Жесткие эксклюзивные реакции с передачей барионного числа: современное состояние и перспективы

К. Семенов-Тян-Шанский[1]

[1] НИЦ «Курчатовский Институт» - ПИЯФ, Гатчина, Россия

Объединенный семинар ОФВЭ и ОТФ ПИЯФ, 12 ноября 2026

In collaboration with B. Pire, L. Szymanowski, P. Sznajder,

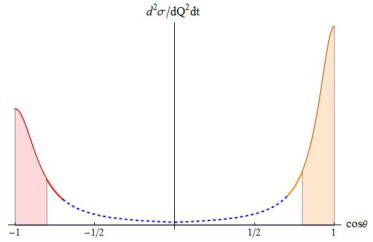


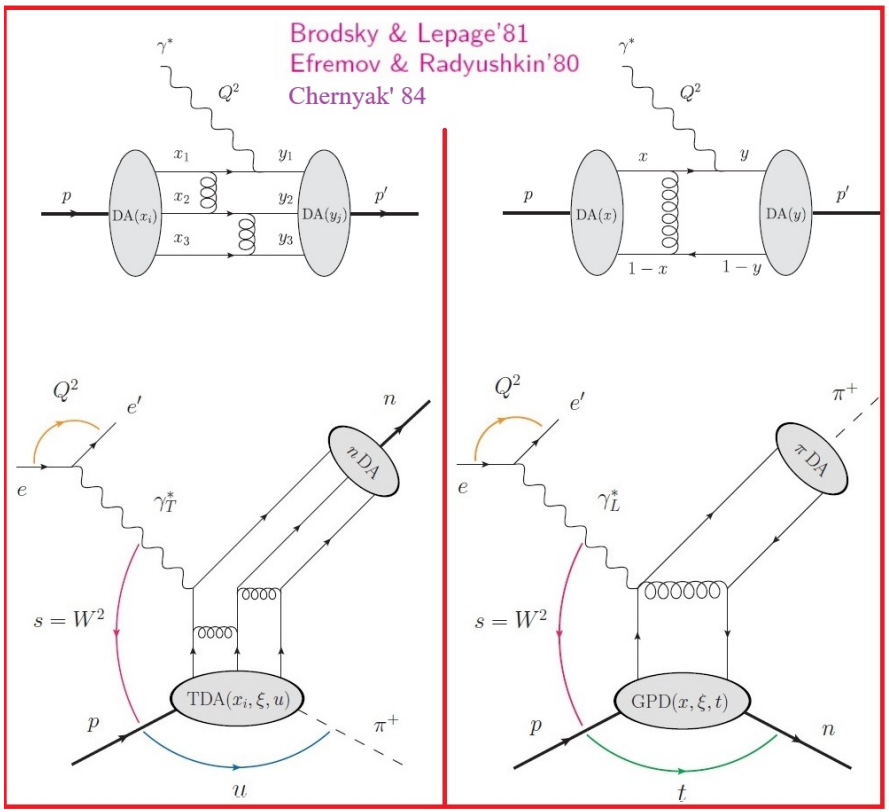
Petersburg Nuclear Physics Institute

Factorization regimes for hard meson production

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

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





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 $\gamma^*(q)+p\to\bar{B}(q+\Delta)+B_2(p-\Delta)$....''

arXiv:hep-ph/0211263v1 16 Nov 2002

NOVEL HARD SEMIEXCLUSIVE PROCESSES AND COLOR SINGLET CLUSTERS IN HADRONS.

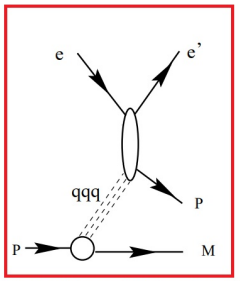
LEONID FRANKFURT
Physics Department, Tel Aviv University, Tel Aviv, Israel

M.V. POLYAKOV
Institut für Theoretische Physik II, Ruhr–Universität Bochum, D-44780 Bochum, Germany

M. STRIKMAN
Department of Physics, Pennsylvania State University, University Park, PA 16802, USA

D.ZHALOV
Department of Physics, Pennsylvania State University, University Park, PA 16802, USA

M.ZHALOV
Petersburg Nuclear Physics Institute, Gatchina, Russia



Production of a fast baryon and recoiling mesonic system.

Hard scattering to a three cluster final state is suggested as a method to probe configurations in hadrons containing small size color singlet cluster and a residual quark-gluon system of a finite mass. Examples of such processes include $e+N\to e+p+M_X(\Lambda+M_X'),p+p\to p+p+M_X(p+\Lambda+M_X')$ where $M_X(M_X')$ could be a pion(kaon) or other state of finite mass which does not increase with momentum transfer (Q^2).

- $u\sim 0$ (near-backward kinematics): nucleon-to-meson TDAs B. Pire, L. Szymanowski'05, 07 and nucleon DAs. Recent progress in proof of the factorization: TBD later.

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

Physics Reports 940 (2021) 0–120

Contents lists available at ScienceDirect

Physics Reports

journal homepage: www.elsevier.com/locate/physrep



Transition distribution amplitudes and hard exclusive reactions with baryon number transfer

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

Eur. Phys. J. A (2021) 57:342
https://doi.org/10.1140/epja/s10050-021-00625-2

THE EUROPEAN PHYSICAL JOURNAL A

Regular Article - Experimental Physics

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

C. Ayerbe Gayoso[1], Ł. Bibrzycki[2], S. Diehl[3,4], S. Heppelmann[5], D. W. Higinbotham[6], G. M. Huber[7], S. J. D. Kay[7], S. R. Klein[8], J. M. Laget[6], W. B. Li[6,9,a], V. Mathieu[10,11], K. Park[12], R. J. Perry[13], B. Pire[14], K. Semenov-Tian-Shansky[15,16], A. Stanek[8], J. R. Stevens[9], L. Szymanowski[17], C. Weiss[6], B.-G. Yu[18]

GPDs, DAs, GDAs and TDAs

- 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:

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

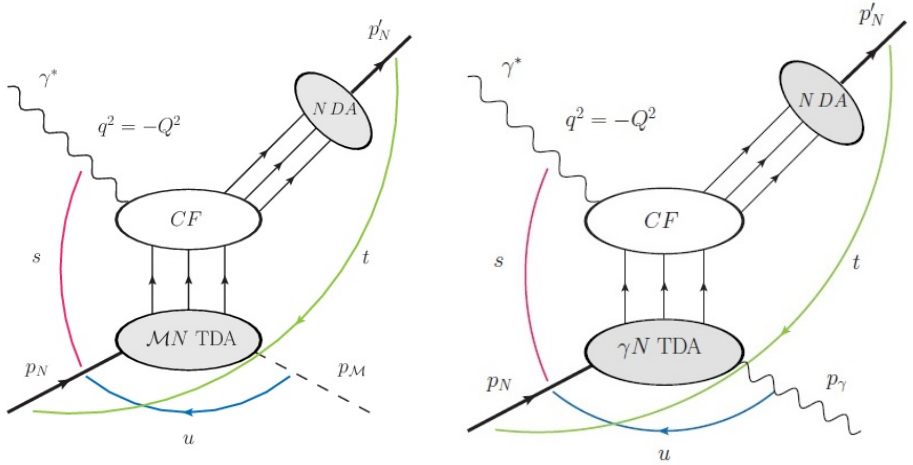
- $\langle A| = \langle 0|$; $|B\rangle$ - nucleon; $\Rightarrow$ nucleon DAs;
- Let $\langle A|$ be a meson state $\mathcal{M}$ =(π, η, ρ, ω, ...) or a photon γ; $|B\rangle$ - nucleon; $\Rightarrow$ $\mathcal{M}N$ TDAs; and γN TDAs
- $\langle A| = \langle 0|$; $|B\rangle$ - nucleon-meson state; $\Rightarrow$ nucleon-meson GDAs.

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

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

$$\xi = -\frac{(p_A - p_B)\cdot n}{(p_A + p_B)\cdot n}; \qquad \xi \simeq \frac{x_B}{2 - x_B}.$$

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;

Leading twist-3 πN TDAs

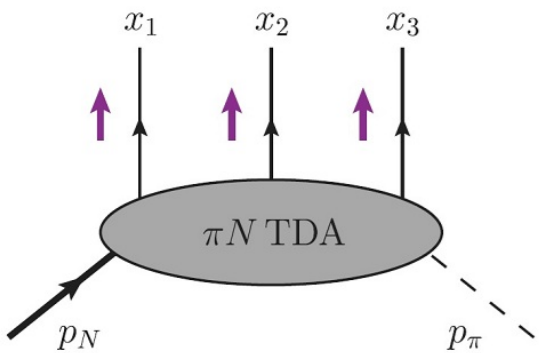
Proton-to-π^0 TDAs:

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

$$4(P\cdot n)^3 \int \left[\prod_{k=1}^{3} \frac{dz_k}{2\pi} e^{i x_k z_k (P\cdot n)}\right] \langle \pi^0(p_\pi)| \varepsilon_{c_1 c_2 c_3}\, u_\rho^{c_1}(z_1 n) u_\tau^{c_2}(z_2 n) d_\chi^{c_3}(z_3 n) |N^p(p_1, s_1)\rangle$$
$$= \delta(2\xi - x_1 - x_2 - x_3) i \frac{f_N}{f_\pi m_N} \sum_s \left(s^{\pi N}\right)_{\rho\tau,\chi} H_s^{\pi N}\left(x_1, x_2, x_3, \xi, u; \mu^2\right).$$

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

- Momentum flow (ERBL):

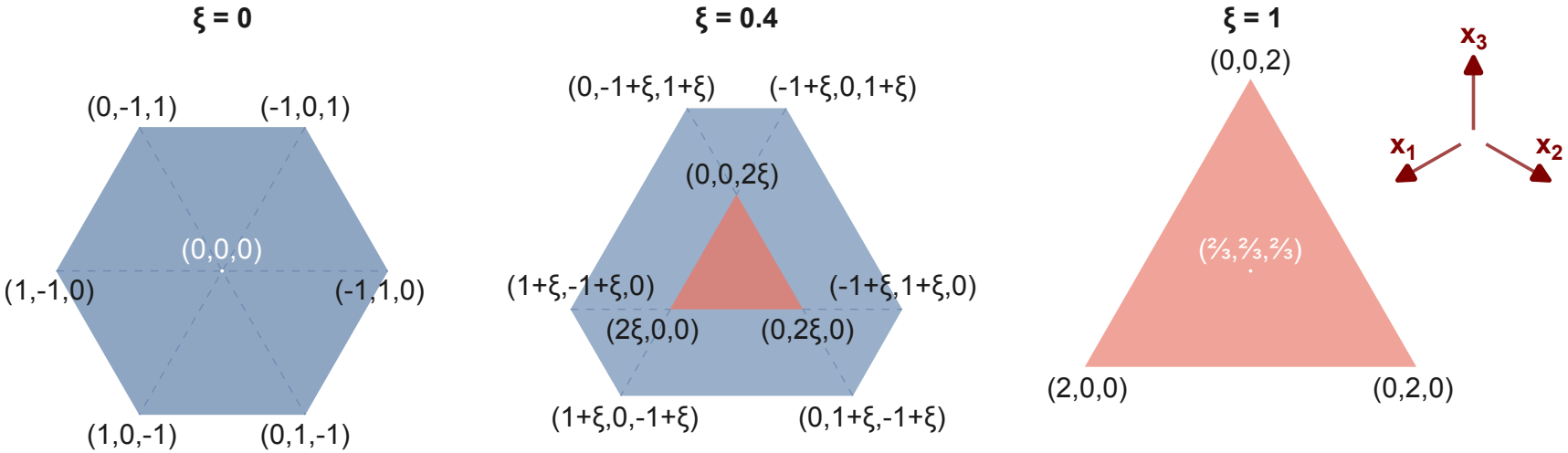


- TDAs: 3 sets of quark-diquark coordinates ($i = 1, 2, 3$)

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

Fundamental properties I: support & polynomiality

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



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

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

Can be studied on the lattice!

- Polynomiality in ξ of the Mellin moments in x_k:

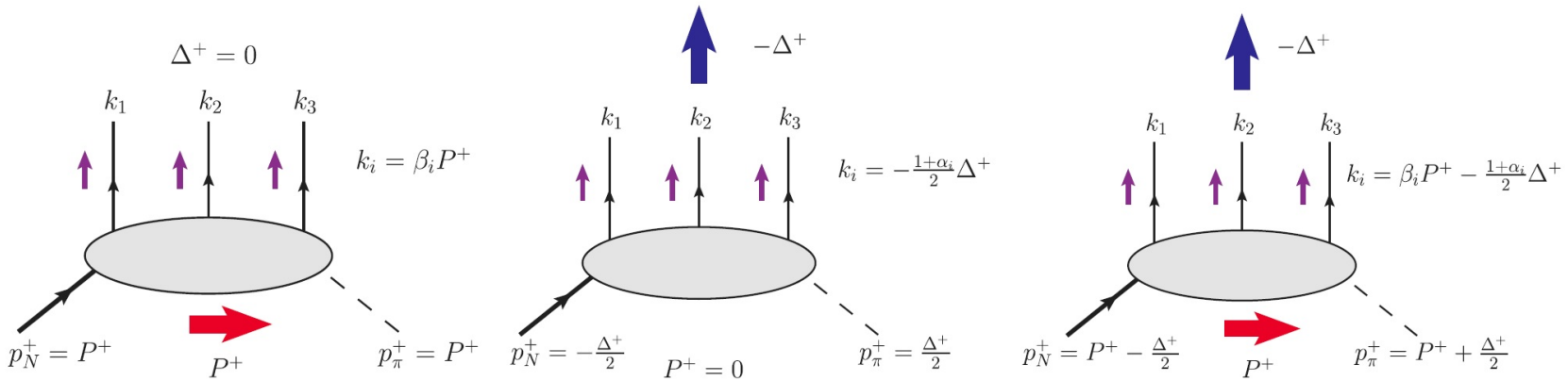
$$\int_{-1+\xi}^{1+\xi} dx_1\,dx_2\,dx_3\,\delta\Big(\sum_k x_k - 2\xi\Big)x_1^{n_1}x_2^{n_2}x_3^{n_3}H^{\pi N}(x_1,\,x_2,\,x_3,\,\xi,\,\Delta^2)$$
$$= \text{[Polynomial of order } n_1+n_2+n_3\{+1\}\text{]}\,(\xi).$$

Fundamental properties II: spectral representation and evolution

- Spectral representation A. Radyushkin'97 generalized for πN TDAs ensures polynomiality and support B. Pire, L. Szymanowski and K.S.'10:

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

- Ω_i: $\{|\beta_i| \leq 1,\ |\alpha_i| \leq 1 - |\beta_i|\}$: 3 copies of the 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 of 3-quark light-cone operator: V. Braun, S. Derkachov, G. Korchemsky, A. Manashov'99.
- Evolution equations for TDAs: B. Pire, L. Szymanowski'07 in the ERBL and DGLAP regions.

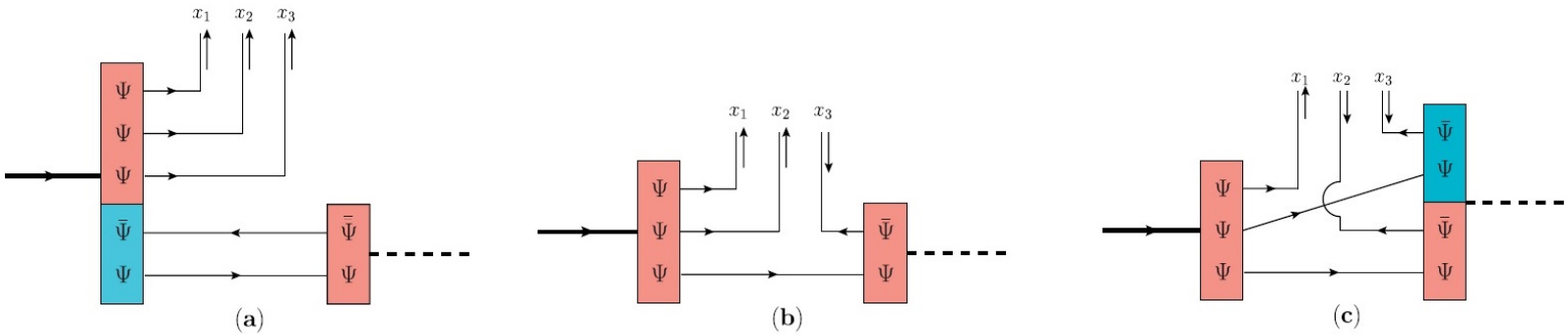


TDAs and light-front wave functions

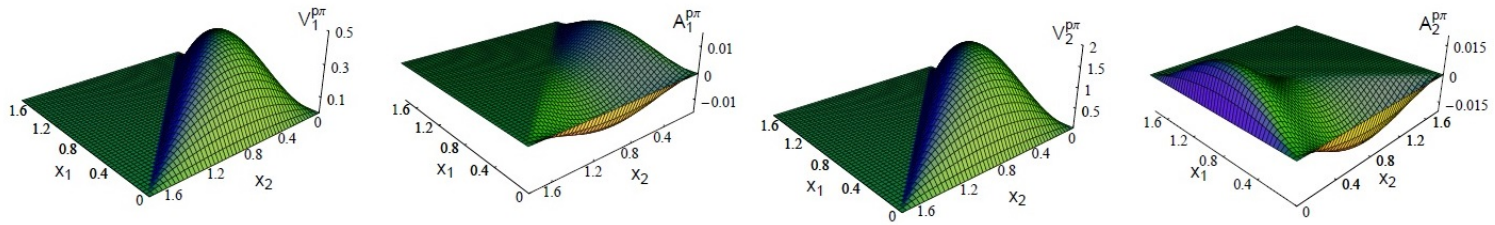
- Light-front quantization approach: πN TDAs provide information on next-to-minimal Fock components of light-cone wave functions of hadrons:

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

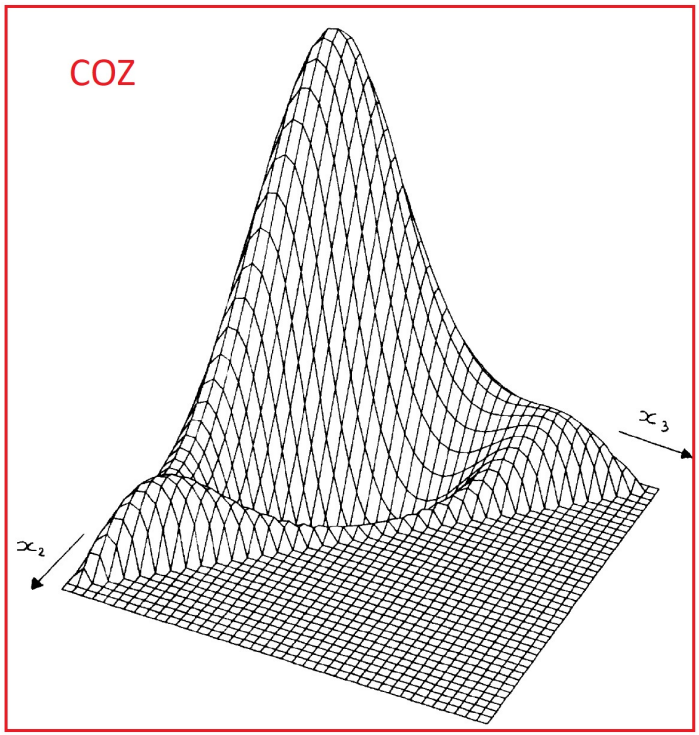
$$|M\rangle = \underbrace{\psi_{(q\bar{q})}|q\bar{q}\rangle}_{\text{Described by meson DA}} + \psi_{(q\bar{q}+q\bar{q})}|q\bar{q}\,q\bar{q}\rangle + \ldots$$



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

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

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

TDAs and the quark-diquark picture

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

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

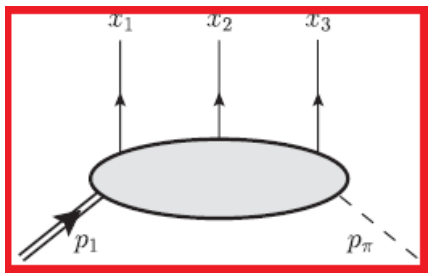
- The TDA support in quark-diquark coordinates:

$$-1 \le w_2 \le 1; \quad -1 + \left|\xi - \xi_2'\right| \le v_2 \le 1 - \left|\xi - \xi_2'\right|$$

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

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

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

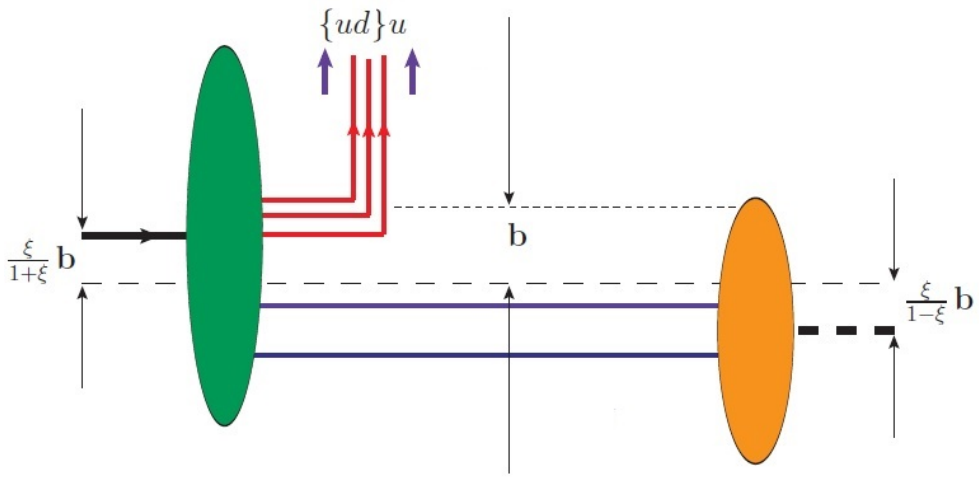


An interpretation in the impact parameter space

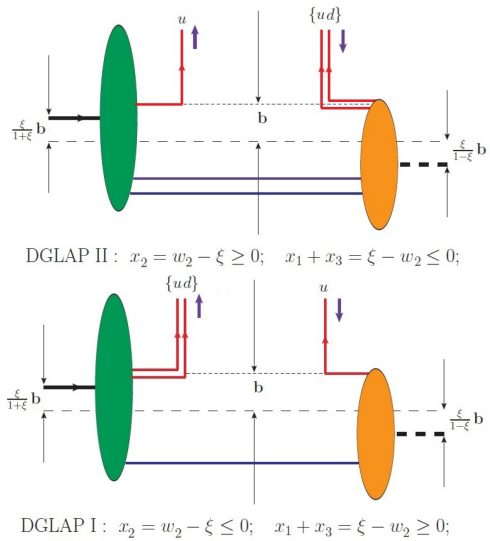
- A generalization of M. Burkardt'00,02; M. Diehl'02 for the ν-integrated TDAs.
- Fourier transform with respect to

$$D_\perp = \frac{p_{\pi\perp}}{1-\xi} - \frac{p_{N\perp}}{1+\xi}; \qquad \Delta^2 = -2\xi\left(\frac{m_\pi^2}{1-\xi} - \frac{m_N^2}{1+\xi}\right) - (1-\xi^2)D^2{}_\perp.$$

- A representation depends on the domain:



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

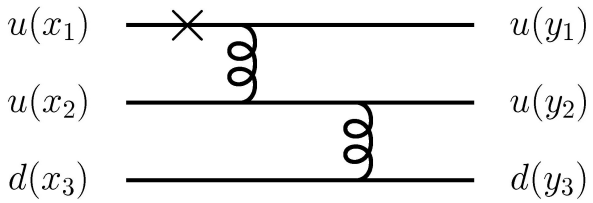


DGLAP II : $x_2 = w_2 - \xi \geq 0; \quad x_1 + x_3 = \xi - w_2 \leq 0;$

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

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;



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

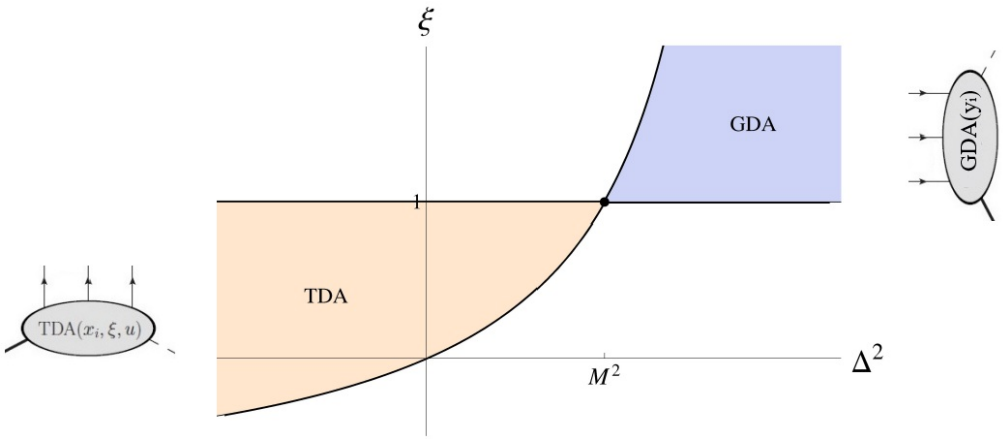
$R_\alpha \sim K_\alpha(x_1, x_2, x_3, \xi) \times Q_\alpha(y_1, y_2, y_3) \times$
[combination of πN TDAs] $(x_1, x_2, x_3, \xi) \times$ [combination of nucleon DAs] (y_1, y_2, y_3)

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

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

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

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

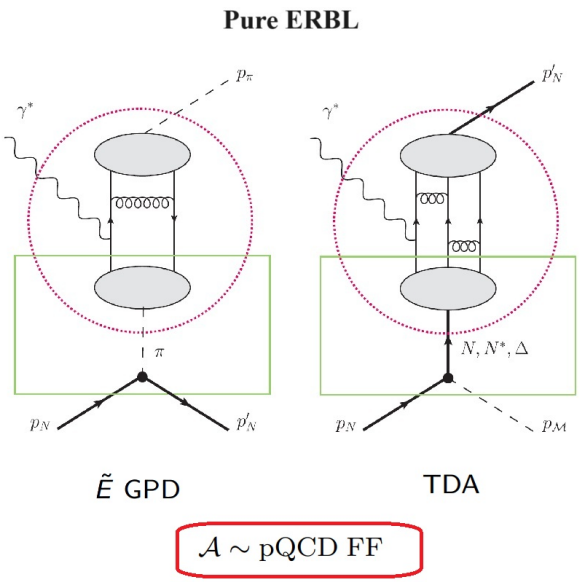
πN GDA at the threshold $\xi = 1$, $\Delta^2 = m_N^2$ fixed in terms of nucleon DAs V^p, A^p, T^p.

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

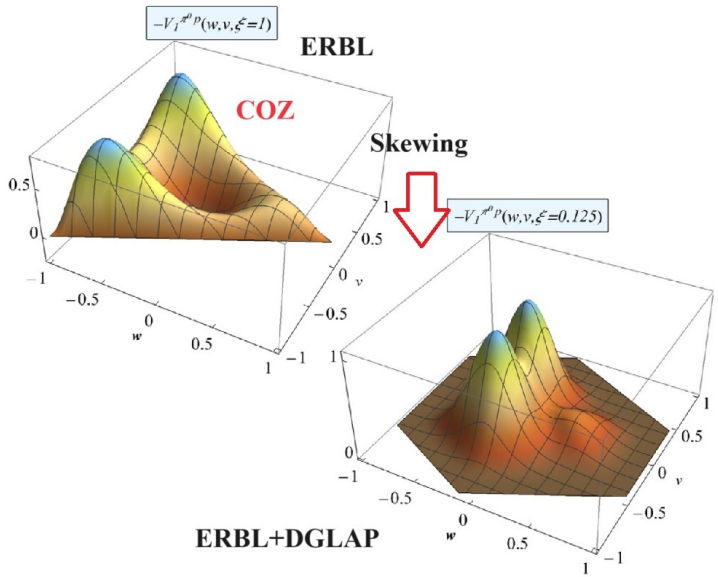
1. support in x_ks and polynomialty;
2. isospin + permutation symmetry;
3. crossing πN TDA $\leftrightarrow$ πN GDA and chiral properties: soft pion theorem;

- 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;

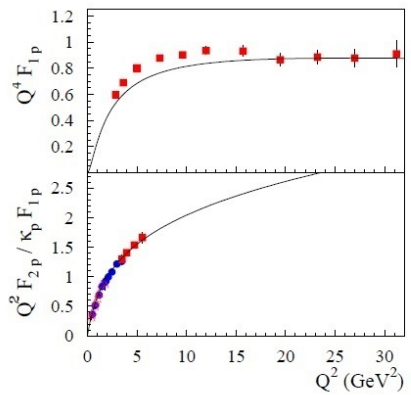


- A factorized Ansatz for quadruple distributions with input at $\xi = 1$: Phys. Rev. D 85, 054021 (2012)

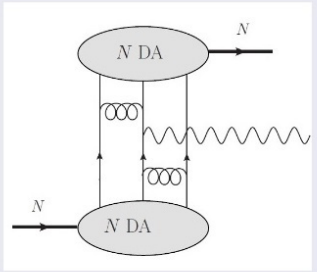


E.m. FF: a word of caution. Can we rely on collinear factorization?

- 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 rescattering mechanism contribution;

- Some good news on NLO pQCD analysis of nucleon FF: Y. K. Huang, B. X. Shi, Y. M. Wang and X. C. Zhao, Phys. Rev. Lett. 135, 061901 (2025); L. B. Chen, W. Chen, F. Feng, S. Hu and Y. Jia, Phys. Rev. Lett. 135, 131903 (2025);

Backward π^0 electroproduction: LO and NLO kernels

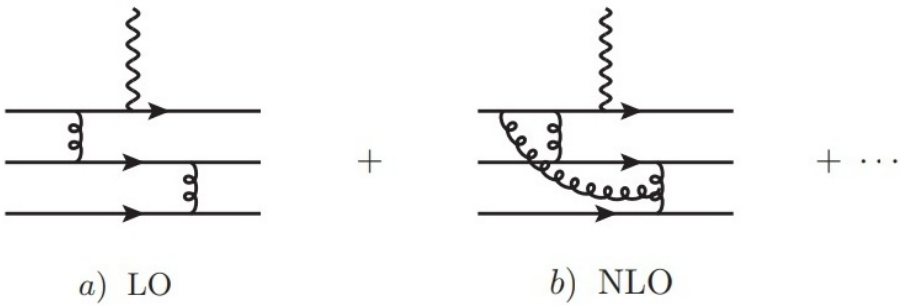
F. Feng, Y. Ji, 76-pages GPT-6 Astra generated note

Hard-Scattering Kernels for Backward Neutral-Pion Electroproduction

From TDA Operators to LO and NLO Matching, Evolution, and Model Phenomenology

Collaboration working manuscript

6 November 2026



a) LO b) NLO

NLO: mapped F_1 calculation

- Reuse one-loop F_1 open-spinor coefficients: 5,583 exported components; 24 tensor labels.
- Retain $d = 4 - 2\epsilon$ tensors through renormalization and subtraction; *project onto physical channels last*.

NLO matching: key result and current status

One-loop pole cancellation:

$$H^{(1)}_{\text{bare}} = \frac{H_{-2}}{\epsilon^2} + \frac{H_{-1}}{\epsilon} + H_{\text{finite}} + O(\epsilon).$$

$$H^{(1)}_{\text{poles}} + H^{(1)}_{\text{QcD ct}} + H^{(1)}_{\text{DA ct}} + H^{(1)}_{\text{TDA ct}} = 0.$$

Validated results:

- One-loop input mapped from F_1; not a fresh full-diagram calculation.
- Double poles cancel in 20 open-spin structures.
- Krankl-Manashov'2011-consistent finite terms and signed-support causal continuation.
- **N.B.** one-loop consistency check, *not* an all-order proof.

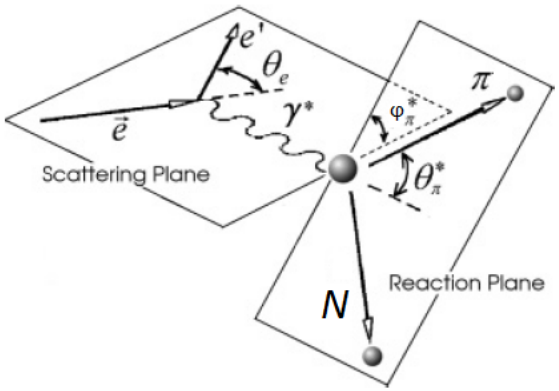
How to check that the TDA-based reaction mechanism is relevant?

Distinguishing features

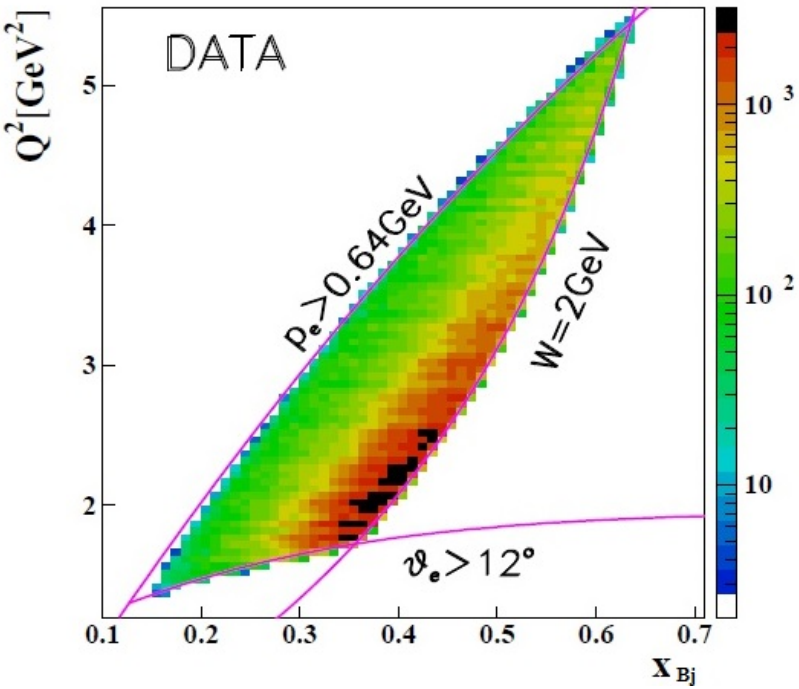
- Characteristic backward peak of the cross section. Special behavior in the near-backward region;
- Scaling behavior of the cross section in Q^2: $\frac{d\sigma}{dt} \sim Q^{-10}$;
- Dominance of the transverse cross section σ_T;
- Polarization observables
- Universality of TDAs: cross channel counterpart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

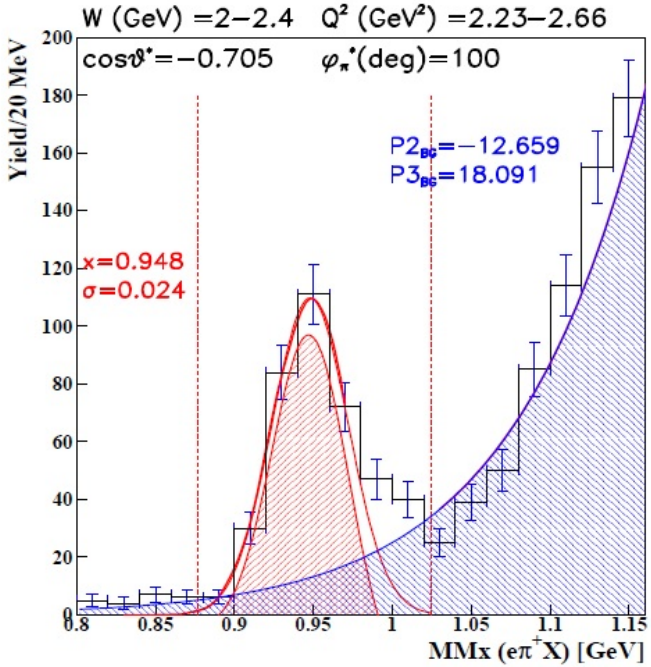
$$e + A(Z) \to e' + p' + A'(Z-1) + \pi^0 \quad \text{v.s.} \quad e + p \to e' + p' + \pi^0.$$

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)





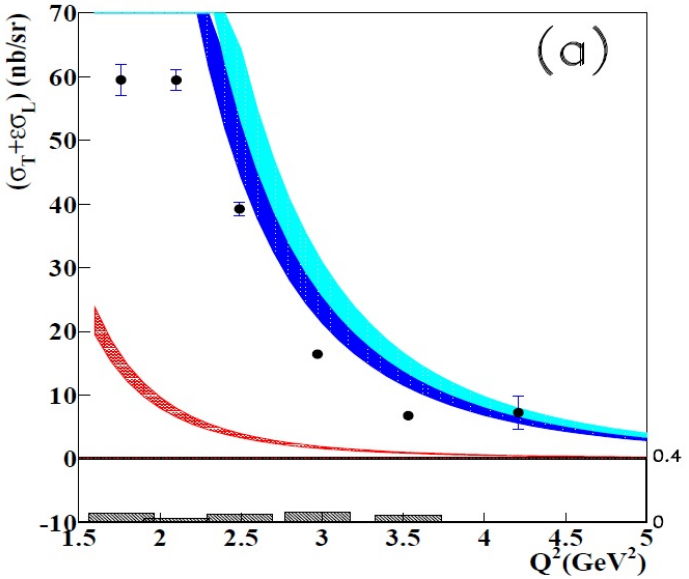
Backward pion electroproduction @ CLAS II

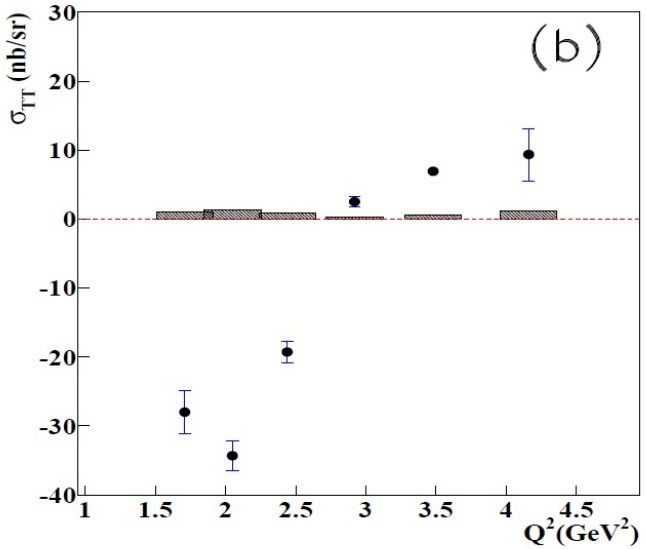
$$\frac{d\sigma}{d\Omega_\pi^*} = A + B\cos\varphi_\pi^* + C\cos 2\varphi_\pi^*,$$ where

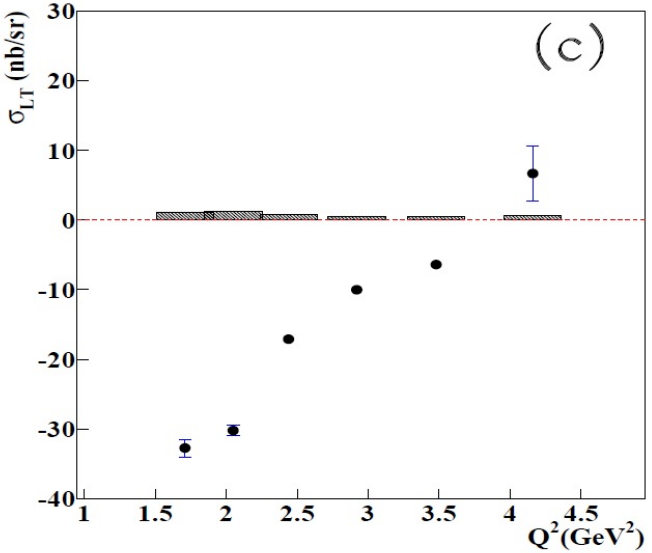
$A = \sigma_T + \epsilon\sigma_L$; $B = \sqrt{2\epsilon(1+\epsilon)}\sigma_{LT}$;
$C = \epsilon\sigma_{TT}$

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).

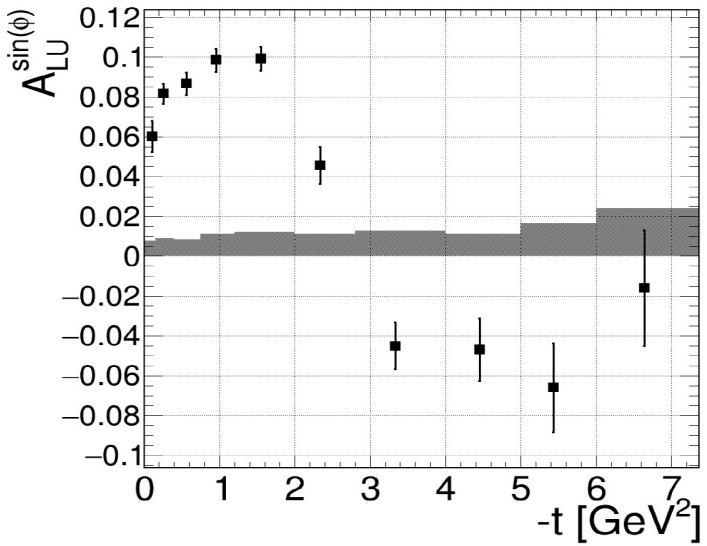
- The cross section can be expressed as

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

- Beam Spin Asymmetry

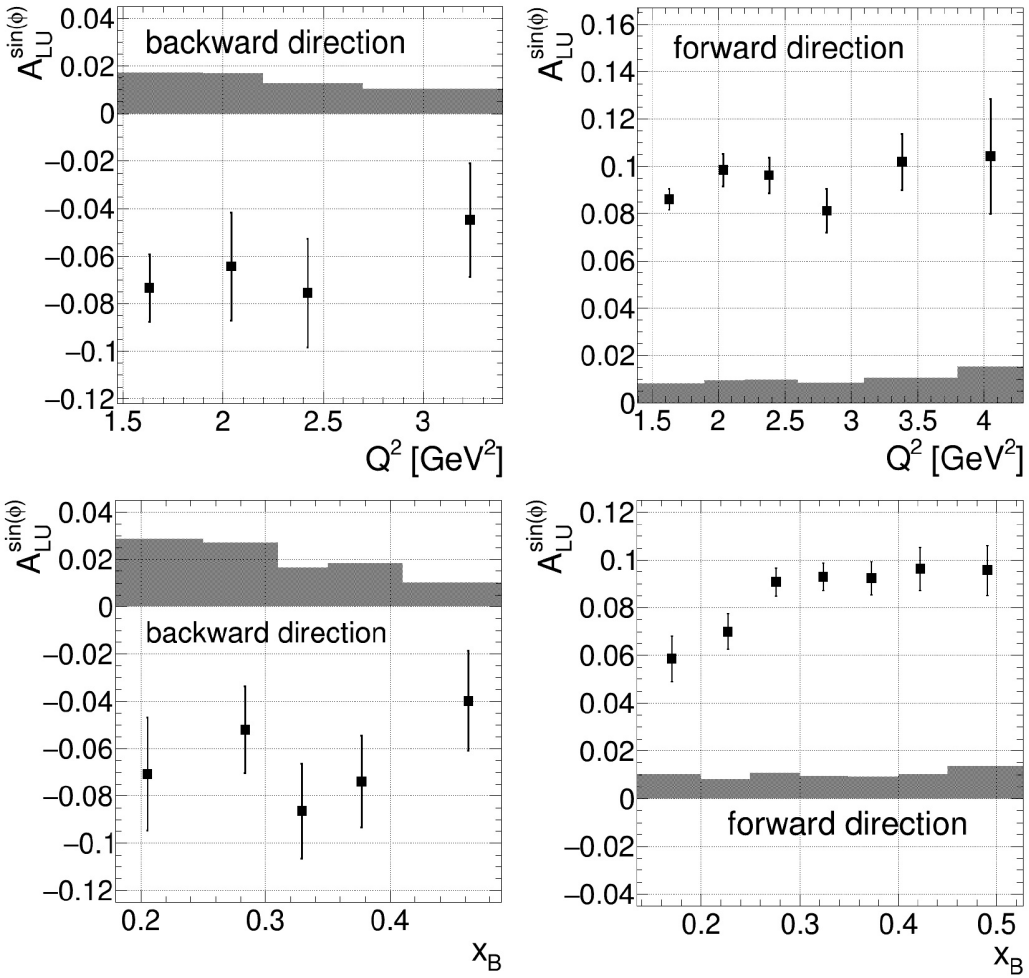
$$\mathrm{BSA}\left(Q^2, x_B, -t, \varphi\right) = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{A_{LU}^{\sin(\varphi)} \cdot \sin(\varphi)}{1 + A_{UU}^{\cos(\varphi)} \cdot \cos(\varphi) + A_{UU}^{\cos(2\varphi)} \cdot \cos(2\varphi)};$$

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



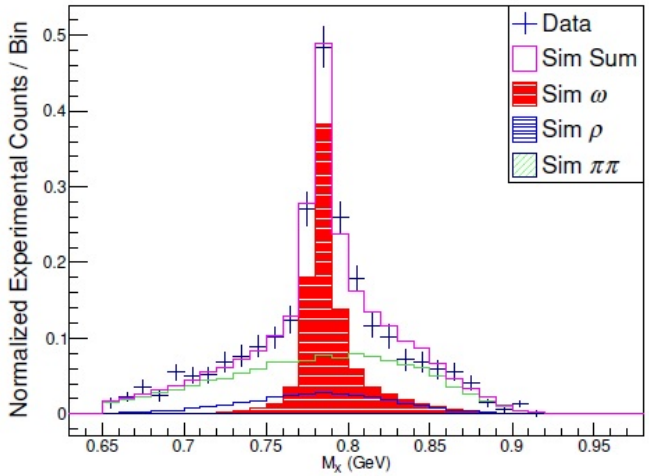
Backward pion electroproduction @ CLAS IV

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



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 $ep \to e'p\omega$.

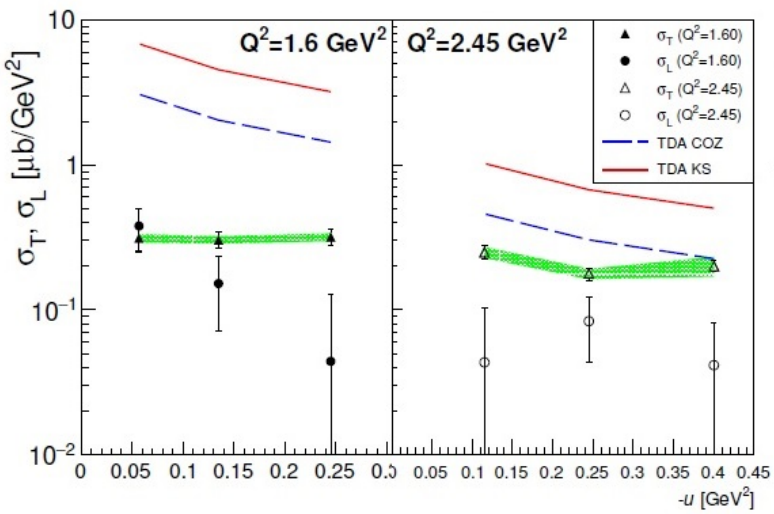


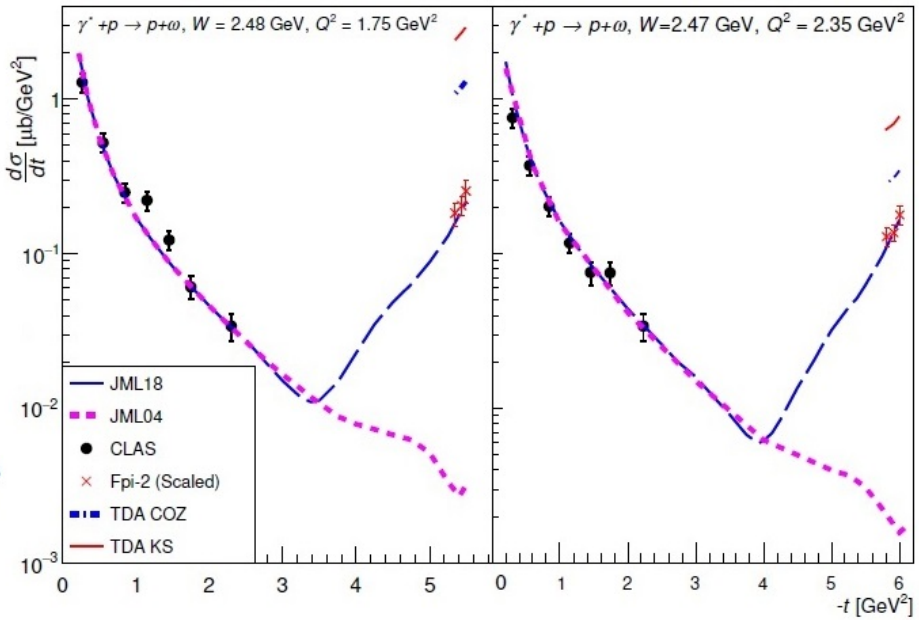
- Full Rosenbluth separation: σ_{T} and σ_{L} extracted to address $\sigma_{\mathrm{T}} \gg \sigma_{\mathrm{L}}$ issue.

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

Backward ω-production at JLab Hall C II

- For $Q^2 = 2.45$ GeV^2: $\sigma_L/\sigma_T < \mu^2/Q^2$ and $\sigma_T \gg \sigma_L$;





- 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.

Polarization observables: SSAs and DSAs

$$\left[\frac{\alpha_{\rm em}}{8\pi^3}\frac{y^2}{1-\varepsilon}\frac{1-x_B}{x_B}\frac{1}{Q^2}\right]^{-1}\frac{d^5\sigma}{dx_B dQ^2 dt d\phi d\psi}$$

$$= \underbrace{\frac{1}{2}\left(\frac{d\sigma^{++}_{++}}{dt}+\frac{d\sigma^{--}_{++}}{dt}\right)}_{d\sigma_T/dt} + \varepsilon\frac{d\sigma^{++}_{00}}{dt} - \varepsilon\cos(2\phi)\,\mathrm{Re}\frac{d\sigma^{++}_{+-}}{dt} - \sqrt{\varepsilon(1+\varepsilon)}\cos\phi\,\mathrm{Re}\left(\frac{d\sigma^{++}_{+0}}{dt}+\frac{d\sigma^{--}_{+0}}{dt}\right)$$

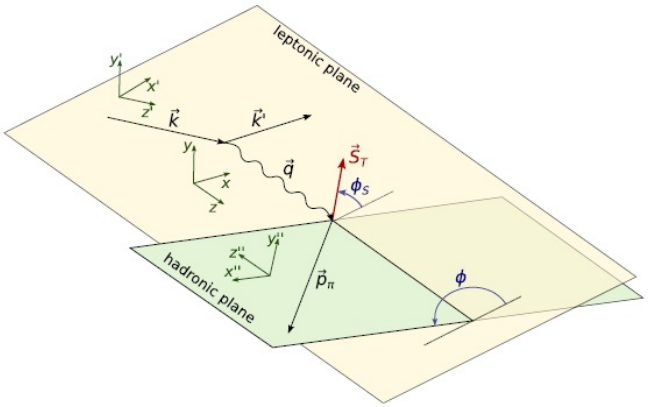
$$+ P_\ell\sqrt{\varepsilon(1-\varepsilon)}\sin\phi\,\mathrm{Im}\left(\frac{d\sigma^{++}_{+0}}{dt}+\frac{d\sigma^{--}_{+0}}{dt}\right) + S_L\left[\varepsilon\sin(2\phi)\,\mathrm{Im}\frac{d\sigma^{++}_{+-}}{dt} + \sqrt{\varepsilon(1+\varepsilon)}\sin\phi\,\mathrm{Im}\left(\frac{d\sigma^{++}_{+0}}{dt}-\frac{d\sigma^{--}_{+0}}{dt}\right)\right]$$

$$+ S_L P_\ell\left[\underbrace{\sqrt{1-\varepsilon^2}\frac{1}{2}\left(\frac{d\sigma^{++}_{++}}{dt}-\frac{d\sigma^{--}_{++}}{dt}\right)}_{A_{LL}^{\rm const.}} - \sqrt{\varepsilon(1-\varepsilon)}\cos\phi\,\mathrm{Re}\left(\frac{d\sigma^{++}_{+0}}{dt}-\frac{d\sigma^{--}_{+0}}{dt}\right)\right]$$

$$+ S_T\left[\underbrace{\mathrm{Im}\left(\frac{d\sigma^{+-}_{++}}{dt}+\varepsilon\frac{d\sigma^{+-}_{00}}{dt}\right)}_{A_{UT}^{\sin(\phi-\phi_S)}}\sin(\phi-\phi_S) + \frac{\varepsilon}{2}\sin(\phi+\phi_S)\,\mathrm{Im}\frac{d\sigma^{+-}_{+-}}{dt}\right.$$

$$\left. + \frac{\varepsilon}{2}\sin(3\phi-\phi_S)\,\mathrm{Im}\frac{d\sigma^{-+}_{+-}}{dt} + \sqrt{\varepsilon(1+\varepsilon)}\sin\phi_S\,\mathrm{Im}\frac{d\sigma^{+-}_{+0}}{dt} + \sqrt{\varepsilon(1+\varepsilon)}\sin(2\phi-\phi_S)\,\mathrm{Im}\frac{d\sigma^{-+}_{+0}}{dt}\right]$$

$$+ S_T P_\ell\left[\underbrace{\sqrt{1-\varepsilon^2}\,\mathrm{Re}\frac{d\sigma^{+-}_{++}}{dt}}_{A_{LT}^{\cos(\phi-\phi_S)}}\cos(\phi-\phi_S) - \sqrt{\varepsilon(1-\varepsilon)}\cos\phi_S\,\mathrm{Re}\frac{d\sigma^{+-}_{+0}}{dt} - \sqrt{\varepsilon(1-\varepsilon)}\cos(2\phi-\phi_S)\,\mathrm{Re}\frac{d\sigma^{-+}_{+0}}{dt}\right].$$



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

$$A_{UT} = \frac{d\sigma^{\Uparrow} - d\sigma^{\Downarrow}}{d\sigma^{\Uparrow} + d\sigma^{\Downarrow}}.$$

DSA 1

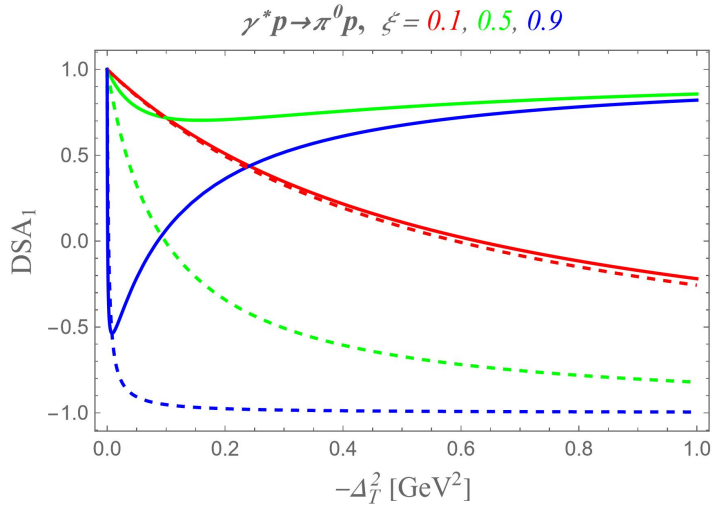
- Experimental definition for DAS_1:

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

- 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:



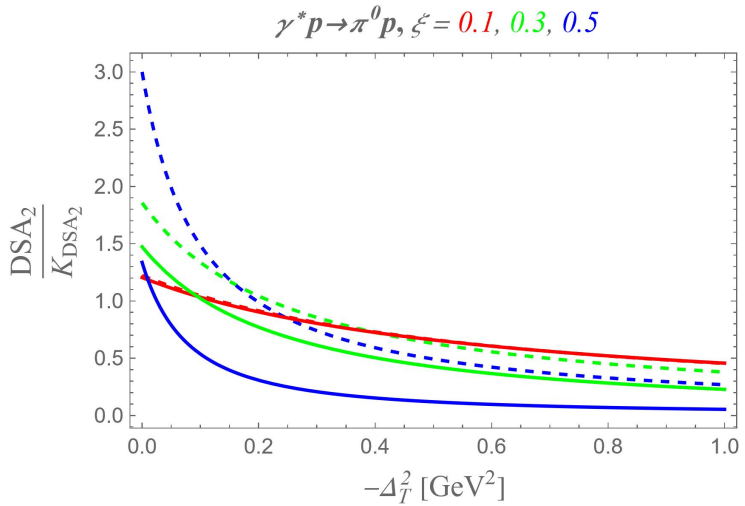
DSA 2

- 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}:

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



On polarization observables VII

What we may learn from these polarization observables?

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

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

W. B. Li, G. M. Huber et al., arXiv:2008.10768 [nucl-ex] :

PAC48 REPORT

PR12-20-007

August 10-14, 2020

September 25, 2020

Jefferson Lab

Scientific Rating: B

Recommendation: Approved

Beam time scheduled for 2027



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

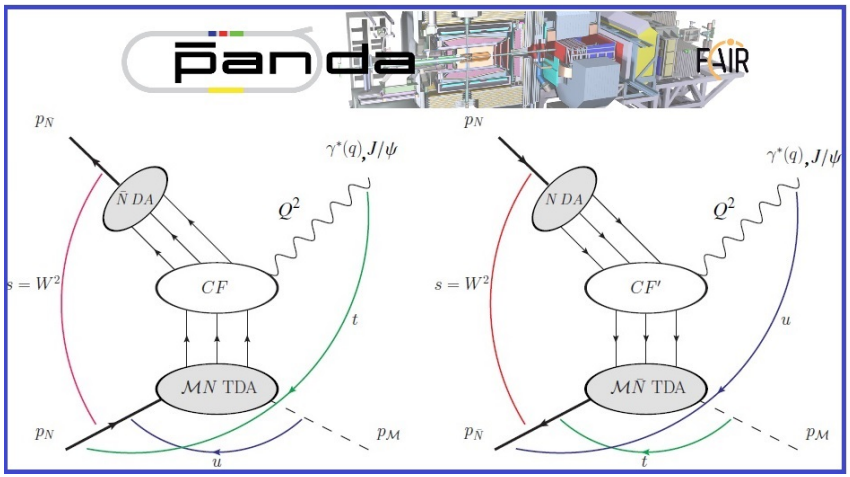
Spokespersons: W. Li (contact), J. Stevens, G. Huber

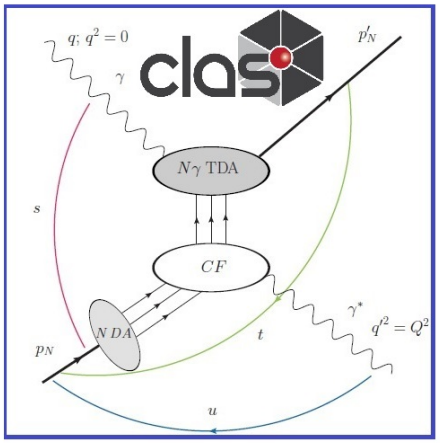
Motivation: This proposal aims at measuring backward-angle exclusive π^0 production above the resonance region with a proton target. Theoretical models to describe this process include a soft mechanism (Regge exchange) and a hard QCD mechanism in terms of so-called transition distribution amplitudes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

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

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

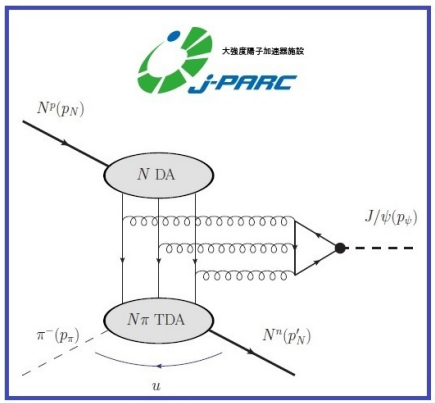
- Complementary experimental options and universality of TDAs.

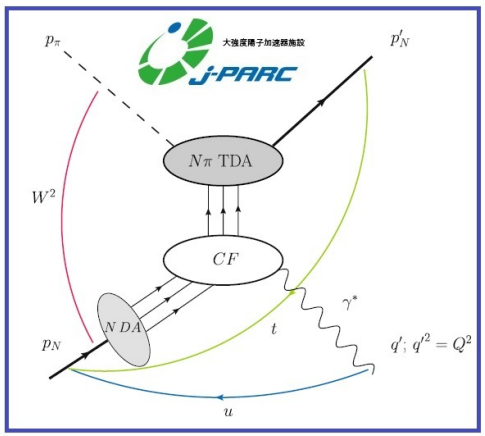


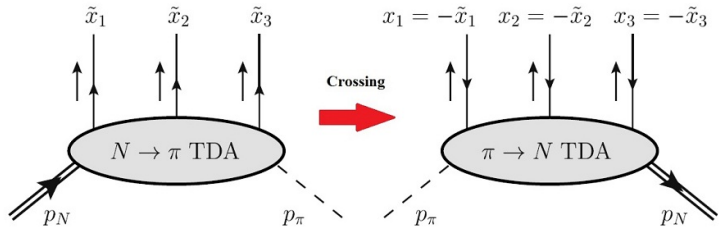


Backward TCS: B.Pire, K.S., A. Shaikhutdinova, L.Szymanowski, Eur. Phys. J. C 82, 656 (2022)

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



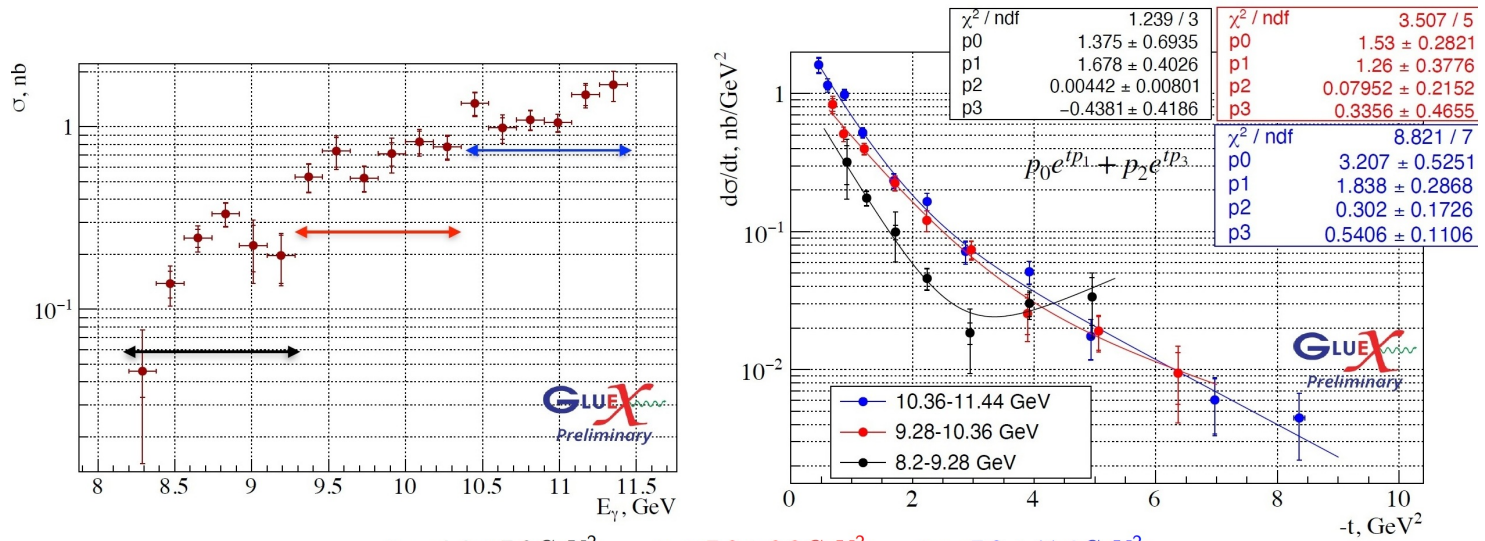




Charmonium photoproduction

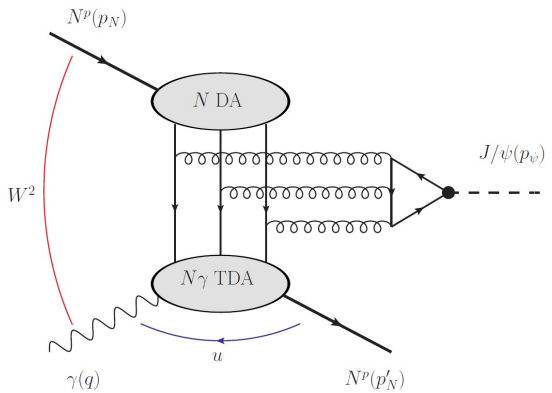
GlueX Collaboration, Phys.Rev.C 108 (2023) 2, 025201

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



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

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



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

New models for πN TDAs: a generalization of RDDA

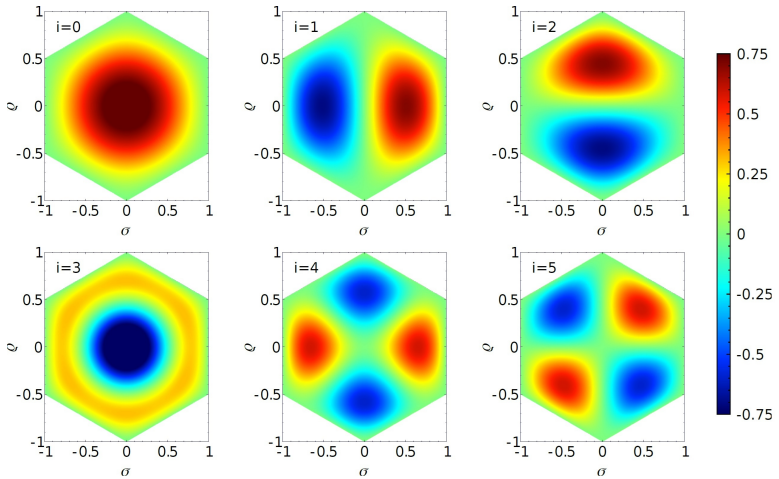
Flexible parametrization B. Pire, K.S., L. Szymanowski and P. Sznajder, Phys.Rev.D 112 (2025)

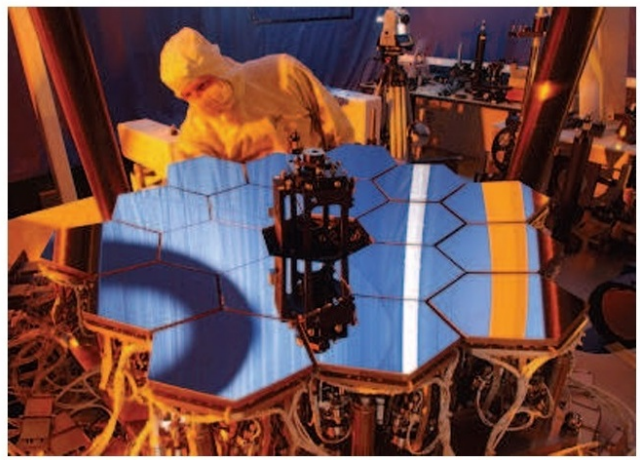
$$F(\beta_1,\beta_2,\beta_3,\alpha_1,\alpha_2,\alpha_3;\,u) = \underbrace{F^{(0)}(\beta_1,\beta_2,\beta_3,\alpha_1,\alpha_2,\alpha_3;\,u)}_{\text{Fixed from soft pion theorem at } \xi=1} + (1-\xi)\,\underbrace{F^{(1)}(\beta_1,\beta_2,\beta_3,\alpha_1,\alpha_2,\alpha_3;\,u)}_{\text{Free model input, fitted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

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

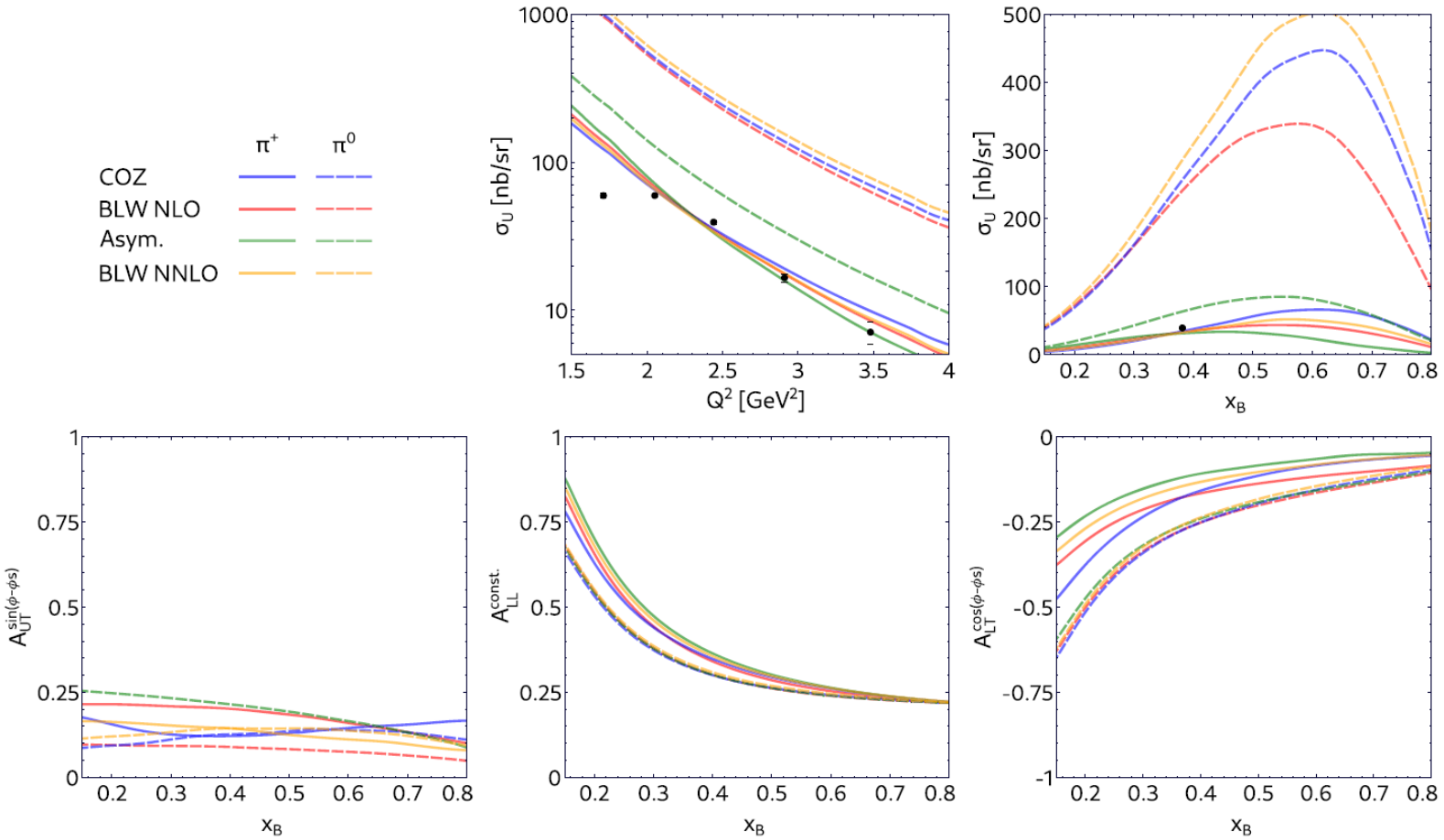
$$F^{(1)}(\sigma,\rho,\omega,\nu;u) = f(\sigma,\rho)\ \underbrace{h(\sigma,\rho,\omega,\nu)}_{\text{profile function}}\ G(u)\,.$$

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





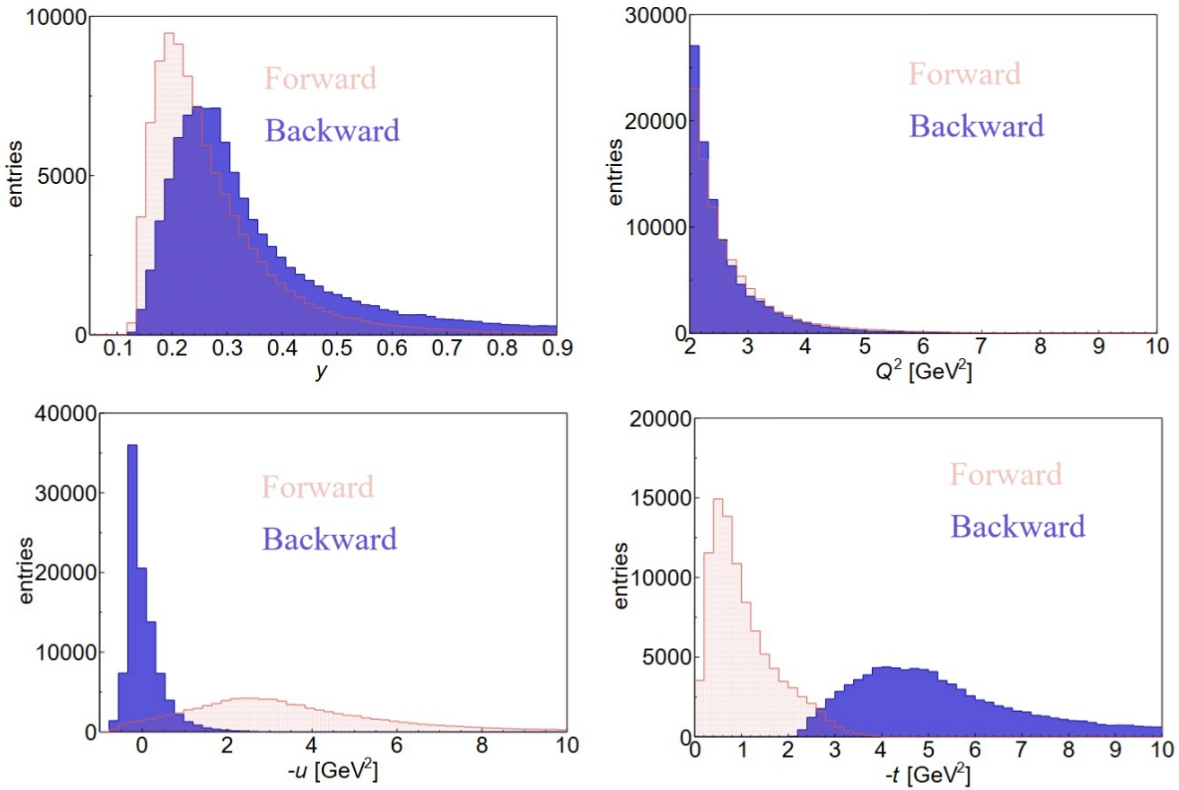
New models for πN TDAs: results I



- A model normalized to JLab 6 GeV data for π^+ channel;
- Selected observables:
  - as a function of Q^2 for $W = 2.2$ GeV and $-u = 0.5$ GeV^2;
  - x_B for $Q^2 = 2.44$ GeV^2 and $-u = 0.5$ GeV^2.

New models for πN TDAs: results II

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



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

More options: backward reactions off pions I

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

- Pion-to-γ TDAs:

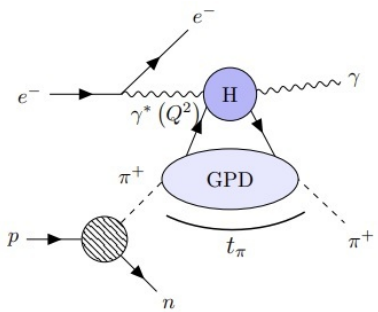
$$\frac{e}{f_\pi}(\epsilon\cdot\Delta)A^{\pi\gamma}(x,\xi,u;\mu) = \frac{1}{2}\int\frac{dz^-}{2\pi}e^{ixP^+z^-}\left\langle\gamma\left(q',\epsilon\right)\right|\bar\psi_d(-z/2)\gamma^+\gamma_5\psi_u(z/2)\left|\pi\left(p_\pi\right)\right\rangle\Big|_{z^+=z^i_\perp=0}$$

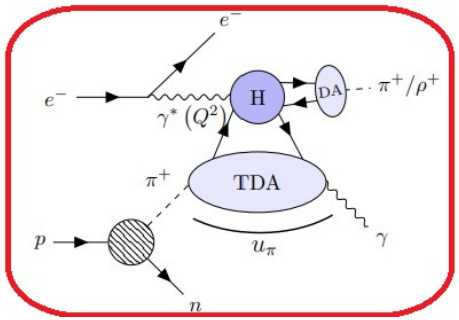
$$\frac{i}{P^+}\frac{e}{f_\pi}\varepsilon_{\mu\nu\rho\sigma}n^\mu\epsilon^\nu P^\rho\Delta^\sigma_\perp V^{\pi\gamma}(x,\xi,u;\mu) = \frac{1}{2}\int\frac{dz^-}{2\pi}e^{ixP^+z^-}\left\langle\gamma\left(q',\epsilon\right)\right|\bar\psi_d(-z/2)\gamma^+\psi_u(z/2)\left|\pi\left(p_\pi\right)\right\rangle\Big|_{z^+=z^i_\perp=0}$$

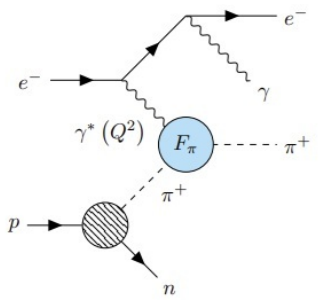
- Normalization to pion vector and axial FFs accessed in $\pi^+\to\ell^+\nu_\ell\gamma$ decays:

$$\int_{-1}^{1}dxA^{\pi\gamma}(x,\xi,u,\mu) = \frac{f_\pi}{m_\pi}F_A(u);\qquad \int_{-1}^{1}dxV^{\pi\gamma}(x,\xi,u,\mu) = \frac{f_\pi}{m_\pi}F_V(u).$$

- Can be accessed through the Sullivan process:

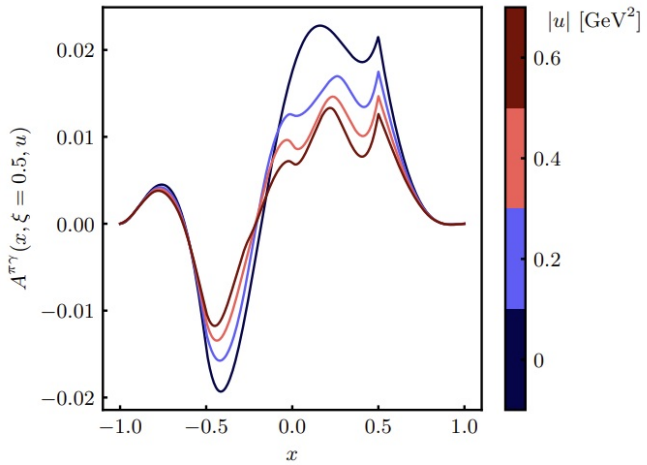


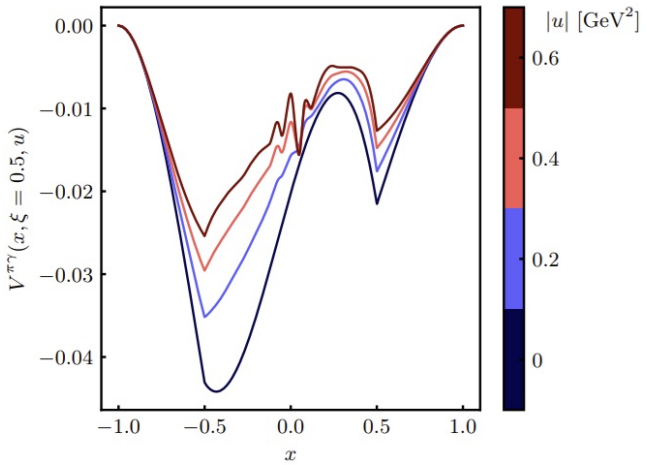




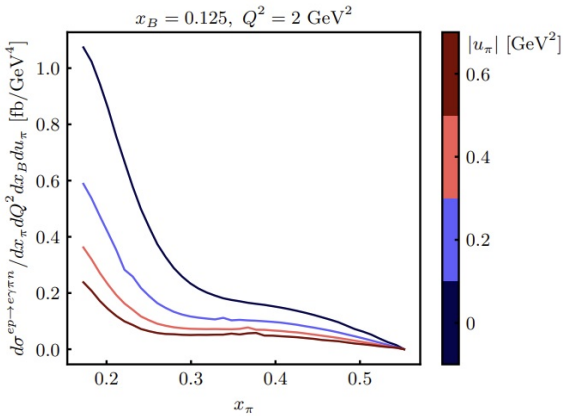
More options: backward reactions off pions II

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

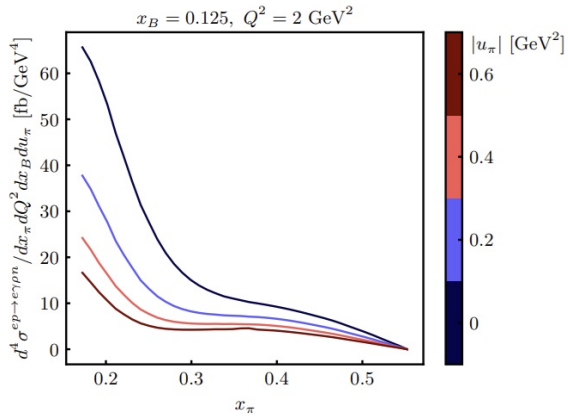




- Cross section estimates for JLab@22 GeV:



(a) $ep \to e\gamma\pi n$

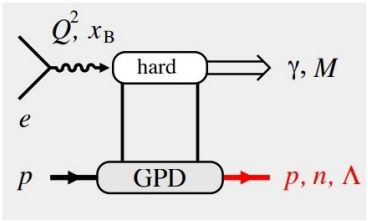


(b) $ep \to e\gamma\rho n$

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

Conclusions & Outlook

1. Nucleon-to-meson TDAs provide new information about correlation of partons inside hadrons. A consistent picture for the integrated TDAs emerges in the impact parameter representation;
2. We strongly encourage to consider backward electroproduction for various mesons (π, η, ω, ρ) and cross channel counterpart reaction;
3. First evidences for the onset of the factorization regime in backward $\gamma^* N \to N'\omega$ 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 (?), more on physical interpretation (?), phenomenological models ✓;
5. Backward DVCS and TCS: options for EIC;
6. Backward scattering off mesons through the Sullivan process;



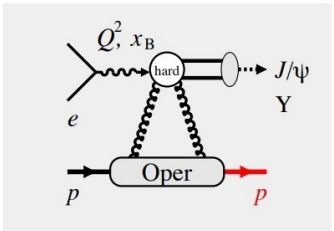
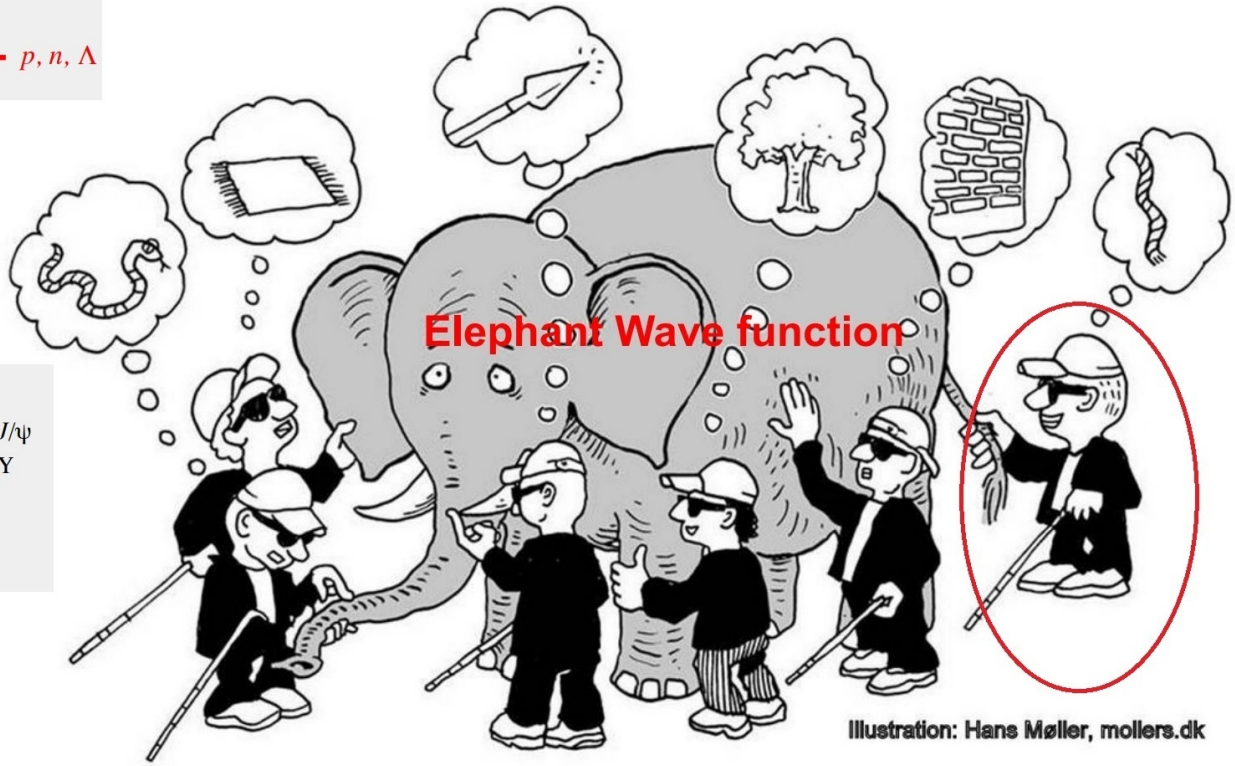
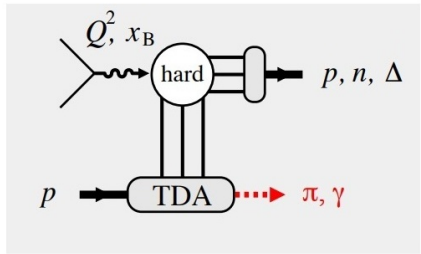


Illustration: courtesy of Bill Li



Forward angle → Backward angle

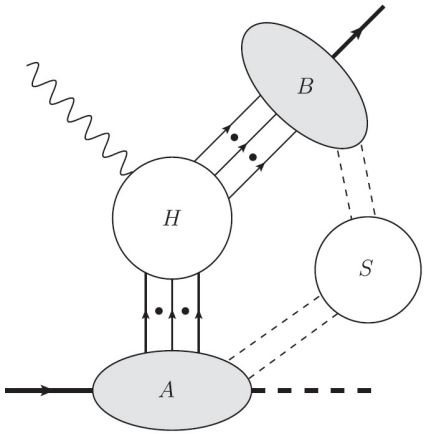
$-t$



Thank you for your attention!

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

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

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

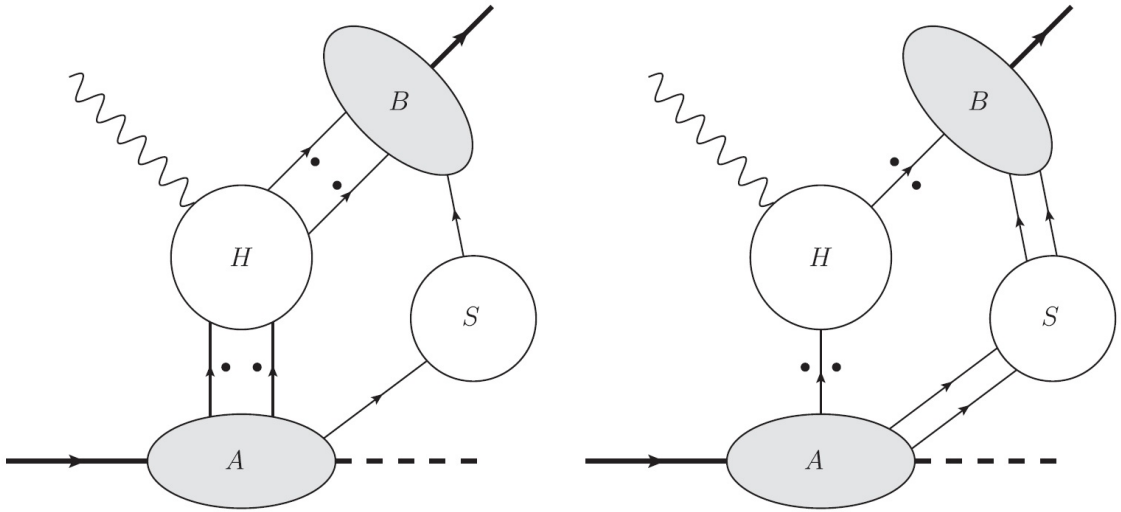
- Leading asymptotic behavior:

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

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!