Hard exclusive reactions with baryon number transfer: status and perspectives

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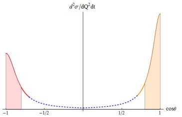
In collaboration with B. Pire, L. Szymanowski, P. Sznajder,

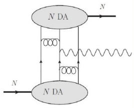
Factorization regimes for hard meson production

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

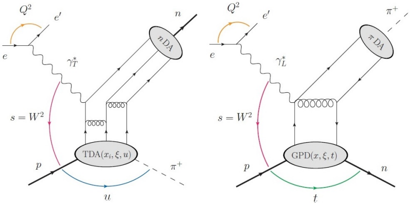
- $t \sim 0$ (forward peak) factorized description in terms of GPDs J. Collins, L. Frankfurt, M. Strikman'97;
- $u \sim 0$ (backward peak) factorized description in terms of TDAs L. Frankfurt, P.V. Pobylitsa, M. V. Polyakov, M. Strikman'99;



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



Brodsky & Lepage'81
Efremov & Radyushkin'80



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

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Transition distribution amplitudes and hard exclusive reactions with baryon number transfer

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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:

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

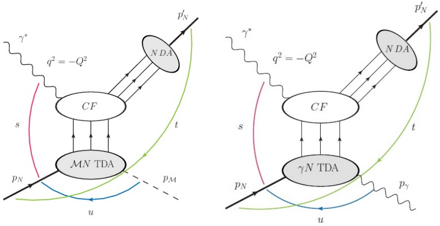
- $\langle A| = \langle 0|$; $|B\rangle$ - nucleon; $\Rightarrow$ nucleon DAs;
- Let $\langle A|$ be a meson state $\mathcal{M} =(\pi,\ \eta,\ \rho,\ \omega,\ ...)$ or a photon γ; $|B\rangle$ - nucleon; $\Rightarrow$ $\mathcal{M}N$ TDAs; and γN TDAs
- $\langle A| = \langle 0|$; $|B\rangle$ - nucleon-meson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

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

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



Learn more about QCD technique

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

Why TDAs are interesting?

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

Leading twist-3 πN TDAs

Proton-to-π^0 TDAs:

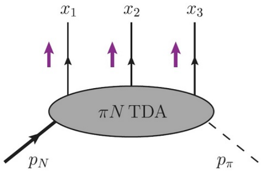
J.P.Lansberg, B.Pire, L.Szymanowski and K.S.'11 $\left(n^2 = p^2 = 0;\ 2p \cdot n = 1;\ \text{LC gauge}\ \boxed{A \cdot n = 0}\right)$.

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

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

- $\frac{2^3 \cdot 2}{2} = 8$ 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):

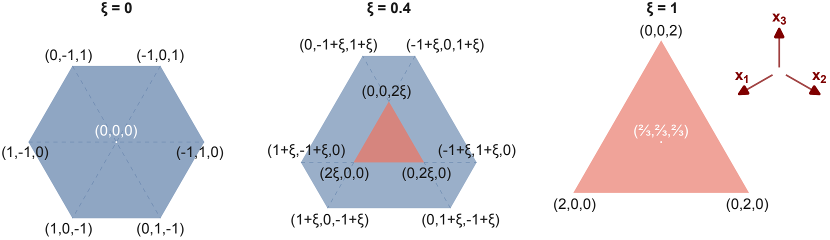


- TDAs: 3 sets of quark-diquark coordinates ($i = 1, 2, 3$)

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

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 $x_k \Rightarrow \pi N$ 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:

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

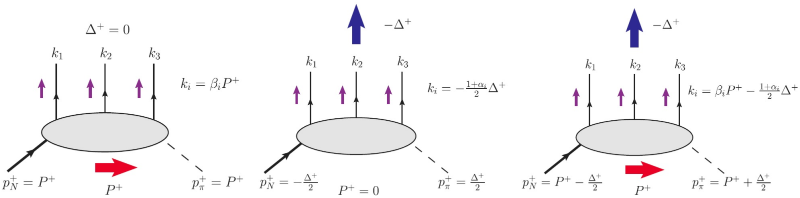
$$= [\text{Polynomial of order } n_1 + n_2 + n_3\{+1\}](\xi).$$

Fundamental properties II: spectral representation and evolution

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

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

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

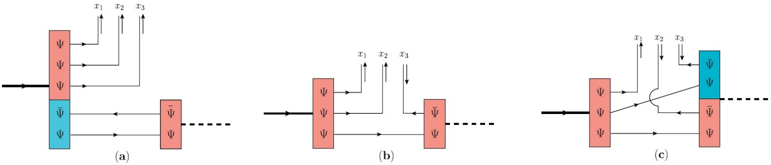


TDAs and light-front wave functions

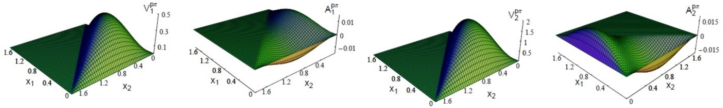
- Light-front quantization approach: πN TDAs provide information on next-to-minimal Fock components of light-cone wave functions of hadrons:

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

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



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

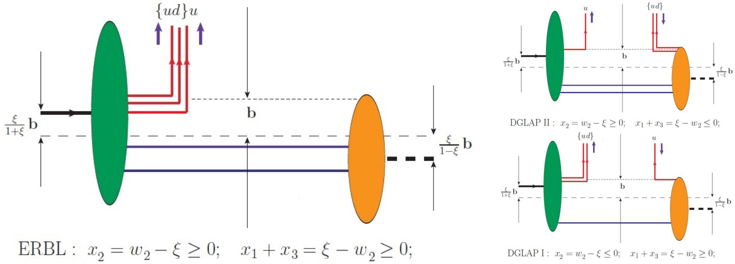


An interpretation in the impact parameter space

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

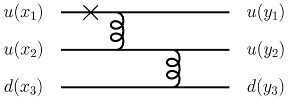
$$\mathbf{D} = \frac{\mathbf{p}_\pi}{1-\xi} - \frac{\mathbf{p}_N}{1+\xi}; \qquad \Delta^2 = -2\xi \left(\frac{m_\pi^2}{1-\xi} - \frac{m_N^2}{1+\xi} \right) - (1-\xi^2)\mathbf{D}^2.$$

- A representation depends on the domain:



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)

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

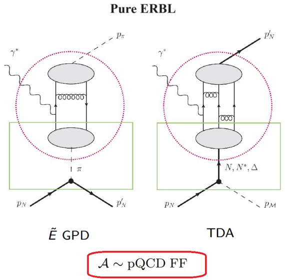
$$\text{C.f.} \quad A(\xi) = \int_{-1}^{1} dx \frac{H(x,\xi)}{x \pm \xi \mp i\epsilon} \int_0^1 dy \frac{\phi_M(y)}{y}$$

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

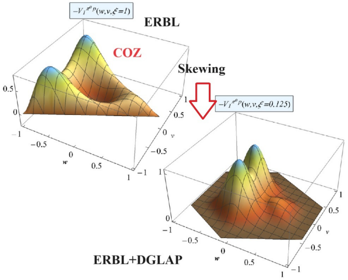
1. support in x_ks and polynomialty;
2. isospin + permutation symmetry;
3. crossing πN TDA $\leftrightarrow$ πN GDA and chiral properties: soft pion theorem;

- 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;

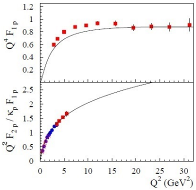


- A factorized Ansatz for quadruple distributions with input at $\xi = 1$: Phys. Rev. D **85**, 054021 (2012)

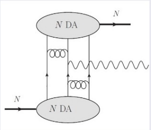


E.m. FF: a word of caution. Can we rely on collinear factorization?

- 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: Yong-Kang Huang et al. arXiv:2407.18724; W. Chen et al. arXiv:2406.19994;

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

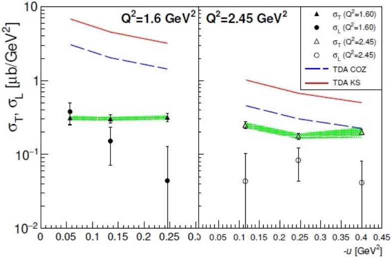
Distinguishing features

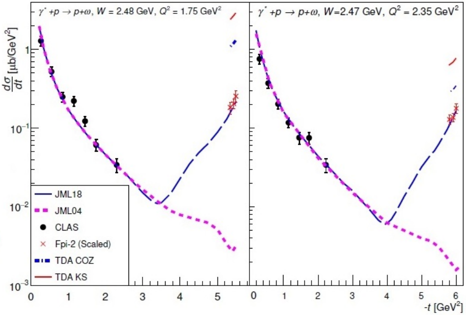
- Characteristic backward peak of the cross section. Special behavior in the near-backward region;
- Scaling behavior of the cross section in Q^2: $\frac{d\sigma}{dt} \sim Q^{-10}$;
- Dominance of the transverse cross section σ_T;
- Polarization observables
- Universality of TDAs: cross channel counterpart 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

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

Status of experiment I

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



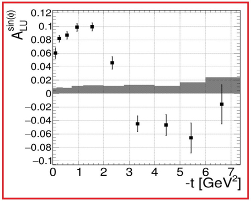


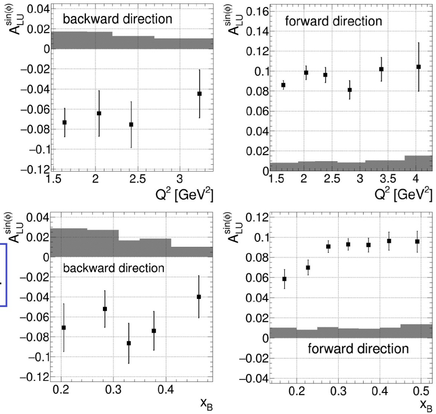
Polarization observables: Beam Spin Asymmetry @ CLAS

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

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

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





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

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

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

PAC48 REPORT

August 10-14, 2020

September 25, 2020

Jefferson Lab

PR12-20-007

Scientific Rating: B

Beam time scheduled for 2026

Recommendation: Approved

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

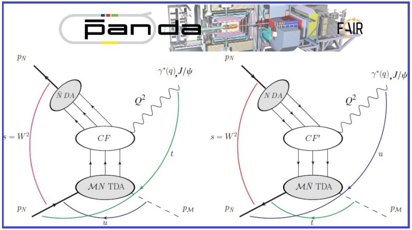
Spokespersons: W. Li (contact), J. Stevens, G. Huber

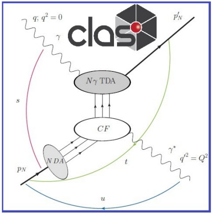
Motivation: This proposal aims at measuring backward-angle exclusive π^0 production above the resonance region with a proton target. Theoretical models to describe this process include a soft mechanism (Regge exchange) and a hard QCD mechanism in terms of so-called transition distribution amplitudes (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.

Cross channel counterpart reactions: P̄ANDA, J-PARC and backward TCS at JLab

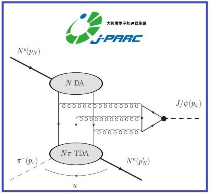
- Complementary experimental options and universality of TDAs.

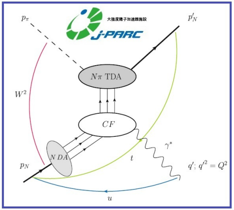


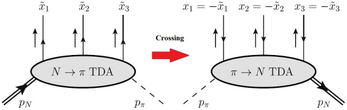


Backward TCS: B.Pire, K.S., A. Shaikhutdinova, L.Szymanowski, Eur. Phys. J. C **82**, 656 (2022)

- 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.



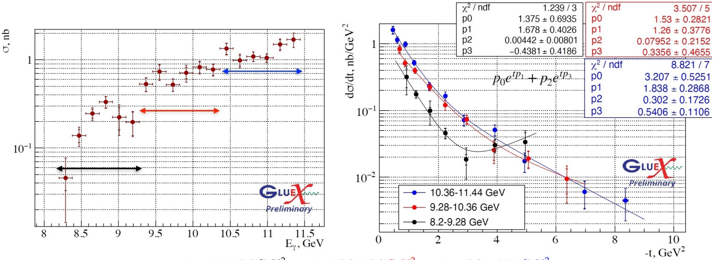




Charmonium photoproduction

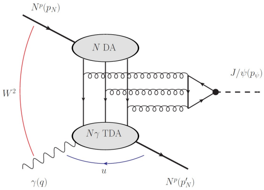
GlueX Collaboration, Phys.Rev.C 108 (2023) 2, 025201

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

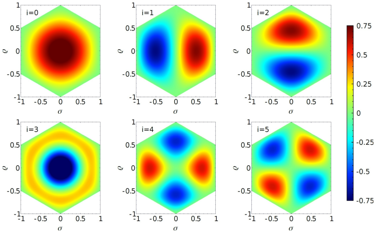
Flexible parametrization under development, in collaboration with B. Pire, L. Szymanowski and P. Sznajder:

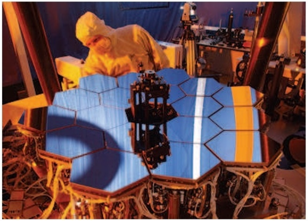
$$F(\beta_1,\beta_2,\beta_3,\alpha_1,\alpha_2,\alpha_3;\,u)=\underbrace{F^{(0)}(\beta_1,\beta_2,\beta_3,\alpha_1,\alpha_2,\alpha_3;\,u)}_{\text{Fixed from soft pion theorem at } \xi=1}+(1-\xi)\underbrace{F^{(1)}(\beta_1,\beta_2,\beta_3,\alpha_1,\alpha_2,\alpha_3;\,u)}_{\text{Free model input, fitted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

- 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 $\xi = 0$:

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

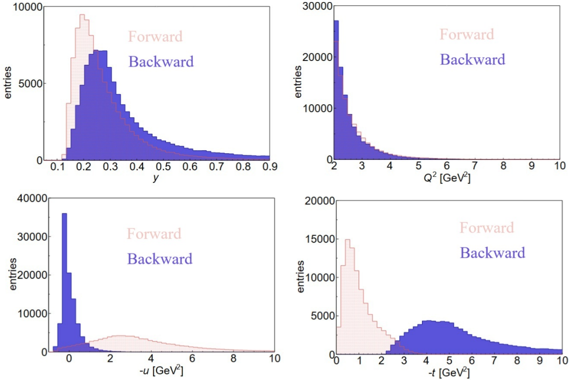
- Forward function $f(\sigma,\rho)$ can be expanded over the set of orthogonal polynomials on the hexagon: generalization of the Zernike polynomials;





New models for πN TDAs: results

- Events from EpIC MCG for "forward" and "backward" $ep \to ep\pi^0$ for $E_e = 10.6\,\mathrm{GeV}$;
- $0.05 < y < 0.9$; $2\,\mathrm{GeV}^2 < Q^2 < 10\,\mathrm{GeV}^2$;
- $0 < |t - t_0| < 1.5\,\mathrm{GeV}^2$ (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;



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

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 reactions with J-PARC and $\bar{\text{P}}$ANDA;
3. First evidences for the onset of the factorization regime in backward $\gamma^* N \to N' \omega$ from JLab Hall C analysis and BSA measurements in $\gamma^* p \to \pi^+ n$ from CLAS;
4. PAC 48 decision is a challenge both for the experiment and for theory. An effort is required. Factorization theorem, physical interpretation, phenomenological models;
5. Backward DVCS and TCS: options for EIC and EicC;
6. Backward charmonium photoproduction can bring information on $N\gamma$ TDAs. Intriguing results for near-backward region from GlueX.

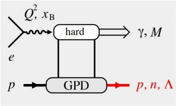
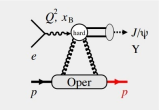
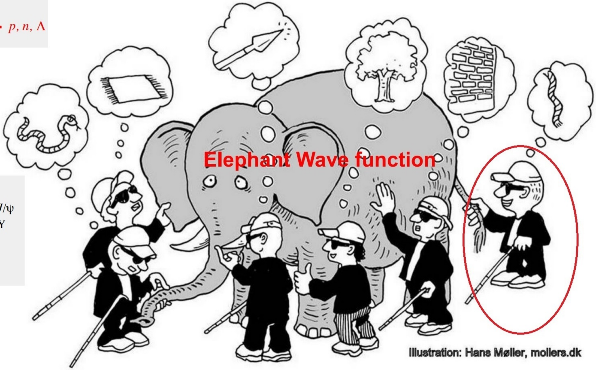
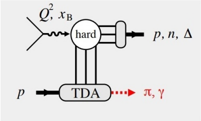


Illustration: courtesy of Bill Li







Forward angle → $-t$ → Backward angle

Thank you for your attention!