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Evaluation report for doctoral thesis

To the National Center for Nuclear Research

Candidate MSc Arantxa Tymowska

Title *Next-to-eikonal corrections in the Color Glass Condesate*

Discipline Theoretical Physics

Supervisor prof. NCBJ dr. hab. Tolga Altinoluk

The thesis manuscript is approximately 120 pages long. Some of the research results presented in the thesis have also been presented in published journal articles where the PhD candidate is an author:

1. T. Altinoluk, G. Beuf, A. Czajka and A. Tymowska, "Quarks at next-to-eikonal accuracy in the CGC: Forward quark-nucleus scattering," Phys. Rev. D **104** (2021) no.1, 014019 [arXiv:2012.03886 [hep-ph]].
2. T. Altinoluk, G. Beuf, A. Czajka and A. Tymowska, "DIS dijet production at next-to-eikonal accuracy in the CGC," Phys. Rev. D **107** (2023) no.7, 074016 [arXiv:2212.10484 [hep-ph]].

The topic of the thesis is to develop new theoretical tools for QCD scattering processes in the high energy limit. The experimental context for this study are measurements in deep inelastic scattering (DIS) experiments such as at the HERA collider at DESY and in particular in the future Electron-Ion Collider (EIC) at Brookhaven, and hadronic and nuclear collisions at the LHC and at RHIC. One of the goals of the experimental program at these facilities is to access the gluon saturation regime of QCD, where nonlinear multiparticle interactions between gluons in the proton or nucleus dominate the scattering dynamics. Typically in the literature in the field, these interactions are studied in the strict limit of high scattering energy, where one can use the *eikonal* approximation. In this limit, the energy and longitudinal momentum of the partonic probe is so large, that it allows a significant simplification to the description of the scattering process: the probe only couples to a specific component of the gauge field of the target, the longitudinal extent of the target is Lorentz-contracted so that the transverse coordinate of the probe does change in the scattering, and the scattering is too fast to be sensitive to the internal dynamics of the target. At realistic collision energies, however, the eikonal approximation is likely to be an oversimplification. The goal of the thesis is to systematically develop the theory of the next-to-eikonal (NEik) corrections to this limit, and to apply these corrections to specific scattering processes.

Chapter 1 presents a concise introduction to perturbative QCD and the partonic picture of hadronic bound states. The conventional collinear approach is discussed starting from the interpretation of DIS scattering in terms of the parton model. The chapter then introduces the concept of gluon saturation and the Color Glass Condensate (CGC) effective theory that provides the quantitative framework to analyze it, serving as the starting point for the work in this thesis.

Chapter 2 focuses in more detail on the eikonal approximation, which is one of the building blocks of the CGC framework. The candidate first introduces the relevant power counting argument for how different coordinates and gauge field components behave under a longitudinal Lorentz boost, which provides the organizing principle for a series expansion in inverse powers of the collision energy. Then, the fermion propagator for multiple eikonal interactions with an external gauge field is derived, in a very careful way explicitly resumming arbitrary numbers of interactions with the field and performing the necessary spinor algebra and integrations. An essential part of this propagator is the Wilson line, a path ordered exponential in the gauge field of the target, which encodes the all of the degrees of freedom in the target that are relevant in the eikonal limit. The section then discusses in general the three kinds of corrections that need to be taken into account when going beyond the eikonal limit: the inclusion of transverse components of the gauge field, accounting for the finite size of the target in the longitudinal direction, and including the effect of internal time dependence in the target during the interaction process. The text of this chapter is based on the more introductory parts of the journal publications, and also includes a nice review of how subeikonal effects have been discussed in the recent literature.

Chapter 3 goes into more detail on the calculation done in publication 1. First, the quark propagator is derived taking into account two of the three subeikonal corrections: the finite longitudinal extent of the medium in Sec. 3.1. Due to the coupling between the longitudinal and transverse coordinate in the phase factor, this correction ends up resulting in a correction proportional to a derivative of the eikonal Wilson line. To this, the transverse component of the gauge field is added in Sec. 3.2. These two effects are then very elegantly combined in Sec. 3.3. into an expression in terms of covariant derivatives acting on the Wilson lines. This reorganization has the effect of bringing the result into a manifestly gauge covariant form, which should make it easier to connect the formulation to an operatorial definition of a gluon distribution in the target. The chapter then continues with a very explicit and valuable exposition of the LSZ reduction relating the quark propagator to a scattering amplitude. This enables then the use of the obtained NEik fermion propagator to obtain an expression for the quark cross section for a quark-proton or quark-nucleus collision. This NEik effects cross section are then very nicely discussed in terms of the exchanged quantum numbers and for polarized and unpolarized cross sections separately. Indeed the physics of the proton spin is one of the most important experimental contexts for these noneikonal effects.

Chapter 4 discusses the calculation in publication 2. First, the LSZ-type reduction formula for calculating a DIS diquark cross section for a transverse or longitudinal photon is derived, providing a way to relate the quark propagator in a backgound field to a measurable cross section. Then, an expression for the fermion

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propagator in a background field at the full NEik accuracy is derived. This includes, in addition to the types of corrections considered in the preceding chapter, also the effect of the internal dynamics of the target during the interaction. These latter type of effects cannot, unlike the other noneikonal effects, be expanded in a series, but must rather be included in a "generalized eikonal" expression for the propagator. The fermion propagator is then used to derive the production cross section for dijets in DIS at the full NEik accuracy. While in many aspects similar to the calculation in the previous section, this expression involves much more lengthy calculations. It also exposes additional types of Wilson line correlators ("decorated" in different ways) that are needed to characterize the target.

Chapter 5 describes ongoing work that will also be separately reported in a future paper. Here, the full NEik accuracy quark propagator is applied in a qualculation of photon + jet production in quark-nucleus or quark-proton production at high energy, relevant for proton-nucleus and proton-proton collisions at high energy. In terms of the calculation, this process is relatively similar to the ones discussed in Chapter 3 and 4, involving the quark propagator both in the vacuum and inside the target color field. Again the result in analyzed in terms of the helicity-dependent and helicity-independent parts of the cross section. The calculation in this chapter demostrates the general applicability and increasing maturity of the methods developed in the thesis, which enables them to be applied to a variety of different scattering processes in a consistent manner.

Finally, Chapter 6 draws overall conclusions on the work on the thesis. The text stresses the importance of the different kinds of violations to the eikonal approximation and the need to treat them completely, and the relevance for the methods developed here to different scattering processes. The new quantities ("decorated" Wilson line operators) still need to be modeled or extracted from experimental data in order to make the cross section calculations quantitative. The work in this thesis nicely sets the stage for such efforts in the future. Additionally, basic notations on light cone variables are reviewed in Appendix A, and Appendix B contains some longer derivations from Chapter 5 that would overly distract from the main text.

The calculations in the thesis as a whole demonstrate a technical ability to perform reliable calculations in a modern, still evolving framework for doing perturbative QCD calculations. The two published and one in-progress article each represent a significant calculational effort, and overall the amount of new scientific results is clearly more than sufficient for a good doctoral thesis in theoretical physics. The individual contributions of the candidate in the joint publications are very clearly explained in the text, and the independent role of the candidate in this work is also clearly demonstrated by the talks at major scientific conferences where the candidate has presented the results.

The thesis manuscript itself is organized in a logical and clear way. The discussion and references also demonstrate that the candidate is well aware of both the basic literature in the field and the work of other research groups on related and similar topics. The references are cited according to good scientific practice. The list of 75 references is not excessive, but covers well the literature specifically relevant for the purpose of this work. The thesis is also written in a good, clear English language and typeset in a professional manner. There are some small

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typos here and there, but they are very few in consideration of the length of the manuscript and do not distract from following the text. Overall the text is very readable, to the extent allowed by the technical nature of the work.

As a conclusion, I find that the thesis fulfills all the requirements for a good doctoral thesis in theoretial physics. ***Thus I recommend that the thesis be accepted for oral defence.***

Jyväskylä, August 4, 2023

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