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Report on the Ph.D. Thesis „ Effective-Model Perspective on QCD Phenomenology", authored by mgr Michał Marczenko

The thesis by Michał Marczenko was prepared at the University of Wrocław under the supervision of Dr. hab. Chihiro Sasaki. The subject of thesis can be put in the broad context of phenomenology of Quantum Chromodynamics (QCD). Without any doubt, QCD *is* the theory of strong interaction – but the fact, that the hadronic spectroscopy belongs generally to the realm of strong coupling, invalidating perturbative expansions, poses a serious challenge to quantitative predictions of the theory and experimental verification in nonperturbative regime. A powerful alternative to the fundamental non-perturbative calculation is provided by the phenomenological models. Such models have to take into account, at various level of rigidity, basic features of QCD alike exact symmetries, approximate symmetries, spontaneous/explicit breaking of the symmetries, confinement and the universal character of the phase transitions. In recent years, such models started to face another challenge – more accurate data from terrestial, high energy collision experiments, astrophysical signature from extra-terrestial objects, and last, but not least, more and more precise calculations *ab initio* in lattice (Euclidean) QCD.

The thesis of Mr Marczenko precisely addresses this last challenges.

The dissertation is written in very good English language, and is composed out of 151 pages. The thesis is composed out of 7 chapters, two appendices and very rich bibliography (253 positions). The content is based on the results by the Author, published with his Advisor and other collaborators of the Advisor within 2015-2018 in 7 (seven) top ranked international journals in the area of high-energy physics.

First two chapters have an introductory character. Then the thesis has two hard scientific cores, representing original results by the Author. First one deals with finite temperature/vanishing density regime of the QCD (Chapter 3). The second deals with cold, but dense regime of the QCD (Chapters 4-6). Last Chapter 7 summarizes the thesis, and two appendices explain the group theoretical conventions used by the Author and mathematical details of the asymptotic expansions of cumulants.

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Let me now review the contents of the thesis in more detailed way.

Chapter 1 is a short, but elegant overview of the structure of the thesis, and places the thesis in the landscape of contemporary investigations of the QCD phenomenology. Chapter 2 is a review of the QCD. The Author has concentrated only on such aspects, which are important for the further parts of the thesis – i.e. on crucial symmetries and on statistical properties of fluctuating chapters. I like this choice very much, because sometimes, introductory chapters in dissertations involve a lot of redundant information, at least from the point of the view of the area of the thesis. Chapter 3 starts this part of the thesis, where the Author presents his own results. It covers the topic of thermal properties of the hadrons. Since decades, this area was governed by the hadron resonance model (HRM). In its simplest version, hadronic degrees of freedom are represented by point-like, independent objects. Such an additive model allows easily calculations of basic thermodynamical observables and leads, on the basis of some simple underlying string models, to the Hagedorn phenomenon. Whereas such model quite successfully describes qualitative thermodynamic properties of the hot medium, recent lattice analysis suggests, that perhaps some of the initial assumptions of the model have to be reconsidered with care. This is particularly visible when concentrating on the fluctuations of the charges, especially the strangeness charge.

So, first, the Author probes to what extend the overshooting of thermodynamical features in HRG model can be traced to the fact, that perhaps, several hadrons contributing to Hagedorn spectrum were not yet detected experimentally. On the basis of simple, minimal number of parameters extension of the spectral formula, Author confirms this option. However, this observation is not sufficient to explain all the discrepancies between the minimal model and the data, so one has to dwell the problem further – the next step is to question the point-like, independent nature of the resonances, by introducing the interaction between the resonances, leading to finite width and decay properties of them. Such step requires a powerful theoretical framework, so the author introduces the S-matrix approach to thermodynamics. Concentrating mainly on resonances in the pion-kaon channel, Mr Marczenko still finds this approach not successful in explaining all discrepancies between the HRG and the lattice data. Similar in spirit is the S-matrix approach in the blast-wave model for particle emissions from the fireball. Here the Author looks at the effects of the finite width of the rho meson on the positive pion's momenta and their transverse mass distributions, observing that indeed such modification improves the predictions of the HRG in comparison to ALICE (CERN) experimental data. Last, but not least, the Author reconsiders the so-called excluded volume approximation, introduced already in HRG in the eighties of the previous century in order to mimic the short distance baryonic repulsion. Novelty of the approach is based on combining this scenario with S-matrix approach. The outcome of this description is very strong – Author points, that an attempt to describe the repulsive forces between the hadrons by a single, phenomenological parameter is doomed to fail. To summarize, this part of the thesis, based on publications [1-5] from the list of publication by the Author leads to the general, important conclusion - the understanding of the experimental results requires a very consistent approach going beyond the HRG model. Such approach requires new data and new lattice measurements of some phase shifts, combined with rich theoretical framework. One can expect, that this immense task will be completed in the near future. The Author's important contribution points at some of the most sensitive areas of such global picture.

Chapter 4 starts the second scientific core of the dissertation, based on approach of the Author to cold, but dense hadronic medium. This is an important corner of the QCD, since it describes in principle the properties of strongly compressed nuclear matter, including the cores of the neutron stars. Even more extreme densities lead to novel, theoretically accessible regime of QCD, where color superconductivity can emerge. The Author does not look at such extreme densities, concentrating mainly on few times nuclear densities, relevant for extraterrestrial, astrophysical observables. The crucial bottleneck in the finite density regime comes from the fact, that lattice calculations, so helpful in the case of hot medium, fail this time, because of the notorious and still unsolved sign problem. So the current hope is based on constructing effective models. In constructing such model it is crucial to take the chiral properties of baryons into account. If one does not like to consider baryons as topological objects, one can in principle introduce explicit baryonic terms in the lagrangian in two ways, basing either on naive or on mirror assignment for the fermionic fields. The latter one requires the dilaton field, contributed to the trace anomaly of the QCD. The main result of Chapter 4 is the presentation of an extension of such model (done by the Author with his Advisor) toward explicit inclusion of quark degrees of freedom. Such model, named as Hybrid Quark Meson Nucleon Model (QMN), mimics quark confinement in a statistical way, by making a simple Ansatz for Fermi-Dirac function. This allows to study the phase structure in such model. To see the basic features of such scenario, Author considers mean-field approximation for two massless flavors. Interestingly, in such scenario chiral and deconfinement phase transitions are separated. In the following Chapter 5 the Author applies the enriched (by adding arbitrary isospin asymmetry) QMN to the description of the compact (neutron) star, by investigating equation of state of cold dense matter. Fixing the relation between the mass and radius of the star from recent pulsar data (PSR J0348+0432) and putting the constraints originating from the model on cooling process, leads to the strong conclusion, that, provided mirror scenario is realized in Nature, famous critical endpoint (experimentally most hunted phenomenon in the phase diagram of the QCD) may appear at quite low temperatures (less then 30 MeV) or, may even disappear in the case of isospin symmetric matter. The last Chapter 6 (from three dedicated to high density regime) deals with fluctuations of the net-baryon number density in the framework of the Hybrid QMN model. The Author concentrates systematics of first order deconfinement transition on the higher order cumulants of net baryon density. He observes much larger sensitivity of the cumulants in the vicinity of the chiral phase transition, comparing to "deconfinement phase transition" in such model.

As in the case of the first scientific core, this part (Chapters 4-6) is also documented by two recent (2018) publications in Physical Review D (positions 6-7 in the provided list of publications by the Author). The presented results are quite intriguing, and thought provoking. In my opinion, it would be extremely interesting to broaden the presented analysis by addition of the hyperon degrees of freedom.

From the formal side, the dissertation is edited in a very careful way. Searching hard for the possible misprints and errors, I have found only few trivial misprints and one unimportant ambiguity in eq. 2.7, where it is not clear if the Author uses hermitian or anti-hermitian convention. Of course, these minor details have no impact on my high appreciation of this work. Before reaching the final conclusions, I would like to make a general comment. As I have mentioned in this review, the dissertation is composed on two topics, dealing with either high temperature –low density regime or the opposite one. The material presented in each of these parts separately, is, in my opinion, sufficient for fulfilling the requirement of the very good Ph.D. thesis. The first part, documented by 5 publications is more focused on current data and discrepancies in heavy-ion phenomenology. The second part, documented by two publications, is more speculative and therefore equally interesting. Two such parts combined in one thesis significantly exceed the requirements for the Ph.D. thesis. This is the reason why I intend to submit this dissertation for the **distinction** (*magna cum laude – in Polish "wyróżnienie"*).

To summarize: **The presented dissertation fulfills all the formal and scientific requirements needed to obtain the scientific degree "doctor of physical sciences" (pol. stopień naukowy doktora, dziedzina: nauki scisłe i przyrodnicze, dyscyplina: nauki fizyczne) according to and in agreement with the article 13 of the "Act on academic degrees and academic title and degrees and title in art" (Dz. U. Nr 84, poz. 455, z późn. Zm.).** My final mark on the thesis of mgr Michał Marczenko is **very good (5.0).**

I am recommending further steps towards the completion of the PhD. Process.

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