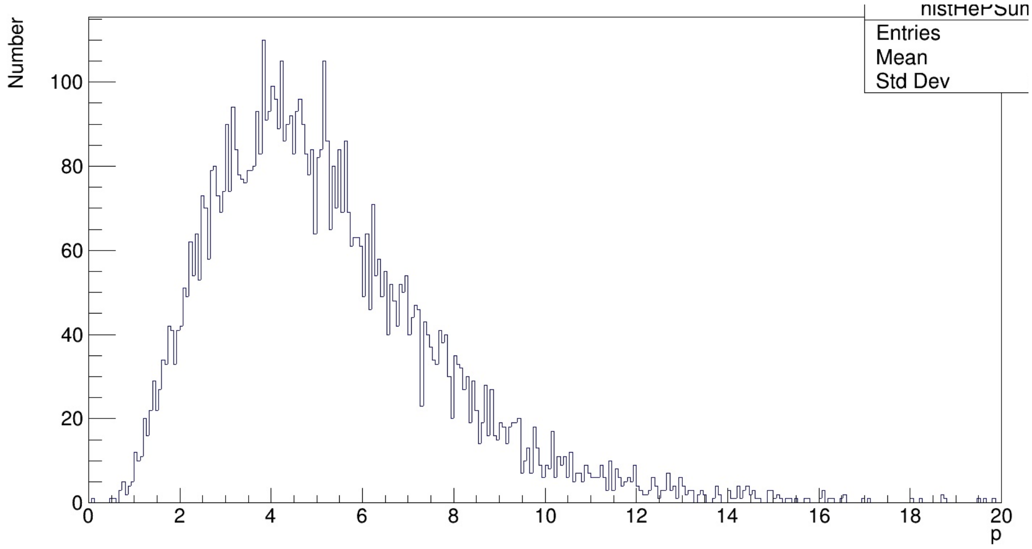

Figure 1.3: Distribution of total momentum for ${}^{3}He$

We can also look at the ratio of momenta between ^3He and π^-, in order to further take into account what values these values lie within at fig.1.4.

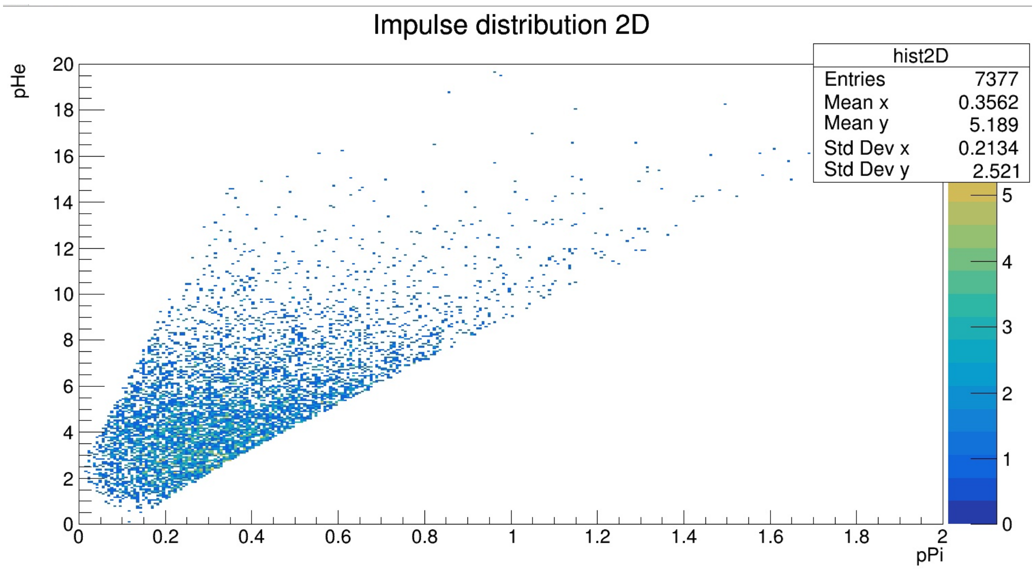

Figure 1.4: Distribution of ^3He and π^- momentum

1.6 Hypertritons only. Reconstruction

When we reconstruct events, errors occur, meanings are blurred. We get a dataset in which the StsTrack and BmnGlobalTrack branches are of most interest. The first one contains information about particle tracks that were registered with STS detectors. They contain information about the particles at the time of flight, namely the coordinates, the sign of the charge, the total momentum, and the tangent of the momentum along the X and Y axes relative to Z. All particles fly along the Z axis. The magnetic field is taken into account, so particles of different signs deviate in different directions . The second branch, BmnGlobalTrack, contains information about particles that passed through the TOF400 or TOF700 detectors. These detectors determine the coordinates poorly, but determine the particle momentum and the momentum-to-mass ratio well.

1.7 Data generated with DCMSMM

When generating events using DCMSMM and artificially adding hypertritons to events, we get a large amount of data with different values. The data is very noisy, so it is necessary to impose many restrictions on various parameters in order to improve the situation. It is required to generate a large number of events on the cluster so that the statistics are not cut off to single events when the cuts are applied. The analysis is complicated by simulation and reconstruction errors, so it is impossible to say for sure about the reality of some values. С помощью этих значений можно построить так называемый "banana-plot". The dependence of $\beta = \sqrt{\frac{p^2}{m^2+p^2}}$ on momentum p is plotted. Then each line on the graph will correspond to its own type of particles. An example is shown in fig.1.5:

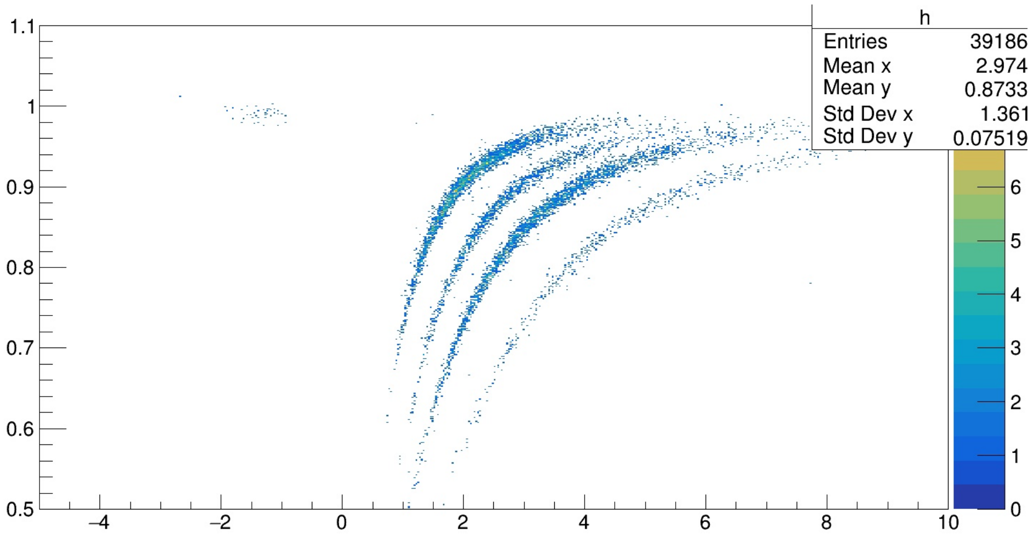

Figure 1.5: Banana-plot

The first line on the left corresponds to the deuteron, the second to helium-3, and the third to the proton.

Imposing cuts on data and the results of this

In order to single out the peak corresponding to the hypertriton in the distribution of the invariant mass, it is necessary to correctly select various restrictions on the data. To do this, we will iterate over pairs of particle tracks in each event. For this pair, consider the invariant mass. Let's single out several main features that events should correspond to:

- The restored vertex in the — event is obtained from the PrimaryVertex, must be near the actual location of the target. We use the deviation from this value as a parameter and limit it.
- The number of tracks in the event must be greater than 1. Otherwise, it will not turn out that the hypertriton was in the event and broke up.
- At least one helium-3 must be present in the event. How this selection takes place will be described below.

The first step in considering the particle tracks themselves is to consider BmnGlobalTrack. You can get the β values for banana-plot, but don't look at it specifically because the plot is in the form of curved lines. Instead, we express mass and plot mass versus momentum. On this graph, straight lines limit the zone into which helium-3 can fall. If there are tracks in the event that fall into this zone, then they are written to the vector, and the rest of the particles will be moved further only with elements of this vector. If not a single helium-3 was detected in the event, then it is skipped. We chose ^3He over π^- as it is a heavier particle that travels straight enough to reach the TOF400 or TOF700 detectors. Next, we put the rest of the particle tracks in this event into another array, and consider them in pair with the supposed helium-3. We assume that this particle may be π^-, so we check if they meet the following criteria:

- The particle track is reconstructed in the vertex plane by the Kalman filter.
- The particle has a negative charge.
- There must be at least one such particle in the event.

Now we have two arrays. One contains the suggested ^3He, the other contains the suggested π^-. The enumeration of these pairs among themselves begins.

For each pair, a point is sought at which the distance between them is minimal. This means that the hypertriton could presumably decay at this point. The search is carried out using the Kalman filter. Since this is only an approximation, it is impossible to say for sure that the particles moved along the tracks that the Kalman filter suggests. This leads to an increase in error and an increase in the number of errors.

When the minimum distance is found, we write each pair as BmnParticlePair. The following is a list of the parameters of each pair that we apply cuts to:

- Invariant mass of two particles;
- Path from vertex to decay point;
- DCA12 – minimal distance between particles;
- V0X – coordinate of decay point
- V0Y – coordinate of decay point
- V0Z – coordinate of decay point

- DCA1 — distance from the point restored in the plane of the vertex to the vertex;
- DCA2 — distance from the point restored in the plane of the vertex to the vertex;
- Momentum — momentum of each particle;
- Tx — momentum projection ratio $\frac{p_x}{p_z}$ for each particle;
- Ty — momentum projection ratio $\frac{p_y}{p_z}$ for each particle;

Next, we run through all these pairs and impose restrictions on them. For this, the dependences of the invariant mass on these quantities are constructed. Those values that do not correspond to the desired value of the invariant mass are limited. Thus, we suppress the background by discarding the pairs.

The following is the distribution of the invariant mass after applying the optimal cuts. Of the 1,600,000 pairs obtained after the simulation, about 60,000 satisfied the conditions, that is, only about 4%.

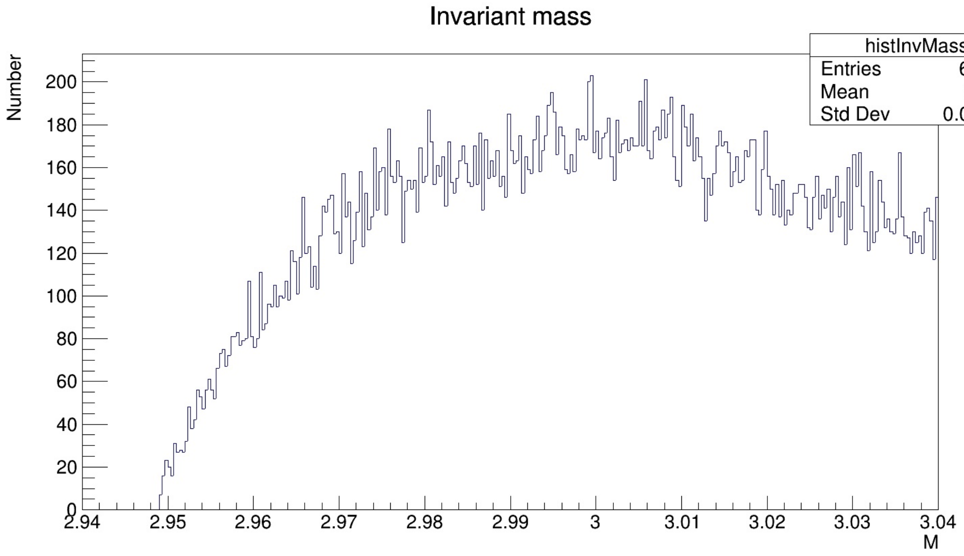

Figure 1.6: Distribution of invariant mass in data

You can compare the resulting distribution with fig.1.2. Despite the fact that a significant part of the background was cut off, no significant peaks appeared on the graph. In the future, it is necessary to prepare qualitative events containing only hypertritons, and, for example, protons. Reconstruction of such events should help to see a clear picture, which is restored by algorithms. Thus, the problem may be related to the imperfection of the simulation and event recovery algorithms. Hypertritons can blur and dissipate, so it could be that we see a very blurry peak in fig.1.6.

Summary

During the summer student program, significant progress was made in the reconstruction of hypertritons. Various possible constraints on the track parameters were investigated to distinguish hypertritons from other particles. The realism of generation and reconstruction of tracks was also investigated. As we have seen, algorithms are not perfect and deviate from assumptions. In the future, when the BM@N experiment is carried out, the developed macros will be applied to the obtained data for analysis.

Bibliography

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