Search for a Λnn bound state in Pb-Pb collisions with ALICE at the LHC

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Abstract. The extreme energy densities reached at the LHC lead to the production of a significant amount of baryons and strangeness. Such a regime allows for an increased production of potentially existing exotic QCD bound states containing nuclei and strange hadrons. An interesting measurement for the phenomenology of the nuclear interaction is the presence of a neutral bound state constituted by one Λ and two neutrons. The excellent particle identification, tracking and vertexing performance of the ALICE experiment allow for the search of this exotic bound state in the decay channel Λnn $\rightarrow {}^3$H+π^- in Pb-Pb collisions. In order to improve detection of this state despite the presence of a huge combinatorial background, the extraction of the signal is performed by means of a multivariate approach with the TMVA (Toolkit for Multivariate Data Analysis with ROOT). So far the indication for the existence of the Λnn state was reported only by the HypHI Collaboration, so the observation by ALICE would crucially contribute to the study of such an exotic state.

1 Introduction

The nuclear state composed by the Λ hyperon and two neutrons, namely the Λnn state, can be considered as an isospin partner state of the ${}^3_\Lambda$H which has a separation energy ≈ 130 keV and this is already a hint that the neutral state can hardly be formed. Theoretical models predict that such a neutral state should not be bound [1, 2], nevertheless recent measurements [3] indicate its formation at a mass of 2.993 GeV/c^2 as shown in Figure 1. The production of a significant amount of baryons and strangeness at LHC energies allows for an increased production of potentially existing exotic QCD bound states. The Λnn state, if existing, can be eventually detected with ALICE via the decay channel Λnn $\rightarrow {}^3$H+π^- and its observation would crucially contribute to the understanding of exotic nuclear bound states.

2 Analysis strategy for Λnn detection

The main challenge of this analysis is that the signal is not only rare, but it may not even exist. The triton identification is the main issue here, because above 2 GeV/c the sample of candidates selected by the Time Projection Chamber (TPC) contain several low mass particles (e.g.: pions and electrons) which enlarge dramatically the combinatorial background. The usage of the Time-Of-Flight detector (TOF) information helps in rejecting the background.

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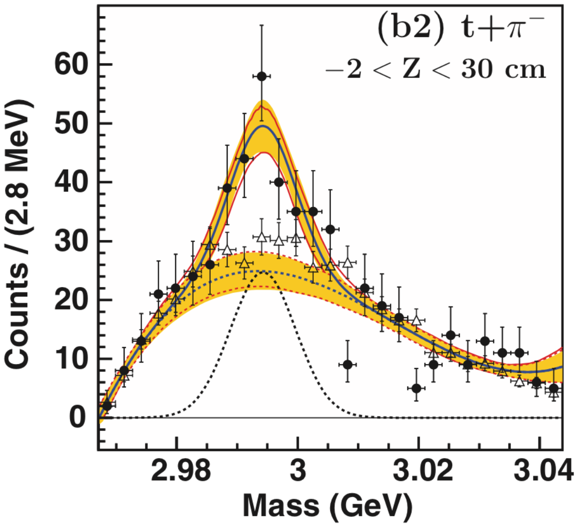

Figure 1. Invariant mass spectrum of the $\Lambda nn \rightarrow ^3$ H+π^- as obtained from the reaction of ^{6}Li projectiles at 2 AGeV on a fixed graphite target at the GSI Helmholtz Centre for Heavy Ion Research (HypHI Collaboration [3]).

Nevertheless the signal efficiency is also reduced. Previous studies made use of rectangular cuts on several variables such as Distance of Closest Approach (DCA) of the mother particle and the daughter particles, momentum ranges, etc. and to improve the signal extraction more complicated cuts were introduced, such as linear combination of independent variables or triangular cuts. Given the difficulties in finding an optimal set of cuts, it was decided to

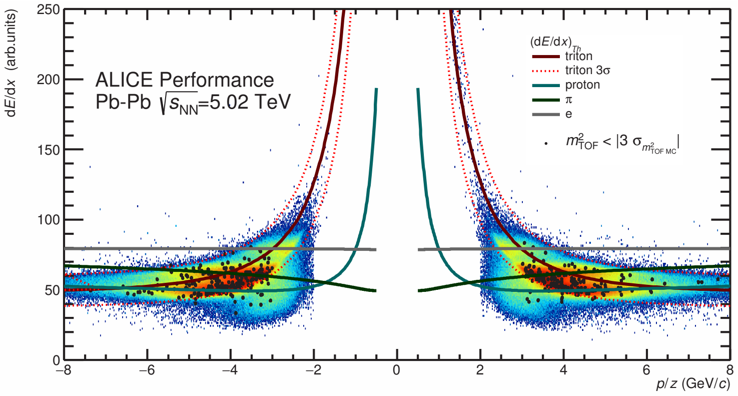

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Figure 2. Energy loss in the TPC of the candidate V^0 daughters that were identified as tritons. The black dots refer to tritons which have a TOF mass in the triton expected range. The theoretical Bethe-Bloch curves of pions, protons and electrons are also shown. The two dotted lines refers to the expected trend of the energy loss a ±3 σ, where σ is the expected triton energy loss width of the specific energy-loss signal in the TPC.

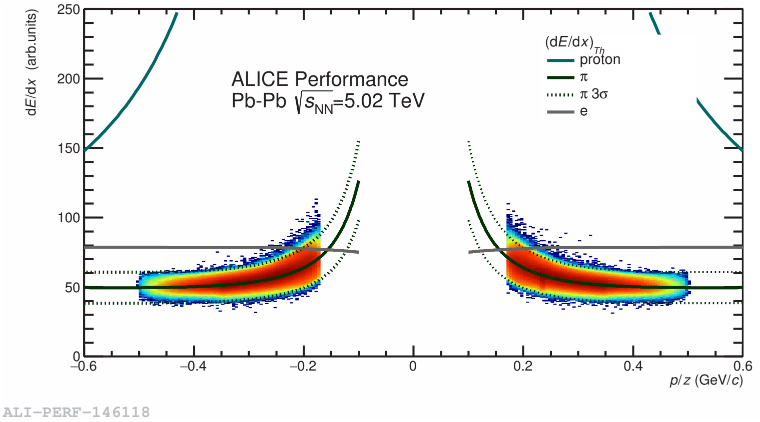

Figure 3. Energy loss in the TPC of the candidate V^0 daughters that were identified as pions. The theoretical Bethe-Bloch curves of pions, protons and electrons are also shown. The two dotted lines refer to the expected trend of the energy loss a ±3 σ, where σ is the expected pion energy loss width of the specific energy-loss signal in TPC.)

use machine learning (ML) tools because such algorithms are trained to understand *all* the features of the signal and of the background. The main advantage of such a technique is that it is able to make n-dimensional cuts more efficiently than standard analysis techniques and they can improve both background rejection and signal yield extraction. In particular the Boost Decision Tree (BDT) algorithm within the TMVA package was used [4] since it already proved to improve the significance of rare hadron identification within a topological driven analysis [5] such as the Λ_C^+. Furthermore the doubtful existence of Λnn may result in a huge effort in signal extraction with a standard analysis. The Machine Learning algorithms, instead, with their supply tools (e.g.: variable ranking for the cuts, fake rate probability, etc.) are able to optimize the selection process and to speed up the analysis results, also in the missing signal case.

In the specific case of the Λnn identification in ALICE, the same procedure was applied at both Pb-Pb collision energies $\sqrt{s_{NN}}$=2.76 TeV and $\sqrt{s_{NN}}$ =5.02 TeV. The Particle IDentification (PID) for tritons was performed via TPC dE/dx and TOF information. The TOF signal was used in parallel to reject protons and pions below 4 GeV/c and then the hadron squared mass by the TOF β measurement was used above 3 GeV/c to have enough statistics. The energy loss in TPC of the selected pions and tritons after such PID cuts is shown in Figures 3 and 2 respectively. After some further checks, only candidates containing antitritons were considered because it improved the performance of the machine learning algorithm.

3 Λnn signal extraction with a Machine Learning approach

The machine learning procedure adopted in this analysis was a supervised one, which means that the signal is extracted from the real data after a *learning* phase of the BDT algorithm. The full procedure foresees an initial stage where the algorithm is trained to identify signal candidates and background candidates, and a final stage which consists in applying the updated algorithm to identify the signal-like candidates in the data. The first stage must consider candidates which should belong only to the signal type and to the background type and this is typically achieved making use of Monte Carlo simulations. The last stage is done always on

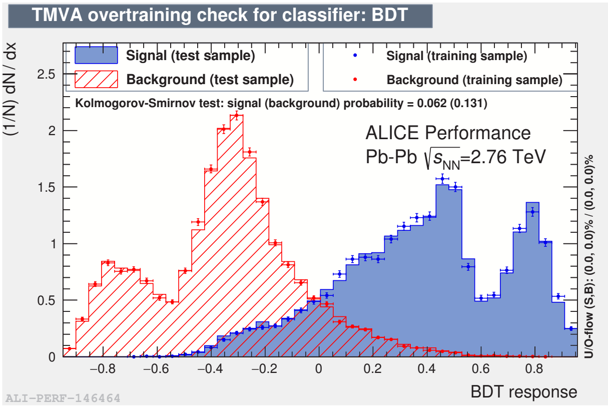

Figure 4. BDT classifier for signal and background Λnn candidates in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$=2.76 TeV.

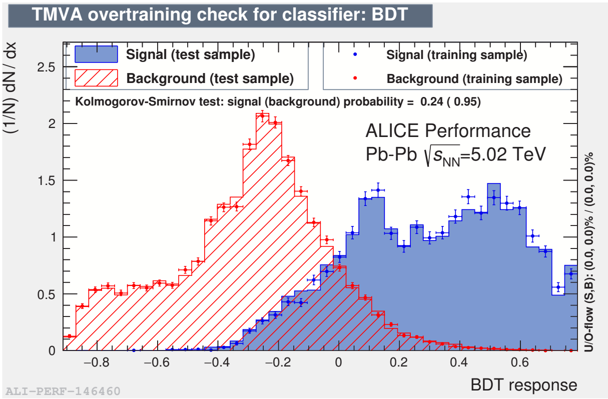

Figure 5. BDT classifier for signal and background Λnn candidates in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$=5.02 TeV.

real data. In this analysis the signal candidates were indeed extracted from Monte Carlo simulations based on the HIJING generator [6] at both energies with injected Λnn signal (flat in p_T) that had a mass value of 2.982 GeV/c^2 that is a bit lower than the measured one to comply with the expected value $p_{\Lambda\rightarrow\pi p}$ = 101 MeV/c [1]. The experimental resolution from simulations was found to be $\sigma_{\mathrm{MC}}(\Lambda\mathrm{nn})$ =2 MeV/c^2. The choice of the background candidates, instead, needed some further study. Due to the missing nuclei simulation in HIJING, the background combinatorics cound not be extracted from the Monte Carlo. It was decided, then, to use the candidates outside the signal region in the invariant mass distribution as background candidates.

In particular the signal region was chosen to be the one between 2.982 GeV/c^2-$3\sigma_{\mathrm{MC}}(\Lambda\mathrm{nn})$ < $M(t\pi)$ <2.993 GeV/c^2+$3\sigma_{\mathrm{MC}}(\Lambda\mathrm{nn})$. The value 2.982 GeV/$c^2$ is considered

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[1] In the two body decay Λnn→^{3}Hπ, if assuming a mass of 2.993 GeV/c^2 then the momentum of the decay products in the rest frame of the mother is higher then the value 101 MeV/c^2, that is the value of the corresponding momentum in the free lambda case $\Lambda\rightarrow\pi p$. In order to have the same value of that momentum, the Λnn state shold have a lower mass value 2.982 GeV/c^2

in the lower limit case because it is expected mass value at the p_Λ = 101 MeV/c of the free Λ, whereas 2.993 GeV/c^2 is the available measured value. The PID selection was applied to tritons to have 10^4 candidates in both the signal sample and the background sample. Four variables were used and they were selected to avoid any correlation with the invariant mass in the background data sample. The results of the machine learning training stage are shown in Figure 4 and 5 for Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$=2.76 TeV and $\sqrt{s_{\mathrm{NN}}}$=5.02 TeV respectively. The classifier distributions for signal and background are well separated providing a low bkg contamination for the selected signal.

Applying the trained BDT algorithm to real data the background rejection was improved and in the end a sample of Λnn was selected. The retrieved number was compatible with the number of expected false positive candidates foreseen by the algorithm (and provided during the training stage). Further work is necessary and studies are ongoing to include positive tritons. The strategy is to improve the triton PID and include the Transition Radiation Detector (TRD) to further reject low mass particles from the selected sample of nuclei.

References

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