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Report on habilitation thesis of Dr. Yizhuang Liu

This report provides an evaluation of the research achievements of **Dr. Yizhuang Liu** in relation to the habilitation procedure.

Information about the Candidate

Dr. Yizhuang Liu graduated in 2012 from University of Science and Technology of China (USTC) with bachelor's degree in Physics. He obtained PhD degree in 2018 from the Department of Physics and Astronomy at SUNY Stony Brook, USA. His PhD thesis '*Non-perturbative studies in QCD*' was performed under the supervision of prof. Ismail Zahed. Following his PhD, Dr. Liu secured postdoctoral position at Tsung-Dao Lee Institute (TDLI) in Shanghai, PRC. He then moved to second postdoctoral position at the University of Regensburg, Germany, where he worked from 2020 to 2021. Since 2021 he has been at the Jagiellonian University, Kraków, Poland, first as a postdoctoral researcher and then as an assistant professor in the Department of Theory of Complex Systems at the Institute of Theoretical Physics where he holds this position until now.

Evaluation of the habilitation thesis

Research interests of Dr. Liu span various aspects of quantum field theories, with focus on quantum theory of strong interactions, quantum chromodynamics (QCD), in both perturbative and non-perturbative domains. For his habilitation thesis he has selected 7 articles, written and published after his PhD, under the common title '*Euclidean formulation of parton distribution functions: factorization, evolution and lattice application*'.

One of the goals of the research particle and nuclear physics is the understanding of the structure of hadrons and nuclei in terms of the fundamental degrees of freedom: gluons and quarks. The experimental information on the hadronic structure can be obtained from the scattering of leptons on hadronic targets, or in collisions of two hadrons in processes with large scales. On a theoretical side, such processes can be described using factorization theorems, where the short distance interaction, tractable by means of perturbative expansion is factorized from the long distance non-perturbative contribution. The non-perturbative parts, which describe the internal structure of hadrons, are called parton distribution functions or PDFs. In principle they cannot be obtained by means of finite perturbative expansion, but their evolution to higher scales can be evaluated in perturbative QCD. These PDFs depend on the longitudinal momentum fraction of the hadron carried by the specific parton. Their knowledge is essential for the calculation of various processes where hard scales are involved. The PDFs are universal i.e., can be extracted in one process and used to predict the other process in perturbative QCD. Usually this extraction is phenomenological i.e., the data are fitted with the (somewhat arbitrary) functional form of the parton distribution function. Precise data from various experiments allow to constrain these PDFs to a great accuracy.

Lattice QCD i.e., numerical evaluation of QCD theory from first principles on a discretized space-time grid, should be able to provide information about the non-pertubative aspects of the hadronic structure. However, the difficulty arises in that the PDFs are formulated on the light-front and thus are dynamical correlators. For lattice QCD computations however, to evaluate the path integral, one needs to make analytical continuation to the imaginary time, thus effectively using Euclidean space-time, so that the weights in the path integral become similar to the Boltzmann weights in statistical mechanics instead of complex phases in Minkowski space-time. Thus, until about a decade ago the lattice evaluation of the PDFs was limited to the computation of few lower Mellin moments of PDFs.

About decade ago, Prof. Xiandong Ji proposed a formulation in which one starts with the quark and gluon distributions in a hadron which has some large but finite momentum. These modified PDFs (or quasi-PDFs) are space-like equal-time correlators in the hadronic state. Objects defined in such manner are Euclidean quantities and thus are accessible by methods of lattice QCD. The price to pay is that such quantities are now dependent on the momentum of the hadron, and the limit to the infinite momentum needs to be performed to recover the standard PDFs. However, as shown by Ji, by means of the large momentum effective theory (LaMET), one can perform matching of the finite momentum quasi-PDFs to the light-front PDFs by perturbatively calculable coefficients and power corrections. This procedure allows lattice QCD to provide important information about PDFs in the region of moderate and large values of longitudinal momentum fractions.

Apart from the standard collinear PDFs mentioned above, which only depend on the fractions of the longitudinal momentum of the hadron carried by the parton, more differential quantities can be defined which provide more detailed information about the hadron structure. These include for example: generalized parton distribution functions (GPDs), transverse momentum dependent PDFs (TMDPDFs), Wigner functions as well as polarized distributions which can inform about the spin structure of hadrons. Specifically, transverse momentum dependent parton distribution functions or TMDPDFs contain information about the transverse momentum dependence of partons in the hadron, in addition to the longitudinal momentum fractions. They can be accessed for example in the semi-inclusive deep inelastic lepton scattering off hadrons. One of the major research goals of the upcoming Electron-Ion Collider (EIC) in the US, is the detailed mapping of the hadronic and nuclear structure, by extracting and constraining the TMDPDFs among other distributions.

The topic of the habilitation thesis by Dr. Yizhuang Liu concerns the Euclidean formulation of the parton distribution functions, LaMET formalism, with particular focus on the development of the formalism involving TMDPDFs.

[H1] publication is focused on the light front wave functions (LFWFs). The LaMET versions of the LFWF are formulated, where the large momentum plays the role of the physical off-light cone regulator. The factorization formula is presented, where the quasi-LFWF can be matched to the physical LFWF in the large momentum limit. It is shown that Collins-Soper kernels can be extracted from the ratio of quasi-LFWF amplitudes. As an application of the general methods results for the LFWF for pseudo-scalar meson are presented. Besides that, this formalism has been extended to more general components of the LFWF containing more than 2 constituents. According to iNSPIRE-HEP database the paper has 33 citations as of April 29, 2024.

In **[H2]** a hybrid renormalization scheme for quasi-light front correlators is presented. In this paper renormalization scheme is discussed which allows to match the correlations functions on the lattice to those in continuum and avoid extra non-perturbative effects at large distances. This is achieved by the hybrid renormalization procedure which removes divergences of the bare matrix elements, and which treats short and long distance separately. According to iNSPIRE-HEP database the paper has 75 citations as of April 29, 2024.

In publication **[H3]** an extraction of the rapidity independent (or intrinsic) part of the soft function is performed in lattice QCD. Soft function is non-perturbative object important for complete description of some processes which require observation of small transverse momentum region, like in Drell-Yan process and in semi-inclusive Deep Inelastic Scattering. The work **[H3]** is the first lattice calculation of this quantity following the light-meson formalism introduced by Dr. Liu. In this work also the rapidity-dependent part of the soft function is extracted, the Collins-Soper kernel, using the large momentum evolution of the quasi TMD wave function. According to iNSPIRE-HEP database the paper has 86 citations as of April 29, 2024.

[H4] is a comprehensive review about LaMET formalism and its applications to lattice QCD. This 75-page article consists of 7 chapters detailing the formalism of quasi-PDFs, renormalization and matching to standard PDFs. It provides description of the formalism for various PDFs, like GPDs and TMDs, light-front wave functions, higher twist-distributions and gluon helicity. It discusses lattice applications and various results on PDFs. This review is already a classic reference on LaMET formalism and is highly cited. According to iNSPIRE-HEP database the paper has 231 citations as of April 29, 2024.

In publication **[H5]** the definition of the quasi-TMDPDF is provided which includes a square root of a rectangular Euclidean Wilson loop. Such modification ensures cancellation of divergences at large distances. In this paper a factorization theorem is developed for quasi-TMDPDFs which demonstrated that it factorizes into physical TMDPDF and a reduced soft factor introduced in **[H6]**. In addition, renormalization group equation is derived for the perturbative matching coefficient. This paper has 74 citations according to iNSPIRE-HEP database as of April 29, 2024.

In **[H6]** a TMD soft function is studied which is a cross section for two color charges moving in opposite light-like directions exchanging soft gluons. Relations between the soft factor and the special form factors of quark pairs have been provided, which opens a possibility to extract non-perturbatively the reduced soft function. This paper formed the so-called light-meson formalism for TMDs, which was utilized in the lattice study performed in **[H3]**. This paper has 74 citations according to iNSPIRE-HEP database as of April 29, 2024.

Finally, recent **[H7]** publication concerns an important problem of computation of PDFs at large values of x. This region is particularly important for probing physics beyond Standard Model. However, it suffers from large threshold logarithms. In this work the matching kernel between the quasi-PDF and standard PDF was found and shown that it factorizes into two functions: the hard kernel and the jet function. Consistency of the obtained results with the NNLO calculations available in the literature is demonstrated. According to iNSPIRE-HEP database the paper has 9 citations as of April 29, 2024.

The above publications contain sound theoretical results. Their importance and influence is substantial, as they already have been shown to pave the way for the lattice extraction of PDFs and in particular TMDPDFs. The results of these works will only gain in their significance in the advent of the EIC, which is designed to unveil three-dimensional structure of hadrons and nuclei. Variety of precise theoretical tools, like those presented in this habilitation, will be indispensable for proper interpretation of the experimental results from the EIC. Dr. Liu made crucial contributions to all the above papers; he played a leading role in most of them.

Evaluation of the overall research

The research portfolio of Dr. Liu includes various topics on perturbative and non-perturbative QCD and in QFT in general. Among the topics he worked on are topological objects and their role in the vacuum and QCD phase transitions, holographic models of strong interactions, random matrix theory, quantum entanglement and Koba-Nielsen-Olesen scaling of multiplicity distributions, chiral rotation effect, near-threshold production of quarkonium, mass decomposition in QFT and energy-momentum tensor form factors and the D-term. Dr. Liu lists 52 research papers, out of which 30 written after his PhD. Vast majority of them were published in high quality peer-reviewed journals. This is an impressive research output for a junior researcher only 6 years after his PhD. Dr. Liu also gave presentations at international workshops and conferences and has been an investigator in several grants. He has been recipient of the Silsbee prize in 2016 for an outstanding graduate student from SUNY Stony Brook, and Prize of Rector of Jagiellonian University for distinguished achievements in research in 2022.

Summary

Research achievements which were selected for the habilitation thesis are of very high quality. Dr. Liu is an expert in the area of quasi-PDFs and LaMET formalism. The results in these publications are original, significant, and already have a lasting impact onto the field of PDFs. These results will be instrumental in the extraction of the PDFs from lattice calculations. It is worth noting that apart from the topic presented in this thesis Dr. Liu works on many other subjects in QCD. His research portfolio is diverse, and is steadily growing at a very fast pace, which is a hallmark of a highly creative, independent researcher.

In my opinion Dr. Liu's research achievements meet the criteria for the habilitation as defined in Article 219 of The Law on Higher Education and Science Act of July 20, 2018 [Art. 219 Ustawy z dn. 20 lipca 2018, Prawo o szkolnictwie wyższym i nauce]. I recommend the Candidate's application to be further considered in habilitation procedure.

Yours sincerely,

Anna Staśto

Professor of Physics