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# LEPTOPRODUCTION OF $\rho$ MESONS AS DISCRIMINATOR FOR THE UNINTEGRATED GLUON DISTRIBUTION IN THE PROTON*

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The gluon content of the proton, in the high-energy regime, is embodied by the unintegrated gluon distribution (UGD), which describes the gluon emission probability, with a given longitudinal momentum fraction and transverse momentum. The UGD, formulated within the $\kappa$-factorization approach, has universal validity, and several models for it have been proposed so far. We will show that the polarized $\rho$-meson leptoproduction at HERA is a non-trivial testfield for discriminating among existing models of UGD.

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## 1. Introduction

An increasingly detailed understanding on the structure of the proton is the fundamental point of our ability to investigate the dynamics of strong interactions at the LHC and find new physics. In the description of the collision processes, the information about the inner structure of the proton is enclosed in the partonic distribution functions which enter the factorized expression for the cross section. In the deep inelastic scattering (DIS), featuring high photon virtuality, $Q^2$, and large center-of-mass-energy of the virtual photon–proton system $W$, $W \gg Q \gg \Lambda_{\rm QCD}$, which implies small $x = Q^2/W^2$, the

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suitable factorization approach is provided by *$\kappa$-factorization*. Here, the DIS cross section becomes the convolution of the unintegrated gluon distribution (UGD) in the proton with the impact factor (IF) for the $\gamma^* \to \gamma^*$ transition. The UGD, in its original definition, obeys the BFKL [1] evolution equation in the $x$ variable and, being a nonperturbative quantity, it is not well-known and a good number of models for it have been introduced so far (see, for instance, [2]). The goal is to show that HERA data on polarization observables in vector meson (VM) leptoproduction can be employed to constrain the $\kappa$ dependence of the UGD in the HERA energy domain. The observable under investigation is the ratio of the two dominant amplitudes for the polarized leptoproduction of $\rho$ mesons, namely the longitudinal VM production from longitudinally polarized virtual photons and the transverse VM production from transversely polarized virtual photons. First, we illustrate the expression of the dominant amplitudes just mentioned above; then we provide a pattern with the essential details of a few models for UGD and compare theoretical predictions [3, 4] from the tested models of UGD with the HERA data.

## 2. Theoretical framework

Fruitful and exhaustive analyses of the hard exclusive production of the $\rho$ meson in *ep* collisions, given by $\gamma^*(\lambda_\gamma)p \to \rho(\lambda_\rho)p$, are provided by H1 and ZEUS collaborations, where $\lambda_{\rho,\gamma}$ represent the meson and photon helicities, respectively, and can take the values 0 for the longitudinal polarization and $\pm 1$ for the transverse ones. The helicity amplitudes $T_{\lambda_\rho \lambda_\gamma}$ measured at HERA [5] reveal a peculiar ordering: $T_{00} \gg T_{11} \gg T_{10} \gg T_{01} \gg T_{-11}$. The H1 and ZEUS collaborations have analyzed data in distinct intervals of $Q^2$ and $W$. From here on, we will refer only to the H1 ranges, $2.5\,\text{GeV}^2 < Q^2 < 60\,\text{GeV}^2$ and $35\,\text{GeV} < W < 180\,\text{GeV}$, and will focus only on the dominant helicity amplitude ratio, $T_{11}/T_{00}$. At small $x$, the forward helicity amplitude for the $\rho$-meson leptoproduction can be expressed, in $\kappa$-factorization, as the convolution of the $\gamma^* \to \rho$ IF, $\Phi^{\gamma^*(\lambda_\gamma)\to\rho(\lambda_\rho)}(\kappa^2, Q^2)$, with the UGD $\mathcal{F}(x, \kappa^2)$, and reads

$$T_{\lambda_\rho \lambda_\gamma}\left(s, Q^2\right) = \frac{is}{(2\pi)^2} \int \frac{\mathrm{d}^2\kappa}{(\kappa^2)^2} \Phi^{\gamma^*(\lambda_\gamma)\to\rho(\lambda_\rho)}(\kappa^2, Q^2) \mathcal{F}\left(x, \kappa^2\right) , \qquad x = \frac{Q^2}{s} . \tag{1}$$

The definitions of the IFs, for the longitudinal and transverse cases, assume the form given by Eq. (33) and Eq. (38) in [8]. Peculiarly, the longitudinal IF embodies the twist-2 distribution amplitude (DA) [7]; while the transverse IF is expressed through DAs which embodies both genuine twist-3 and Wandzura–Wilczek (WW) contributions [7, 9].

## 3. Models of unintegrated gluon distribution

Pursuing the goal to compare distinct approaches, we deal with a collection of six models, introducing here only the functional form $\mathcal{F}(x,\kappa^2)$ of the UGD. We refer the reader to the original papers for a detailed treatment about the derivation of each model.

**An $x$-independent model (ABIPSW)**
An expression for the proton impact factor [9] provides a very simple and $x$-independent UGD: $\mathcal{F}(x,\kappa^2) = \frac{A}{(2\pi)^2 M^2}\left[\frac{\kappa^2}{M^2+\kappa^2}\right]$, where $M$ represents the nonperturbative hadronic scale.

**Gluon momentum derivative**
This model is given by $\mathcal{F}(x,\kappa^2) = \frac{\mathrm{d}xg(x,\kappa^2)}{\mathrm{d}\ln\kappa^2}$ and encloses the collinear gluon density $g(x,\mu_\mathrm{F}^2)$, fixed at $\mu_\mathrm{F}^2 = \kappa^2$.

**Ivanov–Nikolaev' (IN) UGD: a soft–hard model**
In the large-$\kappa$ range, DGLAP parametrizations for $g(x,\kappa^2)$ are used in this model. Furthermore, for the extrapolation of the hard gluon densities to small $\kappa^2$, an Ansatz is proposed [10]. The gluon density at small $\kappa^2$ is endowed with a nonperturbative soft part. This model has the form of

$$\mathcal{F}\left(x,\kappa^2\right) = \mathcal{F}^{(B)}_\mathrm{soft}\left(x,\kappa^2\right)\frac{\kappa^2_\mathrm{soft}}{\kappa^2+\kappa^2_\mathrm{soft}} + \mathcal{F}_\mathrm{hard}\left(x,\kappa^2\right)\frac{\kappa^2}{\kappa^2+\kappa^2_\mathrm{hard}}\,. \tag{2}$$

We refer the reader to [11] for a meticulous treatment of the parameters and of the expressions for the soft and the hard components.

**Hentschinski–Sabio Vera–Salas' (HSS) model**
The application of this model occurs, originally, in the study of DIS structure functions [12]. Subsequently, it has been used in the description of single-bottom quark production at the LHC in [13], in the investigation of the photoproduction of $J/\Psi$ and $\Upsilon$ in [14] and in the forward Drell–Yan dilepton production [15]. This UGD takes the form of a convolution between the BFKL gluon Green's function and an LO proton impact factor

$$\mathcal{F}\left(x,\kappa^2,M_h\right) = \int\limits_{-\infty}^{\infty}\frac{\mathrm{d}\nu}{2\pi^2}\,\mathcal{C}\,\frac{\Gamma\left(\delta-i\nu-\frac{1}{2}\right)}{\Gamma(\delta)}\left(\frac{1}{x}\right)^{\chi\left(\frac{1}{2}+i\nu\right)}\left(\frac{\kappa^2}{Q_0^2}\right)^{\frac{1}{2}+i\nu}$$
$$\times\left\{1+\frac{\bar{\alpha}_\mathrm{s}^2\beta_0\chi_0\left(\frac{1}{2}+i\nu\right)}{8N_\mathrm{c}}\log\left(\frac{1}{x}\right)\left[-\psi\left(\delta-\frac{1}{2}-i\nu\right)-\log\frac{\kappa^2}{M_h^2}\right]\right\}, \tag{3}$$

where $\chi_0(\frac{1}{2}+i\nu)$ and $\chi(\gamma)$ are respectively the LO and the NLO eigenvalues of the BFKL kernel. We adopted here the so called *kinematically improved* values for the parameters $Q_0$, $\delta$ and $\mathcal{C}$ describing the proton impact factor, (for further details, see Sec. III A of [3]).

**Golec-Biernat–Wüsthoff' (GBW) UGD**

This type of UGD comes from the effective dipole cross section $\sigma(x,r)$ for the scattering of a $q\bar{q}$ pair off a nucleon [16], through a Fourier transform

$$\mathcal{F}\left(x,\kappa^2\right) = \kappa^4 \sigma_0 \frac{R_0^2(x)}{8\pi} e^{\frac{-k^2 R_0^2(x)}{4}} . \tag{4}$$

We refer to [16] for insights and discussion of the parameters of this model.

**Watt–Martin–Ryskin' (WMR) model**

The UGD proposed in [17] reads

$$\begin{aligned}\mathcal{F}\left(x,\kappa^2,\mu^2\right) \;=\; & T_g\left(\kappa^2,\mu^2\right)\,\frac{\alpha_s\left(\kappa^2\right)}{2\pi}\int\limits_x^1 \mathrm{d}z\left[\sum_q P_{gq}(z)\,\frac{x}{z} q\left(\frac{x}{z},\kappa^2\right)\right.\\ & \left. + P_{gg}(z)\,\frac{x}{z} g\left(\frac{x}{z},\kappa^2\right)\,\Theta\left(\frac{\mu}{\mu+\kappa}-z\right)\right], \end{aligned} \tag{5}$$

where the term $T_g(\kappa^2,\mu^2)$, whose expression is provided in [17], indicates the probability of evolving from the scale $\kappa$ to the scale $\mu$ without parton emission. This UGD model depends on an extra-scale $\mu$, fixed at $Q$.

## 4. Numerical analysis

We propose our predictions for the helicity-amplitude ratio $T_{11}/T_{00}$, as obtained with the selection of six UGD models presented in Sec. 3, and compare them with the HERA data. Figure 1 exhibits the comparison between the $Q^2$ dependence of $T_{11}/T_{00}$ for all six models at $W = 100$ GeV and the experimental result. We exploited here the *asymptotic* twist-2 DA $(a_2(\mu^2) = 0)$ and the WW approximation for twist-3 contributions. The fact that the

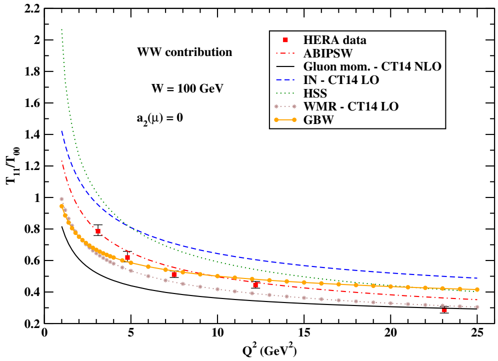


Fig. 1. $Q^2$ dependence of $T_{11}/T_{00}$ for the six UGD models at $W = 100$ GeV.

$T_{11}/T_{00}$ is measured on a large $Q^2$ interval allows to strongly constrain the $\kappa$ dependence of UGDs. None of the models is able to describe data over the entire $Q^2$ range; only the $x$-independent ABIPSW model and the GBW model seem to better catch the intermediate-$Q^2$ behavior of data. In order to calibrate the effect of the approximation made in the DAs, we performed the $T_{11}/T_{00}$ ratio with the GBW model, at $W = 35$ and 180 GeV, by varying $a_2(\mu_0 = 1\ \text{GeV})$ in the range of 0 to 0.6 and suitably taking into account its evolution. Besides, for the same UGD model as we observe in Fig. 2, we relaxed the WW approximation in $T_{11}$ and examined also the genuine twist-3 contribution. This plot illustrates that our predictions for $T_{11}/T_{00}$ are rather insensitive to the form of the meson DAs. The stability of $T_{11}/T_{00}$ under the lower cut-off for $\kappa$, in the range of $0 < \kappa_{\min} < 1$ GeV, has been probed. The result of this test is illustrated in Fig. 3 for the GBW model

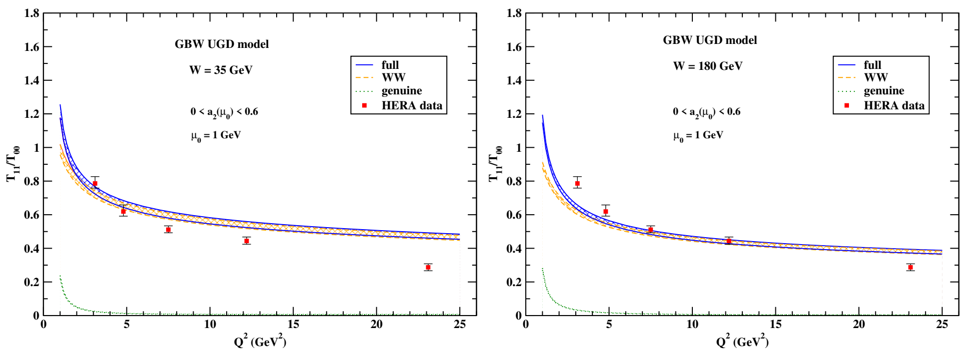


Fig. 2. $Q^2$ dependence of $T_{11}/T_{00}$ for the GBW UGD model at $W = 35$ (left) and 180 GeV (right). The full, WW and genuine contributions are shown. The bands give the effect of varying $a_2(\mu_0 = 1\ \text{GeV})$ between 0 and 0.6.

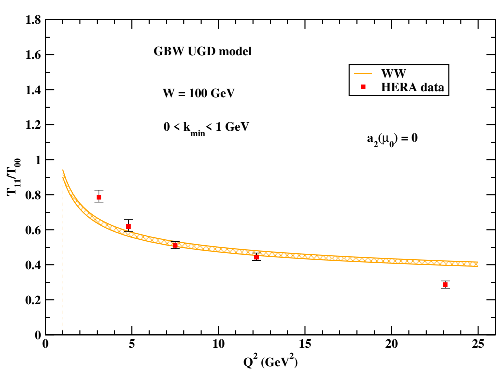


Fig. 3. $Q^2$ dependence of $T_{11}/T_{00}$ for the GBW UGD model at $W = 100$ GeV. The band is the effect of a lower cutoff in the $\kappa$ integration, ranging from 0 to 1 GeV.

at $W = 100$ GeV. It is clear that the small-$\kappa$ region gives only a marginal contribution. This is a crucial point because it supports the main underlying assumption of this work, namely that *both* the helicity amplitudes, $T_{11}$ and $T_{00}$, are dominated by the large-$\kappa$ region.

## 5. Conclusions

We have proposed the helicity amplitudes for the leptoproduction of vector mesons at HERA as a nontrivial testing ground for models of the UGD in the proton. We have provided some theoretical arguments that both cases, the transverse and the longitudinal are dominated by the kinematic region where small-size color dipoles interact with the proton. Furthermore, this investigation shows that some of the most popular models for the UGD in the literature give very sparse predictions for the ratio $T_{11}/T_{00}$.

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