Review
for the dissertation work of YUSHKEVYCH Tetiana Vladyslavivna on the topic "Perturbative and Non-Perturbative Aspects of Hadronic Physics", submitted for the degree of Doctor of Philosophy in the field of knowledge 10 Natural Sciences in the specialty 104 Physics and Astronomy

Relevance of the topic of the dissertation research. Hadron physics stands out among other sections of elementary particle physics precisely because it is necessary to combine perturbative and non-perturbative methods for research. The obvious complexity of such research is manifested in the presence of a multitude of different theoretical and phenomenological approaches and models. It is reasonable to expect that the number of such approaches and models will continue to grow in the future, which underscores the relevance of the dissertation research topic. Moreover, this research is complex, it presents both a theoretical dynamic model with a theoretical calculation method, and an analysis of experimental data and Monte Carlo generation within the framework of parton phenomenology using cutting-edge computer technologies (neural networks, machine learning).

The goal formulated in the dissertation corresponds to the chosen direction of research, the results obtained have scientific novelty and contribute to achieving the goal.

The connection of the dissertation work with scientific programs, scientific directions of the University and the department. The work was carried out in accordance with the state budget research works “Calculation of cross sections of inelastic scattering of hadrons by the Laplace method” (state registration number 0116U004527) and “Development of a method of multi-particle fields for elastic and inelastic scattering of hadrons” (state registration number 0119U103982) in accordance with the research work program of the Ministry of Education and Science of Ukraine, as well as within the framework of the Marie Skladovska-Curie postdoctoral fellowship, which was provided within the framework of the MSCA4Ukraine Action funded by the European Union and supported by the “Scholar at Risk” program. The scholarship supported the mobility of the applicant and her research activities at the University of Turin. The project was carried out in the broad context of international efforts to develop QCD-based descriptions of hadronic structure and scattering.

Scientific novelty of the obtained results. The dissertation uses a dynamic model of multiparticle fields, which differs significantly from existing quantum field theories that operate with the occupancy numbers of single-particle states. Of course, existing theories study multiparticle effects, for example, through the study of multiparticle Green's functions, but the main dynamic quantities of the theory are single-particle - these are field operators that depend on a single event in Minkowski space. That is, existing field theories implicitly accept the postulate that multiparticle effects are the result of the dynamics of single-particle fields. The dynamic model developed in this dissertation questions this assumption and instead identifies the primary dynamic object as a multiparticle field, defined by a set of simultaneous events relative to the observer. That is, the dissertation considers the dynamics of a field that depends on simultaneous events with respect to the observer with three quarks that make up a proton. The dynamics of these inner quarks are described non-perturbatively. The dynamics of gluons that form their bound state – glueballs – are also described non-perturbatively. Instead, there is a possibility of perturbative description of the processes of interaction of those quark multiparticle fields corresponding to protons with two-gluon fields corresponding to glueballs. While similar approaches have been discussed in the literature, this work represents the first application of these specific dynamic equations to the description of experimental data.

Another element of scientific novelty is associated with the application of the Laplace method to the perturbative description of elastic proton scattering. Here it is worth emphasizing not so much the result itself—which undoubtedly requires further refinement—but rather the idea, which may prove to be highly useful for future research, not only by the author of the dissertation but also by other researchers. This idea can be formulated as follows. When considering a perturbative calculation using loop diagrams, one encounters a very complex integrand, which is a complex-valued function with a highly intricate "landscape" of real and imaginary parts. In contrast, the dependencies measured in experiments (such as the differential cross-section examined in the dissertation), although they possess their own characteristic features, remain comparatively simple relative to the aforementioned "landscape" of the integrand. This indicates that not all details of that "landscape" are essential for describing the experimental data. The dissertation proposes, based on certain formal (and potentially also physical) considerations, a procedure for selecting those features of the "landscape" that may be the most relevant. This very idea should be highlighted as an element of scientific novelty, since its implementation may indeed enable the use of Feynman diagrams to describe physical processes in a way they have not been employed before.

In the dissertation, as a criterion for "selecting" the most significant elements of the "landscape," it is proposed to identify the regions where the largest number of Feynman denominators approach zero. Evidently, in such regions the integrand attains its largest values within the integration domain, which makes this choice appear logical. At the same time, the "height" of a maximum during integration is compensated by its narrow "width," ensuring the finiteness of the integral. However, there may also exist regions where the maxima are "lower" but "broader," and thus their contribution to the integral may be no less significant than the one considered. Nevertheless, the relatively successful reproduction of experimental behavior can, to some extent, justify the choice made. When moving to more complex diagrams, it is doubtful that such a selection criterion can be strictly maintained; however, the very idea of selection remains, and it may eventually make feasible the calculation of contributions from multi-loop diagrams. For this reason, this idea should be regarded as an important element of scientific novelty.

Theoretical and Practical Significance of the Obtained Results. The approaches, algorithms, computer programs, and conclusions proposed in the dissertation may be utilized by a wide range of researchers, as they pertain both to theoretical calculations and to the analysis of phenomenological models. They may also serve as a foundation for further improvements, for which there is considerable potential.

Reliability and Validity of the Obtained Results. The reliability and validity of the research findings are ensured by the application of a number of modern theories, models, and computational methods, including the method of multiparticle fields; the theory of relativistic scattering; quantum field theory and secondary quantization; R. Feynman's diagrammatic method; the Laplace method, among others.

The calculations were performed strictly within the framework of the dynamic model, without introducing additional assumptions. The results obtained were compared with well-known and repeatedly verified experimental data, which demonstrate the non-monotonic dependence of the differential cross-section on the square of the transferred four-momentum. The findings of the dissertation reproduce this experimental fact, albeit at the level of qualitative behavior.

The results were also compared with widely known experimental data published in peer-reviewed scientific journals. The classification methodology based on the "AFFINITY" tool was validated through large-scale numerical simulations and Monte Carlo methods, ensuring its stability, reproducibility, and consistency with existing experimental data across different energy scales. The agreement of the obtained results with established theoretical expectations and experimental observations further confirms their reliability.

The research findings were presented and discussed at renowned international scientific conferences, seminars, and schools, where they underwent critical evaluation by experts in the field. The positive and constructive feedback from the scientific community further substantiates the scientific soundness and credibility of the proposed models and conclusions.

Completeness of the Presentation of Dissertation Results in Published Works. The dissertation consists of four chapters and three appendices. *The first chapter* contains the introduction and literature review. It is devoted to approaches related to the parton model and Regge theory. *The second chapter* addresses the application of the multiparticle fields method and the Laplace method to the description of elastic proton scattering and to the calculation of contributions from the simplest loop diagrams to the elastic scattering amplitude. *The third chapter* is devoted to the development and improvement of tools and methods for analyzing different kinematic regions of secondary hadron production within the framework of the parton model. *The fourth chapter* presents conclusions and considerations for further research.

The main results obtained in the dissertation are presented in 8 publications, 3 of which are indexed in Scopus and WoS, including 2 articles in journals classified as Q1 according to the SCImago Journal and Country Rank:

1. N. Chudak, I. Sharph, O. Potiienko, A. Milieva, K. Merkotan, T. Yushkevych, and V. Rusov (2022). *Laplace's method for elastic scattering diagrams within multiparticle fields model. Phys. Rev. D 106, 036023.* https://doi.org/10.1103/PhysRevD.106.036023

2. O. Potiienko, K. Merkotan, N. Chudak, D. Ptashynskiy, T. Zelentsova, T. Yushkevich, I. Sharph, and V. Rusov (2020). *New method of accounting for interference contributions within a multiperipheral model. Phys. Rev. D 101, 7.* https://doi.org/10.1103/PhysRevD.101.076021

1. D. A. Ptashynskiy, T. M. Zelentsova, N. O. Chudak, K. K. Merkotan, O. S. Potiienko, V. V. Voitenko, O. D. Berezovskiy, V. V. Opyatyuk, O. V. Zharova, T. V. Yushkevich, I. V. Sharph, & V. D. Rusov (2019). *Multiparticle Fields on the Subset of Simultaneity. Ukrainian Journal of Physics, 64(8), 732.* https://doi.org/10.15407/ujpe64.8.732

The results were also additionally presented in the proceedings of 5 international conferences:

2. T. Yushkevych, M. Boglione, A. Prokudin, *Affinity tool. Comparison between JLab12 and JLab22*, *Science at the Luminosity Frontier: Jefferson Lab at 22 GeV* (9–12 December, Frascati, Italy, 2024). https://agenda.infn.it/event/39742/contributions/247698/

3. T. Yushkevych, N. Chudak, O. Potiienko, I. Sharph, *Laplace method for single-loop diagrams of elastic proton scattering, 21st Gamow International Astronomical Conference-School "Astronomy and Beyond: Astrophysics, Cosmology and Gravitation, High Energy Physics, Astroparticle Physics, Radioastronomy and Astrobiology",* August 15–21, 2021, Odessa, Ukraine. https://gamow.odessa.ua/wp-content/uploads/2021/08/gamow-abstracts-2021.pdf

4. T. Yushkevych, N. Chudak, O. Potiienko, A. Mileva, *Application of the Laplace method for one-loop diagrams of elastic scattering of protons in the framework of multiparticle fields, International Conference of Students and Young Researchers in Theoretical and Experimental Physics "HEUREKA-4 2021",* May 18–20, 2021, Lviv, Ukraine. https://physics.lnu.edu.ua/conferences/heureka2021/

5. T. Yushkevych, O. Potiienko, H. Neboga, *Modeling the interference effects in elastic hadron scattering with the Monte Carlo event generator based on Laplace's method, 20th Gamow International Astronomical Conference-School "Astronomy and Beyond: Astrophysics, Cosmology and Gravitation, High Energy Physics, Astroparticle Physics, Radioastronomy and Astrobiology",* August 9–16, 2020, Odessa, Ukraine. http://gamow.odessa.ua/wp-content/uploads/2020/10/

6. D. A. Ptashynskiy, T. V. Yushkevich, I. V. Sharph, V. D. Rusov, et al., *Multi-particle fields on a subset of simultaneity, International Conference on New Trends in High-Energy Physics,* May 12–18, 2019, Odessa, Ukraine. https://indico.bitp.kiev.ua/event/1/contributions/62/

The publications cover all chapters of the dissertation and adequately reflect the content and results of the research presented.

Absence (or Presence) of Academic Misconduct. The dissertation contains the author's original research results. The use of ideas, results, and texts of other authors is properly referenced. No instances of academic misconduct have been identified in the scientific publications or in the dissertation materials of the candidate.

Remarks on the Dissertation

1. In the dissertation, the contribution to the integral is calculated from the regions in which two of the four Feynman denominators vanish. This region indeed has the highest order in $\left(\frac{1}{\varepsilon}\right)$, namely $\left(\frac{1}{\varepsilon}\right)^2$. At the same time, the "width" of the maximum is of order ε^2. As a result, a finite contribution to the integral is obtained. However, the question arises: can a subset of the integration domain, in which only one denominator vanishes, have a "width" of order ε? In such a case, these subsets should yield contributions comparable to the one calculated. The significance of the contributions from such regions is not discussed in the dissertation.

7. The dissertation considers the contribution from singularities of the integrand, but the contribution from the region between singularities has not been examined. Since the singularities give a finite contribution to the integral, this contribution is not necessarily much larger than that from the remaining integration domain. This issue has likewise not been addressed in the work.

The above remarks do not affect the overall positive evaluation of the dissertation and do not diminish the scientific or practical value of the results obtained. Rather, they should be regarded as suggestions for future research. Given the complexity of the problem and the extensive calculations involved, the “step-by-step” approach adopted appears reasonable: to first study the contribution from a part of the integration domain and assess whether the experiment can be described in this way. The dissertation makes the first step in this direction, and the remarks concern the subsequent steps.

General Conclusion on the Compliance of the Dissertation with Established Requirements

The dissertation of Tetiana Vladyslavivna Yushkevych on the topic “Perturbative and Non-perturbative Aspects of Hadronic Physics” is a coherent, independent, and completed scientific study of applied scientific significance, whose topic and content correspond to the specialty 104 — Physics and Astronomy.

Given the relevance of the dissertation topic, the validity of the scientific statements, conclusions, and recommendations formulated in the work, their scientific novelty and practical value, the completeness of their presentation in scientific publications, and the absence of violations of academic integrity, I conclude that the dissertation meets the requirements of the *“Regulations on the Awarding of the Doctor of Philosophy Degree and the Revocation of the Decision of a One-Time Specialized Academic Council of a Higher Education Institution or Research Institution on the Awarding of the Doctor of Philosophy Degree”*, approved by the Resolution of the Cabinet of Ministers of Ukraine of January 12, 2022, No. 44 and its author, Tetiana Vladyslavivna Yushkevych, fully deserves to be awarded the academic degree of Doctor of Philosophy in the field of knowledge 10 — Natural Sciences, specialty 104 — Physics and Astronomy.

Reviewer,

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