# Backward meson electroproduction and baryon-to-meson transition distribution amplitudes

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# Outline

1. Introduction: Forward and backward kinematical regimes, DAs, GPDs, TDAs
2. $\pi N$ TDAs: definition, properties, support, spectral representation, chiral constrains
3. Factorized Ansatz for quadruple distributions.
4. $\gamma^* N \to \pi N$ cross section estimates.
5. Summary and Outlook

B. Pire, K. S., L. Szymanowski Phys. Rev. D **82**, 094030 (2010)

B. Pire, K. S., L. Szymanowski, Phys. Rev. D **84**, 074014 (2011)

J.P. Lansberg, B. Pire, K. S., L. Szymanowski, Phys. Rev. D **85**, 054021 (2012)

J.P. Lansberg, B. Pire, K. S., L. Szymanowski, Phys. Rev. D **86**, 114033 (2012)

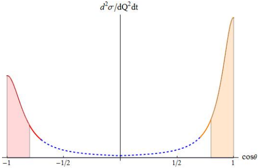
B. Pire, K. S., L. Szymanowski, Phys. Lett. B **724**, 99 (2013)

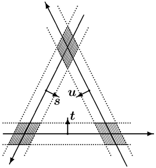
# Factorization regimes for hard meson (or photon) production

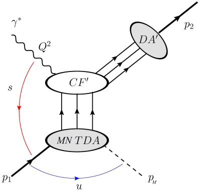
Factorization regimes for $\gamma^* N \to MN$ (or $\gamma^* N \to \gamma N$) in the generalized Bjorken limit ($-q^2 = Q^2$, $s \equiv W^2$ – large; $x_B = \frac{Q^2}{2p \cdot q}$ – fixed)

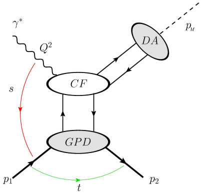
**Two complementary regimes:**

- $t \sim 0$ (forward peak) factorized description in terms of GPDs J. Collins, L. Frankfurt, M. Strikman'97;
- $u \sim 0$ (backward peak) factorized description in terms of TDAs L. Frankfurt, M. V. Polyakov, M. Strikman et al.'02;









# Hard Exclusive Processes: GPDs, DAs

- Main objects: matrix elements of QCD light-cone ($z^2 = 0$) operators.

- Quark bilinear light-cone operator:

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

⇒ PDFs, meson DAs, GPDs, transition GPDs, etc.

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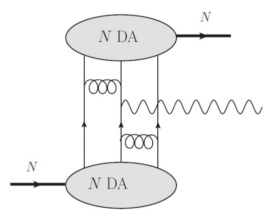
- $\langle A| = \langle 0|;\ |B\rangle$ - baryon $\Rightarrow$ baryon DA. QCD description of nucleon e.m. FF.

# Nucleon DA: well known examples

**Nucleon e.m. FF**

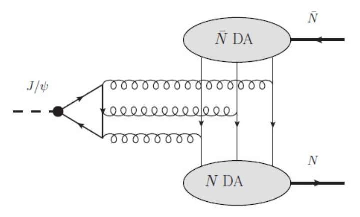
Brodsky & Lepage'81 Efremov & Radyushkin'80



**Charmonium decay**

$$J/\psi \to \bar{N} + N$$

Brodsky & Lepage'81 Chernyak, Ogloblin, and Zhitnitsky'89



- Valid at $Q^2$ =???

- Seems to be valid for $Q^2 = M^2_{J/\psi} \approx 10$ GeV$^2$.

- Looking for the experimental evidences for the validity of factorized description has major importance.

# Baryon-to-meson TDAs

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

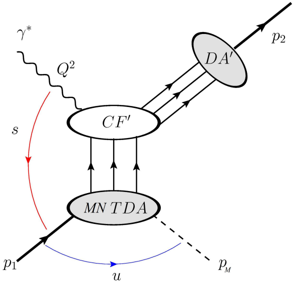
- Let $\langle A|$ be a photon $\gamma$ or a light meson state $(\pi,\ \eta,\ \rho,\ \omega,\ ...)$; $|B\rangle$ - a baryon $\Rightarrow$ baryon-to-photon or baryon-to-meson TDAs.

**Common features with**

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

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

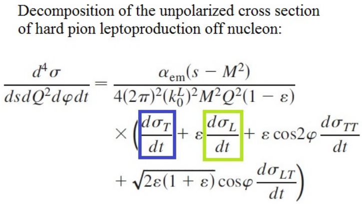
# Status of the formalism



- Baryon-to-photon TDAs. Can be accessed through backward DVCS (potentially the cleanest process). First development in J.P. Lansberg, B. Pire, L. Szymanowski'06. Some problems with implementing properly gauge invariance (resolvable issue, currently underway).
- Baryon-to-(pseudo)scalar meson TDAs. Backward $\pi$- and $\eta$-electroproduction J.P. Lansberg, B. Pire, L. Szymanowski'07. Detailed formalism developed in B. Pire, K. S., L. Szymanowski'11, J.P. Lansberg, B. Pire, K. S., L. Szymanowski'12.
- Baryon-to-vector meson TDAs. Backward $\rho$- , $\omega$ and $\phi$-electroproduction. B. Pire, K. S., L. Szymanowski, in preparation.

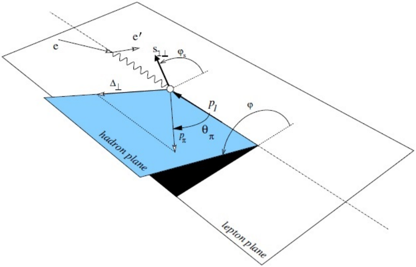
# Essential points allowing to judge on the validity of the factorized description

For definiteness consider backward pion electroproduction.



Decomposition of the unpolarized cross section of hard pion leptoproduction off nucleon:

$$\frac{d^4\sigma}{ds\,dQ^2\,d\varphi\,dt} = \frac{\alpha_{\rm em}(s-M^2)}{4(2\pi)^2(k_0^L)^2M^2Q^2(1-\varepsilon)} \times \left(\boxed{\frac{d\sigma_T}{dt}} + \varepsilon\boxed{\frac{d\sigma_L}{dt}} + \varepsilon\cos 2\varphi\frac{d\sigma_{TT}}{dt} + \sqrt{2\varepsilon(1+\varepsilon)}\cos\varphi\frac{d\sigma_{LT}}{dt}\right)$$

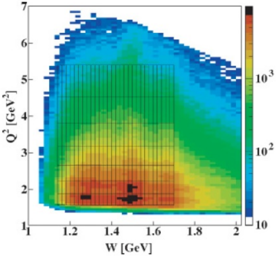


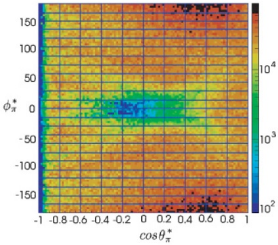
- Marking signs:
  1. $1/Q^8$ scaling behavior of $d^2\sigma/d\Omega_\pi$ cross section.
  2. Off-shell photon is transversally polarized at leading twist ⇒ proper component of the cross section to be separated through harmonic analysis.
  3. Universality of TDAs.

Needed: analysis similar to I. Bedlinskiy et al. [CLAS Collaboration], Exclusive $\pi^0$ electroproduction at $W > 2$ GeV with CLAS," arXiv:1405.0988 [nucl-ex].

# Backward pion electroproduction: JLab @ 6 GeV I

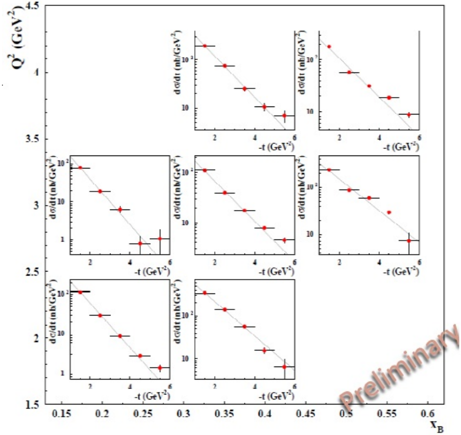
- Data from JLab @ 6 GeV exist for the backward $\gamma^* p \to \pi^+ n$. Analysis is still on-going by Kijun Park.
- Kinematical coverage for $\pi^+$ of the CLAS experiment K. Park et al., analysis note under preparation.





# Backward pion electroproduction: JLab @ 6 GeV II

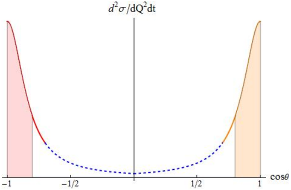
- Analysis of backward $\gamma^* p \to \pi^0 p$. A. Kubarovsky, CIPANP 2012; AIP Conf.Proc. 1560 (2013).

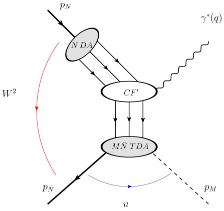


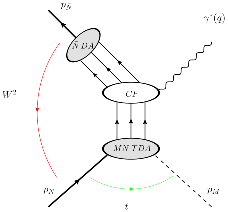
$$\frac{d\sigma}{dt} = A \cdot e^{Bt} \quad \text{(away from the forward peak)}$$

# Baryon to meson TDAs at $\bar{\text{P}}$ANDA I

- Factorized description of $\bar{N} + N \to \gamma^*(q) + M \to \ell^+ + \ell^- + M$ in terms of $MN$ TDAs.
- Time-like process with same universal TDAs.
- Two regimes (forward $t \sim 0$ and backward $u \sim 0$). $C$ invariance $\Rightarrow$ perfect symmetry. (Lansberg et al.'12)



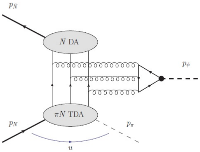


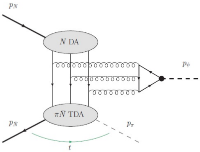


- Planned to be done with the proton FF studies in the timelike region.
- First detailed feasibility studies of $\bar{p}p \to e^+e^-\pi^0$: PANDA Collaboration and K.S. "Experimental access to Transition Distribution Amplitudes with the $\bar{\text{P}}$ANDA experiment at FAIR" arXiv:1409.0865, submitted to EPJ C.

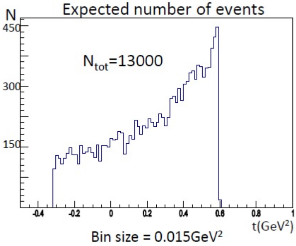
# Baryon to meson TDAs at P̄ANDA II

- Charmonium production in association with a pion $\bar{N} + N \to J/\psi + \pi$: B. Pire K.S. and L. Szymanowski'13.
- Goes along with P̄ANDA heavy quarkonium program.
- Same TDAs ⇒: test of universality.





- Feasibility tests for P̄ANDA: B. Ma, PhD thesis, Orsay 2014.
  First study for $W^2 = 12.25$ GeV$^2$, near forward regime assumed integrated luminosity: 2 fb$^{-1}$ (4 months of beamtime at full luminosity) with 100% efficiency.
- Detailed studies: E. Atomssa, B. Ramstein, K.S., in preparation.



## Leading twist-3 $\pi N$ TDA

J.P.Lansberg, B.Pire & L.Szymanowski'07:

$$\begin{aligned}
&4(P\cdot n)^3 \int \left[\prod_{i=1}^{3} \frac{dz_i}{2\pi} e^{ix_i z_i (P\cdot n)}\right] \langle \pi(p_\pi)|\, \varepsilon_{c_1 c_2 c_3} \Psi_\rho^{c_1}(z_1 n)\Psi_\tau^{c_2}(z_2 n)\Psi_\chi^{c_3}(z_3 n)\,|N(p_1,s_1)\rangle \\
&= \delta(2\xi - x_1 - x_2 - x_3)\, i \frac{f_N}{f_\pi M} \\
&\times \Big[ V_1^{\pi N}(\hat P C)_{\rho\tau}(\hat P U)_\chi + A_1^{\pi N}(\hat P \gamma^5 C)_{\rho\tau}(\gamma^5 \hat P U)_\chi + T_1^{\pi N}(\sigma_{P\mu} C)_{\rho\tau}(\gamma^\mu \hat P U)_\chi \\
&+ V_2^{\pi N}(\hat P C)_{\rho\tau}(\hat \Delta U)_\chi + A_2^{\pi N}(\hat P \gamma^5 C)_{\rho\tau}(\gamma^5 \hat \Delta U)_\chi + T_2^{\pi N}(\sigma_{P\mu} C)_{\rho\tau}(\gamma^\mu \hat \Delta U)_\chi \\
&+ \frac{1}{M} T_3^{\pi N}(\sigma_{P\Delta} C)_{\rho\tau}(\hat P U)_\chi + \frac{1}{M} T_4^{\pi N}(\sigma_{P\Delta} C)_{\rho\tau}(\hat \Delta U)_\chi \Big]
\end{aligned}$$

- $P = \frac{1}{2}(p_1 + p_\pi)$; $\Delta = (p_\pi - p_1)$; $n^2 = p^2 = 0$; $2p\cdot n = 1$; $\sigma_{P\mu} \equiv P^\nu \sigma_{\nu\mu}$;
- $C$: charge conjugation matrix;
- $f_N = 5.2 \cdot 10^{-3}$ GeV$^2$ (V. Chernyak and A. Zhitnitsky'84);
- $\xi = -\frac{\Delta\cdot n}{2P\cdot n}$
- 8 TDAs: $H(x_1, x_2, x_3, \xi, \Delta^2, \mu^2) \equiv \{V_i, A_i, T_i\}(x_1, x_2, x_3, \xi, \Delta^2, \mu^2)$ (only 3 are relevant for $\Delta_T^2 \approx 0$).
- c.f. 3 leading twist nucleon DAs: $V^p$, $A^p$, $T^p$

# Interpretation and modelling of $\pi N$ TDAs I

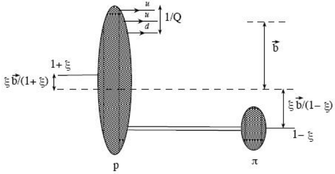
- Mellin moments in $x_i \Rightarrow \pi N$ matrix elements of local operators

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

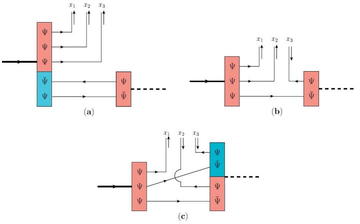
- Same problem as for higher Mellin moments of GPDs: at the moment no bright interpretation of hadronic structural information. Some hint can be given by M.V. Polyakov, PLB 555, 57: tensorial characteristics of the quark (gluon) matter inside hadrons and nuclei.
- The corresponding Mellin moments can in principle be studied on the lattice. See the recent progress in the nucleon DA lattice calculations V.M. Braun et al., Phys.Rev. D89 (2014) 9, 094511.
- $\pi N$ matrix elements of related operators were studied in a different context of nucleon decay processes by Y. Aoki et al..

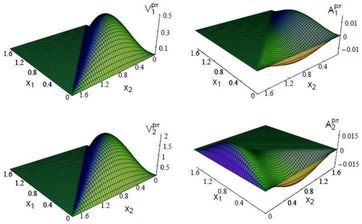
# Interpretation and modelling of $\pi N$ TDAs II

- Impact parameter space interpretation: the Fourier transform $\Delta_T \to b_T$ of TDAs $\Rightarrow$ transverse picture of the proton from a new perspective



- $\pi N$ TDAs provides information on the next to minimal Fock state. Light-cone quark model interpretation B. Pasquini et al. 2009:

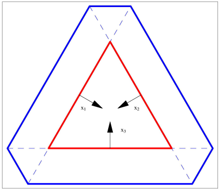




# Fundamental theoretical requirements for $\pi N$ TDAs:

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

1. restricted support in $x_1$, $x_2$, $x_3$: intersection of three stripes $-1+\xi \le x_i \le 1+\xi$ ($\sum_i x_i = 2\xi$)
2. polynomialty in $\xi$ of the Mellin moments in $x_i$
3. isospin + permutation symmetry
4. crossing: $\pi N$ TDA $\leftrightarrow$ $\pi N$ GDA
5. chiral properties: soft pion theorem P. Pobylitsa, M. Polyakov and M. Strikman'01 constrains $\pi N$ GDA at the threshold $\xi = 1$, $\Delta^2 = M^2$ in terms of nucleon DAs
6. QCD evolution



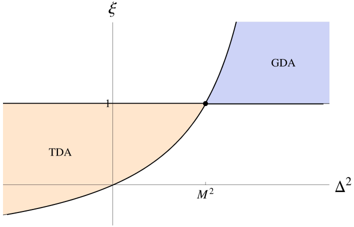
- Spectral representation A. Radyushkin'97 for $\pi N$ TDAs: polynomiality and support:

$$H(x_1,\, x_2,\, x_3 = 2\xi - x_1 - x_2,\, \xi)$$
$$= \left[\prod_{i=1}^{3} \int_{\Omega_i} d\beta_i d\alpha_i\right] \delta(x_1 - \xi - \beta_1 - \alpha_1 \xi)\,\delta(x_2 - \xi - \beta_2 - \alpha_2 \xi)$$
$$\times \delta(\beta_1 + \beta_2 + \beta_3)\delta(\alpha_1 + \alpha_2 + \alpha_3 + 1) F(\beta_1,\, \beta_2,\, \beta_3,\, \alpha_1,\, \alpha_2, \alpha_3)\,;$$

- $\Omega_i$: $\{|\beta_i| \le 1,\ |\alpha_i| \le 1 - |\beta_i|\}$ are copies of the usual DD square ;
- $F(\ldots)$: six variables that are subject to two constraints $\Rightarrow$ quadruple distributions

## Crossing $\pi N$ TDA $\leftrightarrow$ $\pi N$ GDA and soft pion theorem

- Crossing relates $\pi N$ TDAs in $\gamma^* N \to \pi N'$ and $\pi N$ GDAs (light-cone wave function)
- Physical domain in $(\Delta^2, \xi)$-plane (defined by $\Delta_T^2 \leq 0$) in the chiral limit $(m = 0)$:



- Soft pion theorem Pobylitsa, Polyakov and Strikman'01 ($Q^2 \gg \Lambda^3_{\mathrm{QCD}}/m$) constrains $\pi N$ TDAs/GDAs at the threshold $\xi = 1$, $\Delta^2 = M^2$. in terms of nucleon DAs $V^p$, $A^p$, $T^p$ (see V. Braun, D. Ivanov, A.Lenz, A.Peters'08).

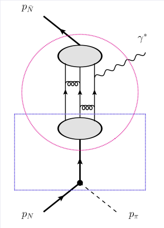
# Realistic strategy for modeling $\pi N$ TDAs

## How to model quadruple distributions?

- No enlightening $\xi = 0$ limit as for GPDs
- In the limit $\xi \to 1$ $\pi N$ TDAs are fixed due to soft pion theorems in terms of nucleon DAs
- Start from $\xi = 1$ limit rather than the forward limit $\xi = 0$ to fix the overall magnitude of quadruple distributions: factorized Ansatz inspired by RDDA for GPDs
- Phenomenological solutions for nucleon DA (COZ, KS, GS, BLW, BK, etc.) can be taken as numerical input

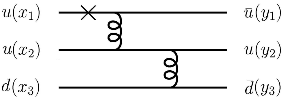
## Two component model

- $u$-channel nucleon exchange is complementary to the spectral representation: $D$-term
- non-zero in the ERBL-like region $0 \leq x_i \leq 2\xi$



## Calculation of the amplitude

- LO amplitude for $\gamma^* p \to p\pi^0$ can be computed as in J.P. Lansberg, B. Pire and L. Szymanowski'07
- 21 diagrams contribute (7 once employing better notations)



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

Each $R_\alpha$, has the structure:

$$R_\alpha \sim K_\alpha(x_1,x_2,x_3) \times Q_\alpha(y_1,y_2,y_3) \times$$
$$\text{[combination of } \pi N \text{ TDAs]} \times \text{[combination of nucleon DAs]}$$

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

$$\text{c.f.} \quad \int_{-1}^{1} dx \frac{H(x,\xi)}{x \pm \xi \mp i\epsilon} \int_0^1 dy \frac{\phi_M(y)}{y} \quad \text{for HMP}$$

# Cross section calculation

- Leading order amplitude of backward hard pion production reads:

$$\mathcal{M}^{s_1 s_2}_{\lambda} = -i\frac{(4\pi\alpha_s)^2\sqrt{4\pi\alpha_{em}}f_N^2}{54 f_\pi}\frac{1}{Q^4}\Big[\mathcal{S}^{\lambda}_{s_1 s_2}\underbrace{\int d^3x\int d^3y\left(2\sum_{\alpha=1}^{7}T_\alpha+\sum_{\alpha=8}^{14}T_\alpha\right)}_{\mathcal{I}}$$

$$-\mathcal{S}'^{\lambda}_{s_1 s_2}\underbrace{\int d^3x\int d^3y\left(2\sum_{\alpha=1}^{7}T'_\alpha+\sum_{\alpha=8}^{14}T'_\alpha\right)}_{\mathcal{I}'}\Big].$$

- Spin structures $\mathcal{S}$ and $\mathcal{S}'$ are defined as

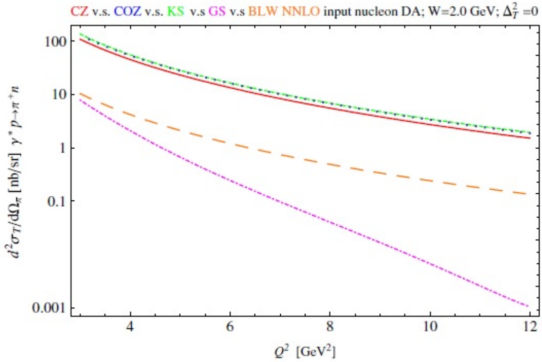
$$\mathcal{S}^{s_1 s_2}_{\lambda} \equiv \bar{u}(p_2, s_2)\hat{\varepsilon}(\lambda)\gamma^5 u(p_1, s_1)\,; \quad \mathcal{S}'^{s_1 s_2}_{\lambda} \equiv \frac{1}{M}\bar{u}(p_2, s_2)\hat{\varepsilon}(\lambda)\hat{\Delta}_T\gamma^5 u(p_1, s_1).$$

- Unpolarized cross section

$$\frac{d^2\sigma_T}{d\Omega_\pi} = |\mathcal{C}|^2\frac{1}{Q^6}\frac{\Lambda(s, m^2, M^2)}{128\pi^2 s(s-M^2)}\frac{1+\xi}{\xi}\left(|\mathcal{I}|^2-\frac{\Delta_T^2}{M^2}|\mathcal{I}'|^2\right).$$

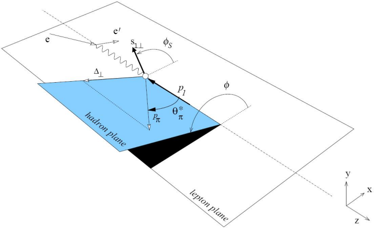
# Cross section estimates

- Numerical input: COZ, KS, GS, BLW NNLO phenomenological solutions for nucleon DAs
- Strong dependence on $\alpha_s$: $\sim \alpha_s^4$. Here we set $\alpha_s = \bar{\alpha}_s = 0.3$
- Nucleon pole contribution mostly dominates over the spectral part.

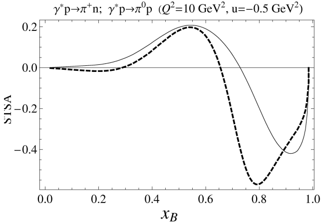


# Transverse Target Single Spin Asymmetry $\gamma^* N \to \pi N$

- TSA$= \sigma^{\uparrow} - \sigma^{\downarrow} \sim \mathrm{Im}$ part of the amplitude
- it probes the contribution of the DGLAP-like regions
- One expects a TSA vanishing with $Q^2$ and $W^2$ for (simple) baryon-exchange approaches
- Non vanishing and $Q^2$-independent TSA within TDA approach



$$\mathcal{A} = \frac{1}{|\vec{s}_1|}\left(\int_0^{\pi} d\tilde{\phi}|\mathcal{M}_T^{s_1}|^2 - \int_{\pi}^{2\pi} d\tilde{\phi}|\mathcal{M}_T^{s_1}|^2\right)\left(\int_0^{2\pi} d\tilde{\phi}|\mathcal{M}_T^{s_1}|^2\right)^{-1}$$



# Conclusions & Outlook

1. Nucleon to meson TDAs provide new information about $3D$-picture with focus on some correlations of partons inside nucleon
2. We strongly encourage to try to detect near forward and backward signals for various mesons ($\pi$, $\eta$, $\omega$, $\rho$, $\phi$): there is interesting physics around!
3. Theoretical understanding is growing up: spectral representation for $\pi N$ TDA based on quadruple distributions; factorized Ansatz for quadruple distributions with input at $\xi = 1$ is proposed.
4. Formalism for backward vector meson electroproduction is being developed.
5. $\phi$-meson case is of particular interest due to the new way to access strangeness contents of the nucleon.
6. Detailed feasibility studies of $\bar{p}N \to \pi \ell^+ \ell^-$ and $\bar{p}N \to \pi J/\psi$ for $\bar{\text{P}}$ANDA are underway.
7. JLab at 12 GeV analysis is crucial to check the validity of the suggested factorized description!
8. Open questions: proof of factorization theorems, interpretation in the impact parameter space, interpretation of the Mellin moments, access to nucleon-to-photon TDAs through backward DVCS, lattice calculations of the moments of the TDAs.