Warszawa, 10.04.2022 r.

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Review Report on the PhD thesis

Study of the e^+e^- production in π^-p collisions in HADES at GSI

Thesis author: Naredra Shankar Singth Rathod

Background & research goals

The topic of the PhD thesis “Study of the e+e- production in π-p collisions in HADES at GSI” by Mr. Naredra Shankar Singth Rathod is related to studies of nuclear matter created in reactions of heavy ions at high energies. In such collisions, a state of matter with quark and gluon degrees of freedom can be created if the energy density of the system is sufficiently high. Measurement of dilepton ($\mu^+\mu^-$ or e^+e^-) production is a rich source of information about such a system. For example, dileptons originating from thermal radiation from a fireball provide insights into space time-evolution of the system, high mass Drell-Yan (quark+antiquark$\rightarrow$ l^+l^-) production gives access to the parton distribution function in a nucleus. In addition, lepton pairs from semileptonic decays of charmed and beauty hadrons may provide information about azimuthal correlation (or decorrelation) of charm and beauty quarks. Moreover, a modification of the invariant mass spectrum of vector mesons could be connected to the restoration of chiral symmetry in nuclear collisions.

Given all these opportunities, measurements of dilepton production were carried out by (among others) the CERES and NA60 experiments at the Super Proton Synchrotron at CERN, STAR and PHENIX at Relativistic Heavy Ion Collider at Brookhaven National Laboratory and ALICE at the Large Hadron Collider at CERN.

The wealth of the information carried by the dileptons comes with the price of complications in interpreting experimental data. The observed distibution is a convolution of many sources of a signal. To correctly interpret the results, one needs to understand each contribution to model them reliably for a complicated environment of heavy-ion collisions. Thus, there is a need to study dilepton production in more straightforward cases, for instance, proton-proton or meson-proton reactions.

The thesis addresses one of these processes: virtual photon bremsstrahlung at low invariant mass using π^- - proton collisions registered by the HADES experiment. Therefore, the selected research problem is interesting and important for understanding and interpreting the results of nucleus-nucleus collisions.

Thesis structure and content

The thesis has a classical structure, starting with an introduction to the research goal, then describing the experimental apparatus and experimental techniques used for particle track reconstruction and particle identification in the HADES spectrometer. Chapters 4 - 6 present the central part of the thesis, namely data analysis (Chapter 5) and corresponding Monte Carlo simulations (Chapter 4), while Chapter 6 contains the results obtained by the author and their

discussion. Chapter 7 presents the summary of the research and concludes the dissertation. The overall structure is appropriate for the given topic, with the most prominent part devoted to the experimental techniques, data analysis and related simulations, and the final results.

Overall, the thesis is carefully prepared. The text is well written, the figures and illustrations are of good quality, and they support the content well. I have found only a few minor issues, some of them I list for reference below.

Introduction and state of the art

The thesis briefly introduces the experimental results on dilepton measurements at the energy range of a few GeV and the theory of bremsstrahlung radiation. This part is short, although supported with enough references and thus sufficient given it is an experimental work. The general goals and specific objectives of the conducted research are clearly identified.

Presentation of experimental apparatus and techniques

The HADES detector and experimental techniques used for particle track reconstruction and identification are presented in detail and well developed. The thesis provides all the relevant information, including the determination of the beam momentum and its uncertainties, particle tracking, detector signal used for particle identification, and quality assurance criteria applied in the analysis.

The procedure used for Monte Carlo simulation of bremsstrahlung signal and source of background is clearly presented with a sufficient level of detail, including verification of the calculations implemented by the author. My only complaint is missing discussion of possible systematic uncertainties on the simulation results and whether they may (or not) impact the interpretation of the experimental data.

Overall, the text convincingly demonstrates the author has an in-deep understanding of the experimental techniques and all the complicated steps necessary to obtain final physics results.

Data analysis and results

The work presents a study of electron-positron pairs production in π^--proton interactions registered by the HADES experiment at a pion beam momentum of 0.685 GeV/c.

The thesis covers analysis of four channels that include in e^+e^- pair ($\pi^-pe^+e^-$, e^+e^- + anything, $\pi^-e^+e^-$ + anything, pe^+e^- + anything) in the final state in the π^--proton reactions. The analysis strategy is based on measurement of the e^+e^- production in the given channel in pion collision on a stationary polyethylene target ($(C_2H_2)_n$), and then subtraction of the background due to reactions of pions with carbon target (the background is evaluated in independent analysis of π^--C reactions.)

The research methodology is well justified and credible as it includes standard techniques employed in high-energy particle and nuclear experiments. Hadron identification is performed using measurement of energy loss dE/dx and time-of-flight as a function of momentum, while electrons and positrons are identificated via Cherenkov radiation in the RICH detector. Then the signal is taken as the invariant mass of electron-positron pairs and the missing mass of the final state particle system. Finally, the data are compared with the expectations from the Monte Carlo simulations.

The analysis and the results are described in sufficient detail. The decisions made at various stages of the studies are sensible, and the interpretation of the results is sound and credible in general. Although, I have a few questions and remarks, which I list below.

The results consist of e^+e^- invariant mass and missing mass distributions, the cross section as a function of the invariant mass, transverse momentum, rapidity, and angular distributions. Next, the author obtained cross section for π^0 production in $\pi^-p \rightarrow \pi^-p\pi^0$ reactions, and bremsstrahlung cross section for π^- scattering on a polyethylene target using e^+e^- + anything, $\pi^-e^+e^-$ + anything channels. Finally, the thesis presents the results of the estimation of the cross section for virtual bremsstrahlung in π^-p reactions.

The conclusions are sound and sensible. I find the statement about the significant role of bremsstrahlung in the electron-positron pair production with the mass range above π^0 mass especially interesting. Overall, I think the thesis results are an important addition to the field, especially the cross section for virtual bremsstrahlung, despite the limited precision of the latter.

Questions and remarks

1. Given the experimental character of the thesis, systematic uncertainties deserve more attention. Specifically, it is unclear how the uncertainties on hadron identification are estimated. Also, what are the uncertainties on the efficiency and acceptance correction factors obtained from the Monte Carlo simulation?
2. The author correctly noted that the geometrical mean could underestimate combinatorial background in the case of low electron/positron yields per even. Why then was this method used to estimate the systematic uncertainties on the combinatorial background?
3. For the inclusive bremsstrahlung results in the e^+e^- + anything channel: How large is the uncertainty on the simulated η Dalitz decay? Was it included in the uncertainty budget of results presented in Tab. 6.5?
4. The meaning of results of missing mass for combinatorial background (Fig. 5.12 and 5.13 on page 75) is unclear to me. Given that there has to be additional electron/positron produced in the collision to have same-sign electron or positron pairs, why missing mass should be around zero? How exactly was the missing mass calculated for the combinatorial background?
5. How proton, pion, and electron/positron identification efficiencies are estimated? Does the efficiency change with particle momentum?
6. Minor comments and issues to be fixed if the electronic version of the thesis is published online:
    1. Adding the formula used to calculate the missing mass would help following the analysis flow.
    2. I suggest using consistent naming for polyethylene thought the thesis. The author uses CH_2 vs $(C_2H_4)_n$ and PE, which could be confusing. For example: In Fig. 5.26 and 5.27, the caption mentions $(C_2H_4)_n$ while the legend uses PE for polyethylene. I have a similar comment to Fig. 6.2 – 6.2: the legends use CH_2 while in the text or captions $(C_2H_4)_n$ is written.
    3. I suspect Fig. 1.2 and 1.3 should have a reference for their sources unless they were prepared by the thesis author or they are in the public domain.
    4. The formatting of the bibliography is inconsistent (some entries include DOI information while others do not, missing space after a journal name, Ph.D vs PhD).
    5. Figures 5.7 and 5.8: the x-axis titles should be improved, including adding units.

The last question is an invitation for a discussion at the PhD thesis defense: Would any measurement in polarized electron-proton reactions, either at HERA or future electron-ion collider, help accessing the virtual bremsstrahlung process?

Summary and final evaluation

The thesis presents extensive experimental data analysis of electron-positron pair production at low invariant mass in the π^--proton collisions registered by the HADES experiment at GSI. It includes reconstruction of the signal in four channels, Monte Carlo simulations of the expected signal and background, evaluation and subtraction of physics and combinatorial background, and finally, calculation of cross section for bremsstrahlung in polyethylene and proton target, including uncertainty evaluation.

The author demonstrated a good understanding of the underlying theory and knowledge of other experimental results and state of the art in his research topic. In addition, the thesis clearly establishes that the author mastered all the technical and data analysis skills that a researcher needs to work in high-energy particle or nuclear experiments. The thesis also shows that the author understands very well the strengths and limitations of the experimental apparatus and methods he used.

I find the presented results original, sound, and solid, and I think they form a significant scientific achievement. The thesis is convincing evidence of the scientific maturity of the author and that he is capable of independently conducting research projects in the field of experimental high energy physics.

In my opinion, the thesis demonstrates that Mr. Naredra Rathod meets the requirements laid down by the Polish law (*Prawo o szkolnictwie wyższym i nauce*, Dz. U. z 2020 r. poz. 85 z późniejszymi zmianami) for candidates for the degree of Doctor of Philosophy in Physics.