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Review of doctoral thesis by Ms. Arantxa Tymowska

entitled

"Next-to-eikonal corrections in the Color Glass Condensate"

1 Overview, main results, scientific quality

In her doctoral thesis Ms. Arantxa Tymowska addresses an advanced theoretical problem of next-to-leading power corrections to high energy limit of scattering amplitudes in quantum chromodynamics (QCD). The context of the thesis is spanned by physics studied at the current largest particle collider — the Large Hadron Collider (LHC), at the next most important future experiment in high energy nuclear physics — the Electron–Ion Collider (EIC), and by the current precision Era in collider particle physics. Getting together these aspects of contemporary collider physics is one of the reasons for which the thesis is very much up-to-date and scientifically relevant.

The Author goes beyond the eikonal approximation (Eik), that has been the canonical approach to the analysis of high energy scattering amplitudes in QCD since about 50 years, when Gribov, Lipatov, Fadin, Kuraev and Balitsky discovered an exceptionally important connection between QCD at high energies and the before-QCD Regge model of hadronic scattering amplitudes. In particular, the eikonal approximation in which only the leading power of the invariant collision energy E it retained, is the very basis of theoretical description of non-linear effects in high energy scattering in QCD, that paved the way to theoretical understanding of gluon density saturation phenomenon. Particle scattering in the regime of high parton density may be described e.g. in terms of the Color Glass Condensate (CGC) framework, which is the main framework of the thesis.

Within the CGC approach, the description of high energy scattering off nuclear targets is very well developed. The formalism is based on Wilson lines or contours built from sections of Wilson lines, that resume multiple interactions a scattering colored particles in the background color field of the target. There exist numerous results in this framework in the eikonal approximation at the leading and next-to-leading accuracy in perturbative expansion in QCD. The motion of fast particles

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along straight lines assumed in this picture is a direct consequence of the eikonal approximation. The first step to improve this approximation is calculation of the first non-vanishing correction in the $1/E$ expansion of the exact amplitudes, that is leads to the Next-to-eikonal (NEik) approximation. This improvement is particularly important for the EIC physics, where the scattering energy is moderately high, and the targets may be heavy nuclei with large size, that enhances the NEik effects. In the NEik approximation the Wilson lines are modified by inclusion of additional operators and become "decorated Wilson lines".

The results presented in the thesis contribute strongly to a new interesting research line focused on analysis of NEik effects in CGC, that has been developed since several years. In the thesis the NEik corrections are obtained for selected processes with projectile quark and virtual photon scattering off a dense target (nucleus): the inclusive and helicity dependent quark scattering, the dijet virtual photoproduction, and the jet plus photon production by a quark. These results are essentially novel and contribute significantly to improving the CGC framework. They were published in two original papers (in Physical Review D), and the results on photon plus jet production at NEik accuracy were presented at renowned international conferences, the full paper should follow. The already published papers enjoy high interest in the scientific scientific community, each one getting about 10 citations per year according to INSPIRE database, which is a high score.

To sum up, the thesis presents high quality and up-to-date scientific results, that make a significant impact on the research field.

2 Methodology

The content of the thesis is highly technical, it mostly presents the calculations, which is a rather standard case in theoretical particle physics. The calculations are perfomed using perturbation theory in light-cone longitudinal variables, using both the position and momentum space. This is a sophisticated formalism within quantum field theory, well suited for the description of high energy scattering. Moreover, it allows for a clear and straightforward physics interpretation of the obtained results. In the CGC framework Wilson lines are the basic objects used in the calculations. They are composite objects that emerge from all-order resummations in QCD, so the CGC calculus requires advanced theoretical methods to be applied. A great advantage of the Wilson lines is their gauge invariance. In fact, it the thesis the calculations are performed with gauge invariant quantities which is definitely a strong point.

The processes analyzed in the thesis are well chosen, and the main line of the analysis is clear. The first, most fundamental, step is the analysis of the quark and antiquark propagator in the color field of the target at the NEik accuracy. Then more phenomenologicaly oriented results are obtained for the cross sections for quark / antiquark scattering off a nucleus, including the helicity dependence. Next, the dijet electroproduction in Deep Inelastic Scattering (DIS) is considered, that includes quark–antiquark pair creation from the virtual photon inside or out side the target, and the related quark / antiquark propagation through the target. Finally, a related process is considered of quark to quark plus photon transition in the target field.

In the analysis of these processes three types of subeikonal effects have been isolated: those that come from deviations from the straight line motion of a fast

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particle, those that come from an interaction of the fast particle with a sub-leading color field potential component $A_\perp$, and those that originate from longitudinal variation of the color field in the target. This classification is important to build clear physics understanding and organize the calculations.

A remarkable feature of the thesis is the connection between the sophisticated formalism and the observables. In particular, this connection is fruitful for the quark scattering off a nucleus, where unpolarized and helicity dependent cross sections for quark scattering off nucleus are presented. The performed analysis leads to isolating the contributions to the cross sections with quantum numbers of the Pomeron, Odderon and subleading Reggeons. This gives additional theoretical insight into the process and could be also useful in building connection to other framworks for scattering on nuclei, e.g. one based on DGLAP.

To conclude this part, the calculations perfomed in the thesis required using advanced field-theoretical methods, and in addition, developing new applications of these methods. The thesis uses cutting-edge methodology in theoretical studies of next-to-eikonal corrections in Color Glass Condensate.

3 References and literature review

The thesis begins with a concise description of QCD and to Color Glass Condensate formalism in Section 1, in which the general context of the studies is presented. In Section 2 eikonal and Next-to-eikonal approximations in CGC are discussed, and the review of literature relevant for the topic is performed. These two sections and the related part of bibliography provide a good introduction to the studies done within the thesis, and the basis of the original research is clearly desribed there. The bibliography with 75 positions covers well the literature of the subject.

Sections 3, 4 and 5 present original scientific results. Each of these sections is based on a separate publication coauthored by Ms. Arantxa Tymowska (for Section 5 — a publication in preparation). The results were obtained in teams of four researchers, which is a very standard case in theoretical high energy physics. The calculational complexity of the studied problems is rather high, so cross checks of calculations are necessary within the team. In addition, all of the problems solved have a rather rich substructure, so the final result of each publications contains a large number of highly non-trivial partial results. The overlap of the content of Sec. 3 and Sec. 4 and the published papers is significant, but the Author made it very clear what her contribution was to the obtained results. In my view, this procedure shows excellent level of scientific integrity of the Author, and this is highly appreciated. In Sec. 5 essentially new content is presented, related to a conference presentation of the Author. Clearly, the original research contributions declared by the Author show her very good scientific perfomance.

4 Presentation

The thesis is well written. It is well structured, with 2 introductory sections followed by three main sections with original results, a concise Conclusions section, bibliography and an Appendix. The main content of the thesis are analytical calculations, and they are presented very well. The reader is well lead through complex derivations, well explained and referenced. The logic is clear and all crucial steps

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are given, allowing to understand and reproduce the obtained results. The notation is well chosen, clear, uniform and consistent through the whole thesis. Where possible, several general formulas are illustrated with well designed figures. As already said, the presented formalism is advanced, the derivations and results are quite complex, so it is remarkable how clearly the formulas are presented. Definitely, the Author keeps the highest quality here.

The editorial quality of the remaining text is also high. I have spotted several slips, but they are just a few occurences in a long text (117 pages). Examples of typos found: (i) — a symbol is probably missing in the 1st sentence after Eq. (2.7), (ii) — "perfmorming" in the text after (2.9), (iii) — "are are" in the last sentence of Sec. 3.3, (iv) "Y.V. Kovchekov and E. Lenvin" in [17] of bibliography, (v) punctation marks in formulas are not always consistent. All of these are minor points and they occur really rarely.

Hence, all in all, the presentation is excellent.

5 Questions, open problems

Concerning the obtained results, I have several questions on the formalism applied:

Question 1: I have not found in the thesis a clear statement on whether the calculations are performed using standard quantization or the light-front quantization. It would be highly appreciated to have this point clearly stated.

Question 2: The reason for an occurence of double $A_\perp$ contribution in the NEik approximation is only briefly described. I would like to ask for a broader explanation of this point. Please, refer also to Eq. (3.27) of the thesis.

Question 3: Figure 2.1 shows a diagram that defines a Wilson line for a fast scattering of a quark on a gluon field off a dense target. How are included other topologies for this scattering, including diagrams with crossed gluon legs?

The other points that I would like to address, are open problems that are related to completness of the obtained results in the context of collider phenomenology and the relation of the NEik CGC framework to other existing approaches.

Problem 1: the Author considers quark and antiquark propagation in the gluon field of a large and dense target. For the case of a general hadronic projectile and target, the fast parton may be also a gluon. In the case, when a forward jet is produced e.g. in pA collision it may be experimentally difficult to distinguish a gluon jet from a quark jet. Two questions follow: (i) is it possible to extend the formalism to describe NEik gluon scattering? (ii) is it possible to perform an experiment in such a way, that the contributions of quark and gluon components of the projectile are separated?

Problem 2 — is related to quark and antiquark degrees of freedom in the target. The contribution of quark / antiquark exchange in high energy scattering in known to be a subeikonal effect. Can one estimate the importance of such exchanges? How do they scale with energy E? How do they compare to NEik gluon exchange effects considered in the thesis?

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Problem 3: Expectation values of operators, the evolution. The new operators that appear at NEik accuracy involve gradients of the gluon fields and the $A_\perp$ components. Can expectation values of these operators be directly obtained or estimated from the eikonal approximation of CGC? If yes — how? If not — how to obtain such estimates from theory or experiment? Along the same line — one class of NEik effects found in the thesis is related to "target dynamics". This leads to a natural question — are there NEik effects in the evolution of target fields? Is it possible to formulate evolution equations that would govern the decorated Wilson lines? Finally, is it possible to cross check the calculations described in the thesis with results from another framework e.g. the collinear factorization framework? Is there a limit in which one could compare the NEik CGC amplitudes with coefficient functions in DGLAP approximation?

6 Overall assessment

The doctoral thesis of Ms. Arantxa Tymowska is of high scientific relevance and of high quality. The obtained original results lead to a strong progress along the NEik CGC research line, and they make significant impact on the scientific community and they enhance theoretical description of physics at the Electron–Ion–Collider. The methodology applied is advanced. The thesis has clear logic and the presentation is excellent. The Author has showed very good skills to carry out independent research in theoretical physics and high level of scientific integrity. The thesis is very well written and edited. **I evaluate the dissertation as very good.**

In conclusion: the doctoral thesis definitely meets the international standards and fulfills Polish statutory requirements. I recommend that Ms. Arantxa Tymowska be admitted to further steps of the procedure of awarding the degree of PhD in physics.

W języku polskim: **Podsumowując, z przyjemnością stwierdzam, że przedstawiona przez panią Arantxę Tymowską rozprawa doktorska spełnia wszystkie zwyczajowe i ustawowe wymagania oraz wnoszę o dopuszczenie pani Arantxy Tymowskiej do dalszych etapów postępowania w sprawie nadania stopnia naukowego doktora w dyscyplinie Nauki Fizyczne.**

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