Strong QCD from Hadron Structure Experiments 2019

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Experimental access to baryon-to-meson transition distribution amplitudes: A new window to the 3 dimensional nucleon structure

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Outline

- Introduction to TDAs and comparison to GPDs
- Theoretical modelling and features of the TDA based desciption
- Experimental access to TDAs at JLAB (CLAS and HALL C)
- Perspectives for the experimental access to TDAs with PANDA at FAIR and at JPARC
- Summary and Outlook

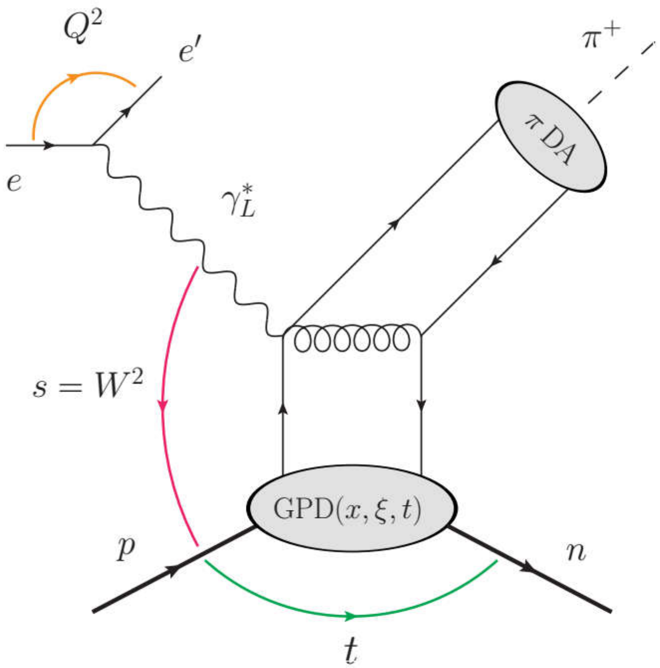
Theory collaborators: B. Pire, L. Szymanowski, K. Semenov-Tian-Shansky

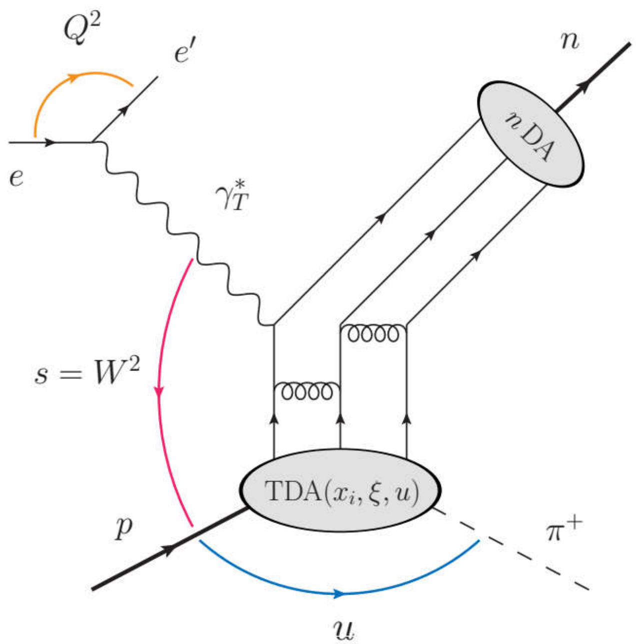
Hard exclusive π⁺ electroproduction $ep \rightarrow en\pi^+$

J. Collins, L. Frankfurt, M. Strikman '97 — **colinear factorization theorem** — L. Frankfurt, M. V. Polyakov, M. Strikman et al.'02

GPD based description
large Q^2 and s, x_B fixed
small t channel contribution
➔ π⁺ in forward region

TDA based description
large Q^2 and s, x_B fixed
small u channel contribution
➔ π⁺ in backward region





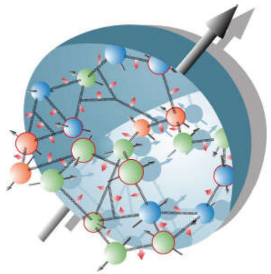
Physics motivation

GPDs

➔ Light-cone matrix elements of non-local bilinear quark and gluon operators

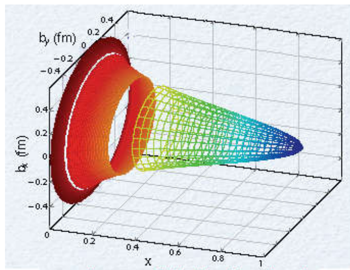
➔ Describe hadronic structural information in terms of quark and gluon degrees of freedom

➔ Spin-dependent 2D transverse coordinate space + 1D longitudinal momentum space images of the nucleon



➔ Tool to study the nature and origin of the nucleon spin

➔ Impact parameter space: spatial femto-photographs of the hadron structure in the transverse plane

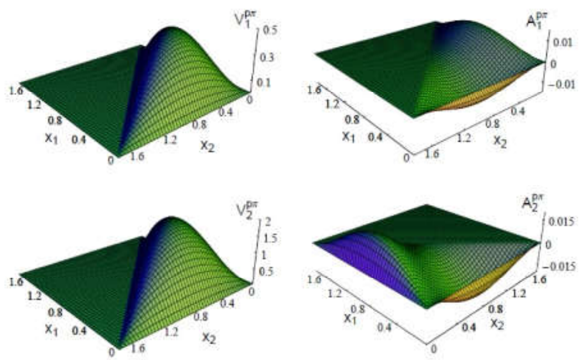


courtesy of Z.E. Meziani

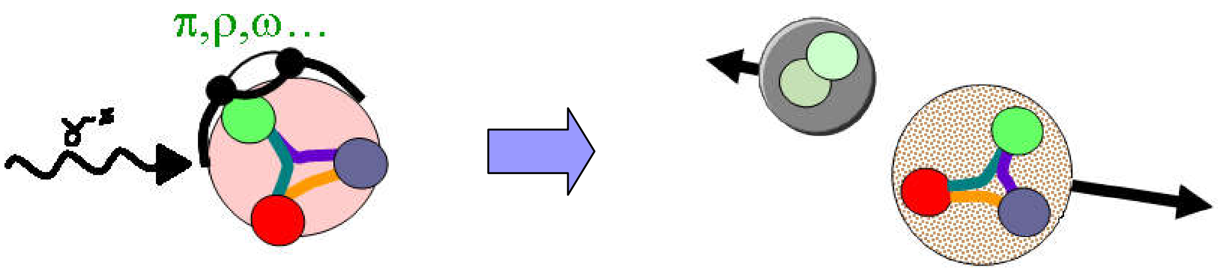
Physics motivation

Baryon to meson TDAs

- ➔ Light-cone matrix elements of non-local three quark operators
- ➔ Encoded physical picture close to GPDs
- ➔ Probe partonic correlations between states of different baryonic charge
  - ➔ Access to non-minimal Fock components of baryon light-cone wave functions



- ➔ Impact parameter space: Femto-photography of hadrons from a new perspective
  - ➔ Spatial imaging of the structure of the pion cloud inside the nucleon



"knocking a proton out of a proton"

Theoretical modelling of TDAs

GPDs: Description in the skewness $\xi = 0$ limit

TDAs: The soft pion theorems fixe the $\xi \to 1$ limit in terms of nucleon DAs and thus provides the overall magnitude of TDAs

➔ A factorized Ansatz with input at $\xi = 1$ designed in

J.P. Lansberg, B. Pire, K. Semenov and L. Szymanowski (2012)

➔ Provides the **unpolarized cross section** for hard leptoproduction of a pion off nucleon:

$$\frac{d^5\sigma}{dE' d\Omega_{e'} d\Omega_\pi} = \Gamma \times \frac{\Lambda\left(s, m^2, M^2\right)}{128\pi^2 s\left(s - M^2\right)} \times \sum_{s_1, s_2} \left\{ \frac{1}{2} \left(\left|\mathcal{M}^{1}_{s_1 s_2}\right|^2 + \left|\mathcal{M}^{-1}_{s_1 s_2}\right|^2 \right) + \ldots \right\} = \Gamma \times \left(\frac{d^2\sigma_T}{d\Omega_\pi} + \ldots \right)$$

$N\gamma^* \to \pi N$ helicity amplitudes

➔ **Polartized terms**:
Need dominant leading twist transverse amplitude
\+ next-to-leading twist subdominant longitudinal amplitude
(twist-4 nucleon DAs or twist-4 nucleon-to-pion TDAs)

Experimental acessible features of the TDA based mechanism

Characteristic features of the TDA-based mechanism:

➔ Dominance of the transverse polarisation of the virtual photon leads to a suppression of the longitudinal cross section σ_L at large Q^2 by at least a factor $1/Q^2$

➔ The transverse cross section σ_T shows a charakteristic $1/Q^8$ scaling behaviour for fixed x_B

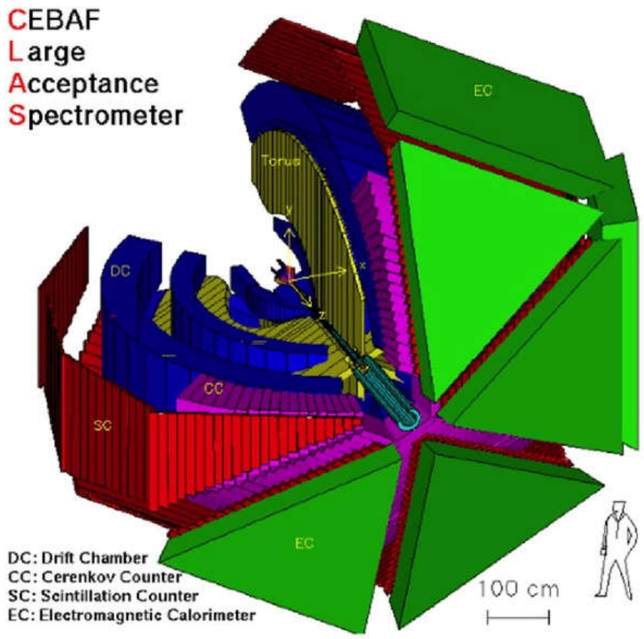
More distinguishing features become accesible with a polarized target:

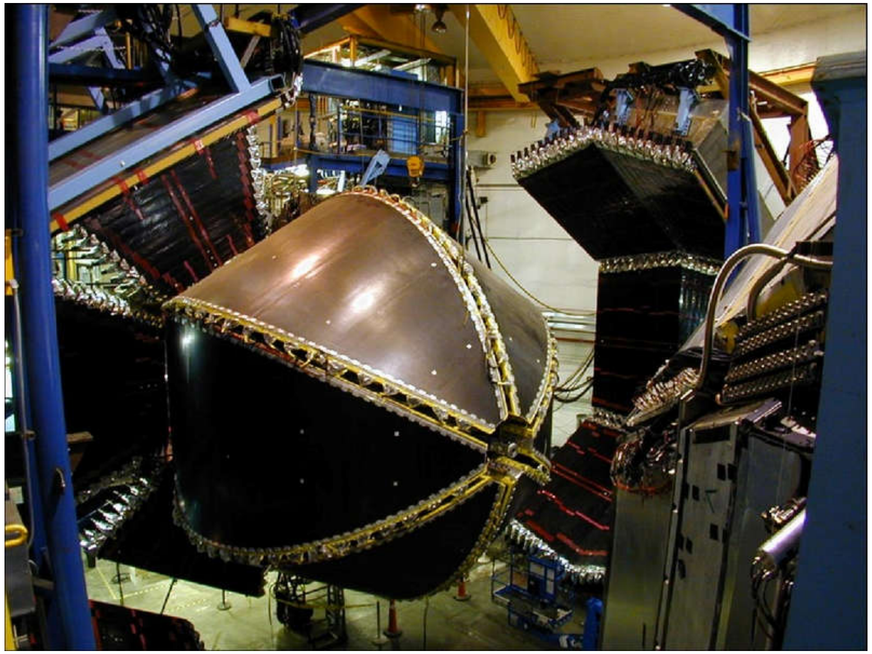
➔ Transverse target single spin asymmetry ~ *Im* part of the amplitude

➔ TDA approach predicts a non vanishing and Q^2-independent TSA

➔ Two component TDA model predicts 10-15 % TSA for $\gamma^* N \rightarrow \pi N$

Backward π electroproduction with CLAS at JLAB



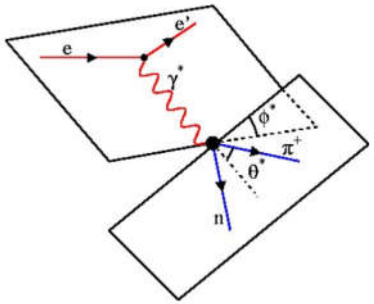


- CLAS (e16 + e1f run period)
- 5.5, 5.75 GeV longitudinally polarized electron beam
- unpolarized hydrogen target

- **Electron ID** based on electromagnetic calorimeter and Cherenkov counters
- **π ID** based on a maximum likelyhood particle selection from TOF based β vs p correlation

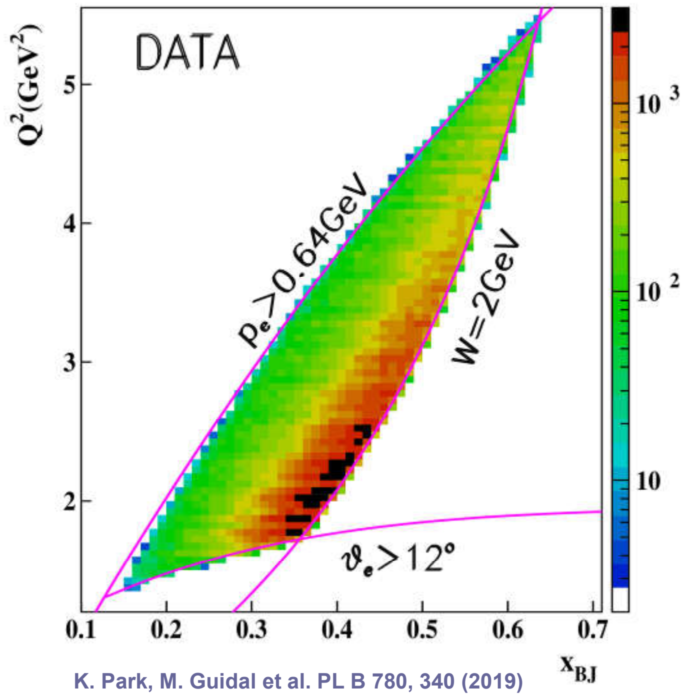
Hard exclusive π⁺ electroproduction cross section in the backward direction

$$ep \rightarrow en\pi^+$$

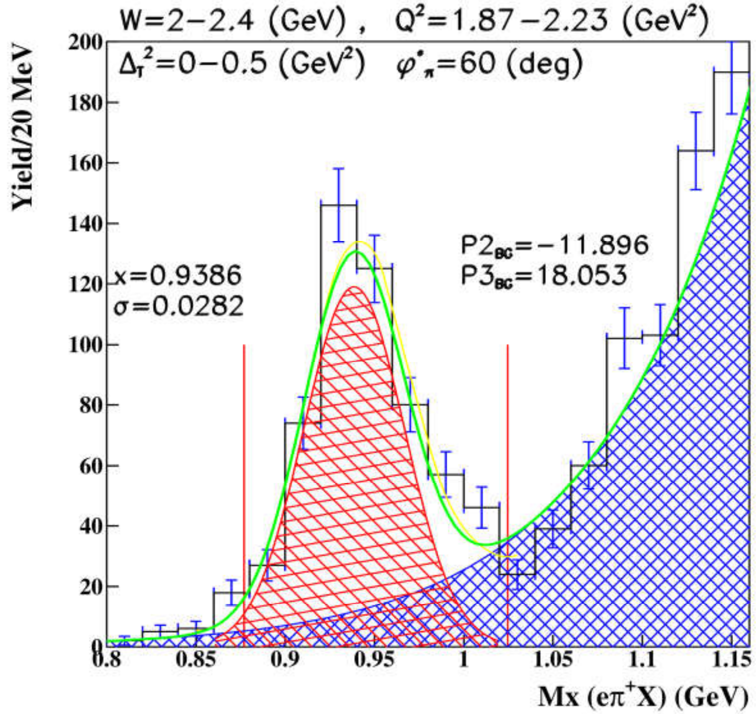


K. Park, M. Guidal et al. PL B 780, 340 (2018)

Variable	Number of bins	Range	Bin size
W	1	2.0–2.4 GeV	400 MeV
Q^2	6	1.6–4.5 GeV^2	varying
Δ_T^2	1	0–0.5 GeV^2	0.5 GeV^2
φ_π^*	9	0°–360°	40°



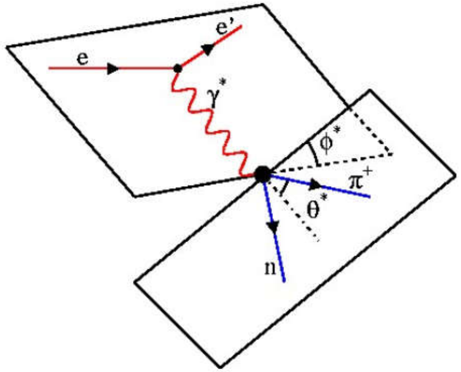
K. Park, M. Guidal et al. PL B 780, 340 (2019)



K. Park, M. Guidal et al. PL B 780, 340 (2019)

Hard exclusive π⁺ electroproduction

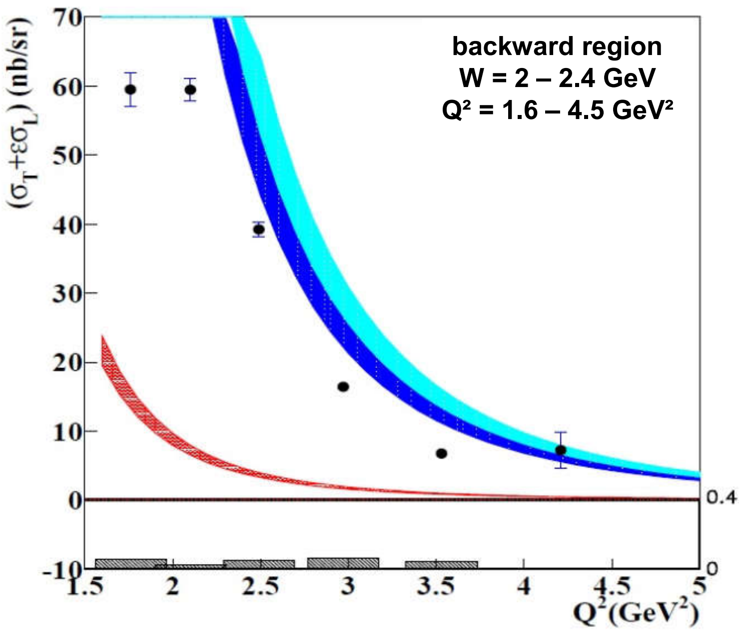
$$ep \rightarrow en\pi^+$$



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

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

$$C = \epsilon\sigma_{TT}$$



K. Park, M. Guidal et al. PL B 780, 340 (2019)

TDA model calculations for σ_U:

→ Results depend on the input for the nucleon distribution aplitude

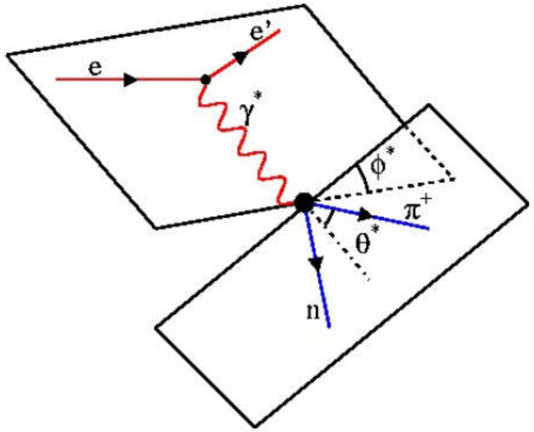
dark blue (COZ): V.L. Chernyak et al., Z. Phys. C 42, 583 (1989)

light blue (KS): I.D. King, C.T. Sachrajda, Nucl. Phys. B 279, 785 (1987)

red: NNLO calculation: A. Lenz et al., Phys. Rev. D 79, 093007 (2009)

Hard exclusive π⁺ electroproduction beam spin asymmetry

$$ep \to en\pi^+$$

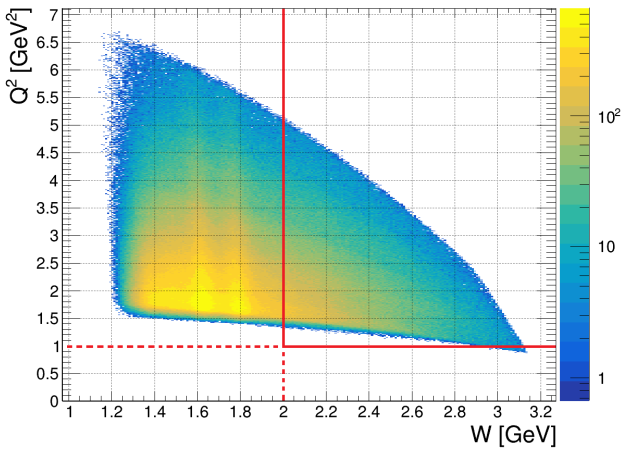


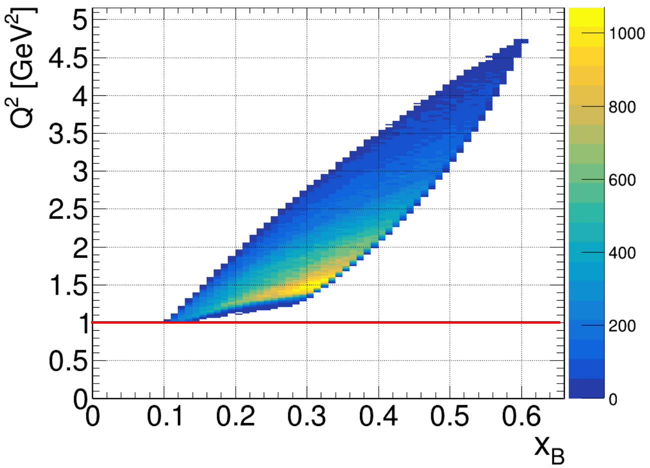
Cross section **(longitudinally pol. beam and unpol. target):**

$$d\sigma = d\sigma_0(1 + A_{UU}^{\cos(2\phi)} \cos(2\phi) + A_{UU}^{\cos(\phi)} \cos(\phi) + hA_{LU}^{\sin(\phi)} \sin(\phi))$$

$$BSA = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} = \frac{A_{LU}^{\sin\phi} \sin\phi}{1 + A_{UU}^{\cos\phi} \cos\phi + A_{UU}^{\cos(2\phi)} \cos(2\phi)}$$

Kinematic coverage and exclusivity cuts



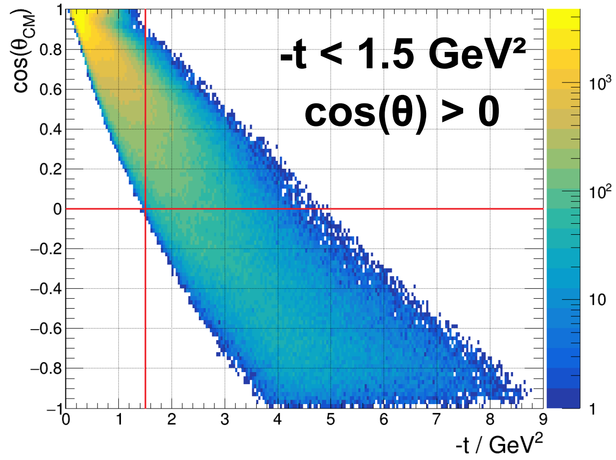


DIS cuts:

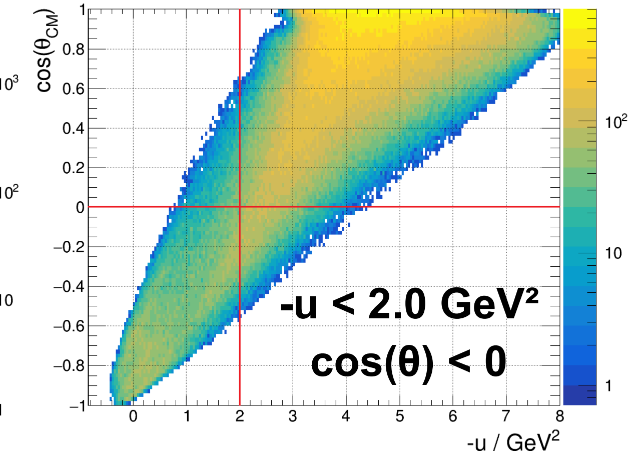
W > 2 GeV

$Q^2 > 1$ GeV²

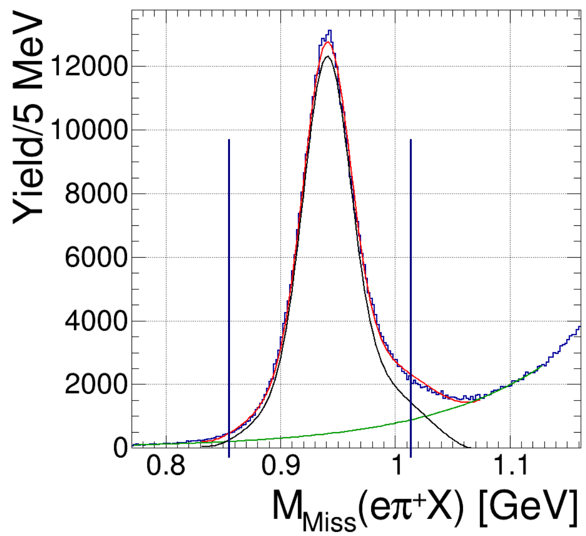
forward region „small t“



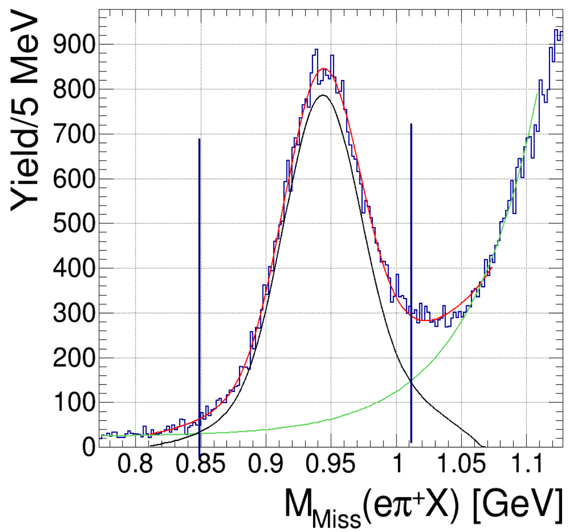
backward region „small u“



missing mass



missing mass

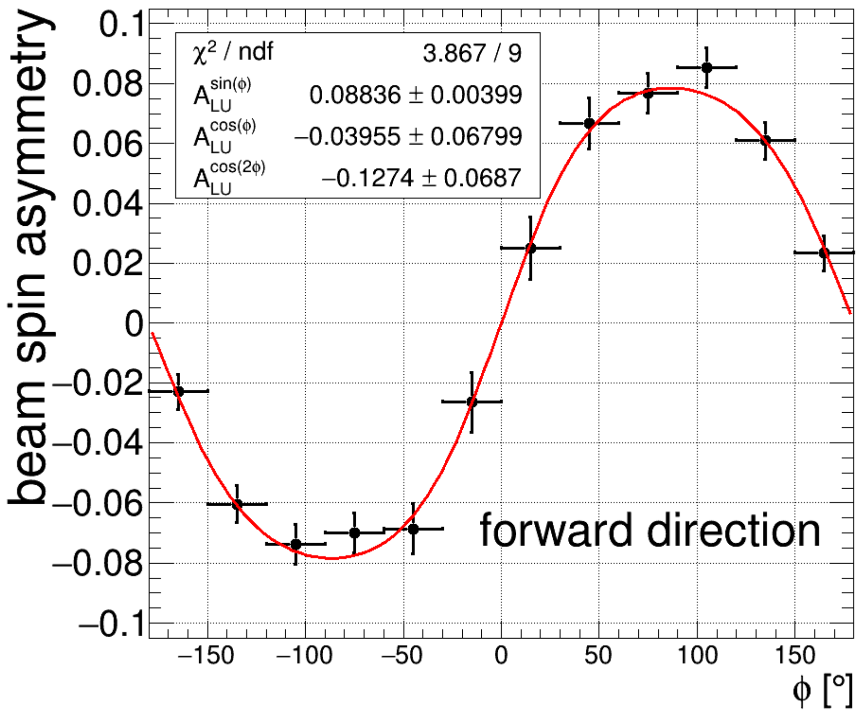


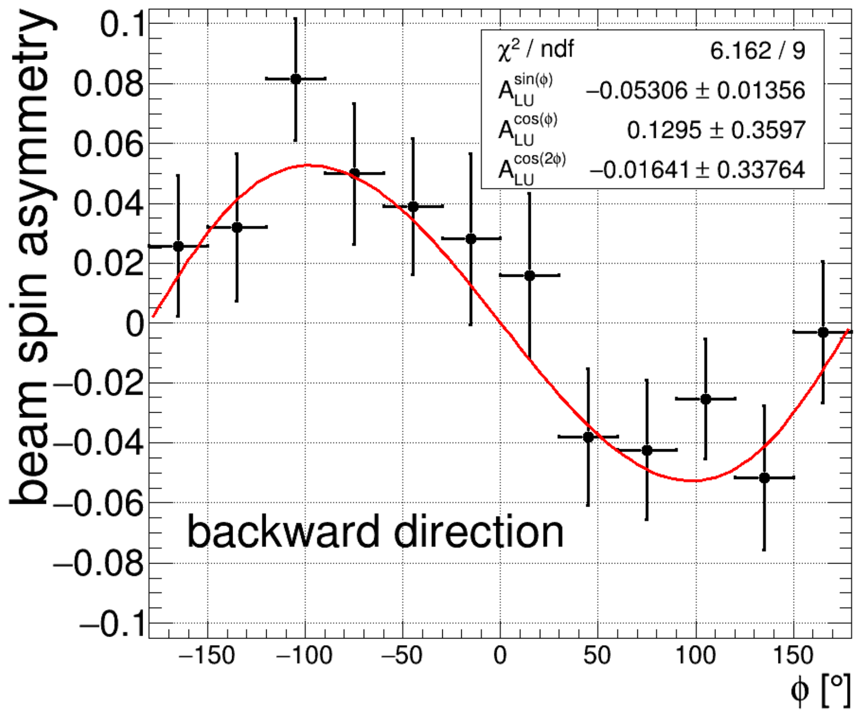
Beam spin asymmetry

$$BSA_i = \frac{1}{P_e} \cdot \frac{N_i^+ - N_i^-}{N_i^+ + N_i^-}$$

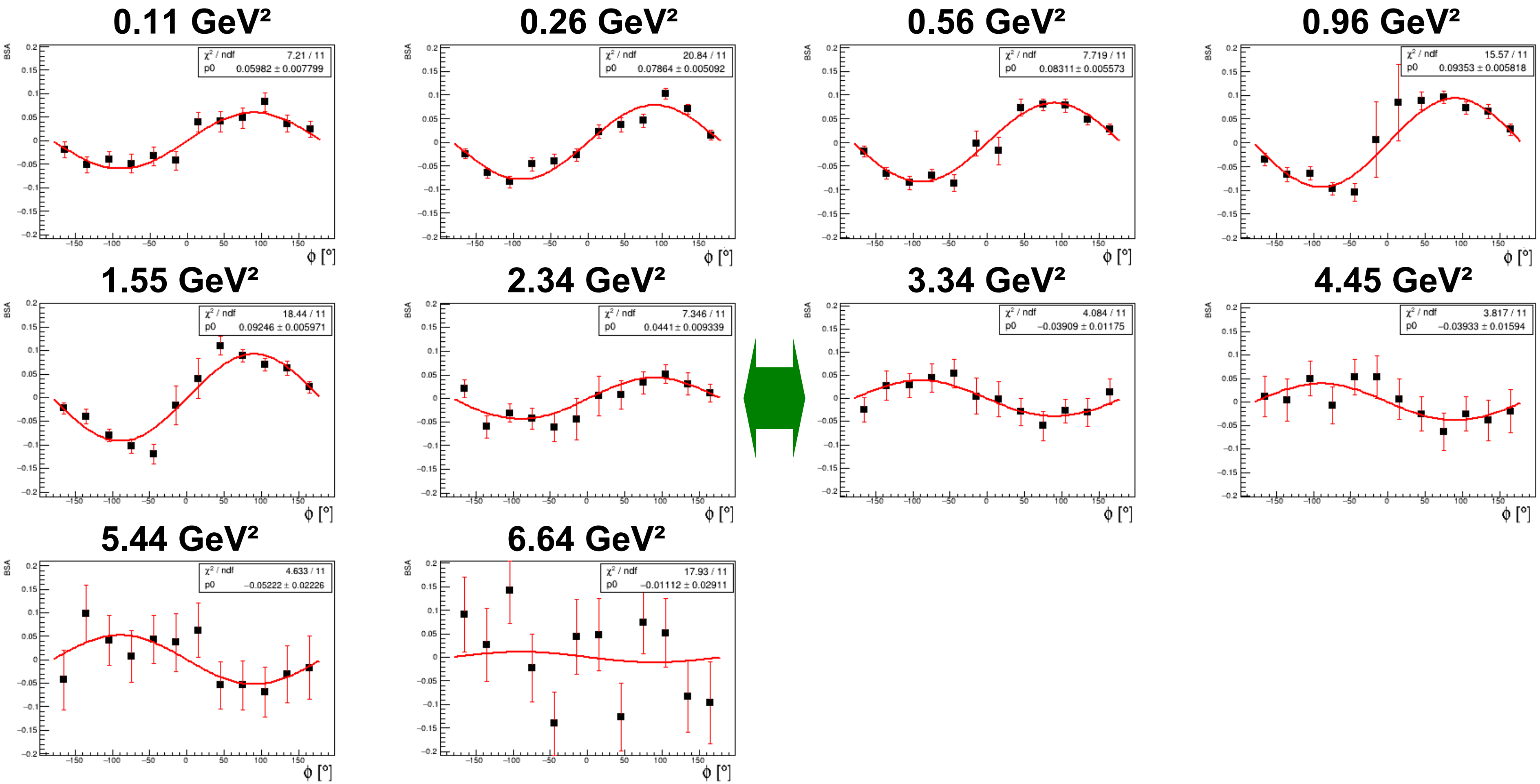
P_e = 75 % : average e⁻ beam polarisation

Integrated over all kinematic variables in forward / backward region:

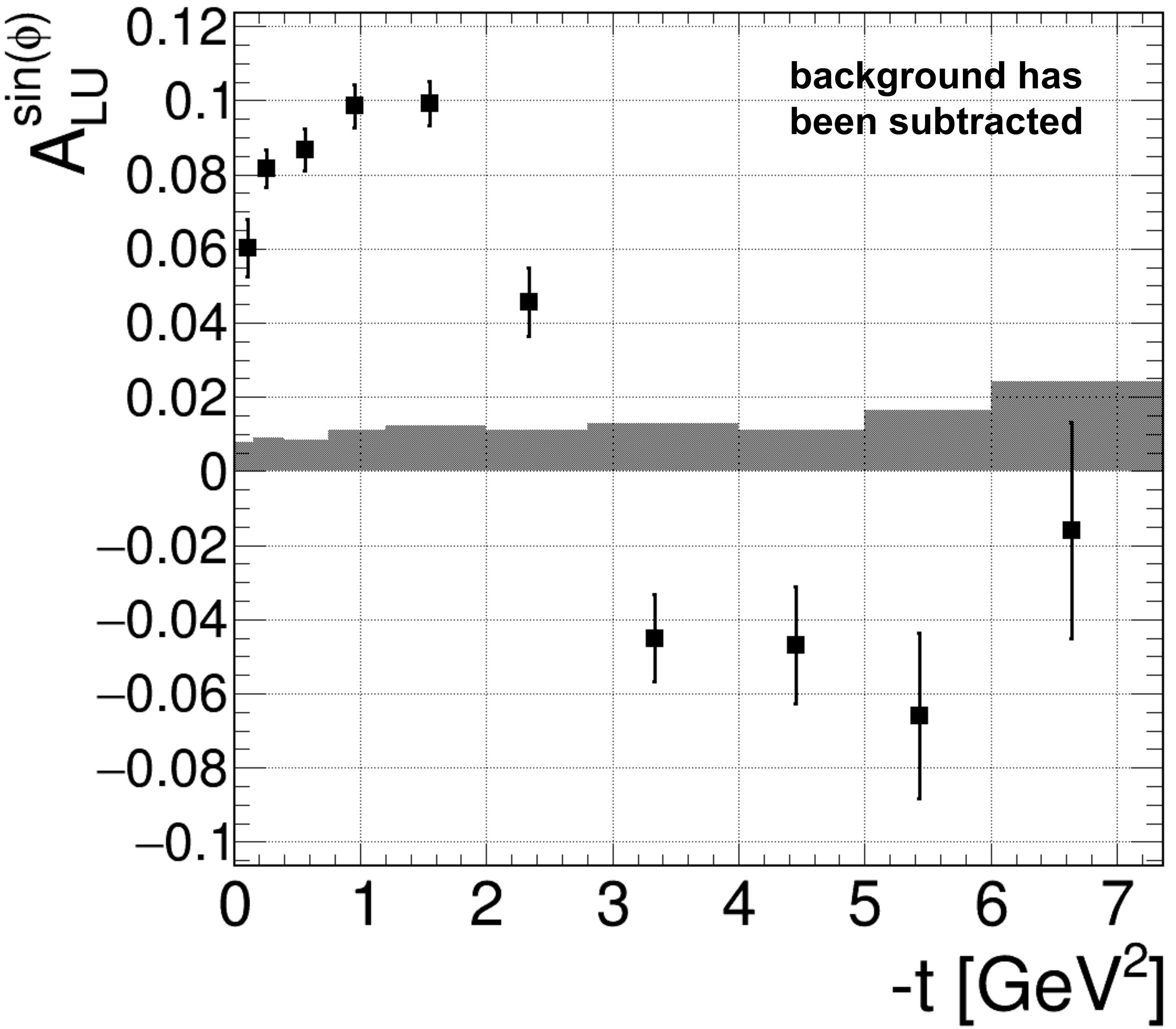




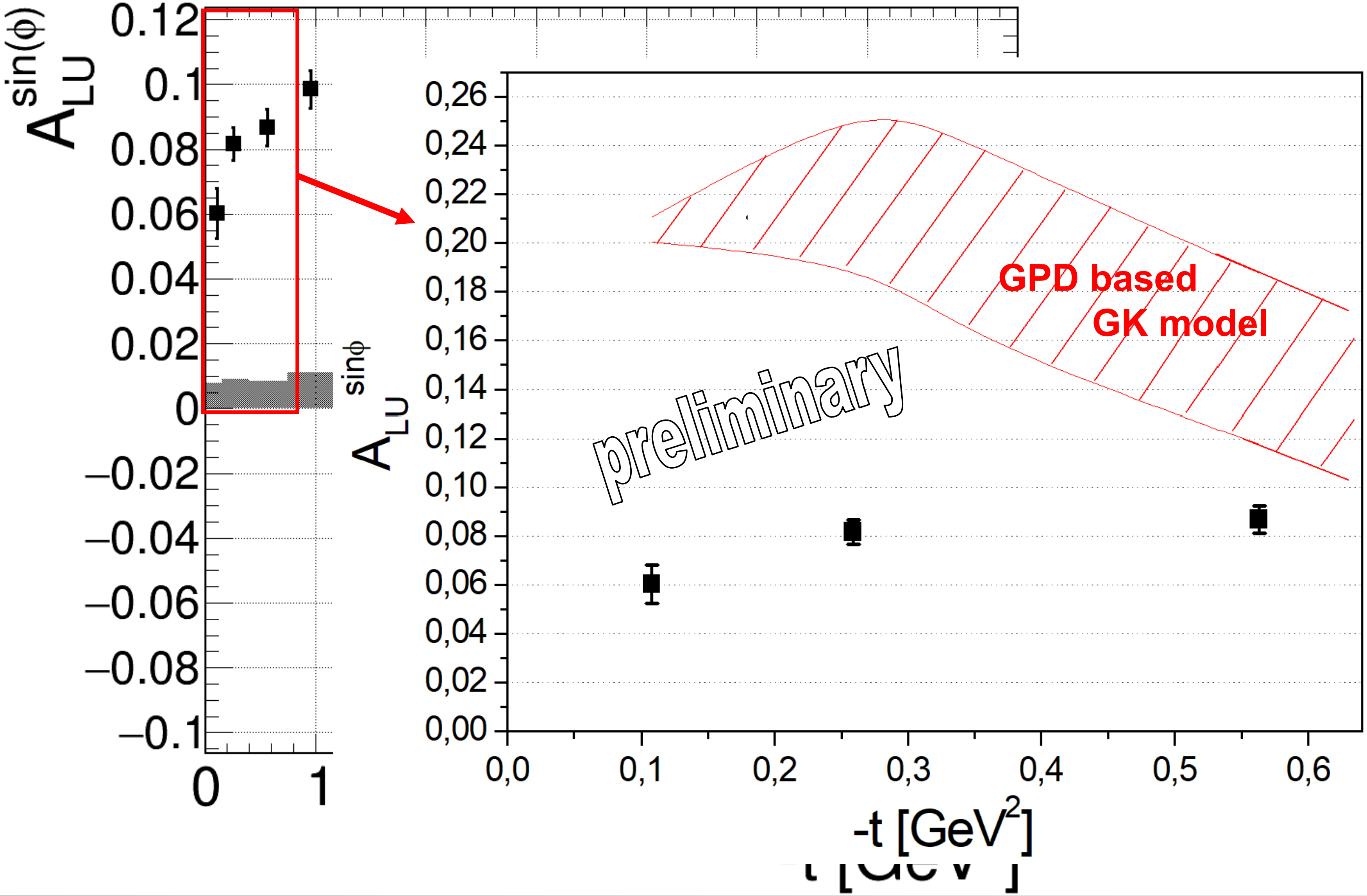
BSA for different -t bins



-t dependence of $A_{LU}^{\sin(\phi)}$

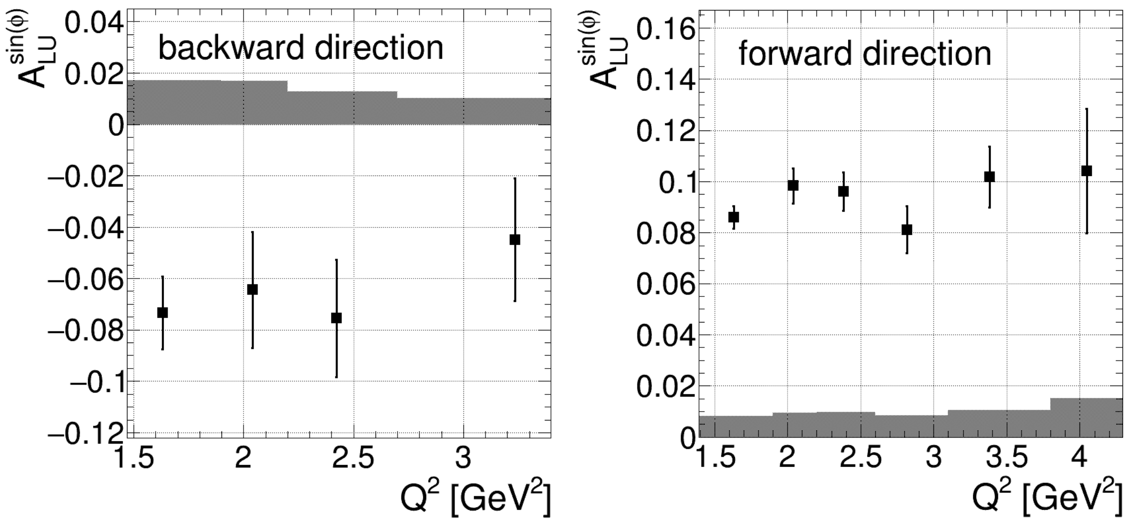


-t dependence of $A_{LU}^{\sin(\phi)}$

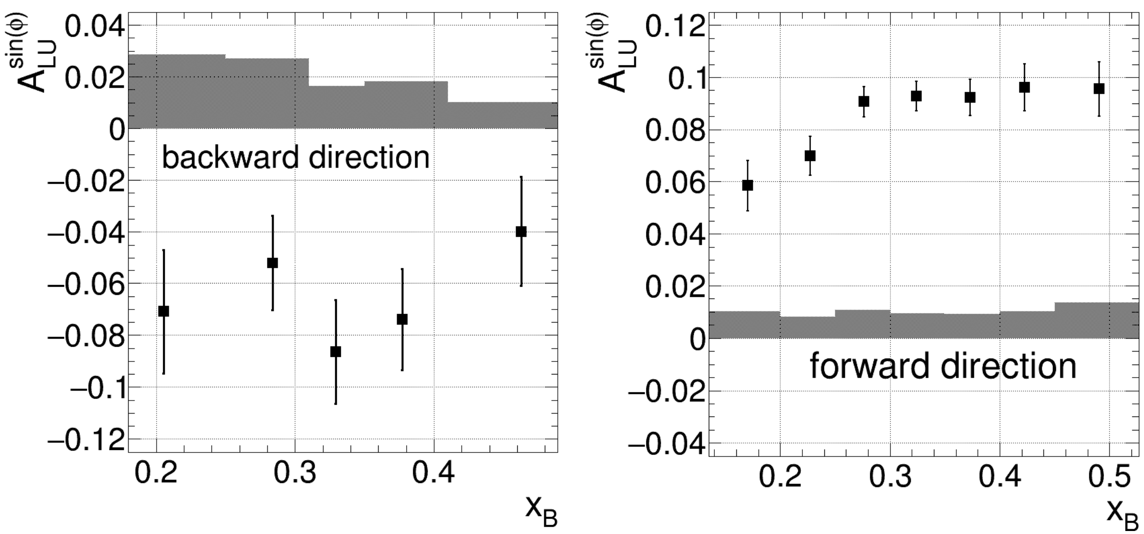


Q^2 and x_B dependence of $A_{LU}^{\sin(\phi)}$

Q^2



x_B



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

Perspectives for CLAS12

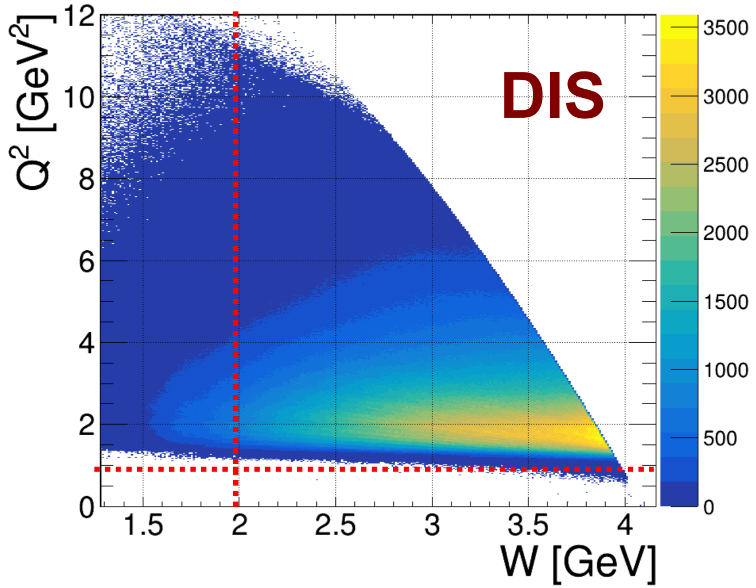
- CLAS 12 can map out froward and backward kinematics for

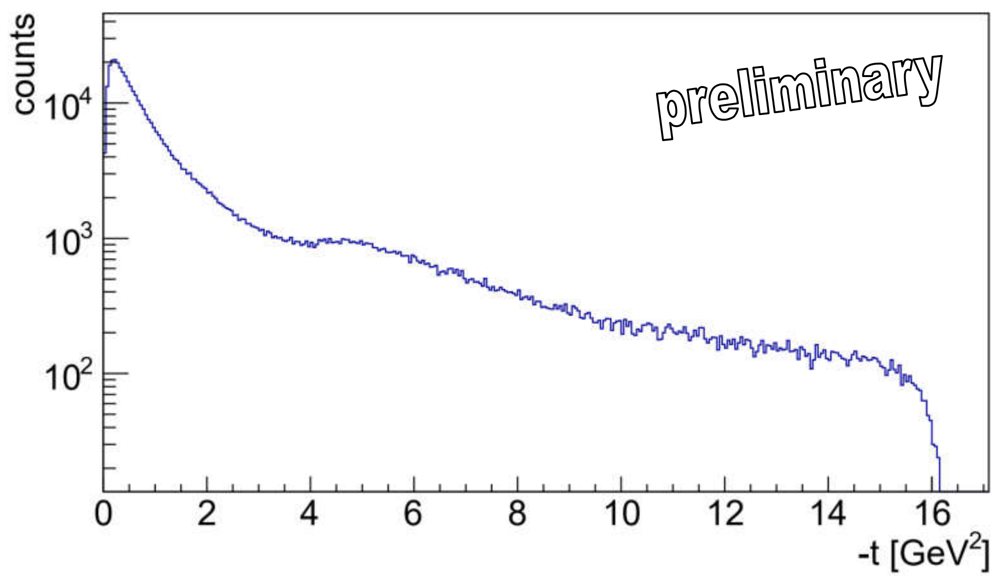
RG-A: $ep \rightarrow e' \, p \, \pi^0$ $ep \rightarrow e' \, n \, \pi^+$ $ep \rightarrow e' \, p \, \omega$

RG-B: $en \rightarrow e' \, p \, \pi^-$

➔ A significant amount of data has already been recorded and is currently in the analysis phase

Example: Kinematic coverage of $ep \rightarrow e' \, \pi^+$ (n)





Backward ω production at JLAB Hall C

Analysis by: W. B. Li, G. Huber *et al.* (Jefferson Lab F_{π} collaboration)
Phys. Rev. Lett. 123, 182501 (2019)

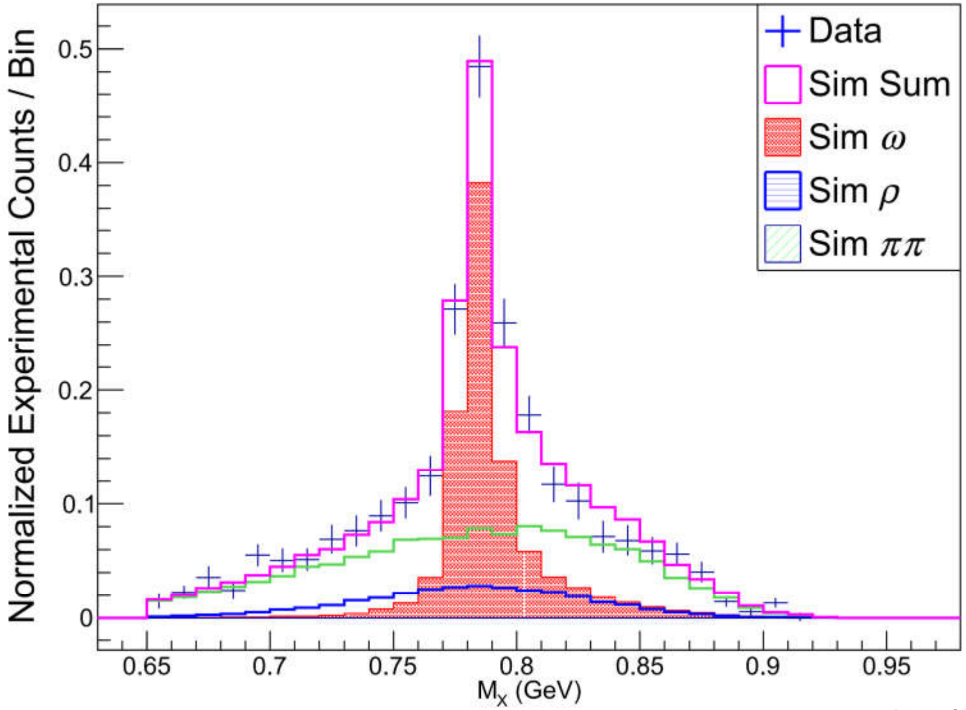
JLAB Hall C: 2.6 - 5.2 GeV electron beam on a liquid hydrogen target

- Recoil protons and scattered electrons detected with the hall C high precision particle spectrometers

- Q^2 = 1.60 and 2.45 GeV^2
- common central W = 2.21 GeV

Missing mass of ep → e′pX:

➔ Clear signal from backward regime of $ep \rightarrow e'p\omega$

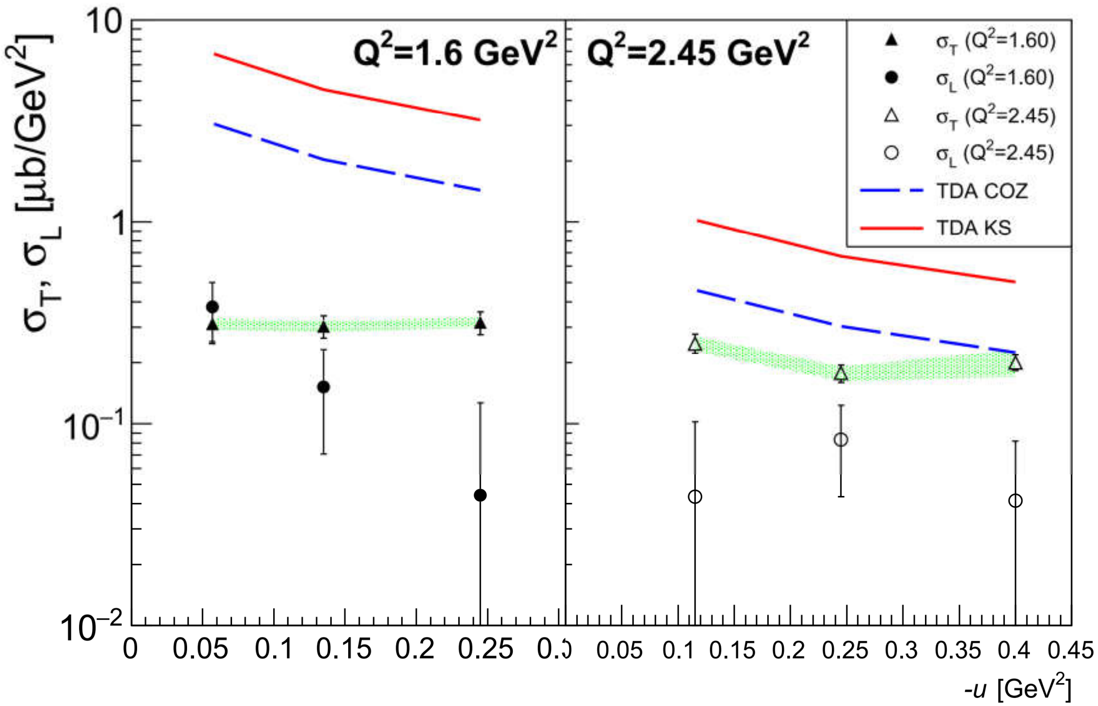


W. B. Li et al. PRL 123 (2019)

Backward ω production at JLAB Hall C

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

➔ Full Rosenbluth separation to extract σ_T and σ_L



W. B. Li et al. (Jefferson Lab F_π Collaboration)
Phys. Rev. Lett. 123, 182501 (2019)

Experiment vs predictions from the cross-channel nucleon exchange model for p→ω TDAs

Theory: B. Pire,L. Szymanowski and K. Semenov-Tian-Shansky (2015)

➔ A generalization of the TDA formalism for the case of light vector mesons (ρ, ω, φ)

For Q^2 = 2.45 GeV²:

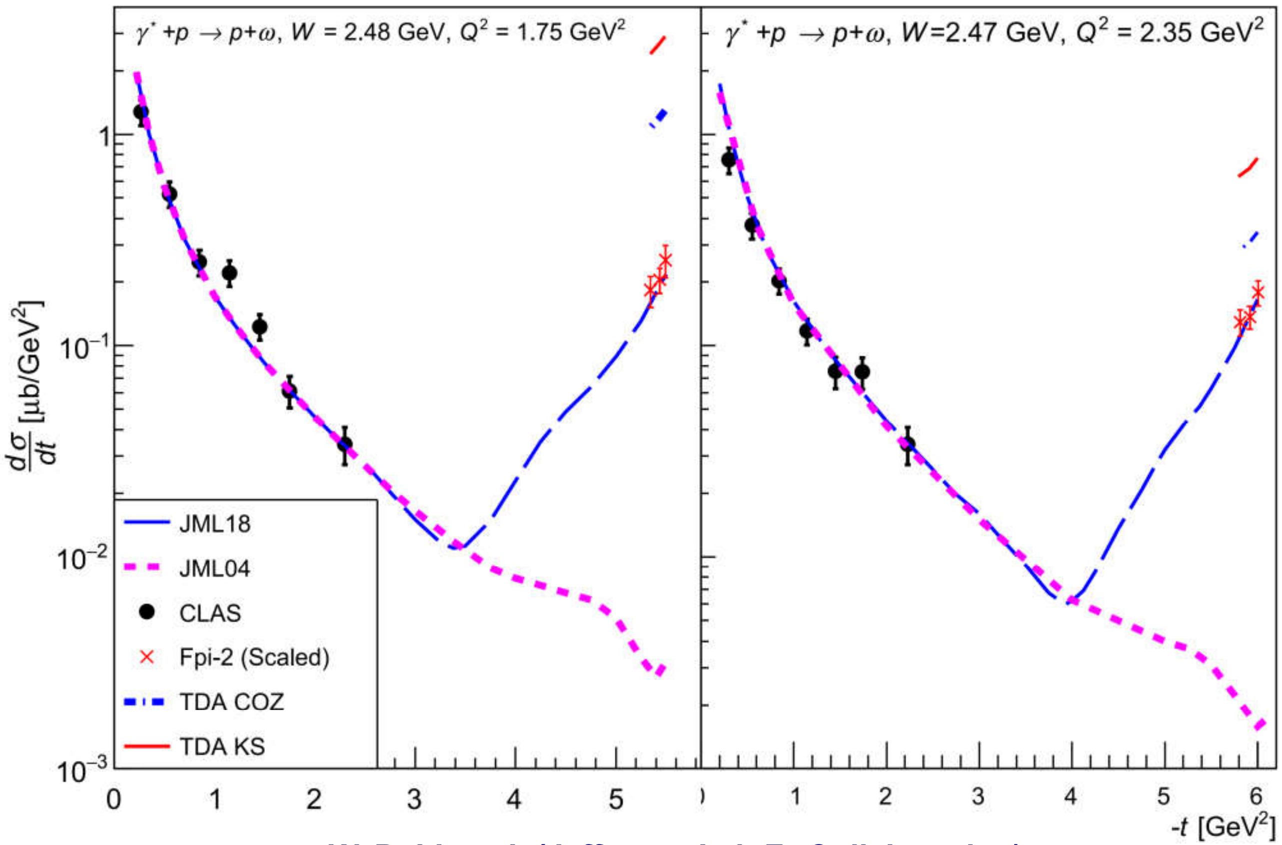
$\sigma_L/\sigma_T < \mu^2/Q^2$

and $\sigma_T \gg \sigma_L$

Backward ω production at JLAB Hall C

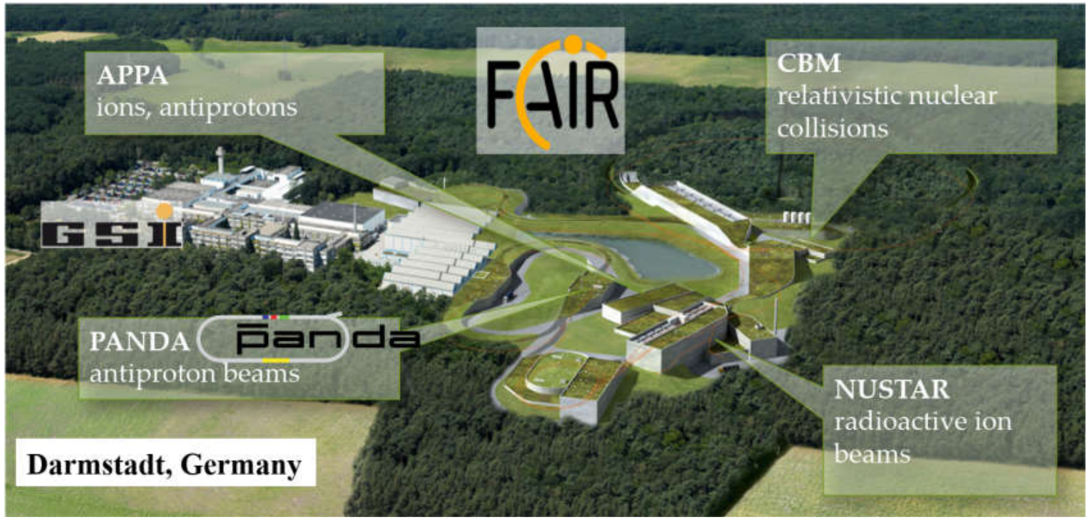
Combined (CLAS and $F_{\pi\text{-}2}$ data for $\gamma^* p \rightarrow \omega p$)

TDA-based predictions vs the Regge-based J.M. Laget's (JML18) model



W. B. Li et al. (Jefferson Lab F_π Collaboration)
Phys. Rev. Lett. 123, 182501 (2019)

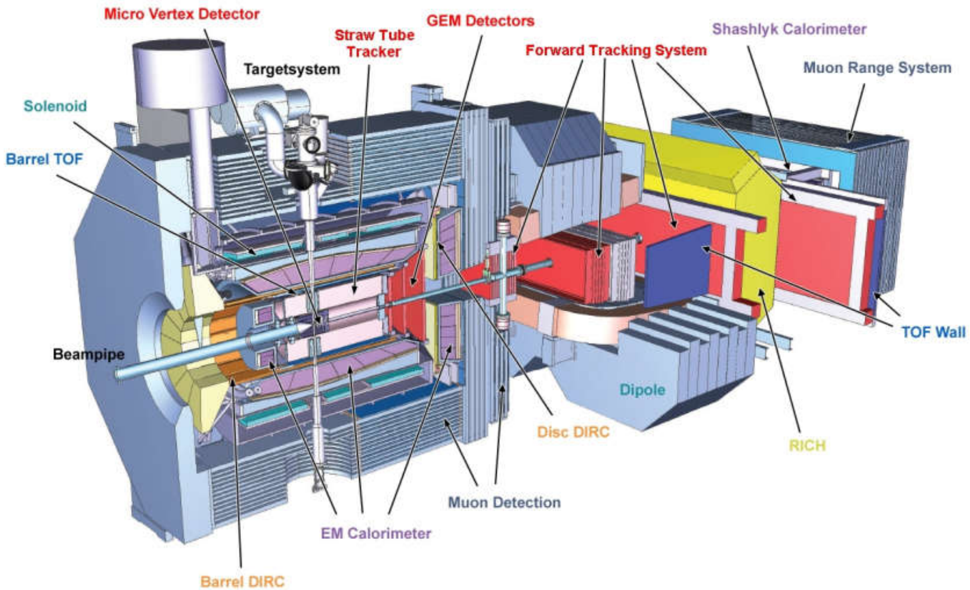
TDA measurements with the future PANDA detector at FAIR



- Antiproton beam
- cluster jet / pellet target
  ($\bar{p}$ p, $\bar{p}$ A)

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

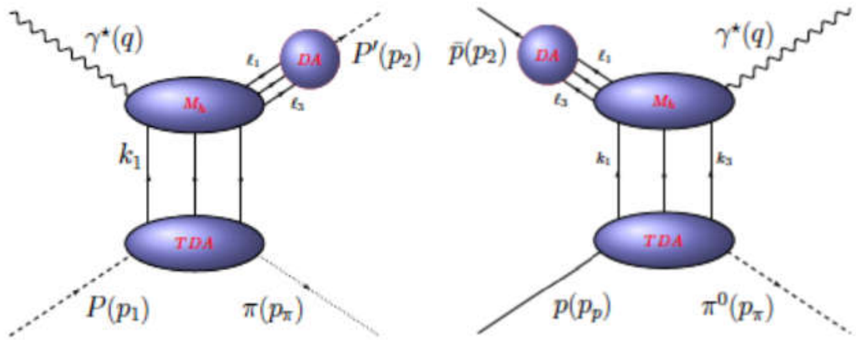
L = 2 · 10^{32} $cm^{-2}s^{-1}$



TDA measurements with the future PANDA detector at FAIR

TDAs also occur in factorized description of:

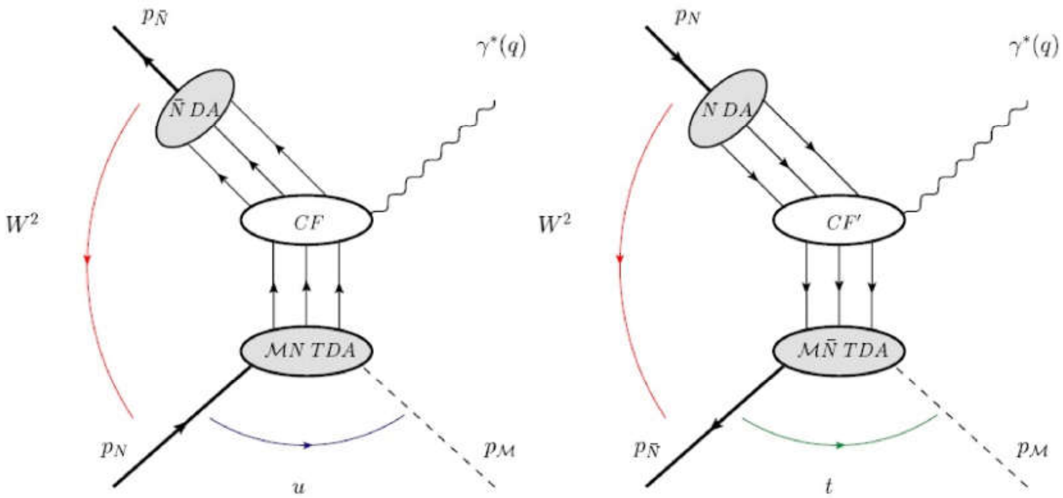
$$\bar{N} + N \to \gamma^*(q) + \pi \to \ell^+ + \ell^- + \pi;$$
$$\bar{N} + N \to J/\psi + \pi \to \ell^+ + \ell^- + \pi;$$



crossing symmetry

Theory: J.P. Lansberg et al. (2012)
B. Pire, L. Szymanowski,
K. Semenov-Tian-Shansky (2013)

Two regimes: forward and backward



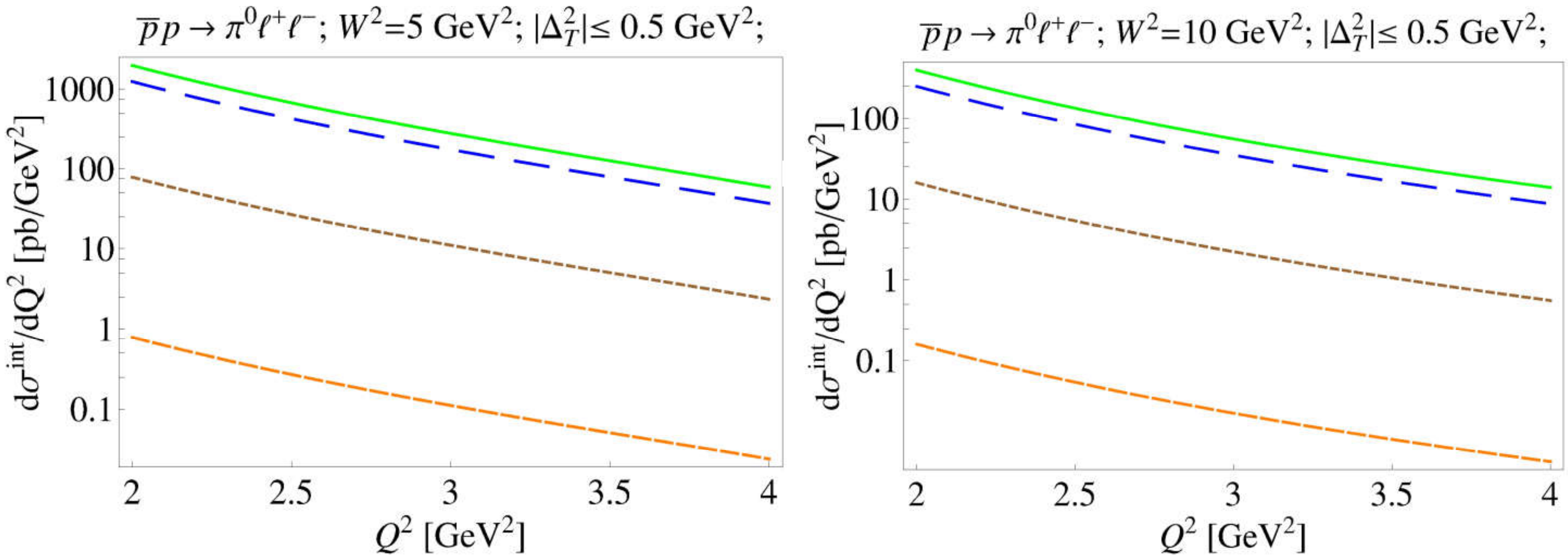
C invariance
→ perfect symmetry

➔ Test of universality of TDAs

TDA measurements with the future PANDA detector at FAIR

$\bar{p}p \to \pi^0\gamma^* \to \pi^0\ell^+\ell^-$ cross section estimates for $\bar{\text{P}}$ANDA

Integrated cross section for different inputs of the nucleon DAs:



B. Pire, L. Szymanowski, K. Semenov-Tian-Shansky (2013)

- Cross section of $\bar{p}\,n \to \pi^- l^+ l^-$ is larger by a factor 2 (neutron target required)

TDA measurements with the future PANDA detector at FAIR

Several feasability studies:

M. C. Mora Espi, M. Zambrana, F. Maas (PANDA collaboration) (2015)
B. Ramstein, E. Atomssa (PANDA collaboration) PRD 95 (2017)

Feasibility study for the measurement of πN TDAs at $\overline{\text{P}}$ANDA in $\bar{p}p \to J/\psi\pi^0$

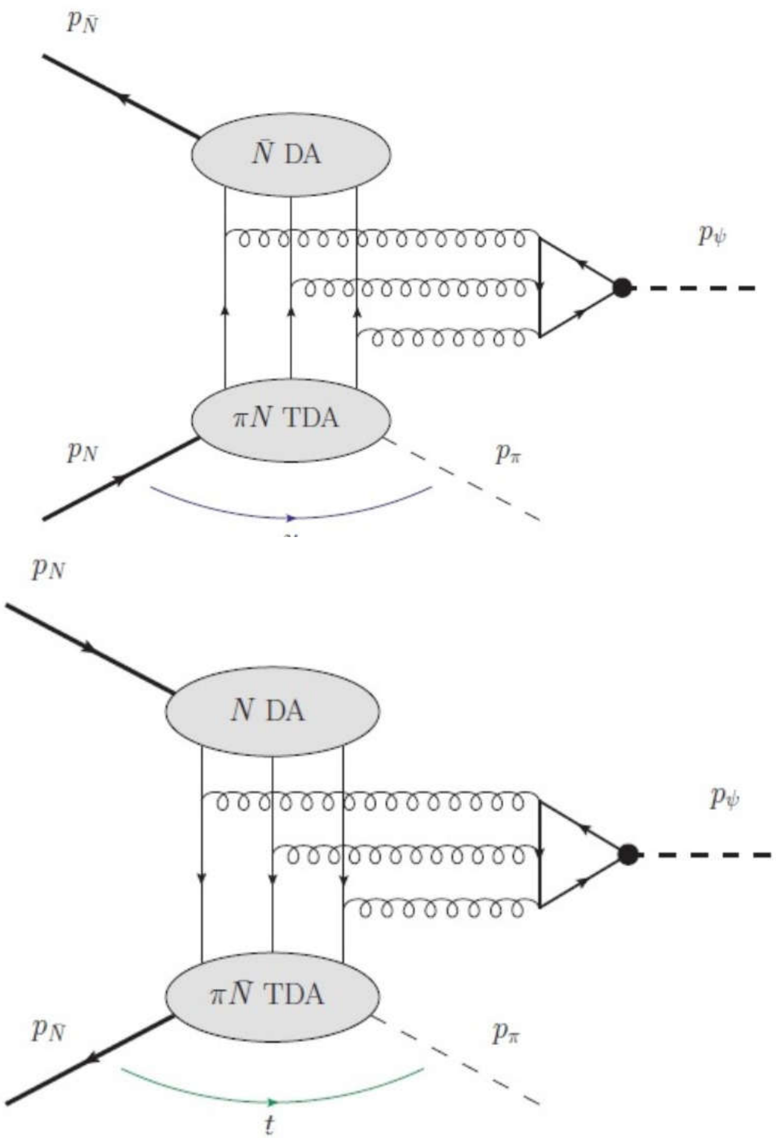
B. Singh,[1] W. Erni,[2] B. Krusche,[2] M. Steinacher,[2] N. Walford,[2] H. Liu,[3] Z. Liu,[3] B. Liu,[3] X. Shen,[3] C. Wang,[3] J. Zhao,[3] M. Albrecht,[4] T. Erlen,[4] M. Fink,[4] F.H. Heinsius,[4] T. Held,[4] T. Holtmann,[4] S. Jasper,[4] I. Keshk,[4] H. Koch,[4] B. Kopf,[4] M. Kuhlmann,[4] M. Kümmel,[4] S. Leiber,[4] M. Mikirtychyants,[4] P. Musiol,[4] A. Mustafa,[4] M. Pelizäus,[4] J. Pychy,[4] M. Richter,[4] C. Schnier,[4] T. Schröder,[4] C. Sowa,[4] M. Steinke,[4] T. Triffterer,[4] U. Wiedner,[4] M. Ball,[5] R. Beck,[5] C. Hammann,[5] B. Ketzer,[5]
....
K. Biguenko,[23] K.T. Brinkmann,[23] V. Di Pietro,[23] S. Diehl,[23] V. Dormenev,[23] P. Drexler,[23] M. Düren,[23] E. Etzelmüller,[23]
....

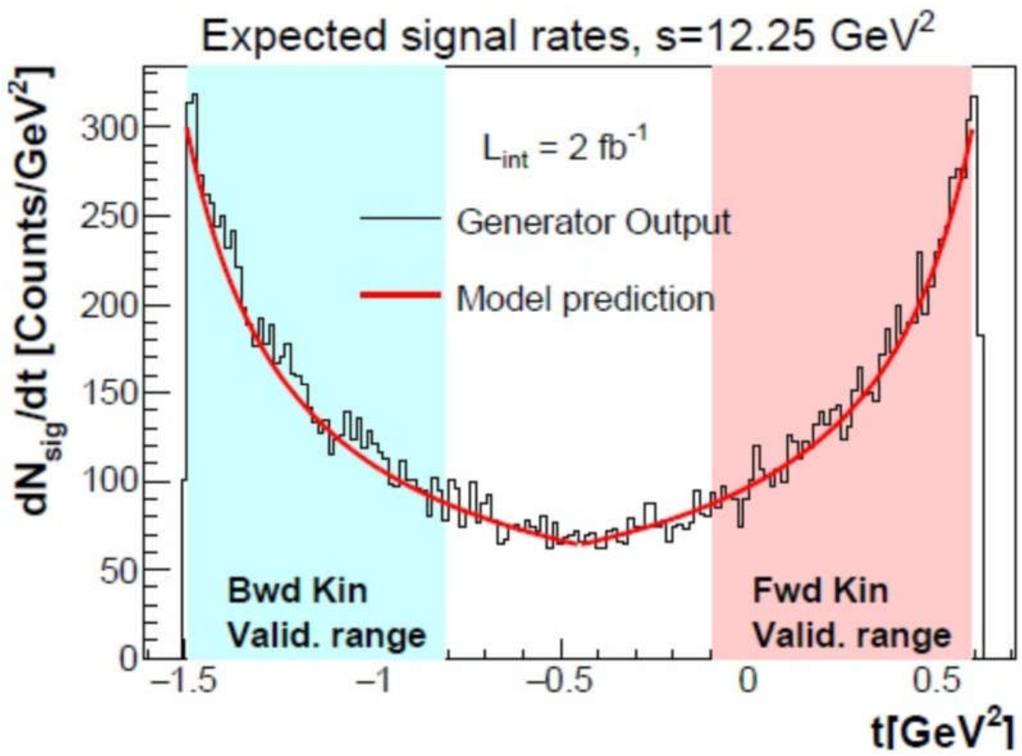
Event generator based on: B. Pire, L. Szymanowski, K. Semenov-Tian-Shansky (2013)

Study of: $\bar{p}\,p \to J/\Psi\,\pi^0$ (signal)
and different background sources ($\bar{p}\,p \to \pi^+\,\pi^-\,\pi^0$, $\bar{p}\,p \to J/\Psi\,\pi^0\,\pi^0$, …)

- Simulations for s = 5 GeV², 10 GeV², 12.2 GeV², 16.9 GeV², 24.3 GeV²
- <u>Assumption</u>: 2 fb^{-1} of integrated luminosity (~ 5 month of high lumi. data taking)

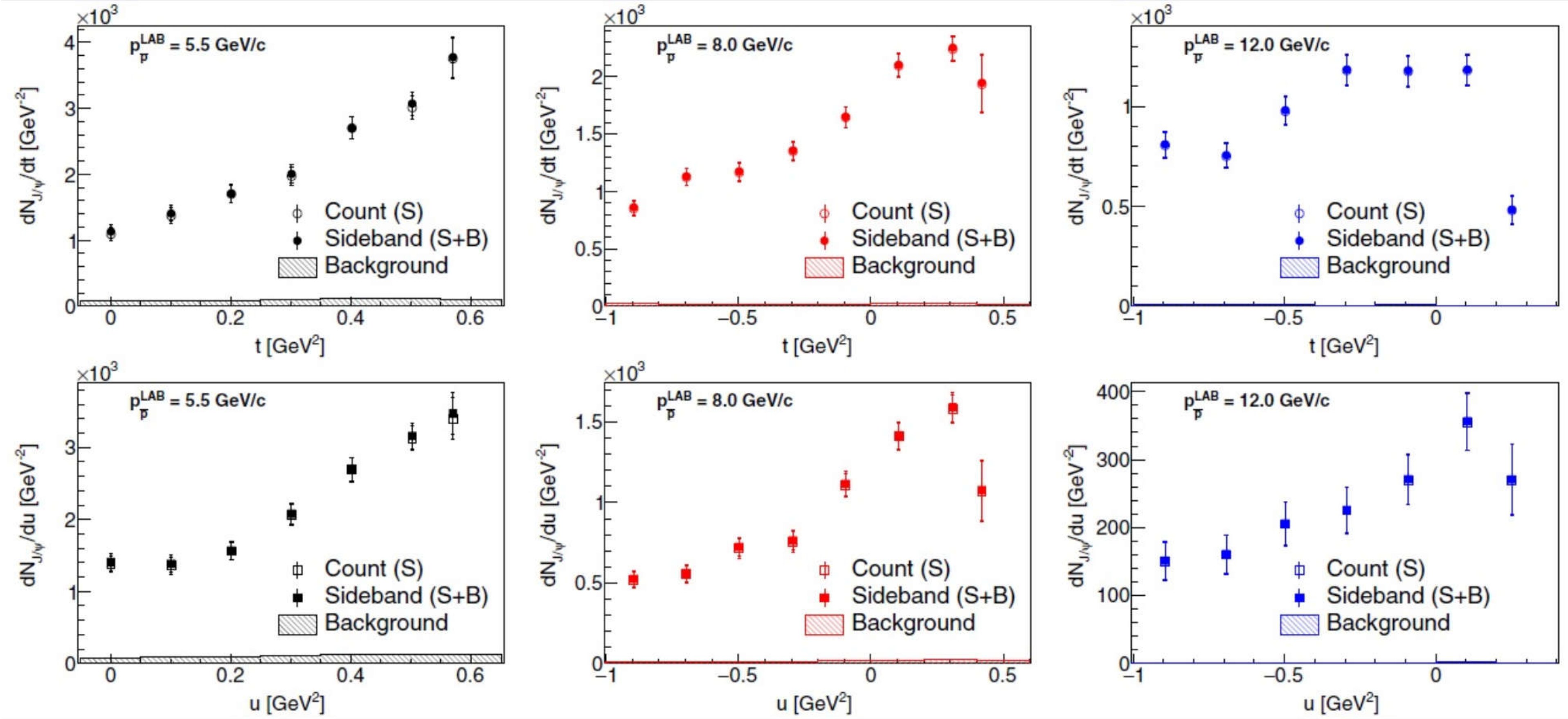
TDA measurements with the future PANDA detector at FAIR





TDA measurements with the future PANDA detector at FAIR

Signal and Background count rates vs *t* and *u*



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

Baryon to Meson TDA measuremets at JPARC

J-PARC: intense pion beams with P_π = 10 – 20 GeV

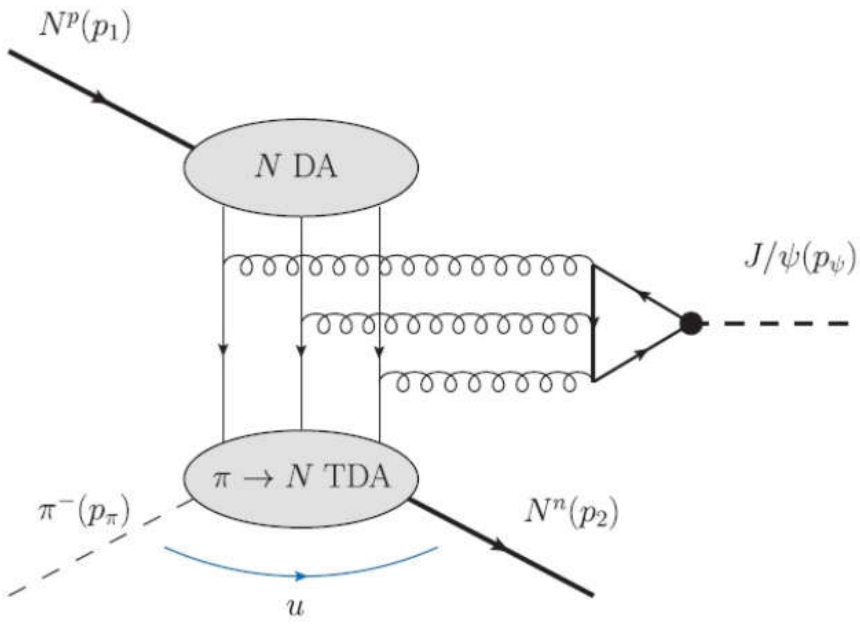
- Charmonium production in assoziation with a nucelon can be used to access TDAs

- **Theory:** B. Pire, L. Szymanowski and K. Semenov-Tian-Shansky, PRD 95 (2017)

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

Near forward regime:

$$|(p_\pi - p_2)^2| \ll W^2,\ M_\psi^2$$



Summary and Outlook

- Nucleon-to-meson TDAs provide new information about correlations of partons inside hadrons
- In the impact parameter space, TDAs provide a spatial imaging of the structure of the pion cloud inside the nucleon
- JLAB 6 GeV data provided first hints for the validity of the TDA based description
- The BSA of the hard exclusive π^+ production shows a clear sign change from forward to backward angles, which may indicate a transition from the GPD to the TDA regime.
- JLAB 12 GeV data will provide more detailed measuremnts in the TDA regime.
- PANDA will allow a check of the universality of TDAs.

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