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Review of the habilitation thesis
"Study of parton saturation effects on protons and nuclei"
by Ing. Jan Čepila, Ph.D

The habilitation thesis of Dr. Jan Čepila is located in the area of strong interactions where quantum chromodynamics (QCD) is the basic theory. Quarks and gluons, the fundamental quanta of QCD, form the basic structure of hadrons which is revealed in high energy scattering experiments with nucleons and nuclei, e.g at the accelerators HERA, RHIC, LHC and future EIC. All the twelve habilitation publications are devoted to phenomenological studies of selected processes at these acccelerators in which the main effects are related to the phenomenon of *parton saturation*, where parton densities get saturated as functions of parton momentum fractions. This is an effect which appears in a particular limit of QCD, called Regge or high-energy limit, in which virtuality of a hard probe is much bigger than the characteristic scale of QCD ($\Lambda_{\rm QCD} \sim 300$ MeV) but much smaller than the scattering energy of colliding particles. In such a case, for sufficient large energy, the virtual probe reveals dense gluon systems inside hadrons which signatures and properties are studied in the habilitation papers. The theoretical methods used in the habilitation papers combine the perturbative QCD results with phenomenological assumptions which have to be made due to confinement effects, since quarks and gluons are permanently bounded in hadrons and the nature of their confinement is still to large extent unknown.

The twelve habilitation papers (listed on page 65 of the Habilitation Thesis) were published in the best journals of the high energy physics in the years 2017-2021, like Physics Letters B, Nuclear Physics A and B, Physical Review C and D and European Physical Journal A and C. According to SPIRES data base, they are well cited (up to 58 citations), taking into account a rather short period of time from their publication. All of them are many author papers in various configurations which shows how important is a diverse expertise in writing good papers. Although I have no doubts that the contribution of Dr. Čepila is essential, I am missing some information in the habilitation thesis on the very nature of his involvement. This remark is provoked by my experience with the Polish habilitation procedure which demands such a specification. On the other hand, such information can be easily obtained from the author during the further steps of the habilitation procedure. Some hints are provided by the statements about Master's or PhD Theses of Dr. Čepila students.

The habilitation thesis consist of three concise chapters (plus Introduction) in which the basic information on the subjects of the habilitation publications is provided. I highly value this presentation since it is written in an optimal form with most important ideas and formulas provided. Each chapter is finished with a short presentation of new results obtained in the habilitation publications. The Thesis is concluded with the journal copies of them

Chapter I, *Introduction*, provides a soft introduction to QCD and clearly introduces two main elements of the habilitation work, namely, the studies with the Balitsky-Kovchegov (BK) equation, which is the basic QCD equation describing gluon saturation, and a phenomenological model of saturation with fluctuating hot spots (regions of strong classical gluon fields) in a hadron. The latter effect stays outside the physics of the BK equation and this is why it was treated phenomenologically.

Chapter 2, *Parton saturation*, is devoted to the saturation studies with the BK equation. The most compelling physical process in which parton saturation can be visible is exclusive vector meson photo or electroproduction. In the high energy limit of QCD, this process can be visualize in the transverse coordinate space (obtained from the Fourier transform of transverse momenta), as a three step process. The virtual electroweak probe splits into a quark-antiquark pair (a dipole) of transverse size r which interacts with the strong gluon fields in a hadronic target and than form a vector meson. The BK equation describes the intermediate step of the dipole interaction with the gluon fields while the vector meson formation is the place for modeling of nonperturbative effects which bind two quarks into a vector meson. The nonperturbative effects are also important in the BK equation in the form of the dependance of the dipole interaction with the hadronic target as a function of the impact parameter b, i.e. the transverse distance of the dipole from the center of the target. This aspect of the BK equation is the main theme of Dr. Čepila studies in publications 5.5, 5.8, 5.9, 5.10, 5.11 and 5.12 (numbering from Chapter 5, *Selected publications*).

The nonlinear BK equation was derived in the year 1999 in the leading logarithmic in energy approximation in which the small strong coupling constant α_s is enhanced by logarithm of energy and powers of such a combination are summed up to infinity.

From this time, various corrrections to this equation were derived, namely the running of α_s was taken into account as well as collinear corrections were added which make contact with the conventional Altarelli-Parisi (DGLAP) equation. Finally, the full next-to-leading logarithmic (NLL) in energy corrections were added to the linear part of the BK equation kernel. The work of Dr. Čepila is based on the systematic development of the numerical code which solves the BK equation with the described above elements, except the NLL corrections. However, he concentrated on the most uncertain aspect of the BK equation, namely, the b dependence which in the standard approach produces long range Coulomb tails, forbidden due to confinement. He proposed strongly suppressed shape of the b dependence of the initial condition to the collinearly improved BK equation with one parameter to be extracted from data. The BK evolution preserves this suppression, at least to the values of rapidity shown in the thesis. Also the azimuthal angle dependence between the dipole vector size $\vec{r}$ and the impact parameter vector $\vec{b}$ was taken into account in the initial condition.

However, in the applications to real data, in order to avoid numerical inefficiency, a simplified factorized ansatz for the initial condition was used with two gaussian distributions in b. Two parameters in this model were chosen to describe existing data on F_2 and exclusive J/ψ meson photoproduction at HERA and LHC. With such a model, successful predictions for the cross sections of exclusive photo and electroproduction of various vector mesons at HERA and LHC were obtained. What is more, predictions for nuclear structure functions were also provided as well as the analysis of coherent J/ψ photoproduction in ultraperipheral Pb-Pb collisions at the LHC was done. Such analyses are of increasing importance in view of the planned new collider EIC at Brookhaven. The first step in this direction has already been done by Dr. Čepila and his collaborators by providing predictions for diffractive structure functions at the EIC in the dipole approach with parton saturation. It is also encouraging that a systematic development of the BK equation code is planned, e.g. by inclusion of the NLL corrections. It would be also good to embed the BK equation into a broader set of evolution equations which are subleading from the point of view of the high energy limit of QCD since the EIC energies are probably not large enough to fully justify the use of the BK equation.

Chapter 3, *The hot-spot model*, is devoted to the spatial distribution of gluons in hadrons in the transverse impact parameter plane (papers 5.1, 5.2, 5.3, 5.4 and 5.7). This is a genuine nonperturbative problem which can be addressed in the exclusive and dissociative vector meson (VM) photo or electroproduction. In the first case, the scattered hadron (e.g. a proton) stays intact while in the second one, it dissociates into excited hadronic states. In the theoretical picture of the Good-Walker formalism, the incoming proton state is a superposition of partonic states which fluctuate event-by-event. The t dependent exclusive VM production cross section is proportional to the square of the scattering amplitude averaged over fluctuating partonic configurations while in the dissociative case, the cross section is given by a variance over these configurations. In the hot-spot model, partonic fluctuations are included in the proton profile function, $T(b)$, which is a sum x dependent Gaussian distributions in b, describing regions of high gluon density (hot-spots). The averaged number of hot spots rises with decreasing Bjorken x, i.e. with rising scattering energy, which is in accord with the general small x picture of DIS. The most interesting finding is the prediction that the dissociative cross section does not grow indefinitely with rising energy but it goes to zero after reaching maximum. It corresponds to the black disk limit of the total cross section when the hot spots fill the whole proton such that their variance goes to zero. This is also the limit imposed by unitarity which is realized according to the parton saturation idea. The comparison of the hot-spot model predictions with the HERA and LHC data on the VM production looks very good. Only for the Υ production the experimental points are much higher than the predictions, although the large experimental errors make the comparison acceptable. I would like to emphasize that once the model parameters were determined from the J/ψ production at HERA, all the other comparisons are genuine predictions. This is why the hot-spot model of the VM production is very important for the future EIC experiments.

Chapter 4, *Uncertainty analysis for vector meson production*, looks less exciting than the previous ones. However, it is very important from the point of view of experimental analyses of data. The standard question which experimentalists often ask theoreticians is: what are the systematic errors of your theoretical predictions? The usual answer is: I do not know or I do not care. Fortunately, this is not the answer of Dr. Čepila. Together with his collaborators, he performed a comprehensive analysis of the most important uncertainties in the dipole model descriptions of the VM production (papers 5.6 and [116]). The most obvious uncertainty is related to the necessity to model the scalar part of the vector meson wave function. In the habilitation papers two mostly used models were considered: Gaussian and boosted non-Gaussian model with several potentials in the Schroedinger equation. In general, this is the least constrained part of the VM production description. Also the energy dependent proton width parameter was analysed, which is essential for a proper t dependence of the VM cross section, following Regge phenomenology with its breaking due to additional Q^2 dependence important for J/ψ and $\Upsilon(1S)$ production. The issue of parton saturation is encoded in the form of the dipole cross section which models the interaction of the $q\bar{q}$ pair with the hadronic target. Several phenomenological parameterizations of this interaction were considered, starting from the historical GBW and ending with the most advanced parameterizations which take into account some features of the BK equation solutions with phenomenologically introduced b dependence. Finally, the effect of the so-called Melosh spin rotation was analysed which is usually neglected in this type of analyses by many authors. The magnitude of this effect is of the order a few percent for the total VM production cross section. The effect of all the uncertainties was clearly shown in a series of comparisons with the existing data.

To summarize the habilitation thesis of Dr. Jan Čepila, I am really impressed by the amount of work done in a relatively short time with a large number of published papers in the best scientific journals. The central theme, parton saturation in the context of the dipole picture of the VM production, was attacked from different angles, using most recent advances in this field of research. I would also like to stress the importance of the group which was formed around these problems with Jan as a master for young researchers. He fully deserves habilitation degree.

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