The 13th Circum-Pan-Pacific Symposium on High Energy Spin Physics

Transition GPDs and N-Δ nondiagonal DVCS at the EIC

In collaboration with

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Hyeon-Dong Son

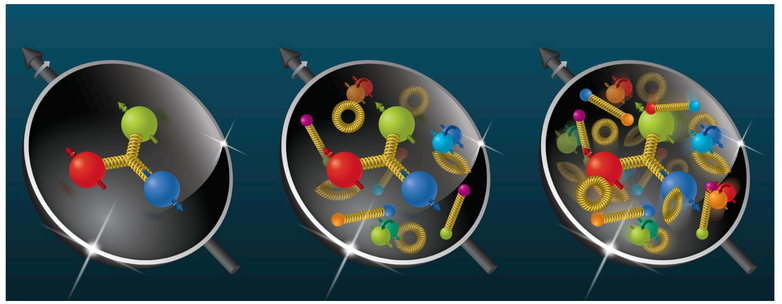
Hadron Theory Group, Inha University

Outline

- Introduction
- N-Δ transition GPDs
- Nondiagonal DVCS amplitudes
- Estimations for N-Δ DVCS process at the EIC
- Summary

Introduction

Partons as constituents of hadrons



Volume 8, number 3 PHYSICS LETTERS 1 February 1964



A SCHEMATIC MODEL OF BARYONS AND MESONS *

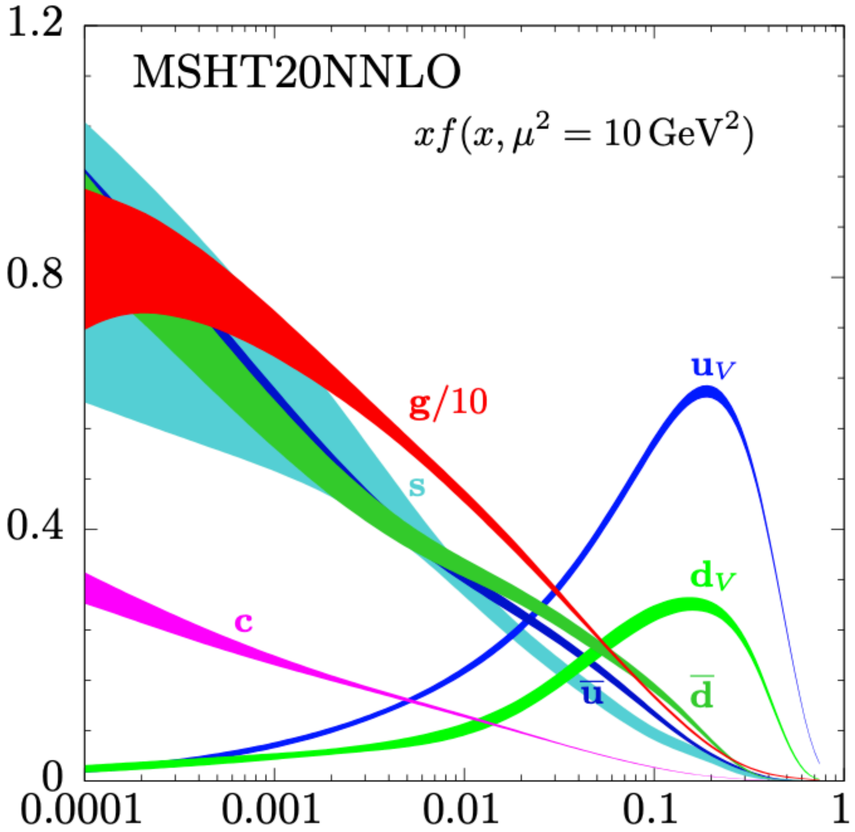
M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

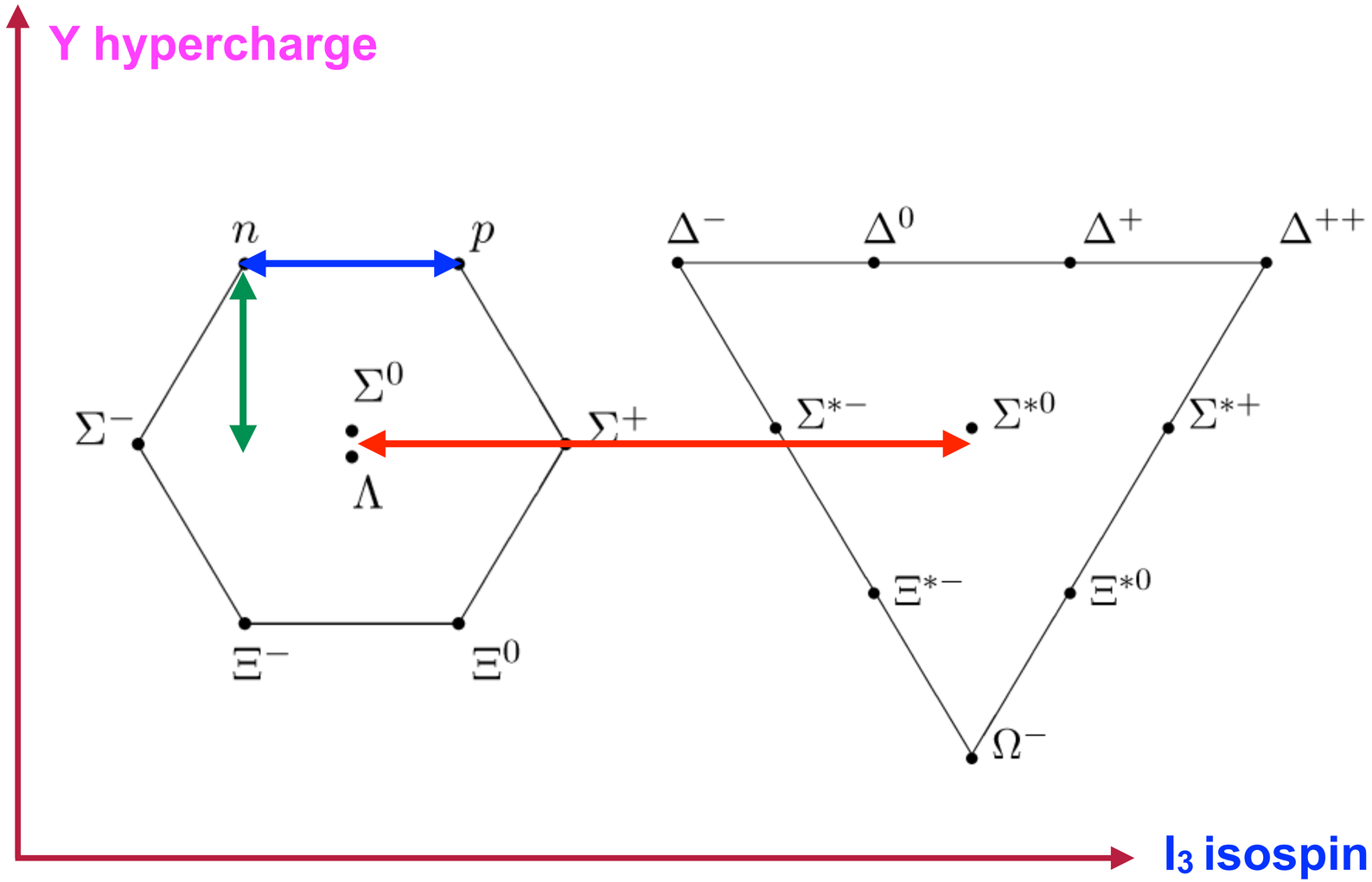
We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" [6] q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

G. Zweig 10.17181/CERN-TH-401 (1964),
M. Gell-Mann, Phys. Lett. 8 (1964)





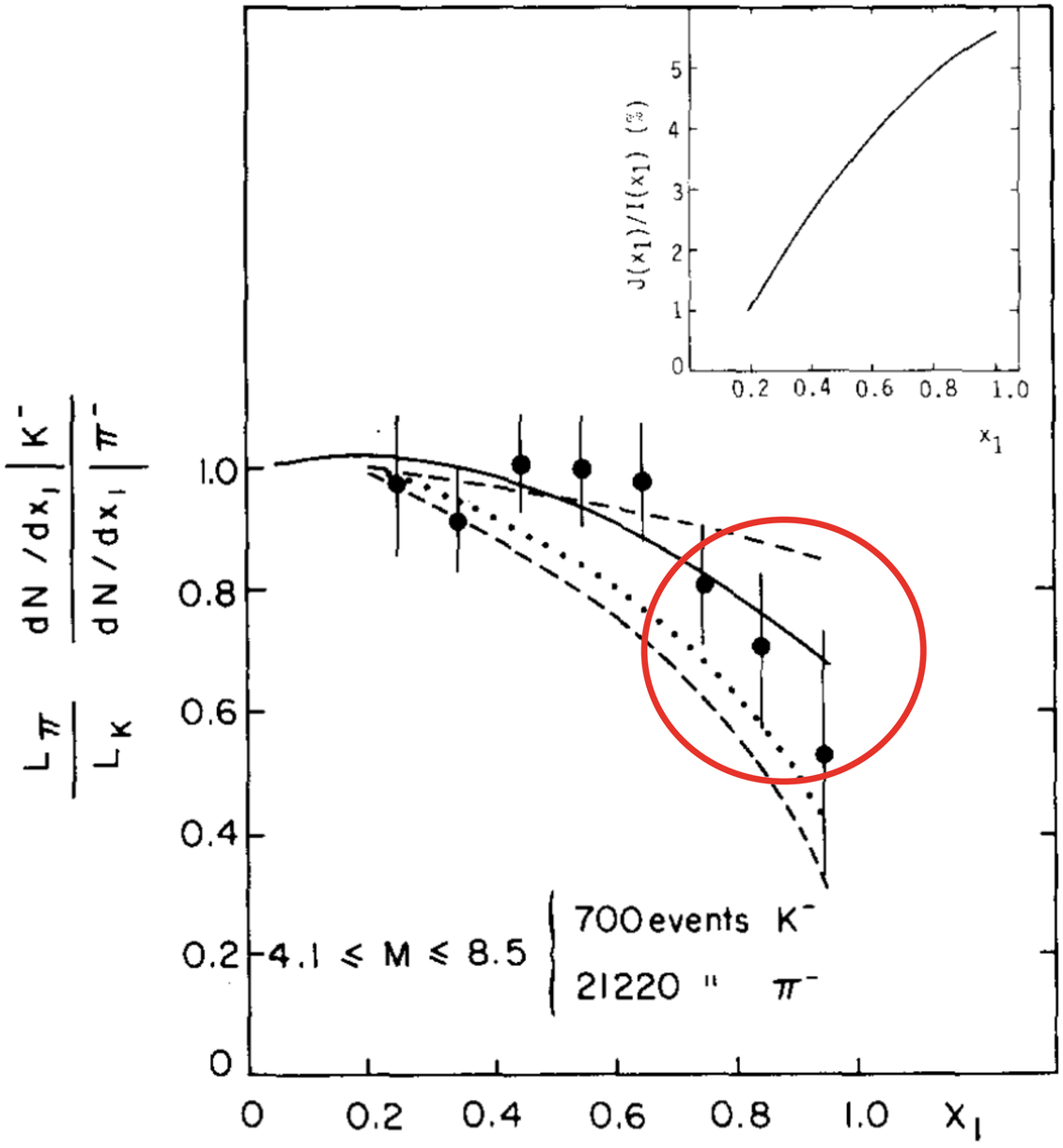
Baryon multiplets and symmetry breaking



Δm due to symmetry breaking

- **Isospin ~ MeV**
- **SU(3) flavor ~ 100 MeV**
- **Large Nc ~ 300 MeV**

Aspect of symmetry breaking: quarks in Kaon



NA3 @ CERN SPS

Ratios for K^- and π^- -induced Drell-Yan cross section

Proportional to $\bar{u}_{K^-}(x)/\bar{u}_{\pi^-}(x)$

Dropping at x > 0.6 :

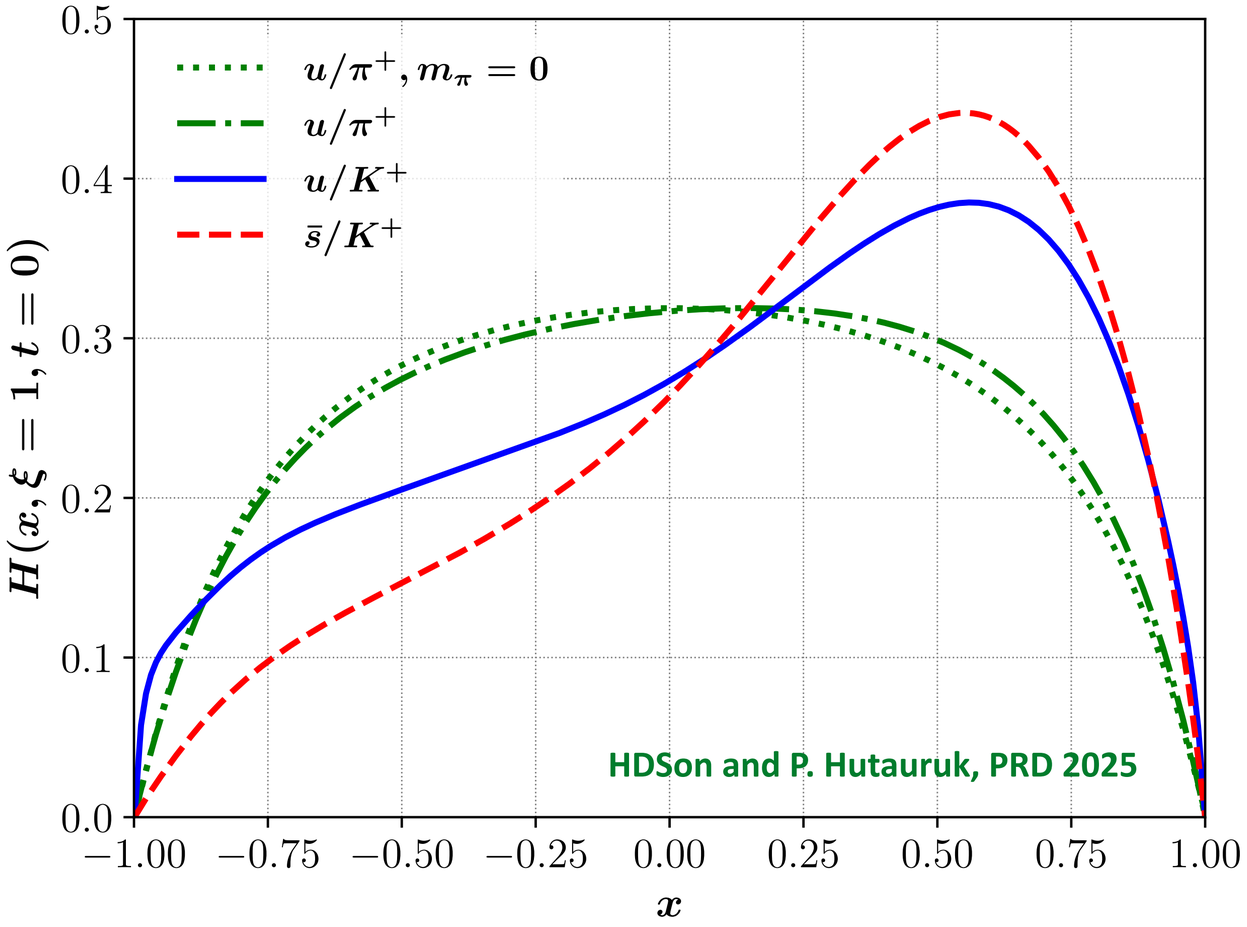
☞ s quark carries more momentum than u quark in a Kaon

☞ u quark in Kaon is softer than u quark in pion

+ J/ψ production data can constrain the kaon PDFs

Badier et al. *Phys.Lett.B* 93 (1980) 354-356

Aspect of symmetry breaking: quarks in Kaon



Exact chiral symmetry: H(x,ξ=1,t=0) even in x

M. Polyakov and C. Weiss, Phys.Rev.D 60 (1999) 114017

..... Pion ($m_\pi = 0$): exactly symmetric

-·-·- Pion ($m_\pi = 140$ MeV): slightly distorted

---- $\bar{s}$ in K^+ ——— u in K^+

Second Mellin moment: gravitational form factors

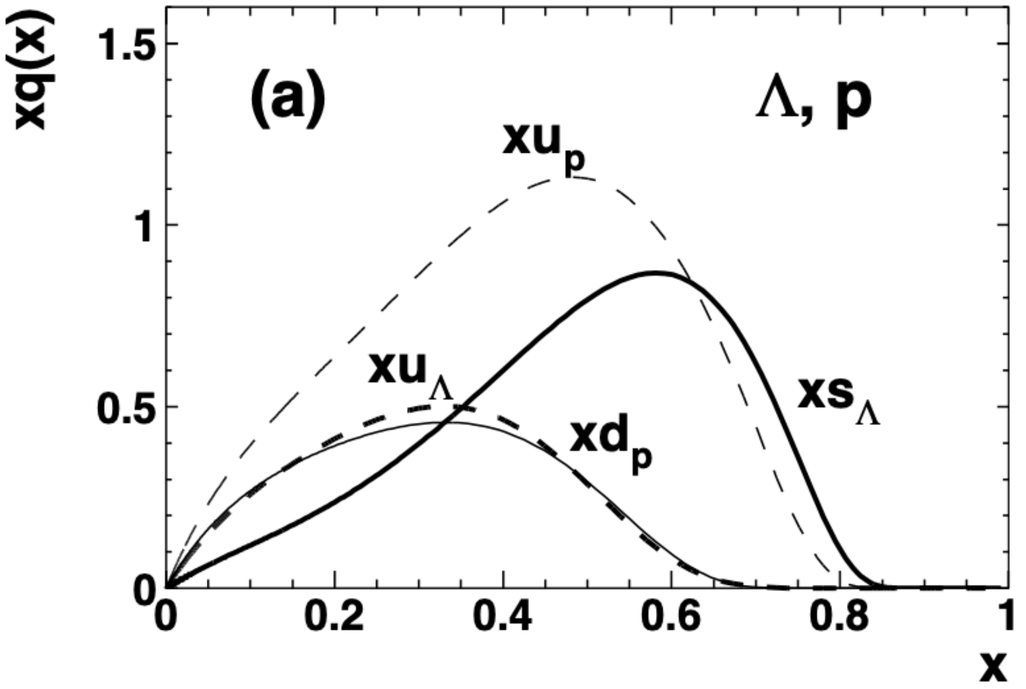
$$\int_{-1}^{1} dx\, x\, 2H(x, \xi = 1, t = 0) = A(0) + D(0) = 0 + \mathcal{O}(m_{\pi,K}^2)$$

$m_K^2/m_\pi^2 \approx 12$

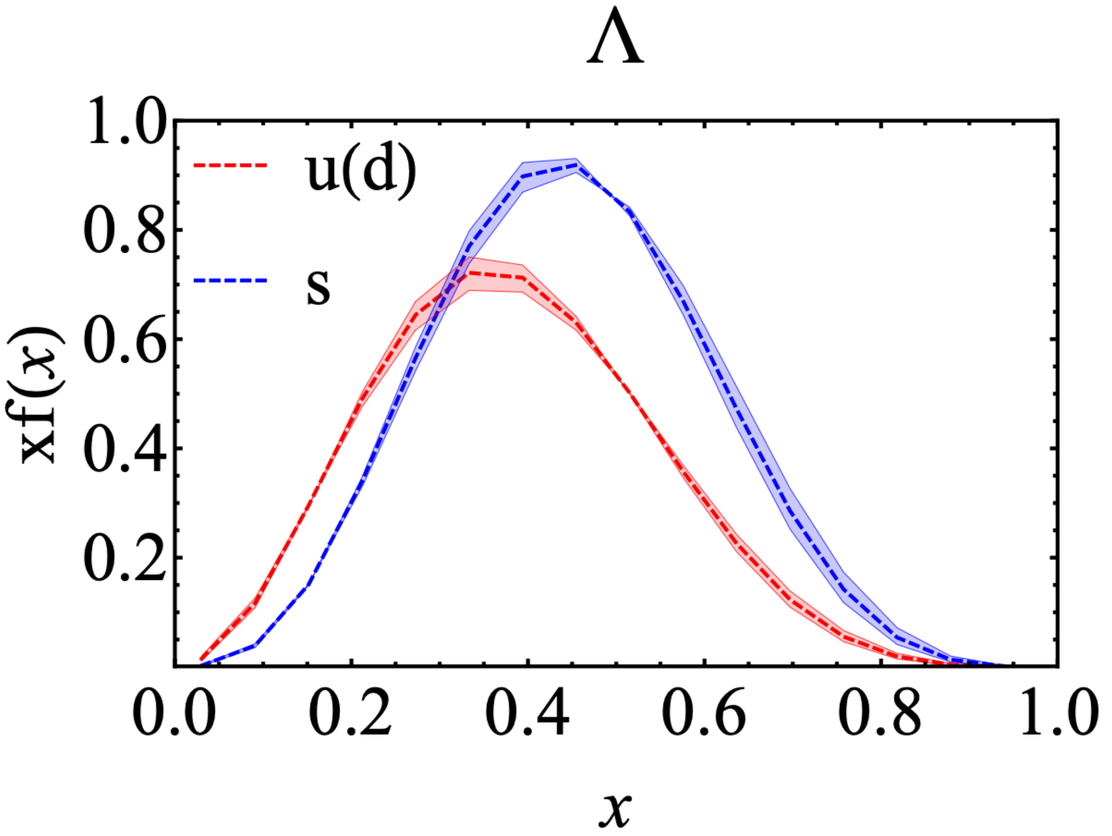
Size of A(0)+D(0) ~ size of asymmetry in xH(x,ξ=1,t=0) ~ O(m²)

Aspect of symmetry breaking: quarks in Hyperons

MIT Bag Boros & Thomas, PRD 60, 074017 (1999)



LF-BLFQ Peng et al. PRD 106, 114040 (2022)



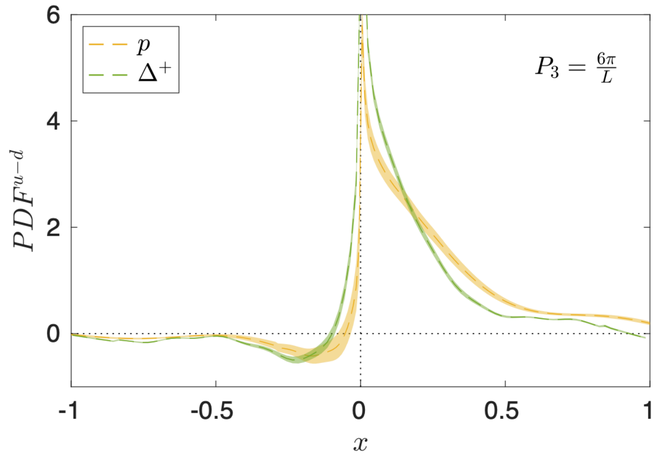
Antiquark flavor asymmetries in hyperons?

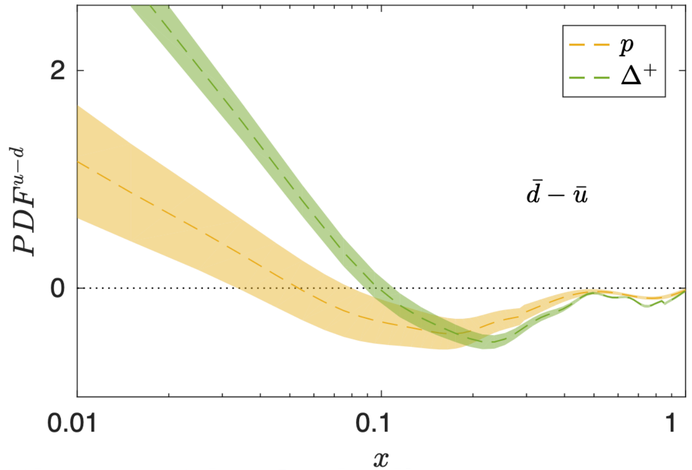
※ Gravitational form factors of hyperons: theoretical quantification of the $SU_f(3)$ breaking effect (Hyun-Chul's talk)

Aspect of symmetry breaking: N vs Δ in the large Nc

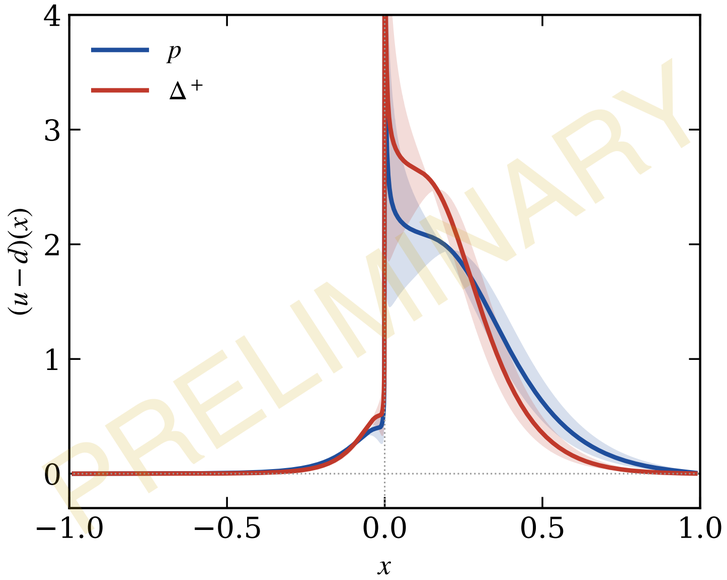
ETMC 2020: (u-d)(x), $m_\pi = 270$MeV ~ $M_\Delta - M_N$

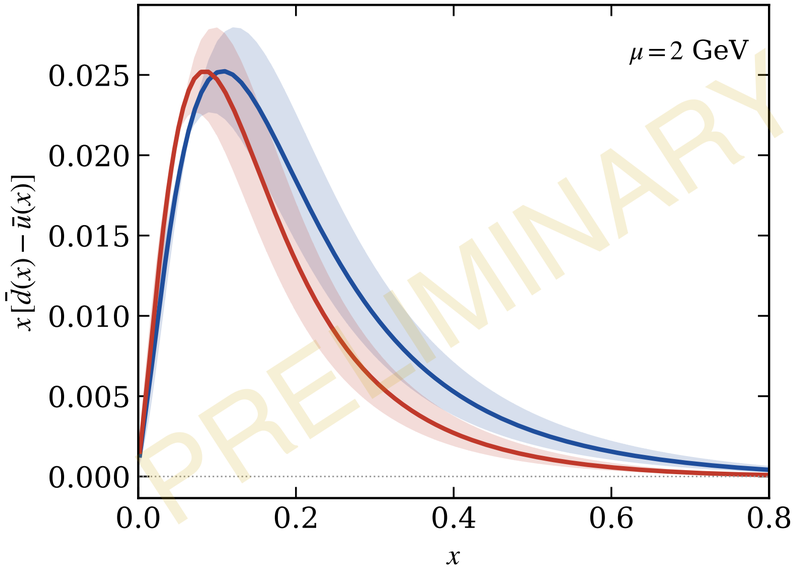
Y. Chai et al. Phys. Rev. D 102, 014508 (2020)





Chiral quark-soliton model (dynamical splitting not included)





HDSon in preparation

Transition GPDs

L. Frankfurt et al. PRD 60, 014010 (1999)
L. Frankfurt et al. PRL 84 (2000) 2589
K. Goeke et al. PPNP 47, 401 (2001)

- Extends GPDs to non-diagonal hadron external states: **p-n**, **N-Y**, **N-Δ**, **N-N***, …
- Retain properties of diagonal GPDs: **transition FFs, polynomiality (no time-reversal symmetry)**

  → **n=2 moments: transition via EMT operator** H. Alharazin et al. *JHEP* 03 (2024) 007
- **Accessible in exclusive DIS with proton to X**

  → Background for DVCS and DVMP for usual nucleon GPD measurement
- Tomography of transition processes J. Kim Phys.Rev.D 108 (2023) 3, 034024,
  J. Kim and H.-Ch. Kim. *PRD* 114 (2026) 7, 074023
- A recent white paper S. Diehl et al. *Eur.Phys.J.A* 61 (2025) 6, 131

Long-term goal: parton structure of N→Δ, N→Y, … transitions

This talk: the first step — feasibility of N→Δ DVCS at the EIC

Reactions involving transition GPDs

transition	symmetry	JLab	J-PARC (π, K, p)	EIC
$p \to n$	**Isospin** ~ MeV	$ep \to e\pi^+ n$ [1,2]	$\pi^- p \to \ell^+\ell^- n$ [3–6], $\pi N \to \gamma\gamma N$ [7], $pp \to p\,\pi^+ n$ [8]	$ep \to e\pi^+ n$
$p \to \Lambda,\ \Sigma,\ \Sigma^*$	**SU(3)** ~ 100 MeV	$ep \to eK^+\Lambda$ [9]	$K^- p \to \ell^+\ell^-\Lambda$ [6,9], $\ell^+\ell^-\Sigma^{*0}$	$ep \to eK^+\Lambda$
$N \to \Delta$	**$1/N_c$** ~ 300 MeV	$ep \to e\pi^-\Delta^{++}$ [10,11], $ep \to e\gamma\Delta^+$ [12–14]	$\pi^+ p \to \ell^+\ell^-\Delta^{++}$, $pp \to p\,\pi^-\Delta^{++}$, $p\,\pi^+\Delta^0$ [8]	$ep \to e\gamma\Delta^+$ [15]
$N \to N^*(1440)$, $N(1520)$, $N(1535)$	**Excited N**	$ep \to e\gamma(\pi N, \eta N)$ [13,14]	$\pi^- p \to \ell^+\ell^- N^*$	$ep \to e\gamma N^*$
$N \to X$	**Exotica**	?	?	?

[1] S. Diehl et al. (CLAS), PRL 125 (2020) 182001; [2] Goloskokov, Kroll, EPJC 65 (2010) 137; [3] Goloskokov, Kroll, PLB 748 (2015) 323; [4] Sawada et al., PRD 93 (2016) 114034; [5] J-PARC LoI, *Studying GPDs with exclusive Drell–Yan at J-PARC* (2018); [6] Jia et al., arXiv:2607.15214; [7] Qiu, Yu, PRD 109 (2024) 074023; [8] Kumano et al., PRD 80 (2009) 074003; [9] Kroll, EPJA 55 (2019) 76; [10] S. Diehl et al. (CLAS), PRL 131 (2023) 021901; [11] Kroll, Passek-Kumerički, PRD 107 (2023) 054009; [12] Guichon et al., PRD 68 (2003) 034018; [13] Semenov-Tyan-Shansky, Vanderhaeghen, PRD 108 (2023) 034021; [14] S. Diehl et al., EPJA 61 (2025) 131 (white paper); [15] S. Son et al., in preparation (This work)

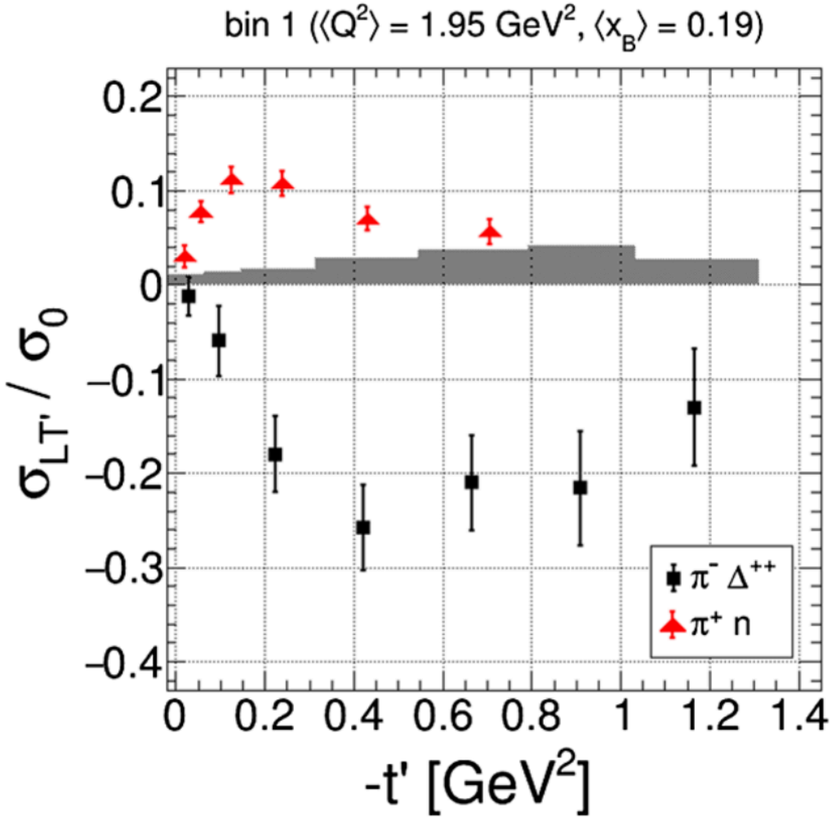
Δ(1232, 3/2+) resonance

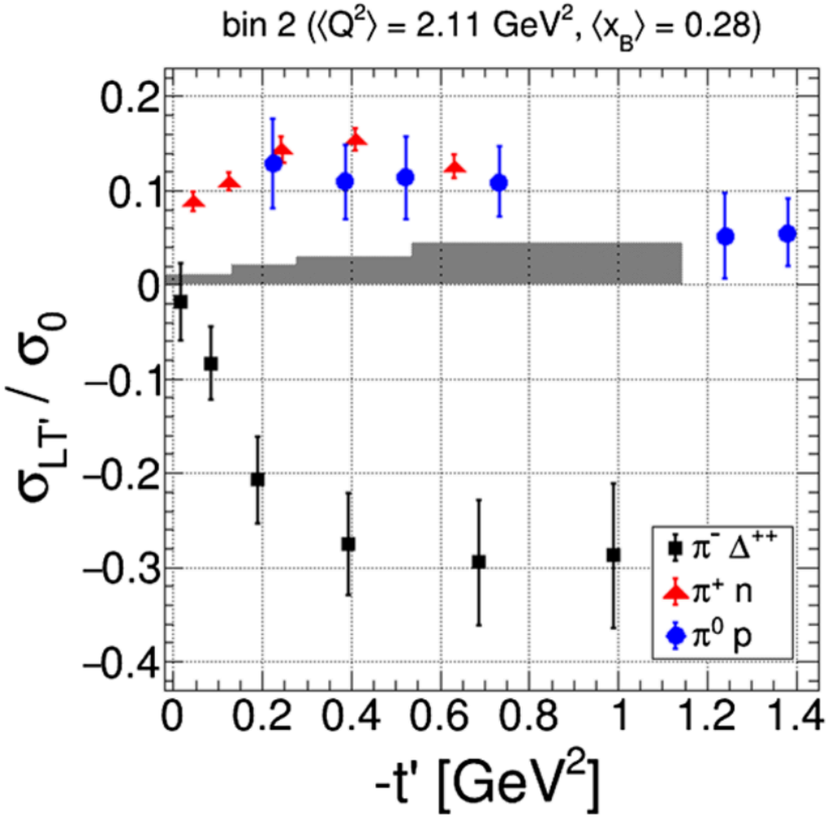
- Lightest light-baryon resonance
- Identical to the nucleon in the strict large Nc limit
- 1/Nc effect $M_{N\Delta}$~300 MeV: strongest in symmetry-breaking strength
- Simple decay channel: Nπ (99.4%)
- Isospin 3/2: $\Delta^{++} \rightarrow p\pi^{+}$ channel is separated from all N* resonances
- Transition form factors are well studied

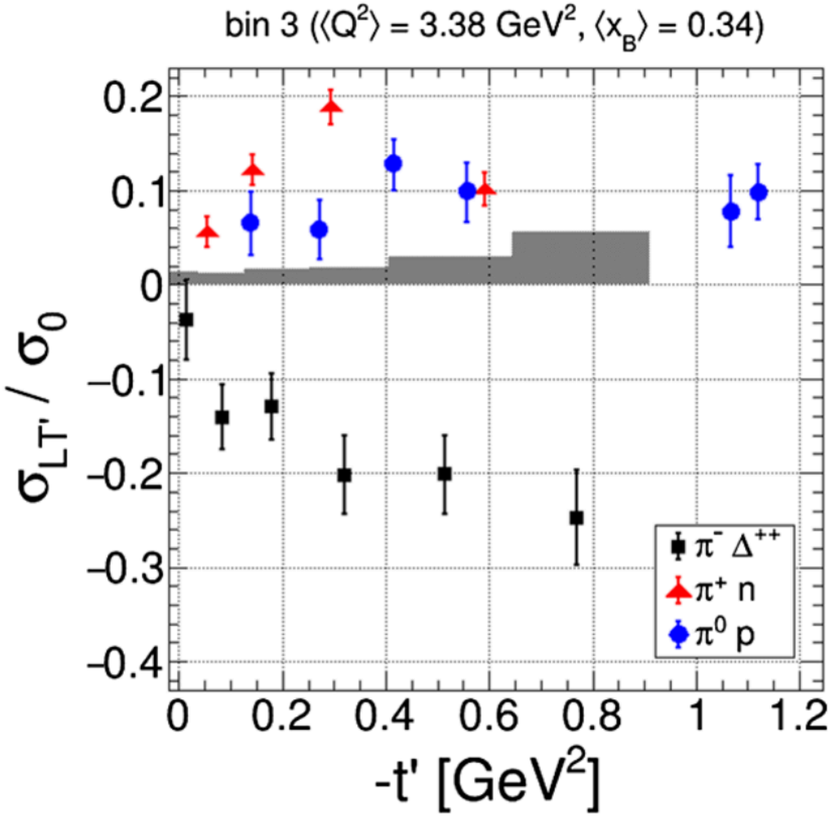
First nondiagonal DVMP measurement from CLAS12

$\sigma_{LT'}/\sigma_0$ sensitive to the chiral-odd transition GPDs

S. Diehl et al.,*Phys.Rev.Lett.* 131 (2023) 2, 021901

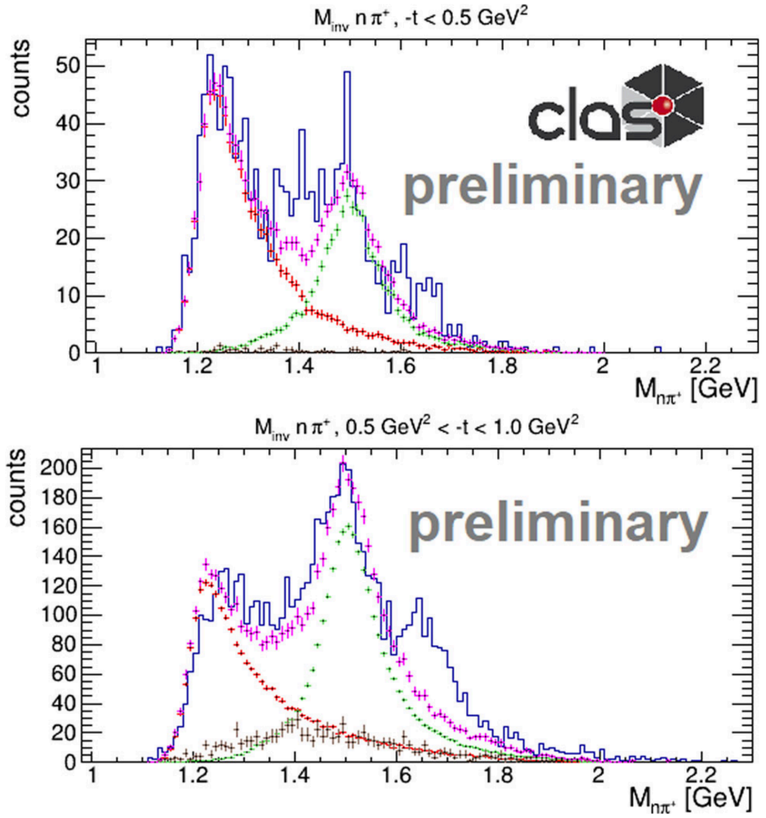




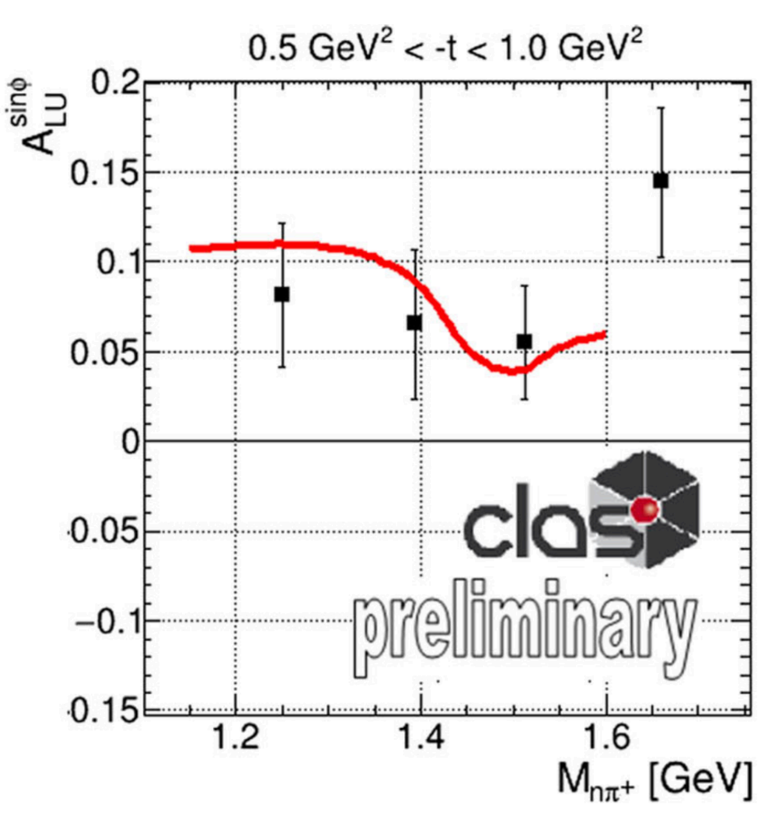


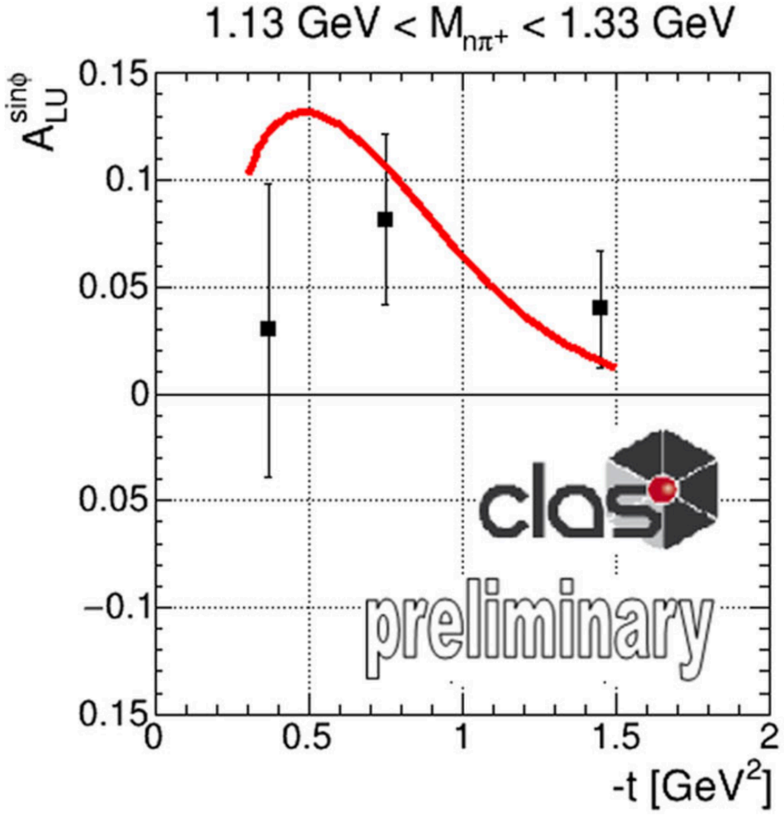
Invariant mass distributions for $e^- p \to e^- \gamma n \pi^+$

Cross section



BSA





Preliminary results from S. Diehl,
TGPD white paper *Eur.Phys.J.A* 61 (2025) 6, 131
Theoretical curves: K. Semenov and M. Vanderhaeghen
Phys.Rev.D 108 (2023) 3, 034021

Test for applicability of GPD framework under the collinear factorization in non-diagonal processes

N-Δ transition GPDs

N-Δ Transition GPDs

L.L. Frankfurt et al. PRL 84 (2000) 2589

J.-Y. Kim et al. PRD 111 (2025)

Vector GPDs

$$\int \frac{d\lambda}{2\pi} e^{i\lambda x} \langle \Delta(p_\Delta)| \bar{\psi}(-\lambda n/2) \not{n} \tau^3 \psi(\lambda n/2) |N(p_N)\rangle$$

$$= \sqrt{\frac{2}{3}} \bar{R}_\beta(p_\Delta) \Big[H_M(x,\xi,t) \mathcal{K}_M^{\beta\mu} n_\mu + H_E(x,\xi,t) \mathcal{K}_E^{\beta\mu} n_\mu + H_C(x,\xi,t) \mathcal{K}_C^{\beta\mu} n_\mu + H_X(x,\xi,t) \mathcal{K}_X^{\beta\mu} n_\mu \Big] N(p_N),$$

Mellin moments of vector GPDs

$$\begin{aligned} H_M(x,\xi,t) &\xrightarrow{\int_{-1}^{1} dx} 2g_M(t) \\ H_E(x,\xi,t) &\xrightarrow{\int_{-1}^{1} dx} 2g_E(t) \\ H_C(x,\xi,t) &\xrightarrow{\int_{-1}^{1} dx} 2g_C(t) \\ H_X(x,\xi,t) &\xrightarrow{\int_{-1}^{1} dx} 0 \end{aligned}$$

} N-Delta vector transition ffs (related to Jones-Scadron)

Pascalutsa, Vanderhaeghen, Yang, Phys. Rept. 437 125 (2007)

N-Δ Transition GPDs

L.L. Frankfurt et al. PRL 84 (2000) 2589

J.-Y. Kim et al. PRD 111 (2025)

Axial vector GPDs

$$\int \frac{d\lambda}{2\pi} e^{i\lambda x} \langle \Delta(p_\Delta) | \bar{\psi}(-\lambda n/2) \not{n} \gamma_5 \tau^3 \psi(\lambda n/2) | N(p_N) \rangle$$

$$= \bar{R}_\beta(p_\Delta) \left[C_1(x,\xi,t) \tilde{\mathcal{K}}_1^{\beta\mu} n_\mu + C_2(x,\xi,t) \tilde{\mathcal{K}}_2^{\beta\mu} n_\mu + C_3(x,\xi,t) \tilde{\mathcal{K}}_3^{\beta\mu} n_\mu + C_X(x,\xi,t) \tilde{\mathcal{K}}_X^{\beta\mu} n_\mu \right] N(p_N)$$

Mellin moments of axial vector GPDs

$$\sqrt{\frac{2}{3}} \int_{-1}^{1} dx$$

$C_1(x,\xi,t)$	$2\left[C_5^A(t) + \frac{m_\Delta^2 - m_N^2}{m_N^2} C_4^A(t)\right]$
$C_2(x,\xi,t)$	$2\left[C_6^A(t) + \frac{1}{\xi} C_4^A(t)\right]$
$C_3(x,\xi,t)$	$2C_3^A(t)$
$C_X(x,\xi,t)$	0

} N-Delta axialvector transition ffs

Pascalutsa, Vanderhaeghen, Yang, Phys. Rept. 437 125 (2007)

Transition GPDs in the large Nc limit

L.L. Frankfurt et al. PRL 84 (2000) 2589
Goeke, Polyakov, Vanderhaeghen PPNP 47 (2001) 401

Large Nc limit of QCD:

nucleon and Δ are different rotational excitation (1/Nc) states

from the same classical soliton

→Large Nc relation of the N-Δ GPDs and nucleon GPDs

$$H_M(x,\xi,t) = \sqrt{2}\left[E_u(x,\xi,t) - E_d(x,\xi,t)\right],$$

$$C_1(x,\xi,t) = \sqrt{3}\left[\tilde{H}_u(x,\xi,t) - \tilde{H}_d(x,\xi,t)\right],$$

$$C_2(x,\xi,t) = \frac{\sqrt{3}}{4}\left[\tilde{E}_u(x,\xi,t) - \tilde{E}_d(x,\xi,t)\right].$$

Isovector dominance follows from the nucleon GPDs

Cx = 0 (not known)

All other GPDs are 1/Nc suppressed; set to zero

Based on the large Nc relation,

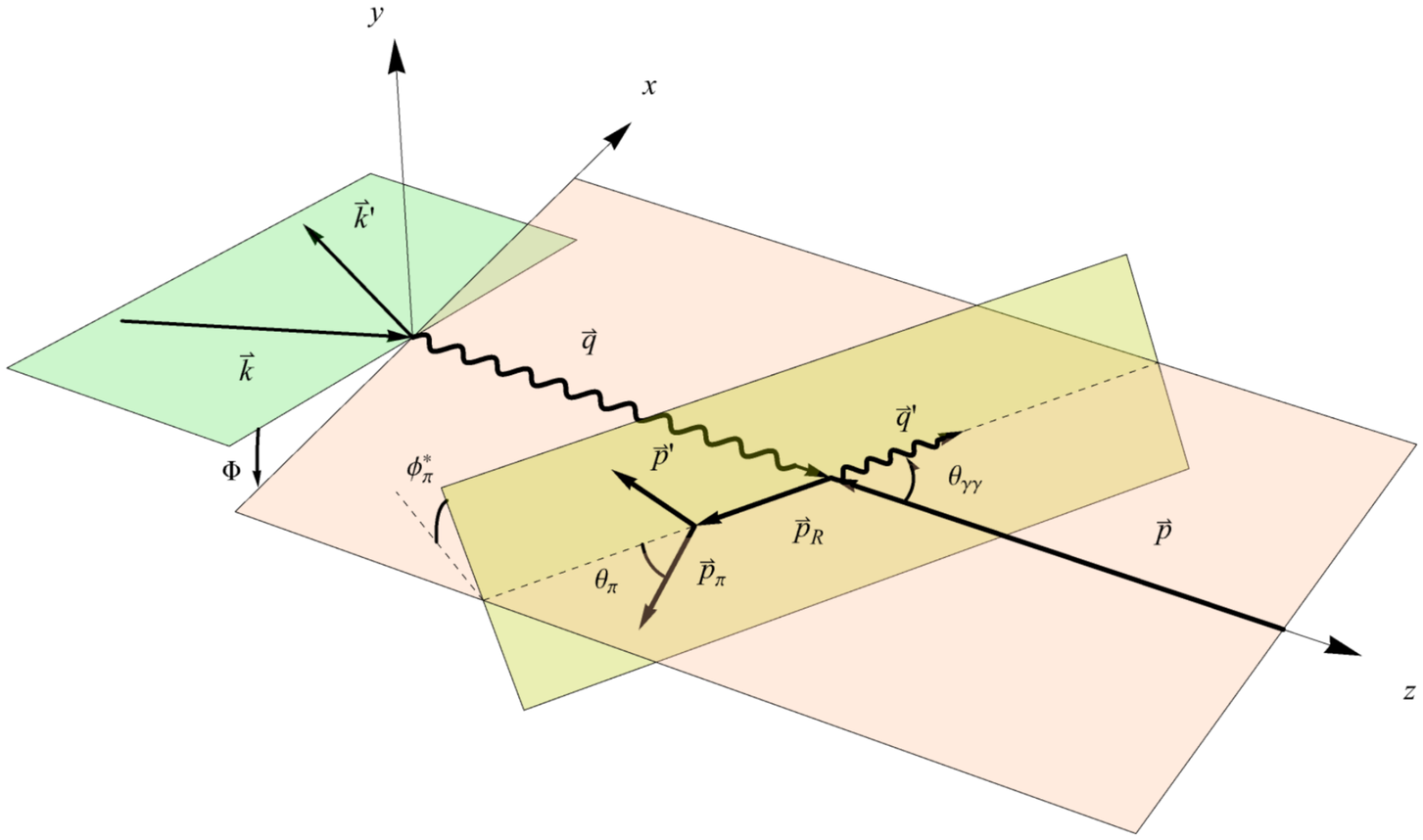
we use the phenomenological models for the nucleon GPDs to design the transition GPDs

Nondiagonal N-Δ DVCS amplitudes

Nondiagonal DVCS

K. Semenov and M. Vanderhaeghen *Phys.Rev.D* 108 (2023) 3, 034021

$$e(k) + N(p) \to e'(k') + \gamma^*(q) + N(p) \to e'(k') + \gamma(q') + \pi(p_\pi) + N'(p')$$



Differential cross section:

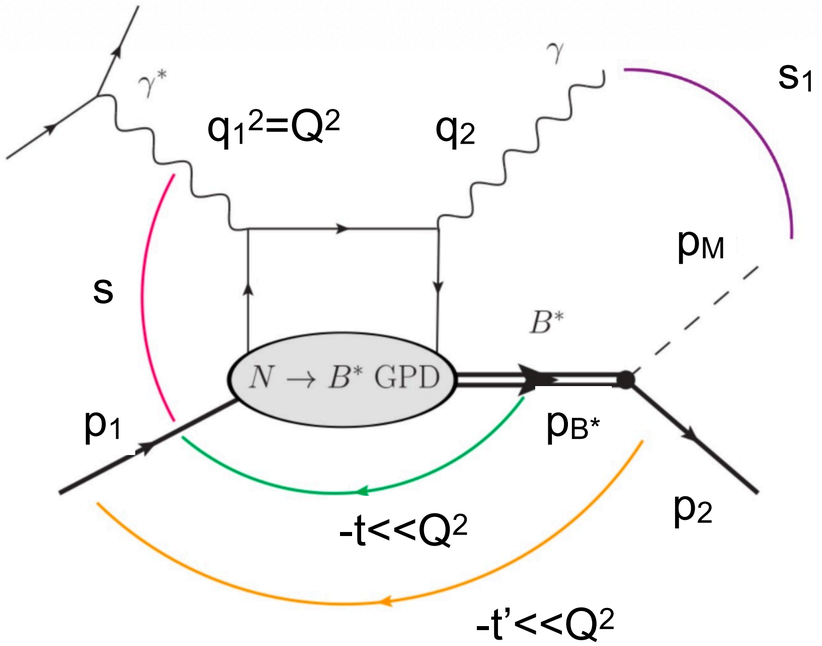
$$\frac{d^7\sigma}{dQ^2 dx_B dt d\phi dW^2_{\pi N} d\Omega^*_\pi}$$

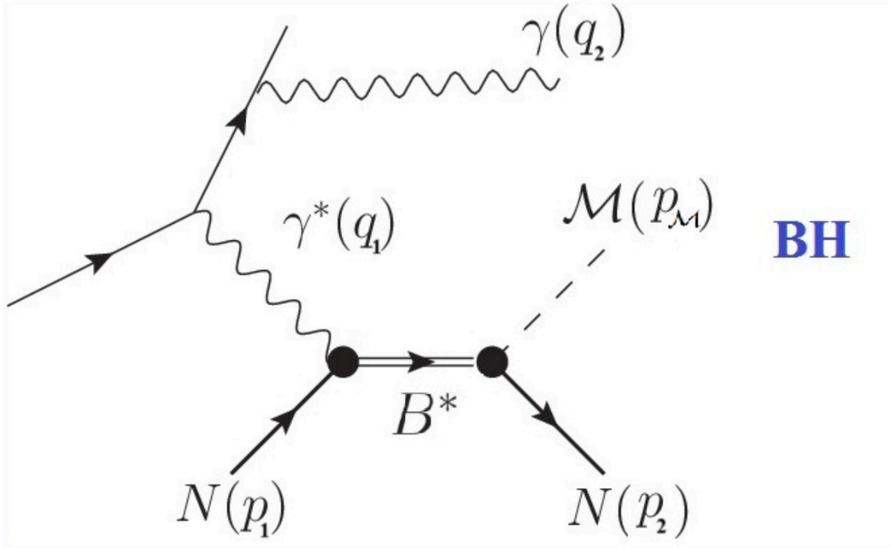
$\gamma^* N \to B^* \gamma$ Transition subprocess

$B^* \to \pi N'$ Resonance decay

Nondiagonal DVCS

$$\gamma^*(q) + N(p) \to \gamma(q') + [\mathcal{M}(p_{\mathcal{M}})N(p')]; \quad \mathcal{M} = \pi, \eta, \rho, \omega, \ldots$$





BH

Factorization in terms of N → B* GPDs in the generalized Bjorken kinematics:

$$-q_1^2;\ s = (p_1 + q_1)^2;\ s_1 = (p_{\mathcal{M}} + q_2)^2 - \text{large}; \qquad x_B = \frac{-q_1^2}{2p_1 \cdot q_1} - \text{fixed};$$

$$-t = -(p_{B^*} - p_1)^2; \quad -t' = -(p_2 - p_1)^2; \quad W^2_{\mathcal{M}N} = (p_2 + p_{\mathcal{M}})^2 \quad \text{of hadronic scale.}$$

N-Δ DVCS

Narrow decay width approximation

P. Guichon et al., 2003

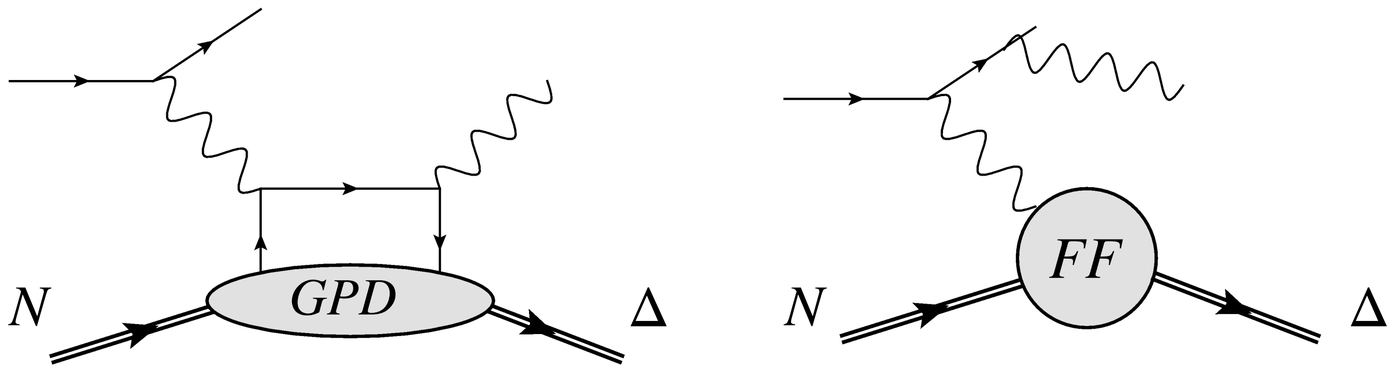
$$\int_{(m_N+m_\pi)^2}^{\infty} dW_{\pi N}^2 \, \frac{d\sigma(eN \to e\gamma B^* \to e\gamma\pi N)}{dQ^2\, dx_B\, dt\, d\Phi\, dW_{\pi N}^2}$$

$$\propto \boxed{\frac{d\sigma(eN \to e\gamma B^*)}{dQ^2\, dx_B\, dt\, d\Phi}} \underbrace{\int_{(m_N+m_\pi)^2}^{\infty} dW_{\pi N}^2 \, \frac{W_{\pi N}\Gamma(W_{\pi N})}{(W_{\pi N}^2 - m_{B^*}^2)^2 + m_{B^*}^2\Gamma^2(W_{\pi N})}}_{\sim \mathcal{O}(1) \quad \text{for} \quad \Gamma(m_{B^*})/m_{B^*} \ll 1}$$

$eN \to e'\gamma\Delta$ amplitude: VCS + BH

$$\frac{\Gamma(m_\Delta)}{m_\Delta} \simeq 10\ \%$$

We treat the Δ as a stable hadron state (T_{int} ~ 0.1 fm vs T_Δ ~ 1 fm)



N-Δ DVCS amplitudes

Harmonic expansion in the angle ϕ between the leptonic and production planes

$$|\mathcal{M}_{\rm BH}|^2 = \frac{e^6}{x_B^2 y^2 t \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left[\sum_{n=0}^{2} c_n^{\rm BH}\cos(n\phi) + s_1^{\rm BH}\sin\phi\right],$$

$$|\mathcal{M}_{\rm VCS}|^2 = \frac{e^6}{y^2 Q^2} \left[\sum_{n=0}^{2} c_n^{\rm VCS}\cos(n\phi)\right],$$

$$\mathcal{I} = \frac{e^6}{x_B y^3 t \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left\{c_0^{\mathcal{I}} + \sum_{n=1}^{3}\left[c_n^{\mathcal{I}}\cos(n\phi) + s_n^{\mathcal{I}}\sin(n\phi)\right]\right\}$$

Cf. Diagonal DVCS:
Belitsky, Müller, Kirchner, *Nucl.Phys.B* 629 (2002) 323-392

Spin asymmetries and azimuthal angle modulations

Leading-twist harmonics; large-N_c CFFs

observable	harmonic	CFF combination	remark
A_{LU}	$\sin\phi$	Im $\mathcal{H}_M$	$\mathcal{C}_1$ weight $\propto x_B$: $< 1\%$ at the EIC
A_{UL}	$\sin\phi$	Im $\mathcal{H}_M$, Im $\mathcal{C}_1$	$\propto \xi$: $\lesssim 0.02$ at the EIC
$\sigma_{UU}^{\mathcal{I}}, A_{LL}$	$\cos\phi$	Re $\mathcal{H}_M$, Re $\mathcal{C}_1$	A_{LL} dominated by BH

- $\mathcal{C}_2$ (pion pole): real, absent from single-spin asymmetries
- $\mathcal{H}_M$ (M1): weight $\propto (t_{\text{min}} - t)$
- Higher harmonics: suppressed by powers of $K \propto \sqrt{(t_{\text{min}} - t)/Q^2}$

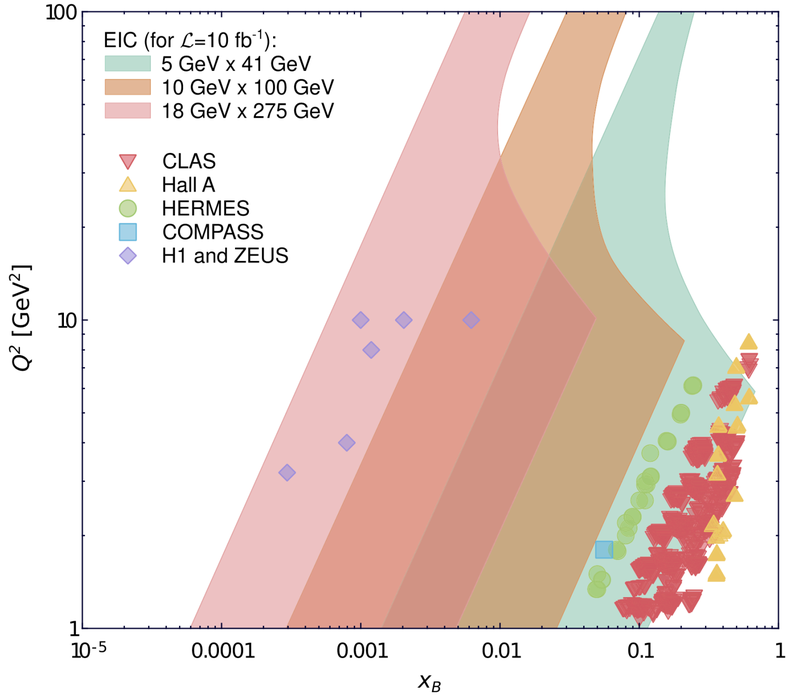
Preliminary Results and Discussions

Opportunities for DVCS at the EIC

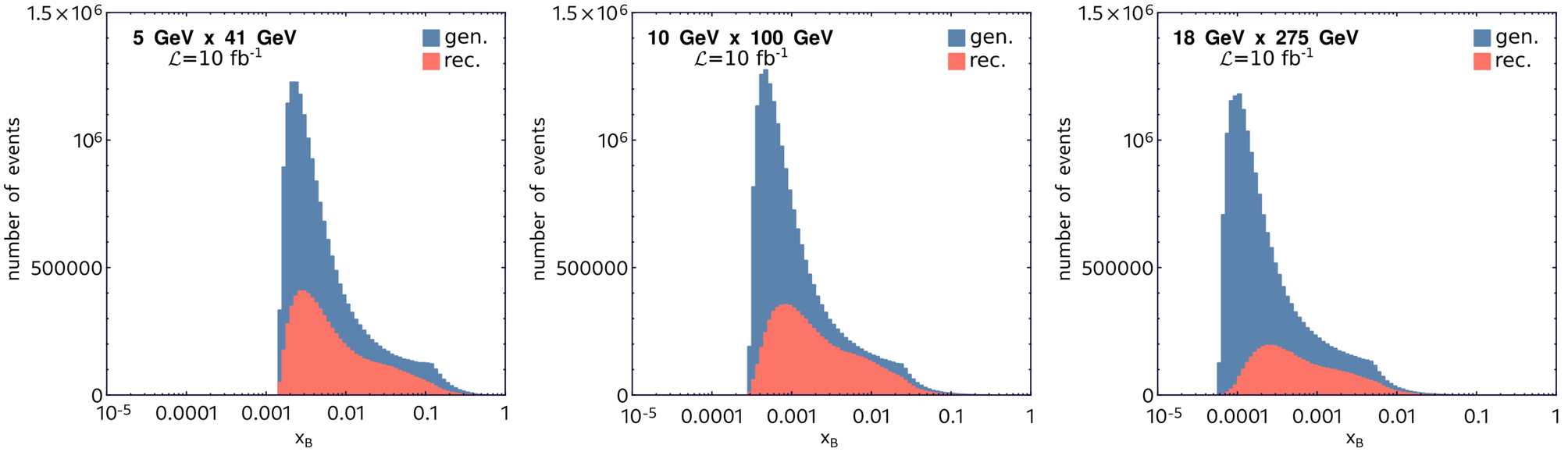
EIC promises

EIC Yellow report, 2022

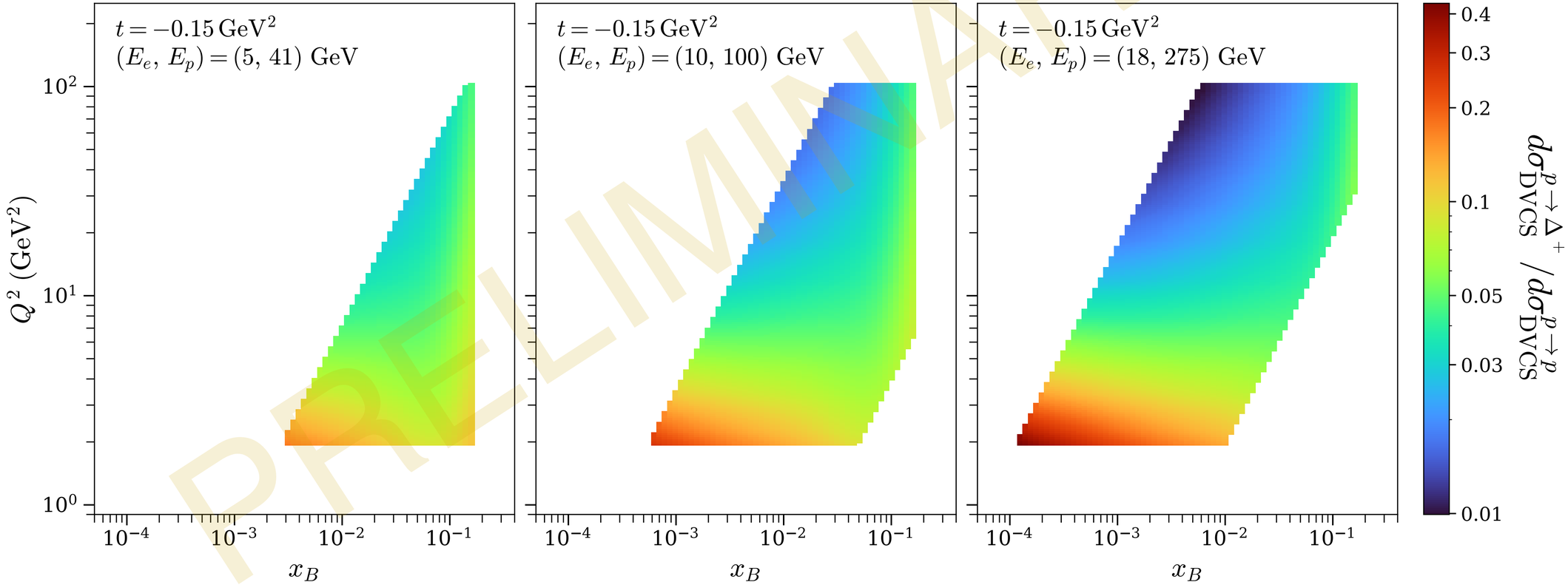
- Broad kinematic coverage across the valence and sea regions
- Polarized lepton and proton beams
- High luminosity



Dedicated study for diagonal DVCS off a proton,
E. Aschenauer et. al., PRD 112 (2025)



vs. diagonal DVCS



PRELIMINARY

At small xB, proton $\mathcal{H}$ (singlet sea) grows with Q^2 by evolution;

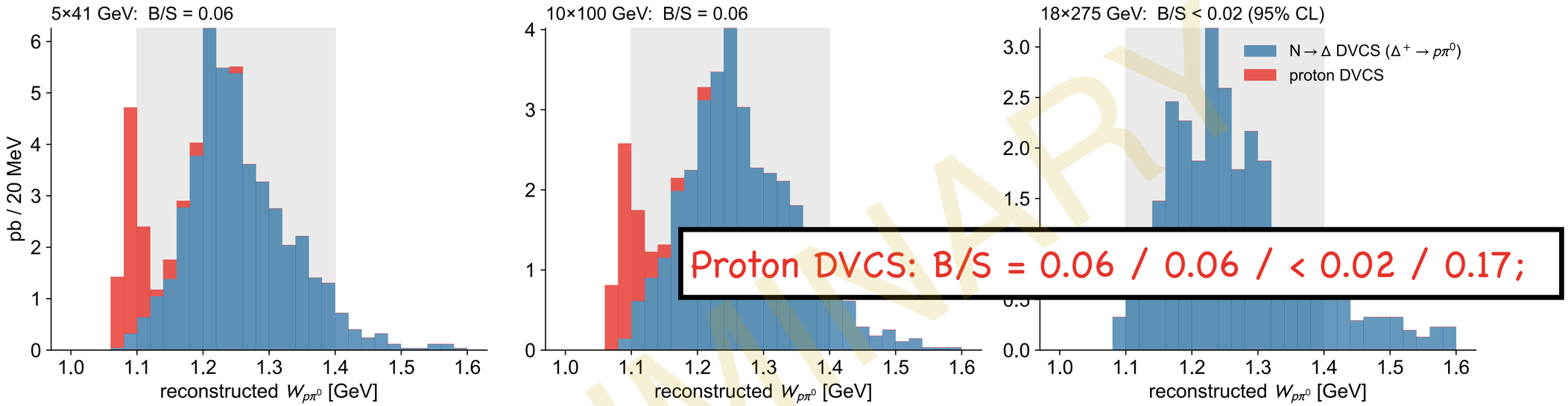
$\mathcal{H}_M = \sqrt{2}\mathcal{E}^{u-d}$ (nonsinglet) does not $\longrightarrow$ ratio falls with Q^2 growing

$$\frac{d\sigma_{\mathrm{DVCS}}(p \to \Delta^+)}{d\sigma_{\mathrm{DVCS}}(p \to p)}$$

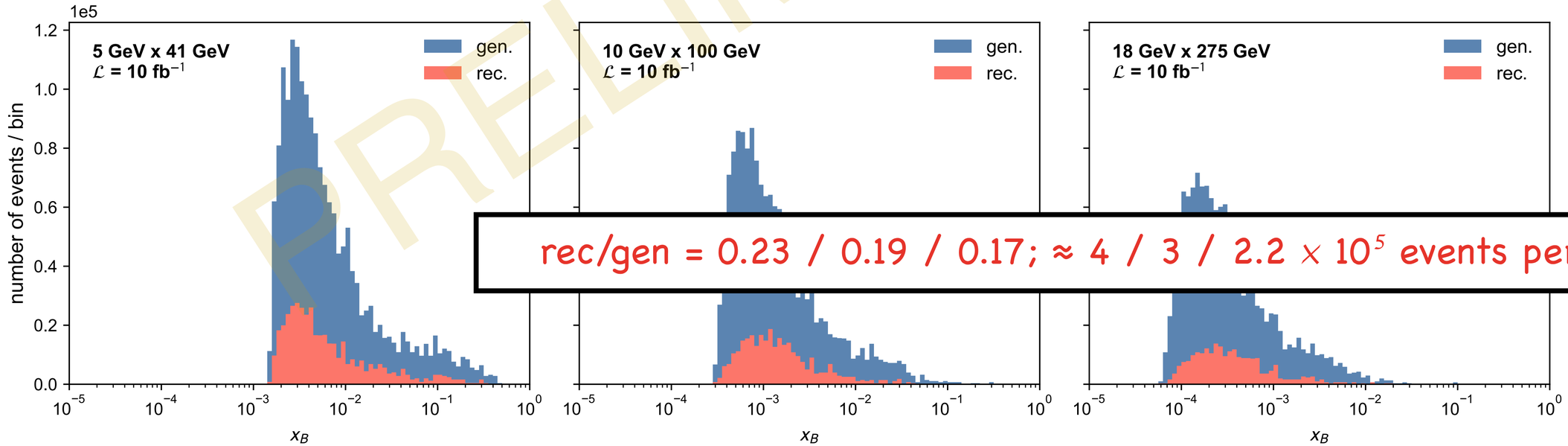
~ 10^{-2} to 10^{-1} of the DVCS cross section is expected

ePIC simulation

ePIC software (DD4hep/Geant4 + EICrecon), eic.github.io;
EpIC (EPJC 82, 819) for proton DVCS background



Proton DVCS: B/S = 0.06 / 0.06 / < 0.02 / 0.17;

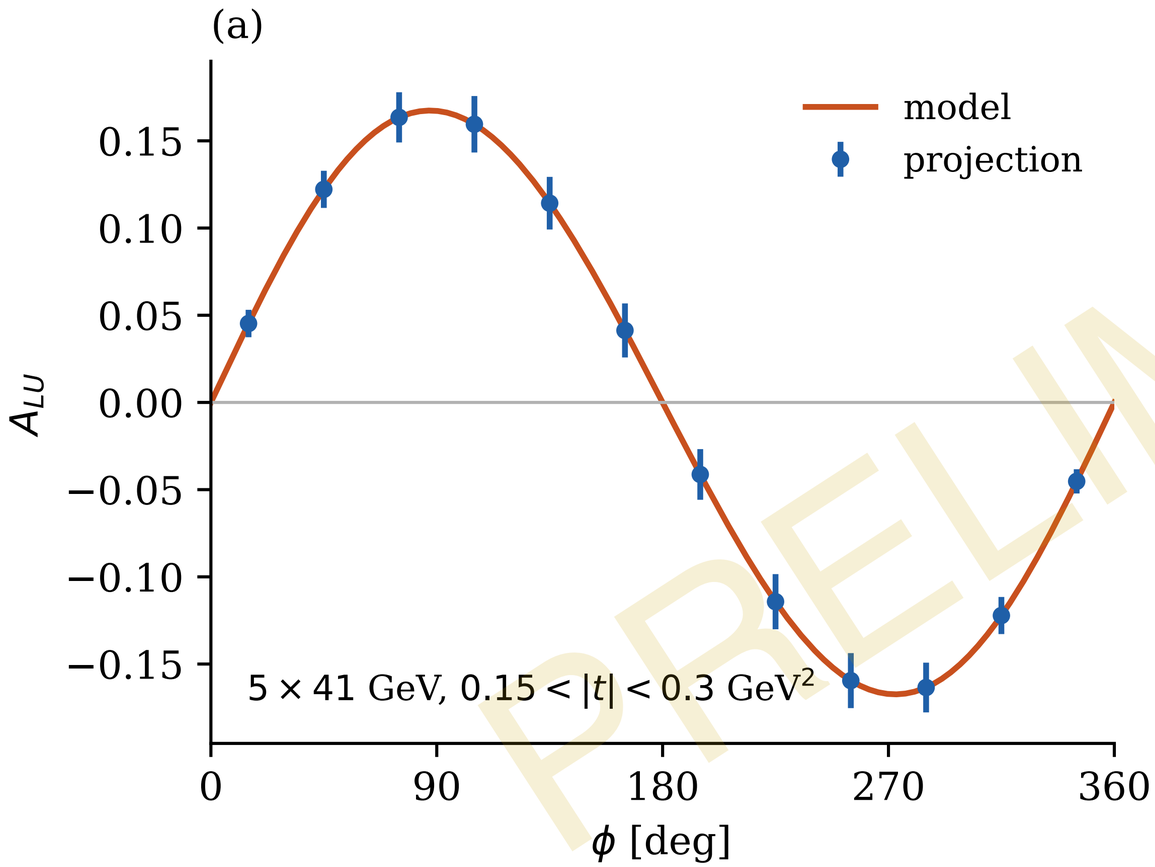


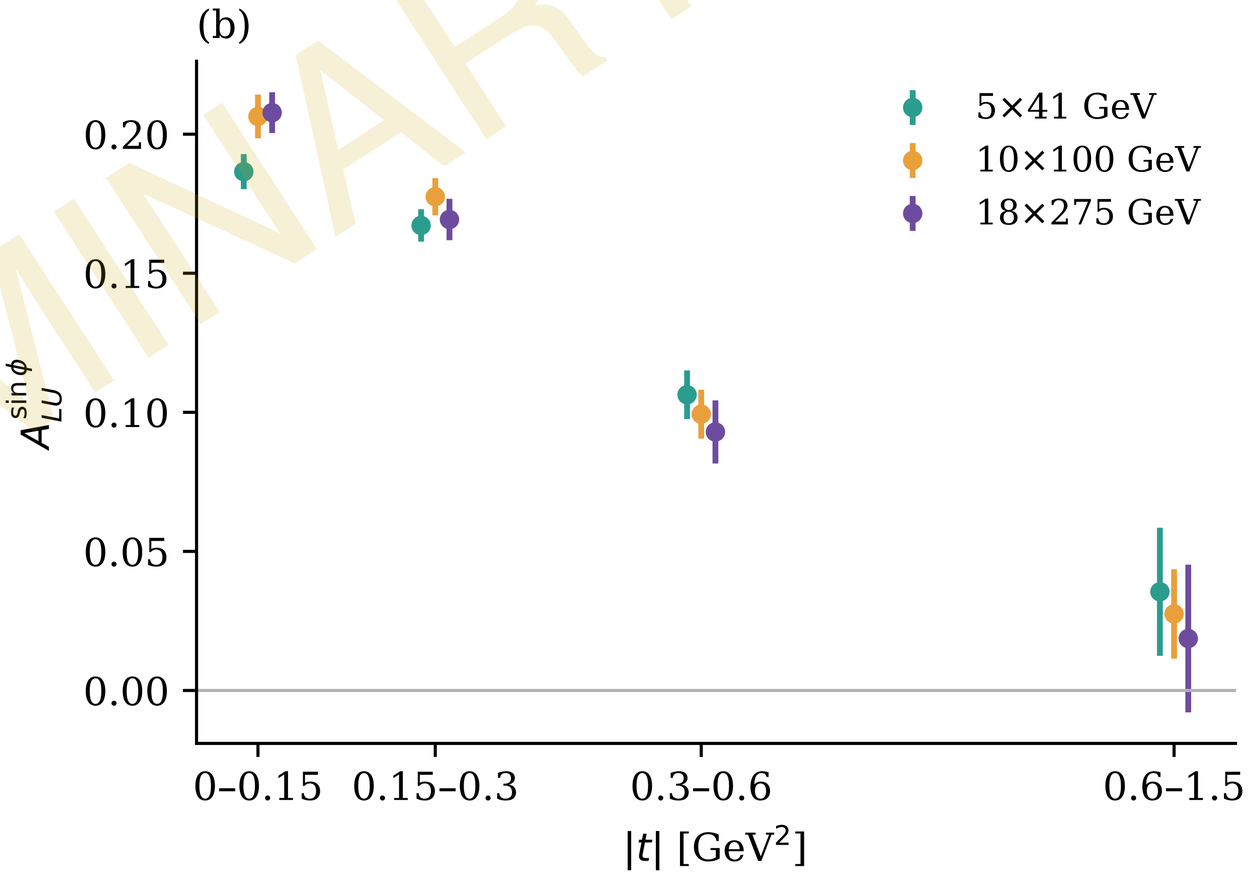
rec/gen = 0.23 / 0.19 / 0.17; ≈ 4 / 3 / 2.2 × 10^5 events per 10 fb^{-1}

per 10 fb^{-1}, $1 < Q^2 < 100$ GeV^2, $0.01 < y < 0.85$, $0.05 < |t| < 1.5$ GeV^2 ($|t| \leq Q^2/4$)

PRELIMINARY

A_{LU}





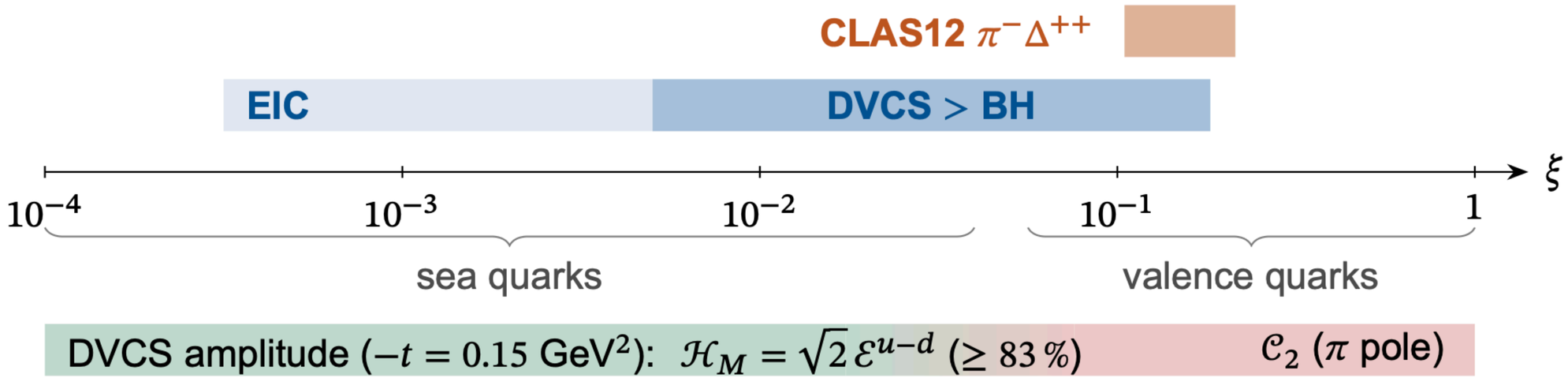
PRELIMINARY

$A_{LU}^{\sin\varphi} \approx 0.1–0.2$ for $|t| < 0.6$ GeV², measured to ±0.006–0.011 per $|t|$ bin (10 fb^{-1}, stat.)

$A_{LU} \propto \mathrm{Im}\,\mathcal{H}_M = \sqrt{2}\,\mathrm{Im}\,\mathcal{E}^{u-d}$: the isovector helicity-flip GPD, including its sea, at $x_B \sim 10^{-4}$–10^{-2}

CLAS12 vs EIC

Skewness $\xi \simeq x_B/(2-x_B)$ of the measured or projected points



	CLAS12	EIC
kinematics	$x_B = 0.19$–0.35, $-t = 0.3$–1.2 GeV^2	$x_B \approx 6\times10^{-4}$–$0.3$ ($Q^2 = 5$ GeV^2), $-t = 0.15$ GeV^2
σ_{VCS} of N-Δ DVCS	$\mathcal{C}_2$ 60–98 %, $\mathcal{H}_M \lesssim 40\,\%$, $\mathcal{C}_1 \lesssim 7\,\%$	$\mathcal{H}_M \geq 96\,\%$ for $x_B \lesssim 10^{-2}$
A_{LU}	Im $\mathcal{H}_M$ and Im $\mathcal{C}_1$	Im $\mathcal{H}_M$ ($\mathcal{C}_1 < 1\,\%$)

Summary and outlook

- **EIC will provide a great opportunity for studying the transition GPDs**

  Kinematic range: small x_B, larger Q^2
  A_LU isolates $\mathcal{H}_M = \sqrt{2}\mathcal{E}^{u-d}$ (incl. sea); $\mathcal{C}_1$ and the pion pole need JLab

- **Feasibility studies at the EIC**

  Sea quark region (small xB) of the transition GPDs
  Expected # of events ≈ (2–4) × 10^5 per 10 fb^{-1}

- **Tasks**

  N-Delta transition process with full GPD sets: test for the large Nc picture

  Other reaction mechanisms for transition GPDs at the EIC: Meson production, hyperons
  SDHEP @J-PARC with meson beams (N. Tomida)

  Properties of the transition GPDs and their moments within ChQSM:
  systematics in the large Nc, interpretation, …

  Complete description of $\gamma^* N \to \gamma N \pi$ (non-resonant transition GPDs)

M. Polyakov and S. Stratmann, hep-ph/0609045
Pion case: S. Son and K. Semenov *JHEP* 01 (2025) 119


Thank you very much!