Experimental TDA program at FAIR, JLAB, EIC and JPARC

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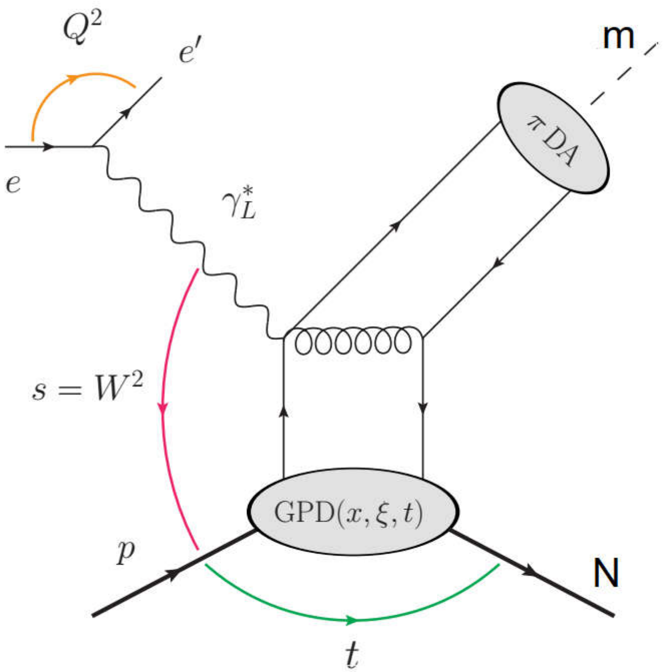
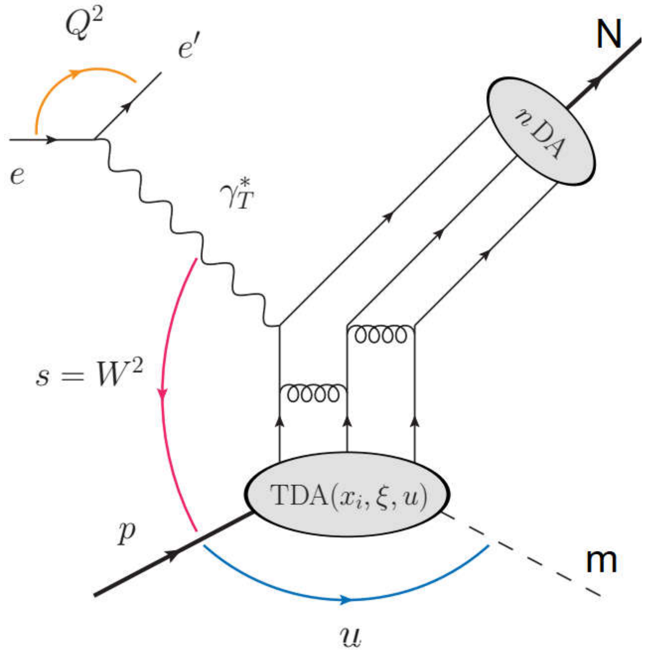
Hard exclusive meson production

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
➔ **meson in forward region**

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



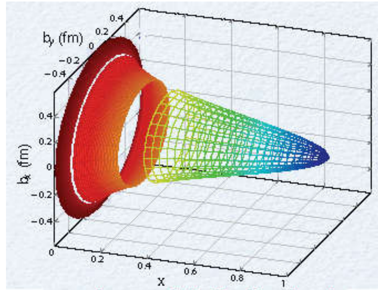


Physics content

GPDs ($-t/Q^2 << 1$)

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

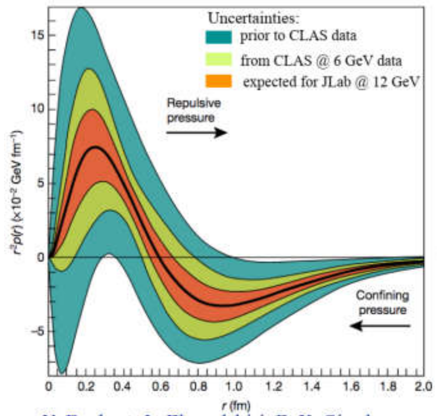
➔ Describe hadronic structural information in terms of quark and gluon degrees of freedom



courtesy of Z.E. Meziani

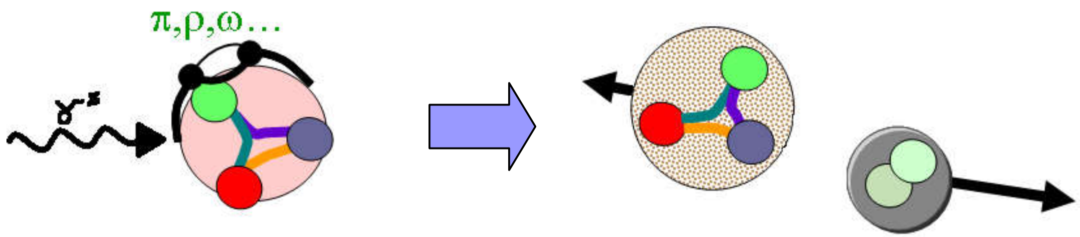
➔ Spin-dependent 2D transverse coordinate space + 1D longitudinal momentum space images of the nucleon

- ➔ Tool to study the nature and origin of the nucleon spin
- ➔ Access to basic properties of the nucleon, like pressure distributions, tensor charge …
- ➔ Impact parameter space: spatial femto-photographs of the hadron structure in the transverse plane



V. Burkert, L. Elouadrhiri, F.-X. Girod, Nature **557**, 396-399 (2018)

K. Kumerički, Nature **570**, E1-E2 (2019)



Physics content

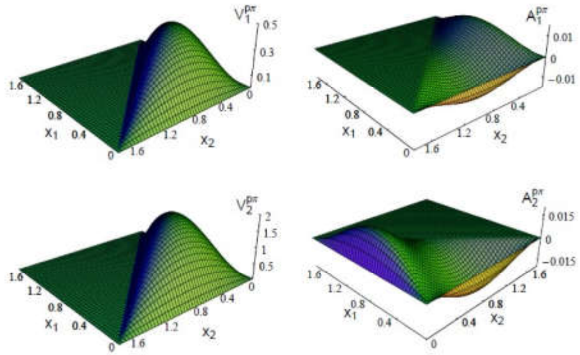
Baryon to meson TDAs (-u/Q² << 1)

➔ Light-cone matrix elements of non-local three quark operators

➔ Encoded physical picture close to GPDs

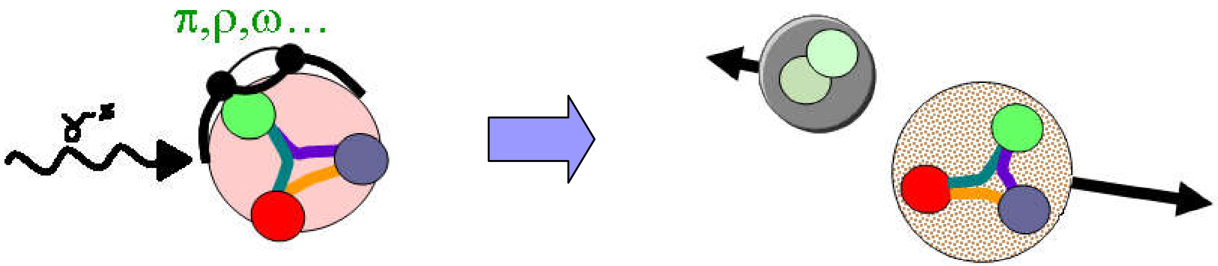
➔ Probe partonic correlations between states of different baryonic charge

  ➔ Access to non-minimal Fock components of baryon light-cone wave functions



➔ Improved access to the valence and sea quark components of the nulceon wave function

➔ Impact parameter space: Femto-photography of hadrons from a new perspective



"knocking a proton out of a proton"

Physics motivation

➔ Exclusive u-channel interactions in the deep regime are mostly unexplored territory

➔ Small cross sections (1/10 – 1/100 of the t-channel peak)

➔ No unified framework available due to the lack of experimental data

➔ Recent and upcoming high statistics experiments (like at JLAB) offer new opportunites to study the u-channel regime

Goals for theory ↔ experiment:

➔ Obtain new insights in the nucleon structure, complementary to the forward regime

- Develope a **unified Regge model**
  - → Validate our understanding of the relevant exchange mechanisms
  - → Probe the soft-hard transition in QCD for different kinematic regions
  - → Available Regge models including backward angles:

    i.e. J. M. Laget, Unitarity constraints on meson electroproduction at backward angles, Phys. Rev. C **104**, 025202 (2021)

- Develop a **TDA framework** similar to GPDs in the forward region

The TDA model: Experimentaly accessible features

Transition distribution amplitudes and hard exclusive reactions with baryon number transfer

Physics Reports 940 (2021) 1–121

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

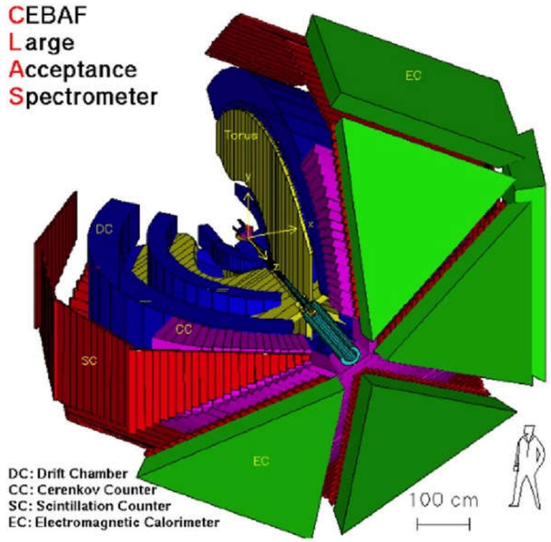
Characteristic features of the TDA-based mechanism:

- ➔ 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 $1/Q^2$ $\rightarrow \sigma_T >> \sigma_L$
- ➔ The transverse cross section σ_T shows a characteristic $1/Q^8$ scaling behaviour for fixed x_B

More distinguishing features become accesible with a polarized target:

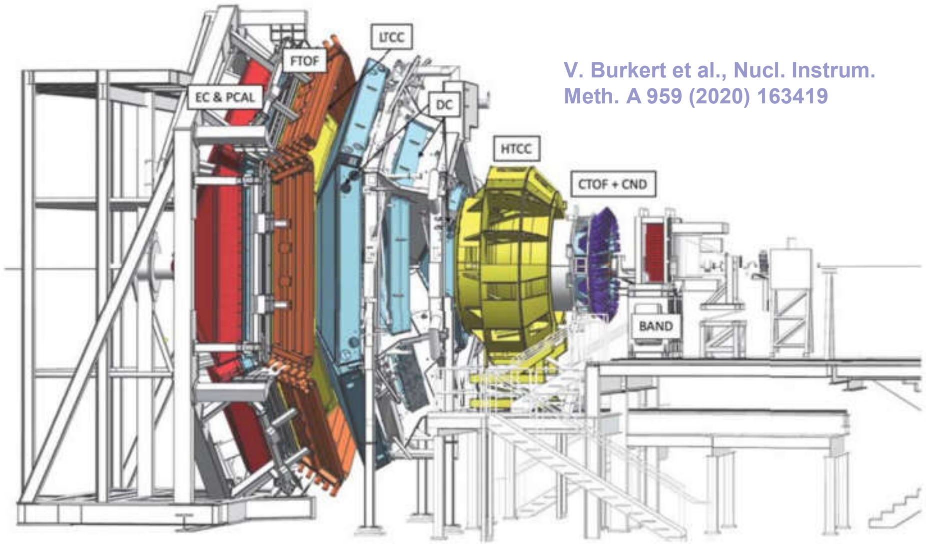
- ➔ Transverse target single spin asymmetry ~ *Im* part of the amplitude
- ➔ TDA approach predicts a non vanishing and Q^2-independent TSA
- ➔ Two component TDA model predicts 10-15 % TSA for $\gamma^* N \rightarrow \pi N$

Experimental facilities at JLAB



Hall B

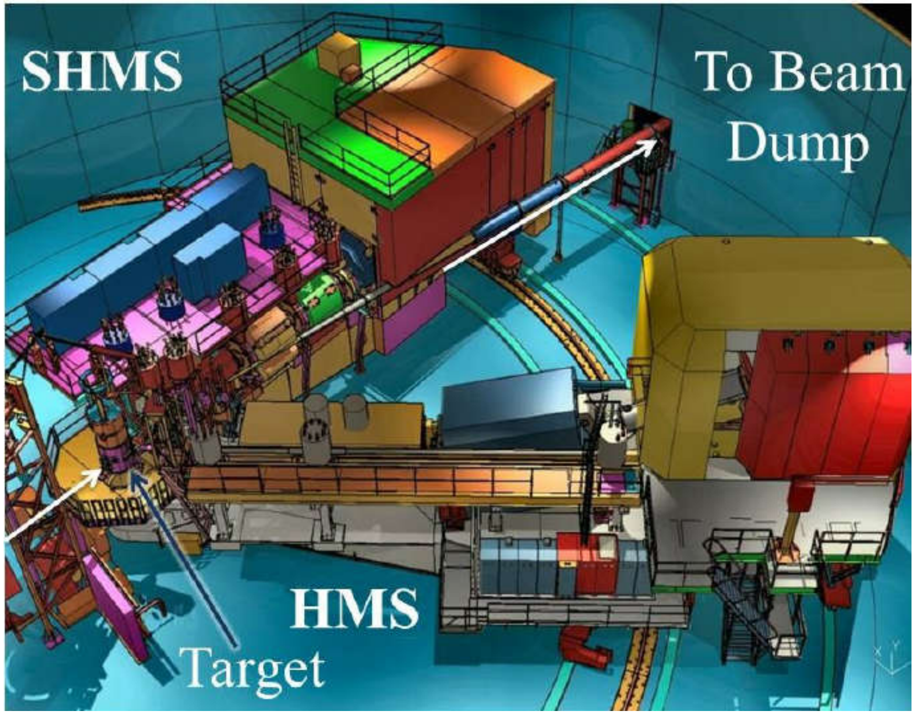
- **CLAS** (operation till 2012)
- up to 6 GeV longitudinally polarized electron beams
- unpolarized hydrogen target
- large acceptance spectrometer



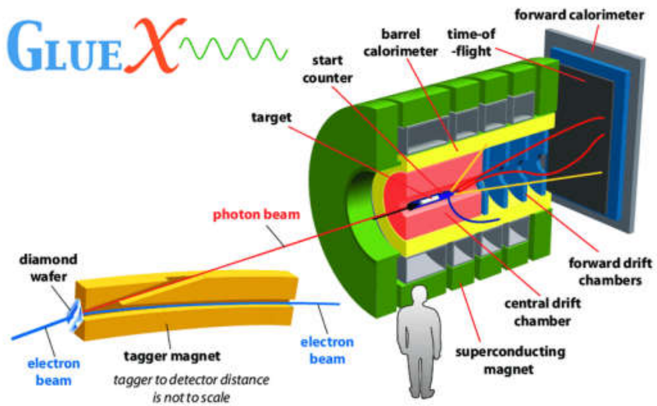
V. Burkert et al., Nucl. Instrum. Meth. A 959 (2020) 163419

- **CLAS12** (operation since 2018)
- 10.6, 6.6, 7.5 GeV longitudinally polarized electron beams
- unpolarized and polarized hydrogen targets and deuterium (neutron) target

Experimental facilities at JLAB



- **HALL C**
- longitudinally polarized electron beams with different beam energies (< 6, 11 GeV)
- different targets i.e. unpolarized hydrogen
- two arm high precision spectrometer



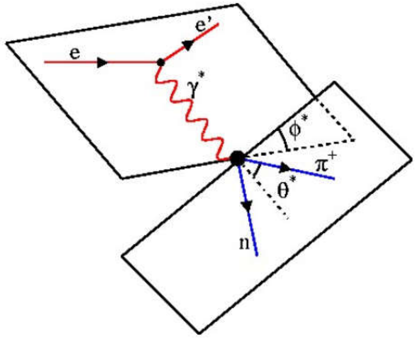
- **HALL D (GlueX)**
- tagged photon beam
- different targets (i.e. hydrogen)
- u-channel photoproduction

Hard exclusive π⁺ electroproduction in the backward regime

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

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

$$\frac{d^4\sigma}{dsdQ^2d\phi dt} = C \times \left[\frac{d\sigma_T}{dt} + \varepsilon\frac{d\sigma_L}{dt} + \varepsilon\cos 2\phi\frac{d\sigma_{TT}}{dt} + \sqrt{2\varepsilon(1+\varepsilon)}\cos\phi\frac{d\sigma_{LT}}{dt} + h\sqrt{2\varepsilon(1-\varepsilon)}\ \frac{d\sigma_{LT'}}{dt}\sin\phi\ \right]$$

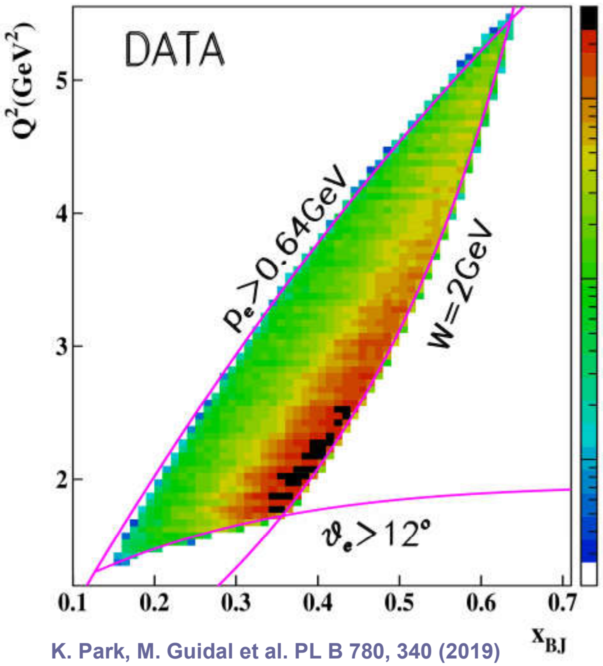


W = 2.0 - 2.4 GeV

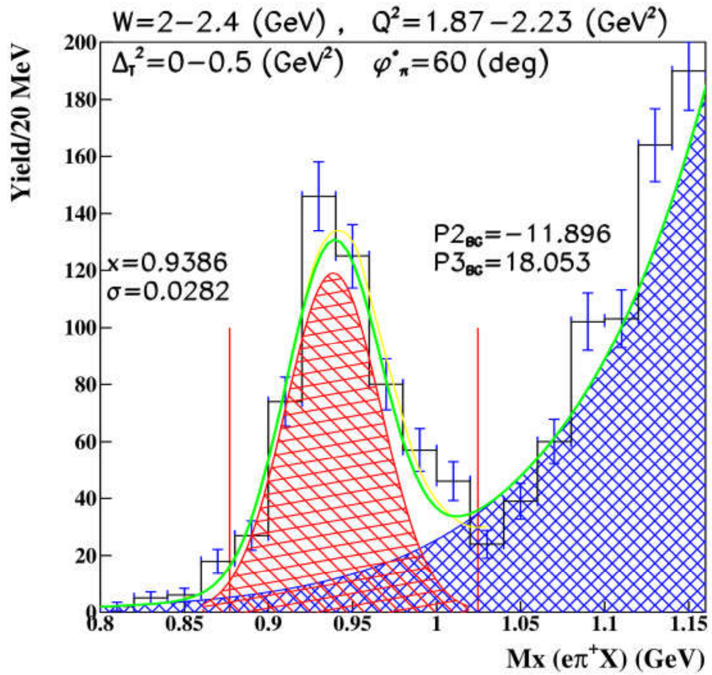
Q^2 = 1.6 - 4.5 GeV²

-u = 0.5 GeV²

ϕ = 0° - 360°



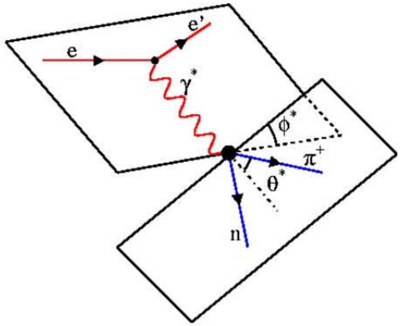
K. Park, M. Guidal et al. PL B 780, 340 (2019)



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

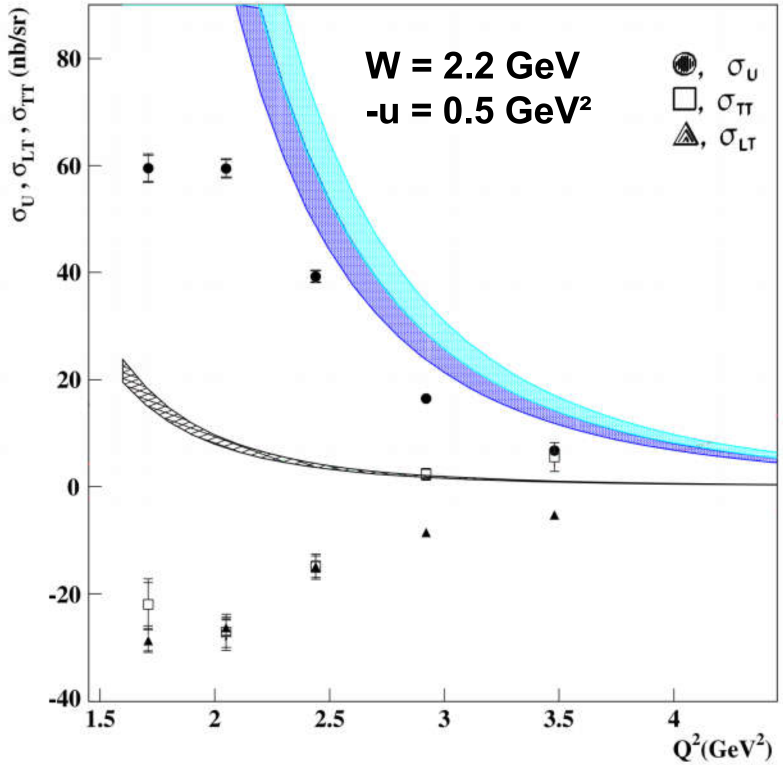
Hard exclusive π⁺ electroproduction in the backward regime

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



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

$$\sigma_U = \sigma_T + \varepsilon\sigma_L \qquad B = \sqrt{2\epsilon(1+\epsilon)}\sigma_{LT} \qquad C = \epsilon\sigma_{TT}$$



TDA model calculations for σ_U:

→ Results depend on the input for the nucleon distribution amplitude

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)

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

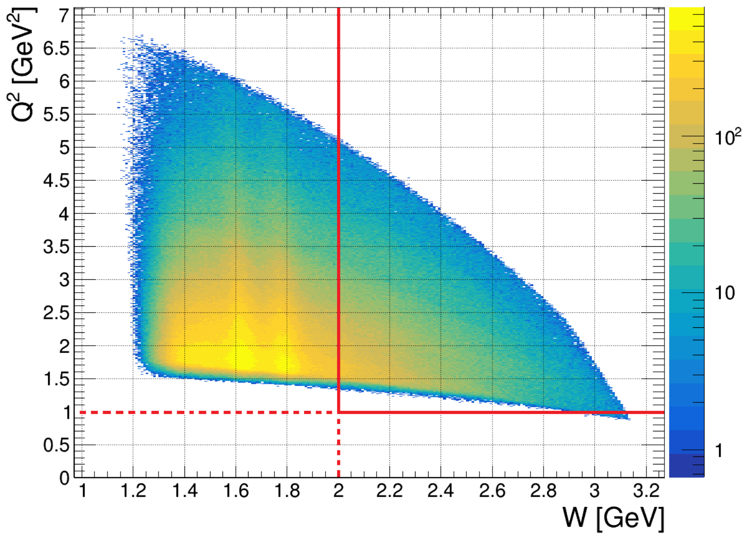
K. Park, M. Guidal et al. PL B 780, 340 (2019)

Hard exclusive π⁺ electroproduction beam spin asymmetry

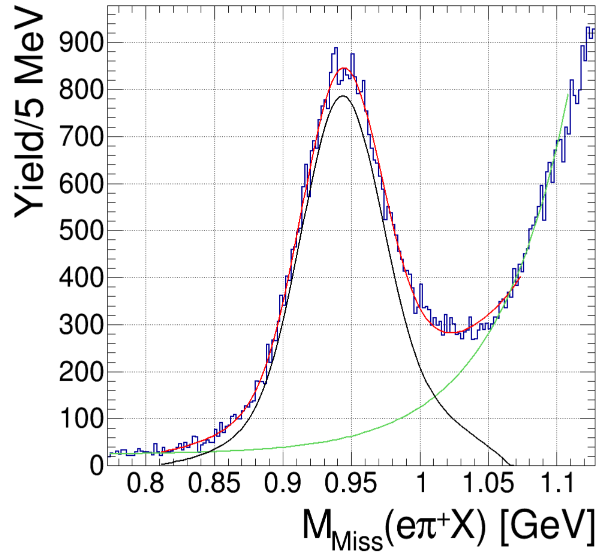
CLAS: $ep \rightarrow en\pi^+$

S. Diehl et al., Phys. Rev. Lett. 125, 182001 (2020)

https://doi.org/10.1103/PhysRevLett.125.182001



DIS cuts:
W > 2 GeV
Q² > 1 GeV²

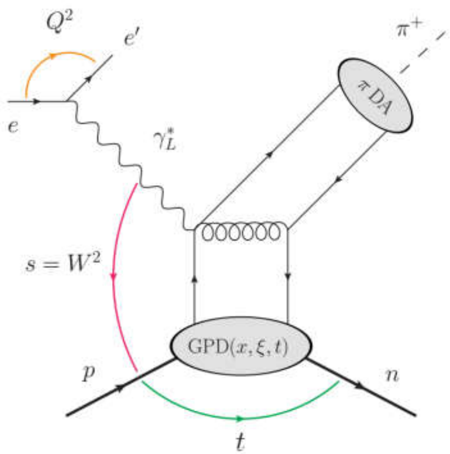


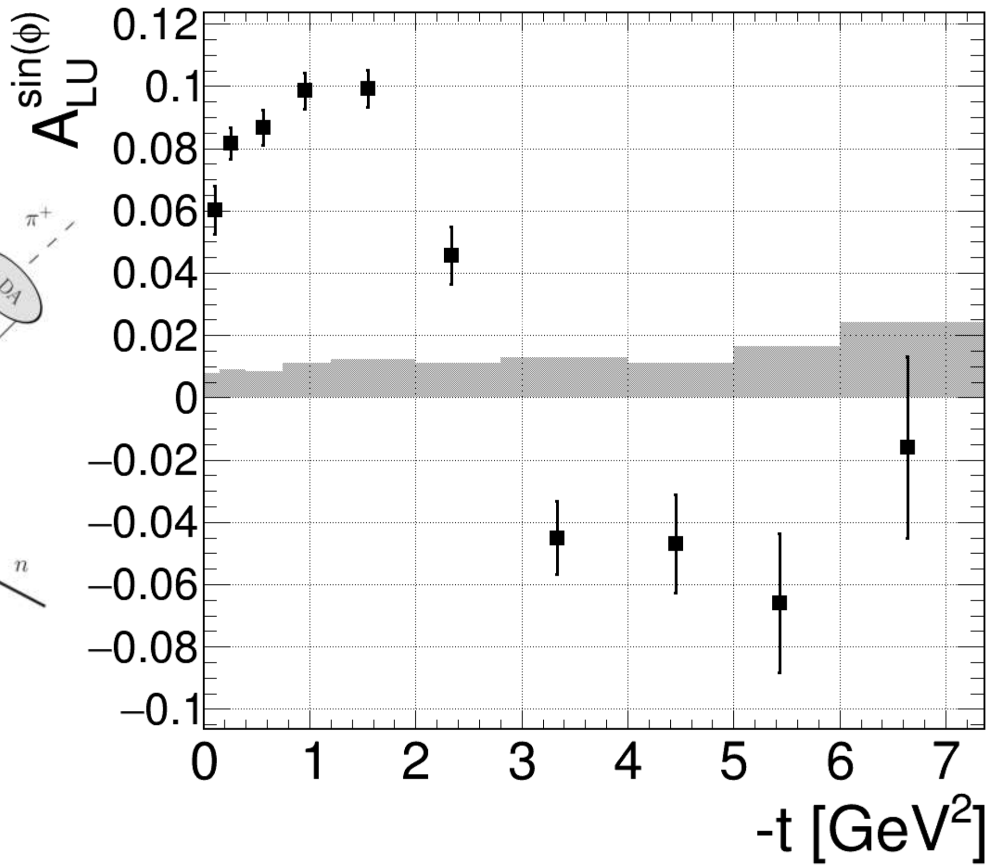
$$BSA = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} = \frac{A_{LU}^{\sin\phi} \sin\phi}{1 + A_{UU}^{\cos\phi} \cos\phi + A_{UU}^{\cos(2\phi)} \cos(2\phi)}$$

$$A_{LU}^{\sin\phi} = \frac{\sqrt{2\varepsilon(1-\varepsilon)}\ \sigma_{LT'}}{\sigma_T + \varepsilon\sigma_L}$$

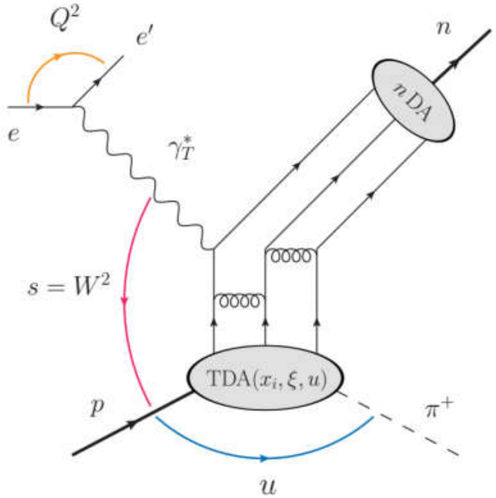
Hard exclusive π⁺ electroproduction beam spin asymmetry

GPD regime





TDA regime



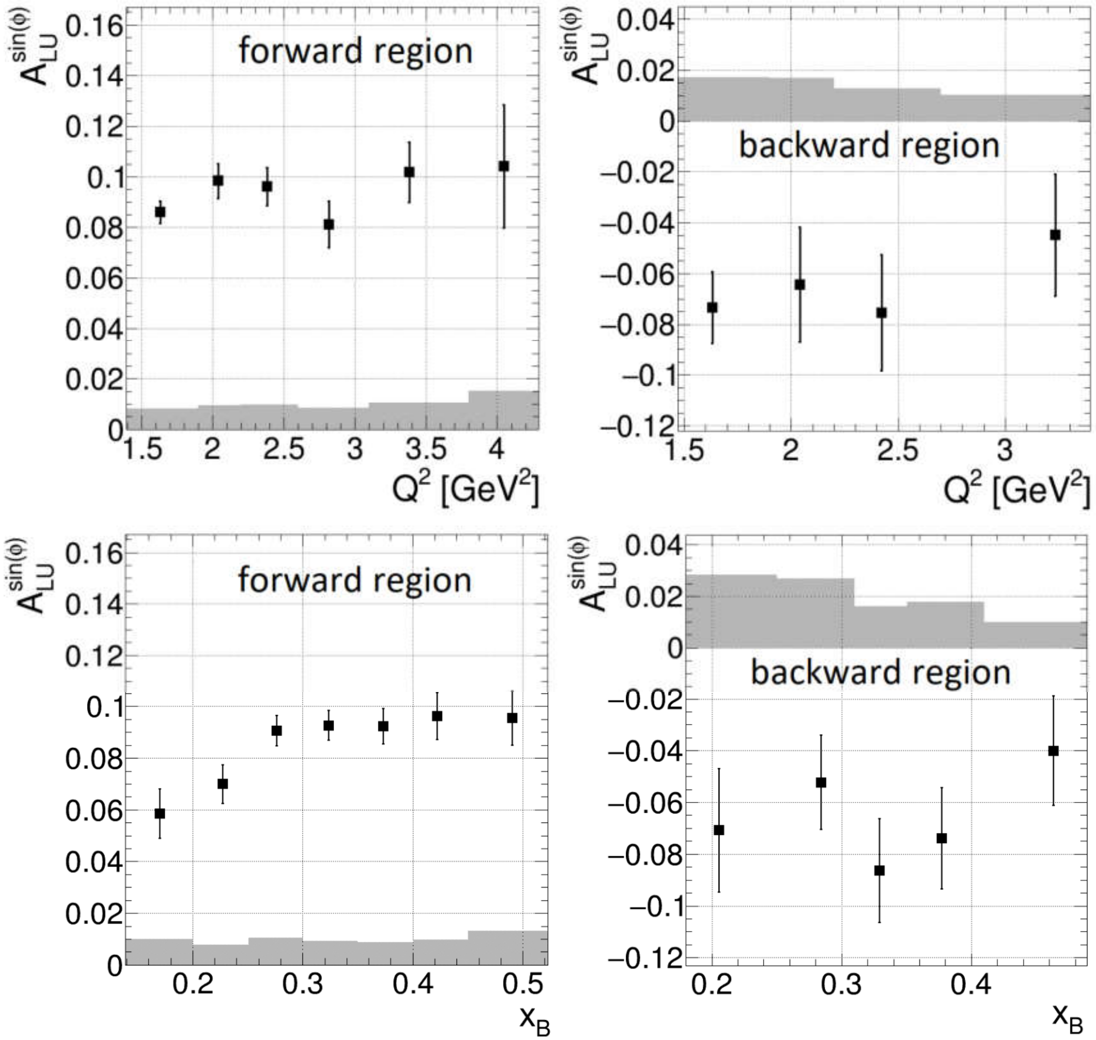
S. Diehl et al., Phys. Rev. Lett. 125, 182001 (2020)

Hard exclusive π⁺ electroproduction beam spin asymmetry

small -t **small -u**

Q^2

x_B



S. Diehl et al., Phys. Rev. Lett. 125, 182001 (2020)

Backward ω production in hall C at JLAB

Hall C: **Analysis by:** W. B. Li, G. Huber *et al.* (Jefferson Lab F_π collaboration)
Phys. Rev. Lett. 123, 182501 (2019)

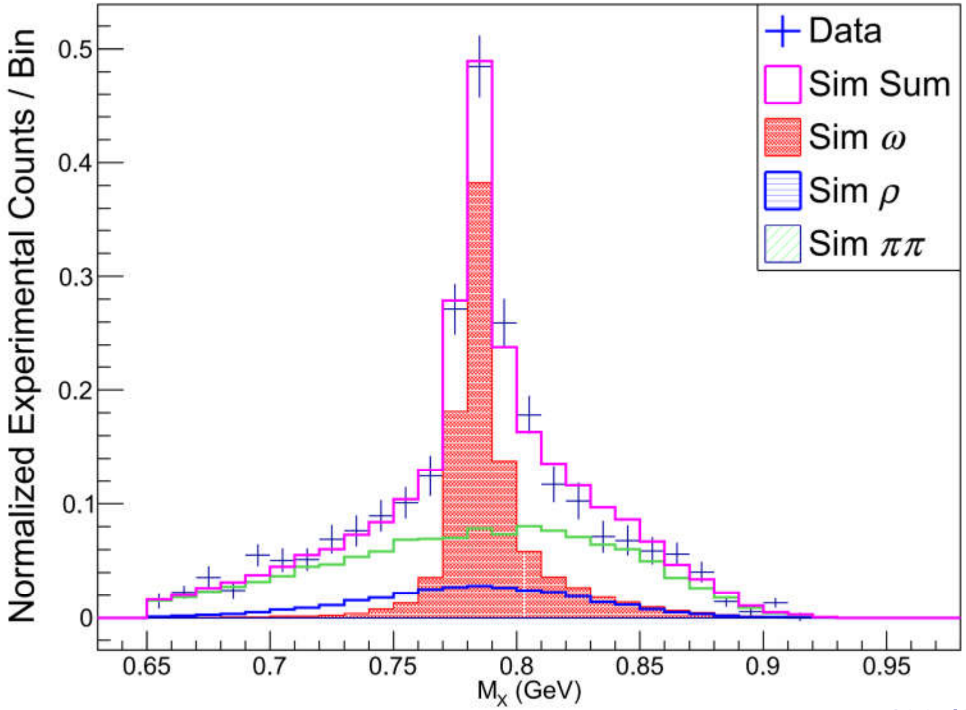
JLAB Hall C: 2.6 - 5.2 GeV electron beam on a liquid hydrogen target

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

- Q^2 = 1.60 and 2.45 GeV^2
- <W> = 2.21 GeV

Missing mass of ep → e′pX:

➔ Clear signal from backward regime for *ep →e′pω*

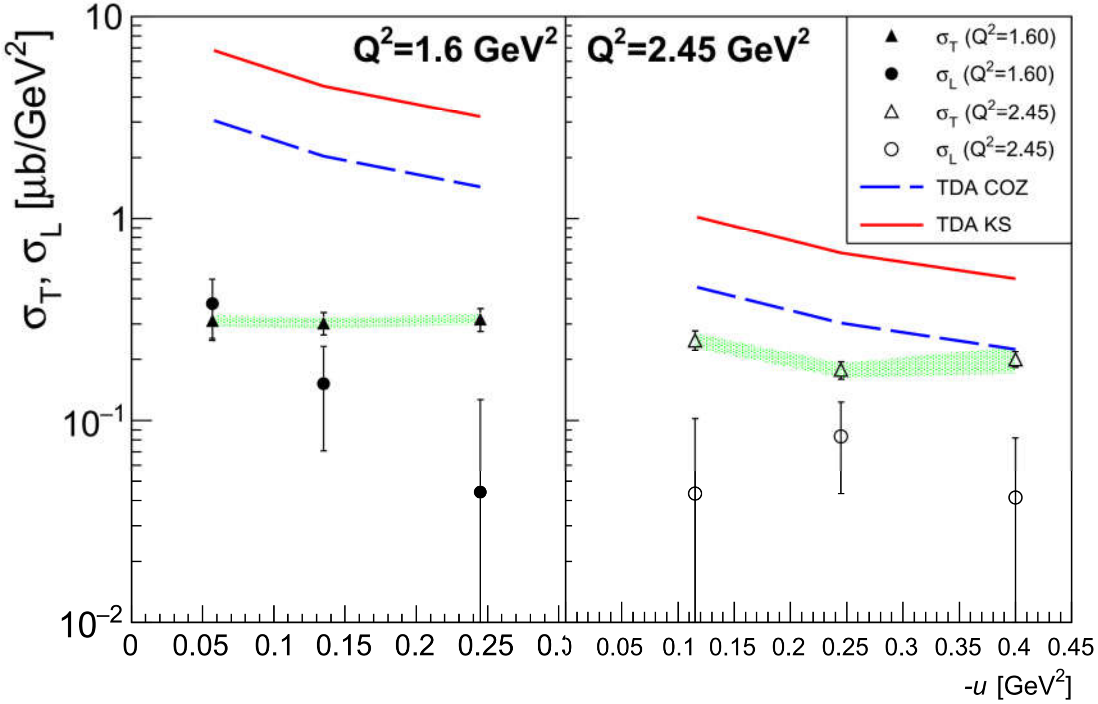


W. B. Li et al. PRL 123 (2019)

Backward ω production in hall C at JLAB

$$\frac{d^2\sigma}{dt} = \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt}$$

➔ 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)

Theory: Cross-channel nucleon exchange model for p→ω TDAs

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:

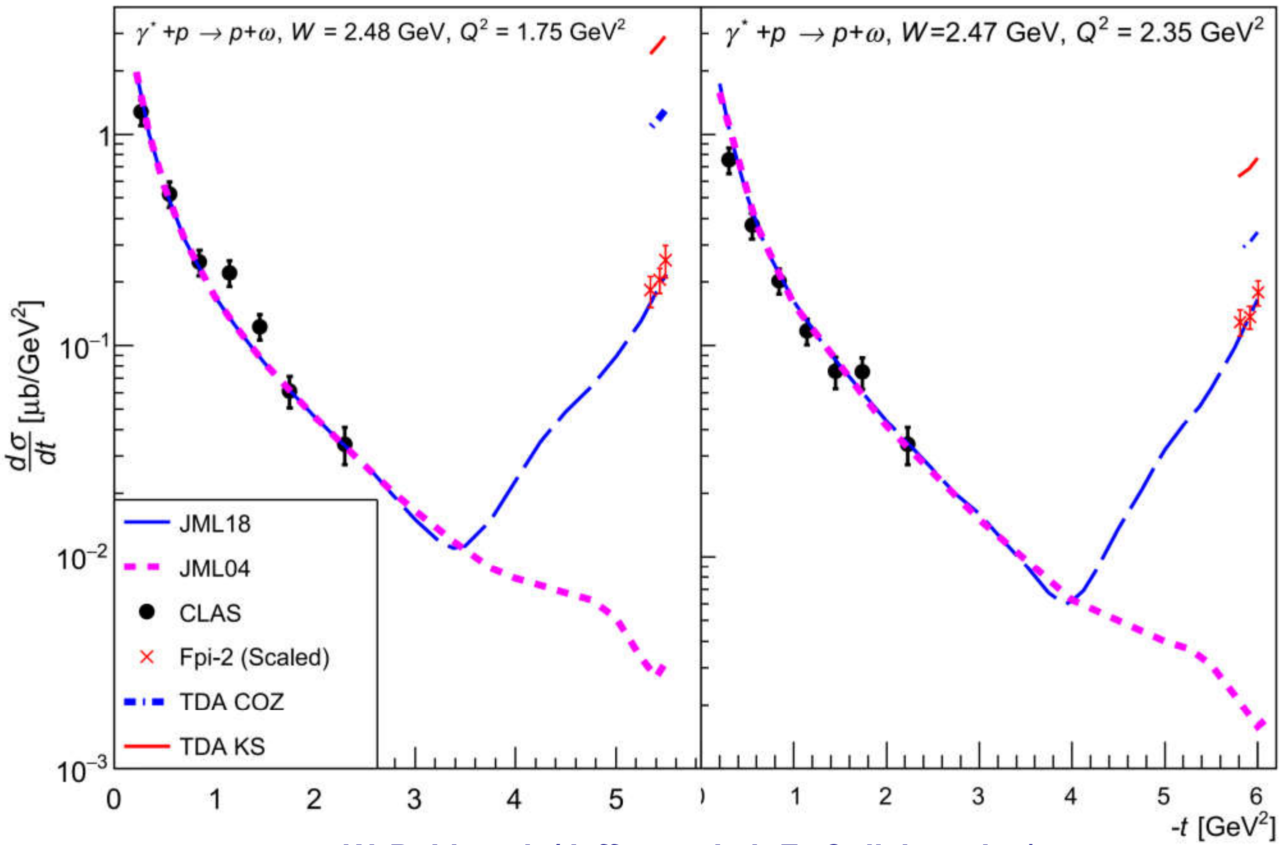
$\sigma_L/\sigma_T < \mu^2/Q^2$

and $\sigma_T \gg \sigma_L$

Backward ω production in hall C at JLAB

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)

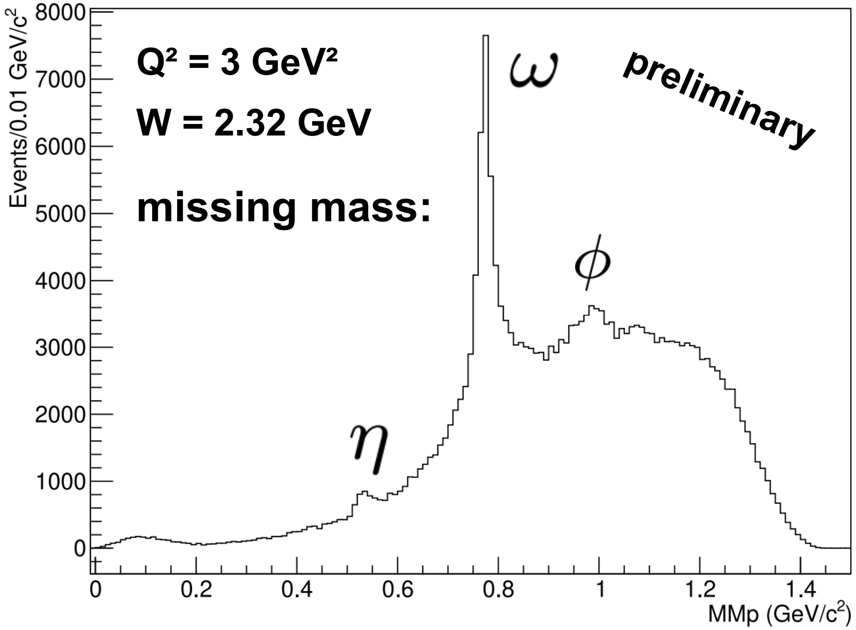
Perspectives for hall C

- Additional data was recorded in hall C with the KaonLT experiment

  → Parallel recording of $p(e,e'p)X$

u-channel ϕ: Access to $s\bar{s}$ content of the nucleon

- More data from the PionLT experiment (Q^2 = 8.5 GeV²)



C. Ayerbe Gayoso et. al, Progress and Opportnities in Backward angle (u-channel) Physics, accepted by Eur. Phys. J. A

JLAB experiment E12-0-007: Approved by PAC 48 for hall C

spokespersons: W. Li, J. Stevens, G. Huber

→ First dedicated u-channel experiment

→ Study of the TDA framework by probing ${}^1\mathrm{H}(e,e'p)\pi^0$ exclusive electroproduction

$$W = 3.1\ \mathrm{GeV}\ (s = 10\ \mathrm{GeV}^2) \qquad 2 < Q^2 < 6.25\ \mathrm{GeV}^2$$

Perspectives for CLAS12

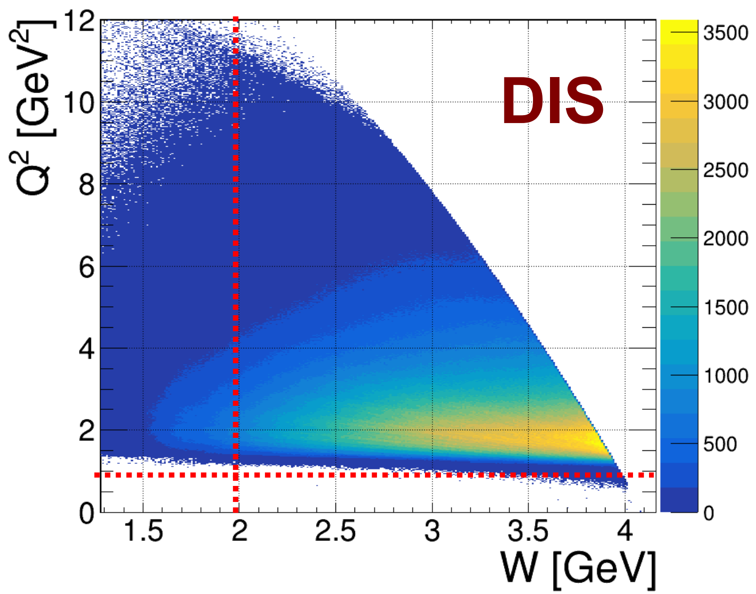
- CLAS 12 can access the TDA regime for the following reactions:

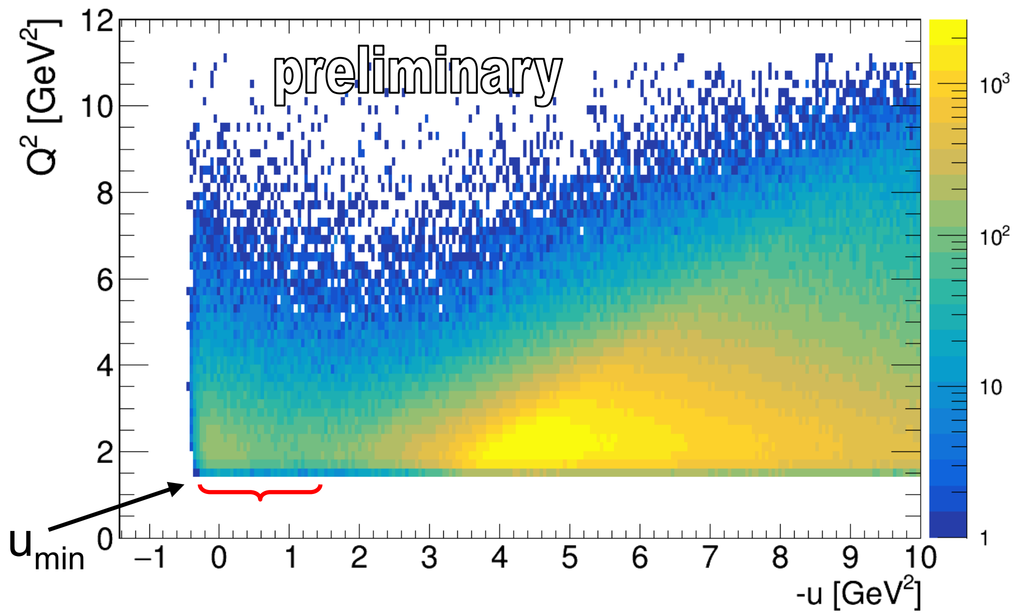
RG-A + RG-K: $ep \rightarrow e' n \pi^+$ $ep \rightarrow e' p \rho$ $(ep \rightarrow e' p \omega)$ $(ep \rightarrow e' p \phi)$

RG-B: $en \rightarrow e' p \pi^-$ **upcoming RGs:** polarized targets

➔ A significant amount of data has already been recorded and is currently in the analysis phase (BSA and all cross section terms)

Example: CLAS12 kinematic coverage of $ep \rightarrow e' \pi^+ (n)$



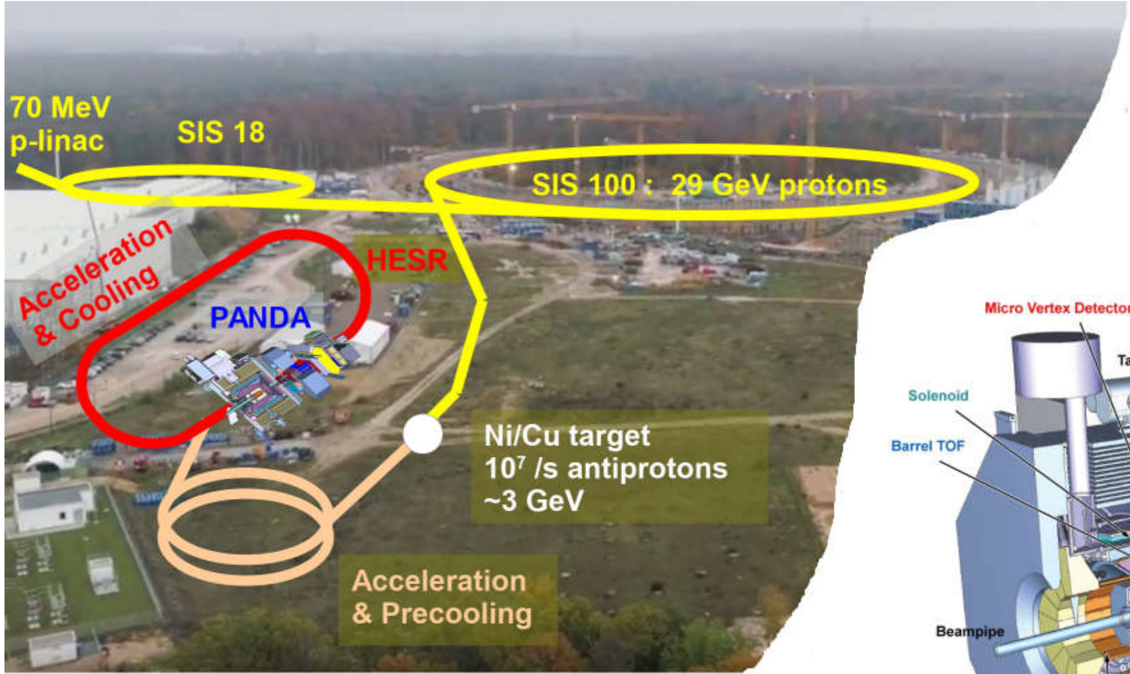


Summary of the TDA program status at JLAB

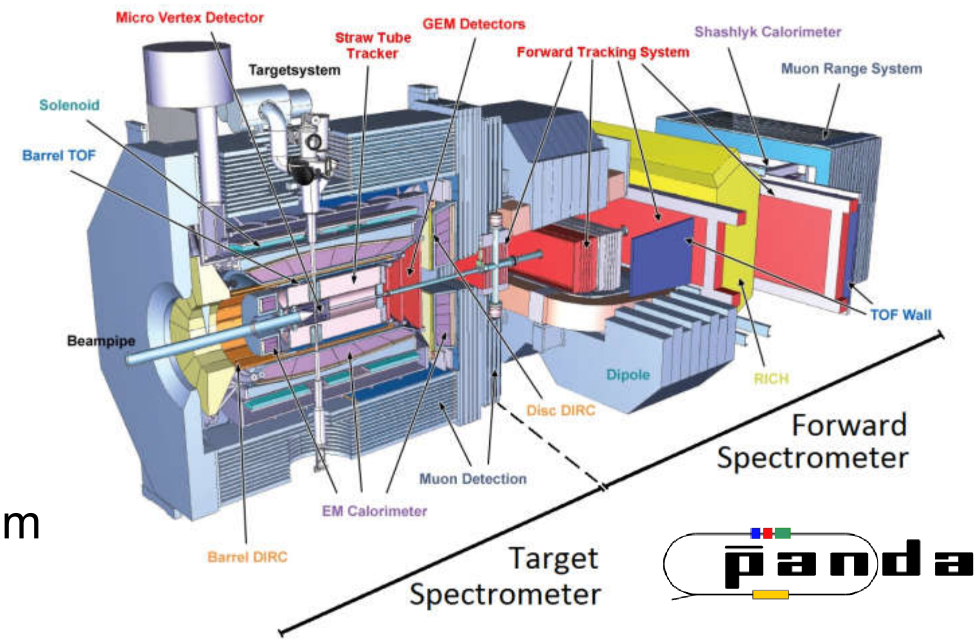
	$\sigma_T > \sigma_L$	$1/Q^8$ Scaling	
π^0	○	○	hall C
π^+	✓	✓✓	CLAS / CLAS12
π^-		✓	CLAS12
K^0			
$K^\pm$			
η	✓	✓	hall C
ρ	✓	✓	CLAS12
ω	✓✓	✓	hall C / CLAS12?
η'	✓	✓	hall C
ϕ	✓	✓	hall C
VCS	△	△	hall C

○: experiment approved
△: in the early planning stage
✓: parasitic data may be available
✓✓: confirmed by existing data

TDA measurements with the future PANDA detector at FAIR



start of operation ~ 2026



- 1.5 GeV/c – 15 GeV/c antiproton beam
- cluster jet / pellet target
- L = 2 10^{32} $cm^{-2}s^{-1}$

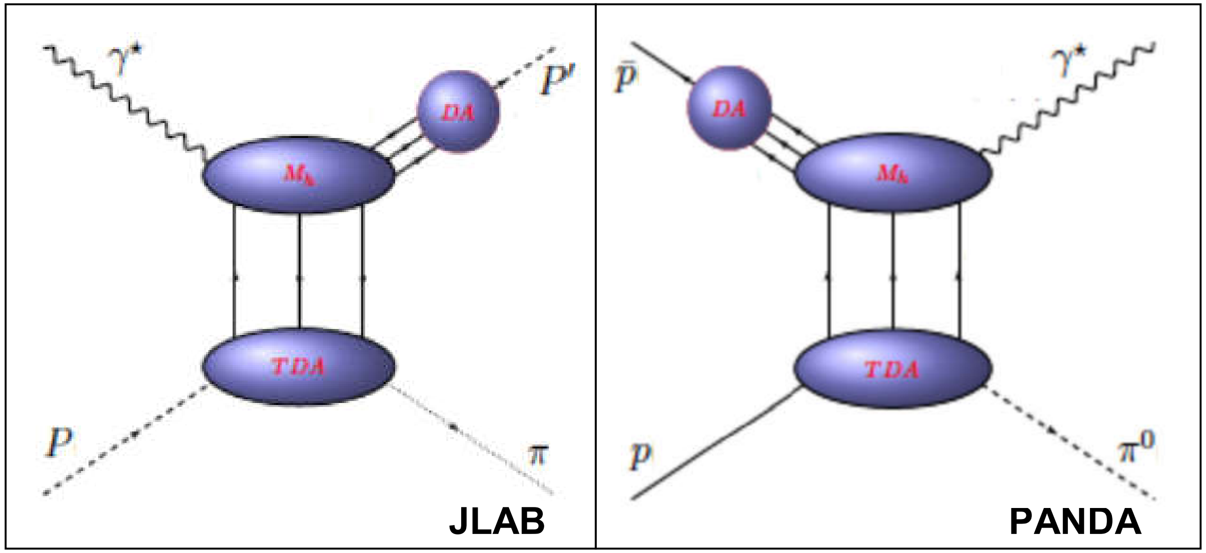
- Barrel with endcaps and forward spectrometer
- ~ 4π coverage

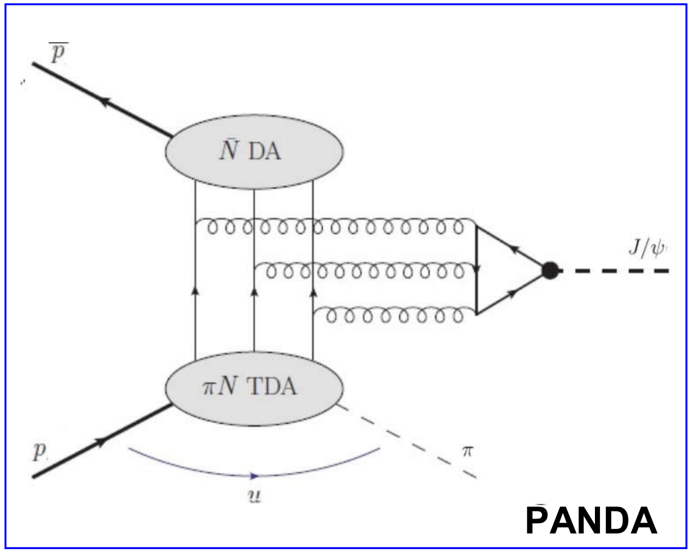
TDA measurements with the future PANDA detector at FAIR

TDAs also occur in the 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

➔ Check for the universality of TDAs

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

TDA measurements with the future PANDA detector at FAIR

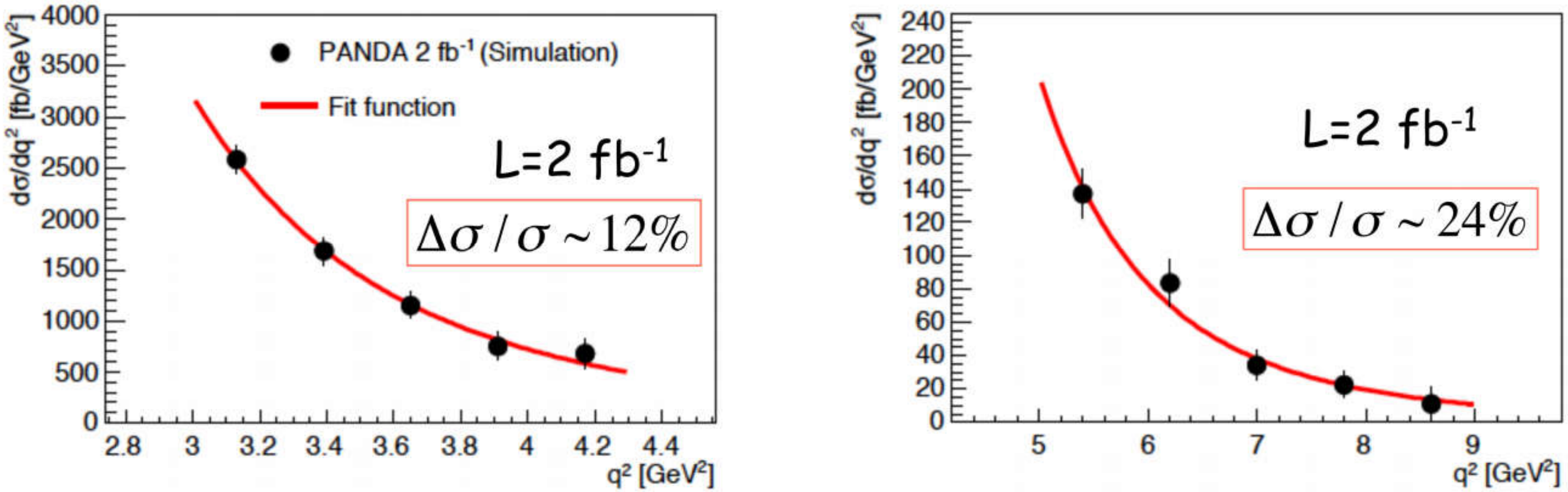
$$\bar{p}p \rightarrow \gamma^{*}\pi^{0} -> e^{+}e^{-}\pi^{0}$$

$$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}t\ \mathrm{d}q^2\ \mathrm{d}\cos\theta_\ell^*}\right|_{\text{Leading twist}} = \frac{K}{s-4M^2}\frac{1}{(q^2)^5}(1+\cos^2\theta_\ell^*)$$

$$\frac{d\sigma}{dq^2} \sim \frac{1}{(q^2)^5}$$

➔ q^2 scaling of the cross section is a test for the QCD factorisation

s = 5 GeV² **s = 10 GeV²**



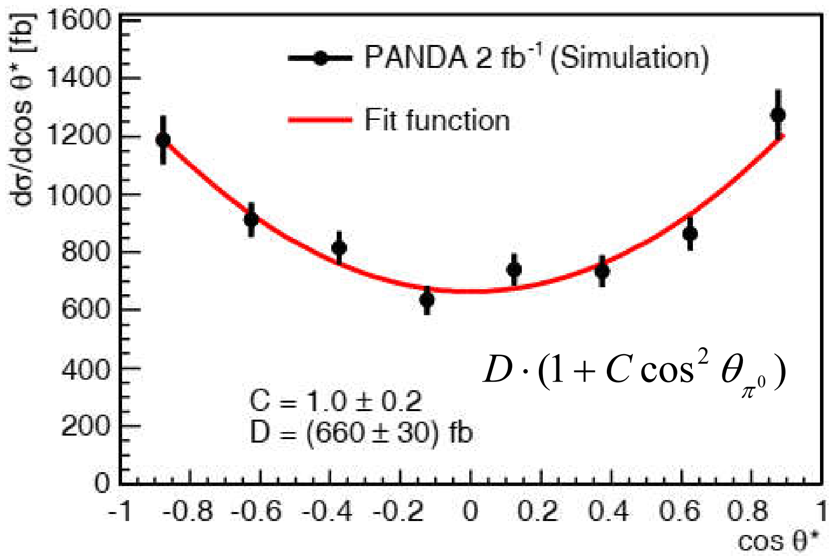
Eur.Phys.J. A51 (2015) 8, 107

TDA measurements with the future PANDA detector at FAIR

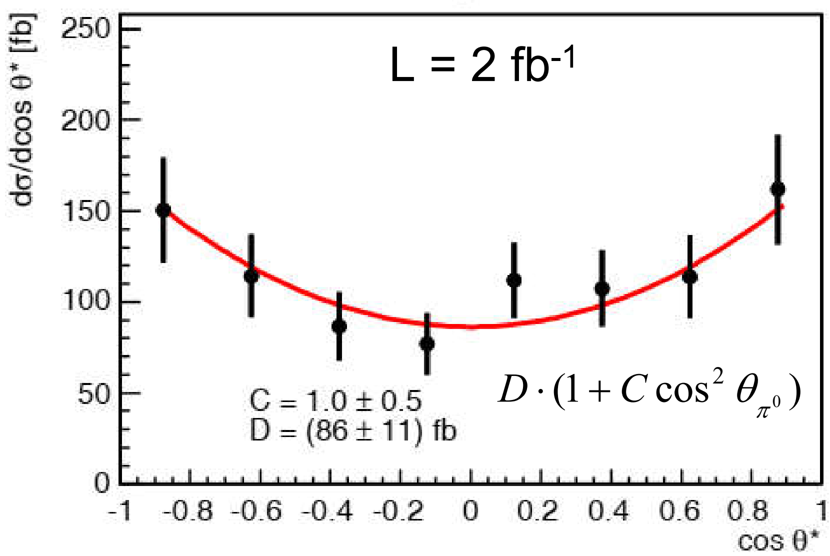
$$\frac{d\sigma}{dq^2} \sim (1 + \cos^2 \theta_\ell^*)$$

➔ Test of the dominance of the transverse polarisation of the virtual photons

s = 5 GeV²



s = 10 GeV²



➔ Very clean signal (S/B > 10)

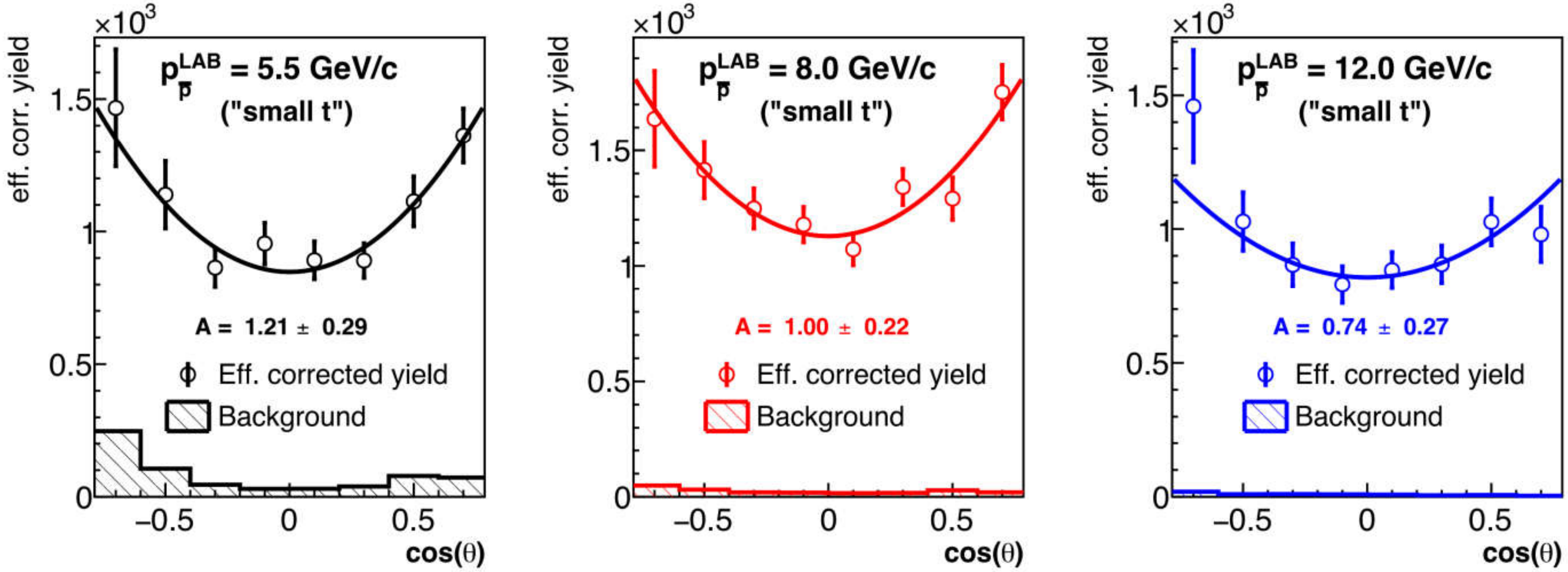
Eur.Phys.J. A51 (2015) 8, 107

TDA measurements with the future PANDA detector at FAIR

$$\bar{p}p \rightarrow J/\Psi \ \pi^0 \rightarrow e^+e^-\pi^0$$

$$\frac{d\sigma}{dq^2} \sim (1 + \cos^2\theta^*_\ell)$$

L = 2 fb^{-1}

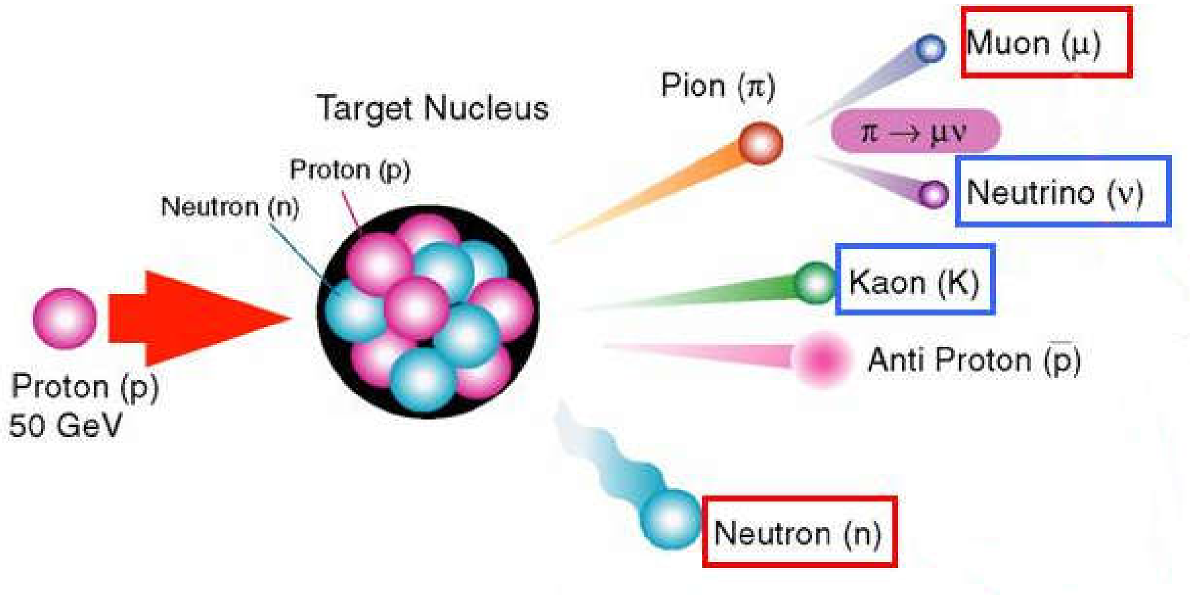


$$\Delta\sigma(t,u)/\sigma(t,u) \sim 5\% - 10\%$$

Eur.Phys.J. A51 (2015) 8, 107

Opportunities for TDA measuremets at JPARC

J-PARC: Intense pion and kaon beams with p = 10 – 20 GeV/c



- **Different opportunities for TDA studies**

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

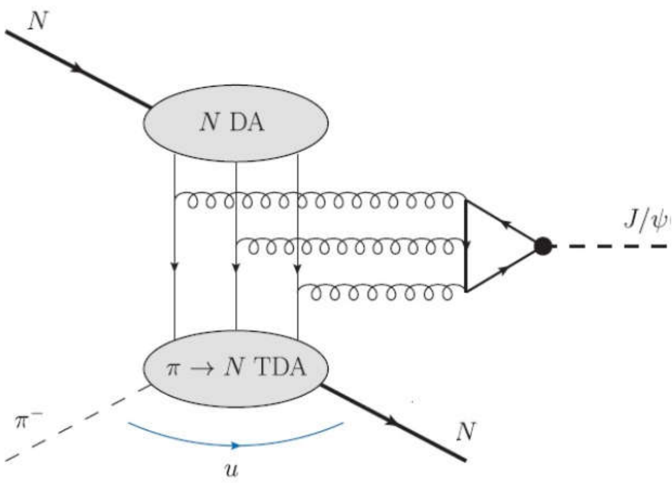
J.P. Lansberg et al. (2012)

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

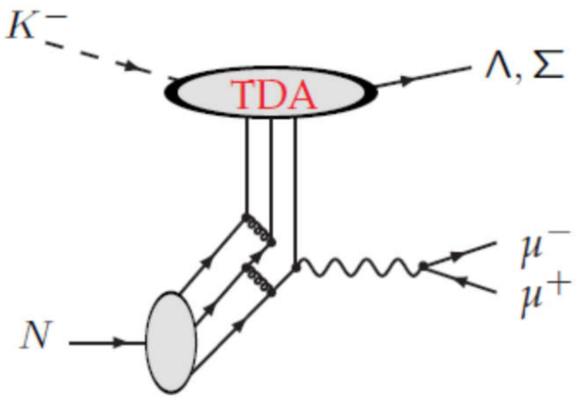
Opportunities for TDA measuremets at JPARC

- Charmonium production in association with a nucelon
- Hyperon production in assoziation with a virtual photon
- Antiproton annihilation

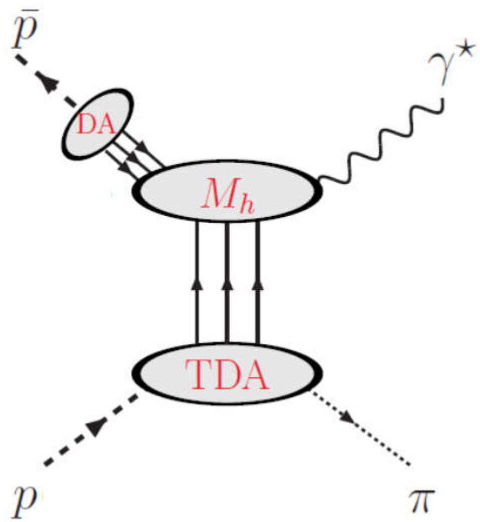
$\pi^- p \to n + J/\psi$



$K^- N \to \Lambda\gamma^*$



$\overline{p}N \to \gamma^* \pi$



➔ Check for the universality of TDAs

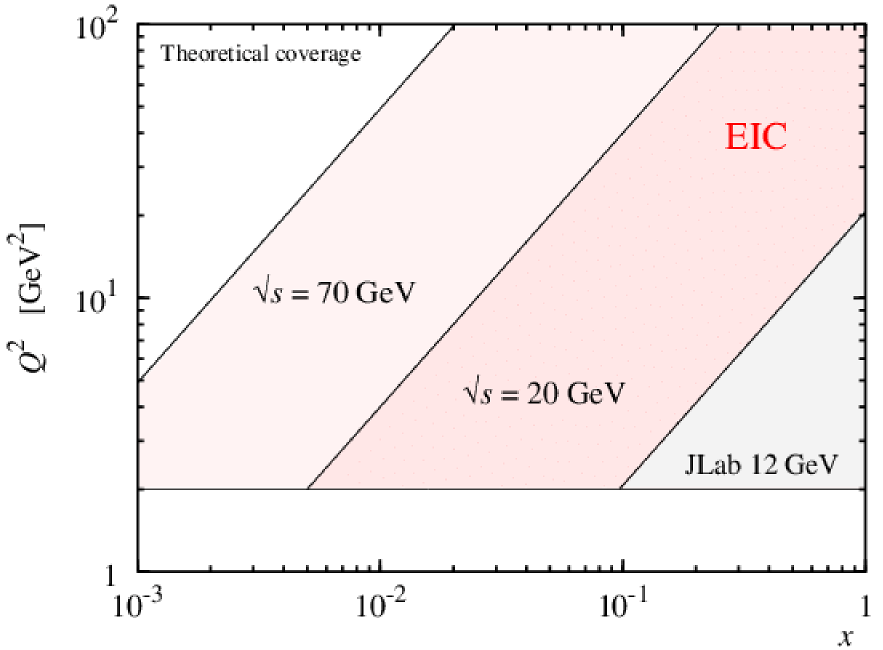
see PANDA

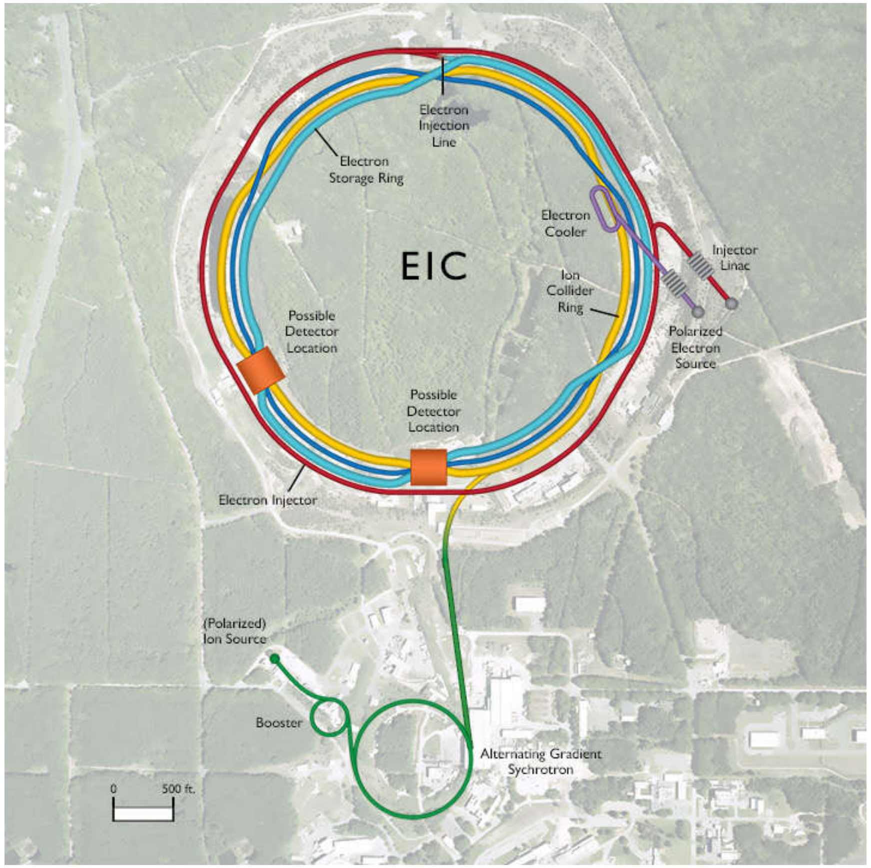
Opportunities for TDA measuremets at the EIC

electron – proton and

electron – ion collisions

with up to 18 GeV/c x 275 GeV/c





➔Extension of the TDA program into the high energy, high Q^2 regime

➔ Access to heavy (charmed) mesons

Opportunities for TDA measuremets at the EIC

First feasability studies for

$$e + p \rightarrow e' + p' + \pi^0$$

➔ Can be well measured in u-channel kinematics

- 4π coverage of the EIC detector

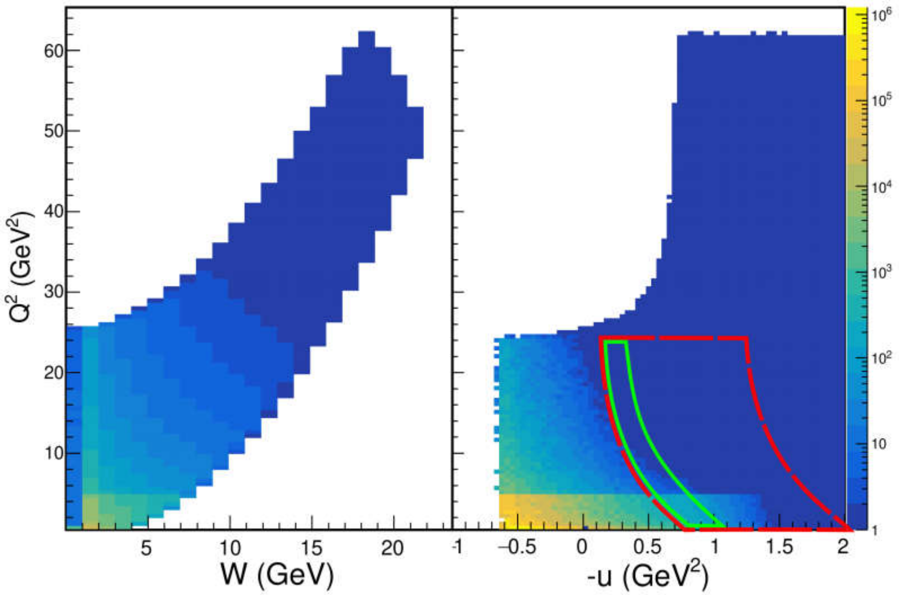
- capability for forward proton tagging

➔ Also the backward production of

$$e + p \rightarrow e' + p' + \omega$$

has been found to be feasable

accessible kinematics for 5 x 100 GeV colissions:



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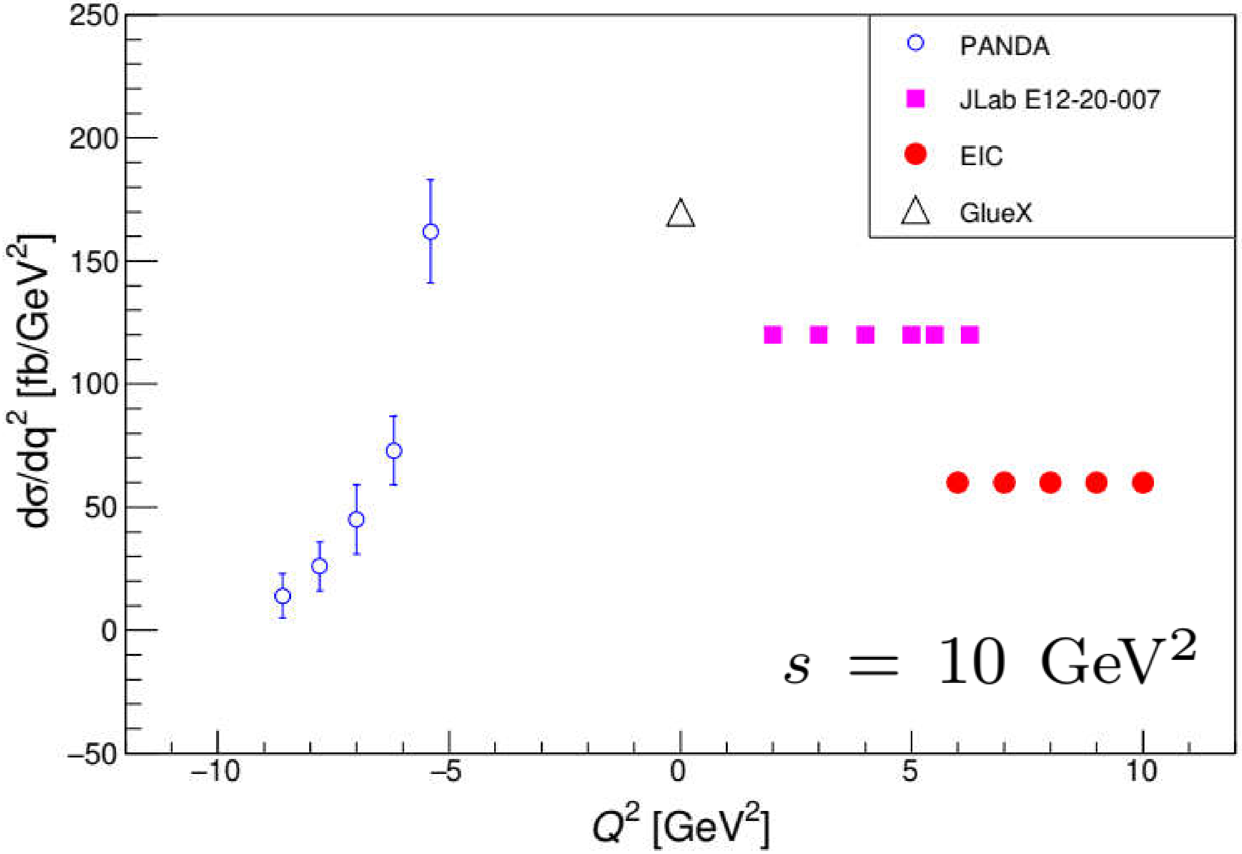
➔ More channels like the exclusive J/Ψ and Y meson production are under investigation for the different detector proposals

Expected global dataset for u-channel π^0 production

$$e + p \rightarrow e' + p' + \pi^0 \quad \text{for} \quad u \sim u_{\text{min}}$$



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Summary and Outlook

- Nucleon-to-meson TDAs provide new information about correlations of partons inside the nucleon
- 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
- JLAB 12 GeV data will provide more detailed measurements in the TDA regime
- PANDA and J-PARC will allow a check of the universality of TDA
- The EIC will enable an extension of the JLAB program to higher energies and higher Q^2

Progress and Opportunities in Backward angle (u-channel) Physics

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