Hard exclusive reactions with baryon number transfer: status and perspectives.

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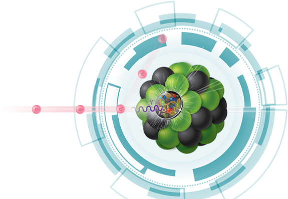

Outline

1. Introduction: Forward and backward kinematical regimes, DAs, GPDs, TDAs;
2. Nucleon-to-meson TDAs: definition and properties;
3. Physical contents of nucleon-to-meson TDAs;
4. Some ideas for future experiments: polarization observables; tests of universality;
5. Summary and Outlook.

In collaboration with: B. Pire and L. Szymanowski;
Experimental status: see the talk of B. Li;

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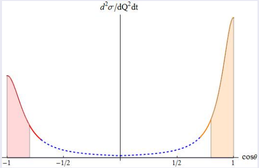
Transition distribution amplitudes and hard exclusive reactions with baryon number transfer

B. Pire [a], K. Semenov-Tian-Shansky [b,c,*], L. Szymanowski [d]

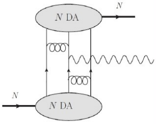
Factorization regimes for hard meson production

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

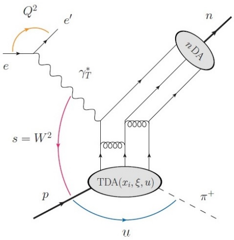
- $t \sim 0$ (forward peak) factorized description in terms of GPDs J. Collins, L. Frankfurt, M. Strikman'97;
- $u \sim 0$ (backward peak) factorized description in terms of TDAs L. Frankfurt, P.V. Pobylitsa, M. V. Polyakov, M. Strikman, PRD 60, '99;

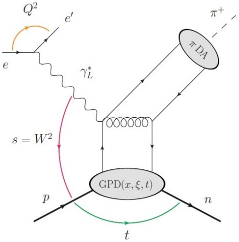


LO pQCD description of the nucleon e.m. FF:



Brodsky & Lepage'81
Efremov & Radyushkin'80





GPDs, DAs, GDAs and TDAs

- 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:

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

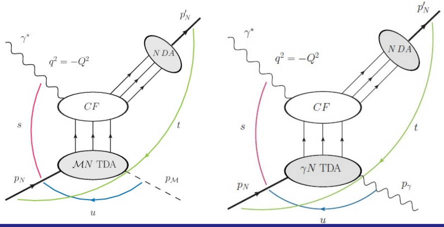
- $\langle A| = \langle 0|$; $|B\rangle$ - baryon; $\Rightarrow$ baryon DAs;
- Let $\langle A|$ be a meson state $\mathcal{M} = (\pi, \eta, \rho, \omega, ...)$ $|B\rangle$ - nucleon; $\Rightarrow$ $\mathcal{M}N$ TDAs;
- Let $\langle A|$ be a photon state $|B\rangle$ - nucleon; $\Rightarrow$ nucleon-to-photon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



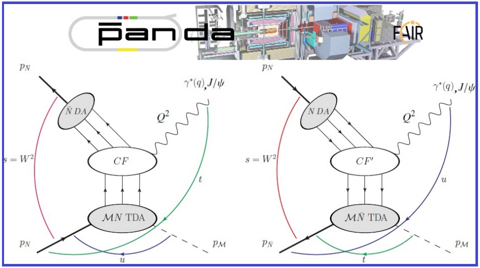
Learn more about QCD technique

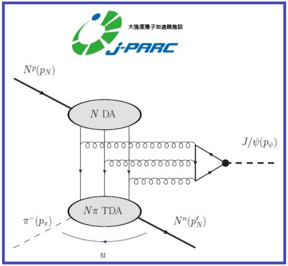
- A testbed for the QCD collinear factorization approach;
- πN and $\pi\eta$ TDAs: chiral dynamics playground;
- A challenge for the lattice QCD & functional approaches based on DS/BS equations;

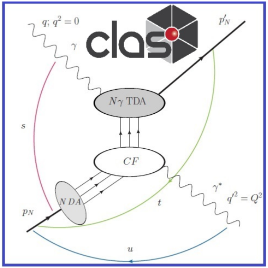
Why TDAs are interesting?

- 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, ...) 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.

- Complementary experimental options and universality of TDAs.







A list of key issues:

- 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?
- Can we access backward reactions experimentally?
- Status of phenomenological models.

Leading twist-3 πN TDAs

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

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

Proton-to-π^0 TDAs:

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

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

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

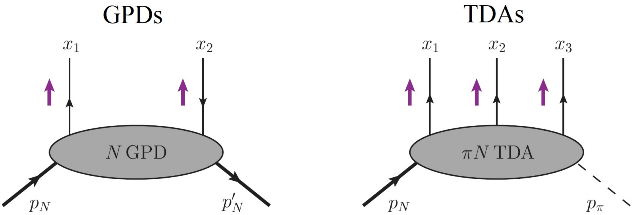
$$+ V_2^{\pi N}(\hat{P}C)_{\rho\tau}(\hat{\Delta}U)_\chi + A_2^{\pi N}(\hat{P}\gamma^5 C)_{\rho\tau}(\gamma^5 \hat{\Delta}U)_\chi + T_2^{\pi N}(\sigma_{P\mu}C)_{\rho\tau}(\gamma^\mu \hat{\Delta}U)_\chi$$

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

- $P = \frac{p_1 + p_\pi}{2}$; $\Delta = (p_\pi - p_1)$; $\sigma_{P\mu} \equiv P^\nu \sigma_{\nu\mu}$; $\xi = -\frac{\Delta\cdot n}{2P\cdot n}$
- 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:

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

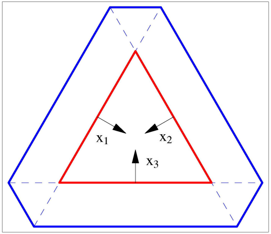
- TDAs: 3 sets of quark-diquark coordinates ($i = 1,\, 2,\, 3$)

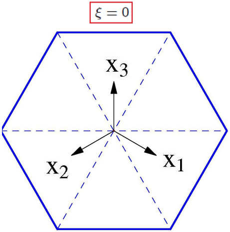
$$x_1 + x_2 + x_3 = 2\xi; \quad w_i = x_i - \xi; \quad v_i = \frac{1}{2}\sum_{k,l=1}^{3} \varepsilon_{ikl} x_k;$$

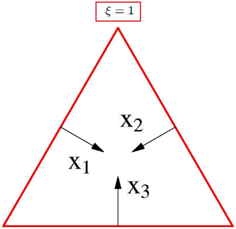
Fundamental properties I: support & polynomiality

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

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







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

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

  Can be studied on the lattice!

- Polynomiality in ξ of the Mellin moments in x_k:

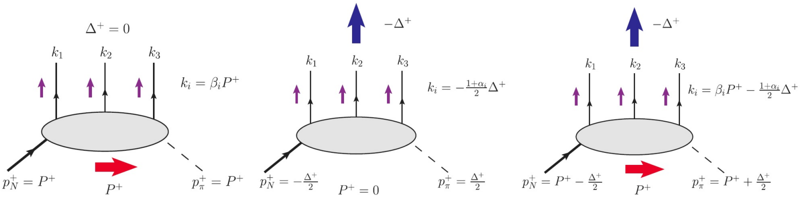
$$\int_{-1+\xi}^{1+\xi} dx_1 dx_2 dx_3 \delta(\sum_k x_k - 2\xi) x_1^{n_1} x_2^{n_2} x_3^{n_3} H^{\pi N}(x_1, x_2, x_3, \xi, \Delta^2)$$

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

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

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

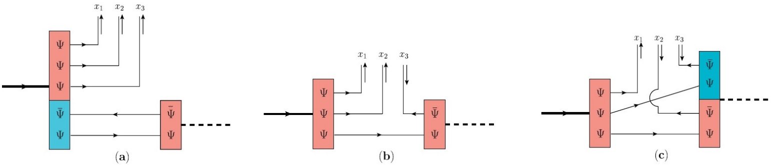
- Ω_i: $\{|\beta_i| \le 1,\ |\alpha_i| \le 1 - |\beta_i|\}$ are copies of the usual DD square support;
- $F(...)$: six variables that are subject to two constraints $\Rightarrow$ quadruple distributions;
- Can be supplemented with a D-term-like contribution (pure ERBL-like support);
- Evolution properties 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 ERBL and DGLAP regions.



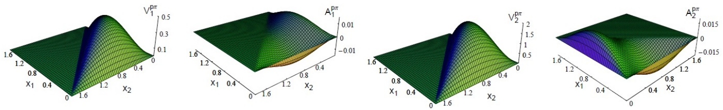
- Light-front quantization approach: πN TDAs provide information on next-to-minimal Fock components of light-cone wave functions of hadrons:

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

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



- B. Pasquini et al. 2009: LFWF model calculations



A connection to the quark-diquark picture

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

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

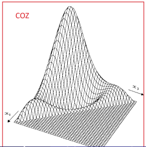
- The TDA support in quark-diquark coordinates
$\left(v_2 = \frac{x_3 - x_1}{2}; \quad w_2 = x_2 - \xi; \quad x_1 + x_3 = 2\xi_2'; \quad \left(\xi_2' \equiv \frac{\xi - w_2}{2}\right)\right)$:

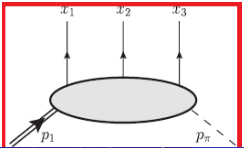
$$-1 \leq w_2 \leq 1; \quad -1 + |\xi - \xi_2'| \leq v_2 \leq 1 - |\xi - \xi_2'|$$

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

$$\int_{-1+|\xi-\xi_2'|}^{1-|\xi-\xi_2'|} dv_2 H^{\pi N}(w_2, v_2, \xi, \Delta^2)$$

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



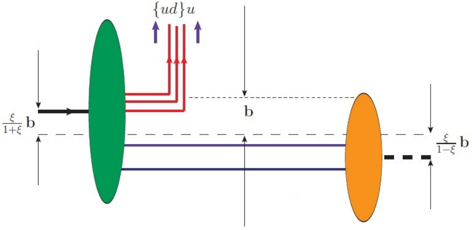


An interpretation in the impact parameter space

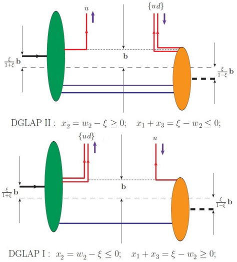
- A generalization of M. Burkardt'00,02; M. Diehl'02 for v-integrated TDAs.
- Fourier transform with respect to

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

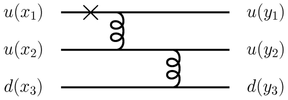
- A representation depends on the domain:



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



- 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)

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

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

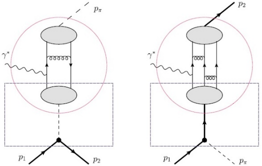
Key requirements:

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

How to model quadruple distributions?

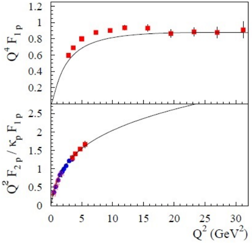
- No enlightening $\xi = 0$ limit as for GPDs.
- $\xi \to 1$ limit fixed from chiral dynamics.
- A factorized Ansatz with input at $\xi = 1$ designed in J.P. Lansberg, B. Pire, K.S. and L. Szymanowski'12
- Can one design Radyushkin DD-type Ansatz with built-in Regge behavior for quadruple distributions?

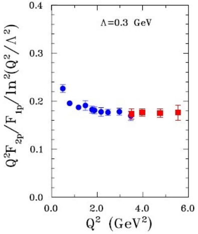
- "Poor man's TDA model": N and $\Delta(1232)$ cross-channel exchanges $\Rightarrow$ D-term-like contribution: $\tilde{E}$ GPD v.s. TDA; $\mathcal{A} \sim \mathrm{FF}^2$.

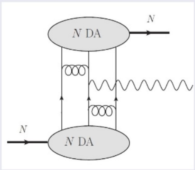


Troubles with e.m. FF: a word of caution

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

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.M. Huber et al., arXiv:2202.04470;

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

- 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 (The JLab F_π Collaboration), PRL 123, 2019
- S. Diehl et al. (CLAS collaboration), PRL 125 (2020) : extraction of BSA in $\gamma^* p \to \pi^+ n$.
- Feasibility studies for PANDA and JPARC.

More details in the talk of Bill Li, Thursday.

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

PAC48 REPORT

August 10-14, 2020

September 25, 2020

Jefferson Lab

PR12-20-007

Scientific Rating: B

Recommendation: Approved

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?

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).

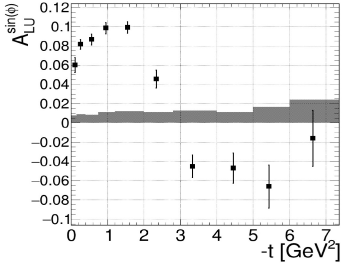
- The cross section can be expressed as

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

- Beam Spin Asymmetry

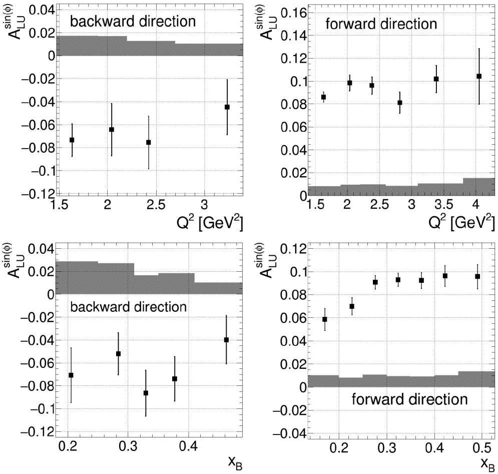
$$\mathrm{BSA}\left(Q^2, x_B, -t, \varphi\right) = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{A_{LU}^{\sin(\varphi)} \cdot \sin(\varphi)}{1 + A_{UU}^{\cos(\varphi)} \cdot \cos(\varphi) + A_{UU}^{\cos(2\varphi)} \cdot \cos(2\varphi)};$$

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

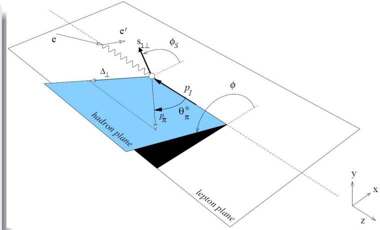


Beam Spin Asymmetry @ CLAS

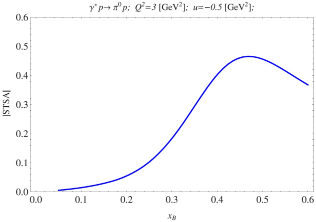
- Beam Spin Asymmetry is a subleading twist effect both in the forward and backward regimes.



- 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.

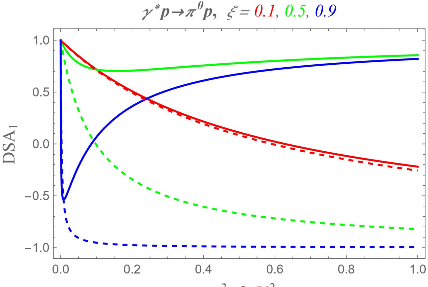
- Experimental definition for DAS_1:

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

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

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

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



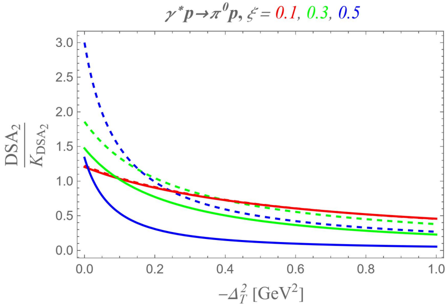
Polarization observables VI

- 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}:

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



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. $\{V,\ A,\ T\}_2$.

Nucleon-to-meson TDAs at J-PARC

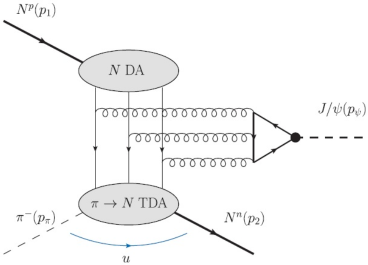
- J-PARC intense pion beam option: $P_\pi = 10 - 20$ GeV.

大強度陽子加速器施設 J-PARC

- Complements GPD program at J-PARC, S. Kumano, Wednesday talk;
- Charmonium production in association with a nucleon B. Pire, L. Szymanowski and K.S., PRD 95, 2017.

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

- Near-forward regime: $|(p_\pi - p_2)^2| \ll W^2, M_\psi^2$.



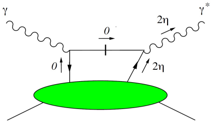
Time-like Compton scattering

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

- 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.



(b)

$$q'^2 = +Q'^2 > 0$$

- A complementary access to GPDs. Check of universality.

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

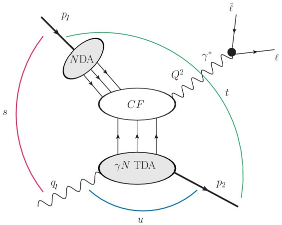
  at NLO $\mathcal{H}_{TCS} = \mathcal{H}^*_{DVCS} - i\pi Q^2 \frac{d}{dQ^2}\mathcal{H}^*_{DVCS}$; $\tilde{\mathcal{H}}_{TCS} = -\tilde{\mathcal{H}}^*_{DVCS} + i\pi Q^2 \frac{d}{dQ^2}\tilde{\mathcal{H}}^*_{DVCS}$

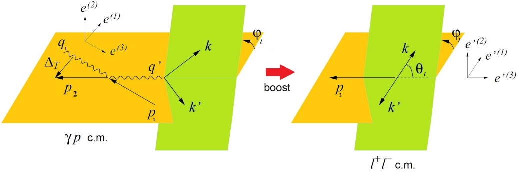
- First experimental data on TCS from CLAS12 Phys.Rev.Lett. 127 (2021).

B. Pire, K.S. and L. Szymanowski Eur. Phys. J. C 82

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

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.

Vector meson dominance

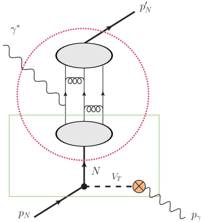
- J. J. Sakurai'1960s VMD for photoproduction reactions: A and B - hadron states

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

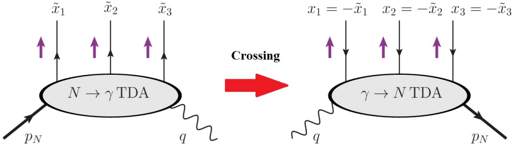
- VMD-based model for nucleon-to-photon TDAs

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

- 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:



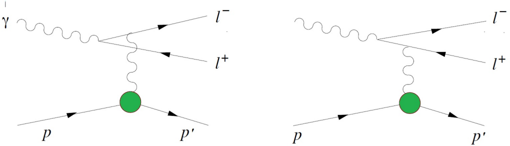
- Coupling constants: $\Gamma\left(\mathrm{V} \to e^+ e^-\right) \approx \frac{1}{3}\alpha^2 m_\mathrm{V}\left(f_\mathrm{V}^2/4\pi\right)^{-1}, \quad \mathrm{V} = \rho, \omega, \phi.$



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

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

BH contribution in the near-backward regime I



$$\frac{d\sigma_{BH}}{dQ'^2\, dt\, d(\cos\theta)\, d\varphi} = \frac{\alpha_{em}^3}{4\pi(s-M^2)^2}\, \frac{\beta}{-tL} \left[\left(F_1^2 - \frac{t}{4M^2} F_2^2 \right) \frac{A}{-t} + (F_1+F_2)^2 \, \frac{B}{2} \right]$$

$$\begin{aligned} A &= (s-M^2)^2 \Delta_T^2 - t\, a(a+b) - M^2 b^2 - t\,(4M^2-t) Q'^2 \\ &\quad + \frac{m_\ell^2}{L} \left[\left\{ (Q'^2-t)(a+b) - (s-M^2)\, b \right\}^2 + t\,(4M^2-t)(Q'^2-t)^2 \right]; \\ B &= (Q'^2+t)^2 + b^2 + 8 m_\ell^2 Q'^2 - \frac{4m_\ell^2 (t+2m_\ell^2)}{L} (Q'^2-t)^2; \end{aligned}$$

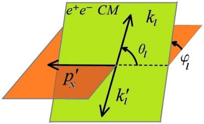
$$a = 2(k-k')\cdot p', \qquad b = 2(k-k')\cdot(p-p');$$

$$L = \left[(q-k)^2 - m_\ell^2 \right] \left[(q-k')^2 - m_\ell^2 \right] = \frac{(Q'^2-t)^2 - b^2}{4}; \quad \beta = \sqrt{1 - 4m_\ell^2/Q'^2}.$$

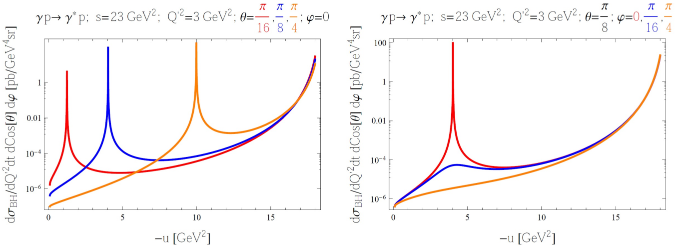
- BH contribution dominates in the near-forward regime: $\frac{F_1(t)}{t} \sim \frac{1}{t}$.

BH contribution in the near-backward regime II

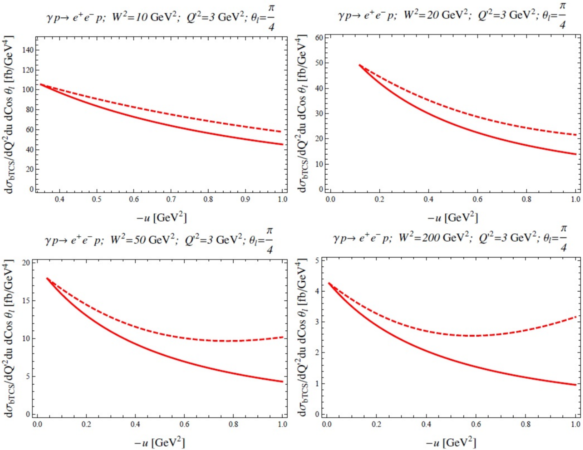
- The BH cross section peaks once ℓ goes "on-shell": L -small.
- Effect of the cut in the lepton polar angle θ: keep the BH peak out of the near-backward kinematics.



- The left peak is very narrow.



Cross section estimates: near-backward TCS



$$\frac{d\sigma}{du dQ'^2 d\cos\theta_\ell} = \frac{\int d\varphi_\ell \overline{|\mathcal{M}_{N\gamma\to N'\ell^+\ell^-}|^2}}{64(s-m_N^2)^2(2\pi)^4}.$$

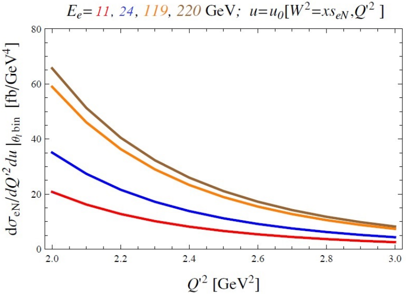
Cross section estimates for JLab, EIC and EicC

- Quasi-real photoproduction

$$\sigma_{eN} = \int dx \sigma_{\gamma N}(x) f(x); \quad x = \frac{s_{\gamma N} - m_N^2}{s_{eN} - m_N^2}.$$

- Weizsacker-Williams distribution

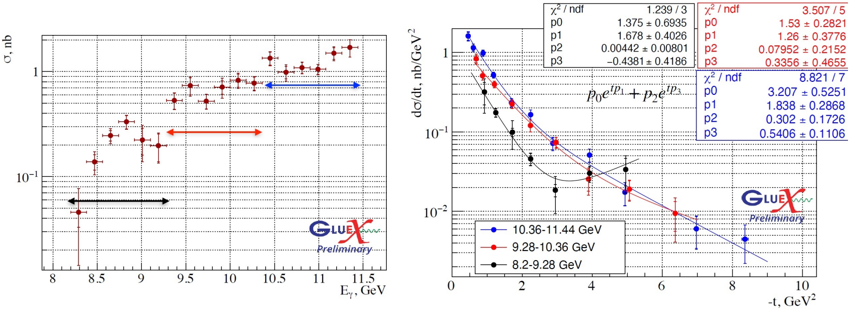
$$f(x) = \frac{\alpha_{\rm em}}{2\pi} \left\{ 2m_e^2 x \left(\frac{1}{Q^2_{\rm max}} - \frac{1-x}{m_e^2 x^2} \right) + \frac{\left((1-x)^2 + 1 \right) \ln \frac{Q^2_{\rm max}(1-x)}{m_e^2 x^2}}{x} \right\}.$$



Z. Meziani

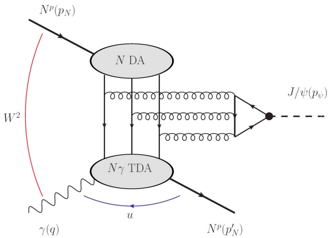
Preliminary GlueX results: total and differential cross-sections

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

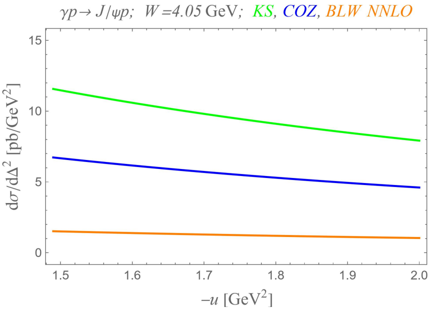


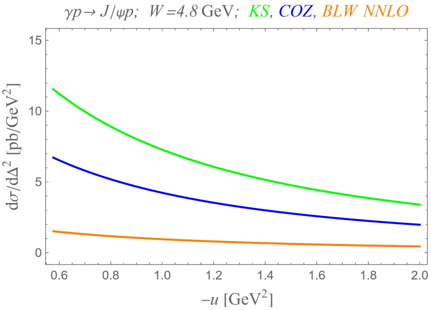
From Lubomir Pentchev's talk, ECT Trento, October 2022

$$-t_0 = 4.4 \div 7.0\,\mathrm{GeV}^2; \quad -t_0 = 7.0 \div 9.3\,\mathrm{GeV}^2; \quad -t_0 = 7.2 \div 11.4\,\mathrm{GeV}^2;$$



- Cross section estimates in the VMD based model for γN TDAs.

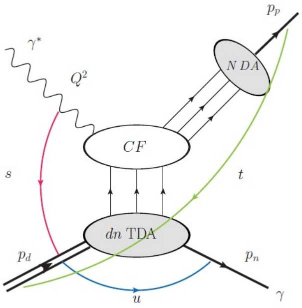




Deep deuteron electrodissociation with a $B = 1$ exchange in the cross channel

- More use for $3q$ light-cone operator: TDAs for $B \to B - 1$ baryons as a tool for nuclear physics.
- Deep deuteron electrodissociation with a baryon number exchange in the cross channel:

$$\gamma^*(q) + d(p_d) \to p(p_p) + n(p_n); \quad |u| = |(p_d - p_n)^2| \ll Q^2, \; W^2 = (q + p_d)^2.$$



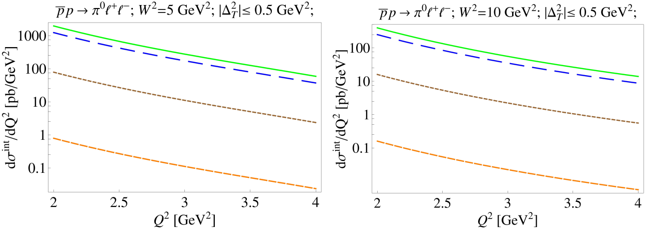
Conclusions & Outlook

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 detect near forward and backward signals for various mesons (π, η, ω, ρ) and backward TCS and DVCS!
3. PAC 48 decision is a challenge both for the experiment and for theory. An effort is required. Factorization theorem, physical interpretation, models.
4. 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.
5. New polarization observables (double spin asymmetries) non-vanishing at the leading twist-3.
6. Backward time-like Compton scattering and backward DVCS may provide access to nucleon-to-photon TDAs. Seems to be sizable enough to be studied with JLab Hall C and A and future EIC. BH contribution is small in the near-backward regime.
7. $\bar{p} N \to \pi \ell^+ \ell^-$ (q^2 - timelike) and $\bar{p} N \to \pi J/\psi$ $\bar{\text{P}}$ANDA and $\pi N \to N' \ell^+ \ell^-$, $\pi N \to N' J/\psi$ would allow to check universality of TDAs.
8. Backward charmonium photoproduction can bring information on $N\gamma$ TDAs.

Thank you for your attention!

Model predictions and feasibility studies for P̄ANDA

- J.P.Lansberg, B. Pire, L. Szymanowski and K.S.'12: $\bar{p}p \to \pi^0\gamma^* \to \pi^0\ell^+\ell^-$
- Numerical input: COZ, KS, BLW NLO/NNLO solutions for nucleon DAs.



- Feasibility studies: M. C. Mora Espi, M. Zambrana, F. Maas, K.S.'15