Baryon-to-meson transition distribution amplitudes:

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Outline

1. Introduction: DAs, GPDs, TDAs
2. Forward and backward kinematical regimes
3. πN TDAs: definition, properties, support, spectral representation, chiral constrains
4. Factorized Ansatz for quadruple distributions.
5. $N\bar{N} \to \pi\gamma^* \to \pi\ell^+\ell^-$ and $N\bar{N} \to \pi J/\psi$ cross section estimates
6. Summary and Outlook

B. Pire, K. S., L. Szymanowski Phys. Rev. D **82**, 094030 (2010)

B. Pire, K. S., L. Szymanowski, Phys. Rev. D **84**, 074014 (2011)

J.P. Lansberg, B. Pire, K. S., L. Szymanowski, Phys. Rev. D **85**, 054021 (2012)

J.P. Lansberg, B. Pire, K. S., L. Szymanowski, Phys. Rev. D **86**, 114033 (2012)

B. Pire, K. S., L. Szymanowski, Phys. Lett. B **724**, 99 (2013)

- Factorization theorems for hard reactions: amplitude as convolution of perturbative and non-perturbative parts.
- Main objects: matrix elements of QCD light-cone ($z^2 = 0$) operators.

- Quark bilinear light-cone operator:

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

$\Rightarrow$ PDFs, meson DAs, GPDs, transition GPDs, etc.

Hard Exclusive Processes: GPDs, DAs

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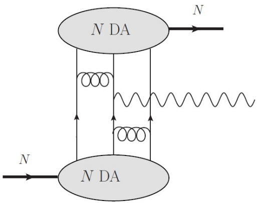
- $\langle A| = \langle 0|$; B - baryon $\Rightarrow$ baryon DA. QCD description of nucleon e.m. FF.

Nucleon DA: well known examples

Nucleon e.m. FF

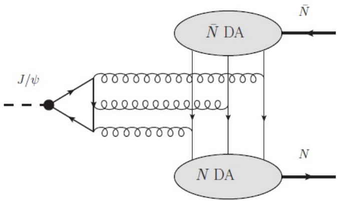
Brodsky & Lepage'81 Efremov & Radyushkin'80



Charmonium decay

$$J/\psi \to \bar{N} + N$$

Brodsky & Lepage'81 Chernyak, Ogloblin, and Zhitnitsky'89



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

- Let $\langle A|$ be a light meson state $(\pi, \eta, \rho, \omega, ...)$ B - a baryon $\Rightarrow$ baryon-to-meson TDAs.

Common features with

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

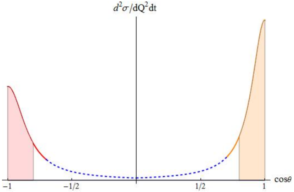
$$\xi = -\frac{(p_A - p_B) \cdot n}{(p_A + p_B) \cdot n}.$$

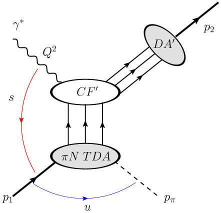
Factorization regimes for hard meson production

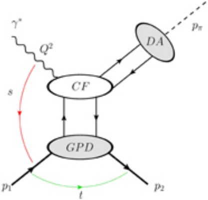
Generalized Bjorken limit ($-q^2 = Q^2$, W^2 – large; $x_B = \frac{Q^2}{2p \cdot q}$ – fixed)

Two complementary regimes:

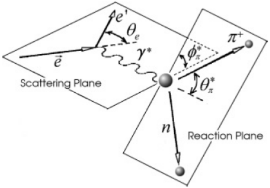
- $t \sim 0$ (forward peak) factorized description in terms of GPDs J. Collins, L. Frankfurt, M. Strikman'97;
- $u \sim 0$ (backward peak) factorized description in terms of TDAs L. Frankfurt, M. V. Polyakov, M. Strikman et al.'02;



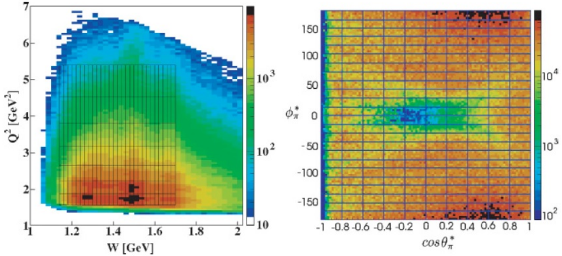




Backward meson electroproduction @ CLAS I



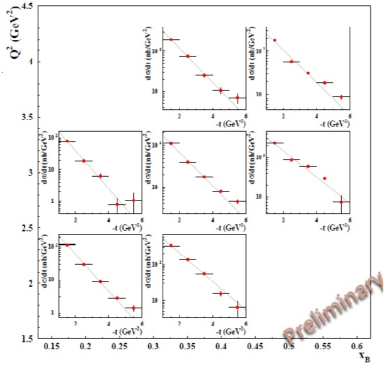
- Data from JLab @ 6 GeV exist for the backward $\gamma^* p \to \pi^+ n$. Analysis on-going Kijun Park.



- Kinematical coverage for π^+ of the CLAS experiment K. Park et al., PRC77:015208, 2008.

Backward meson electroproduction @ CLAS II

- Analysis of backward $\gamma^* p \to \pi^0 p$. V. Kubarovsky, CIPANP 2012.



$$\frac{d\sigma}{dt} = A \cdot e^{Bt} \quad \text{(away from the forward peak)}$$

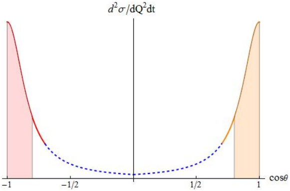
- G. Huber clear signal from backward ω production at Jlab Hall C.

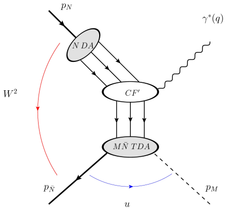
Baryon to meson TDAs at $\bar{\text{P}}$ANDA I

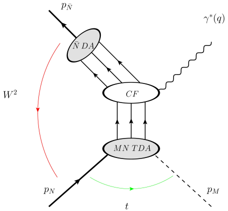
- Factorized description of

$$\bar{N} + N \to \gamma^*(q) + \pi \to \ell^+ + \ell^- + \pi$$

  in terms of MN TDAs.
- Two regimes (forward and backward). C invariance $\Rightarrow$ perfect symmetry. (Lansberg et al.'12)







$\bar{\text{P}}$ANDA @ GSI-FAIR

- $E_p \leq 15$ GeV; $W^2 \leq 30$ GeV^2

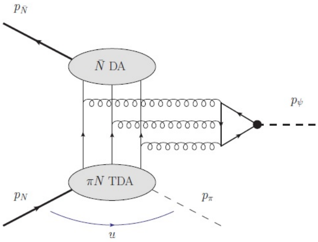
- Planned to be done with the proton FF studies in the timelike region.
- M.C. Mora Espí, F.Maas, M. Zambrana (in preparation): detailed feasibility studies of $\bar{p}p \to e^+e^-\pi^0$ @$\bar{\text{P}}$ANDA.

Baryon to meson TDAs at $\bar{\text{P}}$ANDA II

- Charmonium production in association with a pion Pire et at.'13

$$\bar{N} + N \to J/\psi + \pi.$$

- Same TDAs $\Rightarrow$ test of universality.
- Forward and backward regimes.



Twist-3 πN TDA

J.P.Lansberg, B.Pire & L.Szymanowski'07:

$$4(P\cdot n)^3 \int \left[\prod_{i=1}^{3} \frac{dz_i}{2\pi} e^{ix_i z_i (P\cdot n)}\right] \langle \pi(p_\pi)|\, \varepsilon_{c_1 c_2 c_3} \Psi_\rho^{c_1}(z_1 n) \Psi_\tau^{c_2}(z_2 n) \Psi_\chi^{c_3}(z_3 n)\, |N(p_1, s_1)\rangle$$

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

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

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

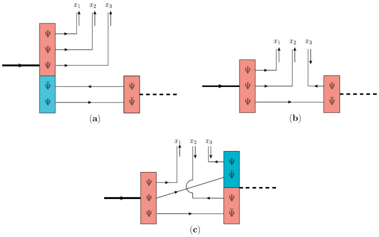
$$\left. + \frac{1}{M} T_3^{\pi N} (\sigma_{P\Delta} C)_{\rho\tau} (\hat{P} U)_\chi + \frac{1}{M} T_4^{\pi N} (\sigma_{P\Delta} C)_{\rho\tau} (\hat{\Delta} U)_\chi \right]$$

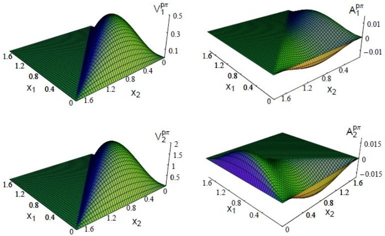
- $P = \frac{1}{2}(p_1 + p_\pi)$; $\Delta = (p_\pi - p_1)$; $n^2 = p^2 = 0$; $2p\cdot n = 1$; $\sigma_{P\mu} \equiv P^\nu \sigma_{\nu\mu}$;
- C: charge conjugation matrix;
- $f_N = 5.2\cdot 10^{-3}$ GeV^2 (V. Chernyak and A. Zhitnitsky'84);
- $\xi = -\frac{\Delta\cdot n}{2P\cdot n}$
- 8 TDAs: $H(x_1, x_2, x_3, \xi, \Delta^2, \mu^2) \equiv \{V_i, A_i, T_i\}(x_1, x_2, x_3, \xi, \Delta^2, \mu^2)$
- c.f. 3 leading twist nucleon DAs: V^p, A^p, T^p

- Mellin moments in $x_i \Rightarrow \pi N$ matrix elements of local operators

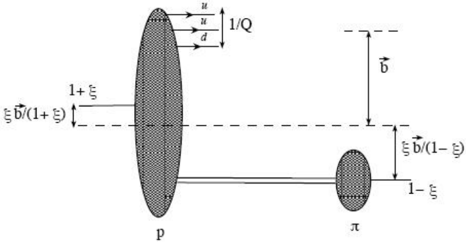
$$\left[i\vec{D}^{\mu_1}\dots i\vec{D}^{\mu_{n_1}}\Psi_\rho(0)\right]\left[i\vec{D}^{\nu_1}\dots i\vec{D}^{\nu_{n_2}}\Psi_\tau(0)\right]\left[i\vec{D}^{\lambda_1}\dots i\vec{D}^{\lambda_{n_3}}\Psi_\chi(0)\right].$$

  Can be studied on the lattice Y. Aoki et al..
- πN TDAs provides information on the next to minimal Fock state. Light-cone quark model interpretation B. Pasquini et al. 2009:





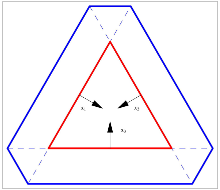
- Impact parameter space interpretation: the Fourier transform $\Delta_T \to b_T$ of TDAs $\Rightarrow$ transverse picture of pion cloud in the proton



Fundamental theoretical requirements for πN TDAs:

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

1. restricted support in x_1, x_2, x_3: intersection of three stripes $-1+\xi \le x_i \le 1+\xi$ ($\sum_i x_i = 2\xi$)
2. polynomialty in ξ of the Mellin moments in x_i
3. isospin + permutation symmetry
4. crossing: πN TDA $\leftrightarrow$ πN GDA
5. chiral properties: soft pion theorem P. Pobylitsa, M. Polyakov and M. Strikman'01 constrains πN GDA at the threshold $\xi = 1$, $\Delta^2 = M^2$ in terms of nucleon DAs
6. QCD evolution

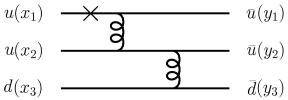


- Spectral representation A. Radyushkin'97 for πN TDAs: polynomiality and support:

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

- Ω_i: $\{|\beta_i| \le 1,\ |\alpha_i| \le 1 - |\beta_i|\}$ are copies of the usual DD square ;
- $F(...)$: six variables that are subject to two constraints $\Rightarrow$ quadruple distributions

- LO amplitude for $\bar{p}p \to \gamma^* \pi^0$ can be computed as in J.P. Lansberg, B. Pire and L. Szymanowski'07
- 21 diagrams contribute



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

Each R_α, has the structure:

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

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

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

$$\mathcal{M}^{\lambda}_{s_p s_{\bar{p}}} = -i\frac{(4\pi\alpha_s)^2\sqrt{4\pi\alpha_{em}}f_N^2}{54 f_\pi}\frac{1}{Q^4}\left[\mathcal{S}^{\lambda}_{s_p s_{\bar{p}}}\mathcal{I}(\xi,\Delta^2) - \mathcal{S}'^{\lambda}_{s_p s_{\bar{p}}}\mathcal{I}'(\xi,\Delta^2)\right],$$

where

$$\mathcal{S}^{\lambda}_{s_p s_{\bar{p}}} \equiv \bar{V}(p_{\bar{p}}, s_{\bar{p}})\hat{\epsilon}^*(\lambda)\gamma_5 U(p_p, s_p);$$
$$\mathcal{S}'^{\lambda}_{s_p s_{\bar{p}}} \equiv \frac{1}{M}\bar{V}(p_{\bar{p}}, s_{\bar{p}})\hat{\epsilon}^*(\lambda)\hat{\Delta}_T\gamma_5 U(p_p, s_p),$$

$\bar{p}p \to \gamma^*\pi \to \ell^+\ell^-\pi$ cross section

$$\frac{d\sigma}{dt dQ^2 d\cos\theta_\ell} = \int d\varphi_\ell \frac{2\pi e^2(1+\cos^2\theta_\ell)}{Q^2}\frac{|\overline{\mathcal{M}_T}|^2}{64 W^2(W^2-4M^2)(2\pi)^4}.$$

Essential points of the approach

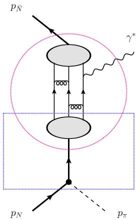
- Off-shell photon is transversally polarized at leading twist $\Rightarrow$ characteristic behavior in lepton azimuthal angle: $1 + \cos^2\theta_l$
- $1/Q^8$ scaling behavior of the $p\bar{p} \to \gamma^*\pi$ cross section
- Non-zero imaginary part of the amplitude.

How to model quadruple distributions?

- No enlightening $\xi = 0$ limit as for GPDs
- In the limit $\xi \to 1$ πN TDAs are fixed due to soft pion theorems in terms of nucleon DAs
- Start from $\xi = 1$ limit rather than the forward limit $\xi = 0$ to fix the overall magnitude of quadruple distributions
- Phenomenological solutions for nucleon DA (COZ, KS, GS, BLW, BK, Heterotic Ansatz etc.) can be taken as numerical input

Two component model

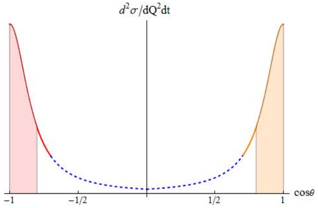
- u-channel nucleon exchange is complementary to the spectral representation: D-term
- non-zero in the ERBL-like region $0 \leq x_i \leq 2\xi$



Cross section estimates

$$\frac{d\sigma}{dt dQ^2 d\cos\theta_\ell} = \int d\varphi_\ell \frac{2\pi e^2 (1+\cos^2\theta_\ell)}{Q^2} \frac{|\overline{\mathcal{M}_T}|^2}{64 W^2 (W^2 - 4M^2)(2\pi)^4}.$$

- Useful cut: $|\Delta_T^2|$-cut $\Leftrightarrow$ cut in θ_{CMS}.
- This helps to focus on forward (backward) regime.

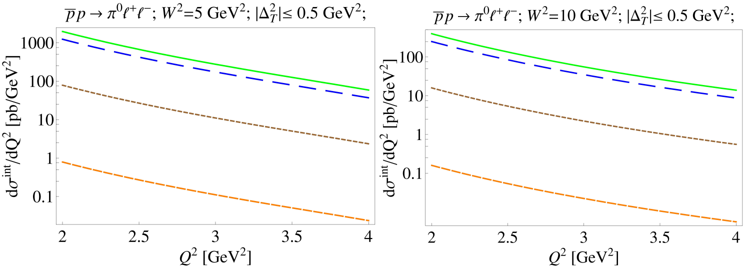


Integrated cross section

$$\frac{d\sigma^{\text{int}}}{dQ^2}(|\Delta_T^2|_{\max}) \equiv \int_{t_{\min}}^{t_{\max}} dt \int d\theta_\ell \frac{d\sigma}{dt dQ^2 d\cos\theta_\ell}$$

$\bar{p}p \to \pi^0\gamma^* \to \pi^0\ell^+\ell^-$ cross section

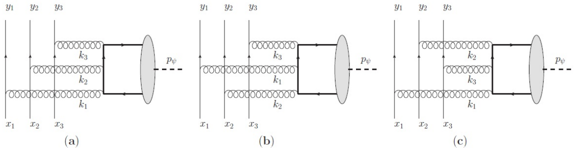
- Nucleon pole dominates over quadruple distribution part for PANDA conditions
- Numerical input: COZ, KS, BLW NLO, BLW NNLO phenomenological solutions for nucleon DAs

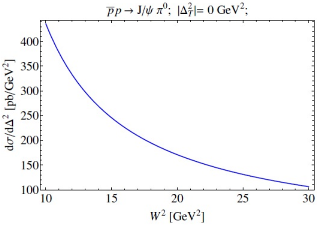


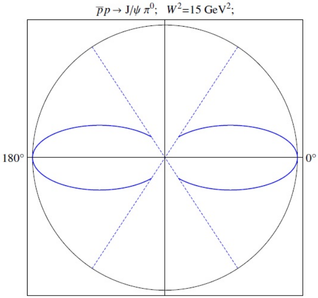
- Cross section of $\bar{p}n \to \pi^-\gamma^* \to \pi^-\ell^+\ell^-$ is larger by factor 2. But requires neutron target.

Amplitude calculation and cross section estimates B. Pire, KS, L. Szymanowski'13

Unpolarized cross section and angular distribution



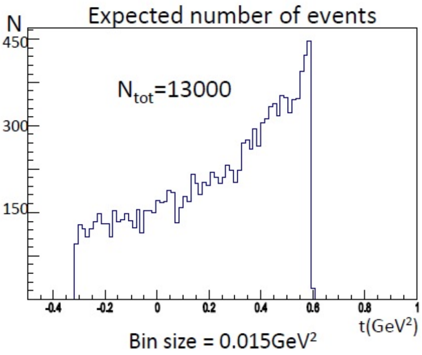




c.f. Q. -Y. Lin, H. -S. Xu et al. 2012

First feasibility studies

- B. Ma & B.Ramstein, PANDA Collaboration meeting at Bochum, September 2013: a new EvtGen Model in PandaRoot
- First study for $W^2 = 12.25$ GeV^2, near forward regime
- Assumed integrated luminosity: 2 fb^{-1} (4 months of beamtime at full luminosity); 100% efficiency: this number will be reduced by efficiency and analysis cuts, but it is very promising!

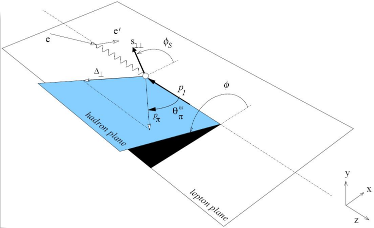


Conclusions & Outlook

1. Nucleon to meson TDAs provide new information about correlation of partons inside hadrons
2. We strongly encourage to try to detect near forward and backward signals for various mesons (π, η, ω, ρ): there could be interesting physics around!
3. Theoretical understanding is growing up: spectral representation for πN TDA based on quadruple distributions; factorized Ansatz for quadruple distributions with input at $\xi = 1$ is proposed
4. Some experimental success achieved for backward $\gamma^* N \to N'\pi$, $\gamma^* N \to N'\eta$ (q^2 - spacelike) @ Jlab already at 6 GeV (and more is expected at 12 GeV)
5. $\bar{p}N \to \pi\ell^+\ell^-$ (q^2 - timelike) and $\bar{p}N \to \pi J/\psi$ @ PANDA would allow to check universality of TDAs
6. Open questions: proof of factorization theorems, interpretation in the impact parameter space, analytic properties of the amplitude

Transverse Target Single Spin Asymmetry $\gamma^* N \to \pi N$

- TSA$= \sigma^\uparrow - \sigma^\downarrow \sim \mathrm{Im}$ part of the amplitude
- it probes the contribution of the DGLAP-like regions
- One expects a TSA vanishing with Q^2 and W^2 for (simple) baryon-exchange approaches
- Non vanishing and Q^2-independent TSA within TDA approach



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