

EXCLUSIVE LEPTOPRODUCTION OF A LIGHT VECTOR MESON AT THE TWIST-3 IN A GTMD FRAMEWORK*

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*Received 14 January 2025, accepted 27 January 2025,
published online 6 March 2025*

We provide the most general description of the exclusive leptonproduction of a light vector meson at high center-of-mass energy, within the CGC/shockwave formalism. We keep a twist-3 accuracy in the s channel, thus being able to describe all possible helicity amplitudes, including the ones for the production of a transversally polarized meson. In this latter case, we overcome the well-known issue of endpoint singularities by promoting the GPD to a GTMD given by matrix elements of dipole and double-dipole operators. The all-twist treatment of the proton (nucleon) target allows to safely twist-expand the general vacuum-to-meson matrix elements. Therefore, unlike previous attempts in the modified perturbative approach, our final results are expressed in terms of the twist-3 collinear distribution amplitudes, introduced in the context of the higher-twist collinear formalism.

DOI:10.5506/APhysPolBSupp.18.1-A25

1. Introduction

The semi-classical effective approach to QCD at small x [1, 2] is the established tool for the exploration of semi-hard processes at the Large Hadron Collider (LHC) and at the future Electron–Ion Collider (EIC). Besides the inclusive channels (see, for instance, [3–6]), in recent times, there has been an increasing attention towards exclusive [7–13] and semi-inclusive [14–18]

* Presented at the Diffraction and Low- x 2024 Workshop, Trabia, Palermo, Italy, 8–14 September, 2024.

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diffractive processes. Among them, the electroproduction of a light vector meson is a golden channel and it has been extensively studied at the HERA experiments [19, 20], where an exhaustive experimental analysis of the spin-density matrix elements of the $\gamma^{(*)}P \rightarrow M(\rho, \phi, \omega)P$ process has been provided. The largest contribution to this spin matrix is the one describing the longitudinal photon to longitudinal meson transition. This latter, from a theoretical point of view, corresponds to the leading-twist contribution and the description of all other transitions requires a treatment beyond leading twist. Unfortunately, at the twist-3, the above-mentioned process does not factorize in the sense of the standard collinear factorization [21, 22]. An attempt to solve this problem is the modified perturbative approach [23], in which distribution amplitudes (DAs) are promoted to light-cone wavefunctions. Another idea is to move to k_T -factorization from the target side. Then, the divergences are regularized by the off-shellness of the gluons in the t -channel [24]. We will follow this second approach in the spirit and develop a framework combining the higher-twist formalism of exclusive processes in the s -channel with the semi-classical effective description of small- x physics in the t -channel. As a result, we will get the result of all helicity amplitudes of the exclusive light vector-meson production at small x , including the saturation regime, and in the most general non-forward kinematics.

2. Semi-classical small- x formalism with effective operators

We work within the k_T -factorization scheme and introduce a light-cone basis using vectors n_1 and n_2 , which specify the $+/-$ directions and such that $n_1 \cdot n_2 = 1$ and $l^\mu = l^+ n_1^\mu + l^- n_2^\mu + l_\perp$, with l a generic four-momenta. The direction of the photon is taken along the $+$ direction, while the one of the incoming proton, along the $-$ one. To investigate the light vector-meson production at high energy, we rely on the semi-classical effective approach to QCD at small x [1, 2], in which the gluonic field $\mathcal{A}(k)$ is split into classical background fields $b(k)$ (small k^+) and quantum fields $A(k)$ (large k^+). Then, in the projectile frame, the target gluon field is effectively treated as a QCD shockwave, *i.e.*

$$b^\mu(x) = b^- (x^+, x_\perp) n_2^\mu = \delta(x^+) \mathbf{B}(x) n_2^\mu. \quad (1)$$

Multiple re-scattering with the target background field yields a Wilson line located at $x^- = 0$

$$W_z = \mathcal{P} \exp \left(ig \int dz^+ b^{-a}(z) \mathbf{T}_r^a \right),$$

where $\mathcal{P}$ denotes the path-ordering operator in the $+$ direction and $\mathbf{T}_r^a$ is a color matrix in the r representation of the gauge group. In particular, $W_z = V_z$ ($W_z = U_z$) in the fundamental (adjoint) representation.

Our general aim is to obtain a result expressed in terms of general vacuum-to-meson matrix elements, *i.e.* without any reference to light-cone expansion at the first stage. To achieve such a description, it is convenient to introduce effective background field operators [25, 26], which take into account the infinite eikonal interactions between the projectile and the classical fields at the operator level. We have

$$[\psi_{\text{eff}}(z_0)]_{z_0^+ < 0} = - \int d^D z_2 G_0(z_{02}) V_{\mathbf{z}_2}^\dagger \gamma^+ \psi(z_2) \delta(z_2^+) , \quad (2)$$

$$[\bar{\psi}_{\text{eff}}(z_0)]_{z_0^+ < 0} = \int d^D z_1 \bar{\psi}(z_1) \gamma^+ V_{\mathbf{z}_1} G_0(z_{10}) \delta(z_1^+) , \quad (3)$$

and

$$[A_{\text{eff}}^{\mu a}(z_0)]_{z_0^+ < 0} = 2i \int d^D z_3 \delta(z_3^+) F_{-\sigma}^b(z_3) G^{\mu\sigma\perp}(z_{30}) U_{\mathbf{z}_3}^{ab} , \quad (4)$$

where $G_0(x)$ is the free quark propagator, $G^{\mu\sigma\perp}(x)$ is the free gluon propagator in the n_2 light-cone gauge, and $F_{\mu\nu}^a(x) = \partial_\mu A_\nu^a(x) - \partial_\nu A_\mu^a(x) - gf^{abc}A_\mu^b(x)A_\nu^c(x)$ is the QCD field strength tensor.

3. Exclusive light vector meson production at the twist-3

A complete and exhaustive description of the process at the twist-3 requires taking into account both *kinematic* and *genuine* twist effects. The kinematic twist effects are related to the relative transverse motion between the constituents of the leading Fock state wave function. Instead, the genuine twist effects take into account the fact that beyond the leading twist, higher Fock states (non-minimal parton configuration) contribute to the meson wave function. These two effects are physically different, but related to each other by the QCD equations of motion.

As anticipated, the kinematic twist contribution requires to calculate the $\gamma^{(*)}P \rightarrow M(\rho, \phi, \omega)P$ amplitude, in which the meson is produced starting from a quark-antiquark pair. Using the effective operator formalism, we obtain

$$\mathcal{A}_2 = \int_0^1 dx \int d^2\mathbf{r} \Psi_2(x, \mathbf{r}) \int d^d\mathbf{b} e^{i(\mathbf{q}-\mathbf{p}_M)\cdot\mathbf{b}} \langle P(p') | \mathcal{U}_{\mathbf{b}+\bar{x}\mathbf{r} \mathbf{b}-x\mathbf{r}} | P(p) \rangle , \quad (5)$$

where q (p_M) is the photon (meson) momenta, x is the longitudinal fraction of meson momenta carried by the quark, $\bar{x} \equiv 1 - x$, $\mathcal{U}_{\mathbf{b}+\bar{x}\mathbf{r} \mathbf{b}-x\mathbf{r}}$ is the dipole operator, and $\Psi_2(x, \mathbf{r})$ is a two-body photon-meson wavefunction overlap (PMWO). The explicit expression of $\Psi_2(x, \mathbf{r})$ can be found in Refs. [25,

[26], here, we limit to recall that it contains the two-body vacuum-to-meson matrix elements

$$\phi_{\Gamma^\lambda} = \int \frac{dr^-}{2\pi} e^{ix\mathbf{p}_M \cdot \mathbf{r} - ixp_M^+ r^-} \langle M(p_M) | \bar{\psi}(r) \Gamma^\lambda \psi(0) | 0 \rangle_{r^+=0}, \quad (6)$$

where $\Gamma^\lambda = \{\gamma^+, \gamma^+ \gamma^5\}$. The most general expression of $\Psi_2(x, \mathbf{r})$ contains an infinite kinematic twist, via the off-light-cone matrix elements in Eq. (6). In order to express the final result in terms of collinear twist-3 DAs, one has to perform the non-local operator product expansion (OPE) [27] in powers of the deviation from the light-cone $r^2 = r_\perp^2 = 0$. In the case of light vector-meson DAs, this program was achieved up to the twist-4 in Ref. [28]. Paying attention to some formal subtleties¹, the pioneering formalism of Ref. [28] can be used to achieve the twist-expansion of (6) to finally get

$$\begin{aligned} [\Psi_2(x, \mathbf{r})]_{\text{twist-3}} &= e_q m_M f_M \delta \left(1 - \frac{p_M^+}{q^+} \right) \left(\varepsilon_{q\mu} - \frac{\varepsilon_q^+}{q^+} q_\mu \right) \left(\varepsilon_{M\alpha}^* - \frac{\varepsilon_M^{*+}}{p_M^+} p_{M\alpha} \right) \\ &\times \left[-ir_\perp^\alpha \left(h(x) - \tilde{h}(x) \right) \left(2x\bar{x}q^\mu + (x - \bar{x}) \frac{-i\partial}{\partial r_{\perp\mu}} \right) \right. \\ &\left. + \epsilon^{\mu\nu+-} \epsilon^{+\alpha-\delta} r_{\perp\delta} \left(\frac{g_\perp^{(a)}(x) - \tilde{g}_\perp^{(a)}(x)}{4} \right) \frac{\partial}{\partial r_\perp^\nu} \right] K_0 \left(\sqrt{x\bar{x}Q^2 \mathbf{r}^2} \right), \end{aligned} \quad (7)$$

where m_M is the meson mass, e_q the quark electric charge, ε_q (ε_M^*) is the polarization vector of the photon (meson), and f_M is the standard vector decay constant [28]. Moreover, $h(x)$ and $g_\perp^{(a)}(x)$ are the kinematic twist-3 DAs, while

$$\begin{aligned} \tilde{h}(x) &= \frac{f_{3M}^V}{f_M} \int_0^x dx_q \int_0^{1-x} dx_{\bar{q}} \frac{V(x_q, x_{\bar{q}})}{(1 - x_q - x_{\bar{q}})^2}, \\ \tilde{g}_\perp^{(a)}(x) &= 4 \frac{f_{3M}^A}{f_M} \int_0^x dx_q \int_0^{1-x} dx_{\bar{q}} \frac{A(x_q, x_{\bar{q}})}{(1 - x_q - x_{\bar{q}} + i\epsilon)^2} \end{aligned} \quad (8)$$

are gauge-link related terms, where $V(x_1, x_2)$ ($A(x_1, x_2)$) is the genuine vector (axial) twist-3 DA. f_M^V and f_M^A are the vector and axial normalization constants [28].

¹ In Ref. [28], the parametrization of the vacuum-to-meson matrix elements is obtained for the correlator expressed in the most general gauge-invariant form.

The genuine twist contribution requires calculating the $\gamma^{(*)}P \rightarrow MP$ amplitude, in which the meson is produced starting from a quark-antiquark-gluon system. In this case, the factorization formula is

$$\begin{aligned} \mathcal{A}_3 = & \left(\prod_{i=1}^3 \int dx_i \int d^2 \mathbf{z}_i e^{i x_i \mathbf{q} \mathbf{z}_i \theta(x_i)} \right) \delta \left(1 - \sum_i x_i \right) \Psi_3(\{x_i\}, \{\mathbf{z}_i\}) \\ & \times \left\langle P(p') \left| \mathcal{U}_{\mathbf{z}_1 \mathbf{z}_3} \mathcal{U}_{\mathbf{z}_3 \mathbf{z}_2} - \mathcal{U}_{\mathbf{z}_1 \mathbf{z}_3} - \mathcal{U}_{\mathbf{z}_3 \mathbf{z}_2} + \frac{\mathcal{U}_{\mathbf{z}_1 \mathbf{z}_2}}{N_c^2} \right| P(p) \right\rangle, \end{aligned} \quad (9)$$

where $\mathcal{U}_{\mathbf{z}_1 \mathbf{z}_3} \mathcal{U}_{\mathbf{z}_3 \mathbf{z}_2}$ is the double-dipole operator, $\Psi_3(\{x_i\}, \{\mathbf{z}_i\})$ is a three-body PMWO, and $\{a_i\} = \{a_1, a_2, a_3\}$. Again, the expression of $\Psi_3(\{x_i\}, \{\mathbf{z}_i\})$ can be found in Refs. [25, 26] and it depends on the three-body vacuum-to-meson matrix elements, *i.e.*

$$\begin{aligned} \chi_{\Gamma^\lambda, \sigma} = & \int_{-\infty}^{\infty} \frac{dz_1^-}{2\pi} \frac{dz_2^-}{2\pi} \frac{dz_3^-}{2\pi} e^{-i x_1 q^+ z_1^- - i x_2 q^+ z_2^- - i x_3 q^+ z_3^-} \\ & \times \left\langle M(p_M) \left| \bar{\psi}(z_1) g \Gamma^\lambda F_{-\sigma}(z_3) \psi(z_2) \right| 0 \right\rangle_{z_{1,2,3}^+ = 0}. \end{aligned} \quad (10)$$

Performing the twist-3 expansion of $\Psi_3(\{x_i\}, \{\mathbf{z}_i\})$ is rather straightforward since, within this accuracy, the correlators (10) coincide with those in [28]. We do not report the explicit expression for compactness. It can be found in Refs. [25, 26] and is a function of the genuine twist-3 DAs $A(x_1, x_2)$ and $V(x_1, x_2)$, introduced previously.

4. Summary and conclusion

We introduced a general framework to deal with beyond-leading-power corrections at small x and applied it to the transversely polarized light vector-meson production, $\gamma^{(*)}P \rightarrow M(\rho, \phi, \omega)P$, which starts at the next-to-leading power and for which a purely collinear treatment leads to endpoint singularities. Existing and future measurements of the whole spin density matrix require to go beyond leading twist, since some of these matrix elements simply vanish at leading twist.

This project has received funding from the European Union’s Horizon 2020 research and innovation program under grant agreement STRONG-2020 (WP 13 “NA-Small- x ”). The work by M.F. is supported by Agence Nationale de la Recherche under the contract ANR-17-CE31-0019. M.F. acknowledges support from the Italian Foundation “Angelo Della Riccia”. The work of

L.S. is supported by grantNo. 2019/33/B/ST2/02588 of the National Science Center (NCN), Poland. L.S. thanks the P2IO Laboratory of Excellence (Programme Investissements d’Avenir ANR-10-LABEX-0038) and the P2I — Graduate School of Physics of Paris-Saclay University for support. This work was also partly supported by the French CNRS via the GDR QCD.

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