Exclusive Processes at JLab

Mechanical properties of hadrons: Structure, dynamics, visualization

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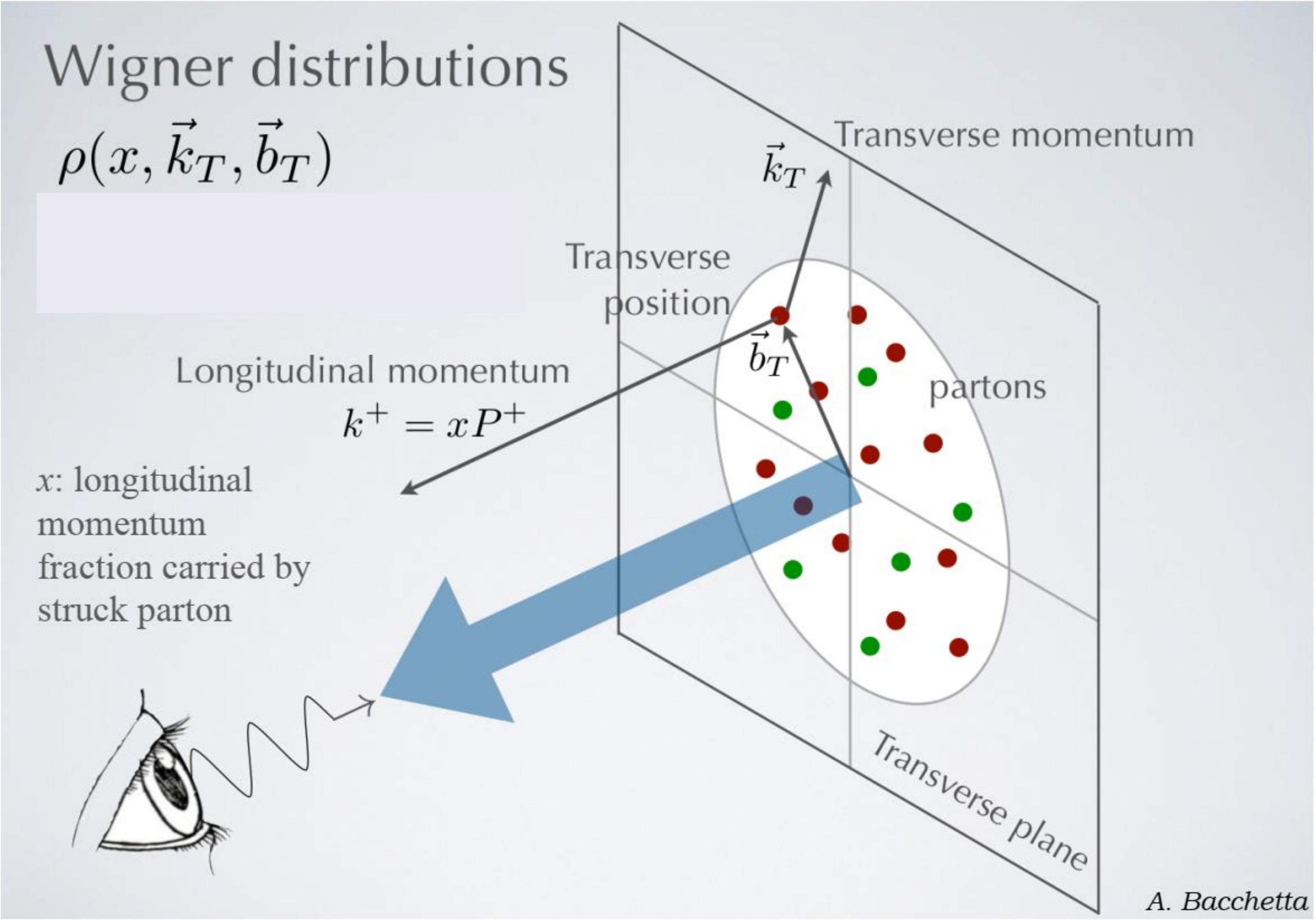
UCONN | UNIVERSITY OF CONNECTICUT

3-Dimensional Imaging of Quarks and Gluons



Generalized Parton Distributions (GPDs)

$$W_\Gamma(\mathbf{r},k) = \frac{1}{2M_N}\int \frac{d^3\mathbf{q}}{(2\pi)^3} e^{-i\mathbf{q}\cdot\mathbf{r}} \left\langle \mathbf{q}/2 \left| \hat{\mathcal{W}}_\Gamma(0,k) \right| -\mathbf{q}/2 \right\rangle$$

S. Liuti et al., Phys. Rev. D 84, 034007 (2011) (GGL)

P. Kroll et al., Eur. Phys. J. A 47, 112 (2011) (GK)

Integrate over transverse ***momentum*** space

↓

Generalized Parton Distributions (GPD)

↓

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

quark pol.

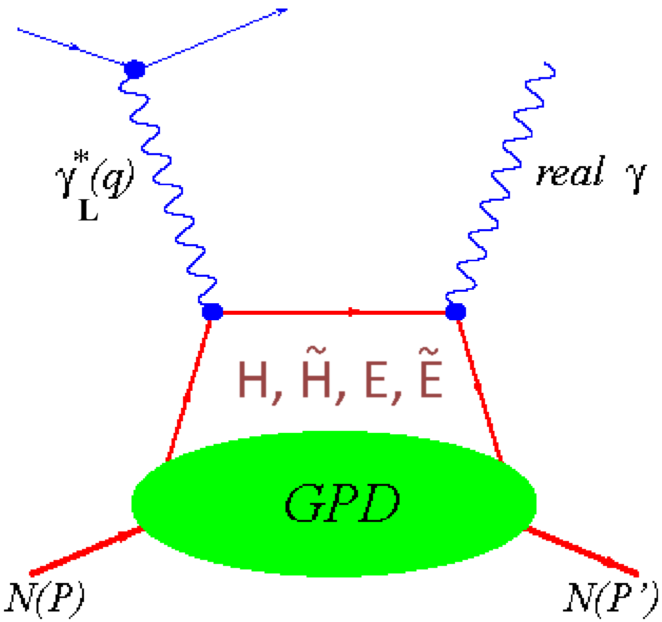
nucleon pol.

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

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

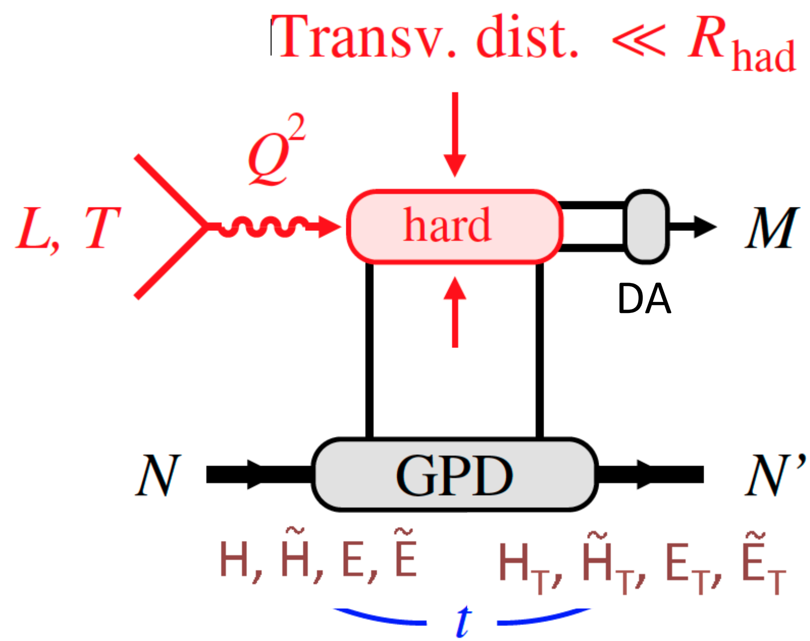
Study GPDs: Deeply Exclusive Processes

Deeply Virtual Compton Scattering (DVCS)



+ Clean process
- Only sensitive to chiral even GPDs

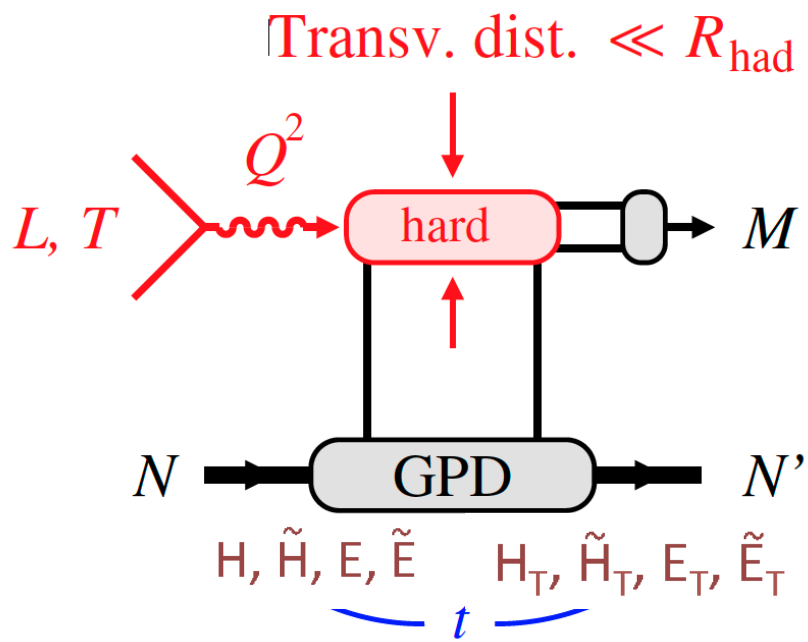
Deeply Virtual Meson Production (DVMP)



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

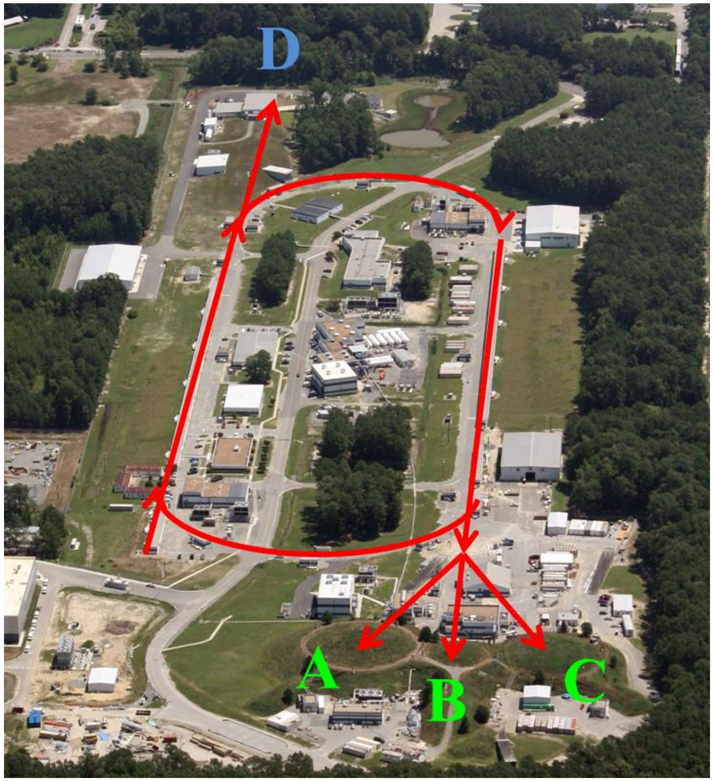
Deeply Virtual Meson Production in the GPD regime

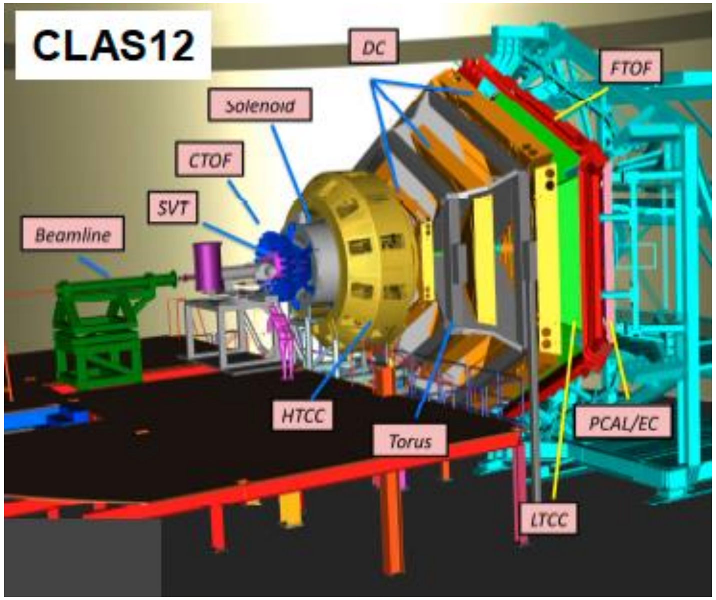
	Meson	Flavor
$\mathcal{H}_T, \mathcal{E}_T$, $\tilde{\mathcal{H}}, \tilde{\mathcal{E}}$	π^+	$\Delta u - \Delta d$
	π^0	$2\Delta u + \Delta d$
	η	$2\Delta u - \Delta d + 2\Delta s$
$\mathcal{H}, \mathcal{E}$	ρ^+	$u - d$
	ρ^0	$2u + d$
	ω	$2u - d$
	ϕ	g

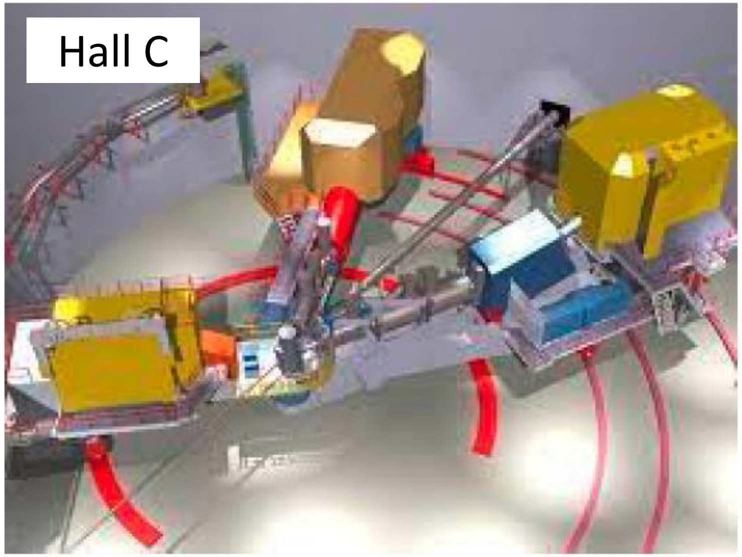


- DVMP enables Flavour decomposition of GPDs.
- The small-size regime: the production of q-qbar pair with sizes << hadronic size dominates.
  - ❖ QCD factorization and GPD extraction assume that this regime is attained.

Thomas Jefferson National Accelerator Facility (Jefferson Lab)







- CEBAF Upgrade completed in September 2017
  - → electron beam
  - → E_{max} = 12 GeV
  - → I_{max} = 90 μA
  - → Pol_{max} ~ 90%

CLAS12 run groups

Run Group A (Unpolarized LH_2 target)

- ★ **unpolarized** **cross section** off proton
- ★ A_{LU} **in Beam Spin Asymmetries**

Run Goup B (Unpolarized LD_2 target)

- ★ Complementary to RG-A
  → allow for ***u/d*** **quark flavor separation**

Run Group C (**longitudinally** polarized NH_3 and ND_3)

- ★ $\mathbf{F_{UL}}$ and $\mathbf{F_{LL}}$

Run Group K (Unpolarized LH_2 target)

- ★ 6.5, 7.5, 8.4 GeV e- beam
- ★ $F_{UU,L}$, $F_{UU,T}$ Separation

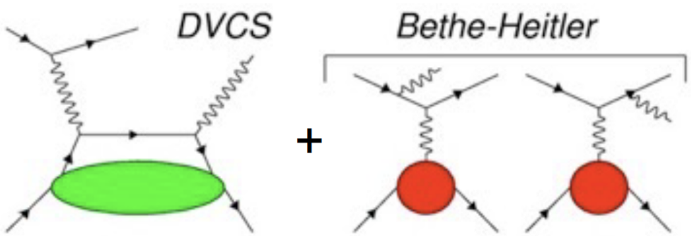
Run Group H (**transversely** polarized NH_3)

- ★ $\mathbf{F_{UT}}$ structure function

➔ scheduled for FY 2029

DVCS- Golden Reaction to Study GPDs

Program covers measurements of beam helicity, longitudinal and transverse polarized target asymmetries using detectors in Halls A, B, and C.

ep→epγ = 

$$\mathcal{T}^2 = |\mathcal{T}_{BH}|^2 + |\mathcal{T}_{DVCS}|^2 + \mathcal{T}^*_{DVCS}\mathcal{T}_{BH} + \mathcal{T}^*_{BH}\mathcal{T}_{DVCS}$$

$$\mathcal{T}_{DVCS} \sim CFF \quad \mathcal{H}(\xi,t) = \underbrace{i\pi\left[H(\xi,\xi,t) - H(-\xi,\xi,t)\right]}_{Im} + \underbrace{P\int_{-1}^{+1} dx\left(\frac{1}{\xi - x} \pm \frac{1}{\xi + x}\right)\left[H(x,\xi,t) \mp H(-x,\xi,t)\right]}_{Re}$$

Spin asymmetries, beam and target – p (n) and total cross sections,

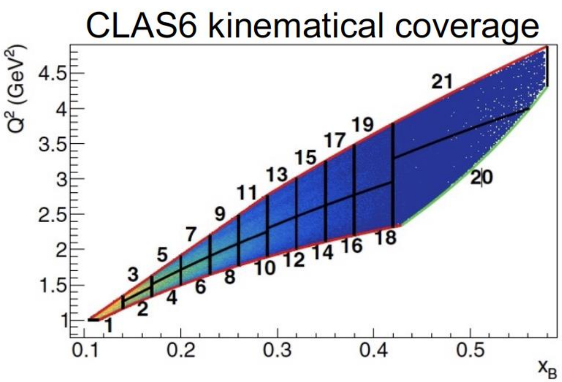
$$A_{LU} \propto Im\mathcal{H}(\widetilde{\mathcal{H}}) \qquad A_{LL} \propto Re\widetilde{\mathcal{H}}(\mathcal{H})$$

$$A_{UL} \propto Im\widetilde{\mathcal{H}}(\mathcal{H}) \qquad A_{UT} \propto Im\mathcal{E}\,(\mathcal{H})$$

and lepton charge asymmetries when positron beams will be available.

CLAS DVCS – BSA and Cross Sections

The first dedicated DVCS experiment with CLAS, 2005, uses a small angle calorimeter.

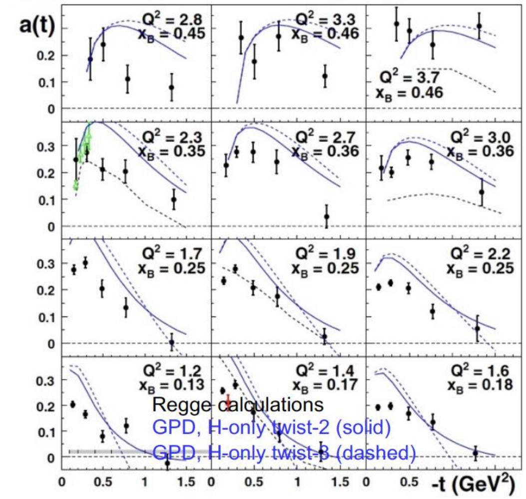


$$ep \rightarrow e'p'\gamma$$

The most extensive set of data at that time.

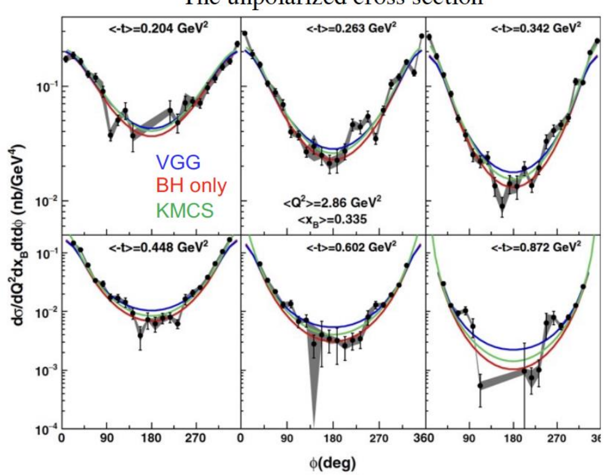
$$A_{LU} = \frac{a \sin\phi}{1 + c\cos\phi + d\cos 2\phi}$$

F.X. Girod et al., Phys. Rev. Lett **100**, 162002 (2008)

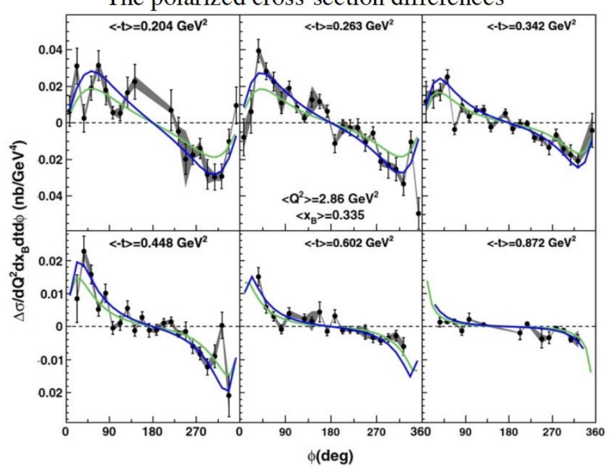


N. Saylor *et al.*, Phys. Rev. C **98**, 045203 (2018)

The unpolarized cross section



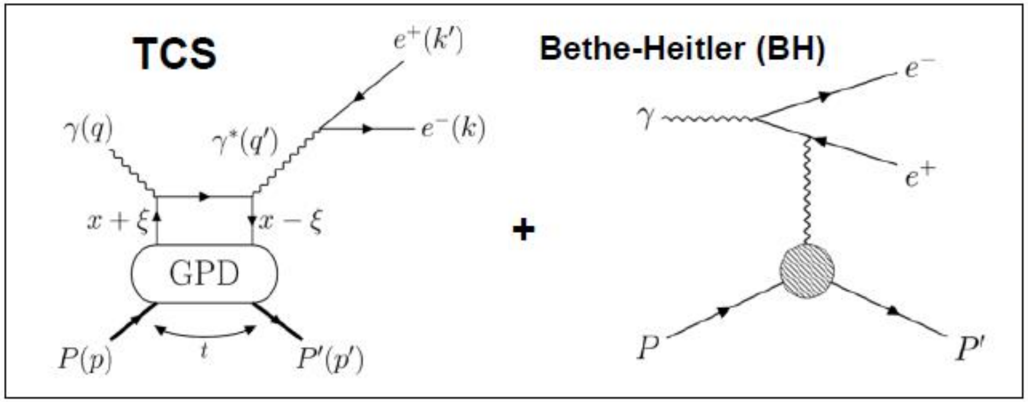
The polarized cross-section differences



Theoretical calculations from the Vanderhaeghen, Guichon, and Guidal (VGG) and Kroll, Moutarde, Sabatié, and Chouika (KMSC) models.

Both models generally reproduce the data, and the theory expectations are in fair agreement with the cross section and differences

First Measurements of TCS with CLAS12



P. Chatagnon *et al.* (CLAS Collaboration), Phys. Rev. Lett. 127, 262501

➔ Time-reversal symmetric process to DVCS

- incoming photon is real
- outgoing photon has large time like virtuality

$$\frac{d^4\sigma_{INT}}{dQ'^2 dt d\Omega} = A\frac{1+\cos^2\theta}{\sin\theta}\left[\cos\phi\ \mathrm{Re}\tilde{M}^{--} - \nu\cdot\sin\phi\ \mathrm{Im}\tilde{M}^{--}\right]$$

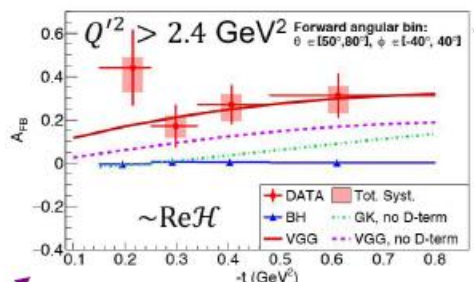
$$\tilde{M}^{--} = \left[F_1\mathcal{H} - \xi(F_1+F_2)\tilde{\mathcal{H}} - \frac{t}{4m_p^2}F_2\mathcal{E}\right]$$

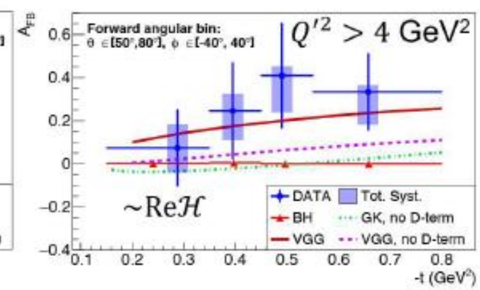
$$A_{FB}(\theta,\phi) = \frac{d\sigma(\theta,\phi) - d\sigma(180° - \theta, 180° + \phi)}{d\sigma(\theta,\phi) + d\sigma(180° - \theta, 180° + \phi)}$$

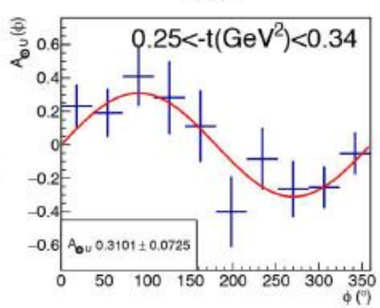
~ Re(*H*) CFF

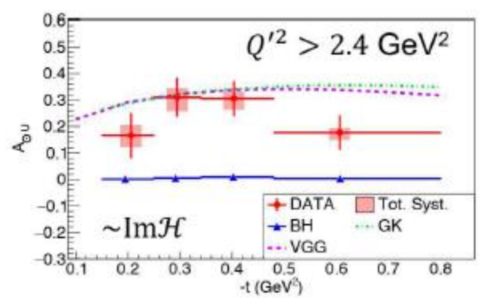
$$A_{\odot U} = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-}$$

~ Im(*H*) CFF



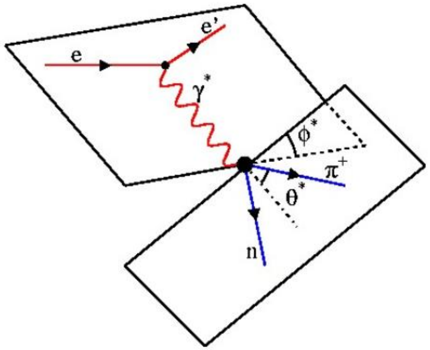


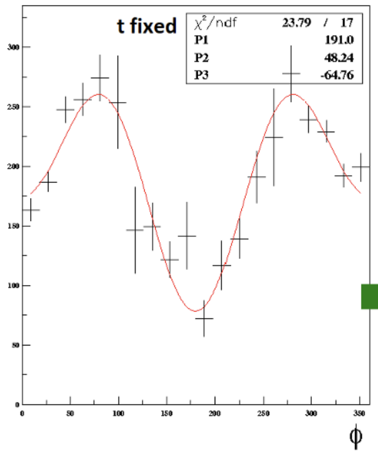


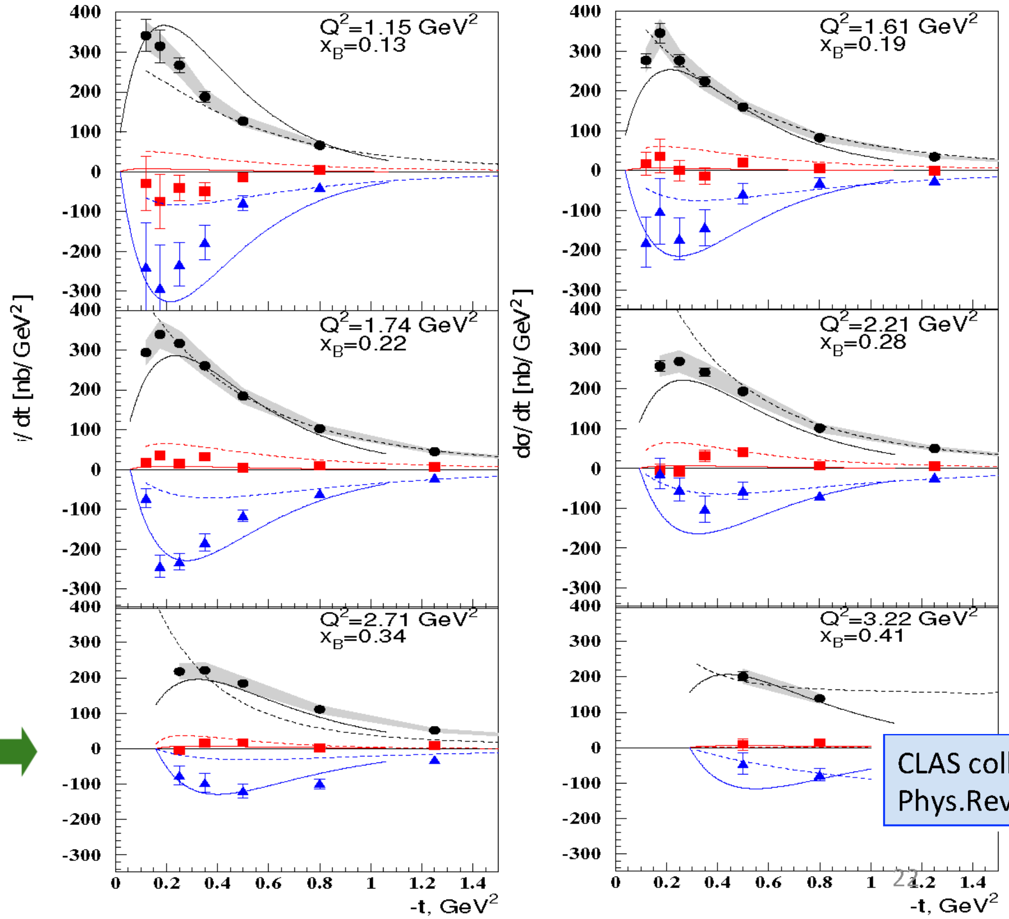


DVMP (π^0) Differential Cross Section with CLAS

$$2\pi \frac{d^2\sigma}{dt d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)} \frac{d\sigma_{LT}}{dt} \cos\phi + \varepsilon \frac{d\sigma_{TT}}{dt} \cos 2\phi$$







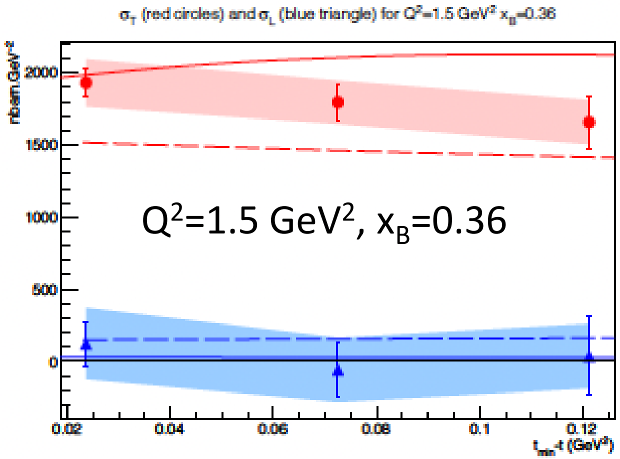
CLAS in Hall B
E=6 GeV

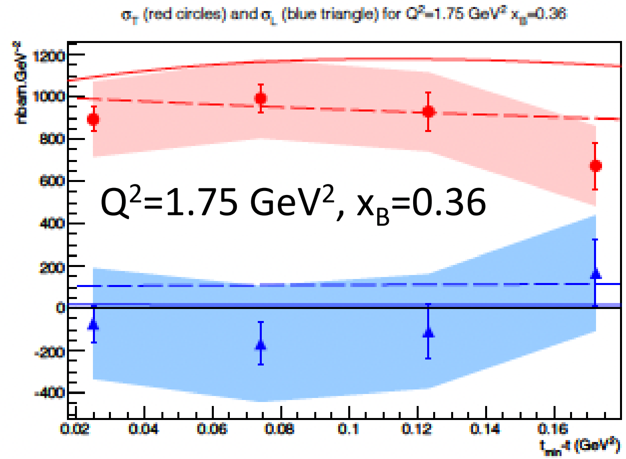
- σ_0
- σ_{TT} → cos(2φ)
- σ_{LT} → cos(φ)

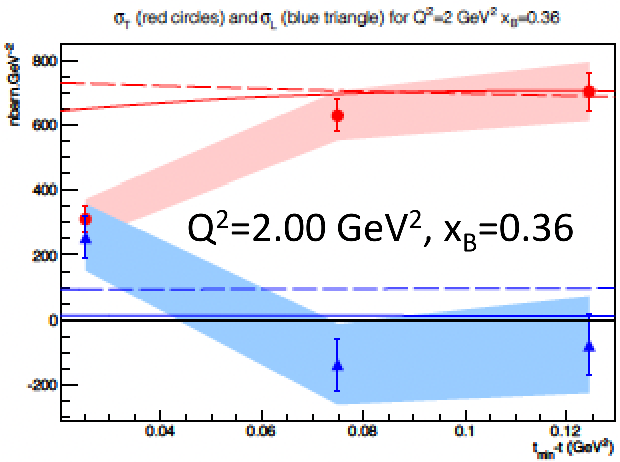
— GK
--- GGL

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

DVMP (π^0) L/T Separation







Hall A

E=3.35 -5.55 GeV

Red: σ_T

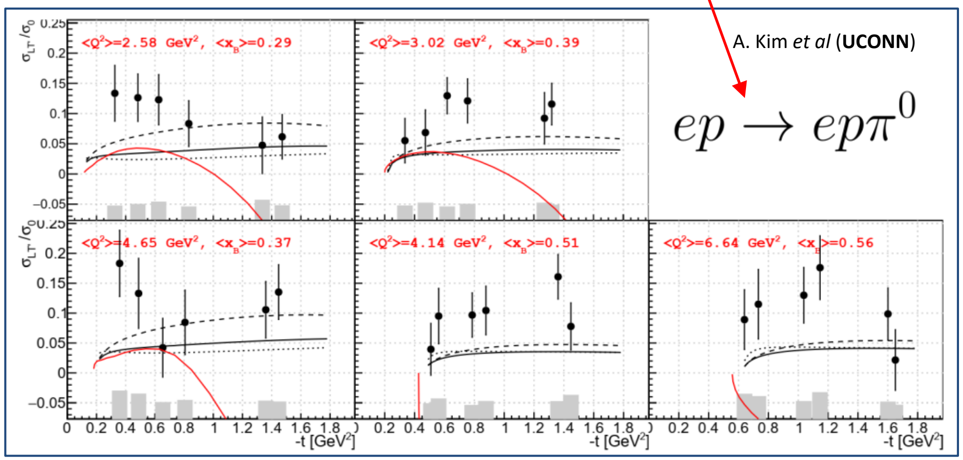
Blue: σ_L

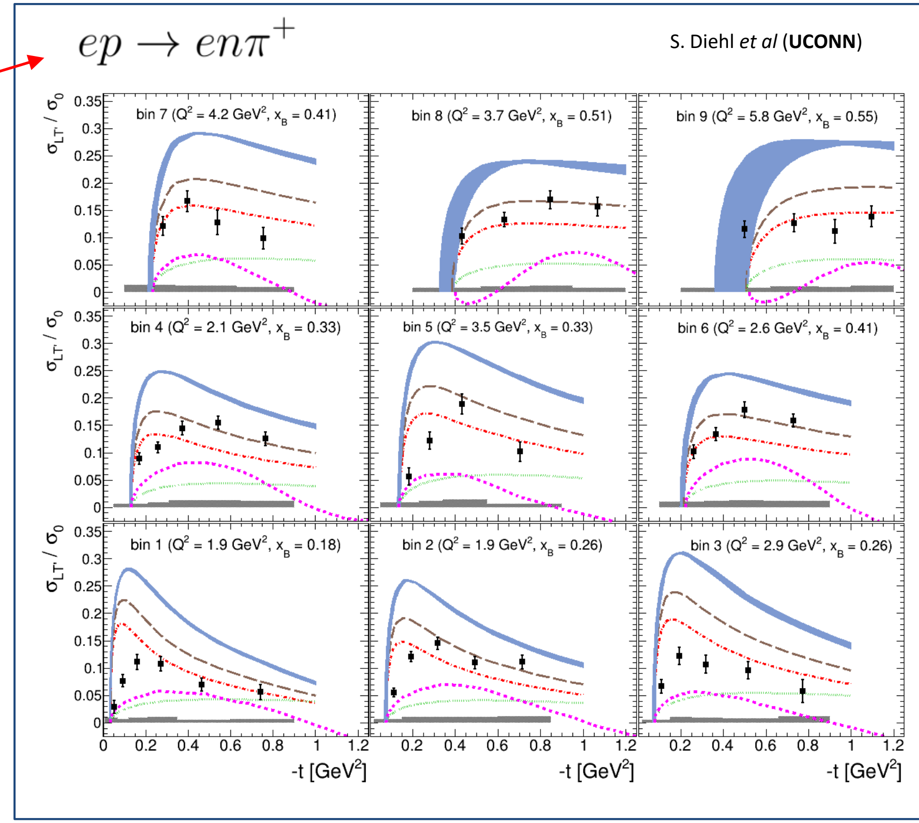
M. Defurne Phys. Rev. Lett. 117 (2016) 26, 262001

Pseudoscalar meson electroproduction with CLAS12

E=10.6 GeV

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





GK model

JML model

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

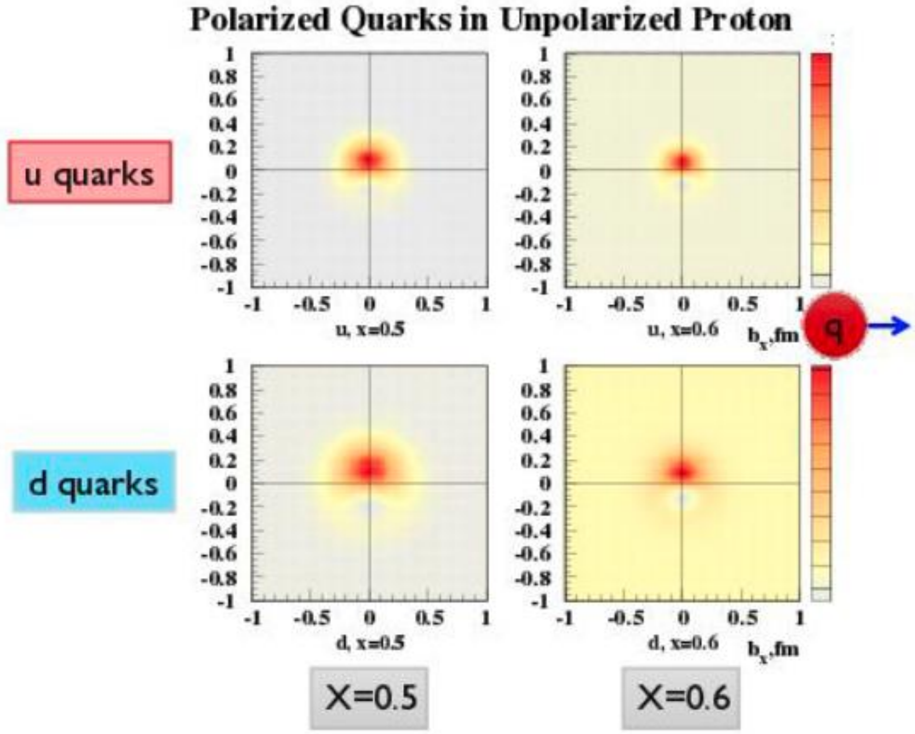
H_T is related to the proton's tensor charge.

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

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

Transverse densities for u and d quarks in the proton (after global fit)

- $\bar{E}_T$ is related to the distortion of the polarized quark distribution in the transverse plane for an unpolarized nucleon



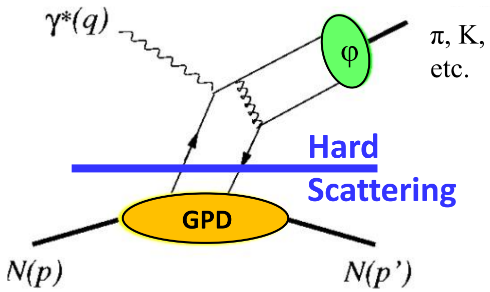
V. Kubarovsky et al.

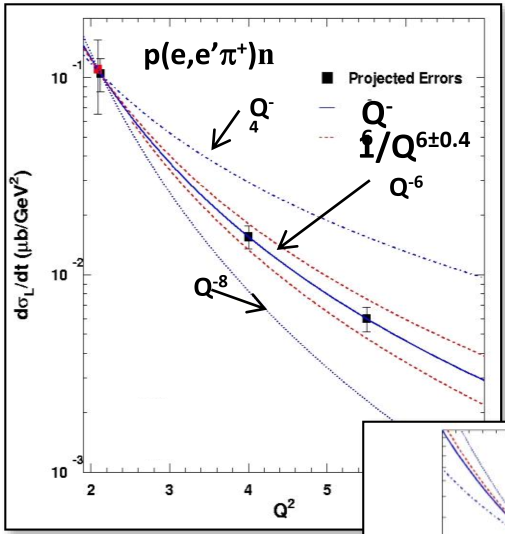
The fit results agree with the large-N_c limit analysis by P. Schweitzer and C. Weiss *Phys.Rev.C* 94 (2016) 4, 0452 02

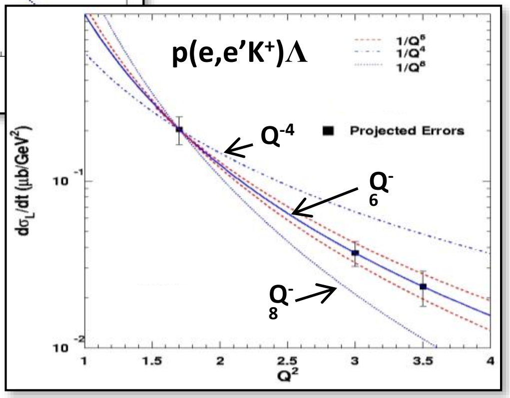
GPD parameterization used in GK model can be improved through global fit using exisiting Hall A and Hall B data

L/T Separated π^+/K^+ Cross Sections in Hall C with **12 GeV**

Light pseudoscalar mesons (π^+, K^+, π^0)







π^+: to Q^2~9 GeV^2
K^+: to Q^2~6 GeV^2

Fit: $1/Q^n$

- One of the most stringent tests of the reaction mechanism is the Q^2 dependence of cross section
  - –σ_L scales to leading order as Q^{-6}
  - –σ_T does not
- Need to validate the reaction mechanism for reliable interpretation of the GPD program – key are precision longitudinal-transverse (L/T) separated data over a range of Q^2 at fixed x/t
  - **If σ_T is confirmed to be large, it could allow for detailed investigations of transversity GPDs. If, on the other hand, σ_L is measured to be large, this would allow for probing the usual GPDs**

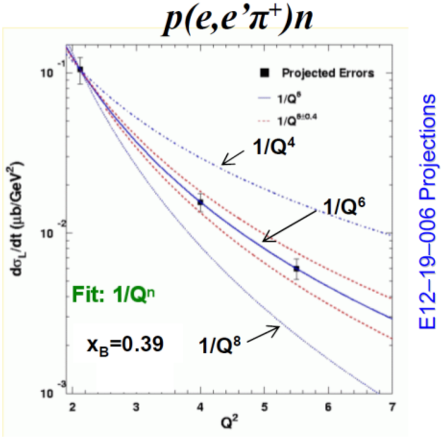
Q^{-n} scaling test range doubles with 18+ GeV beam and HMS+SHMS

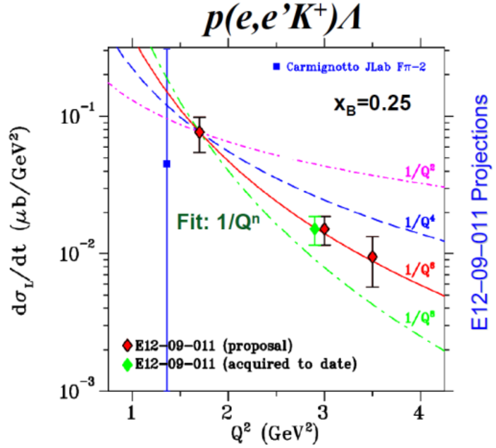
L/T Separated π^+/K^+ Cross Sections in Hall C with **18+ GeV** JLab

Light pseudoscalar mesons (π^+, K^+, π^0)

The Hall C Future Light Pseudoscalar Meson Team Leads
- Dave Gaskell, JLab
- Tanja Horn, CUA
- Stephen Kay, U. Regina
- Wenliang (Bill) Li, Stony Brook U.
- Pete Markowitz, FIU,
- Garth Huber, U. Regina

We welcome interested groups of collaborators for Hall C Future Studies





x	Q^2 (GeV^2)	W (GeV)	$-t_{min}$ (GeV^2)
0.31	1.45–3.65	2.02–3.07	0.12
	1.45–6.5	2.02–3.89	
0.39	2.12–6.0	2.05–3.19	0.21
	2.12–8.2	2.05–3.67	
0.55	3.85–8.5	2.02–2.79	0.55
	3.85–11.5	2.02–3.23	

x	Q^2 (GeV^2)	W (GeV)	$-t_{min}$ (GeV^2)
0.25	1.7–3.5	2.45–3.37	0.20
	1.7–5.5	2.45–4.05	
0.40	3.0–5.5	2.32–3.02	0.50
	3.0–8.7	2.32–3.70	

PHASE 1 SCENARIO

Q^{-n} scaling test range nearly doubles with 18 GeV beam and HMS+SHMS

Opportunities with the Neutral Particle Spectrometer (NPS) in Hall C

Light pseudoscalar mesons (π^+, K^+, π^0)

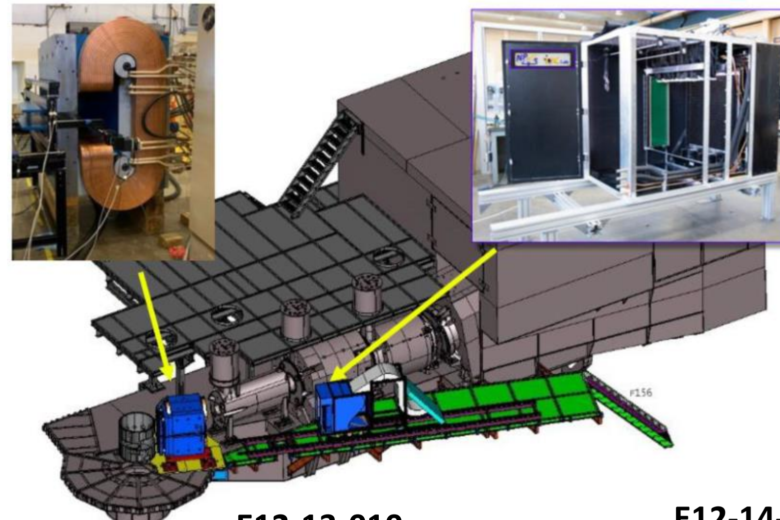
The NPS is a facility in Hall C, utilizing the well-understood HMS and the SHMS infrastructure, to allow for precision (coincidence) cross section measurements of neutral particles (γ and π^0).

Experiment	Exp #	Beam	Target	PAC Days	Rating
π^0 SIDIS	E12-13-007	$\vec{e}^-$	L H_2	(26)	A⁻
DVCS and Exclusive π^0	E12-13-010	$\vec{e}^-$	L H_2	53	A
Wide Angle Compton Scattering (WACS)	E12-14-003	e^-, γ	L H_2	18	A⁻
Wide Angle Exclusive π^0 photoproduction	E12-14-005	e^-, γ	L H_2	(18)	B
DVCS – days moved from Hall A	E12-06-114	$\vec{e}^-$	L H_2	35	A
A_{LL} & A_{LS} Polarization Observables in WACS at large s, t, and u	E12-17-008	CPS: $\vec{\gamma}$	$N\vec{H}_3$	46	A⁻
Timelike Compton Scattering (TCS) off a Transversely Polarized Proton	C12-18-005	CPS: $\vec{\gamma}$	$[N\vec{H}_3]_T$	35	C2

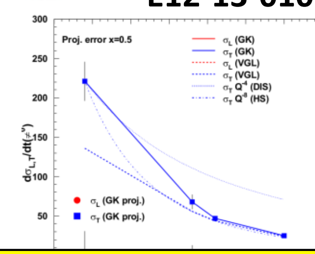
E12-13-010 will provide relative σ_L and σ_T contributions to the π^0 cross section up Q^2~6 GeV^2 to verify reaction mechanism

E12-14-005 data will help confirm scaling in exclusive photoproduction of π^0 mesons and tests of the handbag mechanism

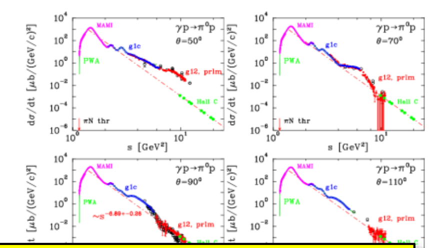
NSF MRI PHY-1530874



E12-13-010



E12-14-005

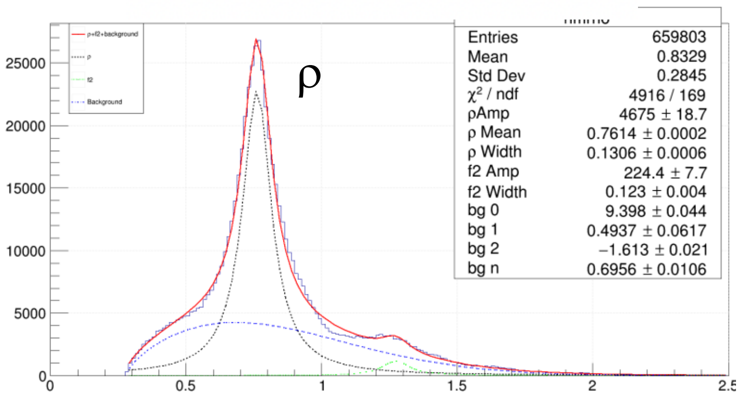


Q^{-n} scaling test range increases with 18+ GeV beam and NPS – need to check in detail

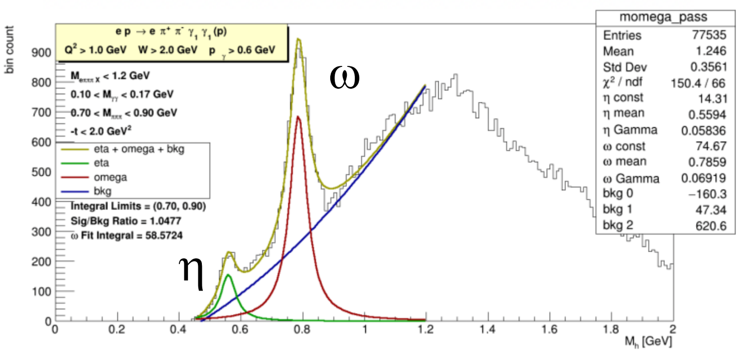
Exclusive ρ/ω production with CLAS12

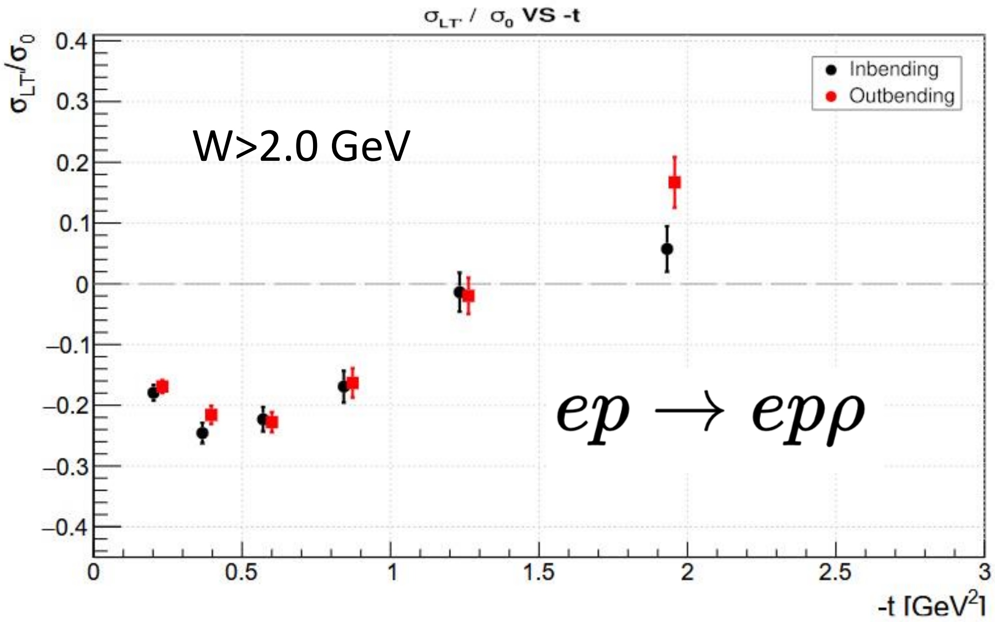
$$\sigma_{LT'} \sim r^8_{00} \sim \text{Im}\left[\langle H_T\rangle^*\langle E\rangle + \langle \bar{E}_T\rangle^*\langle H\rangle\right]$$

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



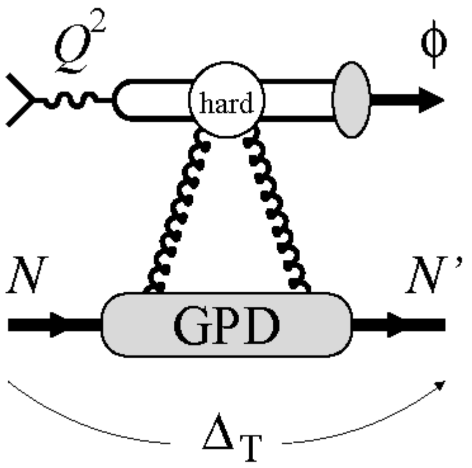
Invariant Mass: $\pi^+ + \pi^- + \pi^0$





Exclusive ϕ production with CLAS12

Exclusive Φ production

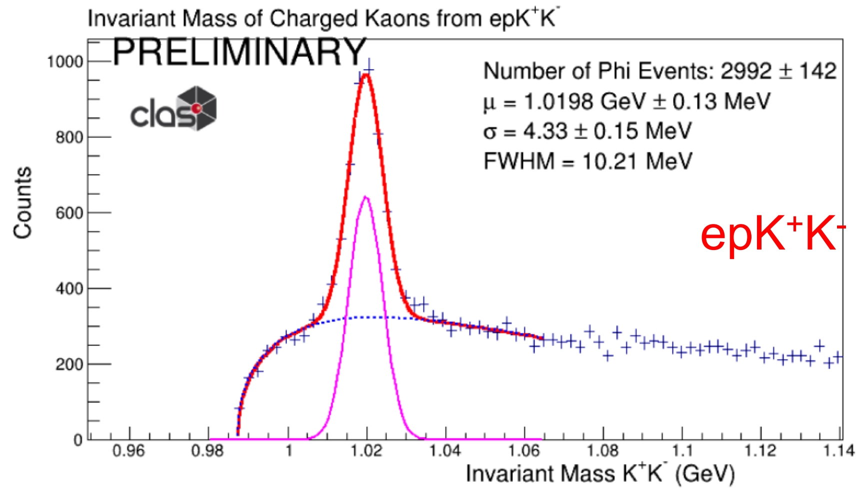


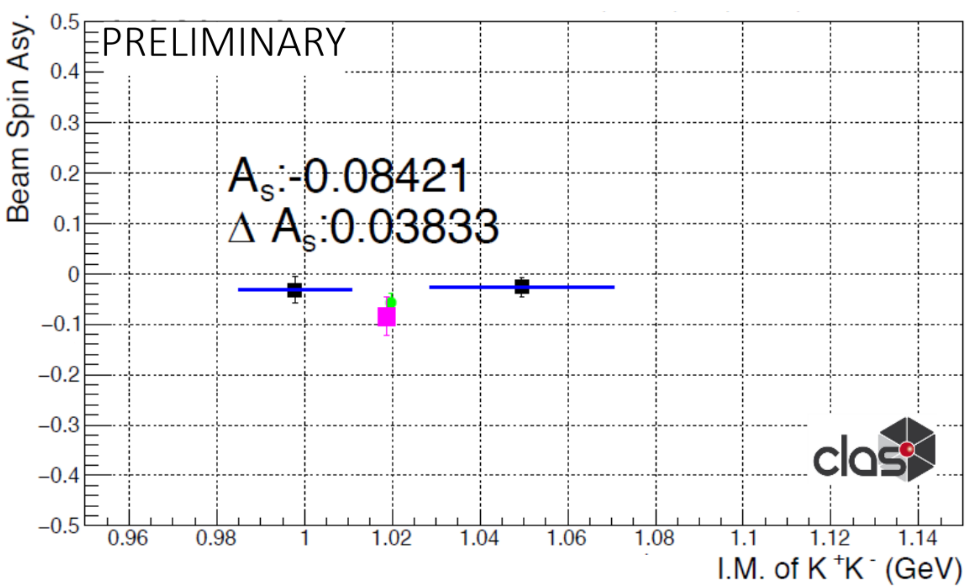
- Exclusive Φ production probes gluon GPDs
- Transverse spatial distribution of gluons

x < 0.01 measured at HERA, FNAL

x > 0.1 practically unknown

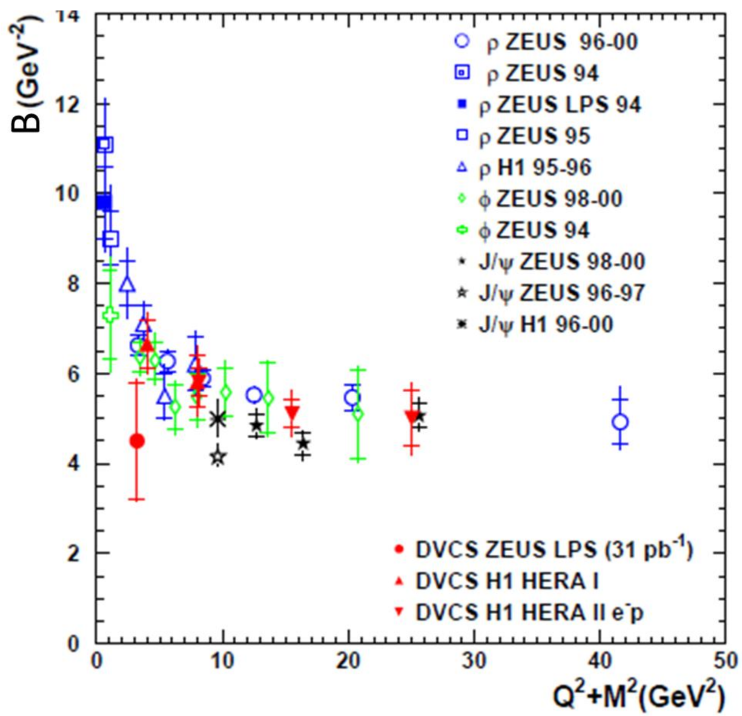
$$A_{LU}^{sin(\phi_t)} \sim \mathrm{Im}[\langle \bar{E}_T \rangle_{LT}^* \langle H \rangle_{LL} + \frac{1}{2} \langle H_T \rangle_{LT}^* \langle E \rangle_{LL}]$$

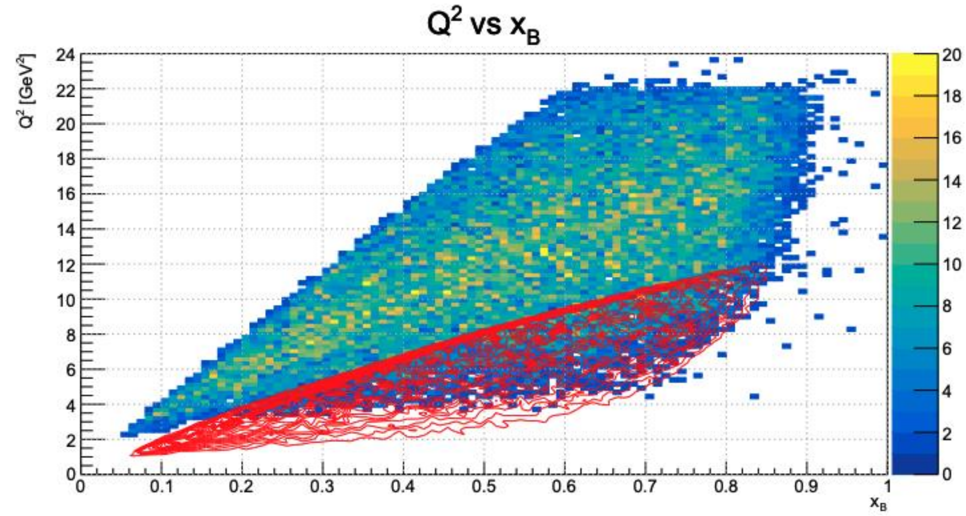




B. Clary (UConn)

Exclusive ρ/ω/ϕ production with 20+ GeV in Hall B





- Below Q^2 = 10 GeV^2 : decrease of the slope with Q^2 (related to meson production in large-size configurations which slowly dies out.
- Above Q^2 = 10 GeV^2: universal t-slope that can be attributed to the gluon GPD.

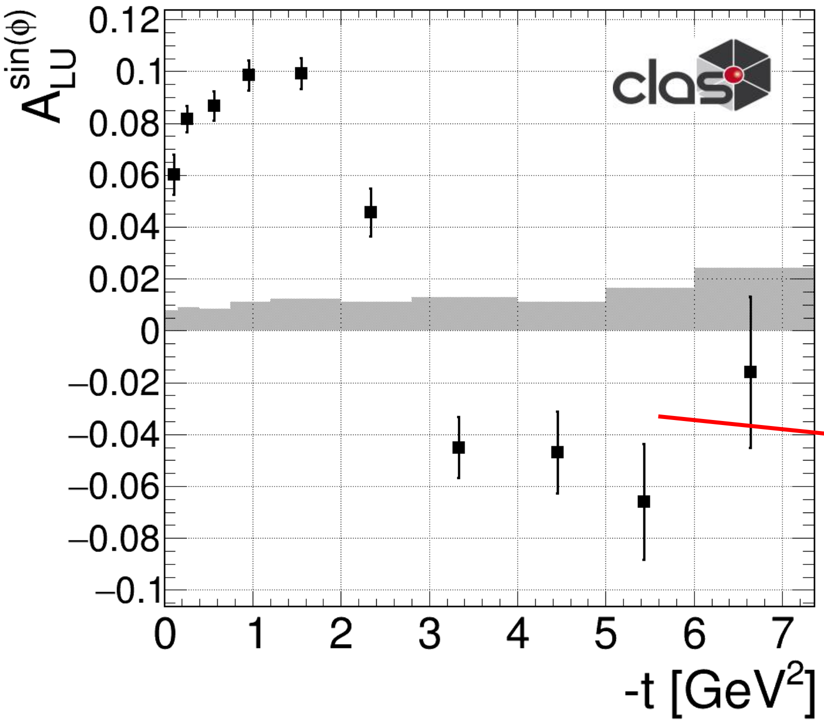
- At present 12 GeV kinematics, the small size regime is very questionable.
- At 20+ GeV one could go to higher Q2 (assuming sufficient luminosity) at moderate x and be much closer to the small size regime.

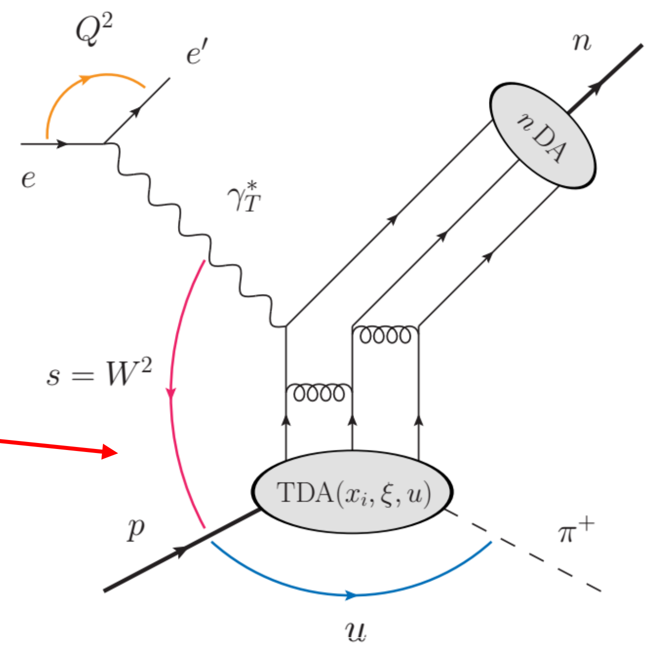
From GPDs to Transition Distribution Amplitudes (TDAs) with CLAS

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

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

CLAS data
E = 5.4 GeV

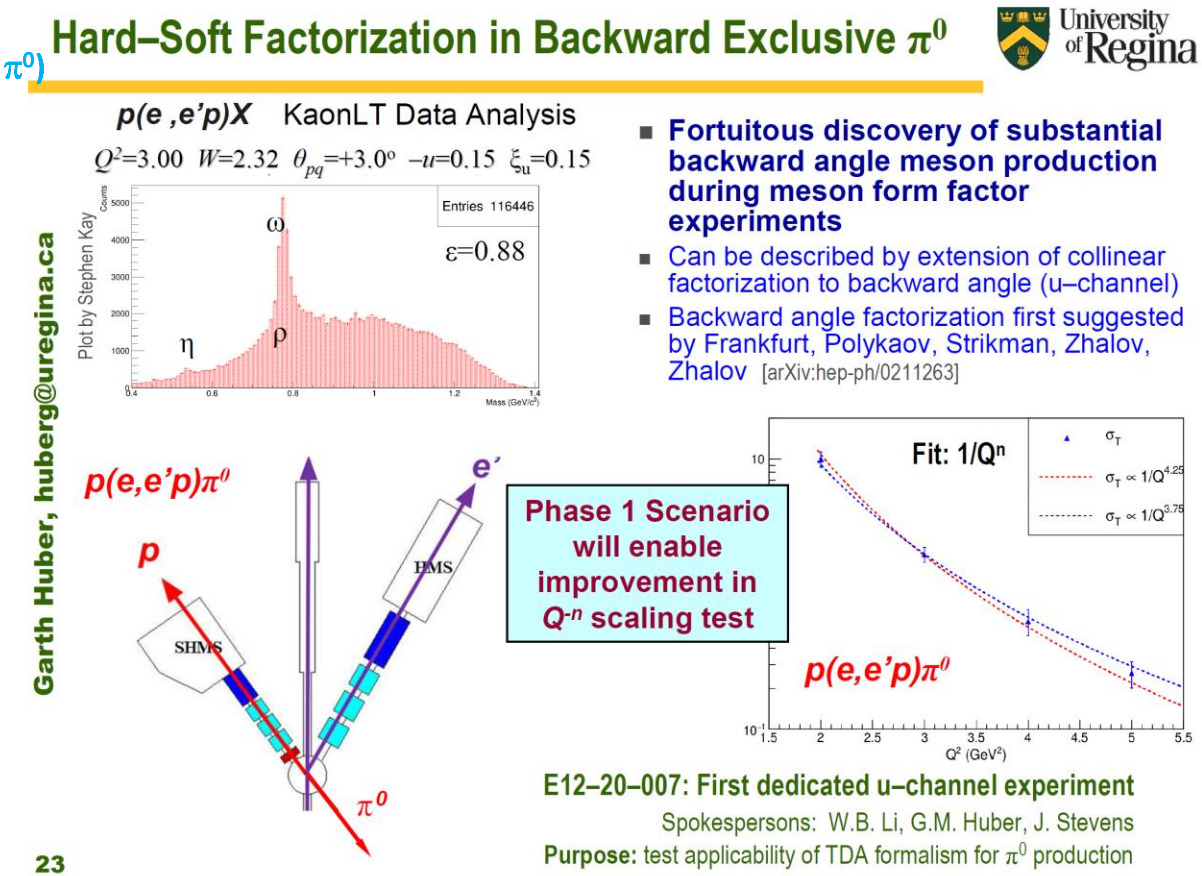




➔ „Backward physics“ opens a new window to the 3D nucleon structure!

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

Light pseudoscalar mesons (π^+, K^+, π^0)

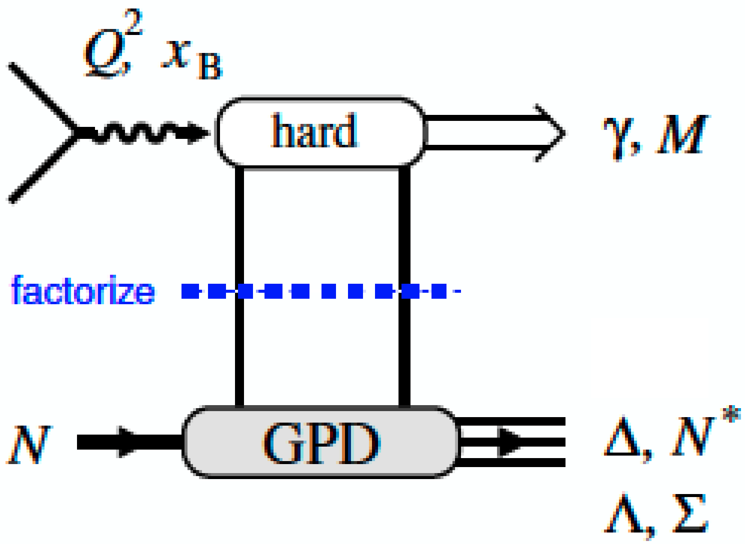


The Hall C Future Light Pseudoscalar Meson Team Leads

- Dave Gaskell, JLab
- Tanja Horn, CUA
- Stephen Kay, U. Regina
- Wenliang (Bill) Li, Stony Brook U.
- Pete Markowitz, FIU,
- Garth Huber, U. Regina

We welcome interested groups of collaborators for Hall C Future Studies

Exploring Transition GPDs with CLAS12



Transition GPDs

Factorization of hard exclusive processes

GPDs for resonance final states

Theoretical methods: Chiral dynamics, $1/N_c$ expansion of QCD

Processes

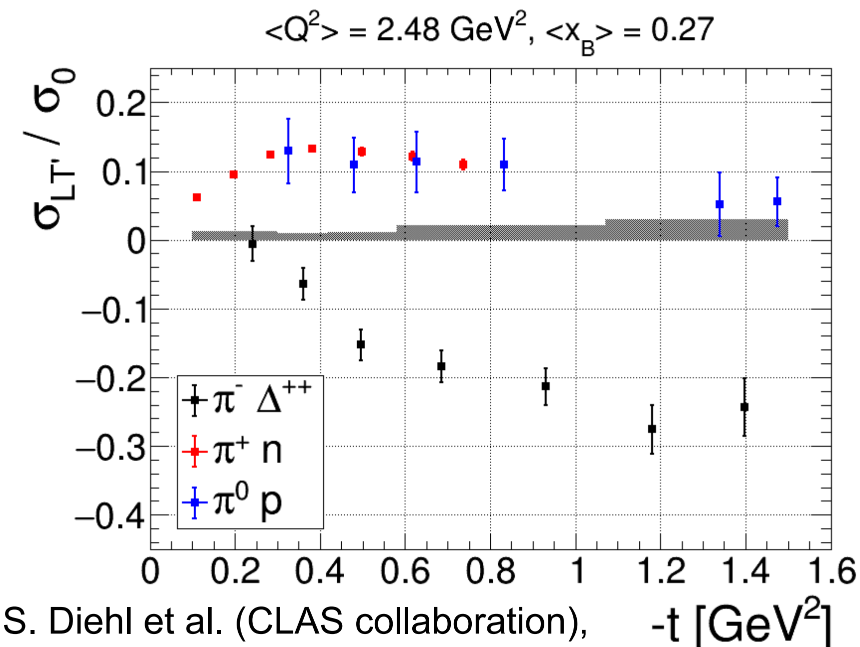
$N \rightarrow \Delta$ in DVCS

$N \rightarrow \Delta, N^*$ in π, η production

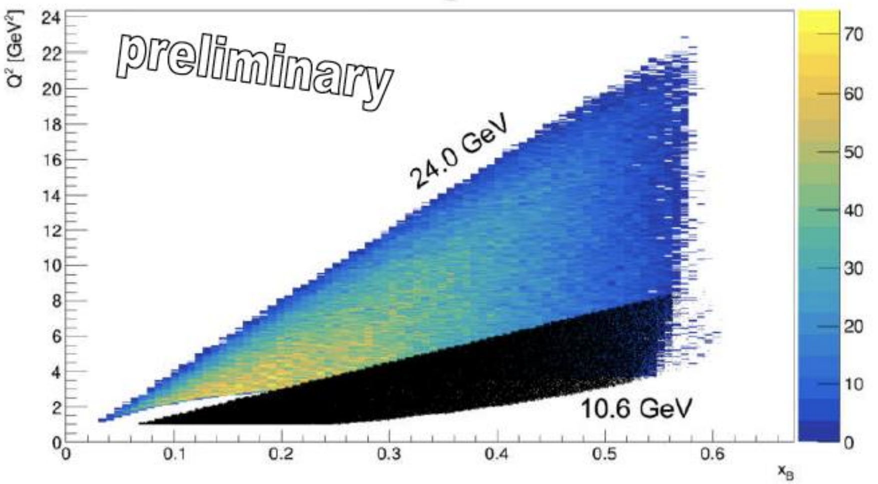
$N \rightarrow \Lambda, \Sigma$ in K, K^* production

Exploring Transition GPDs at CLAS12 and 20+ GeV

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



S. Diehl et al. (CLAS collaboration), to be summitted to PRL



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

➔ Provides access to p-Δ transition GPDs

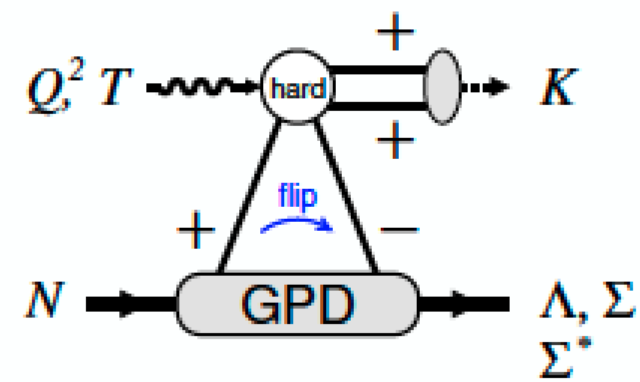
➔ 3D structure of the Δ resonance and of the excitation process

Extended Q² range

→ Advantage for factorisation

- Similar for non-diagonal DVCS

N ⟶ Λ, Σ, Σ* GPDs in K production with CLAS12



Production mechanism

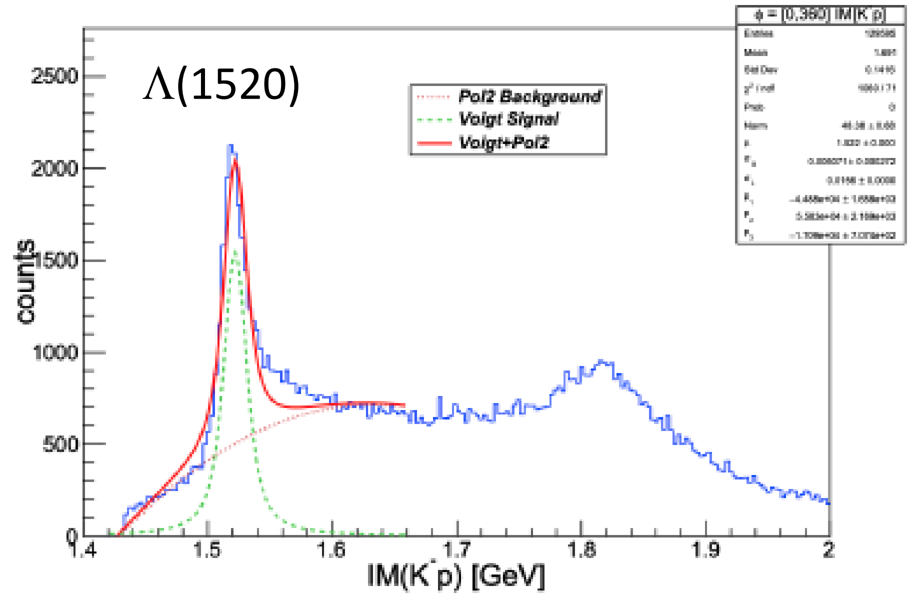
Same twist-3 mechanism with chiral-odd structures as π, η production

Symmetry relations for strange chiral-odd GPDs

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

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

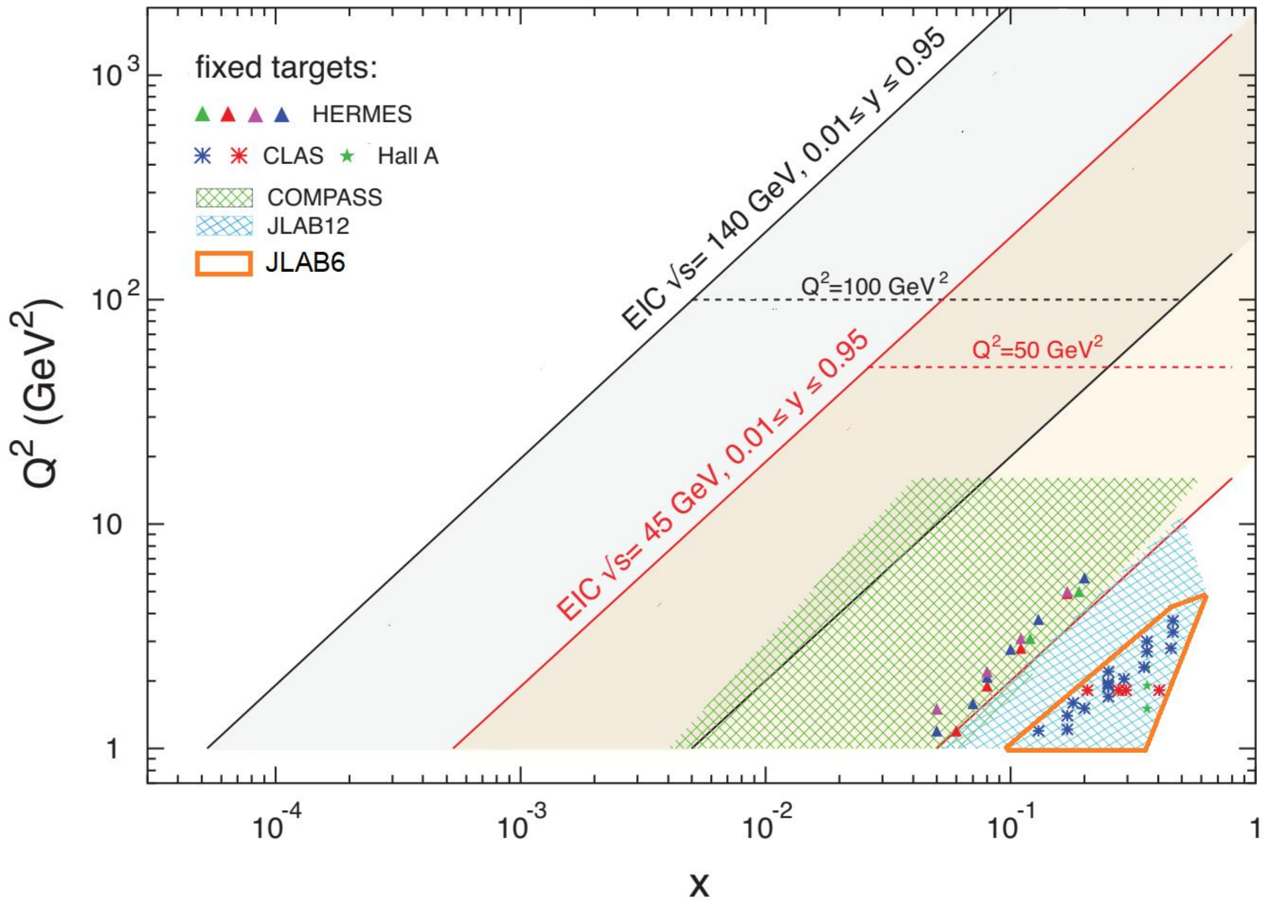
Predictive power; quantitative predictions possible



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

22 GeV kinematic coverage will be similar to exlcusive vecgtor meson production

From CLAS to JLAB to COMPASS to EIC



➔DVMP is also pursed at COMPASS and EIC
➔JLab (12+22 GeV) would be complementary to EIC

Conclusion and Outlook

1. Exclusive meson production processes are important in accessing GPDs which provide a unifying framework to study the 3D structure of hadrons.

2. One essential point concerns the approach to the small-size regime, where the production of q-qbar pair with sizes << hadronic size dominates. QCD factorization and GPD extraction assume that this regime is attained (!).

3. At present 12 GeV kinematics, whether we attain this regime is under investigation.

4. At 20+ GeV energy and luminosity upgrade, one could go to higher Q^2 (assuming sufficient luminosity) at moderate x and be much closer to this regime.

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