Exclusive Mesons Production with CLAS12 At Jefferson Lab

Kyungseon Joo

University of Connecticut

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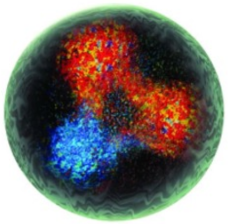
clas

Generalized Parton Distributions (GPDs)



Wigner function: full phase space parton distribution of the nucleon

$$\rho(x, \vec{k}_T, \vec{b}_T)$$ 5D

$$\int d^2 k_T$$

quark pol. / **nucleon pol.**

N/q	U	L	T
U	H		$\bar{E}_T$
L		$\widetilde{H}$	$\widetilde{E}_T$
T	E	$\widetilde{E}$	$H_T, \widetilde{H}_T$

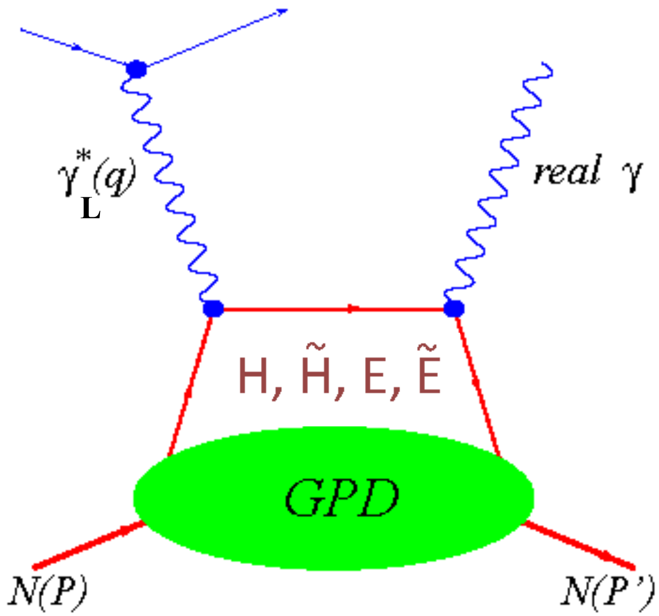
$$\bar{E}_T = 2\widetilde{H}_T + E_T$$

Generalized Parton Distributions (GPD)

3-D nucleon images in the transverse coordinate and longitudinal momentum space

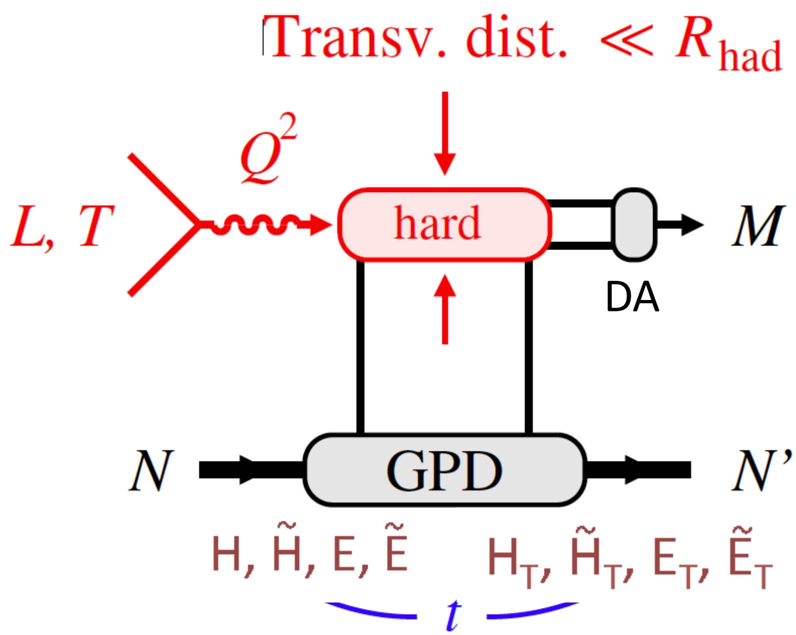
Study GPDs: Deeply Exclusive Processes

Deeply Virtual Compton Scattering (DVCS)



+ Clean process
- Only 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

Deeply Virtual Meson Production

	Meson	Flavor
$\mathcal{H}_T, \mathcal{E}_T$ $\widetilde{H}, \widetilde{E}$	π^+	$\Delta u - \Delta d$
	π^0	$2\Delta u + \Delta d$
	η	$2\Delta u - \Delta d + 2\Delta s$
$\mathcal{H}, \mathcal{E}$	ρ^+	$u - d$
	ρ^0	$2u + d$
	ω	$2u - d$
	ϕ	g

H_T is related to the protons tensor charge

$$\delta_T^{u,d} = \int dx H_T^{u,d}(x, \xi = 0, t = 0)$$

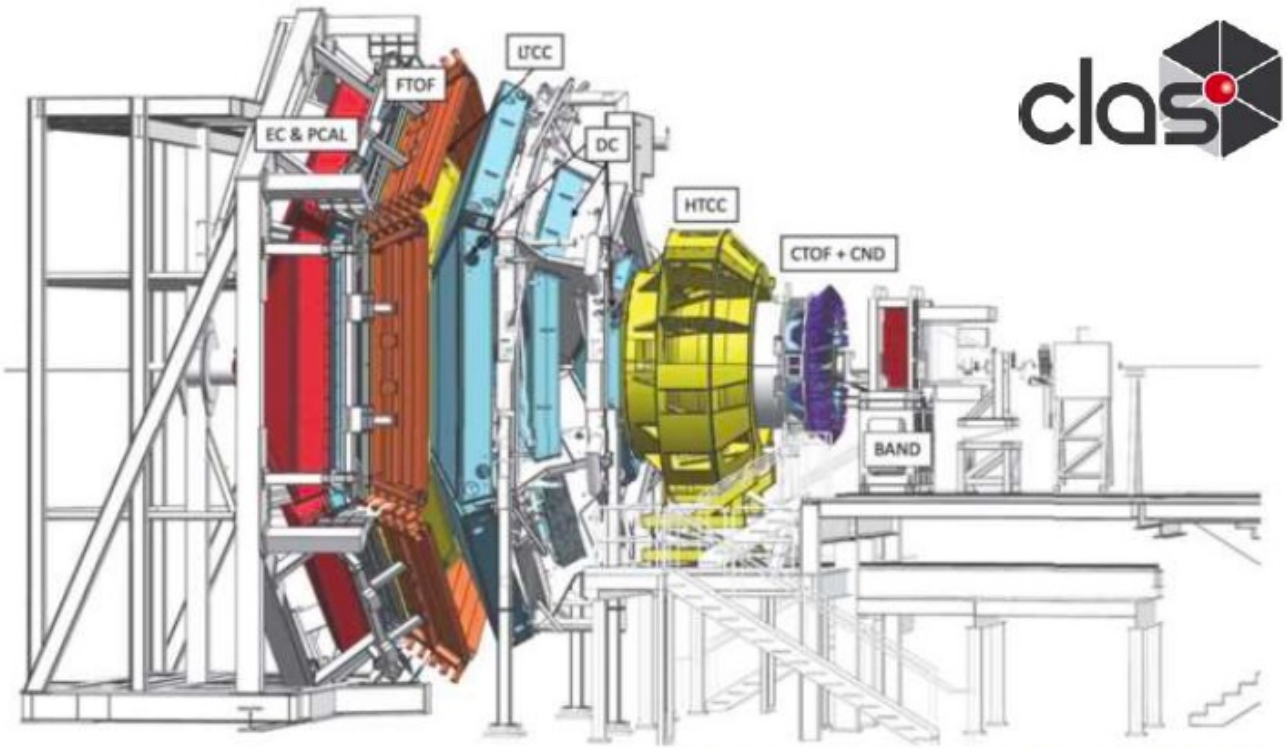
➔ Absolute magnitude of transversly polarized valence quarks inside a transv. polarized nucleon

$\bar{E}_T$ is related to the protons anomalous tensor magnetic moment

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

$$\bar{E}_T = 2\tilde{H}_T + E_T$$

CLAS12 at JLAB

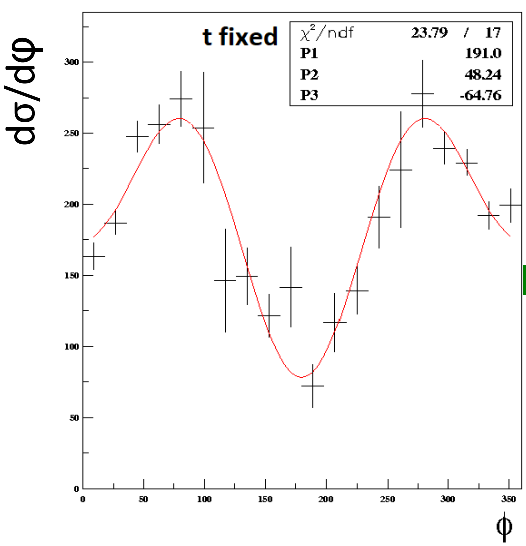


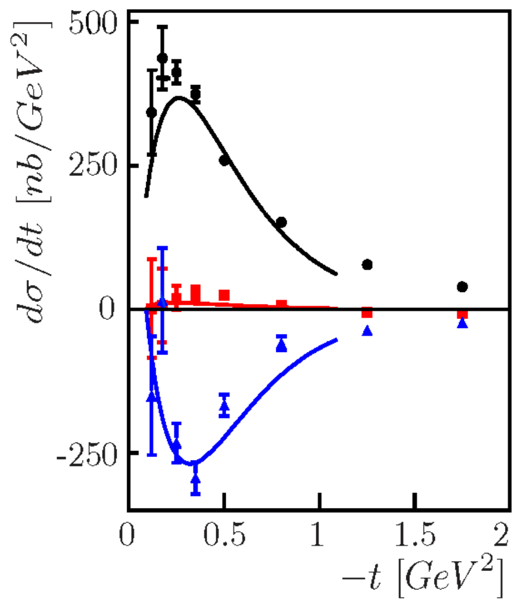
V. Burkert et al., Nucl. Instr. Meth. A 959, 163419 (2020)

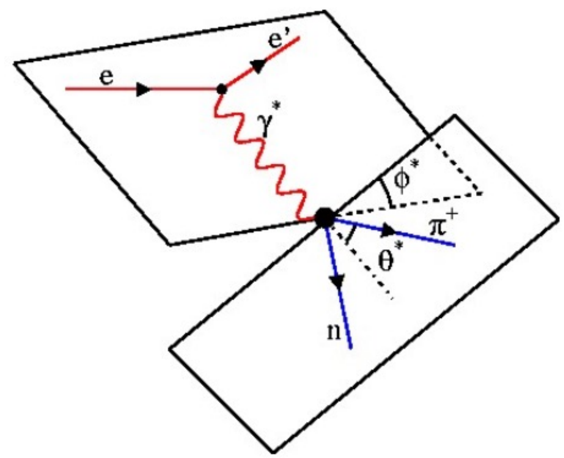
- ➔ Data recorded with CLAS12 during fall 2018 and spring 2019 (RG-A)
  - ➔ 10.6 GeV / 10.2 GeV electron beam ~ 86 % average polarization
  - ➔ liquid H_2 target

Differential Cross Section of DVMP (π^0)

$$\frac{d^4\sigma}{dQ^2 dx_B d\phi dt} \propto \boxed{\sigma_T + \epsilon\sigma_L} + \epsilon\boxed{\sigma_{TT}} \cdot \cos(2\phi) + \sqrt{2\epsilon(1+\epsilon)} \cdot \boxed{\sigma_{LT}} \cdot \cos(\phi)$$







CLAS collaboration. I Bedlinskiy et al. Phys.Rev.Lett. 109 (2012) 112001

$$\sigma_{TT} \propto \frac{t'}{Q^4}\left|\bar{E}_T\right|^2 \qquad \sigma_{LT} \propto \frac{\sqrt{-t'}}{Q^4}\,\xi\,\sqrt{1-\xi^2}\;Re\left[\langle H_T\rangle^* \left\langle \widetilde{E} \right\rangle\right]$$

Unpolarized π^0 Cross Section and Theory Predictions

<u>2 theoretical models:</u>

Goloskokov, Kroll (GK)
Eur. Phys. J. A. 47: 112 (2011)
→ Chiral odd GPDs parameterized using latest results from lattice QCD and transversity parton distribution functions with emphasis on H_T and $\bar{E}_T$

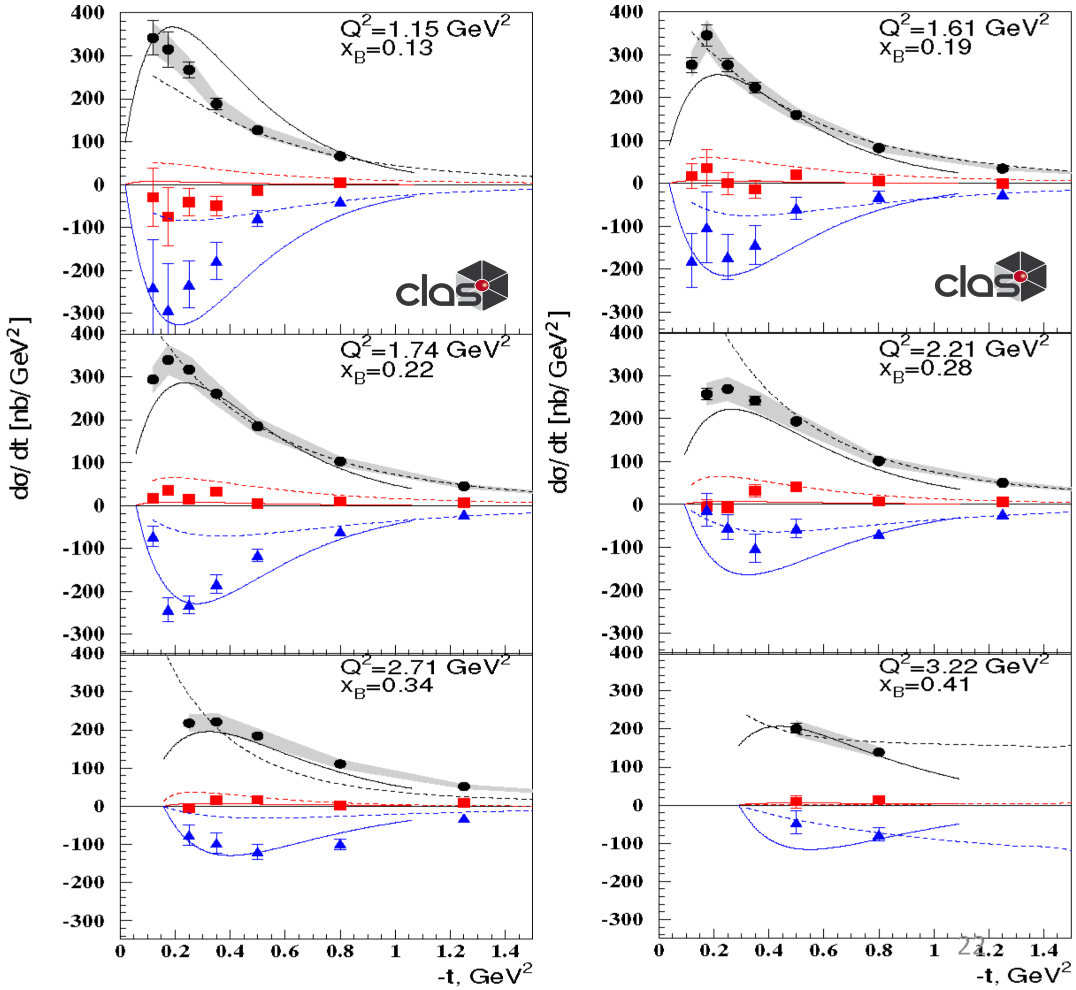
Goldstein, Hernandez, Liuti (GGL)
Phys. Rev. D 84, 034007 (2011)
→ Chiral odd GPDs parameterized via linear relations to chiral even GPDs under parity and charge conjugation symmetries in Reggied diquark model

■ σ_0

■ σ_{TT} → cos(2φ)

■ σ_{LT} → cos(φ)

e p → e p π^0



Solid: S. Goloskokov and P. Kroll
Dots: S. Liuti and G. Goldstein

CLAS collaboration. I Bedlinskiy et al. Phys.Rev.Lett. 109 (2012) 112001

Pseudoscalar meson electroproduction with CLAS12

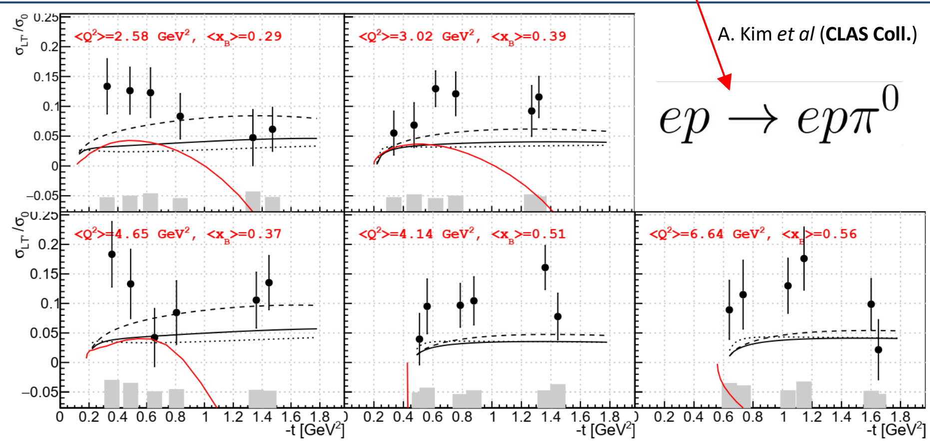
$$\frac{d^4\sigma}{dQ^2 dx_B d\phi dt} \propto \sigma_T + \epsilon\sigma_L + \epsilon\sigma_{TT}\cdot\cos(2\phi) + \sqrt{2\epsilon(1+\epsilon)}\cdot\sigma_{LT}\cdot\cos(\phi) + P_b\cdot\boxed{\sqrt{2\epsilon(1-\epsilon)}\cdot\sigma_{LT'}\cdot\sin(\phi)}$$

E=10.6 GeV

$$\sigma_{LT'} = \xi\sqrt{1-\xi^2}\frac{\sqrt{-t'}}{2m}\times$$
$$\times\ \mathrm{Im}\left[\langle H_T\rangle^*\langle\tilde{E}\rangle + \langle\bar{E}_T\rangle^*\langle\tilde{H}\rangle\right]$$

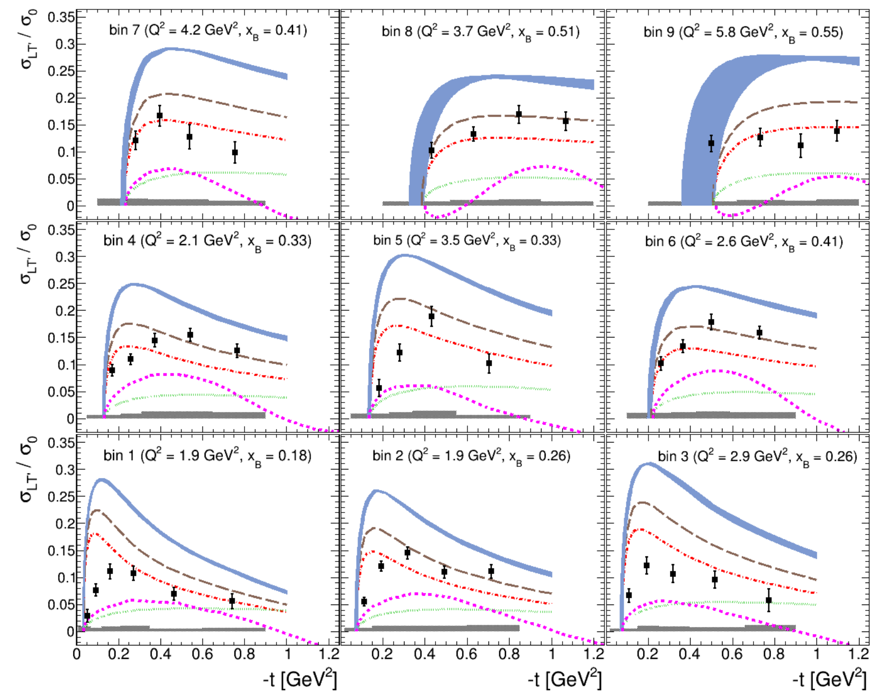
A. Kim *et al* (**CLAS Coll.**)

$ep \to ep\pi^0$



$ep \to en\pi^+$

S. Diehl et al. (CLAS collab.)
Phys. Lett. B 839, 137761 (2023)



A. Kim et al. (CLAS collab.)
Phys. Lett. B 849, 138459 (2024)

GK model

JML model

$\bar{E}_T$ is related to the proton's anomalous tensor magnetic moment.

H_T is related to the proton's tensor charge.

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

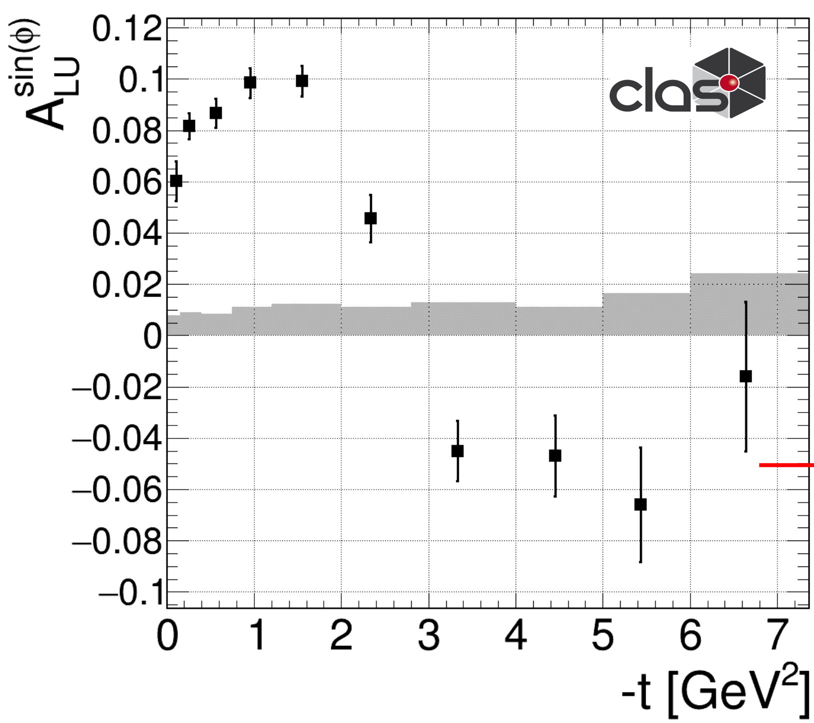
$$\kappa_T^d = \int dx\bar{E}_T^d(x,\xi,t=0) \qquad \delta_T^d = \int dx H_T^d(x,\xi,t=0)$$

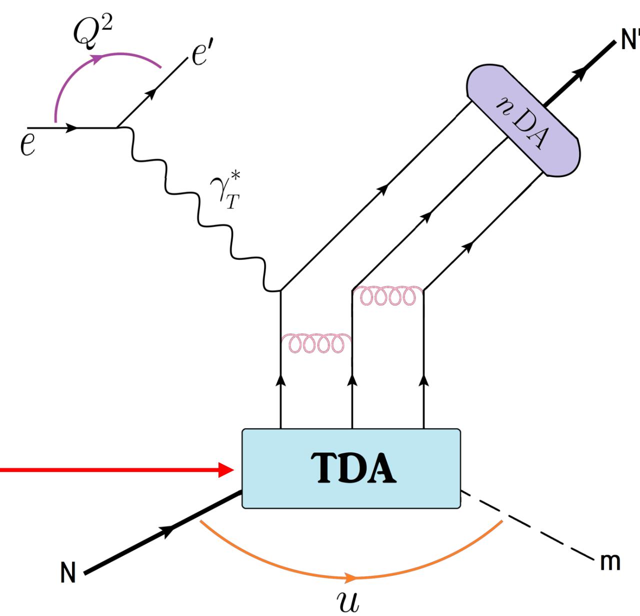
From GPDs to Transition Distribution Amplitudes (TDAs)

$$ep \rightarrow en\pi^{+} \qquad A_{LU}^{\sin\phi} = \sqrt{2\epsilon(1-\epsilon)}\,\frac{\sigma_{LT'}}{\sigma_T + \epsilon\sigma_L}$$

CLAS data E = 5.4 GeV

W > 2 GeV $Q^2 > 1$ GeV^2





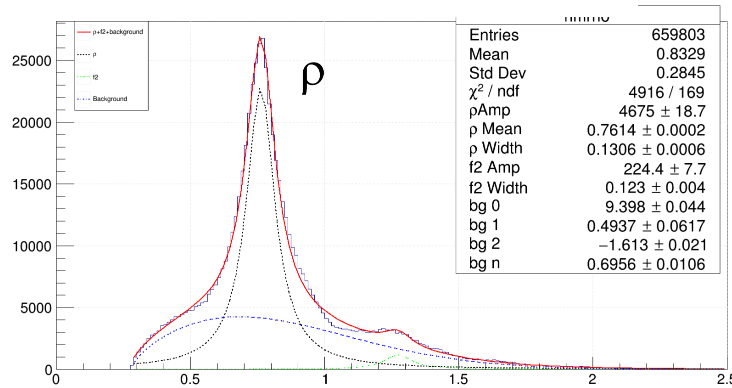
S. Diehl et al. (CLAS collaboration), Phys. Rev. Lett. 125, 182001 (2020)

➔ “Backward physics" opens a new window to the 3D nucleon structure!

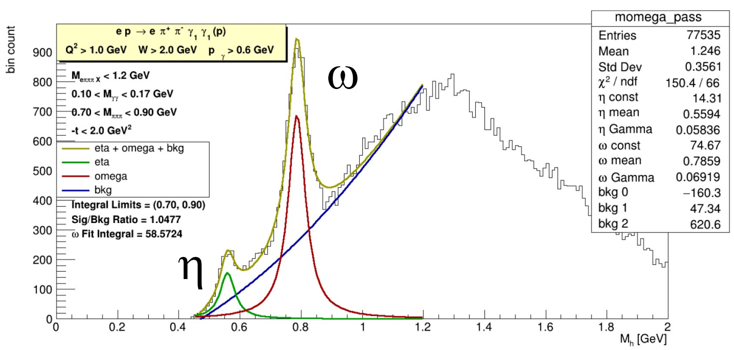
Exclusive ρ/ω production with CLAS12, ep-> ep (ρ/ω)

$$\sigma_{LT'} \sim r^8_{00} \sim \mathrm{Im}\left[\langle H_T\rangle^* \langle E\rangle + \langle \bar{E}_T\rangle^* \langle H\rangle\right]$$

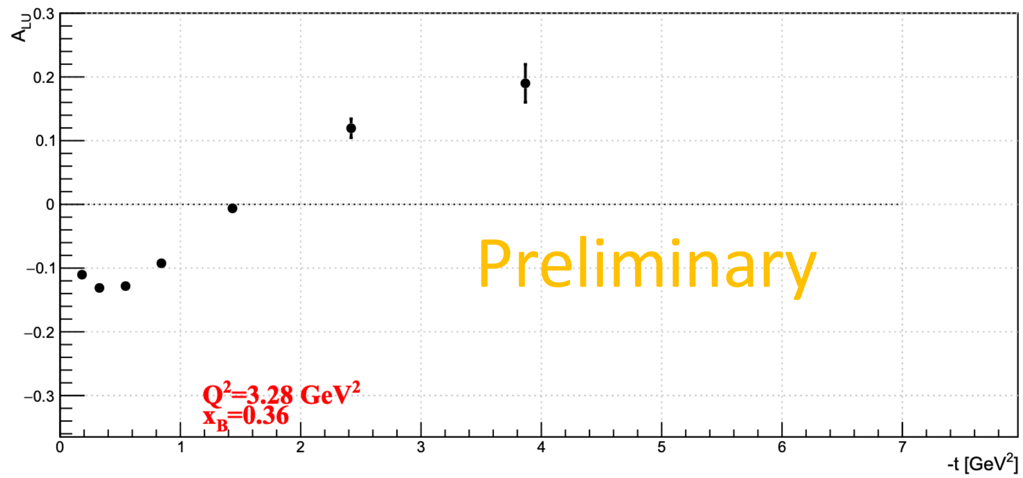
Invariant Mass: $\pi^+ + \pi^-$



Invariant Mass: $\pi^+ + \pi^- + \pi^0$

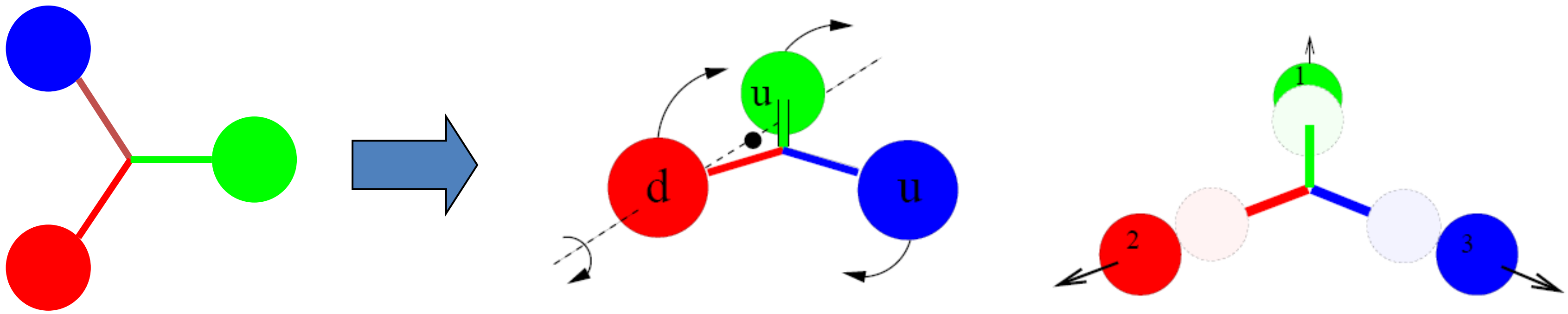


$$ep \rightarrow ep\rho$$



N. Trotta *et al* (UCONN)

From the ground state nucleon to resonances



How does the exitation affect the 3D structure of the Nucleon?

→ Pressure distributions, tensor charge, … of resonances?

Traditional way: Study of transition form factors (**2D picture** of transv. position)

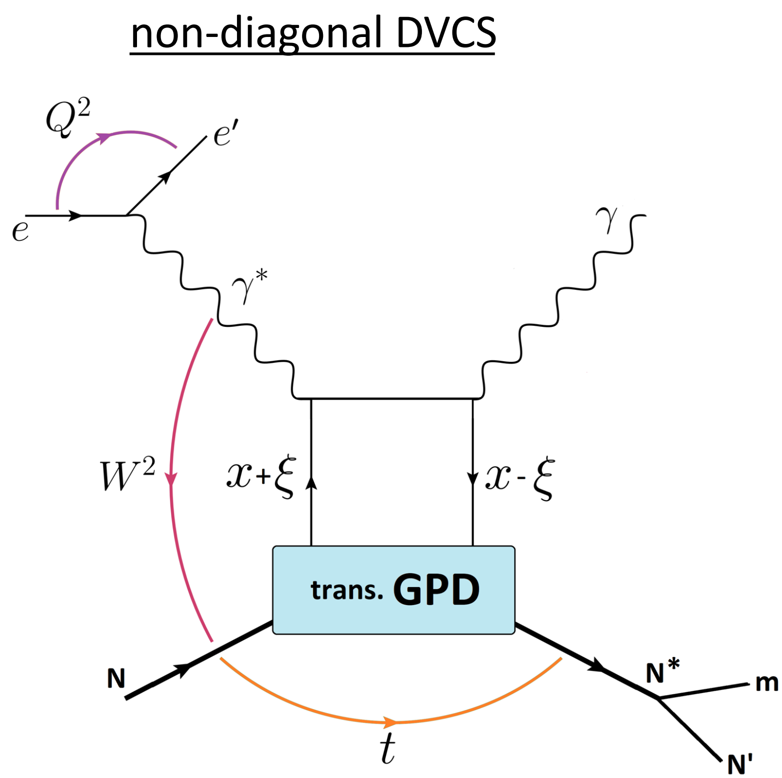
3D picture of the exitation process: Encoded in **transition GPDs**

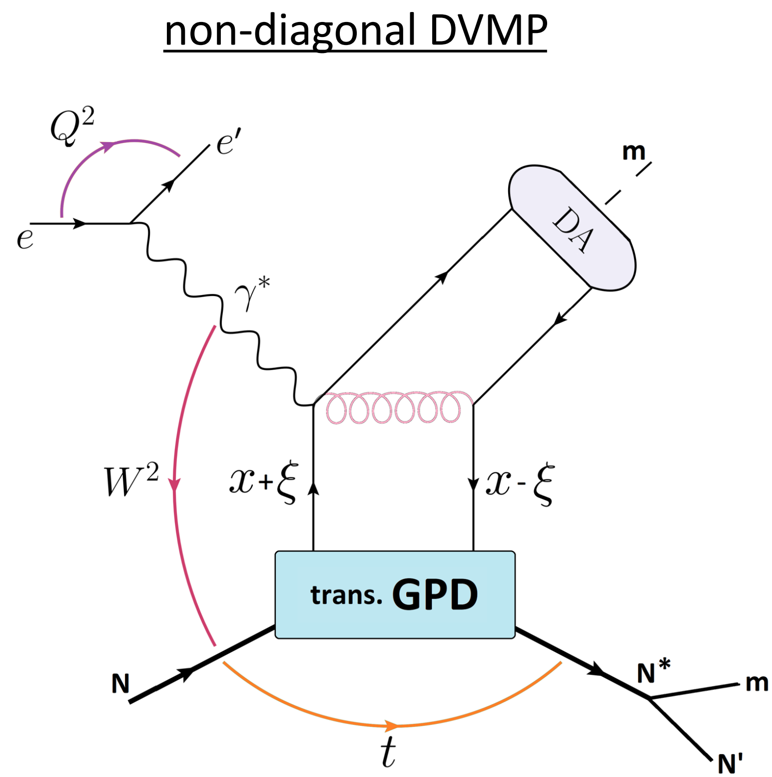
Simplest case: N→Δ transition → **16 transition GPDs**

P. Kroll and K. Passek-Kumericki, Phys. Rev. D 107, 054009 (2023).
K. Semenov, M. Vanderhaeghen, arXiv:2303.00119 (2023).

- **8 helicity non-flip transition GPDs (twist 2)**
  - Related to the Jones-Scardon and Adler EM FF for the N → Δ transition
- **8 helicity flip transition GPDs (transversity)**

Non-diagonal DVCS / DVMP

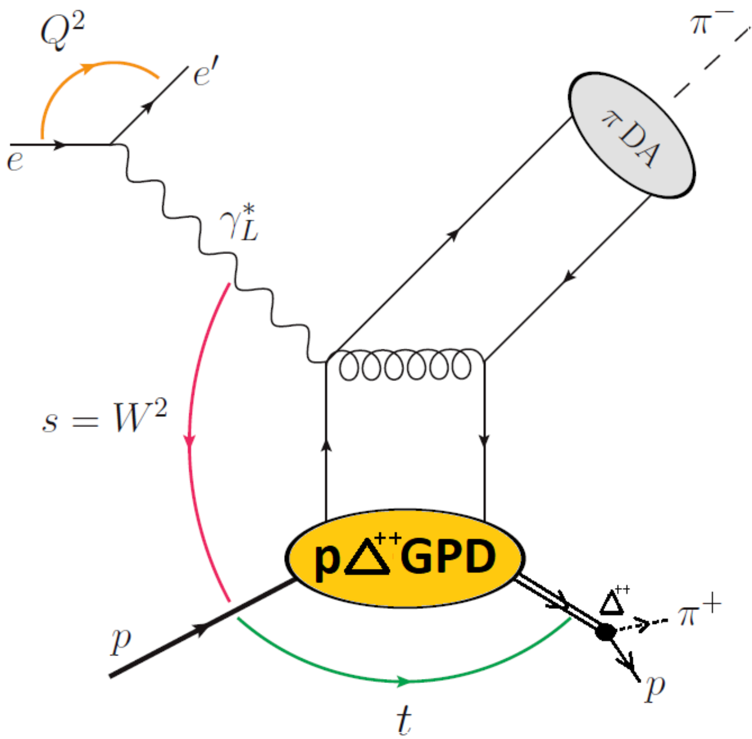




factorization expected for: $-t/Q^2$ small, $Q^2 > M^2_{N^*}$ x_B fixed

N->$\Delta(1232)$ transition GPDs: 8 twist-2 GPDs: 4 unpolarized, 4 polarized. K. Semenov, M. Vanderhaeghen, arXiv:2303.00119 (2023)

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



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

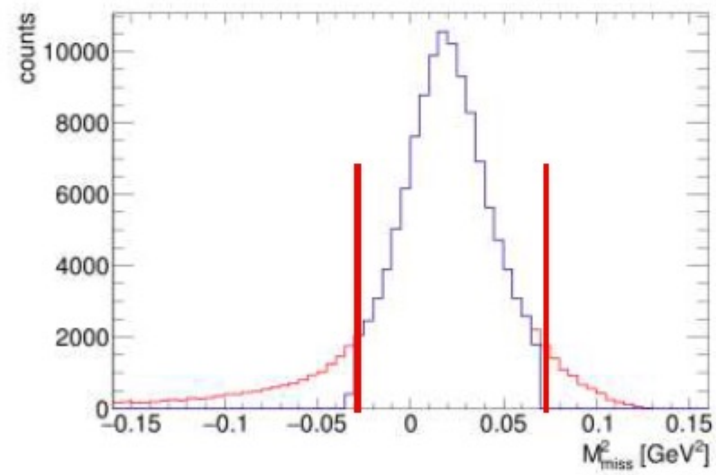
- ❑ The $p\pi^+$ final state can **only** be populated by **Δ-resonances ->** Large gap between Δ(1232) and higher resonances

Event Selection and Kinematic Cuts

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

$$X = \pi^{+}$$

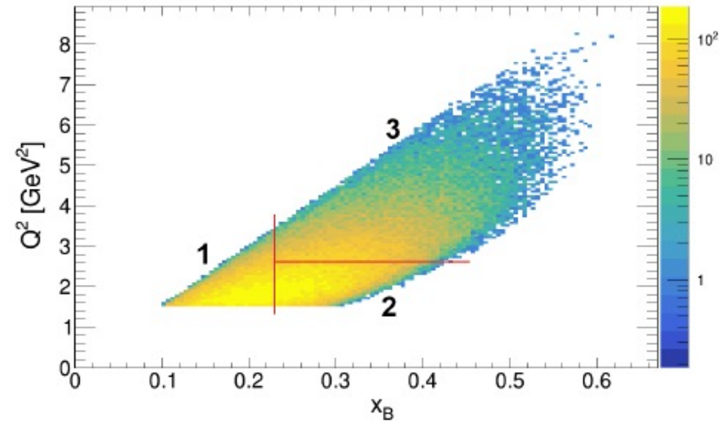
➔ 2 sigma cut around the missing π^{+}



Kinematic cuts:

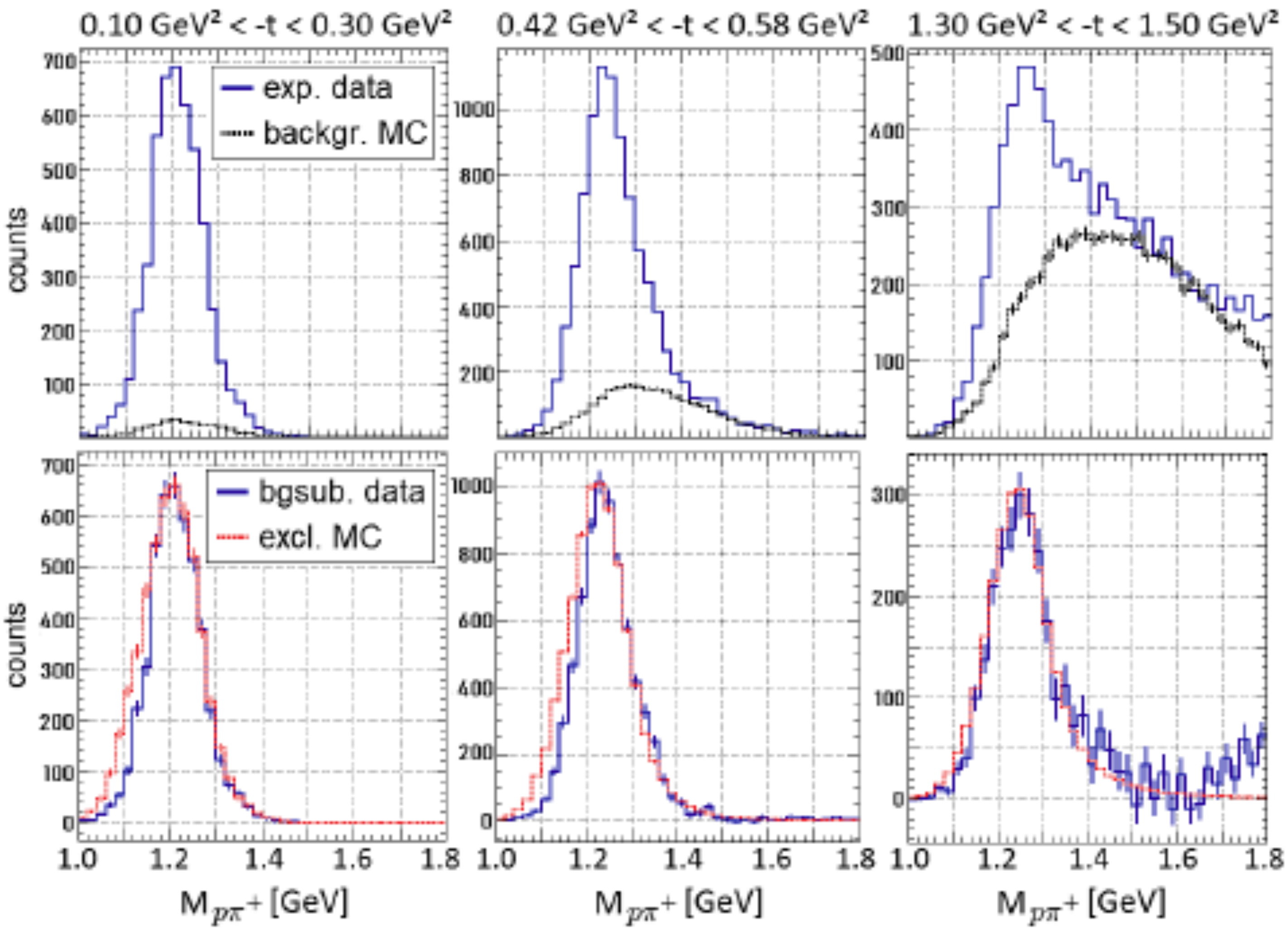
$Q^2 > 1.5$ GeV^2 $\quad$ $W > 2$ GeV

$y < 0.75$ $\quad$ $-t < 1.5$ GeV^2

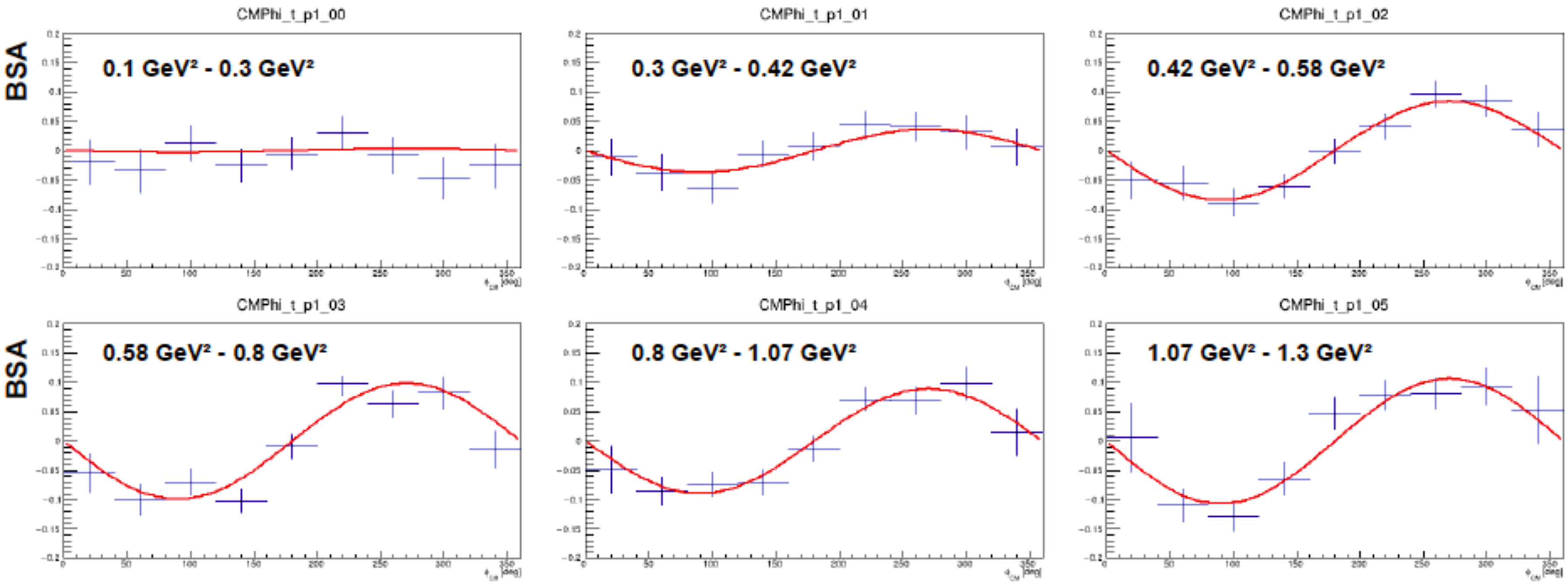


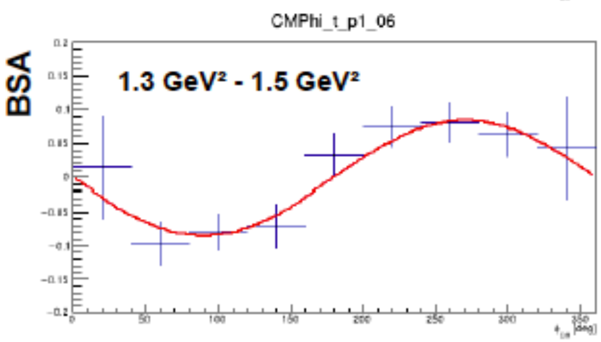
Signal and Background Separation

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



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)
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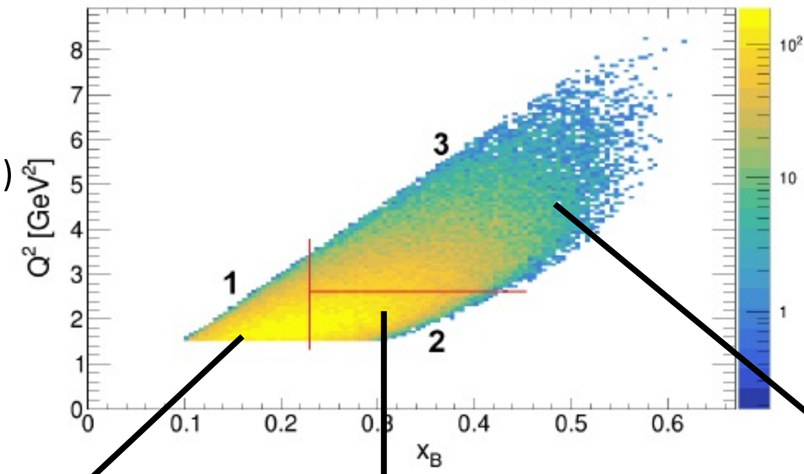
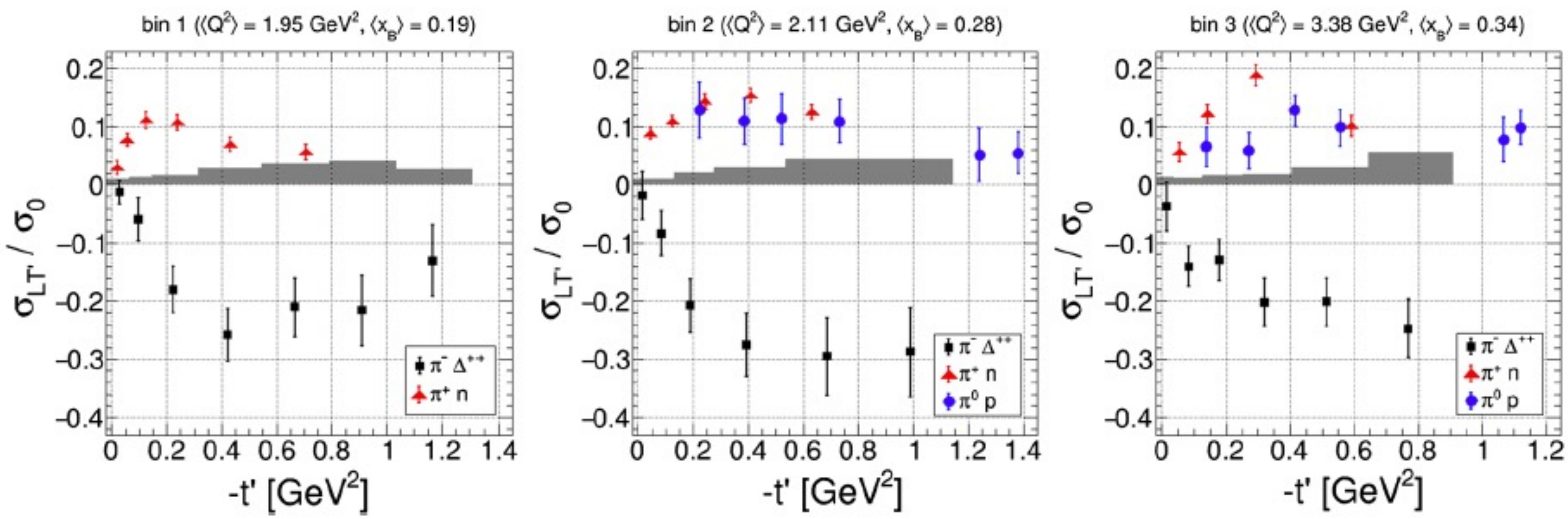
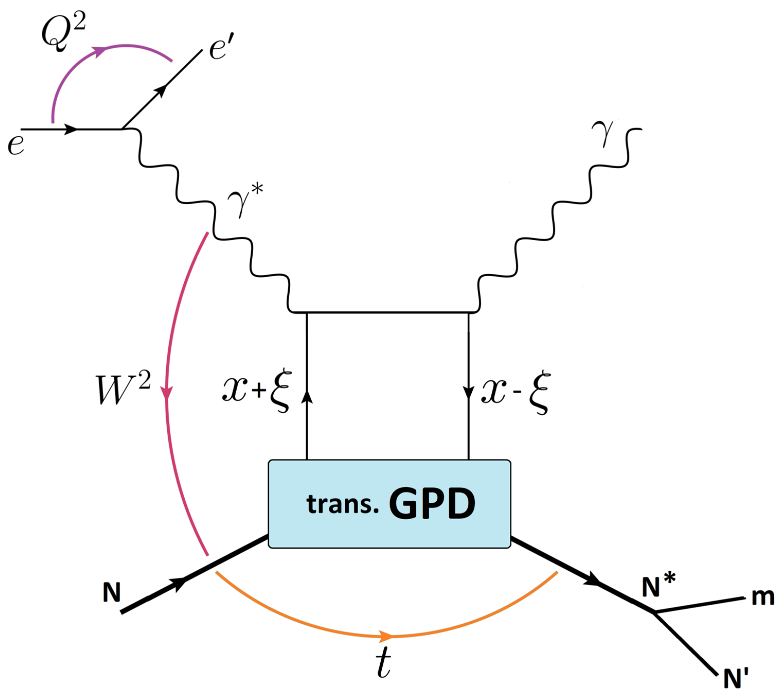


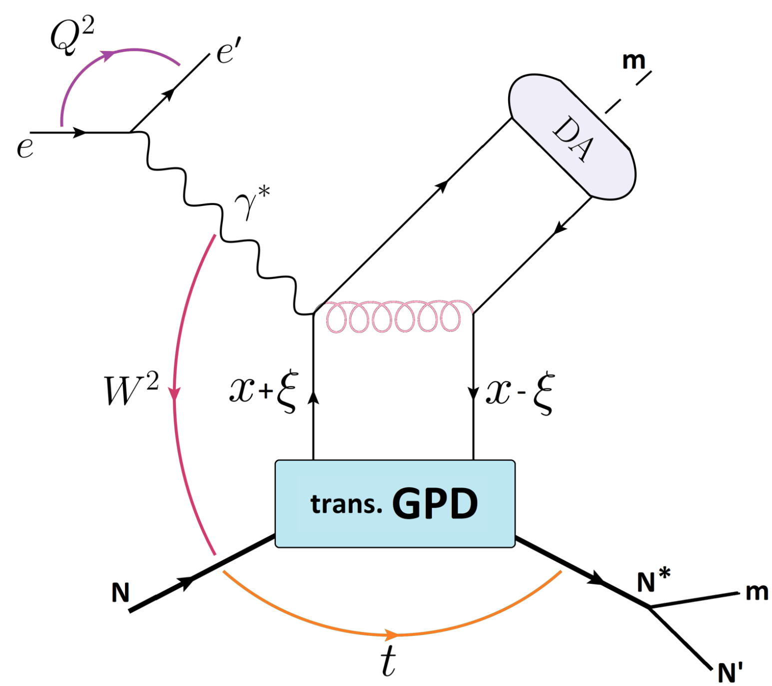


Non-diagonal DVCS / DVMP

non-diagonal DVCS



non-diagonal DVMP



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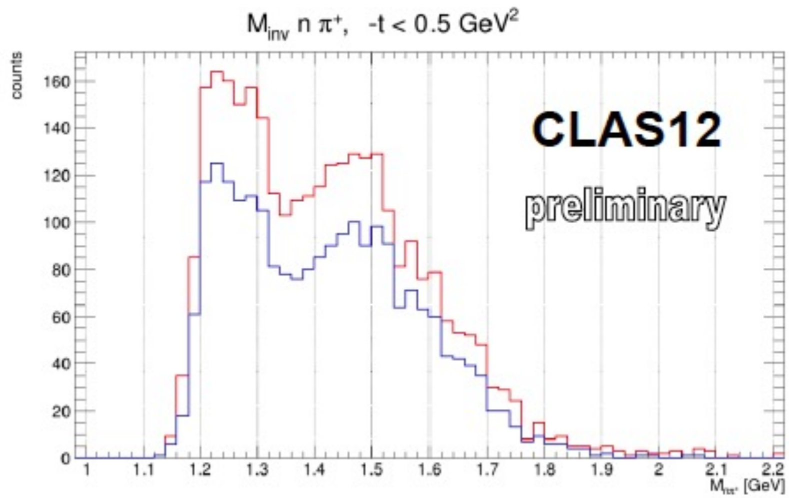
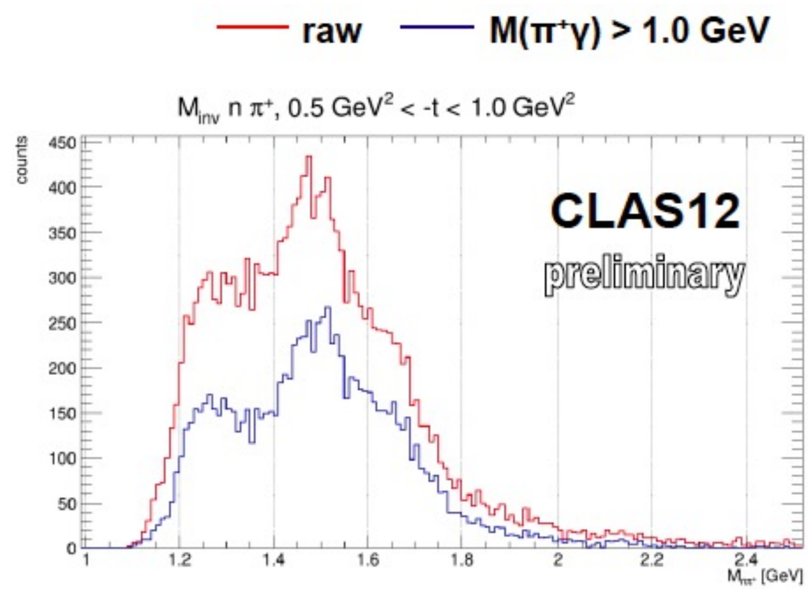
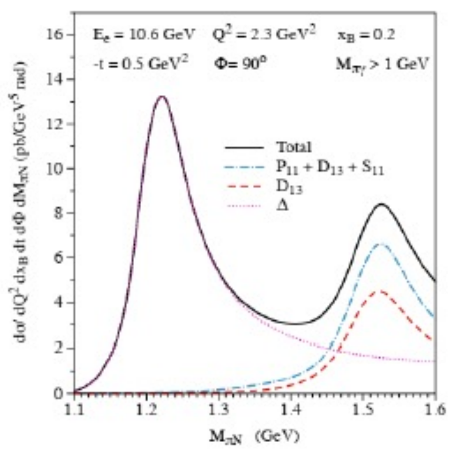
e p → e' Δ⁺ γ → e' n π⁺ γ

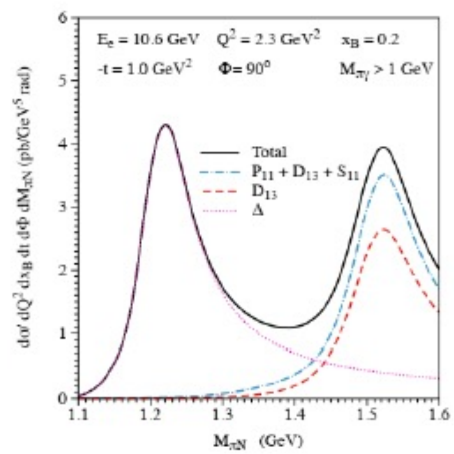
e p → e' Δ⁺ γ → e' n π⁺ γ





Semenov-Tian-Shansky, Vanderhaeghen, arXiv:2303.00119 (2023)

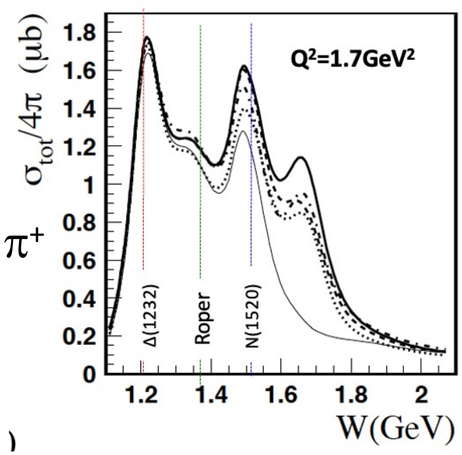


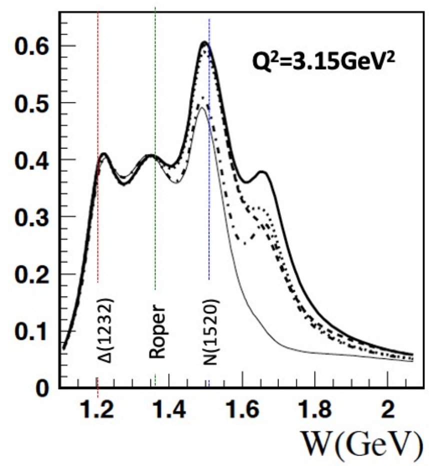


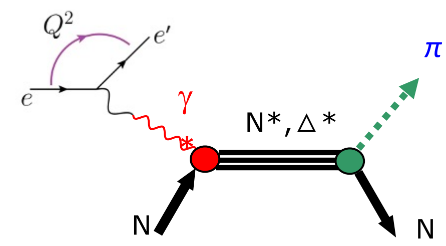
- **study in progress**
- **π⁺ mainly in CD and low momentum**
- **Good agreement of BSA**
- **awaiting pass 2**

$ep \to en\pi^+$ vs. $ep \to e\gamma n\pi^+$

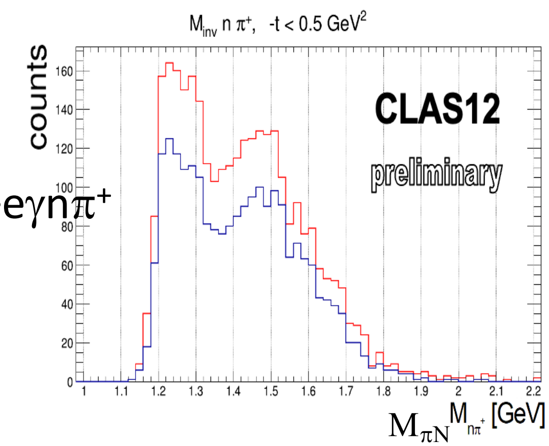
ep->enπ+

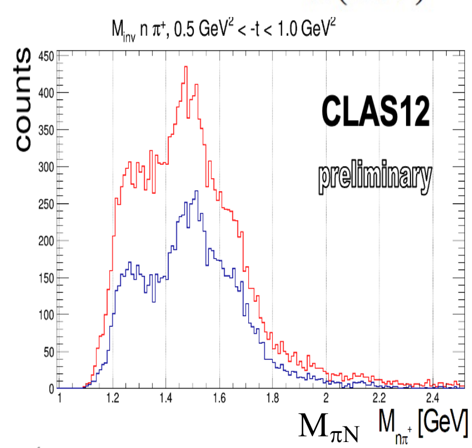




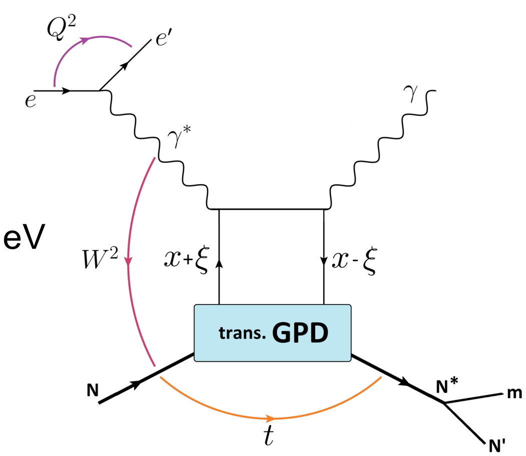


ep->eγnπ+

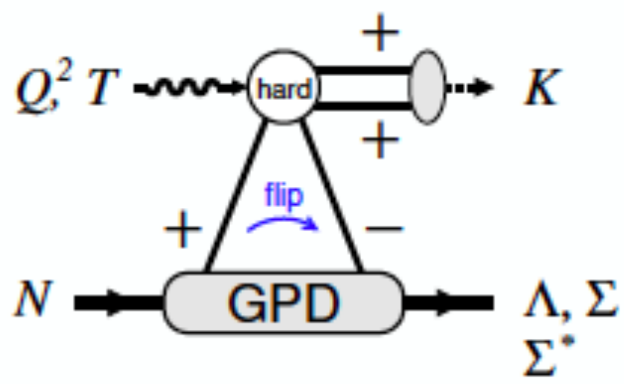




W > 2 GeV



N $\longrightarrow \Lambda, \Sigma, \Sigma^*$ GPDs in K production with CLAS12



Production mechanism

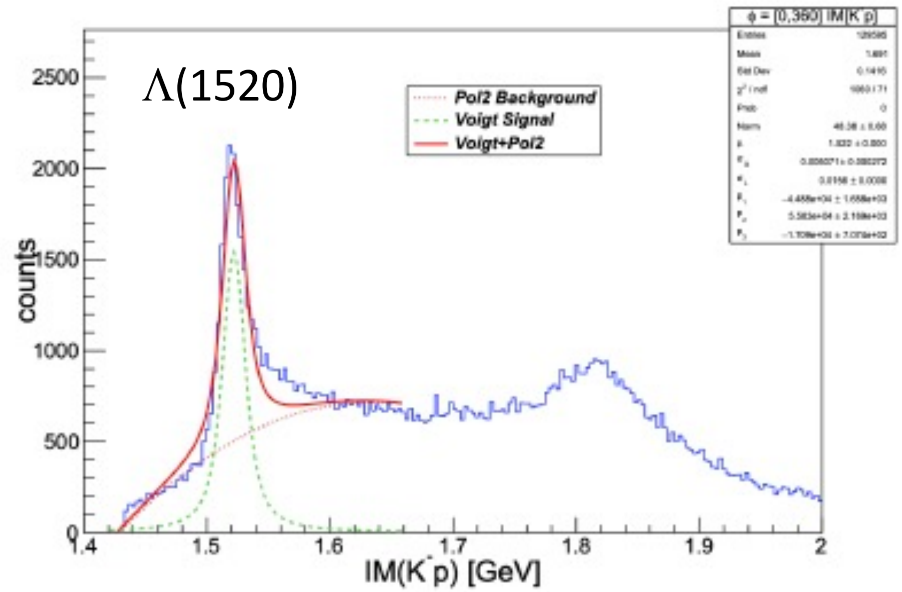
Same twist-3 mechanism with chiral-odd structures as π, η production

Symmetry relations for strange chiral-odd GPDs

$N \rightarrow \Lambda, \Sigma$ related to $N \rightarrow N$
by conventional SU(3) flavor symmetry

$N \rightarrow \Sigma^*$ related to $N \rightarrow N, \Lambda, \Sigma$
by SU(6) spin-flavor symmetry in large-N_c limit

Predictive power; quantitative predictions possible



Invariant mass distribution of pK^- after $ep \rightarrow e'p'K^+K^-$ events are selected.

U. Shrestha (UConn)

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^*

Summary

- GPDs provide a unifying framework to study the 3-D quark and gluon structure of the nucleon
- 3-D imaging of nucleons uncovers the rich dynamics of QCD.
- CLAS12 allows high precision measurements of Exclusive channels to study ground nucleon GPDs and transition GPDs with large kinematic coverages in the valence quark regime!
- The nucleon-to-resonance (N->N*) transition GPDs may provide a unique tool for exploring the 3D structure of baryon resonances.

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