Experimental Overview Generalized Parton Distributions (GPDs)

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Lattice Hadron Physics
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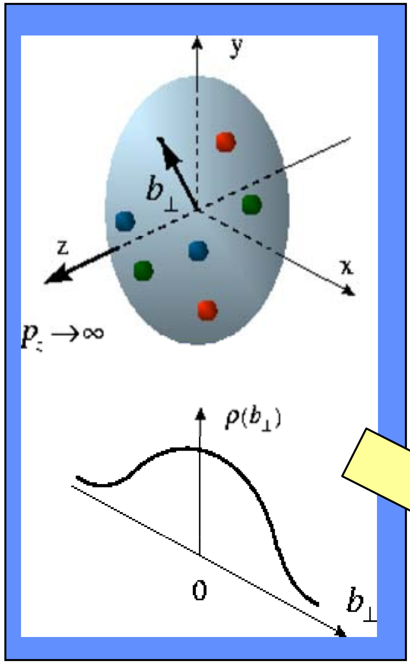
Outline

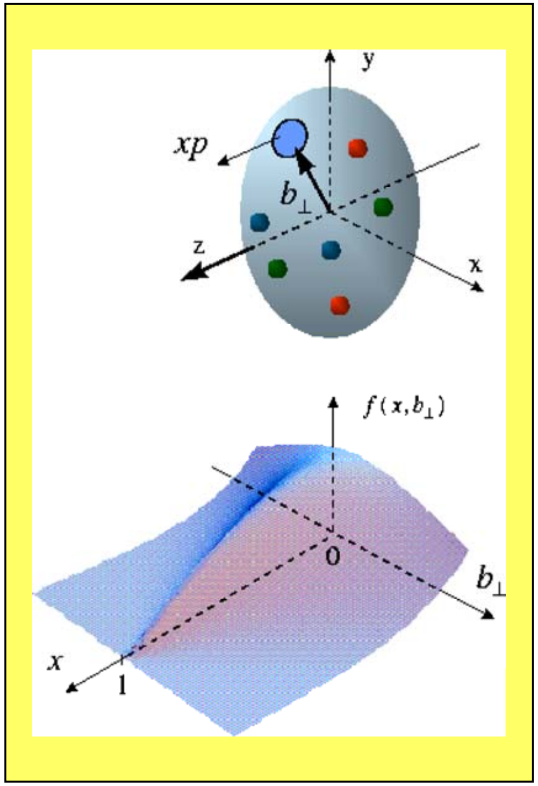
- Generalized Parton Distributions - a unifying framework of hadron structure
- Experiments to access GPDs
  - Deeply Virtual Compton Scattering
  - Deeply Virtual Meson Production
- JLab @ 12 GeV – A GPD factory
- Summary

How is the Proton Charge Density Related to its Quark Momentum distribution?

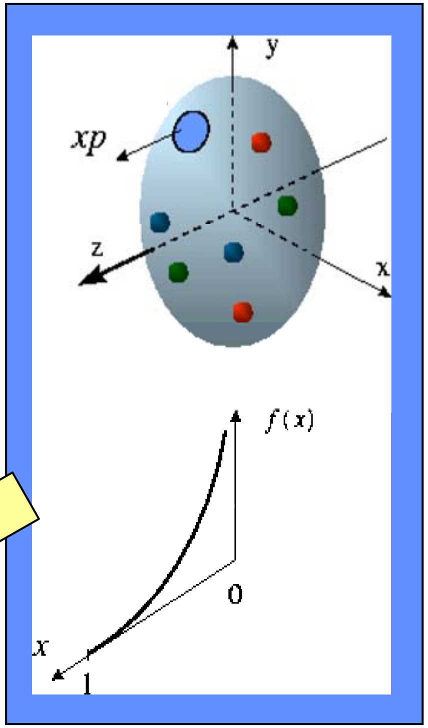
D. Mueller, X. Ji, A. Radyushkin, A. Belitsky, …
M. Burkardt, … Interpretation in impact parameter space



Proton form factors, transverse charge & current densities



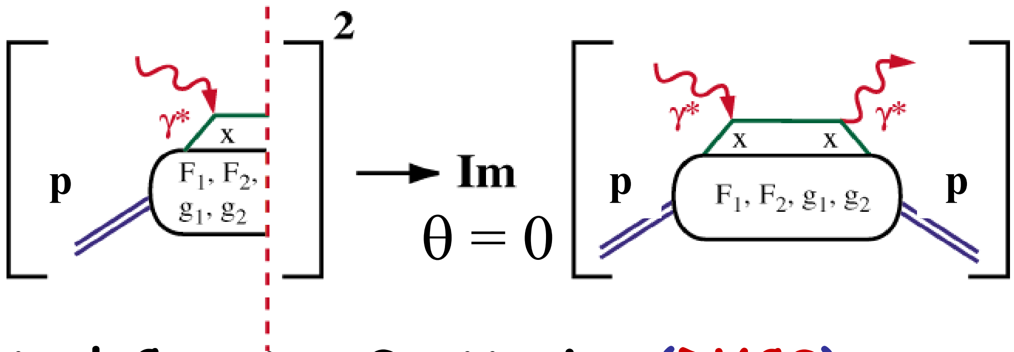
Correlated quark momentum and helicity distributions in transverse space - GPDs



Structure functions, quark longitudinal momentum & helicity distributions

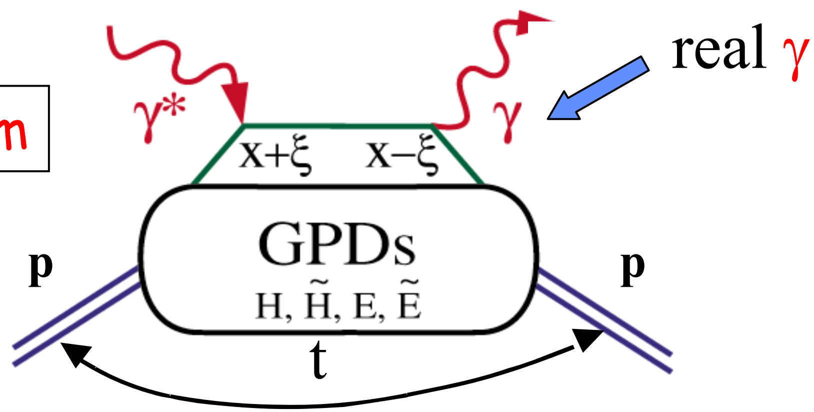
From Inclusive to Exclusive Scattering

Inclusive Scattering → Compton Scattering



Deeply Virtual Compton Scattering (DVCS)

Handbag mechanism



2ξ - longitudinal momentum transfer

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

GPDs depend on 3 variables, e.g. $H(x, \xi, t)$. They probe the quark structure at the amplitude level.

Link to DIS and Elastic Form Factors

Form factors (sum rules)

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

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

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

DIS at $\xi = t = 0$

$$H^q(x,0,0) = q(x)$$

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

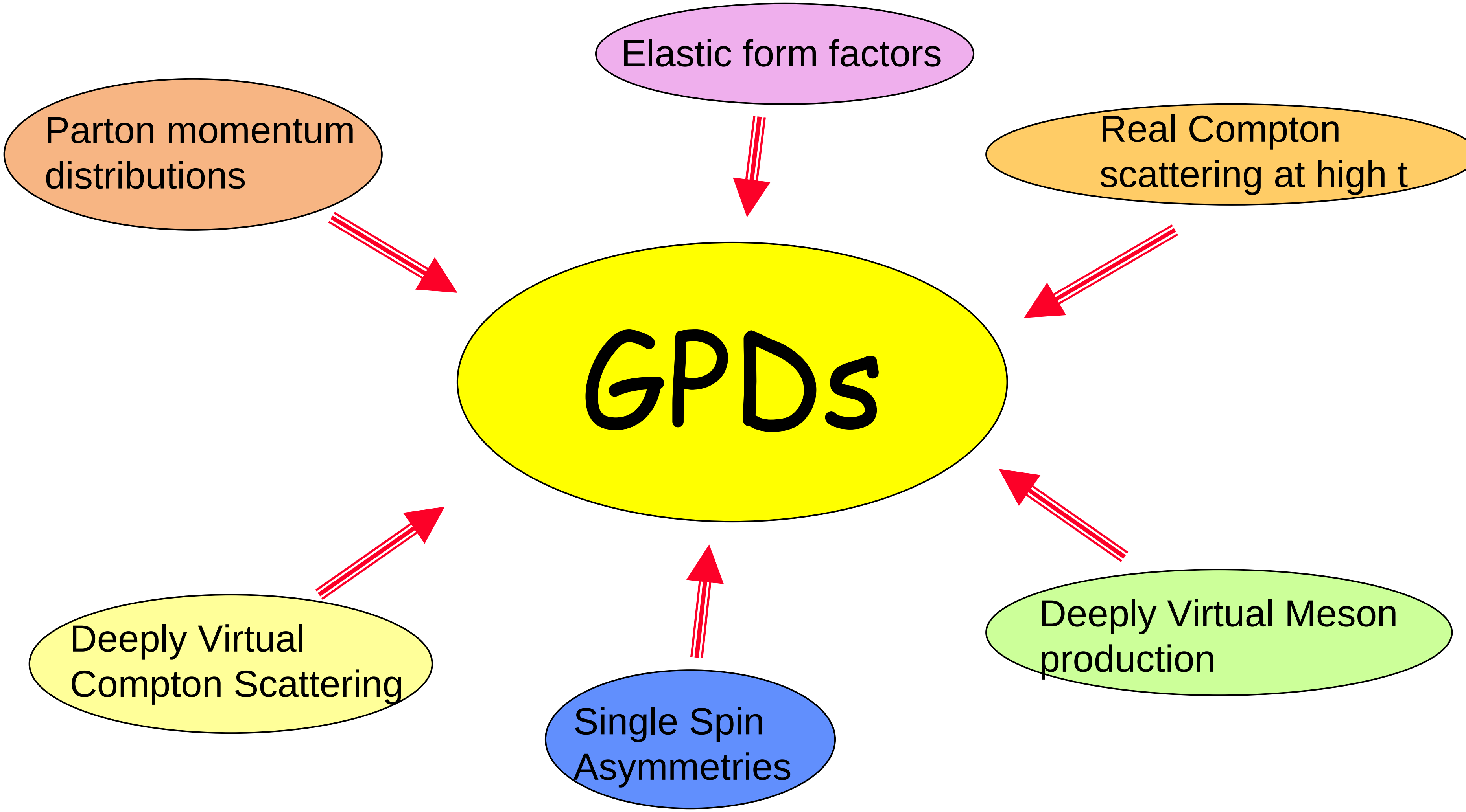
$$H^q, E^q, \tilde{H}^q, \tilde{E}^q(x,\xi,t)$$

Angular Momentum 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)

Universality of GPDs



How can we determine the GPDs?

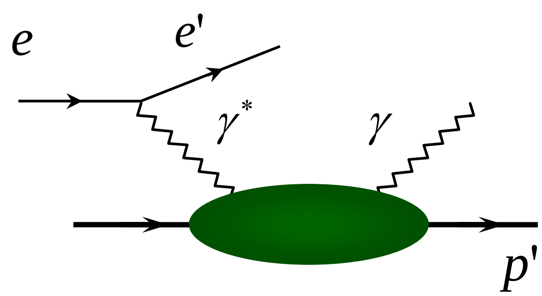
Accessing GPDs in exclusive processes

- Deeply virtual Compton scattering (clean probe, flavor blind)

$ep \to e' p' \gamma$ — *Sensitive to all GPDs.*

$ep \to e' p' L^+ L^-$ — *Insensitive to quark flavor*

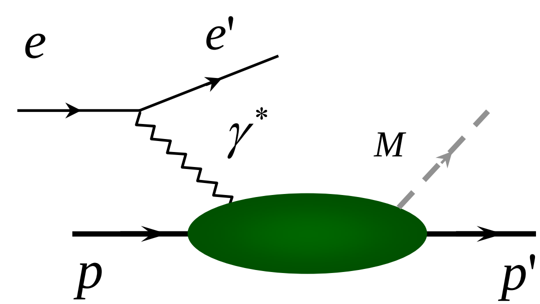
…



- Hard exclusive meson production (quark flavor filter)

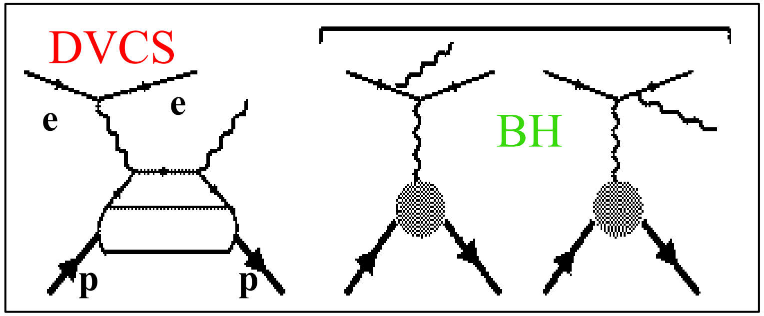
$ep \to e' p' \pi$ — *Sensitive to $\tilde{H}$, $\tilde{E}$*

$ep \to e' p' \rho$
$ep \to e' p' \omega$ } *Sensitive to H, E*



- 4 GPDs in leading order, 2 flavors (u, d) $\to$ 8 measurements

Accessing GPDs through DVCS



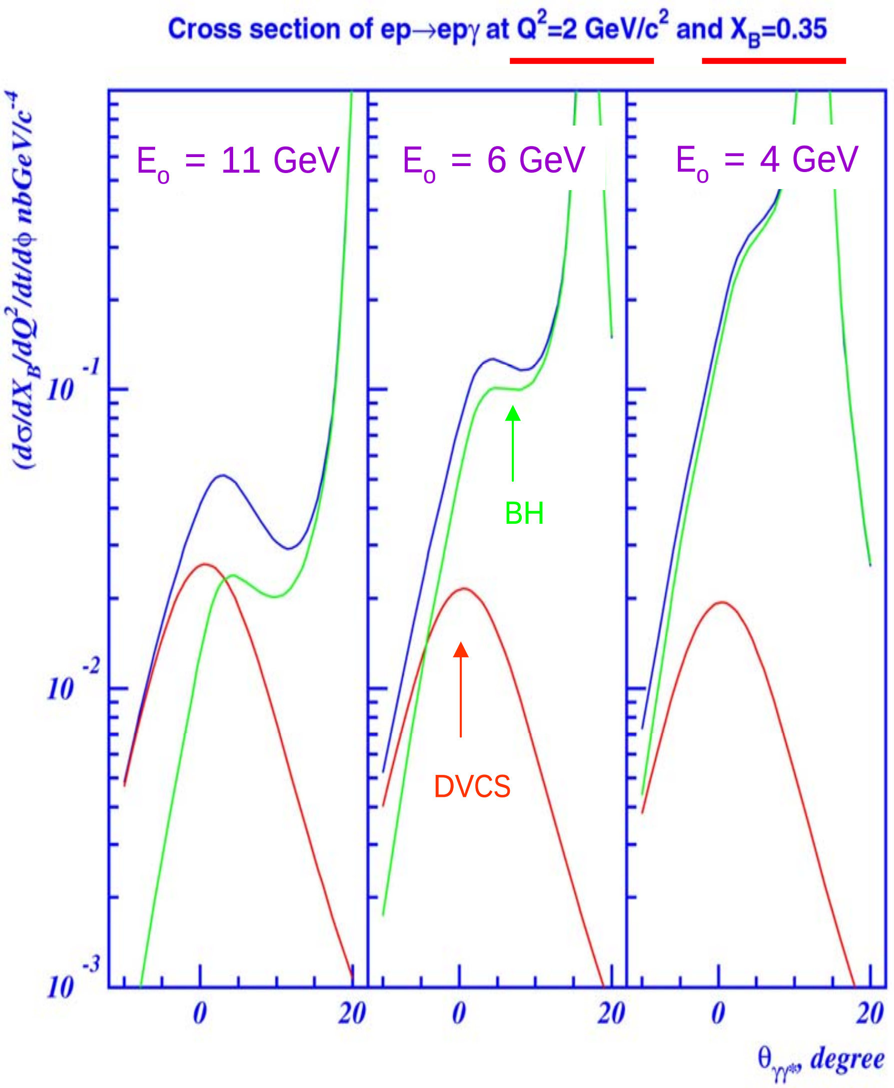
$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} \sim |T^{DVCS} + T^{BH}|^2$$

T^{BH}: given by elastic form factors F_1, F_2

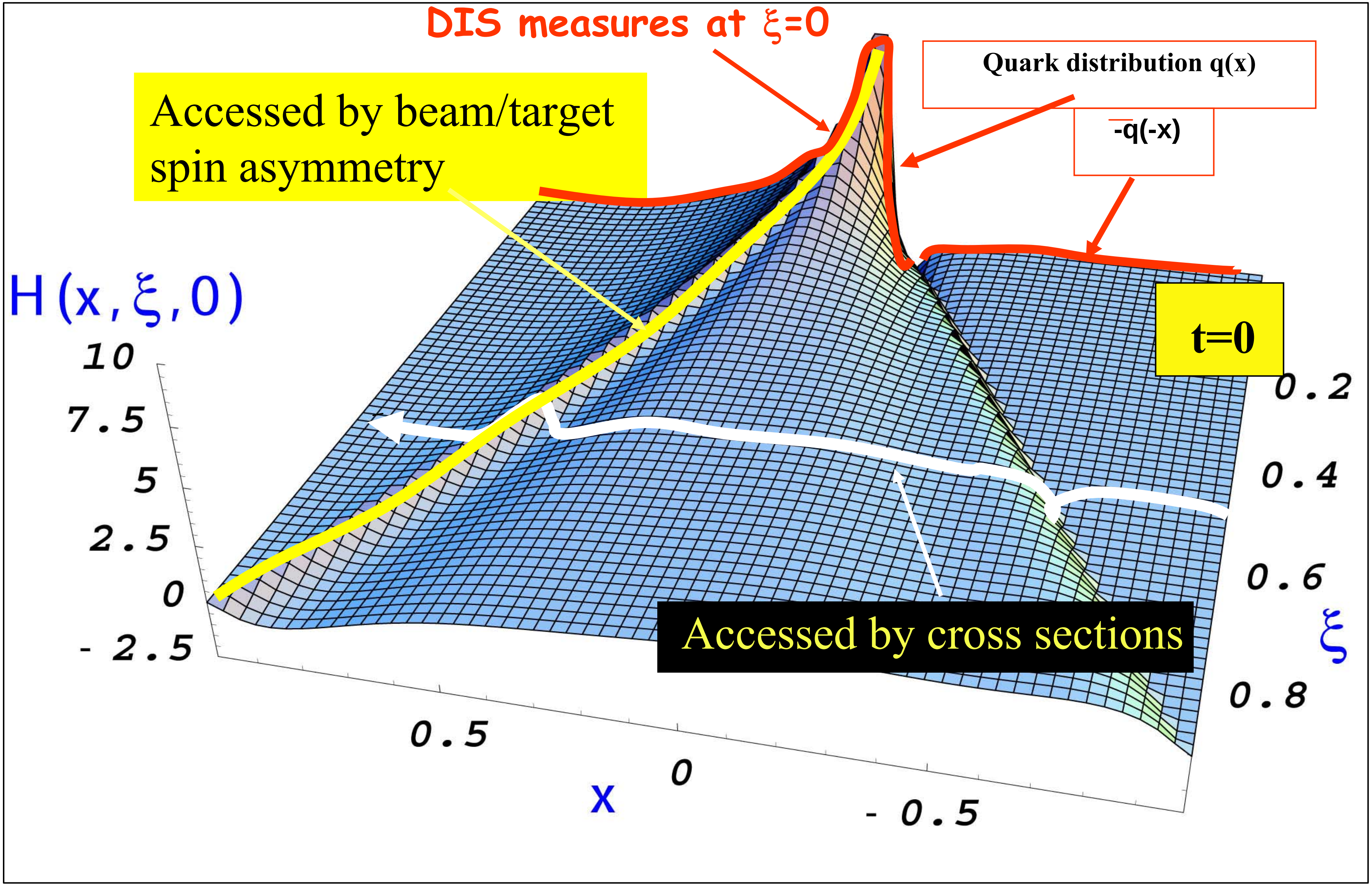
T^{DVCS}: determined by GPDs

$$I \sim (T^{BH}) \mathrm{Im}(T^{DVCS})$$

BH-DVCS interference generates *beam and target polarization asymmetries* that carry the proton structure information.



Model representation of GPD H(x,ξ,0)



Measuring GPDs through polarization

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

Polarized beam, unpolarized target:

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

Kinematically suppressed

⇒ $H(\xi,t)$

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

$k = t/4M^2$

Unpolarized beam, longitudinal target:

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

Kinematically suppressed

⇒ $\tilde{H}(\xi,t)$

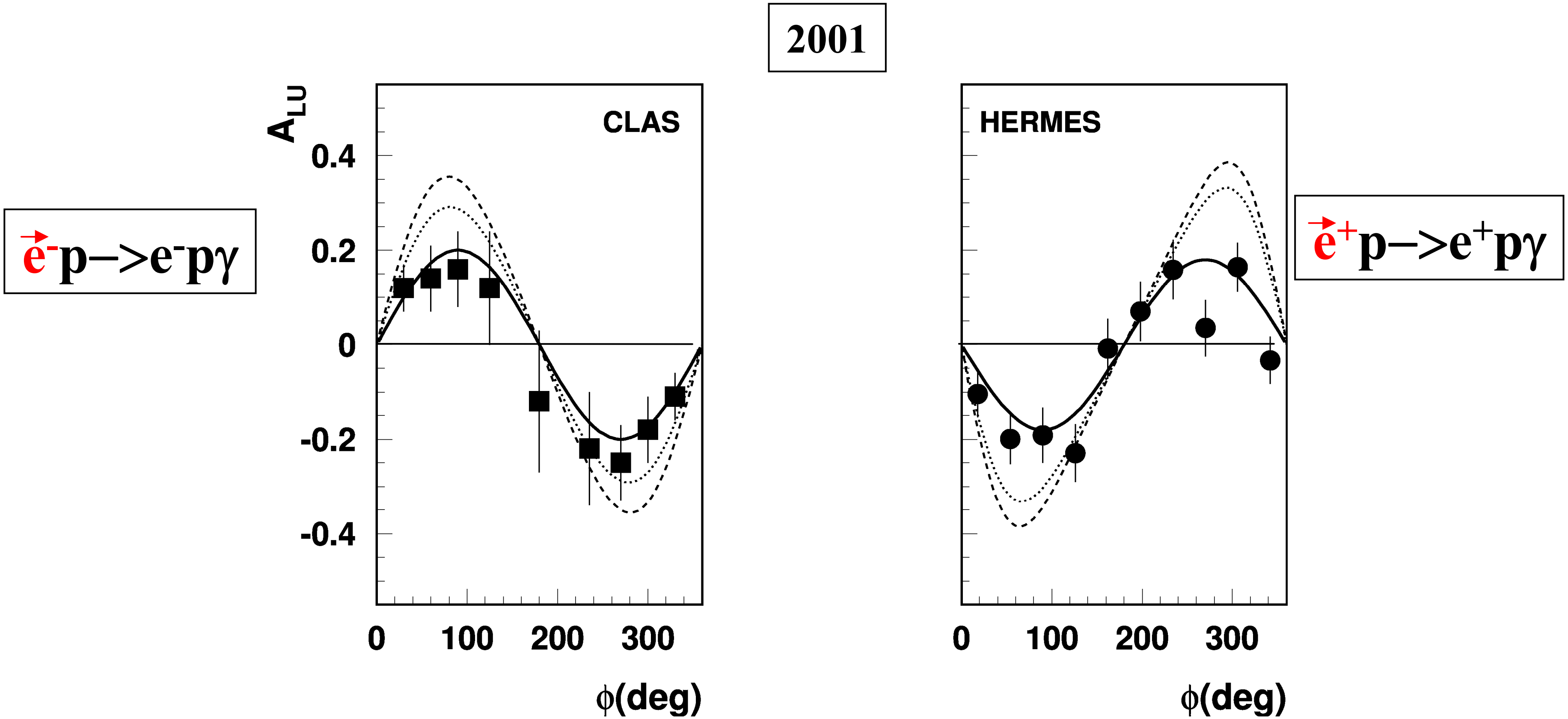
Unpolarized beam, transverse target:

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

Kinematically suppressed

⇒ $H(\xi,t)$, $E(\xi,t)$

Pioneering experiments observe interference



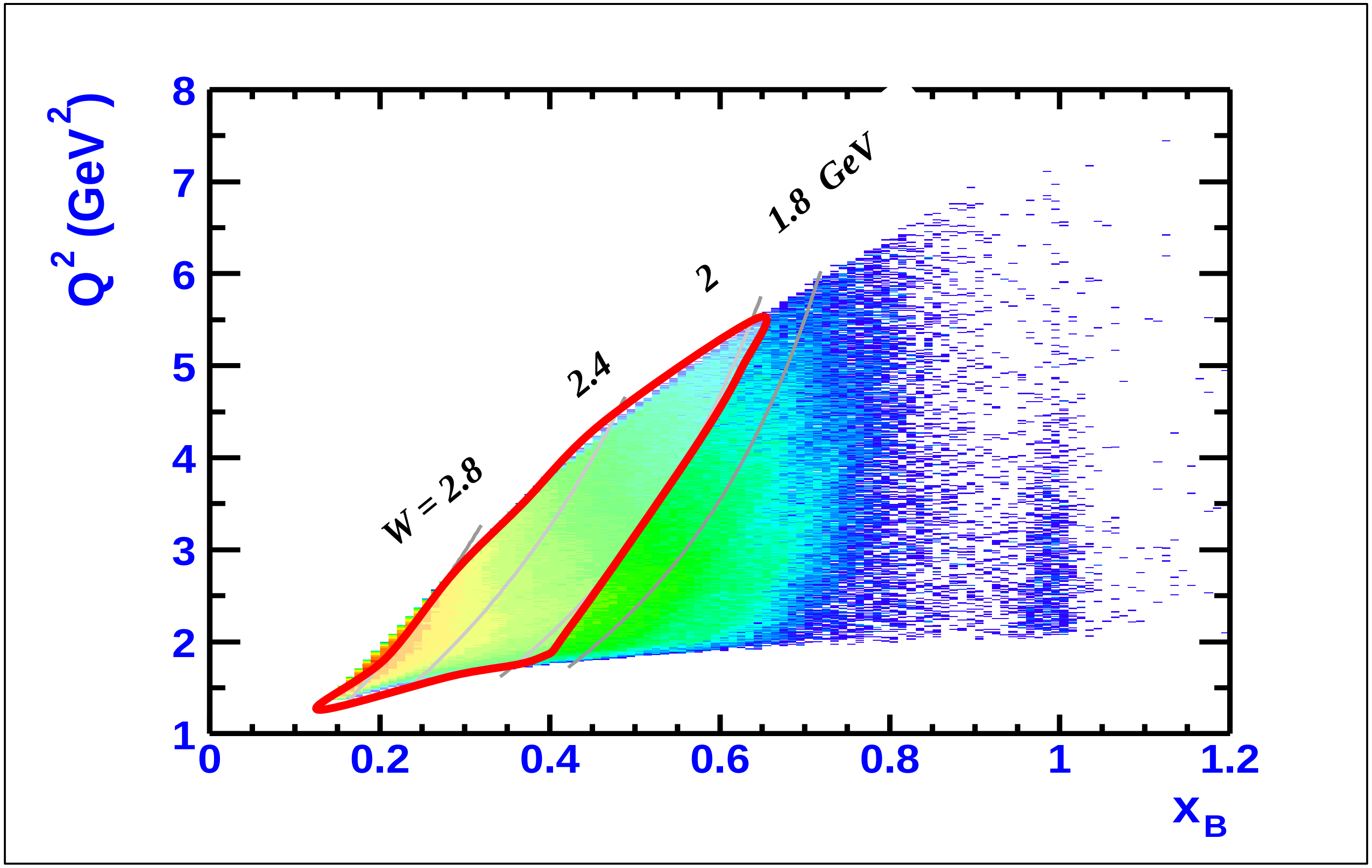
$$A_{UL} = \alpha \sin\phi + \beta \sin 2\phi$$

twist-2 twist-3

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

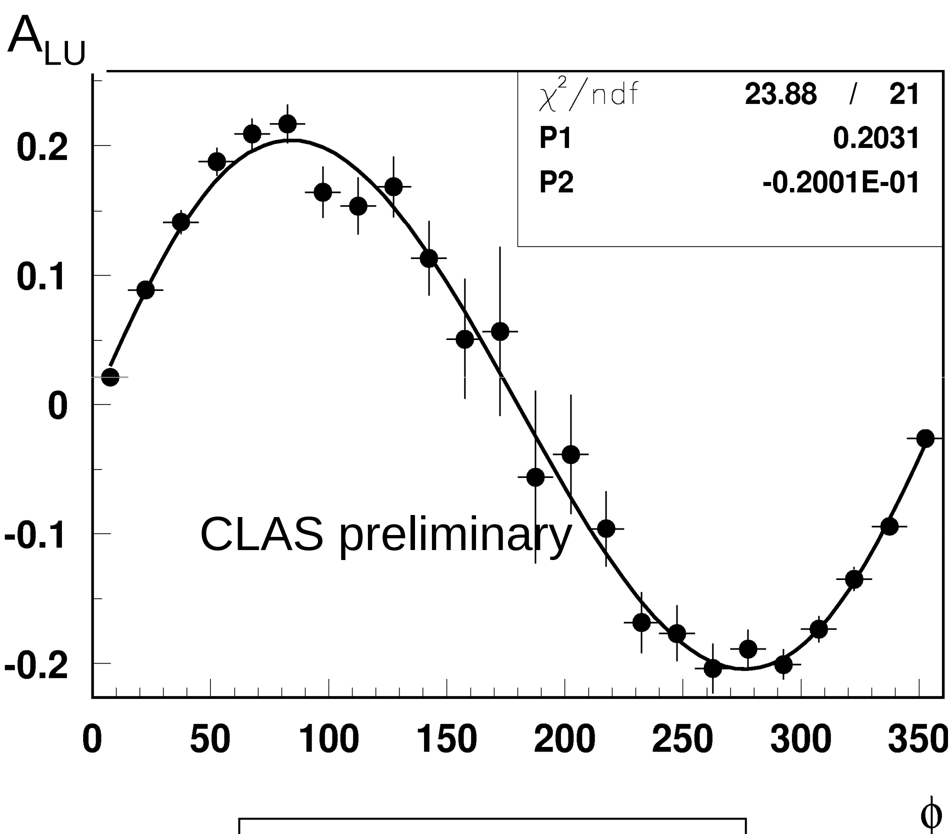
First JLab experiment with GPDs in mind.

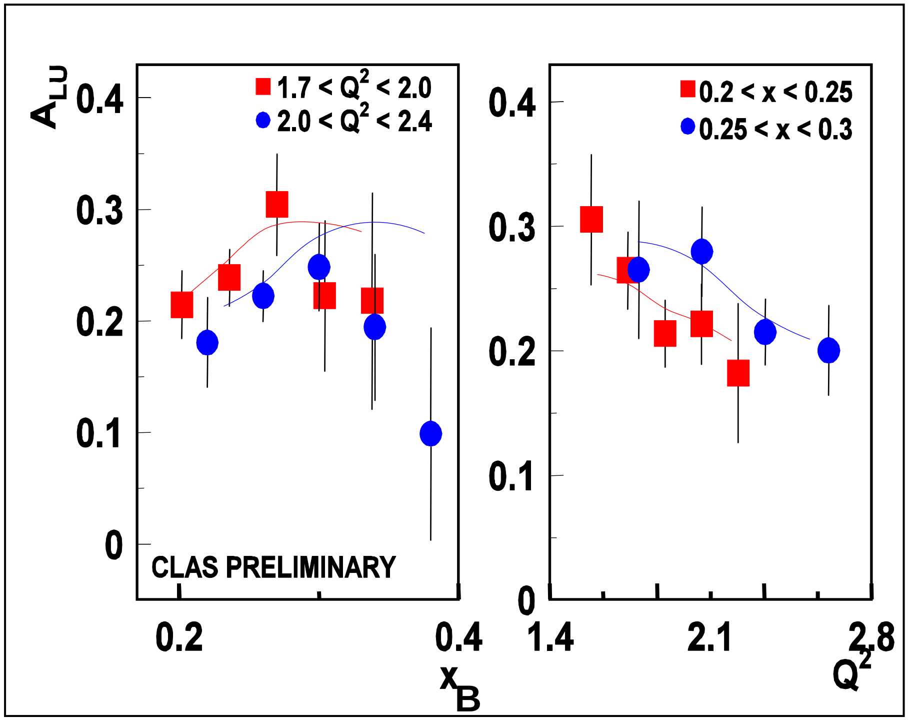
- Polarized electrons, E = 5.75 GeV
- Q^2 up to 5.5 GeV^2
- x_B from 0.2 to 0.6
- Hadronic invariant mass W < 2.8 GeV



A first view at kinematical dependencies

$$\Delta\sigma_{LU} \sim \sin\phi \, \mathrm{Im}\{F_1 H + \xi(F_1+F_2)\tilde{H} - t/4m^2 F_2 E\} d\phi$$





$$A_{UL} = \alpha \sin\phi + \beta \sin 2\phi$$
$$\beta/\alpha \sim 0.1$$

Model with GPD parametization and quark k_T corrections describes data.

Target Spin Asymmetry (LTSA): t- Dependence from CLAS

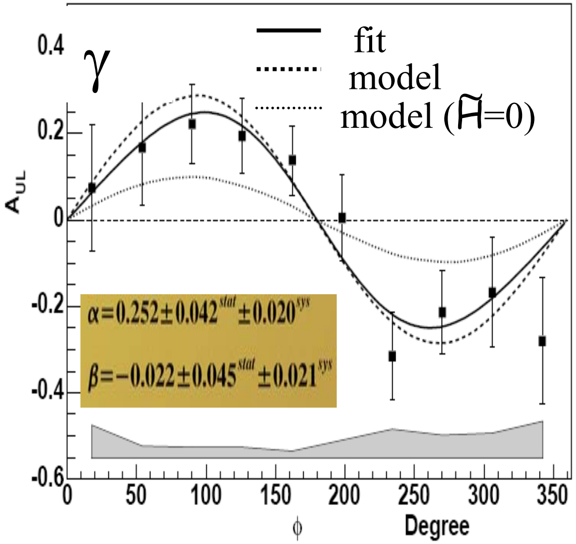
Unpolarized beam, longitudinal target:

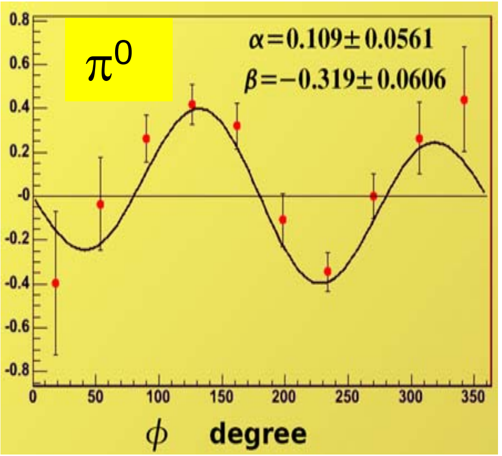
$$\Delta\sigma_{UL} \sim \sin\phi \, \mathrm{Im}\{F_1\tilde{H} + \xi(F_1+F_2)(H + .. \}$$

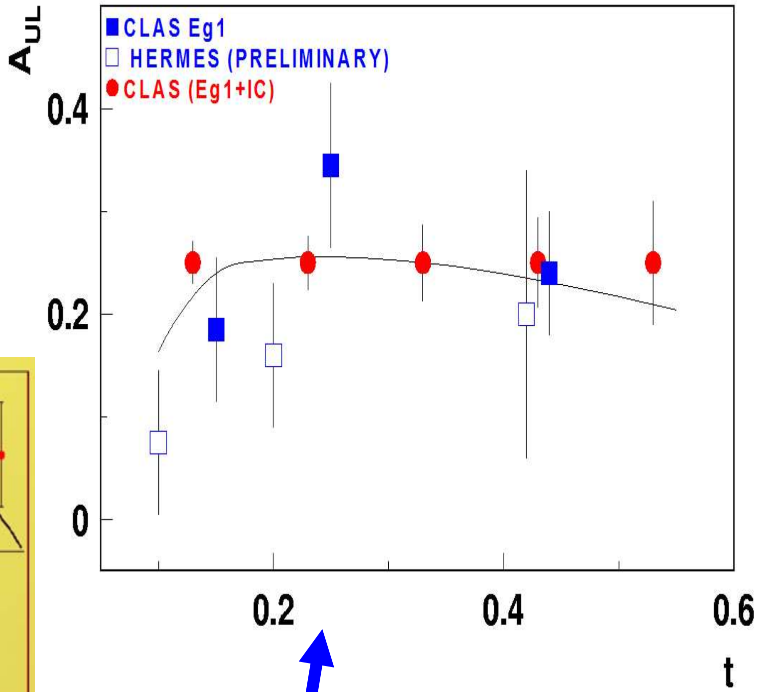
$$\Delta\sigma_{LL} \sim \cos\phi \, \mathrm{Re}\{F_1\tilde{H} + \xi(F_1+F_2)(H + .. \}$$

Kinematically suppressed

$\alpha \sin\phi + \beta \sin 2\phi$







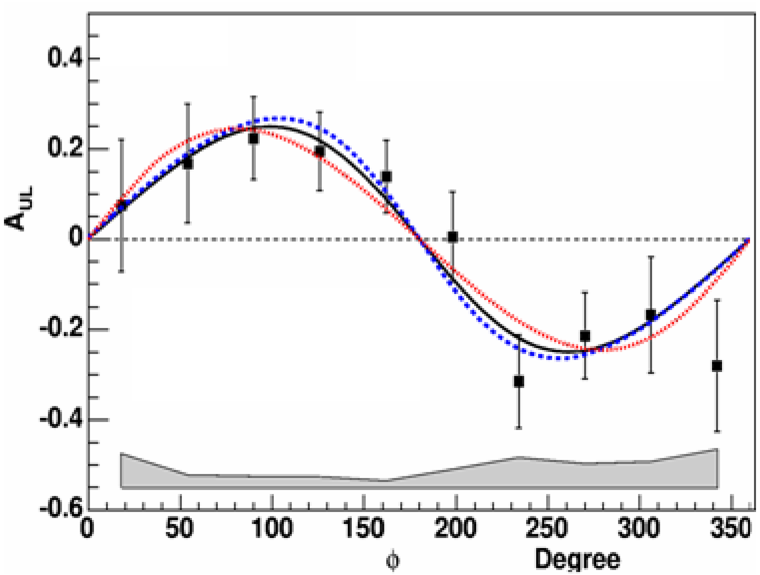
First data available(5 CLAS days), more(60 days) to come at 6 GeV

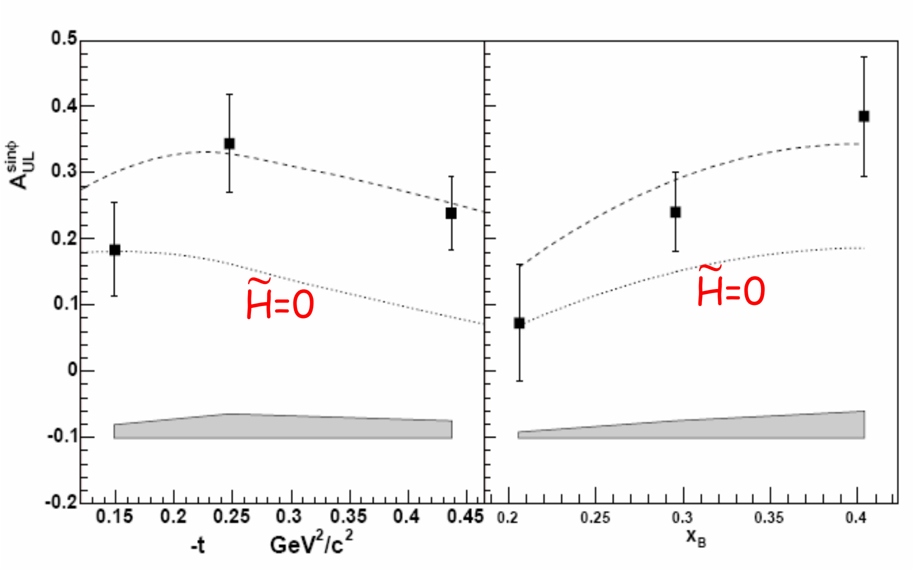
Measurements with polarized target will constrain the polarized GPDs and combined with beam SSA measurements would allow precision measurement of unpolarized GPDs.

First DVCS measurement with spin-aligned target

Unpolarized beam, longitudinally spin-aligned target:

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





α = 0.252 ± 0.042
β = -0.022 ± 0.045

Planned experiment in 2008 will improve accuracy dramatically.

Dedicated DVCS experiment at JLab Hall-A, 2004 - 2005

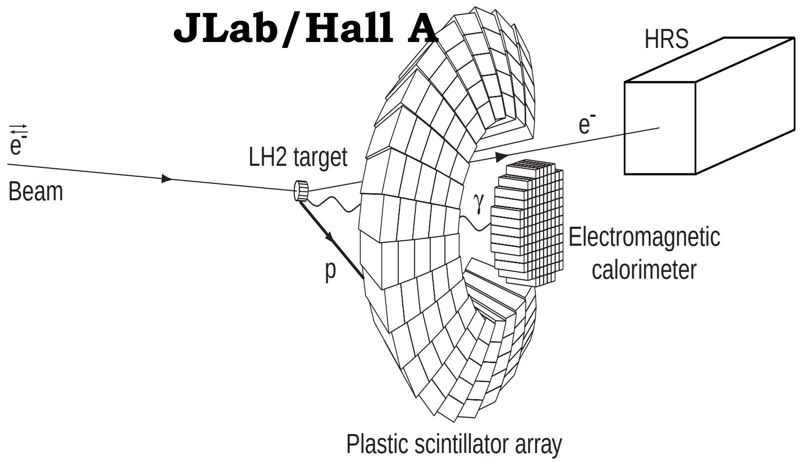
Dedicated, high statistics, DVCS experiments

→ Detection of 3 particles e, p and γ in final state(cross section difference ~5%)

→ Establish scaling laws ($Q^2 \sim 1$- 3 GeV^2),

→ Measure x-section difference and sum.

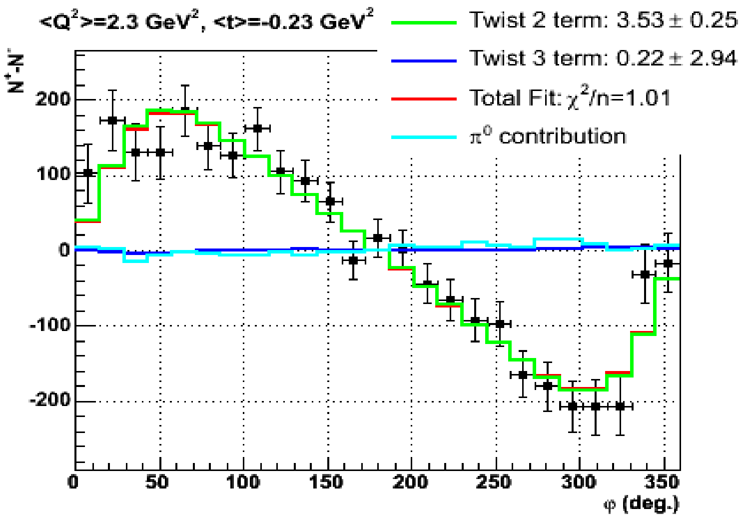
JLab/Hall A

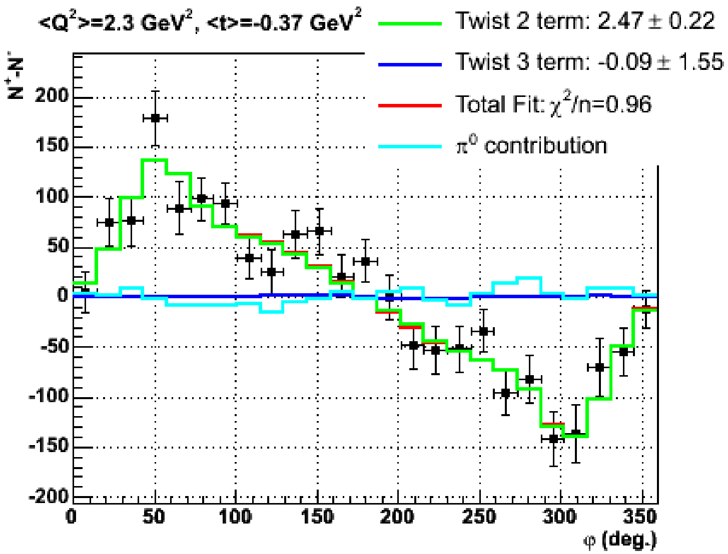


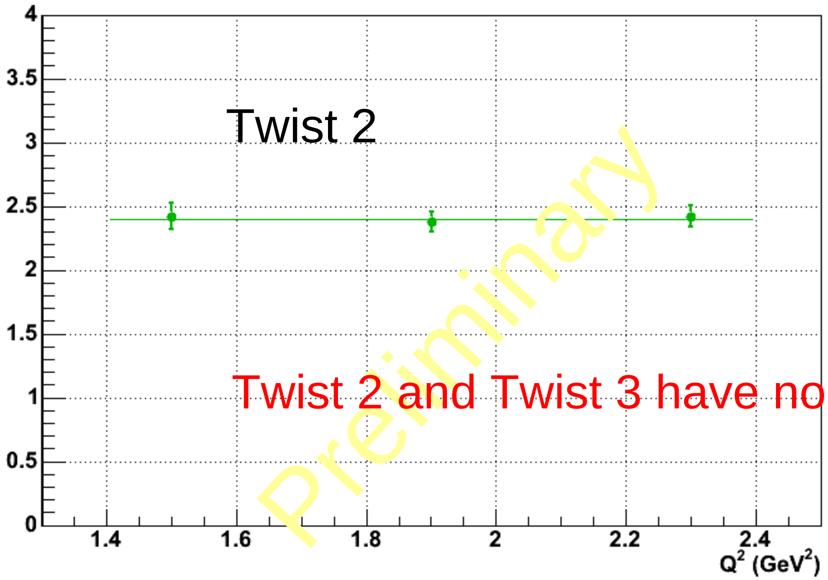
HRS + PbF_2 + Plastic scintillator

H(e,e'γp)

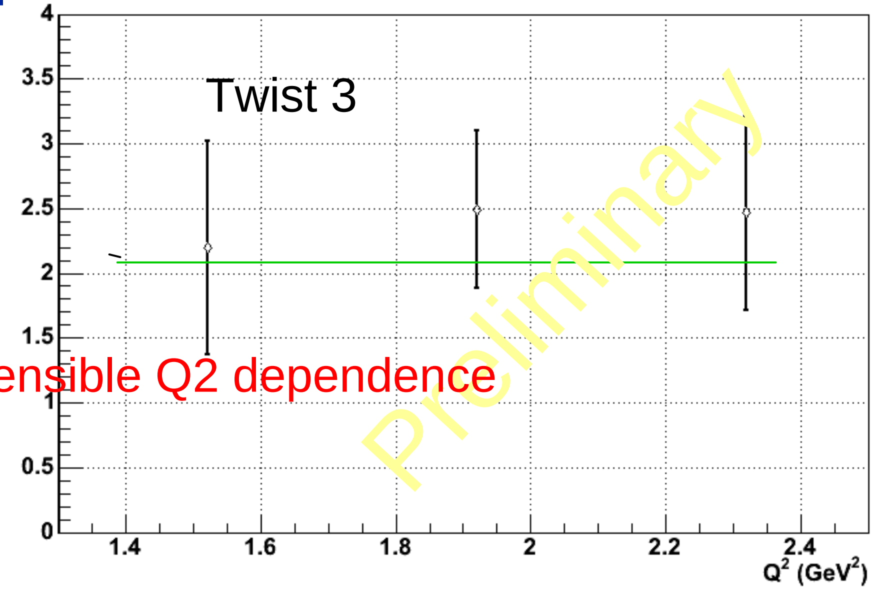
D(e,e'γN)N

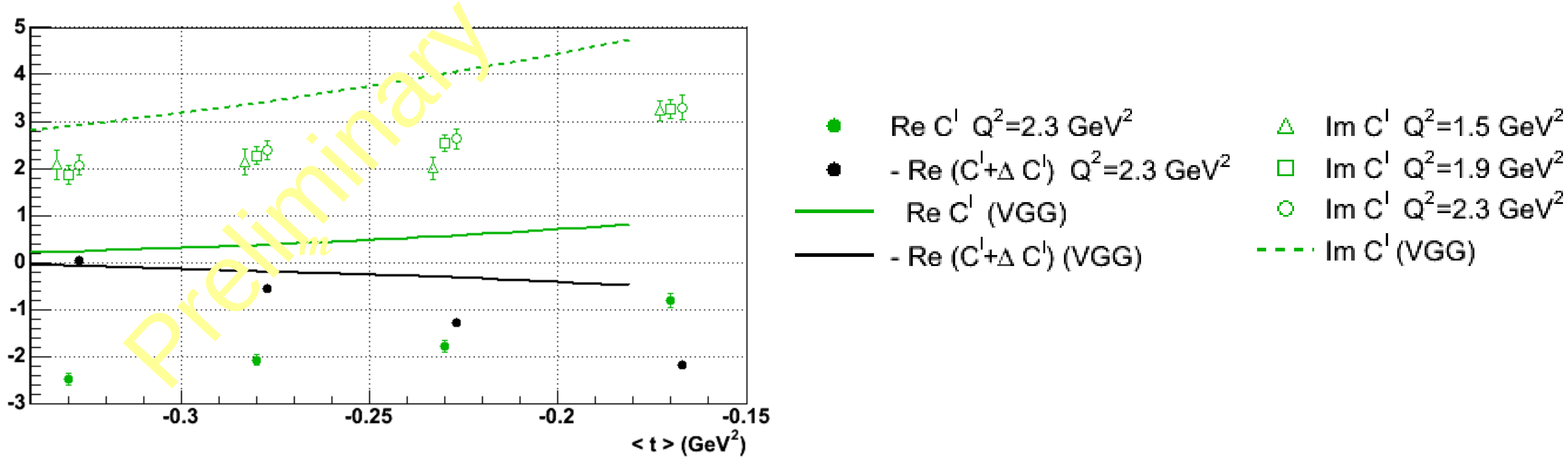




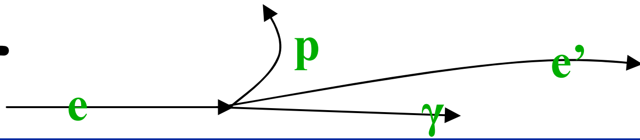


Twist 2 and Twist 3 have no sensible Q2 dependence





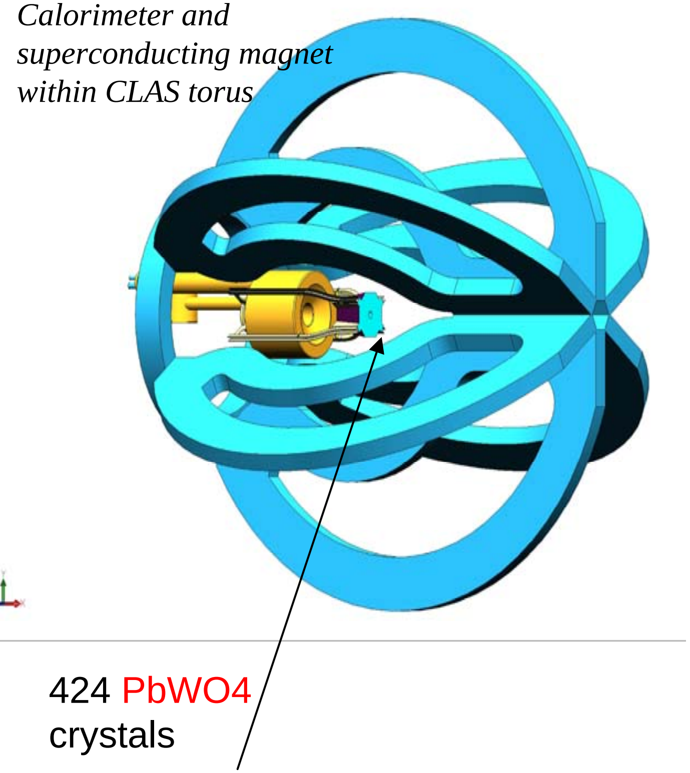
Dedicated CLAS DVCS experiment



→ Detection of 3 particles e, p and γ in final state
→ Large kinematical coverage in x_B and t

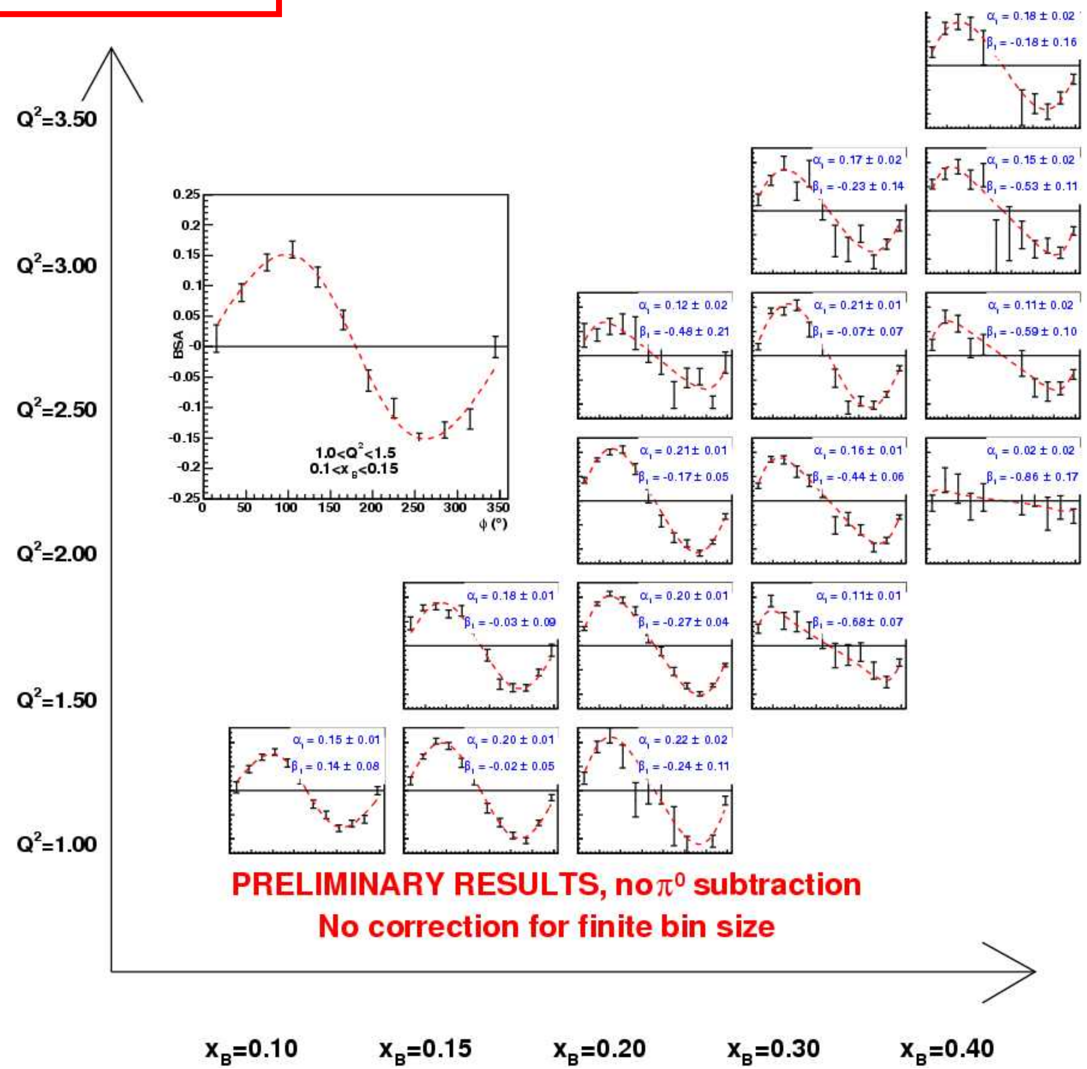
40% of data taken in 2005

Calorimeter and superconducting magnet within CLAS torus



424 PbWO4 crystals

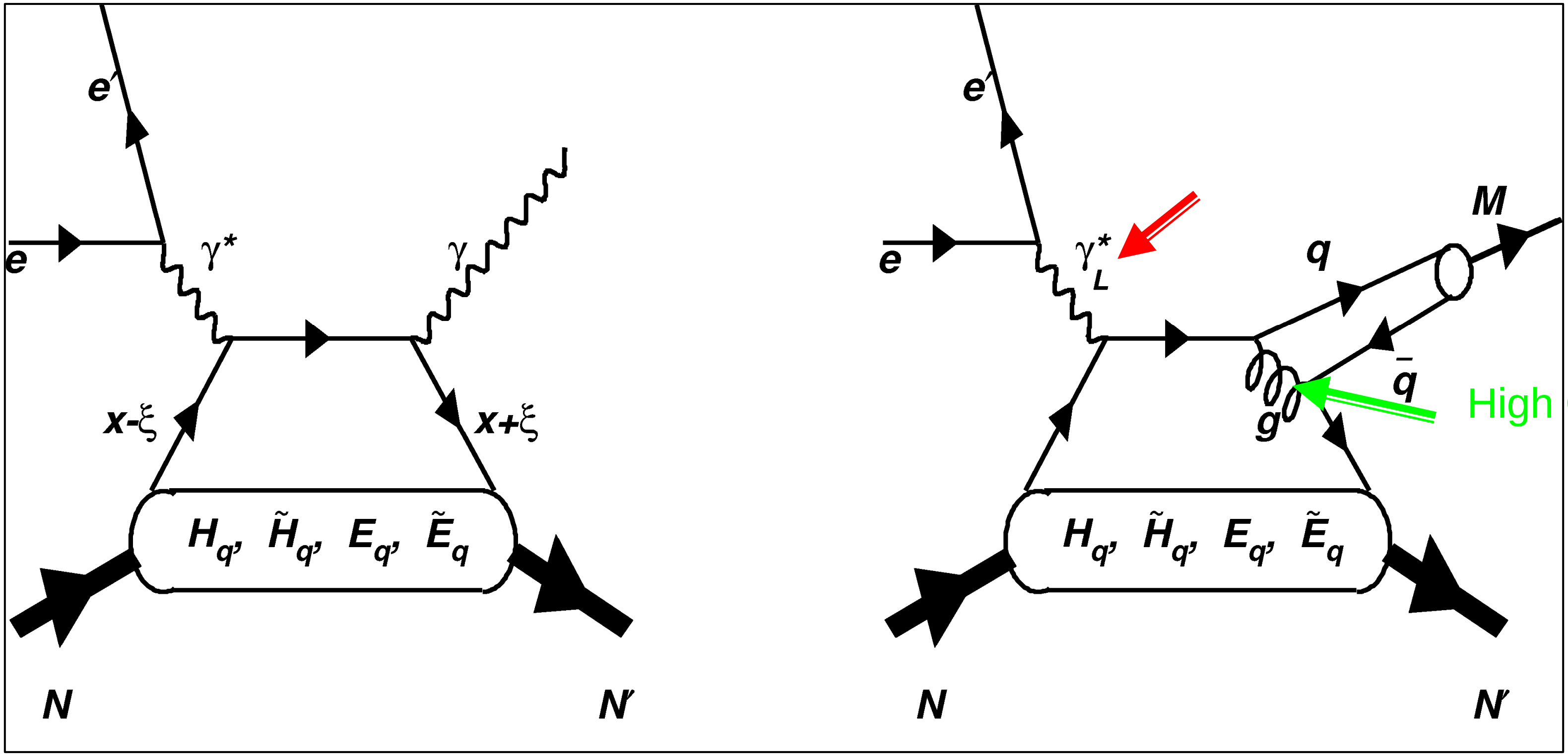
dedicated calorimeter (IC) detect photons from 5º



GPDs – Flavor separation

DVCS

DVMP
longitudinal photons only

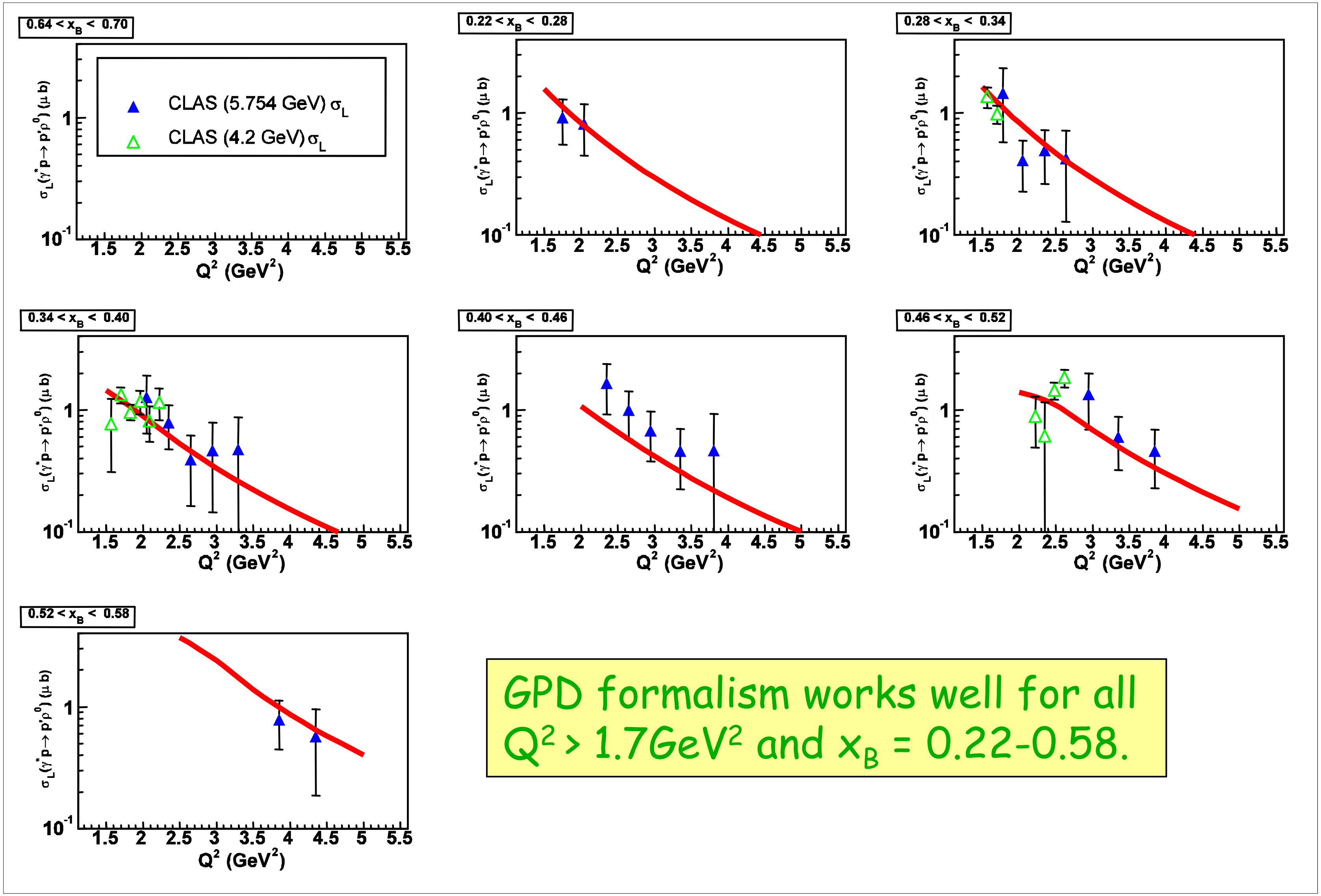


Photons cannot separate u/d quark contributions.

M = ρ^0/ρ^+, ω select H, E, for u/d quarks

M = π, η, K select $\tilde{H}$, $\tilde{E}$

Cross section σ_L ($\gamma^*_L p \rightarrow p \rho_L^0$)



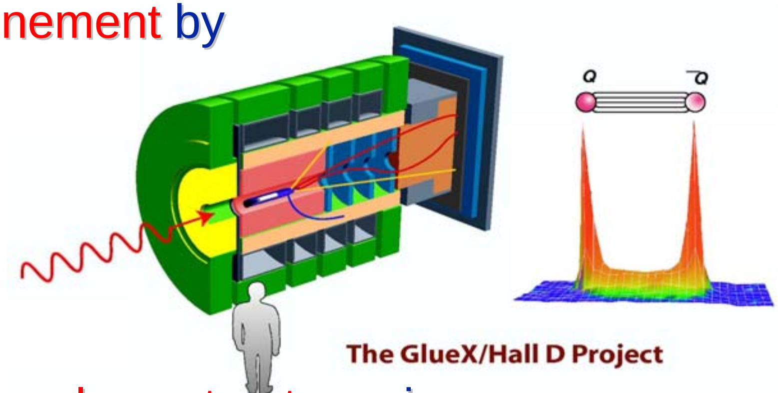
GPD formalism works well for all $Q^2 > 1.7 GeV^2$ and x_B = 0.22-0.58.

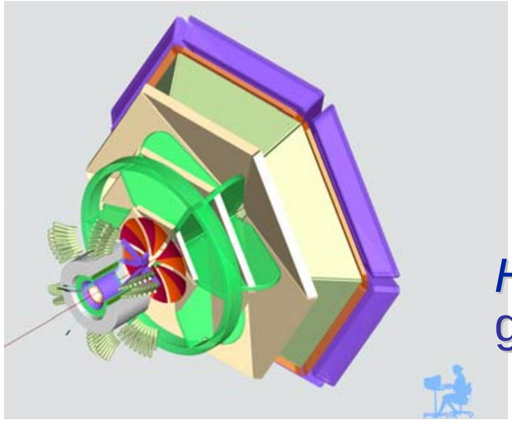
In the past few years, we have made a start in the quest to unravel the Structure of the Proton.

What does the future hold?

Overview of 12 GeV Physics Program

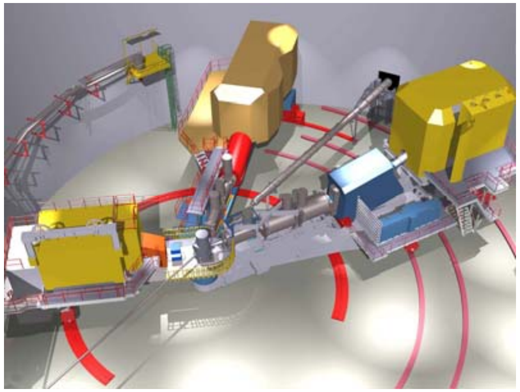
Hall D – exploring origin of confinement by studying exotic mesons

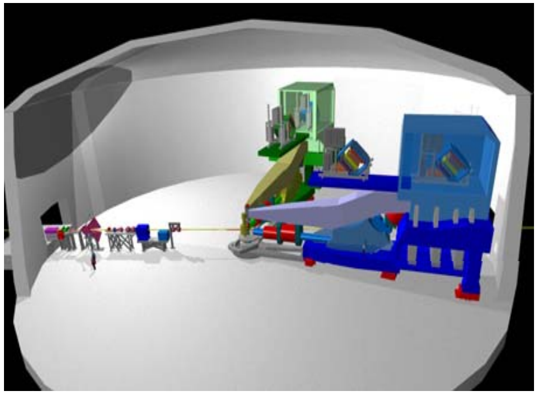




Hall B – understanding nucleon structure via generalized parton distributions

Hall C – precision determination of valence quark properties in nucleons and nuclei



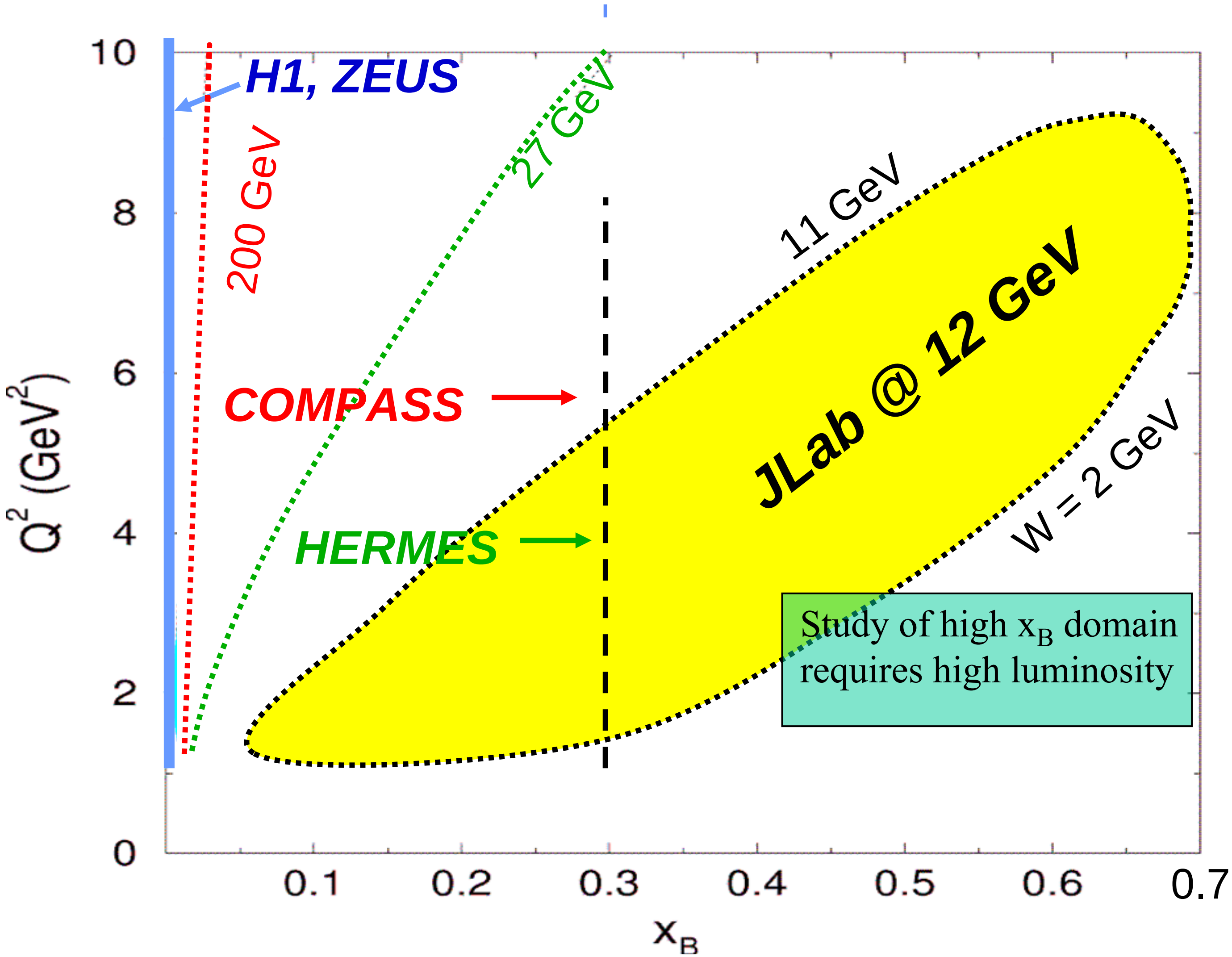


Hall A – short range correlations, form factors, hyper-nuclear physics, future new experiments

Initial Physics Program in Hall B at 12 GeV

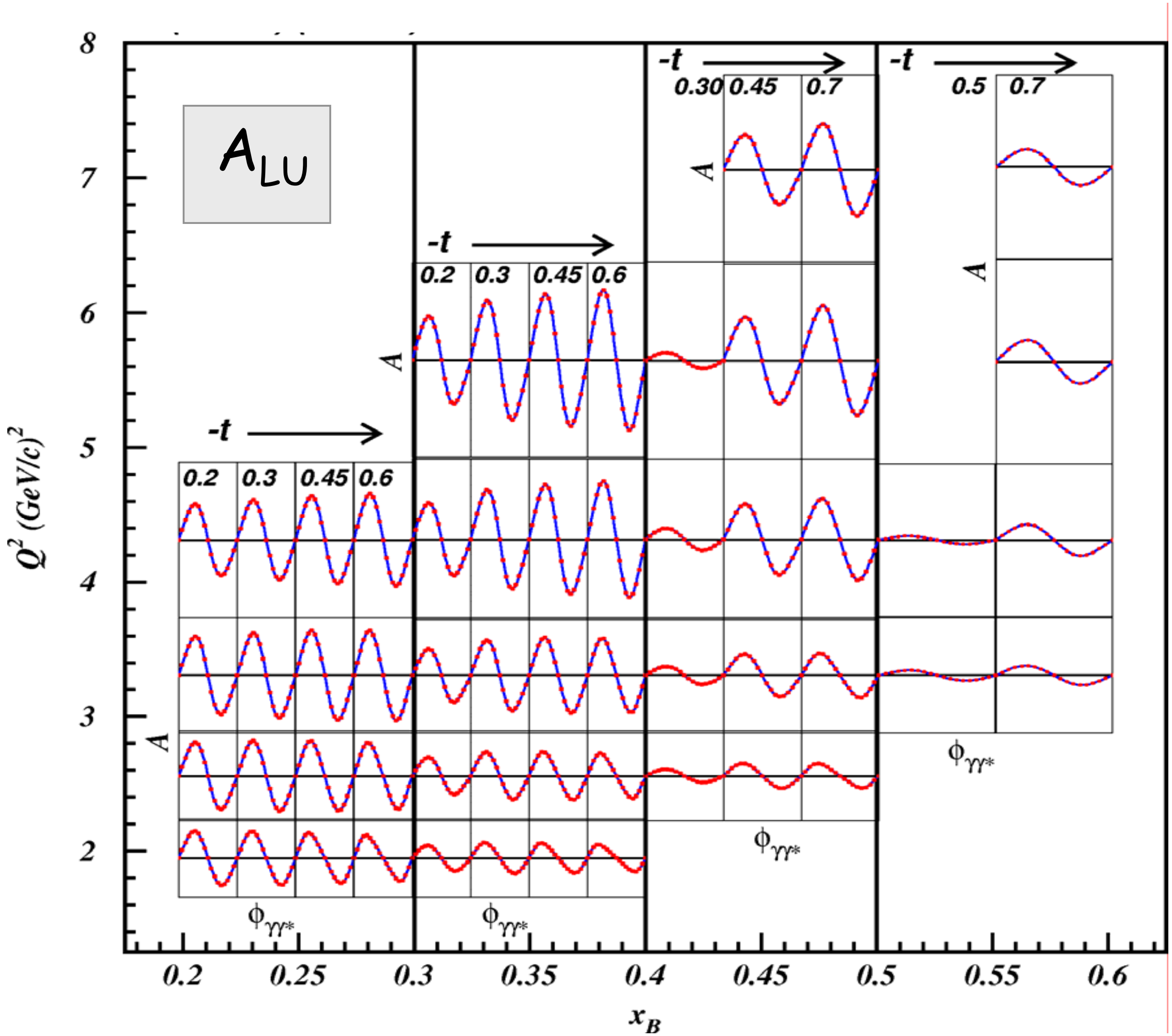
- **GPD's** and **3D-Imaging of the Nucleon**
- **Valence Quark Distributions**
- **Form Factors and Resonance Excitations**
- **Hadrons in the Nuclear Medium**
- **Hadron Spectroscopy with quasi-real Photons**

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



DVCS/BH- Beam Asymmetry

$E_e = 11$ GeV



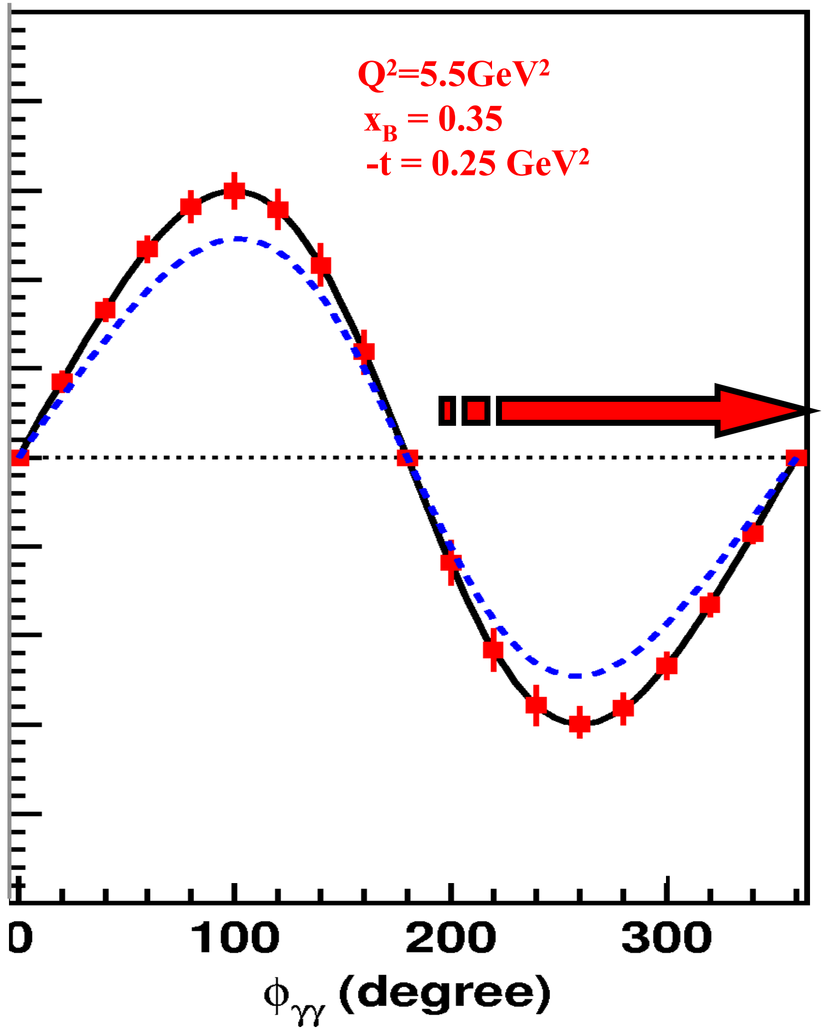
With large acceptance, measure large Q^2, x_B, t ranges simultaneously.

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

CLAS12 - DVCS/BH- Beam Asymmetry

$E_e = 11$ GeV

Luminosity = 720fb^{-1}



CLAS12 - DVCS/BH Beam Asymmetry

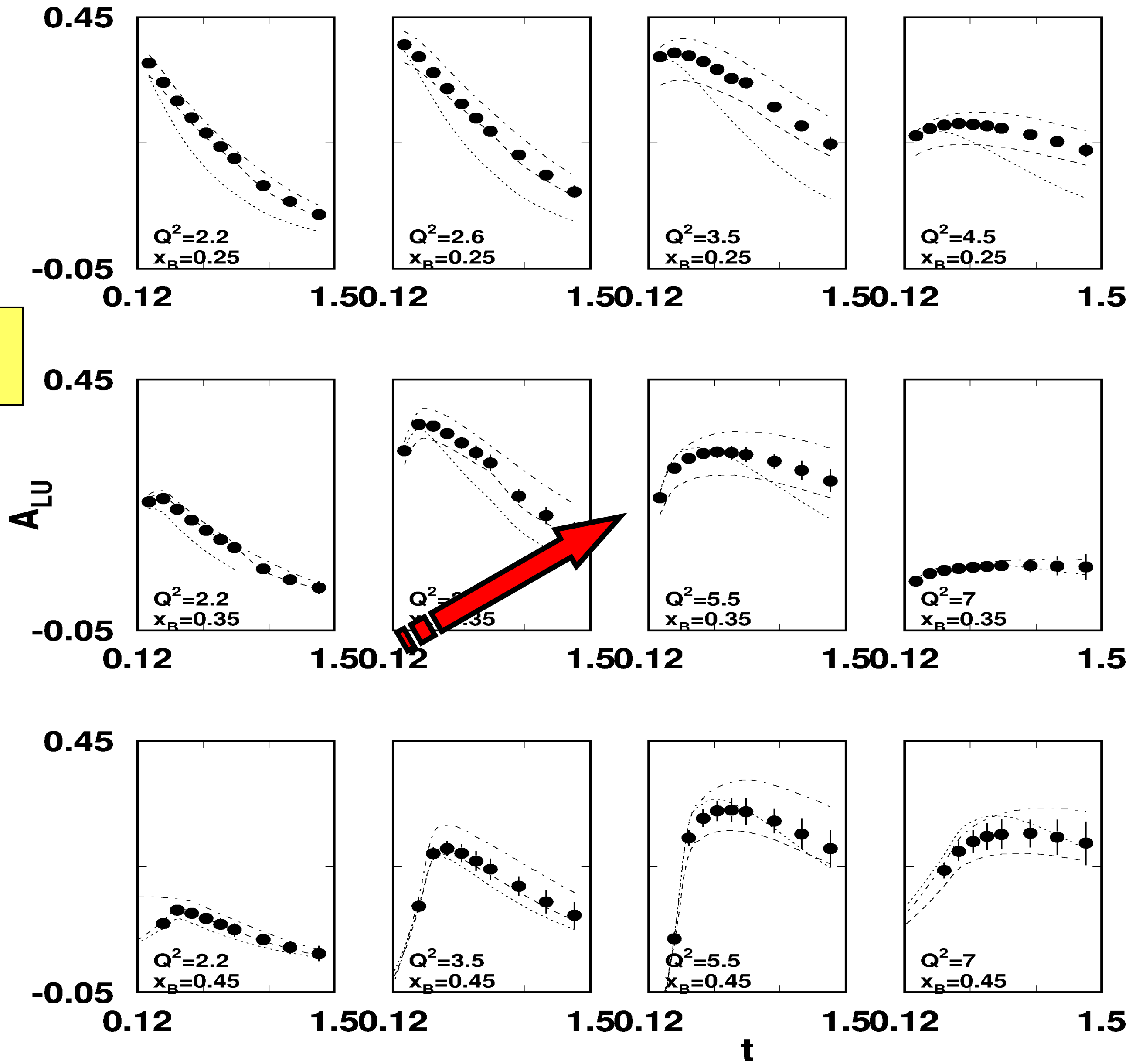
$\vec{e}\,p \longrightarrow ep\gamma$

E = 11 GeV

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

Selected Kinematics

$L = 1\times10^{35}$
$T = 2000$ hrs
$\Delta Q^2 = 1\ GeV^2$
$\Delta x = 0.05$



CLAS12 - DVCS/BH Target Asymmetry

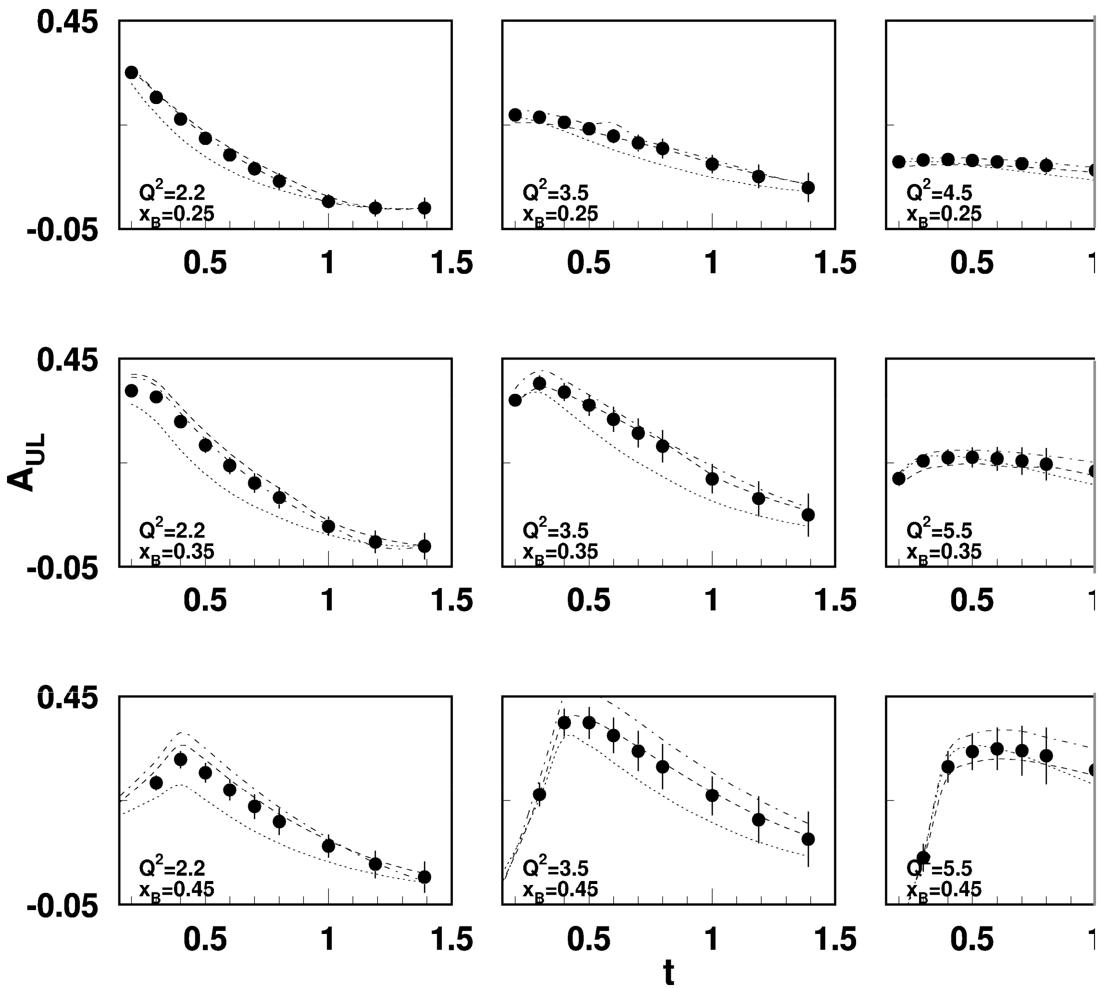
$e\vec{p} \longrightarrow e p \gamma$

E = 11 GeV

L = 2x10^35 cm^-2s^-1
T = 1000 hrs
ΔQ^2 = 1GeV^2
Δx = 0.05

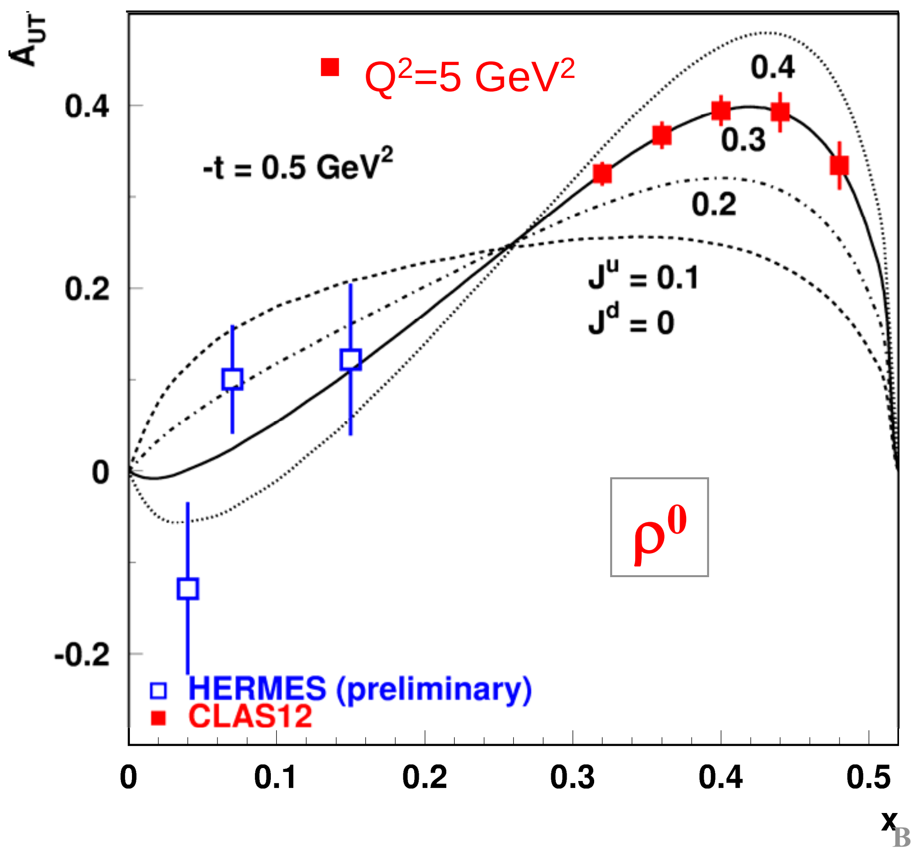
Longitudinally polarized target

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



Exclusive ρ^0 production on transverse target

$$A_{UT} \sim 2\Delta_\perp(\mathrm{Im}(AB^*))$$



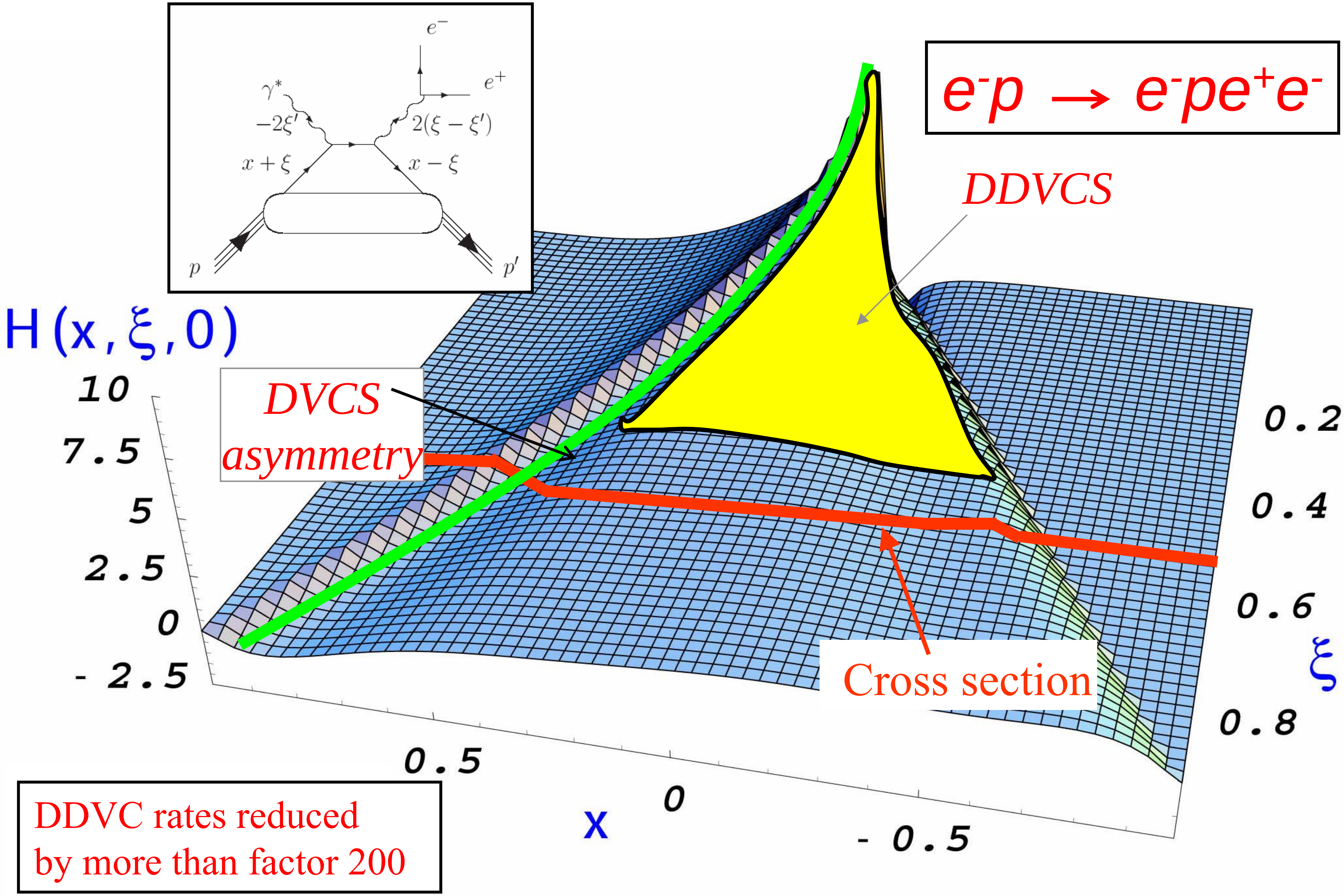
K. Goeke, M.V. Polyakov, M. Vanderhaeghen, 2001

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

ρ^+: $A \sim H^u - H^d$, $B \sim E^u - E^d$

E^u, E^d allow to map the *orbital motion of quarks*.

Double DVCS (DDVCS)



Summary

- DVCS beam spin asymmetries was extracted from two different CLAS data sets and for two different samples and was used to study GPDs.
- DVCS target spin asymmetry was extracted and compared with GPD based predictions (in publication) .
- Studies of the exclusive π^0 background performed. Beam and target SSA extracted.
- High luminosity, polarized CW beam, wide kinematic and geometric acceptance allow studies of exclusive meson production in hard scattering kinematics, providing data needed to study GPDs.

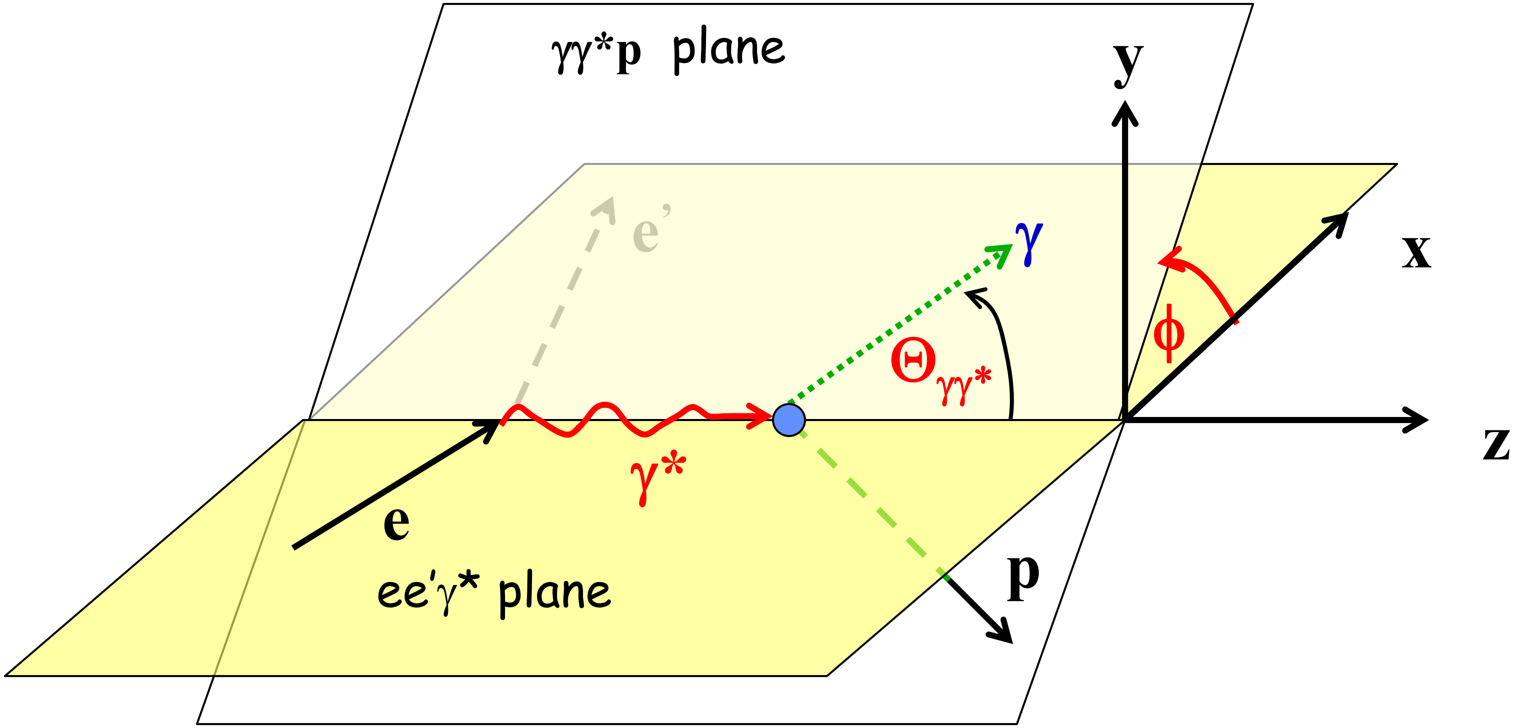
Outlook

➢ *Upgraded JLab:* Combination of full acceptance, (CLAS12) and high luminosity detector will provide high precision measurements of 3D PDFs in the valence region.

Deeply Virtual Compton Scattering

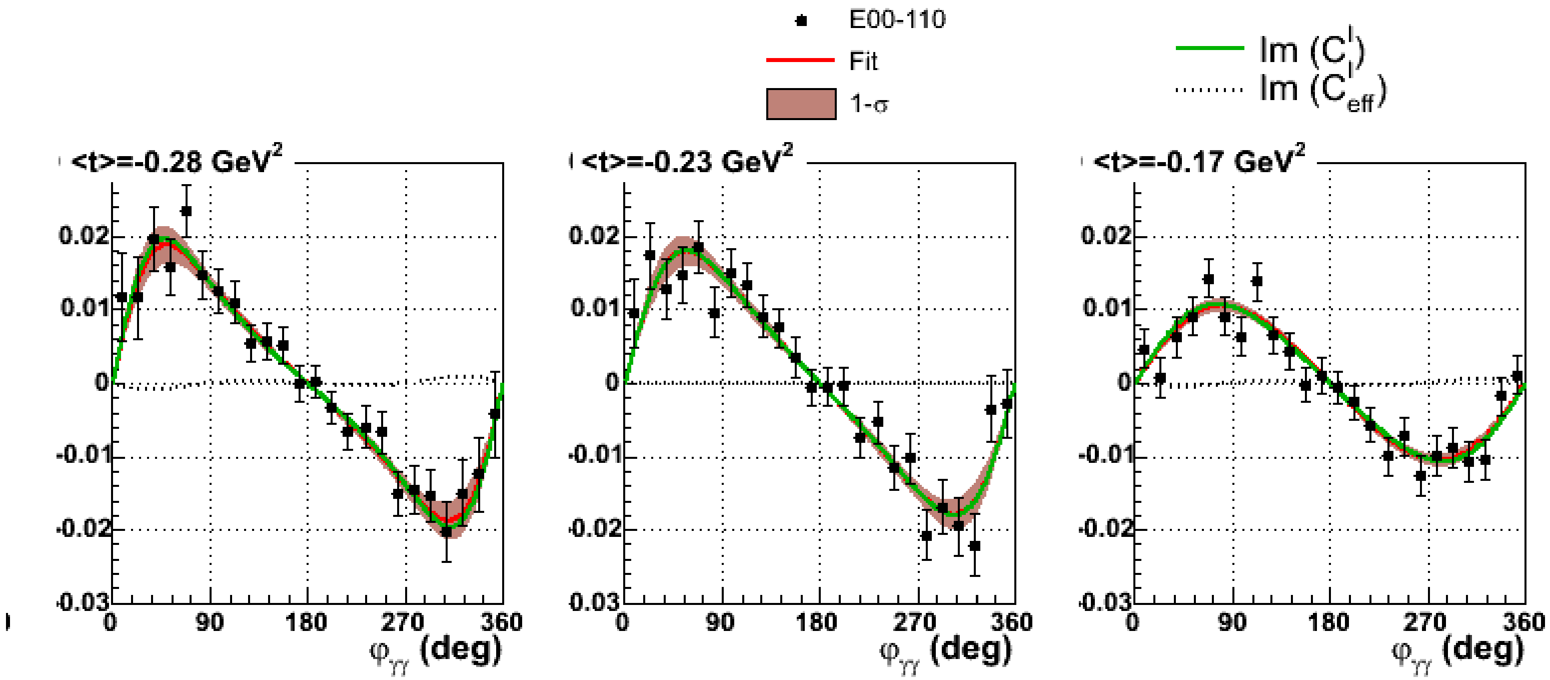
$ep \longrightarrow ep\gamma$

Kinematics



$$\frac{d^4\sigma^+}{dx_B dQ^2 d\varphi\, dt} - \frac{d^4\sigma^-}{dx_B dQ^2 d\varphi\, dt} \quad [\text{nb/GeV}^4]$$

Corrected for real and virtual radiation

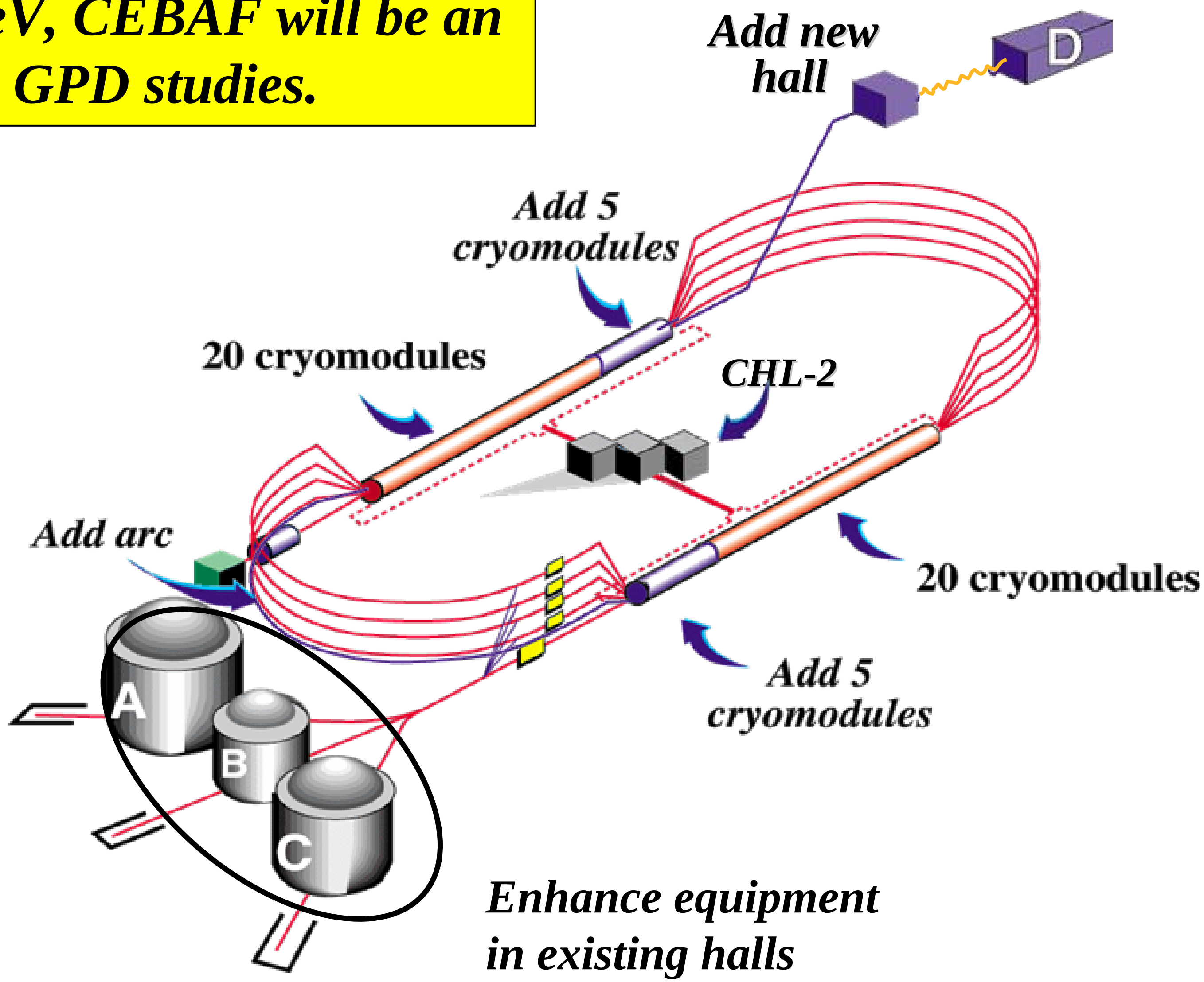


Twist 2 contribution

Twist 3 contribution strongly suppressed

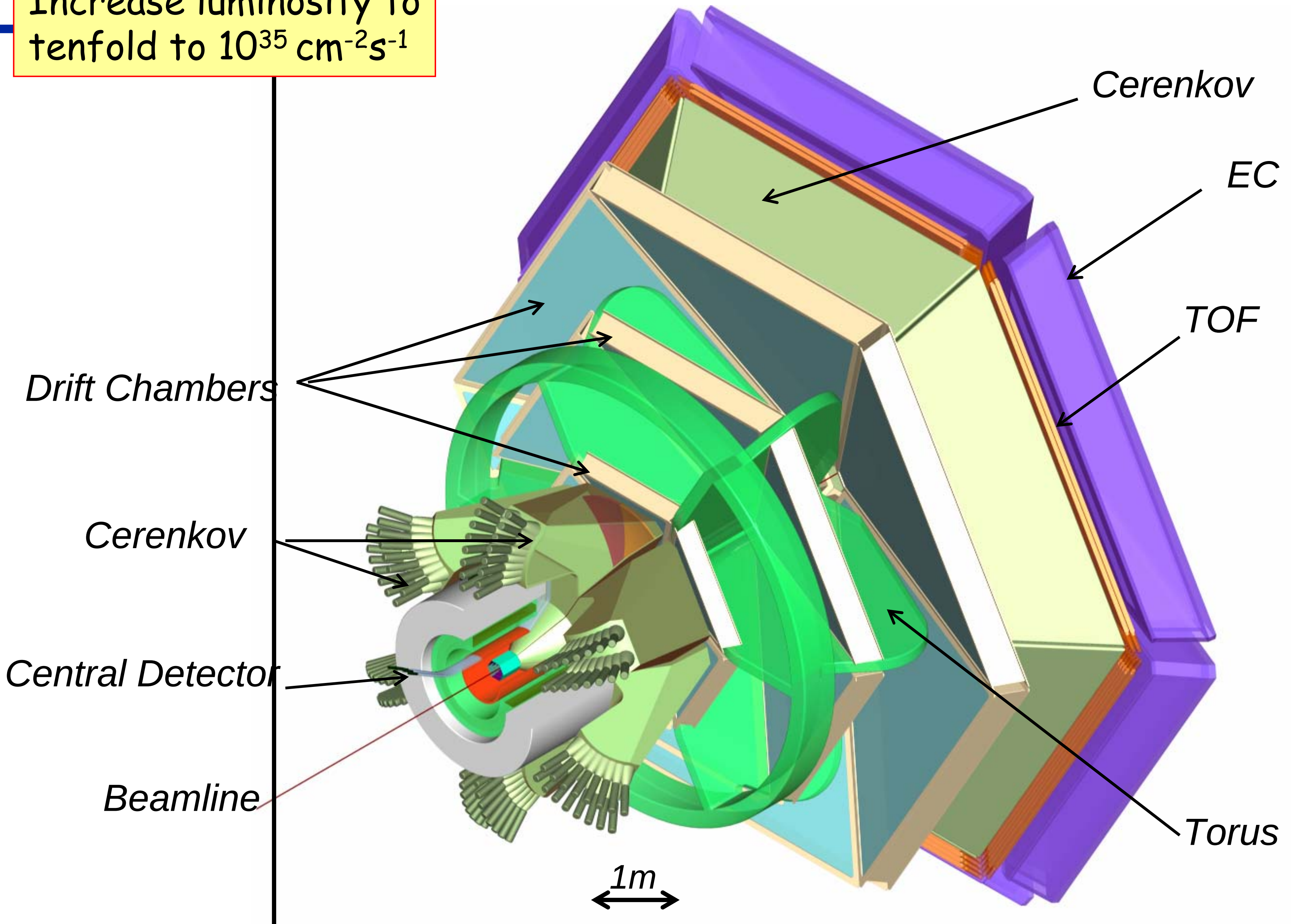
JLab Upgrade to 12 GeV

At 12 GeV, CEBAF will be an ideal for GPD studies.

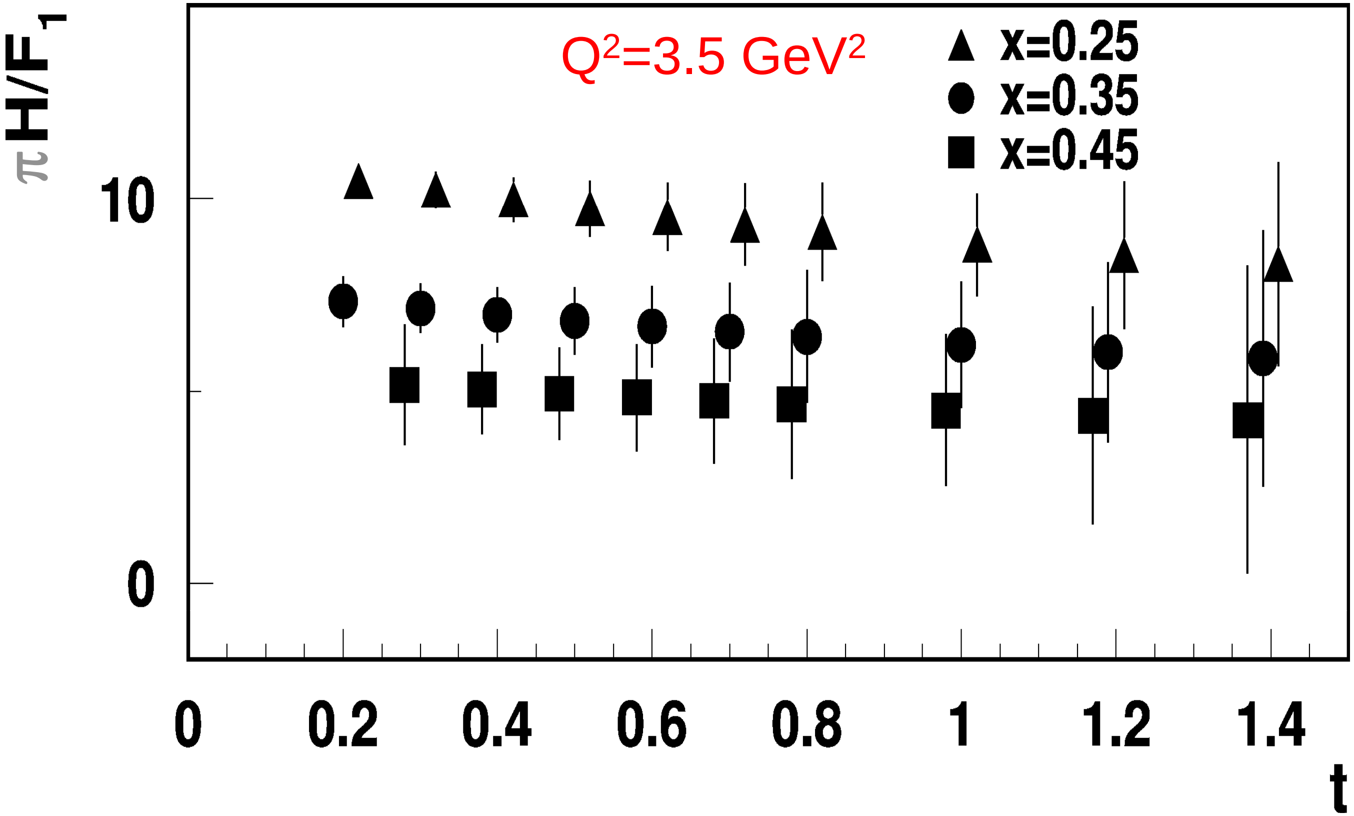


CLAS12

Increase luminosity to tenfold to 10^{35} cm^{-2}s^{-1}



GPD H from expected DVCS A_{LU} data



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

MRST02 NNLO distribution

- Other kinematics measured concurrently

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

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

A_{UTx} Target polarization in the scattering plane

A_{UTy} Target polarization perpendicular to the scattering plane

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