Exploring the 3D Structure of Baryon Resonances with Transition Generalized Parton Distributions

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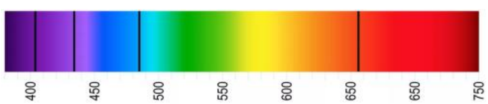
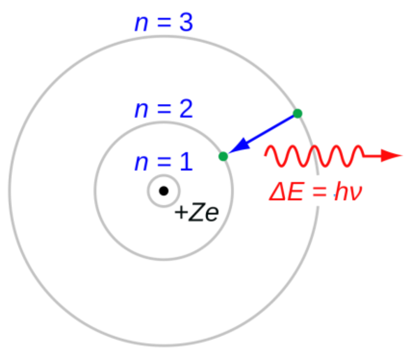
Introduction

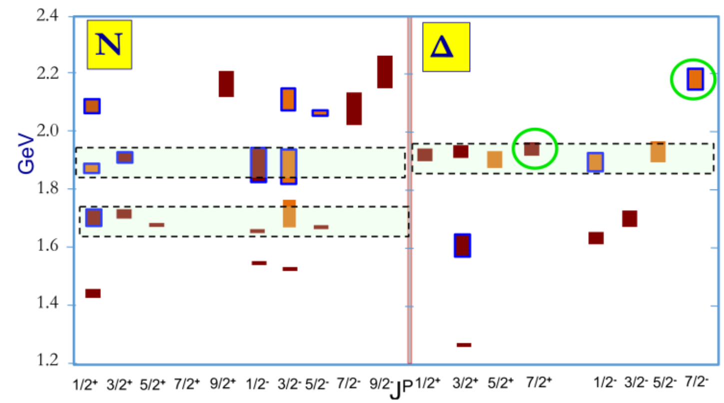
- Baryons and their resonances are emergent phenomena of QCD
- Elementary QCD dynamics expressed in spectrum and structure of the hadronic states

  ➔ Both aspects are essential for a complete understanding of strong interactions

- Connection between the internal motion and the excitation spectrum:







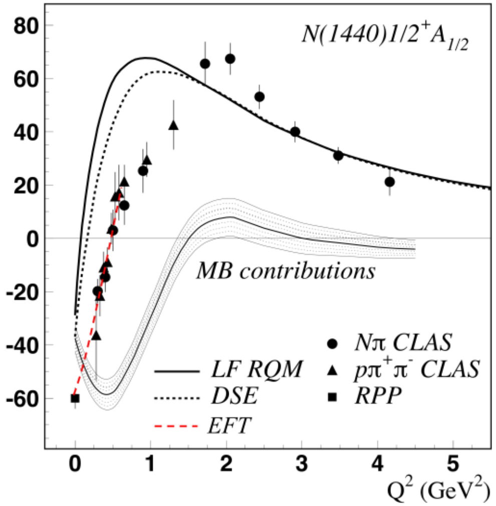
➔ A rich spectrum of baryon resonances emerges from QCD

- <u>Baryon resonances play an important role:</u>
  - Behavior of matter at high densities and temperatures (early universe, stellar structure)
  - Existence of hypothetical strange matter (neutron stars)
  - Theory of nuclear forces (*e.g.* the Δ isobar)
  - Decription of neutrino interactions with nuclei at a few GeV

➔ **Understanding the internal structure of the baryon resonances is of fundamental interest and practical importance**

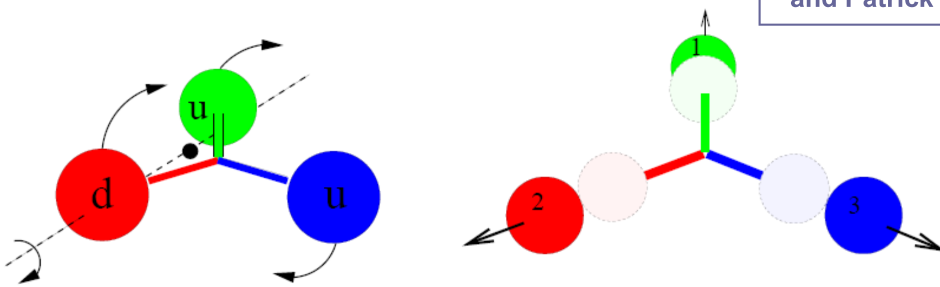
Introduction

Electroproduction experiments: Information on the structure of baryon resonances from **electromagnetic transition form factors**

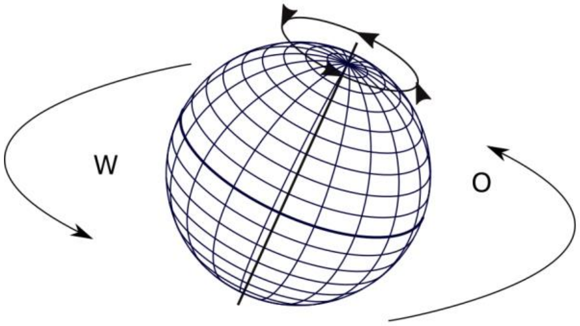


➔ Spatial (2D) distribution of charge and current in dynamical systems

talks by Victor Mokeev and Patrick Achenbach



source: www.prosieben.de/serien/galileo

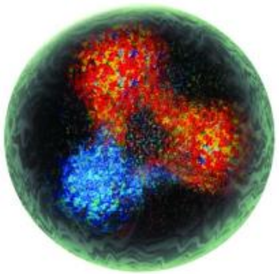


source: www.weltkugel-globus.de/die-erde

- **Not all phenomena can be explained in a 2D picture**

$$L \sim \mathbf{r} \times \mathbf{p}$$

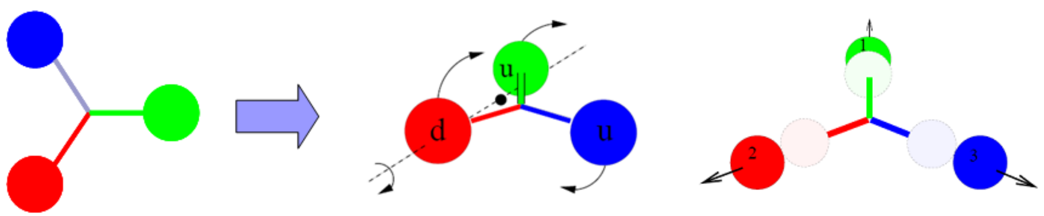
Generalized Parton Distributions (GPDs)

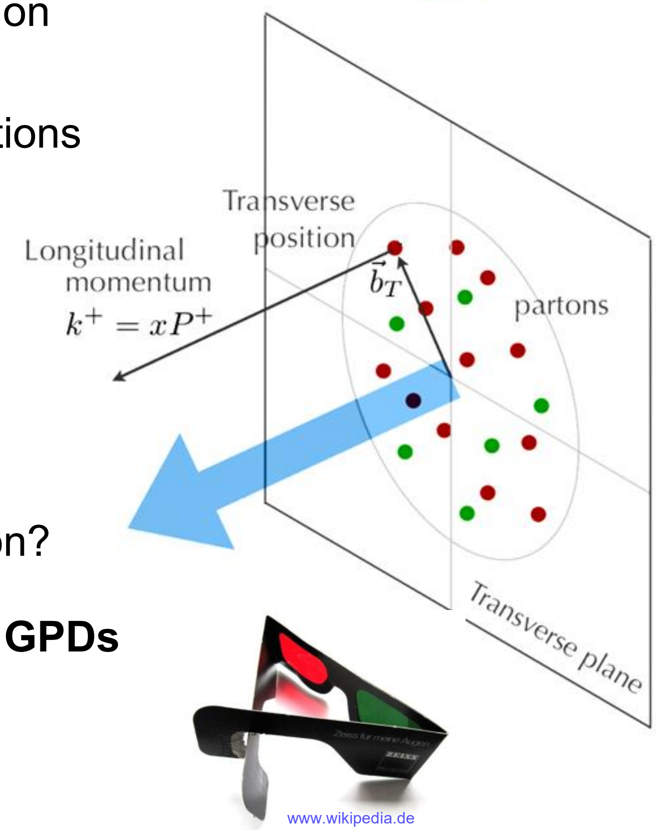


- Significant advances in the study of the ground-state nucleon structure over the last two decades
- **Generalized Parton Distributions (GPDs)** connect the transverse position and the longitudinal momentum space

  ➔ Unification of elastic nucleon form factors and quark/gluon particle densities (PDFs)

  ➔ 3D tomographic images of the quark and gluon distributions + Access to the mechanical properties of the nucleon





How does the excitation affect the 3D structure of the nucleon?

<u>**3D picture** of the excitation process:</u> Encoded in **transition GPDs**

➔ Characterisation of baryon resonance structure based on quark/gluon tomography

Transition GPDs for the N→Δ Transition

N→Δ transition: 16 transition GPDs

• **8** twist-2 **helicity non-flip** transition GPDs

unpolarized:

$$\int_{-1}^{1} dx G_1(x;\xi;t) \propto G_M^*(t),$$
$$\int_{-1}^{1} dx G_3(x;\xi;t) \propto G_C^*(t),$$
$$\int_{-1}^{1} dx G_2(x;\xi;t) \propto G_E^*(t),$$
$$\int_{-1}^{1} dx G_4(x;\xi;t) = 0,$$

} Jones-Scardon EM FF for the N → Δ transition

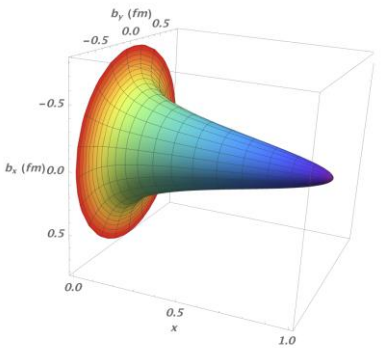
polarized:

$$\int_{-1}^{1} dx \widetilde{G}_1(x;\xi;t) \propto C_5^A(t)$$
$$\int_{-1}^{1} dx \widetilde{G}_3(x;\xi;t) \propto C_3^A(t)$$
$$\int_{-1}^{1} dx \widetilde{G}_2(x;\xi;t) \propto C_6^A(t)$$
$$\int_{-1}^{1} dx \widetilde{G}_4(x;\xi;t) \propto C_4^A(t)$$

} Adler form factors

+ 8 helicity flip transition GPDs (twist-3, transversity)

Physics Content of Transition GPDs



➔ 3D (x-dependent) imaging of the excitation process

➔ N → N* transition charge / magnetization densities

➔ Transition GPDs connect the spin and angular momentum of resonances to the motion and distribution of the partons within the exited baryon

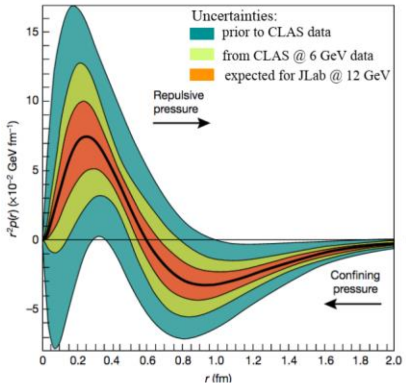
$$\int_{-1}^{1} dx\, x h_M(x,\xi,0) = 2J^{u-d}_{p\to\Delta^+}$$

C. C. Granados, C. Weiss, Phys. Lett. B **797**, 134847 (2019)

J.Y. Kim, H.Y. Won, J. Goity, C. Weiss, Phys.Lett. B **844**, 138083 (2023)

➔ Access to shear forces and pressure distributions within nucleon resonances via gravitational form factors

$$\int dx\ x\ H(x,\xi,t) = M_2(t) + \frac{4}{5}\xi^2 d_1(t)$$



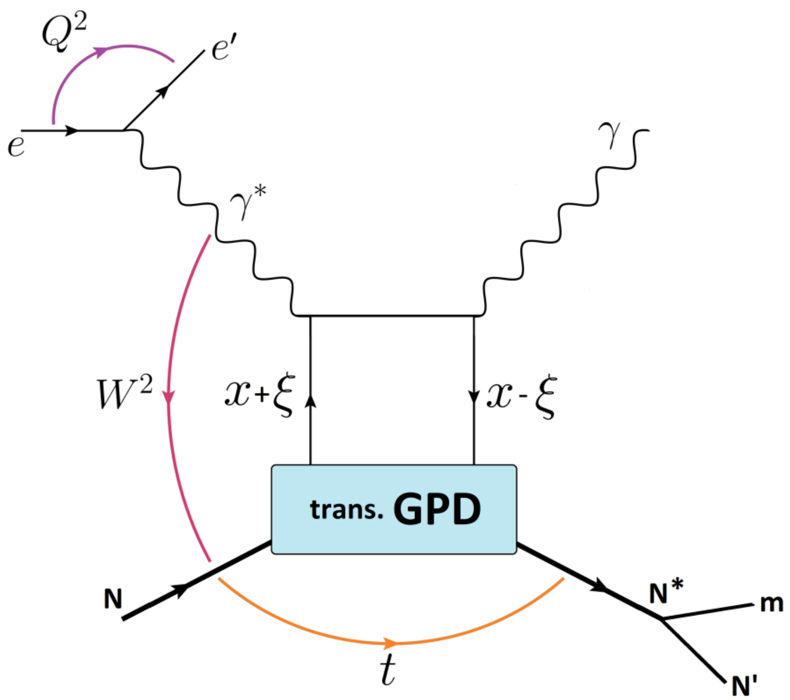
V.D. Burkert, L. Elouadrhiri, F.X. Girod, Nature **557**, 396 (2018)

➔ Access to the anomalous magnetic moment and to the tensor charge of resonance

$$k_T^{u,d} = \int dx \bar{E}_T^{u,d}(x,\xi=0,t=0) \qquad \delta_T^{u,d} = \int dx H_T^{u,d}(x,\xi=0,t=0)$$

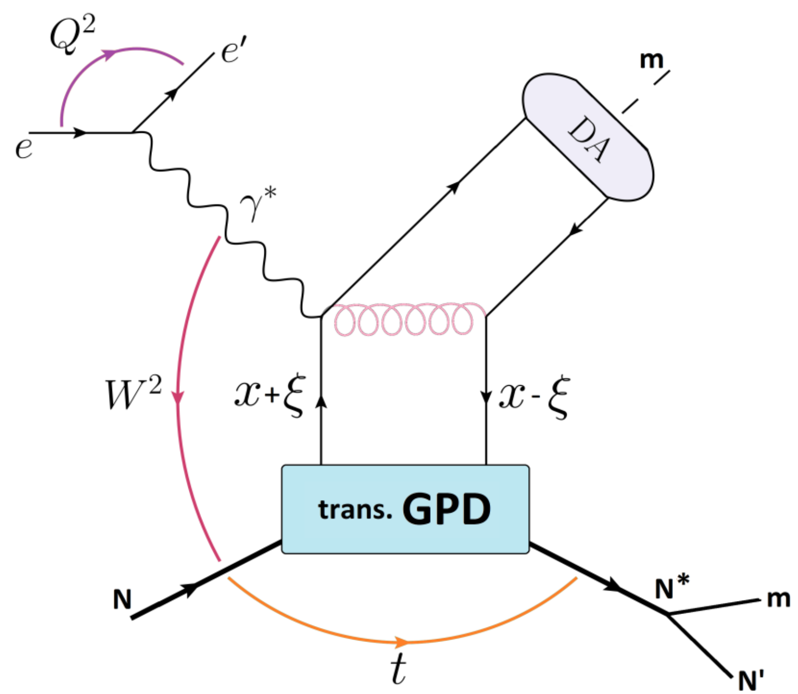
Experimental Access to Transition GPDs

N→N* DVCS



Access to the helicity non-flip transition GPDs

N→N* DVMP



+ Access to the helicity flip transition GPDs

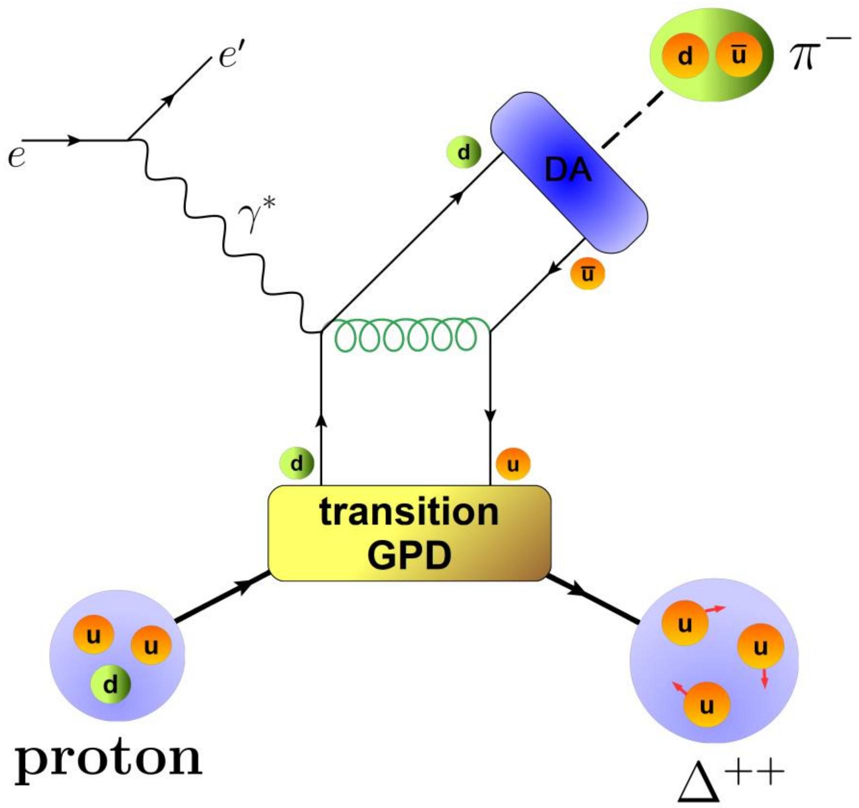
W > 2 GeV

Factorisation expected for: $-t / Q^2 << 1$, x_B fixed and $Q^2 > M^2_{N^*}$

The N →N* DVMP Processes

$$ep \to eN^{*0}\pi^+ \to e(p\pi^-)\pi^+$$
$$\to e(n\pi^0)\pi^+$$

$$ep \to e\Delta^+\pi^0 \to e(n\pi^+)\pi^0$$
$$\to e(p\pi^0)\pi^0$$



$$ep \to e\Delta^{++}\pi^- \to ep\pi^+\pi^-$$

➔ Provides access to the **d-quark** content of the nucleon

➔ Provides acess to **p-Δ transition GPDs**

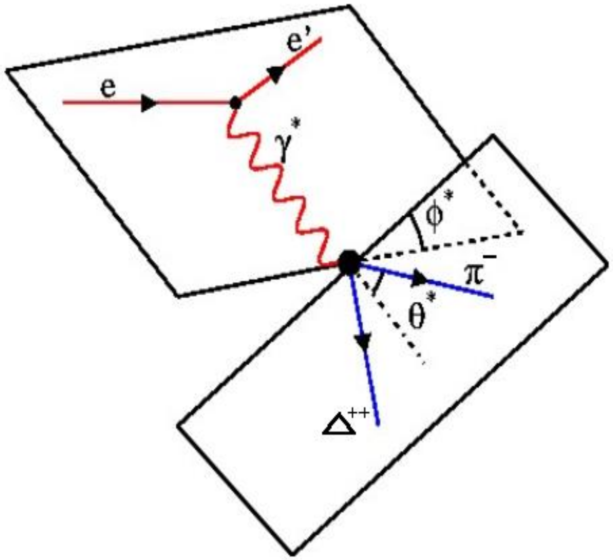
Peter Kroll, Kornelija Passek-Kumerički, Phys. Rev. D 107, 054009 (2023)
https://doi.org/10.1103/PhysRevD.107.054009

S. Diehl et al. (CLAS Collaboration), Phys. Rev. Lett. 131, 021901 (2023)
https://doi.org/10.1103/PhysRevLett.131.021901

DVMP Electroproduction Cross-Section and BSA

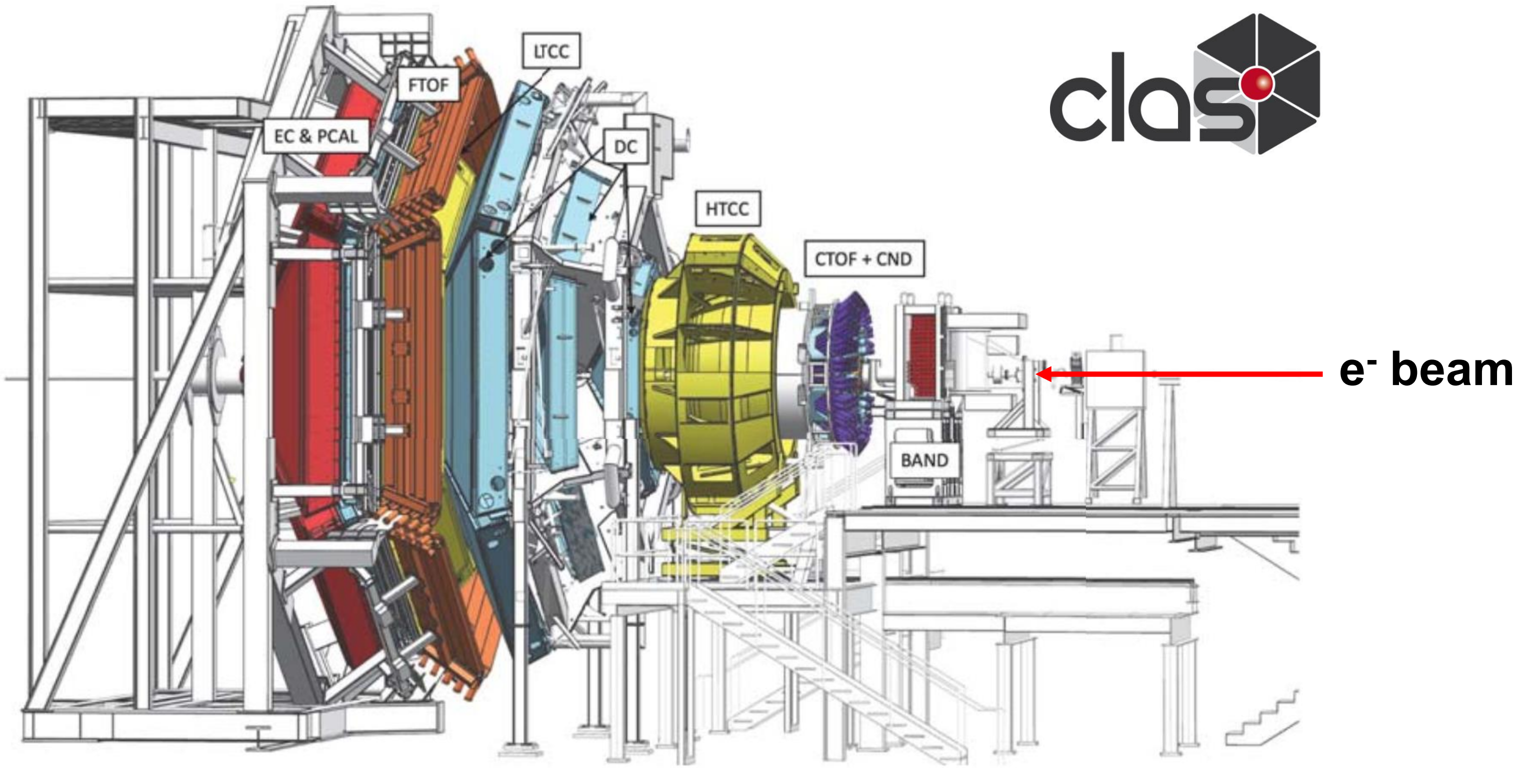
Cross section **(longitudinally pol. beam and unpol. target):**

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



$$BSA(t,\phi,x_B,Q^2) = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} = \frac{\sqrt{2\epsilon(1-\epsilon)} \frac{\sigma_{LT'}}{\sigma_0} \sin\phi}{1 + \sqrt{2\epsilon(1+\epsilon)} \frac{\sigma_{LT}}{\sigma_0} \cos\phi + \epsilon \frac{\sigma_{TT}}{\sigma_0} \cos 2\phi}$$

Experiment: CLAS12 at JLAB



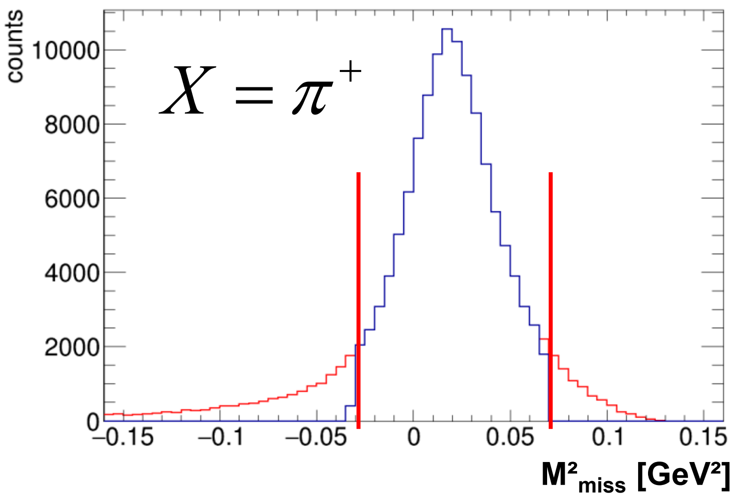
V. Burkert et al., Nucl. Instr. Meth. A 959, 163419 (2020)

➔ Data recorded with CLAS12 during fall 2018 and spring 2019 (RG-A)

- ➔ 10.6 GeV / 10.2 GeV electron beam ~ 86 % average polarization
- ➔ liquid H_2 target

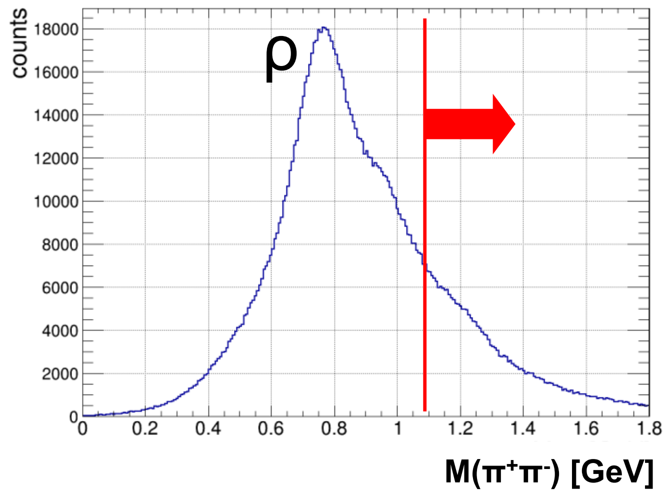
$\pi^-\Delta^{++}$ DVMP: Event Selection and Kinematic Cuts

Event selection: $ep \rightarrow ep\pi^- X$



➔ 2 sigma cut around the missing π^+

BG: $ep \rightarrow ep\rho \rightarrow ep\pi^+\pi^-$



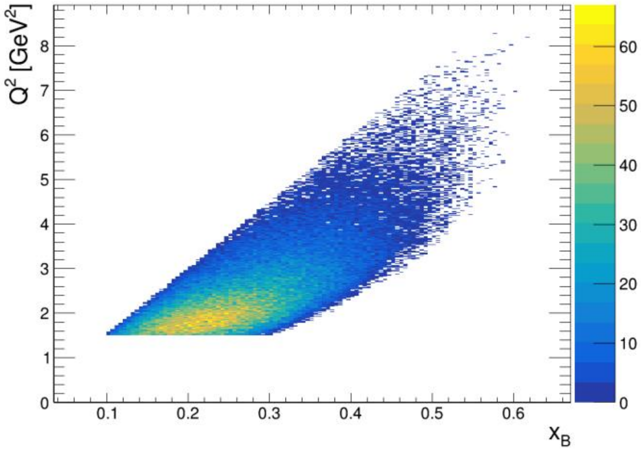
$M(\pi^+\pi^-) > 1.1$ GeV (ρ cont. < 0.8%)

Kinematic cuts:

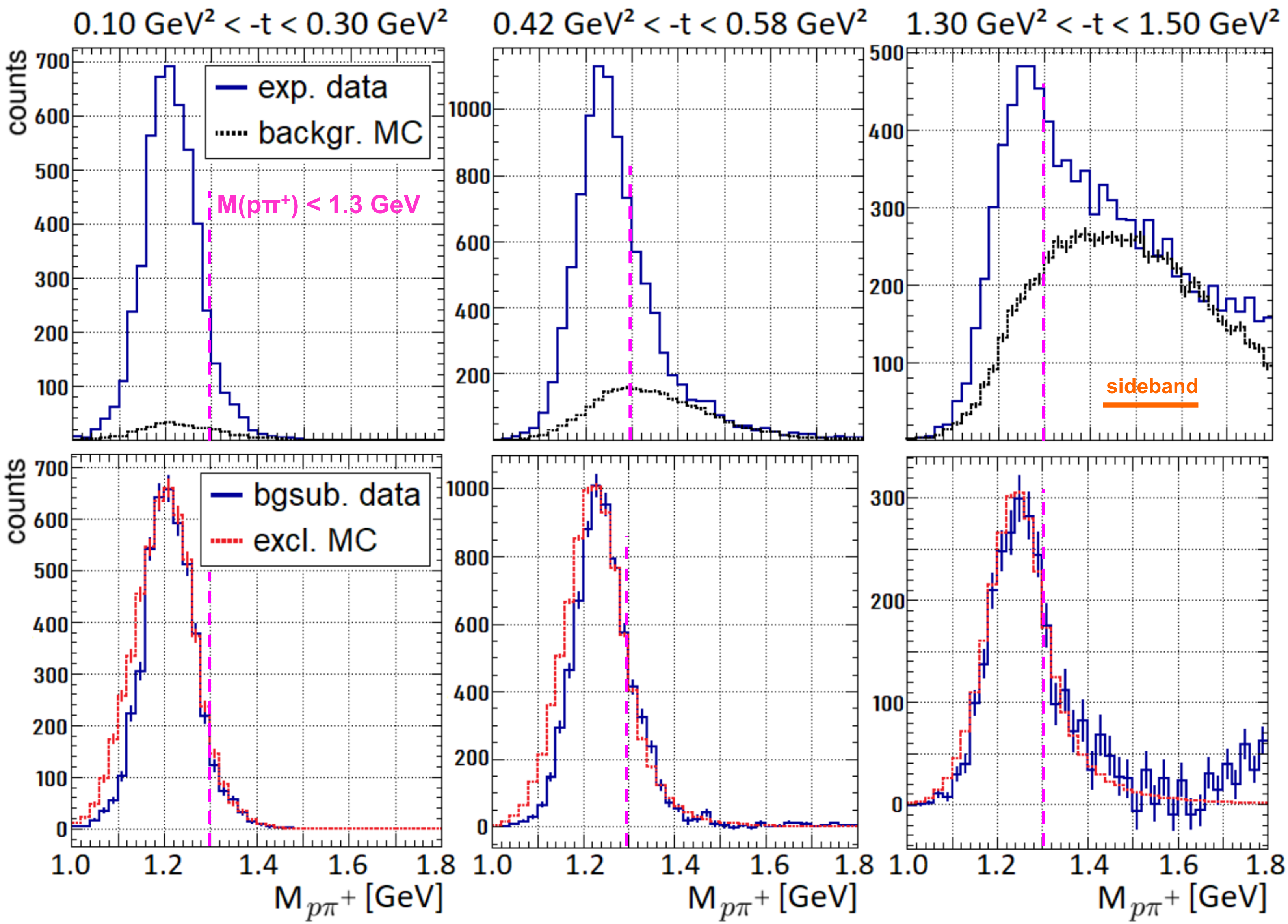
$Q^2 > 1.5$ GeV²

$W > 2$ GeV

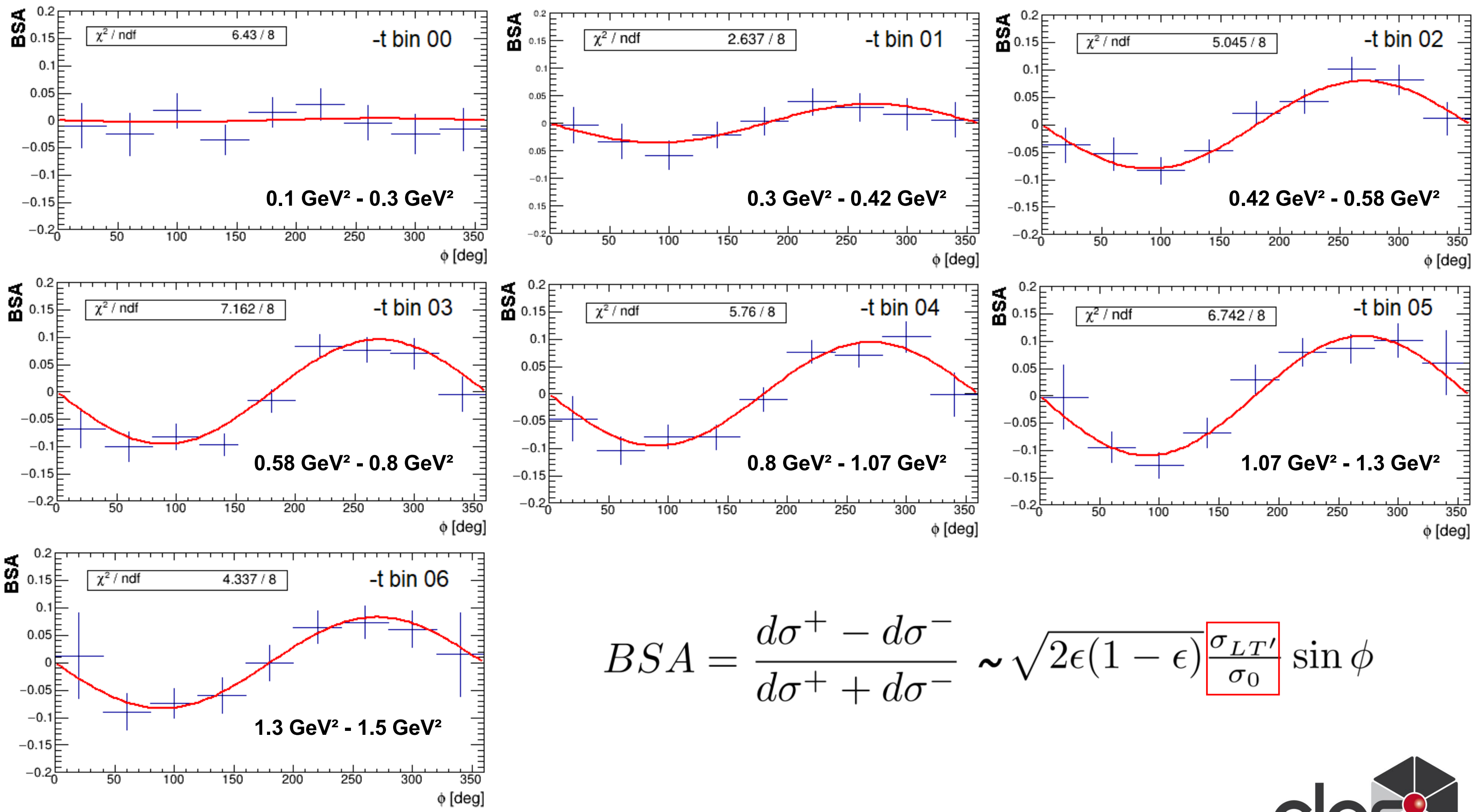
$-t < 1.5$ GeV²



$\pi^-\Delta^{++}$ DVMP: Signal and Background Separation



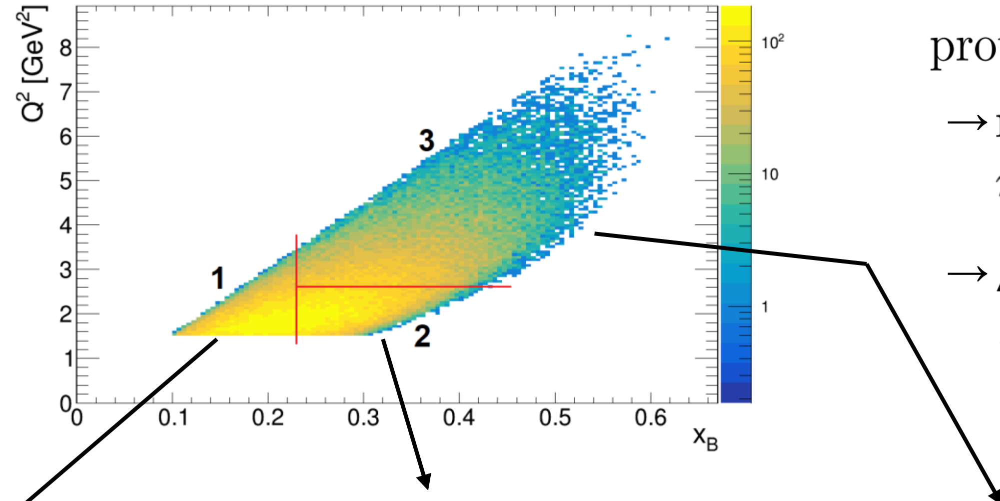
$\pi^- \Delta^{++}$ DVMP: Beam Spin Asymmetries (Q^2-x_B integrated)



$$BSA = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} \sim \sqrt{2\epsilon(1-\epsilon)}\,\boxed{\frac{\sigma_{LT'}}{\sigma_0}}\,\sin\phi$$

$\pi^- \Delta^{++}$ DVMP: Results

S. Diehl et al. (CLAS Collaboration),
Phys. Rev. Lett. 131, 021901 (2023).
https://doi.org/10.1103/PhysRevLett.131.021901



proton (uud)

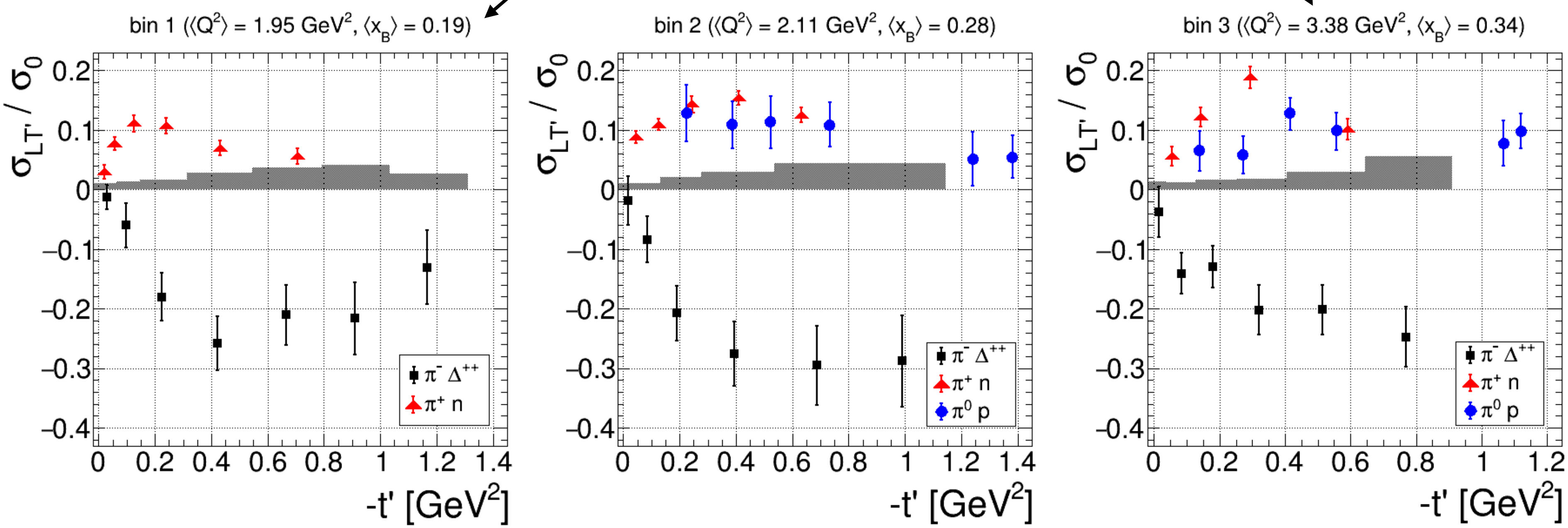
$\rightarrow$ neutron (udd)

$\pi^+ \; (|u\bar{d}\rangle)$

$\rightarrow \Delta^{++} \; (uuu)$

$\pi^- \; (|d\bar{u}\rangle)$

sys. uncertainty

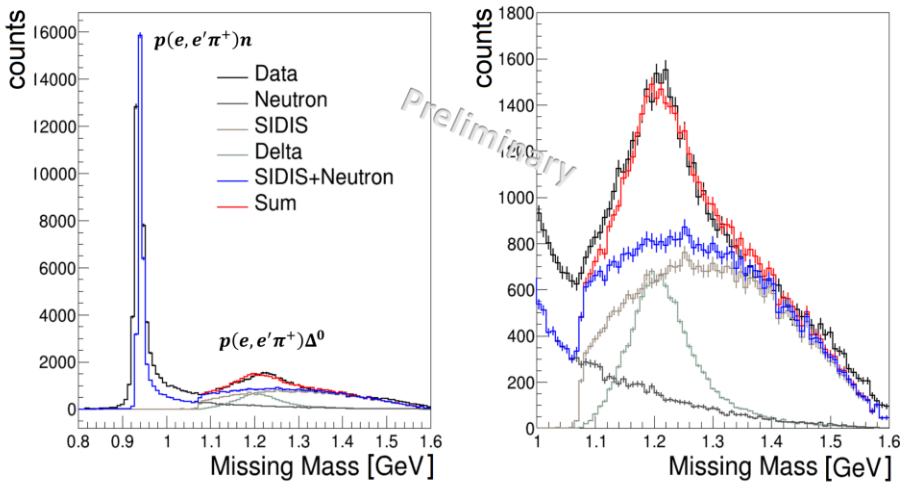


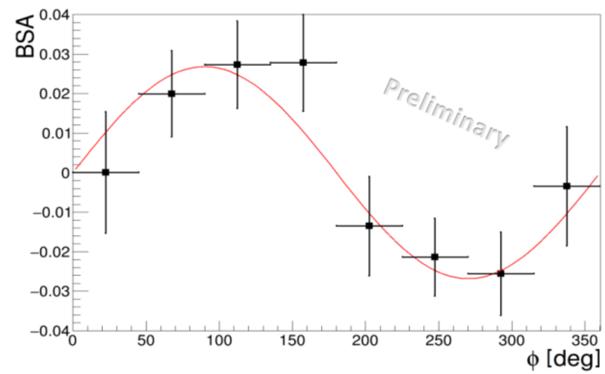
First Results on Other N → N* DVMP Channels

JLAB hall C (high resolution two arm spectrometer): $e'\pi^+\Delta^0$

➔ Electron and π^+ detected, final state reconstructed through missing mass

➔ Capability to perform high Q^2 longitudinal / transverse separation of the cross-section





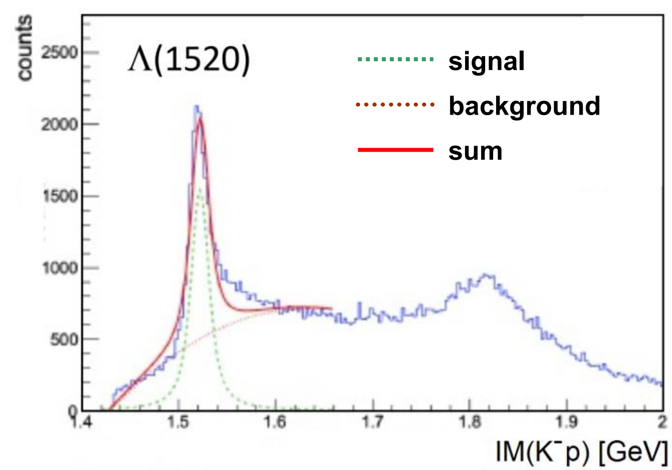
A. Usman (U. Regina)

CLAS12: Hyperon transitions

➔ Access to strange quark chiral-odd GPDs

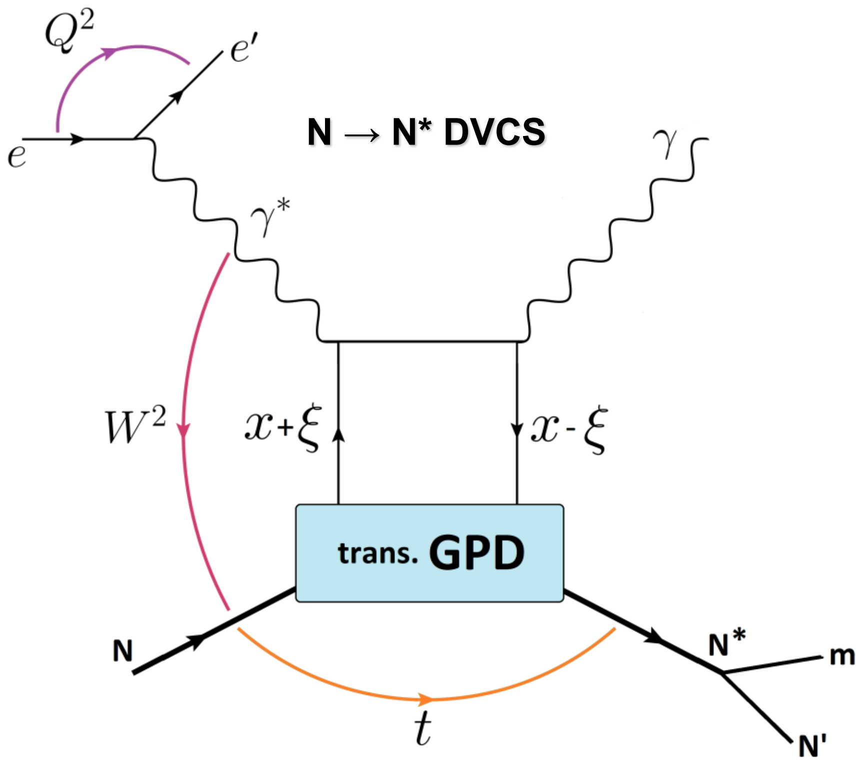
➔ Exclusive e p → e' p K^+ K^- events

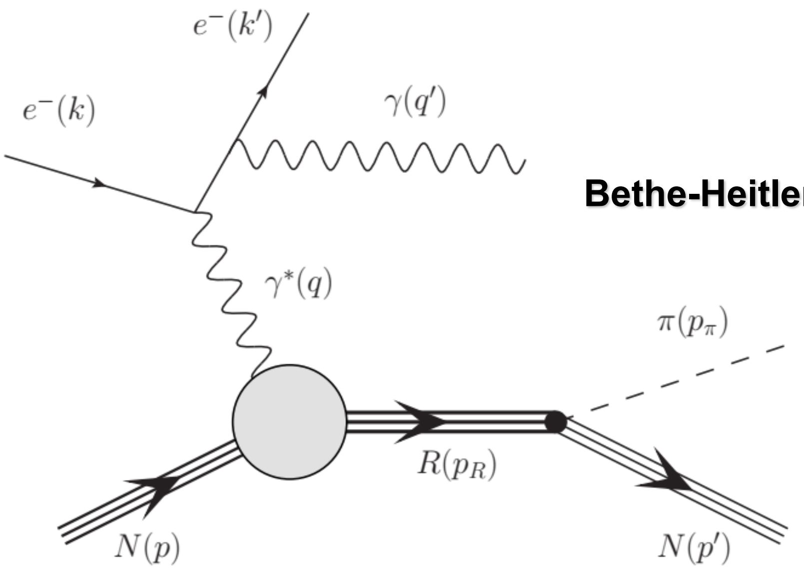
U. Shrestha (UConn)



The N → N* DVCS Process

$$\gamma^* p \rightarrow N^* \gamma \rightarrow N \ meson \ \gamma$$





➔ **Sensitive to twist-2 transition GPDs**

K. M. Semenov-Tian-Shansky, M. Vanderhaeghen, Phys. Rev. D **108**, 034021 (2023)

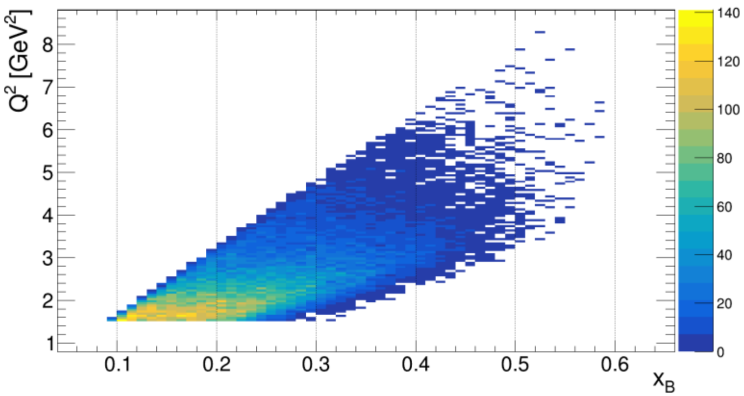
N → N* DVCS: Event Selection

Event selection: **$e\,p \rightarrow e'\,N^{*+}\,\gamma \rightarrow e'\,n\,\pi^{+}\,\gamma$**

- Exclusivity cuts on the missing masses, missing energy, missing transverse momentum and missing cone angle

Kinematic cuts: $W > 2$ GeV $Q^2 > 1.5$ GeV²

$y < 0.8$ $-t < 2$ GeV²



$\langle Q^2 \rangle = 2.47$ GeV² $\langle x_B \rangle = 0.25$

Physics background: $e\,p \rightarrow e'\,n\,\rho^{+} \rightarrow e'\,n\,\pi^{+}\,\gamma$ (very rare)

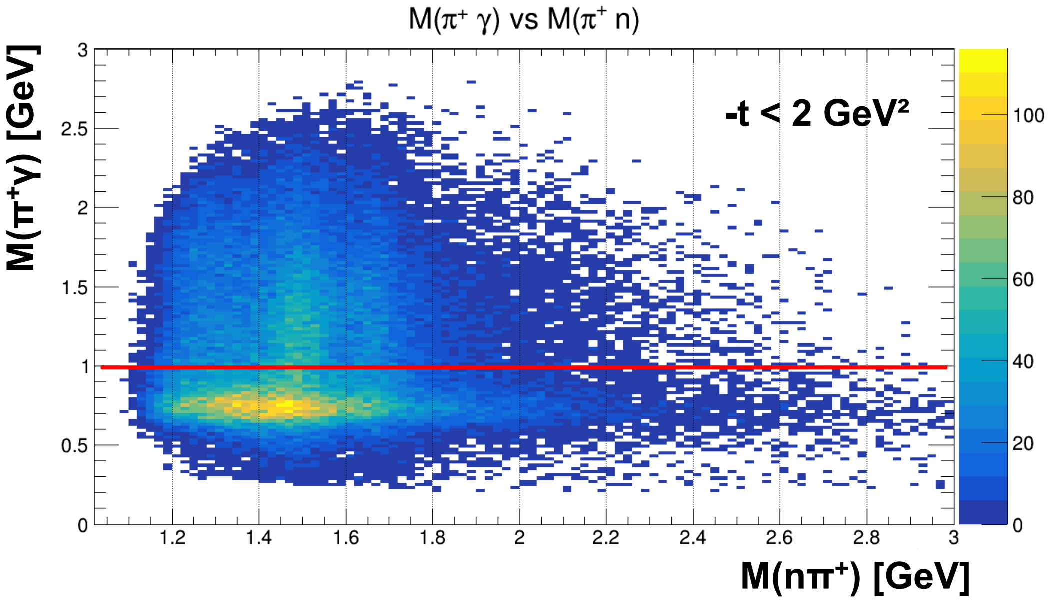
Event selection background: $e\,p \rightarrow e'\,n\,\rho^{+} \rightarrow e'\,n\,\pi^{+}\,\pi^{0} \rightarrow e'\,n\,\pi^{+}\,\gamma\,(\gamma)$

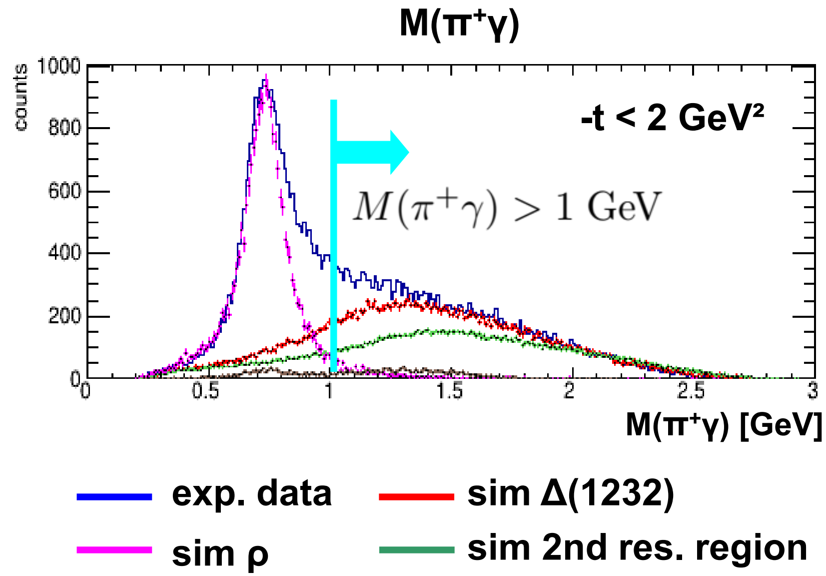
➔ Can be suppressed (next slide)

$e\,p \rightarrow e'\,N^{*+}\,\pi^{0} \rightarrow e'\,n\,\pi^{+}\,\pi^{0} \rightarrow e'\,n\,\pi^{+}\,\gamma\,(\gamma)$

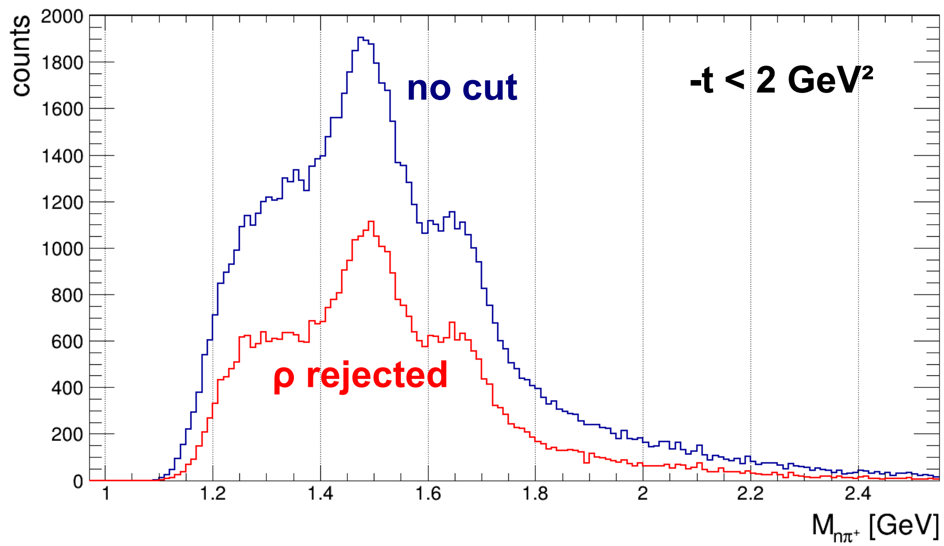
➔ Needs to be subtracted bin by bin

N → N* DVCS: ρ^+ Background Rejection





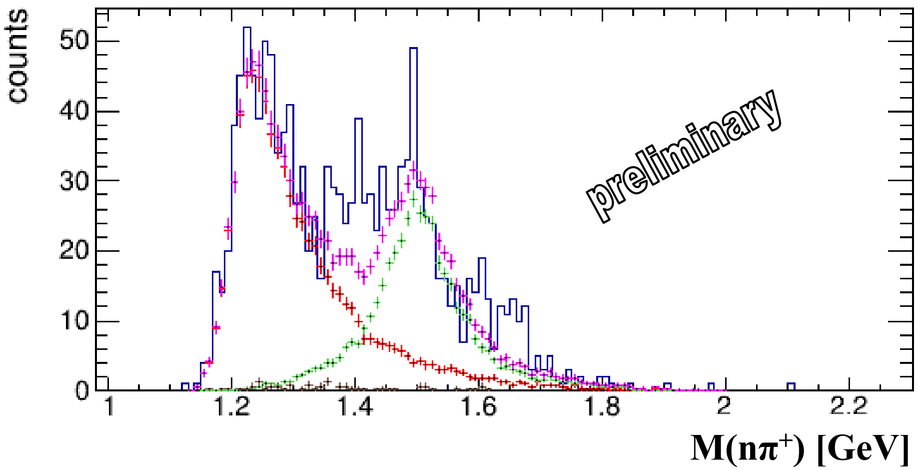
$M(\pi^+\gamma) > 1$ GeV



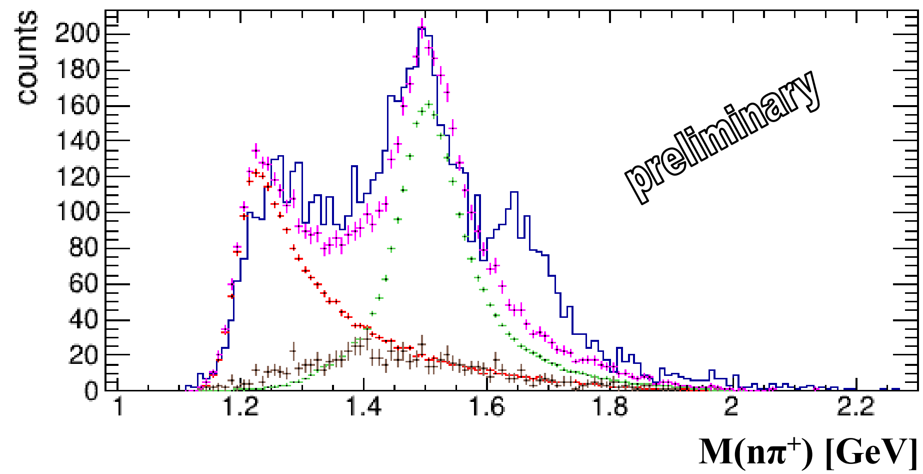
N → N* DVCS: Resonance Mass Spectra

$W > 2$ GeV, $Q^2 > 1.5$ GeV^2

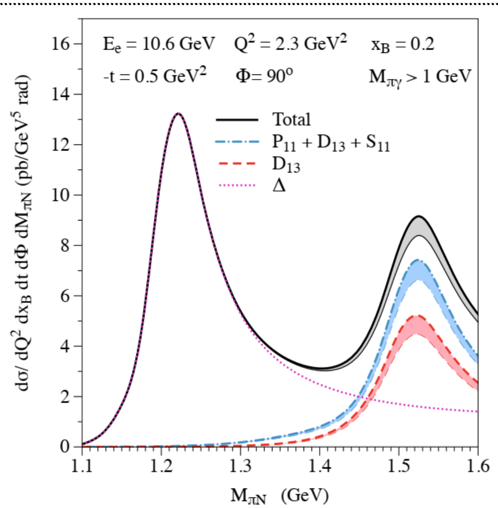
$-t < 0.5$ GeV^2



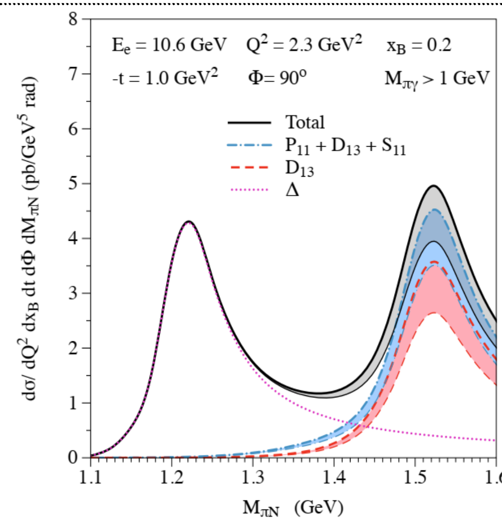
0.5 GeV$^2 < -t < 1.0$ GeV^2



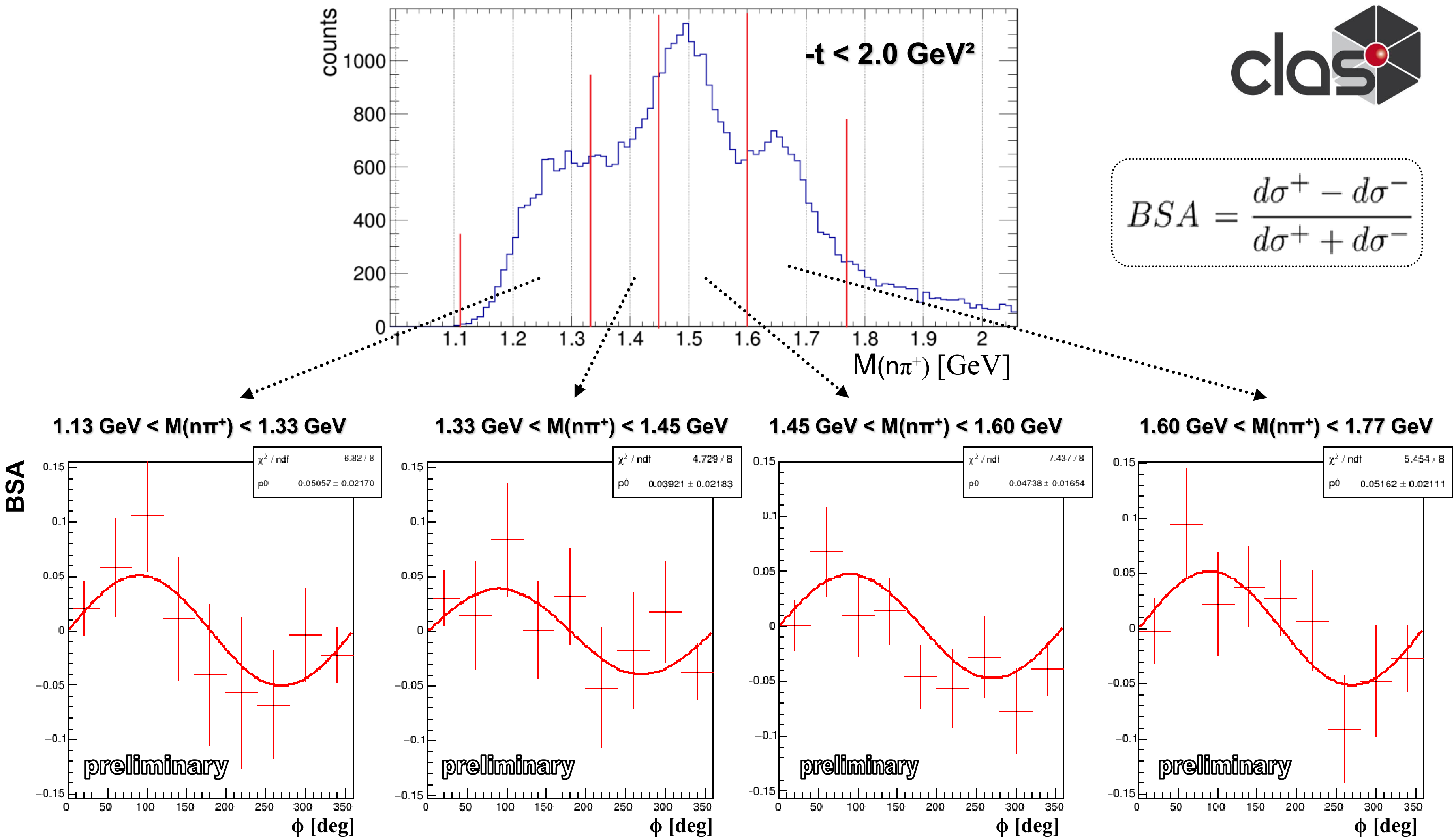
exp. data — sim. Δ(1232) / 2nd res. region — sim. full DIS — sim. sum



K. Semenov-Tian-Shansky, M. Vanderhaeghen, Phys. Rev. D 108, 034021 (2023)



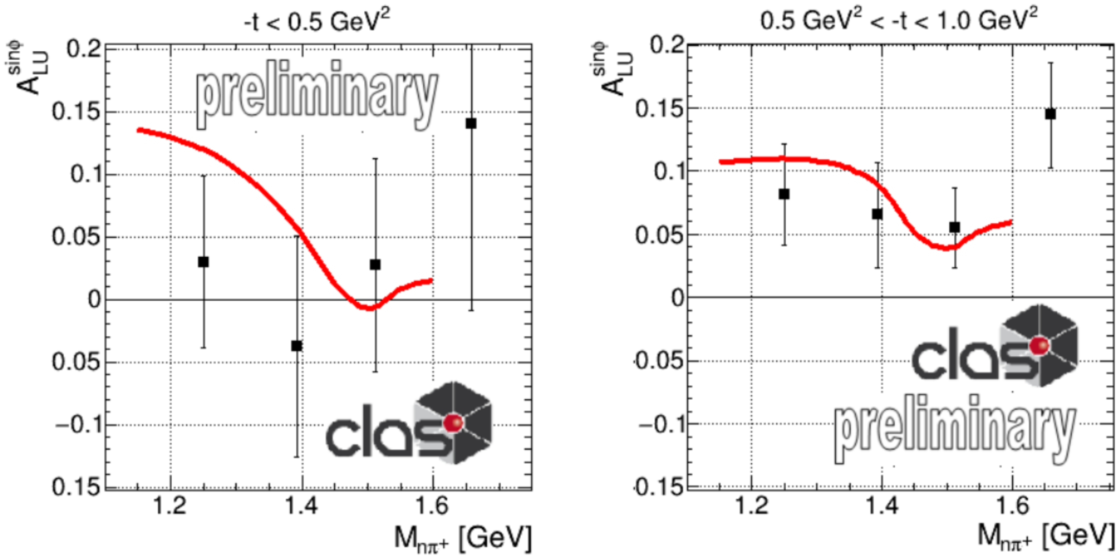
N → N* DVCS: Beam Spin Asymmetries



$$BSA = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-}$$

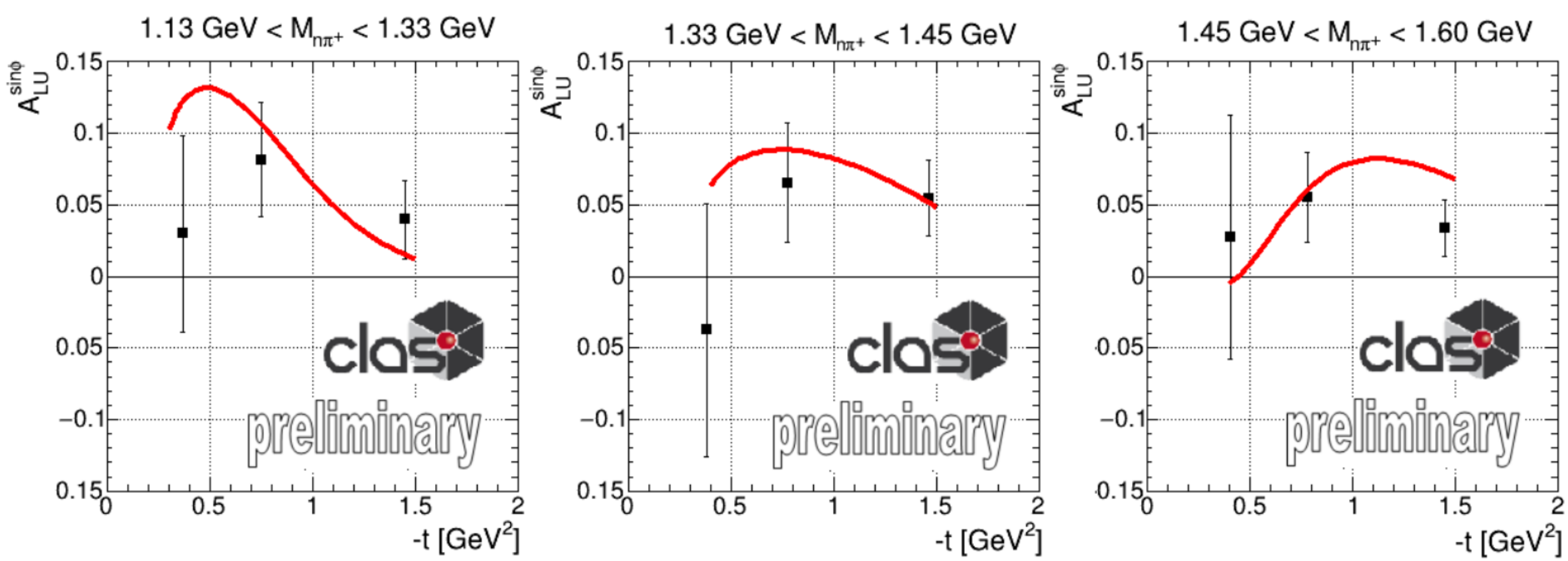
$$BSA \sim A_{LU}^{\sin(\phi)} \cdot \sin(\phi)$$

Results for N → N* DVCS (<Q²> = 2.47 GeV², <x$_B$> = 0.25)

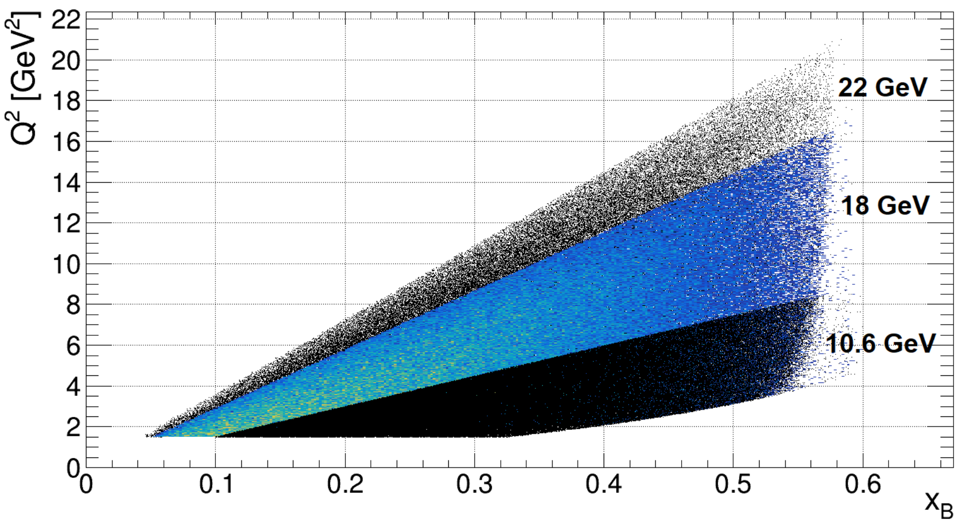


Theory curves in CLAS12 kinematics from:
K. M. Semenov-Tian-Shansky, M. Vanderhaeghen, Phys. Rev. D **108**, 034021 (2023)

Data:
No π^0 background subtraction so far!



Future: Perspectives for a 22 GeV JLAB Upgrade



$$ep \to e\Delta^{++}\pi^{-} \to ep\pi^{+}\pi^{-}$$

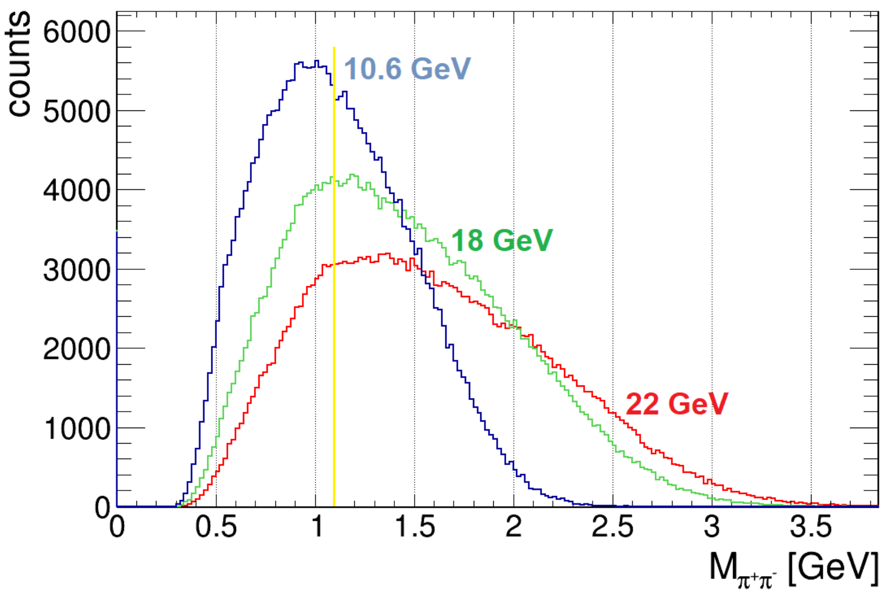
$$ep \to e\,\Delta^{+}\,\gamma \to e\,n\,\pi^{+}\,\gamma$$

Extended Q^2 range

➔ **Advantage for factorisation**

Better signal / background separation

➔ **Higher efficiency**



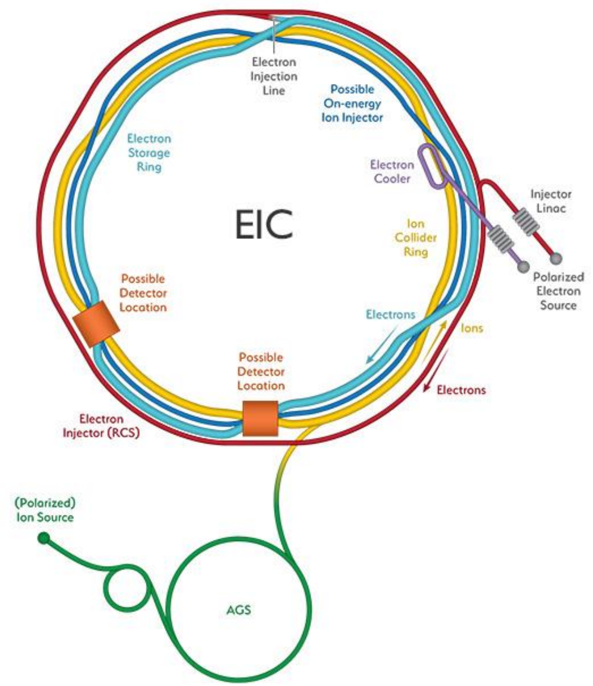
Transition GPDs are a potential part of the science program for a 22 GeV JLAB upgrade:

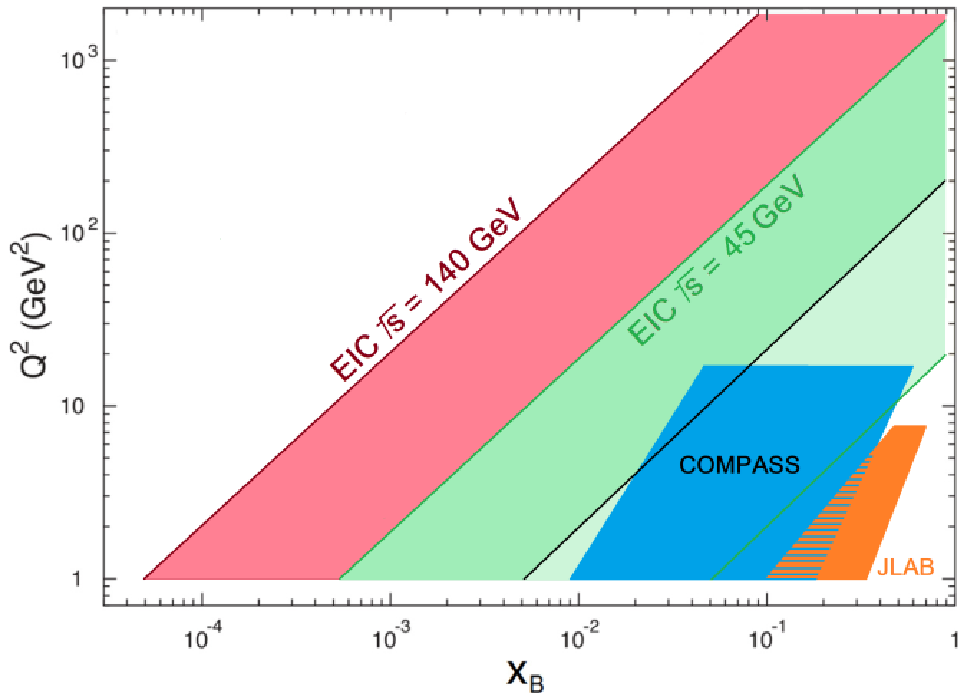
A. Accardi, P. Achenbach, D. Adhikari et al., Strong Interaction Physics at the Luminosity Frontier with 22 GeV Electrons at Jefferson Lab (2023). https://doi.org/10.48550/arXiv.2306.09360

Future: Transition GPDs at EIC and EicC

- Extension of the kinematic regime to the sea-quark and gluonic sector

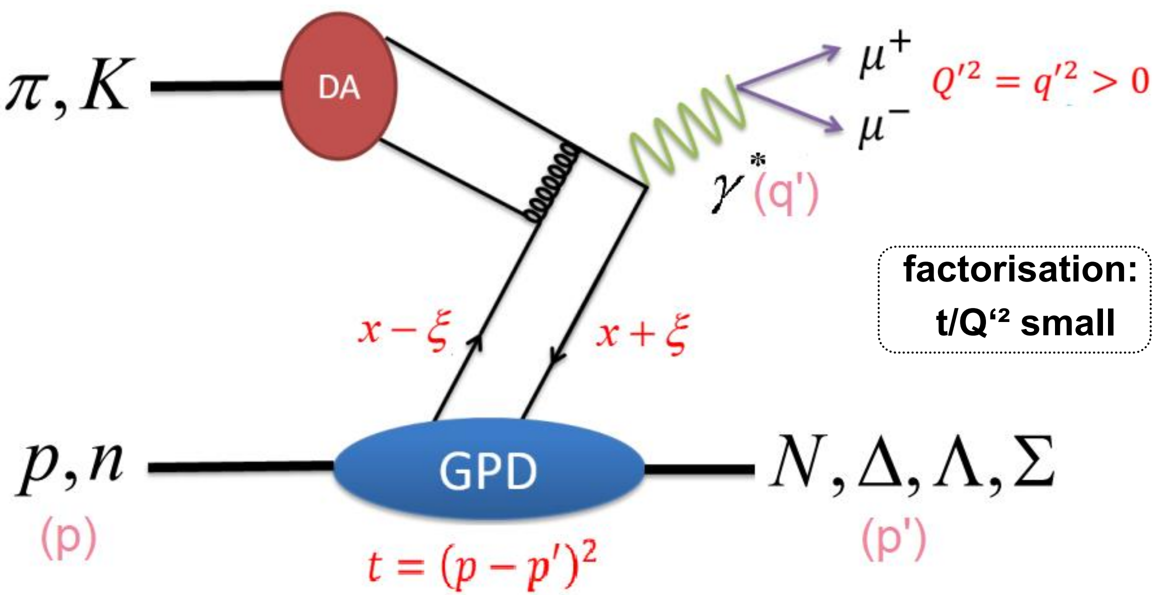
➔ Low x_B and higher Q^2 values





➔ Potential for unique insights into the contributions of sea quarks and gluons to the excitation process and to the characteristics of baryon resonances

Future: Transition Processes in Hadron Scattering

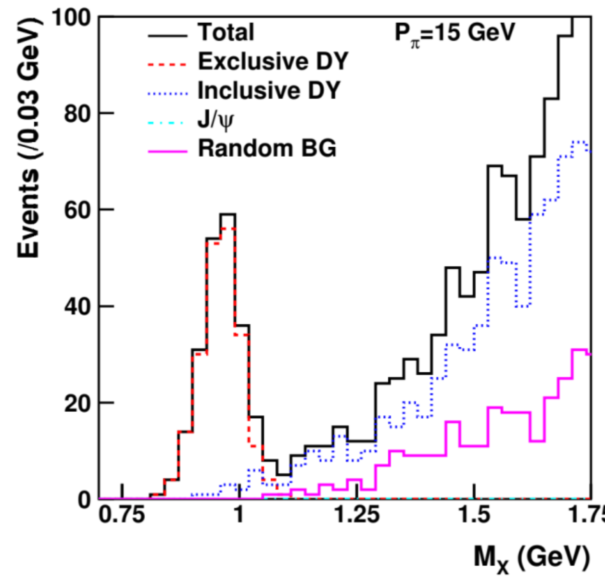


factorisation:
t/Q'² small

J-PARC (up to 20 GeV/c π,K beams):

- Large acceptance and good momentum resolution spectrometer system

$e\mu^+\mu^-X$ (X = p) missing mass:



S. Kumano + W.C. Chang

- $\pi^- p \to \gamma^* \Delta^0$
- $\pi^- n \to \gamma^* \Delta^-$
- $\pi^+ p \to \gamma^* \Delta^{++}$
- $\pi^+ n \to \gamma^* \Delta^+$

- $K^- p \to \gamma^* \Lambda$
- $K^- p \to \gamma^* \Lambda(1405)$
- $K^- p \to \gamma^* \Lambda(1520)$
- $K^- n \to \gamma^* \Sigma^-$
- $K^+ n \to \gamma^* \Theta^+$

➔ Probes universality of GPDs and trans. GPDs

+ Different kinematic regime in x and ξ than e- scatt.

- **Potentially also with AMBER @ CERN** (up to 190 GeV/c π, K beams)

Summary and Outlook

- Transition GPDs can help us to better understand baryon resonances and the exitation process itself, by relating their properties to the 3D motion and distribution of the partons

- Hard exclusive $\pi^-\Delta^{++}$ production and N→N* DVCS can be well measured with CLAS12 (first published observable sensitive to transition GPDs)

- First results on N→N* DVCS BSAs show a very promising agreement with theory predictions

- A JLAB energy upgrade will help to significantly improve these measurements and the extraction of transition GPDs

- Further opportunities: EIC, COMPASS / AMBER, J-PARC

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Summary and Outlook

The first workshop on transition GPDs took place in August 2023 at ECT* Trento

FONDAZIONE BRUNO KESSLER | ECT* EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

STRONG-2020

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apctp asia pacific center for theoretical physics

https://indico.ectstar.eu/event/176/

- A whitepaper has been submitted to EPJ-A (under review) and to arXiv: http://arxiv.org/abs/2405.15386

Exploring Baryon Resonances with Transition Generalized Parton Distributions: Status and Perspectives

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