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Referee report on doctoral thesis: „Measuring $\Lambda(1520)$ production in proton-proton and proton-nucleus collisions with HADES detector" by Krzysztof Nowakowski

Submitted Thesis under the title „ Measuring Λ(1520) production in proton-proton and proton-nucleus collisions with HADES detector" describes the analysis focused on studying of selected hyperon decay channel observed by the HADES detector operating at the accelerator facility FAIR at Darmstadt. The final decay, $\Lambda(1520) \to \Lambda^0\pi^+\pi^-$, has been observed in both proton-proton and proton-nucleus interactions, and for both measurements, the cross-section has been evaluated. The Author also presented an analysis based on simulated samples regarding selected decay channels, including Dalitz processes $N^* \to Ne^+e^-$, that will be part of the upgraded HADES detector physics programme.

The Thesis consists of seven chapters (including a short summary presented at the end of the Thesis). A clear statement concerning the Author's various contributions, explaining the scope of his activities and role within the HADES collaboration, is placed at the beginning of the text. Original work done by the Author is supported by four nominations to present the results on behalf of the HADES collaboration at four international conferences.

The first Chapter contains an excellent description of the motivation of the Thesis. It provides a compact and self-contained introduction to the physics aspects of analyses discussed by the Author. Although the long-established Quantum Chromodynamics performs well in describing the static properties of hadronic particles and predicting the behaviour of quarks at high energies, the non-perturbative limits still pose a serious challenge for both theory and experiment. Even with the huge progress of the lattice QCD calculations, predicting the properties of the excited states comprising light quarks are problematic. The Author indicates that differences between the observed and predicted properties of baryons are largest for the states with strange quarks, which makes the described analyses particularly interesting. There are a number of models that can be applied to predicting the key properties of baryons. Among them, there is a phenomenological one that attempts to describe a baryon as a dynamic system with interacting quarks and a meson cloud (pretty much as we model, for instance, an interacting electron that is surrounded by a cloud of virtual photons). The most interesting fact is that the cloud, say composed of pions, can significantly modulate the properties of baryons, and this can be tested in experiments. A significant success of this model is related to the analysis of the electromagnetic Dalitz decays that seem to support the significant role of the pion cloud. Thanks to the excellent tracking capabilities of the HADES detector, it can operate using both proton-proton and proton-nucleus collisions and a comparison of hyperon production cross-sections with and without the influence of nuclear matter is possible. For instance, one of the most interesting results of the HADES experiment was an observation of significant cascade hyperons production in proton-nucleus collisions. Comparison with the theoretical predictions showed disagreement that exceeds one order of magnitude.

Studying hyperon properties using electromagnetic probes is also very promising where the so-called Dalitz processes can be explored. The cross-sections for electromagnetic Dalitz decays can be expressed via electromagnetic transition form factors, which can provide an intuitive interpretation of the results by analogy to the form-factor functions describing the charge distribution within a composite particle. Observables involving partial width dependency on produced di-lepton invariant mass are going to be explored during the upgrade runs of the HADES detector.

Chapter 2 provides an exhaustive description of the experimental setup. The detector, High Acceptance Di-Electron Spectrometer (HADES), operates at GSI institute and uses the beams provided by the SIS 18 synchrotron. It is a relatively simple yet capable device optimised for a very specific physics programme regarding the hyperons. HADES must provide high-precision track and PID reconstruction. The tracker, MDC, comprises multi-wire drift chambers and a superconducting magnet. The relative momentum resolution achieved by the MDC is $\frac{\Delta p}{p} \approx 2 - 3\%$. The PID system comprises high-resolution Time-of-Flight detectors and Ring Imaging Cherenkov (RICH). Further, the identification is enhanced by the MDC via energy loss measurement. Combined PID information allows for an excellent separation of protons, pions, kaons and electrons over the large interval of particle momenta. HADES is currently undergoing a deep upgrade that allows it to significantly extend its angular acceptance, which is especially important for Λ^0 decays reconstruction. The group from Jagiellonian University is very active in the upgrade activities and is responsible for the preparation of the Forward Detector.

It is worth mentioning that proton-proton and proton-nucleus collisions are possible with the HADES detector via exchanging the target. For the former, liquid hydrogen (LH2) target was used, whilst, for the latter, a carbon tube with niobium roundels was installed.

The Author took part in HADES runs and data taking. The presented description confirms his knowledge of the experimental setup, which for sure helped in the preparation of such demanding data analysis.

The remainder of the Thesis describes the results of analyses performed by the Author. Chapter 3 contains a discussion on the intelligent model, based on an Artificial Neural Network (ANN), used for signal and background classification. The Author uses a challenging approach to the training process by applying a fully data-driven technique, which is still quite novel in the field of particle physics. The labels (events type A and B in the Thesis) are assigned without any Monte-Carlo samples but rather using the $p\pi^-$ invariant mass distribution, where “signal” events are defined as these being inside the Λ^0 mass window. The employed model is quite simple (a shallow fully-connected ANN). Interestingly only topological variables are used in the training process. Most probably, using kinematic variables of the final state particles (or their combinations) would help increase the performance of the trained classifier. It would be really useful to present distributions for a selected subset of variables for regions A and B of the $p\pi^-$ invariant mass system and discuss their correlations. In the case of using a purely data-driven approach, it is very difficult to choose the optimal operating (or working) point of the model. Typically, a sub-optimisation procedure is performed using a figure-of-merit (FoM) variable evaluated based on the properties of candidates that were not presented to the model during the training. The presented analysis used a combination of signal selection efficiency and background rejection factor to choose the most optimal threshold. The ROC curve was presented as the performance metric of the trained model. Judging by the area under the ROC curve and the response of the classifier, the selected model is sensitive to signal and background events.

Chapter 4 is devoted to the analysis of the inclusive production of excited hyperon state $\Lambda(1520)$ in proton-proton collisions. This is a pioneering analysis in many respects. This mass state has never been studied at the energies used in the HADES experiment, the production cross-section has never been evaluated and finally it was the first analysis of the decay to the final state containing $\Lambda^0\pi^+\pi^-$. Author indicates also, that the precise cross-section measurement will provide a vital input for the planned HADES runes in 2022. At the beginning Author describes the overall strategy for the analysis. The absolute normalisation (necessary in the case of cross-section measurements), defined by the means of integrated luminosity, comes from the elastic proton-proton scattering observed previously by the HADES experiment. The cross-section estimate relies on the proper counting of the signal events and the reconstruction efficiency obtained via Monte-Carlo simulations. Along comes also the discussion on possible background contamination and control channels. The former are the processes that lead to the final state containing one hyperon Λ^0 and one neutral kaon. The leading background channels are: $\Lambda^0\Delta^{++}K^0$, $\Sigma^0\Delta^{++}K^0$ and $\Sigma(1385)\Delta^{++}K^0$. If partially reconstructed these decays can mimic signal events having contained both Λ^0 hyperon and pion pair.

The preselection step is based on searching for final states containing at least four charged tracks reconstructed within the detector acceptance. Combinatorics pions result in multiple $\Lambda(1520)$ candidates that are sorted according to the daughter's track fit quality. Slight observed charge asymmetry is attributed to the asymmetric initial state containing two protons. Ambiguities related to the assignment of the right pion to form Λ^0 is solved by tight mass window cut. The missing mass distribution analysis allowed to work out a very effective cut to discriminate the background and retaining the most of the signal events at the same time. The whole preselection procedure presented in the Thesis is very elegant and indicates a deep understanding of the underlying physics of the production process. The same reasoning was used in case of the pre-selection of events candidates in proton-nucleus scattering.

Next, the Λ^0 signal selection is performed with the ANN model. After applying the trained model a sample of 1000 Λ^0 events has been selected. The remaining combinatorics background was further suppressed by the fit with appropriately modelled sidebands. The final Λ^0 sample was used to reconstruct both the signal decay and the control one (Λ^0K^0). The control channel is clearly visible in the selected data. Corresponding associated production semi-inclusion cross-sections were evaluated using the simulated efficiency functions.

Final signal selection was performed based on the simulation studies that helped to identified the most effective cuts. This analysis indicated that the distance between the primary and secondary vertex and the angle between the Λ^0 momentum direction and the direction of line connecting the primary and secondary vertex play critical role. Optimal values for these cuts were chosen via signal-to-background scan. Since the dominant background expected within the mass window of the Λ^0 should mostly come from the multiple pion production, again, the sideband modelling was used to suppress the combinatorial contribution and select the best Λ^0 events. Those, were subsequently used to reconstruct the signal decays. The background subtracted mass peak of the $\Lambda(1520)$ events is shifted with respect to the PDG value (also simulation sample shows similar behaviour). A possible explanation is energy loss of the pions in HADES detector. Finally, the inclusive production cross-section of the signal decay has been estimated to be $\sigma_{pp\rightarrow\Lambda(1520)X} = 7.1 \pm 1.1^{+0.0}_{-2.14}$ $[\mu b]$ with the systematic errors estimated by cut variations.

Chapter 5 presents a complementary analysis of $\Lambda(1520)$ production in proton-nucleus scattering with a niobium target. Although the general idea of the signal selection follows the selection used for the proton-proton case, there is a major problem with the background modelling. A special simulation package, UrQMD (Ultrarelativistic Quantum Molecular Dynamics), had to be used. Data used for this analysis were collected in 2008 at the energy of the proton beam of 3.5 GeV. Λ^0 signal is selected with the same ANN model used for the analysis described in Chapter 4, and the background is handled via sidebands. Interestingly, proton-nucleus data yield better energy resolution, which might be a bit counter-intuitive. Again a semi-inclusive $\Lambda^0 K^0$ production was used as a control channel. This is of crucial importance, allowing not only the signal cross-section measurement but also facilitating the comparison between proton-proton and proton-nucleus cross-sections. The control process cross-section has never been measured before, so as a sanity check, a scaling to the proton-nucleus was applied, and as a result, a reference cross-section was evaluated to be $\sigma_{\Lambda^0 K^0} = 1.38 \pm 0.038\ [mb]$.

Signal hyperon, $\Lambda(1520)$, reconstruction was again performed as in the proton-proton case. Obtained mass peak, after the subtraction of the background, is skewed and much broader that in the case of proton-proton production. Author correctly indicates, that most probably this is caused by the non-resonant contribution of $\Lambda^0\pi^+\pi^-$. Also, some significant hyperon width broadening is expected because of the decays in nuclear medium. In order to improve the result UrQMD simulation was used to model the non-resonant background in the $p\pi^-\pi^+\pi^-$ mass spectrum. Also, as additional cross-checks distributions of transverse momentum, p_T, and rapidity, Y, of $\Lambda(1520)$ were studied. Generated UrQMD events were processed in the same way as data sample and subtracted. The resulting distribution features much better symmetry, the fit parameters have better agreement with the PDG but with a significant uncertainty. Similarly, the shift in the central mass value persists (as in the case of the proton-proton data).

Before the production cross-section estimation was attempted Author used a thermal model to improve the agreement between selected kinematical variables in simulated and data samples. The dedicated generator, PLUTO, featuring a thermal model was used. Subsequently, total reconstruction efficiency was evaluated to be $\sigma^{pNb}_{\Lambda(1520)} = 4.97 \pm 0.45 \pm^{3.58}_{2.53}\ [mb]$. This result can be compared to the corresponding result for proton-proton production using the $A^{2/3}$ scaling, which gives $0.145 \pm 0.022^{+0.0}_{-0.044}\ [mb]$. The significant discrepancy between proton-proton and proton-Nb production cross-sections is super interesting, given, that for the control channel we observe a very good agreement.

The last part of the Thesis, Chapter 6, present simulation studies for the new HADES runs with the 4.5 GeV proton beam, that is the maximum energy for the SIS 18 machine. The increased energy beam will allow to study doubly-strange $\Xi^-(1322)$ baryons, explore proton-nucleus and nucleus-nucleus scattering, as well as analyse fascinating Dalitz decays of hyperons. Author did an extensive analysis of the simulated samples to improve the selection of signal channels and estimate the cross-sections for expected signal channels. Especially interesting are the branching ratio predictions, since such processes have never been measured before.

In summary, I believe that the presented Thesis makes a very solid and valuable contribution to the field of particle physics. The Author presented two involved data analyses that would be worthy of the Thesis in the first place. In addition, he also performed an interesting simulation analysis that is of vital importance for the ongoing new HADES runs with an increased energy beam. His discussion of physics aspects of presented analyses and the reconstruction of signals proved that the Author is an accomplished young physicist. His work allowed for the exploration of new exciting hyperon decays for the first time and yielded very interesting and unexpected results for the cross-section of the production in collisions with the niobium target. I found both interesting and fascinating the discussion regarding the importance of interactions within nuclear matter.

In conclusion, the dissertation presented by Krzysztof Nowakowski contains valuable and original results and satisfies all the formal and customary requirements for a doctoral thesis, and I hereby agree and strongly support his public defence.

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