Reconstruction of hypernuclei for the CBM experiment

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Abstract

The advent of hypernuclei physics was with the discovery of the first hyperfragment in 1953 by Polish physicists M. Danysz and J. Pniewski. However, extensive experimental studies since then have been lacking due to the dearth of available data, as these particles are extremely rare in nature. The Compressed Baryonic Matter experiment will overcome this problem as there will be enough statistics for hypernuclei within the first few weeks of operating. This report details the reconstruction of Λ hypernucleus ${}^{3}_{\Lambda}H$ and double Λ hypernucleus ${}^{4}_{\Lambda\Lambda}H$ in a CBM detector setup. The setup contains a new MVD (Micro Vertex Detector) for which this analysis has been done for the first time. In addition, particle detection was done using Time-of-flight detector (TOF) of the CBM setup.

Declaration

I hereby declare that the project entitled "**Reconstruction of hypernuclei for the CBM experiment**" is my own work and that I have correctly acknowledged the work of others.

Acknowledgements

This project would not be possible without the amalgamation of the efforts of quite a few people, starting with Prof. Dr. Peter Senger, who I am grateful to, for giving me the chance to come to GSI. I am thankful to Dr. Iouri Vassiliev who was a constant support and guidance during the length of the project, and it was an absolute pleasure to work with him. To the friends I made in this place and my colleagues at KBW 2.003, I am grateful for being so warm and kind.

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Chapter 1

Introduction

1.1 General

The CBM (Compressed Baryonic Matter) experiment would probe the QCD phase diagram at high baryon densities and moderate temperatures in nucleus-nucleus collisions. It also provides a unique opportunity to create and investigate extreme states of strongly interacting matter in laboratory. The transition from hadronic to partonic degrees of freedom will be probed, which is of immense consequence in the early universe, and in the core of neutron stars. In particular, at such high densities, new phases of strongly interacting matter are expected. The CBM experiment is also aimed at discovering the first order phase transition of the QCD phase diagram. Since FAIR is designed to produce heavy-ion collisions, it will be a rich source to produce particles carrying strangeness. Therefore, CBM is uniquely poised to investigate hyperons (baryons with one or more strange particles), and their bound states like ${}^{3}_{\Lambda}H$, ${}^{4}_{\Lambda\Lambda}H$ etc. The interaction rates at the CBM experiment can go up to 10 MHz.

1.1.1 Hypernuclei

Hyper nuclei are nuclei with at least one hyperon instead of a nucleon. The Λ baryon is the one with the least mass, about 20% higher than that of nucleon. It has isospin $I = 0$ and no charge. It is unstable and decays via weak interaction to nucleon and pion. Weak interaction doesn't conserve strangeness.

Single Λ hypernuclei like hypertritium (${}^{3}_{\Lambda}H$) are produced with enough statistics in recent experiments like STAR and ALICE and are used to investigate the strangeness nuclear physics. Although double Λ hypernuclei haven't been probed yet due to lack of statistics, it is expected from theoretical models that there would be enough data from the CBM experiment. The maximum yield will be in the region of SIS100 energies [1] & [2] where hydrogen and helium hypernuclei will be produced in huge amounts. To study the perfomance of multi-strange hyperon and hypernuclei reconstruction, two sets of 5.10^6 Au+Au UrQMD and PHSD events at 10 AGeV were simulated.

1.1.2 CBM experiment at FAIR

The CBM experiment is a multi-purpose detector designed for heavy-ion collisions at SIS100 and SIS300 at FAIR. It will provide heavy ion beam energies from 2-14 AGeV for SIS100 setup. The rate of interactions registered by CBM will be around 0.1 to 10 MHz. The Micro Vertex Detector (MVD) will be useful in reconstructing particles which decay near the collision vertex, however for now it operates at 0.1 MHz.

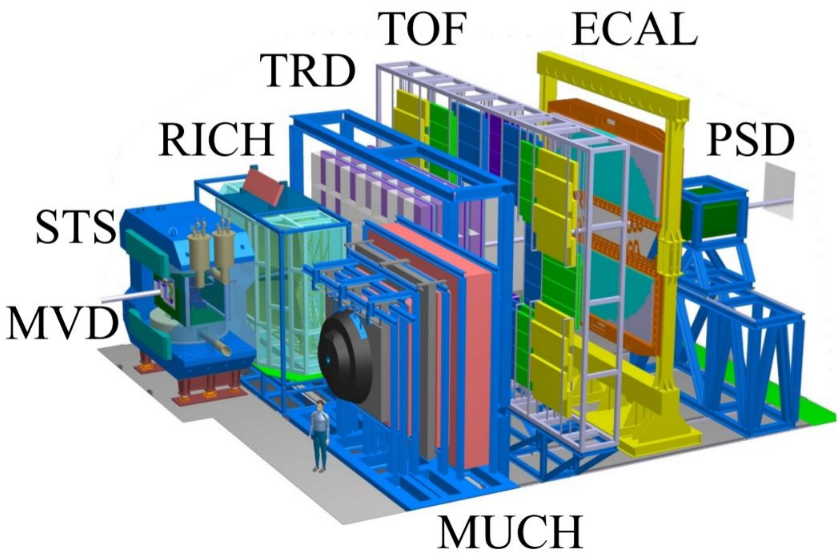

Figure 1.1: The detector at CBM

The Silicon Tracking Stations(STS) measures particle momenta and tracks for the produced particles. Both of them are enclosed in a superconducting magnet. Particle identification for electrons is done in RICH (Ring Imaging Cherenkov) detector, while TRD (Transition Radiation Detectors) and TOF (Time of Flight) Detectors identify hadrons. This is the electron setup and the one that has been used for this analysis.

Chapter 2

Hypernuclei Reconstruction

This analysis follows earlier work done on reconstruction of $\Lambda\Lambda$ hypernuclei in a CBM experiment containing the MVD. The Micro Vertex Detector is new (*v17a_tr*) and hence the reconstruction procedure was repeated for $^{3}_{\Lambda}H$ and $^{4}_{\Lambda\Lambda}H$.The MVD allows us to measure the mother particles' trajectories.

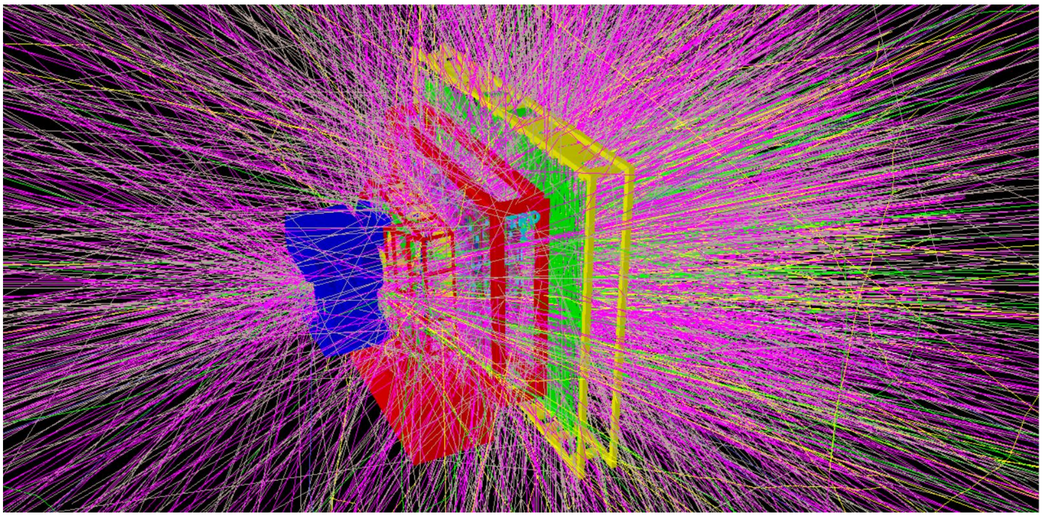

Figure 2.1: A simulated CBM event of a Au+Au collision. The TOF detector identifies hadrons i.e. pions, kaons, protons and fragments.

The current *KFParticleFinder* package in the ***CBMROOT*** framework allows the reconstruction of Λ hypernuclei: bound states like $\{\Lambda n\}_b$, $^{3}_{\Lambda}H$, $^{4}_{\Lambda}H$, $^{4}_{\Lambda}He$, $^{5}_{\Lambda}He$, and double Λ hypernuclei like $^{4}_{\Lambda\Lambda}H$, $^{5}_{\Lambda\Lambda}H$ and $^{6}_{\Lambda\Lambda}He$. Hypernuclei are reconstructed using their decay into charged hadrons and pions, which are separated from the primary vertex. One event in an Au+Au collision is shown below as an example of reconstruction in the STS tracks.

2.1 Reconstruction procedure

The UrQMD and PHSD models do not contain hyper nuclei. Therefore, to reconstruct the invariant mass spectrum of the hypernuclei, a different approach was used. A pure signal generated using thermal models is embedded into an Au+Au central or minimum bias collision, where the latter serves as a background. 10^3 pure signal events have been simulated along with 5.10^6 Au+Au 10 AGeV central events. Following this, the invariant mass spectra was normalised to $N_0 = 10^{11}$ events which is the expected yield from CBM experiment, when it operates at 1 MHz (Although, currently with the MVD, the rates can only go as high as 0.1 MHz). To correctly account for the expected yield of hypernuclei, the pure signal is normalised to the total number of events N_0 using the relation

$$N_X = M.\epsilon.BR.N_0 \tag{2.1}$$

N_X is the number of entries for the particle X, M is the multiplicity of the particle, ϵ is the reconstruction efficiency, and BR is the branching ratio of a specific decay mode of particle X.

The efficiency is calculated separately by embedding the pure signal in a background of 10^3 central events and then calculating the number of tracks that are reconstructed. As an exercise, we reconstructed the hypernuclei from the pure signal too, and we observed that the efficiency always goes down by a factor of 2. This is attributed to the fact that the track density increases when we embed the signal in a background, and hence the efficiency decreases.

Table 1 lists the decay modes, multiplicity, branching ratios, and efficiency for ${}^3_\Lambda H$ and ${}^4_{\Lambda\Lambda} H$ particles which were investigated in this report. The efficiency is a conservative estimation as we embedded the signal in central collision events. The efficiency is expected to be better for minimum bias events.

#	decay mode	multiplicity	BR	efficiency
${}^3_\Lambda H$	${}^3He + \pi^-$	3.6×10^{-2}	0.25	6.5%
${}^4_{\Lambda\Lambda} H$	${}^4He + \pi^-$	1.5×10^{-4}	0.06	1.7%

Table 2.1: Decay modes, corresponding multiplicities, branching ratios, and efficiency for the considered hypernuclei

Chapter 3

Results

3.1 Topology Reconstruction

The two decays have been reconstructed[3] and are shown in figure 3. The hypernuclei is reconstructed from its decay products. For ${}^{3}_{\Lambda}H$, the fragments are ${}^{3}He$ and π^- which were identified using their hits in the STS detectors and the MVD, and then reconstructed. This is a simple two body decay, whereas for the next hypernuclei ${}^{4}_{\Lambda\Lambda}H$, the decay is more complicated. Initially it decays to ${}^{4}_{\Lambda}He$ and π^-.

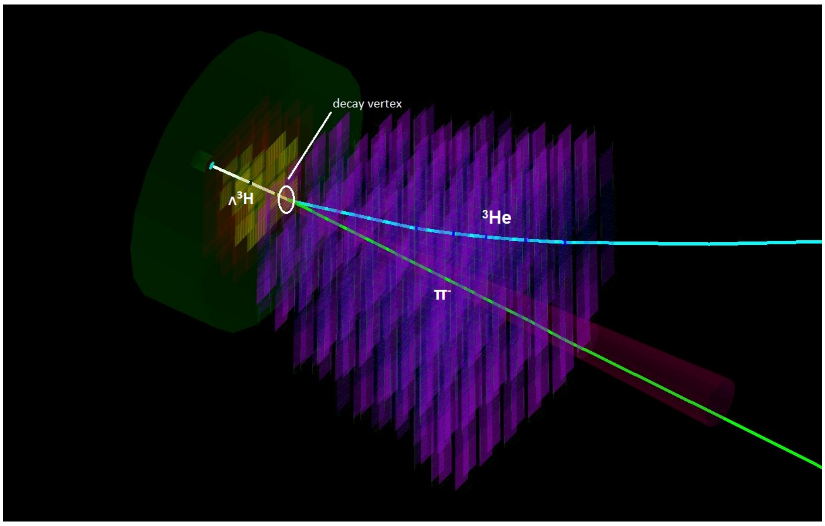

Figure 3.1: Reconstructed decay topology of a ${}^{3}_{\Lambda}H \rightarrow^{3} He + \pi^-$ event

Furthermore, the ${}^{4}_{\Lambda}He$ decays to ${}^{3}He$, p^+ and π^-. The reconstruction is initially done for ${}^{3}He$, p^+ and π^- to get the ${}^{4}_{\Lambda}He$ at the secondary vertex, following which another reconstruction gives ${}^{4}_{\Lambda\Lambda}H$.

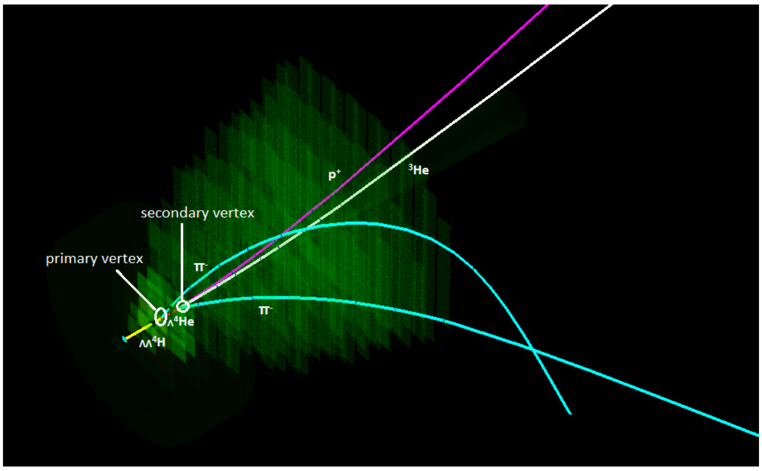

Figure 3.2: Reconstructed decay topology of a ${}^4_{\Lambda\Lambda}H \rightarrow^4_\Lambda He + \pi^- \rightarrow^3 He + p^+ + \pi^-$ event

3.2 Embedding the signal in background

The obtained invariant mass spectra for the embedded signal of ${}^3_\Lambda H$ and ${}^4_{\Lambda\Lambda}H$ are presented below. Each plot shows a clear signal peak, located at 2994 MeV/c^2 for ${}^3_\Lambda H$ and at 4108 MeV/c^2 for ${}^4_{\Lambda\Lambda}H$.

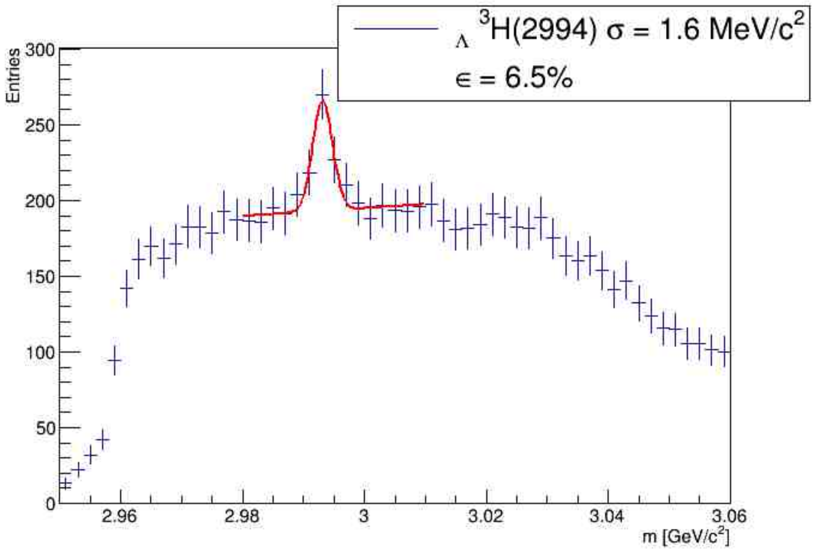

Figure 3.3: Reconstructed invariant mass spectrum for ${}^3_\Lambda H$, normalised to 10^11 events

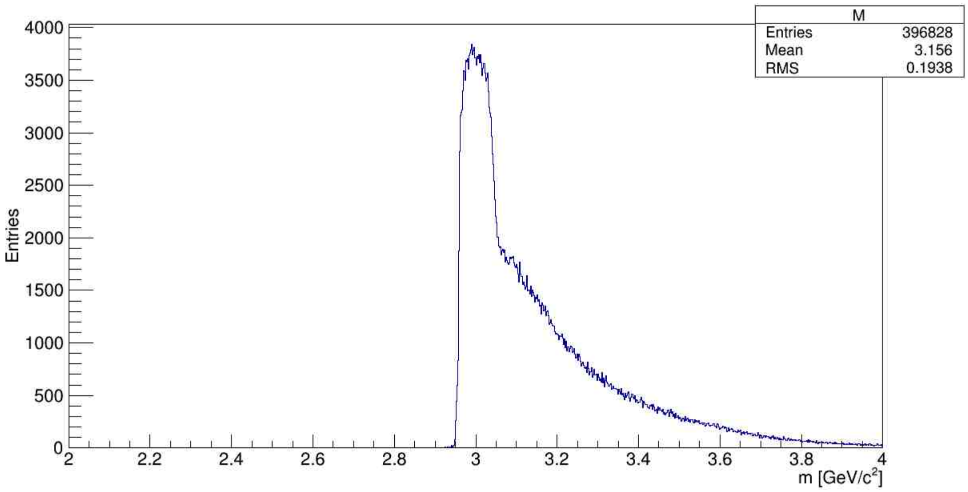

Figure 3.4: Background for ${}^{3}_{\Lambda}H$ generated from UrQMD, 10 AGeV Au+Au central events

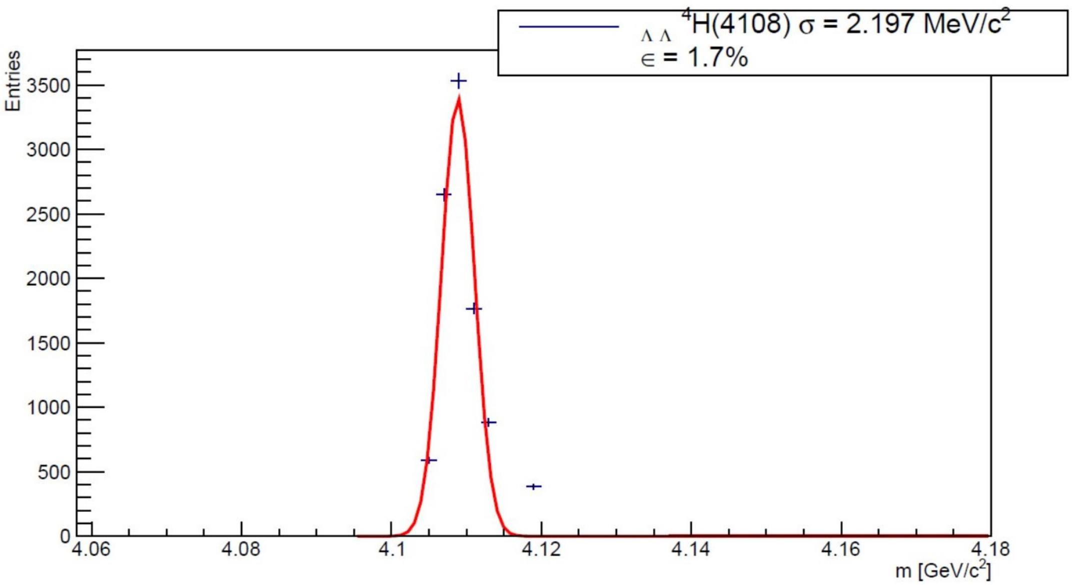

Figure 3.5: Reconstructed invariant mass spectrum for ${}^{4}_{\Lambda\Lambda}H$, normalised to $10^{1}1$ events

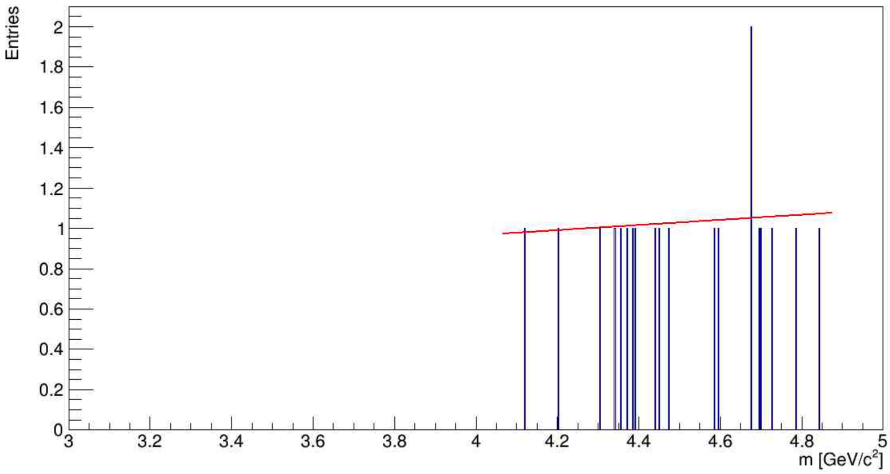

Figure 3.6: Background for ${}^{4}_{\Lambda\Lambda}H$ generated from PHSD, 10 AGeV Au+Au minimum bias events. The background is fitted with a 1st order polynomial, as there are not enough counts.

3.3 Particle identification using TOF

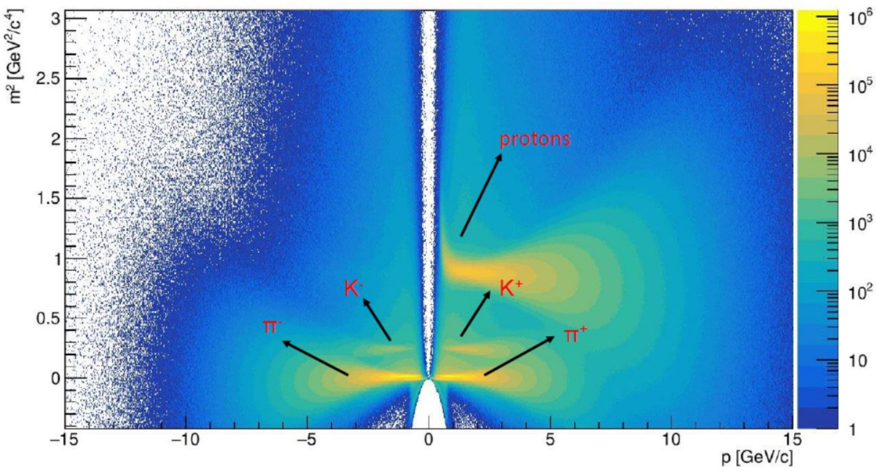

Figure 3.7: Square of invariant mass vs momentum as recorded by the Time of flight detector of the CBM electron setup. At 1 $\mathrm{GeV}^2/\mathrm{c}^4$, there are protons, at 0.25 $\mathrm{GeV}^2/\mathrm{c}^4$, there are kaons, and at 0.01 $\mathrm{GeV}^2/\mathrm{c}^4$, there are pions.

Chapter 4

Conclusion and Further Work

4.1 Similar analysis for other hypernuclei

For now, the invariant mass spectra have been generated for only 2 hypernuclei. The plan ahead is to repeat this exercise for ${}^{4}_{\Lambda}H$,${}^{5}_{\Lambda\Lambda}H$ and ${}^{6}_{\Lambda\Lambda}He$ among others. The pure signal would be embedded in minimum bias collision events, and then the dependence of the efficiency of reconstruction would be explored as a function of track multiplicity.

4.2 Measurement of lifetime for ${}^{3}_{\Lambda}H$

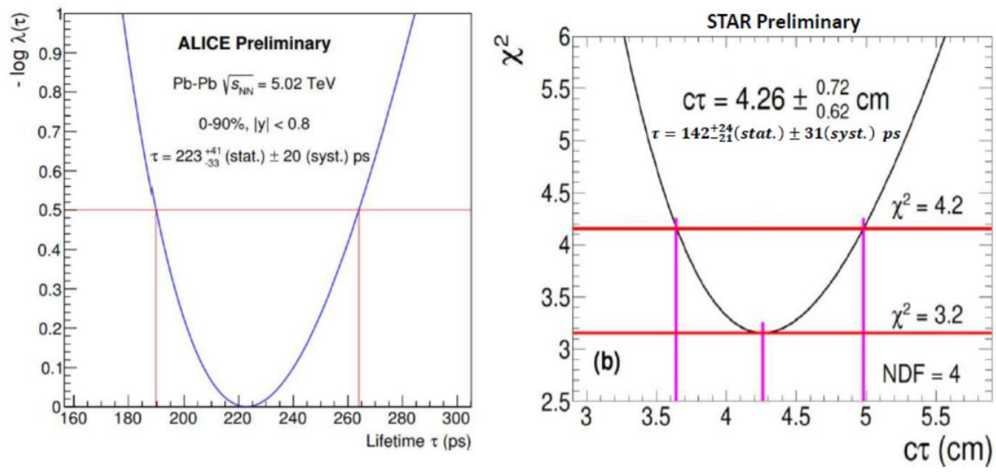

Figure 4.1: Measurements of lifetime of hypertritium as reported by ALICE and STAR. The discrepancy is greater than 2σ.

As reported in QM2018[4] , the $c\tau$ measurements for hypertritium($^{3}_{\Lambda}H$) are different beyond statistical and experimental errors. The two measurements are shown in the figure 4.1. We aim to measure the $c\tau$ value from CBM by plotting the number of particles as a function of distance from the reaction point to the primary vertex (scaled by $1/\beta\gamma$).

4.3 Conclusion

The CBM experiment, while using the MVD, is expected to collect statistics of $10^{10} - 10^{11}$ events over a period of a week at an interaction rate of $0.1 - 1$ MHz. With this statistics, $^{3}_{\Lambda}H$ and $^{4}_{\Lambda\Lambda}H$ have been uniquely identified in this new geometry, and their invariant mass spectra have been reported. The background used was suppressed with information from the TRD, based on work done previously [5]. The reconstruction efficiencies have also been reported.

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