High energy rho meson leptoproduction *

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Abstract
We investigate the longitudinal and transverse polarized cross-sections of the leptoproduction of the ρ meson in the high energy limit. Our model is based on the computation of the impact factor \( \gamma^* (\lambda_\gamma) \rightarrow \rho (\lambda_\rho) \) using the twist expansion in the forward limit and expressed in the impact parameter space. This treatment involves in the final stage the twist 2 and twist 3 distribution amplitudes (DAs) of the ρ meson and the dipole scattering amplitude. Taking models that exist for the DAs and for the dipole cross-section, we get a phenomenological model for the helicity amplitudes, we compare our predictions with HERA data and get a fairly good description for large enough virtualities of the photon.

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1 Introduction
We study the high energy diffractive leptoproduction of ρ meson
\[
\gamma^* (q, \lambda_\gamma) N(p) \rightarrow \rho(p_\rho, \lambda_\rho) N(p'),
\]
where \( N \) is the nucleon target, \( \lambda_\rho \) and \( \lambda_\gamma \) are respectively the polarizations of the ρ meson and of the virtual photon. The longitudinal and transverse polarized cross-sections \( \sigma_L \) and \( \sigma_T \) of the process (1) can be expressed in terms of the helicity amplitudes, which are denoted \( T_{\lambda_\rho, \lambda_\gamma} \). In the limit of high energy in the center of mass of the \( \gamma^* N \) system, the helicity amplitudes can be factorized, using the \( k_T \)-factorization scheme, into the convolution of the impact factor \( \Phi^{\lambda_\gamma, \rightarrow \rho \lambda_\rho} \) associated to the process
\[
\gamma^* (q, \lambda_\gamma) g(k_1) \rightarrow \rho(p_\rho, \lambda_\rho) g(k_2),
\]
and the unintegrated gluon density $F(x,k)$. In our kinematics we use the Sudakov decomposition along the light cone vectors $p_1$ and $p_2$, such as
\[ p_\rho \sim p_1, \quad p \sim p_2, \quad q \sim p_1 - \frac{Q^2}{s} p_2, \quad s = (q+p)^2 \sim 2p_1 \cdot p_2 \gg (Q^2, m_\rho^2). \] (3)

The $t$-channel gluon momenta, illustrated in fig. 1 read $k_1 = \frac{\kappa + Q^2 + k^2}{s} p_2 + k_\perp$

\[ \begin{array}{ccc}
\gamma^* & \Phi^{\rho \gamma* \rightarrow \rho \lambda} & \rho \\
& k_1 & k_2 \\
p & p' & \mathcal{F}(x,k) \\
\end{array} \]

Figure 1: Impact factor representation of the helicity amplitudes.

and $k_2 = \frac{\kappa + k^2}{s} p_2 + k_\perp$, where $\kappa$ is the energy in the center of mass of the system $\gamma^*(q) g(k_1)$. The helicity amplitudes are

\[ T_{\lambda \rho \lambda} = i s \int \frac{d^2 k}{(k^2)^2} \Phi^{\gamma \gamma* \rightarrow \rho \lambda} (k) \mathcal{F}(x,k). \] (4)

Assuming the virtuality of the photon $Q^2 (Q^2 = -q^2)$ is large compared to the QCD scale $\Lambda_{QCD}$, the impact factors $\Phi^{\rho \gamma* \rightarrow \rho \lambda}$ and $\Phi^{\rho \gamma \rightarrow \rho \lambda}$ were computed in ref. [1], using the collinear factorization on the light-cone. In this approach, the impact factors are parameterized by the leading twist DA of the $\rho$ meson. This computation was extended in refs. [2, 3] to obtain the $\Phi^{\gamma \gamma* \rightarrow \rho \rho}$ impact factor in the limit $|t| \sim 0$. In this last case, the twist 2 contribution vanishes and the amplitude is parameterized by the twist 3 DAs of the $\rho$ meson. The result for $\Phi^{\gamma \gamma* \rightarrow \rho \rho}$ obtained from the light-cone collinear factorization is the sum of two contributions: from a quark antiquark ($q\bar{q}$) Fock state and from a quark antiquark gluon ($q\bar{q}g$) Fock state. Relations between the DAs can be derived from the first principles of QCD and the twist 3 DAs that parameterize the Fourier transforms of the $q\bar{q}$ correlators can be split into two solutions: the Wandzura-Wilczek (WW) solutions, which consist in neglecting the $q\bar{q}g$ DAs, and the ”genuine” solutions, that only depend on the $q\bar{q}g$ DAs. Thus, one can represent the $q\bar{q}$ and the $q\bar{q}g$ contributions to the impact factor $\Phi^{\gamma \gamma* \rightarrow \rho \rho}$ as a sum of a WW contribution and of a genuine contribution. A first phenomenological model proposed in ref. [5] was based on the results of refs. [1, 3] and used a

\[ 1 \text{We denote by } \underline{x} \text{ the 2-dimension euclidean vector associated to the Minkowskian } x, \underline{x}^2 = -x^2. \]
model for the proton impact factor inspired from ref. \cite{4}. The results of this study have led to the conclusion that the soft $t$–channel gluons have a sizable contribution, which calls for the implementation of the saturation effects in this perturbative approach.

For this aim, in ref. \cite{6}, we have performed calculations of the twist 2 and twist 3 impact factors in the impact parameter space. We have shown also the equivalence of obtained results with the ones in momentum space of ref. \cite{3}. The results in the impact parameter representation can be put in the form

\[
\Phi_{\gamma_L^\rightarrow \rho L}(k, Q, \mu^2) = \left( \frac{\delta^{ab}}{2} \right) \int dy \int dL \, \psi_{(q\bar{q})}^{\gamma_L^\rightarrow \rho L}(y, L; Q, \mu^2) \mathcal{A}(r, k), \tag{5}
\]

\[
\Phi_{\gamma_T^\rightarrow \rho T}(k, Q, \mu^2) = \left( \frac{\delta^{ab}}{2} \right) \int dy \int dL \, \psi_{(q\bar{q})}^{\gamma_T^\rightarrow \rho T}(y, L; Q, \mu^2) \mathcal{A}(r, k)
+ \left( \frac{\delta^{ab}}{2} \right) \int dy_2 \int dy_1 \int dL \, \psi_{(q\bar{q}g)}^{\gamma_T^\rightarrow \rho T}(y_1, y_2, L; Q, \mu^2) \mathcal{A}(r, k), \tag{6}
\]

where the functions $\psi_{(q\bar{q})}^{\gamma_L^\rightarrow \rho L}$, $\psi_{(q\bar{q})}^{\gamma_T^\rightarrow \rho T}$ and $\psi_{(q\bar{q}g)}^{\gamma_T^\rightarrow \rho T}$ are respectively our results for the transitions $\gamma_L^\rightarrow (q\bar{q}) \rightarrow \rho L$, $\gamma_T^\rightarrow (q\bar{q}) \rightarrow \rho T$ and $\gamma_T^\rightarrow (q\bar{q}g) \rightarrow \rho T$. $\mathcal{A}(r, k)$ is the scattering amplitude of a color dipole of transverse size $r$ with transverse momenta $k$. In eqs. (5, 6) $a$ and $b$ are the color indices of the $t$–channel gluons in a singlet state. As a result, the well-known wave functions of the virtual photon factorize out in the expressions of $\psi_{(q\bar{q})}^{\gamma_L^\rightarrow \rho L}$ and $\psi_{(q\bar{q}g)}^{\gamma_T^\rightarrow \rho T}$. The $\rho$ meson non-perturbative parts are encoded by the twist 2 and twist 3 DAs and $\mu$ stands for the factorization/renormalization scale of the DAs. We use the model of Ball, Braun, Koike and Tanaka developed in ref. \cite{7} to get explicit expressions for the DAs. This model relies on the conformal expansion of the DAs to separate the longitudinal momentum dependence from the scale dependence in $\mu$. It is customary to call ”asymptotic” (AS) the results in the limit $\mu^2 \rightarrow \infty$. On the other hand, a natural choice for this scale is $\mu^2 = (Q^2 + m_{\rho}^2)/4$. Note that the factorization of the dipole scattering amplitude $\mathcal{A}(r, k)$ is due to the relations between the DAs coming from the equations of motion of QCD.

Inserting the expressions (5, 6) for the impact factor in eq. (4) leads to

\[
\frac{T_{00}}{s} = \int dy \int dL \, \psi_{(q\bar{q})}^{\gamma_L^\rightarrow \rho L}(y, L; Q, \mu^2) \hat{\sigma}(x, L), \tag{7}
\]

\[
\frac{T_{11}}{s} = \int dL \left[ \int dy \psi_{(q\bar{q})}^{\gamma_T^\rightarrow \rho T}(y, L; Q, \mu^2) \right] \hat{\sigma}(x, L)
+ \int dy_2 \int dy_1 \psi_{(q\bar{q}g)}^{\gamma_T^\rightarrow \rho T}(y_1, y_2, L; Q, \mu^2) \hat{\sigma}(x, L), \tag{8}
\]

where $\hat{\sigma}(x, L)$ is the dipole cross-section. These expressions are the starting point for our phenomenological analysis.
2 Confronting our predictions with HERA data

In ref. [8], we have compared our predictions for the transverse and longitudinal polarized cross-sections, shown in fig. 2, with the data from H1 [9]. These predictions are obtained using the dipole scattering amplitude of ref. [10], which is based on numerical solutions of the running coupling Balitsky-Kovchegov (rcBK) equation [11]. This model of dipole scattering amplitude allows to account for the saturation effects in our description of the \( \rho \) meson leptoproduction. Note that as we use a model of dipole cross-section already fitted on inclusive structure functions then we do not need to adjust value of any parameter. The results are in good agreement with the data for \( Q^2 \gtrsim 5 \text{ GeV}^2 \) and they are weakly dependent on the choice of the factorization/renormalization scale \( \mu \). The discrepancy for smaller virtualities \( Q^2 \lesssim 5 \text{ GeV}^2 \) indicates that higher twist corrections to the impact factors can become important for such values of \( Q^2 \).

In fig. 3 we show our predictions for the total cross-section \( \sigma \) of the diffractive leptoproduction of \( \rho \) meson and compared them with the data of H1 [9] and
ZEUS [12], as a function $W$. The $W$–dependence of our predictions is given by the dipole cross-section model [10]. In this way we obtain a good agreement between the predictions and the data for the $W$–dependence.

![Graph](image)

Figure 3: Predictions for the total cross-section $\sigma$ vs $W$ compared to H1 [9] (left) and ZEUS [12] (right) data.

3 Conclusions

The success of the model we have presented to describe the $W$– and the $Q^2$–dependencies with the proper normalizations for large enough $Q^2$, relies on the computations from first principles of the impact factors $\Phi^{\gamma^* \to \rho}$ and the models for the twist 2 and twist 3 DAs as well as the model for the dipole scattering amplitude. Consequently, this approach constitutes a good way to unravel the non-perturbative aspects of the leptoproduction of the $\rho$ meson. The perspectives of this study are numerous, as it could be extended in the non-forward kinematics and for other helicity amplitudes. This could allow to probe the impact parameter dipole/nucleon target dependence of the dipole scattering amplitudes. The higher twist correction effects could lead to a better
description of the data for lower values of $Q^2$ closer to the saturation scale in the HERA kinematics.

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