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

FINAL REPORT ON THE START PROGRAMME

Feasibility study of K_s^0 in the BM@N experiment

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Abstract

Relativistic heavy ion collisions enable the study of nuclear matter in cases of extreme density and temperatures. Nuclear matter is being heated up and compressed for a very short period of time during such collisions. At higher temperatures there is a presence of a mixture of baryons, antibaryons and mesons[1], denoted as hadronic matter or baryonic matter, if baryons dominate. In case of the energy density in the formed fireball being sufficiently large, the quark-gluon substructure of nucleons becomes visible. At even higher temperatures or in case of larger densities the hadrons melt and the constituents (quarks and gluons) form the so-called Quark-Gluon Plasma (QGP). It is possible to study the following features of the strongly interacting matter at these extreme conditions: the equation-of-state (EoS) of strongly interacting matter at high temperatures and high net-baryon densities, the microscopic structure of strongly interacting matter as a function of temperature and baryon density, the in-medium modifications of hadrons which might provide information on the onset of chiral symmetry restoration. As theoretical models suggest different possible scenarios to describe these features of strongly interacting matter, new experimental data with high resolution is needed to be able to keep track of all the different theoretical predictions [1], [2].

[1] All strongly interacting particles.

Contents

1 Introduction

1.1 BM@N experiment

The BM@N[2] experiment is being presented in Figure 1. The aim of the experiment is the study of collisions of elementary particles and ions with a fixed target at energies up to 4 GeV per nucleon[3] in the laboratory system. The experimental facility is one of the main elements of the first stage of the NICA collider development and will be used to study hot and dense matter in heavy ion collisions.

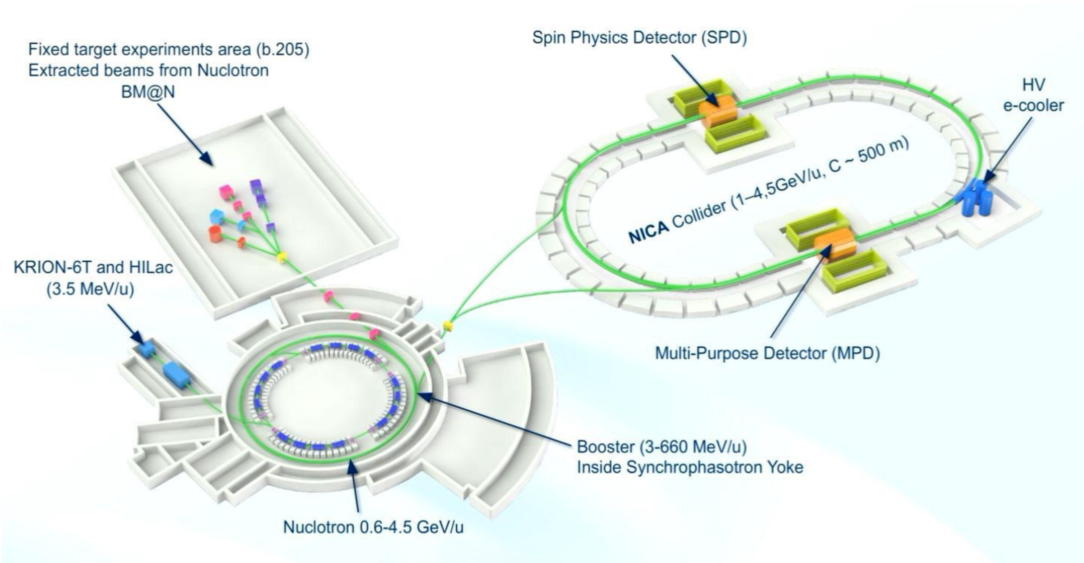

Figure 1: BM@N experiment extracted from the Nuclotron beam [3]

[2]Short for Baryonic Matter at the Nuclotron.
[3]For Au^{79+}.

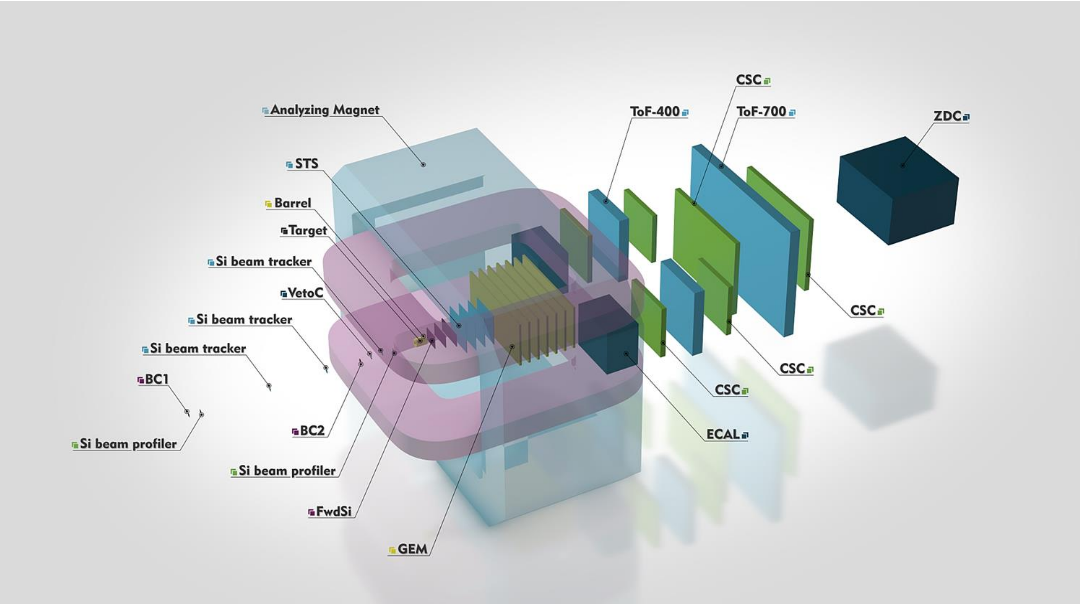

Figure 2: A 3D view of the BM@N facility

Figure 2 conveys a 3D view of the BM@N facility. The proposed themes of study are the following: elementary reactions (p + p, p + n) and cold nuclear matter (p + A), the properties of dense baryonic matter in heavy ion collisions with fixed target, in-medium effects, hypermatter production, strangeness and hadron femtoscopy. Such parameters as particle yields, tranverse momentum spectra, rapidity and angular distribution will be studied as a function of the collision energy and centrality.

The facility has to identify the produced particles with a high efficiency and estimate their parameters with high precision in order to able to perform a proper study of the hot matter. To achieve this high precision and efficiency BM@N combines high precision track measurements with time-of-flight information registered by detectors[4] and total energy measurements for event characterization. The setup as shown in Figure 2 divides the detectors for particle identification into "near to magnet" and "far from magnet" to measure particles with both low and high momenta.

The target of the beam is located inside the large-acceptance dipole magnet with the magnetic field of up to 0.35 T for the y-projection. In order to increase the efficiency of particle identification, the intermediate detectors occupy the space between the magnet and the "far" detectors. A ToF (Time-of-Flight) detector is used to identify hadrons and light nuclei, while ZDC (Zero Degree Calorimeter) is used to measure centrality of the collisions. The recoil detector is emloyed for the independent analysis of collision centrality by measuring the energy of the target fragments.

1.2 BmnRoot framework

In order to support the BM@N experiment, a software framework BmnRoot has been developed. It is a powerful tool for detector performance studies, event simulation and de-

[4] For particle identification.

velopment of algorithms for reconstruction and physics analysis of data of the fixed target events registered at the facility. The framework is implemented in the C++ programming language and is based on the ROOT environment [4] and object-oriented framework FairRoot[5] [5].

The strength of the BmnRoot framework is in its modularity. The parts of the framework which are related to physical processes and detection can be realised by different groups. The detector response is currently being simulated by means of a package based on the so-called Virtual Monte Carlo concept[6] and allows an interchange between Geant3, Geant4 and Fluka transport packages without changing the user code. In order to enable a realistic simulation of various physics processes, an interface to event generators for nuclear collisions[7] has been provided.

1.3 Simulation and reconstruction

1.3.1 Virtual Monte Carlo

There are two ways to simulate the behavior of a certain system: an analytical description of its evolution[8] or a probabilistic approach[9]. When dealing with interactions of particles with matter, one usually opts for the second approach due to the variety of possible physical processes and their discrete nature. Such a methodology is known as "Monte Carlo" method because of it being based on pseudo-random numbers.

TVirtualMC class of the ROOT environment provides a virtual interface to Monte Carlo applications, which enables the user to create a simulation independent of any actual underlying Monte Carlo implementation itself. It is possible to select one of the concrete Monte Carlo implementations [10] at run time, which allows one to have a comparison between different engines[11] using a single application. The concept of a Virtual Monte Carlo was originally developed by the Alice Software Project [6].

Monte Carlo simulators describe the "input" particles of the process at hand, their interactions and the detector in question. The definition of all of the above-mentioned parameters occurs during the initialization phase. Tracing happens in the following discrete fashion: the volume of the detector is found where the particle is located at the time[12], which is then followed by the saydrawing[13] of one of the many possible physical processes to simulate the interaction of the particle within the matter. In case of an interaction taking place, the energy lost by the particle due to this event is computed and subtracted

[5] A framework for the FAIR experiment at GSI Institute.

[6] This concept will be explained in detail later on in the report.

[7] Such as UrQMD, Pythia and FastMC.

[8] In this case computers are used to find the solution of the dynamic equations.

[9] In this case pseudo-random numbers are used at each step to select one physical process amongst many.

[10] Such as Geant3, Geant4 and Fluka.

[11] This is necessary to estimate the theoretical uncertainties.

[12] At each step.

[13] Pseudo-random numbers are employed in this process.

from its kinetic energy. As soon as the value of the latter reaches zero, the particle stops propagating through the volume and thus the computation is concluded.

After having computed all the energy losses of all the particles, one has to simulate the behaviour of the read-out electronics. This process usually also involves usage of pseudo-random generators, at least to simulate finite resolution of any real measuring device.

The Virtual Monte Carlo (VMC) enables one to run different Monte Carlo simulations without changing the user code and therefore the input and output format, as well as the geometry and detector response definition. It provides a set of interfaces which completely decouple the dependencies between the user code and concrete Monte Carlo. The implementation of the VMC interface is provided for two Monte Carlo transport codes, Geant3 and Geant4 and is now fully integrated with ROOT geometry package TGeo. Users can easily define their VMC application by means of TGeo geometry definition, as is shown in Figure 3.

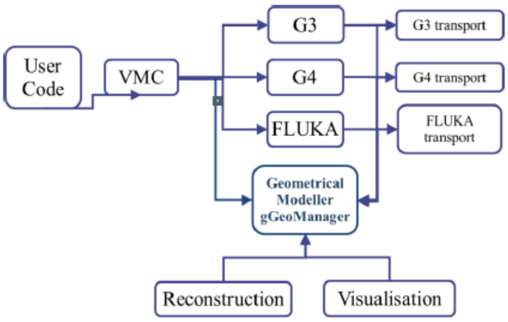

Figure 3: Geometrical Modeller for the MC simulation and subsequent use in reconstruction and visualization [3]

1.3.2 Event generators

Event generators are software libraries that randomly generate high-energy particle physics events. Monte Carlo (MC) generators are nowadays essential components of experimental analyses and also widely used by theorists[14].

MC generators allow one to include theoretical models, phase space integration in multiple dimensions, detector effects, efficiency and acceptance determination for new physics processes. All events generators split the simulation up into a set of phases, such as initial-state composition and substructure, hard process, parton shower, resonance decays, multiple scattering, hadronization and further decay. As a result, event generator produces final state particles which are then fed into the detector simulation, allowing a precise prediction and verification for the entire experimental setup.

BmnRoot supports an extended set of event generators for particle collisions, many of which are commonly being used in HEP experiments. The complete list of the supported generators is provided in Figure 4.

[14] To compare experimental results with theoretical predictions.

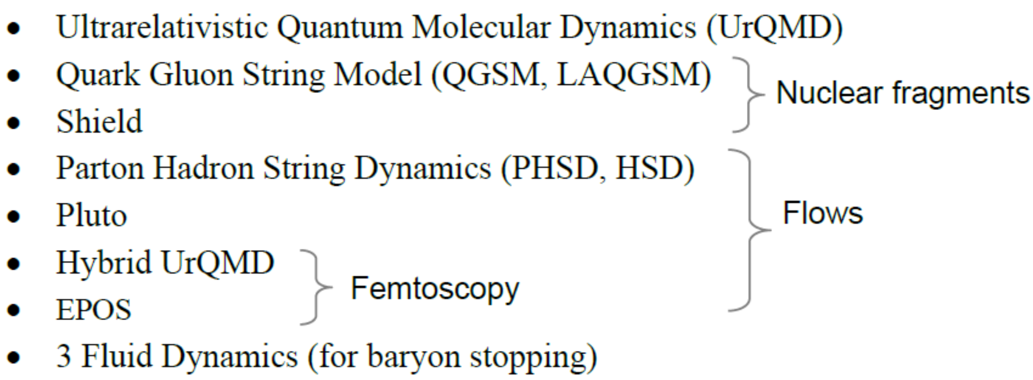

Figure 4: List of the event generators supported by the framework BmnRoot

The place of event generators in the process chain of a high energy physics experiment is shown in Figure 5.

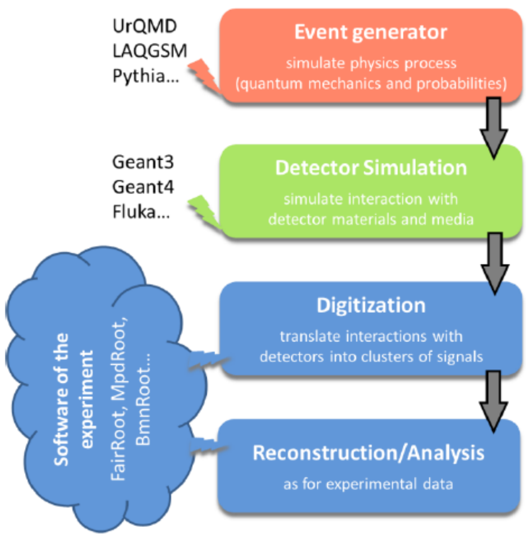

Figure 5: Simulation and analysis steps of high energy physics experiment

Figure 6 zooms in on the chain conveyed in Figure 5, but explicitly for the BmnRoot framework.

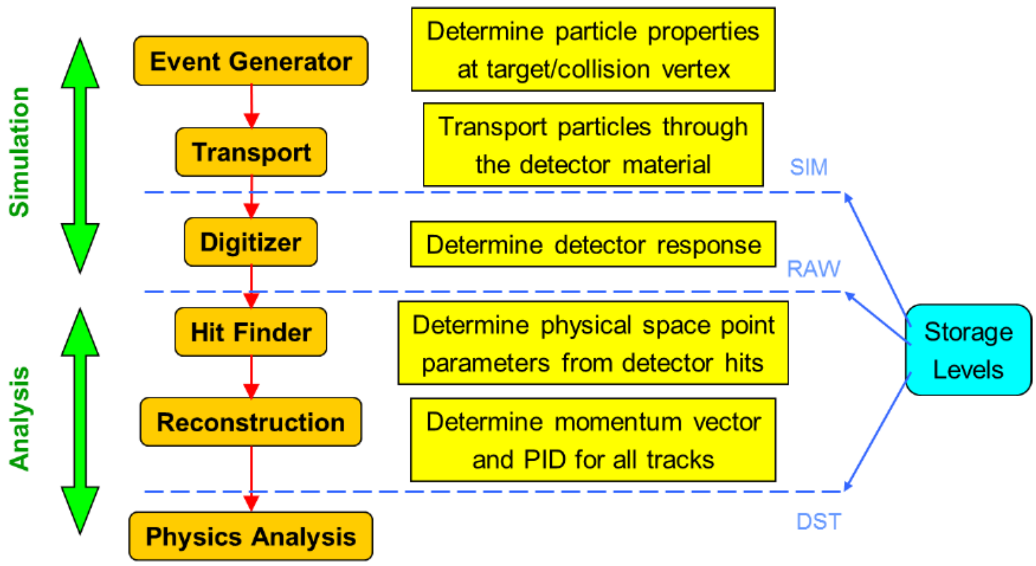

Figure 6: Simulation and analysis steps of the BM@N experiment

1.3.3 Simulation of the BM@N experiment

Simulation of the BM@N experiment encompasses particles of interest, their interactions, geometry of the detecting system, materials used, generation of test events of particles, records of energies and tracks and visualization of the detector system and collision events.

Transport packages are used to move the particles through the experimental setup from initial state[15]. One of such packages is Geant[16], which was developed at CERN and is most commonly used today.

Transport packages entail detailed description of detector geometries and propagation of all the particles through detector materials and media, while the detector geometries are described by Geant and native geometric models. During tracking Geant creates detector responses[17], which are then being employed in the process of reconstruction. In order to evaluate both software and detector performance, reconstructed information concerning the particles is compared with the information taken directly from Monte Carlo generation.

1.3.4 BM@N event reconstruction

Event reconstruction refers to the process of interpreting electronic signals produced by the detector to determine the original particles that passed through, several of their characteristics[18] and the primary vertex of the event. Event reconstruction consists of the following main steps:

[15] Origin files produced by event generators.
[16] Short for "geometry and tracking".
[17] More often referred to as hits.
[18] Momenta and directions.

- Hit reconstruction in subdetectors
- Track reconstruction
- Vertex finding
- Particle identification

One of the common approaches to the track reconstruction in experimental high energy physics is the so-called Kalman filtering technique. This particular method enables one to combine the processes of pattern recognition and track fitting[19]. Kalman filter is a set of mathematical equations that provides a recursive solution of the least-squares method. The algorithm starts off with track candidates[20], which are then propagated to some surface[21]. A new covariance matrix can now be obtained using the Jacobian matrix of the transformation. Another method of track reconstruction being employed by BmnRoot is the L1 (CBM) tracking.

Tracks are usually defined by an integer identification number[22], the parent track[23] and a particle object. Each track also might contain a set of "daughters", which refers to the secondary tracks originating from them.

Vertex finding is interesting to us due to the fact that knowledge of the position of the primary vertex improves the moment resolution and the efficiency of finding the second vertices. The primary vertex is found by extrapolating all the reconstructed primary tracks back to the origin. The global average of the distribution of the primary track's extrapolation at the origin is the vertex position. Figure 7 shows the processing chain for experimental and simulated data.

[19] The technique handles multiple scattering in a proper way as well.
[20] Vectors of initial parameters and covariance matrices are evaluated for these candidates.
[21] Detector or intermediate point.
[22] Also known as the "PDG code from Particle Data Group"
[23] If there are any.

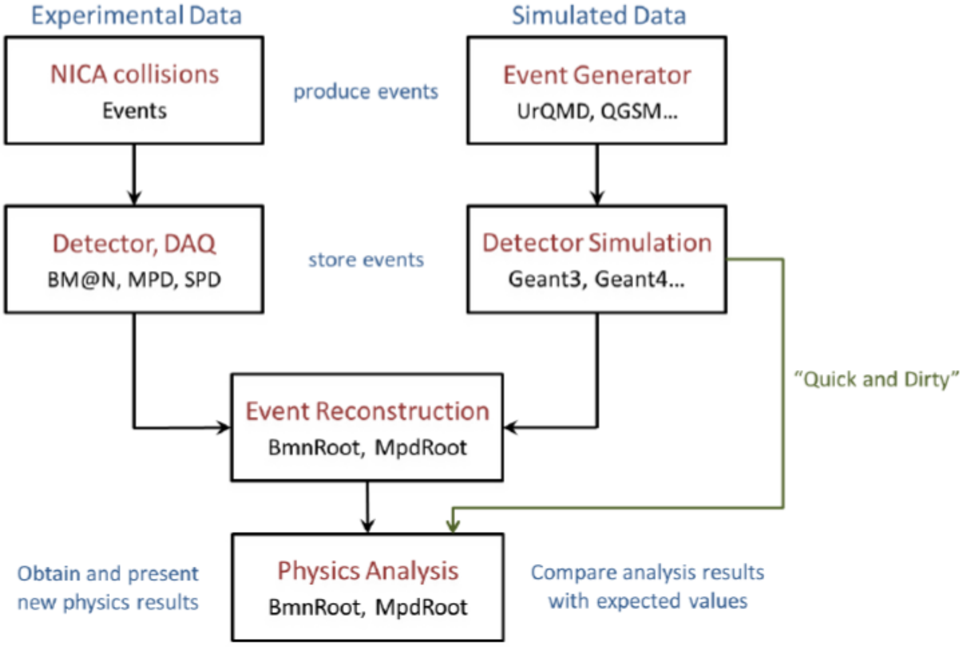

Figure 7: Processing chain for experimental and simulated data

2 Goal of the project

As mentioned in the abstract and section 1.1 of this report, it is expected from the theoretical models that the transition from the hadronic matter to Quark-Gluon-Plasma is accompanied by the formation of strange particles. The aim of this work was to show whether it is possible to find one of these particles, K^0_s, from the reconstructed tracks. Firstly, a quick acquaintance with the software employed at the BM@N experiment occurred. Secondly, data from the event generators was examined in order to ensure the correctness of the proposed algorithms for particle search. Finally, the algorithms mentioned above were set loose on actual experimental data.

3 Methods of work

The BmnRoot framework was used in order to perform all the necessary simulations, reconstructions, data storage, calculations and visualizations. All the scripts were written in C++ programming language and NICA Cluster was employed in order to parallelize the computations.

4 Results

Although our interest lies in finding K_s^0 in reconstructed tracks, one needs to keep in mind that it will decay after a certain amount of time[24]. There are two possibilities:

$$K_s^0 \rightarrow \pi^+ + \pi^- \tag{1}$$

$$K_s^0 \rightarrow \pi^0 + \pi^0 \tag{2}$$

As neutrally charged particles are not being detected at the BM@N experiment, only decay (1) is of interest.

Figure 8 conveys the invariant mass of K_s^0 [25].There is a clear peak slightly below 0.5 GeV[26], as one would expect.

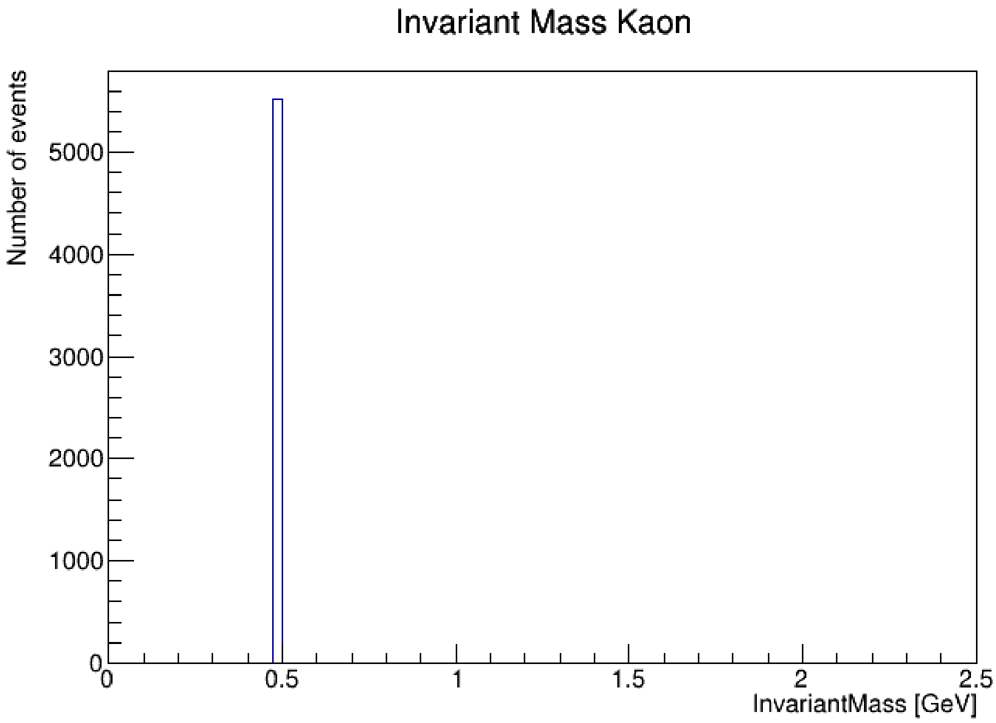

Figure 8: Invariant mass of K_s^0

Figure 9 shows the invariant mass for the sum of the two pions, once again according to our expectations.

[24]The mean lifetime of K_s^0 is $(8.954 \pm 0.004) * 10^{-11} s$.
[25]The PDG identification was employed in the algorithm used.
[26]The mass of K_s^0 is 497.611 ± 0.013 GeV

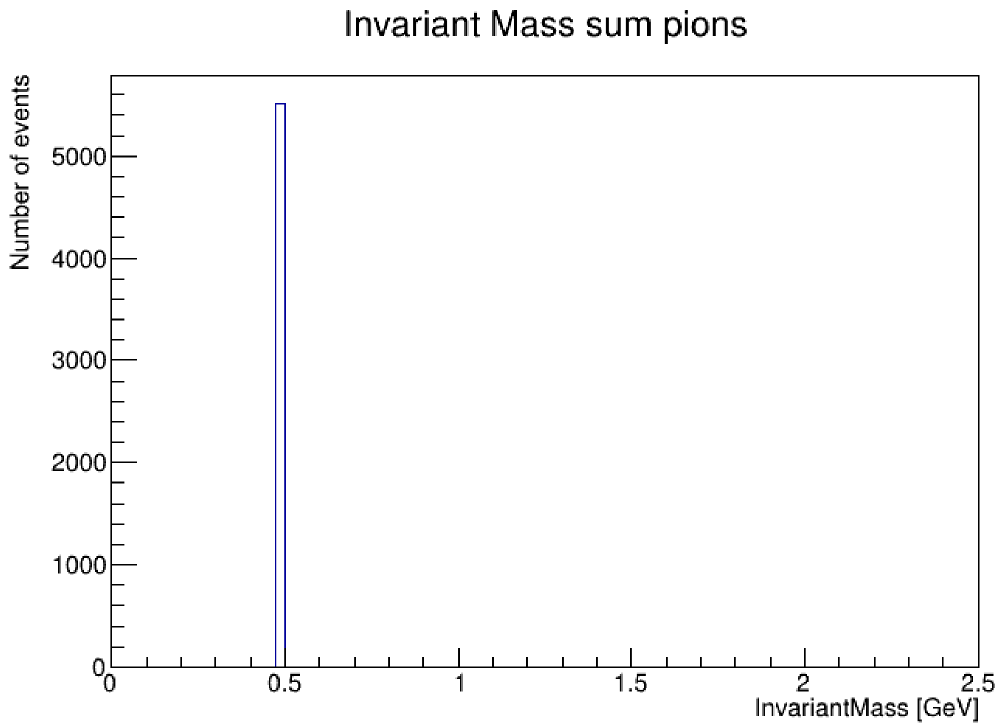

Figure 9: Invariant mass of the sum of pions

In order to be able to locate the kaons of our interest, one must study the invariant mass of all the particles that have slipped through the searching algorithm. To improve the efficiency of kaon observation, a closer look was taken at the dependencies between several parameters and the invariant mass of the reconstructed particle. Several of these parameters are displayed in Figure 10.

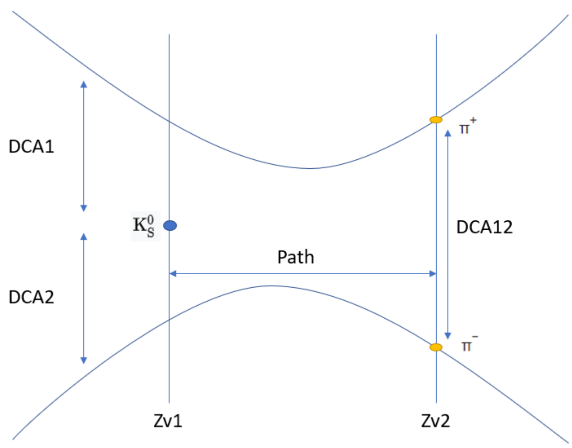

Figure 10: Different parameters considered when looking for K_s^0

The blue dot on the left is the supposed kaon. V_1 is the first vertex and is the assumed place of first appearance of (in the reconstruction) of K_s^0. V_2 is the second vertex and is the assumed place of decay of K^0_s into two pions. Z_{v1} and Z_{v2} are the locations[27] of the first and second vertex respectively. Path is the distance which the kaon is going to travel before its decay. Parabolic lines represent the movement (on the right side of the yellow circles) and reconstruction by means of Kalman filtering (on the left side of the yellow circles) of the two pions[28]. DCA12 is the distance between the two pions, while DCA1 and DCA2 are the distances between one of the pions and K^0_s. As our search of interest is limited to K^0_s, one would like DCA12 to be as small as possible and both DCA1 and DCA2 to be as large as possible[29]. Other parameters of interest are the impulses of the pions and their pseudorapidities.

Figure 11, Figure 12, Figure 13, Figure 14, Figure 15 convey a one-dimensional plot of the invariant mass and four two-dimensional plots of the invariant mass against several parameters of interest respectively.

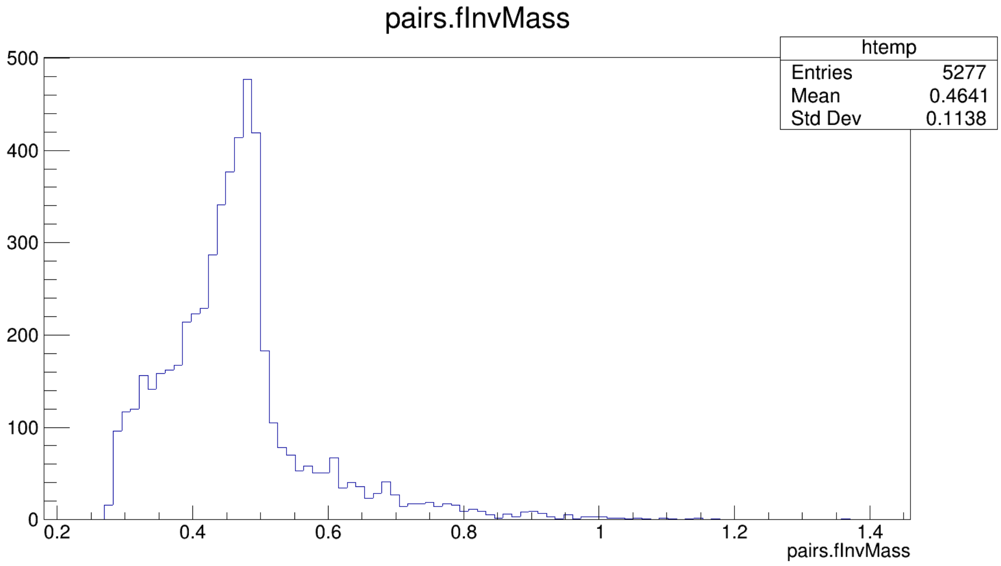

Figure 11: Invariant mass in case of event generation data and usage of PDG identification

[27] Z-coordinates, to be precise.

[28] The mirroring of the parabolas is due to charge difference of the pions.

[29] With reasonable limitations, of course.

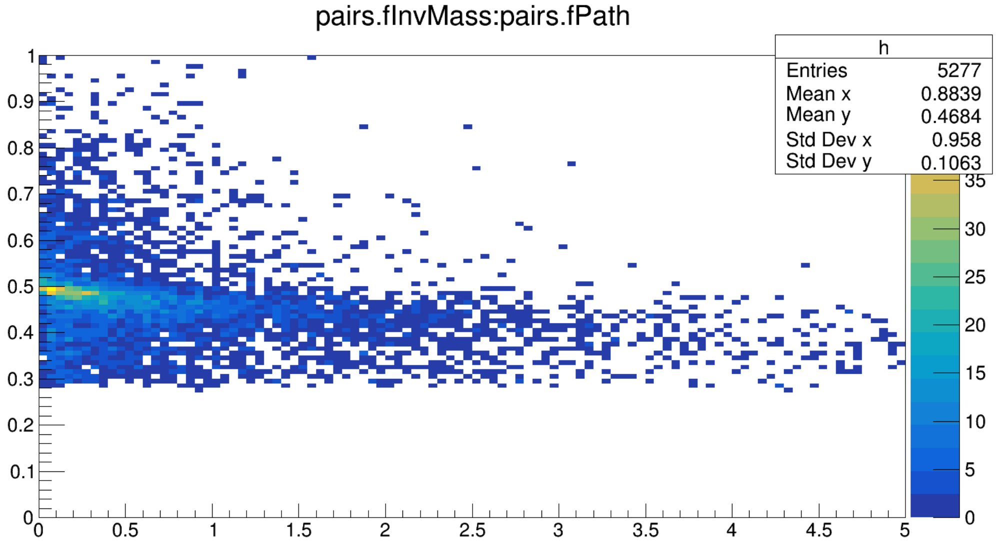

Figure 12: Invariant mass vs path in case of event generation data and usage of PDG identification

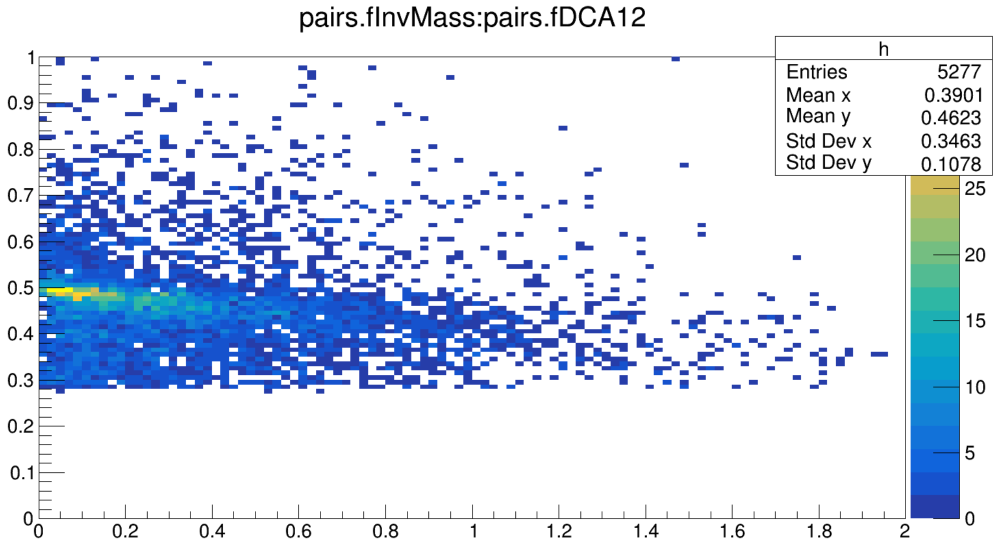

Figure 13: Invariant mass vs DCA12 in case of event generation data and usage of PDG identification

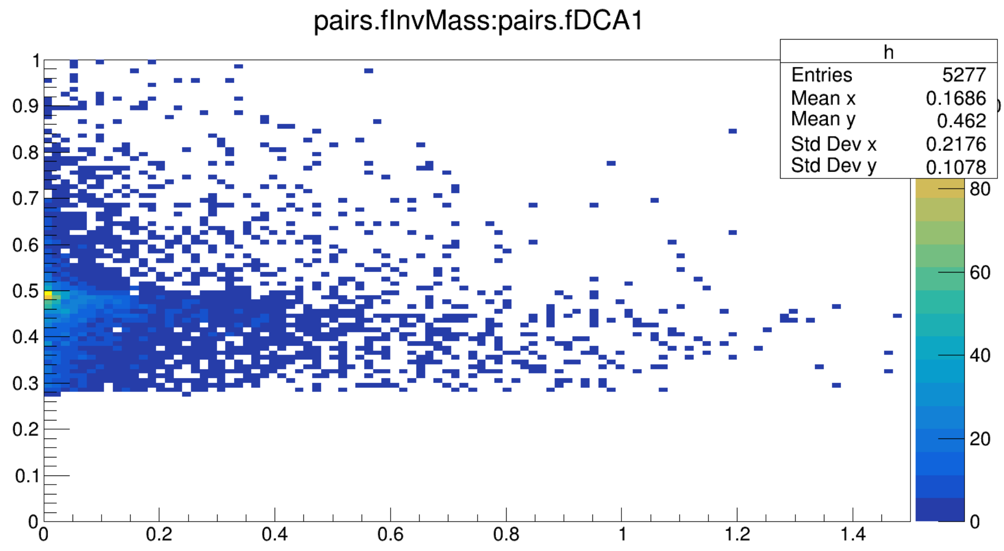

Figure 14: Invariant mass vs DCA1 in case of event generation data and usage of PDG identification

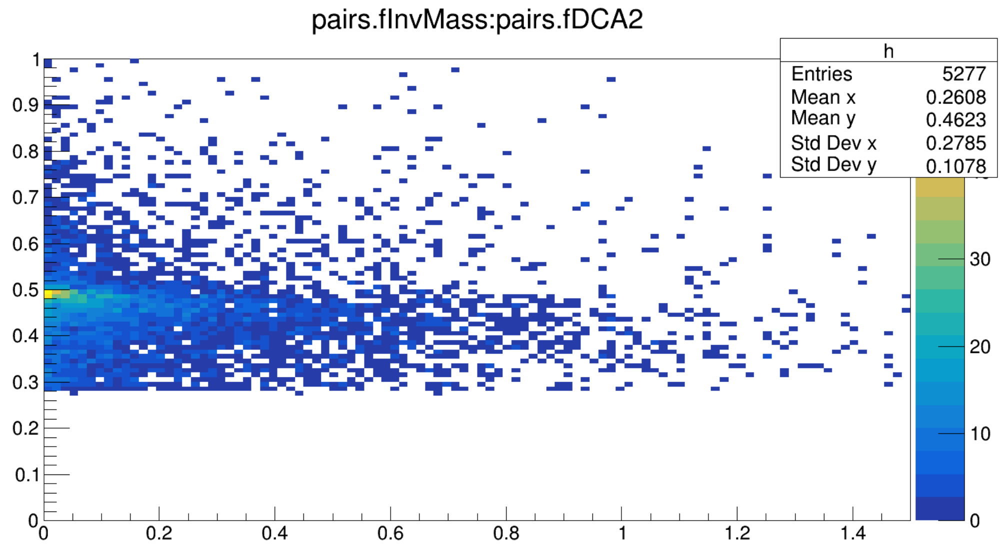

Figure 15: Invariant mass vs DCA2 in case of event generation data and usage of PDG identification

There is a clearly noticeable peak just below the value of 0.5 GeV in Figure 11 and there is a trace around the same value in Figure 12, Figure 13, Figure 14, Figure 15. However, this value does deviate from the mass of K_s^0, which implies that even when employing event generation and PDG identification of particles there is quite a lot of noise one has to deal with.

Figure 16 shows the invariant mass in case of employment of the searching algorithm on experimental data, while Figure 17 conveys two-dimensional plots of relationships between the above-mentioned parameters and the invariant mass.

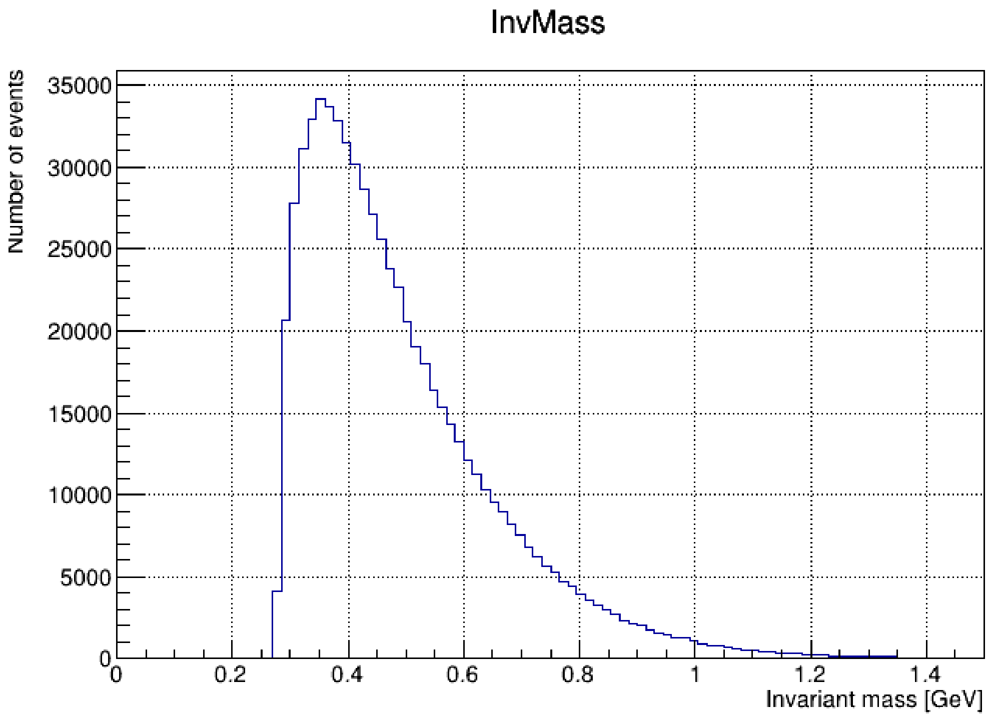

Figure 16: Invariant mass in case of working with experimental data

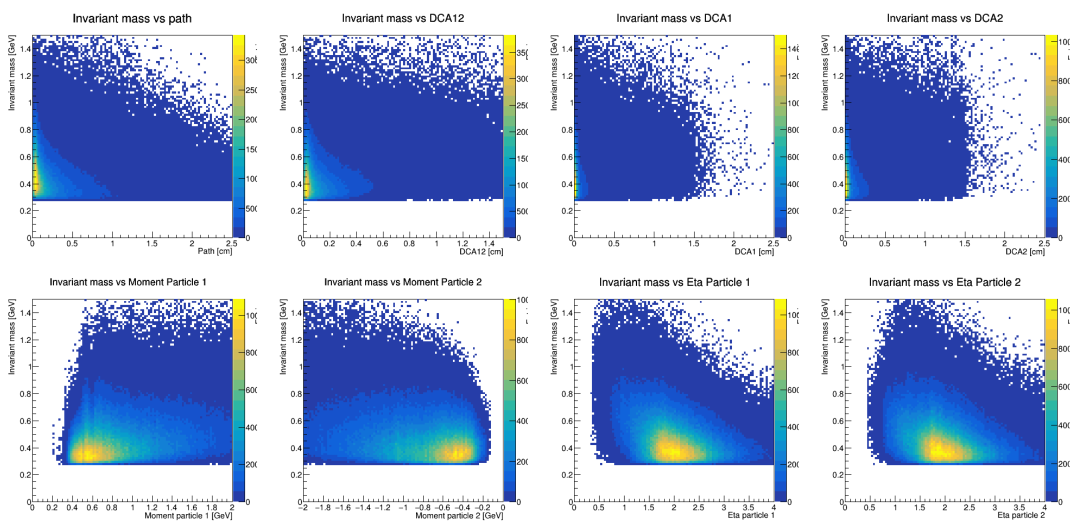

Figure 17: Two dimensional plots of relationships between the above-mentioned parameters and the invariant mass

There is no noticeable peak around 0.5 GeV in Figure 16 and there is nothing very promising to observe in Figure 17. That means that the search for K^0_s in experimental data has yet to be concluded.

5 Conclusion and future work

An acquaintance with the BmnRoot framework has taken place and K_s^0 was located in case of event generated data. Unfortunately, the particle has yet to be observed when making use of experimental data.

The next logical step would be to increase the amount of data in order to ensure that the desired signal does not disappear in all the noise that falls outside our interest. This work is currently ongoing.

References

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