Transition GPDs: Recent Results from CLAS12 and Beyond

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UCONN | UNIVERSITY OF CONNECTICUT

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clas

APCTP Workshop on the Physics of Electron Ion Collider

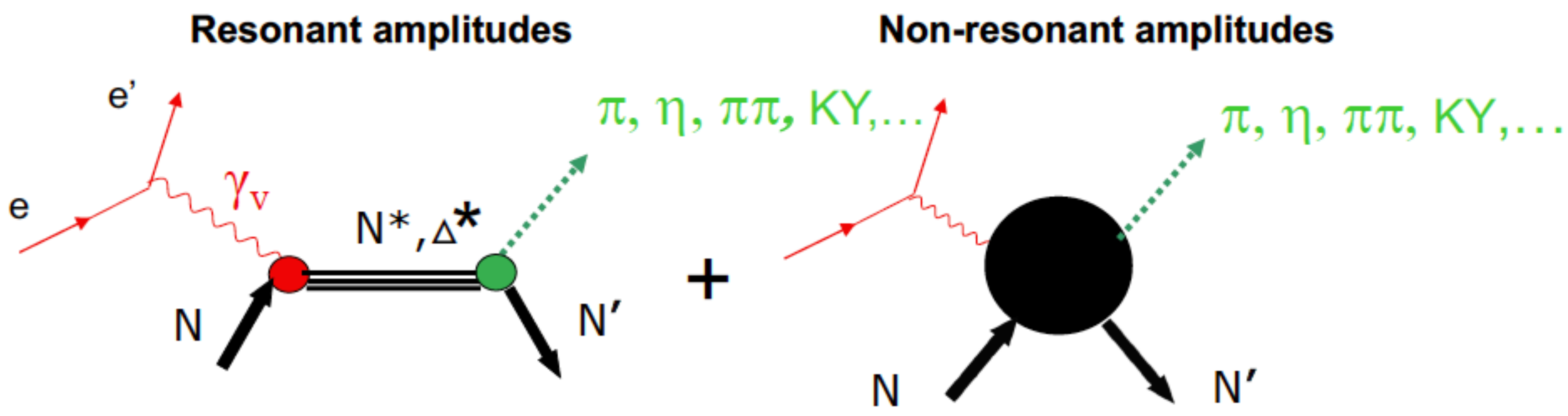
Nov 2, 2022, 8:00 AM → Nov 4, 2022, 7:30 PM Asia/Seoul

Howard Johnson Incheon Airport Hotel

Abhay Deshpande (Stony Brook University), Yuji Goto (BNL), Kyungseon Joo (Co-Chair) (University of Connecticut), Yongsun Kim (Sejong University), Yongseok Oh (Co-Chair) (Kyungpook National University), Christian Weiss (Jefferson Lab)

Professor Yongseok OH (1964 – 2023)

N* Electroexcitation studies with CLAS



1. N* program was a flagship program with JLab 6 GeV.
2. A rich spectrum of baryon resonances is known to emerge from QCD.
3. Results on $\gamma_v pN^*$ electrocouplings of spin-isospin flip, radial, and orbital excited nucleon resonances have been mapped out for a large range of Q^2.
4. Measured electromagnetic transition (N->N*) form factors in electroproduction experiments describe the spatial distribution of charge and current in the dynamical system.

Summary of Published CLAS Data on Exclusive Meson Electroproduction off Protons in N* Excitation Region

Hadronic final state	Covered W-range, GeV	Covered Q^2-range, GeV^2	Measured observables
$\pi^+ n$	**1.1-1.38** **1.1-1.55** **1.1-1.70** **1.6-2.00**	**0.16-0.36** **0.3-0.6** **1.7-4.5** **1.8-4.5**	**$d\sigma/d\Omega$** **$d\sigma/d\Omega$** **$d\sigma/d\Omega$, A_b** **$d\sigma/d\Omega$**
$\pi^0 p$	**1.1-1.38** **1.1-1.68** **1.1-1.39** **1.1-1.80**	**0.16-0.36** **0.4-1.8** **3.0-6.0** **0.4-1.0**	**$d\sigma/d\Omega$** **$d\sigma/d\Omega$, A_b,A_t,A_{bt}** **$d\sigma/d\Omega$** **$d\sigma/d\Omega$, A_b**
ηp	**1.5-2.3**	**0.2-3.1**	**$d\sigma/d\Omega$**
$K^+\Lambda$	**thresh-2.6**	**1.40-3.90** **0.70-5.40**	**$d\sigma/d\Omega$** **P^0, P'**
$K^+\Sigma^0$	**thresh-2.6**	**1.40-3.90** **0.70-5.4**	**$d\sigma/d\Omega$** **P'**
$\pi^+\pi^- p$	**1.3-1.6** **1.4-2.1** **1.4-2.0**	**0.2-0.6** **0.5-1.5** **2.0-5.0**	**Nine 1-fold differential cross sections**

- $d\sigma/d\Omega$–CM angular distributions
- A_b,A_t,A_{bt}-longitudinal beam, target, and beam-target asymmetries
- P^0, P' –recoil and transferred polarization of strange baryon

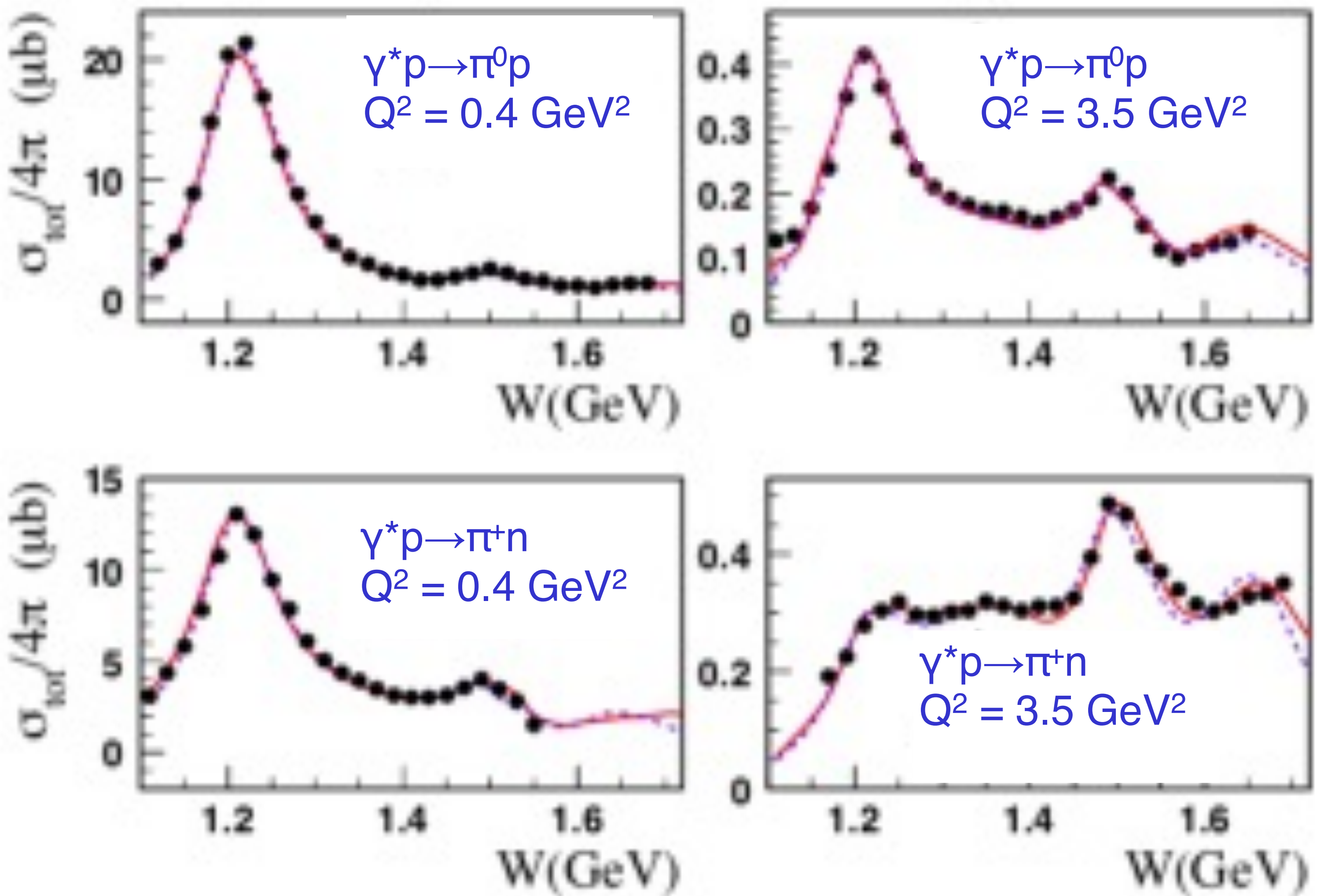
Over 150,000 data points!

Almost full coverage of the final state hadron phase space

The measured observables from CLAS are stored in the CLAS Physics Data Base http://clas.sinp.msu.ru/cgi-bin/jlab/db.cgi

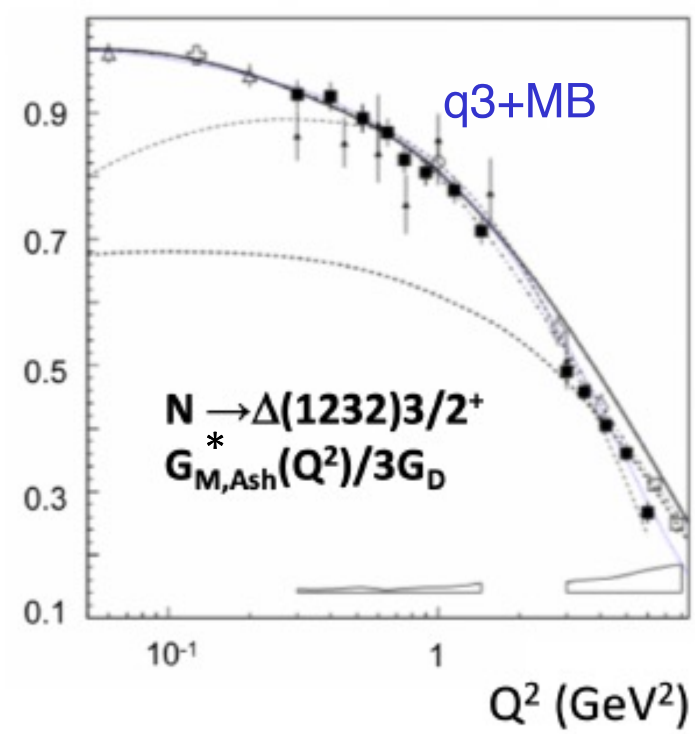
Integrated cross section at W < 2 GeV for γ*p→π⁺n and γ*p→π⁰p

→ **States with different quantum numbers respond differently to increase in Q^2.**

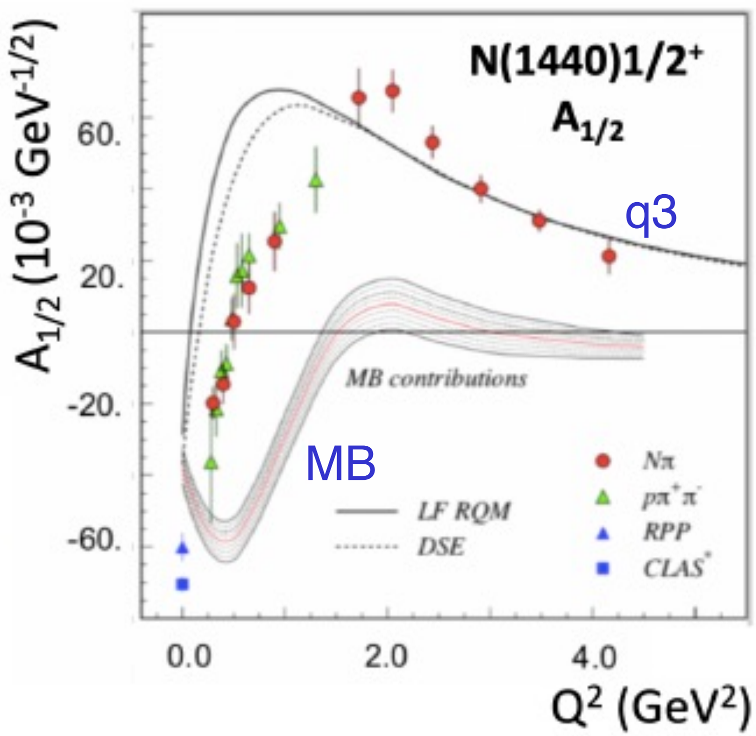


q3 and MB contributions in Δ(1232)3/2⁺ and Roper N(1440)1/2⁺

Δ(1232)3/2⁺



Roper N(1440)1/2⁺



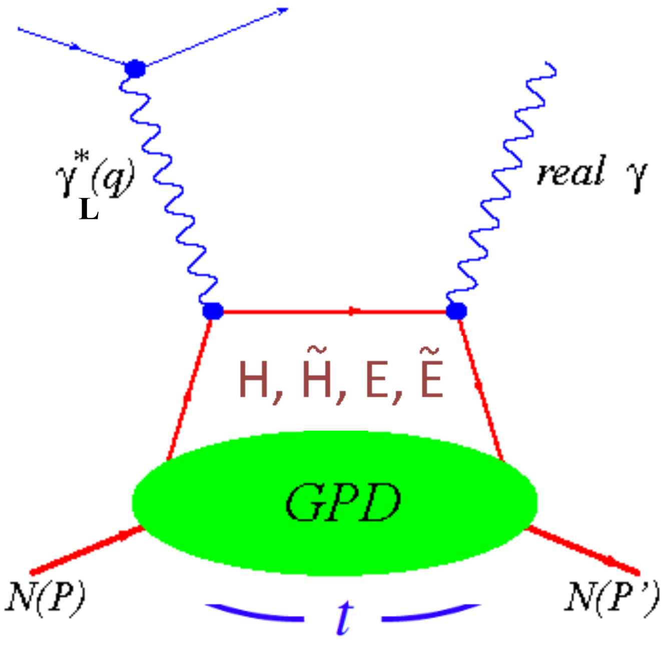
The meson-baryon cloud becomes the biggest contribution for $Q^2 < 1$ GeV^2, but almost vanishes for $Q^2 > 2$ GeV^2.

Generalized Parton Distributions (GPDs)

1. GPDs unify the concepts of the elastic nucleon form factors and the quark/gluon particle densities.
2. GPDs encode the 3-dimensional partonic structure of the nucleon by correlating the internal transverse position of the partons with their longitudinal momentum fraction.
3. GPDs quantify the distribution of energy, momentum, angular momentum, and forces in the nucleon, which allows one to discuss the mechanical properties of the quantum system.
4. Total 8 independent GPDs of which 4 do not flip the parton helicity (twist-2), while the other 4 flip the parton helicity and are also known as transversity GPDs (twist-3) indicated by T in the subscript: $H, \tilde{H}, E, \tilde{E}$ and $H_T, \tilde{H}_T, E_T, \tilde{E}_T$.
5. "Nucleon imaging" is a flagship program of JLab 12 GeV.

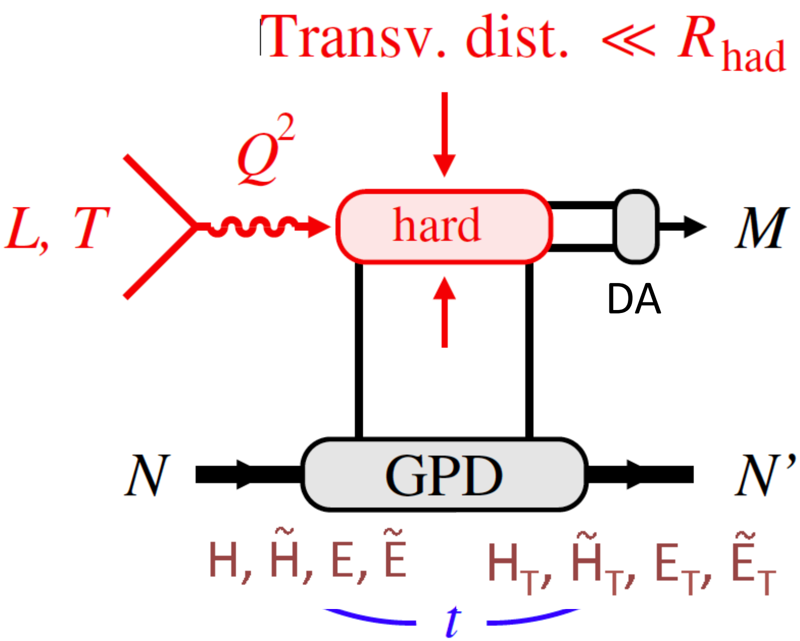
Study GPDs: Deeply Exclusive Processes

Deeply Virtual Compton Scattering (DVCS)



+ Clean process
- Sensitive to chiral even GPDs

Deeply Virtual Meson Production (DVMP)

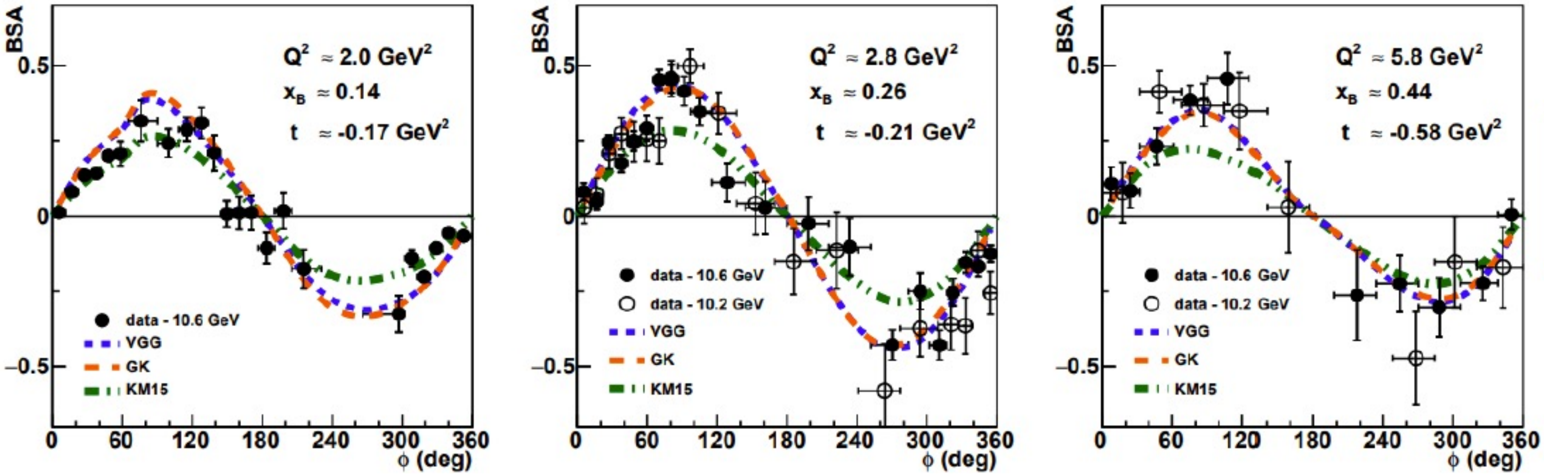


+ Access to transversity degrees of freedom described by chiral-odd GPDs
- Distribution Amplitude (DA) is involved as additional soft non pert. quantity

Beam spin asymmetry for DVCS and DVMP on the proton with CLAS12

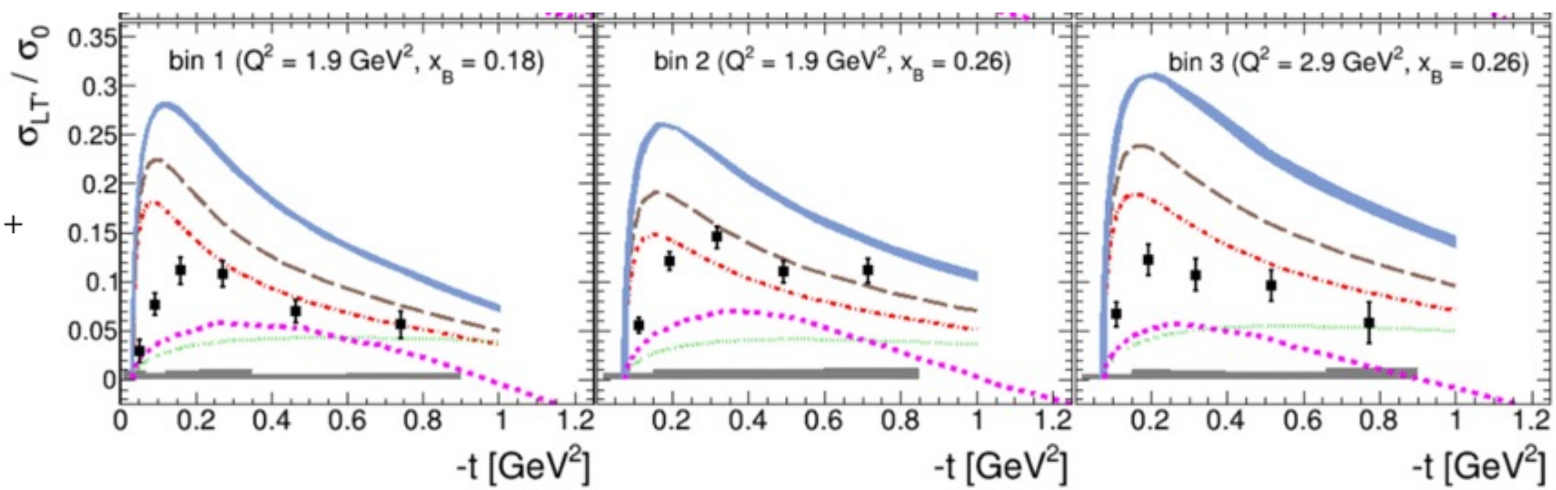
G. Christiaens et al. (CLAS), Phys. Rev . Lett 130 (2023)

$\vec{e}p \rightarrow e'p\gamma$



S. Diel et al. (CLAS), Phys. Lett B 839 (2023)

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



N→N* Transition GPDs

1. What is the spatial distribution of quarks in excited baryon states, and how does it differ from the ground state? Can we construct tomographic images of the baryon resonances?
2. What are the distributions of energy, momentum, and angular momentum carried by quarks and gluons in baryon resonances? Can we quantify the mechanical properties of the baryon resonances?
3. What is the distribution of quark tensor charge in baryon resonances? What is the gluonic structure of resonances?
4. The transition GPDs allow one to construct tomographic images of the N* at the same level as the nucleon and discuss the QCD structure of resonances in these terms.

N→N* Transition GPDs

K. Semenov, M. Vanderhaeghen, arXiv:2303.00119 (2023)

For the N→Δ transition: 8 twist-2 transition GPDs

unpolarized:

$$\int_{-1}^{1} dx H_M(x;\xi;t) = 2G_M^*(t)$$
$$\int_{-1}^{1} dx H_E(x;\xi;t) = 2G_E^*(t)$$
$$\int_{-1}^{1} dx H_C(x;\xi;t) = 2G_C^*(t)$$
$$\int_{-1}^{1} dx H_4(x;\xi;t) = 0$$

Jones-Scardon EM FF for the N → Δ transition

polarized:

$$\int_{-1}^{1} dx C_1(x;\xi;t) = 2C_5^A(t)$$
$$\int_{-1}^{1} dx C_2(x;\xi;t) = 2C_6^A(t)$$
$$\int_{-1}^{1} dx C_3(x;\xi;t) = 2C_3^A(t)$$
$$\int_{-1}^{1} dx C_4(x;\xi;t) = 2C_4^A(t)$$

Adler form factors

For N→P_{11}(1440) transition: 4 (2+2) twist-2 transition GPDs

For N→D_{13}(1520) transition: 8 (4+4) twist-2 transition GPDs

For N→S_{11}(1520) transition: 4 (2+2) twist-2 transition GPDs

Physics content of transition GPDs

➔ Transition GPDs connect the 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 distribution within nucleon resonances via gravitational form factors ➔ Extension of the formalism to resonances needed!

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

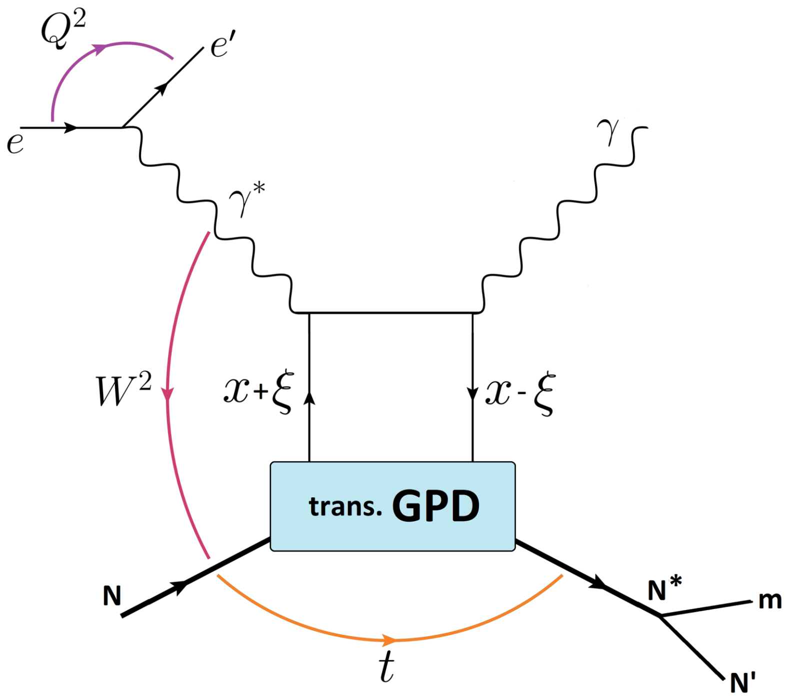
V.D. Burkert, L. Elouadrhiri, F.X. Girod, Nature **557**, 396 (2018)

➔ Access to the anomalous magnetic moment and to the tensor charge of resonances
➔ Extension of the formalism needed ➔ Twist-3 transition GPDs

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

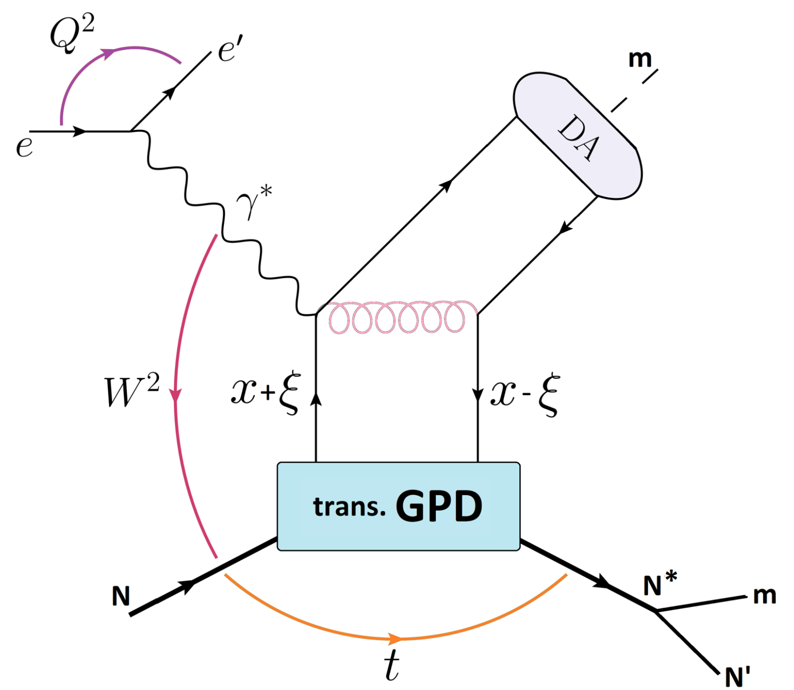
Non-diagonal DVCS / DVMP

non-diagonal DVCS



Access to the helicity non-flip transition GPDs

non-diagonal DVMP



+ Access to the helicity flip transition GPDs

factorization expected for: $-t/Q^2$ small, $Q^2 > M^2_{N*}$ x_B fixed, W > 2GeV

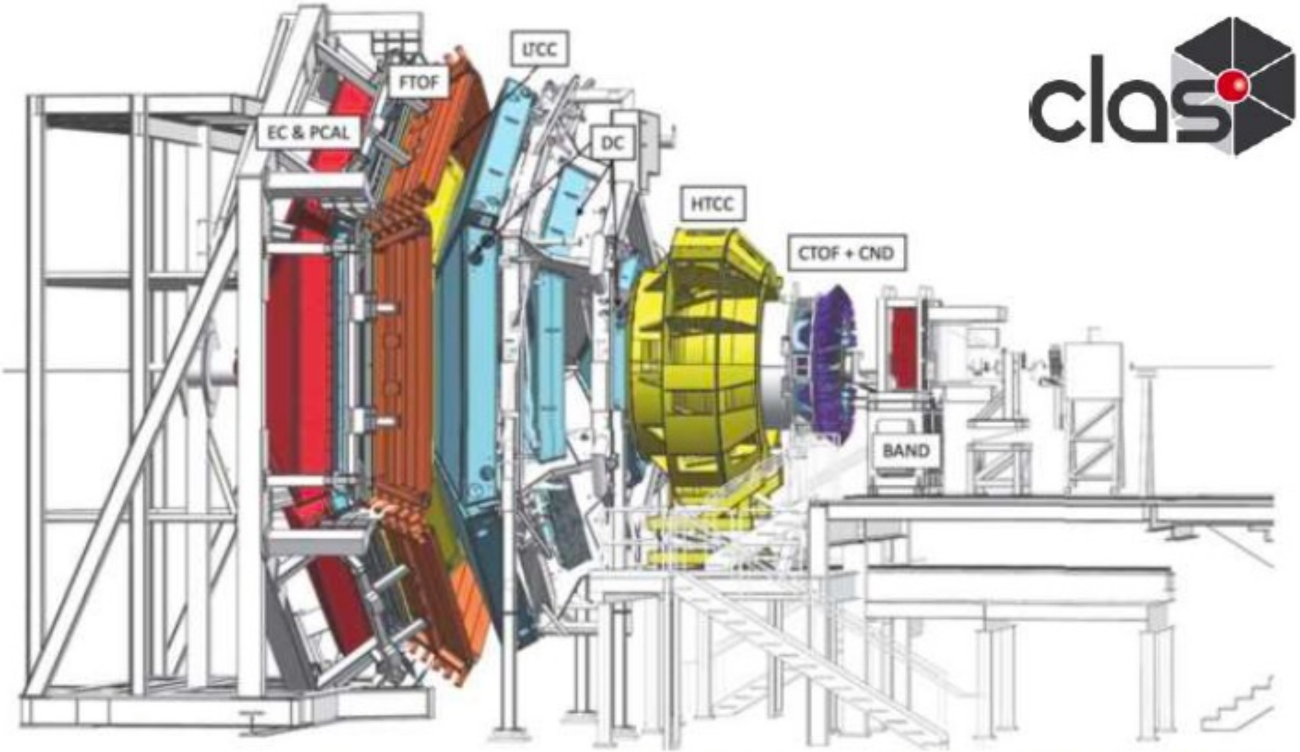
PHYSICAL REVIEW LETTERS **131,** 021901 (2023)

First Measurement of Hard Exclusive $\pi^- \Delta^{++}$ Electroproduction Beam-Spin Asymmetries off the Proton

S. Diehl,[34,6] N. Trotta,[6] K. Joo,[6] P. Achenbach,[39] Z. Akbar,[46,12] W. R. Armstrong,[1] H. Atac,[38] H. Avakian,[39] L. Baashen,[11] N. A. Baltzell,[39] L. Barion,[15] M. Bashkanov,[45] M. Battaglieri,[17] I. Bedlinskiy,[28] F. Benmokhtar,[8] A. Bianconi,[42,20] A. S. Biselli,[9] F. Bossù,[4] K.-T. Brinkmann,[34] W. J. Briscoe,[13] D. Bulumulla,[33] V. Burkert,[39] R. Capobianco,[6] D. S. Carman,[39] J. C. Carvajal,[11] A. Celentano,[17] G. Charles,[21,33] P. Chatagnon,[39,21] V. Chesnokov,[36] G. Ciullo,[15,10] P. L. Cole,[25] M. Contalbrigo,[15] G. Costantini,[42,20] V. Crede,[12] A. D'Angelo,[18,35] N. Dashyan,[48] R. De Vita,[17] A. Deur,[39] C. Djalali,[32,37] R. Dupre,[21] M. Ehrhart,[21,*] A. El Alaoui,[40] L. El Fassi,[27] L. Elouadrhiri,[39] S. Fegan,[45] A. Filippi,[19] G. Gavalian,[39] D. I. Glazier,[44] A. A. Golubenko,[36] G. Gosta,[42,20] R. W. Gothe,[37] Y. Gotra,[39] K. Griffioen,[47] K. Hafidi,[1] H. Hakobyan,[40] M. Hattawy,[33,1] T. B. Hayward,[6] D. Heddle,[5,39] A. Hobart,[21] M. Holtrop,[29] I. Illari,[13] D. G. Ireland,[44] E. L. Isupov,[36] H. S. Jo,[24] R. Johnston,[26] D. Keller,[46] M. Khachatryan,[33] A. Khanal,[11] A. Kim,[6] W. Kim,[24] V. Klimenko,[6] A. Kripko,[34] V. Kubarovsky,[39] S. E. Kuhn,[33] V. Lagerquist,[33] L. Lanza,[18,35] M. Leali,[42,20] S. Lee,[1] P. Lenisa,[15,10] X. Li,[26] I. J. D. MacGregor,[44] D. Marchand,[21] V. Mascagna,[42,41,20] G. Matousek,[7] B. McKinnon,[44] C. McLauchlin,[37] Z. E. Meziani,[1,38] S. Migliorati,[42,20] R. G. Milner,[26] T. Mineeva,[40] M. Mirazita,[16] V. Mokeev,[39] P. Moran,[26] C. Munoz Camacho,[21] P. Naidoo,[44] K. Neupane,[37] S. Niccolai,[21] G. Niculescu,[23] M. Osipenko,[17] P. Pandey,[33] M. Paolone,[30,38] L. L. Pappalardo,[15,10] R. Paremuzyan,[39,29] S. J. Paul,[43] W. Phelps,[5,13] N. Pilleux,[21] M. Pokhrel,[33] J. Poudel,[33,†] J. W. Price,[2] Y. Prok,[33] A. Radic,[40] B. A. Raue,[11] T. Reed,[11] J. Richards,[6] M. Ripani,[17] J. Ritman,[14,22] P. Rossi,[39,16] F. Sabatié,[4] C. Salgado,[31] S. Schadmand,[14] A. Schmidt,[13,26] Y. G. Sharabian,[39] U. Shrestha,[6,32] D. Sokhan,[4,44] N. Sparveris,[38] M. Spreafico,[17] S. Stepanyan,[39] I. Strakovsky,[13] S. Strauch,[37] M. Turisini,[16] R. Tyson,[44] M. Ungaro,[39] S. Vallarino,[15] L. Venturelli,[42,20] H. Voskanyan,[48] E. Voutier,[21] D. P. Watts,[45] X. Wei,[39] R. Williams,[45] R. Wishart,[44] M. H. Wood,[3] M. Yurov,[27] N. Zachariou,[45] Z. W. Zhao,[7,33] and M. Zurek[1]

(CLAS Collaboration)

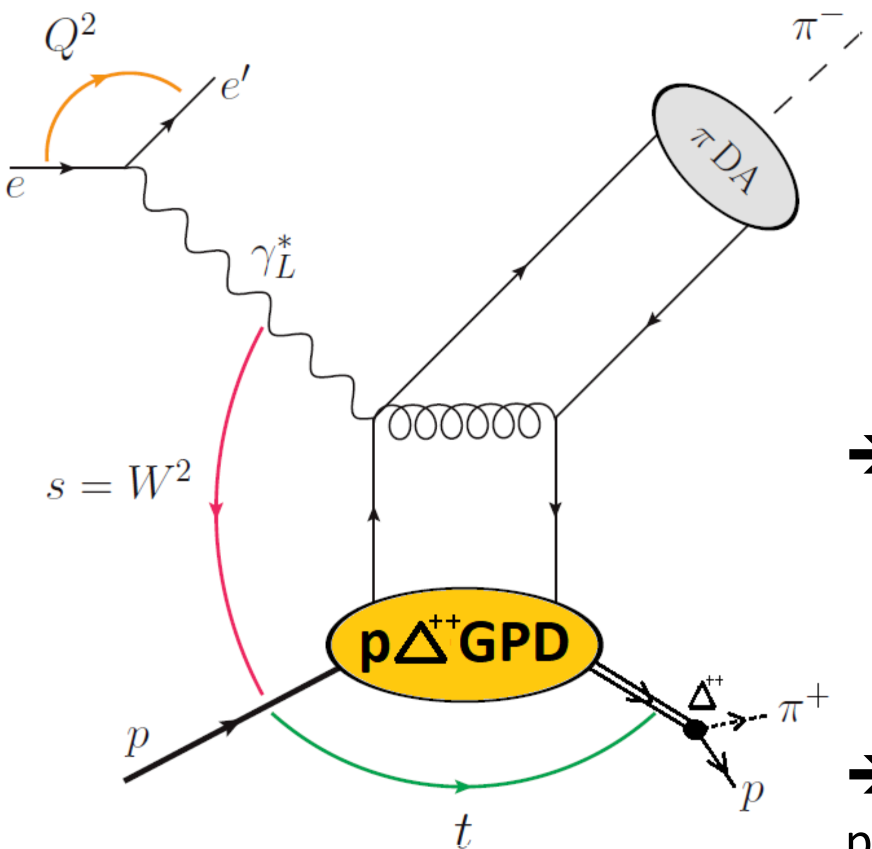
$ep \rightarrow e\Delta^{++}\pi^- \rightarrow ep\pi^+\pi^-$ with CLAS12



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

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



Factorization expected for:

$-t / Q^2 << 1$, x_B fixed, and $Q^2 > M_\Delta^2$

➔ Provides access to p-Δ transition GPDs

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

I_z = +3/2

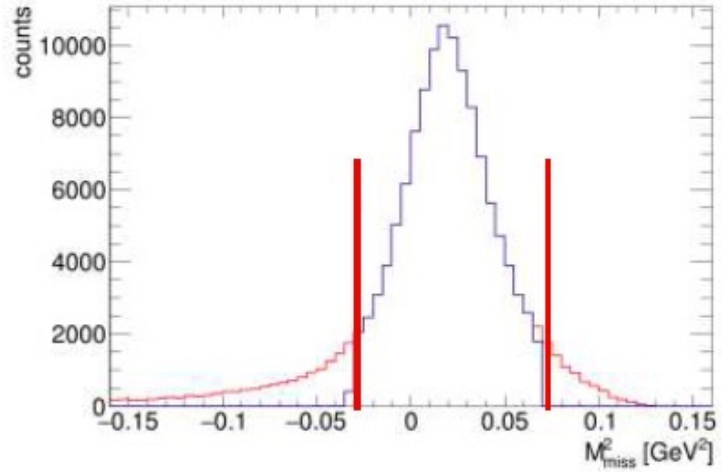
➔ The pπ^+ final state can **only** be populated by **Δ-resonances ->** Large gap between Δ(1232) and higher resonances

Event Selection and Kinematic Cuts

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

$$X = \pi^+$$

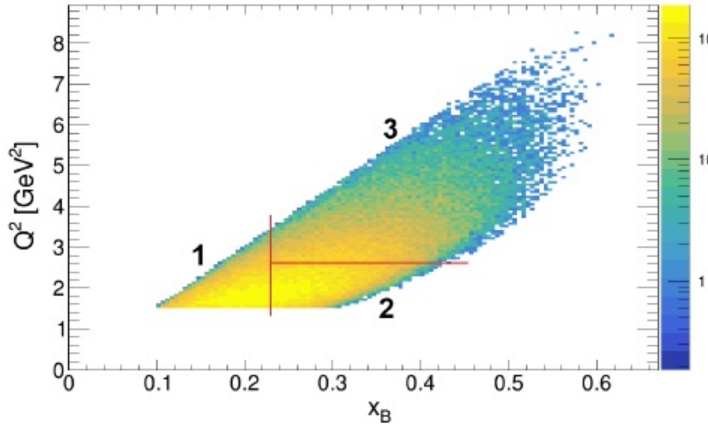
➔ 2 sigma cut around the missing π⁺



Kinematic cuts:

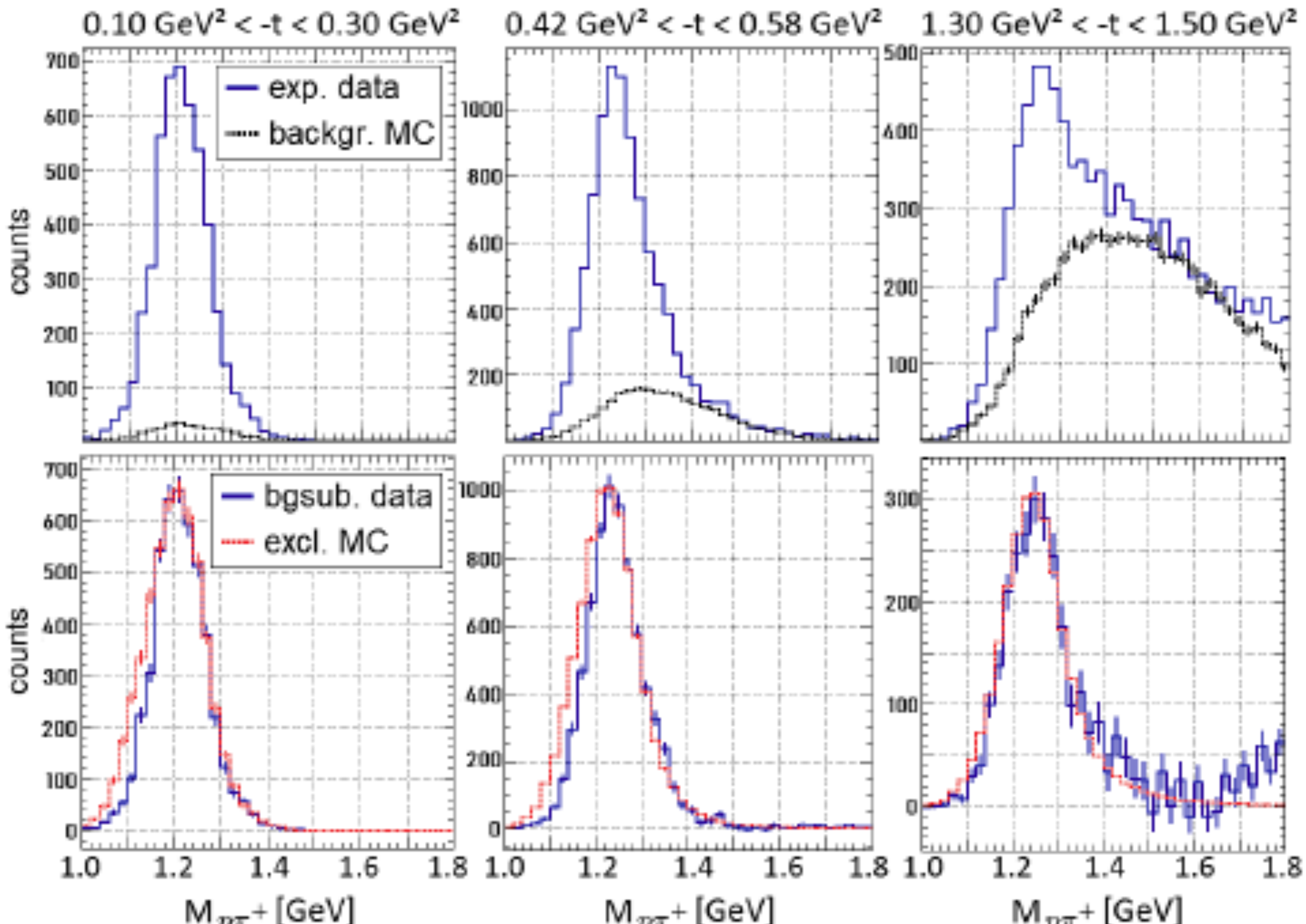
$Q^2 > 1.5$ GeV² $\quad W > 2$ GeV

$y < 0.75$ $\quad -t < 1.5$ GeV²

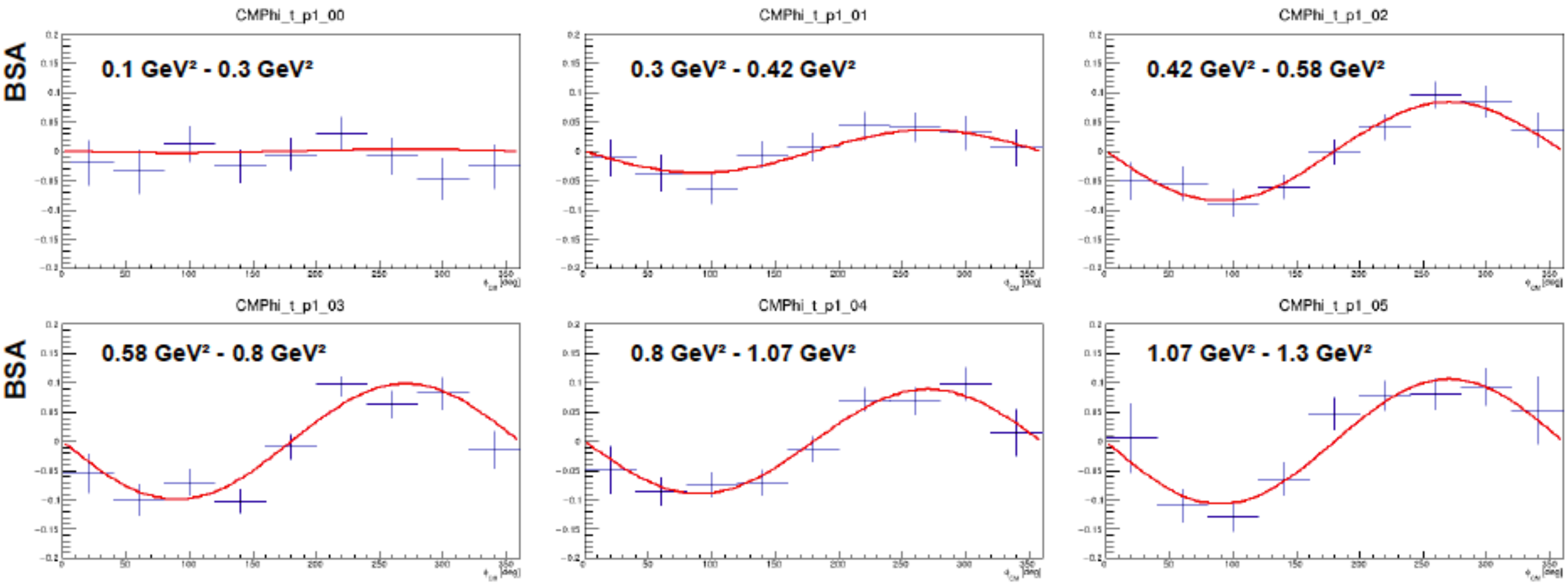


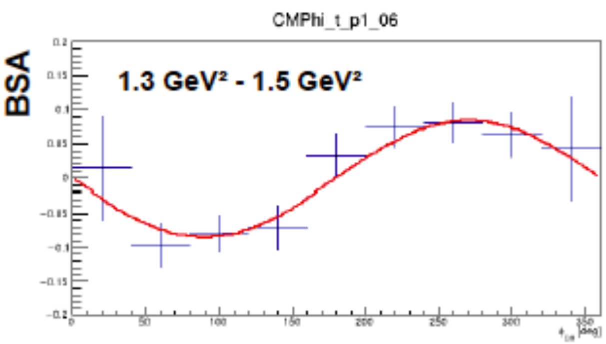
Signal and Background Separation

M(π⁺π⁻) > 1.1 GeV



Resulting Beam Spin Asymmetries (Q^2-x_B integrated)



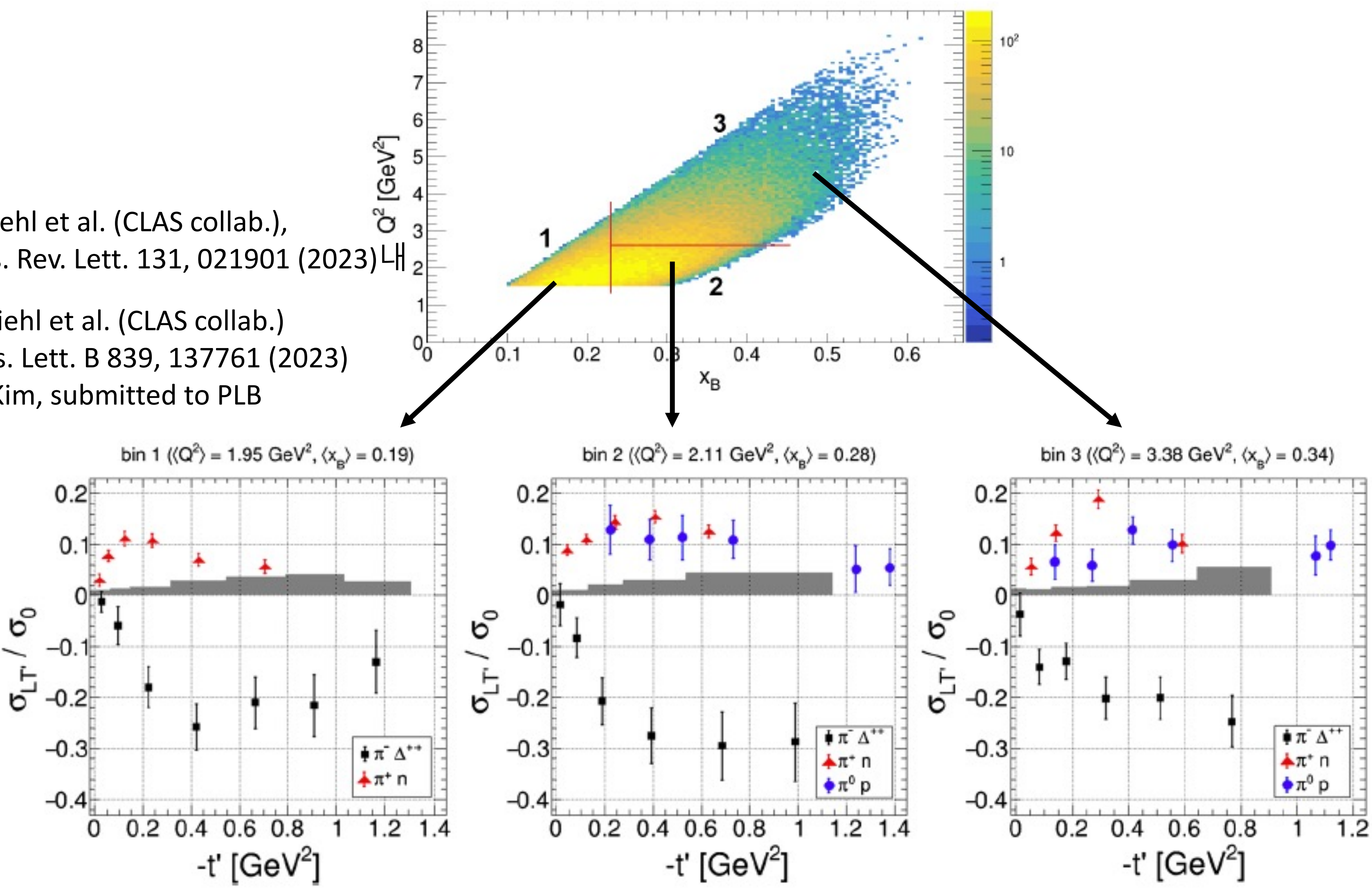


$$BSA_i = \frac{1}{P_e}\frac{N_i^+ - N_i^-}{N_i^+ + N_i^-} \sim \sqrt{2\epsilon(1-\epsilon)}\frac{\sigma_{LT'}}{\sigma_0}\sin\phi$$

Results

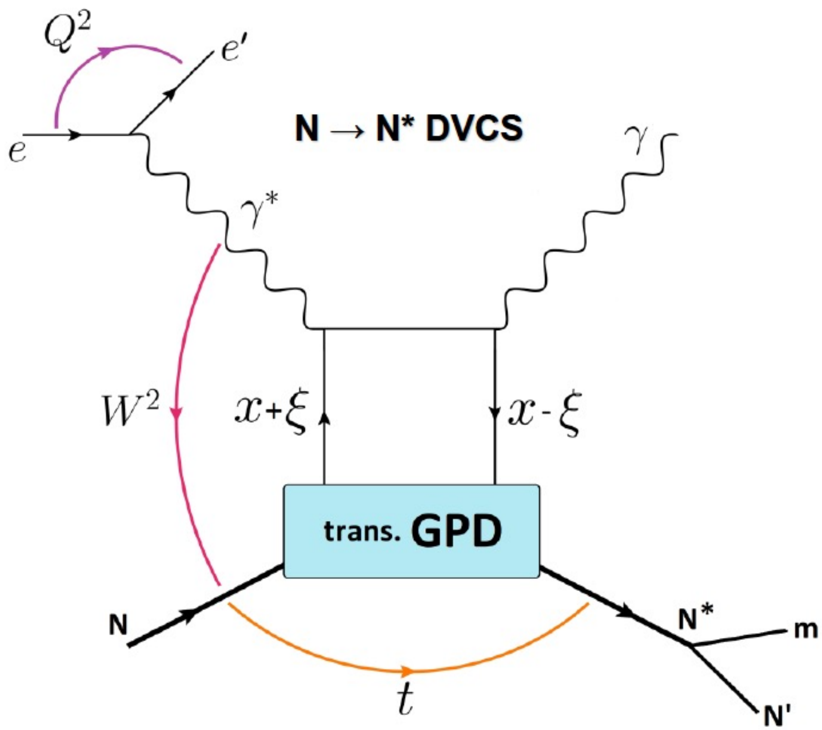
S. Diehl et al. (CLAS collab.),
Phys. Rev. Lett. 131, 021901 (2023)

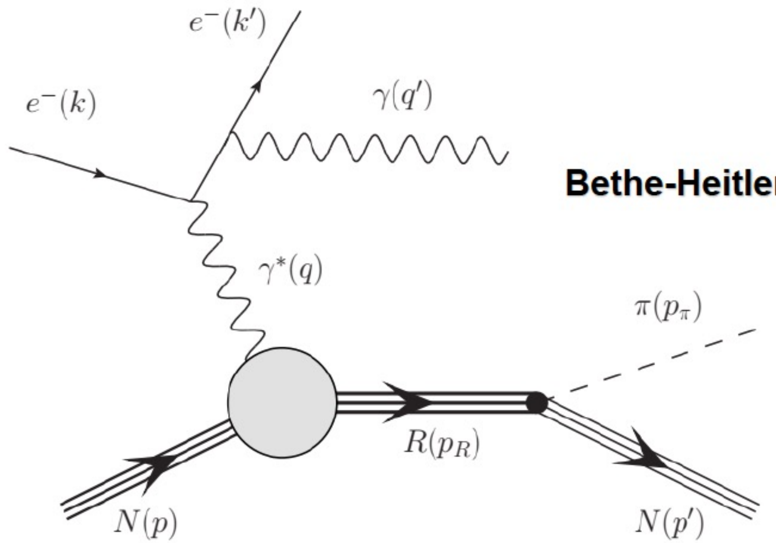
S. Diehl et al. (CLAS collab.)
Phys. Lett. B 839, 137761 (2023)
A. Kim, submitted to PLB



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)

$e p \to e' N^{*+} \gamma \to e' n \pi^+ \gamma$

CLAS12 RG-A: **fall 2018 inbending**, **fall 2018 outbending** } **E_{beam} = 10.6 GeV**
spring 2019 inbending } **E_{beam} = 10.2 GeV**

- One electron in the FD $p > 2.1$ GeV
  → Fiducial cuts for DC and PCAL + v_z cut + PID refinements
- One π^+ in the FD or CD (no other charged particles) $p > 0.2$ GeV
  → Fiducial cuts for the DC + Δv_z cut + $|chi2PID| < 3$
- At least one neutron in the FD or CD $0.25 \text{ GeV} < p < 1.95$ GeV
- At least one photon in the FT or FD $E > 2$ GeV
  → Fiducial cuts for the PCAL ($v,w > 14$ cm) + $0.9 < \beta < 1.1$

Kinematic cuts: **$W > 2$ GeV** **$Q^2 > 1.5$ GeV²** **$y < 0.8$** **$-t < 2$ GeV²**

Background rejection

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

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

➔ Also radative decays of other mesons (e.g. f_2) and nucleon resonances are very rare!

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

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

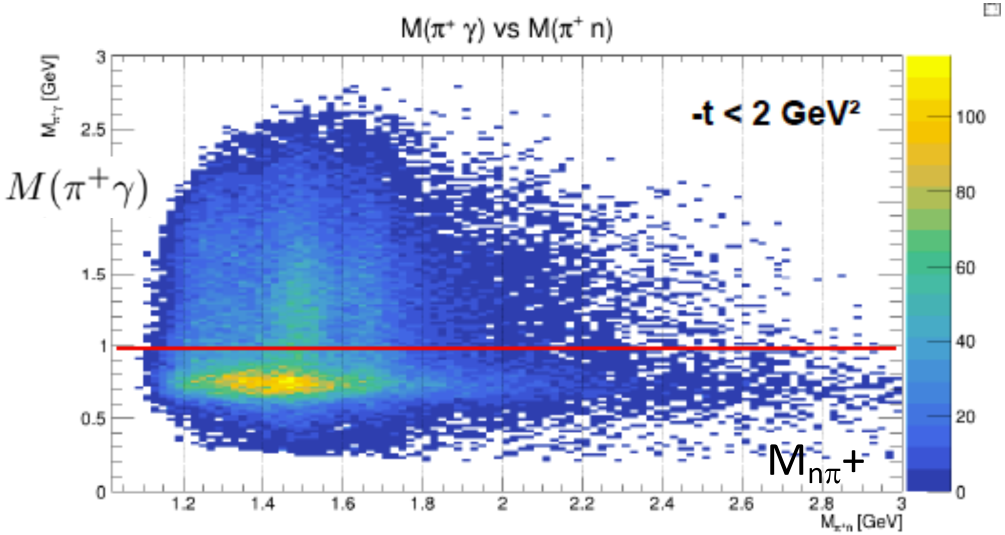
➔ This are the main background channels

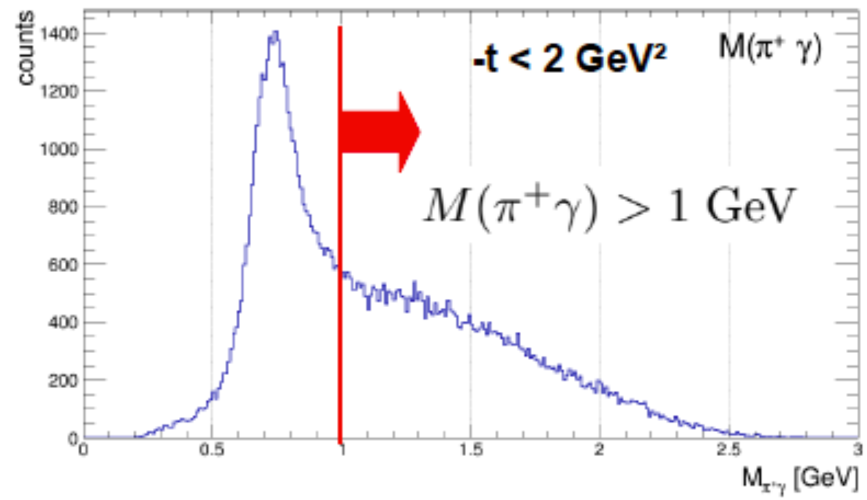
I: Can be suppressed (next slide)

II: Needs to be subtracted on a bin by bin (work in progress)

Background rejection

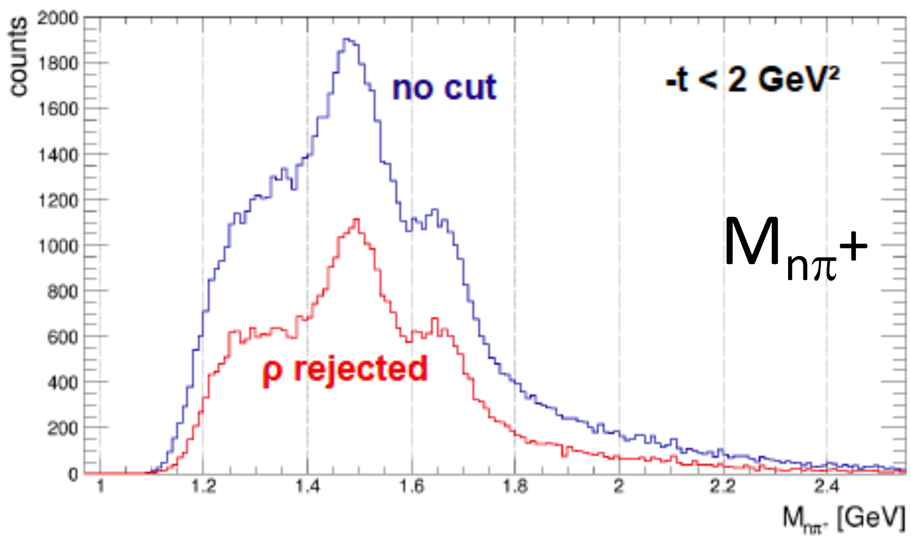
$e\,p \rightarrow e'\,n\,\rho^+$





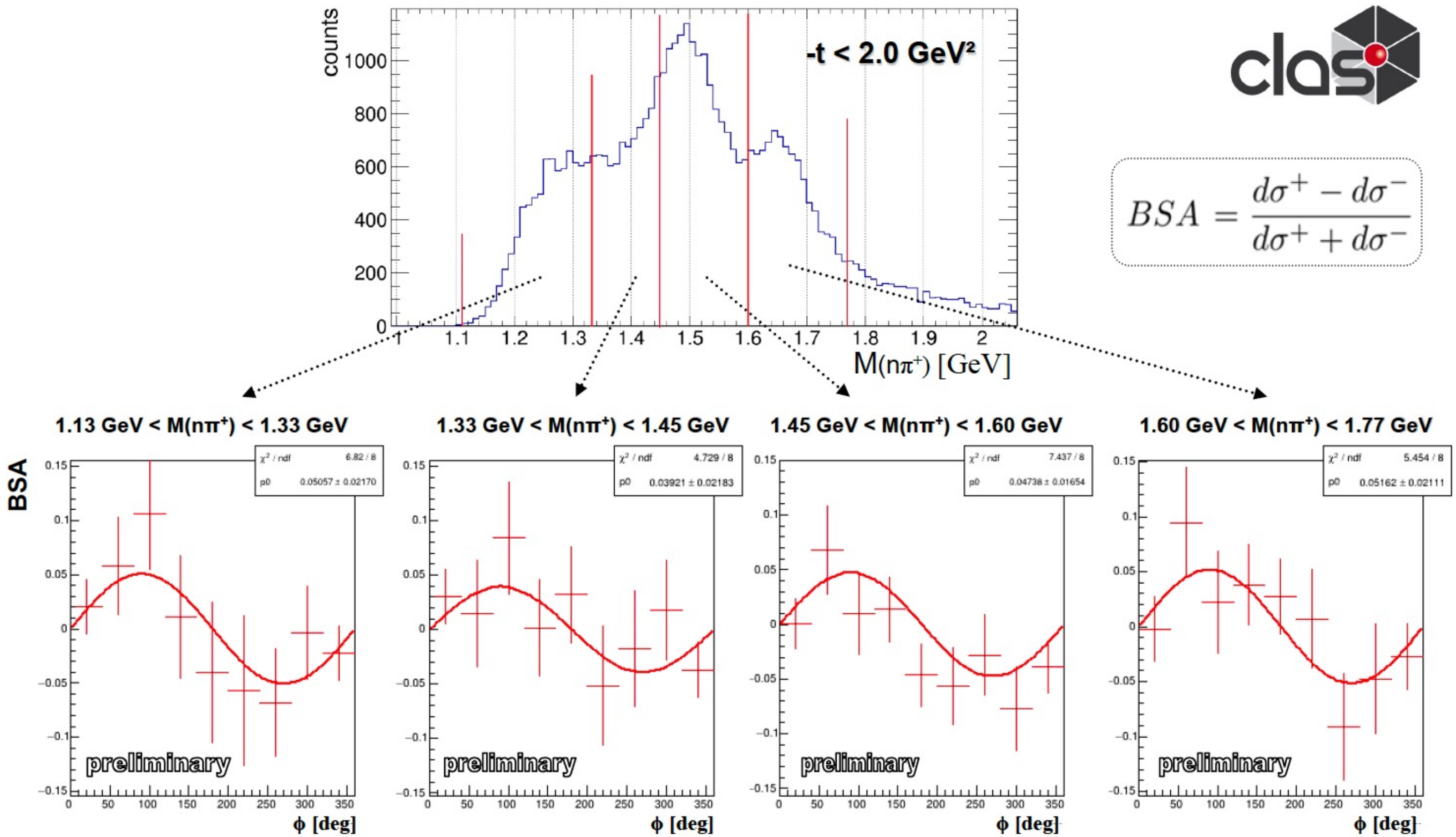
$ep \to e\gamma n\pi^+$

W > 2 GeV



S. Diehl (Giessen+UConn)

N → N* DVCS: Beam Spin Asymmetries

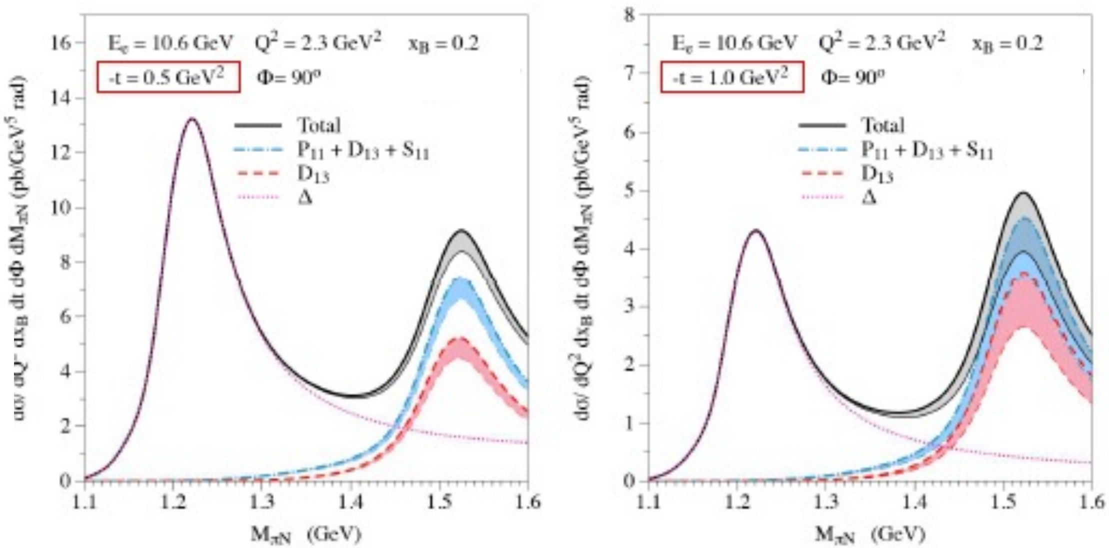


$$BSA = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-}$$

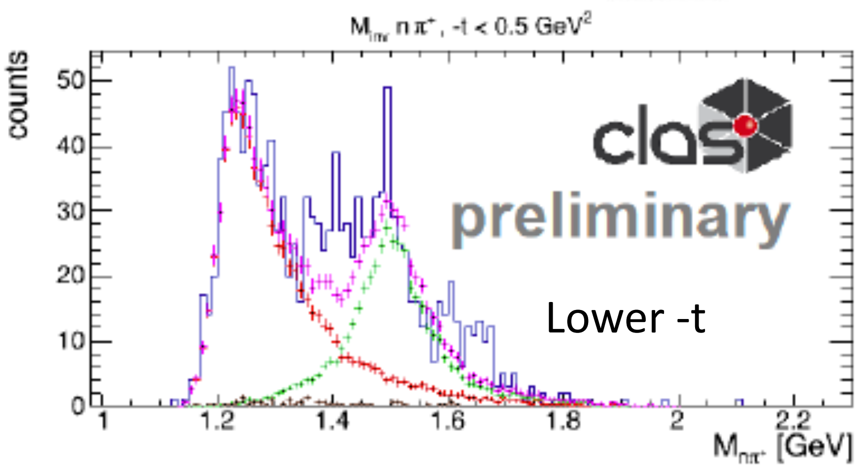
$$BSA \sim A_{LU}^{\sin(\phi)} \cdot \sin(\phi)$$

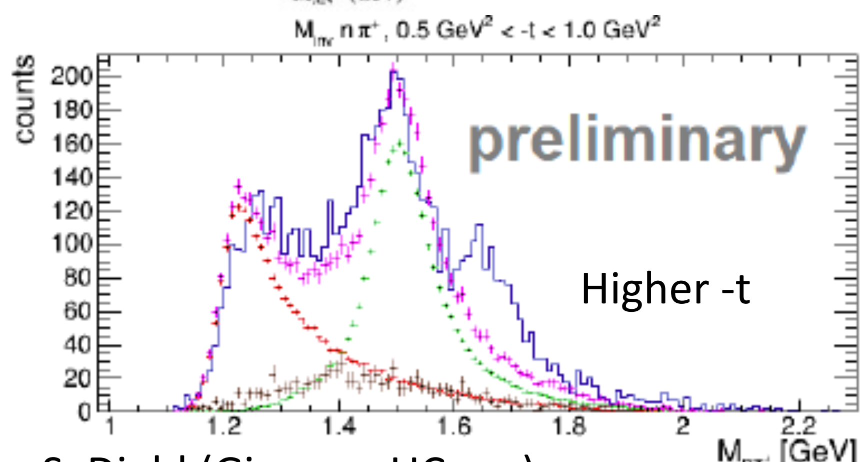
Theoretical predictions for CLAS12 kinematics

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



- exp. data
- sim Δ(1232)
- sim 2nd res region
- sim SIDIS (CLASDIS)
- sum of all simulations



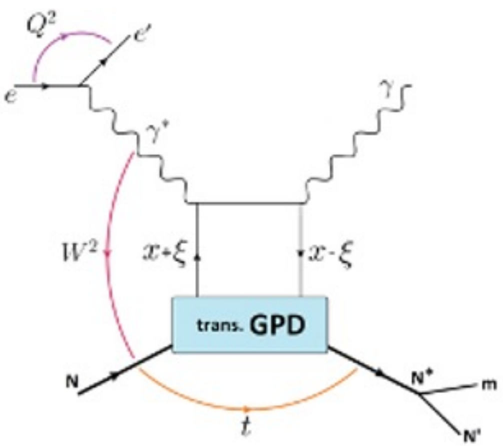


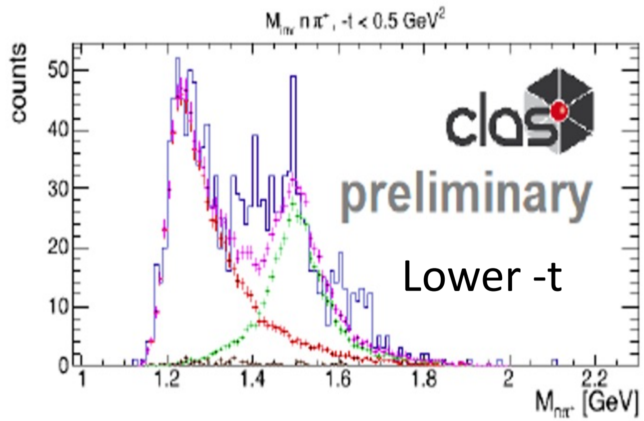
S. Diehl (Giessen+UConn)

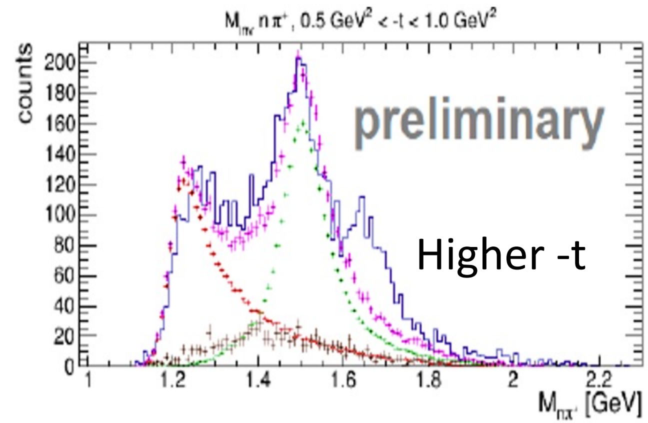
ep->eγnπ^+ vs. ep->enπ^+

S. Diehl (Giessen+UConn)

ep->eγnπ^+ W > 2 GeV

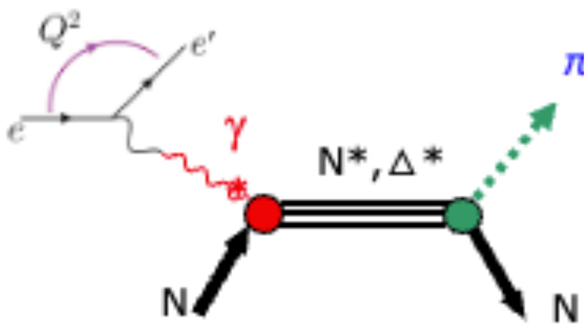


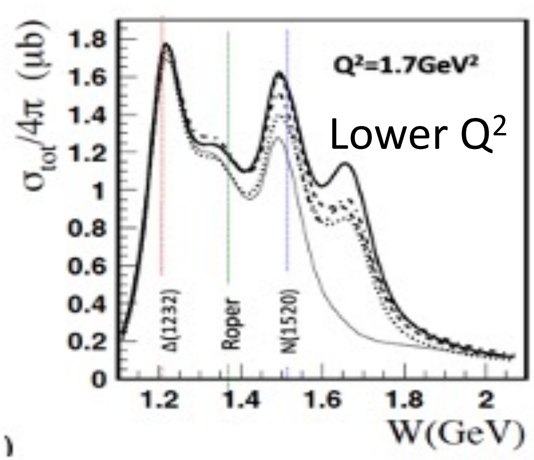


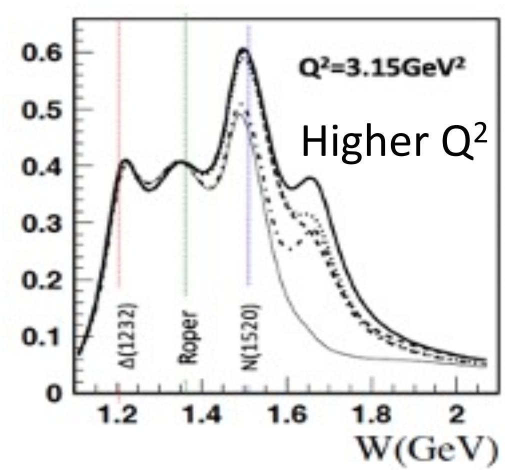


ep->enπ^+

K. Park et al., PR C77 (2008) 015208; PR C91 (2015) 045203







Electron Scattering Binning Scheme

	Resonance Region	DIS Region
Inclusive Scattering	Q^2, W	Q^2, x_B
Exclusive Process (γ, π, ρ, ϕ, ..)	Q^2, W, $\cos\theta^*$, ϕ	Q^2, x_B, $-t$, ϕ

Off-diagonal DVCS or DVMP	Q^2, x_B, $-t$, ϕ, $M_{\pi N}$, $\cos\theta^*$, ϕ^*

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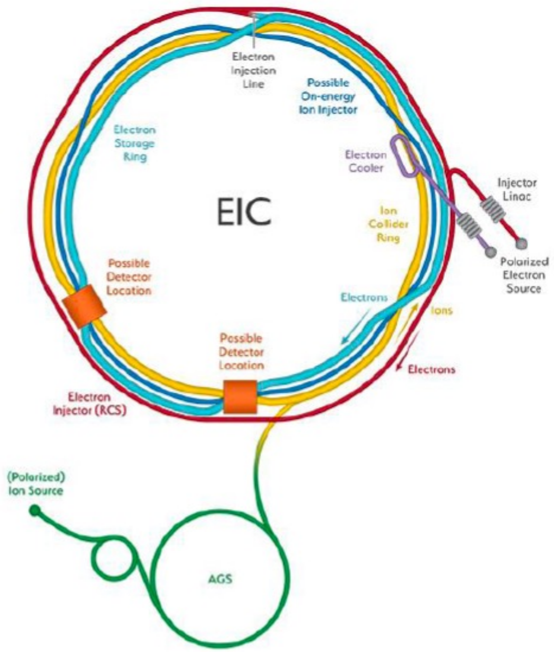
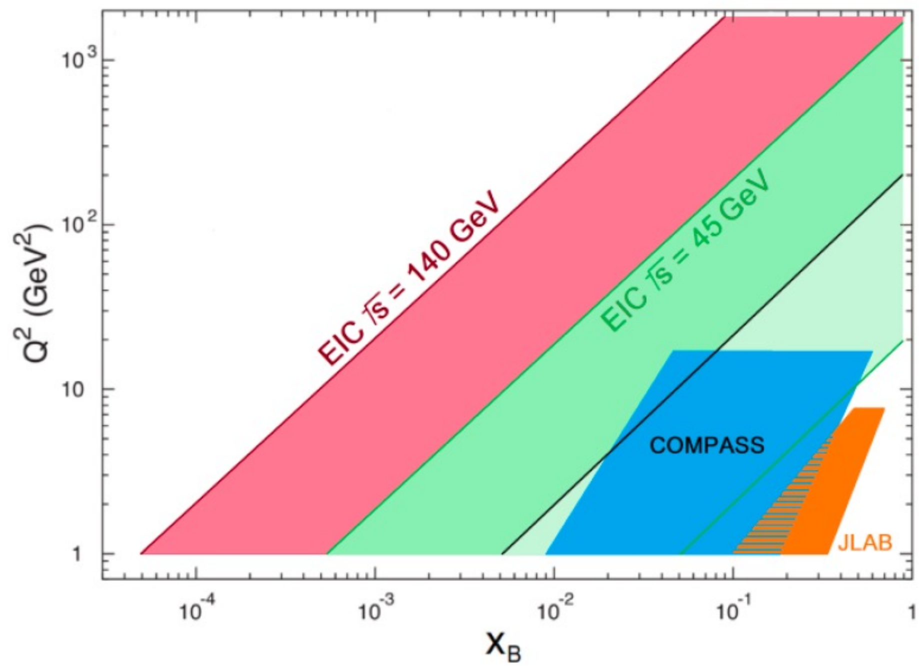
Future: Transition GPDs at EIC and EicC

- 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

Summary and Outlook

1. Hard exclusive $\pi^-\Delta^{++}$ production has been measured with CLAS12 and provides a first observable sensitive to N->Δ transition GPDs. (Phys. Rev. Lett. 131, 021901 (2023))
2. The obtained BSA is clearly negative and ~ 2 times larger than for π^+

Outlook

1. The N->N* DVCS and N->N* DVMP processes are under investigation by scanning a wide range of invariant mass of Nπ.
2. First data on these reactions are becoming available from experiments at JLab12, but detailed strategies for their analysis and theoretical interpretation need to be developed.
3. A new proposal would be submitted to JLAB PAC in the near future for high statistics run in 7D: Q^2, x_B, t, ϕ, $M_{N\pi}$, θ^*, ϕ^*
4. Future opportunities: COMPASS/AMBER, EIC, …

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clas

BACKUP

Sources of Systematic Uncertainty

1. Uncertainty of the background subtraction

→ 2 sources of uncertainty: S/B ratio and sideband asymmetry

→ Both sources were varied within their uncertainty range

➔ Typically in the order of 1.5 % (low -t) - 12.5 % (high -t) (stat. ~ 12 – 25 %)

➔ Dominant sys. uncertainty for the high -t bins

2. Uncertainty of the beam polarization ~ 3.1 %

3. Effect of the extraction method and the denominator terms ~ 2.8 %

4. Acceptance and bin-migration effects ~ 2.9 %

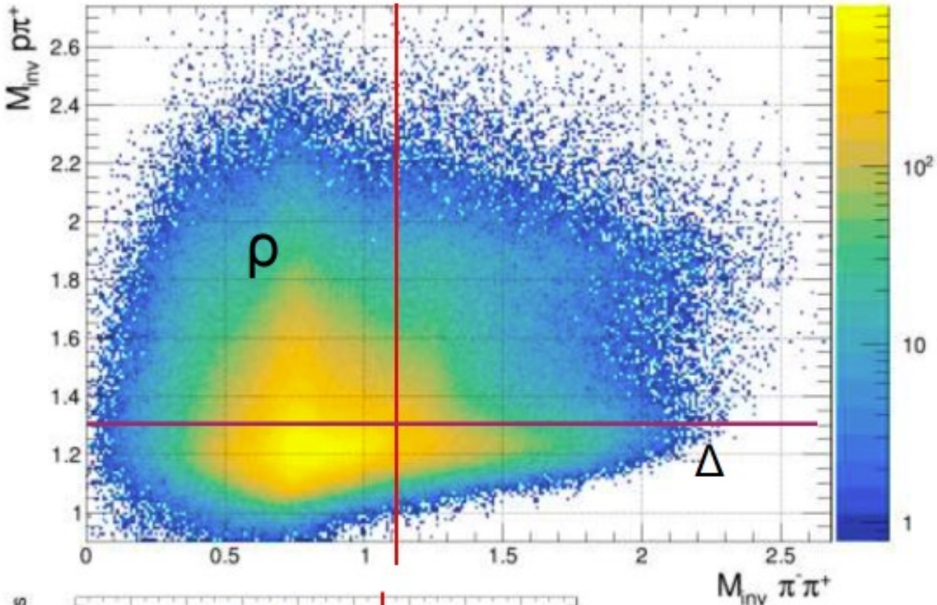
→ Comparison of injected and reconstructed BSA in the MC

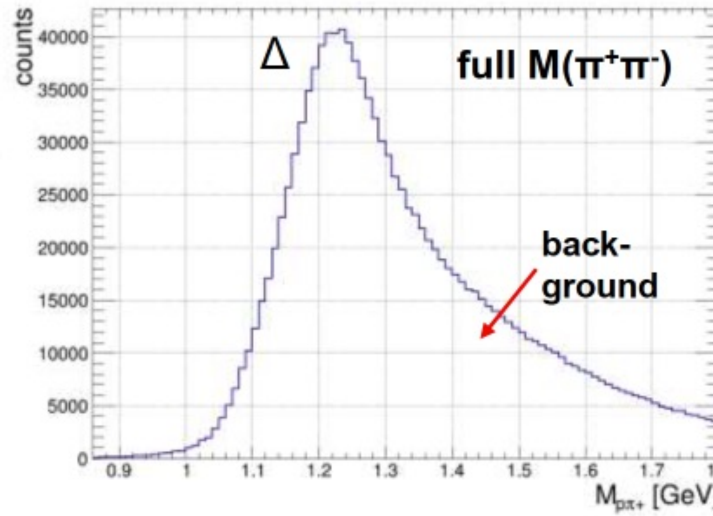
5. Radiative effects ~ 3.0 %

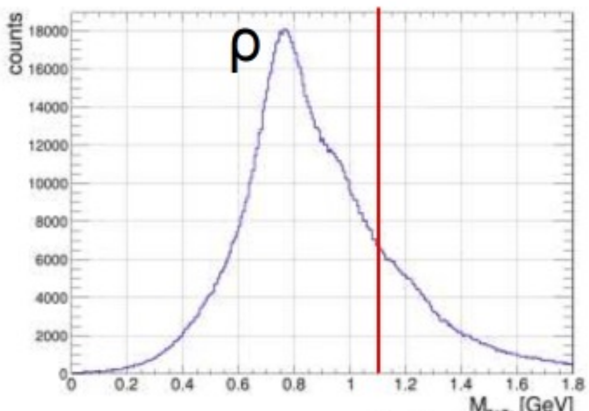
6. Other sources (particle ID, fiducial cuts, …) < 2.0 %

Total: 7.1 - 14.3 %

Event Selection and Background Rejection







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

M(π⁺π⁻) > 1.1 GeV

ρ contamination

< 0.8 %