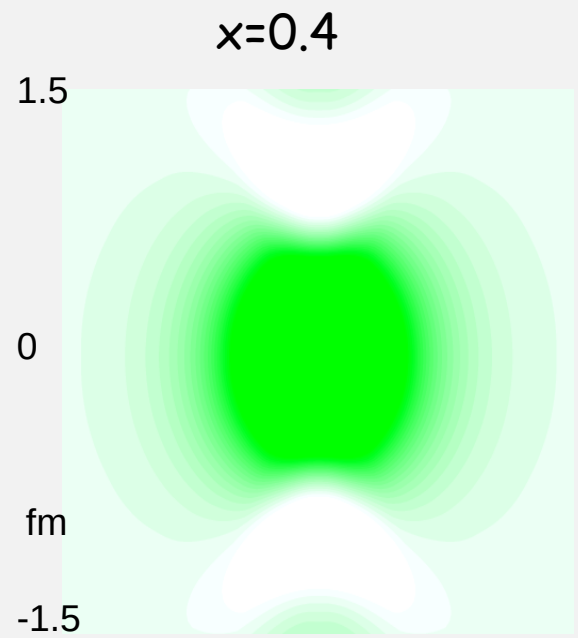
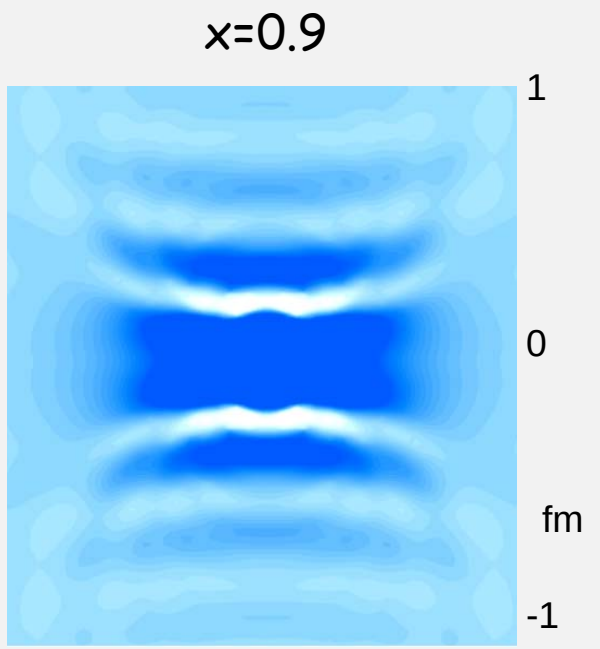
Generalized Parton Distributions and the Structure of the Nucleon



Volker D. Burkert
Jefferson Lab



April Meeting

Fundamental questions in hadron physics?

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

- Elastic scattering
  - ⇨ the proton is not a point-like particle
    - charge and current distribution in the proton, F_1/F_2

1960-1990: What is the internal structure of the proton?

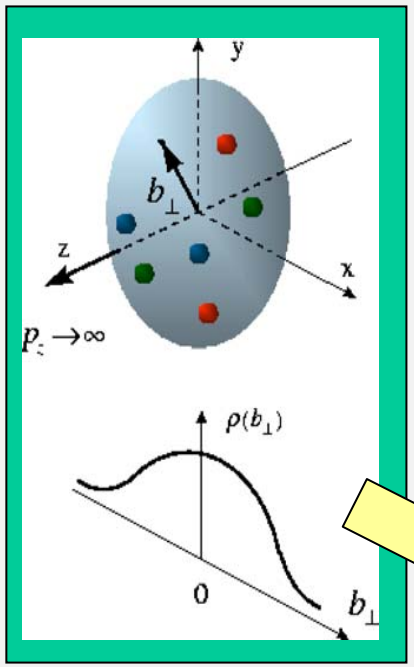
- Deep inelastic scattering
  - ⇨ discover quarks
    - quark momentum and spin distributions $q(x)$, $\Delta q(x)$

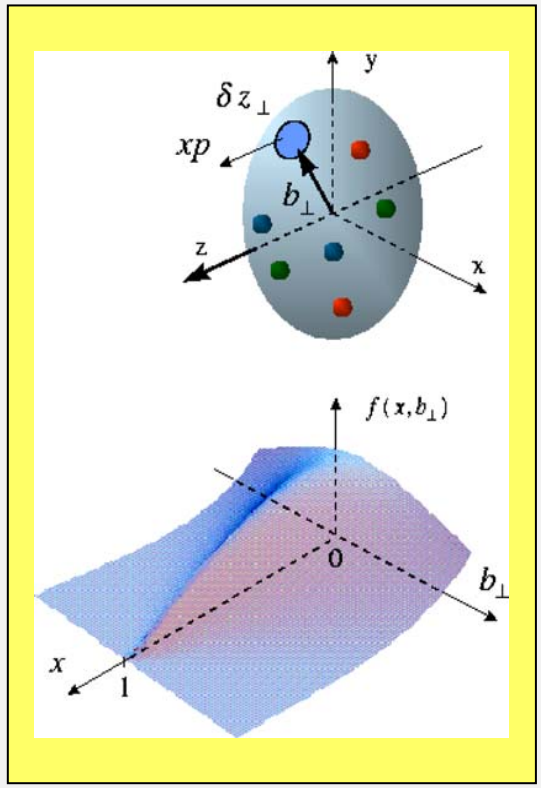
Today: How are these representations of the proton, charge/current distributions and quark momentum/spin distributions fundamentally connected?

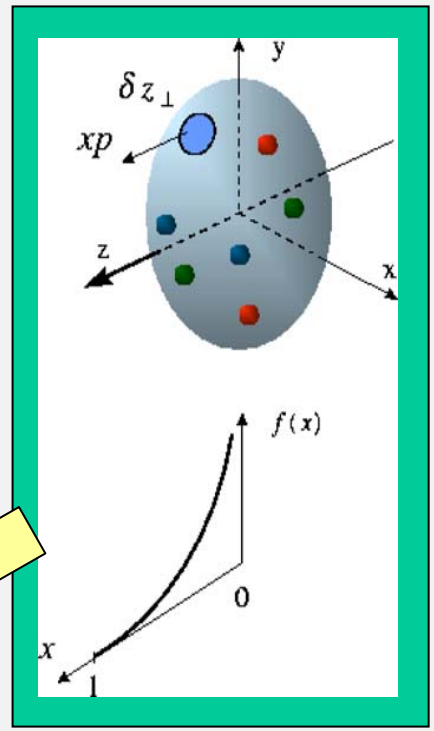
Beyond charge and quark distributions – Generalized Parton Distributions (GPDs)

X. Ji, D. Mueller, A. Radyushkin (1994-1997), …
M. Burkardt, A. Belitsky (2000) …

Infinite momentum frame







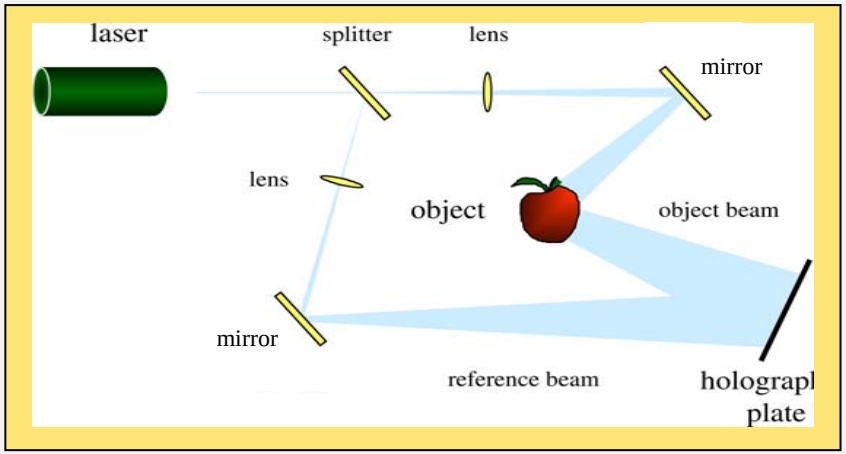
Transverse charge & current densities

Correlated distributions in transverse space - GPDs

Quark longitudinal momentum & helicity distributions

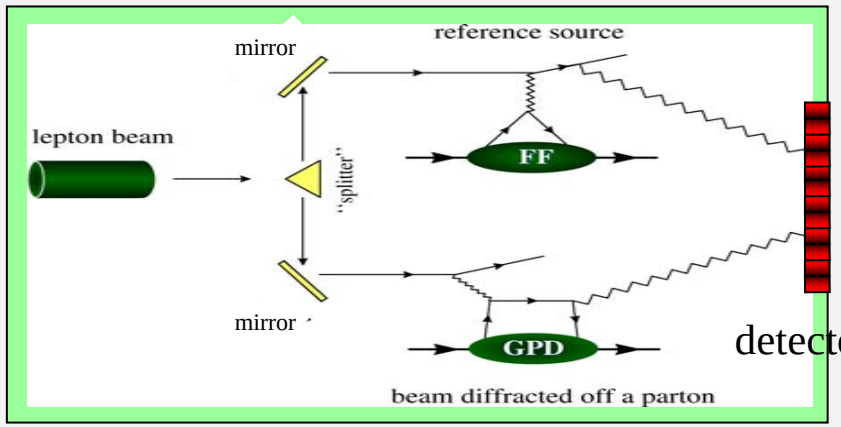
From Holography to Tomography

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



An Apple

A Proton

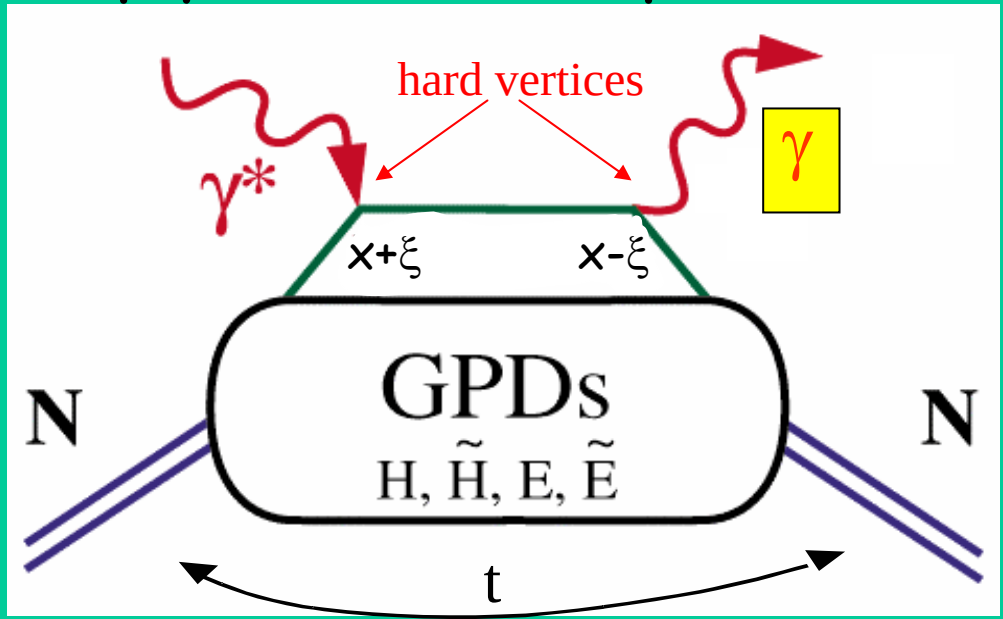


By varying the energy and momentum transfer to the proton we probe its interior and generate tomographic images of the proton ("femto tomography").

Deeply Virtual Exclusive Processes & GPDs

"handbag" mechanism

Deeply Virtual Compton Scattering (DVCS)



x – longitudinal quark momentum fraction

2ξ – longitudinal momentum transfer

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

$H(x,\xi,t),\ E(x,\xi,t),\ \ldots$

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

Link to DIS and Elastic Form Factors

DIS at $\xi = t = 0$

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

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

Form factors (sum rules)

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

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

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

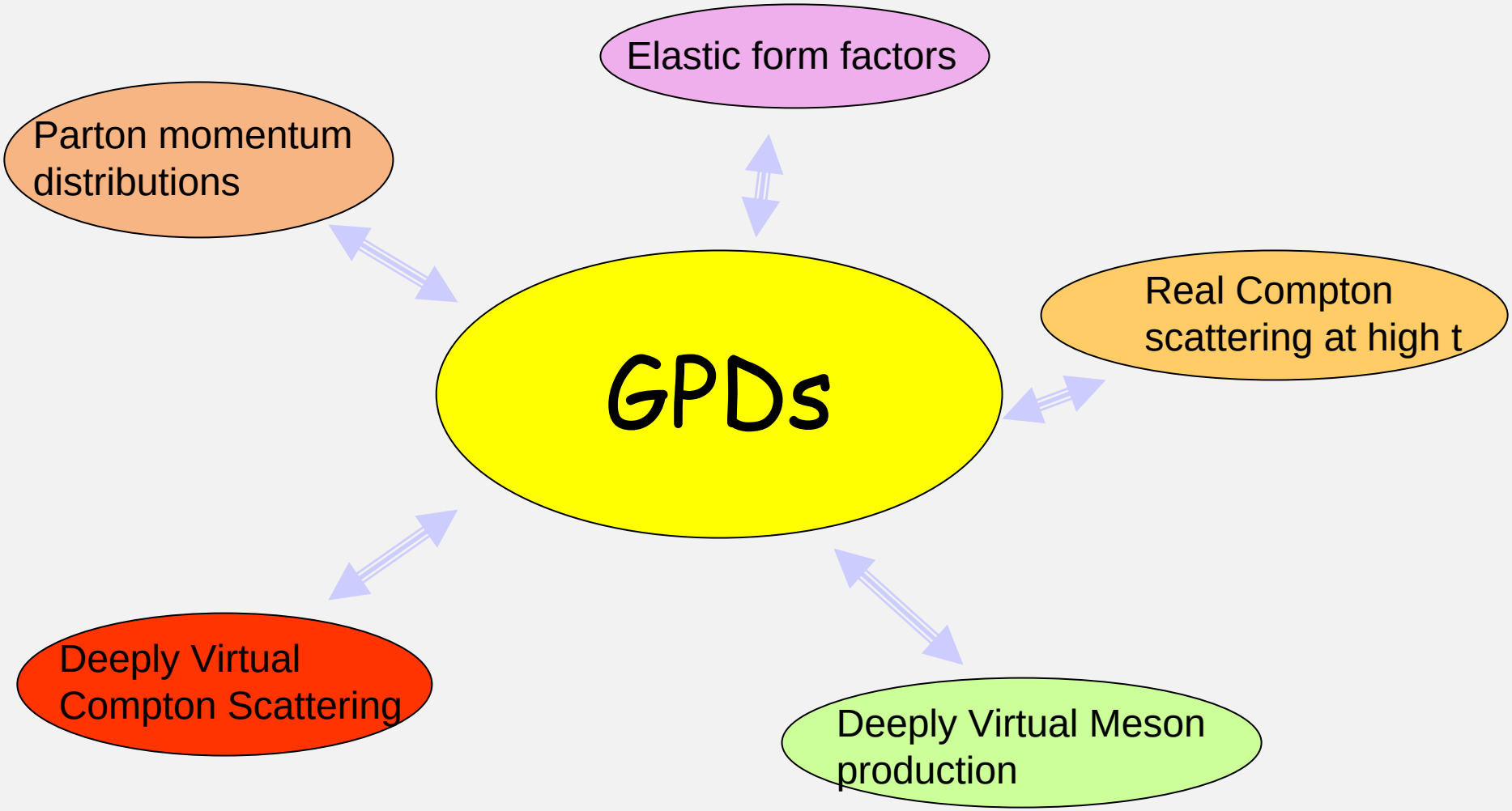
$$H, E, \tilde{H}, \tilde{E}\ (x,\xi,t)$$

Quark angular momentum (Ji's sum rule)

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

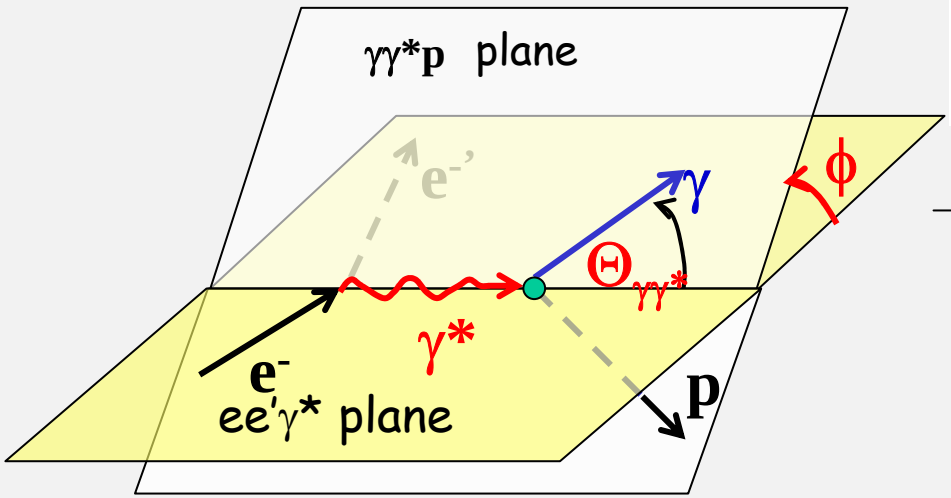
X. Ji, Phy.Rev.Lett.78,610(1997)

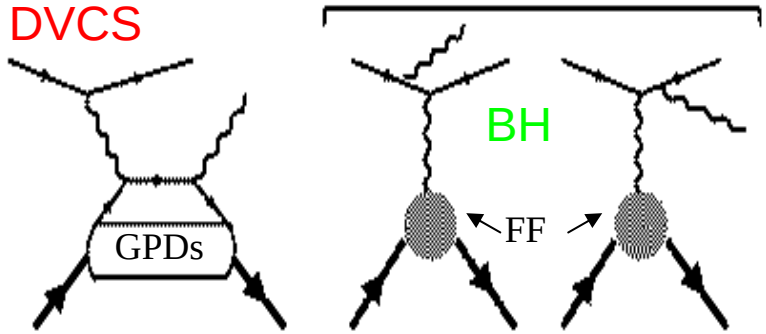
A Unified Description of Hadron Structure



Accessing GPDs through DVCS

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





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

$$\sim |\text{DVCS}|^2 + |\text{BH}|^2 + \text{BH}*\text{Im}(\text{DVCS})$$

BH : given by elastic form factors
DVCS: determined by GPDs

$$\Delta\sigma_{LU} \sim \text{BH}\ \text{Im}(\text{DVCS})\sin\phi + \text{higger twist.}$$

Separating GPDs through polarization

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

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

$k = t/4M^2$

Polarized beam, unpolarized target:

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

Kinematically suppressed

$\mathbf{H}, \tilde{\mathbf{H}}, \mathbf{E}$

Unpolarized beam, longitudinal target:

$$\Delta\sigma_{UL} \sim \sin\phi\{F_1\tilde{H} + \xi(F_1+F_2)(H + \ldots\}d\phi$$

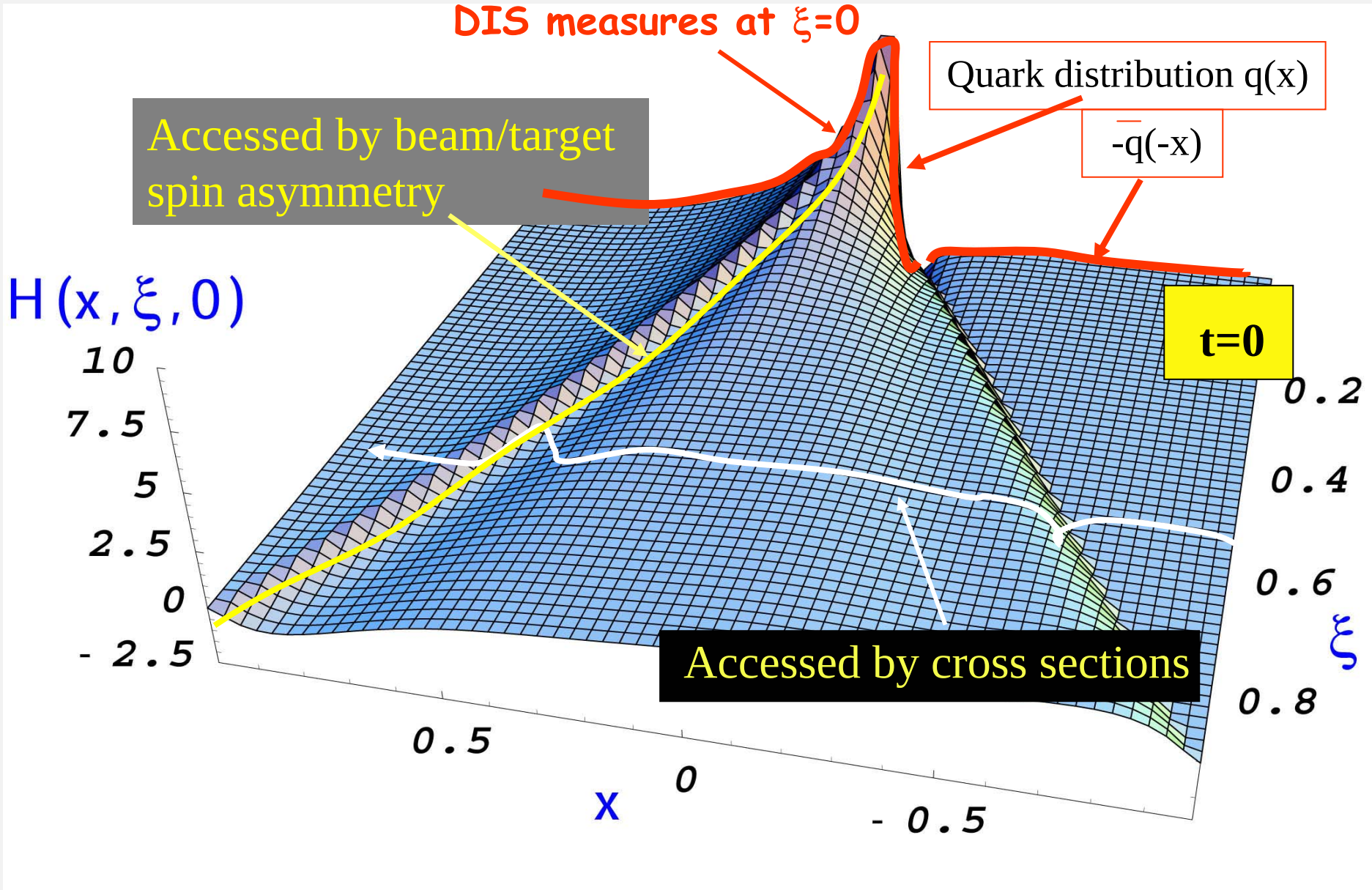
$\mathbf{H}, \tilde{\mathbf{H}}$

Unpolarized beam, transverse target:

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

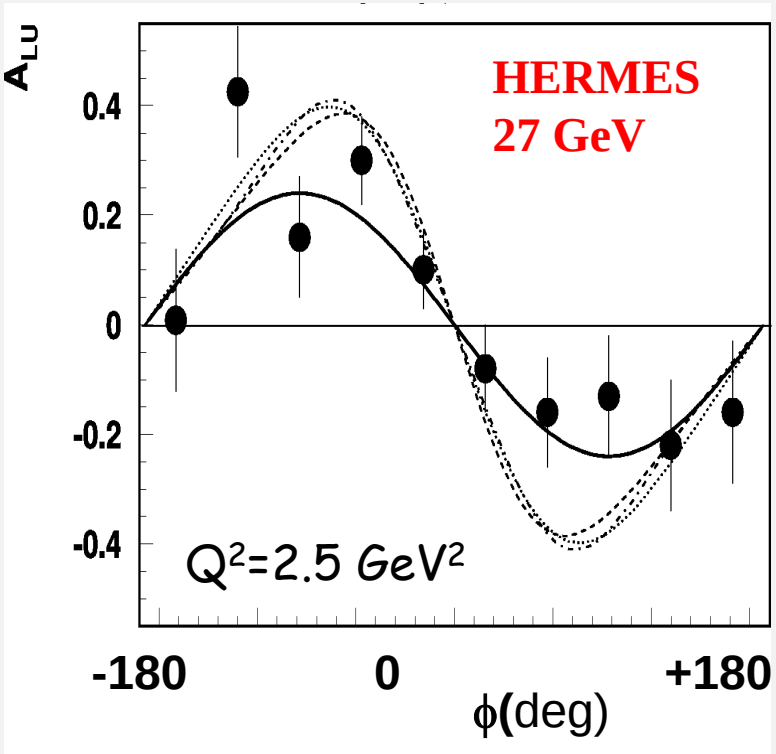
$\mathbf{H}, \mathbf{E}$

Access GPDs through x-section & asymmetries



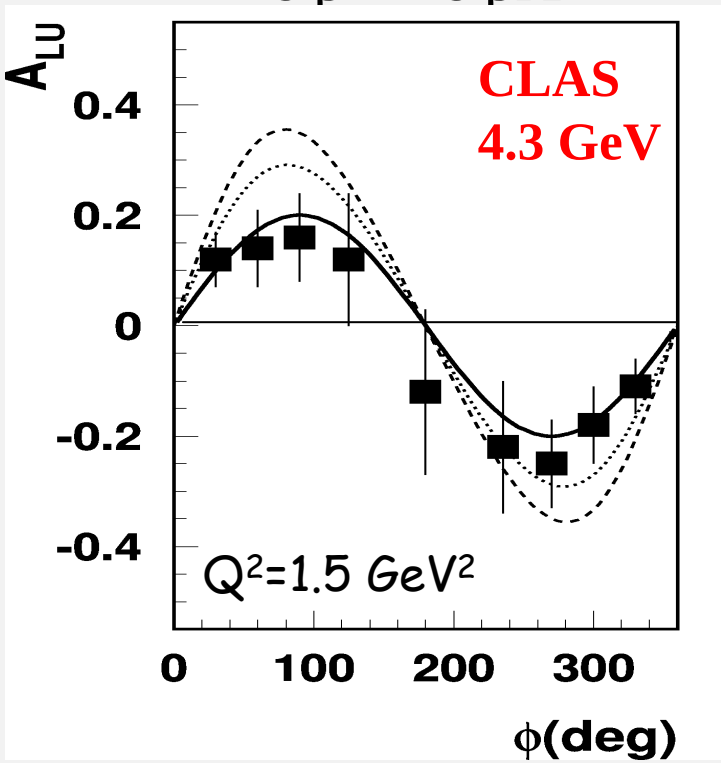
First observation of DVCS/BH beam asymmetry

$e^+p \rightarrow e^+\gamma X$



2001

$e^-p \rightarrow e^-pX$



GPD analysis of CLAS/HERMES/HERA data in LO/ NLO shows results consistent with handbag mechanism and lowest order pQCD
A. Freund, PRD 68,096006 (2003), A. Belitsky, et al. (2003)

$A(\phi) = \alpha\sin\phi + \beta\sin2\phi$

$\beta/\alpha << 1 \rightarrow$ twist-3 << twist-2

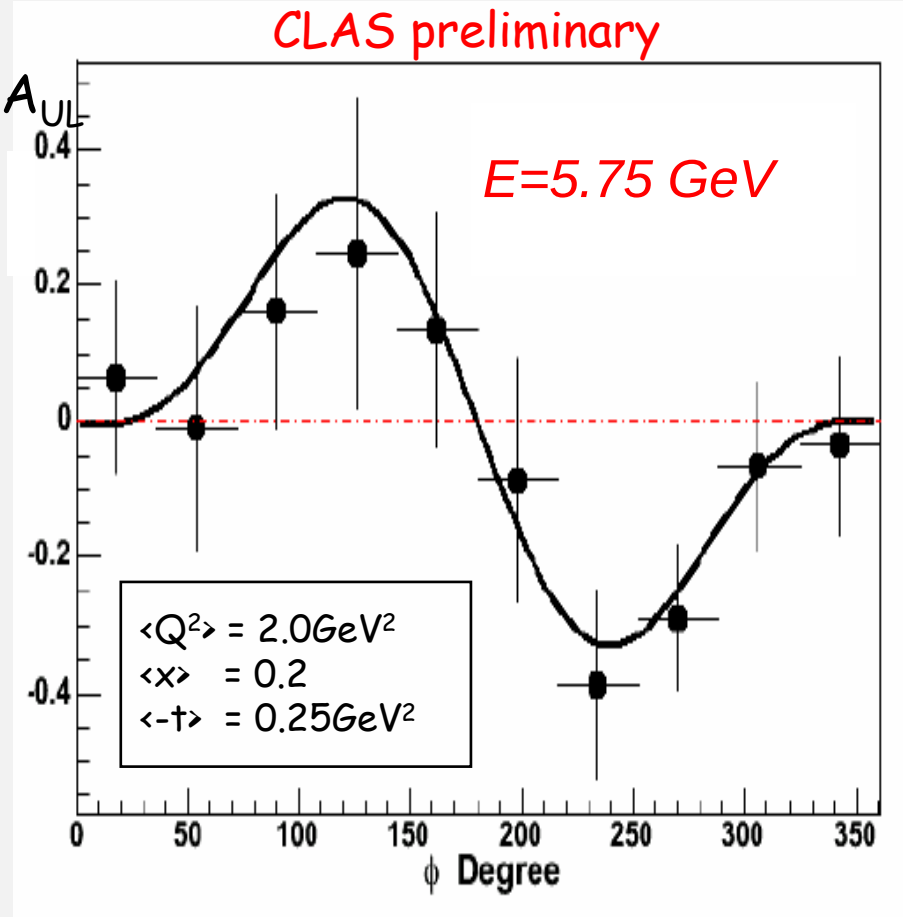
DVCS/BH target asymmetry

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

Longitudinally polarized target

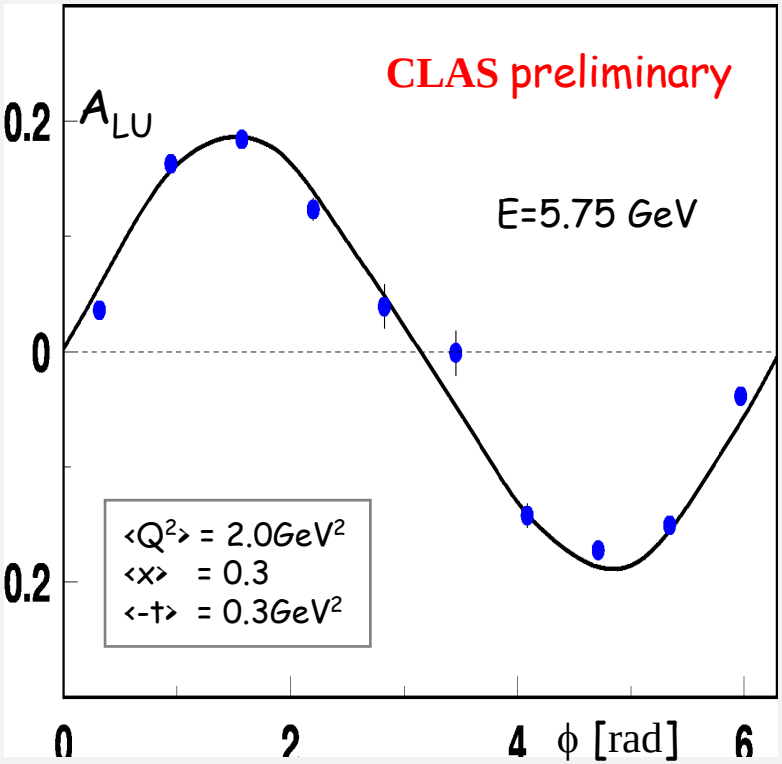
$$A_{UL} \sim \sin\phi\{F_1\tilde{H} + \xi(F_1+F_2)H\ldots\}d\phi$$

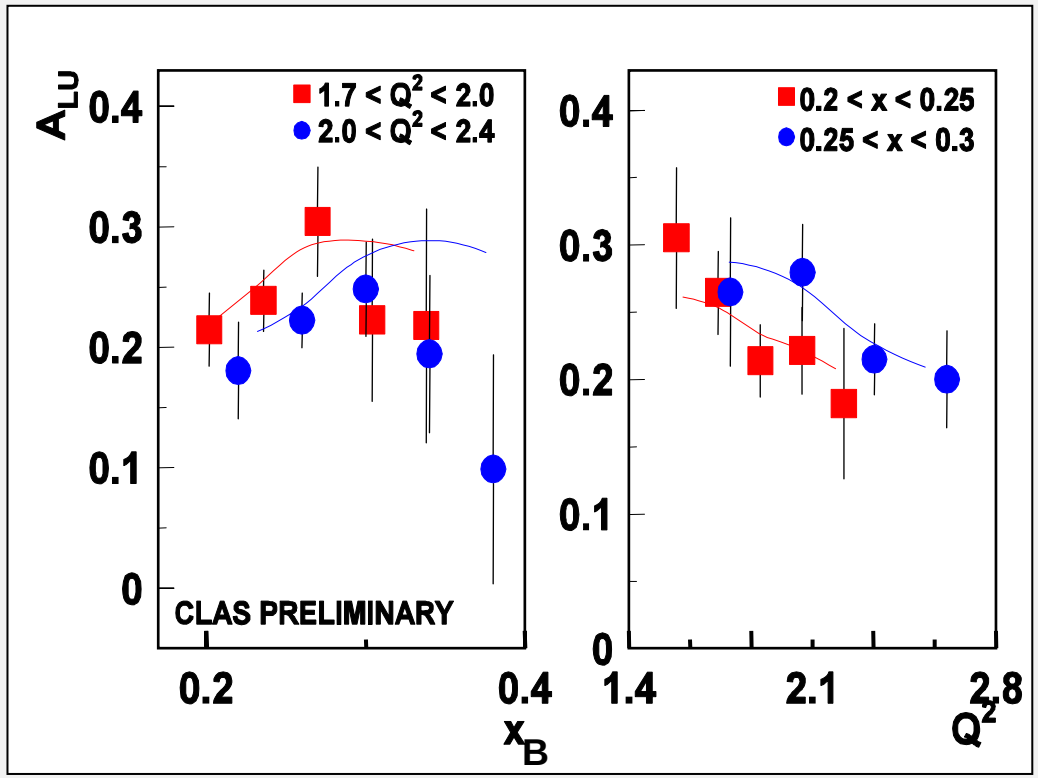
Asymmetry observed at about the expected magnitude. Much higher statistics, and broad kinematical coverage are needed.



HERMES data on deuterium target

First DVCS experiment with GPDs in mind





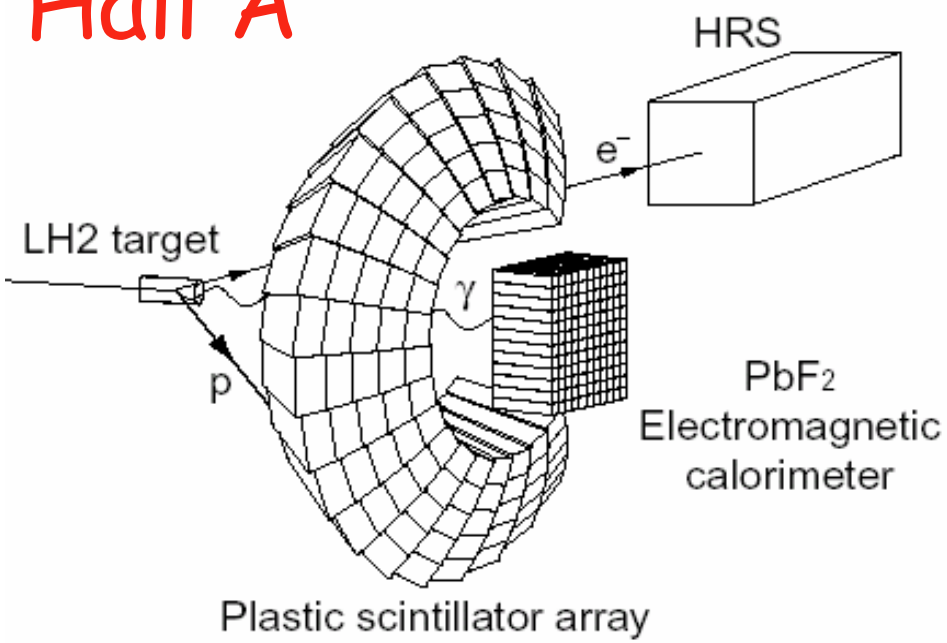
Twist-2 + twist-3: Kivel, Polyakov, Vanderhaeghen (2000)

Model with GPD parametrization and quark k_T corrections describes data.

First Dedicated DVCS Experiments at JLab

=> Full reconstruction of all final state particles e, p, γ
=> High luminosity

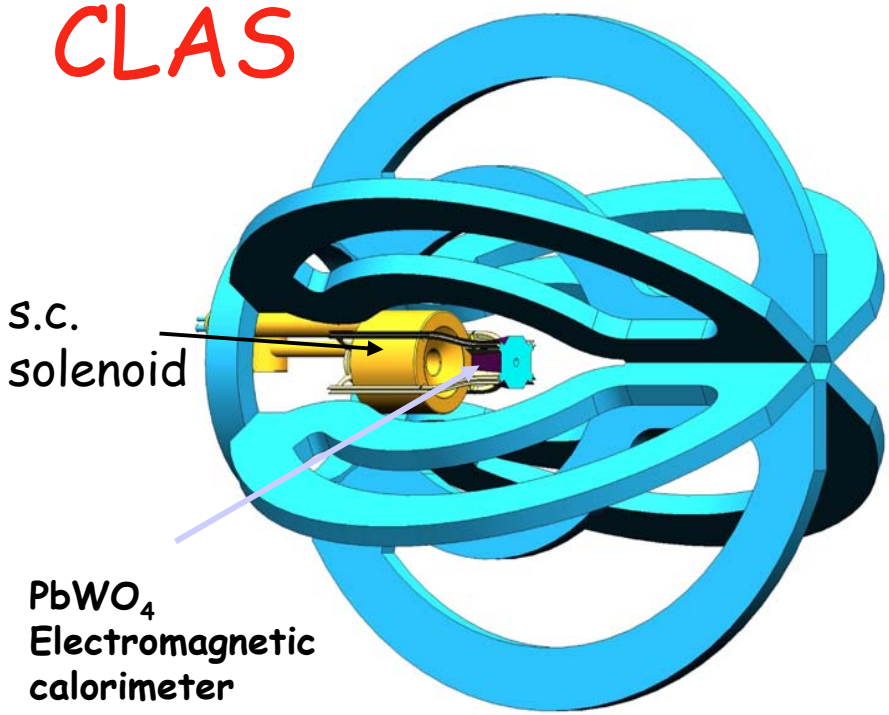
Hall A



Azimuthal and Q^2 dependence of Im(DVCS) at fixed ξ. Test Bjorken scaling.

Data taking completed

CLAS



ξ, t, Q^2 - dependence of Im(DVCS) in wide kinematics. Constrain GPD models.

Currently taking data

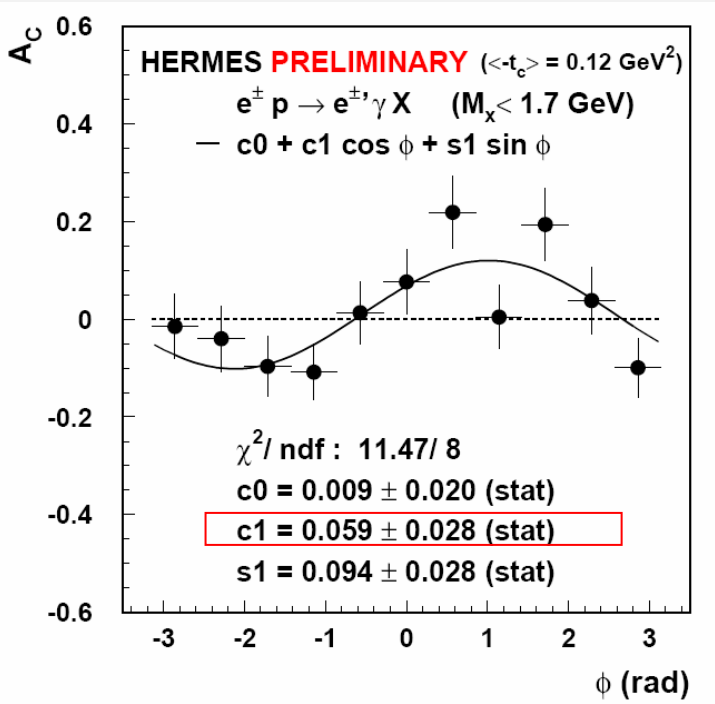
DVCS/BH Beam-Charge Asymmetry

HERMES

The e^+- e^- beam asymmetry measures real part of convolution integral for GPDs.

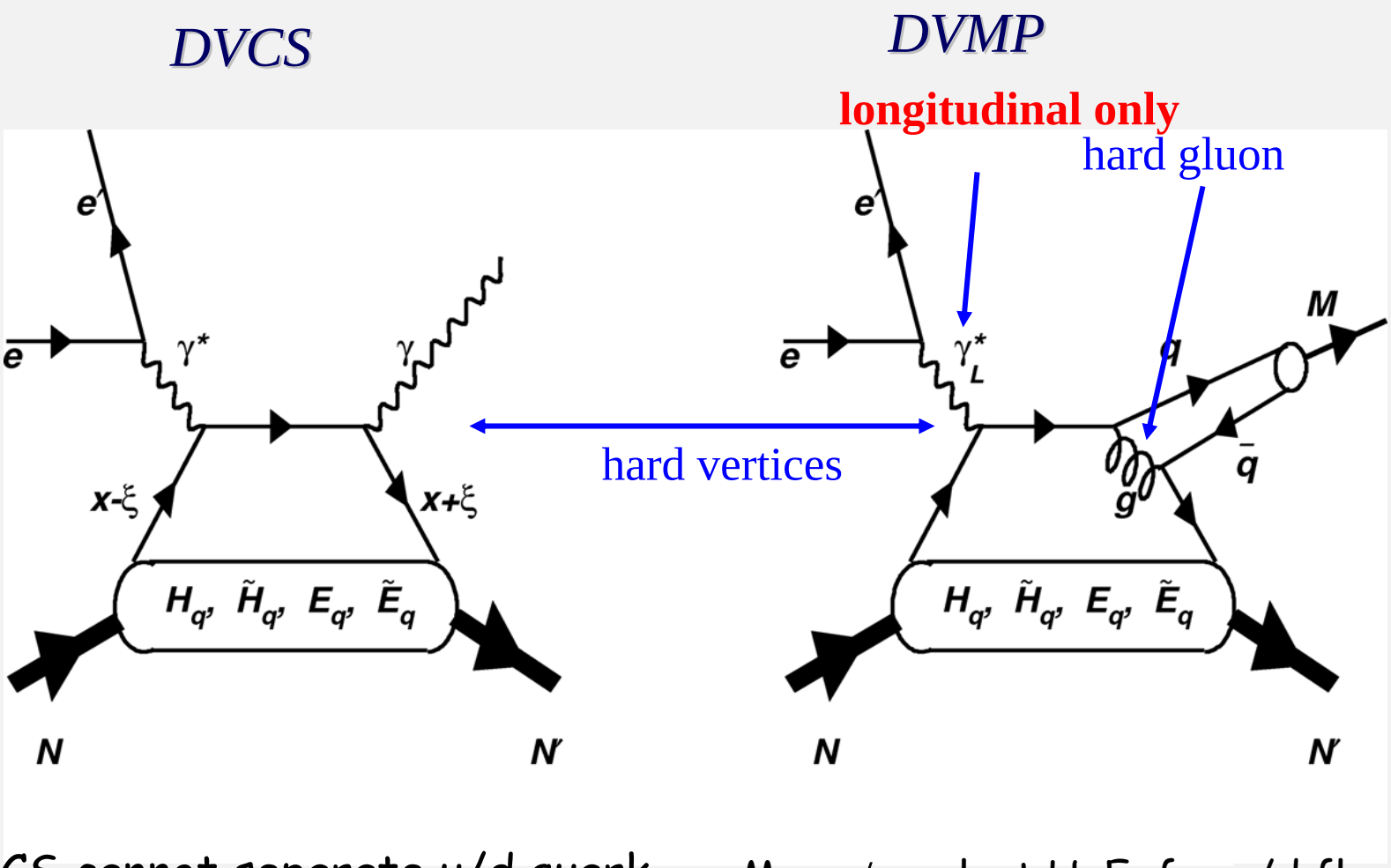
$$\mathcal{H}(\xi, t) = \int \frac{H^q(x, \xi, t)dx}{x-\xi}$$

$$\Delta\sigma_C \sim \cos\phi\{F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} + kF_2\mathcal{E}\}d\phi$$



- Improved statistics and control of systematic expected in future run
- Measurements proposed for COMPASS experiment at CERN in μ^+–μ^-.

GPDs – Flavor separation

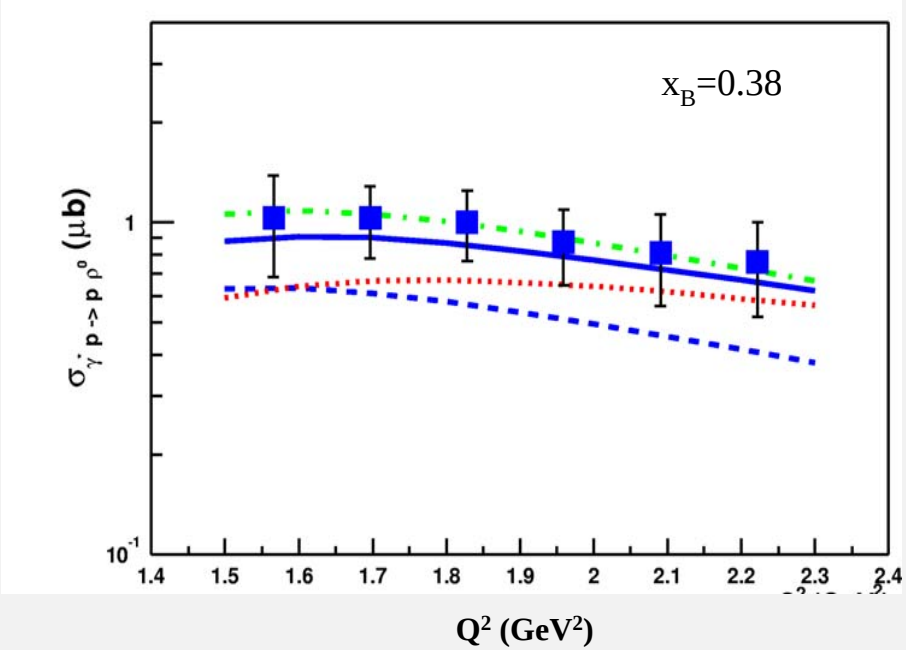


DVCS cannot separate u/d quark contributions.

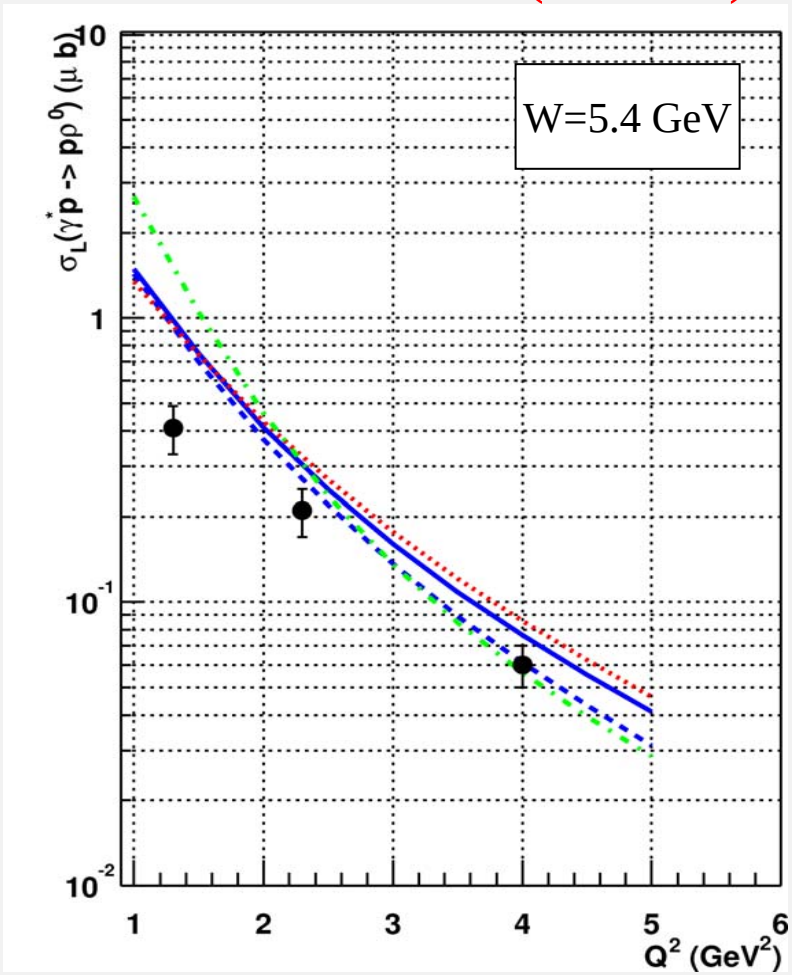
M = ρ/ω select H, $\tilde{E}$, for u/d flavors
M = π, η, K select $\tilde{H}$, $\tilde{E}$

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

CLAS (4.3 GeV)



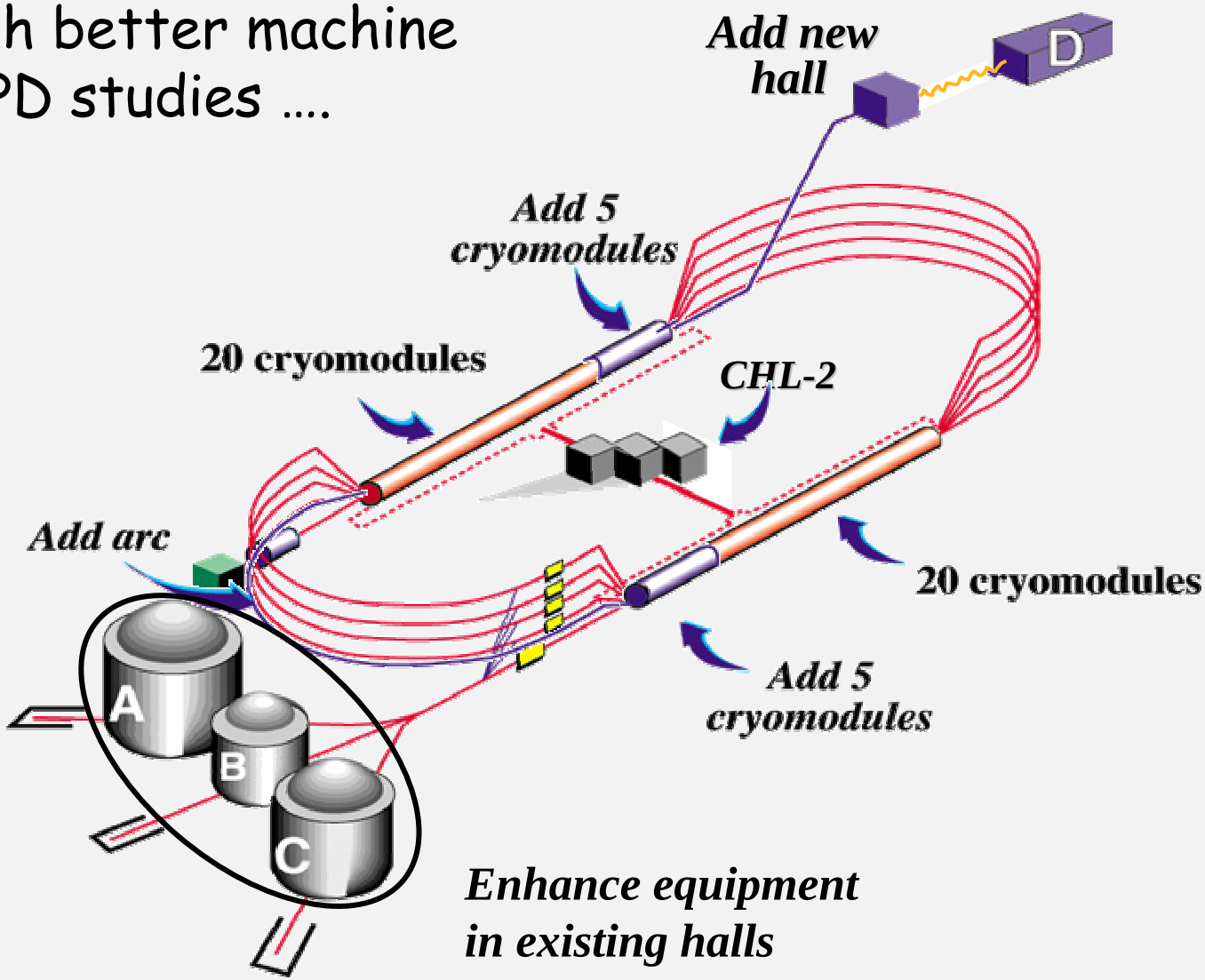
HERMES (27GeV)



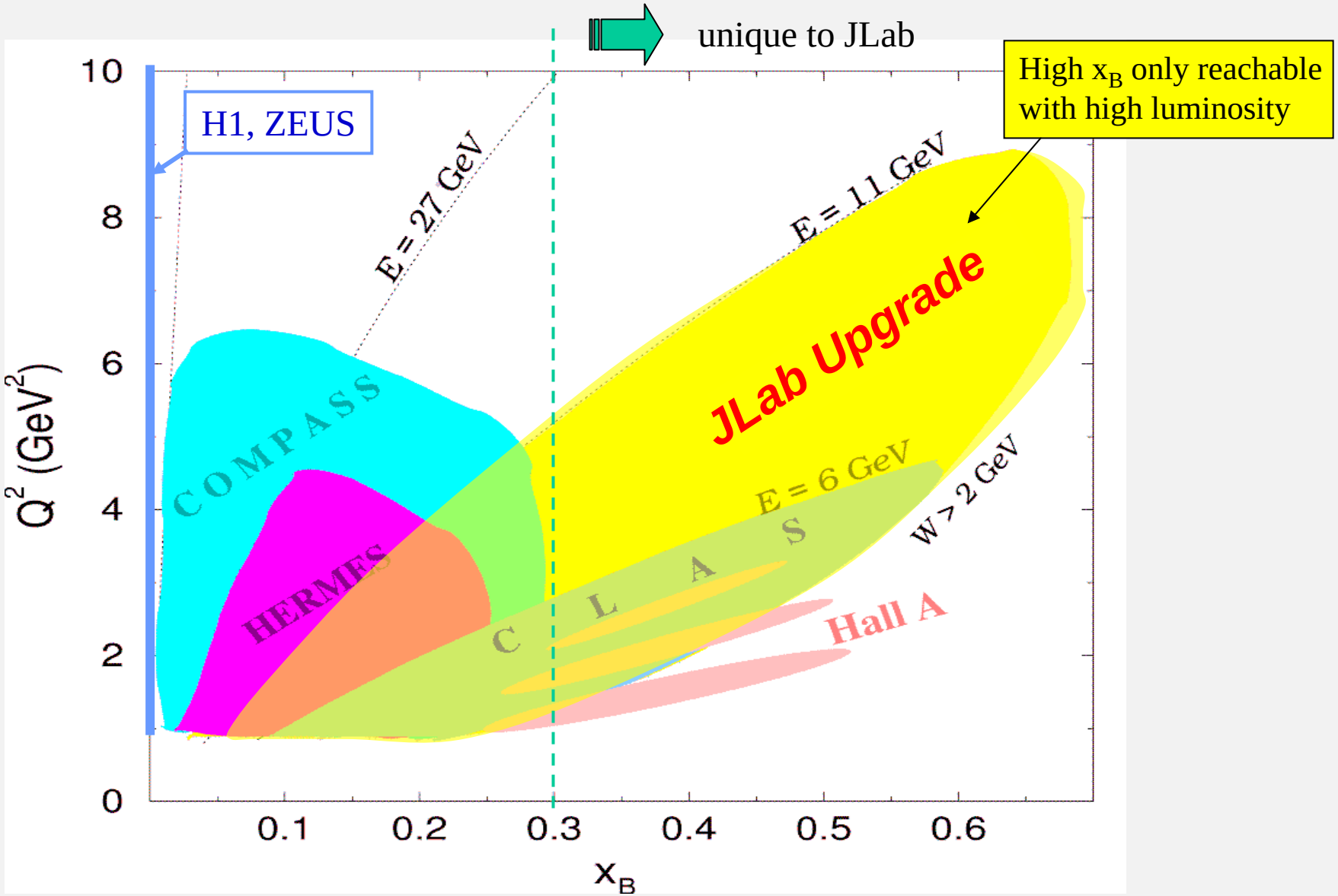
GPD formalism approximately describes CLAS and HERMES data $Q^2 > 2$ GeV^2

JLab Upgrade to 12 GeV Energy

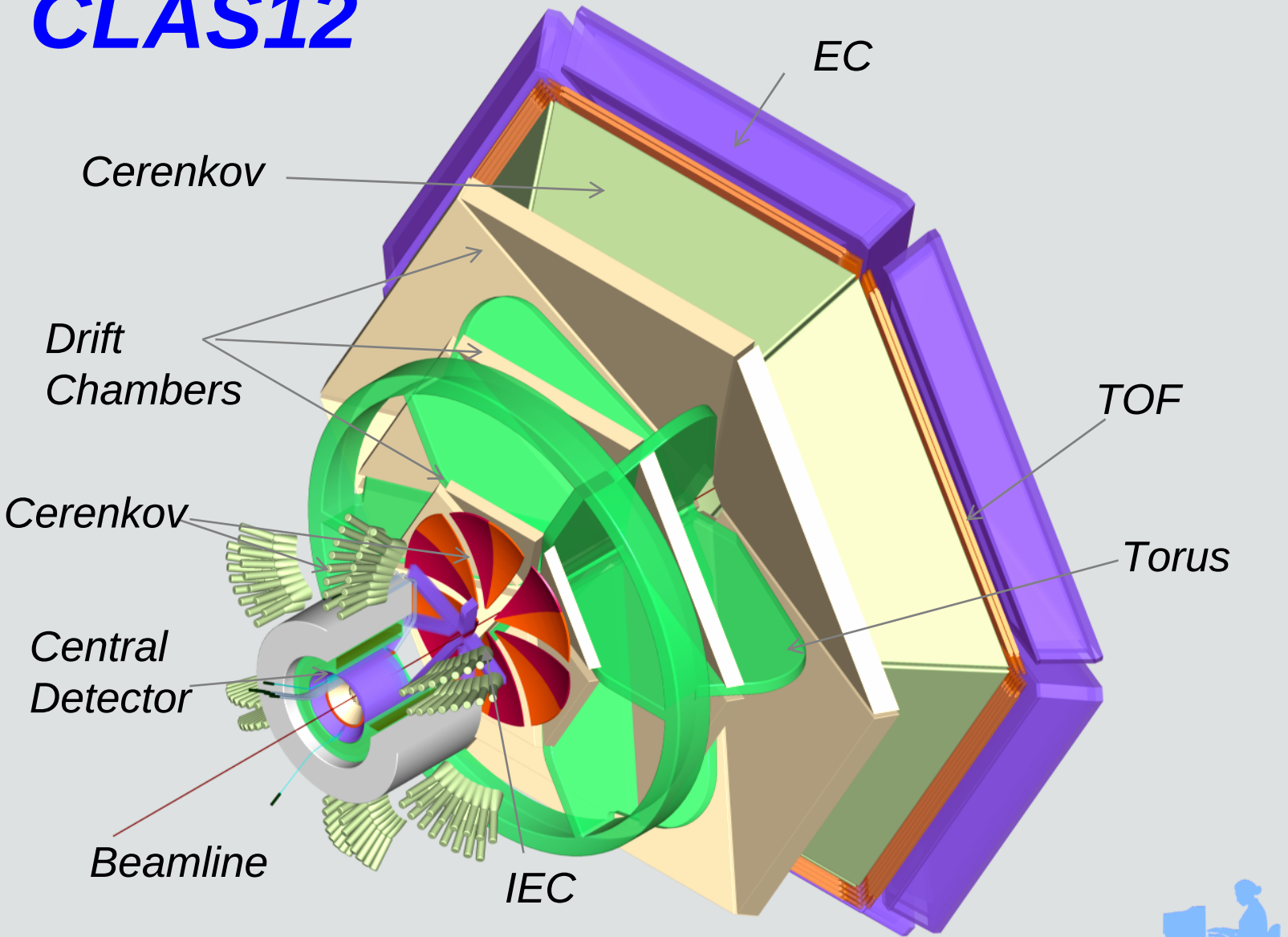
A much better machine for GPD studies ….



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



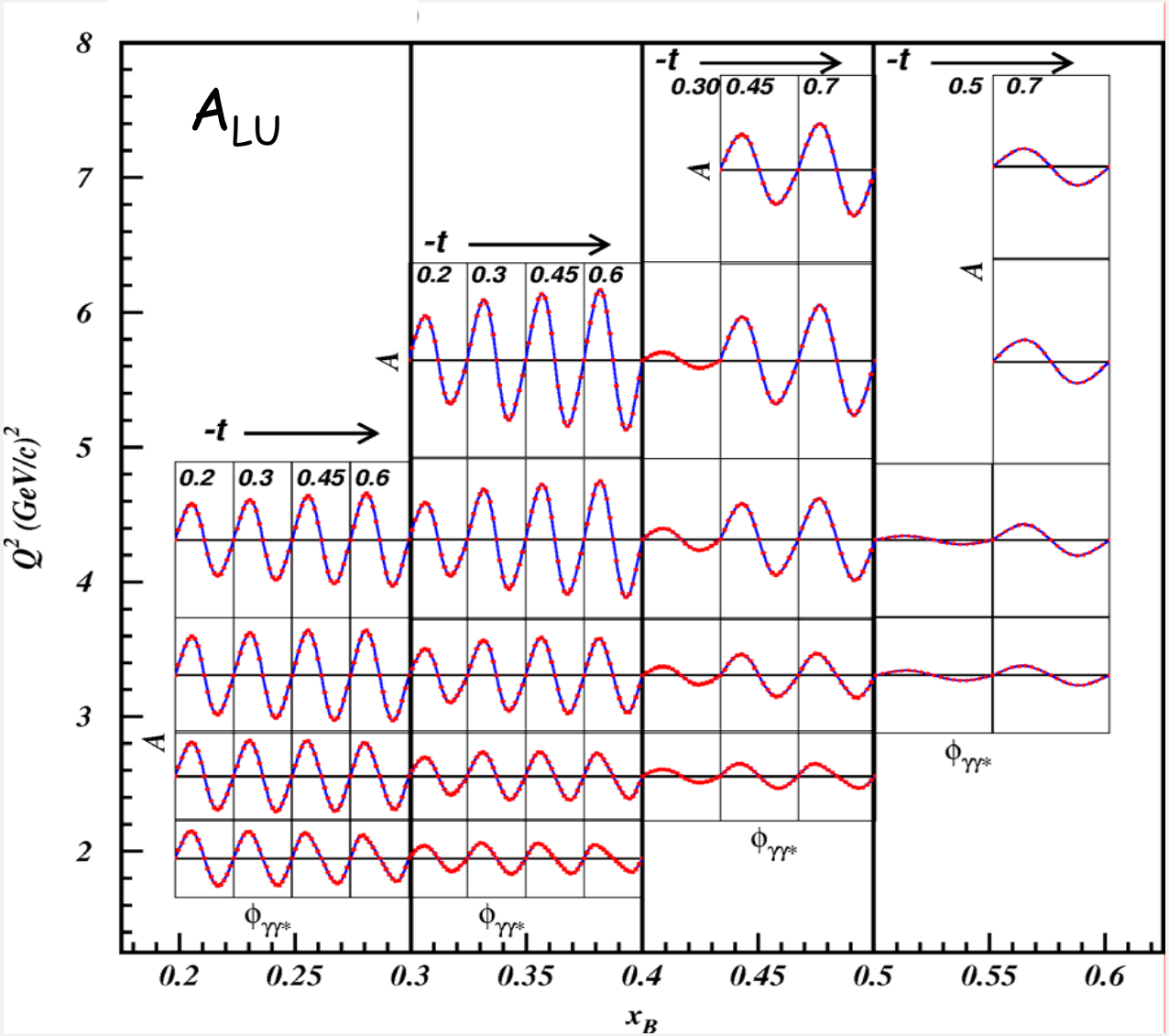
CLAS12



Luminosity > $10^{35} cm^{-2} s^{-1}$

DVCS/BH- Beam Asymmetry

$E_e = 11$ GeV

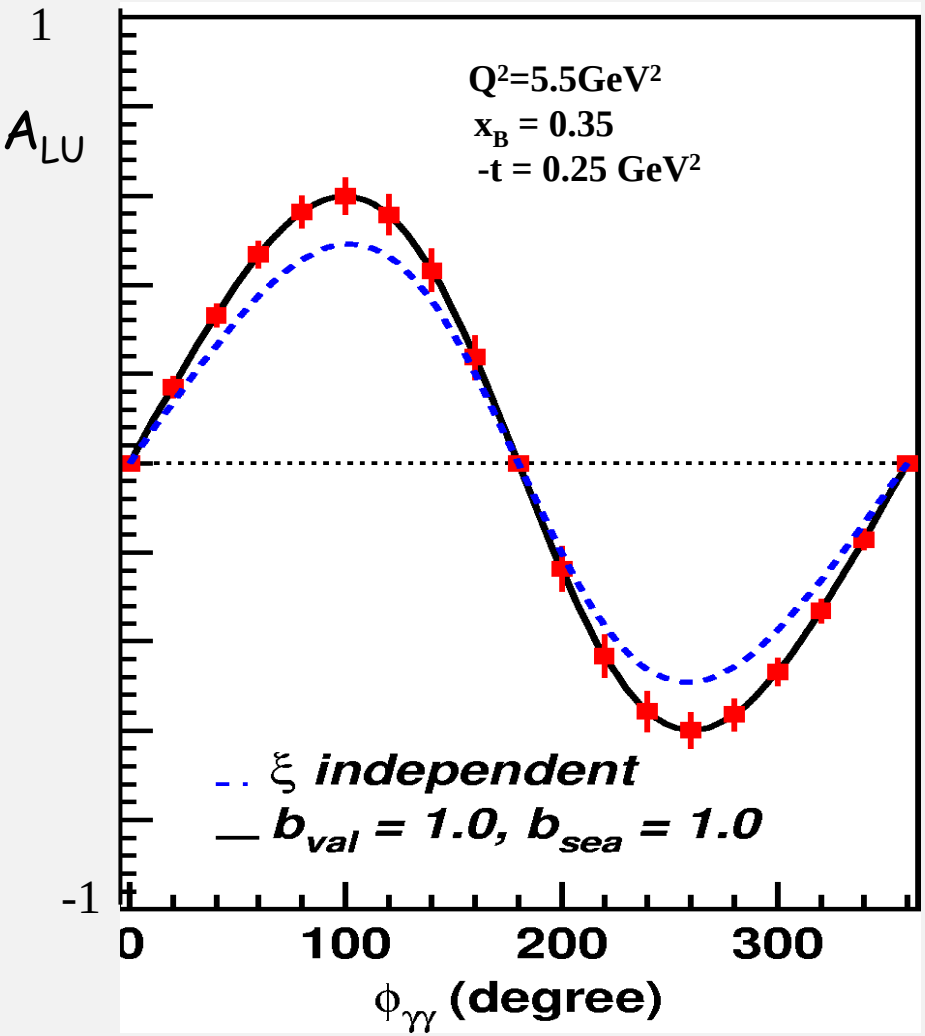


With large acceptance, measure large Q^2, x_B, t ranges simultaneously.

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

CLAS12 - DVCS/BH- Beam Asymmetry

$E_e = 11$ GeV



CLAS12 - DVCS/BH Beam Asymmetry

Projected data:

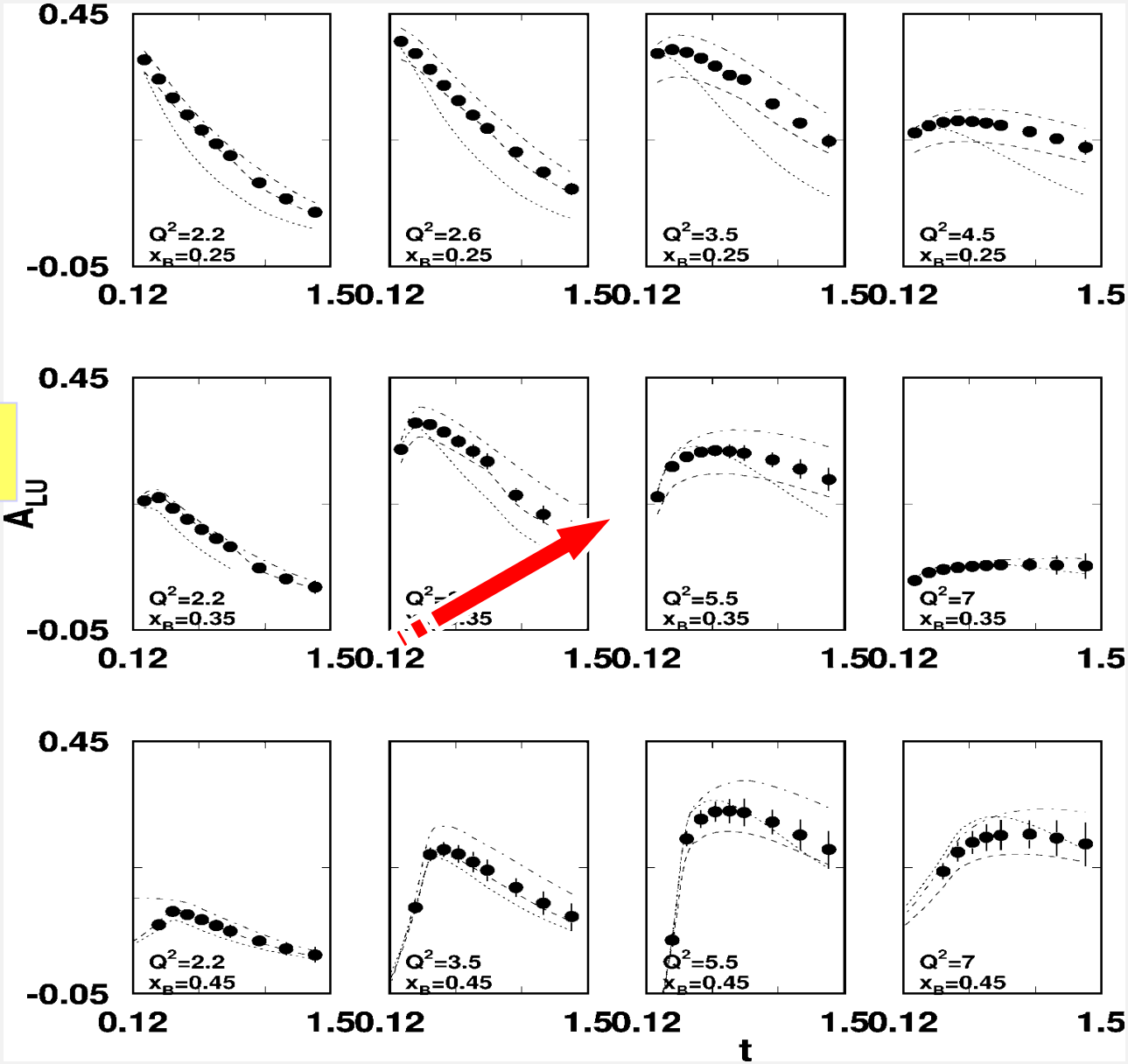
$\vec{e}\,p \longrightarrow ep\gamma$

E = 11 GeV

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

Integrated luminosity ~ 720 fb^{-1}

L = 1x10^{35}
T = 2000 hrs
ΔQ^2 = 1 GeV^2
Δx = 0.05



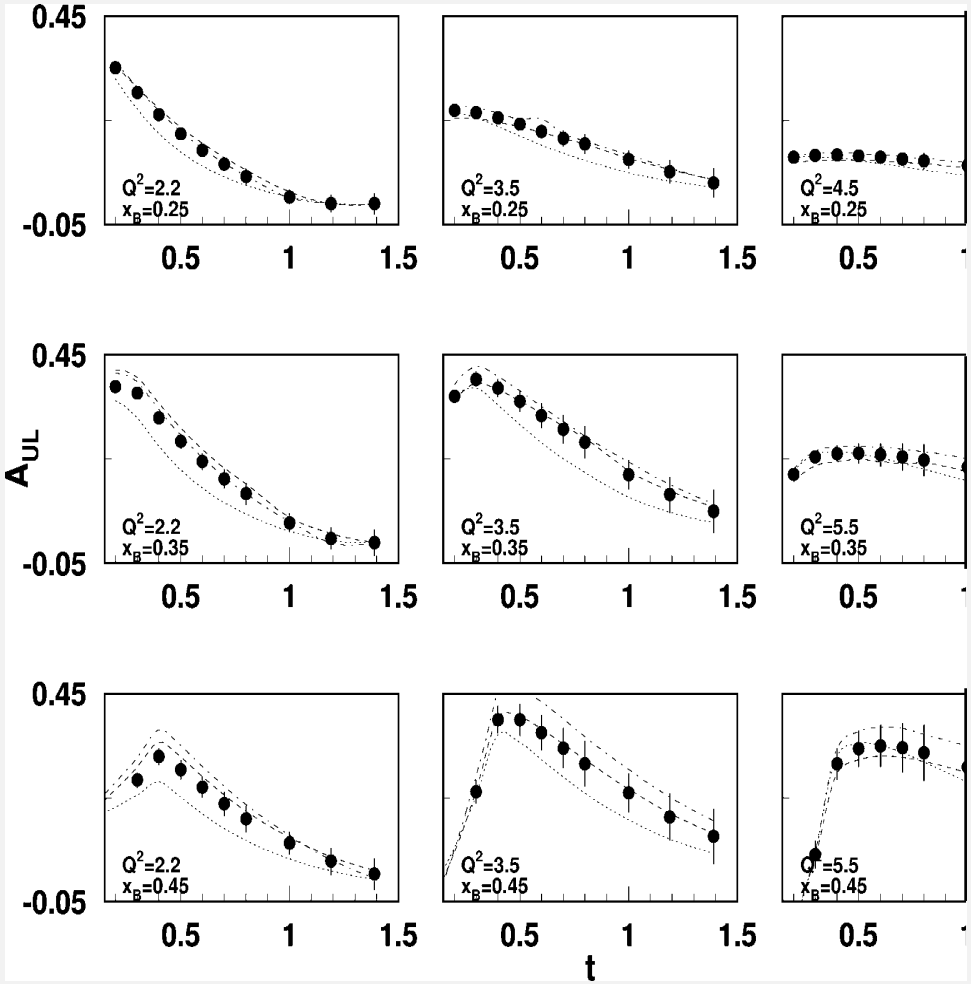
CLAS12 - DVCS/BH Target Asymmetry

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

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

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

Selected kinematics

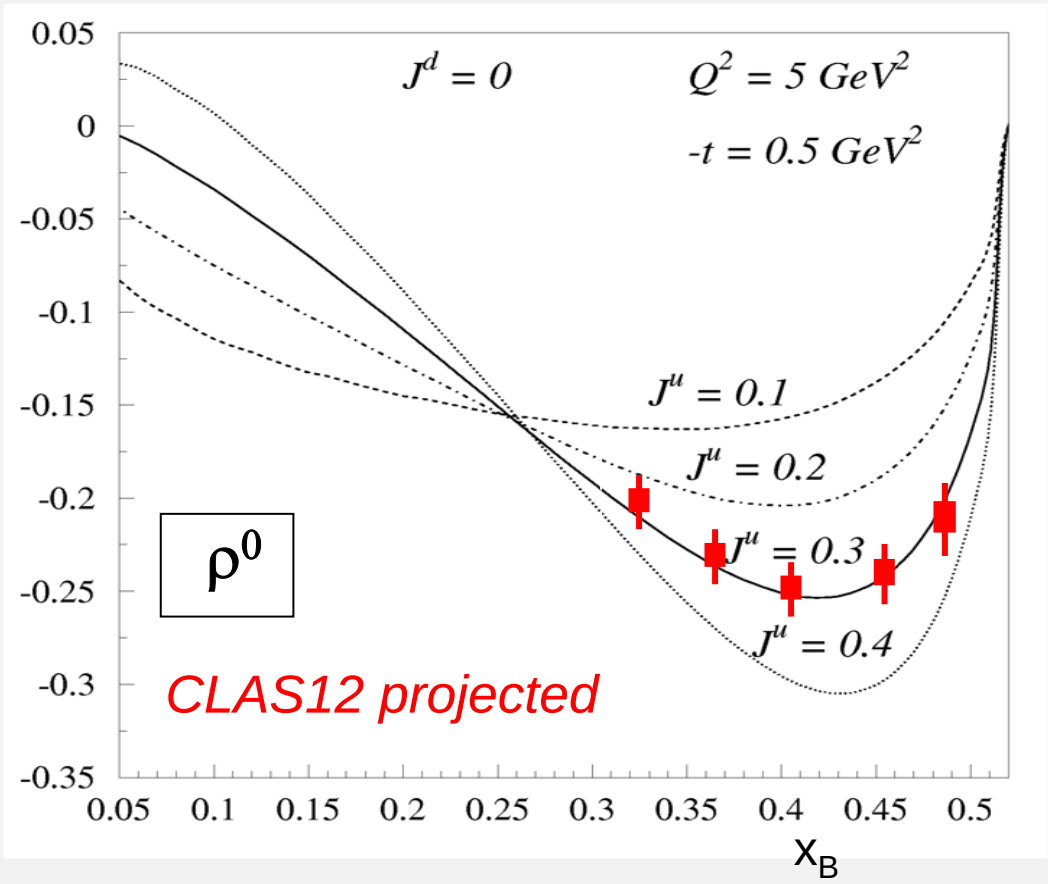


Exclusive ρ production on transverse target

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

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** in Ji's sum rule.

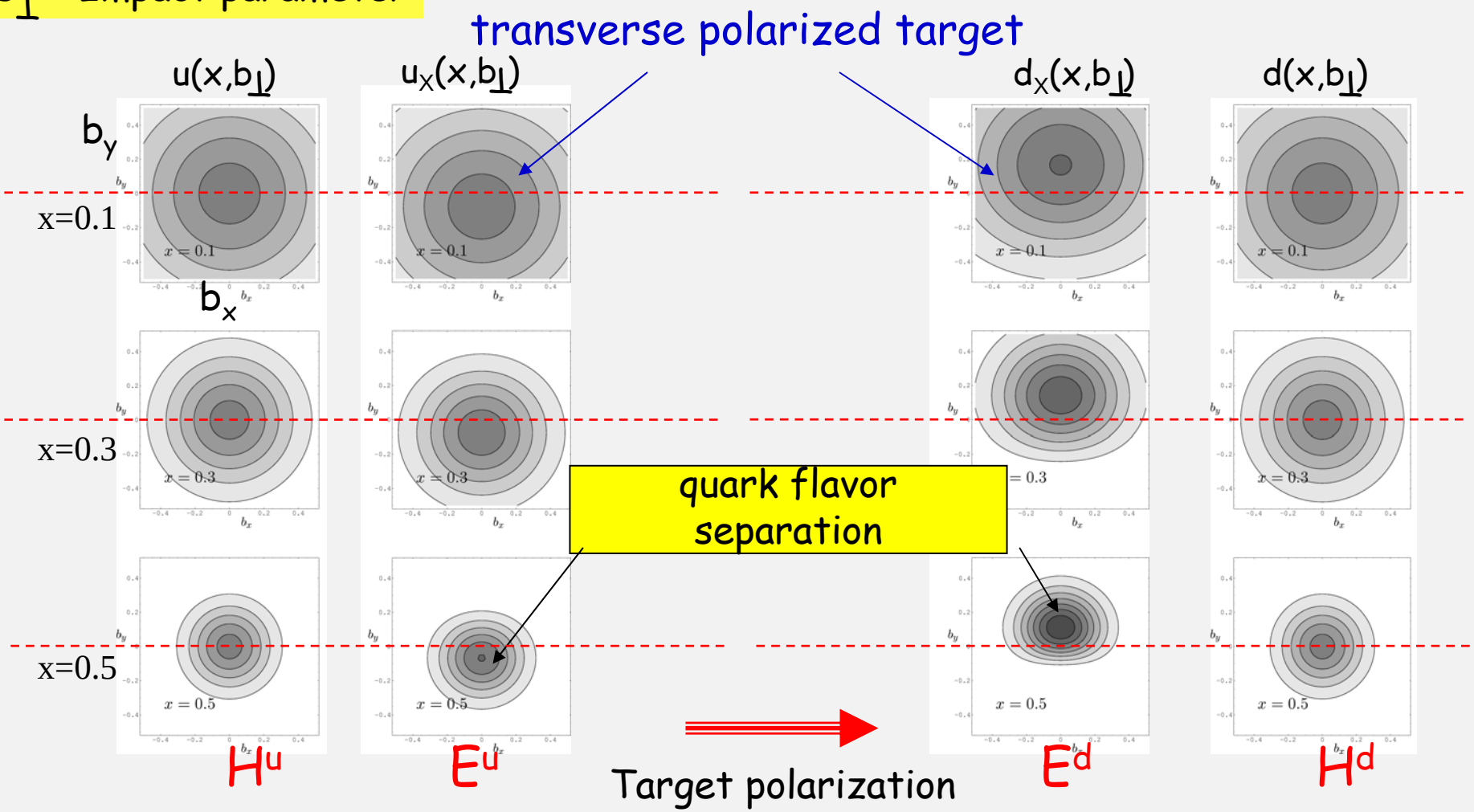
ρ^0 **and** ρ^+ measurements allow separation of E^u, E^d

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

Images of the Proton's Quark Content

M. Burkardt (2002)

$b_\perp$ - Impact parameter



Summary

- The discovery of Generalized Parton Distributions has opened up a new and exciting area of hadron physics that needs exploration in dedicated experiments.

- Moderate to high energy, very high luminosity, and large acceptance spectrometers are needed to measure GPDs in deeply virtual exclusive processes.

- The JLab 12 GeV Upgrade will provide the tools to do this well and explore the nucleon at a deeper level.