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Report on the PhD-thesis

Reconstruction of virtual photons from Au+Au collisions at 1.23 GeV/u

by M.Sc. Szymon Harabasz

In his thesis, Szymon Harabasz has studied the reconstruction of virtual photons produced in collisions of gold nuclei at a beam energy of 1.23 GeV per nucleon. The data was obtained with the HADES detector at GSI in Darmstadt, Germany in 2012.

Unravelling the properties of strongly interacting (QCD) matter at non-zero temperatures and densities is essential for our understanding of physics at the smallest and largest scales, from nuclei to neutron stars, supernova explosions and the early universe. In the laboratory, QCD matter is studied in nuclear collisions, where matter under extreme conditions is produced in a transient state. The conditions reached in such collisions can be altered by choosing different beams and by varying the collision energy. In particular, matter at high temperatures is explored in nucleus-nucleus collisions at relativistic energies.

In collisions of relativistic nuclei, matter at the highest temperatures and densities available in laboratory experiments is created for a brief moment in time in microscopic systems of nuclear size. Owing to the very high pressure in the interaction volume, the system expands and cools rapidly. By examining different probes, one gains complementary information on the conditions that prevail in such collisions and consequently on the properties of such extreme states of matter. One of the goals of the HADES experiment is to explore the properties of hot and dense strongly interacting matter using electromagnetic probes. The present thesis provides an important step towards this goal.

The first generation of experiments detecting dileptons in nucleus-nucleus collisions were done with the DLS spectrometer at the Bevalac at the LBNL in Berkeley and with the HELIOS and CERES experiments at the SPS at CERN. From the very beginning, one of the basic objectives of these experiments was to obtain information on the in-medium properties of hadrons and in particular to explore the possible connection between these and the restoration of chiral symmetry in QCD matter at high temperatures and densities. This quest is continued by the second generation dilepton experiments STAR and PHENIX at RHIC and by HADES at GSI.

In this thesis, the candidate presents novel results on the data analysis of the dilepton mass spectrum obtained by the HADES experiment. The analysis was based on the algorithms for reconstructing rings in the Ring-Imaging-Cerenkov-Detector (RICH).

In particular, the candidate analyzed the methods for constructing the combinatorial background (which is subtracted) intensively. This work lead him to define a so called k-factor, which corrects for artefacts introduced by asymmetry in the reconstruction efficiency for like- and unlike-sign pairs.

The candidate has also employed neural networks, so called multilayer perceptrons, for single lepton identification. This technique is presented in the thesis in a clear and edifying manner. Using this technique, an excellent purity of the lepton sample is achieved. The candidate stresses that future work in this direction can improve the efficency of the approach.

Based on a detailed analysis, the candidate presents a very careful assessment of the systematic uncertainties of the data. He then presents results for the low-mass dilepton excess and compares these with theoretical models and experiments at other energies and with other systems. Moreover, he extacts the temperature of the system, by an analysis of the invariant mass spectra. This yields a temperature of about 70 MeV, which is in good agreement with the temperature obtained from the π^0 spectrum, after the blueshift due to collective flow has been removed.

The candidate concludes that the data considered is consistent with a sizable reduction of the quark condensate and thus a partial restoration of the chiral symmetry, compared to the situation in vacuum.

As a member of his PhD committee, I have followed the work of the Szymon during his tenure as a PhD student. Given this, I find that the thesis accurately reflects the important contributions by him to the project.

I now turn to a more detailed discussion of the thesis.

Section 1. Strongly interacting matter and its electromagnetic probes

In the first section, the candidate presents an overview of the field and puts his thesis work in a wider context. In particular, the relevant theoretical concepts are discussed and the case is made for unravelling the properties of dense and hot strongly interacting matter using electromagnetic probes.

The discussion starts out with a presentation of the four known interactions, gravity, the weak, the electromagnetic and the stong interactions. He proceeds with a brief introduction to the standard model of particle physics. The discussion is then focussed on the strong interaction, i.e., on quantum chromodynamics (QCD). Thereby, the differences between QED and QCD, which leads to confinement and asymptotic freedom, are briefly discussed. Then, the presentation continues with the broken symmetries of QCD. In particular, the breaking of the center symmetry of colour SU(3) and confinement in pure Yang-Mills theory and the corresponding order parameter, the Polyakov loop, is discussed.

The spontaneous breaking of the chiral symmetry is also outlined in this section. The candidate starts off by presenting the chiral symmetry transformations. He then discusses the signatures of spontaneous breaking of the chiral symmetry in the hadron spectrum and in the vector and axial vector spectral functions obtained from τ decays. Finally, possible scenarios for chiral symmetry restoration at non-zero densities and temperatures are presented.

After discussion of the phase diagram of QCD matter and of the evolution of matter in a nucleus-nucleus collision, the candidate turns to the possibilities for probing the properties of QCD matter in nuclear collisions with photons. He discusses a characteristic dilepton spectrum as well as dilepton spectra obtained in various system, ranging from proton-nucleus to lead-lead collisions at several accelerators, ranging from SIS18 to SPS, RHIC and LHC.

Section 2. The HADES apparatus

In this section the candidate describes the HADES detector and target system.

Section 3. Data analysis tools and techniques

Here the candidate discusses the tools and techniques employed in the thesis for analysing the data. In particular, the neural network employed for lepton identification is presented in detail. The candidate has demonstrated that a very high purity of the lepton sample can be obtained using this technique.

Section 4. Efficiency corrections

In this section a systematic discussion of the various efficiency corrections is presented. The presentation is well structured and clear.

Section 5. Subtraction of the cobinatorial background

Here the candidate discusses the pros and cons of different background subtraction techniques, and clarifies the role of the k-factor, which accounts for the asymmetry in the reconstruction efficiency for like-sign vs. unlike-sign pairs.

Section 6. Summary of systematic uncertainties

This section sumarizes the systematic uncertainties that apply to the data.

Section 7. Interpretation of dilepton spectra

In the final section the candidate discusses the interpretation of the dilepton data that was analysed by him in the course of his PhD work. The data is compared to a reference spectrum, which is given by the average of that obtained in proton-proton and proton-neutron collisions, with a cocktail, which is determined by the decays of hadrons present at the freeze-out of the collision volume as well as with dilepton spectra of other nucleus-nucleus collisions. All comparisons show that the gold-gold data exhibits a stong enhancement of the dilepton yield in the invariant mass range from 200 MeV to the ρ/ω mass.

The candidate has also analysed the slopes of the invariant mass dilepton spectra, which are independent of the collective flow. By contrast, the slope of particle spectra as function of the transverse momentum or transverse mass are affected by the collective flow. After subtracting this contribution, the pion spectra yields a temperature, which is in good agreement with that deduced from the dilepton spectrum, i.e., about 70 MeV.

Finally, the candidate also confronts theoretical models with the data. Here both the coarsed grained transport model, UrQMD, and the HSD model reproduce the data pretty well. Superficially the main contribution to the dilepton spectrum is due to different sources in the two models. To resolve this issue requires a dedicated effort by the model builders to unravel the connections between the two approaches. Moreover, more differential data may be needed to distinguish between different models.

Criticism and questions:

- Confusing use of the concepts hadrons, mesons nucleons, nuclei. Constituents of nuclei are generally called nucleons. They are of course also hadrons, but using the term nucleons in this context is preferred (p.23, Fig. 1.16, p. 35).
- The discussion of chiral symmetry is, compared to the presentation of the center symmetry, in my opinion too condensed. Since chiral symmetry is a central concept for the investigations described in this thesis, further discussion would have been appropriate. The following are examples of topics could have been presented: i) why does a non-zero quark mass break the chiral symmetry explicitly, ii) restoration of chiral symmetry at non-zero temperature and density (lattice and model results).
- Chiral symmetry: Goldstone bosons of chiral SU(3) pions and kaons? Any other ones? (p. 31)
- Chiral partners: a_1 and ρ is fine, but how do we know that $f_1(1260)$ and ω or $f_1(1420)$ and ϕ are chiral partners? (p.31)
- The ρ meson dominates vector meson dominance? Since the widths of ω and ϕ are much smaller than that of ρ, this is not so obvious for invariant masses near those of the vector mesons. At the pole, Im$D_i \sim 1/\Gamma_i$. (p. 35 and 150)
- Fig 1.9: I do not understand how cutting the diagram in the left panel yields the one on the right.
- Which baryon number vanishes on the temperature axis of the QCD phase diagram? (p. 38)
- How does the relation $N_{\pi^0} \simeq \frac{1}{2}(N_{\pi^+} + N_{\pi^-})$ follow from isospin symmetry?
- The spectra are normalized to the number of π^0. How does this work in Fig. 7.12?
- Can one make the “resonance clock” quantitative? Is it not difficult, since e.g. for the ρ, the width and possibly also the mass, changes in medium. Thus the lifetime of a ρ in matter is shorter than in vacuum. Moreover, there is no resonance peak visible, which one could use to identify the ρ meson. (p. 142)
- On the one hand it is stated that the ”quantitative results of the models can now be regarded as reflecting the reality”. On the other, it is found the models have different physical input. For instance, the HSD model includes only the Δ resonance, while the coarse grained UrQMD takes also higher lying baryon resonances into account. Yet, both models describe the data reasonably well. In view of the lack of sensitivity to the input, how can one conclude that the models reflect reality?
- Does it make sense to consider the contribution of the Δ-Dalitz decay to the dilepton spectrum 500 MeV away from its mass? (Fig. 7.15)

In this thesis M.Sc. Szymon Harabasz presents a demanding and comprehensive study of a topic of high current interest. The work is of high quality and the complex matter is well presented. The thesis clearly demonstrates the candidate has acquired the ability to carry out independent scientific work. This confirms the very positive impression I have gained from discussions with him in the PhD committee of the graduate school HGS-HIRe.

I conclude that the presented thesis clearly fulfills the requirements for a PhD in physics and I recommend that it be accepted by the Faculty.

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