Baryon-to-meson Transition Distribution Amplitudes: basic properties, physical interpretation and experimental perspectives

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Outline

1. Introduction: Forward and backward kinematical regimes, DAs, GPDs, TDAs;
2. Baryon-to-meson TDAs: definition and properties;
3. Physical contents of baryon-to-meson TDAs;
4. Current status of experimental analysis at JLab;
5. Summary and Outlook.

In collaboration with:
Factorization regimes for hard meson production I

- J. Collins, L. Frankfurt and M. Strikman’97: the collinear factorization theorem for

\[ \gamma^*(q) + N(p) \rightarrow N(p') + M(p_M) \]

in the generalized Bjorken limit

\[-q^2 = Q^2, \; W^2 \; - \; \text{large}; \; x_B = \frac{Q^2}{2p \cdot q} \; - \; \text{fixed}; \; -t = -(p' - p)^2 \; - \; \text{small}.\]

- Description in terms of nucleon GPDs and meson DAs.

- A complementary factorization regime:

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**Hard exclusive pseudoscalar meson electroproduction and spin structure of the nucleon**

L. L. Frankfurt,1,2 P. V. Pobylitsa,2,3 M. V. Polyakov,2,3 and M. Strikman2,4,*

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(Received 5 February 1999; published 4 June 1999)
Two complementary regimes in generalized Bjorken limit:

- $t \sim 0$ (near-forward kinematics): GPDs and meson DAs;
- $u \sim 0$ (near-backward kinematics): baryon-to-meson TDAs and nucleon DAs B. Pire, L. Szymanowski’05;
GPDs, DAs and TDAs

- Quark-antiquark bilinear light-cone \((z^2 = 0)\) operator:

\[
\langle A|\bar{\Psi}(0)[0;z]\Psi(z)|B\rangle
\]

\(\Rightarrow\) PDFs, meson DAs, GPDs, transition GPDs, etc.

- Three-quark trilinear light-cone \((z_i^2 = 0)\) operator:

\[
\langle A|\Psi(z_1)[z_1;z_2]\Psi(z_2)[z_2;z_3]\Psi(z_3)[z_3;z_1]|B\rangle
\]

- \(\langle A| = \langle 0|\); \(|B\rangle\) - baryon; \(\Rightarrow\) baryon DAs.
- Let \(\langle A|\) be a meson state \((\pi, \eta, \rho, \omega, ...)|B\rangle\) - baryon \(\Rightarrow\) baryon-to-meson TDAs.

TDAs have common features with:

- baryon DAs: same operator;
- GPDs: \(\langle B|\) and \(|A\rangle\) are not of the same momenta \(\Rightarrow\) skewness

\[
\xi = -\frac{(p_A - p_B) \cdot n}{(p_A + p_B) \cdot n}.
\]

- TDAs are universal non-perturbative objects with known evolution properties
Nucleon e.m. FF: a well known examples

Nucleon e.m. FF in pQCD at leading order
S. Brodsky & P. Lepage’81 A. Efremov & A. Radyushkin’80

A word of caution:

\[
\frac{G_{E_p}}{G_{M_p}} \text{ Ratio by Polarization Transfer in } \bar{e} p \rightarrow e \bar{p}
\]
(The Jefferson Lab Hall A Collaboration)
A list of questions:

- What are the properties and physical contents of baryon-to-meson TDAs?
- Can we build models for baryon-to-meson TDAs?
- Can we access backward reactions experimentally?
- What are the marking signs for the onset of the collinear factorization regime?
- What new information can we get about hadrons?
Leading twist proton-to-$\pi^0$ TDAs

J.P. Lansberg, B. Pire, L. Szymanowski and K.S.'11 \( (n^2 = p^2 = 0; \ 2p \cdot n = 1; \ \text{LC gauge } A \cdot n = 0) \).

- 8 TDAs: \( H^{\pi N}(x_1, x_2, x_3, \xi, \Delta^2, \mu^2) \equiv \{ V_i^{\pi N}, A_i^{\pi N}, T_i^{\pi N} \} \ (x_1, x_2, x_3, \xi, \Delta^2, \mu^2) \)
- C.f. 3 leading twist nucleon DAs: \( \{ V^p, A^p, T^p \} \ (y_1, y_2, y_3) \)

\[
4(P \cdot n)^3 \int \left[ \prod_{k=1}^{3} \frac{dz_k}{2\pi} e^{i x_k z_k (P \cdot n)} \right] \langle \pi^0(p_\pi) | \varepsilon_{c_1 c_2 c_3} u^c_\rho(z_1 n) u^c_\tau(z_2 n) d^c_\chi(z_3 n) | N^p(p_1, s_1) \rangle
\]

\[
= \delta(2\xi - x_1 - x_2 - x_3) i \frac{f_N}{f_\pi M} \times \left[ V_1^{\pi N}(\hat{P} C)_{\rho \tau} (\hat{P} U)_{\chi} + A_1^{\pi N}(\hat{P} \gamma^5 C)_{\rho \tau} (\gamma^5 \hat{P} U)_{\chi} + T_1^{\pi N}(\sigma_{P \mu} C)_{\rho \tau} (\gamma^\mu \hat{P} U)_{\chi}
+ V_2^{\pi N}(\hat{P} C)_{\rho \tau} (\hat{\Delta} U)_{\chi} + A_2^{\pi N}(\hat{P} \gamma^5 C)_{\rho \tau} (\gamma^5 \hat{\Delta} U)_{\chi} + T_2^{\pi N}(\sigma_{P \mu} C)_{\rho \tau} (\gamma^\mu \hat{\Delta} U)_{\chi}
+ \frac{1}{M} T_3^{\pi N}(\sigma_{P \Delta} C)_{\rho \tau} (\hat{P} U)_{\chi} + \frac{1}{M} T_4^{\pi N}(\sigma_{P \Delta} C)_{\rho \tau} (\hat{\Delta} U)_{\chi} \right]
\]

- \( P = \frac{p_1 + p_\pi}{2} \); \( \Delta = (p_\pi - p_1) \); \( \sigma_{P \mu} \equiv P^\nu \sigma_{\nu \mu} \);
- \( \xi = -\frac{\Delta \cdot n}{2P \cdot n} \)
- C: charge conjugation matrix;
- \( f_N = 5.2 \cdot 10^{-3} \ \text{GeV}^2 \ (V. \ Chernyak \ and \ A. \ Zhitnitsky'84) \);
A list of fundamental properties I:

B. Pire, L. Szymanowski, KS'10,11:

- Restricted support in $x_1, x_2, x_3$: intersection of three stripes $-1 + \xi \leq x_k \leq 1 + \xi$ ($\sum_k x_k = 2\xi$); ERBL-like and DGLAP-like I, II domains.

- Mellin moments in $x_k \Rightarrow \pi N$ matrix elements of local 3-quark operators

$$\left[ i\vec{D}^{\mu_1}\ldots i\vec{D}^{\mu_{n_1}} \psi_\rho(0) \right] \left[ i\vec{D}^{\nu_1}\ldots i\vec{D}^{\nu_{n_2}} \psi_\tau(0) \right] \left[ i\vec{D}^{\lambda_1}\ldots i\vec{D}^{\lambda_{n_3}} \psi_\chi(0) \right].$$

Need to be studied on the lattice!

- Polynomiality in $\xi$ of the Mellin moments in $x_k$:

$$\int_{-1+\xi}^{1+\xi} dx_1 dx_2 dx_3 \delta(\sum_k x_k - 2\xi) x_1^{n_1} x_2^{n_2} x_3^{n_3} H^{\pi N}(x_1, x_2, x_3, \xi, \Delta^2)$$

$$= \text{[Polynomial of order } n_1 + n_2 + n_3 \{+1\} \text{]}(\xi).$$
Spectral representation A. Radyushkin'97 generalized for $\pi N$ TDAs ensures polynomiality and support:

$$H(x_1, x_2, x_3 = 2\xi - x_1 - x_2, \xi)$$

$$= \left[ \prod_{i=1}^{3} \int_{\Omega_i} d\beta_i d\alpha_i \right] \delta(x_1 - \xi - \beta_1 - \alpha_1 \xi) \delta(x_2 - \xi - \beta_2 - \alpha_2 \xi) \times \delta(\beta_1 + \beta_2 + \beta_3) \delta(\alpha_1 + \alpha_2 + \alpha_3 + 1) F(\beta_1, \beta_2, \beta_3, \alpha_1, \alpha_2, \alpha_3);$$

$\Omega_i$: \{|$\beta_i$| $\leq$ 1, |$\alpha_i$| $\leq$ 1 − |$\beta_i$|\} are copies of the usual DD square support;

$F(\ldots)$: six variables that are subject to two constraints ⇒ quadruple distributions;

Can be supplemented with a $D$-term-like contribution (with pure ERBL-like support):

$$\frac{1}{(2\xi)^2} \delta(x_1 + x_2 + x_3 - 2\xi) \left[ \prod_{k=1}^{3} \theta(0 \leq x_k \leq 2\xi) \right] D \left( \frac{x_1}{2\xi}, \frac{x_2}{2\xi}, \frac{x_3}{2\xi} \right).$$
TDAs and light-cone wave functions

Light-front quantization approach: $\pi N$ TDAs provide information on next-to-minimal Fock components of light-cone wave functions of hadrons B. Pasquini et al. 2009:

$$|N\rangle = \psi_{(3q)}|qqq\rangle + \psi_{(3q+q\bar{q})}|qqq q\bar{q}\rangle + \ldots$$

Described by nucleon DA

$$|M\rangle = \psi_{(q\bar{q})}|q\bar{q}\rangle + \psi_{(q\bar{q}+q\bar{q})}|q\bar{q} q\bar{q}\rangle + \ldots$$

Described by meson DA
A connection to the quark-diquark picture

- $\varphi_{as}(x) = 120x_1x_2x_3$.
- V. Chernyak, Zhitnitsky'84:

$$\varphi_{CZ}(x) = \varphi_{as}(x) \sum_i c_i A_i(x).$$

- Large asymmetry between quarks in nucleon:

$$\varphi^{(1,0,0)} \sim 0.6; \quad \varphi^{(0,1,0)} \sim \varphi^{(0,0,1)} \sim 0.2.$$ 

- Z. Dziembowski, J. Franklin'90: diquark-like clustering

$$p: \uparrow \downarrow \uparrow \quad ud \quad \uparrow \downarrow \quad u \uparrow.$$ 

- No confirmation of asymmetric behavior: e.g. V. Braun, A. Lenz, M. Wittmann'06.
A connection to the quark-diquark picture II

- Quark-diquark coordinates (one of 3 possible sets):

\[ v_3 = \frac{x_1 - x_2}{2}; \quad w_3 = x_3 - \xi; \quad x_1 + x_2 = 2\xi'; \quad \left( \xi_3' \equiv \frac{\xi - w_3}{2} \right). \]

- The TDA support in quark-diquark coordinates:

\[-1 \leq w_3 \leq 1; \quad -1 + |\xi - \xi_3'| \leq v_3 \leq 1 - |\xi - \xi_3'|.\]

- \( v_3 \)-Mellin moment of \( \pi N \) TDAs:

\[
\int_{-1 + |\xi - \xi_3'|}^{1 - |\xi - \xi_3'|} dv_3 H^{\pi N}(w_3, v_3, \xi, \Delta^2) \\
\sim h_{\rho\tau\chi}^{-1} \int \frac{d\lambda}{4\pi} e^{i(w_3\lambda)(P\cdot n)} (\pi^0(p_\pi)|u_\rho(-\frac{\lambda}{2} n) u_\tau(-\frac{\lambda}{2} n) d_\chi(\frac{\lambda}{2} n)|N^p(p_1))
\]

\( \hat{O}_{\rho\tau\chi}^d (\frac{\lambda}{2} n, \frac{\lambda}{2} n) \)
An interpretation in the impact parameter space I

- A generalization of M. Burkardt’00,02; M. Diehl’02 for $\nu_3$-integrated TDAs.
- Fourier transform with respect to

$$D = \frac{p_\pi}{1 - \xi} - \frac{p_N}{1 + \xi}; \quad \Delta^2 = -2\xi \left( \frac{m^2_\pi}{1 - \xi} - \frac{M^2_N}{1 + \xi} \right) - (1 - \xi^2)D^2.$$

- A representation in the DGLAP-like I domain:

DGLAP I: $x_3 = w_3 - \xi \leq 0; \quad x_1 + x_2 = \xi - w_3 \geq 0;$
An interpretation in the impact parameter space II

DGLAP II: \[ x_3 = w_3 - \xi \geq 0; \quad x_1 + x_2 = \xi - w_3 \leq 0; \]

ERBL: \[ x_3 = w_3 - \xi \geq 0; \quad x_1 + x_2 = \xi - w_3 \geq 0; \]
Building up a consistent model for $\pi N$ TDAs

Key requirements:

1. support properties in $x_k$ and polynomialty;
2. isospin + permutation symmetry;
3. crossing $\pi N$ TDA $\leftrightarrow$ $\pi N$ GDA;
4. Soft pion theorem P. Pobylitsa, M. Polyakov and M. Strikman’01; V. Braun, D. Ivanov, A. Lenz, A. Peters’08: $\pi N$ GDA at the threshold $\xi = 1$, $\Delta^2 = M^2$ in terms of nucleon DAs.

How to model quadruple distributions?

- No enlightening $\xi = 0$ limit as for GPDs (cf. RDDA A. Radyushkin’97)
- Instead, $\xi \to 1$ fixed from the soft pion theorem;
- A factorized Ansatz with input at $\xi = 1$ designed in J.P. Lansberg, B. Pire, K.S., L. Szymanowski’12
- Cross-channel exchange as a source of the $D$-term-like contribution: $\tilde{E}$ GPD v.s. TDA
Calculation of the amplitude

- LO amplitude for $\gamma^* + Np \rightarrow \pi^0 + Np$
  computed as in J.P. Lansberg, B. Pire and L. Szymanowski'07;
- 21 diagrams contribute;

\[
\mathcal{I} \sim \int_{-1+\xi}^{1+\xi} d^3x \delta(x_1 + x_2 + x_3 - 2\xi) \int_0^1 d^3y \delta(1 - y_1 - y_2 - y_3) \left( \sum_{\alpha=1}^{21} R_\alpha \right)
\]

Each $R_\alpha$, has the structure:

\[
R_\alpha \sim K_\alpha(x_1, x_2, x_3) \times Q_\alpha(y_1, y_2, y_3) \times
\]

[combination of $\pi N$ TDAs] $\times$ [combination of nucleon DAs]

\[
R_1 = \frac{q^\mu(2\xi)^2[(V_{1p}^{\mu}) - A_{1p}^{\mu})(V^p - A^p) + 4 T_1^{p\pi^0} T^p + 2 \frac{\Delta^2_M}{M^2} T_4^{p\pi^0} T^p]}{(2\xi - x_1 + i\epsilon)^2(x_3 + i\epsilon)(1 - y_1)^2y_3}
\]

\[
c.f. \int_{-1}^{1} dx \frac{H(x, \xi)}{x \pm \xi \mp i\epsilon} \int_0^1 dy \frac{\phi_M(y)}{y} \quad \text{for HMP}
\]
\[
\mathcal{M}_{s_1s_2}^{\lambda} = -i \frac{(4\pi \alpha_s)^2 \sqrt{4\pi \alpha_{em} f_N^2}}{54f_\pi} \frac{1}{Q^4} \left[ S_{s_1s_2}^{\lambda} \mathcal{I}(\xi, \Delta^2) - S'_{s_1s_2}^{\lambda} \mathcal{I}'(\xi, \Delta^2) \right],
\]

where \( S_{s_1s_2}^{\lambda} \equiv \bar{U}(p_2, s_2) \hat{c}^* (\lambda) \gamma_5 U(p_1, s_1); \quad S'_{s_1s_2}^{\lambda} \equiv \frac{1}{M} \bar{U}(p_2, s_2) \hat{c}^* (\lambda) \hat{\Delta}_T \gamma_5 U(p_1, s_1), \)

- Unpolarized cross section for hard leptoproduction of a pion off nucleon:

\[
\frac{d^5 \sigma}{dE'd\Omega_{e'}d\Omega_{\pi}} = \Gamma \times \frac{\Lambda(s, m^2, M^2)}{128\pi^2 s (s - M^2)} \times \sum_{s_1, s_2} \left\{ \frac{1}{2} \left( |\mathcal{M}_{s_1s_2}^{1}|^2 + |\mathcal{M}_{s_1s_2}^{-1}|^2 \right) + \ldots \right\} = \Gamma \times \left( \frac{d^2 \sigma_T}{d\Omega_{\pi}} + \ldots \right).
\]

Distinguishing features of the TDA-based mechanism

- Dominance of the transverse cross section \( \frac{d^2 \sigma_T}{d\Omega_{\pi}} \).
- \( 1/Q^8 \) scaling behavior of the cross section.
- Non-zero imaginary part of the amplitude. Transverse Target Single Spin Asymmetry \( \sim \text{Im} \) part of the amplitude.
Backward pion electroproduction @ CLAS I

Analysis of JLab @ 6 GeV data (Oct. 2001-Jan. 2002 run) for the backward $\gamma^* p \rightarrow \pi^+ n$

K. Park et al. (CLAS Collaboration) and B. Pire and K.S., PLB 780 (2018)
Backward pion electroproduction @ CLAS II

\[
\frac{d\sigma}{d\Omega^*_\pi} = A + B \cos \varphi^*_\pi + C \cos 2\varphi^*_\pi, \quad \text{where}
\]

\[
A = \sigma_T + \epsilon \sigma_L; \quad B = \sqrt{2\epsilon(1+\epsilon)}\sigma_{LT}; \quad C = \epsilon \sigma_{TT}
\]

<table>
<thead>
<tr>
<th>Variable</th>
<th>Number of bins</th>
<th>Range</th>
<th>Bin size</th>
</tr>
</thead>
<tbody>
<tr>
<td>(W)</td>
<td>1</td>
<td>2.0 - 2.4 GeV</td>
<td>400 MeV</td>
</tr>
<tr>
<td>(Q^2)</td>
<td>5</td>
<td>1.6 - 4.5 GeV^2</td>
<td>various</td>
</tr>
<tr>
<td>(\Delta_{T}^2)</td>
<td>1</td>
<td>0 - 0.5 GeV^2</td>
<td>0.5 GeV^2</td>
</tr>
<tr>
<td>(\varphi^*_\pi)</td>
<td>9</td>
<td>0° - 360°</td>
<td>40°</td>
</tr>
</tbody>
</table>

Table: Determination of kinematic bin.
The cross section can be expressed as

\[
\frac{d^4\sigma}{dQ^2 dx_B d\varphi dt} = \sigma_0 \cdot \left(1 + A_{UU}^{\cos(0)} \cdot \cos(2\varphi) + A_{UU}^{\cos(\varphi)} \cdot \cos(\varphi) + A_{LU}^{\sin(\varphi)} \cdot \sin(\varphi)\right).
\]

Beam Spin Asymmetry

\[
BSA \left(Q^2, x_B, -t, \varphi\right) = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{A_{LU}^{\sin(\varphi)} \cdot \sin(\varphi)}{1 + A_{UU}^{\cos(\varphi)} \cdot \cos(\varphi) + A_{UU}^{\cos(2\varphi)} \cdot \cos(2\varphi)};
\]

\(\sigma^\pm\) is the cross-section with the beam helicity states \((\pm)\).
Beam Spin Asymmetry is a subleading twist effect both in the forward and backward regimes.

![Graphs showing Beam Spin Asymmetry in forward and backward directions.

Q^2 [GeV^2] vs. A_{LU}^\sin(\phi) for different x_B values.

The plots demonstrate the behavior of the asymmetry for both forward and backward directions as a function of Q^2 and x_B.](image-url)
Backward $\omega$-production at JLab Hall C I

- A generalization of the TDA formalism for the case of light vector mesons ($\rho$, $\omega$, $\phi$) B. Pire, L. Szymanowski and K.S'15.


- Clear signal from backward regime of $ep \to e'p\omega$.

- Full Rosenbluth separation: $\sigma_T$ and $\sigma_L$ extracted.

$$2\pi \frac{d^2\sigma}{dt\,d\phi} = \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)} \frac{d\sigma_{LT}}{dt} \cos\phi + \epsilon \frac{d\sigma_{TT}}{dt} \cos 2\phi$$
Backward ω-production at JLab Hall C II

- For $Q^2 = 2.45$ GeV$^2$: $\sigma_L/\sigma_T < \mu^2/Q^2$ and $\sigma_T \gg \sigma_L$;

- Experiment v.s. the predictions of the cross-channel nucleon exchange model for $p \to \omega$ TDAs.
- Combined (CLAS and $F_\pi$-2 data for $\gamma^* p \to \omega p$).
- TDA-based predictions v.s. the Regge-based J.M. Laget’s JML’18 model.
Baryon to meson TDAs at \( \bar{\text{P}} \text{ANDA} \)

- \( E_\bar{p} \leq 15 \text{ GeV}; \quad W^2 \leq 30 \text{ GeV}^2 \)

- J.P. Lansberg et al.'12; B. Pire, L. Szymanowski, KS,'13: \( \pi N \) TDAs occur in factorized description of

\[
\bar{N} + N \rightarrow \gamma^*(q) + \pi \rightarrow \ell^+ + \ell^- + \pi;
\]

\[
\bar{N} + N \rightarrow J/\psi + \pi \rightarrow \ell^+ + \ell^- + \pi;
\]

- Two regimes (forward and backward). C invariance \( \Rightarrow \) perfect symmetry;

- Test of universality of TDAs;

- \( (1 + \cos^2 \theta_\ell) \) distribution marks the reaction mechanism: transverse polarization dominance (leading twist accuracy).

- M. C. Mora Espi, M. Zambrana, F. Maas, K.S.'15: feasibility of \( \bar{p} p \rightarrow e^+ e^- \pi^0 \).

- B. Ramstein, E. Atomssa and \( \bar{\text{P}} \)ANDA collaboration and K.S., PRD 95'17 feasibility of \( \bar{p} p \rightarrow J/\psi \pi^0 \).
Deep deuteron electrodissociation with a $B = 1$ exchange in the cross channel

- More use for $3q$ light-cone operator: TDAs for $B \rightarrow B - 1$ baryons as a tool for nuclear physics.
- Deep deuteron electrodissociation with a baryon number exchange in the cross channel:
  \[
  \gamma^*(q) + d(p_d) \rightarrow p(p_p) + n(p_n); \quad |u| \equiv |(p_d - p_n)^2| \ll Q^2, \quad W^2 = (q + p_d)^2.
  \]

- BAND coverage in $\theta$: $155 - 176^\circ$.
- Can CLAS measure this reaction?
Backward DVCS and nucleon-to-photon TDAs

- Nucleon-to-photon TDAs J.P. Lansberg, B. Pire, and L. Szymanowski'07: $16 \, N \to \gamma$ TDAs at the leading twist-3.

- Cross channel processes $N\bar{N} \to \gamma^*\gamma$ can be studied with ČPANDA.
- New information on the subtraction constant in the dispersion relation for the DVCS amplitude ($D$-term FF).
- May be important in connection with the $J = 0$ fixed pole universality conjecture S. Brodsky, F. Llanes-Estrada, and A. Szczepaniak'09, D. Müller and K.S.'15.
Conclusions & Outlook

1. Nucleon-to-meson TDAs provide new information about correlation of partons inside hadrons. A consistent picture for integrated TDAs emerges in the impact parameter representation.

2. We strongly encourage to try to detect near forward and backward signals for various mesons ($\pi, \eta, \omega, \rho$) and photons: there is an interesting physics around!

3. The experimental success achieved for backward $\gamma^* N \rightarrow N'\pi$ and $\gamma^* N \rightarrow N'\omega$ already with the old 6 GeV data set (more is expected at 12 GeV).

4. First evidences for the onset of the factorization regime in backward $\gamma^* N \rightarrow N'\omega$ from JLab Hall C analysis.

5. $\bar{p}N \rightarrow \pi\ell^+\ell^- (q^2$ - timelike) and $\bar{p}N \rightarrow \pi J/\psi$ at $\bar{P}$ANDA would allow to check universality of TDAs.

6. TDAs as a tool for nuclear physics: deuteron-to-nucleon TDAs.