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Darmstadt, May 27, 2017

To:
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Ref.: *Report on the PhD thesis of Szymon Harabasz*
"Reconstruction of virtual photons from Au+Au collisions at 1.23 GeV/u"

The PhD thesis of Szymon Harabasz is devoted to a remarkable measurement, that of dielectron production in Au+Au collisions at the low-end of the relativistic heavy-ion collisions, which is unique and long-awaited. The measurements are performed by the HADES collaboration at the SIS18 accelerator of GSI Darmstadt.

The HADES experiment was designed (and subsequently upgraded) to perform such measurements and the data presented in this thesis are a culmination of a long effort, extending over many years, with a series of measurements completed already. In addition, given the complexity of the experiment itself, its operation and data-taking, as well as the calibration and reconstruction, many persons have contributed. For a PhD student working in such an environment, it is an achievement per se to master the complexity of the experiment and its data analysis and physics. It appears that Szymon Harabasz has done this very well and was able to extract the final fruit of the extended effort of the HADES experiment, the dilepton results in Au+Au collisions.

The thesis contains an abstract (in english, german and polish), seven chapters of the main work and an appendix.

Chapter 1 presents an overview of Quantum Chromodynamics (QCD), with focus on the chiral symmetry and containing a discussion of the phase diagram of QCD. An overview of the physics of heavy-ion collisions at high energies is presented, containing: an outline of the dynamics of the system produced in heavy-ion collisions; a discussion of collective flow of hadrons and of the phase diagram as probed with the data on hadron yields; an extended outline of measurements with electromagnetic probes, namely real and virtual photons, the latter as measured via the invariant mass of electron-positron or dimuon pairs. The relevant measurements and their interpretation for all available collision energies are discussed. This provides the setting against which the aim of the thesis is presented at the end of the chapter. I found a typo in the temperature quoted for $\sqrt{s_{NN}}$=200 GeV (PHENIX measuremment) and that an outdated ALICE preliminary Fig. is used, to be replaced by the final published result. Also the crossover temperature for the chiral symmetry restoration needs an update in light of recent lattics QCD calculations (and accordingly as well Fig. 1.5 can be updated to show state-of-the art calculations).

Chapter 2 is devoted to the HADES experiment, which is decribed in very good details, at the level of the full system, including design, construction, trigger and data acquisition. The individual subsystems are described in all relevant details, including construction and working principle and performance. The tracking system, based on multi-wire proportional chambers, allows trakectory econstruction and momentum measurement in the magnetic field. The particle identification system is crucial for the subject of the thesis, dielectron measurements. The Ring Imaging Cherenkov Detector is described and compared with similar systems in other experiments (CLEO III and LHCb). The Time-of-Flight systems, based on scintillators and on Resistive Plate Chambers - an inovative application of these detector type, unique in HADES, providing the impressive time resolution below 70 ps. The preshower detector and the diamond start detector are described as well.

In Chapter 3 the data analysis is described, comprising: the online event selection (trigger); the (offline) centrality determination and selection; track selection; electron identification. The latter, primarily performed with the preshower detector, the time-of-flight and RICH measurements, is central to the present thesis. Given the multitude of of measured quantities and the (rather large) correlations among them, a natural method to combine them is to use artificial neural network methods. A multi-layer perceptron is the method employed in this thesis. A very good description is provided, both at principle level and as applied for the HADES data for the identification of electrons and positrons. The selection of variables, the training of the network and the comparison of its results to those using the standard cut-based analysis. Perhaps surprisingly, the net improvement in electron identificaton given by tht neural network method is rather modest (about 7% increase in signal yield at same purity) for one of the 2 system configurations ('called "System 0") and practically not present for the other configuration ("System 1"). I see this as a remarkable confirmation that the cut-based analysis, developed and refined over many years of data analysis, is already giving the ultimate performance of the detector. Everything is well described and the balance between the abundance of technical details and readability is very good. I found a sentence (in sub-section 3.7.2) that may need to be completed/extended for better readability as well as the need to explain a bit more the cases shown in Fig. 3.27.

In Chapter 4 the efficiency corrections are presented. A principially-simple component of any measurement, this is the one that best illustrates that "the devil is in the details". All details are well outlined in the thesis and no "devil" is to be found (fortunately), after all possible candidates have beed addressed. The single-electron efficiency is determined based on Monte Carlo events (with UrQMD as underlying model) as a function of momentum and polar and azimuthal angles. The dependence on the centrality of the collision is investigated and found to be very mild. An embedding of electron and positron tracks into real and simulated events isused to obtain the most-realistic efficiency corection factors. The variation of detector efficiency during the data-taking period is carefully analysed and corrected based on average factors derived from data, whose effectiveness is convincingly demonstrated. The whole procedure is checked with Monte Carlo events. An pair-efficiency loss for small pair opening angles is fund and a correction derived and applied. A systematic uncertainty is assigned based on the maximum deviation per bin in the ratio of invariant mass distributions of simulated π^0 and η mesons. I found this criterion very conservative, but maybe understandable at this stage of the analysis. An effect which is not yet understood, namely the increase in statistical uncertainty of the data after the efficiency corrections discussed above. The way around is to perform the efficiency correction at the pair level. This requires a tuning of all dielectron sources, the so-called "cocktail". The inputs and assumptions for building the cocktail used in the thesis are outlined: thermal distributions with certain temperature values as well as the folding with the experimental momentum resolution. A bit of a conceptual difficulty seems to be thet for the ρ^0 meson an in-medium spectral function (as given by theory which describes existing measurements) is assumed, while this is the physics question tgo be investigated with th edielectron measurements reported here. The dependence of the pair-level correction on centrality is discussed as well as its model dependence and the corresponding uncertainty assigned. The final correction applied is that for inactive detector sectors, for which again a conservative uncertainty is assigned. The whole complex procedure is principially tested via the comparison of the raw (corrected only for the geometric factor due to missing sectors)) invariant mass distribution and the cocktail distribution with the application of the experimental selection and efficiencies. The agreement is very good and provides clear confidence in the procedure.

Chapter 5 is devoted to the subtraction of the combinatorial background arising from pairs built from an electron and a positron originating each from a different source. The justification for usage of the geometric mean of the $++$ and $--$ like-sign pairs is given and the factor to account for the loss of efficiency in the like-sign pair reconstruction is introduced. It is derived employing event mixing, in which the members of a pair are combined from different events. Several methods to extimate this corerction factor, which is a function of the invariant mass, are presented and the corresponding systematic uncertainty is estimated.

In Chapter 6 a summary of all the components of the systematic uncertainties, discussed in the previous two chapters.

Chapter 7 contains the final physics results. Usually the normalization of dilepton spectra is presented with respect to pion multiplicities. An analysis is presented of charged pion yields, which has a systematic uncertainty of about 10%, dominated by extrapolation to uncovered rapidity ranges. I note here that it would be appropriate, for the sake of reducing uncertainties, to present the measurement in the rapidity range covered by the experiment, which is broad and relevant, being centered at midrapidity (a difficulty may arise though in the comparison to the measurement in elementary collisions). The dielectron invariant mass distribution is compared to expectations from a hadronic cocktail and to elementary nucleon-nucleon collisions, from which an excess yield is extracted for the intermediate mass region and compoared to measurements at higher energies (from the STAR experiment). The observed excess is similar to that at lower energies, considering the uncertainties and that the data at lower energies are an average over all collisions, while the HADES data are for the 0-40% most-central collisions. The dilepton yield is presented as a function of centrality, with not significant dependence observed. The temperature parameters for the contribution of π^0 in the dielectron mass distribution is extracted via Boltzmann fits to transverse mass distributions and found similar to those extracted for charged pions - an important "global" consistency check. The temperature of the intermediate-mass dileptons is extracted. A value significantly smaller than that extracted at higher energies is found, as expected. The present data are discused in comparison to measurements by HADES in lighter collisions systems (rescaled to correspond to the collision energy for Au+Au). The data in Au+Au presented in this thesis represent a signifiant extension in the "dynamic range" of the HADES measurements, and, as mentiond earlier, a culmination of the HADES experimental program. Only such comprehensive measurements have the potential to unravel the properties of the hot and dense matter produced in collisions of nuclei at high energies. Comparisons to two theoretical models are shown. The models decribe the data faily well, considering the current uncertainties. It remains to be seen if the presently-observed differences are significant and, if so, what their meaning is. In any case, a medium-modified ρ meson spectral function seems required by the data. But as the author notes, in one of the models (HSD), a large number of Δ baryon (re)generation is included; it remains to be seen (via complementary measurements) whether this theoretical implementation is realistic. A section of conclusions and outlook closes this chapter and the main body of the thesis.

The Appendix offers a few technical details about the calibration of the preshower detector of HADES as well as about its description in Monte Carlo simulations. The references are well-chosen and comprehensive; some of the references are collaboration-internal, I would recommend refering to public documents as much as possible.

In summary, the thesis by Szymon Harabasz presents a challenging analysis, that of dilepton production in Au+Au collisions at 1.2 AGeV, performed with the HADES spectrometer. The observable is a crucial one for the understading the physics of hot and compressed nuclear matter; complete physics results are achieved; the methods are outlined very well; the physics implications are discussed thoroughly and a perspective towards physics conclusions and further measurements is given.

Obviously, I recommend the thesis for public defense. I suggest its consideration for the distinction (summa cum laude).

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