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Report on the PhD thesis with title
EXPANDING THE ACCESSIBLE KINEMATIC DOMAIN OF GENERALIZED PARTON DISTRIBUTIONS
by
Víctor MARTÍNEZ-FERNÁNDEZ

The present PhD thesis deals with specific processes inherent to the so-called Quantum Chromodynamics (QCD), the theory that describes quarks and gluons and their mutual interactions. In particular, the subject of the thesis is devoted to the study of certain Compton scattering processes and extensions thereof.

A key process of the work is given by:

Electron + Nucleon → Electron + Nucleon + Muon + Antimuon ,

whose detailed analysis delivers information about the structure of the nucleon, especially about the generalized parton distribution functions (GPDs). This process takes place with two virtual photons (Fig. 2.1) which appear in different combinations (the most relevant one is the so-called deeply double virtual Compton scattering, DDVCS).

The thesis deals with a detailed theoretical description of these processes, and how to link measurable cross-sections to the GPDs. The fact that there are two virtual photons in DDVCS processes allows to investigate certain kinematical regions that are not accessible when one of the two photons is on-shell.

Another important topic of the thesis is the extension of the aforementioned process to the following one:

Electron + (pseudo)scalar hadron→ Electron + (pseudo)scalar hadron + Muon + Antimuon ,

where the (pseudo)scalar object can be e.g. the nucleus of the Helium atom or a pion, but in principle it is applicable for any (pseudo)scalar state.

This work is in general close to the experimental activity taking place at the Jefferson Lab (USA) and the planned Electron Ion Collider (EIC). The theoretical expressions are built to provide a connection between the nonperturbative physics of hadrons and the data that can be collected at those experimental facilities. Then, the future measurement of DDVCS would constitute an important tool for improving our understanding of QCD.

Various aspects of quantum field theory in general and QCD in particular are applied in the thesis, showing that Mr. V. Martinez-Fernandez skills as theoretical physicist are well documented.

The thesis is partly based on four articles in which the PhD candidate is a co-author, in particular the exhaustive publication Phys.Rev.D 107 (2023) 9, 094035, as well as related proceedings (refs. [69-72] of the thesis).

Below I summarize the content of the thesis as well as various remarks/questions. In the end, the final remarks and assessment are summarized and presented.

Brief summary of the thesis (chapter by chapter):

1) Chapter 1 contains a very short introduction to QCD and to the main features of the scattering processes that will be studied in the thesis: deep inelastic scattering, parton distribution function (PDF), and generalized parton distribution functions. The general kinematical constrains of the scattering amplitudes and cross sections are described and the concepts of time-like Compton scattering (with one incoming real photon, Fig. 1.5) and DDVCS (with two virtual photons, Fig. 1.6) are introduced. The software 'PARTON' and 'EPIC' employed for the calculation are briefly discussed in the end of the chapter.

2) Chapter 2 focuses on the reaction mentioned above: Electron + Nucleon → Electron + Nucleon + Muon + Antimuon. The different amplitudes are schematically outlined in Fig. 2.1: DDVCS, in which two photons interact with the nucleon, and Bethe-Heitler amplitudes, in which only one photon interacts with the nucleon: the formula summarizing the different contributions is provided in Eq. 2.47. After a detailed account of the reference frames variables, the DDVCS amplitude is studied in the leading twist approximation, in which a single parton interacts with the two virtual photons (Fig. 2.3). The amplitude is the further divided into vector and axial contributions. Next, the BH amplitudes are described and two limits are used for a cross-check: the Deeply Virtual Compton Scattering (DVCS, in which the outgoing photon is on-shell)) and the time-like Compton scattering (TCS, in which the incoming photon is on-shell). Finally, in the end of chapter 2 some numerical studies for cross sections and for GPDs are presented (see e.g. Fig. 2.13).

3) Chapter 3 is linked to the twist decomposition, which is a realization of the operator product expansion (OPE). This expansion is useful because it allows to retain dominant contributions of certain operators (and thus dominant contributions of amplitudes) when selected kinematical constrains are considered. In doing so, an excursus about the trace anomaly of QCD and the Poincaré's algebra is presented. Finally, the expressions for various amplitudes, obtained by using the twist decompositions, are listed.

4) In Chapter 4 the process Electron + (pseudo)scalar object→ Electron + (pseudo)scalar object + Muon + Antimuon is analyzed. Here, the (pseudo)scalar state can be the Helium nucleus or the pion, but the treatment is general and any (pseudo)scalar hadron can be considered. Upon using the twist decomposition of the previous chapter, various expressions for amplitudes are obtained, as for instance the amplitudes listed on page 130. Finally, some numerical examples involving the pion as target are presented in the end of the chapter: the amplitudes are plotted in a series of Figures.

5) This chapter contains a brief summary of the main achievements of the thesis, as well as future perspectives.

Moreover, there is a long list of appendices that deal with (even) more technical details and aspects of the calculations, such as groups, correlator of scalar fields, projectos, tensors, etc..

Remarks and questions:

In the following, I list some remarks/questions.

It should be stressed that these questions aim to clarify some open issues and be the starting point for a discussion during the defense, but do not undermine the overall positive judgment.

1) Different processes are studied in the thesis, such as DDVCS, TCS, BH, which are further divided into sub-contributions. What I miss is a summarizing table that would present –at one look- the main processes and amplitudes under study. I guess that this point can be achieved in the oral presentation.

2) Similarly, a full plethora of techniques, that range from the choice of reference frame, Kleiss-Stirling techniques, twist, operator product expansions, etc. are introduced through the thesis. An overview, in the form of e.g. a steps chart, of all these technical steps and in which context they are applied, is missing. I think that this aspect can be clarified during the defence.

3) The number of acronyms is in the thesis is huge: besides the already mentioned DDVCS, TCS, BH, PDF, GPD, one encounters KS, BDP, ERBL, GK, VGG, MMS, CFF, LT, CFT, etc. All of them are correctly defined the first time they are introduced, nevertheless such a large number of abbreviations make the reading quite difficult. Also in this case, a summarizing table with all the acronyms and abbreviations used in the work would have been useful for the reader.

4) The ultimate goal of the thesis is the understanding of the GPD models. Three of them are mentioned in the second chapter of the thesis, stressing that future measurements could show which one works better. What I miss here is in which physical assumptions these models differ, and hence how the falsification of some of them would improve our physical understanding of the nucleon or the hadron. In the case of the pion, in Eq. 4.292 of chapter 4 a simple parameterization of a pionic GPD is presented, but the motivation behind this expression are not provided.

5) I wonder what would change if, instead of a photon, the Z_0 boson is considered. While this process would be suppressed, I guess that many features of the treatment would still be valid. Also, the scattering with a ‘graviton’ may also be taken into account. Which tensor structure would couple to it?

6) As applications, the Jlab and the EIC are mentioned. I am interested to know if the study of such processes discussed in the thesis would also be possible in the framework of heavy ion collisions (such as the ones investigated by the ALICE experiment at CERN), where both real and virtual photons are generated together with various hadrons.

Final judgment:

The structure of the thesis is clear and well presented. The thesis is well written and delivers many technical details that can be of help for future studies on the topic (and may be useful for future master and doctoral students). The use of scientific English is accurate. The list of citations is long and exhaustive.

Most importantly, the thesis presents novel relevant results for the field of generalized parton distributions and future experimental realizations at Jefferson Lab and EIC.

In conclusion, *the overall judgment of the present PhD thesis is **positive*** and I consider that the thesis by Victor Martinez-Fernandez fulfills all the merit-based requirements of a PhD thesis and I recommend its admission to the public defense.

Francesco Giacosa 8/9/2024, Kielce (Poland)

Signed by /
Podpisano przez:

Francesco
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