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Exclusive photoproduction of open heavy flavor meson pairs

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In this proceeding we argue that exclusive photoproduction of D-meson pairs might be used as a complementary tool for studies of the generalized parton distributions of the target. We analyzed the photoproduction of the pseudoscalar-vector pairs with net zero electric charge (*e.g.* $D^{\pm}D^{*\mp}$, $D^0\overline{D}^{*0}$, $D_s^+D_s^{*-}$) and found that it allows to study the chiral even GPDs in ERBL region. A unique feature of the suggested process is contribution of the gluon and just one of the light quark flavours. We made numerical estimates in the kinematics of the future Electron Ion Collider and found that numerically the production cross-section is reasonably large for experimental studies, thus justifying its viability as a complementary probe of GPDs.

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1. Introduction

The Generalized Parton Distributions (GPDs) nowadays are one of the widely used nonperturbative objects which describe the structure of the hadronic target [1–4], and for this reason got into focus of various theoretical and experimental studies. Due to the nonperturbative nature of GPDs, it is impossible to find them directly from the first principles. Our current knowledge of these objects relies on lattice simulations [5–7], theoretical models based on additional assumptions (and thus requiring experimental confirmation), or outright phenomenological extractions from experimental data. The expected high-luminosity experiments at the future Electron Ion Collider motivated studies of various new channels which could provide better constraints on GPDs. For phenomenological studies of GPDs a special interest present the exclusive $2 \to 3$ processes [8–18]. The factorization theorem for amplitudes of such processes has been proven in the kinematics when all the produced hadrons are well-separated kinematically [19, 20]. Almost all these studies focused on the production of light hadrons or photons by highly virtual photons. In this proceeding we argue that it is possible to study the GPDs using the photoproduction of heavier D-meson pairs. Previously, the possibility to use D-mesons for studies of GPDs was discussed in [21–24], and the production of light meson pairs with large invariant was analyzed e.g. in [25, 26]. The production of heavy meson pairs differs substantially from analogous producion of light mesons pairs, since the heavy quark mass breaks the conventional suppression based on twist counting, and thus eventually leads to new (independent) probes of the GPDs. In our study we consider production of D^+D^{*-}, $D^0\overline{D}^{*0}$ and $D_s^+D_s^{*-}$ meson pairs, whose cross-section is controlled by the chiral-even GPDs. The choice of these final states allows to avoid contaminations by the poorly known chiral odd transversity GPDs [16, 17] or photon-photon fusion mechanism suggested in [27].

This proceeding is structured as follows. In the next Section 2 we define the kinematics and briefly introduce the framework used for evaluations of the cross-section of the process. In essence, we use for our analysis the conventional collinear factorization framework, treating the heavy quark mass as a hard scale (more details may be found in [30, 31]). In Section 3 we estimate numerically the cross-section using publicly available parametrizations of the proton GPDs and D-meson distribution amplitudes in the kinematics of electron-proton collisions at the forthcoming Electron Ion Collider (EIC) [28, 29].

2. Exclusive photoproduction of meson pairs

We will perform our evaluations in the photon-proton collision frame, in which the light-cone decomposition of the photon momentum q and proton momentum p has a form

$$q = \left(-\frac{Q^2}{2q^-},\, q^-,\, \mathbf{0}_\perp\right), \quad P = \left(P^+,\, \frac{m_N^2}{2P^+},\, \mathbf{0}_\perp\right), \quad q^- = E_\gamma + \sqrt{E_\gamma^2 + Q^2}, \quad P^+ = E_p + \sqrt{E_p^2 - m_N^2} \tag{1}$$

where $Q^2 = -q^2$ is the virtuality of the photon, and E_γ, E_p are energies of the photon and proton before collision. The 4-momenta p_1, p_2 of the final-state heavy D-mesons in this frame have a light-cone decomposition

$$p_a = \left(\frac{M_a^\perp}{2}\, e^{-y_a}\,,\; M_a^\perp e^{y_a},\; \boldsymbol{p}_a^\perp\right), \quad M_a^\perp \equiv \sqrt{M_a^2 + (\boldsymbol{p}_a^\perp)^2}, \quad a = 1, 2, \tag{2}$$

where y_a are the rapidities of produced mesons, and $\boldsymbol{p}_a^\perp$ are their transverse momenta. Since the production cross-section decreases rapidly as a function of transverse momenta, in what follows we'll focus on the kinematics of small momenta $p_a^\perp$. If we assume that the invariant energy W of the photon-proton collision is fixed, then the onshellness condition for the 4-momentum of the recoil proton $P' = P + \Delta$ translates into complicated constraints on possible transverse momenta and rapidities of produced D-mesons. For this reason, instead of conventional fixing of the invariant energy W in electroproduction experiments it is easier to work with D-meson momenta as unconstrained independent variables and fix energy of photon from 4-momentum conservation. In this approach it is possible to rewrite all kinematical variables in terms of rapidities and transverse momenta of D-mesons. For example, the photon energy in this kinematics might be approximated as $q^- \approx M_1^\perp e^{y_1} + M_2^\perp e^{y_2}$, and the photoproduction cross-section is given by

$$d\bar{\sigma}_{\gamma p \to M_1 M_2 p} = \frac{dy_1 dp_{1\perp}^2 dy_2 dp_{2\perp}^2 d\phi \left|\mathcal{A}_{\gamma p \to M_1 M_2 p}\right|^2}{4\,(2\pi)^4\, W_0^2 \sqrt{\left(W_0^2 + Q^2 - m_N^2\right)^2 + 4Q^2 m_N^2}}, \tag{3}$$

In what follows we will assume that all the final state hadrons are kinematically well-separated from each other. In this setup it is possible to factorize the amplitude $\mathcal{A}_{\gamma p \to M_1 M_2 p}$ and express it as convolution of nonperturbative distributions of final-state hadrons (target GPDs, distribution amplitudes of the D-mesons) with perturbative partonic-level amplitudes, namely

$$\sum_{\text{spins}} \left|\mathcal{A}_{\gamma p \to M_1 M_2 p}^{(\mathfrak{a})}\right|^2 = \frac{1}{(2 - x_B)^2} \left[4\,(1 - x_B)\left(\mathcal{H}_{\mathfrak{a}}\mathcal{H}_{\mathfrak{a}}^* + \tilde{\mathcal{H}}_{\mathfrak{a}}\tilde{\mathcal{H}}_{\mathfrak{a}}^*\right) - x_B^2\left(\mathcal{H}_{\mathfrak{a}}\mathcal{E}_{\mathfrak{a}}^* + \mathcal{E}_{\mathfrak{a}}\mathcal{H}_{\mathfrak{a}}^* + \tilde{\mathcal{H}}_{\mathfrak{a}}\tilde{\mathcal{E}}_{\mathfrak{a}}^* + \tilde{\mathcal{E}}_{\mathfrak{a}}\tilde{\mathcal{H}}_{\mathfrak{a}}^*\right)\right.$$
$$\left. - \left(x_B^2 + (2 - x_B)^2\,\frac{t}{4m_N^2}\right)\mathcal{E}_{\mathfrak{a}}\mathcal{E}_{\mathfrak{a}}^* - x_B^2\,\frac{t}{4m_N^2}\,\tilde{\mathcal{E}}_{\mathfrak{a}}\tilde{\mathcal{E}}_{\mathfrak{a}}^*\right], \qquad \mathfrak{a} = L, T \tag{4}$$

where the subscript index $\mathfrak{a}$ differentiates the longitudinal and transverse polarization of the incident photon, and, motivated by the earlier analyses of DVCS and DVMP [32, 33], we defined the double meson form factors as

$$\left.\begin{array}{c}\mathcal{H}_{\mathfrak{a}}\,(\xi,\,\Delta y,t)\\ \mathcal{E}_{\mathfrak{a}}\,(\xi,\,\Delta y,t)\end{array}\right\} = \sum_{\kappa=q,g}\int_{-1}^{1} dx \prod_{n=1}^{2}\left(\int_0^1 dz_n \varphi_{D_n}\,(z_n)\right) C_{\mathfrak{a}}^{(\kappa)}\,(x,\,\xi,\,\Delta y, z_1,\, z_2)\left\{\begin{array}{c}H_\kappa\,(x,\xi,t)\\ E_\kappa\,(x,\xi,t)\end{array}\right., \tag{5}$$

$$\left.\begin{array}{c}\tilde{\mathcal{H}}_{\mathfrak{a}}\,(\xi,\,\Delta y,t)\\ \tilde{\mathcal{E}}_{\mathfrak{a}}\,(\xi,\,\Delta y,t)\end{array}\right\} = \sum_{\kappa=q,g}\int_{-1}^{1} dx \prod_{n=1}^{2}\left(\int_0^1 dz_n \varphi_{D_n}\,(z_n)\right) \tilde{C}_{\mathfrak{a}}^{(\kappa)}\,(x,\,\xi,\,\Delta y,t) \times \left\{\begin{array}{c}\tilde{H}_\kappa\,(x,\xi,t)\\ \tilde{E}_\kappa\,(x,\xi,t)\end{array}\right.. \tag{6}$$

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The dummy integration variables $z_1,\ z_2$ correspond to the light-cone fractions of the total momentum carried by c-quarks in D-mesons. Since we consider that the final-state D-mesons are well-separated from each other, the Fock state of the 2-meson system is a direct product of Fock states of individual D-mesons. In the heavy quark mass limit the Fock state of each D-meson is dominated by the 2-quark component described by D-meson distribution amplitudes $\varphi_D\left(z\right)$ [34]. The partonic amplitudes $C_{\mathfrak{a}}^{(\kappa)},\ \tilde{C}_{\mathfrak{a}}^{(\kappa)}$ can be evaluated perturbatively, taking into account all the quark and gluon diagrams which might contribute to the final state. Due to space limitations here we omit explicit expressions for $C_{\mathfrak{a}}^{(\kappa)},\ \tilde{C}_{\mathfrak{a}}^{(\kappa)}$; the reader may find them in [30]. We may see that in (5,6) the GPDs contribute convoluted with effective (integrated) coefficient function

$$C_{\rm int}^{(\kappa)}\left(x,\,\xi,\,\Delta y\right)\equiv\int_0^1 dz_1\int_0^1 dz_2\ \varphi_{D_1}\left(z_1\right)\varphi_{D_2}\left(z_2\right)C_T^{(\kappa)}\left(x,\,\xi,\,\Delta y,\,z_1,\,z_2\right). \tag{7}$$

Due to convolution with relatively broad D-meson distribution amplitudes in (7), the functions $C_{\rm int}^{(\kappa)}$ do not have any singularities and are strongly concentrated in the region $|x|\le\xi$ (the so-called ERBL region), which implies that the cross-section of the process is mostly sensitive to the behavior of GPDs in that domain.

3. Numerical results

For definiteness, we will use for our estimates the Kroll-Goloskokov parametrization of the GPDs [35, 36], fixing the factorization scale as $\mu_F=\mu_R=4\,\text{GeV}\approx 2M_D$. Due to space limitations here we will consider only the production of $D_0\,\overline{D_0}$ meson pairs (an interested reader may find predictions for other mesons in [30]). In general, the cross-sections for all meson pairs have qualitatively the same dependence on kinematic variables, though the absolute values can differ by up to an order of magnitude. The Q^2-dependence of the photoproduction cross-section is controlled by a relatively large invariant mass of the produced pair (M_1+M_2), and in the photoproduction region which analyzed here this dependence is very weak.

The Figure (1) illustrates the dependence of the cross-section (3) on the invariant momentum transfer t , and the associated distributions of the D-meson pairs on transverse momenta and azimuthal angle between them in the photon-proton frame. Since in the collinear factorization framework the transverse momenta are disregarded in the coefficient function, the t-dependence originates entirely from the implemented GPDs. The phenomenological studies show that this dependence should be exponentially suppressed as a function of $|t|$, which implies that in the photon-proton frame the D-meson pairs are produced predominantly in the back-to-back kinematics, with minimal momentum transfer t to the target.

The cross-section grows mildly as a function of average rapidity $Y=(y_1+y_2)/2$ of the produced quarkonia, yet decreases rapidly as a function of rapidity difference $\Delta y=|y_1-y_2|$. This behavior might be understood if we recall that the increase of Y at fixed Δy increases the invariant energy W^2, decreases x_B, ξ and thus leads to growth of the partonic GPDs. On the other hand, the increase of rapidity difference Δy at fixed Y, due to onshellness constraints for recoil proton, leads to increase of the momentum transfer $|t|$ and corresponding suppression of the partonic GPDs (detailed plots for rapidity dependence of different mesons may be found in [30]).

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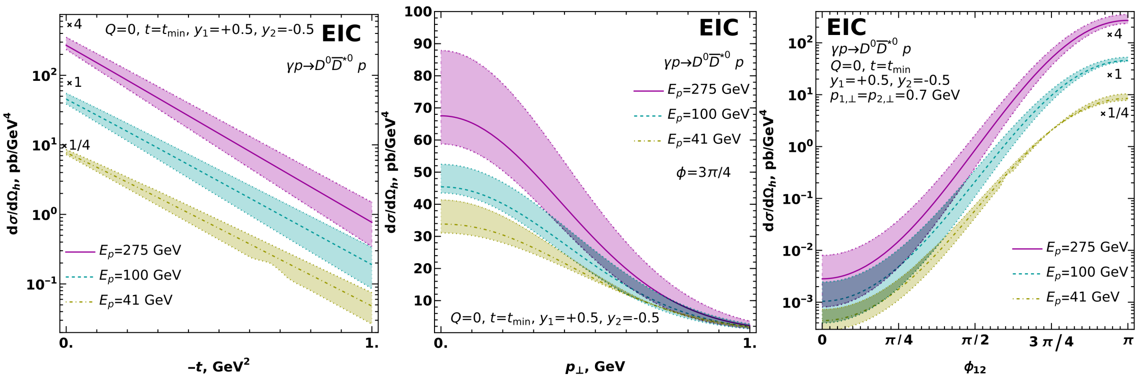

Figure 1: The dependence of the production cross-sections on the invariant momentum transfer t (left), on transverse momentum p_T (central), and on the azimuthal angle ϕ_{12} (right). The width of the colored band in each plot illustrates the uncertainty due to choice of the factorization scale $\mu_F \in (0.5, 2) \times 2m_D$. For the sake of legibility in the left and right plots we multiplied the cross-sections for $E_p = 275$ GeV and $E_p = 41$ GeV by numerical factors $\times 4$ and $\times 1/4$ respectively.

To summarize, we believe that the exclusive photoproduction of the pseudoscalar-vector D-meson pairs (D^+D^{*-}, $D^0\bar{D}^{*0}$ and $D_s^+D_s^{*-}$) can be used as complementary probe of chiral-even GPDs of gluon and one of the light quark flavors in the so-called ERBL region $|x| < \xi$. Numerically, the cross-sections of the proposed channels are comparable to the cross-sections of other $2 \to 3$ processes suggested in the literature [8–17].

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