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

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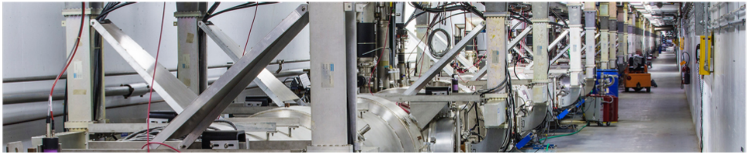

Outline

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. Current status of experimental analysis and feasibility studies.
5. Summary and Outlook.

In collaboration with: B. Pire and L. Szymanowski

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Transition distribution amplitudes and hard exclusive reactions with baryon number transfer

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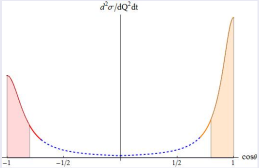
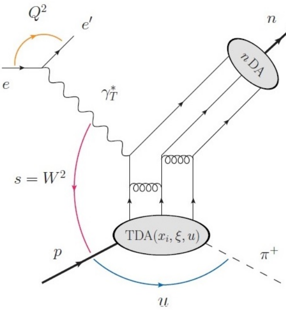
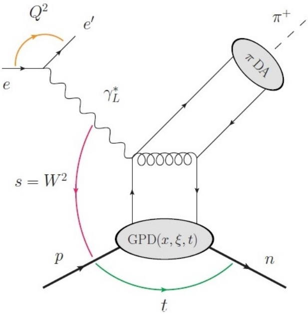
Factorization regimes for hard meson production

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;







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 (π, η, ρ, ω, ...) $|B\rangle$ - nucleon; $\Rightarrow$ nucleon-to-meson 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:

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

On backward regime in the generalized Bjorken limit:

PHYSICAL REVIEW D, VOLUME 60, 014010

Hard exclusive pseudoscalar meson electroproduction and spin structure of the nucleon

L. L. Frankfurt,[1,2] P. V. Pobylitsa,[2,3] M. V. Polyakov,[2,3] and M. Strikman[2,4,*]

(Received 5 February 1999; published 4 June 1999)

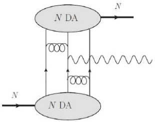
"..... Therefore the factorization theorem is valid also for the production of leading baryons

$$\gamma^*(q)+p \to B(q+\Delta)+M(p-\Delta)$$

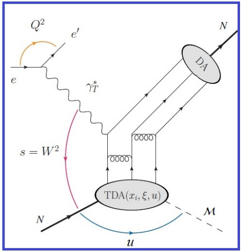
and even leading antibaryons $\gamma^*(q)+p \to \overline{B}(q+\Delta)+B_2(p-\Delta)$...."

- $u \sim 0$ (near-backward kinematics): nucleon-to-meson TDAs B. Pire, L. Szymanowski'05, 07 and nucleon DAs. No rigorous proof of the factorization theorem so far!

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

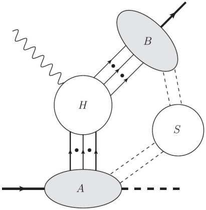


Brodsky & Lepage'81
Efremov & Radyushkin'80



On the status of factorization I

- J. Collins, X.-D. Ji et al.: Coleman-Norton theorem & leading regions;
- A. Radyushkin: α-representation;
- Effective theory approach: SCET;
- Reduced diagram for factorized description of backward meson production



$(l^+, l^-, l_\perp)$:

hard part H : $(\mathcal{O}(Q),\ \mathcal{O}(Q),\ \mathcal{O}(m_N))$;
incoming nucleon : $(\mathcal{O}(Q),\ \mathcal{O}(m_N^2/Q),\ \mathcal{O}(m_N))$;
outgoing meson : $(\mathcal{O}(Q),\ \mathcal{O}(m_{\mathcal{M}}^2/Q),\ \mathcal{O}(m_{\mathcal{M}}))$;
outgoing nucleon : $(\mathcal{O}(m_N^2/Q),\ \mathcal{O}(Q),\ \mathcal{O}(m_N))$;
soft part S : all components of momenta small;

- Power counting formula ($n(H)$ - No of collinear q and transverse g attached to H):

$$p(\pi) = 3 - n(H) - \text{No. } (q \text{ lines from } S \text{ to } A,\ B)$$
$$-3 \cdot \text{No. } (q \text{ lines from } S \text{ to } H) - 2 \cdot \text{No. } (g \text{ lines from } S \text{ to } H),$$

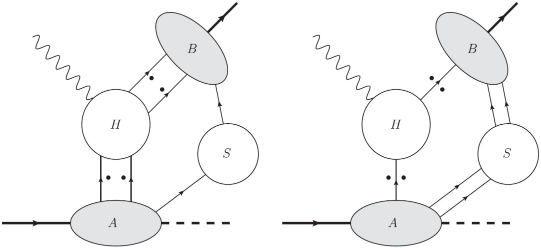
- Leading asymptotic behavior:

$$Q^{p(\pi)} = Q^{-3}.$$

On the status of factorization II

A list of (some of) tricky steps of proof:

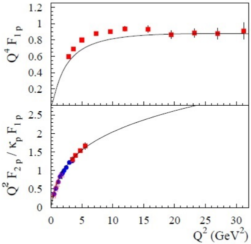
- Proof of "color neutrality" of the final state N (soft gluon subgraphs);
- Implementation of gauge invariance (collinear gluons sum into the Wilson lines);
- Soft rescattering mechanism (endpoint singularities):

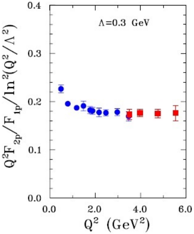


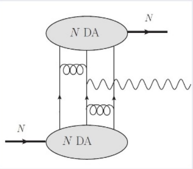
The experiment is crucial to decide on (early) onset of factorization regime!

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

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







Brodsky & Lepage'81
Efremov & Radyushkin'80

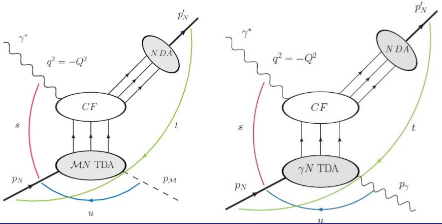
[Picture: Perdrisat, Punjabi and Vanderhaeghen'06]

- 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;

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



Learn more about QCD technique

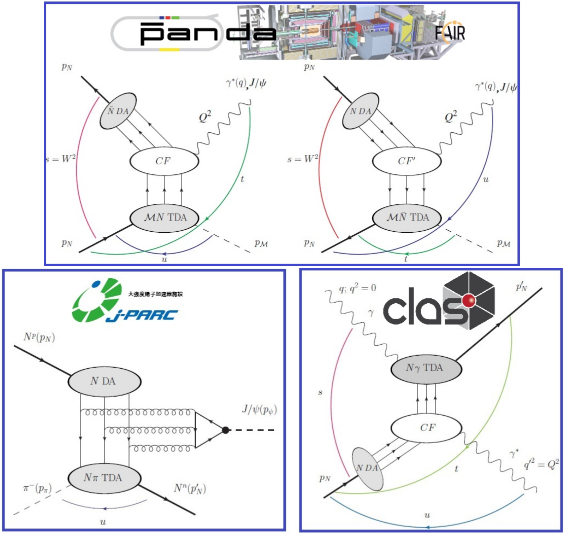
- A testbed for the QCD collinear factorization approach;
- A challenge for the lattice QCD & functional approaches based on DS/BS equations;

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.

Cross channel counterpart reactions: P̄ANDA, JPARC and TCS at JLab

- 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: $\left\{ V^{\pi N}_{1,2},\ A^{\pi N}_{1,2},\ T^{\pi N}_{1,2,3,4} \right\} (x_1,\ x_2,\ x_3,\ \xi,\ \Delta^2, \mu^2)$

Proton-to-π^0 TDAs:

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

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

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

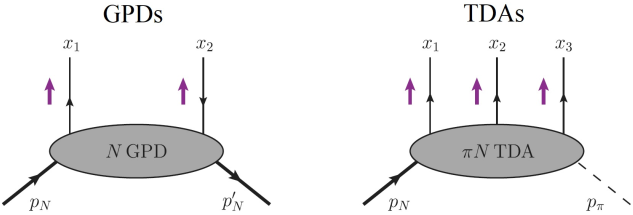
$$+ V_2^{\pi N} (\hat{P} C)_{\rho\tau} (\hat{\Delta} U)_\chi + A_2^{\pi N} (\hat{P} \gamma^5 C)_{\rho\tau} (\gamma^5 \hat{\Delta} U)_\chi + T_2^{\pi N} (\sigma_{P\mu} C)_{\rho\tau} (\gamma^\mu \hat{\Delta} U)_\chi$$

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

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

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

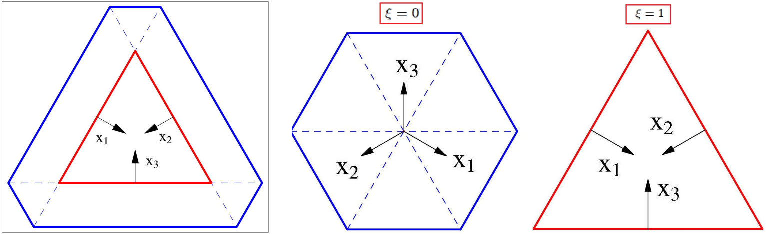
- TDAs: 3 sets of quark-diquark coordinates ($i = 1, 2, 3$)

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

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 $-1+\xi \leq x_k \leq 1+\xi$ ($\sum_k x_k = 2\xi$); ERBL-like and DGLAP-like I, II domains.



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

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

  Can be studied on the lattice!

- Polynomiality in ξ of the Mellin moments in x_k:

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

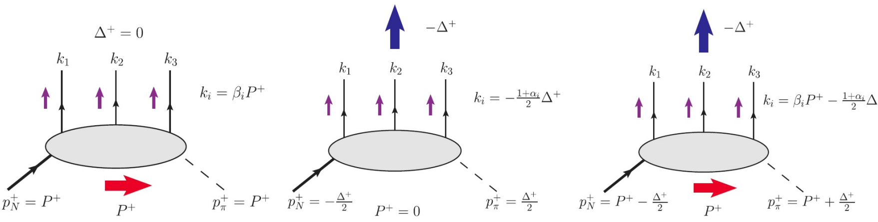
$$= [\text{Polynomial of order } n_1 + n_2 + n_3 \{+1\}](\xi).$$

Fundamental properties II: spectral representation

- 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: $\{|\beta_i| \le 1,\ |\alpha_i| \le 1 - |\beta_i|\}$ 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);



Fundamental properties III: evolution

- 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.
- Conformal basis (Jacobi and Gegenbauer polynomials):

$$\Psi_{N,n}^{(12)3}(y_1,y_2,y_3)=(N+n+4)(y_1+y_2)^n P_{N-n}^{(2n+3,1)}(y_3-y_1-y_2)C_n^{\frac{3}{2}}\left(\frac{y_1-y_2}{y_1+y_2}\right).$$

- The conformal PWs:

$$p_{N,n}^{(12)3}(w,v,\xi)=\theta(|w|\le\xi)\,\theta(|v|\le\xi')\,\xi^{-N-2}\frac{1}{g_{N,n}}$$
$$\times\left(1-\frac{v^2}{\xi'^2}\right)C_n^{\frac{3}{2}}\left(-\frac{v}{\xi'}\right)\left(1-\frac{w}{\xi}\right)^{n+2}\left(1+\frac{w}{\xi}\right)P_{N-n}^{2n+3,1}\left(\frac{w}{\xi}\right).$$

- Conformal PW expansion for πN TDAs:

$$H(w,v,\xi,\Delta^2)=\sum_{N=0}^{\infty}\sum_{n=0}^{N}p_{N,n}^{(12)3}(w,v,\xi)h_{n,N}^{(12)3}(\xi,\Delta^2).$$

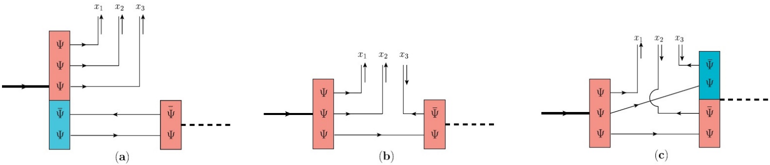
- SO(3) PW expansion of the conformal moments $h_{n,N}^{(12)3}$ $\Rightarrow$ cross-channel picture of baryon exchanges. Dual parametrization, see D. Müller, M.Polyakov, K.S.'15.

TDAs and light-front wave functions

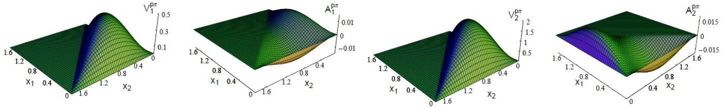
- Light-front quantization approach: πN TDAs provide information on next-to-minimal Fock components of light-cone wave functions of hadrons:

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

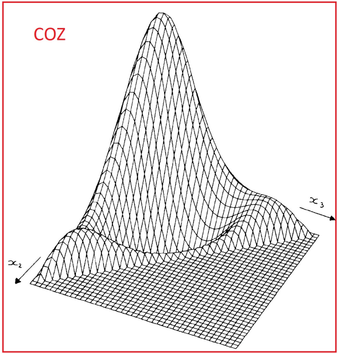
$$|M\rangle = \underbrace{\psi_{(q\bar{q})}|q\bar{q}\rangle}_{\text{Described by meson DA}} + \psi_{(q\bar{q}+q\bar{q})}|q\bar{q}\,q\bar{q}\rangle + \ldots$$



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



A connection to the quark-diquark picture I



- $\varphi_{\rm as}(x) = 120 x_1 x_2 x_3$.
- V. Chernyak, Zhitnitsky'84:

$$\varphi_{\rm CZ}(x) = \varphi_{\rm as}(x) \sum_i c_i A_i(x).$$

- Large asymmetry between quarks in nucleon:

$$\varphi^{(1,0,0)} \simeq 0.6; \quad \varphi^{(0,1,0)} \simeq \varphi^{(0,0,1)} \simeq 0.2.$$

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

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

- No confirmation of asymmetric behavior: e.g. V. Braun, A. Lenz, M. Wittmann'06 .

A connection to the quark-diquark picture II

- Quark-diquark coordinates (one of 3 possible sets):

$$v_2 = \frac{x_3 - x_1}{2}; \quad w_2 = x_2 - \xi; \quad x_1 + x_3 = 2\xi_2'; \quad \left(\xi_2' \equiv \frac{\xi - w_2}{2}\right).$$

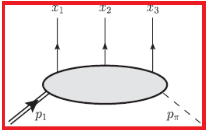
- The TDA support in quark-diquark coordinates:

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

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

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

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

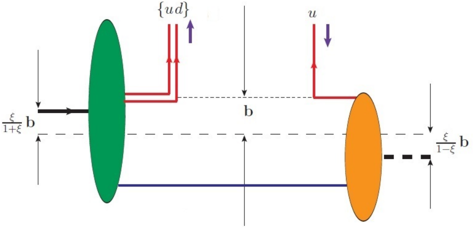


An interpretation in the impact parameter space I

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

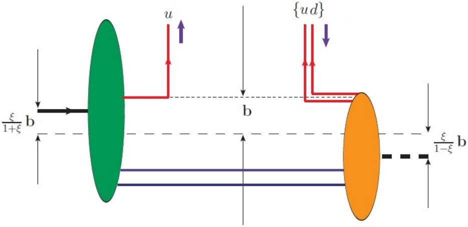
$$\mathbf{D} = \frac{\mathbf{p}_\pi}{1-\xi} - \frac{\mathbf{p}_N}{1+\xi}; \qquad \Delta^2 = -2\xi\left(\frac{m_\pi^2}{1-\xi} - \frac{m_N^2}{1+\xi}\right) - (1-\xi^2)\mathbf{D}^2.$$

- A representation in the DGLAP-like I domain:

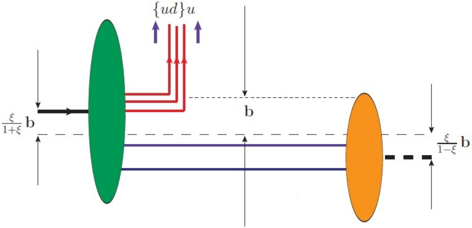


$$\text{DGLAP I}: \quad x_2 = w_2 - \xi \leq 0; \quad x_1 + x_3 = \xi - w_2 \geq 0;$$

An interpretation in the impact parameter space II



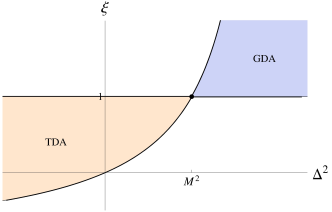
$$\text{DGLAP II}: \quad x_2 = w_2 - \xi \geq 0; \quad x_1 + x_3 = \xi - w_2 \leq 0;$$



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

Crossing, chiral properties and soft pion theorem for πN GDA/TDA

- Crossing relates πN TDAs and πN GDAs (light-cone wave functions of $|\pi N\rangle$ states).
- Physical domain in (Δ^2, ξ)-plane (defined by $\Delta_T^2 \leq 0$) in the chiral limit ($m_\pi = 0$):



- Soft pion theorem P. Pobylitsa, M. Polyakov and M. Strikman'01; V. Braun, D. Ivanov, A. Lenz, A. Peters'08

$$Q^2 \gg \Lambda^3_{\rm QCD}/m_\pi \gg \Lambda^2_{\rm QCD}$$

πN GDA at the threshold $\xi = 1$, $\Delta^2 = m_N^2$ fixed in terms of nucleon DAs V^p, A^p, T^p.

Building up a consistent model for πN TDAs

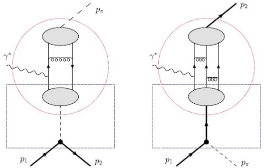
Key requirements:

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?

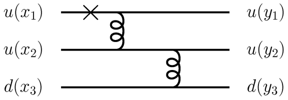
- No enlightening $\xi = 0$ limit as for GPDs.
- $\xi \to 1$ limit fixed from chiral dynamics.
- A factorized Ansatz with input at $\xi = 1$ designed in J.P. Lansberg, B. Pire, K.S. and L. Szymanowski'12
- Can one design Radyushkin DD-type Ansatz with built-in Regge behavior for quadruple distributions?

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



Calculation of the amplitude

- 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;



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

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

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

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

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

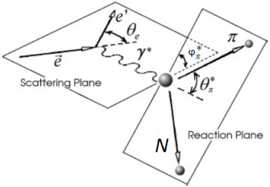
Distinguishing features

- 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 $\sim (1 + \cos^2 \theta_\ell)$;
- Color transparency arguments G.M. Huber et al., arXiv:2202.04470;

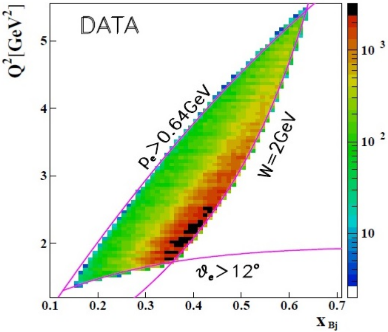
$$e + A(Z) \to e' + p' + A'(Z-1) + \pi^0 \ \ \text{v.s.} \ \ \mathrm{e} + \mathrm{p} \to \mathrm{e}' + \mathrm{p}' + \pi^0.$$

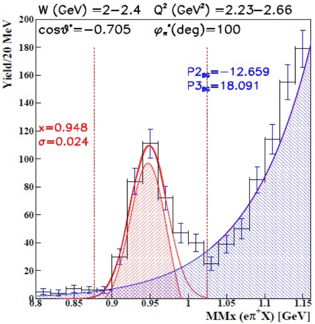
- Pioneering analysis of backward $\gamma^* p \to \pi^0 p$. A. Kubarovsky, CIPANP 2012.
- Analysis of JLab @ 6 GeV data (Oct.2001-Jan.2002 run) for the backward $\gamma^* p \to \pi^+ n$ K. Park et al. (CLAS Collaboration), PLB 780 (2018).
- Backward ω-production at JLab Hall C.
  W. Li, G. Huber (The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

Backward pion electroproduction @ CLAS I



- 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) and B. Pire and K.S., PLB 780 (2018)





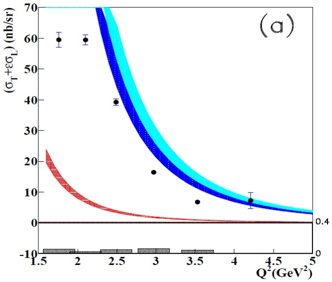
Backward pion electroproduction @ CLAS II

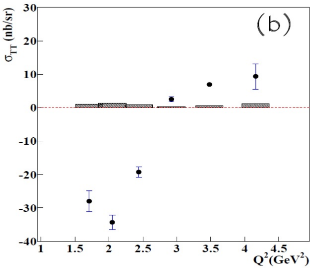
$$\frac{d\sigma}{d\Omega_\pi^*} = A + B\cos\varphi_\pi^* + C\cos 2\varphi_\pi^*,$$ where

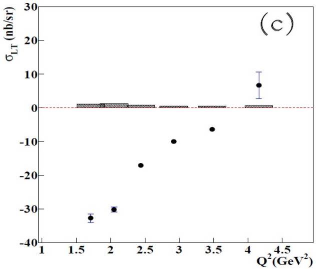
$A = \sigma_T + \epsilon\sigma_L$; $B = \sqrt{2\epsilon(1+\epsilon)}\sigma_{LT}$;
$C = \epsilon\sigma_{TT}$

Table ; Determination of kinematic bin.

Variable	Number of bins	Range	Bin size
W	1	$2.0 - 2.4$ GeV	400 MeV
Q^2	5	$1.6 - 4.5$ GeV^2	various
Δ_T^2	1	$0 - 0.5$ GeV^2	0.5 GeV^2
φ_π^*	9	$0^o - 360^o$	40^o







Backward pion electroproduction @ CLAS III

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

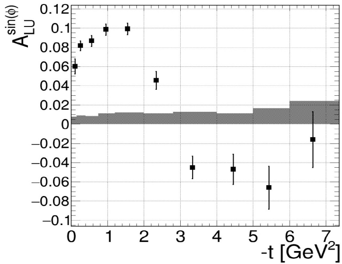
- The cross section can be expressed as

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

- Beam Spin Asymmetry

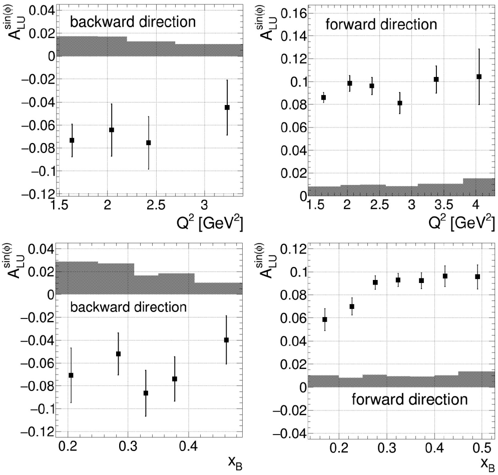
$$\mathrm{BSA}\left(Q^2, x_B, -t, \varphi\right) = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{A_{LU}^{\sin(\varphi)} \cdot \sin(\varphi)}{1 + A_{UU}^{\cos(\varphi)} \cdot \cos(\varphi) + A_{UU}^{\cos(2\varphi)} \cdot \cos(2\varphi)};$$

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



Backward pion electroproduction @ CLAS IV

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



More polarization observables

- Less sensitive to pQCD corrections;
- Smaller experimental uncertainties;

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

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

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

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

⇧ Circular asymmetry

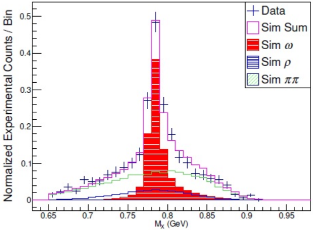
- Left and right circular polarization of γ^*:

$$\varepsilon_\pm = \mp\frac{1}{\sqrt{2}}(\varepsilon_1 \pm i\varepsilon_2)$$

- Circular asymmetry: effect $\sim \sigma_{++}-\sigma_{--}$;
- Leading twist DSAs with the TDA-based formalism; $\sim -t$: potentially large asymmetry (Work in progress).

Backward ω-production at JLab Hall C I

- TDA formalism for the case of light vector mesons (ρ, ω, ϕ) B. Pire, L. Szymanowski and K.S'15. 24 *VN* TDAs at the leading twist.
- The analysis W. Li, G. Huber et al. (The JLab F_π Collaboration), PRL'19
- Clear signal from backward regime of $ep \to e' p\omega$.

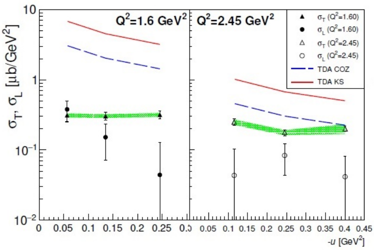


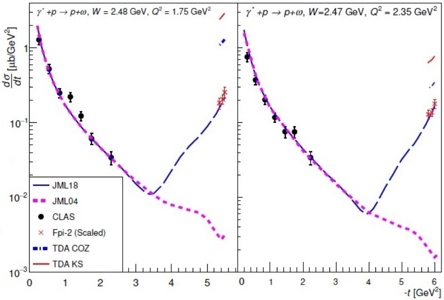
- Full Rosenbluth separation: $\sigma_{\rm T}$ and $\sigma_{\rm L}$ extracted to address $\sigma_{\rm T} \gg \sigma_{\rm L}$ issue.

$$2\pi \frac{d^2\sigma}{dt d\phi} = \frac{d\sigma_{\rm T}}{dt} + \epsilon \frac{d\sigma_{\rm L}}{dt} + \sqrt{2\epsilon(1+\epsilon)} \frac{d\sigma_{\rm LT}}{dt} \cos\phi + \epsilon \frac{d\sigma_{\rm TT}}{dt} \cos 2\phi$$

Backward ω-production at JLab Hall C II

- For $Q^2 = 2.45$ GeV^2: $\sigma_{\mathrm{L}}/\sigma_{\mathrm{T}} < \mu^2/Q^2$ and $\sigma_{\mathrm{T}} \gg \sigma_{\mathrm{L}}$;





- Experiment v.s. the predictions of the cross-channel nucleon exchange model for $p \to \omega$ TDAs.
- Combined (CLAS and F_π-2 data for $\gamma^* p \to \omega p$).
- TDA-based predictions v.s. the Regge-based J.M. Laget's JML'18 model.

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.

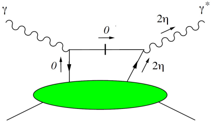
Time-like Compton scattering

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

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

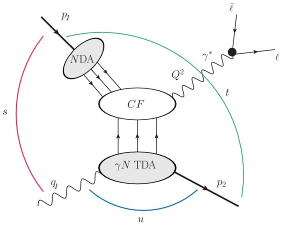
- First experimental data on TCS from CLAS12 Phys.Rev.Lett. 127 (2021).

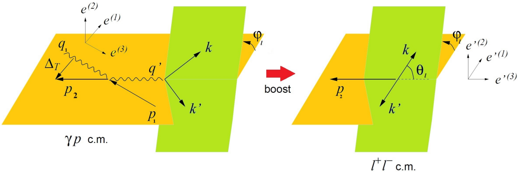
Backward time-like Compton scattering

B. Pire, K.S. and L. Szymanowski arXiv:2201.12853, to appear at Eur. Phys. J. C

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

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

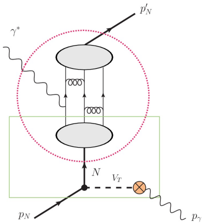
- J. J. Sakurai'1960s VMD for photoproduction reactions: A and B - hadron states

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

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

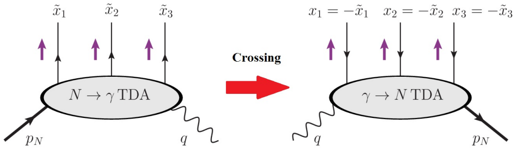
$$V_\Upsilon^{\gamma N} = \frac{e}{f_\rho} V_\Upsilon^{\rho_T N} + \frac{e}{f_\omega} V_\Upsilon^{\omega_T N} + \frac{e}{f_\phi} V_\Upsilon^{\phi_T N};$$

- 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 $\gamma \to N$ to $N \to \gamma$ TDAs

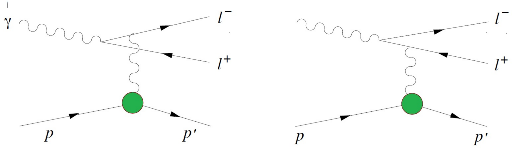


- Crossing relation established in B.Pire, K.S., L. Szymanowski, PRD'95 for $\pi \to N$ and $N \to \pi$ TDAs.

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

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

BH contribution in the near-backward regime I



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

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

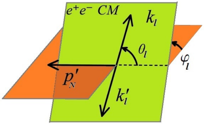
$$a = 2(k-k')\cdot p', \qquad b = 2(k-k')\cdot(p-p');$$

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

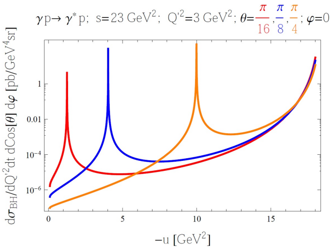
- BH contribution dominates in the near-forward regime: $\frac{F_1(t)}{t} \sim \frac{1}{t}$.

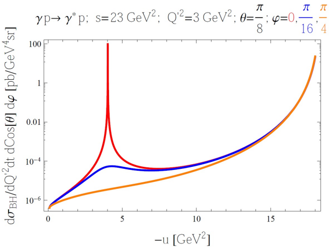
BH contribution in the near-backward regime II

- 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.

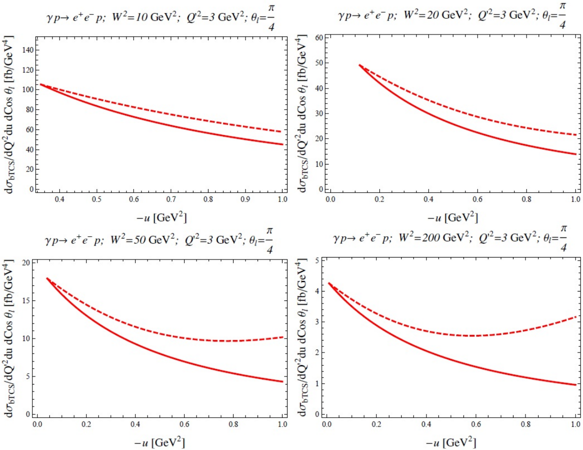


- The left peak is very narrow.





Cross section estimates: near-backward TCS



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

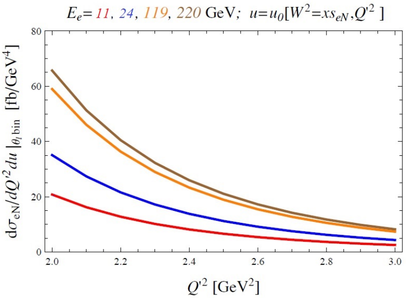
Cross section estimates for JLab, EIC and EicC

- 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

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



- JLab Hall C: assuming luminosity $10^{38} cm^{-2} s^{-1}$ - plenty of events!
- EicC luminosity (ArXiv:2110.094) is $50 fb^{-}1$/year - several tens of events.

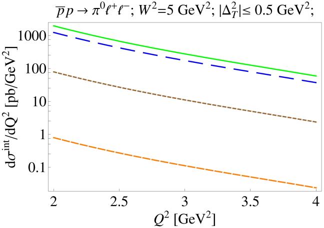
Conclusions & Outlook

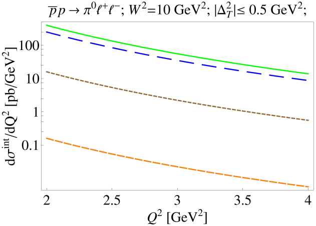
1. Nucleon-to-meson TDAs provide new information about correlation of partons inside hadrons. A consistent picture for the integrated TDAs emerges in the impact parameter representation.
2. We strongly encourage to detect near forward and backward signals for various mesons (π, η, ω, ρ) and backward 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 and EicC. 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 would allow to check universality of TDAs.
8. 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 EicC. BH contribution is small in the near-backward regime.

Thank you for your attention!

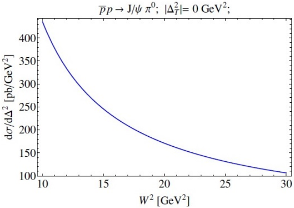
Model predictions and feasibility studies for $\bar{\text{P}}$ANDA

- 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
- B. Pire, L. Szymanowski and K.S.'13 $\bar{p}p \to \pi^0 J/\psi$



- Feasibility studies: B. Ramstein, E. Atomssa and $\bar{\text{P}}$ANDA collaboration and K.S. PRD 95'17