Deep Exclusive Reactions

Lecture 1: Nucleon structure studies with the electromagnetic probe
- Elastic scattering: form factors
- DIS: structure function
- Exclusive reactions: Generalized Parton Distributions

Lecture 2: Deeply Virtual Compton Scattering
- GPDs and DVCS
- DVCS on the proton with JLab@6 GeV
- Extraction of GPDs from data
- Proton tomography and forces in the proton

Lecture 3: DVCS and beyond
- DVMP
- New DVCS experiments@12 GeV
- TCS

Lecture 4: Perspectives
- Upgrades at JLab
- GPDs at the EIC

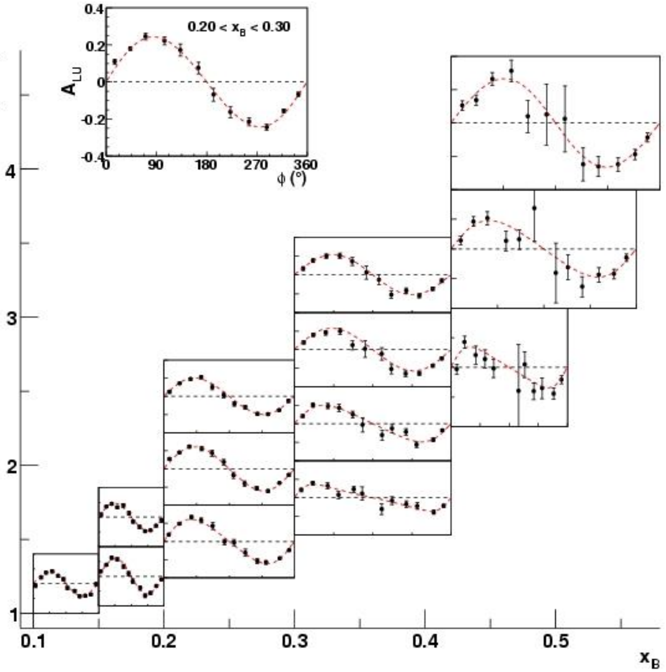
Lecture 5: Tutorial
- Data analysis techniques for exclusive reactions

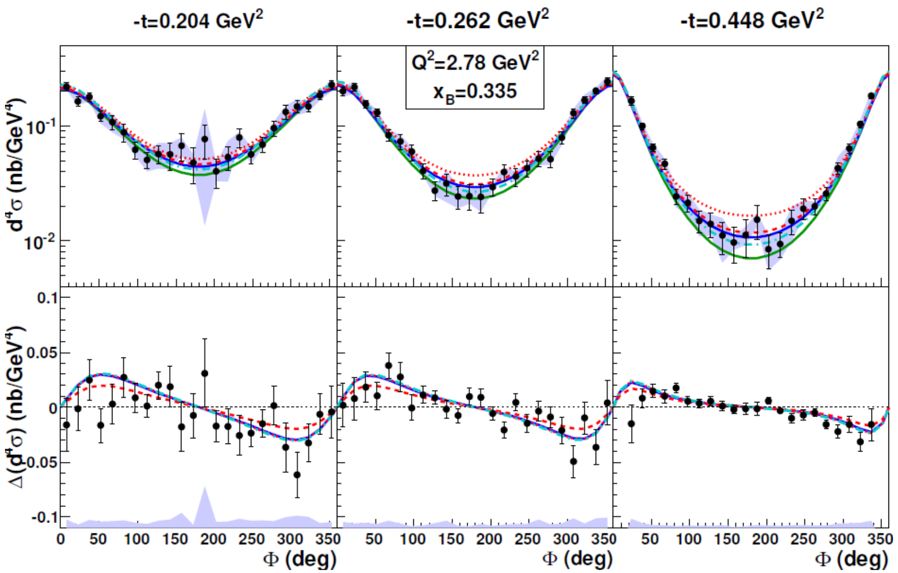
CEBAF Large Acceptance Spectrometer

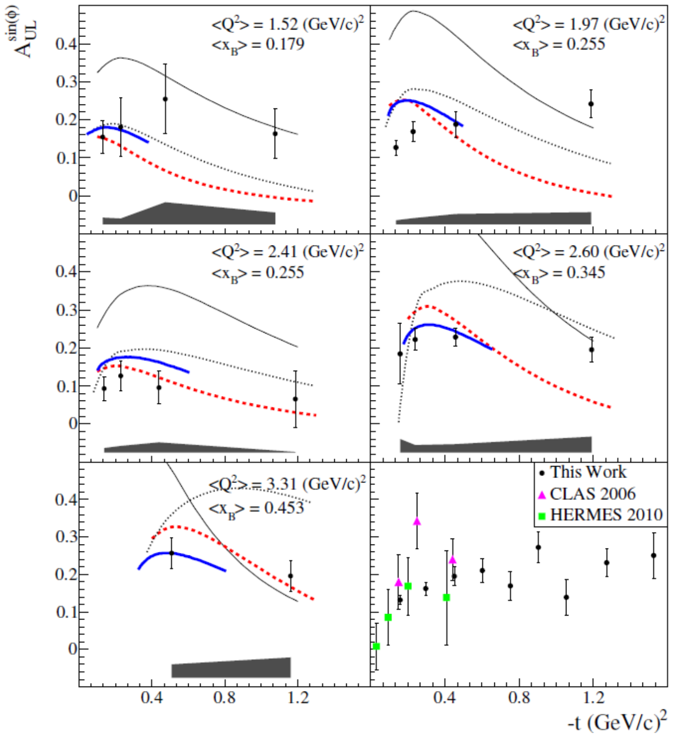
Silvia Niccolai, IJClab Orsay & CLAS Collaboration
HUGS, JLab, June 2023

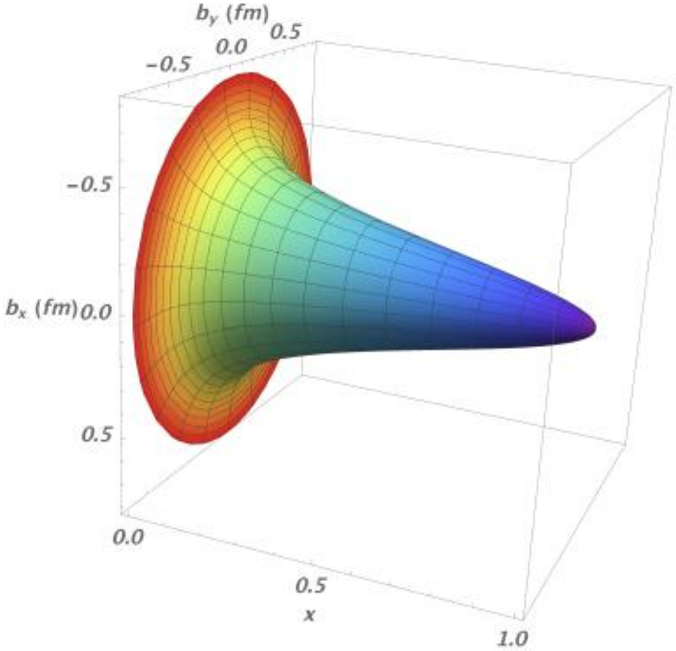
Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

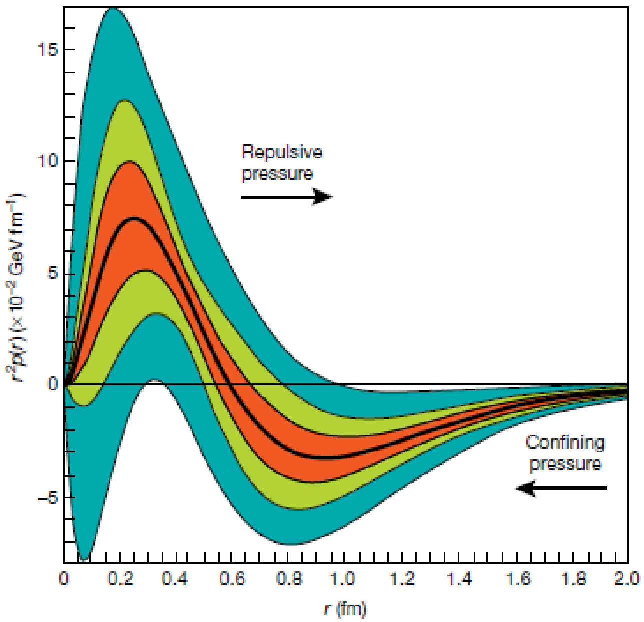
What we have learned from DVCS at 6 GeV

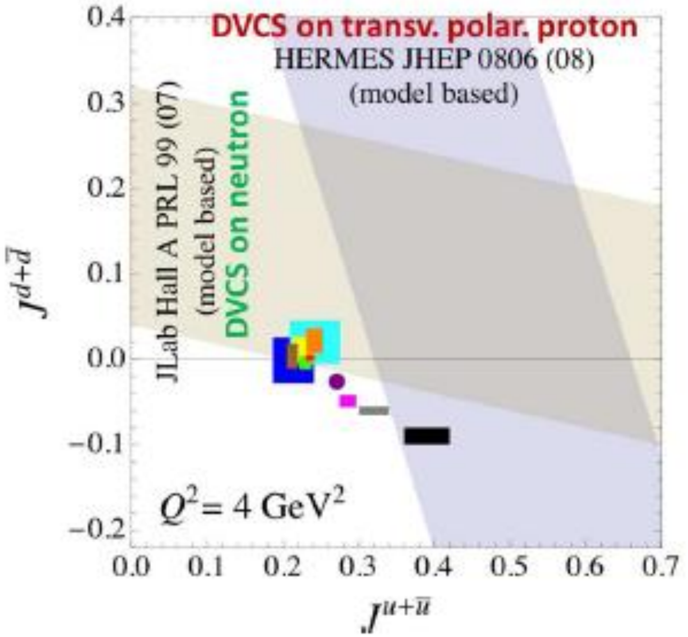




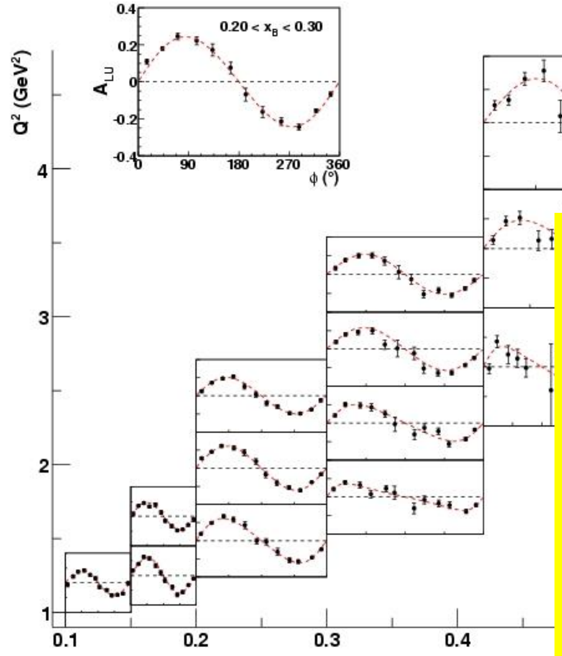


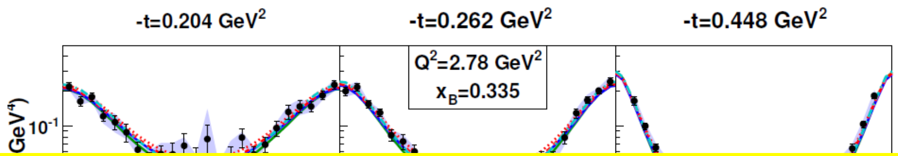


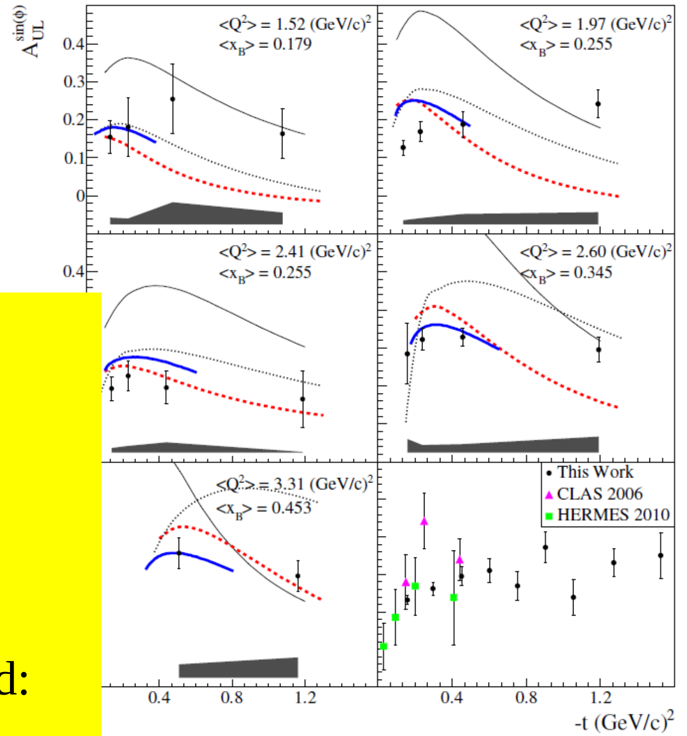




What we have learned from DVCS at 6 GeV





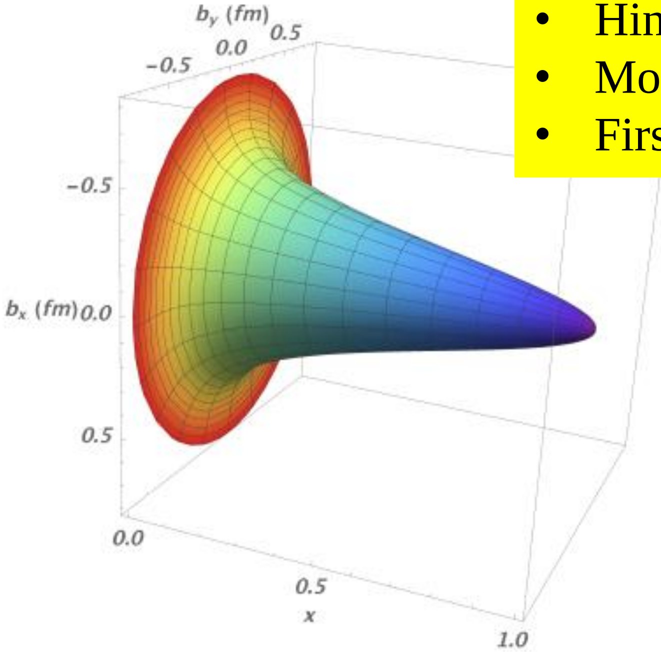


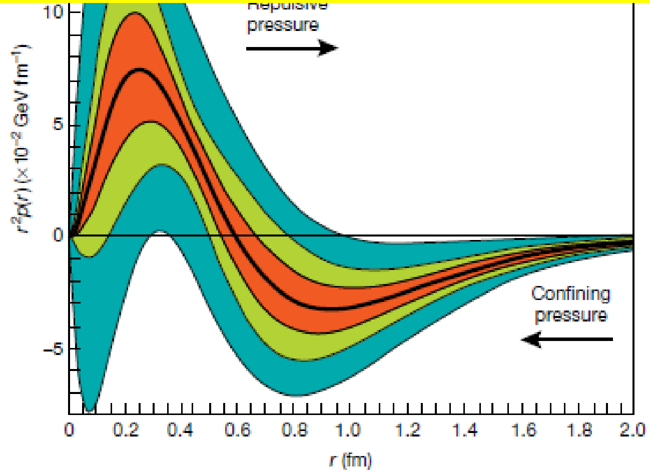
Constraining GPDs requires the measurement of:

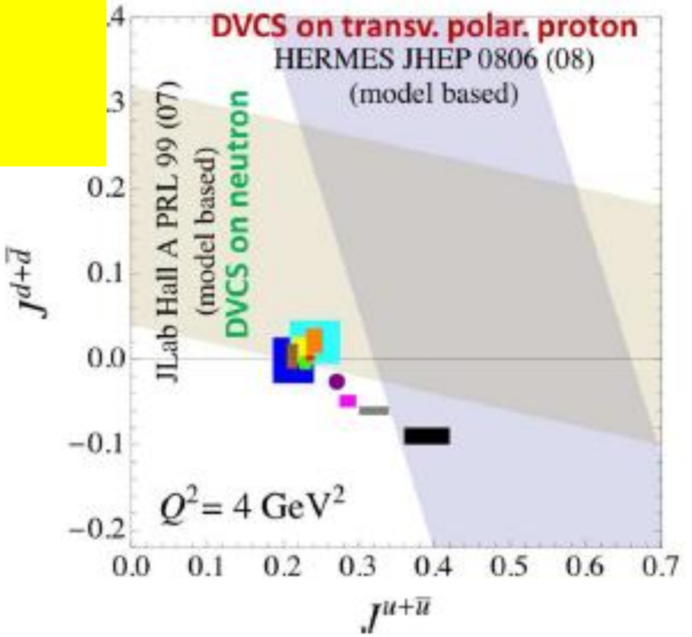
- many DVCS observables
- on a wide kinematic
- for proton and neutron targets

The results from JLab@12 GeV (Hall A and CLAS) and HERMES, along with the first attempts to fit GPDs from the data, have allowed:

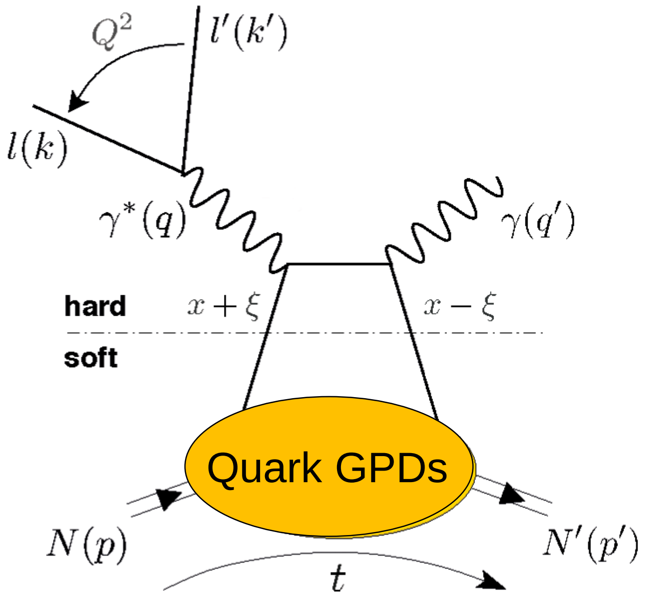
- First tomographic image of the proton
- Hints about distribution of pressure in the proton
- Model-dependent extraction of J_u and J_d
- First glimpses of $\tilde{H}$

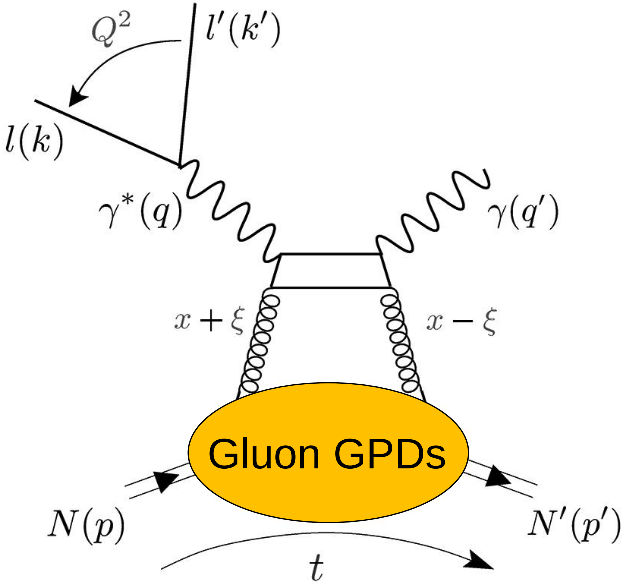




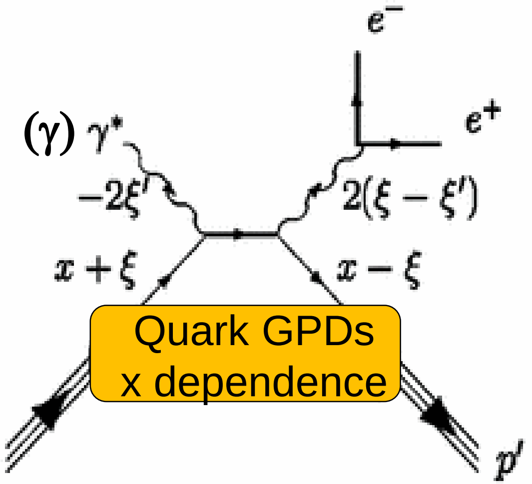


Exclusive reactions giving access to GPDs

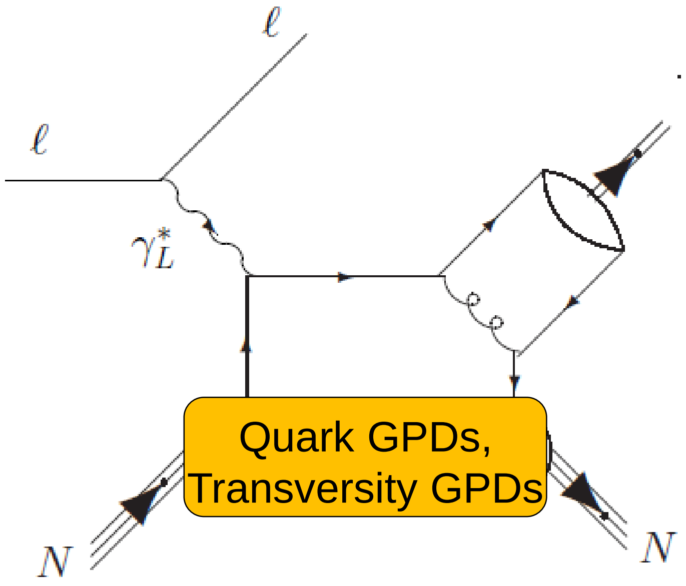




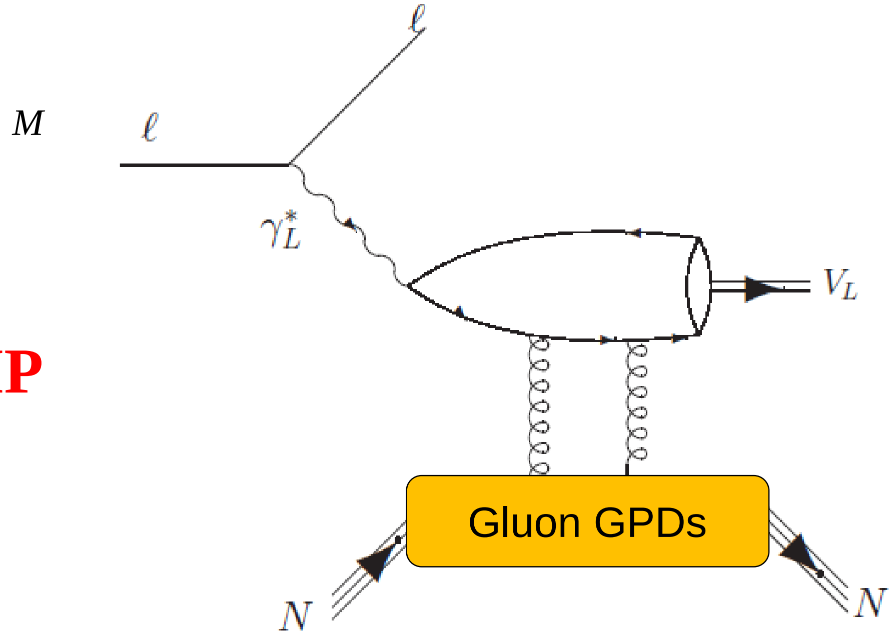
DVCS



(TCS), DDVCS

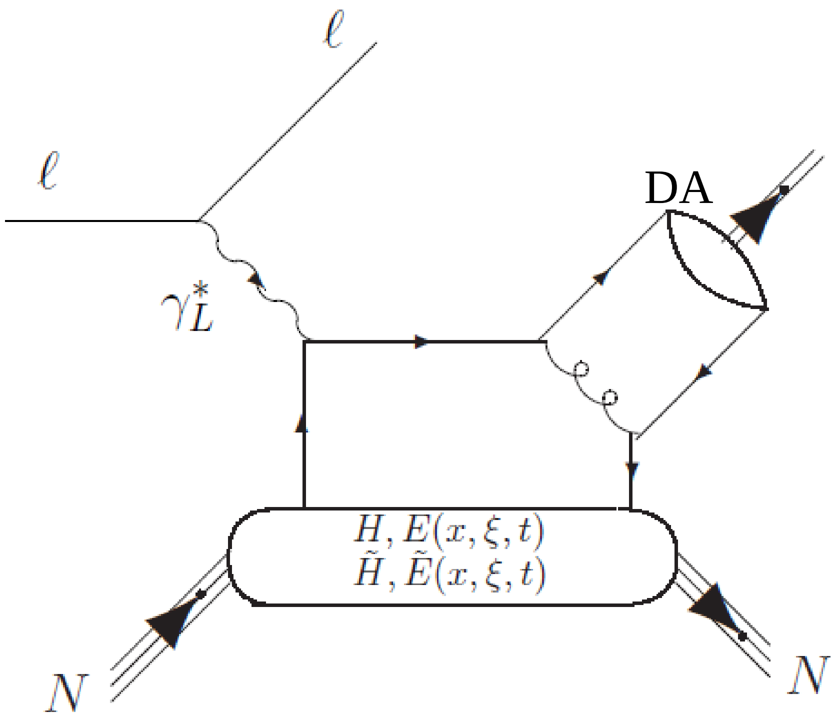


DVMP



Universality of GPDs

Deeply virtual meson production and GPDs



Factorization proven only for **longitudinally polarized** virtual photons

Different mesons → different sensitivity to GPDs

H, E → **Vector** mesons (ρ, ω, ϕ)

$\tilde{H}$, $\tilde{E}$ → **Pseudoscalar** mesons (π, η)

π^0	**2Δu+Δd**
η	**2Δu-Δd**
ρ^0	**2u+d**
ω	**2u-d**
ρ^+	**u-d**

quark flavor decomposition accessible via meson production

Predictions for leading-order handbag:

$\sigma_L \propto \frac{1}{Q^6} \quad \sigma_T \propto \frac{1}{Q^8}$

$$\mathcal{A}_L = -\frac{2ie}{9}\left(\int_0^1 dz \frac{\Phi(z)}{z}\right)\frac{4\pi\alpha_S(Q^2)}{Q}\int_{-1}^{+1} dx \left\{\left[\frac{1}{x-\xi+i\epsilon}+\frac{1}{x+\xi-i\epsilon}\right]F(x,\xi,t)\right\}$$

Complications: effective scale α_s in the hard scattering process, meson Distribution Amplitude (DA)

Deeply virtual meson production at CLAS

$$\frac{d\sigma}{dQ^2 dx_B\, d\phi dt} = \frac{d\Gamma}{dQ^2 dx_B}(Q^2, x_B, E)\,\frac{1}{2\pi}\left(\frac{d\sigma_T}{dt} + \varepsilon\frac{d\sigma_L}{dt} + +\sqrt{2\varepsilon(1+\varepsilon)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\,\frac{d\sigma_{TT}}{dt}\cos 2\phi\right)$$

- Cross section for DVMP>>DVCS → « easier » to measure
- But GPD interpretation is more complicate
- Q^2 needed to reach handbag regime may be higher than for DVCS

Vector mesons: exclusive ρ^0, ω, ϕ and ρ^+ electroproduction on the proton with CLAS

K. Lukashin *et al.*, RRC 63 (2001) **(ϕ@4.2 GeV)**

C. Hadjidakis *et al.*, PLB 605 (2005) **(ρ^0@4.2 GeV)**

L. Morand *et al.*, EPJA 24 (2005) **(ω@5.75GeV)**

J. Santoro *et al.*, PRC 78 (2008) **(ϕ@5.75 GeV)**

S. Morrow *et al.*, EPJA 39 (2009) **(ρ^0@5.75GeV)**

A. Fradi, Orsay Univ. PhD thesis **(ρ^+@5.75 GeV) Not published**

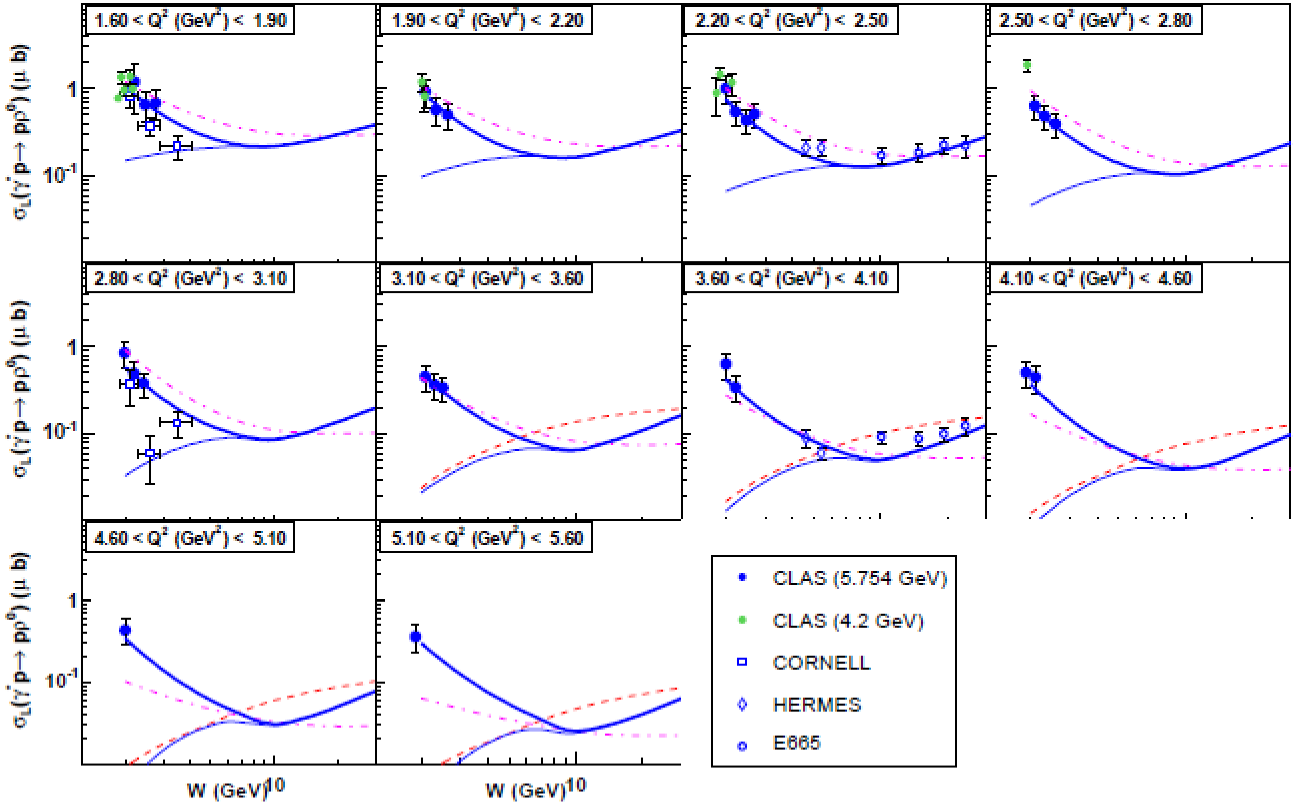
Pseudoscalar mesons: exclusive π^0 and η electroproduction on the proton with CLAS

R. De Masi *et al.*, PRC 77 (2008) **(π^0@5.75GeV)**

K. Park *et al.*, PRC 77 (2008) **(π^+@5.75 GeV)**

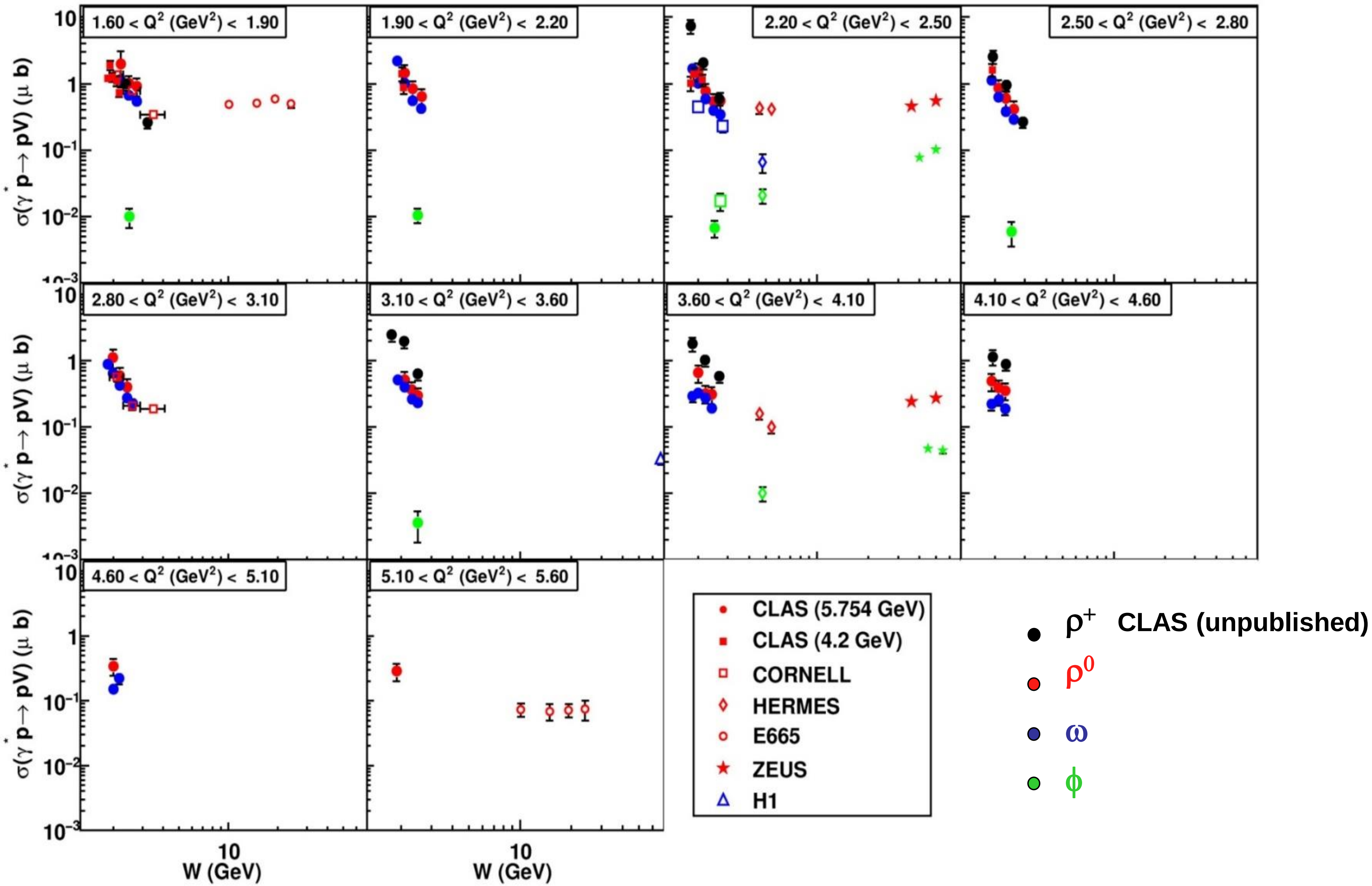
I. Bedlinskiy *et al.*, PRL 109 (2012); PRC 90 (2014) **(π^0@5.75GeV)**

I. Bedlinskiy *et al.*, PRC 95 (2017) **(η@5.75GeV)**

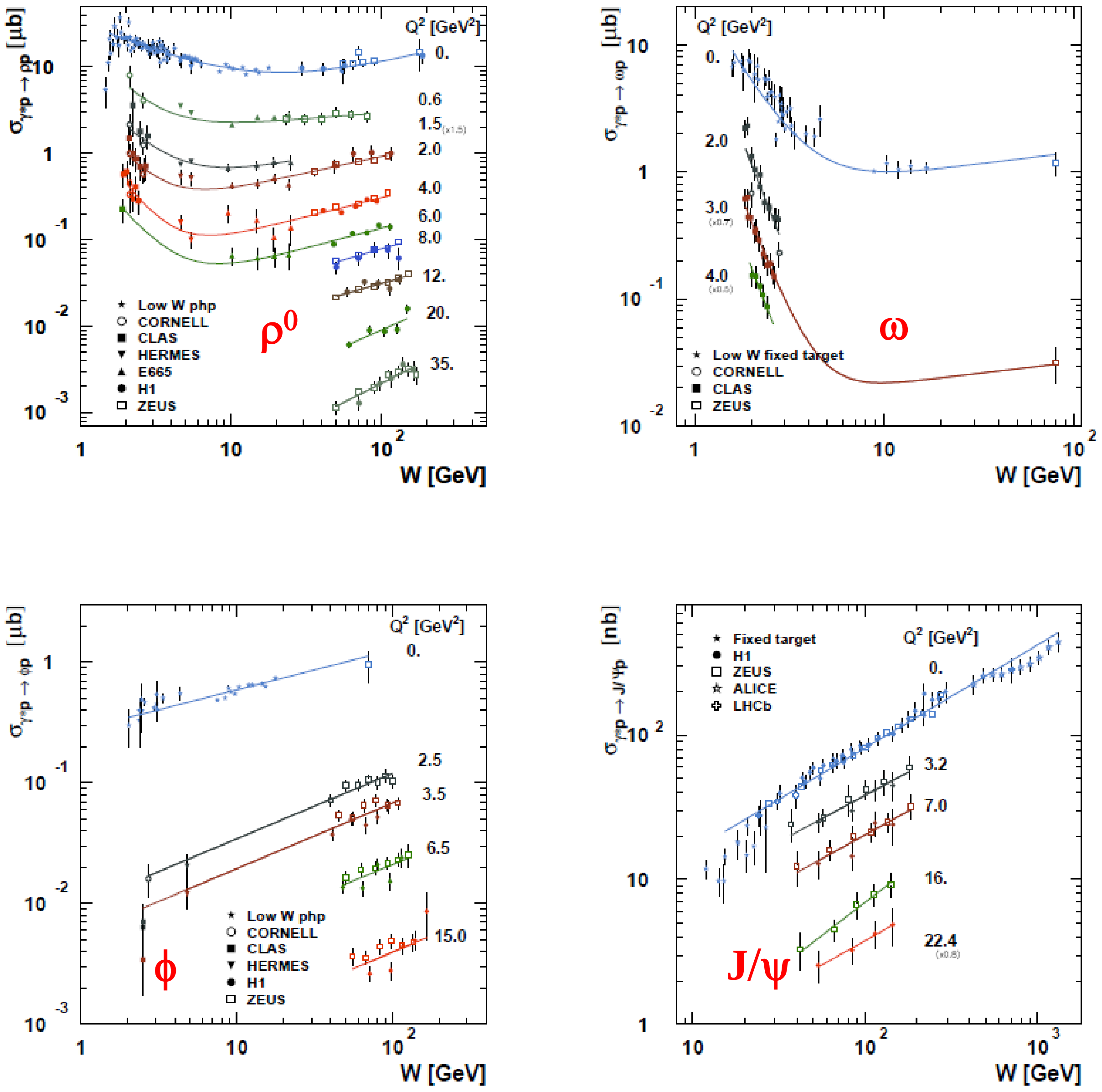


The GPD models fail to reproduce σ_L at **low W** for ρ^0

Comparison between vector mesons (σ)



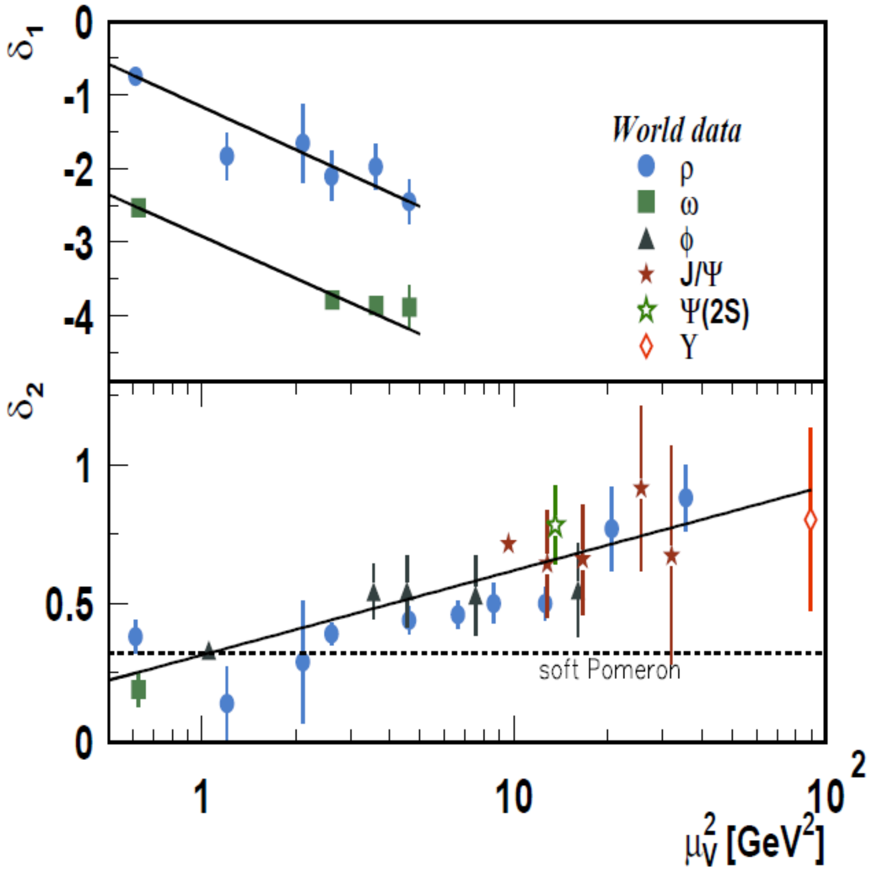
Comparison between vector mesons (σ)



L. Favart, M. Guidal, T. Horn, P. Kroll, EPJA 52 (2016)

→ fit function: $\sigma_V(W, \mu_V^2) = a_1 W^{\delta_1(\mu_V^2)} + a_2 W^{\delta_2(\mu_V^2)}$

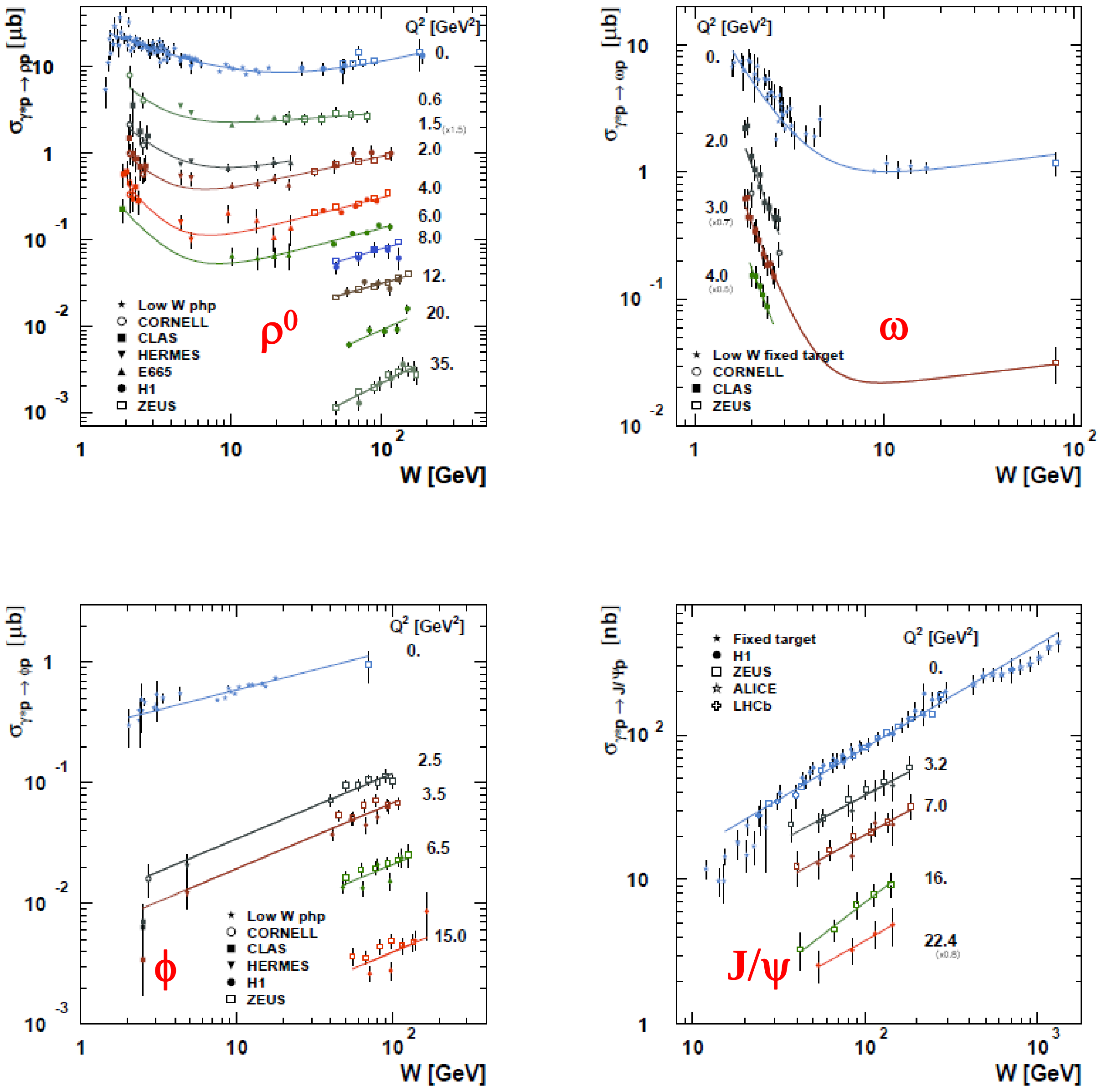
$$\mu_V^2 = Q^2 + M_V^2$$



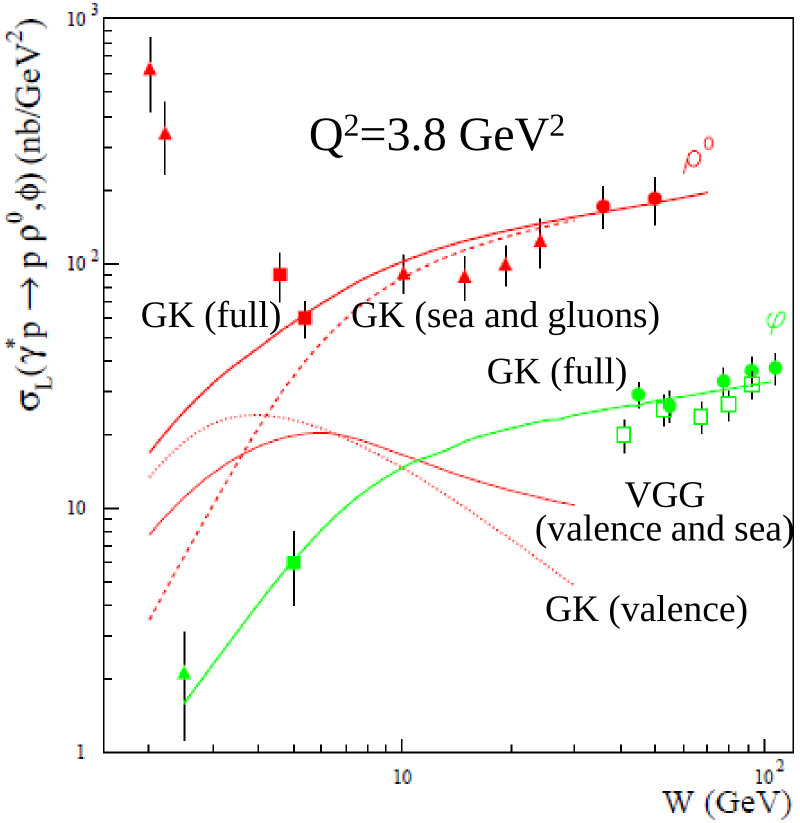
Lighter VM: two W-slope regions (negative at low W, positive at high W)

Heavier VM: only positive W slope

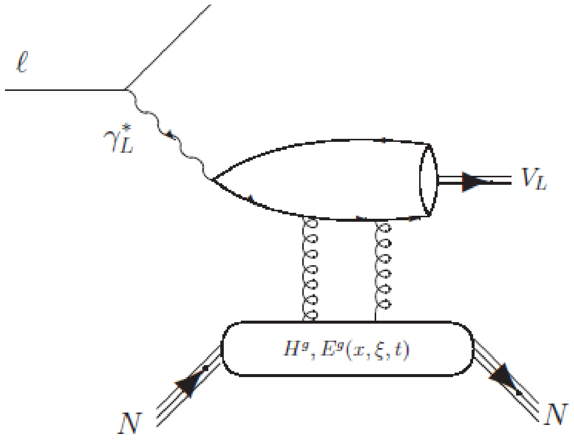
Comparison between vector mesons (σ, σ_L)



L. Favart, M. Guidal, T. Horn, P. Kroll, EPJA 52 (2016)



The GPD models fail to reproduce σ_L at **low W** for ρ^0

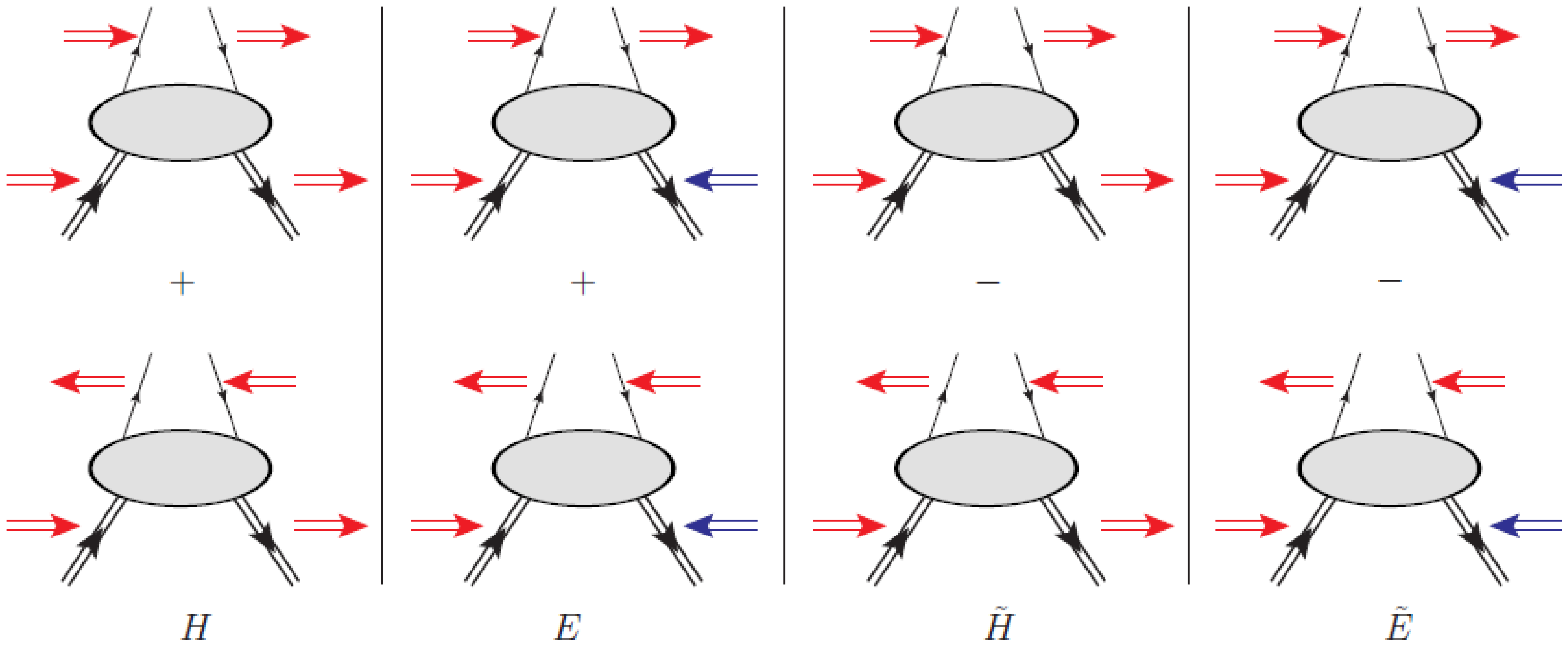


At **high W**, the contribution of **gluons** is necessary to reproduce the measured cross sections

Reminder from Lecture 1: *chiral-even* GPDs and DVCS

4 GPDs for each quark flavor (*leading order, leading twist,* **quark-helicity conservation**)

conserve nucleon spin **flip nucleon spin**



The quark-helicity conservation approximation holds well for DVCS – but what about DVMP?

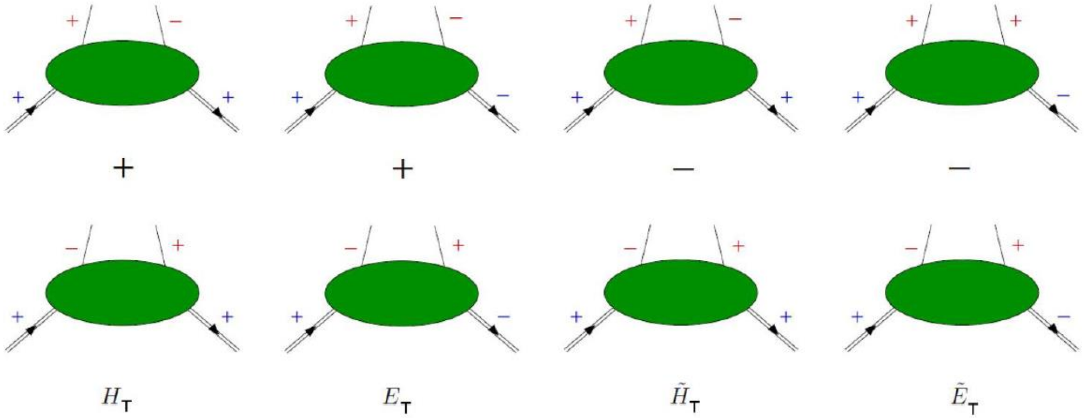
Chiral-odd GPDs

$H_T, \widetilde{H}_T, E_T, \widetilde{E}_T$

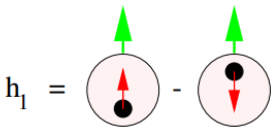
- 4 chiral-odd GPDs (parton helicity flip) at leading twist
- Difficult to access (helicity flip processes are **suppressed**)
- Chiral-odd GPDs are very **little constrained**
- Anomalous tensor magnetic moment:

$$\kappa_T = \int_{-1}^{+1} dx\, \bar{E}_T(x,\xi,t=0) \qquad \bar{E}_T = 2\widetilde{H}_T + E_T$$

- Link to the **transversity** PDF: $H_T^q(x,0,0) = h_1^q(x)$



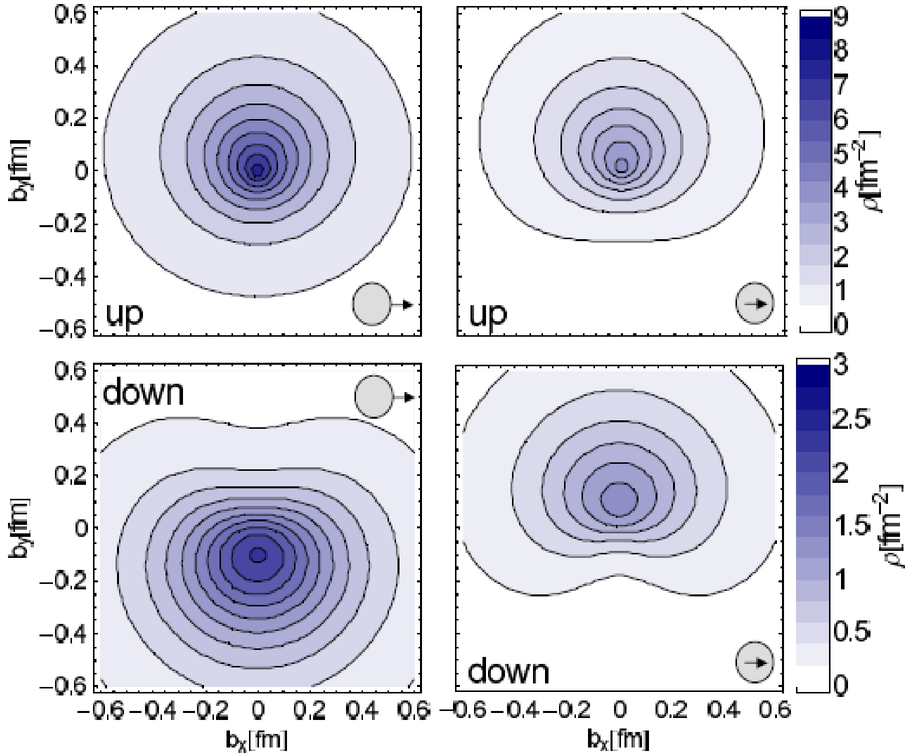
The transversity describes the distribution of transversely polarized quarks in a transversely polarized nucleon



		Quark Polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	H		$2\widetilde{H}_T + E_T$
	L		$\widetilde{H}$	$\widetilde{E}_T$
	T	E	$\widetilde{E}$	$H_T, \widetilde{H}_T$

Distributions of unpolarized quarks in a transversely polarized nucleon, **linked to *E***

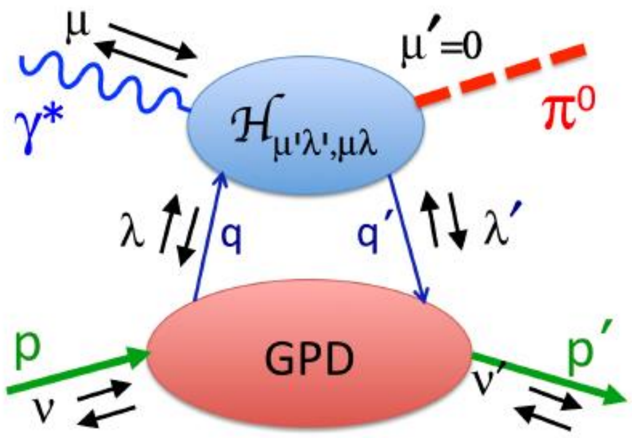
Transverse Densities for u and d quarks in the nucleon

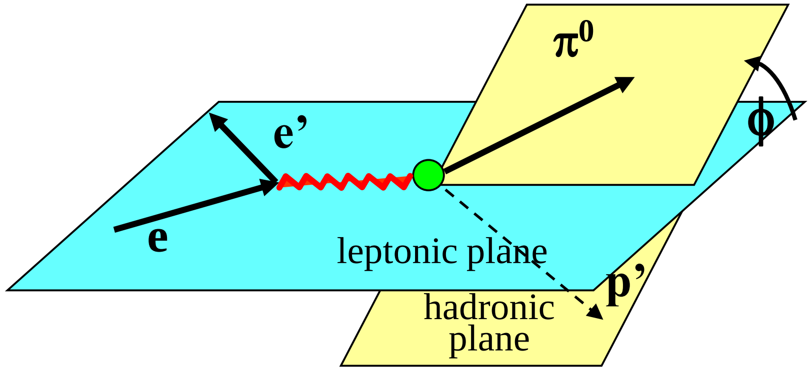


Distribution of transversely polarized quarks in an unpolarized nucleon, **linked to $\bar{E}_T$**

Gockeler et al, Phys. Rev. Lett. 98, (2007), lattice calculation

Exclusive π^0 electroproduction





$$\frac{d\sigma}{dQ^2 dx_B\, d\phi dt} = \frac{d\Gamma}{dQ^2 dx_B}(Q^2, x_B, E)\,\frac{1}{2\pi}\left(\frac{d\sigma_T}{dt} + \varepsilon\frac{d\sigma_L}{dt} + \sqrt{2\varepsilon(1+\varepsilon)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\,\frac{d\sigma_{TT}}{dt}\cos 2\phi\right)$$

$$\epsilon = \frac{1 - y - \frac{Q^2}{4E^2}}{1 - y + \frac{y^2}{2} + \frac{Q^2}{4E^2}}$$ Degree of longitudinal polarization

$$\frac{d^2\,\Gamma_\gamma}{dQ^2 dx_B}(Q^2, x_B, E) = \frac{\alpha}{8\pi}\,\frac{1}{1-\epsilon}\,\frac{1-x_B}{x_B^3}\,\frac{Q^2}{M_p^2 E^2}$$ Virtual photon flux

Leading twist: $$\sigma_L = \frac{4\pi\alpha\phi_e}{k'Q^6}\left[(1-\xi^2)|<\tilde{H}>|^2 - 2\xi^2\,\mathrm{Re}(<\tilde{H}>^* <\tilde{E}>) - \frac{t'}{4m^2}\xi^2|<\tilde{E}>|^2\right]$$

Generalized Compton Form Factors

$$<\tilde{H}> = \sum_\lambda \int_{-1}^{1} dx\, M(x,\xi,Q^2,\lambda)\tilde{H}(x,\xi,t)$$

σ_L is suppressed: $$\tilde{H}^\pi = \frac{1}{3\sqrt{2}}\left[2\tilde{H}^u + \tilde{H}^d\right]$$ $\tilde{H}_u$ and $\tilde{H}_d$ have opposite signes

Transversity GPD models:

- Goloskokov-Kroll
- Liuti-Goldstein
- $\sigma_L \ll \sigma_T$

$$\sigma_T = \frac{4\pi\alpha_e}{2\kappa}\frac{\mu_\pi^2}{Q^4}\left[(1-\xi^2)|<H_T>|^2 - \frac{t'}{8m^2}|<\bar{E}_T>|^2\right]$$

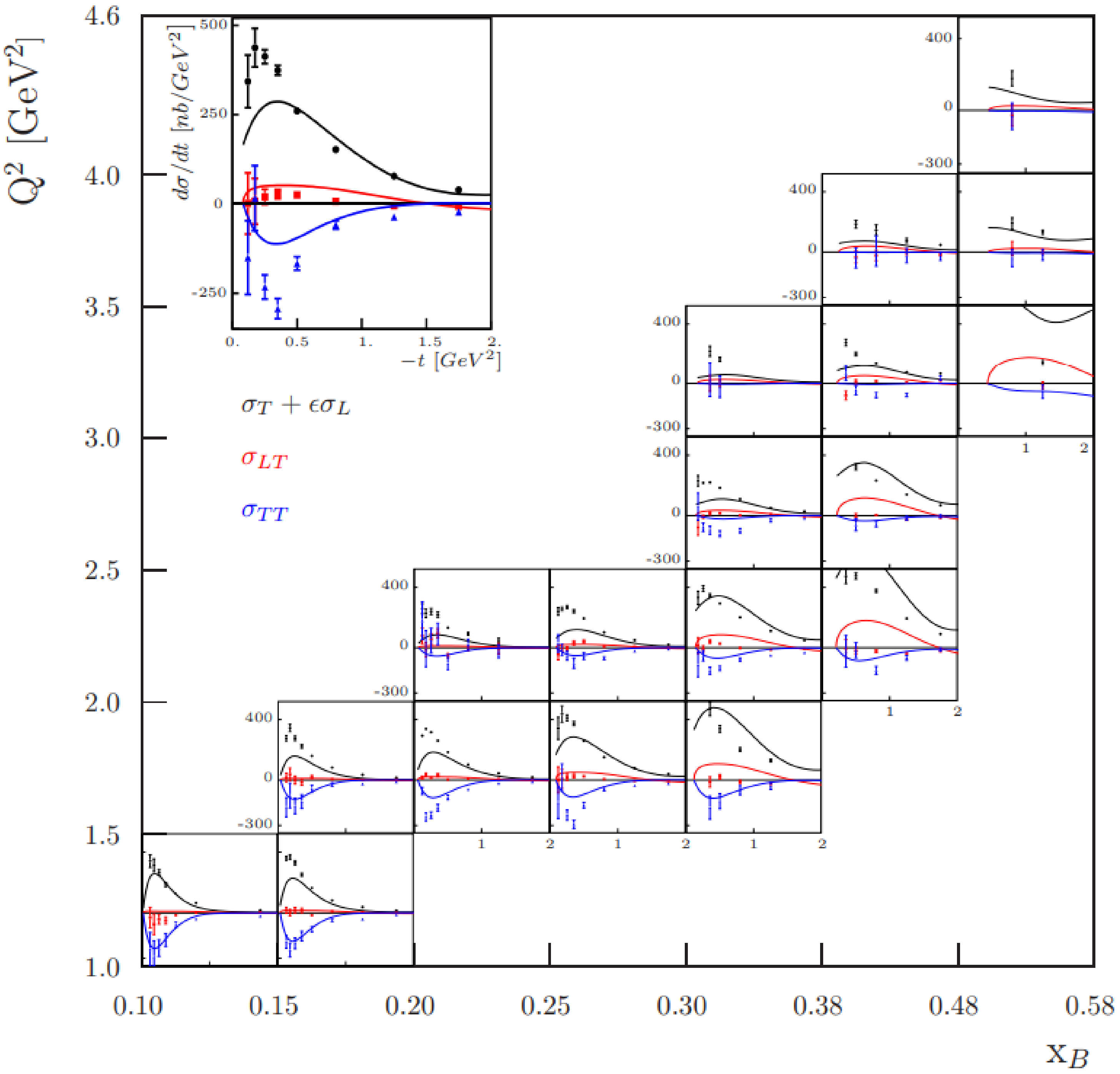
$$\sigma_{TT} = \frac{4\pi\alpha_e}{2\kappa}\frac{\mu_\pi^2}{Q^4}\frac{t'}{8m^2}|<\bar{E}_T>|^2$$

CLAS results

I. Bedlinskiy et al.,
Phys. Rev. Lett. 109 (2012);
Phys. Rev. C 90 (2014)

$\sigma_T + \epsilon\sigma_L$
σ_{LT}
σ_{TT}

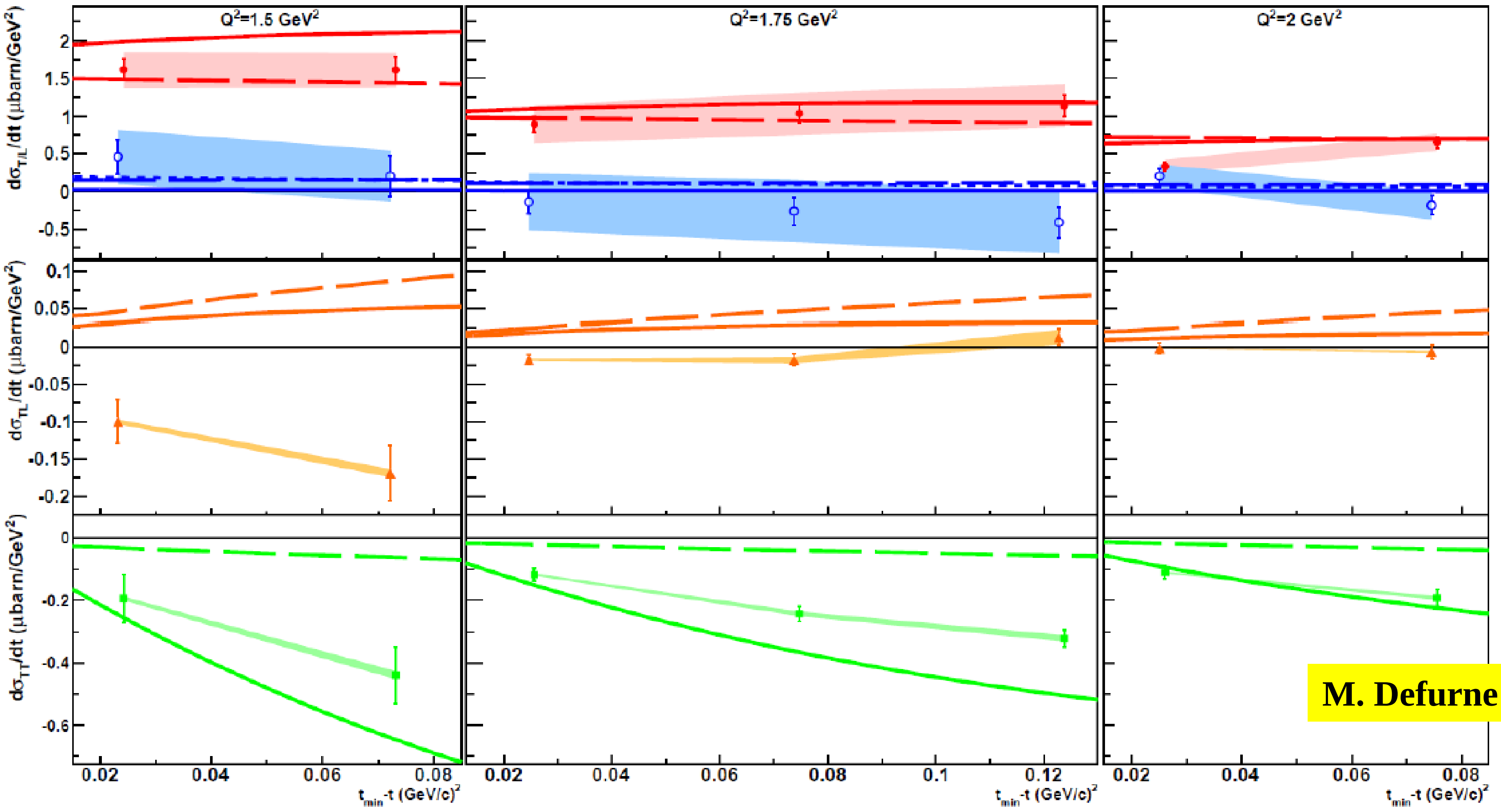
Goloskokov-Kroll model
Transversity GPDs



Hall A: Rosenbluth separation of σ_L and σ_T

$$\frac{d\sigma}{dQ^2 dx_B\, d\phi dt} = \frac{d\Gamma}{dQ^2 dx_B}(Q^2, x_B, E)\,\frac{1}{2\pi}\left(\frac{d\sigma_T}{dt} + \boldsymbol{\varepsilon}\frac{d\sigma_L}{dt} + \sqrt{2\varepsilon(1+\varepsilon)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi\right)$$

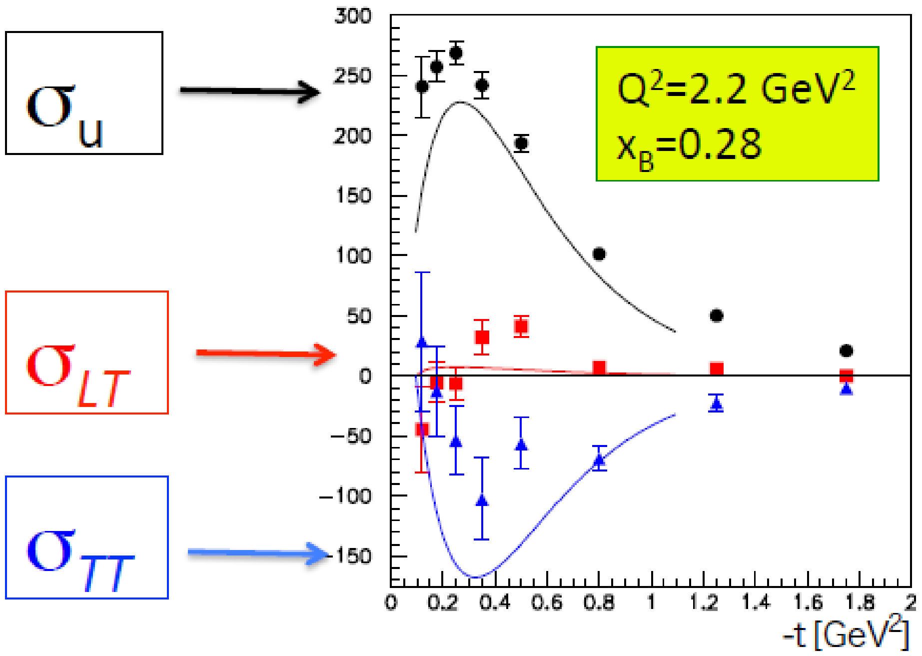
Varying ε by varying beam energy

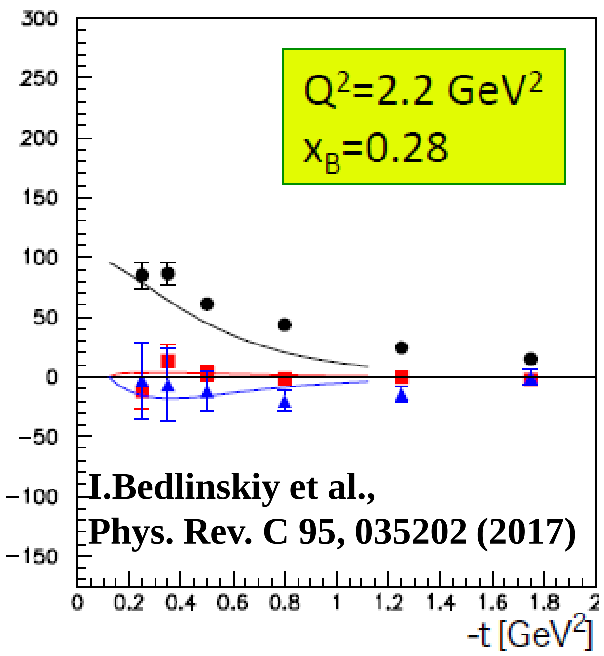


- Experimental proof that the transverse π^0 cross section is dominant
- It opens a direct way to study the transversity GPDs in pseudoscalar exclusive production

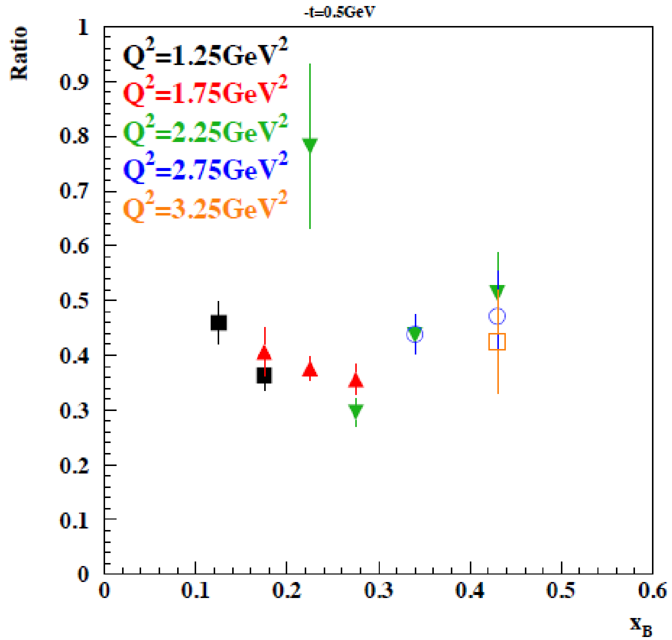
M. Defurne et al., PRL 117 (2016)

Comparison π^0/η



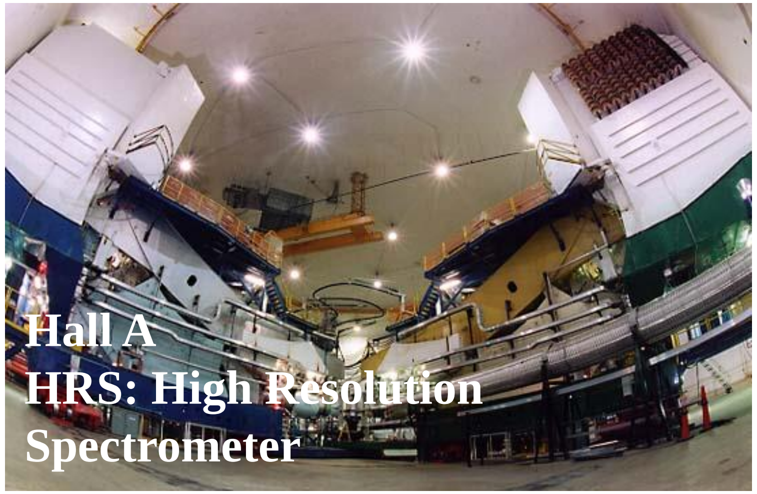


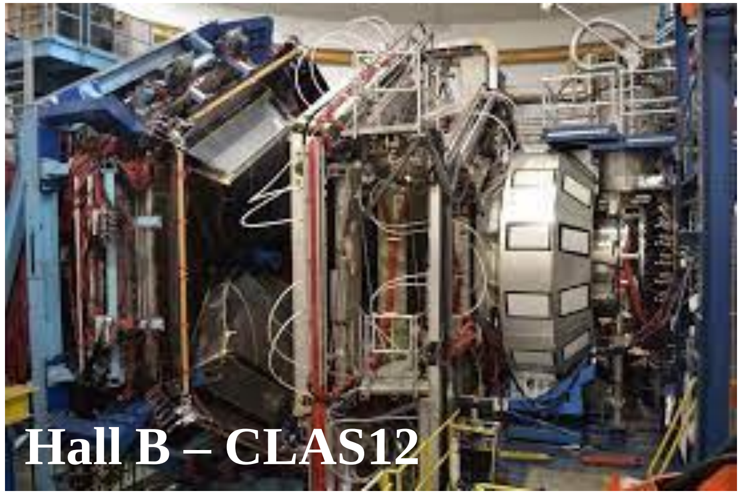
- Very little dependence on x_B and Q^2
- Chiral-odd GPD models predict this ratio to be **~1/3** at CLAS kinematics
- Chiral-even GPD models predict this ratio to be around 1 (at low –t)



Potentially one can perform **flavor separation of transversity GPDs** combining π^0 and η

Jefferson Lab at 12 GeV





Upgraded CEBAF

- Up to 12 GeV continuous polarized electron beam
- 4 experimental halls, 3 devoted to nucleon-structure studies

JLab@12 GeV DVCS program

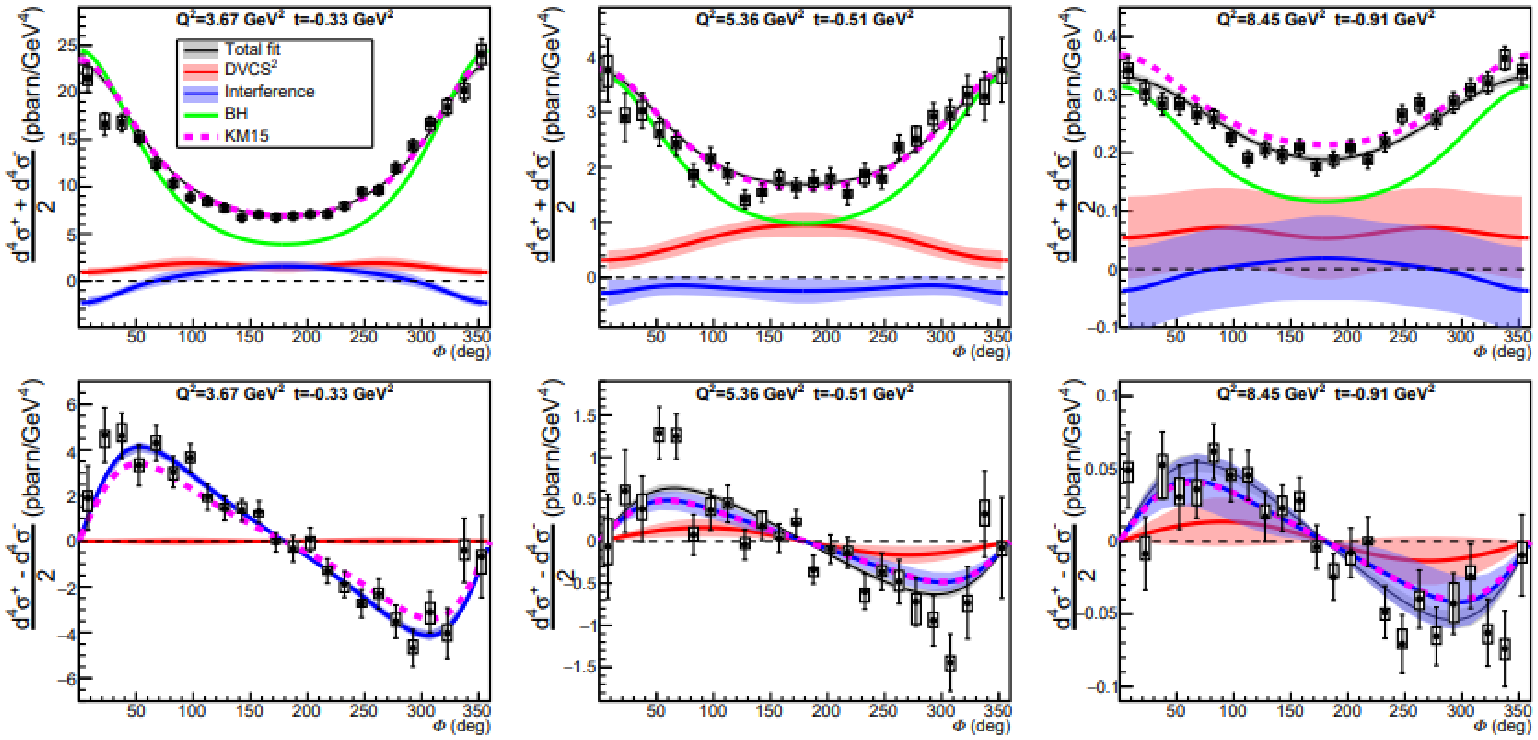
Observable (target)	**12-GeV experiments**	**CFF sensitivity**	**Status**
σ, $\Delta\sigma_{beam}$(p)	Hall A CLAS12 Hall C	Re$\mathcal{H}$(p), Im$\mathcal{H}$(p)	Hall A: data taken in 2016; Phys. Rev. Lett. 128 (2022) CLAS12: data taken in 2018-2019; CS analysis in progress Hall C: experiment planned for 2023-2024
BSA(p)	CLAS12	Im$\mathcal{H}$(p)	BSA: data taken in 2018-2019; Phys. Rev. Lett. 130 (2023)
lTSA(p), lDSA(p)	CLAS12	Im$\widetilde{\mathcal{H}}$(p), Im$\mathcal{H}$(p), Re$\widetilde{\mathcal{H}}$(p), Re$\mathcal{H}$(p)	Experiment just completed!
tTSA(p)	CLAS12	Im$\mathcal{H}$(p), Im$\mathcal{E}$(p)	Experiment foreseen for > 2025
BSA(n)	CLAS12	Im$\mathcal{E}$(n)	Data taken in 2019-2020, BSA analysis undergoing CLAS review
lTSA(n), lDSA(n)	CLAS12	Im$\mathcal{H}$(n), Re$\mathcal{H}$(n)	Experiment just completed!

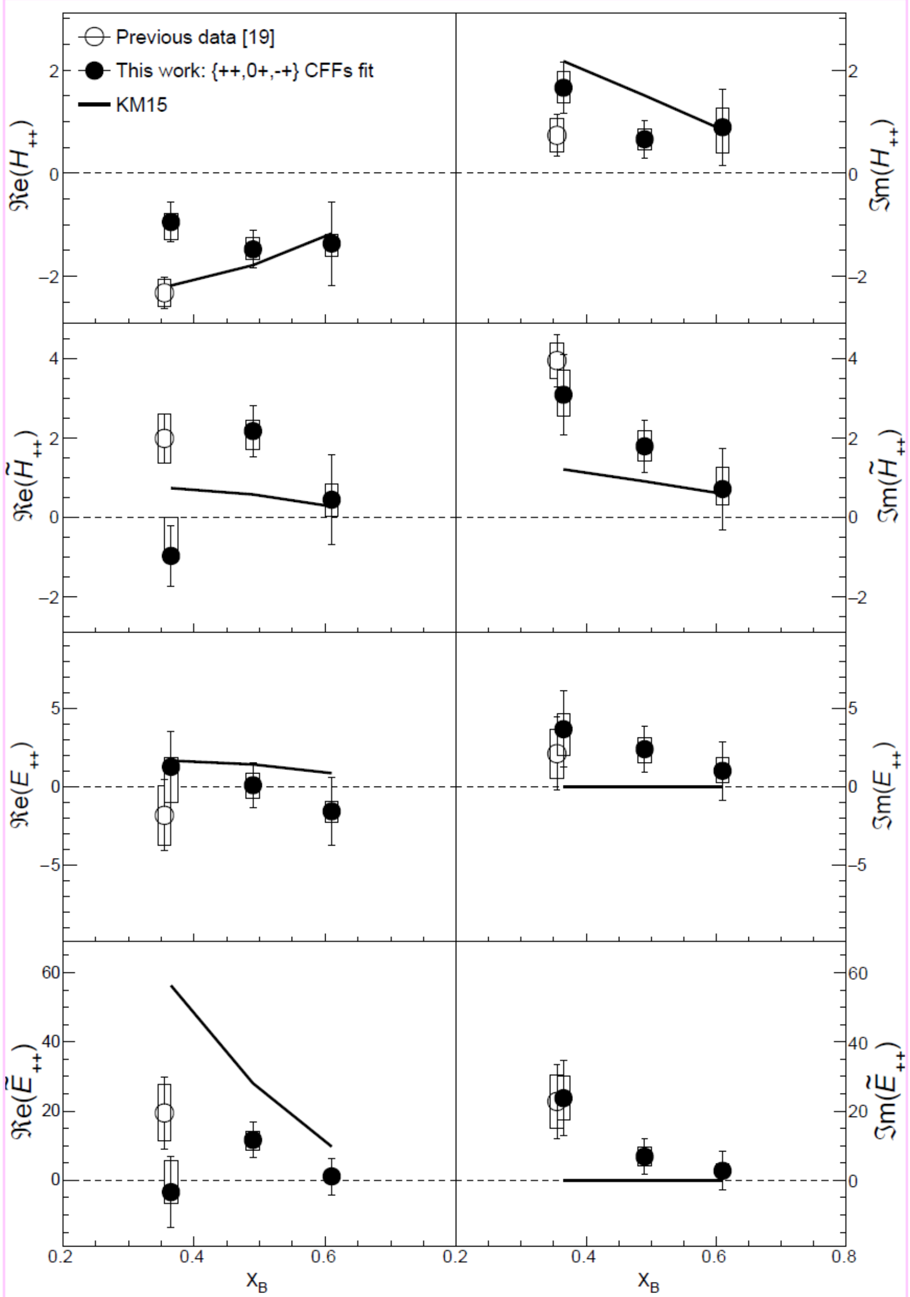
Complementarity of the experimental setups in the JLab Halls A/C and B

- Hall A/C: high luminosity → precision, small kinematic coverage, eγ topology
- Hall B (CLAS12): lower luminosity, large kinematic coverage, fully exclusive final state

Hall-A@11 GeV: high-precision cross sections for DVCS on the proton

$\vec{e}p \to e\gamma(p)$



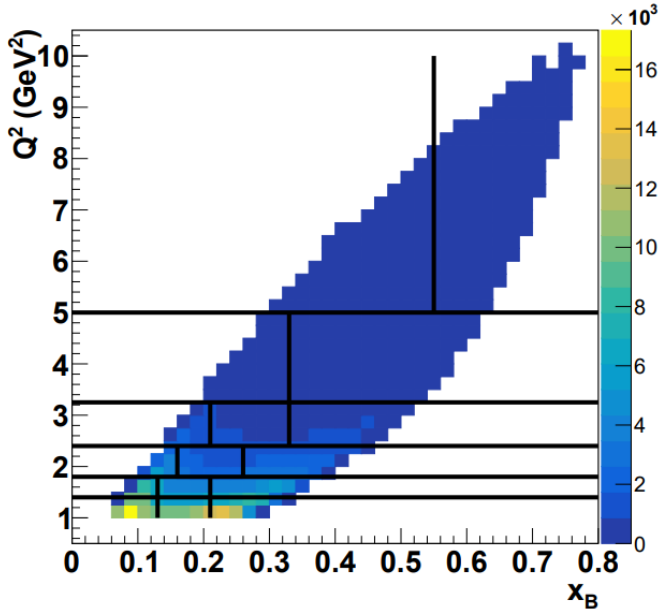


- High precision DVCS cross sections up to large x_B, for 3 beam energies
- Sensitivity to all 4 Compton form factors
- Kinematical power corrections ($\sim t/Q^2$, $\sim M/Q^2$) included in the analysis

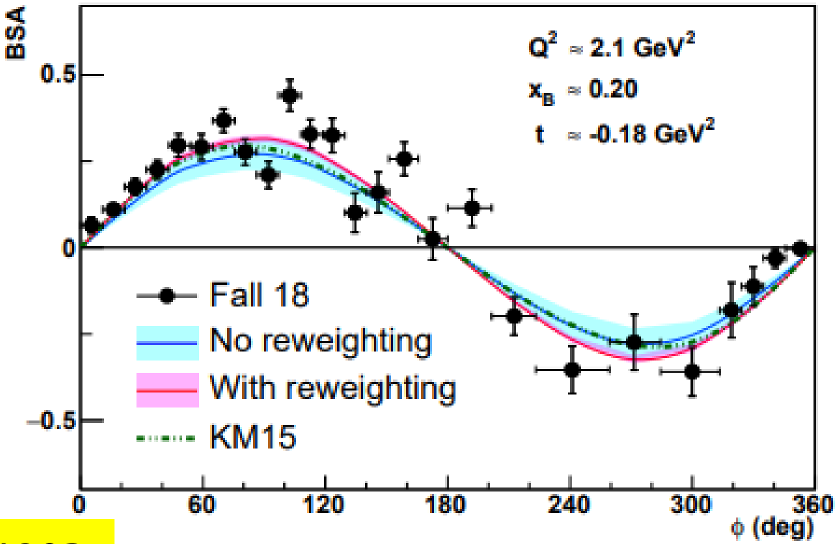
F. Georges et al., Phys. Rev. Lett. 128 (2022)

CLAS12: beam spin asymmetry for DVCS on the proton

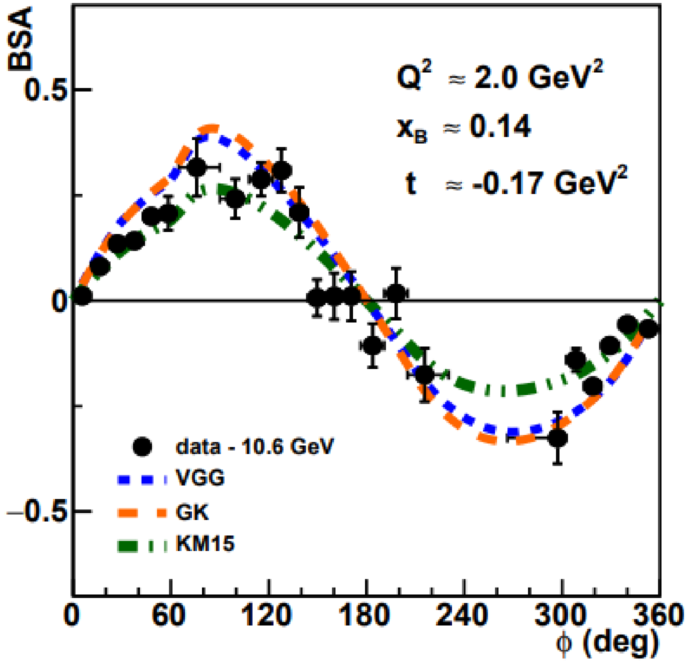
$\vec{e}p \rightarrow ep\gamma$

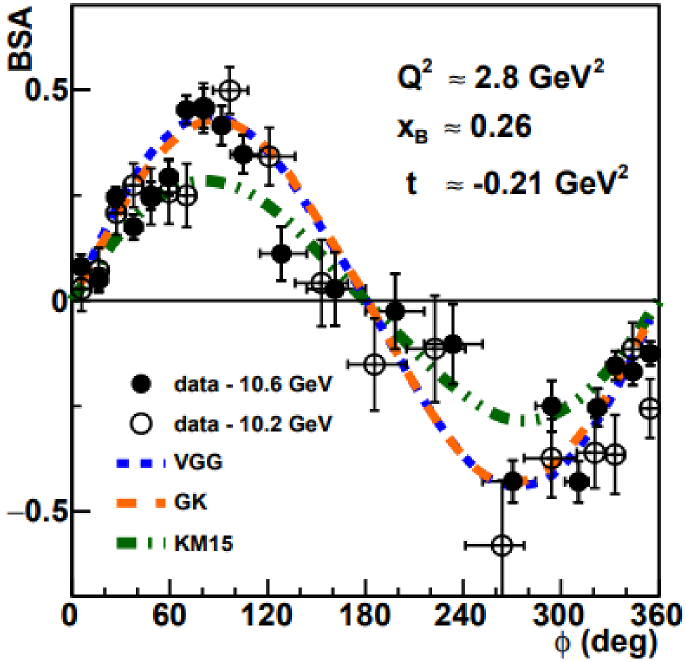


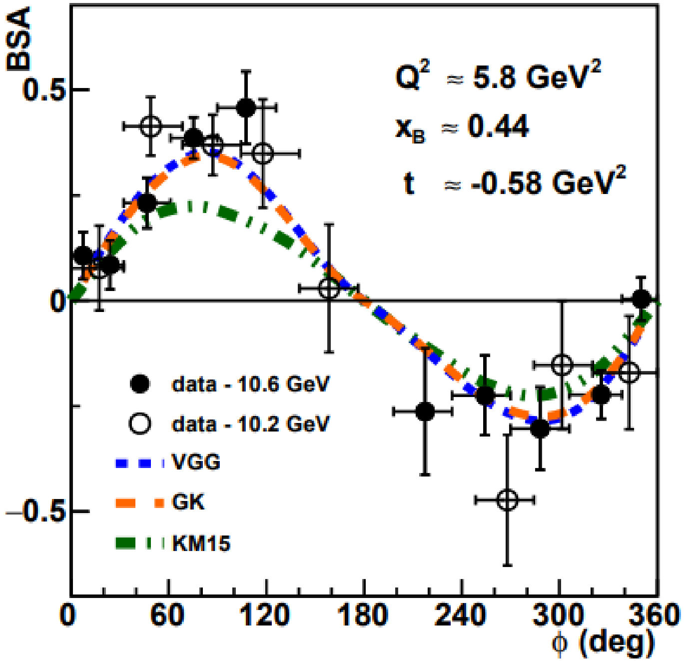
- Polarized beam (86%) with energy 10.6 GeV
- Unpolarized LH2 target
- 64 kinematical bins (Q^2, x_B, -t)
- Many kinematics never covered before
- In previously measured kinematics, the new data are shown to be in good agreement with existing data and improve the precision of GPD fits



G. Christiaens et al., PRL. 130 (2023) 21, 211902





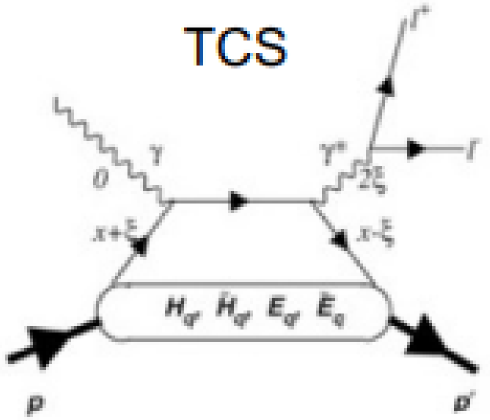


Examples of kinematics only accessible with ~10.6-GeV beam

Beyond DVCS: Timelike Compton Scattering

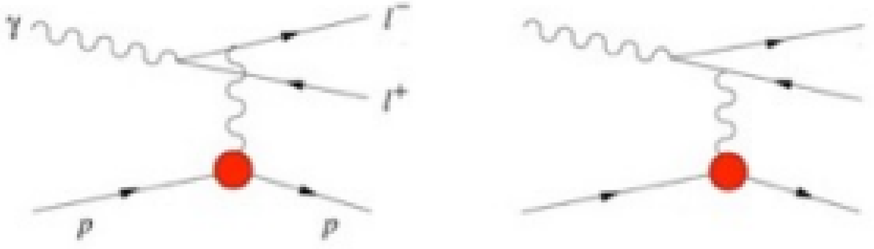
$\gamma p \rightarrow \gamma^* p$

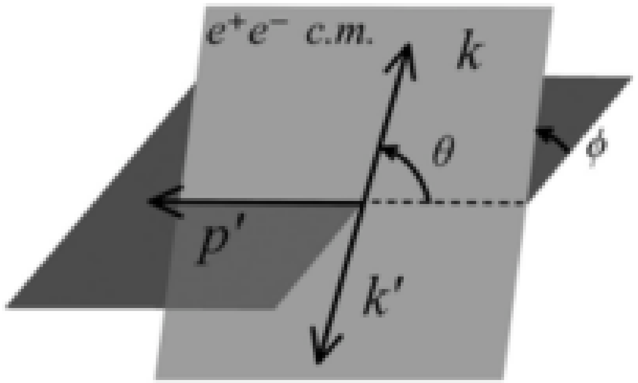
TCS is the time-reversal symmetric process to DVCS:
The incoming photon is real, the outgoing photon is highly virtual and decays in a pair of leptons



+

Bethe-Heitler (BH)



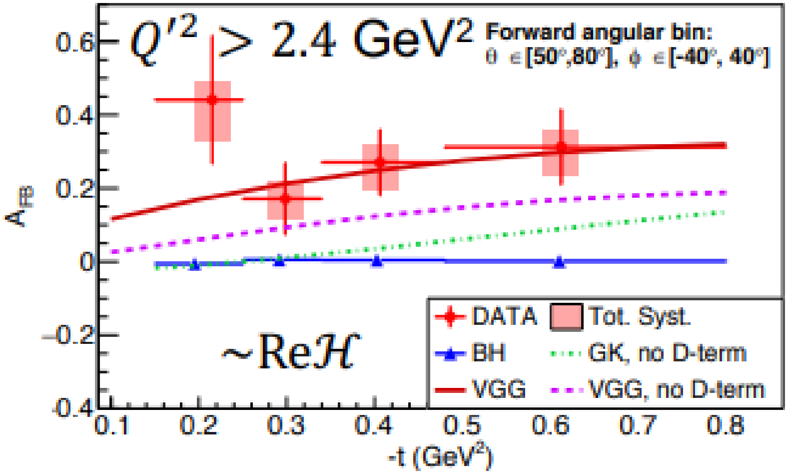


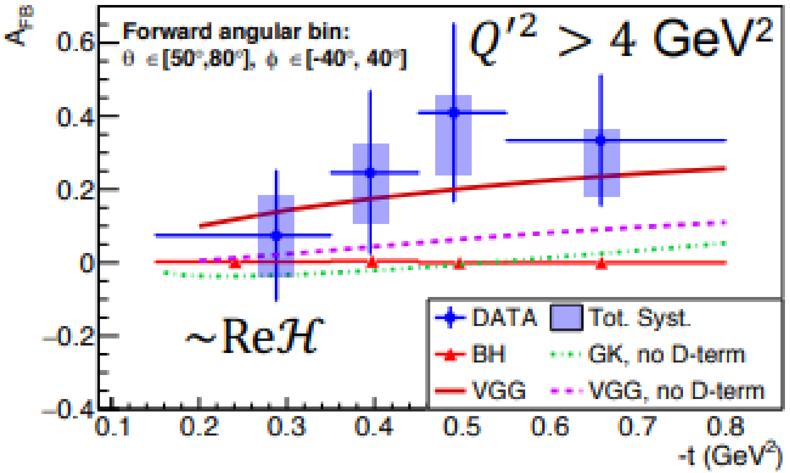
$$\frac{d\sigma_{INT}}{dQ'^2\, dt\, d(\cos\theta)\, d\varphi} = -\frac{\alpha_{em}^3}{4\pi s^2}\,\frac{1}{-t}\,\frac{M}{Q'}\,\frac{1}{\tau\sqrt{1-\tau}}\,\frac{L_0}{L}\left[\cos\varphi\,\frac{1+\cos^2\theta}{\sin\theta}\,\mathrm{Re}\tilde{M}^{--} - \cos 2\varphi\,\sqrt{2}\cos\theta\,\mathrm{Re}\tilde{M}^{0-} + \cos 3\varphi\,\sin\theta\,\mathrm{Re}\tilde{M}^{+-} + O\!\left(\frac{1}{Q'}\right)\right]$$

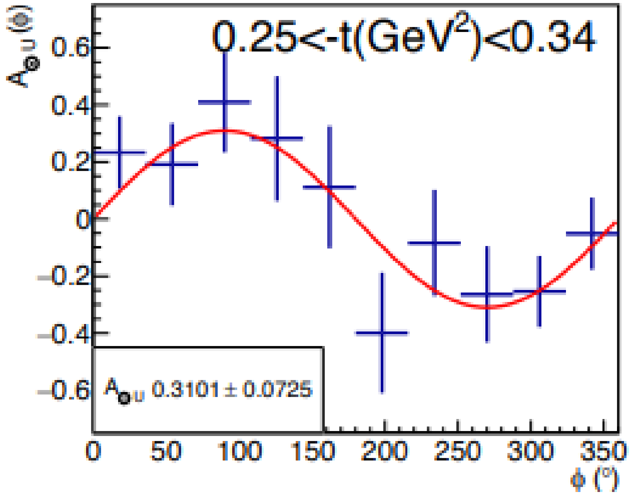
$$-\lambda\,\frac{\alpha_{em}^3}{4\pi s^2}\,\frac{1}{-t}\,\frac{M}{Q'}\,\frac{1}{\tau\sqrt{1-\tau}}\,\frac{L_0}{L}\left[\sin\varphi\,\frac{1+\cos^2\theta}{\sin\theta}\,\mathrm{Im}\tilde{M}^{--} - \sin 2\varphi\,\sqrt{2}\cos\theta\,\mathrm{Im}\tilde{M}^{0-} + \sin 3\varphi\,\sin\theta\,\mathrm{Im}\tilde{M}^{+-} + O\!\left(\frac{1}{Q'}\right)\right].$$

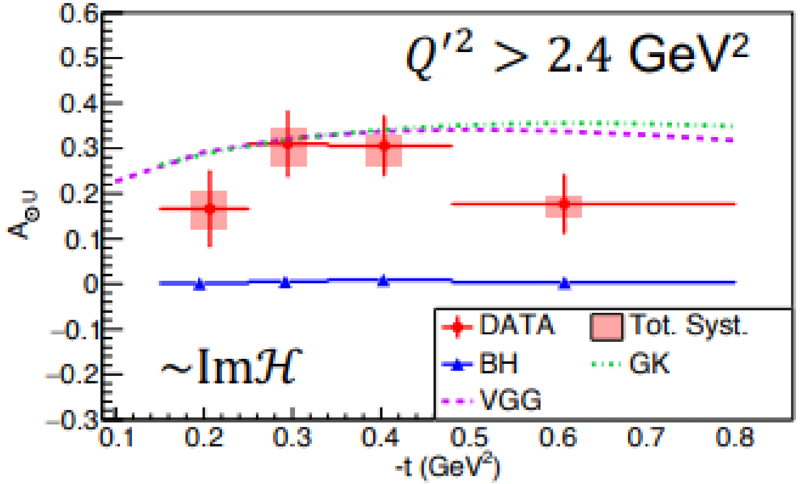
Incoming photon polarization

First-ever measurement of Timelike Compton Scattering (CLAS12)









P. Chatagnon et al. (CLAS), Phys. Rev. Lett. 127 (2021)

$\gamma p \to \gamma^* p \to (e')e^+e^-p$

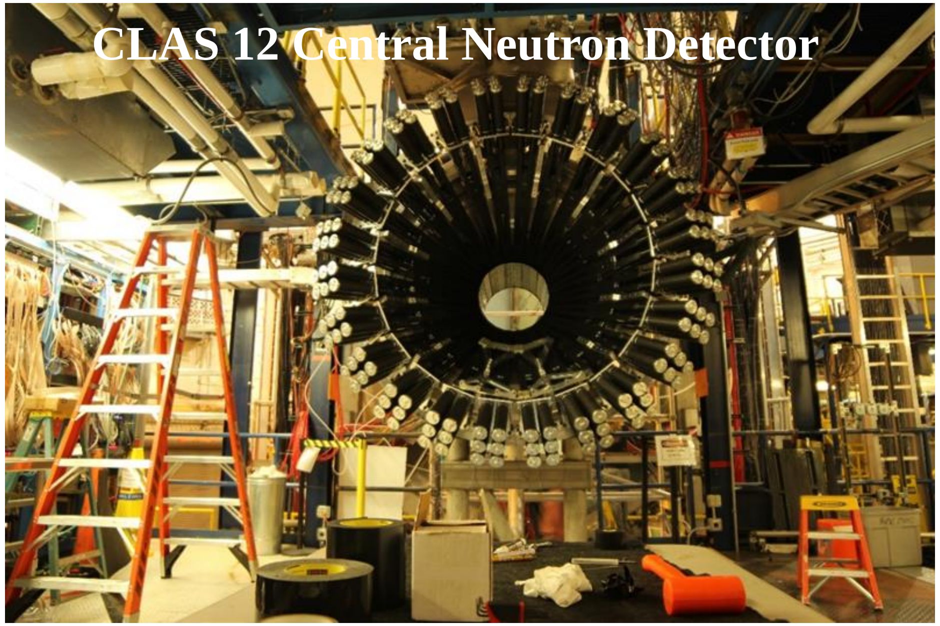
- Quasi-real photo-production (Q^2~0)
- The beam helicity asymmetry of TCS accesses the imaginary part of the CFF in the same way as in DVCS and probes the universality of GPDs
- The forward-backward asymmetry is sensitive to the real part of the CFF → direct access to the Energy-Momentum Form Factor $d_q(t)$ (linked to the D-term) that relates to the mechanical properties of the nucleon (quark pressure distribution)
- This measurement proves the importance of TCS for GPD physics.
- Limits: very small cross section → high luminosity is necessary for a more precise measurement

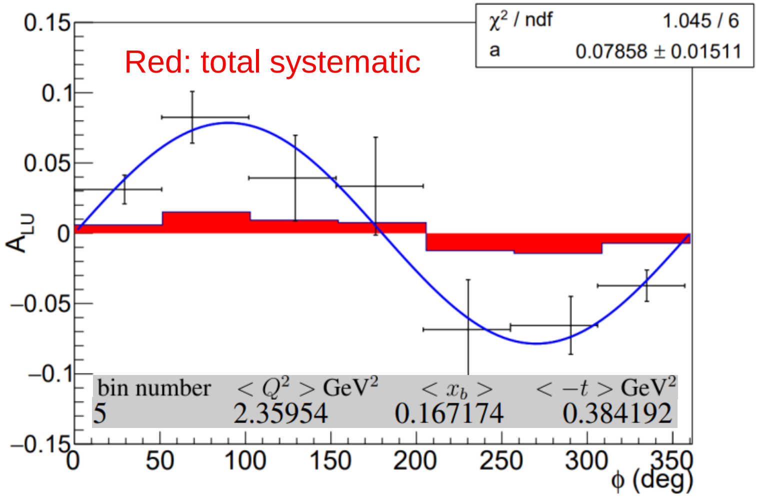
<u>Preliminary</u> CLAS12 results: Beam Spin Asymmetry for neutron DVCS

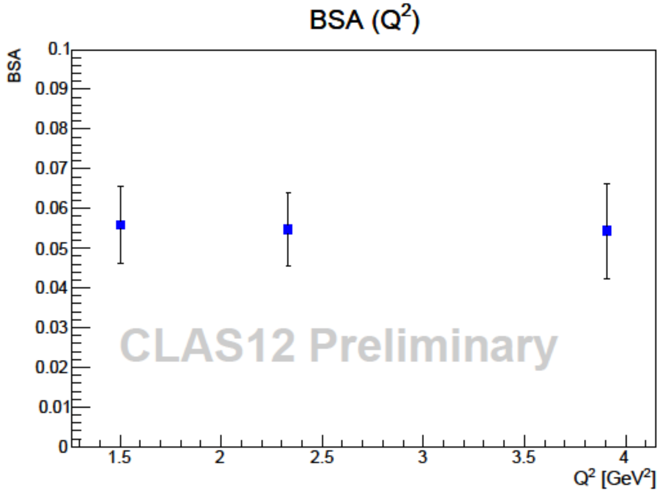
$\vec{e}d \to en\gamma(p)$

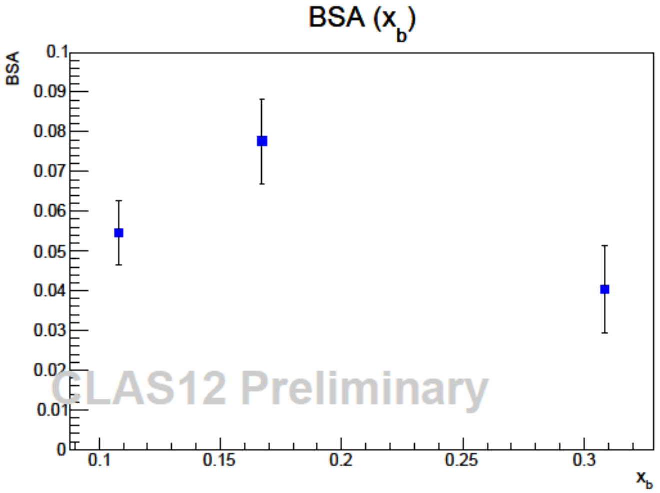
First-time measurement of nDVCS with detection of the active neutron

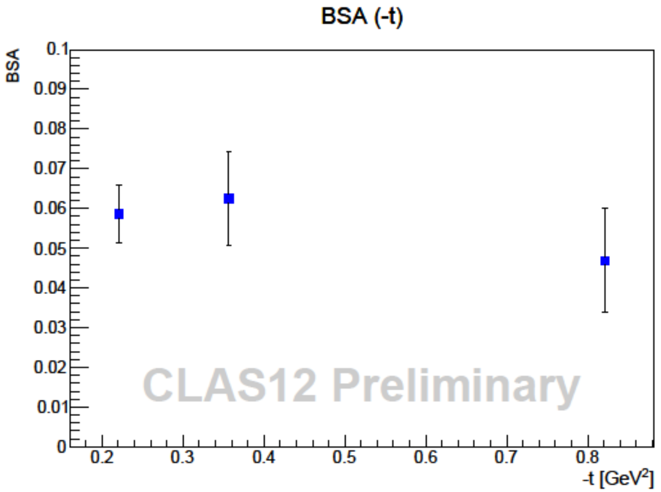
$\Delta\sigma_{LU} \sim \sin\phi\ \mathrm{Im}\{F_1\mathcal{H} + \xi(F_1+F_2)\widetilde{\mathcal{H}} - kF_2\mathcal{E}\}$







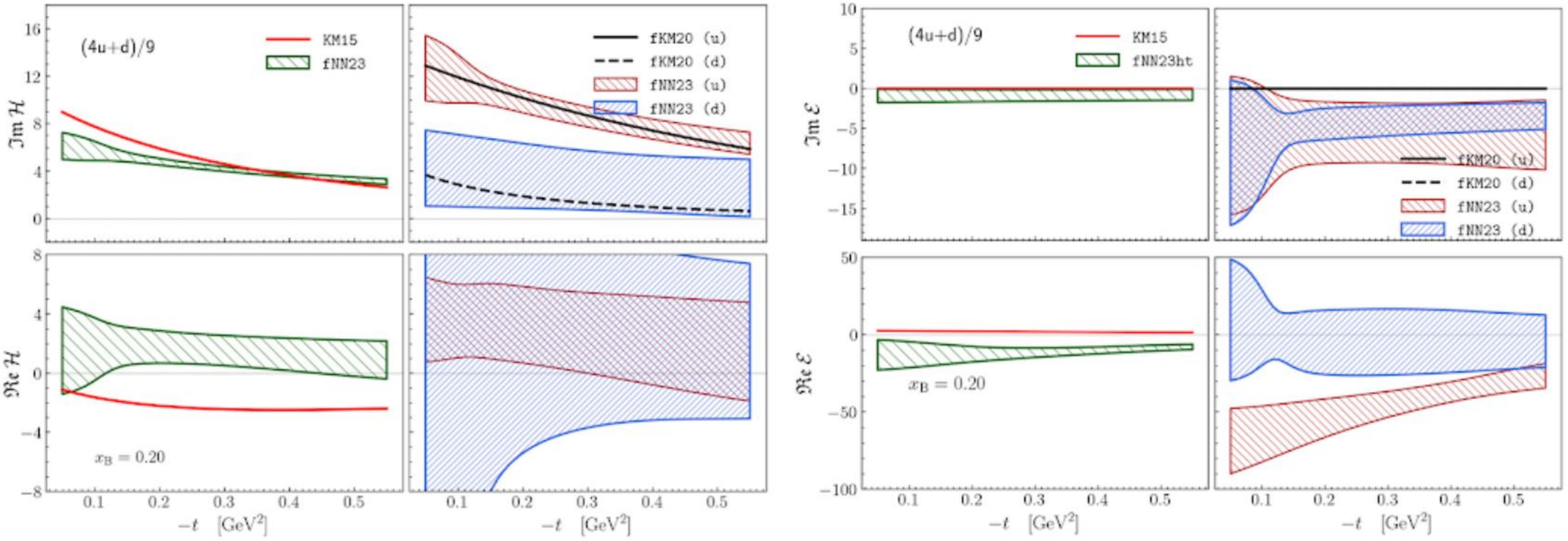




- Scan of the BSA of nDVCS on a wide phase space
- Reaching the high Q^2- high x_B region of the phase space
- Exclusive measurement with the detection of the active neutron → small systematics

Flavor separation of CFFs using the Hall A and CLAS12 p,n DVCS data

- **Preliminary** global fits of CFF using neural networks
- Data used: Hall-A pDVCS (11 GeV) and nDVCS (6 GeV) cross sections, CLAS12 pDVCS and nDVCS BSA



New CLAS12 data bring strong constraints for flavor separation on Im$\mathcal{H}$, Im$\mathcal{E}$, and Re$\mathcal{E}$

Just ran at CLAS12: DVCS (p, n) on longitudinally polarized target

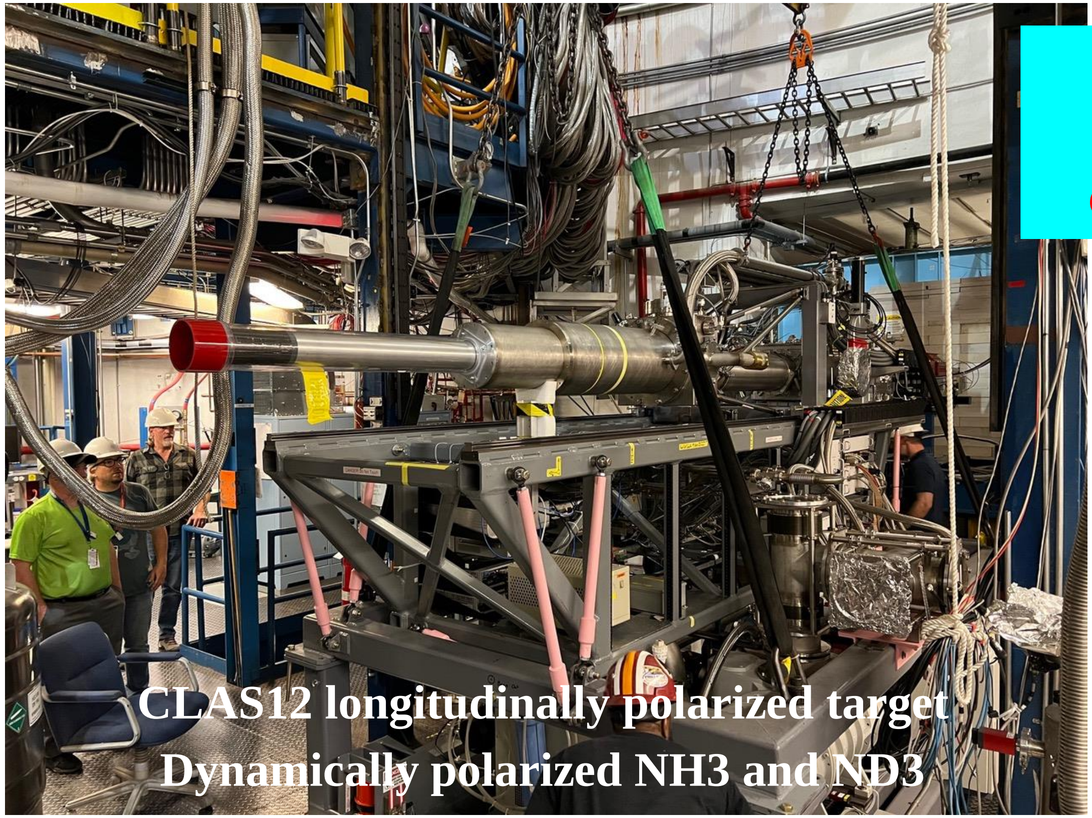
First-time measurement of longitidunal target-spin asymmetry and double (beam-target) spin asymmetry for nDVCS

Ran from June 2022 to March 2023

$$\Delta\sigma_{UL} \sim \sin\phi \; \mathrm{Im}\{F_1\tilde{\mathcal{H}}+\xi(F_1+F_2)(\mathcal{H}+x_B/2\mathcal{E}) - \xi k F_2 \tilde{\mathcal{E}}+\ldots\}$$

$$\Delta\sigma_{LL} \sim (A+B\cos\phi) \; \mathrm{Re}\{F_1\tilde{\mathcal{H}}+\xi(F_1+F_2)(\mathcal{H}+x_B/2\mathcal{E}) - \xi k F_2 \tilde{\mathcal{E}}+\ldots\}$$

→ 3 observables (including BSA), constraints on real and imaginary CFFs of various neutron GPDs

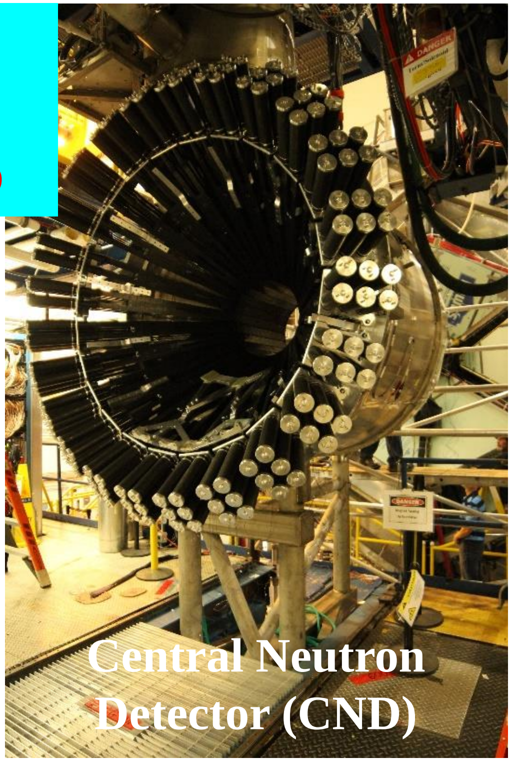


$$e\vec{p} \rightarrow ep\gamma$$
$$e\vec{d} \rightarrow e(p)n\gamma$$

CLAS12 + Longitudinally polarized target + CND

Ultimate goals: flavor separation of CFFs & Ji's sum rule

Noémie Pilleux



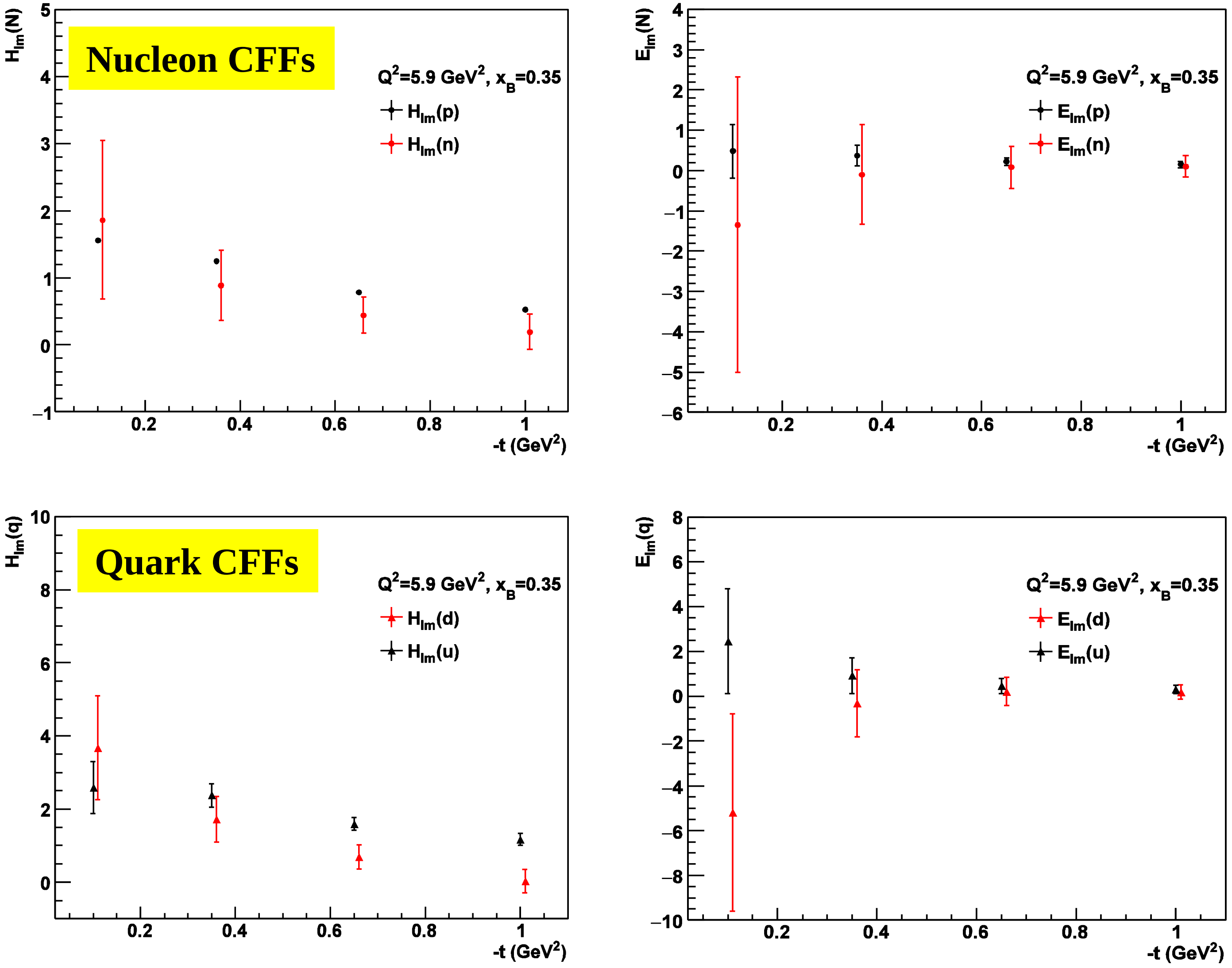
CLAS12: projections for flavor separation with DVCS

$$(H,E)_u(\xi,\xi,t) = {}^{9}\!/_{15}\left[4(H,E)_p(\xi,\xi,t) - (H,E)_n(\xi,\xi,t)\right]$$

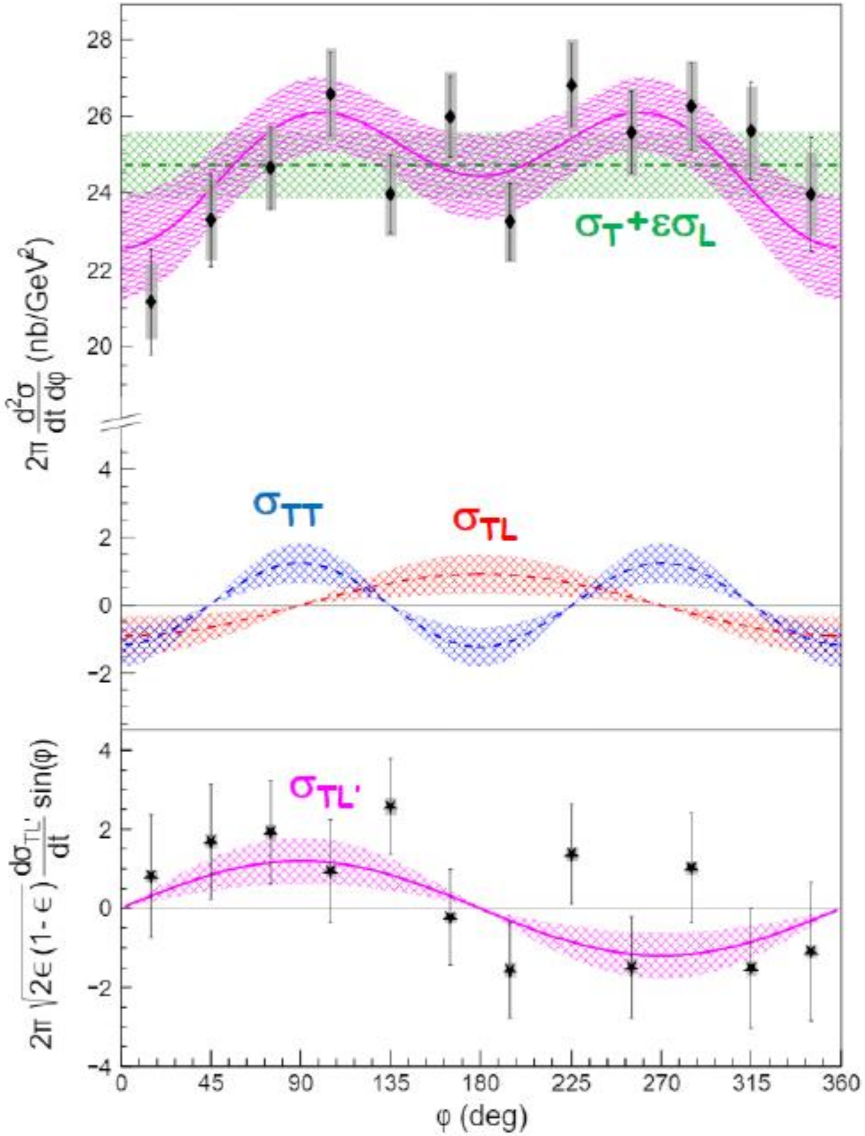
$$(H,E)_d(\xi,\xi,t) = {}^{9}\!/_{15}\left[4(H,E)_n(\xi,\xi,t) - (H,E)_p(\xi,\xi,t)\right]$$

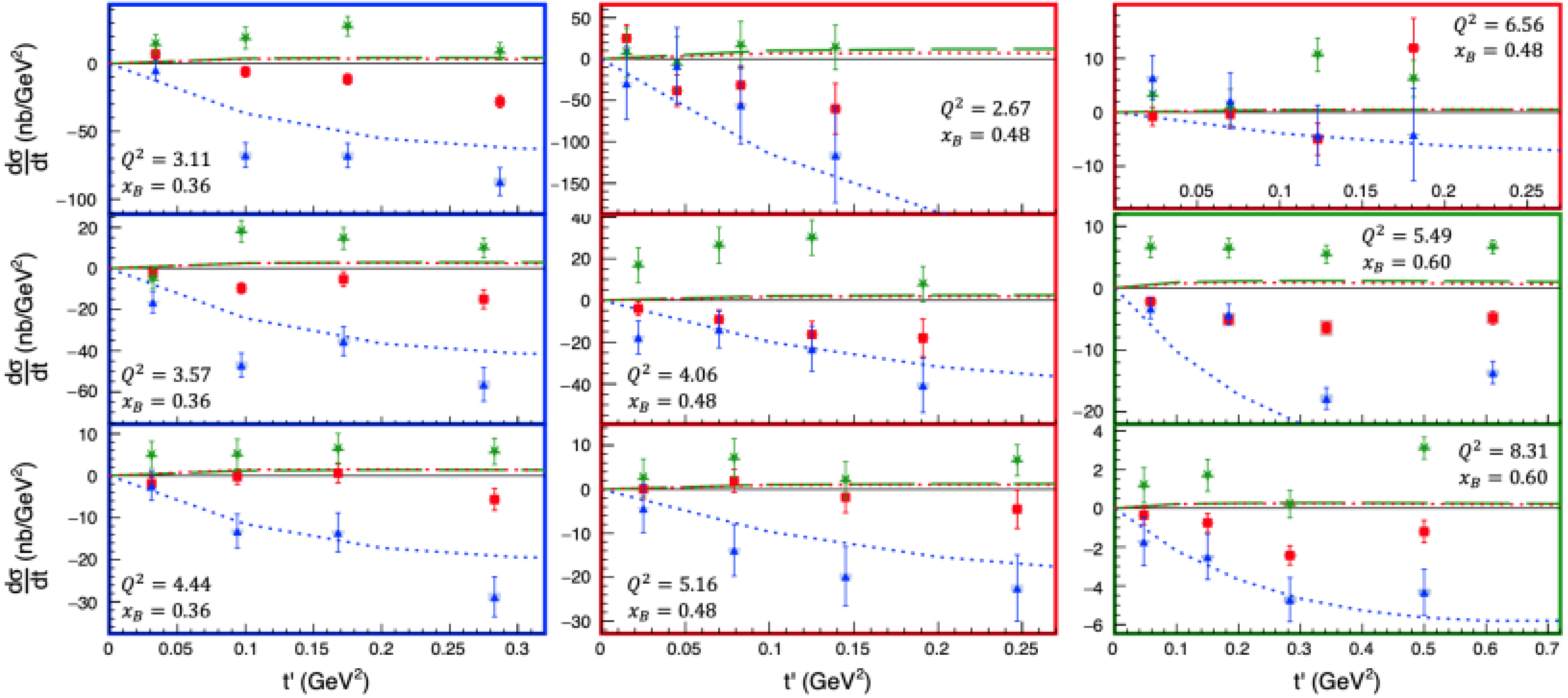
$$\frac{1}{2}\int_{-1}^{1} x dx\left(H^q(x,\xi,t=0) + E^q(x,\xi,t=0)\right) = J^q$$

Local fits (M. Guidal's code) done to all the **projected observables** for **pDVCS** (BSA, lTSA, lDSA, tTSA, CS, DCS) and **nDVCS** (BSA,lTSA, lDSA) of the CLAS12 program



Exclusive π^0 electroproduction in Hall A at 10.6 GeV





σ_{TL} $\sigma_{TL'}$ σ_{TT}

$\sigma_{TT} >> \sigma_{TL}, \sigma_{TL'}$ Indication of significant transverse component

Confirmation of the trend observed in 6-GeV data
→ dominance of transversity GPDs

M. Dlamini et al., PRL 127 (2021)

Summary

- DVMP is another way to access GPDs, beyond DVCS, providing in particular the possibility of quark-flavor separation of GPDs by changing the type of meson
- Several DVMP channels were measured at JLab at 6 GeV:
  - Most of the currently available experimental DVMP data for vector mesons are not in a region in which the leading-twist handbag applies: the data follow the leading-twist predictions only at very small values of x_B, and Q^2 larger than about 50 GeV^2.
  - Substantial contributions of transverse photons is observed in the light pseudoscalar meson channels (exclusive π^0 and η electroproduction)
  - The dominance of transverse photons opens new and unique opportunities for accessing the transversity GPDs over a large kinematic range.

- New results on DVCS and DVMP have started to come out of data taken after the 12-GeV CEBAF upgrade:
  - High precision DVCS and π^0 cross sections from Hall A, confirming the transverse cross section dominance
  - New beam spin asymmetries for pDVCS from CLAS12, covering a wider kinematic range and providing new constraints to CFF fits
  - New beam-spin asymmetries for nDVCS from CLAS12, allowing flavor separation of CFFs using neural-network-based global fits, and having strong sensitivity to $Im\mathcal{E}$
  - The first-time measurement of TCS, at CLAS12, proves the universality of GPDs and the relevance of TCS in the quest to determine the pressure distribution in the proton via the measurement of the D-term

Back-up slides

Particle name	Particle symbol	Antiparticle symbol	Quark content[14]	Rest mass (MeV/c^2)	I^G	J^{PC}	S	C	B'	Mean lifetime (s)	Commonly decays to (>5% of decays)
Pion[1]	π^+	π^-	$u\bar{d}$	139.570 39 ± 0.000 18	1^-	0^-	0	0	0	$2.6033 \pm 0.0005 \times 10^{-8}$	$\mu^+ + \nu_\mu$
Pion[1]	π^0	Self	$\frac{u\bar{u}-d\bar{d}}{\sqrt{2}}$ [a]	134.976 8 ± 0.000 5	1^-	0^{-+}	0	0	0	$8.5 \pm 0.2 \times 10^{-17}$	$\gamma + \gamma$

Particle name	Particle symbol	Antiparticle symbol	Quark content	Rest mass (MeV/c^2)	I^G	J^{PC}	S	C	B′	Mean lifetime (s)	Commonly decays to (>5% of decays)
Phi meson[2]	ϕ(1020)	Self	$s\bar{s}$	1,019.461 ± 0.020	0^-	1^{--}	0	0	0	$1.55 \pm 0.01 \times 10^{-22}$[f]	$K^+ + K^-$ or $K^0_S + K^0_L$ or $(\rho + \pi)$ / $(\pi^+ + \pi^0 + \pi^-)$

Particle name	Particle symbol	Antiparticle symbol	Quark content	Rest mass (MeV/c^2)	I^G	J^{PC}	S	C	B′	Mean lifetime (s)	Commonly decays to (>5% of decays)
Omega meson[6]	ω(782)	Self	$\frac{u\bar{u}+d\bar{d}}{\sqrt{2}}$	782.66 ± 0.13	0^-	1^{--}	0	0	0	$(7.58 \pm 0.11) \times 10^{-23}$ s	$\pi^+ + \pi^0 + \pi^-$ or $\pi^0 + \gamma$

Rho mesons

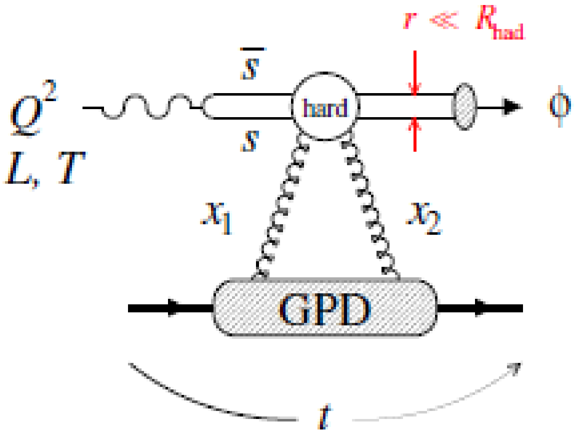
Particle name	Particle symbol	Antiparticle symbol	Quark content[5]	Mass (MeV/c^2)[a]	I^G	J^{PC}	S	C	B'	Mean lifetime (s)[a]	Commonly decays to (>5% of decays)
Charged rho meson[6]	ρ^+(770)	ρ^-(770)	$u\bar{d}$	775.11 ± 0.34	1^+	1^-	0	0	0	$(4.415 \pm 0.024) \times 10^{-24}$[b]	$\pi^\pm + \pi^0$
Neutral rho meson[6]	ρ^0(770)	Self	$\frac{u\bar{u}-d\bar{d}}{\sqrt{2}}$	775.26 ± 0.25	1^+	1^{--}	0	0	0	$(4.453 \pm 0.027) \times 10^{-24}$[b]	$\pi^+ + \pi^-$

Definitions:

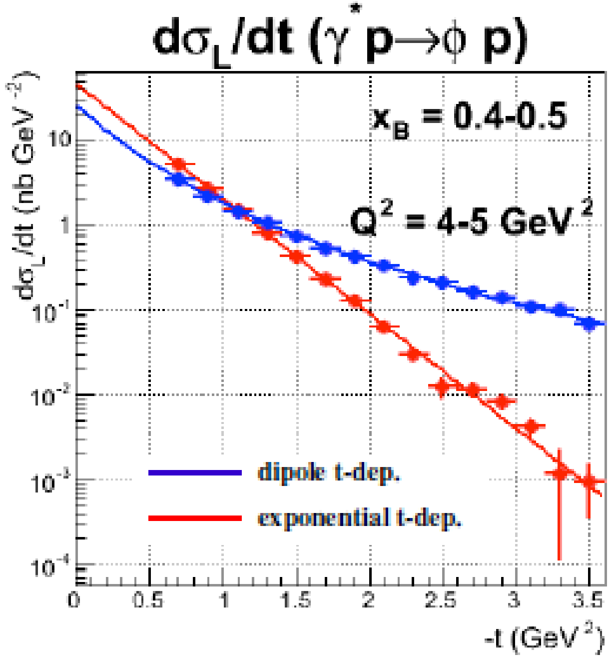
Vector mesons: spin 1, odd parity $J^P=1^-$

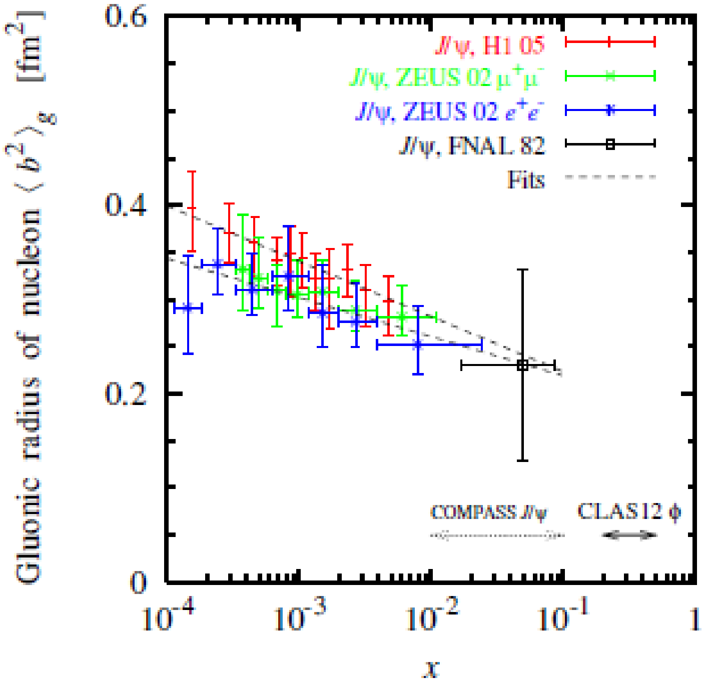
Pseudoscalar meson: spin 0, odd parity $J^P=0^-$

DVMP @ CLAS12: exclusive ϕ electroproduction



- Differential c.s. → extraction of **structure functions**
- **L-T separation** from **ϕ→KK** decay distributions
- t dependence of **$d\sigma_L/dt$**





Transverse distribution of gluons in the proton