

Backward hard exclusive reactions and transition distribution amplitudes

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In collaboration with [B. Pire](#), [L. Szymanowski](#), [P. Sznajder](#),

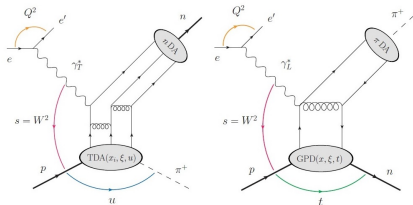
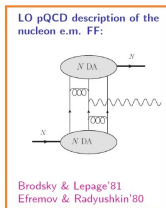


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Factorization regimes for hard meson production

Two complementary regimes in the Bjorken limit ($-q^2 = Q^2$, W^2 – large; $x_B = \frac{Q^2}{2p \cdot q}$ – fixed):

- $t \sim 0$ (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, P.V. Pobylitsa, M. V. Polyakov, M. Strikman'99;



For a review see: [B. Pire, K.S. and L. Szymanowski](#); experimental opportunities: [Eur.Phys.J.A 57 \(2021\) 12, 342](#)



Transition distribution amplitudes and hard exclusive reactions with baryon number transfer

B. Pire^a, K. Semenov-Tian-Shansky^{b,c,d}, L. Szymanowski^d

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Regular Article - Experimental Physics

THE EUROPEAN
PHYSICAL JOURNAL A



Progress and opportunities in backward angle (u -channel) physics

C. Ayerbe Gayoso^a, L. Biberzkycki^a, S. Diehl^{a,d}, S. Heppelmann^a, D. W. Higinbotham^a, G. M. Huber^a, S. J. D. Kay^a, S. R. Klein^a, J. M. Laget^a, W. B. Li^{b,c,e}, V. Mathieu^{b,c,f}, K. Park^g, R. J. Perry^h, B. Pire^a, K. Semenov-Tian-Shansky^{i,j,k}, A. Stancu^a, J. R. Stevens^a, L. Szymanowski^l, C. Weiss^a, B.-G. Yu^h

GPDs, DAs, GDAs and TDAs

- Quark-antiquark bilinear light-cone operator:

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

⇒ PDFs, meson DAs, meson-meson GDAs, GPDs, transition GPDs, etc;

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

$$\langle A | \Psi(z_1)[z_1; z_0] \Psi(z_2)[z_2; z_0] \Psi(z_3)[z_3; z_0] | B \rangle$$

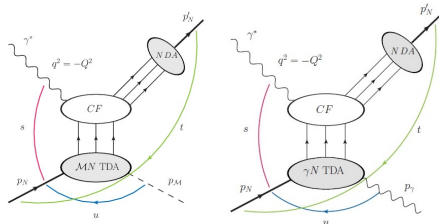
- $\langle A | = \langle 0 |$; $|B\rangle$ - nucleon; ⇒ nucleon DAs;
- Let $\langle A |$ be a meson state $\mathcal{M} = (\pi, \eta, \rho, \omega, \dots)$ or a photon γ ; $|B\rangle$ - nucleon; ⇒ $\mathcal{M}N$ TDAs; and γN TDAs
- $\langle A | = \langle 0 |$; $|B\rangle$ - nucleon-meson state; ⇒ nucleon-meson GDAs.

$\mathcal{M}N$ and γN TDAs have common features with:

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

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

Questions to address with $\mathcal{MN}$ and γN TDAs



[Learn more about QCD technique](#)

- A testbed for the QCD collinear factorization approach;
- πN and $\pi\eta$ TDAs: chiral dynamics playground;
- A challenge for the lattice QCD & functional approaches based on DS/BS equations;

Why TDAs are interesting?

- Possible access to the 5-quark components of the nucleon LC WF;
- γ and various mesons (π^0 , $\pi^\pm$, η , η' , ρ^0 , $\rho^\pm$, ω , ϕ , ...) probe different spin-flavor combinations;
- A view of the meson cloud and electromagnetic cloud inside a nucleon?
- Impact parameter picture: baryon charge distribution in the transverse plane;

Leading twist-3 πN TDAs

Proton-to- π^0 TDAs:

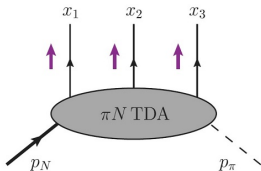
J.P.Lansberg, B.Pire, L.Szymanowski and K.S.'11 $\left(n^2 = p^2 = 0; 2p \cdot n = 1; \text{LC gauge } \boxed{A \cdot n = 0} \right)$.

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

$$= \delta(2\xi - x_1 - x_2 - x_3) i \frac{f_N}{f_\pi m_N} \sum_s \left(s^{\pi N} \right)_{\rho\tau\chi} H_s^{\pi N} \left(x_1, x_2, x_3, \xi, u; \mu^2 \right).$$

- $\frac{2^3 \cdot 2}{2} = 8$ TDAs: $\left\{ V_{1,2}^{\pi N}, A_{1,2}^{\pi N}, T_{1,2,3,4}^{\pi N} \right\} (x_1, x_2, x_3, \xi, \Delta^2; \mu^2)$;
- C.f. 3 leading twist-3 nucleon DAs: $\{V^p, A^p, T^p\}$
- $f_N = 5.2 \cdot 10^{-3} \text{ GeV}^2$ (V. Chernyak and A. Zhitnitsky'84);

- Momentum flow (ERBL):

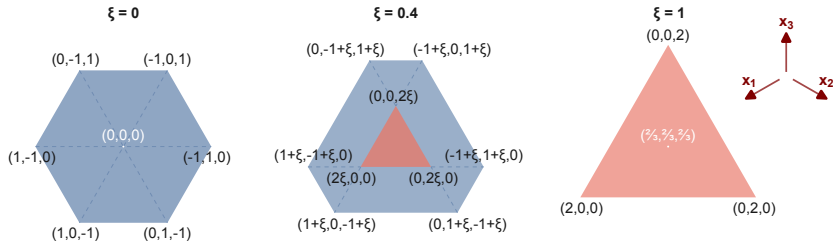


- TDAs: 3 sets of quark-diquark coordinates ($i = 1, 2, 3$)

$$x_1 + x_2 + x_3 = 2\xi; \quad w_i = x_i - \xi; \quad v_i = \frac{1}{2} \sum_{k,l=1}^3 \varepsilon_{ikl} x_k;$$

Fundamental properties I: support & polynomiality

- 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

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

Can be studied on the lattice!

- Polynomiality in ξ of the Mellin moments in x_k :

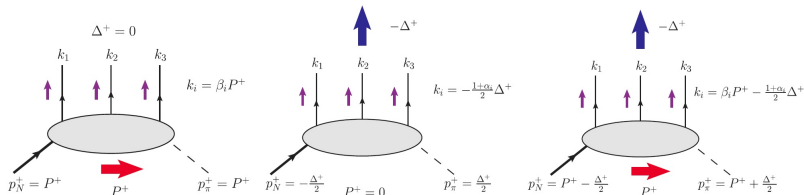
$$\int_{-1+\xi}^{1+\xi} dx_1 dx_2 dx_3 \delta\left(\sum_k x_k - 2\xi\right) x_1^{n_1} x_2^{n_2} x_3^{n_3} H^{\pi N}(x_1, x_2, x_3, \xi, \Delta^2) \\ = [\text{Polynomial of order } n_1 + n_2 + n_3 \{+1\}](\xi).$$

Fundamental properties II: spectral representation and evolution

- Spectral representation [A. Radyushkin'97](#) generalized for πN TDAs ensures polynomiality and support:

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

- Ω_i : $\{|\beta_i| \leq 1, |\alpha_i| \leq 1 - |\beta_i|\}$: 3 copies of the DD square support;
- $F(\dots)$: six variables that are subject to two constraints $\Rightarrow$ **quadruple distributions**;
- Can be supplemented with a D -term-like contribution (pure ERBL-like support);
- Evolution of 3-quark light-cone operator: [V. Braun, S. Derkachov, G. Korchemsky, A. Manashov'99](#).
- Evolution equations for TDAs: [B. Pire, L. Szymanowski'07](#) in the ERBL and DGLAP regions.

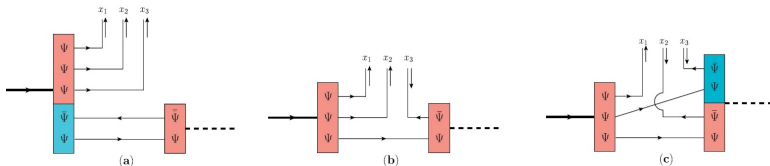


TDAs and light-front wave functions

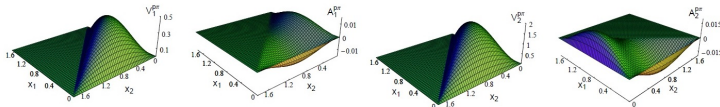
- Light-front quantization approach: πN TDAs provide information on next-to-minimal Fock components of light-cone wave functions of hadrons:

$$|N\rangle = \underbrace{\psi_{(3q)}|qqq\rangle}_{\text{Described by nucleon DA}} + \psi_{(3q+q\bar{q})}|qqq q\bar{q}\rangle + \dots$$

$$|M\rangle = \underbrace{\psi_{(q\bar{q})}|q\bar{q}\rangle}_{\text{Described by meson DA}} + \psi_{(q\bar{q}+q\bar{q})}|q\bar{q} q\bar{q}\rangle + \dots$$



- B. Pasquini et al., 2009; Andrea Schiavi, 2023: LFWF model calculations

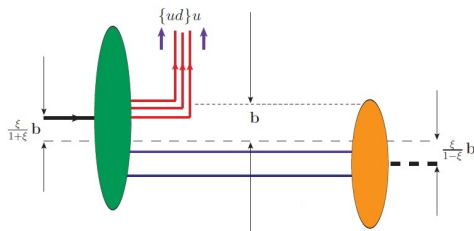


An interpretation in the impact parameter space

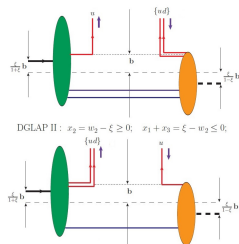
- A generalization of [M. Burkardt'00,02](#); [M. Diehl'02](#) for the v -integrated TDAs.
- Fourier transform with respect to

$$\mathbf{D} = \frac{\mathbf{p}_\pi}{1-\xi} - \frac{\mathbf{p}_N}{1+\xi}; \quad \Delta^2 = -2\xi \left(\frac{m_\pi^2}{1-\xi} - \frac{m_N^2}{1+\xi} \right) - (1-\xi^2)\mathbf{D}^2.$$

- A representation depends on the domain:



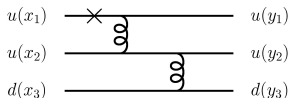
$$\text{ERBL} : x_2 = w_2 - \xi \geq 0; \quad x_1 + x_3 = \xi - w_2 \geq 0;$$



$$\text{DGLAP I} : x_2 = w_2 - \xi \leq 0; \quad x_1 + x_3 = \xi - w_2 \geq 0;$$

Calculation of the amplitude

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



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

$$R_{\alpha} \sim K_{\alpha}(x_1, x_2, x_3, \xi) \times Q_{\alpha}(y_1, y_2, y_3) \times$$

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

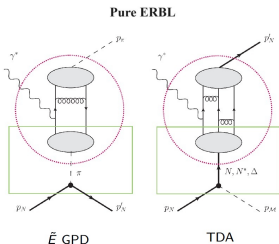
$$R_1 = \frac{q^u (2\xi)^2 [(V_1^{p\pi^0} - A_1^{p\pi^0})(V^p - A^p) + 4T_1^{p\pi^0} T^p + 2\frac{\Delta_T^2}{m_N^2} T_4^{p\pi^0} T^p]}{(2\xi - x_1 + i\epsilon)^2 (x_3 + i\epsilon) (1 - y_1)^2 y_3}$$

$$\text{C.f. } A(\xi) = \int_{-1}^1 dx \frac{H(x, \xi)}{x \pm \xi \mp i\epsilon} \int_0^1 dy \frac{\phi_M(y)}{y}$$

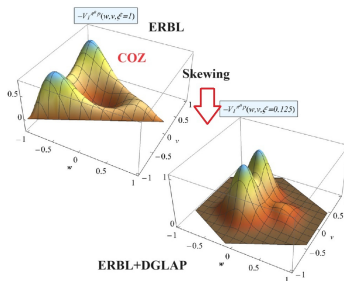
Building up a consistent model for πN TDAs (requirements and models)

- 1 support in x_k s and polynomiality;
- 2 isospin + permutation symmetry;
- 3 crossing πN TDA $\leftrightarrow$ πN GDA and chiral properties: soft pion theorem;
- No enlightening $\xi = 0$ limit as for GPDs;
- $\xi \rightarrow 1$ limit fixed from chiral dynamics in terms of nucleon DAs (soft pion theorem);
- “Poor man’s TDA model”:
 N cross-channel exchange;

- A factorized Ansatz for quadruple distributions with input at $\xi = 1$:
[Phys. Rev. D 85, 054021 \(2012\)](#)

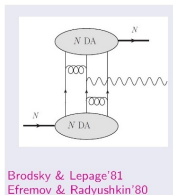
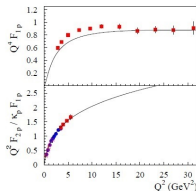


$$\mathcal{A} \sim \text{pQCD FF}$$



E.m. FF: a word of caution. Can we rely on collinear factorization?

- Leading twist dominance fails at $Q^2 \simeq 5 - 10 \text{ GeV}^2$;



Brodsky & Lepage'81
Efremov & Radyushkin'80

[Picture: Perdrisat, Punjabi and Vanderhaeghen'06]

- Delayed scaling regime. Importance of higher twist corrections!
- α_s/π penalty for each loop v.s. $1/Q^2$ suppression of end-point contributions.

How to fix it up:

- 1 TMD-dependant light-cone wave functions [Li and Sterman](#);
 - 2 Light cone sum rules approach: [V. Braun et al.](#);
 - 3 Soft spectator scattering from SCET: [N. Kivel and M. Vanderhaeghen'13](#);
 - 4 CZ-type nucleon DA effectively takes into account (a part of) soft rescattering mechanism contribution;
- Some good news on NLO pQCD analysis of nucleon FF: [Y. K. Huang, B. X. Shi, Y. M. Wang and X. C. Zhao, Phys. Rev. Lett. 135, 061901 \(2025\)](#); [L. B. Chen, W. Chen, F. Feng, S. Hu and Y. Jia, Phys. Rev. Lett. 135, 131903 \(2025\)](#);

How to check that the TDA-based reaction mechanism is relevant?

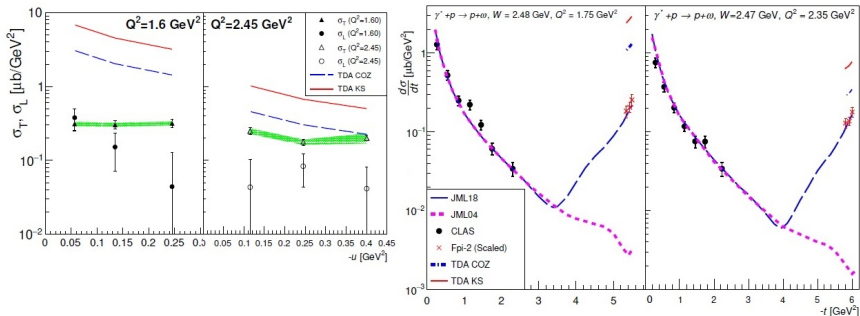
Distinguishing features

- Characteristic backward peak of the cross section. Special behavior in the near-backward region;
- Scaling behavior of the cross section in Q^2 : $\frac{d\sigma}{dt} \sim Q^{-10}$;
- Dominance of the transverse cross section σ_T ;
- Polarization observables
- Universality of TDAs: cross channel counterpart reactions.
- For time-like reactions: specific angular distribution of the lepton pair $\sim (1 + \cos^2 \theta_\ell)$;
- Color transparency arguments [G. Huber et al., MDPI Physics 4 \(2022\) 2, 451](#)

$$e + A(Z) \rightarrow e' + p' + A'(Z - 1) + \pi^0 \text{ v.s. } e + p \rightarrow e' + p' + \pi^0.$$

Status of experiment I

- Pioneering analysis of backward $\gamma^* p \rightarrow \pi^0 p$: [A. Kubarovsky, CIPANP 2012](#);
- Analysis of JLab @ 6 GeV data (Oct.2001-Jan.2002 run) for the backward $\gamma^* p \rightarrow \pi^+ n$
[K. Park et al. \(CLAS Collaboration\), PLB 780 \(2018\)](#);
- Backward ω -production at JLab Hall C.
[W. Li, G. Huber et al. \(The JLab \$F_\pi\$ Collaboration\), PRL 123, \(2019\)](#) :

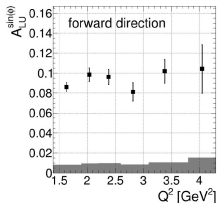
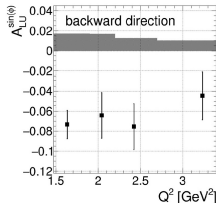
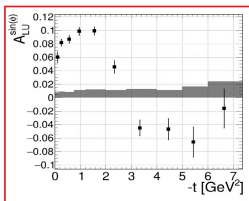


Polarization observables: Beam Spin Asymmetry @ CLAS

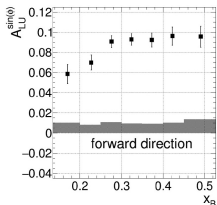
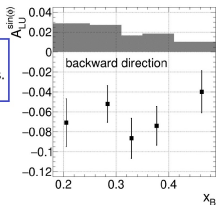
K. Joo, S. Diehl et al. (CLAS collaboration), [PRL 125 \(2020\)](#) ;

- The cross section of $ep \rightarrow e' n \pi^+$:

$$\frac{d^4\sigma}{dQ^2 dx_B d\varphi dt} = \sigma_0 \left(1 + A_{UU}^{\cos 2\varphi} \cos 2\varphi + A_{UU}^{\cos \varphi} \cos(\varphi) + A_{LU}^{\sin \varphi} \sin \varphi \right); \quad \text{BSA} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

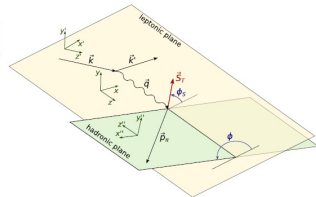


- BSA is a subleading twist effect both in the forward and backward regimes.



Polarization observables: SSAs and DSAs

$$\begin{aligned}
 & \left[\frac{\alpha_{\text{em}}}{8\pi^3} \frac{y^2}{1-x_B} \frac{1-x_B}{x_B Q^2} \right]^{-1} \frac{d^5\sigma}{dx_B dQ^2 dt d\phi d\psi} \\
 &= \underbrace{\frac{1}{2} \left(\frac{d\sigma_{++}^{+-}}{dt} + \frac{d\sigma_{+-}^{+-}}{dt} \right)}_{d\sigma_T/dt} + \varepsilon \frac{d\sigma_{00}^{+-}}{dt} - \varepsilon \cos(2\phi) \text{Re} \frac{d\sigma_{+-}^{+-}}{dt} - \sqrt{\varepsilon(1+\varepsilon)} \cos\phi \text{Re} \left(\frac{d\sigma_{+0}^{+-}}{dt} + \frac{d\sigma_{-0}^{+-}}{dt} \right) \\
 &+ P_\ell \sqrt{\varepsilon(1-\varepsilon)} \sin\phi \text{Im} \left(\frac{d\sigma_{+0}^{+-}}{dt} + \frac{d\sigma_{-0}^{+-}}{dt} \right) + S_L \left[\varepsilon \sin(2\phi) \text{Im} \frac{d\sigma_{+-}^{+-}}{dt} + \sqrt{\varepsilon(1+\varepsilon)} \sin\phi \text{Im} \left(\frac{d\sigma_{+0}^{+-}}{dt} - \frac{d\sigma_{-0}^{+-}}{dt} \right) \right] \\
 &+ S_L P_\ell \underbrace{\left[\sqrt{1-\varepsilon^2} \frac{1}{2} \left(\frac{d\sigma_{++}^{+-}}{dt} - \frac{d\sigma_{+-}^{+-}}{dt} \right) \right]}_{A_{LL}^{\text{const}}} - \sqrt{\varepsilon(1-\varepsilon)} \cos\phi \text{Re} \left(\frac{d\sigma_{+0}^{+-}}{dt} - \frac{d\sigma_{-0}^{+-}}{dt} \right) \\
 &+ S_T \underbrace{\left[\text{Im} \left(\frac{d\sigma_{++}^{+-}}{dt} + \varepsilon \frac{d\sigma_{00}^{+-}}{dt} \right) \sin(\phi - \phi_S) \right]}_{A_{UT}^{\sin(\phi-\phi_S)}} + \frac{\varepsilon}{2} \sin(\phi + \phi_S) \text{Im} \frac{d\sigma_{+-}^{+-}}{dt} \\
 &+ \frac{\varepsilon}{2} \sin(3\phi - \phi_S) \text{Im} \frac{d\sigma_{+-}^{+-}}{dt} + \sqrt{\varepsilon(1+\varepsilon)} \sin\phi_S \text{Im} \frac{d\sigma_{+0}^{+-}}{dt} + \sqrt{\varepsilon(1+\varepsilon)} \sin(2\phi - \phi_S) \text{Im} \frac{d\sigma_{-0}^{+-}}{dt} \\
 &+ S_T P_\ell \underbrace{\left[\sqrt{1-\varepsilon^2} \text{Re} \frac{d\sigma_{++}^{+-}}{dt} \cos(\phi - \phi_S) \right]}_{A_{LT}^{\cos(\phi-\phi_S)}} - \sqrt{\varepsilon(1-\varepsilon)} \cos\phi_S \text{Re} \frac{d\sigma_{+0}^{+-}}{dt} - \sqrt{\varepsilon(1-\varepsilon)} \cos(2\phi - \phi_S) \text{Re} \frac{d\sigma_{-0}^{+-}}{dt}.
 \end{aligned}$$



- Leading twist (Q^2 -independent) DSAs with the TDA-based formalism;
- Transverse target spin asymmetry:

$$A_{UT} = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}.$$

DSA 1

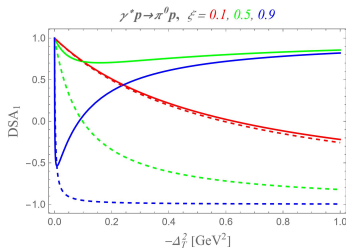
- Experimental definition for DSA_1 :

$$A_{LL}(\phi_i) = \frac{1}{P_B P_T} \frac{(N_i^{\rightarrow\Rightarrow} + N_i^{\leftarrow\Leftarrow}) - (N_i^{\rightarrow\Leftarrow} + N_i^{\leftarrow\Rightarrow})}{N_i^{\rightarrow\Rightarrow} + N_i^{\leftarrow\Leftarrow} + N_i^{\rightarrow\Leftarrow} + N_i^{\leftarrow\Rightarrow}}$$

- DSA_1 for near-backward $\gamma^* N \rightarrow \pi N'$:

$$\text{DSA}_1 = \frac{|\mathcal{I}^{(1)}(\xi, \Delta^2)| + \frac{\Delta_T^2}{m_N^2} |\mathcal{I}^{(2)}(\xi, \Delta^2)|}{|\mathcal{I}^{(1)}(\xi, \Delta^2)| - \frac{\Delta_T^2}{m_N^2} |\mathcal{I}^{(2)}(\xi, \Delta^2)|}.$$

- DSA_1 within cross channel nucleon exchange model v.s. two component model for πN TDAs:



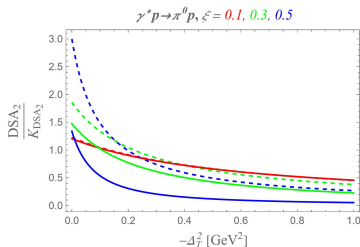
DSA 2

- Longitudinal beam, transverse target DSA:

$$A_{LT}(\phi_i) = \frac{1}{P_B P_{T_T}} \frac{(N_i^{\rightarrow\uparrow} + N_i^{\leftarrow\downarrow}) - (N_i^{\rightarrow\downarrow} + N_i^{\leftarrow\uparrow})}{N_i^{\rightarrow\uparrow} + N_i^{\leftarrow\downarrow} + N_i^{\rightarrow\downarrow} + N_i^{\leftarrow\uparrow}};$$

- DSA₂ - ϕ -independent part of A_{LT} :

$$\text{DSA}_2 = \frac{-2(s_T \cdot \Delta_T)}{m_N} \frac{\text{Re}[\mathcal{I}^{(1)}(\xi, \Delta^2) \mathcal{I}^{(2)*}(\xi, \Delta^2)]}{|\mathcal{I}^{(1)}(\xi, \Delta^2)| - \frac{\Delta_T^2}{m_N^2} |\mathcal{I}^{(2)}(\xi, \Delta^2)|}$$



What we may learn from these polarization observables?

- Q^2 -independence: reaction mechanism cross check;
- Insight for phenomenological models: going beyond the “cross-channel nucleon exchange” model;
- Helps to single out the contribution of different sets of TDAs: $\{V, A, T\}_1$ v.s. $\{V, A, T\}_2$.

Status of experiment II: Backward π^0 -production at JLab Hall C

W. B. Li, G. M. Huber et al., [arXiv:2008.10768 \[nucl-ex\]](https://arxiv.org/abs/2008.10768) :

PAC48 REPORT

PR12-20-007

August 10-14, 2020

September 25, 2020



Scientific Rating: B

Recommendation: Approved

Beam time scheduled for 2027



Title: Backward-angle Exclusive π^0 Production above the Resonance Region

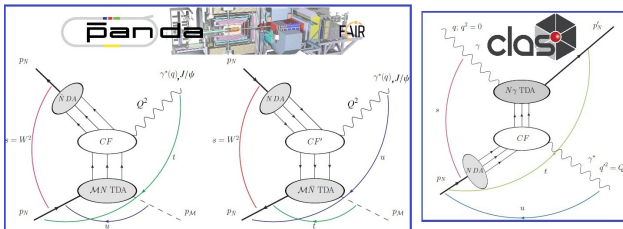
Spokespersons: W. Li (contact), J. Stevens, G. Huber

Motivation: This proposal aims at measuring backward-angle exclusive π^0 production above the resonance region with a proton target. Theoretical models to describe this process include a soft mechanism (Regge exchange) and a hard QCD mechanism in terms of so-called transition distribution amplitudes (TDAs). Since the applicability of the TDA formalism is not guaranteed, the proposal aims at checking two specific predictions: the dominance of the σ_T cross section over σ_L and the $1/Q^8$ behavior of the cross section. The idea of a u -channel exchange is an interesting concept that is worth exploring.

Measurement and Feasibility: The proposed measurement will take place in Hall C.

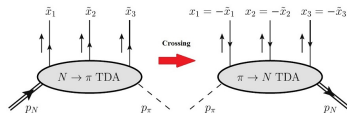
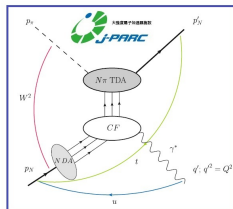
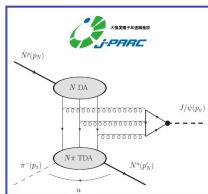
Cross channel counterpart reactions: $\bar{\text{P}}\text{ANDA}$, J-PARC and backward TCS at JLab

- Complementary experimental options and **universality** of TDAs.



Backward TCS: [B.Pire, K.S., A. Shaikhutdinova, L.Szymanowski, Eur. Phys. J. C 82, 656 \(2022\)](#)

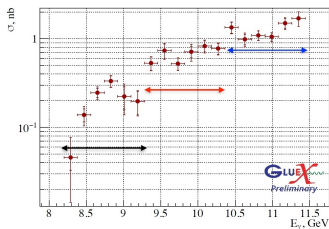
- γ_T^* dominance: $(1 + \cos^2 \theta_\ell)$ angular dependence;
- large $-t$: small BH background.
- Crude cross section estimates: $\text{VMD} + \gamma^* N \rightarrow VN + \text{crossing}$.



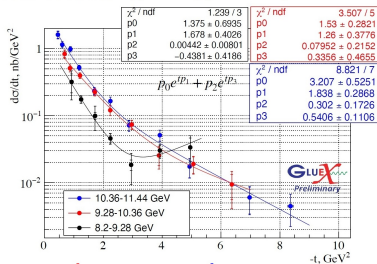
Charmonium photoproduction

GlueX Collaboration, [Phys.Rev.C 108 \(2023\) 2, 025201](#)

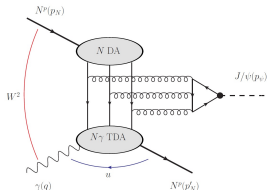
GlueX results: total and differential cross-sections $\gamma p \rightarrow J/\psi p \rightarrow e^+e^-p$



$$-t_0 = 4.4 \pm 7.0 \text{ GeV}^2; \quad -t_0 = 7.0 \pm 9.3 \text{ GeV}^2; \quad -t_0 = 7.2 \pm 11.4 \text{ GeV}^2;$$



B.Pire, K.S., A. Shaikhutdinova, L.Szymanowski, [AAPPS Bull. 33, 26 \(2023\)](#)



- VMD based model for γN TDAs largely underestimates the size of the backward peak;
- Can we normalize our model to data?
- Universality for different E_γ .

New models for πN TDAs: a generalization of RDDA

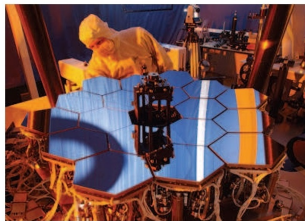
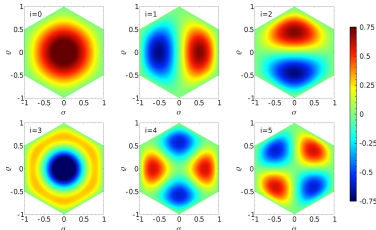
Flexible parametrization B. Pire, K.S., L. Szymanowski and P. Sznajder, [Phys.Rev.D 112 \(2025\)](#)

$$F(\beta_1, \beta_2, \beta_3, \alpha_1, \alpha_2, \alpha_3; u) = \underbrace{F^{(0)}(\beta_1, \beta_2, \beta_3, \alpha_1, \alpha_2, \alpha_3; u)}_{\text{Fixed from soft pion theorem at } \xi = 1} + (1 - \xi) \underbrace{F^{(1)}(\beta_1, \beta_2, \beta_3, \alpha_1, \alpha_2, \alpha_3; u)}_{\text{Free model input, fitted to data}}.$$

- This part is independent from $\xi \rightarrow 1$ limit and can be fitted to data;
- Spectral density designed from a factorized Ansatz with input at $\xi = 0$:

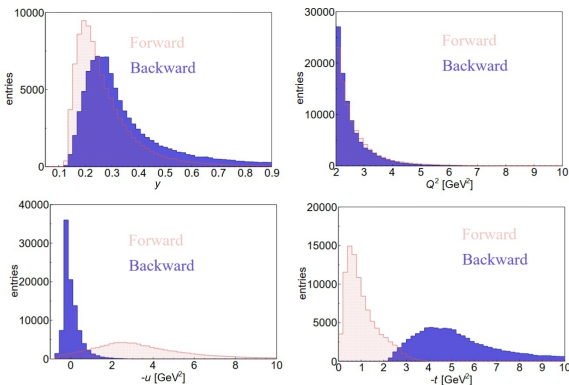
$$F^{(1)}(\sigma, \rho, \omega, \nu; u) = f(\sigma, \rho) \underbrace{h(\sigma, \rho, \omega, \nu)}_{\text{profile function}} G(u).$$

- Forward function $f(\sigma, \rho)$ can be expanded over the set of orthogonal polynomials on the hexagon: generalization of the Zernike polynomials;



New models for πN TDAs: results

- Events from EplC MCG for “forward” and “backward” $ep \rightarrow ep\pi^0$ for $E_e = 10.6$ GeV;
- $0.05 < y < 0.9$; $2 \text{ GeV}^2 < Q^2 < 10 \text{ GeV}^2$;
- $0 < |t - t_0| < 1.5 \text{ GeV}^2$ (for forward events); $0 < |u - u_0| < 1.5 \text{ GeV}^2$ (for backward);
- Forward: Goloskokov-Kroll (GK) model;
- Backward: two component model for TDAs “normalized” to JLab@6 GeV data;



$$u = 2m_N^2 + m_\pi^2 - Q^2 - s - t.$$

Conclusions & Outlook

- 1 Nucleon-to-meson TDAs provide new information about correlation of partons inside hadrons. A consistent picture for the integrated TDAs emerges in the impact parameter representation;
- 2 We strongly encourage to consider backward electroproduction for various mesons (π , η , ω , ρ) and cross channel counterpart reaction;
- 3 First evidences for the onset of the factorization regime in backward $\gamma^* N \rightarrow N' \omega$ from JLab Hall C analysis and BSA measurements in $\gamma^* p \rightarrow \pi^+ n$ from CLAS;
- 4 PAC 48 decision is a challenge both for the experiment and for theory. An effort is required. Factorization theorem (?), more on physical interpretation (?), phenomenological models ✓;
- 5 Backward DVCS and TCS: options for EIC;
- 6 Backward scattering off mesons through the Sullivan process;

More options: backward reactions off pions I

A. Castro, C. Mezrag, J. Morgado Chávez and B. Pire, [Phys.Rev.D 112 \(2025\)](#)

● Pion-to- γ TDAs:

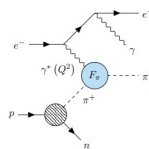
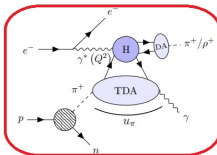
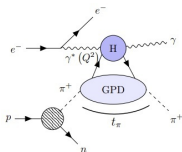
$$\frac{e}{f_\pi} (\epsilon \cdot \Delta) A^{\pi\gamma}(x, \xi, u; \mu) = \frac{1}{2} \int \frac{dz^-}{2\pi} e^{ixP^+z^-} \left\langle \gamma(q', \epsilon) \left| \bar{\psi}_d(-z/2) \gamma^+ \gamma_5 \psi_u(z/2) \right| \pi(p_\pi) \right\rangle \Big|_{z^+=z_\perp^i=0}$$

$$\frac{i}{P^+} \frac{e}{f_\pi} \epsilon_{\mu\nu\rho\sigma} n^\mu \epsilon^\nu P^\rho \Delta_\perp^\sigma V^{\pi\gamma}(x, \xi, u; \mu) = \frac{1}{2} \int \frac{dz^-}{2\pi} e^{ixP^+z^-} \left\langle \gamma(q', \epsilon) \left| \bar{\psi}_d(-z/2) \gamma^+ \psi_u(z/2) \right| \pi(p_\pi) \right\rangle \Big|_{z^+=z_\perp^i=0}$$

● Normalization to pion vector and axial FFs accessed in $\pi^+ \rightarrow \ell^+ \nu_\ell \gamma$ decays:

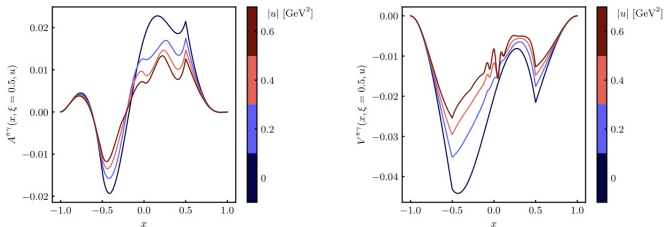
$$\int_{-1}^1 dx A^{\pi\gamma}(x, \xi, u, \mu) = \frac{f_\pi}{m_\pi} F_A(u); \quad \int_{-1}^1 dx V^{\pi\gamma}(x, \xi, u, \mu) = \frac{f_\pi}{m_\pi} F_V(u).$$

● Can be accessed through the Sullivan process:

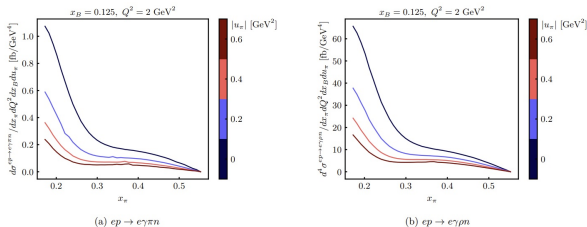


More options: backward reactions off pions II

- Modeling $\gamma\pi$ TDAs in the DGLAP region from the LF wave functions overlap;
- Covariant extension to the ERBL region;



- Cross section estimates for JLab@22 GeV:



- Crossing to backward TCS off a pion; studies under way [M. Dufurne, B. Pire et al. and K.S.](#)

Thank you for your attention!