News on backward exclusive reactions and TDAs

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August 05-09, 2024: Towards improved hadron tomography with hard exclusive reactions ECT*, Trento

Outline

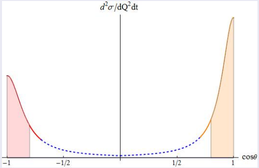
1. Introduction: Forward and backward kinematical regimes, DAs, GPDs, TDAs;
2. Nucleon-to-meson and nucleon-to-photon TDAs: definition and properties;
3. Physical contents of TDAs;
4. Current status of experiment and future prospects;
5. Polarization observables;
6. Backward charmonium photoproduction and implication for TDA models;
7. Summary and Outlook.

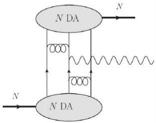
In collaboration with B. Pire and L. Szymanowski, for a review see Phys.Rept. 940 (2021), 1

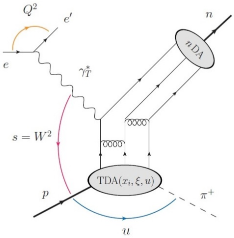
Factorization regimes for hard meson production

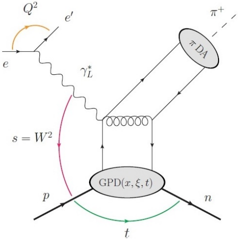
Two complementary regimes in generalized Bjorken limit ($-q^2 = Q^2$, W^2 – large; $x_B = \frac{Q^2}{2p \cdot q}$ – fixed):

- $t \sim 0$ (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, PRD 60, '99;









- Main objects: matrix elements of QCD light-cone ($z^2 = 0$) operators;
- Quark-antiquark bilinear light-cone operator:

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

$\Rightarrow$ PDFs, meson DAs, meson-meson GDAs, GPDs, transition GPDs, *etc*;

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

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

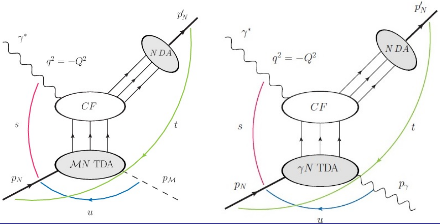
- $\langle A| = \langle 0|$; $|B\rangle$ - baryon; $\Rightarrow$ baryon DAs;
- Let $\langle A|$ be a meson state $\mathcal{M} =(\pi,\,\eta,\,\rho,\,\omega,\,...)$ $|B\rangle$ - nucleon; $\Rightarrow$ $\mathcal{M}N$ TDAs;
- Let $\langle A|$ be a photon state $|B\rangle$ - nucleon; $\Rightarrow$ nucleon-to-photon TDAs;
- $\langle A| = \langle 0|$; $|B\rangle$ - baryon-meson state; $\Rightarrow$ baryon-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 $\Rightarrow$ skewness:

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

Questions to address with $\mathcal{M}N$ 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;

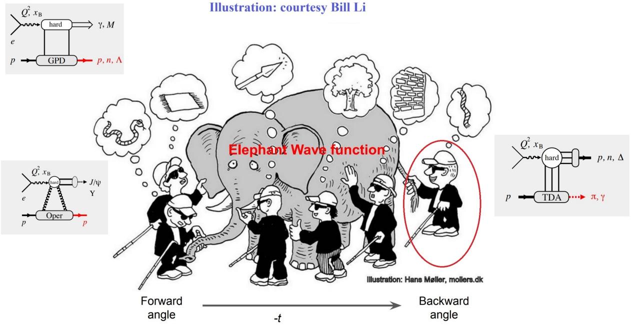
Why TDAs are interesting?

- 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, $\ldots$) 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;

A list of key issues for the rest of the talk:

- What are the properties and physical contents of nucleon-to-meson TDAs?
- What are the marking signs for the onset of the collinear factorization regime?
- Status of phenomenological models;
- Can we access backward reactions experimentally?

More on the opportunities for backward processes: Eur.Phys.J.A 57 (2021) 12, 342



Leading twist-3 πN TDAs

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

- πN: $\frac{2^3 \cdot 2}{2} = 8$ TDAs: $\left\{V_{1,2}^{\pi N},\ A_{1,2}^{\pi N},\ T_{1,2,3,4}^{\pi N}\right\}(x_1,\ x_2,\ x_3,\ \xi,\ \Delta^2, \mu^2)$
- γN: $\frac{2^3 \cdot 2 \cdot 2}{2} = 16$ TDAs; VN: $\frac{2^3 \cdot 2 \cdot 3}{2} = 24$ TDAs;

Proton-to-π^0 TDAs:

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

$$= \delta(2\xi - x_1 - x_2 - x_3) i \frac{f_N}{f_\pi m_N}$$

$$\times [V_1^{\pi N}(\hat{P}C)_{\rho\tau}(\hat{P}U)_\chi + A_1^{\pi N}(\hat{P}\gamma^5 C)_{\rho\tau}(\gamma^5 \hat{P}U)_\chi + T_1^{\pi N}(\sigma_{P\mu} C)_{\rho\tau}(\gamma^\mu \hat{P}U)_\chi$$

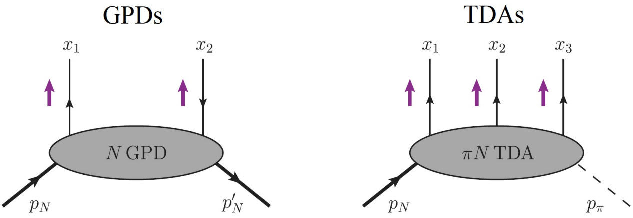
$$+ V_2^{\pi N}(\hat{P}C)_{\rho\tau}(\hat{\Delta}U)_\chi + A_2^{\pi N}(\hat{P}\gamma^5 C)_{\rho\tau}(\gamma^5 \hat{\Delta}U)_\chi + T_2^{\pi N}(\sigma_{P\mu} C)_{\rho\tau}(\gamma^\mu \hat{\Delta}U)_\chi$$

$$+ \frac{1}{m_N} T_3^{\pi N}(\sigma_{P\Delta} C)_{\rho\tau}(\hat{P}U)_\chi + \frac{1}{m_N} T_4^{\pi N}(\sigma_{P\Delta} C)_{\rho\tau}(\hat{\Delta}U)_\chi].$$

- $P = \frac{p_1 + p_\pi}{2}$; $\Delta = (p_\pi - p_1)$; $\sigma_{P\mu} \equiv P^\nu \sigma_{\nu\mu}$; $\xi = -\frac{\Delta \cdot n}{2P \cdot n}$
- C: charge conjugation matrix;
- $f_N = 5.2 \cdot 10^{-3}$ GeV^2 (V. Chernyak and A. Zhitnitsky'84);
- *C.f.* 3 leading twist-3 nucleon DAs: $\{V^p,\ A^p,\ T^p\}$

Three variables and intrinsic redundancy of description

- Momentum flow (ERBL):



- GPDs:

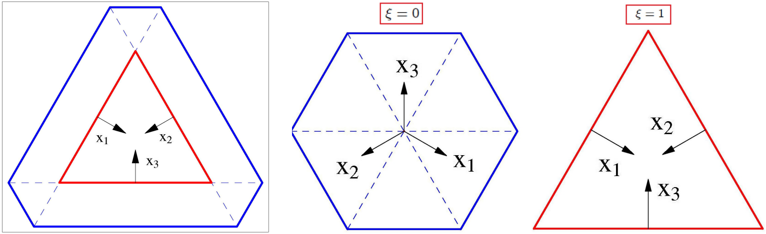
$$x_1 + x_2 = 2\xi; \quad x = \frac{x_1 - x_2}{2};$$

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

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

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

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

Can be studied on the lattice!

- Polynomiality in ξ of the Mellin moments in x_k:

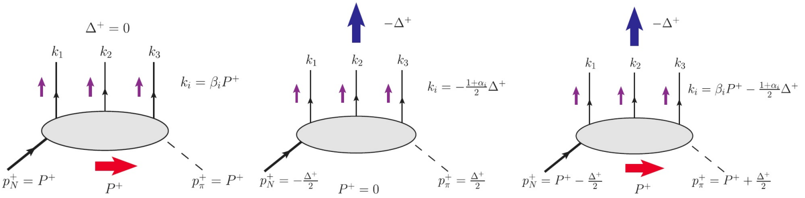
$$\int_{-1+\xi}^{1+\xi} dx_1 dx_2 dx_3 \delta(\sum_k x_k - 2\xi) x_1^{n_1} x_2^{n_2} x_3^{n_3} H^{\pi N}(x_1, x_2, x_3, \xi, \Delta^2)$$

$$= [\text{Polynomial of order } n_1 + n_2 + n_3 \{+1\}](\xi).$$

- Spectral representation A. Radyushkin'97 generalized for πN TDAs ensures polynomiality and support:

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

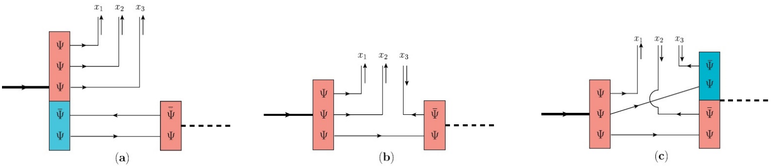
- Ω_i: $\{|\beta_i| \leq 1,\ |\alpha_i| \leq 1 - |\beta_i|\}$ are copies of the usual DD square support;
- $F(\ldots)$: six variables that are subject to two constraints $\Rightarrow$ quadruple distributions;
- Can be supplemented with a D-term-like contribution (pure ERBL-like support);
- Evolution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



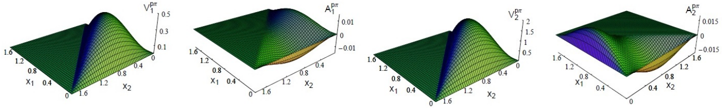
- Light-front quantization approach: πN TDAs provide information on next-to-minimal Fock components of light-cone wave functions of hadrons:

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

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



- B. Pasquini et al., 2009; Andrea Schiavi, 2024: LFWF model calculations



A connection to the quark-diquark picture

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

$$p : \uparrow\downarrow\uparrow \quad \underbrace{ud \uparrow\downarrow} \quad u\uparrow;$$

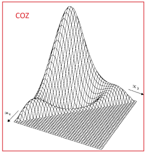
- The TDA support in quark-diquark coordinates
$\left(v_2 = \frac{x_3 - x_1}{2};\ \ w_2 = x_2 - \xi;\ \ x_1 + x_3 = 2\xi'_2;\ \ \left(\xi'_2 \equiv \frac{\xi - w_2}{2}\right)\right)$:

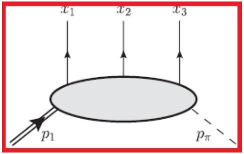
$$-1 \le w_2 \le 1; \quad -1 + \left|\xi - \xi'_2\right| \le v_2 \le 1 - \left|\xi - \xi'_2\right|$$

- v_2-Mellin moment of πN TDAs: "diquark-quark" light-cone operator

$$\int_{-1+|\xi-\xi'_2|}^{1-|\xi-\xi'_2|} dv_2 H^{\pi N}(w_2,\, v_2,\, \xi,\, \Delta^2)$$

$$\sim h^{-1}_{\rho\tau\chi} \int \frac{d\lambda}{4\pi} e^{i(w_2\lambda)(P\cdot n)} \langle \pi^0(p_\pi)| \underbrace{u_\rho(-\frac{\lambda}{2}n) u_\tau(\frac{\lambda}{2}n) d_\chi(-\frac{\lambda}{2}n)}_{\hat{O}^{\{ud\}u}_{\rho\chi\tau}(-\frac{\lambda}{2}n,\, \frac{\lambda}{2}n)} |N^p(p_1)\rangle.$$



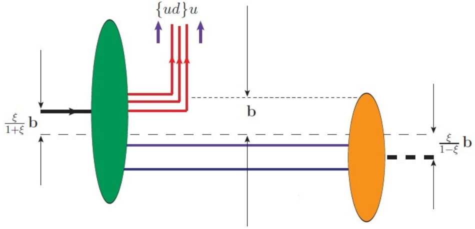


An interpretation in the impact parameter space

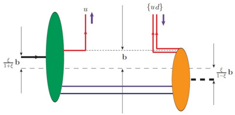
- A generalization of M. Burkardt'00,02; M. Diehl'02 for the v-integrated TDAs.
- Fourier transform with respect to

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

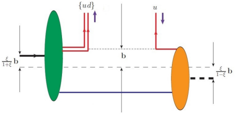
- A representation depends on the domain:



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

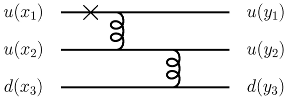


DGLAP II : $x_2 = w_2 - \xi \geq 0$; $\quad x_1 + x_3 = \xi - w_2 \leq 0$;



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

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



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

$$R_\alpha \sim K_\alpha(x_1, x_2, x_3, \xi) \times Q_\alpha(y_1, y_2, y_3) \times$$
[combination of πN TDAs] $(x_1, x_2, x_3, \xi) \times$ [combination of nucleon DAs] (y_1, y_2, y_3)

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

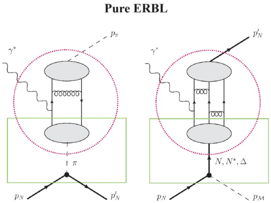
$$\text{C.f.} \quad A(\xi) = \int_{-1}^{1} dx \frac{H(x,\xi)}{x \pm \xi \mp i\epsilon} \int_0^1 dy \frac{\phi_M(y)}{y}$$

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

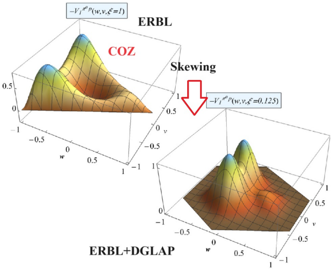
1. support in x_ks and polynomialty;
2. isospin + permutation symmetry;
3. crossing πN TDA $\leftrightarrow$ πN GDA and chiral properties: soft pion theorem;

- No enlightening $\xi = 0$ limit as for GPDs;
- $\xi \to 1$ limit fixed from chiral dynamics in terms of nucleon DAs (soft pion theorem);

- "Poor man's TDA model": N cross-channel exchange $\Rightarrow$ D-term-like contribution: $\tilde{E}$ GPD v.s. TDA; $\mathcal{A} \sim \mathrm{FF}$.

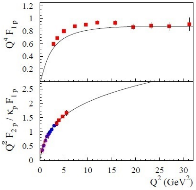


- A factorized Ansatz for quadruple distributions with input at $\xi = 1$: J.P. Lansberg, B. Pire, K.S., L. Szymanowski, Phys. Rev. D **85**, 054021 (2012)

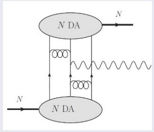


E.m. FF: a word of caution. Can we rely on collinear factorization?

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



[Picture: Perdrisat, Punjabi and Vanderhaeghen'06]



Brodsky & Lepage'81
Efremov & Radyushkin'80

- 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 scattering mechanism contribution;

- Some good news on NLO pQCD analysis of nucleon FF: Yong-Kang Huang et al. arXiv:2407.18724; W. Chen et al. arXiv:2406.19994;

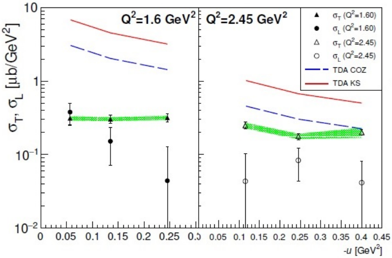
How to check that the TDA-based reaction mechanism is relevant?

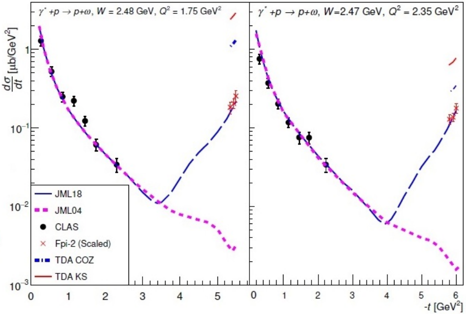
Distinguishing features

- 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;
  - For time-like reactions: specific angular distribution of the lepton pair $\sim (1 + \cos^2 \theta_\ell)$;
- Polarization observables
- Universality of TDAs: cross channel counterpart reactions.
- Color transparency arguments G. Huber et al., MDPI Physics 4 (2022) 2, 451

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

- Pioneering analysis of backward $\gamma^* p \to \pi^0 p$: A. Kubarovsky, CIPANP 2012;
- Analysis of JLab @ 6 GeV data (Oct.2001-Jan.2002 run) for the backward $\gamma^* p \to \pi^+ n$ 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_π Collaboration), PRL 123, (2019) ; Regge perspective: J.M. Laget, Phys. Rev. C **104**, no.2, 025202 (2021);





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]] :

PAC48 REPORT

August 10-14, 2020

September 25, 2020

Jefferson Lab

PR12-20-007

Scientific Rating: B

Recommendation: Approved

Beam time scheduled for 2025/26

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.

Polarization observables I

- Less sensitive to pQCD corrections;
- Smaller experimental uncertainties;
- What asymmetries are leading twist (Q^2-independent)?

What asymmetries can be formed?

$$\boxed{\textit{Set of projection operators}:}$$

- Longitudinal beam spin asymmetry:

$$\varepsilon_+^{\mu}\varepsilon_+^{\nu *} - \varepsilon_-^{\mu}\varepsilon_-^{\nu *} = i\frac{1}{q \cdot p_N}\varepsilon^{q p_N \mu\nu} \sim i\frac{1}{p \cdot n}\varepsilon^{p n \mu\nu},$$

  where $\pm$ refers to the photon helicity;
- Longitudinal target spin asymmetry:

$$U(p_N, h_N)\bar{U}(p_N, h_N) - U(p_N, -h_N)\bar{U}(p_N, -h_N) = h_N(\not{p}_N + m_N)\gamma_5;$$

- Transverse target spin asymmetry:

$$U(p_N, s_T)\bar{U}(p_N, s_T) - U(p_N, -s_T)\bar{U}(p_N, -s_T) = (\not{p}_N + m_N)\gamma_5 \not{s}_T;$$

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

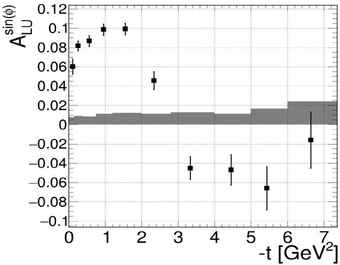
- The cross section of $ep \to e' n \pi^+$ can be expressed as

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

- Beam Spin Asymmetry

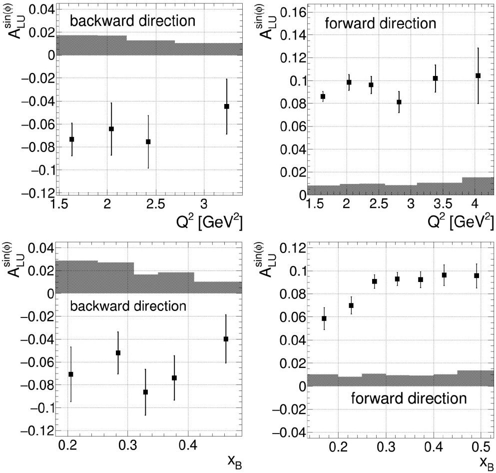
$$\mathrm{BSA}\left(Q^2, x_B, -t, \varphi\right) = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{A_{LU}^{\sin(\varphi)} \cdot \sin(\varphi)}{1 + A_{UU}^{\cos(\varphi)} \cdot \cos(\varphi) + A_{UU}^{\cos(2\varphi)} \cdot \cos(2\varphi)};$$

- $\sigma^\pm$ is the cross-section with the beam helicity states $(\pm)$.



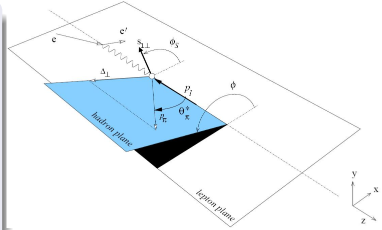
Beam Spin Asymmetry @ CLAS

- Beam Spin Asymmetry is a subleading twist effect both in the forward and backward regimes.

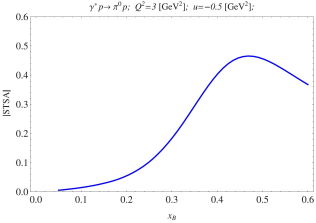


Polarization observables III: Transverse Target Single Spin Asymmetry

- TSA= $\sigma^{\uparrow} - \sigma^{\downarrow} \sim \mathrm{Im}$ part of the amplitude
- 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



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



Polarization observables IV: DSA_1

$$\frac{2\pi}{\Gamma(Q^2,x_B,E)}\frac{d^4\sigma^{ep\to epX}}{dQ^2dx_Bdtd\phi}=\sigma_T+\varepsilon\sigma_L+\sqrt{2\varepsilon(1+\varepsilon)}\sigma_{LT}^{cos(\phi)}cos(\phi)+\varepsilon\sigma_{TT}^{cos(2\phi)}cos(2\phi)$$

$$+P_B\left(\sqrt{2\varepsilon(1-\varepsilon)}\sigma_{LU}^{sin(\phi)}sin(\phi)\right) \quad \text{``beam-spin''}$$

$$+P_T\left(\sqrt{2\varepsilon(1+\varepsilon)}\sigma_{UL}^{sin(\phi)}sin(\phi)+\varepsilon\sigma_{UL}^{sin(2\phi)}sin(2\phi)\right) \quad \text{``target-spin''}$$

$$+P_BP_T\left(\boxed{\sqrt{1-\varepsilon^2}\sigma_{LL}^{const}}+\sqrt{\varepsilon(1-\varepsilon)}\sigma_{LL}^{cos(\phi)}cos(\phi)\right) \quad \text{``double-spin''}$$

⇧ Circular asymmetry

- Longitudinal beam, longitudinal target DSA through $\gamma^* N \to N'\pi$ helicity amplitudes $M_{0\nu',\,\mu\nu}$:

$$A_{LL}^{\rm const}\sigma_0=\sqrt{1-\varepsilon^2}\,\frac{1}{2}\left[|M_{0+,\,++}|^2+|M_{0-,\,++}|^2-|M_{0+,\,-+}|^2-|M_{0-,\,-+}|^2\right];$$

- Leading twist (Q^2-independent) DSAs with the TDA-based formalism; $\sim -t$: potentially large asymmetry.

Polarization observables V

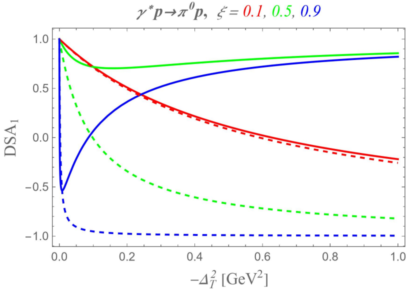
- Experimental definition for DAS_1:

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

- DAS_1 for near-backward $\gamma^* N \to \pi N'$:

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

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



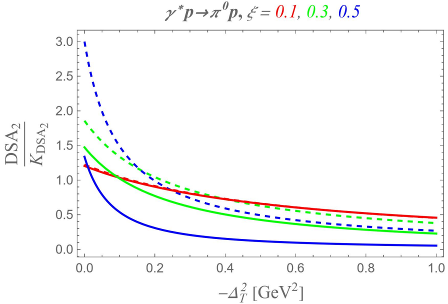
Polarization observables VI

- Longitudinal beam, transverse target DSA:

$$A_{LT}(\phi_i) = \frac{1}{P_B P_{T_T}} \frac{\left(N_i^{\rightarrow\Uparrow} + N_i^{\leftarrow\Downarrow}\right) - \left(N_i^{\rightarrow\Downarrow} + N_i^{\leftarrow\Uparrow}\right)}{N_i^{\rightarrow\Uparrow} + N_i^{\leftarrow\Downarrow} + N_i^{\rightarrow\Downarrow} + N_i^{\leftarrow\Uparrow}};$$

- DSA_2 - ϕ-independent part of A_{LT}:

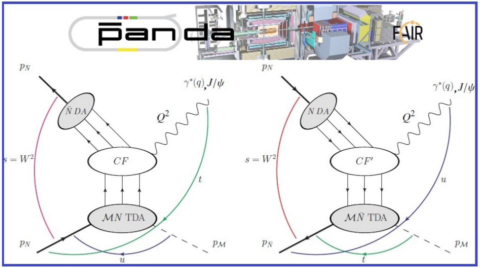
$$\text{DSA}_2 = \frac{-2(s_T \cdot \Delta_T)}{m_N} \frac{\text{Re}[\mathcal{I}^{(1)}(\xi,\Delta^2)\mathcal{I}^{(2)*}(\xi,\Delta^2)]}{|\mathcal{I}^{(1)}(\xi,\Delta^2)| - \frac{\Delta_T^2}{m_N^2}|\mathcal{I}^{(2)}(\xi,\Delta^2)|}$$

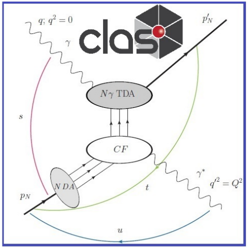


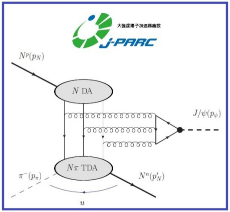
What we may learn from these polarization observables?

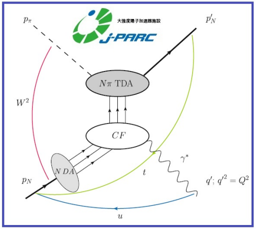
- Q^2-independence: reaction mechanism cross check; early present of scaling behavior?
- Insight for phenomenological models: going beyond the "cross-channel nucleon exchange" model;
- Helps to single out the contribution of different sets of TDAs: $\{V, A, T\}_1$ v.s. $\{V, A, T\}_2$.

- Complementary experimental options and universality of TDAs.









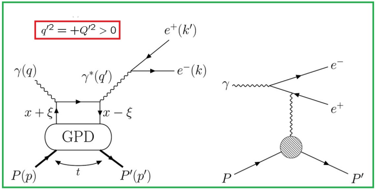
Time-like Compton scattering and universality of GPDs

$$\gamma(q) + N(p_1) \to \gamma^*(q') + N(p_2) \to \ell\bar{\ell} + N(p_2)$$

- Near-forward TCS E. Berger, M.Diehl, B.Pire'01:

$$\text{large} \quad q'^2 = Q'^2 \quad \text{and} \quad s; \quad \text{small} \quad -t.$$

- Fixed $\tau = \frac{Q'^2}{2p_1 \cdot q} = \frac{Q'^2}{s - m_N^2}$: analog of the Bjorken variable.



- A complementary access to GPDs. Check of universality:

at LO : $\mathcal{H}_{TCS} = \mathcal{H}^*_{DVCS}$; $\tilde{\mathcal{H}}_{TCS} = -\tilde{\mathcal{H}}^*_{DVCS}$

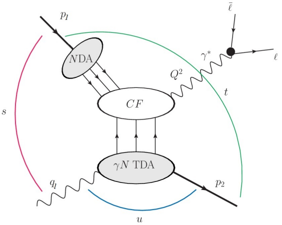
at NLO $\mathcal{H}_{TCS} = \mathcal{H}^*_{DVCS} - i\pi Q^2 \frac{d}{dQ^2}\mathcal{H}^*_{DVCS}$; $\tilde{\mathcal{H}}_{TCS} = -\tilde{\mathcal{H}}^*_{DVCS} + i\pi Q^2 \frac{d}{dQ^2}\tilde{\mathcal{H}}^*_{DVCS}$

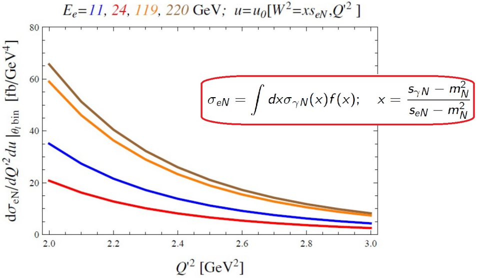
- First experimental data on TCS from CLAS12 Phys.Rev.Lett. 127 (2021).

B.Pire, K.S., A. Shaikhutdinova, L.Szymanowski, Eur. Phys. J. C **82**, 656 (2022)

$$\gamma(q_1) + N(p_1) \to \gamma^*(q') + N(p_2) \to \ell\bar{\ell} + N(p_2)$$

large s and $q_2^2 \equiv Q^2$; fixed x_B; small $-u = -(p_2 - q_1)^2$.





- γ_T^* dominance: $(1 + \cos^2\theta_\ell)$ angular dependence;
- large $-t$: small BH background.
- Crude cross section estimates: VMD + $\gamma^* N \to VN$+ crossing.
- Feasibility studies for the EIC, Zachary Sweger et al., Phys.Rev.C **108** (2023) 5, 055205.

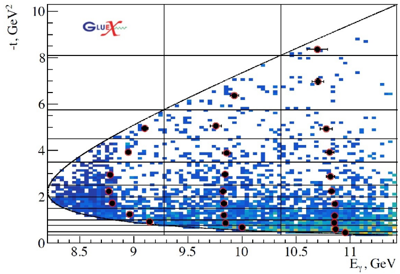
Charmonium photoproduction I

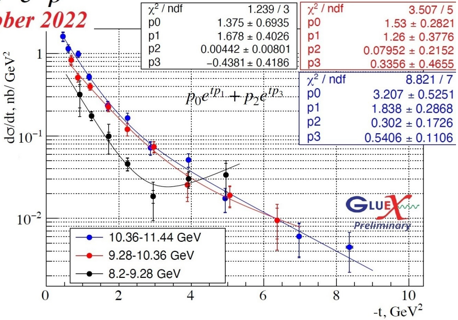
GlueX Collaboration, Phys.Rev.C 108 (2023) 2, 025201

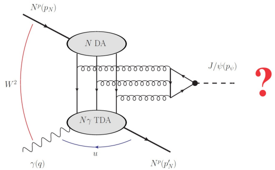
GlueX results: total and differential cross-sections

$$\gamma p \to J/\psi p \to e^+ e^- p$$

Lubomir Pentchev's talk, ECT Trento, October 2022







Vector meson dominance

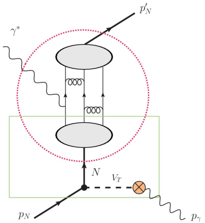
- J. J. Sakurai'1960s VMD for photoproduction reactions: A and B - hadron states

$$[\gamma A \to B] = e\frac{1}{f_\rho}\left[\rho^0 A \to B\right] + (\omega) + (\phi).$$

- VMD-based model for nucleon-to-photon TDAs

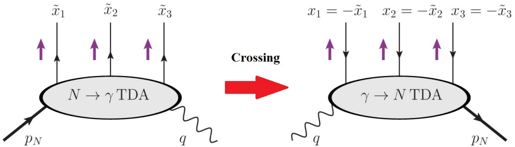
$$V_\Upsilon^{\gamma N} = \frac{e}{f_\rho} V_\Upsilon^{\rho_T N} + \frac{e}{f_\omega} V_\Upsilon^{\omega_T N} + \frac{e}{f_\phi} V_\Upsilon^{\phi_T N};$$

- Check of consistency: transverse polarization of V 16 out of 24 leading twist-3 VN TDAs;
- Cross-channel nucleon exchange model for $V_T N$ TDAs:



- Coupling constants: $\Gamma\left(\mathrm{V} \to e^+e^-\right) \approx \frac{1}{3}\alpha^2 m_\mathrm{V}\left(f_\mathrm{V}^2/4\pi\right)^{-1}, \quad \mathrm{V} = \rho, \omega, \phi.$

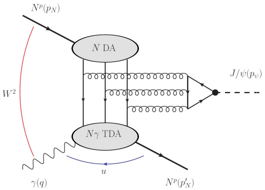
Crossing $\gamma \to N$ to $N \to \gamma$ TDAs



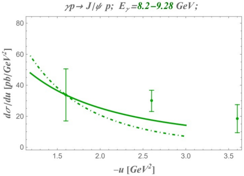
- Crossing relation established in B.Pire, K.S., L. Szymanowski, PRD'95 for $\pi \to N$ and $N \to \pi$ TDAs.

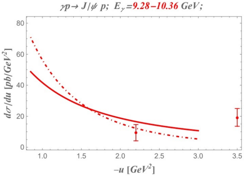
$$V_i^{N\gamma}(x_i, \xi, u) = V_i^{\gamma N}(-x_i, -\xi, u)\,;\, A_i^{N\gamma}(x_i, \xi, u) = A_i^{\gamma N}(-x_i, -\xi, u)$$
$$T_i^{N\gamma}(x_i, \xi, u) = T_i^{\gamma N}(-x_i, -\xi, u)\,.$$

B.Pire, K.S., A. Shaikhutdinova, L.Szymanowski, AAPPS Bull. **33**, 26 (2023)



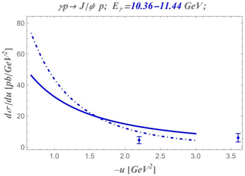
- VMD based model for γN TDAs largely underestimates the size of the backward peak by an order of magnitude;
- Can we normalize our model to data?
- Universality for different E_γ.



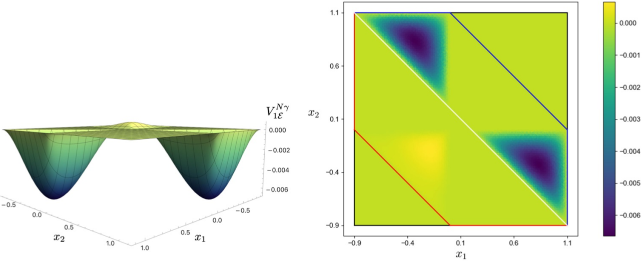


$$G(\Delta^2) = G^{(1)}(\Delta^2) = \frac{C^{(1)}}{\Delta^2 - m_N^2}$$

$$G(\Delta^2) = G^{(2)}(\Delta^2) = \frac{C^{(2)} e^{\alpha \Delta^2}}{\Delta^2 - m_N^2}$$



B. Pasquini, and A. Schiavi, Phys.Rev.D 109 (2024), 114021



(a) (b)

Results for the photon-to-proton $V_{1\mathcal{E}}$ TDA for $\xi = 0.1$.

TABLE VI. Mellin moments (0, 0, 0) of photon-to-proton TDAs for $\xi = 0.1$, expressed in units of 10^{-3} The total results are shown in the second column, while columns 3–6 show the results from the individual partial waves of the proton LFWF. The entries with a slash are forbidden by angular momentum conservation.

	Total	$L_z = 0$	$L_z = +1$	$L_z = -1$	$L_z = +2$
$V_{1\mathcal{E}}^{(0,0,0)}$	−2.3	−1.0	−1.3	/	/
$A_{1\mathcal{E}}^{(0,0,0)}$	0	0	0	/	/
$T_{1\mathcal{E}}^{(0,0,0)}$	−0.4	−0.2	∼0	−0.2	/
$T_{2\mathcal{E}}^{(0,0,0)}$	−0.8	−1.0	∼0	+0.2	/

$$V_{1\mathcal{E}}^{(0,0,0)}\Big|_{\text{VMD accounting } \omega, \rho} = -0.53 \times 10^{-3},$$

New models for πN TDAs: a generalization of RDDA

Flexible parametrization under development, in collaboration with P. Sznajder:

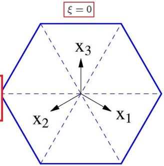
$$
\begin{aligned}
& H(w_i, v_i, \xi) \\
& = \int_{-1}^{1} d\sigma_i \int_{-1+(|\sigma_i|/2)}^{1-(|\sigma_i|/2)} d\rho_i \int_{-1+|\sigma_i|}^{1-|\rho_i-(\sigma_i/2)|-|\rho_i+(\sigma_i/2)|} d\omega_i \int_{-(1/2)+|\rho_i-(\sigma_i/2)|+(\omega_i/2)}^{(1/2)-|\rho_i+(\sigma_i/2)|-(\omega_i/2)} d\nu_i \delta(w_i - \sigma_i - \omega_i \xi) \\
& \times \delta(v_i - \rho_i - \nu_i \xi) \left(G(\sigma_i, \rho_i, \omega_i, \nu_i) - \xi G(\sigma_i, \rho_i, \omega_i, \nu_i) \right),
\end{aligned}
$$

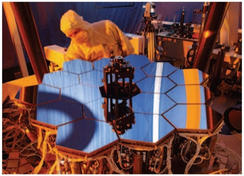
- This part is independent from $\xi \to 1$ limit and can be fitted to data;
- Spectral density designed from a factorized Ansatz with input at $\xi = 0$:

$$
G(\sigma_i, \rho_i, \omega_i, \nu_i) = g(\sigma_i, \rho_i) \times \underbrace{h^{(b)}(\sigma_i, \rho_i, \omega_i, \nu_i)}_{\text{profile function}};
$$

- Forward function $g(\sigma_i, \rho_i)$ can be expanded over the set of orthogonal polynomials on the hexagon;
- Generalization of the Zernike polynomials; employed in design of telescope mirrors;

For $\xi = 0$ $\sigma_i = x_i$; $\rho_i = \frac{1}{2} \sum_{k,l=1}^{3} \varepsilon_{ikl} x_k$;





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 signals for backward electroproduction for various mesons (π, η, ω, ρ) (and also in cross channel counterpart reactions: J-PARC, $\bar{\text{P}}$ANDA);
3. First evidences for the onset of the factorization regime in backward $\gamma^* N \to N' \omega$ from JLab Hall C analysis and BSA measurements in $\gamma^* p \to \pi^+ n$ from CLAS;
4. PAC 48 decision is a challenge both for the experiment and for theory. An effort is required. Factorization theorem, physical interpretation, models: work in progress;
5. Backward time-like Compton scattering and backward DVCS may provide access to nucleon-to-photon TDAs. Sizable enough to be studied with the future EIC. BH contribution is small in the near-backward regime;
6. Backward charmonium photoproduction can bring information on $N\gamma$ TDAs. Intriguing results for near-backward region from GlueX.

Thank you for your attention!