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B. Pire · K. Semenov-Tian-Shansky · L. Szymanowski

Baryon-to-Meson Transition Distribution Amplitudes: Formalism and Models

Abstract In specific kinematics, hard exclusive amplitudes may be factorized into a short distance dominated part computable in a perturbative way on the one hand, and universal, confinement related hadronic matrix elements on the other hand. The extension of this description to processes such as backward meson electroproduction and forward meson production in antiproton-nucleon scattering leads to define new hadronic matrix elements of three quark operators on the light cone, the nucleon-to-meson transition distribution amplitudes, which shed a new light on the nucleon structure.

1 Introduction

Accessing transition distribution amplitudes (TDAs) in specific exclusive reactions is an important goal to progress in our understanding of quark and gluon confinement. The baryon-to-meson TDAs are defined through baryon-meson matrix elements of the nonlocal three quark (antiquark) operators on the light cone ($n^2 = 0$):

$$\hat{O}_{\rho\tau\chi}^{\alpha\beta\gamma}(\lambda_1 n, \lambda_2 n, \lambda_3 n) = \varepsilon_{c_1 c_2 c_3} \Psi_\rho^{c_1\alpha}(\lambda_1 n) \Psi_\tau^{c_2\beta}(\lambda_2 n) \Psi_\chi^{c_3\gamma}(\lambda_3 n), \qquad (1)$$

where α, β, γ stand for the quark (antiquark) flavor indices and ρ, τ, χ denote the Dirac spinor indices. Antisymmetrization is performed over the color group indices $c_{1,2,3}$. Gauge links in (1) are omitted by adopting the light-like gauge $A \cdot n = 0$. These non-perturbative objects, first studied in [1–3], share common features both with baryon distribution amplitudes (DAs) introduced in [4,5] as baryon-to-vacuum matrix elements of the same operators (1) and with generalized parton distributions (GPDs), since the matrix element in question depends on the longitudinal momentum transfer $\Delta^+ = (p_\mathcal{M} - p_N) \cdot n$ between a baryon and a meson characterized by the skewness variable $\xi = -\frac{(p_\mathcal{M} - p_N) \cdot n}{(p_\mathcal{M} + p_N) \cdot n}$ and by a transverse momentum transfer $\boldsymbol{\Delta}_T$.

For the QCD evolution equations obeyed by baryon-to-meson TDAs one distinguishes the Efremov–Radyushkin–Brodsky–Lepage (ERBL)-like domain in which all three momentum fractions of quarks are

B. Pire
Centre de Physique Théorique, École Polytechnique, CNRS, Université Paris-Saclay, 91128 Palaiseau, France
E-mail: bernard.pire@polytechnique.edu

K. Semenov-Tian-Shansky
Petersburg Nuclear Physics Institute, 188300 Gatchina, Russia
E-mail: kirill.semenov@polytechnique.edu

L. Szymanowski (✉)
National Centre for Nuclear Research (NCBJ), 00-681 Warsaw, Poland
E-mail: Lech.Szymanowski@ncbj.gov.pl
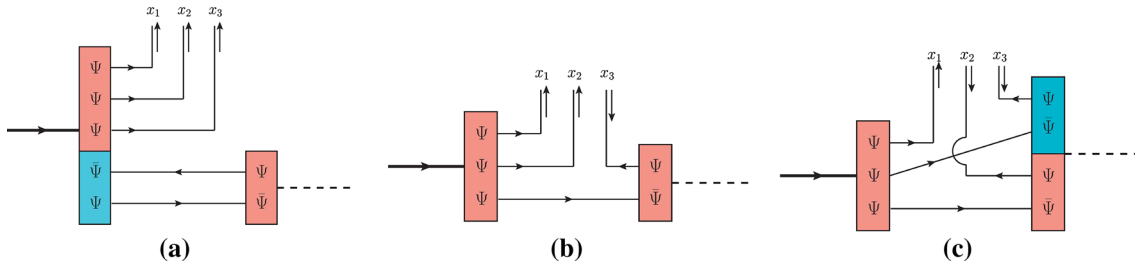
Fig. 1 Interpretation of baryon-to-meson TDAs at low normalization scale. *Small vertical arrows* show the flow of the momentum. **a** Contribution in the ERBL region (all x_i are positive). **b** Contribution in the DGLAP I region (one of x_i is negative). **c** Contribution in the DGLAP II region (two x_i are negative)

positive and two kinds of Dokshitzer–Gribov–Lipatov–Altarelli–Parisi (DGLAP)-like regions in which either one or two momentum fractions of quarks are negative.

The physical picture encoded in baryon-to-meson TDAs is conceptually close to that contained in baryon GPDs and baryon DAs. Baryon-to-meson TDAs characterize partonic correlations inside a baryon and give access to the momentum distribution of the baryonic number inside a baryon. The same operator also defines the nucleon DA, which can be seen as a limiting case of baryon-to-meson TDAs with the meson state replaced by the vacuum. In the language of the Fock state decomposition, baryon-to-meson TDAs are not restricted to the lowest Fock state as DAs. They rather probe the non-minimal Fock components with additional quark-antiquark pair:

$$|\text{Nucleon}\rangle = |\Psi\Psi\Psi\rangle + |\Psi\Psi\Psi; \bar{\Psi}\Psi\rangle + \cdots ; \quad |\text{Meson}\rangle = |\bar{\Psi}\Psi\rangle + |\bar{\Psi}\Psi; \bar{\Psi}\Psi\rangle + \cdots \quad (2)$$

depending on the particular support region in question (see Fig. 1). Note that this interpretation can be justified only at a very low normalization scale and can be significantly altered at higher scales due to the evolution effects.

Similarly to GPDs, by Fourier transforming baryon-to-meson TDAs to the impact parameter space ($\boldsymbol{\Delta}_T \rightarrow \mathbf{b}_T$), one obtains additional insight on the baryon structure in the transverse plane. This allows one to perform the femto-photography of hadrons [6] from a new perspective.

2 Parametrization and Phenomenological Models for Baryon-to-Meson TDAs

Although baryon-to-meson TDAs can be introduced for all types of baryons and mesons, we start our consideration from the simplest case of nucleon-to-pion (πN) TDAs. For a given flavor contents (e.g. *uud* proton-to-π^0 TDA) the parametrization of the leading twist-3 πN TDA involves 8 invariant functions, each depending on the 3 longitudinal momentum fractions x_i, the skewness parameter ξ, momentum transfer squared Δ^2 as well as on the factorization scale μ^2:

$$4(p \cdot n)^3 \int \left[\prod_{j=1}^{3} \frac{d\lambda_j}{2\pi} \right] e^{i \sum_{k=1}^{3} x_k \lambda_k (p \cdot n)} \langle \pi^0(p_\pi)| \varepsilon_{c_1 c_2 c_3} u_\rho^{c_1}(\lambda_1 n) u_\tau^{c_2}(\lambda_2 n) d_\chi^{c_3}(\lambda_3 n) |N^p(p_N, s_N)\rangle$$

$$= \delta(x_1 + x_2 + x_3 - 2\xi) i \frac{f_N}{f_\pi} \Big[V_1^{(p\pi^0)}(x_{1,2,3}, \xi, \Delta^2)(\hat{p}C)_{\rho\tau}(U^+)_\chi$$

$$+ A_1^{(p\pi^0)}(x_{1,2,3}, \xi, \Delta^2)(\hat{p}\gamma^5 C)_{\rho\tau}(\gamma^5 U^+)_\chi + T_1^{(p\pi^0)}(x_{1,2,3}, \xi, \Delta^2)(\sigma_{p\mu}C)_{\rho\tau}(\gamma^\mu U^+)_\chi$$

$$+ m_N^{-1} V_2^{(p\pi^0)}(x_{1,2,3}, \xi, \Delta^2)(\hat{p}C)_{\rho\tau}(\hat{\Delta}_T U^+)_\chi + m_N^{-1} A_2^{(p\pi^0)}(x_{1,2,3}, \xi, \Delta^2)(\hat{p}\gamma^5 C)_{\rho\tau}(\gamma^5 \hat{\Delta}_T U^+)_\chi$$

$$+ m_N^{-1} T_2^{(p\pi^0)}(x_{1,2,3}, \xi, \Delta^2)(\sigma_{p\Delta_T}C)_{\rho\tau}(U^+)_\chi + m_N^{-1} T_3^{(p\pi^0)}(x_{1,2,3}, \xi, \Delta^2)(\sigma_{p\mu}C)_{\rho\tau}(\sigma^{\mu\Delta_T} U^+)_\chi$$

$$+ m_N^{-2} T_4^{(p\pi^0)}(x_{1,2,3}, \xi, \Delta^2)(\sigma_{p\Delta_T}C)_{\rho\tau}(\hat{\Delta}_T U^+)_\chi \Big]. \quad (3)$$

Here $f_\pi = 93$ MeV is the pion weak decay constant and f_N determines the value of the nucleon wave function at the origin. Throughout this paper we adopt Dirac's "hat" notation $\hat{v} \equiv v_\mu \gamma^\mu$; $\sigma^{\mu\nu} = \frac{1}{2}[\gamma^\mu, \gamma^\nu]$;

$\sigma^{\nu\mu} \equiv v_\lambda \sigma^{\lambda\mu}$; C is the charge conjugation matrix and $U^+ = \hat{p}\hat{n}\, U(p_N, s_N)$ is the large component of the nucleon spinor. The parametrization (3), originally introduced in Ref. [7], is extremely convenient for the phenomenological applications since in the limit $\Delta_T \to 0$ just three invariant amplitudes $V_1^{(p\pi^0)}$, $A_1^{(p\pi^0)}$ and $T_1^{(p\pi^0)}$ do survive. An alternative parametrization which is better suited to address the symmetry properties of πN TDAs was introduced in [8]. In particular, within this latter parametrization πN TDAs turn to satisfy the polynomiality property of the Mellin moments in x_i in its most simple form. The relation between the two parametrizations in presented in the Appendix C of [8].

Working out the physical normalization of baryon-to-meson TDAs and building up consistent phenomenological models for them represents a considerable task. Below we present a short overview of the approaches available at the present moment.

The first attempt to provide a model for πN TDAs relying on chiral dynamics was performed in [7] (see Ref. [8] for the detailed derivation). The soft-pion theorem [9,10] allows to express πN TDAs $V_1^{(p\pi)}$, $A_1^{(p\pi)}$ and $T_1^{(p\pi)}$ in the soft pion limit ($\xi = 1$; $\Delta^2 = m_N^2$) in terms of the 3 leading twist nucleon DAs $\{V^p, A^p, T^p\}(y_1, y_2, y_3) \equiv \{V^p, A^p, T^p\}(y_i)$. This results in a simple model for πN TDAs summarized in the Erratum to [7][1]:

$$\{V_1^{(p\pi^0)},\, A_1^{(p\pi^0)}\}(x_i, \xi) = -\frac{1}{2} \times \frac{1}{4\xi}\{V^p,\, A^p\}\left(\frac{x_i}{2\xi}\right); \quad T_1^{(p\pi^0)}(x_i, \xi) = -\frac{1}{2} \times \frac{3}{4\xi} T^p\left(\frac{x_i}{2\xi}\right); \quad (4)$$

Despite its obvious drawbacks (like the very narrow validity range limited to the close vicinity of the threshold and lack of an intrinsic Δ^2-dependence) this simple model for the first time provided a quantitative estimate of the physical normalization for πN TDAs. In particular, the predictions of the revised soft-pion-limit model (4) were recently employed in the first feasibility studies [11] for accessing πN TDAs with $\bar{\text{P}}$ANDA through $\bar{p}p \to \gamma^*\pi^0$.

Another simple model for πN TDAs suggested in Ref. [8] accounts for the contribution of the cross-channel nucleon exchange. As one can see from Fig. 2, this model is conceptually similar to the pion exchange model for the polarized nucleon GPD $\tilde{E}$ suggested in Ref. [12]. With the use of the πN TDA parametrization (3) the nucleon pole model reads:

$$\left\{V_1,\, A_1,\, T_1\right\}^{(p\pi^0)}(x_i, \xi, \Delta^2)\Big|_{N(940)} = \Theta_{\text{ERBL}}(x_k) \times \frac{g_{\pi NN}\, m_N f_\pi}{\Delta^2 - m_N^2} \frac{1}{(2\xi)} \frac{1-\xi}{1+\xi}\{V^p,\, A^p,\, T^p\}\left(\frac{x_i}{2\xi}\right);$$

$$\left\{V_2,\, A_2,\, T_2,\, T_3\right\}^{(p\pi^0)}(x_i, \xi, \Delta^2)\Big|_{N(940)} = \Theta_{\text{ERBL}}(x_k) \times \frac{g_{\pi NN}\, m_N f_\pi}{\Delta^2 - m_N^2} \frac{1}{(2\xi)}\{V^p,\, A^p,\, T^p,\, T^p\}\left(\frac{x_i}{2\xi}\right);$$

$$T_4^{(p\pi^0)}(x_i, \xi, \Delta^2)\Big|_{N(940)} = 0;$$

$$\left\{V_{1,2},\, A_{1,2},\, T_{1,2,3,4}\right\}^{(p\pi^+)}(x_i, \xi, \Delta^2)\Big|_{N(940)} = -\sqrt{2}\left\{V_{1,2},\, A_{1,2},\, T_{1,2,3,4}\right\}^{(p\pi^0)}(x_i, \xi, \Delta^2)\Big|_{N(940)}. \quad (5)$$

Here $\Theta_{\text{ERBL}}(x_k) \equiv \prod_{k=1}^{3} \theta(0 \le x_k \le 2\xi)$ ensures the pure ERBL-like support of TDAs and $g_{\pi NN} \approx 13$ is the pion-nucleon phenomenological coupling. This turns to be a consistent model for πN TDAs in the ERBL-like region and satisfies the polynomiality conditions and the appropriate symmetry relations.

By an obvious change of couplings the model (5) can be generalized to the case of other light mesons (η, η', K, ... etc.). Also it is not necessarily limited to the contribution of the cross-channel nucleon exchange. In Ref. [8] the contribution of the cross-channel $\Delta(1232)$ into πN TDAs was worked out explicitly. Finally, very recently in Ref. [13] the cross-channel nucleon exchange model was generalized for the case of nucleon-to-vector meson TDAs.

Still the aforementioned baryon-to-meson TDA model describes TDAs only within the ERBL-like support region. To get a model defined on the complete support domain one may rely on the spectral representation

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[1] Note the relative signs and the overall factor $\frac{1}{2}$ missed in the Erratum to [7].
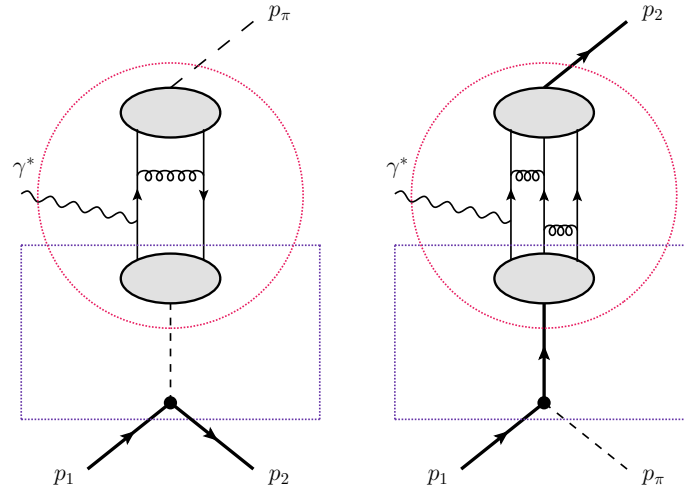
Fig. 2 *Left* Pion pole exchange model for the polarised GPD $\tilde{E}$; *lower* and *upper* blobs depict pion DAs; the *dashed circle* contains a typical LO graph for the pion electromagnetic form factor in perturbative QCD; the *rectangle* contains the pion pole contribution into GPD. *Right* Nucleon pole exchange model for πN TDAs; *dashed circle* contains a typical LO graph for the nucleon electromagnetic form factor in perturbative QCD; the *rectangle* contains the nucleon pole contribution into πN TDAs

for baryon-to-meson TDAs in terms of quadruple distributions suggested in Ref. [14]:

$$
\begin{aligned}
H^{(\mathcal{M}N)}&(x_1, \, x_2, \, x_3 = 2\xi - x_1 - x_2, \, \xi, \, t) \\
&= \left[\prod_{i=1}^{3} \int_{\Omega_i} \mathrm{d}\beta_i \mathrm{d}\alpha_i \right] \delta(x_1 - \xi - \beta_1 - \alpha_1 \xi) \, \delta(x_2 - \xi - \beta_2 - \alpha_2 \xi) \, \delta(\sum_i \beta_i) \delta(\sum_i \alpha_i + 1) f(\beta_i, \, \alpha_i, \, t),
\end{aligned}
$$
(6)

where Ω_i denote three copies of the usual domain in the spectral parameter space. The spectral density f is an arbitrary function of six variables, which are subject to two constraints and therefore effectively is a quadruple distribution.

Similarly to the familiar double distribution representation for GPDs the quadruple distribution representation (6) for TDAs turns to be the most general way to implement the support properties of TDAs as well as the polynomiality property for the x_i-Mellin moments, which is a direct consequence of Lorentz invariance (see Ref. [15]).
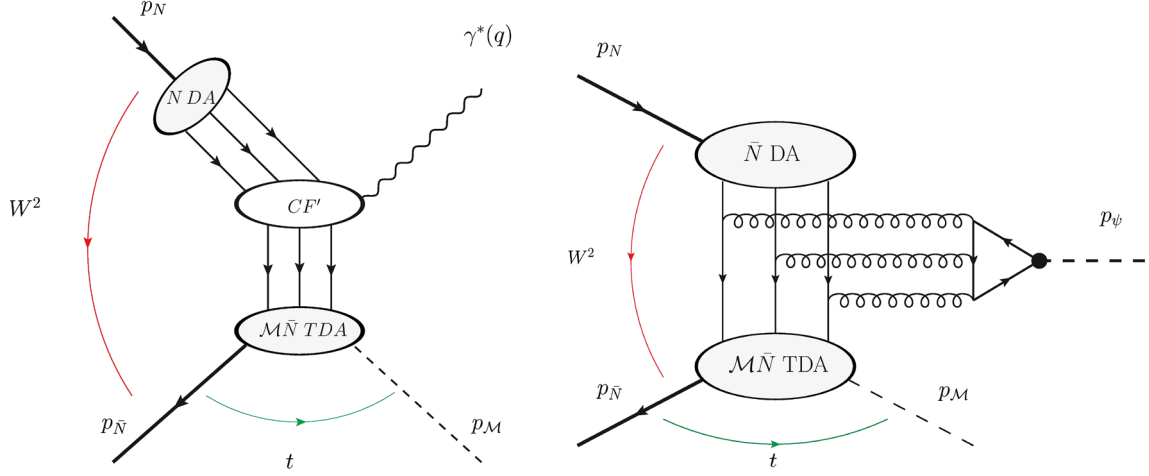
Contrarily to GPDs, TDAs do not possess the comprehensive forward limit $\xi \to 0$. This complicates the construction of a phenomenological Ansatz for quadruple distributions. However, a partial solution was proposed for the case of πN TDAs. In this case one can rely on the complementary $\xi \to 1$ limit, in which, as already discussed above, πN TDAs $V_1^{\pi N}$, $A_1^{\pi N}$, $T_1^{\pi N}$ are constrained by chiral dynamics (see Eq. (4) for $\xi = 1$). In Ref. [15] we proposed a factorized Ansatz designed as a universal profile function multiplying the nucleon DA combination to which the πN TDA in question reduces in the $\xi = 1$ limit.

In loose words our Ansatz for quadruple distributions is based on "skewing" the $\xi = 1$ limit. At this point we are similar to the famous Radyushkin factorized Ansatz for double distributions [16]. In that case rather the $\xi = 0$ limit, where GPDs reduce to usual parton densities, is "skewed" to provide a non trivial ξ-dependence for GPDs. For practical details we refer the reader to Ref. [15].

Also similarly to the GPD case, in order to satisfy the polynomiality condition in its complete form, the spectral part (6) is to be complemented by a D-term-like contribution defined solely in the ERBL-like region and responsible for the highest possible power of ξ occurring for a given x_i-Mellin moment. The simplest possible model for such a D-term is the contribution of the nucleon exchange into πN TDAs (5). Note that we avoid double counting since the nucleon exchange contribution into πN TDAs $V_1^{(\pi N)}$, $A_1^{(\pi N)}$, $T_1^{(\pi N)}$ dies out in the $\xi \to 1$ limit.

In this way we come to the so-called "two component" model for πN TDAs [15] which contains a spectral part fixed from the $\xi \to 1$ limit and a D-term-like contribution coming from the cross-channel nucleon

Fig. 3 *Left* Collinear factorization of $\gamma^* N \to N \mathcal{M}$ in the near-backward kinematics regime. $\mathcal{M}N$ TDA stands for the nucleon-to-meson TDA; N DA stands for the nucleon DA; CF denotes hard subprocess amplitudes (coefficient functions). *Right* Unpolarized cross section $\frac{\mathrm{d}^2\sigma_T}{\mathrm{d}\Omega_\pi}$ (in nb/sr) for strictly backward $\gamma^* p \to \pi^+ n$ as a function of Q^2 for $x_B = 0.35$ with various input phenomenological nucleon DA solutions: COZ (*long blue dashes*); KS (*solid green line*); BLW NLO (*medium orange dashes*) and NNLO modification [21] of BLW (*short brown dashes*) (color figure online)

exchange. This model provides a lively x_i and ξ dependence for πN TDAs. However, integrating a flexible but reasonable $t-$dependence still remains an open question.

Reference [15] contains the first attempts of phenomenological application of the "two component" πN TDA model for the description of backward pion electroproduction off nucleons for the typical JLab kinematical conditions. πN TDAs within this model do not nullify at the cross-over trajectories separating the ERBL-like and DGLAP-like TDA support regions. This results in the non-zero contribution into the imaginary part of the relevant elementary amplitude. The observable quantity sensitive to this issue is the transverse target single spin asymmetry (STSA) [17]. The "two component" πN TDA model predicts a sizeable value of STSA for x_B typical for JLab@12 GeV conditions.

3 Phenomenology

3.1 Baryon-to-Meson TDAs from Backward Meson Electroproduction at JLab

Within the generalized Bjorken limit, in which $Q^2 = -q^2$ and $s = (q + p_1)^2 = W^2$ are large, $x_B \equiv \frac{Q^2}{2 p_1 \cdot q}$ is fixed and the u-channel momentum transfer squared is small compared to Q^2 and s ($|u| \equiv |(p_2 - p_1)^2| \ll Q^2$, s) the amplitude of the hard subprocess of the exclusive electroproduction of mesons off nucleons

$$e(k) + N(p_1, s_1) \to \left(\gamma^*(q, \lambda_\gamma) + N(p_1, s_1)\right) + e(k') \to e(k') + N(p_2, s_2) + \mathcal{M}(p_\mathcal{M}), \qquad (7)$$

is supposed to admit a collinear factorized description in terms of nucleon-to-meson TDAs and nucleon DAs, as it is shown on Fig. 3. The small u corresponds to the meson being produced in the near-backward direction in the $\gamma^* N$ center-of-mass system (CMS). This regime, referred as the near-backward kinematics, is complementary to the more conventional near-forward kinematical regime ($Q^2 = -q^2$, $s -$ large, $x_B -$ fixed, $|t| \equiv |(p_2 - p_1)^2| \ll Q^2$, s) in which the factorized description in terms of GPDs and meson DAs applies to hard meson production subprocess.

The details of the formalism for the case of backward electroproduction of light pseudoscalar mesons (π, η) and rough cross section estimates for the kinematics conditions of JLab can be found in Refs. [7,15]. A generalization for the case of vector mesons (ρ, ω, ϕ) was proposed in [13].

As an example of our predictions, on the right panel of Fig. 3 we present out estimates of the backward $\gamma^* p \to \pi^+ n$ cross section within the factorized description involving πN TDAs using the cross channel nucleon exchange model (5). The cross section turns out to very sensitive to the form of the input phenomenological solution for nucleon DA. We show the results for Chernyak–Ogloblin–Zhitnitsky (COZ) [18] (long blue dashes); King–Sachrajda (KS) [19] (solid green line); Braun–Lenz–Wittmann next-to-leading-order

Fig. 4 *Left* Collinear factorization of the annihilation process $N\bar{N} \to \gamma^*(q)\mathcal{M}(p_\mathcal{M})$. (near-forward kinematics). *Right* Collinear factorization of the annihilation process $N + \bar{N} \to J/\psi + \mathcal{M}$ (near-forward kinematics). DA stands for the distribution amplitude of a nucleon; $\mathcal{M}\bar{N}$ TDA stands for the TDA from an antinucleon to a meson. By *thick black dot* we denote the light-cone wave function of heavy quarkonium

(BLW NLO) [20] (medium orange dashes) and NNLO modification [21] of BLW (short brown dashes). The solutions close to the asymptotic form of the nucleon DA $\phi(y_i) = 120 y_1 y_2 y_3$ result in a very small cross section, while those significantly different from the asymptotic form like COZ and KS result in larger cross sections. We refer the reader e.g. to the discussion in Ref. [22] on various phenomenological inputs for nucleon DAs.

A first experimental signal may have been detected at JLab [23] in backward kinematics for $e^- N \to e^- \pi N$ and for $e^- N \to e^- \omega N$ [24]. We expect the accessible kinematical domain to be more adequate to a factorized leading twist analysis in higher energy experiments at JLab@12 GeV.

3.2 Study of Baryon-to-Meson TDAs at P̄ANDA

Another tempting possibility to get experimental access to baryon-to-meson TDAs is to consider the time-like counterpart of reaction (7): the nucleon-antinucleon annihilation into a high invariant mass lepton pair in association with a light meson $\mathcal{M}$:

$$\bar{N}(p_{\bar{N}}, s_{\bar{N}}) + N(p_N, s_N) \to \gamma^*(q) + \mathcal{M}(p_\mathcal{M}) \to \ell^+(p_{\ell^+}) + \ell^-(p_{\ell^-}) + \mathcal{M}(p_\mathcal{M}). \tag{8}$$

The factorization mechanism for (8) suggested in [25,26] applies within two kinematic regimes referred as the near-forward[2] with ($s = (p_N + p_{\bar{N}})^2 \equiv W^2$, Q^2 large with $\xi^t = -\frac{(p_\mathcal{M} - p_{\bar{N}}) \cdot n^t}{(p_\mathcal{M} + p_{\bar{N}}) \cdot n^t}$ fixed; and $|t| = |(p_\mathcal{M} - p_{\bar{N}})^2| \sim 0$) (see the left panel of Fig. 4) and the near-backward one, which differs by the obvious change of kinematical variables ($p_N \to p_{\bar{N}}$, $p_{\bar{N}} \to p_N$, $t \to u$). The charge conjugation invariance results in perfect symmetry between the two kinematical regimes. The suggested reaction mechanism manifests itself through the characteristic forward and backward peaks of the $N\bar{N} \to \gamma^*\mathcal{M}$ cross section. The characteristic features of the TDA-based description of (8) are the scaling behavior in $1/q^2$ of the cross-section and the specific behavior in $\cos\theta_\ell^*$ (by θ_ℓ^* we denote the lepton polar angle defined in the CMS of the lepton pair) resulting from the leading twist dominance of the transverse polarization of the virtual time-like photon. A detailed feasibility study for accessing πN TDAs through $\bar{p} p \to \gamma^* \pi^0 \to e^+ e^- \pi^0$ at P̄ANDA was performed in [11]. As a phenomenological input, the predictions of the simple πN TDA model (4) were employed. The results of this analysis are promising concerning the experimental perspectives for accessing πN TDAs within P̄ANDA@GSI-FAIR experiment. On Fig. 5 we present the integrated cross section $d\bar{\sigma}/dQ^2$ with $|\Delta_T^2| \le 0.2 \text{ GeV}^2$ for $\bar{p} p \to e^+ e^- \pi^0$ as a function of Q^2 for $W^2 = 10 \text{ GeV}^2$ and $W^2 = 20 \text{ GeV}^2$ within the collinear factorization approach. We employ the cross channel nucleon exchange model (5) for πN TDAs with various phenomenological DAs used as inputs.

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[2] With respect to the positive direction defined along the antiproton beam.
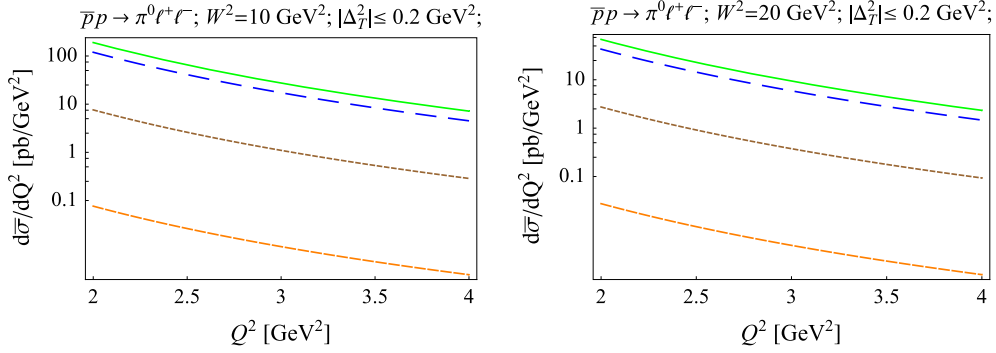
Fig. 5 Integrated cross section $\mathrm{d}\bar{\sigma}/\mathrm{d}Q^2$ for $\bar{p}p \to \ell^+\ell^-\pi^0$ as a function of Q^2 for $W^2 = 10\,\mathrm{GeV}^2$ and $W^2 = 20\,\mathrm{GeV}^2$ for various phenomenological nucleon DA solutions: COZ (*long blue dashes*); KS (*solid green line*); BLW NLO (*medium orange dashes*) and NNLO modification [21] of BLW (*short brown dashes*) (color figure online)
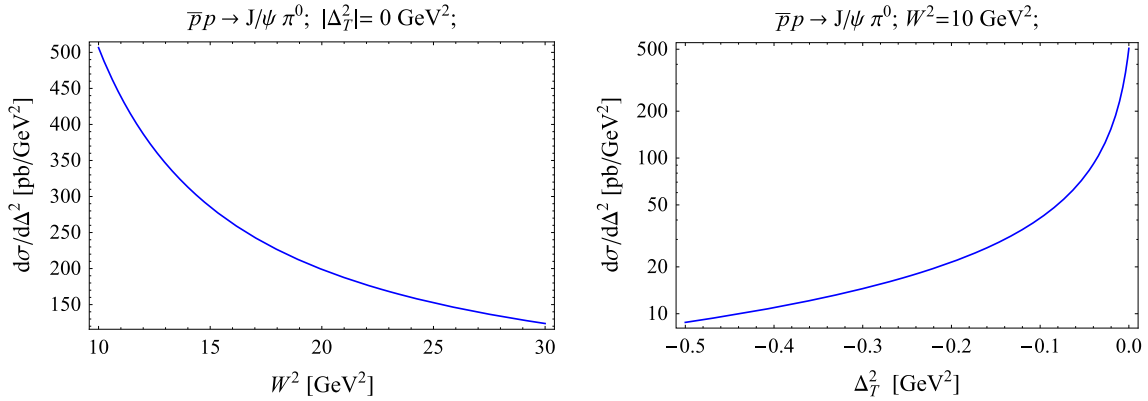
Fig. 6 *Left* Cross section $\frac{\mathrm{d}\sigma}{\mathrm{d}\Delta^2}$ for $p\bar{p} \to J/\psi\pi^0$ as a function of W^2 for $\Delta_T^2 = 0$; *Right* Same cross section for $W^2 = 10\,\mathrm{GeV}^2$ as a function of the transverse momentum transfer squared Δ_T^2

The mechanism involving nucleon-to-meson TDAs was also proposed in Ref. [27] for the reaction

$$N(p_N) + \bar{N}(p_{\bar{N}}) \to J/\psi(p_\psi) + \mathcal{M}(p_{\mathcal{M}}), \tag{9}$$

which can also be studied at $\bar{\mathrm{P}}$ANDA alongside with the investigation of the spectrum of charmonium states. Similarly to (8), one can consider the near-forward (see the right panel of Fig. 4) and the near-backward kinematic regimes symmetric due to charge conjugation invariance. On Fig. 6 we show the differential cross section $\frac{\mathrm{d}\sigma}{\mathrm{d}\Delta^2}$ for $p\bar{p} \to J/\psi\,\pi^0$ as a function of W^2 for exactly forward (backward) pion production ($\Delta_T^2 = 0$) and as a function of Δ_T^2 for a fixed value of W^2. The cross channel nucleon exchange model (5) is employed for the relevant πN TDAs. To cope with the strong $\sim \alpha_s^6$ dependence of the cross section we fix the value of α_s from the requirement that it allowed to reproduce the experimental value of $\Gamma(J/\psi \to p\bar{p})$ within the perturbative QCD description of Ref. [18]. Based on the cross-section estimates presented in Ref. [27] a detailed feasibility study for accessing $p\bar{p} \to J/\psi\pi^0$ at $\bar{\mathrm{P}}$ANDA has been performed [11,28,29].

4 Conclusion

Baryon-to-meson TDAs are new non-perturbative objects which have been designed to help us scrutinize the inner structure of nucleons. Experimentally, one may access TDAs both in the space-like domain with backward electroproduction of mesons at JLab and COMPASS and in the time-like domain in antiproton nucleon annihilation at $\bar{\mathrm{P}}$ANDA. We also expect [30] the time-reversed $\pi \to N$ TDAs to be accessible at J-Parc through the reactions: $\pi^- p \to J/\psi\,n$; $\pi^- p \to \gamma^* n \to \mu^+\mu^- n$. Extracting TDAs from space-like and time-like reactions will be a stringent test of their universality [31], and hence of the factorization property

of hard exclusive amplitudes. This hopefully will help us to disentangle details of the complex dynamics of quark and gluon confinement in hadrons.

The special πN TDA case does not exhaust all interesting possibilities, and the vector meson sector should be experimentally accessible as well as the pseudoscalar meson sector [13]. A double handbag description of other processes such as charm meson pair production in proton-antiproton annihilation may also necessitate the introduction of baryon to charmed meson TDAs [32].

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