The Femtography Project

LETTER OF INTEREST: SNOWMASS 2021

The Femtography Project's goal is to develop an original approach to reconstruct the 3D structure of hadrons from experiment which, in turn, is a key step towards solving the proton spin puzzle. By combining cutting-edge experimental technology to perform high-energy polarized scattering experiments with theory guided state-of-the-art machine learning based techniques for the data analysis, we will be able to realize the quest to take the first images of the proton's interior. This ambitious endeavour was initiated at the recently founded Center for Nuclear Femtography at SURA and will draw resources from an ever growing international community.
Contact person: Simonetta Liuti
email: sl4y@virginia.edu

Authors: P. Alonzi (UVA), M. Boer (Virginia Tech), M. Burkardt (NMSU), G. Cates (UVA), N. Chrisochoides (ODU), M.Constantinou (Temple U), L. Elouadrhiri (Jefferson Lab), G. Gavalian (Jefferson Lab), T. Horn (CU), J. Hoskins (Mary Washington U), C. Hyde (ODU), X. Ji (UMD and SURA), Y. Li (ODU), S. Liuti (UVA), N. Liyanage (UVA), A. Rajan (ODU), D. Richards (Jefferson Lab), J. Zhang (Stonybrook)

The 3D spatial structure of the proton as well as its mechanical properties including angular momentum [1], pressure and shear forces [2] can be accessed experimentally through deeply virtual exclusive scattering processes. Our research group, a founding component of the recently established Center for Nuclear Femtography headed by Xiangdong Ji, recognizes the fundamental importance and discovery potential of extracting spatial distributions of quarks and gluons from experiment, thus advancing our knowledge towards the solution of the proton spin puzzle. This letter expresses our interest in including studies of the 3D structure of the nucleon in the Snowmass 2021 future planning of high energy physics. Our scientific interest is in line with the topical group of the Energy Frontier in QCD and strong interactions, EF06, as well as with the Theory and Computational Frontiers (Algorithms, Theory, Machine Learning, User Analysis, Quantum Computing). Because of its interdisciplinarity, this project is also strongly aligned with the Community Engagement effort.
The theoretical backdrop for studying spatial distributions in a highly relativistic strongly interacting system is provided by the Generalized Parton Distributions (GPDs) [1, 3] describing momentum slices of successive spatial parton distributions (tomography) in various polarization configurations [4]. Together, experimental and theoretical efforts define the science of Nuclear Femtography whose ultimate goal is to attain a full image of the internal structure of the proton. Experimental information on GPDs is obtained from a wide variety deeply virtual exclusive processes, or coincidence experiments where all the particles in the final state are either directly or indirectly detected (see review in [5]). Extracting GPDs from data involves a much larger number of variables than in inclusive deep inelastic scattering. Each process, in either lepton or hadron scattering experiments will add contributions to the picture. The inherent complexity of the kinematics and phenomenology, coupled to the need of harnessing information from all different experiments, makes our problem virtually

impossible to solve with traditional methods: for high precision femtography which is required to obtain proton images, we are developing more sophisticated analyses. Working towards this goal, a major component of our project is focused on developing both Artificial Intelligence (AI) and visualization tools for the extraction of GPDs from data.

Finally, GPDs are specific projections in fewer dimensions of more comprehensive objects known as Wigner distributions, which define the complete phase-space distributions in quantum mechanics [6, 7]. Open questions to be addressed in future studies are what type of information one can extract from Wigner distributions on the quark and gluon dynamics in QCD. An original theoretical avenue we explore is connecting the QCD Wigner distributions with quantum information aspects derived from Wigner Distributions in quantum optics.

Similar to the much better known Parton Distributions (PDFs), GPDs can be extracted from data by building models and flexible parametrizations for the valence quarks, antiquarks and gluons distributions that make use of all available information including lattice QCD calculations [8]. GPDs, however, involve an additional step in their extraction from experiment in that the momentum fraction, x, of the active quark/gluon is only accessible indirectly through convolution integrals. In PDFs, on the contrary, the momentum fraction is directly accessible through the Bjorken variable. On the other side, GPDs, at variance with Transverse Momentum Distributions (TMDs), are collinear objects, therefore a careful extraction of their scale dependence from data can be performed and tested against known QCD evolution equations. This program will require a global effort combining data from different experiments in a wide range of momentum scales. Global analyses will be enabled by developing open access platforms that can the be easily used by model builders to fit deeply virtual exclusive data sets, allowing researchers to tap into the various aspects of GPDs. In this context a particularly important role is and will be played by AI algorithms to fit DVCS data in a controlled way.

In summary, the various components that are necessary to reconstruct femtographic images of the proton will use data from a variety of deeply virtual exclusive experiments, in a wide range of four-momentum transfer including the ranges attainable at future colliders, in particular the EIC. A novel approach including the development of AI tools will be fundamental for the realization of this physics program. This effort will require first of all, assembling a global network to harness data from a wide range of deeply virtual exclusive experiments including both lepton scattering – Deeply Virtual Compton Scattering and related channels – and hadron scattering – both pion and proton induced exclusive Drell Yan processes. Qualitatively new tools will be developed to both solve the inverse problem which is inherent to the extraction of GPDs from all data sets, and to construct grids to store and efficiently retrieve data. These tools will allow an extensive nuclear/particle physics community to develop femtographic images of the nucleon as new data become available [9].

Community Engagement is essential to this effort as computer and data science experts will collaborate with physicists. The development of visualization tools including Virtual Reality, movies and improved graphics for public outreach will be a substantial effort in this context.

---

[1] X.-D. Ji, Phys. Rev. Lett. **78**, 610 (1997), arXiv:hep-ph/9603249 [hep-ph].

[2] M. V. Polyakov, Phys. Lett. **B555**, 57 (2003), arXiv:hep-ph/0210165 [hep-ph].

[3] A. V. Radyushkin, Phys. Rev. **D56**, 5524 (1997), arXiv:hep-ph/9704207 [hep-ph].

[4] M. Burkardt, Phys. Rev. D **62**, 071503 (2000), [Erratum: Phys.Rev.D 66, 119903 (2002)], arXiv:hep-ph/0005108.
[5] K. Kumericki, S. Liuti, and H. Moutarde, Eur. Phys. J. A **52**, 157 (2016), arXiv:1602.02763 [hep-ph].
[6] C. Lorcé, B. Pasquini, X. Xiong, and F. Yuan, Phys. Rev. **D85**, 114006 (2012), arXiv:1111.4827 [hep-ph].
[7] A. V. Belitsky, X.-d. Ji, and F. Yuan, Phys. Rev. D **69**, 074014 (2004), arXiv:hep-ph/0307383.
[8] M. Constantinou *et al.*, (2020), arXiv:2006.08636 [hep-ph].
[9] P. Foteinos and N. Chrisochoides, Engineering with Computers **31** (2015), doi:10.1007/s00366-014-0380-z.