Baryon-to-meson transition distribution amplitudes: formalism and experimental perspectives

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Outline

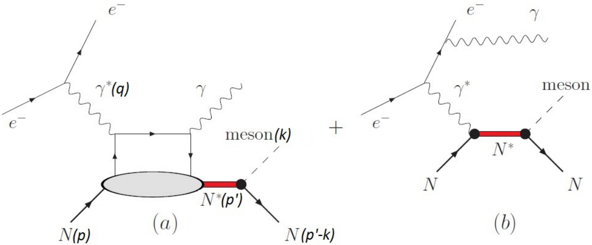
1. Introduction: DAs, GPDs, TDAs
2. Forward and backward kinematical regimes
3. πN TDAs: definition, properties, support, spectral representation, crossing and chiral constrains.
4. Current status of experimental analysis at Jlab and feasibility studies for $\bar{\text{P}}$ANDA.
5. Summary and Outlook

For references see B. Pire, K. S., L. Szymanowski, Few Body Syst. 58 (2017)

Motivation: new tools for baryon spectroscopy

- Hadronic probes (πN scattering).
- Electromagnetic (and weak) probes: $\langle N^*(p')| \sum_f e_f \bar{\Psi}_f \gamma_\mu \Psi_f |N(p)\rangle$.
- Baryon spectroscopy program with non-diagonal DVCS for Jlab@12GeV: M. Amarian, M. Polyakov, I. Strakovsky and K.S.'08. Excitation of N^* by non-local quark-gluon operators:

$$\langle N^*|\bar{\Psi}(0)[0;\, z]\Psi(z)|N\rangle; \quad \langle N^*|F_{\alpha\beta}(0)[0;\, z]F_{\mu\nu}(z)|N\rangle; \quad (z^2 = 0).$$



N.b. $-q^2$, $(p+q)^2$ - large; $|(p'-p)^2|$, p'^2 - moderate.

- Excitation of resonances by arbitrary spin probe.
- Explicit access to gluons.

- 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.

- Three quark bilinear light-cone operator

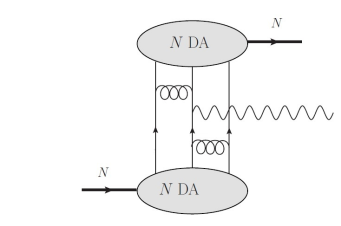
$$\langle A|\Psi(z_1)[z_1;z_2]\Psi(z_2)[z_2;z_3]\Psi(z_3)[z_3;z_1]|B\rangle$$

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

Nucleon DA: well known examples

Nucleon e.m. FF

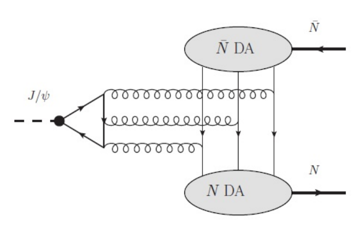
Brodsky & Lepage'81 Efremov & Radyushkin'80



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 - baryon $\Rightarrow$ baryon-to-meson TDAs.

Common features with

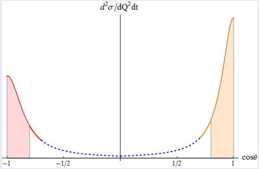
- baryon DAs: same operator;
- GPDs: $\langle B|$ and $|A\rangle$ are not of the same momentum $\Rightarrow$ skewness:

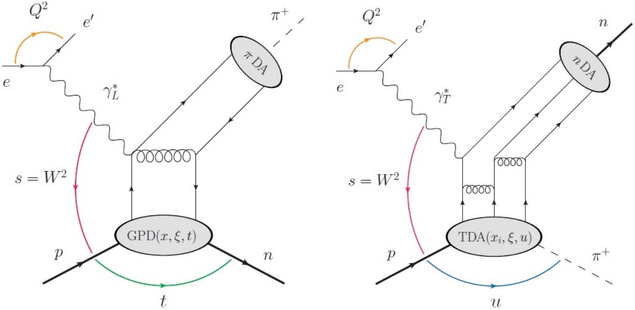
$$\xi = -\frac{(p_A - p_B)\cdot n}{(p_A + p_B)\cdot n}.$$

Factorization regimes for hard meson production

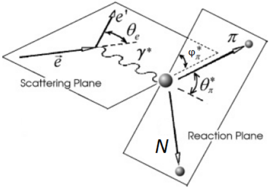
Two complementary regimes in generalized Bjorken limit ($-q^2 = Q^2$, W^2 – large; $x_B = \frac{Q^2}{2p\cdot q}$ – fixed):

- $t \sim 0$ (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, M. V. Polyakov, M. Strikman et al.'02;

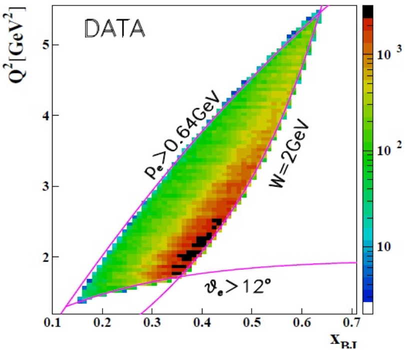


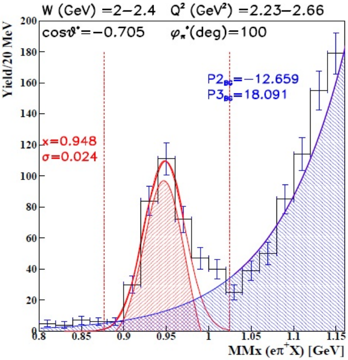


Backward meson electroproduction @ Jlab

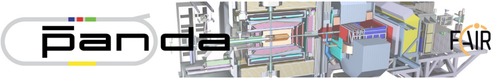


- Data from JLab @ 6 GeV exists for the backward $\gamma^* p \to \pi^+ n$;
- Analysis (Oct.2001-Jan.2002 run) K. Park, M. Guidal, B. Pire and K.S., in preparation





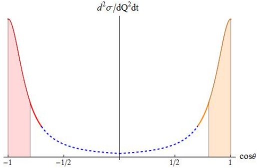
Baryon to meson TDAs at P̄ANDA I

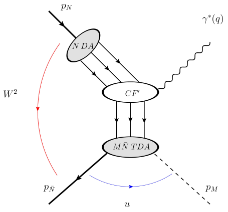


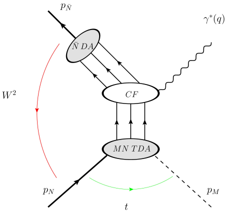
- Lansberg et al.'12: πN TDAs occur in factorized description of

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

- Two regimes (forward and backward). C invariance $\Rightarrow$ perfect symmetry.







P̄ANDA @ GSI-FAIR

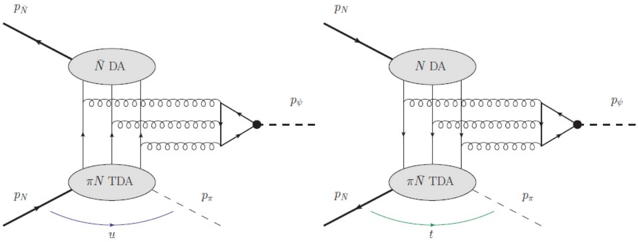
- $E_{\bar{p}} \leq 15$ GeV; $W^2 \leq 30$ GeV^2

- Planned to be done with the proton FF studies in the timelike region.
- M. C. Mora Espi, M. Zambrana, F. Maas, K.S.'15: feasibility of $\bar{p}p \to e^+e^-\pi^0$ @P̄ANDA.

- 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.

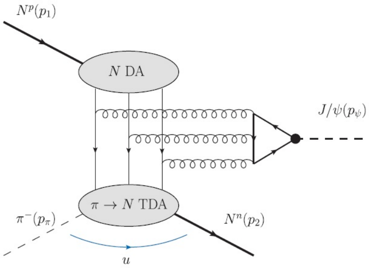


Baryon to meson TDAs at J-Parc

- J-Parc intense pion beam option: $P_\pi = 10 - 20$ GeV.
- Charmonium production in association with a nucleon B. Pire, L. Szymanowski and K.S. , PRD 95, 2017.

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

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



Twist-3 πN TDA

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

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

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

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

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

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

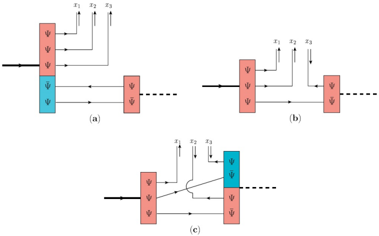
- $P = \frac{1}{2}(p_1 + p_\pi)$; $\Delta = (p_\pi - p_1)$; $n^2 = p^2 = 0$; $2p\cdot n = 1$; $\sigma_{P\mu} \equiv P^\nu \sigma_{\nu\mu}$;
- C: charge conjugation matrix;
- $f_N = 5.2 \cdot 10^{-3}$ GeV^2 (V. Chernyak and A. Zhitnitsky'84);
- $\xi = -\frac{\Delta\cdot n}{2P\cdot n}$
- 8 TDAs: $H(x_1,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

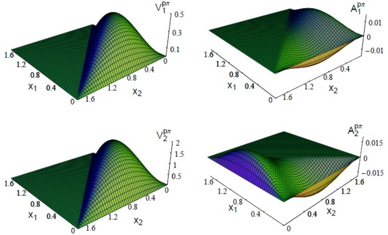
- Mellin moments in $x_i \Rightarrow \pi N$ matrix elements of local operators

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

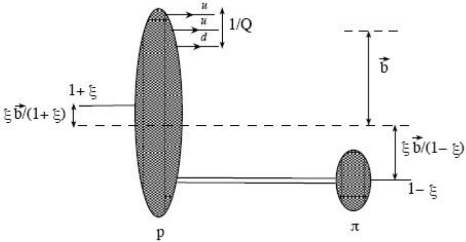
  Can be studied on the lattice Y. Aoki et al..

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



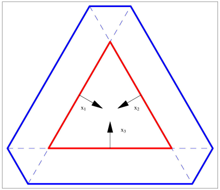


- Impact parameter space interpretation: the Fourier transform $\Delta_T \to b_T$ of TDAs $\Rightarrow$ transverse imaging of the nucleon



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 $-1+\xi \leq x_i \leq 1+\xi$ ($\sum_i x_i = 2\xi$)
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
6. QCD evolution

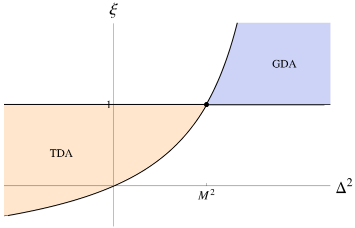
- Spectral representation A. Radyushkin'97 generalized for πN TDAs ensures polynomiality and support:

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

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

Crossing and soft pion theorem for πN GDA/TDA

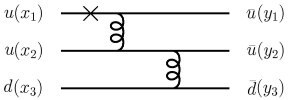
- Crossing relates πN TDAs in $\gamma^* N \to \pi N'$ and πN GDAs (light-cone wave function)
- Physical domain in (Δ^2, ξ)-plane (defined by $\Delta_T^2 \leq 0$) in the chiral limit $(m_\pi = 0)$:



- Soft pion theorem P. Pobylitsa, M. Polyakov and M. Strikman'01 $(Q^2 \gg \Lambda^3_{\rm QCD}/m_\pi)$ constrains πN GDA at the threshold $\xi = 1$, $\Delta^2 = M^2$ in terms of nucleon DAs V^p, A^p, T^p (see V. Braun, D. Ivanov, A. Lenz, A. Peters'08).

Calculation of the amplitude

- 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:

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

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

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

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

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

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

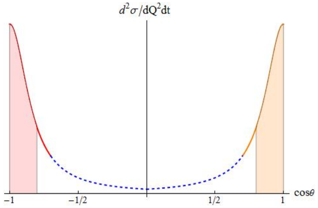
Essential points of the approach

- Off-shell photon is transversally polarized at leading twist $\Rightarrow$ characteristic behavior in lepton polar 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.

Cross section estimates

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

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

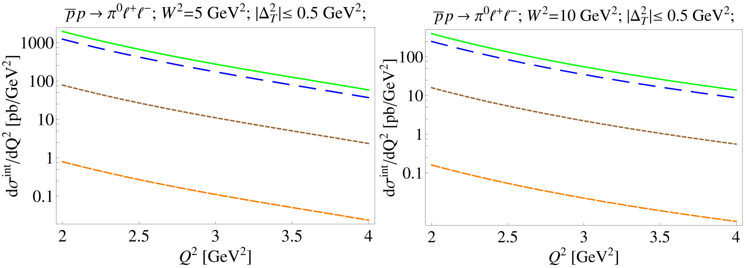


Integrated cross section

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

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

First feasibility studies for $\bar{\text{P}}$ANDA

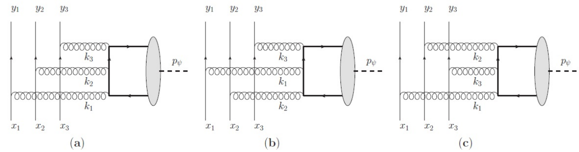
M. C. Mora Espi, M. Zambrana, F. Maas, K.S' 15

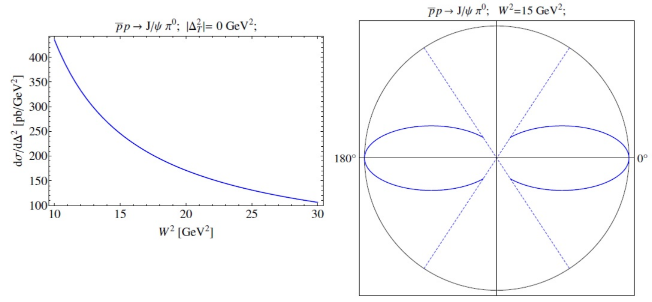
- Study of $p\bar{p} \to e^+e^-\pi^0$ (signal) with $p\bar{p} \to \pi^+\pi^-\pi^0$ (main hadronic background).
- Simulations performed for $s = 5$ GeV^2 and $s = 10$ GeV^2
- $|\cos\theta^*_\pi| > 0.5$ cut imposed
- Modified version of Lansberg, Pire, Szymanowski.'07 model used for πN TDAs used as input for MC.
- 2 fb^{-1} of integrated luminosity assumed (~ 5 months High Lumi.)
- Expected number of signal events then is 3350 and 465 for $s = 5$ GeV^2 and $s = 10$ GeV^2

$N\,\bar{N} \to J/\psi\,\pi$ at $\bar{\text{P}}$ANDA

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

Unpolarized cross section and angular distribution



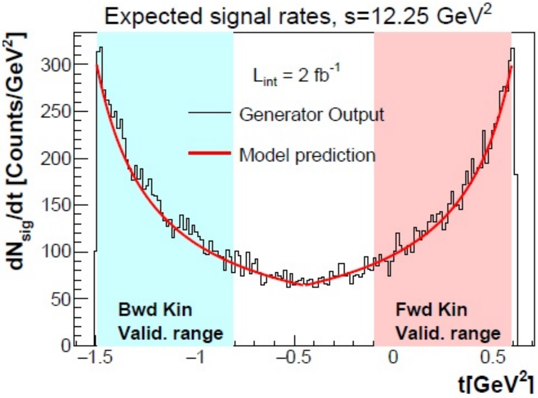


c.f.

Feasibility study of $\bar{p}p \to J/\psi\pi^0$ at $\bar{\text{P}}$ANDA

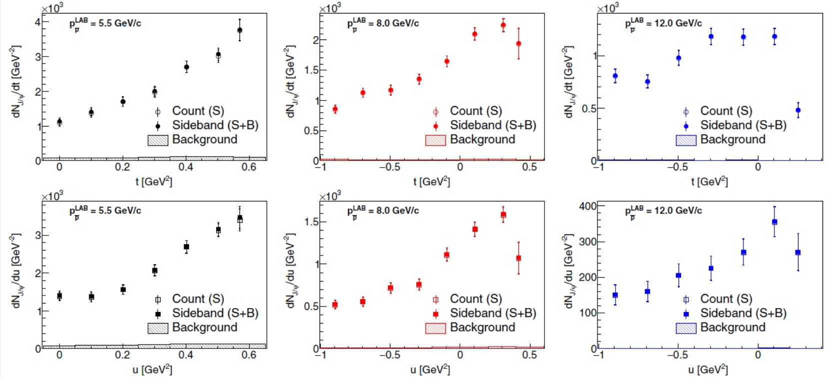
B. Ramstein, E. Atomssa and $\bar{\text{P}}$ANDA collaboration and K.S. PRD 95'17

- Event generator based on TDA model prediction Pire et al.'13.
- Simulations performed for $s = 12.2$ GeV^2, $s = 16.9$ GeV^2 and $s = 24.3$ GeV^2.
- Study of $p\bar{p} \to J/\psi\pi^0$ (signal) with background from $p\bar{p} \to \pi^+\pi^-\pi^0$ and $p\bar{p} \to J/\psi\pi^0\pi^0$ and other sources.



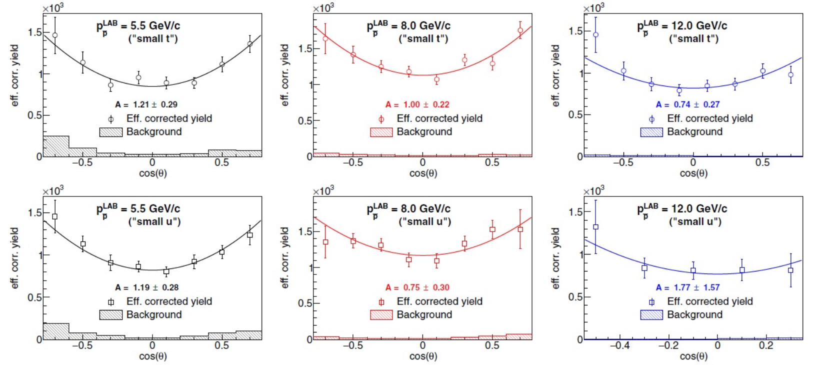
Feasibility study of $\bar{p}p \to J/\psi\pi^0$ at $\bar{\text{P}}$ANDA

Signal and Background Count Rates vs. t and u



- Signal and background count rates for 2 fb^{-1} ($\sim$ 5 months in High Luminocity mode)
- Worst case scenario at $p_{\bar{p}} = 5.5$ GeV/c: S/B at least factor 10.

Angular distribution of J/ψ decay electrons



- Signal count extracted from fits corrected for efficiency
- Free fit with $B(1 + A\cos^2\theta^*_\ell)$.

Pion electroproduction at backward angles with CLAS

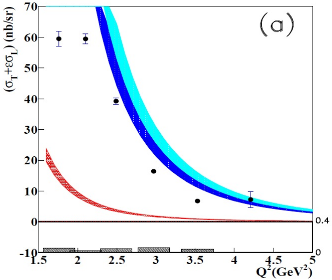
K. Park et al. *in preparation*

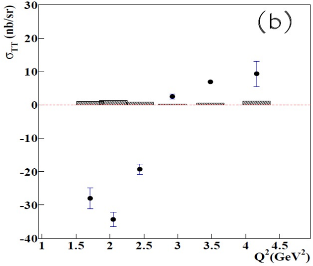
$$\frac{d\sigma}{d\Omega^*_\pi} = A + B\cos\varphi^*_\pi + C\cos 2\varphi^*_\pi,$$ where

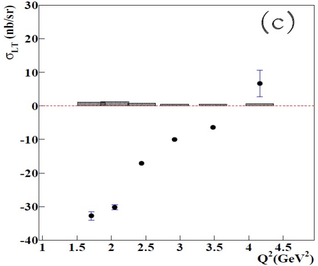
$A = \sigma_T + \epsilon\sigma_L$; $B = \sqrt{2\epsilon(1+\epsilon)}\sigma_{LT}$;
$C = \epsilon\sigma_{TT}$

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





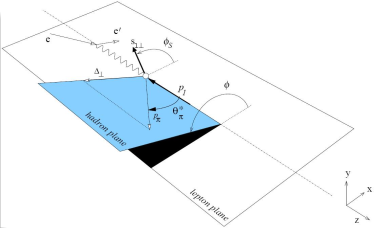


Conclusions & Outlook

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 $\xi = 1$.
4. Some experimental success achieved for backward $\gamma^* N \to N'\pi$ 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



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