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

FINAL REPORT ON THE START PROGRAMME

Analysis of hypernuclei in simulated data of the BM@N experiment

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Abstract

This work is devoted to the study of the simplest hypernuclei, namely $^3H_\Lambda$ (consisting of one proton, one neutron, and one Λ-hyperon) and $^4H_\Lambda$ (consisting of one proton, two neutrons, and one Λ-hyperon). They may be one of the possible markers of the phase transition from nuclear matter to quark-gluon plasma in high-energy ion collisions.

The aim of this work is to reconstruct the hypernuclei peak in the invariant mass distribution for simulated data for the BM@N experiment. In the report algorithm of geometrical parameters selection for both decays presented. Estimation of reconstruction efficiency in phase space $\{p_t, y\}$ done. Approach to calculate lifetime of observed hypernuclei is presented.

Introduction

This report is devoted to the study of the properties of hypernuclei. Hypernuclei are similar to ordinary atomic nuclei, but contain at least one hyperon (a particle with non-zero strangeness) in addition to protons and neutrons. They belong to the category of baryonic particles carrying a non-zero strangeness quantum number, which is conserved in strong and electromagnetic interactions.

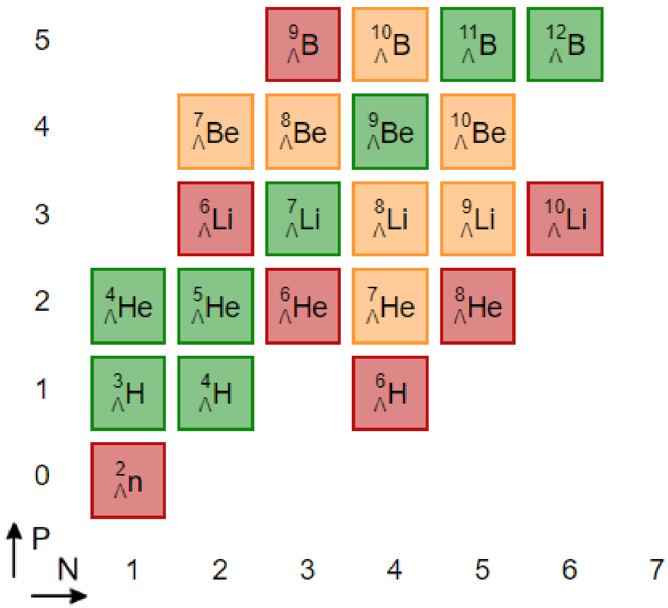


Figure 1 - Chart of arrangement of the lightest hypernuclei by the number of protons and neutrons [1]

Hypernuclei, containing the lightest hyperon (Λ^0), are usually bound more tightly than ordinary nuclei, although they can decay under weak forces with an average lifetime of about 260 ps [1].

The study of hyperons and hypernuclei is of interest because the increased yield of strange particles may be a sign of a phase transition between quark-gluon plasma and nuclear matter, expected at high baryonic densities and energies up to 10 GeV in the center-of-mass system (Fig. 2). In addition, the study of hypernuclei is important for understanding the structure and interactions of elementary particles and for expanding our knowledge of the fundamental laws of nature.

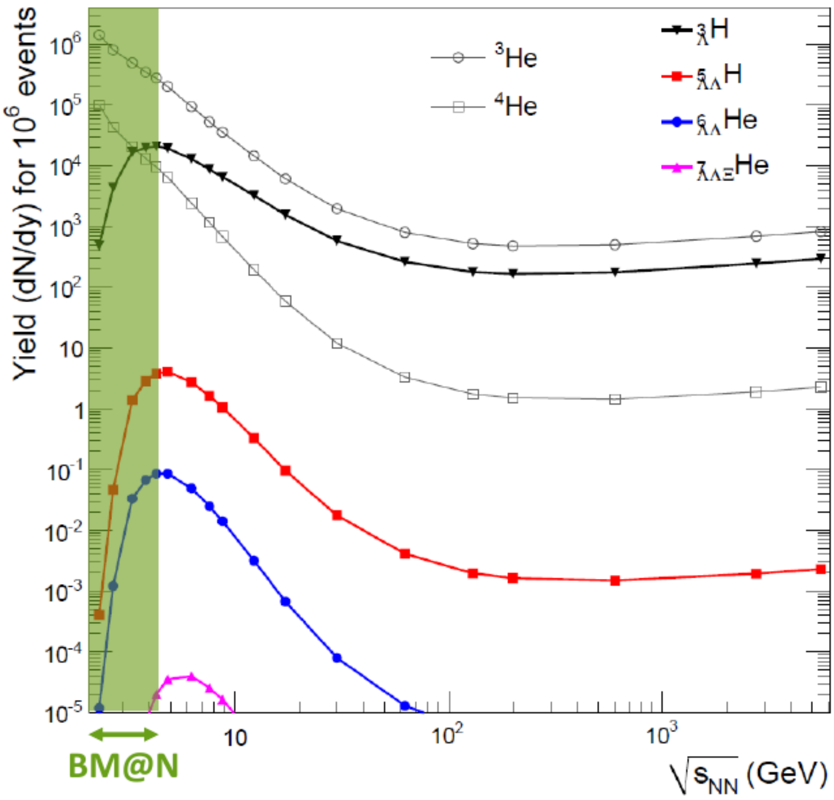


Figure 2 - Yields of different hypernuclei predicted by the thermal model [2]

The Joint Institute for Nuclear Research (Dubna) is finalizing the creation of the NICA (Nuclotron-based Ion Collider fAcility) [2] complex aimed at studying the properties of dense baryonic matter. One of the key experimental facilities BM@N (Baryonic Matter at Nuclotron) is already operating at the complex, even before the collider is under construction. The BM@N is aimed at studying collisions of relativistic ions with a fixed target [3].

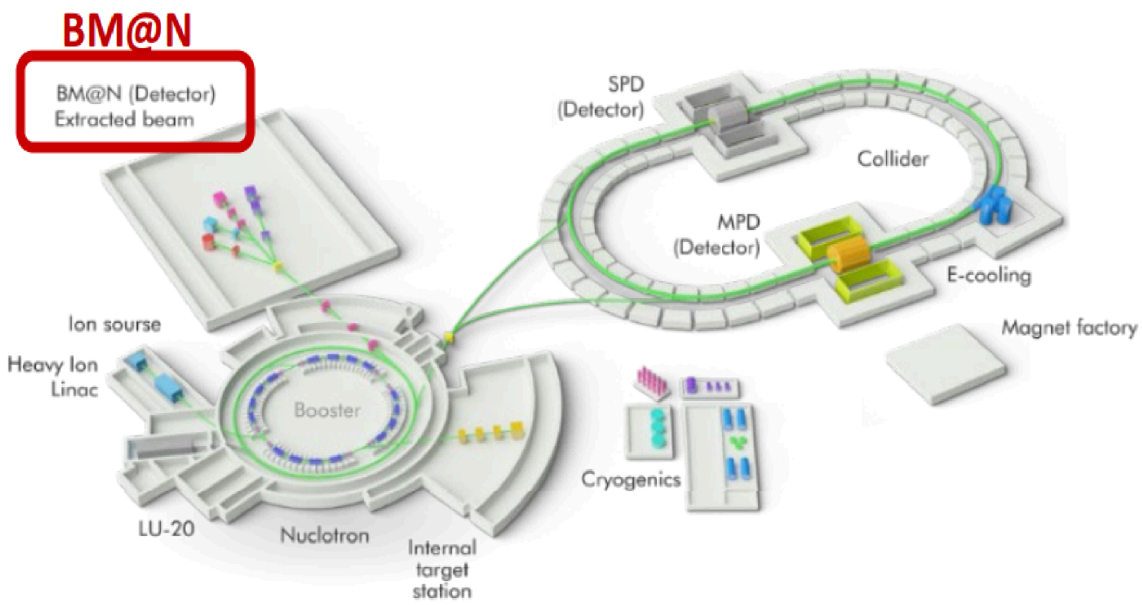


Figure 3 - Scheme of the NICA Complex [2]

The experiment combines high-precision measurements of track parameters with time-of-flight information for particle identification and involves a hadron calorimeter total energy measurement to analyze the centrality of collisions. The charged track momentum and multiplicity are measured using a set of silicon detectors (FSD) (8) and 7 planes of Gaseous Electron Multiplier (GEM) detectors mounted downstream from the target inside a dipole magnet. The vertical gap between the poles of the analyzing magnet to install the detectors is about 1 m. The magnetic field can reach a maximum value of 1 T, which allows optimizing the BM@N geometric acceptance and momentum resolution for different processes and beam energies. Time-of-flight detectors (11) and (13) are used to identify hadrons and light nuclei, and a lead calorimeter (20) is used to measure collision centrality. Outer tracker based on two drift chambers (DCH) and cathode strip chambers (CSC) are used to refine the trajectories outside the magnet [3].

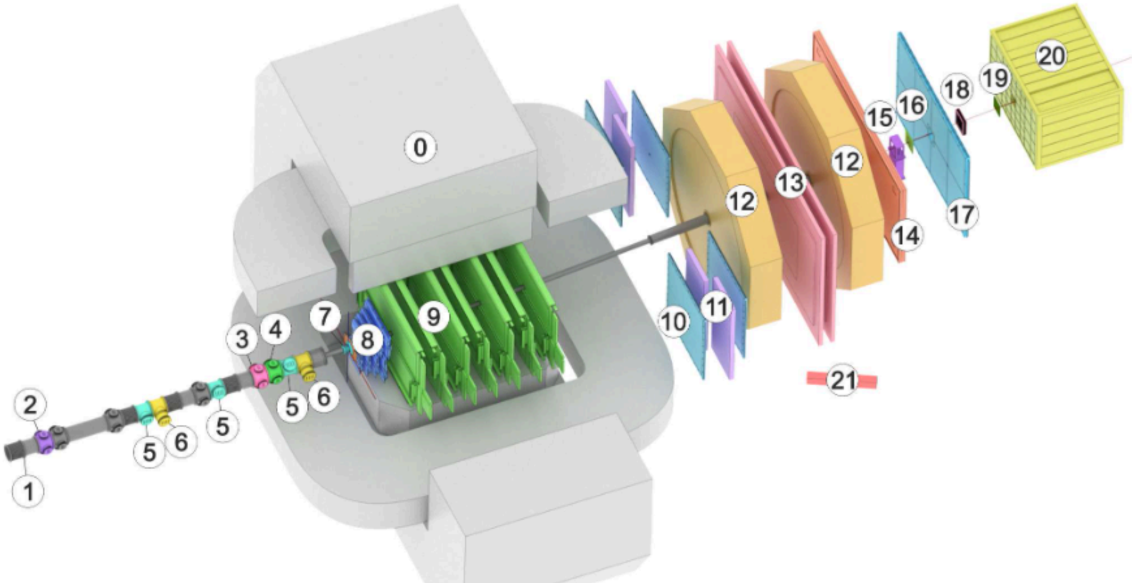


Figure 4 - Scheme of the BM@N setup in a xenon run (2023-2024)

1. Data preparation

This work is devoted to the study of the simplest hypernuclei, namely $^3H_\Lambda$ (consisting of one proton, one neutron, and one Λ-hyperon) and $^4H_\Lambda$ (consisting of one proton, two neutrons, and one Λ-hyperon). For each of these hypernuclei there are several possible decay modes, but in current study for both hypernuclei only two-particle decays were considered:

$$^3H_\Lambda \rightarrow \pi^- + {}^3He$$

$$^4H_\Lambda \rightarrow \pi^- + {}^4He$$

Simulation, reconstruction and data analysis were performed in the BmnRoot environment [4]. At the first stage, using the macro **run_sim_bmn.C**, the events of collision of a xenon beam with a caesium-iodine target were simulated. In heavy-ion collisions, hypernuclei are born quite rarely, which necessitates simulation of a large number of events. This problem can be solved by artificially adding hypernuclei to each event. The current discrepancy with reality allows us to obtain a sufficient number of investigated particles among the data, in order to tune the algorithms for analyzing their birth. For this purpose, the **MpdHypYPtGenerator** is used to customize the type of hypernuclei, the probability of their birth, their number in the event and their distribution in terms of rapidity and transverse momentum. In the current study, 10^5 events were simulated for both types of hypernuclei.

The next step in the study of hypernuclei is the event reconstruction, which in the BmnRoot environment is performed using the macro **run_reco_bmn.C**. The algorithm of track reconstruction inside the magnet is based on a cellular automaton. First, cells are created and links are formed between all neighboring detector planes. Next, the states of the cells are iteratively calculated. If the cells share a hit at the same angle, their state is changed. Once the final states are computed, candidate tracks are created for all cells. Cells are merged with their neighbors if their state difference is equal to one. The result is an array of track candidates. If less than four hits were recorded, the candidate is rejected and no track is created. After that, the remaining tracks are processed and their parameters are improved using Kalman filter [5].

The final step in data preparation procedure is the creation of candidate pairs of hypernucleus decay products. Among the reconstructed tracks the macro selects pairs of positive and negative particles and performs selection by momentum, vertex and other parameters. Having constructed pairs it is necessary to select the decays on the necessary channel under conditions of a large combinatorial background.

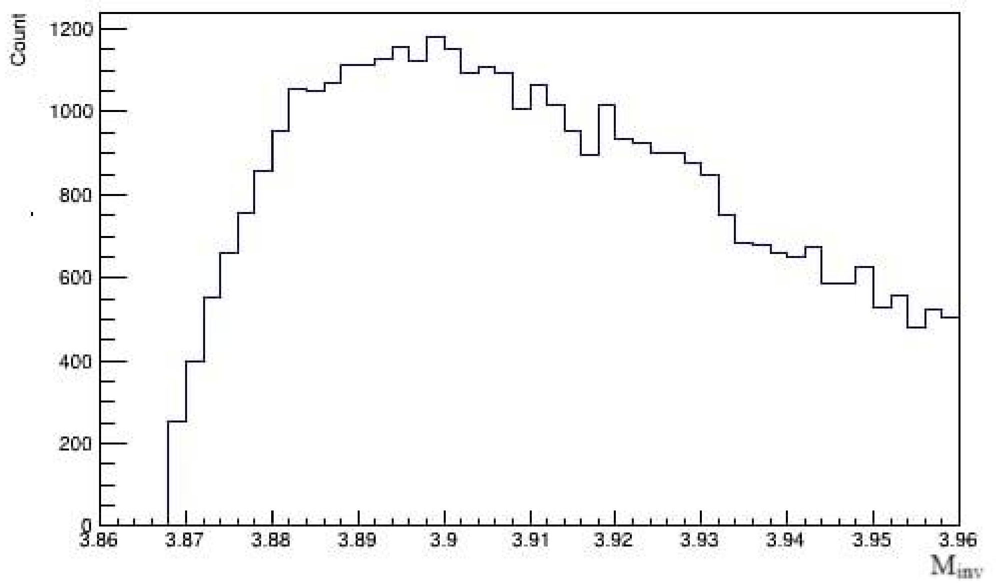


Figure 5 - Example of $^4H_\Lambda$ invariant mass distribution with unsuppressed background

An example of such a large background is shown in Fig. 5. To suppress the combinatorial background arising due to a large number of falsely selected pairs, the parameters from the decay scheme are used (see Fig. 6).

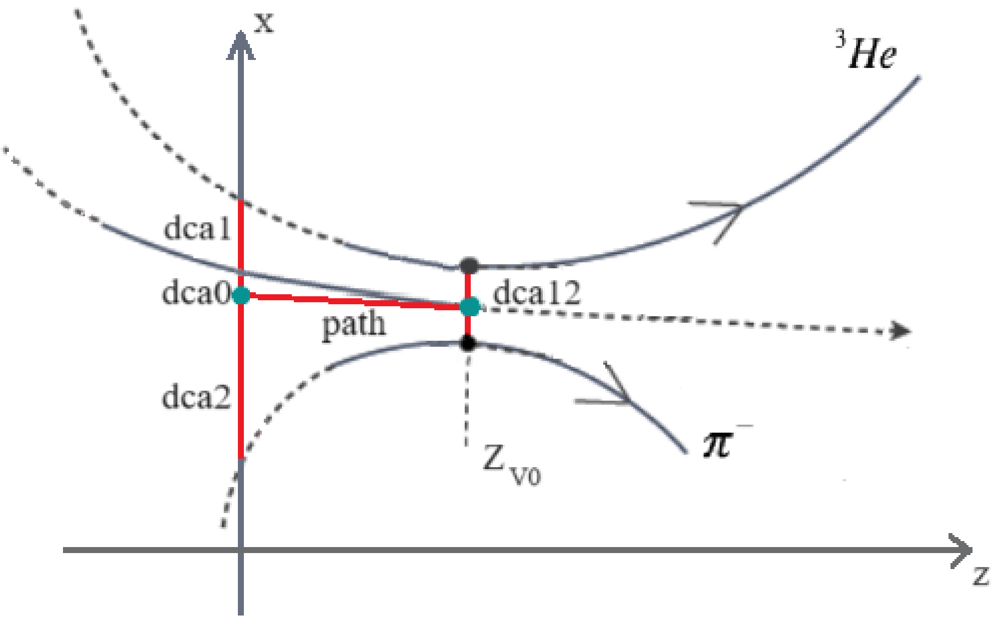


Figure 6 - Schematic view of the $^3H_\Lambda$ decay. The red lines indicate geometrical cuts, variation of which allows to suppress the combinatorial background.

From the scheme shown in Figure 6, the varying parameters are as follows:

- dca12 - the minimum distance between the trajectories of two particles from the pair under consideration,
- dca1 - distance from the primary vertex to the trajectory of the positive particle in the plane of the primary vertex,
- dca2 - distance from the primary vertex to the trajectory of the negative particle in the plane of the primary vertex,
- path - distance from the primary vertex to the decay point V_0,
- dca0 - distance from the primary vertex to the momentum projection in the plane of the primary vertex.

The parameters dca2 and dca12 are considered in χ^2-space, i.e. after normalization by the corresponding parameter errors.

Together with these parameters, constraints on the mass obtained in the time-of-flight detector (mTof) for the positive particle in the pair, the momentum of the negative particle (mom2), the positive particle (mom1), and the momentum ratio (m1m2) are used.

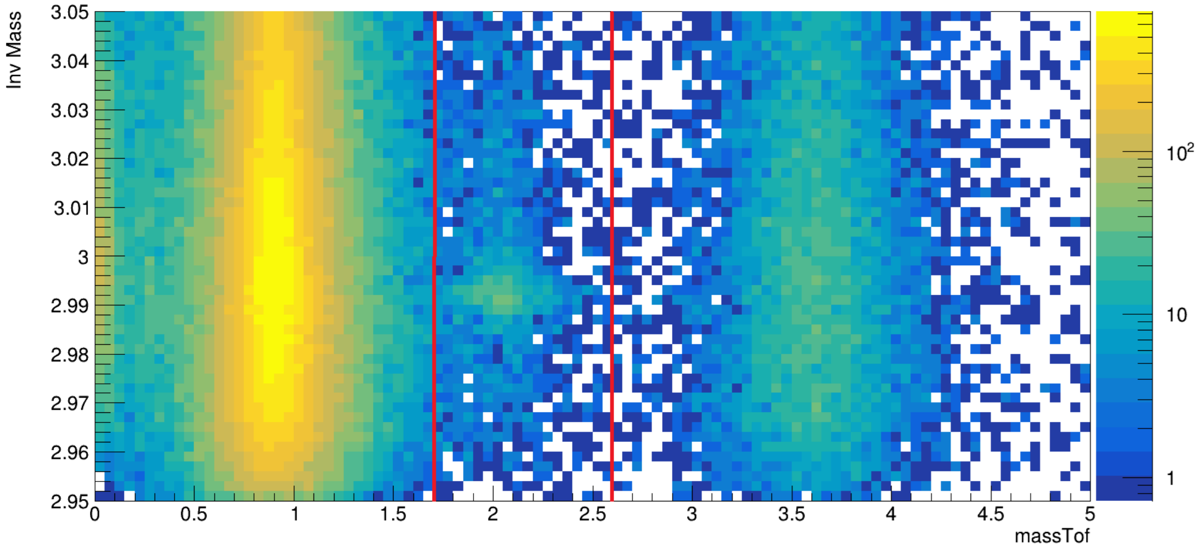


Figure 7 - Mass distribution where the mass region corresponding to ^3He is highlighted in red lines

2. Data analysis

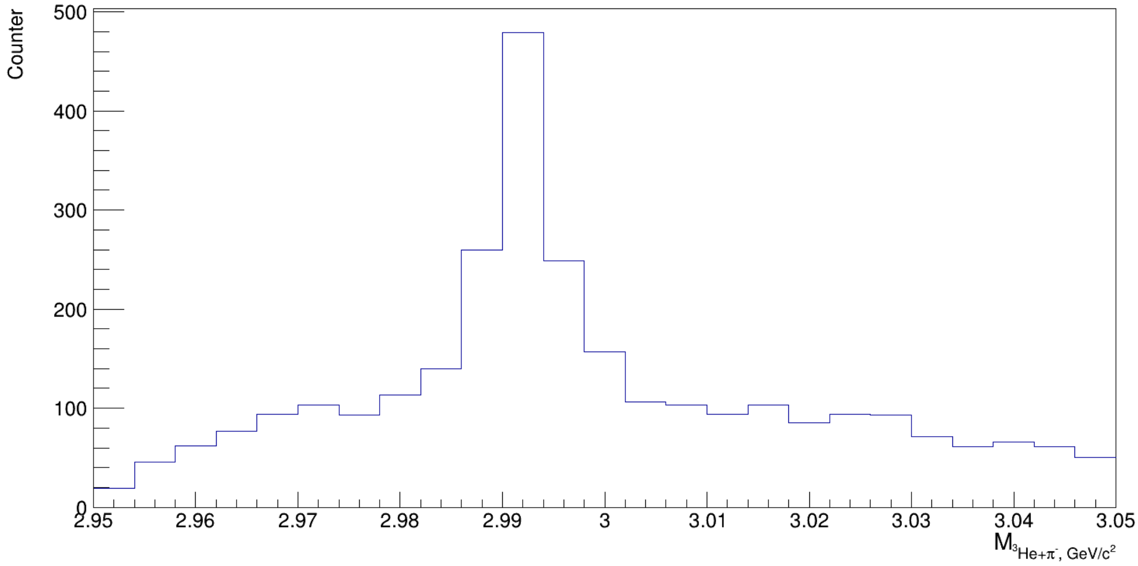


Figure 8 - Candidate pair invariant mass distribution for $^3H_\Lambda$ after background suppression procedure using

Figure 8 shows the distribution of pairs by invariant mass, with the geometric constraints imposed on them. Turning to the evaluation of the quality of the obtained peak, first of all, it is necessary to evaluate the background and then to fit the distribution.

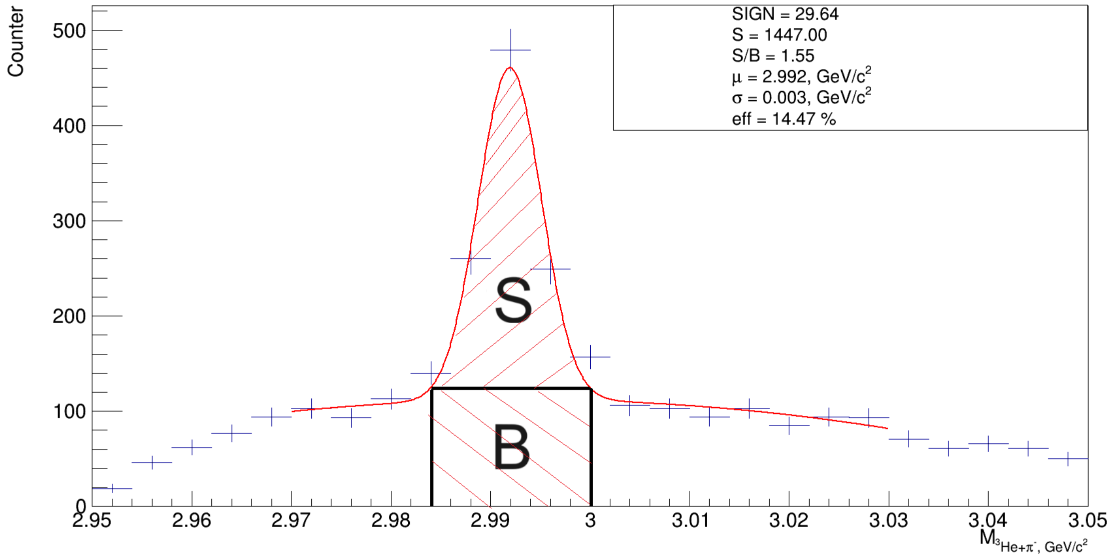


Figure 9 - $^3H_\Lambda$ invariant mass distribution, with fitting

Figure 9 shows schematically the main parameters for the analysis: signal (S) corresponds to the area under the plot in range $\pm$ 3σ around the center of the peak above the background; background (B) corresponds to the area under the plot in the same range without the signal peak. The algorithm for finding the best geometric constraints was based on combinatorial search in the space of all constraints. Significance maximization (sign) was chosen as a quality criterion:

$$sign \;= \frac{S}{\sqrt{S+B}} \rightarrow max$$

Significance can be interpreted as the value of a signal expressed in units of standard deviations.

Table 1 - Best parameters for each decay

Parameters	$^3H_\Lambda$		$^4H_\Lambda$	
	min	max	min	max
path, cm	1.4	50.0	2.1	50.0
dca2	1.45	100.0	1.7	100
dca12	0	1.1	1.7	100
mTof, GeV/q/c^2	1.7	2.6	2.8	4.45
mom1, GeV/q/c	1.0	6.0	1.0	7.0
mom2, GeV/q/c	-0.80	-0.36	-1.0	-0.4

m1m2	4.0	13.0	5.0	50.0
dca0, cm	0.0	0.5	0.0	0.3
S	1450± 40		360± 20	
B	940± 30		1590± 40	
S/B	1.55±0.06		0.23± 0.01	
SIGN	29.6±1.7		8.2± 1.5	
eff	1.45%		0.36%	

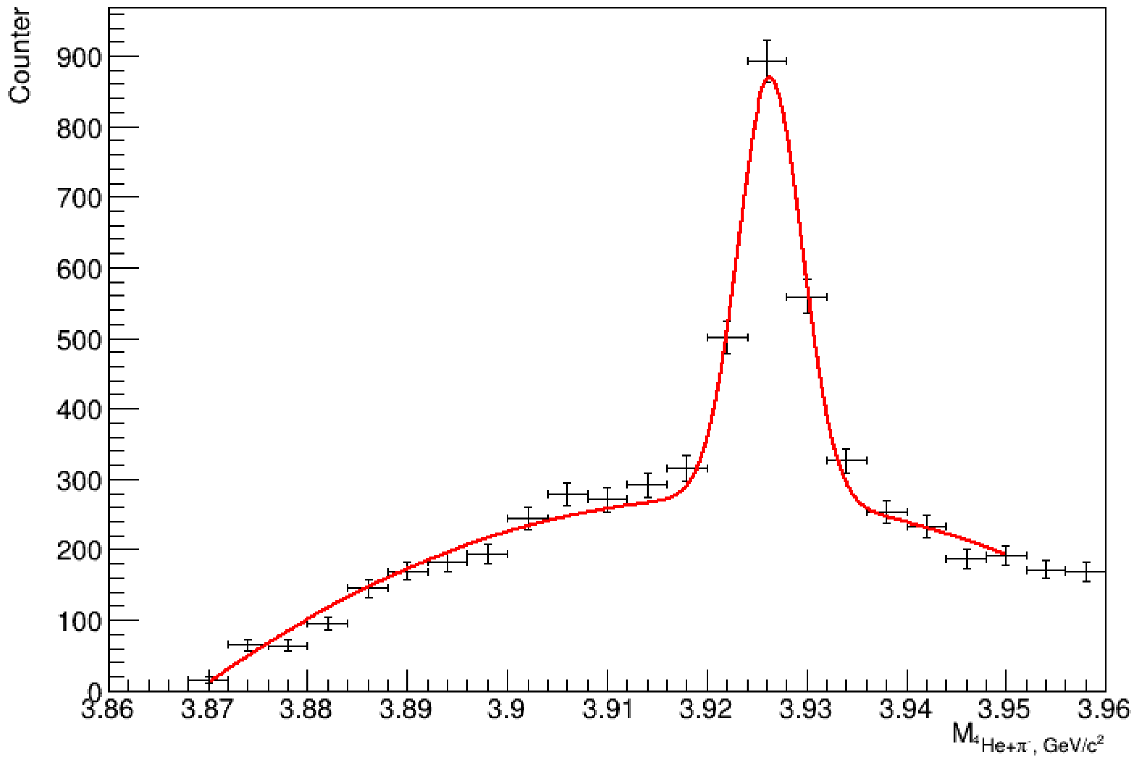


Figure 10 - $^4H_\Lambda$ invariant mass distribution with fit

Using geometrical and kinematic cuts from Table 1 the resulting invariant macc distribution is shown in Fig. 10. The plot shows the invariant mass distribution for $^4H_\Lambda$, where it can be seen that the peak is at a value of ~3.927 GeV/c^2 and is in good agreement with the theoretical value.

After a stable signal was obtained, the distribution of the reconstructed hypernuclei in transverse momentum and rapidity space was examined and the efficiencies in these spaces were evaluated.

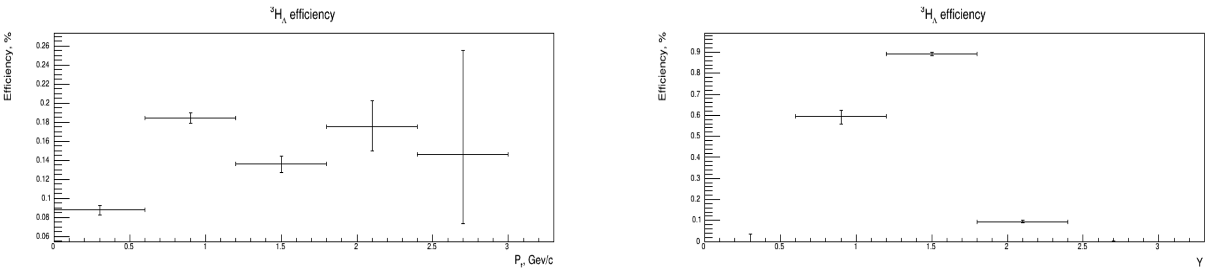


Figure 11 - Efficiency distributions by transverse momentum and rapidity for $^{3}H_{\Lambda}$

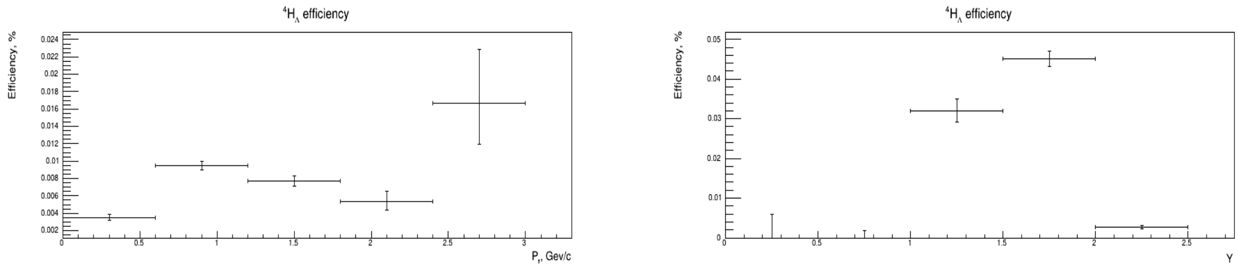
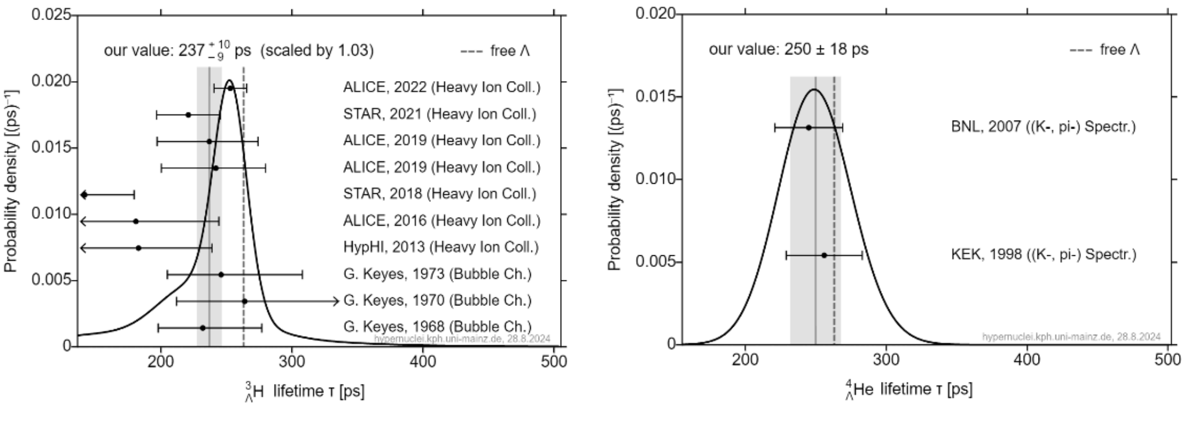


Figure 12 - Efficiency distributions by transverse momentum and rapidity for $^{4}H_{\Lambda}$

In Fig. 11 and Fig. 12, the distributions of efficiency in transverse momentum (P_t) and rapidity (Y) are plotted. These plots were obtained by dividing the distributions of the model data by the distribution of the reconstructed data. The estimation of the hypernuclei reconstruction efficiency is necessary to obtain their yields and cross sections in the subsequent processing of experimental data.

One of the most interesting parameters for the study of hypernuclei is their lifetime [6]. So far, ~10 lifetime measurements for $^{3}H_{\Lambda}$ and $^{4}H_{\Lambda}$ are known, but the experimental estimations are scattered over a large range (see Fig. 13a and Fig. 13b) [1].

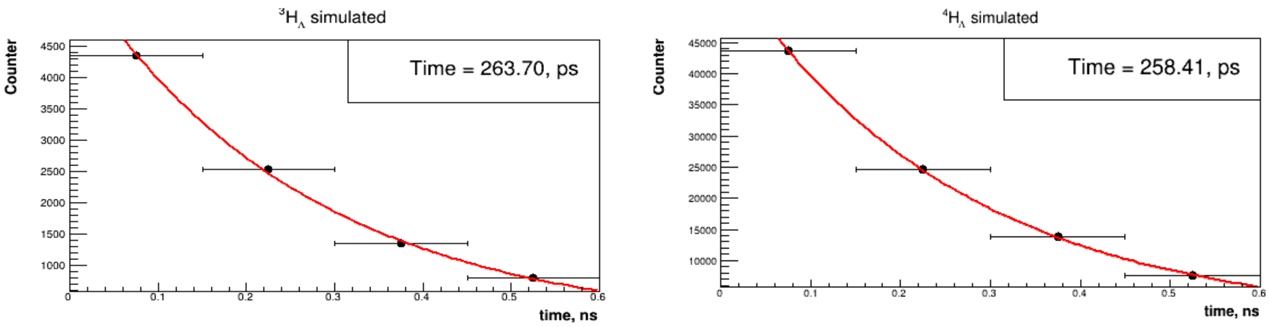


a *b*

Figure 13(a,b) - Worldwide lifetime estimations for $^{3}H_{\Lambda}$ (a) and $^{4}H_{\Lambda}$ (b) [5]

In this work, the lifetimes for the considered hypernuclei have been estimated. This makes it possible to tune the algorithms for obtaining them and compare them with the values incorporated in the model.

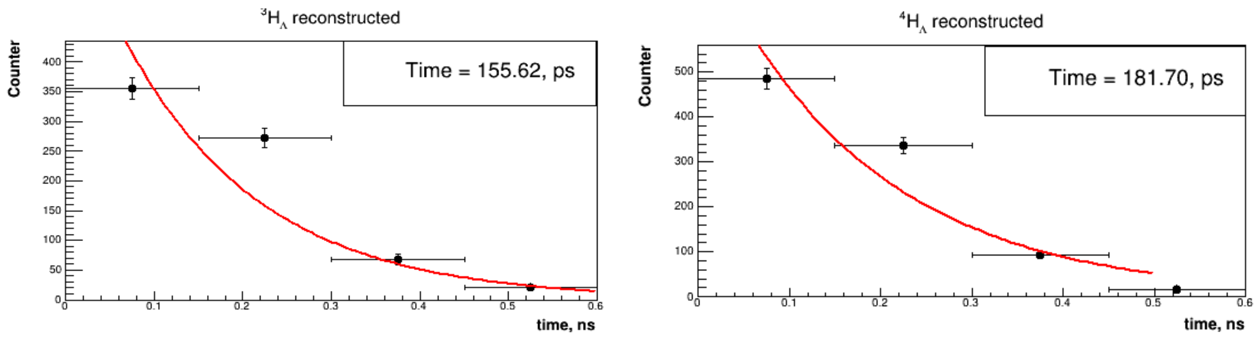
Figure 14 shows the distributions over the time bins for the model values of $^3H_\Lambda$ and $^4H_\Lambda$. These distributions are fit with an exponential function and the lifetime is extracted from it.



a *b*

Figure 14 - Lifetime distribution of model data for $^3H_\Lambda(a)$ and $^4H_\Lambda(b)$

For the reconstructed data (see Fig. 15), the fit does not lie so well, and the lifetime values are severely underestimated. This effect can be explained by the lack of enough statistics. It is planned to test these values with larger statistics in the future.



a *b*

Figure 15 -Distribution of reconstructed lifetime data for $^3H_\Lambda(a)$ and $^4H_\Lambda(b)$

Conclusion

This work was devoted to the study of the parameters of the simplest hypernuclei that can be observed in the BM@N experiment. The report presents an algorithm for suppressing the combinatorial background, estimates the efficiency of hypernucleus reconstruction, and obtains estimates of their lifetime. In future work, it is planned to simulate more data to improve lifetime and efficiency estimation, analyze the three-particle decay channels and start work with experimental data.

References

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