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(data i miejsce)

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Recenzja pracy doktorskiej

Rupam Samanta
....
(imię i nazwisko doktoranta / doktorantki)

pod tytułem **Study of the hottest droplet of fluid through correlations and fluctuations of collective variables**
....

przygotowanej pod kierunkiem:

prof. dr. hab. Piotr Bożek
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(imię i nazwisko promotora)

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(imię i nazwisko promotora / promotora pomocniczego)

1. Podstawa opracowania

Recenzja została wykonana na zlecenie Rady Dyscypliny Nauki fizyczne Akademii Górniczo-Hutniczej im. Stanisława Staszica w Krakowie.

Podstawa prawna art. 187 Ustawy z dnia 20 lipca 2018 r. „Prawo o szkolnictwie wyższym i nauce" (z późn. zm.)

Opinia dotycząca przedmiotowej rozprawy doktorskiej zawiera trzy elementy:

1) Ocenę wraz z uzasadnieniem czy rozprawa doktorska prezentuje ogólną wiedzę teoretyczną Doktoranta w dyscyplinie nauki fizyczne;
2) Ocenę wraz z uzasadnieniem czy rozprawa doktorska wykazuje umiejętność samodzielnego prowadzenia pracy naukowej przez Doktoranta ubiegającego się o nadanie stopnia doktora;
3) Ocenę wraz z uzasadnieniem czy rozprawa doktorska stanowi oryginalne rozwiązanie problemu naukowego.

2. Charakterystyka i opis rozprawy

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Kraków, September 25, 2024 r.

Review report on the doctoral thesis of Mr. Rupam Samanta titled *Study of the hottest droplet of fluid through correlations and fluctuations of collective variables*

Mr. Samanta's dissertation, titled *Study of the Hottest Droplet of Fluid through Correlations and Fluctuations of Collective Variables*, was prepared under the supervision of Prof. Dr. hab. Piotr Bożek and submitted in partial fulfillment of the requirements for the Doctor of Physical Sciences degree at the Faculty of Physics and Applied Computer Science, AGH University of Science and Technology, Kraków. The dissertation is based on the findings from six original scientific papers published in *Physical Review C*, a leading international journal in theoretical and experimental nuclear physics. These publications are collaborative efforts, with two excluding the supervisor. Notably, Mr. Samanta is the first author of four of the papers, breaking the typical alphabetical order of authorship. Interestingly, the list of publications forming the core of the thesis does not include contributions from proceedings in *Acta Physica Polonica* and *EPJ Web of Conferences*, despite these works presenting key findings from the thesis at the Quark Matter conference – the largest conference dedicated to high-energy nuclear physics.

The main objective of the presented research was to investigate the properties and dynamics of matter produced in ultra-relativistic heavy-ion collisions by analyzing event-by-event fluctuations and correlations of collective observables. These processes are currently the focus of intense theoretical and experimental research at high-energy collider facilities such as the Relativistic Heavy-Ion Collider (RHIC) and the Large Hadron Collider (LHC). The ultimate goal of these investigations is to deepen our understanding of the properties and behavior of strongly interacting matter under extreme temperatures and densities, akin to conditions in the early universe or the cores of compact stellar objects.

The underlying dynamics of the matter produced in these experiments is governed by highly complex non-equilibrium quantum field theory, making the use of hydrodynamics – which is based on relatively simpler classical field theory – representing significant simplification in their modeling. This simplification comes at the price of introducing various uncertainties due to the unknown macroscopic properties of the system and its initial state. Despite these challenges, the data collected over the last decades from these studies demonstrate that theoretical models based on relativistic dissipative hydrodynamics provide an unexpectedly accurate description of these processes. In particular, the results show that matter behaves like a fluid soon after the initial nuclear impact, with dissipative corrections being minimal.

This leads to fundamental questions regarding the sources of collectivity, the surprising effectiveness and range of applicability of fluid dynamics, and the extremely rapid thermalization of the produced matter. A key factor in addressing these questions is determining the initial state of the collision, which serves as a crucial input for hydrodynamic models and is a major source of uncertainty in their predictions. The event-by-event fluctuations and correlations of final-state observables examined in this research largely arise from various types of fluctuations in the initial state, providing a unique and precise tool for constraining it.

Consequently, the research presented in this thesis addresses some of the most pressing questions in the field and holds significant relevance for advancing the understanding of current high-energy experiments. The research is highly timely, coherent with latest experimental measurements, and the methods developed, along with the results obtained, offer valuable insights into the systems under study.

The doctoral dissertation by Mr. Samanta is composed in English, featuring a logical and coherent structure. The text has been edited to a somewhat average standard, and it contains a considerable number of editorial errors. However, in my view, these errors do not substantially hinder the reader's comprehension of the material and therefore do not impact my overall assessment of the quality of the research presented. For the sake of readability, I will refrain from detailing all suggested corrections. The main body of the dissertation is preceded by an abstract, a table of contents, lists of figures and tables, and the notation used throughout the text. It is organized into seven chapters, accompanied by two appendices, and supplemented with a comprehensive bibliography.

Chapter 1 offers a very brief introduction to the phenomenology of hot and dense QCD matter produced in relativistic nuclear collisions and situates the research within the wider field of high-energy physics. It concludes with an outline of the thesis and a list of the papers that contributed to it.

Some topics introduced in the first chapter are further developed in **Chapter 2**, which provides a thorough overview of various aspects of heavy-ion collision modeling creating a solid basis for the discussions in subsequent parts of dissertation. In this chapter, the author presents the essential concepts and definitions related to kinematics, collision geometry, and Glauber modeling of the initial state, including its Monte Carlo implementation. A significant portion of the text is dedicated to a theoretical introduction to relativistic viscous hydrodynamics, which represents a core element of the tools employed for the studies presented in the thesis. The author discusses the dynamical laws for conserved currents and the latest formulations of equations of motion for dissipative fluxes, and supplements them with a description of the thermal properties of QCD in different coupling regimes. The chapter closes with a detailed discussion on the various stages of the evolution of matter produced in relativistic heavy-ion collisions, emphasizing the specific models used for these stages in the presented study. All concepts vital for understanding the motivation behind the work are present.

In both this chapter and the subsequent ones, the concepts presented are thoroughly discussed and accompanied by extensive references to the literature, indicating that Mr. Samanta has a solid understanding and familiarity with the pertinent professional literature in his field.

In my opinion, Chapter 2 might improve by omitting certain concepts, such as the presentation of the QCD Lagrangian, which are not critical to the work's context. Instead, a more in-depth discussion and justification regarding the selected model setup and its parameters could be provided in relation to the research conducted. For instance, a comment on the distinction in terms of underlying physics between the HIJING and MUSIC models, used later in the text, would be beneficial.

Chapter 3 presents a study of event-by-event fluctuations of collective flow characteristics. Its beginning is largely devoted to an overview of the well-established theoretical and experimental methods of flow analysis. It reviews the basic quantifiers of the spatial anisotropy of the participant region, which constitutes the initial state of the heavy-ion collision, as well as their phenomenological relation to the azimuthal anisotropy of the momentum distribution of particles in the final state. The chapter extensively describes various aspects of different azimuthal Fourier flow harmonics and introduces and discusses various experimental methods used for their characterization and extraction. The main focus is on the cumulant method involving multi-particle correlations and its role in non-flow contamination removal.

Particularly instructive and enlightening are the discussions interlacing the text on the suitability for experimental measurements of the quantities discussed, especially when considering limited statistics. The primary focus concerns the event-by-event fluctuations of n-th order harmonic flow components, which are studied in terms of so-called factorization-breaking coefficients. These coefficients describe the degree of factorization between flow harmonics of n-th order in different kinematic bins. At the linear order, the factorization-breaking coefficients of the flow vector are introduced in terms of two-particle correlators, and their significance in describing flow decorrelation is discussed. At the second order, the discussion is extended to four-particle correlators, and analogous factorization-breaking coefficients for flow magnitude and flow angle are constructed. To address the experimental difficulty of measuring these quantities, which at high momentum relates to the simultaneous detection of two particles in the same momentum bin, the definitions are modified by considering the reference flow vector momentum averaged. Using defined observables within a hydrodynamics based numerical model, it is shown explicitly that the increase in bin separation leads to a decrease of the factorization-breaking coefficients, signaling flow decoherence. The model predictions are compared with ALICE data from 5.02 TeV lead-lead collisions and only equalitative agreement is observed. The mismatch is attributed non-flow contributions hence an improved experimental analysis with pseudorapidity gaps introduced is desirable. Moreover, it is found that the flow magnitude decorrelation accounts for approximately half of the flow vector decorrelation, which is also nicely explained within a simple random toy model, which in my opinion represents a very neat result.

Among minor comments, at this point, a more in-depth discussion of the source of the differences between the model predictions for the two initial conditions considered would be useful, and would ease understanding of the underlying physics. Clearly, the dependence on initial condition model suggest that the model parameters can be tuned to descrive the data. Was such issue investigated in the study? If so, which parameters of the initial state model the results can put constraits on? A comment on experimental uncertainties of the used ALICE data points as well as respective references to measurements in figure captions itself would be also usefull.

The Chapter closes with the analysis of the mixed-flow factorization breaking which involve correlators between the flow vectors of different order and provide a measure of non-linearities in hydrodynamic expansion and correlations in the initial state.

In the first part of **Chapter 4**, the author focuses on the event-by-event fluctuations of the mean transverse momentum of charged particles measured by the ATLAS collaboration in lead-lead collisions at 5.02 TeV. The motivation for this study is provided by results showing a centrality estimator dependence of the variance of mean transverse momentum fluctuations, which exhibits a sharp decrease over a narrow multiplicity range in the regime of ultracentral collisions. This behavior is not captured by theoretical models that treat the collision as a superposition of independent nucleon-nucleon collisions, with HIJING model given as an example.

Based on numerical results for event-by-event fluctuations of mean transverse momentum and charged particle multiplicity at zero impact parameter, obtained by the author within a hydrodynamic model, a relatively large positive correlation between the two quantities is observed. Using simple theoretical considerations, this correlation is interpreted as a consequence of the thermalization and flow of the produced medium. In particular, it is argued that, at fixed charged particle multiplicity, a decrease in volume, resulting from an increase in impact parameter, leads to an increase in charged particle density. If the system is thermalized, this increase must be converted through flow gradients into the larger mean transverse momentum observed in the final state. This simple yet robust mechanism is then verified using a model of a correlated two-dimmensional Gaussian distribution between mean transverse momentum and multiplicity.

Using the model one separates the variance of mean transverse momentum into two contributions: one exclusively reflecting impact-parameter fluctuations and the other representing intrinsic fluctuations. The model fit is shown to describe the experimentally measured variance very well for both centrality estimators considered (multiplicity and transverse energy deposited in the forward calorimeters). While the two contributions in the model are of comparable size away from the ultracentral regime, the term sourced by impact-parameter fluctuations gradually vanishes as one approaches ultracentral collisions. A byproduct of this analysis is the steady increase in mean transverse momentum when nearing this regime. Supplementing the analysis with simultaneous fitting for two centrality estimators reveals similarity in values of Pearson's correlation coefficients, implying a strong correlation between particles deposited at different angles. This part concludes with a discussion of the dependence of the variance on the considered transverse momentum interval, which provides further evidence for the hydrodynamic nature of the observed fluctuations.

The second part of Chapter 4 is devoted to investigating non-Gaussian features of mean transverse momentum fluctuations, typically accessed by higher order cumulants. To address this, the author first explains the origin of non-Gaussian features using a simplified model of mean transverse momentum fluctuations, relating them to the truncation of the distribution due to boundary conditions imposed by centrality. Subsequently, a more realistic model used in previous part is employed, with the centrality dependence of the standard deviation of multiplicity estimated using the TRENTO initial conditions from standard collision models by the Duke and JETSCAPE groups. These models provide parameter sets for initial state obtained by tuning it to experimental data through Bayesian analysis.

The resulting standardized skewness and excess kurtosis exhibit significant, nontrivial, non-monotonic variations just before the ultracentral collision regime. These results are fairly insensitive to the adopted collision models, representing robust quantitative predictions. Since, in the presented model, the non-Gaussian features arise solely from impact parameter fluctuations, their experimental verification is of particular interest. Comparisons with ALICE data on skewness, which conclude this section, show promising similarities to the presented model predictions, providing motivation for more systematic future analyses. At this point a discussion of the remaining models results plotted in figure 4.11 would be interesting.

The first part of **Chapter 5** presents an interesting study of the correlations between event-by-event fluctuations of mean transverse momentum and the squared n-th order harmonic flow coefficients. This analysis is conducted using the Pearson correlation coefficient between the two quantities, which is expected to be fairly insensitive to statistical fluctuations and medium properties, thus providing a robust probe of initial state fluctuations. The results obtained for the centrality dependence of the Pearson coefficient for elliptic and triangular flow, using the MUSIC hydrodynamic model with Glauber initial conditions, reproduce only the qualitative trends observed in the ATLAS data. The results for quadrangular flow represent a model prediction that awaits experimental verification.

To address the presence of additional effects arising from multiplicity fluctuations (which are largely absent in data which was obtained within narrow centrality bins), so called partial correlation coefficient is studied, and the impact this effect is shown to be especially important for the second flow harmonic. Using the moments of the initial density, a linear predictor based on hydrodynamic response coefficients is constructed for the Pearson coefficient, which turns out to agree well with the hydrodynamic predictions. In order to get additional insights into the correlations between mean transverse momentum and harmonic flow coefficients, for the first time, higher-order normalized symmetric cumulants between the two bservables are introduced and studied as a function of centrality. They represent genuine higher-order correlations and are significantly smaller than second-order cumulant. All of them are showing deviations from zero as peripheral collisions are approached. Cumulants involving multiplicity, also presented in this section, are particularly interesting measures in the case of deformed nuclei, where multiplicity fluctuations are substantial – they are studied in Chapter 6.

The second part of **Chapter 5** extends the previous Pearson coefficient studies to the case of momentum-dependent flow harmonics. Analyzing such quantities offers several advantages over momentum-averaged ones. Among them are possibility of accessing finer details of the initial state as well as probing medium properties. The momentum-dependent Pearson correlation simulated with MUSIC with Glauber initial condition shows strong momentum dependence for elliptic flow, while for triangular flow, the momentum dependence is relatively weak. Analogously to the definition of momentum-dependent harmonic flow, a possible experimentally accessible definition for this coefficient is also introduced.

Using TRENTO initial conditions, the granularity of the initial density profile is studied through momentum-dependent Pearson correlation definitions for elliptic and triangular flows. The results show similar momentum dependence for both quantities, and experimental verification of these findings could provide precise constraints on the granularity of the initial state. Similar calculations are performed to study the correlation's sensitivity to shear and bulk viscosities, with results showing their less significant role.

Motivated by experimental limitations, an alternative definition for momentum-dependent correlation coefficients is proposed, which is more experimentally favorable. Importantly, this alternative definition yields predictions very close to the original ones. The chapter concludes with a study of the covariance between mean transverse momentum and momentum-dependent harmonic flow, exploring its potential usefulness in further constraining the granularity of the initial state and the medium's viscosity.

Quadrupole deformation of the uranium nucleus has been found to significantly influence the event-by-event fluctuations of mean transverse momentum and harmonic coefficients in uranium-uranium collisions. This finding motivates the studies presented in **Chapter 6**. To investigate this phenomenon, the nuclear deformation of the uranium nucleus is incorporated into the Woods-Saxon density distribution, which is then used to sample nucleon positions prior to the collision. Only ultracentral collisions are considered in the analysis. The impact of nuclear deformation on the collective observables is analyzed with the methods developed in the preceding chapters using hydrodynamic simulations with TRENTO initial conditions.

Two extreme collision configurations, referred to as tip-tip and body-body collisions, are used to provide a qualitative discussion of the influence of the initial density profile on the final mean transverse momentum and harmonic coefficients. The two configurations are characterized, respectively, by enhanced mean transverse momentum and eccentricity. This offers a unique opportunity to probe the structure of such deformed colliding nuclei through correlations and fluctuations.

The study of the factorization-breaking coefficient between flow vectors, with one of them momentum-averaged in the 0-5% centrality range, shows a significant reduction in decorrelation as a function of momentum. This reduction arises from a substantial geometric component in the total eccentricity during collisions of deformed nuclei. In this case, the contribution of fluctuations becomes subleading, resembling the behavior observed in semi-peripheral collisions of spherical nuclei. The effect of deformation on decorrelation is further enhanced in more central collisions. Obtained predictions can potentially be verified quantitatively through experimental data.

Finally, using the Pearson correlation coefficient between mean transverse momentum and elliptic flow, as well as normalized symmetric cumulants, an anticorrelation between these two observables due to nuclear deformation is observed. This anticorrelation becomes more pronounced, turning negative, as the events become more central. In contrast, the deformation has an almost negligible impact on the correlation coefficient for triangular and quadrangular flow.

Based on a naive expectation, one might anticipate an additional geometric contribution to the quadrangular flow in body-body collision configurations, arsing from the events with the principal axes of the colliding nuclei oriented at a 90-degree angle with respect to each other. Has such an effect been considered or studied?

Finally, in **Chapter 7**, results presented in thesis are summarized and the outlook for future studies is outlined.

Evaluation summary

Mr. Samanta's doctoral dissertation presents original, thorough, and high-quality research. Motivated by experimental measurements Mr. Samanta utilizes various theoretical tools and conducts comprehensive analyses of various fluctuation and correlation observables. These studies result in significant contributions to the understanding of the nuclear structure of collided nuclei, initial state profiles of the collisions, as well as dynamical properties of the matter produced in heavy-ion collisions. Importantly, the dissertation bridges theoretical models and experimental measurements, demonstrating a high level of understanding of both theoretical and experimental methods, as well as proficiency in analytical and numerical tools. Finally, the presented work stimulates various new potential research directions which proves its importance.

To summarize, I conclude that the reviewed dissertation meets the requirements of the Act on Academic Degrees and Titles and Degrees and Titles in the Field of Art, as specified in Article 187 of the Act of July 20, 2018, Law on Higher Education and Science (with later amendments), and I recommend its admission to the further stages of the procedure for awarding the degree of doctor in the field of Natural Sciences in the discipline of Physical Sciences.

[Podsumowując stwierdzam, że recenzowana rozprawa spełnia wymagania ustawy o stopniach naukowych i tytule naukowym oraz stopniach i tytule w zakresie sztuki określonej w art. 187 ustawy z dnia 20 lipca 2018 r. Prawo o szkolnictwie wyższym i nauce (z późn.zm.) i wnioskuję o jej dopuszczenie do dalszych etapów postępowania o nadanie stopnia doktora w dziedzinie nauk ścisłych i przyrodniczych w dyscyplinie nauki fizyczne.]

Considering the high substantive quality and the relevance of the topic, I classify the dissertation as exceptionally good and deserving of distinction. Therefore, I propose recognizing Mr. Rupam Samanta's doctoral dissertation as outstanding.

[Biorąc pod uwagę wysoki poziom merytoryczny oraz aktualność tematyki zaliczam rozprawę do kategorii wybitnie dobrej i zasługującej na wyróżnienie. Tym samym wnioskuję o uznanie rozprawy doktorskiej Pana Rupama Samanty za wyróżniającą się.]

Digitally signed by Radosław Ryblewski
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