Generalized Parton Distributions and Nucleon Structure

Volker D. Burkert
Jefferson Lab

With pQCD established we have the tool to understand matter at a deeper level.
Nobel prize 2004 - D. Gross, D. Politzer, F. Wilzcek

- GPDs - a unifying framework of hadron structure
- DVCS and DVMP at 12 GeV
- Extracting GPDs from polarization measurements
- 3D Imaging of the Nucleon Quark Structure
- Transverse momentum dependent PDFs
- A five year program with *CLAS12*
- Summary

DOE Science Review for the JLab Upgrade to 12 GeV, Jefferson Lab, April 6-8, 2005

Fundamental questions in hadron physics?

1950-1960: Does the proton have finite size and structure?

- Elastic electron-proton scattering
  - ⇨ the proton is not a point-like particle but has finite size
    - charge and current distribution in the proton, G_E/G_M

Nobel prize 1961- R. Hofstadter

1960-1990: What are the internal constituents of the nucleon?

- Deeply inelastic scattering
  - ⇨ discover quarks in ‘scaling’ of structure function and measure their momentum and spin distributions

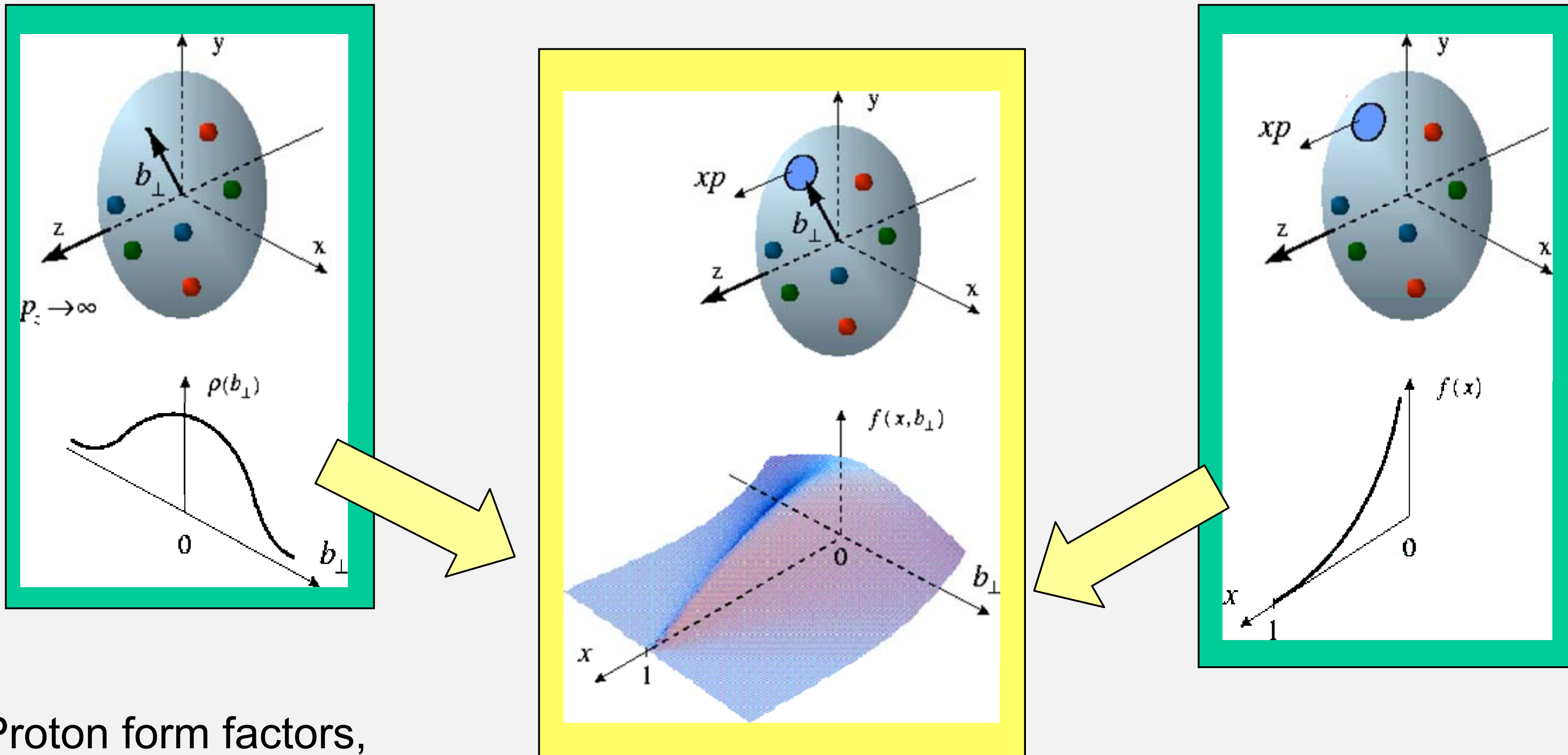
Nobel prize 1990 - J. Friedman, H. Kendall, R. Taylor

Today: How are the nucleon’s charge & current distributions related to the quark momentum & spin distributions?

Beyond form factors and quark distributions – Generalized Parton Distributions (GPDs)

X. Ji, D. Mueller, A. Radyushkin, …

M. Burkardt, … Interpretation in impact parameter space



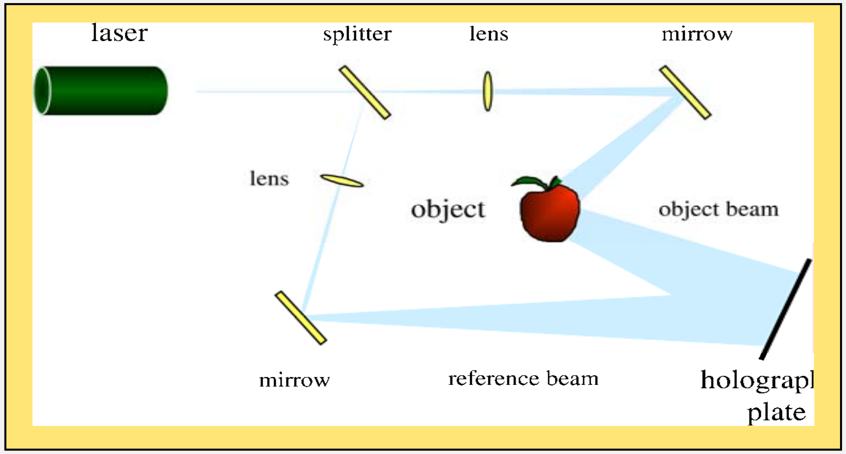
Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & helicity distributions

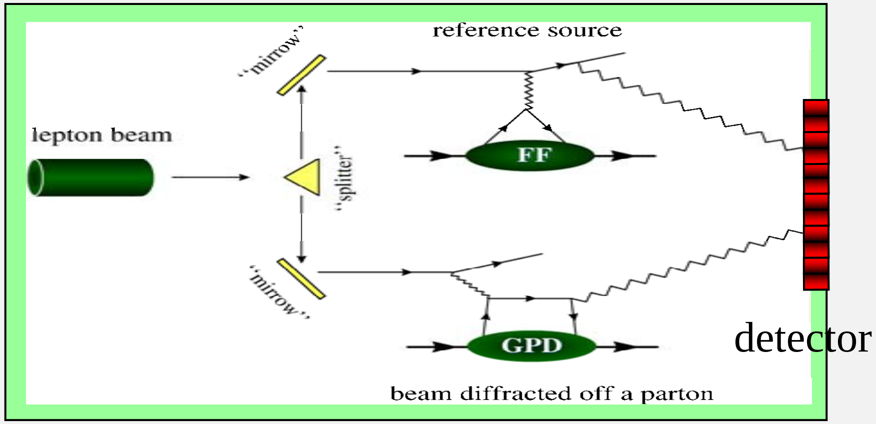
From Holography to Tomography

A. Belitsky, B. Mueller, NPA711 (2002) 118



An Apple

A Proton

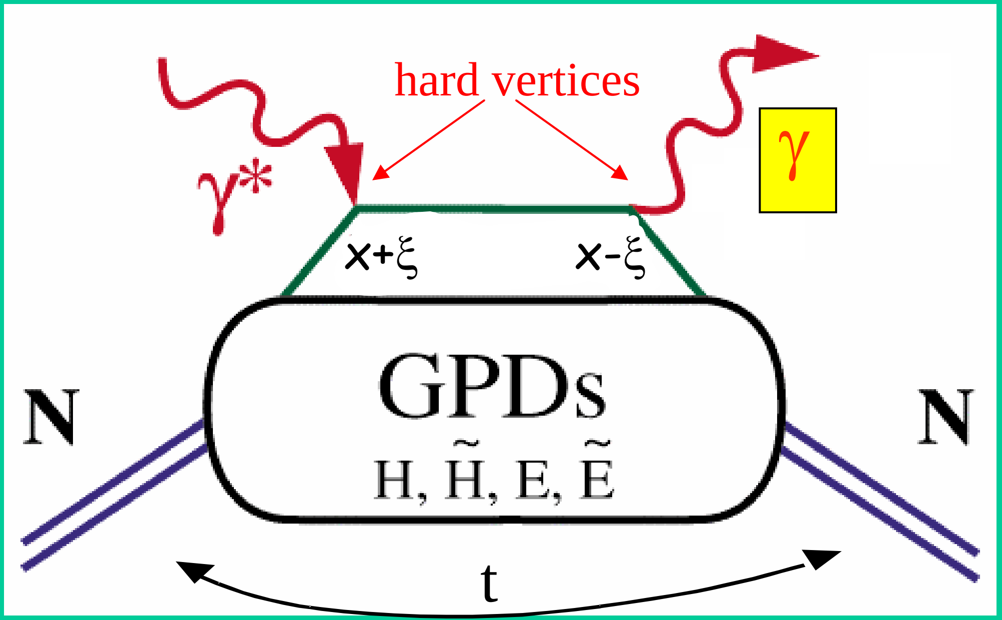


By varying the energy and momentum transfer to the proton we probe its interior and generate tomographic images of the proton ("femto tomography").

GPDs & Deeply Virtual Exclusive Processes

"handbag" mechanism

Deeply Virtual Compton Scattering (DVCS)



x – longitudinal quark momentum fraction

2ξ – longitudinal momentum transfer

$\sqrt{-t}$ – Fourier conjugate to transverse impact parameter

H(x,ξ,t), E(x,ξ,t), . .

$$\xi = \frac{x_B}{2-x_B}$$

Link to DIS and Elastic Form Factors

DIS at $\xi = t = 0$

$$H^q(x,0,0) = q(x), \quad -\bar{q}(-x)$$

$$\tilde{H}^q(x,0,0) = \Delta q(x), \quad \Delta\bar{q}(-x)$$

Form factors (sum rules)

$$\int_{-1}^{1} dx \sum_q \left[H^q(x,\xi,t) \right] = F_1(t) \quad \text{Dirac f.f.}$$

$$\int_{-1}^{1} dx \sum_q \left[E^q(x,\xi,t) \right] = F_2(t) \quad \text{Pauli f.f.}$$

$$\int_{-1}^{1} dx\, \tilde{H}^q(x,\xi,t) = G_{A,q}(t), \quad \int_{-1}^{1} dx\, \tilde{E}^q(x,\xi,t) = G_{P,q}(t)$$

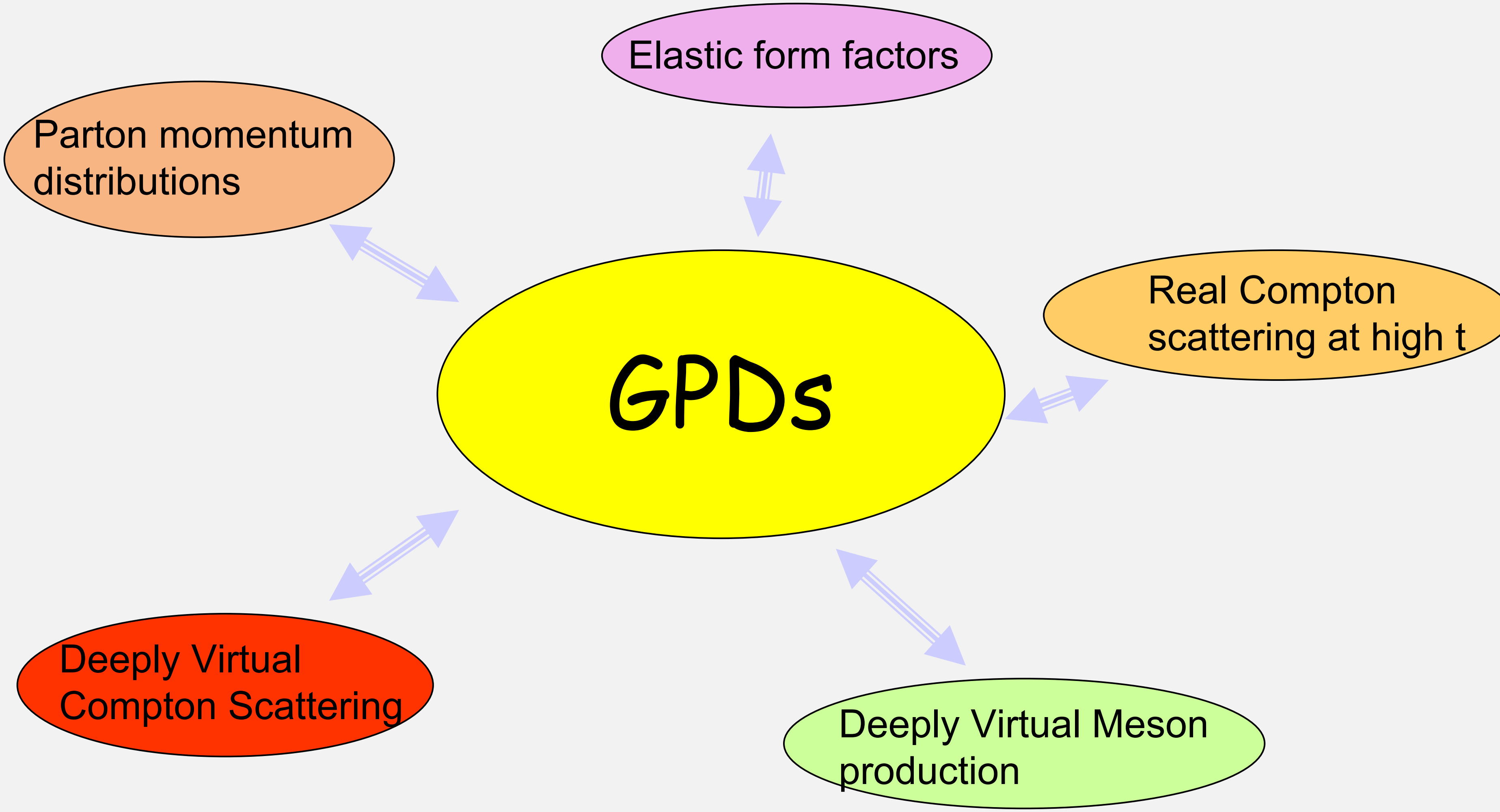
$$H^q, E^q, \tilde{H}^q, \tilde{E}^q(x,\xi,t)$$

Quark angular momentum (Ji's sum rule)

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

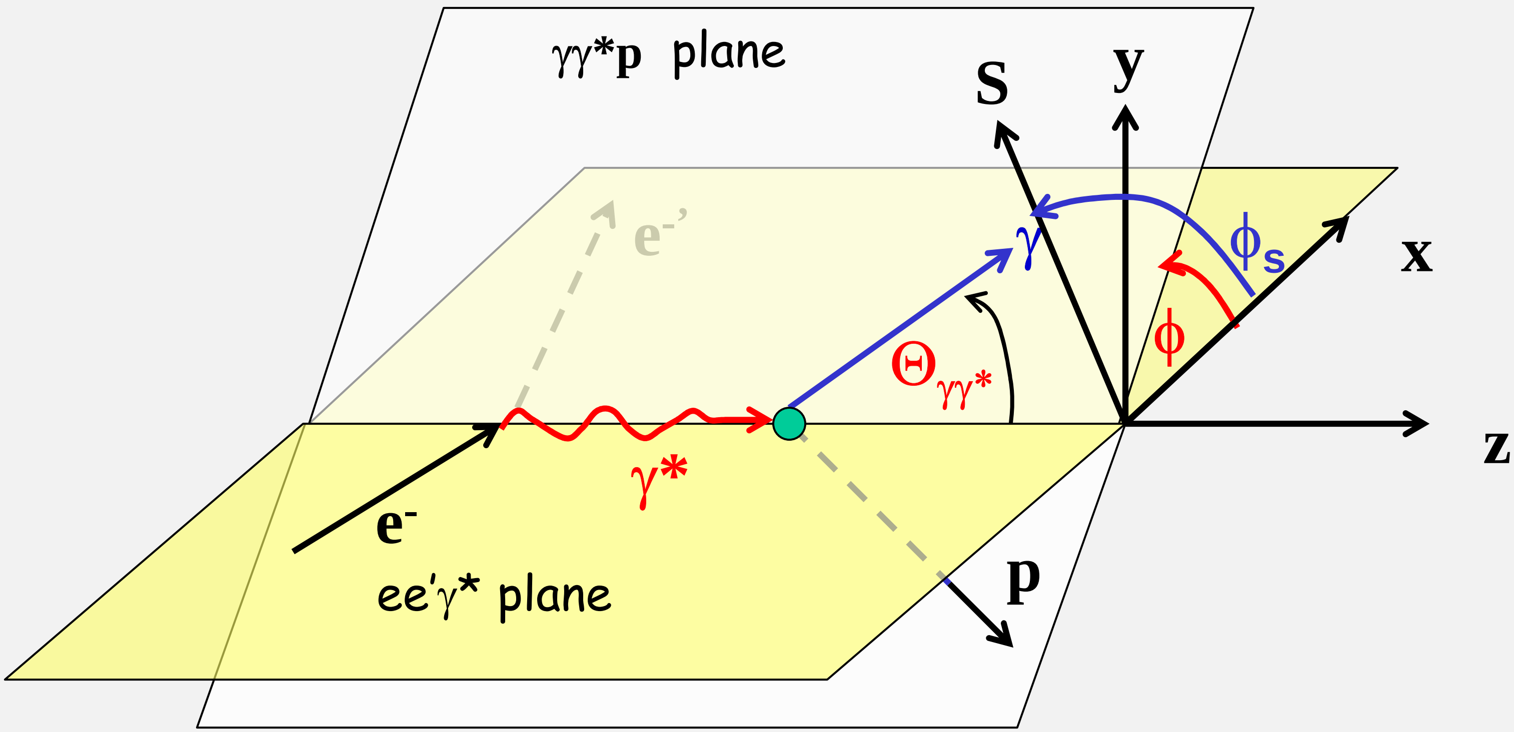
X. Ji, Phy.Rev.Lett.78,610(1997)

A Unified Description of Hadron Structure



DVCS – Kinematics

$ep \longrightarrow ep\gamma$

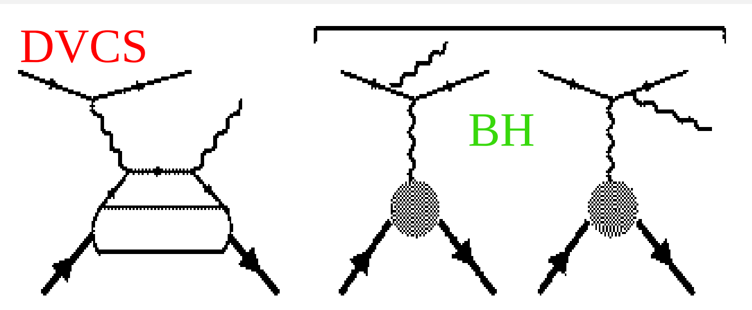


A_{LU} : Beam Longitudinally polarized, Target Unpolarized
A_{UL} : Beam Unpolarized, Target Longitudinally polarized
A_{UT} : Beam Unpolarized, Target Transversely polarized

Accessing GPDs through DVCS

- GPDs are universal, they can be determined in any suitable process

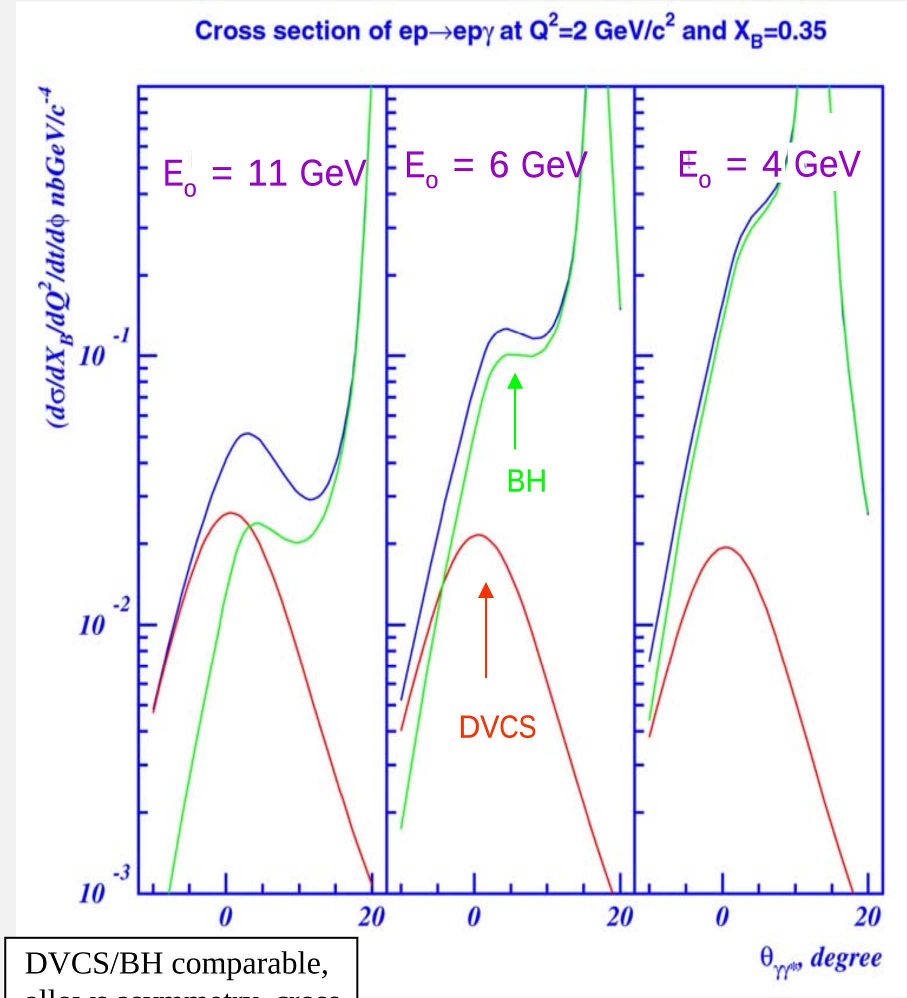
$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} \sim |T^{DVCS} + T^{BH}|^2$$



T^{BH}: given by elastic form factors
T^{DVCS}: determined by GPDs

$A_{LU} \sim$ (BH) Im(DVCS) $\sin\phi$ + h.t.

BH-DVCS interference generates beam and target asymmetries that carry the nucleon structure information.



DVCS/BH comparable, allows asymmetry, cross section measurements

Measuring GPDs through polarization

$$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta\sigma}{2\sigma}$$

Polarized beam, unpolarized target:

$$\Delta\sigma_{LU} \sim \sin\phi \, \mathrm{Im}\{F_1 H + \xi(F_1+F_2)\tilde{H} + kF_2 E\}d\phi \quad \Rightarrow \quad H(\xi,t)$$

Kinematically suppressed

$\xi = x_B/(2-x_B)$

$k = t/4M^2$

Unpolarized beam, longitudinal target:

$$\Delta\sigma_{UL} \sim \sin\phi \, \mathrm{Im}\{F_1\tilde{H} + \xi(F_1+F_2)(H + \xi/(1+\xi)E) - .. \}d\phi \quad \Rightarrow \quad \tilde{H}(\xi,t),\ H(\xi,t)$$

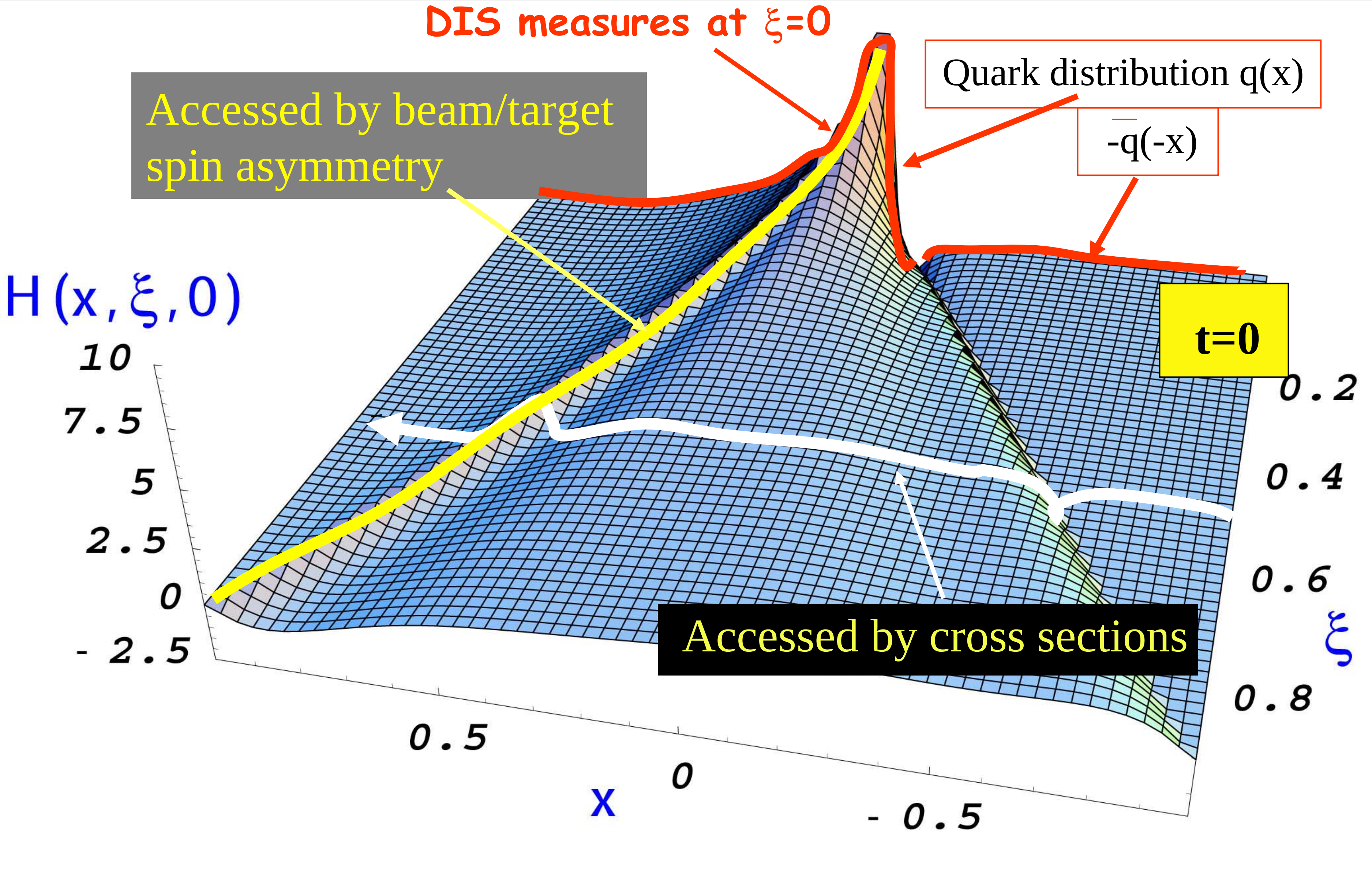
Kinematically suppressed

Unpolarized beam, transverse target:

$$\Delta\sigma_{UT} \sim \sin\phi \, \mathrm{Im}\{k(F_2 H - F_1 E) + \ldots.. \}d\phi \quad \Rightarrow \quad H(\xi,t),\ E(\xi,t)$$

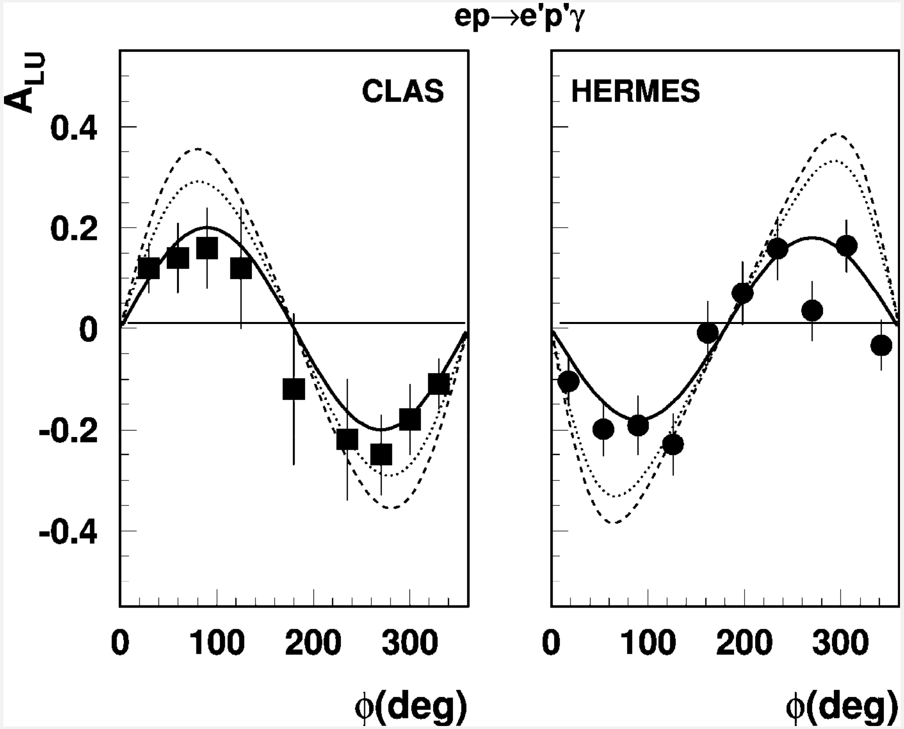
Kinematically suppressed

Access GPDs through x-section & asymmetries



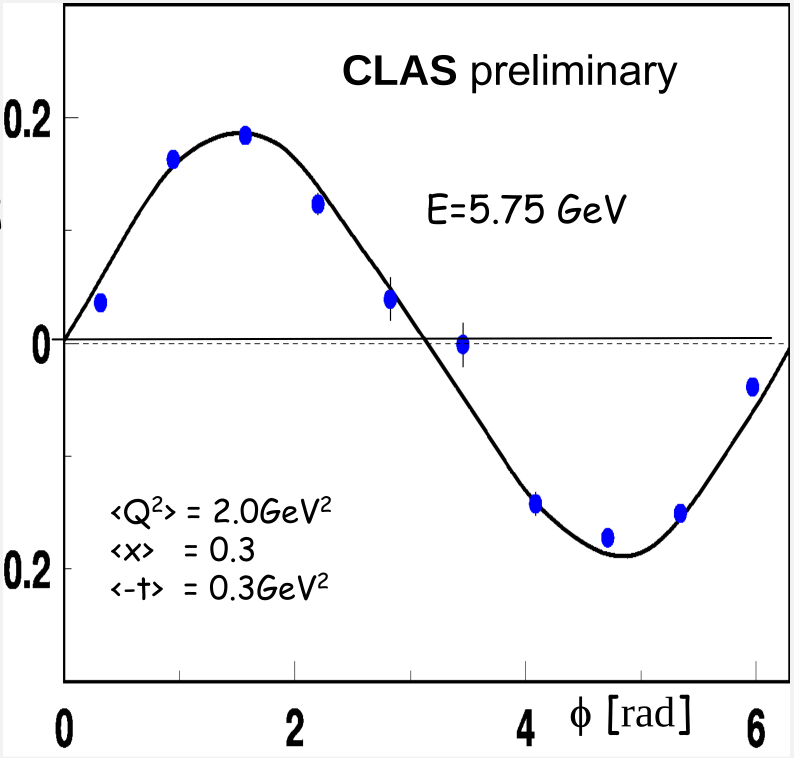
DVCS interpreted in pQCD at $Q^2 > 1$ GeV^2

Pioneering DVCS experiments



First GPD analyses of HERA/CLAS/HERMES data in LO/NLO consistent with **$\alpha \sim 0.20$.**
A. Freund (2003), A. Belitsky et al. (2003)

Full GPD analysis needs high statistics and broad coverage

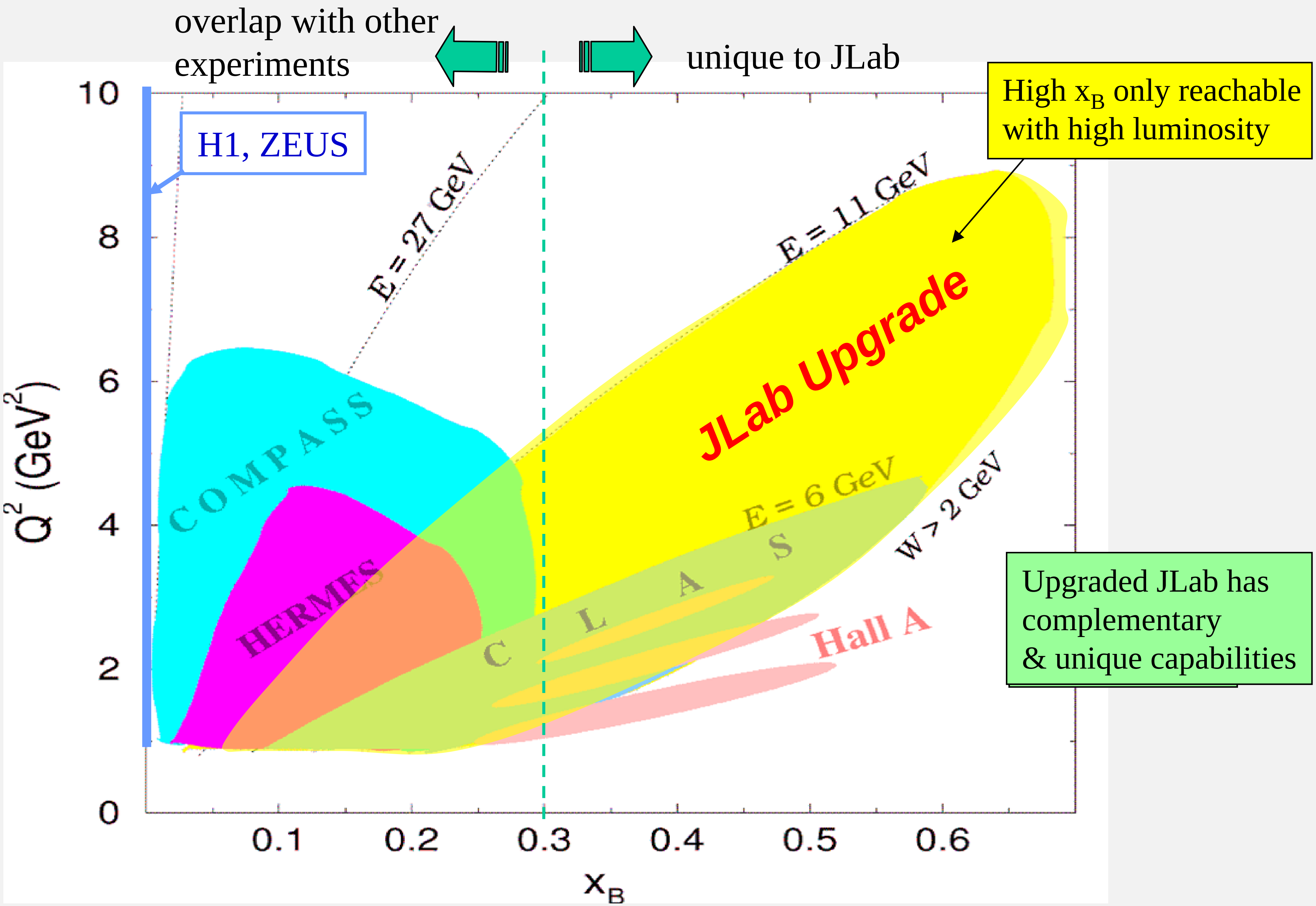


$$A_{UL} = \alpha \sin\phi + \beta \sin 2\phi$$

↑ twist-2 (α) ↑ twist-3 (β)

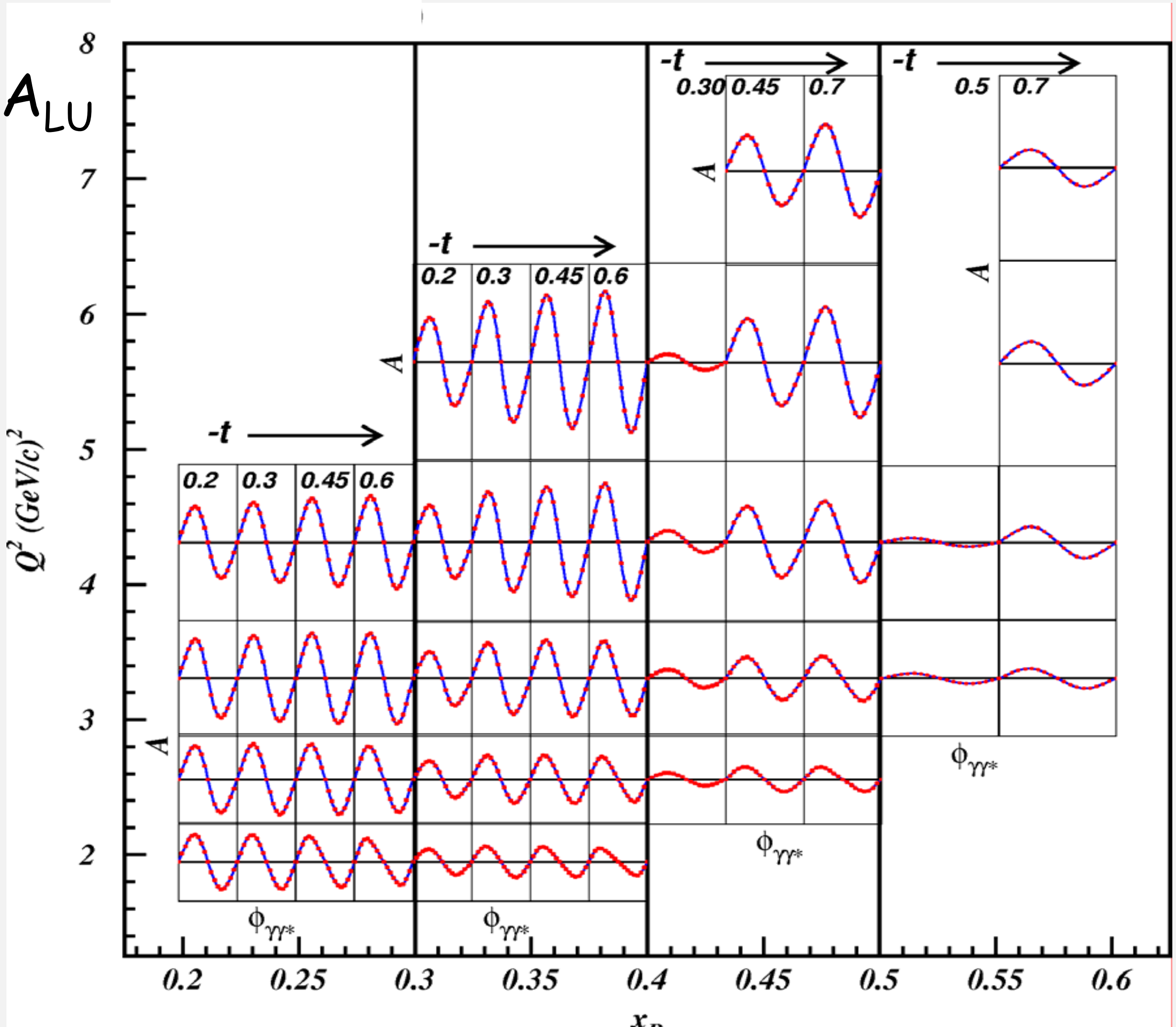
twist-3 contributions are small

Deeply Virtual Exclusive Processes - Kinematics Coverage of the 12 GeV Upgrade



DVCS/BH- Beam Asymmetry

$E_e = 11$ GeV

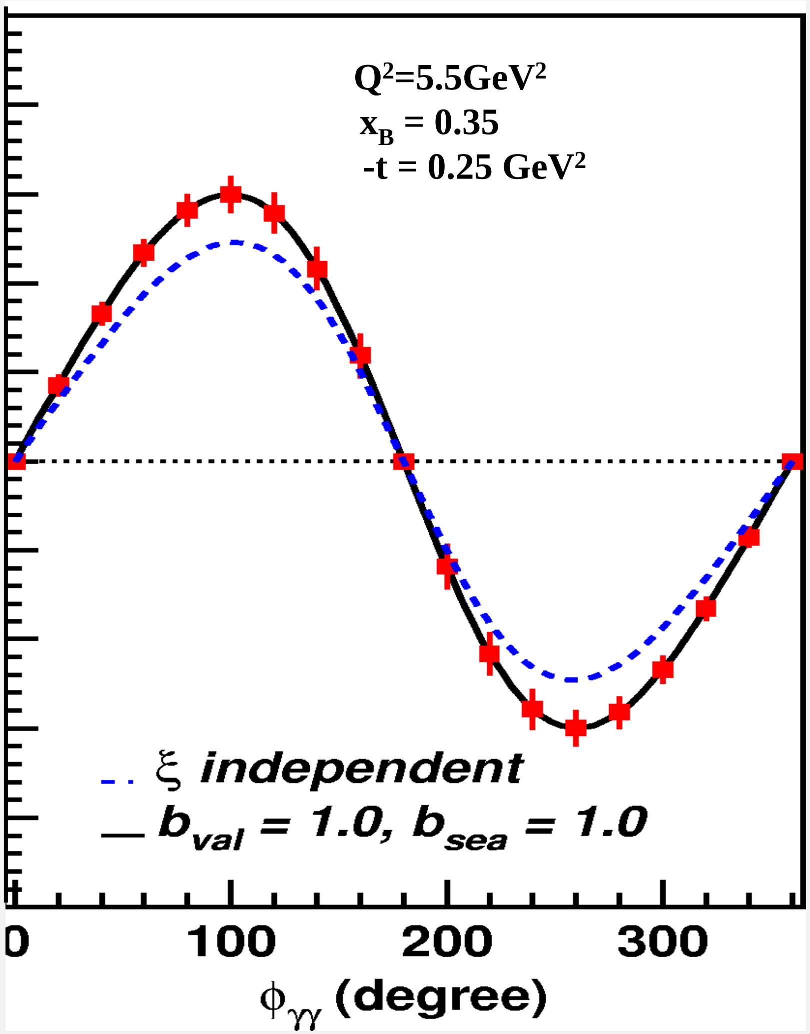


With large acceptance, measure large Q^2, x_B, t ranges simultaneously.

$A(Q^2,x_B,t)$
$\Delta\sigma(Q^2,x_B,t)$
$\sigma\ (Q^2,x_B,t)$

CLAS12 – DVCS/BH- Beam Asymmetry

$E_e = 11$ GeV



CLAS12 – DVCS/BH Beam Asymmetry

$\vec{e}\,p \longrightarrow e p \gamma$

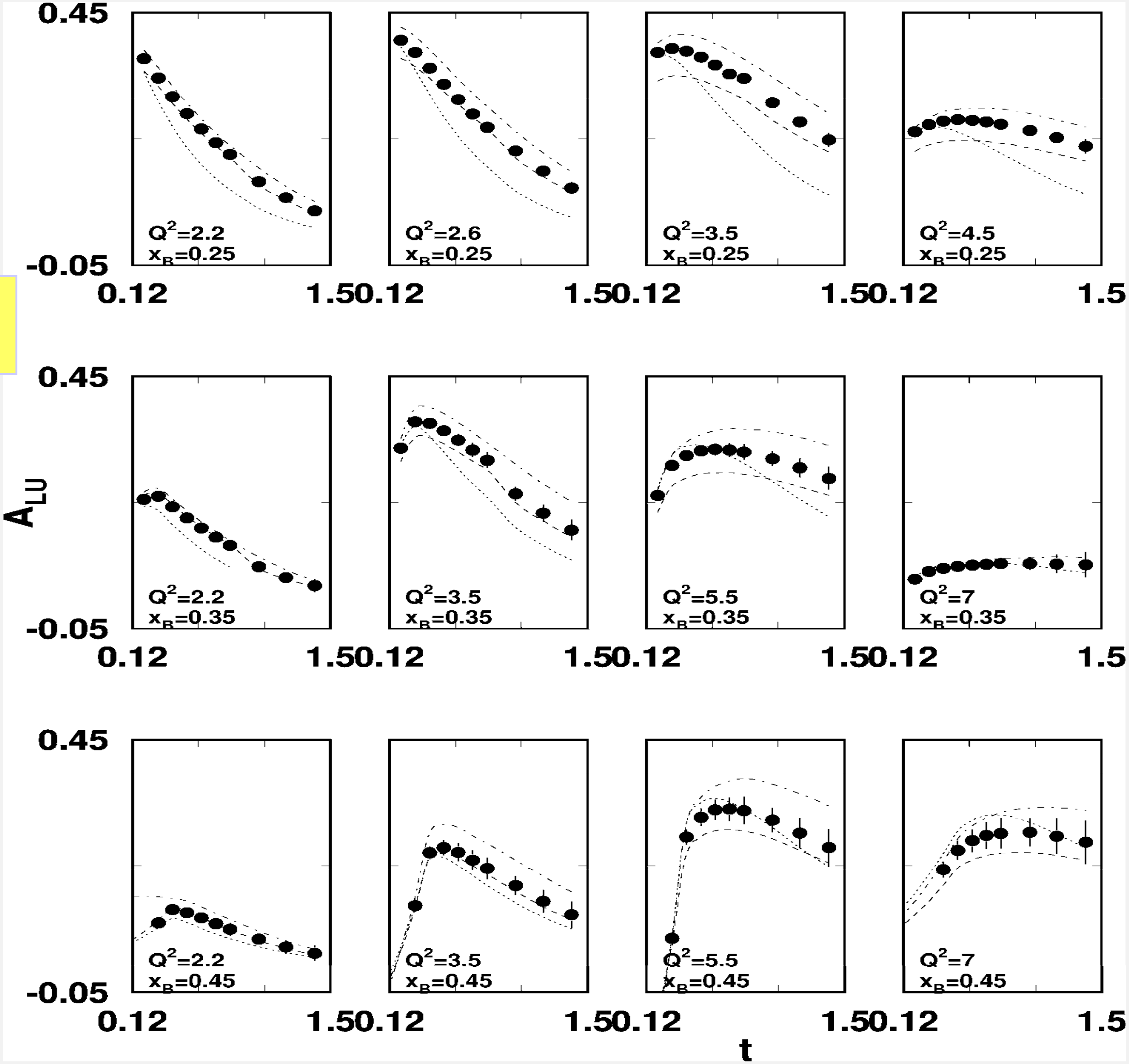
E = 11 GeV

$\Delta\sigma_{LU} \sim \sin\phi \, \mathrm{Im}\{F_1 H + ..\} d\phi$

Sensitive to GPD ***H***

Selected Kinematics

$L = 1\mathrm{x}10^{35}$
T = 2000 hrs
$\Delta Q^2 = 1\ GeV^2$
$\Delta x = 0.05$



CLAS12 – DVCS/BH Target Asymmetry

$e\,\vec{p} \longrightarrow ep\gamma$

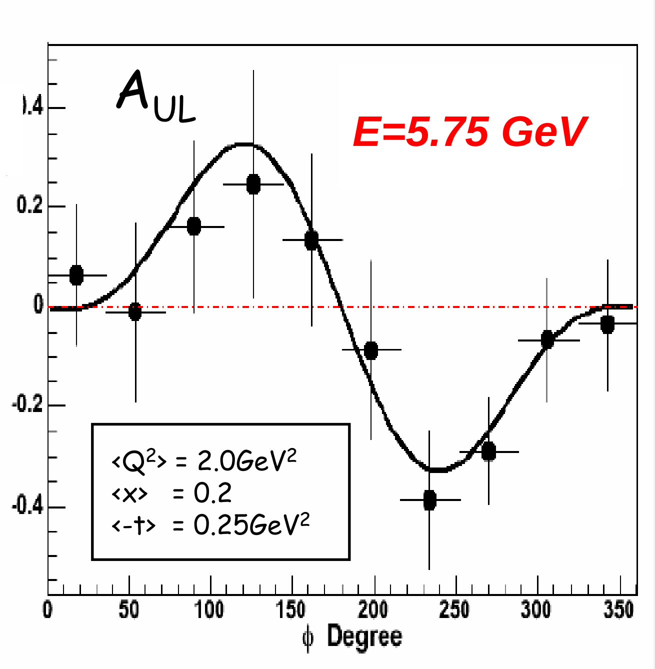
E = 11 GeV

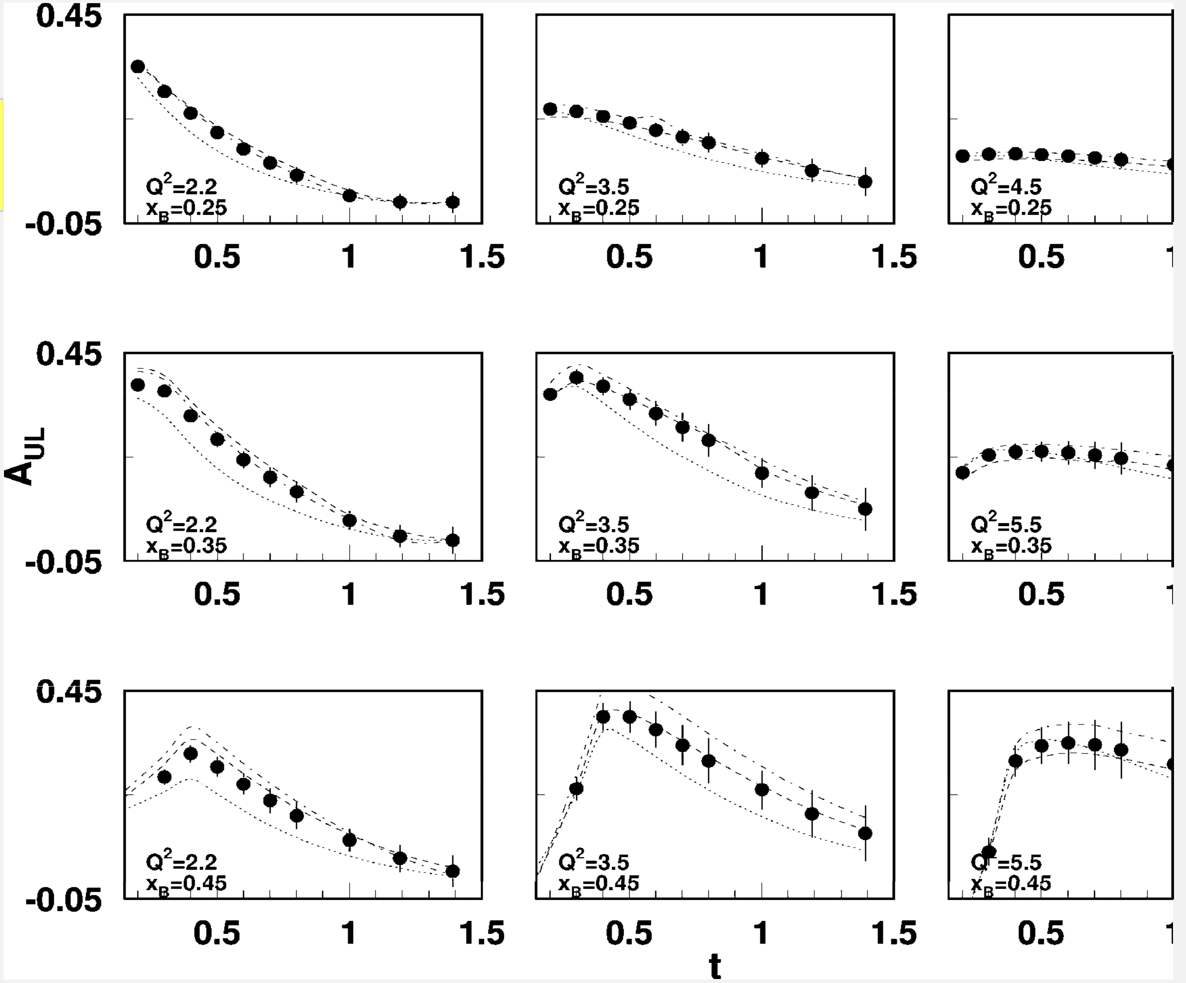
L = 2×10^{35} $cm^{-2}s^{-1}$
T = 1000 hrs
ΔQ^2 = 1GeV^2
Δx = 0.05

Longitudinally polarized target

$$\Delta\sigma \sim \sin\phi \, \mathrm{Im}\{F_1\tilde{H} + \xi(F_1+F_2)H \ldots\}d\phi$$

CLAS preliminary





CLAS12 - DVCS/BH Target Asymmetry

$e\,p^{\uparrow} \longrightarrow e p \gamma$

E = 11 GeV

Sample kinematics

Q^2=2.2 GeV^2, x_B = 0.25, -t = 0.5GeV^2

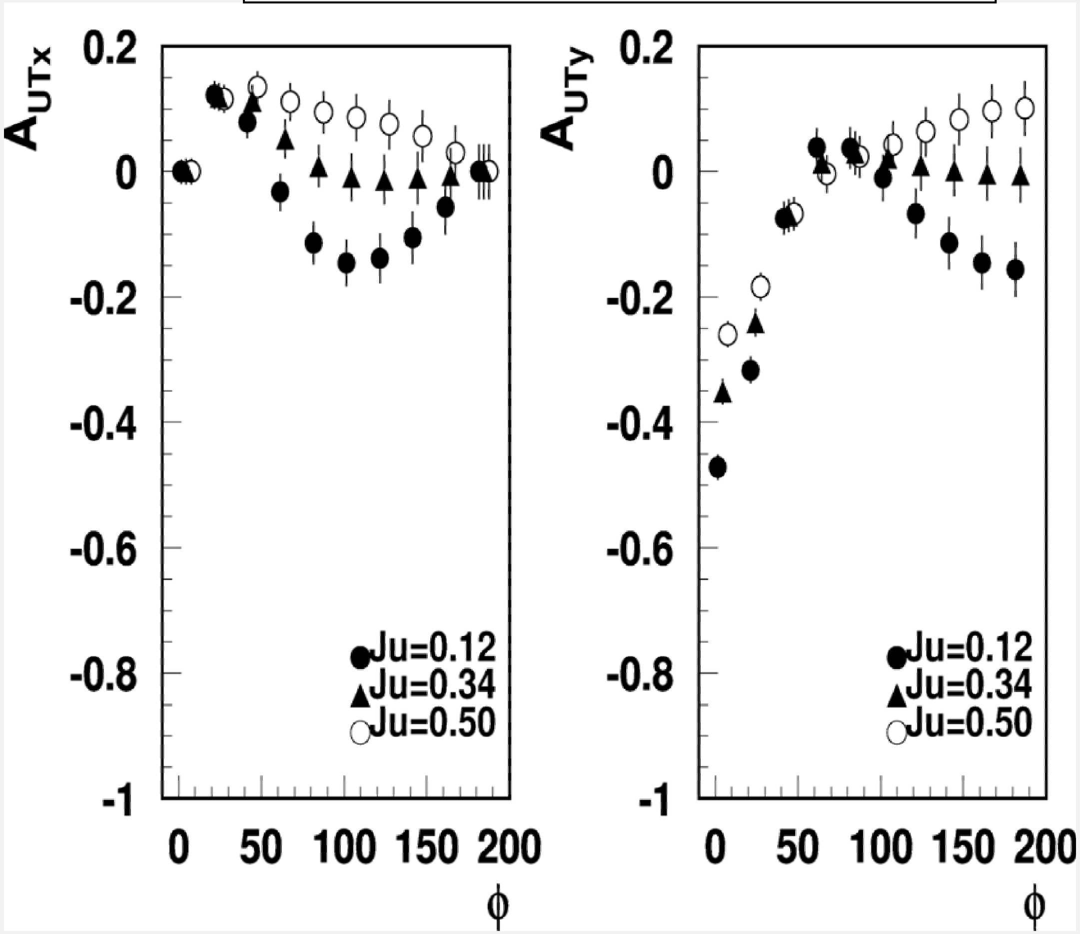
Transverse polarized target

$$\Delta\sigma \sim \sin\phi \, \mathrm{Im}\{k_1(F_2 H - F_1 E) + \ldots\} d\phi$$

A_{UTx} Target polarized in scattering plane

A_{UTy} Target polarized perpedicular to scattering plane

- Asymmetry highly sensitive to the u-quark contributions to proton spin.



From Observables to GPDs

Procedures to extract GPDs from experimental data are currently under intense development.

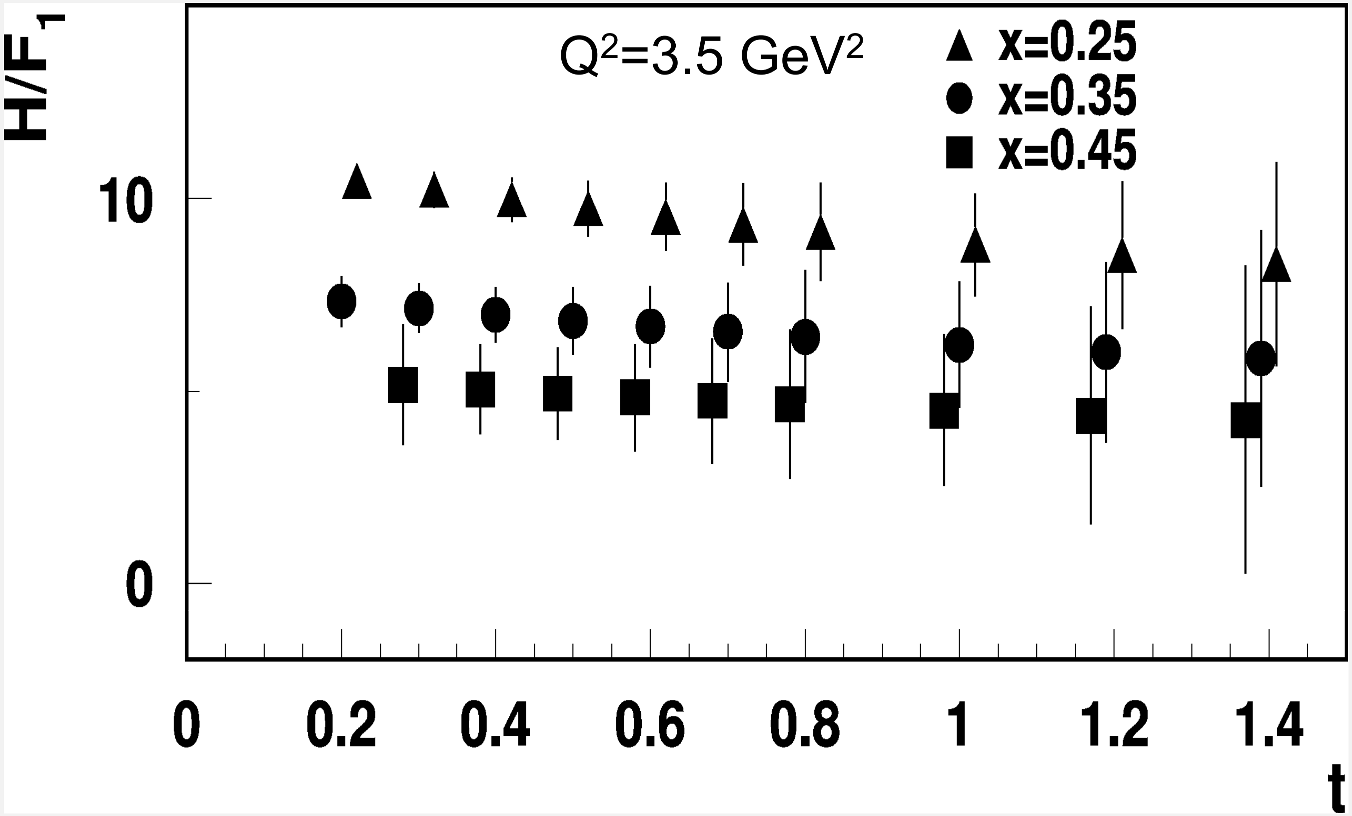
- Approximations for certain kinematics (small ξ, t), allow extraction of dominant GPDs directly.

- Fit parametrizations of GPDs to large sets of DVCS/DVMP cross section and SSA data.
  - Constraint by “forward” parton distribution
  - Polynomiality conditions
  - Elastic form factors
  - Meson distribution amplitudes

- Partial wave expansion techniques.
  - GPDs are given by sum over t-channel exchanges

See: talk by M. Vanderhaeghen

GPDs *H* from expected DVCS A_{LU} data

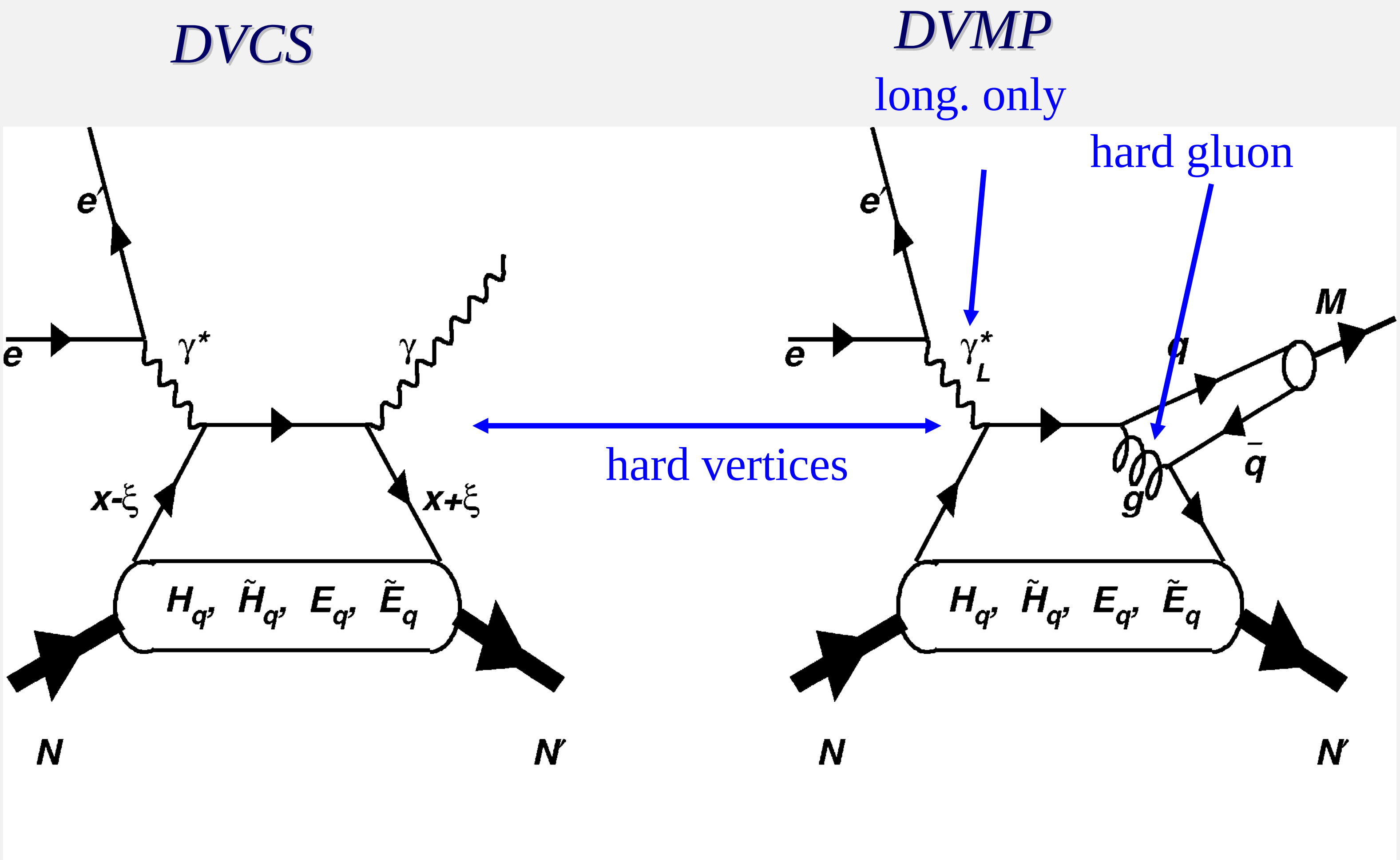


$b_{val}=b_{sea}=1$

MRST02 NNLO distribution

- Other kinematics measured concurrently

GPDs – Flavor separation



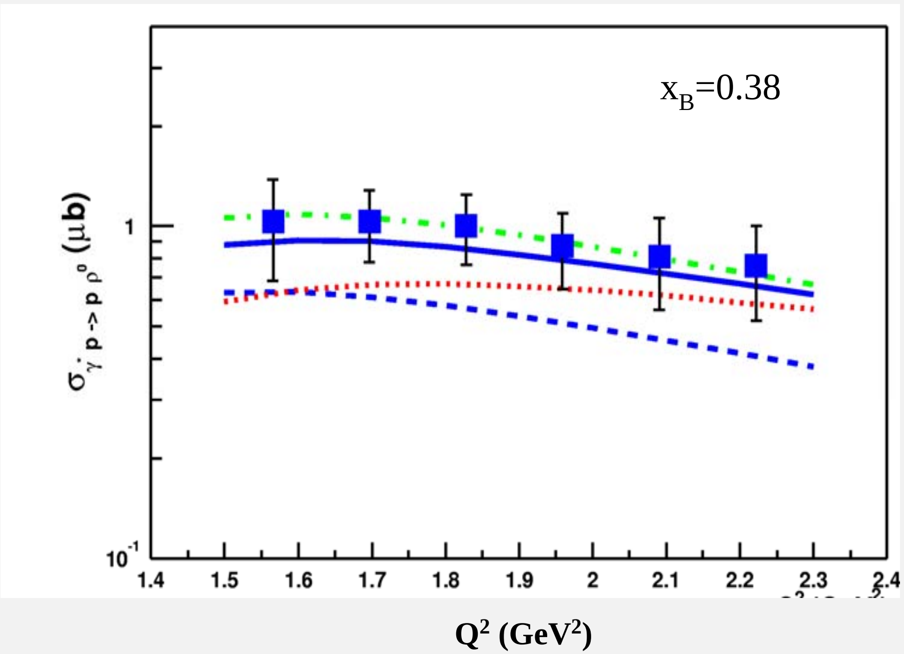
Photons cannot separate u/d quark contributions.

M = ρ/ω select H, E, for u/d flavors
M = π, η, K select $\tilde{H}$, $\tilde{E}$

Exclusive $ep \longrightarrow ep\rho^0_L$ production

HERMES (27GeV)

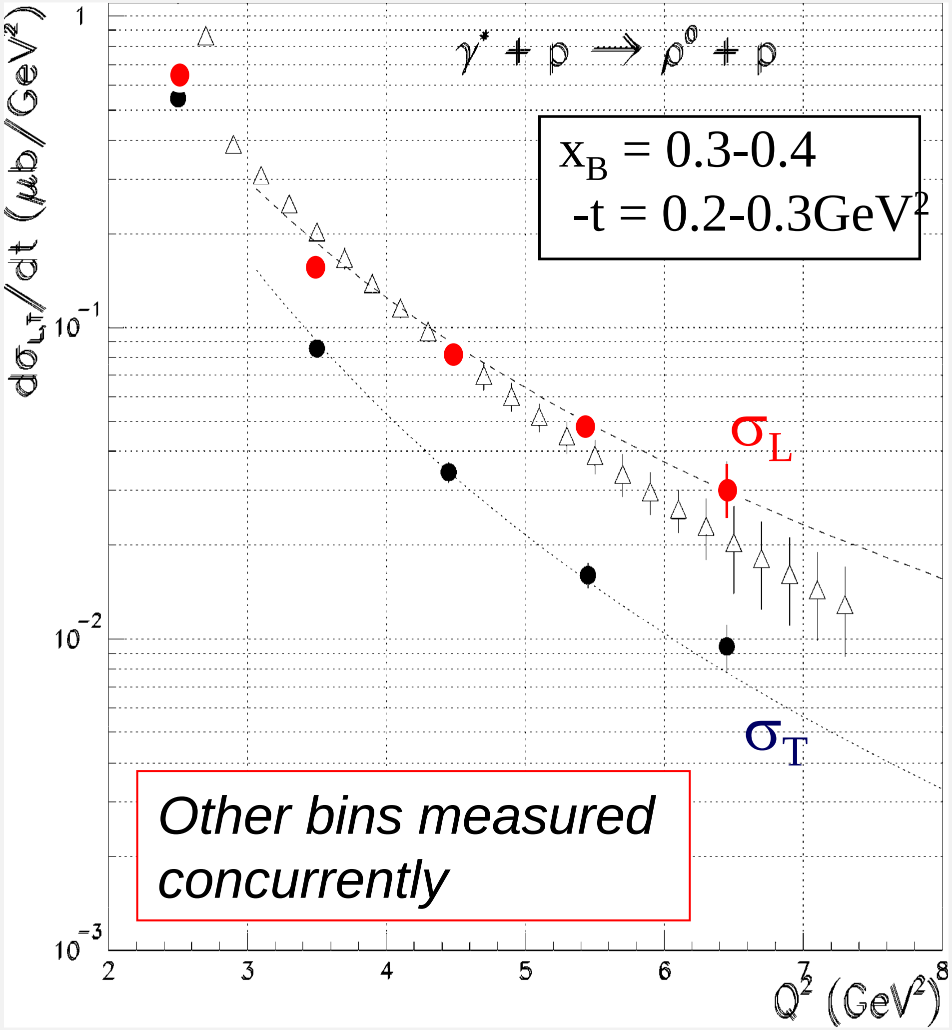
CLAS (4.3 GeV)



W=5.4 GeV

GPD formalism approximately describes CLAS and HERMES data Q^2 >1.5 GeV^2

CLAS12 - L/T Separation $ep \longrightarrow ep\rho^o (\pi^+\pi^-)$

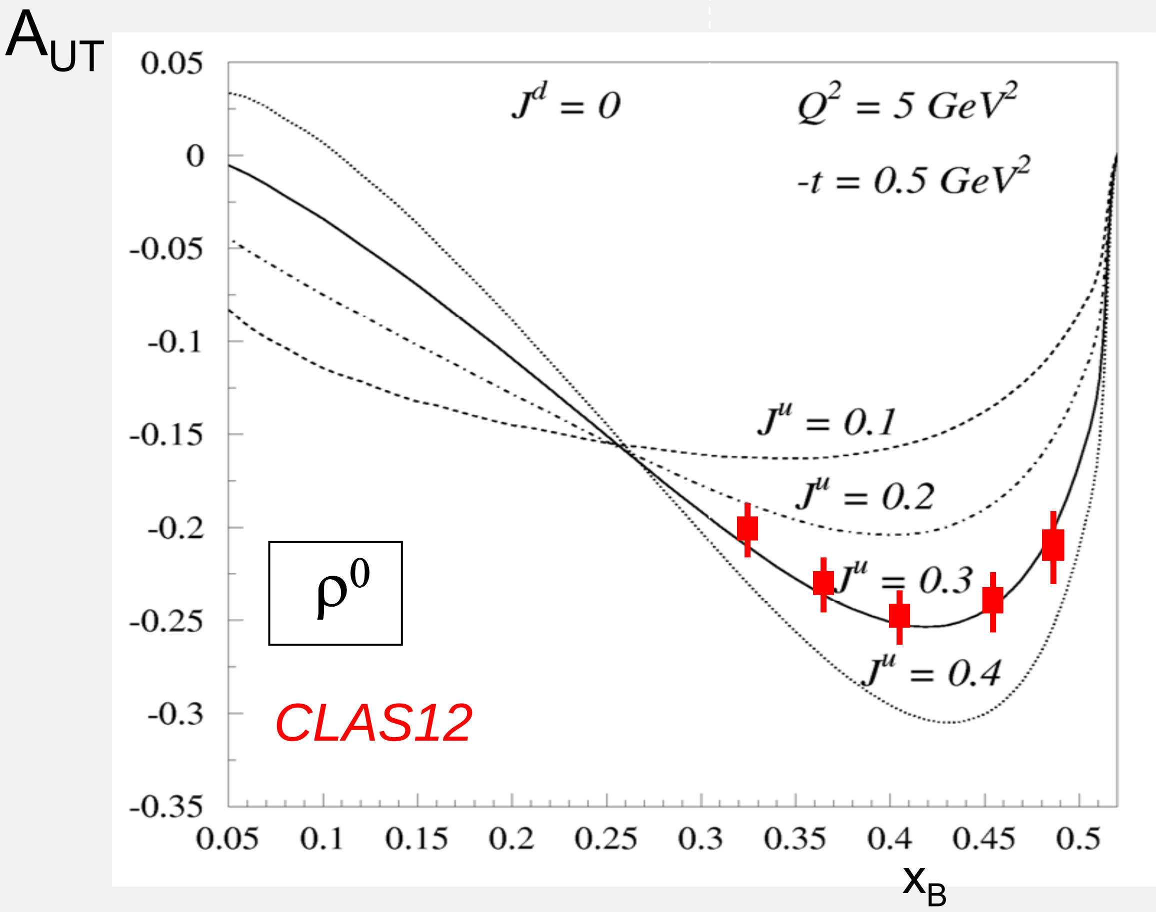


Projections for 11 GeV
(sample kinematics)

Exclusive ρ^0 production on transverse target

$$A_{UT} = -\frac{2\Delta_\perp (\mathrm{Im}(AB^*))/\pi}{|A|^2(1-\xi^2) - |B|^2(\xi^2+t/4m^2) - \mathrm{Re}(AB^*)2\xi^2}$$

ρ^0	$A \sim 2H^u + H^d$ $B \sim 2E^u + E^d$
ρ^+	$A \sim H^u - H^d$ $B \sim E^u - E^d$



Asymmetry depends linearly on the GPD E, which enters Ji's sum rule.

K. Goeke, M.V. Polyakov, M. Vanderhaeghen, 2001

3D Images of the Proton's Quark Content

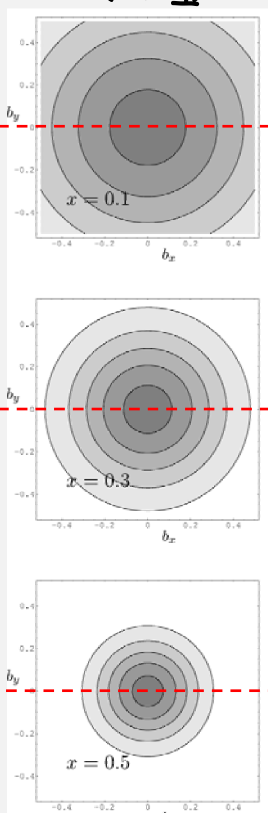
M. Burkardt PRD 66, 114005 (2002)

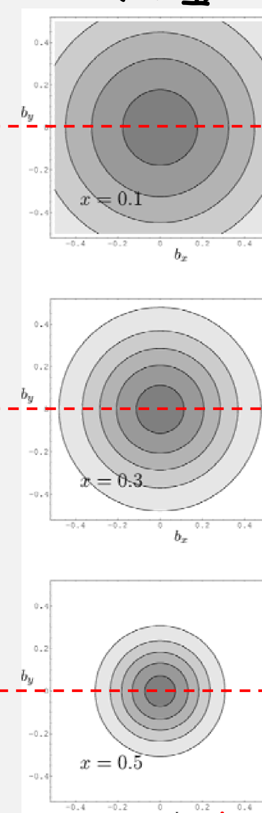
$$q(x,\mathbf{b}_\perp) = \int \frac{d^2\mathbf{\Delta}_\perp}{(2\pi)^2} e^{-i\mathbf{\Delta}_\perp\cdot\mathbf{b}_\perp} H(x,0,-\mathbf{\Delta}_\perp^2).$$

$b_\perp$ - Impact parameter

transverse polarized target

$u(x,b_\perp)$ $u_X(x,b_\perp)$ $d_X(x,b_\perp)$ $d(x,b_\perp)$





quark flavor polarization

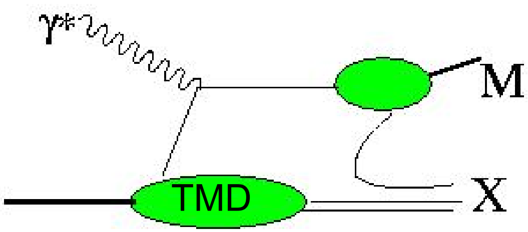
Accessed in Single Spin Asymmetries.

Needs: H^u E^u E^d H^d

Transverse Momentum Dependent GPDs (TMDs)

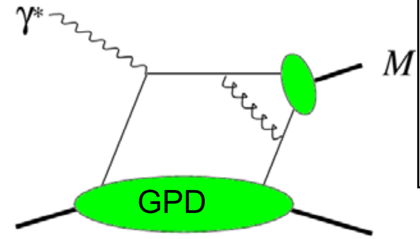
$W_p^u(x,\mathbf{k},\mathbf{r})$ "Parent" Wigner distributions

Probability to find a quark **u** in a nucleon **P** with a certain polarization in a position **r** and momentum **k**



d^3r

d^2k_T (FT)



TMD PDFs: $f_p^u(x,k_T), g_1, f^{\perp}_{1T}, h^{\perp}_{1L}$

GPDs: $H_p^u(x,\xi,t)$, $E_p^u(x,\xi,t)$,…

Measures momentum transfer to quark.

d^2k_T

$\xi=0, t=0$

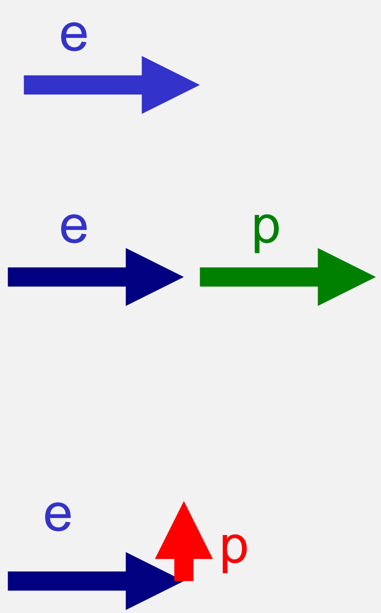
dx

Measure momentum transfer to nucleon.

PDFs $f_p^u(x)$, g_1, h_1

FFs $F_{1p}^u(t), F_{2p}^u(t)$..

SIDIS at leading twist



N \ q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

$h_1^{\perp}$ → Boer

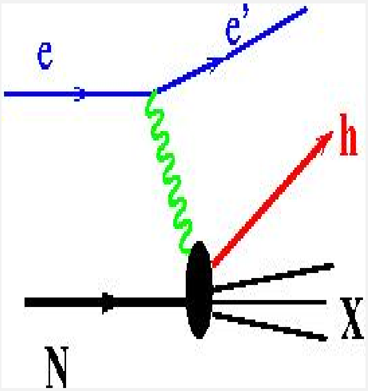
$h_{1L}^{\perp}$ → Mulders

$f_{1T}^{\perp}$ → Sivers

h_1 → transversity

Off-diagonal PDFs vanish if quarks only in s-state! In addition T-odd PDFs require FSI (Brodsky et al., Collins, Ji et al. 2002)

Semi-Inclusive Deep Inelastic Scattering (SIDIS)



- Give access to quark distributions weighted by fragmentation function
- Probes orbital motion of quarks through quark transverse momentum distribution
- Access to new PFDs not accessible in inclusive DIS.

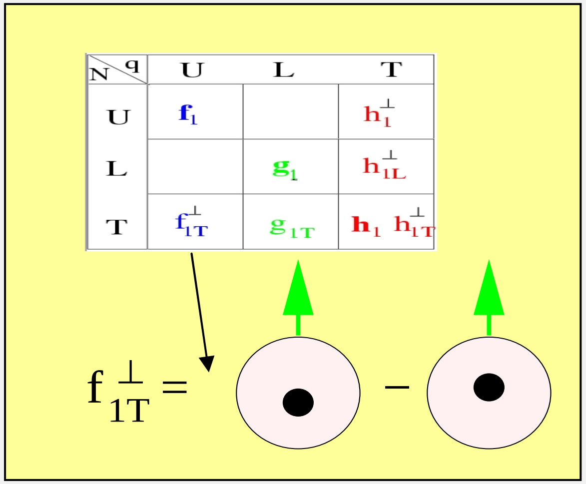
Main focus of SIDIS studies:

- ➢ parton distributions at large x (Z.E. Meziani)
- ➢ orbital angular momentum of quarks through SSA in inclusive meson production.

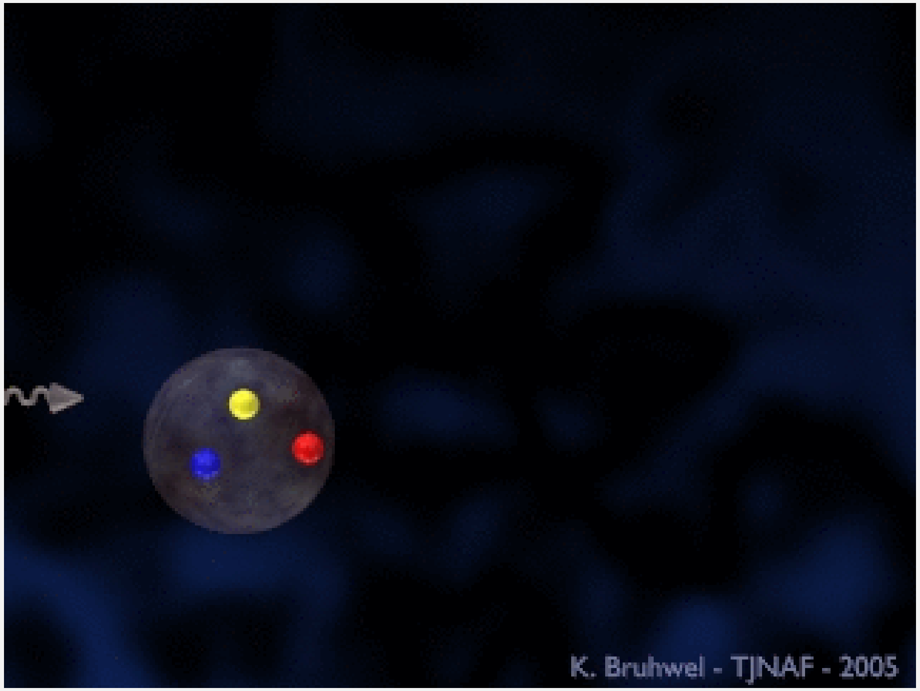
Azimuthal Asymmetry – Sivers Effect

Originates in the quark distribution. It is measured in the azimuthal asymmetry with transverse polarized target.

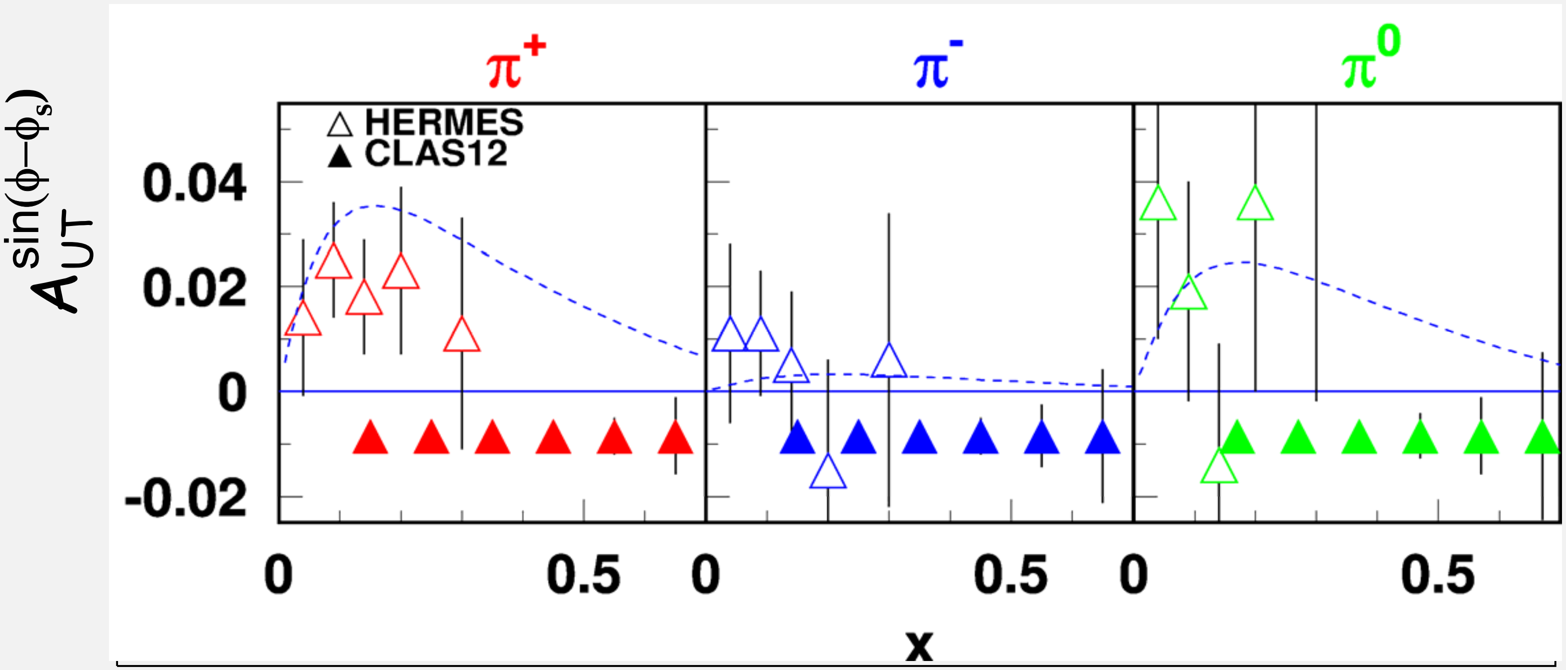
$$A_{UT}^{\sin(\phi-\phi_s)} \sim k f_{1T}^{\perp} D_1$$



Requires: non-trivial phase from the FSI + interference between different helicity states (S. Brodsky)



SIDIS Azimuthal Asymmetry - Sivers effect



- Probes orbital angular momentum of quarks by measuring the imaginary part of s-p-wave interference in the amplitude.

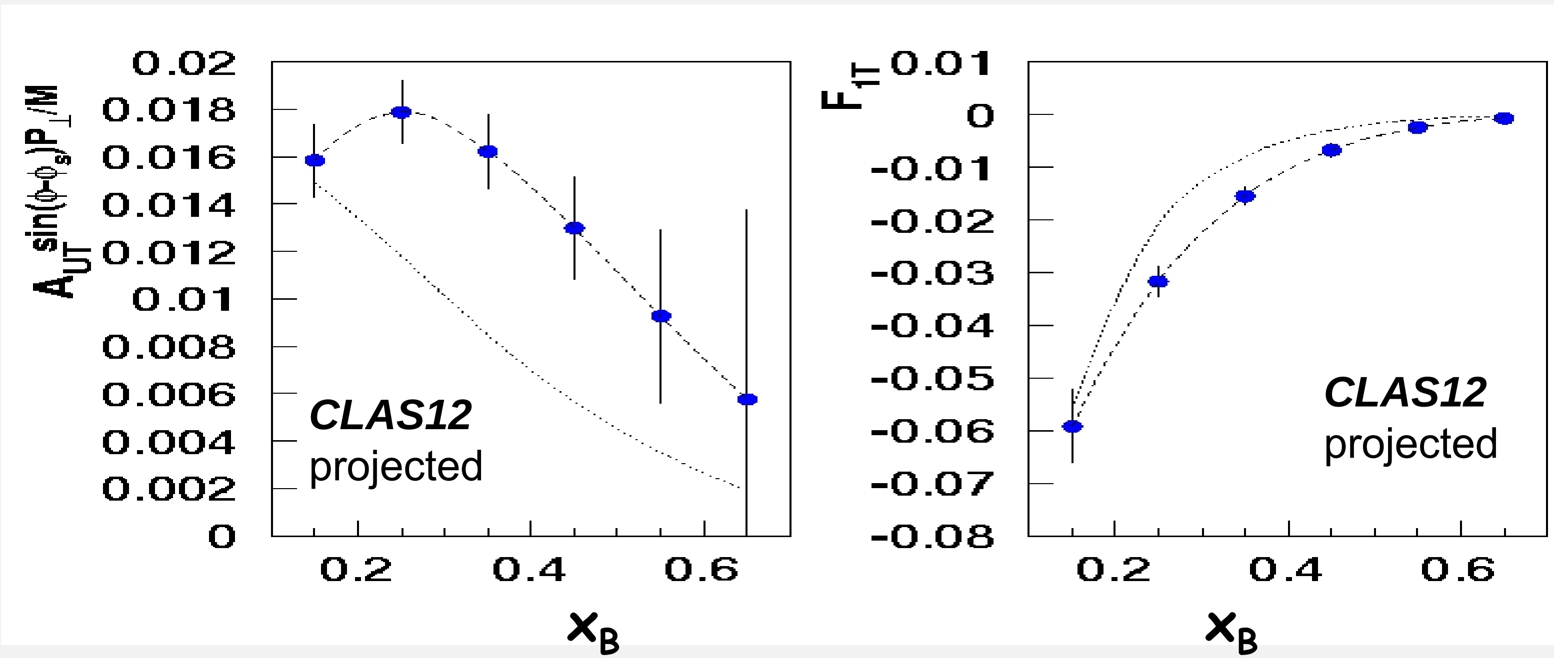
- Extraction of Sivers function $f_{1T}^{\perp}$ from asymmetry.

CLAS12 - Sivers function from A_{UT} (π^0)

In large Nc limit:
$f_{1T}^{u} = -f_{1T}^{d}$

$F_{1T}=1/2\sum_q e_q^2 f_{1T}^{\perp q}$

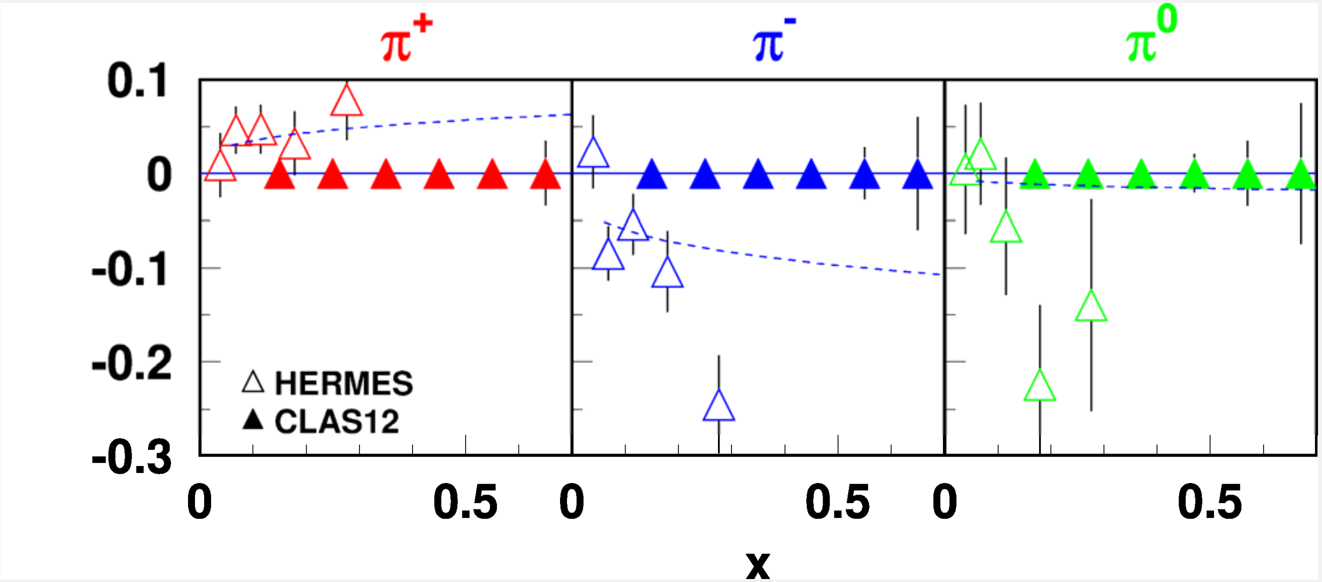
Efremov et al
(large x_B behavior of f_{1T} from GPD E)

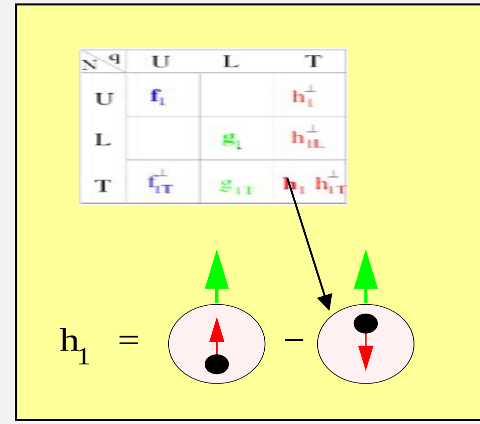


Sivers function extraction from A_{UT} (π^0) does not require information on fragmentation function. It is free of HT and diffractive contributions.

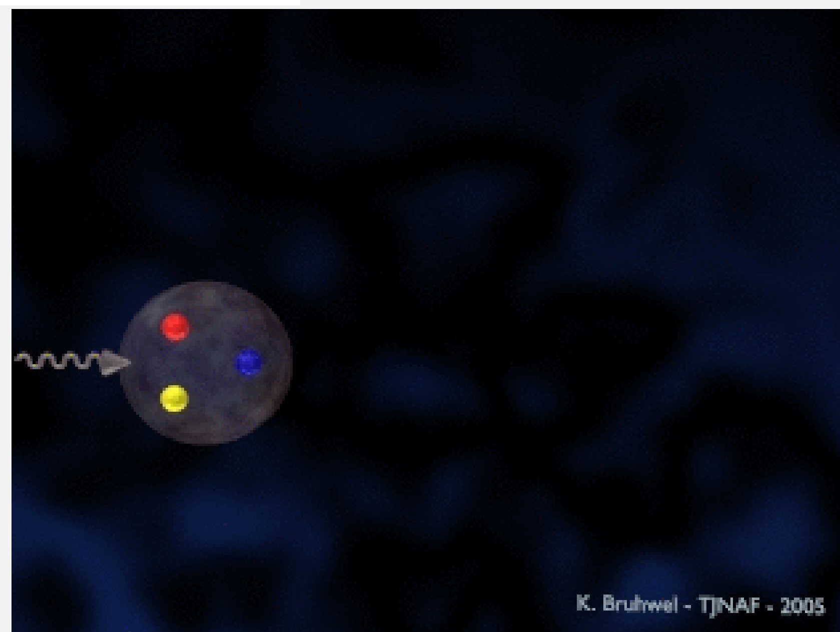
A_{UT} (π^0) on proton and neutron will allow flavor decomposition w/o info on FF.

Azimuthal Asymmetry - Collins Effect



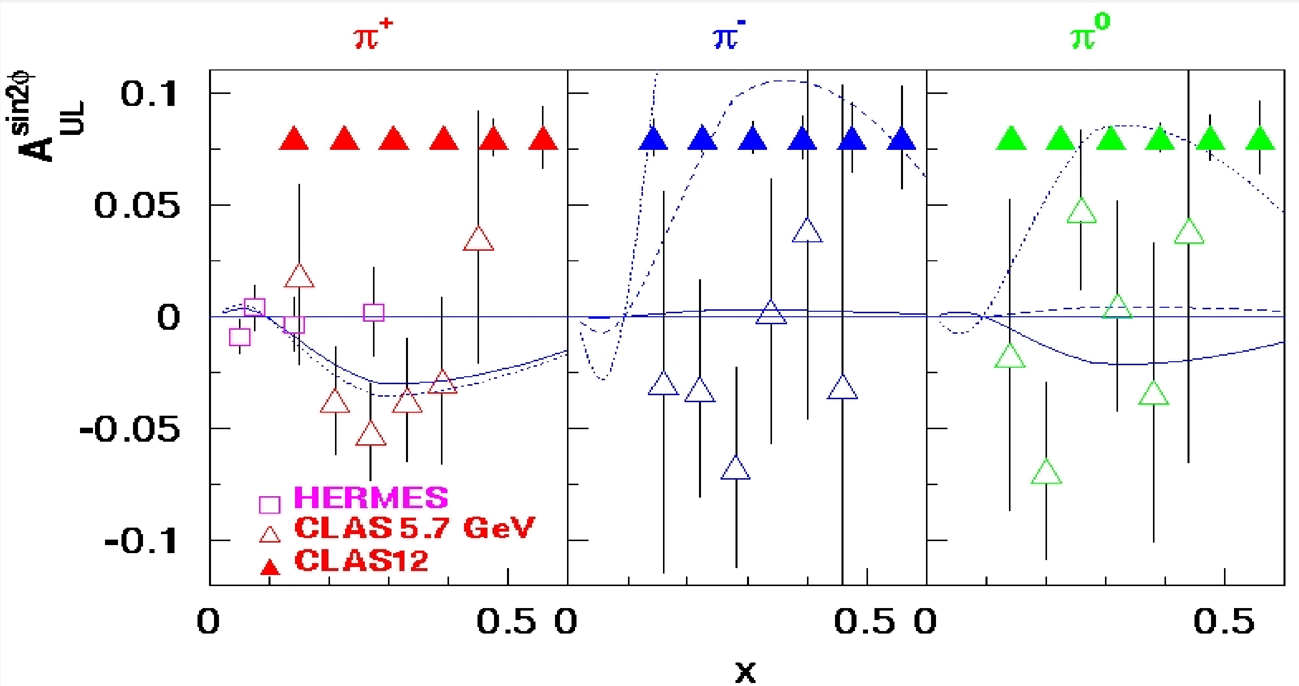


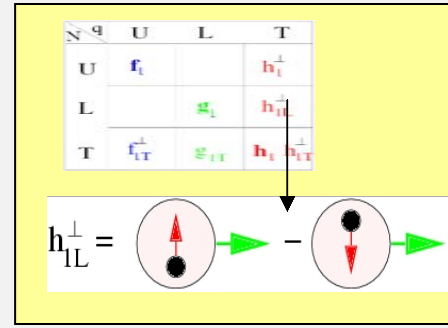
$$\sigma_{UT}^{\sin(\phi+\phi_s)} \sim k\, h_1 H_1^{\perp}$$

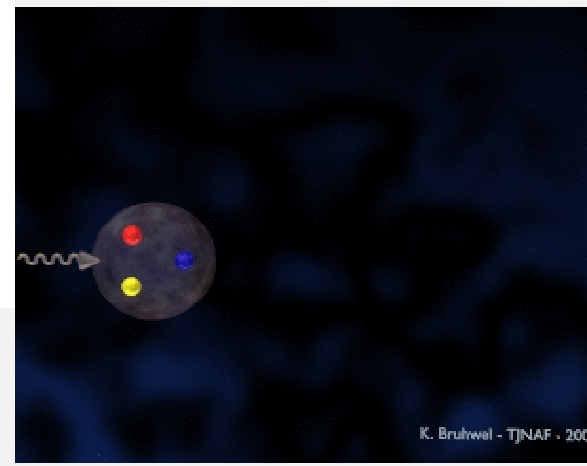


- Access to transversity distribution and fragmentation of polarized quarks.

Collins Effect and Kotzinian-Mulders Asymmetry







$$\sigma_{UL}^{KM} \sim k\, h_{1L}^{\perp} H_1^{\perp}$$

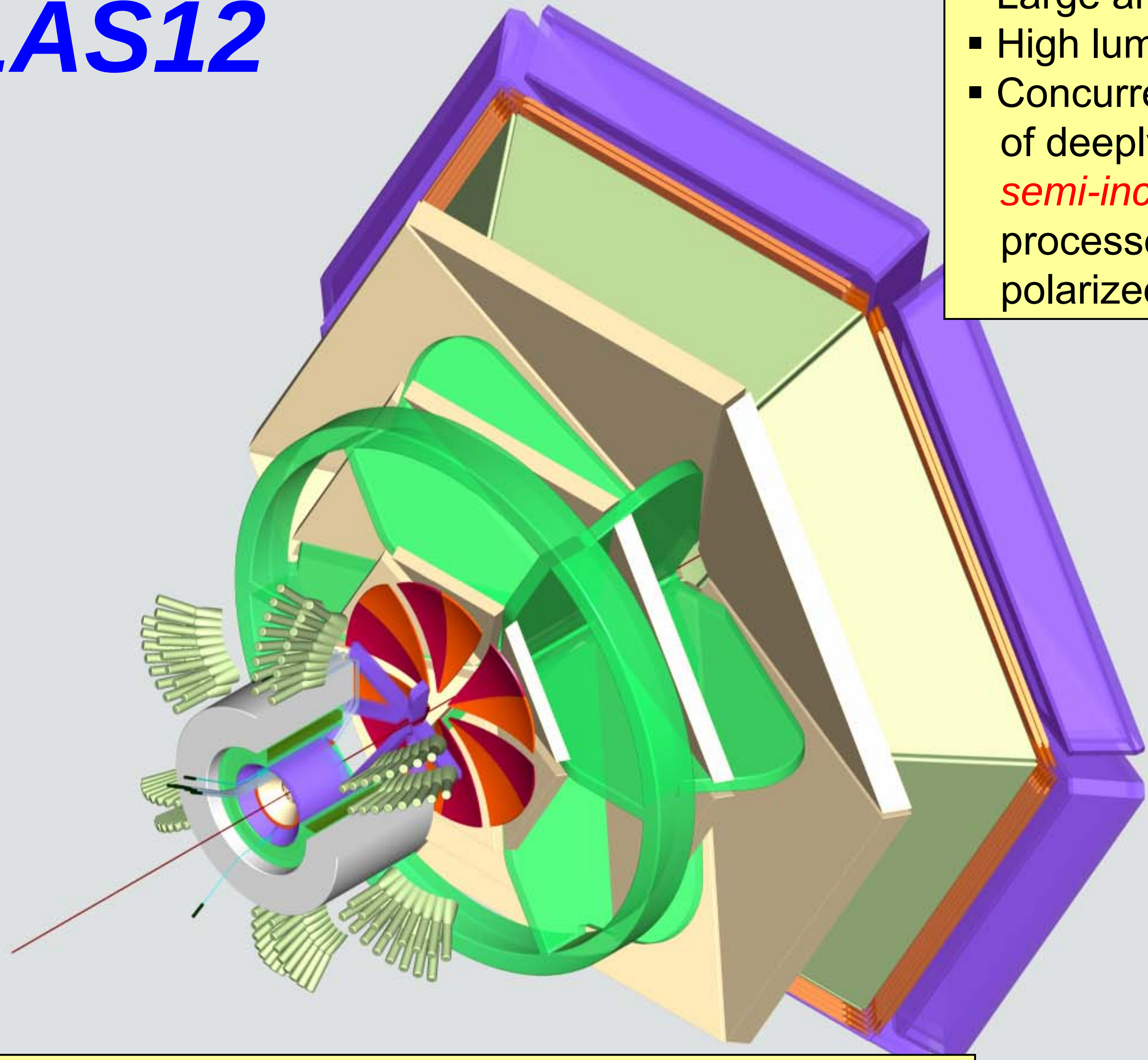
Measures the Collins fragmentation with longitudinally polarized target. Access to the real part of s-p wave interference amplitudes.

What can be achieved in the first five years?

- Precision measurements of DVCS/BH and DVMP, beam asymmetry, target asymmetries, and cross section differences in kinematics
    - Q^2 = 1.5 - 7.0 GeV^2, x_B = 0.1 - 0.6, -t = 0.1-1.5 GeV^2
- Precision measurements of beam and target asymmetries for π^+,π^-,π^0 in current fragmentation region and SIDIS kinematics
- Determine GPDs $H(\xi,\xi,t)$, $\tilde{H}(\xi,\xi,t)$, $E(\xi,\xi,t)$
- Flavor separated $E^{u/d}$, $H^{u/d}$ from ρ^0, ρ^+ production
- Probe the orbital motion of quarks in the nucleon through spin asymmetries.
    - Precision measurement of the Sivers distribution function.
    - Determine transversity in a variety of channels.
- Confront moments of GPDs with Lattice QCD calculations

CLAS12

- Large angle coverage,
- High luminosity, 10^{35} $cm^{-2}s^{-1}$
- Concurrent measurement of deeply virtual *exclusive, semi-inclusive*, and *inclusive* processes, for same target, polarized or unpolarized.



"The CLAS upgrade is essential to the physics mission of the 12 GeV Upgrade." (PAC27, January 2005)

Summary

- A program to study the nucleon Generalized Parton Distributions has been developed for the CEBAF 12 GeV upgrade covering a broad range of kinematics and reactions. This program will provide fundamentally new insights into the internal quark dynamics through the measurement of polarization observables of exclusive and semi-inclusive deep inelastic processes.
It will determine:

  - quark orbital angular momentum contributions to the proton spin,
  - quark flavor contributions to the spin sum rule,
  - quark flavor polarization in polarized nucleons,
  - recently discovered new quark distribution functions, and
  - project 3D images of the nucleon in the infinite momentum frame.

The program of Deeply Exclusive and Semi-Inclusive Experiments at the JLab 12 GeV Upgrade constitutes the next step in the breakthrough experiments to study the internal nucleon structure at a deeper level. It has the potential to revolutionize hadronic physics with electromagnetic probes.