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Review of Ph.D. thesis by Víctor Martínez-Fernández

Expanding the accessible kinematic domain of generalized parton distributions

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The refereed Ph.D. thesis by Mr. Martínez-Fernández deals with one of the most important and timely topics of hadron physics or, more generally, high energy physics. Namely, it concerns the investigations of the internal structure of the nucleon, the key building block of all visible matter, responsible for almost all of its mass. One of the most significant objects that describe this internal structure are generalized parton distributions (GPDs), the main focus of the thesis. GPDs describe the three-dimensional structure of the nucleon and embody crucial information about the angular momentum of the nucleon's constituents, i.e. quarks and gluons. Yet, they are very difficult to access experimentally and even if such studies are possible, they are inherently limited to very special kinematic cases. The main aim of the thesis is to expand this accessible kinematic domain, as emphasized already in the dissertation title.

The Ph.D. thesis is 148 pages long, with additional 18 pages before its main body and 32 pages of appendices. Thus, it is comparatively long, but given its overall quality, certainly not too long. Actually, I rate its length as a perfect compromise between providing all the relevant details of the research work done and getting it too long with unnecessary additions. I also strongly welcome its "traditional" form instead of the one of a collection of papers with a brief introduction. For one thing, it makes the contributions of the Ph.D. student clearer with respect to the typical setup of contemporary papers in physics, which are commonly co-authored by several people. Secondly, the "traditional" form can also demonstrate the student's comprehension of the research topic. Last, but not least, it can also provide excellent pedagogical material for next students or any physicists wishing to understand better the topic. Let me emphasize that the refereed dissertation excels in all three aspects – there is no doubt what were the contributions of Mr. Martínez-Fernández, nor that he achieved very profound understanding of the difficult subject. Finally, the text is very pedagogical and I am sure it can be of great value for many people, exceeding the pedagogical value of the underlying research papers that are necessarily much more concise.

Continuing some general remarks, the thesis reads very well. It is written in very good professional English, with very few minor flaws like typos. The narration is very logical, with just the right amount of details, which was also achieved by putting some of the technical details in appendices. This way, the reader is not overwhelmed or lost in these, while they are still available for reference. The mathematical notation is inherently complicated in these topics, but also this aspect is handled extremely well with a combination of standard notation used in the literature and logical choices of additional notation.

I will now move on to a more detailed analysis of the thesis. It consists of an introduction (chapter 1), three main chapters (2-4) and a final summary discussion of conclusions and future prospects (chapter 5).

Chapter 1 introduces the context of the work. It starts with the fundamentals of quantum chromodynamics (QCD), the quantum field theory underlying the inner structure of the nucleon. Then, the focus moves on to this structure, which is first discussed in the context of the canonical deep inelastic scattering (DIS), the main experimental tool to account for the "basics" of nucleon structure. The example of DIS is used to introduce the key concepts, like partons, Bjorken scaling and light-cone dominance, and the quantitative tools that describe the nucleon structure, like structure functions and parton distribution functions (PDFs). It is argued that the information provided by PDFs is limited and further access to essential properties of the nucleon can be obtained with exclusive reactions. This leads to a detailed discussion of deeply virtual Compton scattering (DVCS) and timelike Compton scattering (TCS), wherein the idea of GPDs naturally emerges. Their major properties are thoroughly analyzed and it is shown that DVCS and TCS are limited in practice to very special kinematics, where the momentum fraction x can be accessed only in close proximity of the skewness variable ξ, reflecting the longitudinal momentum transfer. While this picture is, strictly speaking, a leading-order one, even going beyond this order is argued to be insufficient, due to the subtlety of the so-called shadow GPDs. This provides the crucial motivation to go beyond DVCS and TCS. A natural extension of both these reactions, proposed already around 20 years ago, is to realize a double DVCS

(DDVCS). Physically, this introduces an additional scale from the presence of a second virtual photon. DDVCS becomes either DVCS or TCS in two separate limits, providing thus a powerful framework for the extraction of GPDs. Overall, the first chapter provides a very strong motivation to study DDVCS, which becomes the main focus of the thesis in subsequent chapters.

Chapter 2 is devoted to a detailed analysis of DDVCS in the muon channel, i.e. with the produced lepton-antilepton pair consisting of a muon and an antimuon. It is argued why such a setup is more favorable with respect to detecting electron-positron pairs. The analysis is performed at leading order (LO) in the strong coupling constant and at leading-twist (LT) accuracy. It starts with a general description of DDVCS and introduction of various reference frames, relevant for assessments of experimental feasibility. The main part of this chapter is section 2.4 that presents the derivations of the amplitudes relevant for DDVCS – the actual DDVCS amplitude and the Bethe-Heitler (BH) subprocesses with the same initial and final states, which are pure electromagnetic scatterings that do not probe the nucleon structure. In section 2.5, the DVCS and TCS limits are discussed as special cases of DDVCS. Recovering the known DVCS and TCS results serves as a strong validation of results derived in section 2.4. Section 2.6 uses the DDVCS results for phenomenological estimates of experimental feasibility at EIC and JLab, including its projected update. To this aim, the results for the amplitudes and cross sections of DDVCS and BH were implemented in PARTONS, an open-source framework for comprehensive theoretical and experimental analyses related to GPDs, and EpIC, also an open-source Monte Carlo event generator. This aspect of the Ph.D. thesis is highly commendable and has huge practical importance – since accelerator time is limited, one thing is to derive theoretical results and an entirely different one is to convince experimental steering committees. Hence, such studies are crucial and also very interesting. Observables are proposed, such as single beam spin asymmetry, and it is shown that the results are highly promising from the point of view feasibility.

In my view, if the Ph.D. thesis concluded with results obtained up to the end of section 2, it would already be a good basis for a Ph.D. degree. However, the thesis continues to two additional chapters tackling a very important issue of kinematic higher-twist (HT) corrections. Chapter 3 describes the theoretical framework for the twist decomposition, first explaining the notion of twist and then discussing a state-of-the-art method to calculate the mentioned kinematic HT corrections. Such effects are clearly highly relevant in the attainable kinematic regimes of projected DDVCS experiments, given by the combinations of the momentum transfer, the target mass and the energy scale of the process.

The framework is based on recent powerful developments by Braun, Ji and Manashov using conformal field theory. Although the conformal symmetry is broken in QCD at next-to-leading order, its remnants have been shown to have predictive power, allowing for a conformal twist expansion. This chapter is very technical, but it is of great pedagogical value to potential new students as well as any researchers wanting to understand this difficult approach. It is crucial to emphasize the level of advancement of this material and the challenge it must have obviously been to learn it at a level necessary to apply it in practice.

The theory laid out in chapter 3 is put to use in chapter 4, devoted to inclusion of kinematic twist-3 and twist-4 corrections to DDVCS off a spin-0 target. After setting up the kinematics of the reaction of electroproduction of a muon-antimuon pair off such a target, the Compton tensor is parametrized in terms of (photon) helicity-dependent amplitudes, which can be simply related to Compton form factors (CFFs) of the hadron. At LO in the strong coupling and at LT, there is only one such CFF, while including kinematic HT corrections increases this number to five. These five amplitudes are then addressed in separate subsections, starting with the transverse-helicity conserving $\mathcal{A}^{++}$, the only one contributing at kinematic twist-2. Then, further amplitudes that start beyond twist-2 at LO are derived. All these derivations are given with great detail, proving the profound understanding of the demanding technicalities. What is important, also abundant physical comments are provided, showing that the technicalities do not obscure the picture of the involved physics. For each amplitude, also the DVCS and TCS limits are given, interesting and important in themselves (with the DVCS limit already known from literature and cross-checked against). The chapter is not limited to analytical expressions for the amplitudes, but provides also numerical estimates of kinematic twist corrections for the pion (pseudoscalar) target. This proceeds via convoluting the calculated coefficient functions with expressions from a pion GPD model by Chavez et al. Results are presented using clear figures plotted against a ratio of virtualities that smoothly interpolates between the TCS and DVCS limits. The LT amplitude $\mathcal{A}^{++}$ is shown to receive corrections of up to 50% at the larger of the considered squared momentum transfers (amounting to around one third of the squared energy scale). Importantly, the HT corrections break the LO and LT relation between $\mathcal{A}^{++}$ of DVCS and TCS as complex conjugates, something that needs to be taken into account when testing universality of GPDs from these two types of scatterings. The effects in purely HT amplitudes are shown to be also sizable, although still suppressed with respect to $\mathcal{A}^{++}$. Overall, the results clearly demonstrate that kinematic HT corrections are considerably large and they can affect the extracted observables and thus, be measurable in current and future experiments. The importance of these results lies also in the fact that being able to account for these kinematic corrections allows one to enhance the range of experimental data by including ones with larger ratios of $-t/Q^2$.

The last chapter 5 summarizes the thesis, giving its overview, highlighting the conclusions obtained in the course of the work and presenting also some future prospects. From the point of view of a thesis referee, this chapter confirms that the Author not only mastered the technical aspects, but also has deep understanding of the "big picture".

Overall, I am truly impressed by this thesis. It is a very timely study of high importance for the field. The Author's task was difficult, since the field of GPDs is still rather emerging and many aspects are not clearly established. The techniques required for such studies are still being developed and pose significant difficulties. Mastering them to the point of being able to perform the analysis presented in the dissertation was definitely a challenge, but the Author fully rose to it and in my view, he already became an expert with very unique skills. Obviously, it would not have been possible without the clever guidance of his Supervisors, world-leading experts in the phenomenology of GPDs. However, this does not detract anything from Mr. Martínez-Fernández's achievement. On the contrary, this is what a well-executed Ph.D. project should look like and what leads to the most efficient work in theoretical physics (and probably most other branches of science too). In addition, the thesis has an additional merit that should not be underestimated – it provides exceptional pedagogical material for future students of the field and even researchers intending to learn these techniques.

Before I conclude, I attach some questions that I would like Mr. Martínez-Fernández to address during the Ph.D. defense.

1. How do you judge the prospects of DDVCS in terms of feasibility and the offered physical insights with respect to other ways of overcoming the $x = \xi$ limitation in accessing GPDs?

2. Realistically, do you expect some DDVCS results to be available before the end of the decade or one rather has to wait for the EIC and/or JLab's beam energy update?

3. Could you shortly describe the complications arising in calculating kinematic HT corrections for DDVCS off a spin-1/2 target, such as the nucleon?

4. Can the framework of conformal twist expansion be used also to get insights about genuine higher-twist corrections and what can you say about the relevance of higher-twist GPDs for accurate description of the nucleon's three-dimensional structure?

In summary, according to the argumentation given above, the thesis clearly satisfies all formal and customary requirements for Ph.D. dissertations. Thus, I conclude that the Ph.D. candidate should be admitted to the next stages of the doctoral procedure. Moreover, given the level of difficulty of the topic and its excellent realization, I believe this outstanding dissertation should be awarded a distinction.

Polish translation of the conclusion:
Podsumowując, zgodnie z argumentacją zawartą powyżej, rozprawa doktorska spełnia wszelkie formalne i zwyczajowe wymogi stawiane takim rozprawom. Wnioskuję w związku z tym o dopuszczenie kandydata do dalszych etapów procedury doktorskiej. Ponadto, ze względu na poziom trudności tematu i jego świetną realizację, wnioskuję o wyróżnienie rozprawy.

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Krzysztof Cichy

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