An overview of baryon-to-meson transition distribution amplitudes: formalism and experimental perspectives

K. Semenov-Tian-Shansky

Petersburg Nuclear Physics Institute, National Research Centre “Kurchatov Institute”, Gatchina, Russia

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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 and feasibility studies for PANDA.
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

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

- Description in terms of nucleon GPDs and meson DAs.

- A complementary factorization regime:
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

- Main objects: matrix elements of QCD light-cone \((z^2 = 0)\) operators.
GPDs, DAs and TDAs

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

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- \(\langle A| = \langle 0|\); \(|B\rangle\) - baryon; ⇒ baryon DAs.

Let \(\langle A|\) be a meson state (\(\pi, \eta, \rho, \omega, \ldots\)) \(\langle B|\) - baryon; ⇒ baryon-to-meson TDAs.

TDAs have common features with:
- baryon DAs: same operator;
- GPDs: \(\langle B|\) and \(|A\rangle\) are not of the same momentum ⇒ skewness:

\[
\xi = - (p_A - p_B) \cdot n(p_A + p_B) \cdot n.
\]
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K. Semenov-Tian-Shansky (PNPI)
An overview of baryon-to-meson TDAs
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\]
Nucleon e.m. FF: a well known examples

Nucleon e.m. FF in pQCD at leading order

Brodsky & Lepage'81 Efremov & Radyushkin'80

A word of caution:

$G_{E_p}/G_{M_p}$ Ratio by Polarization Transfer in $e^p \rightarrow e^p$

(The Jefferson Lab Hall A Collaboration)
A list of key issues:

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- What are the marking signs for the onset of the collinear factorization regime?
Leading twist proton-to-$\pi^0$ TDAs

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

- 8 TDAs: \(H_{\pi N}(x_1, x_2, x_3, \xi, \Delta^2, \mu^2) \equiv \{V_{i N}, A_{i N}, T_{i N}\} (x_1, x_2, x_3, \xi, \Delta^2, \mu^2)\)
- 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^{ix_k z_k(P \cdot n)} \right] \langle \pi^0(p_{\pi}) | \varepsilon_{c_1 c_2 c_3} u_{\rho}^{c_1} (z_1 n) u_{\tau}^{c_2} (z_2 n) d_{\chi}^{c_3} (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 N}^{\pi} (\hat{P} C)^{\rho \tau}(\hat{P} U)_{\chi} + A_{1 N}^{\pi} (\hat{P} \gamma^5 C)^{\rho \tau}(\gamma^5 \hat{P} U)_{\chi} + T_{1 N}^{\pi} (\sigma_{P \mu} C)^{\rho \tau}(\gamma^\mu \hat{P} U)_{\chi} \right. \\
+ V_{2 N}^{\pi} (\hat{P} C)^{\rho \tau}(\hat{\Delta} U)_{\chi} + A_{2 N}^{\pi} (\hat{P} \gamma^5 C)^{\rho \tau}(\gamma^5 \hat{\Delta} U)_{\chi} + T_{2 N}^{\pi} (\sigma_{P \mu} C)^{\rho \tau}(\gamma^\mu \hat{\Delta} U)_{\chi} \\
+ \frac{1}{M} T_{3 N}^{\pi} (\sigma_{P \Delta} C)^{\rho \tau}(\hat{P} U)_{\chi} + \frac{1}{M} T_{4 N}^{\pi} (\sigma_{P \Delta} C)^{\rho \tau}(\hat{\Delta} U)_{\chi} \left. \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

$$
\begin{align*}
&\left[i\tilde{D}^{\mu_1} \ldots i\tilde{D}^{\mu_n} \psi_\rho(0)\right] \left[i\tilde{D}^{\nu_1} \ldots i\tilde{D}^{\nu_n} \psi_\tau(0)\right] \left[i\tilde{D}^{\lambda_1} \ldots i\tilde{D}^{\lambda_n} \psi_\chi(0)\right].
\end{align*}
$$

Need to be studied on the lattice!

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

$$
\int_{-1+\xi}^{1+\xi} dx_1 dx_2 dx_3 \delta(\sum_k x_k - 2\xi) x_1^{n_1} x_2^{n_2} x_3^{n_3} H^{\pi N}(x_1, x_2, x_3, \xi, \Delta^2)
= \text{[Polynomial of order } n_1 + n_2 + n_3 \{+1\}\text{]}(\xi).
$$
A list of fundamental properties II:

- 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):

$$\frac{1}{(2\xi)^2} \delta(x_1 + x_2 + x_3 - 2\xi) \left[ \prod_{k=1}^{3} \theta(0 \leq x_k \leq 2\xi) \right] D \left( \frac{x_1}{2\xi}, \frac{x_2}{2\xi}, \frac{x_3}{2\xi} \right).$$
A connection to the quark-diquark picture

- 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:
  \[
  \int_{-1+|\xi - \xi'_3|}^{1-|\xi - \xi'_3|} dv_3 H^{\pi N}(w_3, v_3, \xi, \Delta^2)
  \sim h_{\rho\tau\chi}^{-1} \int \frac{d\lambda}{4\pi} e^{i\cdot (w_3\lambda\cdot (p\cdot n))} \langle \pi^0(p\pi) | u_{\rho}(\frac{\lambda}{2}n) u_{\tau}(\frac{\lambda}{2}n) d_{\chi}(\frac{\lambda}{2}n) | N^p(p_1) \rangle
  \]
  \[
  \bigotimes_{\rho\tau\chi}^{uu} (-\frac{\lambda}{2}n, \frac{\lambda}{2}n)
  \]
An interpretation in the impact parameter space

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

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

- A representation in the DGLAP-like 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: \( x_3 = w_3 - \xi \geq 0; \quad x_1 + x_2 = \xi - w_3 \geq 0; \)
Light-cone quark model interpretation

- $\pi N$ TDAs provides information on the next to minimal Fock states B. Pasquini et al. 2009:

$$\left|qqq\right\rangle + \left|qqq\pi\right\rangle + ...$$

Described by nucleon DA
Crossing relates and $\pi N$ GDAs (light-cone wave functions of $|\pi N\rangle$ states).

Physical domain in $(\Delta^2, \xi)$-plane (defined by $\Delta^2_T \leq 0$) in the chiral limit ($m_\pi = 0$):

- Soft pion theorem P. Pobylitsa, M. Polyakov and M. Strikman’01; V. Braun, D. Ivanov, A. Lenz, A. Peters’08 ($Q^2 \gg \Lambda_{QCD}^3 / m_\pi$): $\pi N$ GDA at the threshold $\xi = 1$, $\Delta^2 = M^2$ in terms of nucleon DAs $V^p, A^p, T^p$. 
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 and chiral properties: soft pion theorem;

How to model quadruple distributions?

- No enlightening $\xi = 0$ limit as for GPDs. RDDA A. Radyushkin’97
- Instead, the soft pion theorems fixes the $\xi \to 1$ limit in terms of nucleon DAs and thus provides the overall magnitude of TDAs.
- A factorized Ansatz with input at $\xi = 1$ designed in J.P. Lansberg, B. Pire, K.S. and 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 $\gamma^* + Np \to \pi^0 + Np$
  computed as in J.P. Lansberg, B. Pire and L. Szymanowski’07;
- 21 diagrams contribute;

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

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]

$$R_1 = \frac{q^u(2\xi)^2 \left[ (V_1^{p\pi^0} - A_1^{p\pi^0})(V^p - A^p) + 4 T_1^{p\pi^0} T^p + 2 \frac{\Delta^2}{M^2} T_4^{p\pi^0} T^p \right]}{(2\xi - x_1 + i\epsilon)^2(x_3 + i\epsilon)(1 - y_1)^2y_3}$$

c.f. $\int_{-1}^{1} dx \frac{H(x, \xi)}{x \pm i \xi \mp i\epsilon} \int_{0}^{1} dy \frac{\phi_M(y)}{y}$ for HMP
$N\gamma^* \to \pi N$ amplitude and the cross section

- $N\gamma^* \to \pi N$ helicity amplitudes:

$$\mathcal{M}^\lambda_{s_1s_2} = -i \frac{(4\pi \alpha_s)^2}{54 f_\pi} \frac{1}{Q^4} \frac{1}{4\pi\alpha_{em} f_N^2} \left[ S^\lambda_{s_1s_2} I(\xi, \Delta^2) - S'_{s_1s_2} I'(\xi, \Delta^2) \right],$$

where $S^\lambda_{s_1s_2} \equiv \bar{U}(p_2, s_2)\hat{\epsilon}^*_{(\lambda)} \gamma_5 U(p_1, s_1)$; $S'_{s_1s_2} \equiv \frac{1}{M} \bar{U}(p_2, s_2)\hat{\epsilon}^*_{(\lambda)} \hat{\Delta} T \gamma_5 U(p_1, s_1)$.

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

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

**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 $\sim \text{Im part of the amplitude}$.
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)
\[ \frac{d\sigma}{d\Omega^*_\pi} = A + B \cos \varphi^*_\pi + C \cos 2\varphi^*_\pi, \]

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>
The cross section can be expressed as

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

Beam Spin Asymmetry

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

$$\sigma^\pm$$ 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.
Backward $\omega$-production at JLab Hall C I

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

- The analysis by W. Li, G. Huber et al. (The JLab $F_\pi$ Collaboration) and B. Pire, L. Szymanowski, J.-M. Laget and K.S., to be published at PRL.

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

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

\[ 2\pi \frac{d^2\sigma}{dtd\phi} = \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} + \sqrt{2}\epsilon(1 + \epsilon) \frac{d\sigma_{LT}}{dt} \cos \phi + \epsilon \frac{d\sigma_{TT}}{dt} \cos 2\phi \]
For $Q^2 = 2.45$ GeV$^2$:

$$\frac{\sigma_L}{\sigma_T} < \frac{\mu^2}{Q^2} \quad \text{and} \quad \sigma_T \gg \sigma_L;$$

Experiment v.s. the predictions of the cross-channel nucleon exchange model for $p \rightarrow \omega$ TDAs.
Backward $\omega$-production at JLab Hall C III

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

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

- J.P. Lansberg et al.'12; B. Pire, L. Szymanowski, KS,'13: \( \pi N \) TDAs occur in factorized description of
  \[
  \bar{N} + N \rightarrow \gamma^*(q) + \pi \rightarrow \ell^+ + \ell^- + \pi; \\
  \bar{N} + N \rightarrow J/\psi + \pi \rightarrow \ell^+ + \ell^- + \pi;
  \]

- To be done with the proton FF studies in the timelike region and heavy charmonium studies.
- Two regimes (forward and backward). \( C \) invariance \( \Rightarrow \) perfect symmetry.
- Test of universality of TDAs.
\[ \frac{d\sigma}{dt dQ^2 d\cos \theta_\ell} = \int d\varphi_\ell \frac{2\pi e^2 (1 + \cos^2 \theta_\ell)}{Q^2} \frac{|\mathcal{M}_T|^2}{64W^2(W^2 - 4M^2)(2\pi)^4}. \]

- Useful cut: \(|\Delta^2_T|\)-cut \Leftrightarrow \text{cut in } \theta_{\text{CMS}}. \text{ Integrated cross section: } \int_{t_{\text{min}}}^{t_{\text{max}}} dt.
- Nucleon pole dominates over the contribution spectral part for \( \bar{P}\text{ANDA} \) conditions.
- Numerical input: COZ, KS, BLW NLO, BLW NNLO phenomenological solutions for nucleon DAs

Cross section of \( \bar{p}n \rightarrow \pi^- \gamma^* \rightarrow \pi^- \ell^+ \ell^- \) is larger by factor 2. But requires neutron target.
Study of $p\bar{p} \to e^+e^-\pi^0$ (signal) with $p\bar{p} \to \pi^+\pi^-\pi^0$ (main hadronic background).

Simulations performed for $s = 5 \text{ GeV}^2$ and $s = 10 \text{ GeV}^2$

$|\cos \theta^*_\pi| > 0.5$ cut imposed

Modified version of Lansberg, Pire, Szymanowski’07 model used for $\pi N$ TDAs used as input for MC.

2 fb$^{-1}$ of integrated luminosity assumed ($\sim 5$ months High Lumi.)

Expected number of signal events then is 3350 and 465 for $s = 5 \text{ GeV}^2$ and $s = 10 \text{ GeV}^2$
$N \bar{N} \rightarrow J/\psi \pi$ at $\bar{P}$ANDA


Unpolarized cross section and angular distribution
Feasibility study of $\bar{p}p \rightarrow J/\psi \pi^0$ at PANDA I

B. Ramstein, E. Atomssa and PANDA collaboration and K.S. PRD 95'17

- Event generator based on TDA model prediction Pire et al.’13.
- Simulations performed for $s = 12.2$ GeV$^2$, $s = 16.9$ GeV$^2$ and $s = 24.3$ GeV$^2$.
- Study of $p\bar{p} \rightarrow J/\psi \pi^0$ (signal) with background from $p\bar{p} \rightarrow \pi^+\pi^-\pi^0$ and $p\bar{p} \rightarrow J/\psi \pi^0\pi^0$ and other sources.

![Expected signal rates, $s=12.25$ GeV$^2$](image.png)
Signal and background count rates for 2 fb$^{-1}$ (≈ 5 months in High Luminosity mode)

Worst case scenario at $p_{\bar{p}} = 5.5$ GeV/c: S/B at least factor 10.
Feasibility study of $\bar{p}p \rightarrow J/\psi \pi^0$ at $\bar{P}$ANDA III

Angular distribution of $J/\psi$ decay electrons

- Signal count extracted from fits corrected for efficiency
- Free fit with $B(1 + A \cos^2 \theta^*_\ell)$. 
J-PARC intense pion beam option: $P_\pi = 10 - 20$ GeV.


$$\pi^- + p \rightarrow n + J/\psi$$

Near-forward regime: $|(p_\pi - p_2)^2| \ll W^2, M^2_\psi$. 
Backward DVCS and nucleon-to-photon TDAs

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

- Cross channel processes $N\bar{N} \rightarrow \gamma^*\gamma$. can be studied with $\bar{P}$ANDA.

- 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 (π, η, ω, ρ) and photons: there is an interesting physics around!

3. The experimental success achieved for backward γ* N → N′π and γ* N → N′ω 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 γ* N → N′ω from JLab Hall C analysis.

5. ¯pN → πℓ+ℓ− (q² - timelike) and ¯pN → π J/ψ at PANDA would allow to check universality of TDAs.

6. TDAs as a tool for nuclear physics: deuteron-to-nucleon TDAs.
Thank you for your attention!
Transverse Target Single Spin Asymmetry $\gamma^* N \rightarrow \pi N$

More distinguishing features with a polarized target

- $\text{TSA} = \sigma^\uparrow - \sigma^\downarrow \sim \text{Im part of the amplitude.}$
- Sensitive to the contribution of the DGLAP-like regions.
- Non vanishing and $Q^2$-independent TSA within TDA approach.
- $10 - 15\%$ TSA for $\gamma^* N \rightarrow \pi N$ with two component TDA model.

$$\mathcal{A} = \frac{1}{|s_1|} \left( \int_0^\pi d\tilde{\phi} |\mathcal{M}^s_{1T}|^2 - \int_{\pi}^{2\pi} d\tilde{\phi} |\mathcal{M}^s_{1T}|^2 \right) \left( \int_0^{2\pi} d\tilde{\phi} |\mathcal{M}^s_{1T}|^2 \right)^{-1}; \quad \tilde{\phi} \equiv \phi - \phi_s$$

K. Semenov-Tian-Shansky (PNPI)