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EXCLUSIVE PRODUCTION OF VECTOR MESONS IN QCD

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We compare results of our studies [1,2] on vector meson production within the QCD factorization at next-to-leading order with HERA data.

1 Introduction

The exclusive vector meson V electro- and photo-productions in photon-proton collisions, $\gamma\ p \to V\ p$, are the subject of HERA collider experiments. The primary motivation for the interests in these processes, both for the light $\rho-$meson electroproduction and for the heavy $J/\Psi-$ or eventually $\Upsilon-$meson photoproduction, is that they can constrain gluon density in a proton. To achieve this aim it is necessary to minimalize the theoretical uncertainties involved in determination of the coefficient functions (CF), i.e. the perturbatively calculable hard part of the scattering amplitudes. The first step in this direction consists in going beyond the leading Born approximation (LO) and requires calculation of the scattering amplitudes at the next-to-leading order (NLO). Recently such studies were completed both, for the processes with light $\rho-$meson [1] and for those with heavy vector meson [2]. The theoretical framework of these researches was the QCD factorization which permits to write the scattering amplitude in a form of the convolution (in fractions of longitudinal momenta) of the perturbatively calculable CF with nonperturbative distribution amplitude (DA) of produced meson V and the generalized parton distributions (GPDs) in a target proton.

We refer the reader to Refs. [1,2] for review of the literature on the subject, for details of derivation and complete set of results. Below we present a first comparison of these new results with HERA data.

Let us remind the main source of theoretical uncertainties of our approach. The QCD factorization involves the dependence of the scattering amplitude on two, a priori independent, scales: the factorization scale μ_F and the renormalization scale μ_R. The dependence of the LO scattering amplitudes on these scales is usually quite strong. By taking into account NLO terms of the amplitudes one hopes to obtain a more consistent description in which the dependence of the amplitudes on μ_F and μ_R is smoother than in the LO case and that the NLO corrections are small in comparison with LO terms.

2 Electroproduction of $\rho-$meson

Electroproduction of longitudinally polarized neutral $\rho-$meson from the longitudinally polarized photon on the proton target, $\gamma^*_L(Q^2)\, p \to \rho_L\, p$, is a classical process studied within the QCD factorization approach. The hard scale required for the validity of perturbative analysis is supplied by the photon virtuality Q^2, the $\gamma_L^* \to \rho_L$ transition dominates.

Fig. 1 shows the comparison of theoretical predictions of Ref. [1] for $\sigma(Q^2)$ with HERA data [3]. The curves denoted by M and C are obtained with two different input GPDs based on forward parton distributions: MRST2001 and CTEQ6M, respectively [4]. The factorization scale μ_F is assumed to be equal to the kinematical hard scale Q of the process. On the other hand, the renormalization scale μ_R is fixed in two different ways: for solid curves $\mu_R = \mu_F$, whereas for dashed curves $\mu_R = Q/\sqrt{e}$. The last condition corresponds to the BLM (Brodsky-Lepage-McKenzie) prescription. Our general conclusion is that the account of the NLO terms results in a better qualitative agreement of predictions with the data. On the other hand, the comparison of different curves shows a strong dependence of theoretical predictions on the input GPDs, especially for Q^2 smaller than 10 GeV^2.

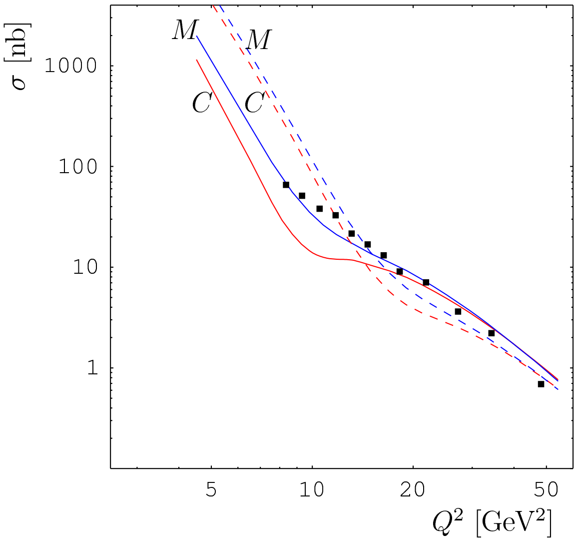

Figure 1. $\sigma(Q^2, W = 95\text{GeV})$ as a function of Q^2 for two NLO GPDs: MRST2001 (denoted by M) and CTEQ6M (denoted by C). The factorization scale μ_f is assumed to be equal to Q. For the solid lines $\mu_R = \mu_F$, for the dashed lines $\mu_R = Q/\sqrt{e}$. The data points are taken from [3].

In Fig. 2 we show the dependence of $\sigma(W)$ on the $\gamma^* - p$ cms scattering energy W. Each plot corresponds to a different value of virtuality Q^2 reported in [3] with the unchanged labeling of curves. We observe again the strong behaviour of predictions on input GPDs. Additionally, our predictions depend on assumed relations between factorization and renormalization scales. This last aspect is analyzed in more details in Fig. 3. It shows a dependence of predictions for $d\sigma/dt|_{t=0}$ on the scale μ_F compared with three different data points measured by ZEUS; on each plot they are denoted by a horizontal line. We use also, the same as previously prescriptions for fixing μ_R. Closer look at Fig. 3 shows that the inclusion of NLO terms in the analysis results in a weaker dependence of predictions on μ_F than in the case when only the LO terms are kept. Nevertheless it remains still quite strong which indicates that the NLO corrections are big in comparison with LO contribution.

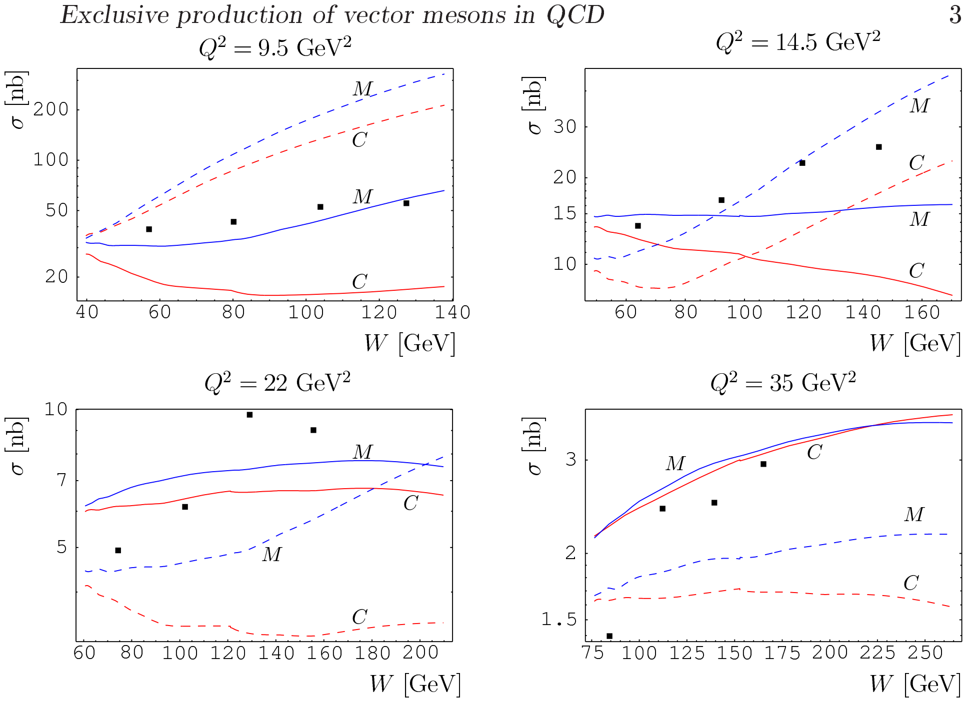

Figure 2. The cross section $\sigma(W)$ as a function of W for four different values of Q^2 and for two NLO GPDs: MRST2001 (denoted by M) and CTEQ6M (denoted by C). The factorization scale μ_f is assumed to be equal to Q. The solid lines correspond to the $\mu_R = \mu_F$, for the dashed lines $\mu_R = Q/\sqrt{e}$. The data points are taken from [3]

This feature is illustrated in Fig. 4 which shows the relative magnitude of different contributions to the scattering amplitude. Firstly we note that, as expected in the small$-x$ HERA kinematics, the imaginary part of scattering amplitude is much larger than its real part. The comparison of LO gluon (gB) and quark (qB) contributions with those including LO and NLO terms (curves denoted as full) shows that the NLO corrections are large and mostly have opposite signs than the Born contributions. Consequently the final predictions are the result of strong cancellations between the LO and the NLO contributions.

3 Photoproduction of heavy vector mesons

In Ref. [2] we studied a photoproduction of transversely polarized vector mesons $V = \Upsilon,\ J/\Psi$, on a proton, $\gamma_T\, p \to V_T\, p$. The hard scale in this process is supplied by the mass of heavy meson.

As was already mentioned, the inclusion of NLO terms leads to a weaker dependence of predictions on scales μ_F and μ_R. In the case of $\Upsilon-$meson photoproduction this fact is illustrated in Fig. 5. The left plot shows the comparison of ZEUS and H1 data with LO predictions (when only gluon GPD contributes) by assuming that $\mu_F = \mu_R$ and they vary in the interval $[1.3-7]$ GeV. In the right plot the same comparison is done with NLO terms included. As result it leads to a weaker variation of theoretical predictions on values of these scales.

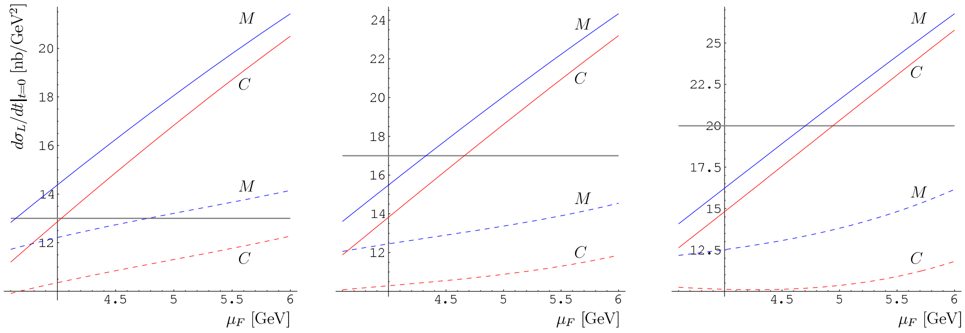

Figure 3. $d\sigma_L/dt(t = 0)$ as a function of μ_F compared with three experimental points $13,\ 17,\ 20\,\mathrm{nb/GeV^2}$ (horizontal lines from left to right) corresponding to three values of $W = 80,\ 110,\ 150\,\mathrm{GeV}$ with $Q^2 = 27\,\mathrm{GeV^2}$. The labeling of curves is the same as in Figs. 1 and 2. The data points are taken from [5]

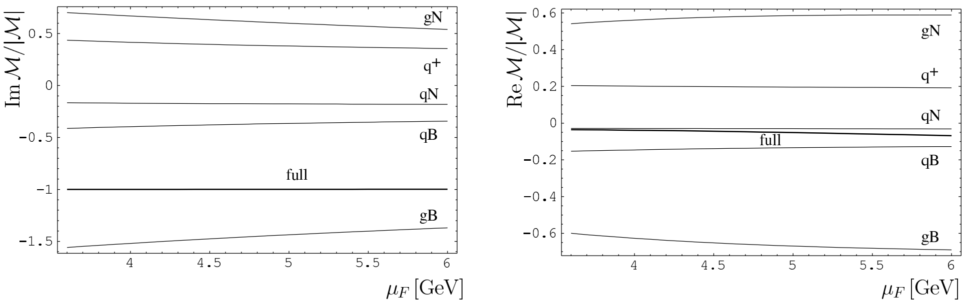

Figure 4. For $Q^2 = 27\,\mathrm{GeV}^2$, $W = 110\,\mathrm{GeV}$ different contributions to $Im\,\mathcal{M}/|\mathcal{M}|$ and $Re\,\mathcal{M}/|\mathcal{M}|$ in dependence on μ_F (for $\mu_R = \mu_F$ and CTEQ6M): gB – gluon contr. at LO, qB – quark contr. at LO, gN – gluon contr. at NLO, qN and q^+ – quark contr. at NLO (see [1] for more details), full – all terms LO and NLO included. $|\mathcal{M}|$ contains always LO plus NLO terms.

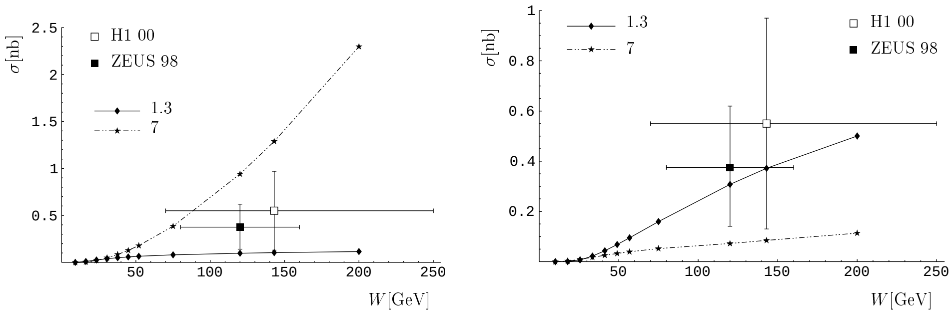

Figure 5. The cross section of the Υ photoproduction; theoretical predictions at LO (left figure) and NLO (right figure) for the scales $\mu_F = \mu_R = [1.3, 7]$ GeV. The data are from ZEUS [6] and H1 [7].

Fig. 6 is the $\Upsilon-$meson production analog of Fig. 4 from $\rho-$meson case. We observe similar feature that the imaginary part of scattering amplitude with LO and NLO terms included (denoted as total) is larger than the corresponding real part. We observe also in this case that the NLO gluon and quark corrections are large in comparison with LO (Born) contributions and have opposite signs. Thus again the final predictions are result of strong cancellations between the LO and the NLO terms.

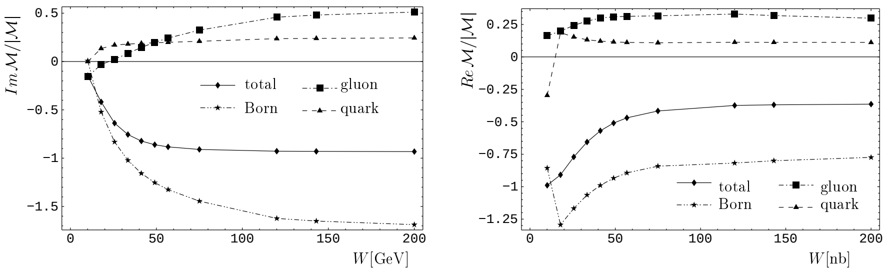

Figure 6. Υ photoproduction, NLO prediction for $\mu_F = \mu_R = 4.9$ GeV and its decomposition into different contributions, see text.

The presently available and cleanest experimentally process which could serve for study of gluon distribution in a nucleon is the J/Ψ photoproduction. The analog of Figs. 5, 6 for this case is shown in Fig. 7. By inspecting the top-left plot one could at first sight to conclude that inclusion on the NLO terms leads to predictions reflecting better the behaviour of data. But a closer look into the left-bottom plot shows that the difference between LO and NLO terms are larger than in the case of Υ production, in fact they have even opposite signs. Moreover, as can be seen also in the right-top plot, the LO plus NLO imaginary part crosses zero at some point, which seems to suggest that our predictions are not numerically stable. The obvious reason for that is too small value of $J/\Psi-$meson mass as a hard scale.

4 Conclusions

The general conclusion which comes out from the comparison of the theoretical predictions on vector mesons production at NLO with experiment is a qualitative improvement of the description at NLO in comparison with the one at LO. This fact is of some value by itself since these results are to big extent model independent. Nevertheless, at HERA kinematics the NLO contributions are large in comparison with the LO terms which calls for the all-order resumation of these terms. Another possibility, related to production of heavy mesons, is to extend the analysis of Ref. [2] to the electroproduction processes involving virtual photon. This would lead to a larger values of hard scale and hopefully to a better numerical stability of predictions. Finally let us also mention that the non-perturbative power corrections are probably not negligible at HERA kinematics.

Acknowledgments

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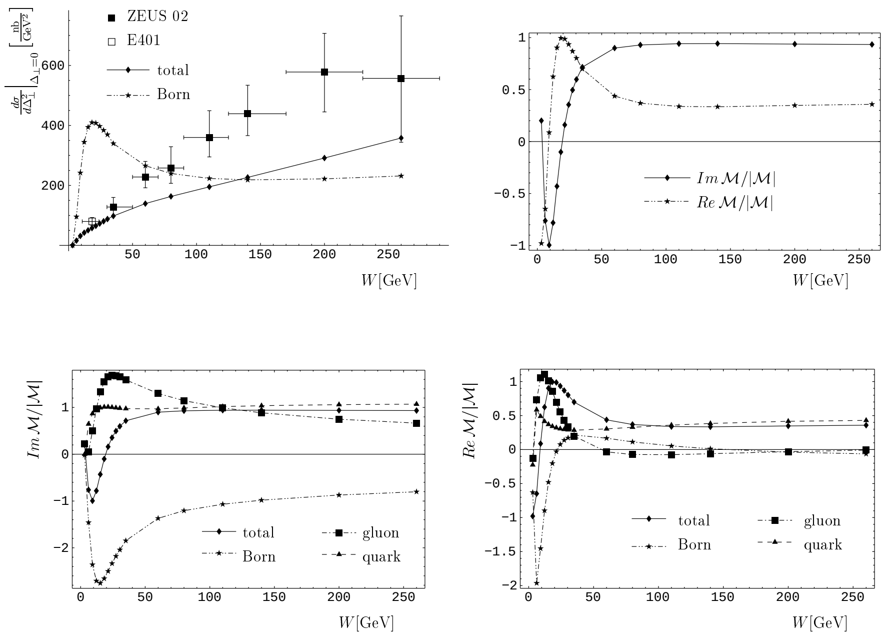

Figure 7. The differential cross section for J/ψ photoproduction, NLO predictions for $\mu_F = \mu_R =$ 1.52 GeV, and the data from E401 [8] and ZEUS [9]. The labeling of the curves is the same as in Fig. 3.

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