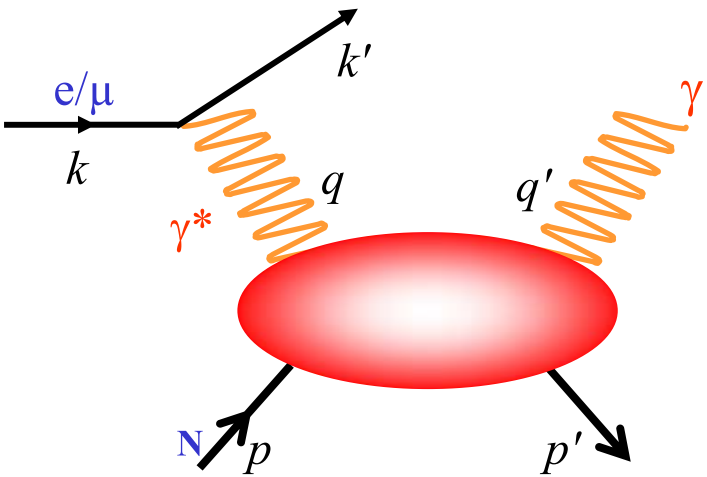
The 12 GeV program to measure Generalized Parton Distributions



$$Q^2 = -q^2 = -(k-k')^2$$
$$t = (p-p')^2 = (q'-q)^2$$
$$x_B = \frac{Q^2}{2p \cdot q}$$

Deeply Virtual Compton Scattering
is one of the key reactions,
indeed the simplest one,
to determine
Generalized Parton Distributions
experimentally.
Deeply Virtual Meson Production
is indispensable
to disentangle the **4 GPDs**
and their flavor decomposition

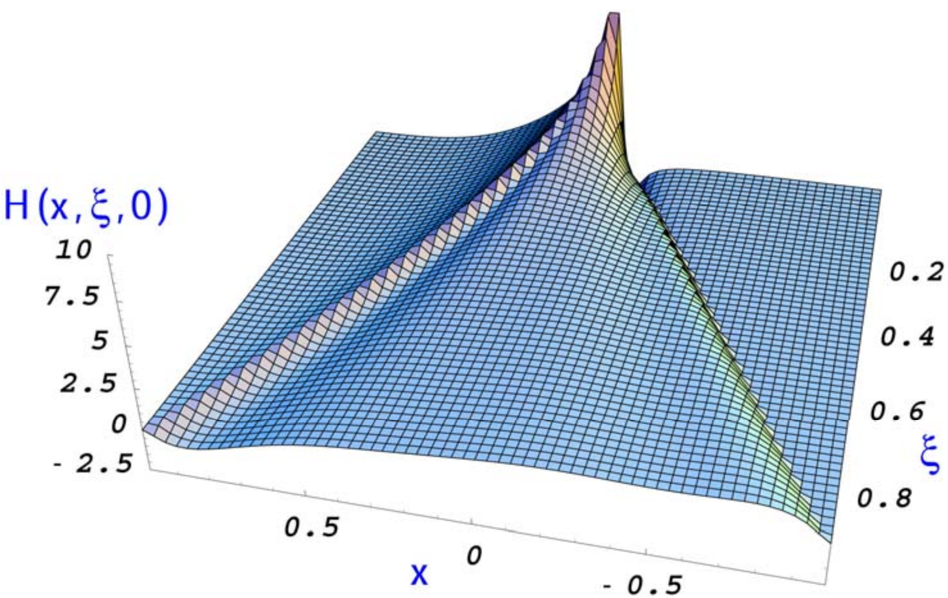
Generalized Parton Distributions: a richer concept of nucleon structure

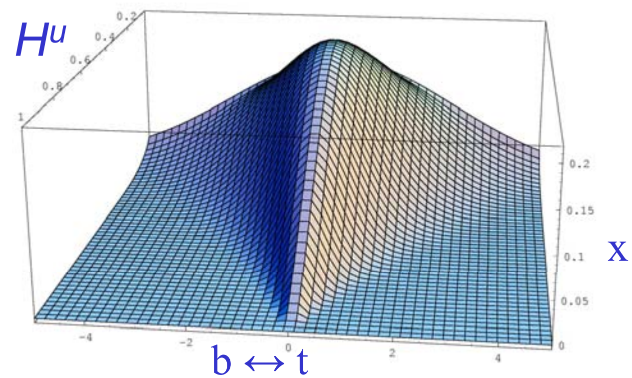
$H, \tilde{H}, E, \tilde{E}\ (x,\xi,t)$

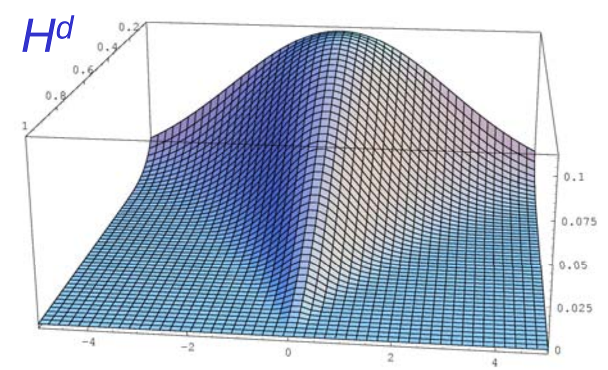
$x-\xi$ correlations

$x-t$ correlations

$\mathcal{F}\{H\ (x,0,t)\}$

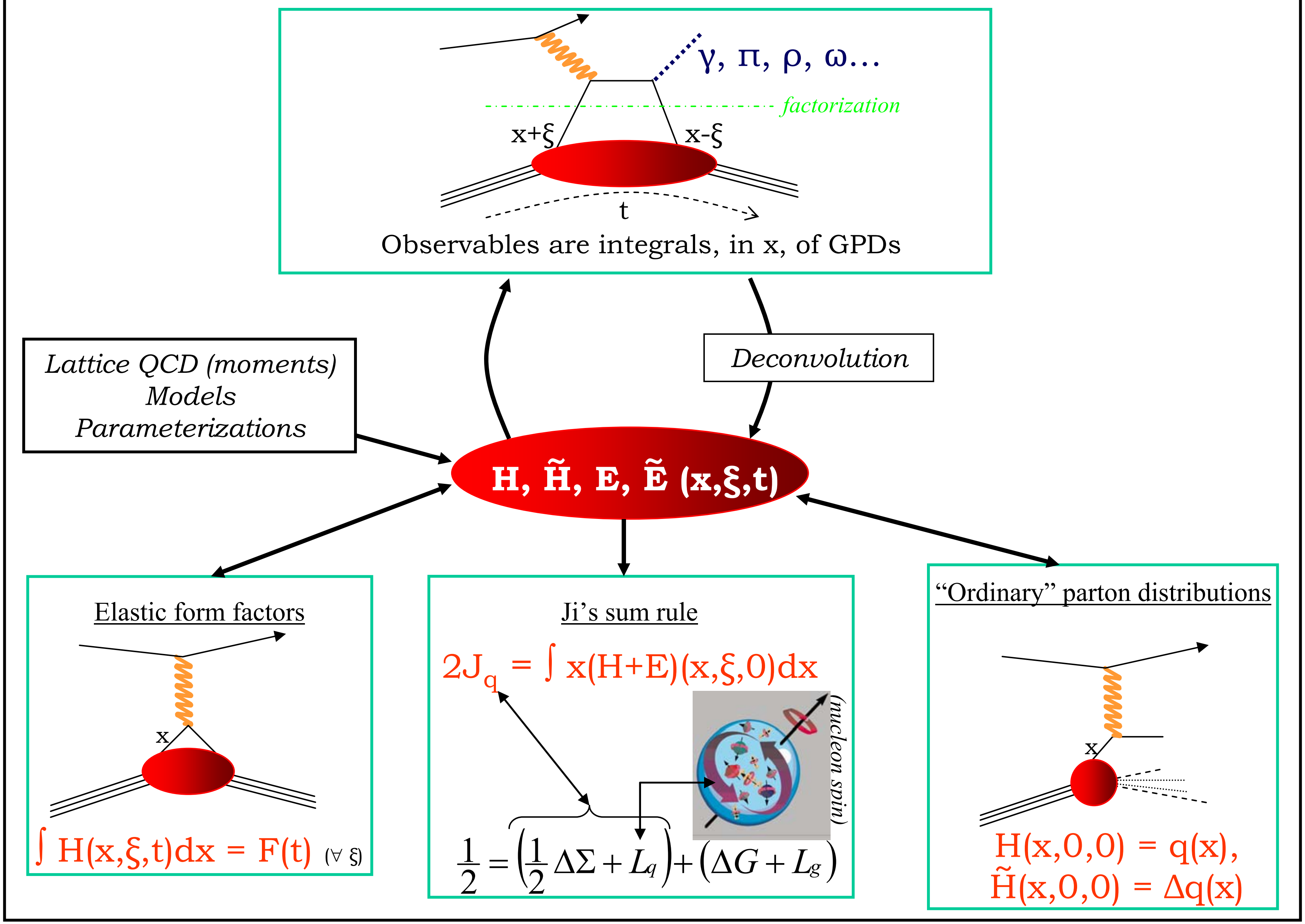






(M. Vanderhaeghen)

GPD: relation with observables & sum rules

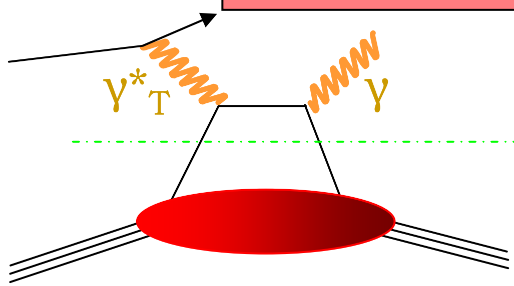


Classification of nucleon GPDs

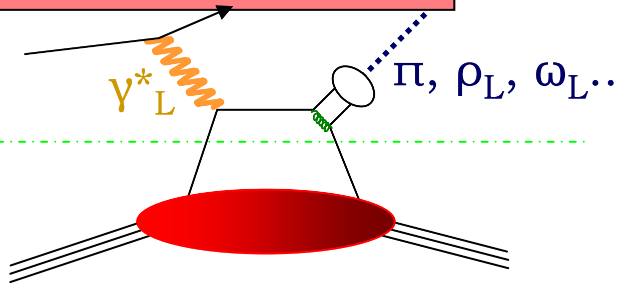
(Chiral-even GPDs only are considered here)

Legend: GPD (Forward limit; Operator at nucleon level; Corresponding form factor)		Operator at quark level
H — $q(x)$ — *Vector* — $F_1(t)$	**E** — – — *Tensor* — $F_2(t)$	Vector $\gamma^{-}_{\alpha\beta}$ **Quark helicity independent (or « unpolarized ») GPDs**
$\tilde{\mathbf{H}}$ — $\Delta q(x)$ — *Pseudo-vector* — $g_A(t)$	$\tilde{\mathbf{E}}$ — – — *Pseudo-scalar* — $h_A(t)$	Axial vector $\gamma^5\gamma^{-}_{\alpha\beta}$ **Quark helicity dependent (or « polarized ») GPDs**
Target helicity conserved	**Target helicity not conserved**	

How to measure GPD's?
Step 1: identify sensitive reactions



Factorization theorems



DVCS
(Virtual Compton)

- Sensitive to all H, E, $\tilde{H}$ and $\tilde{E}$
- Beam spin asymmetry $\rightarrow$ H(p) or E(n) at $x = \pm\xi$
- Target spin asymmetry (long.) $\rightarrow$ $\tilde{H}$ at $x = \pm\xi$,
- Target spin asymmetry (transv.) $\rightarrow$ also E
- Beam charge asymmetry $\rightarrow$ H
- leading order (twist-2) contribution
  dominates down to relatively low Q^2
- Cross sections:
  DVCS/BH increases when energy increases

DVMP
(Meson production)

- Pseudoscalar mesons $\rightarrow$ $\tilde{H}$, $\tilde{E}$
- Vector mesons $\rightarrow$ H, E *(the GPDs entering Ji's sum rule)*
- Different mesons $\rightarrow$ flavor decomposition of GPDs,
- Cross sections: necessary to extract σ_L ($\sim 1/Q^6$)
- Ratios $\sigma_L(\eta)/\sigma_L(\pi^0)$, $\sigma_L(\rho)/\sigma_L(\omega)$
- Asymmetries, e.g. with transverse polarized target
  $A_{UT}(\pi) \sim \tilde{H}\bullet\tilde{E}$, $A_{UT}(\rho) \sim H\bullet E$
- Such ratios and asymmetries may be less sensitive
  to higher-twist contributions.

How to measure GPDs ?

Step 2: how close is leading order to experiment ?

This is where we are

Experiment:

Test scaling laws (test of factorization, of dominance of handbag diagram)

e.g. for DVCS BSA: <sinΦ> ~ 1/Q, <sin2Φ> ~ $1/Q^2$

OK as of ~ 2 GeV^2

for DVMP : $d\sigma_L/dt \sim 1/Q^6$

- theoretical expectation: scaling at higher Q^2
- is ρ apparent success (at the 50% level) real?

→ ***precision experiments, truly exclusive.***

JLab (Hall A & CLAS) dedicated DVCS experiments (2004-2005)

represent a quantitative and qualitative jump

C. Muñoz Camacho et al., PRL **97**, 262002; F.X. Girod et al, in preparation

Theory:

Calculate deviations from leading order, especially in DVMP

May other models (e.g. Regge, color dipole) mimic the handbag contribution?
If yes, what do we learn from this duality ?

How to measure GPDs ?
Step 3: from DVCS to GPDs - and to J

- Use model-independent formalism to extract (combinations of) GPDs at given kinematics.

  (caution: the existing formalism contains approximations of order

  $[4M^2 x_B{}^2/Q^2]^{3/2}$ which should be fixed – D. Mueller)

- Comparison of given GPD model (e.g. VGG) with experiment,

  Extract (model-dependent) information, e.g. on J_u, J_d

- Fit of parameterized GPDs with constraints:

  forward limit, elastic form factors, polynomiality, positivity bounds

  (exists at small x_B, but not yet in the valence sector)

  What is the "best" parameterization (double distributions, Mellin-Barnes moments, etc…)?

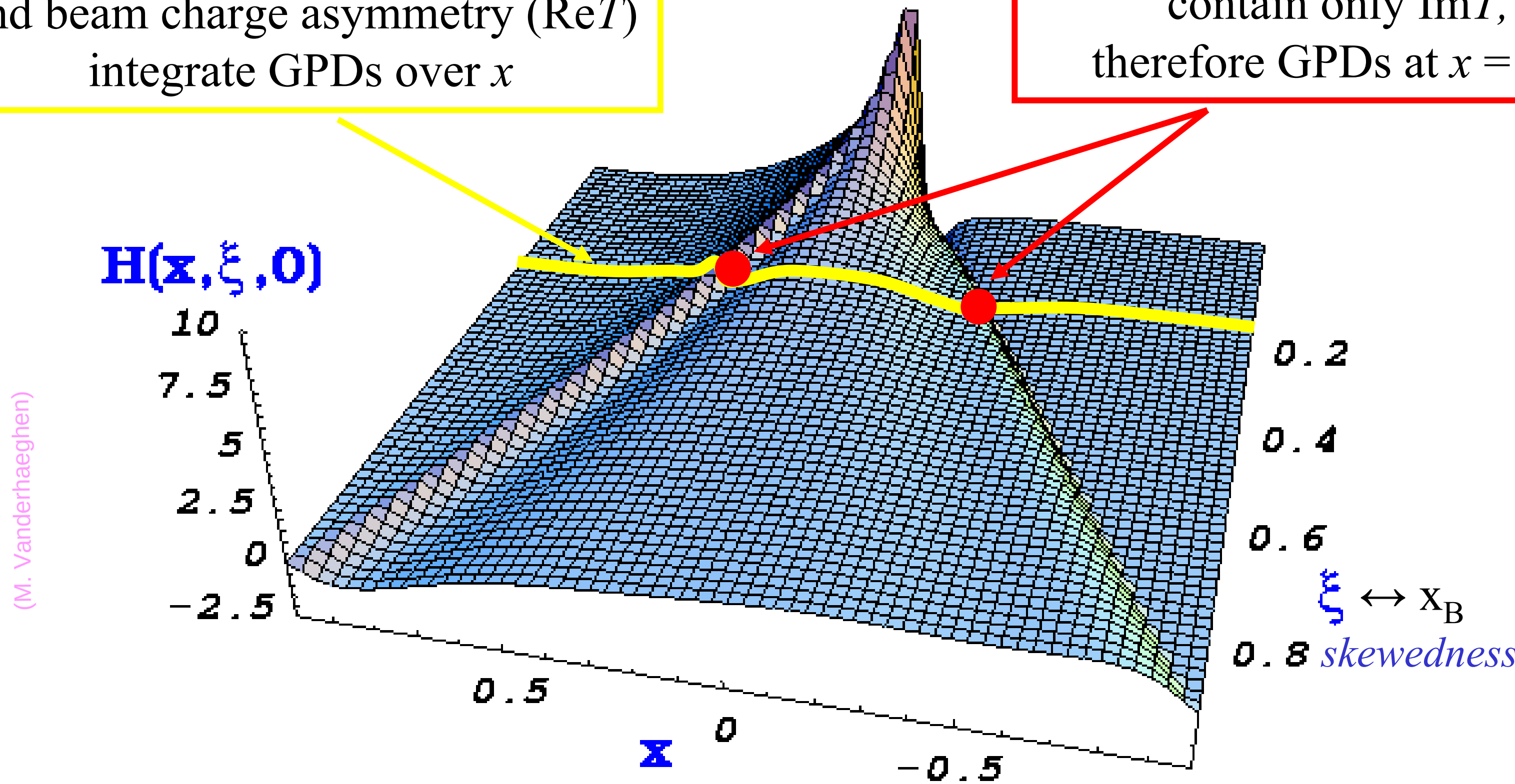
GPD and DVCS

(at leading order:)

$$T \sim \int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi - i\varepsilon} dx + \ldots \sim \quad \mathcal{P}\int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi} dx - i\pi H(\pm\xi,\xi,t) + \ldots$$

Cross-section measurement and beam charge asymmetry (ReT) integrate GPDs over x

Beam or target spin asymmetry contain only ImT, therefore GPDs at $x = \pm\xi$



Scale dependence and finite Q^2 corrections
(real world ≠ Bjorken limit)

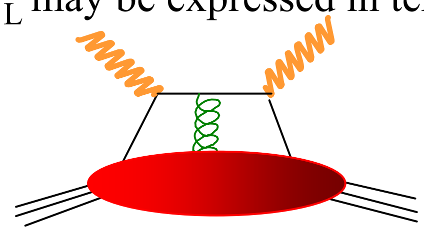
GPD evolution

Dependence on factorization scale μ :

$$\mu \frac{\partial}{\partial \mu} H(x,\xi,t;\mu) = \int \underbrace{K(x,y,\xi;\alpha_S(\mu))}_{\text{Kernel known to NLO}} H(y,\xi,t;\mu)dy$$

Evolution of hard scattering amplitude

***O* (1/Q)**

- (Gauge fixing term)
- Twist-3: contribution from γ^*_L may be expressed in terms of derivatives of (twist-2) GPDs.
- Other contributions such as  small (but measureable effect).

***O* (1/Q^2)**

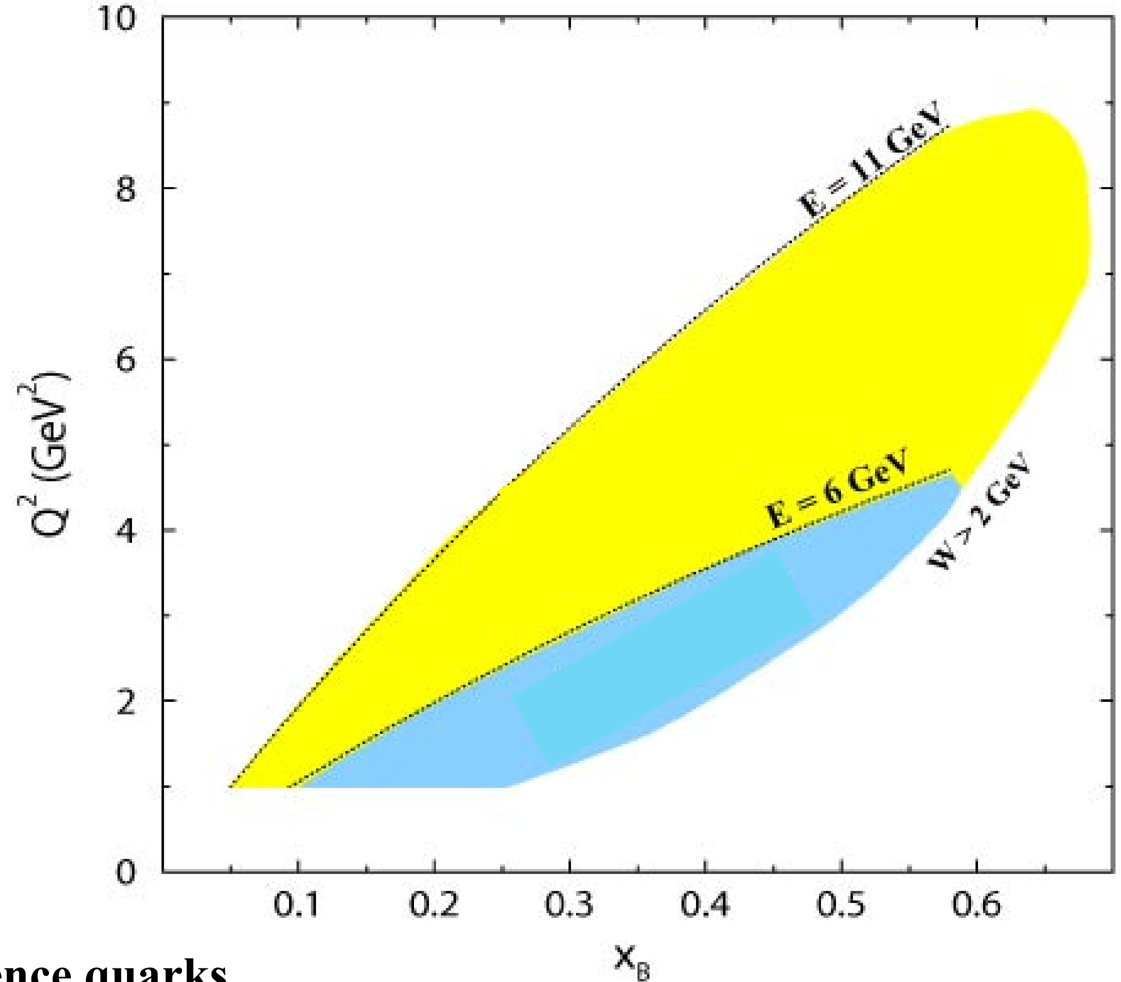
- "Trivial" kinematical corrections, of order $\frac{t}{Q^2}, \frac{M^2}{Q^2}$

- Quark transverse momentum effects (modification of quark propagator)

$$\frac{1}{x+\xi-i\varepsilon} \rightarrow \frac{1}{x+\xi+k_\perp^2/Q^2-i\varepsilon}$$

- Other twist-4 ……

From 6 to 11 GeV !

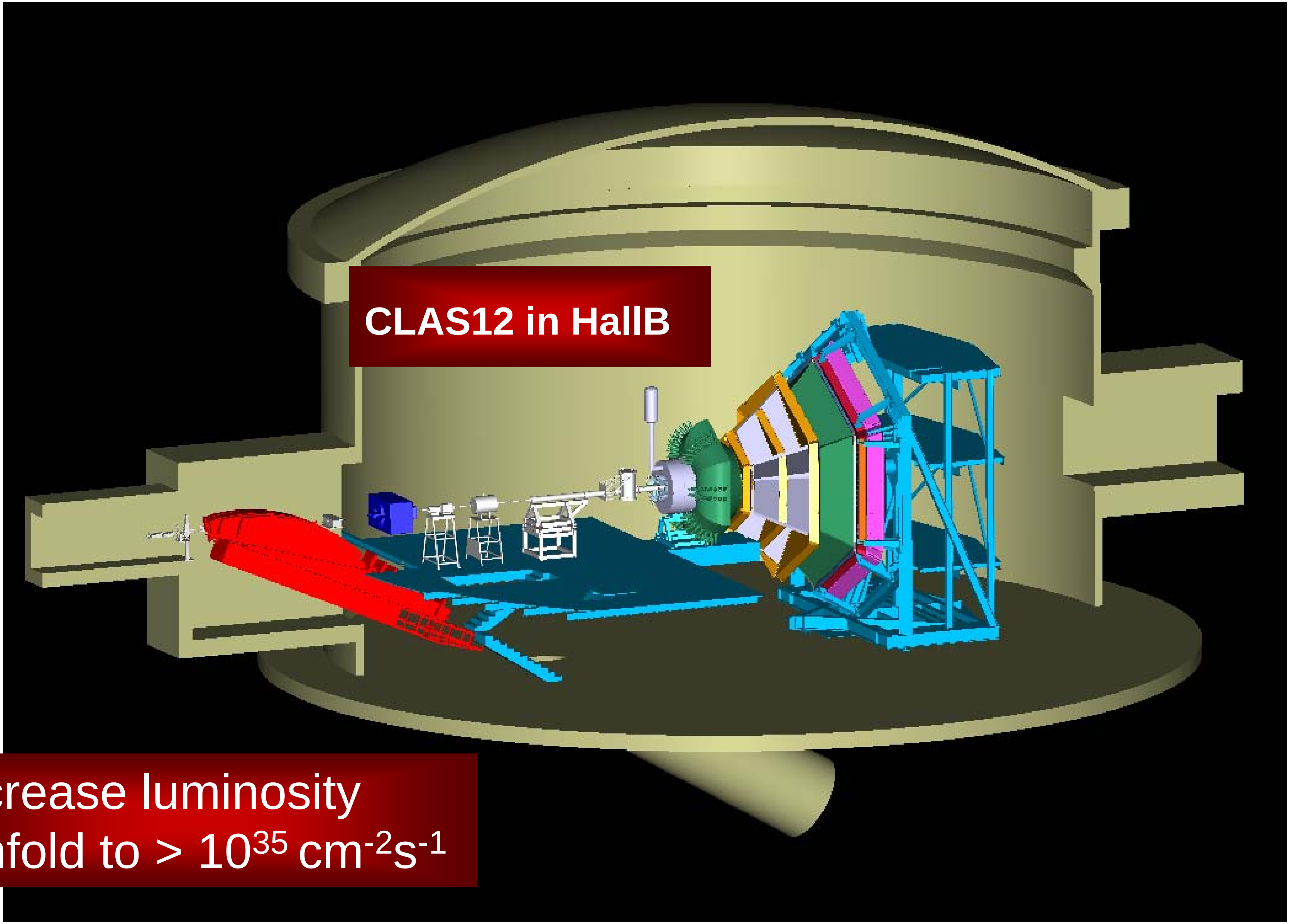


→ **Valence quarks**

→ **High x_B behaviour (important for GPD moments ↔ LQCD, J)**

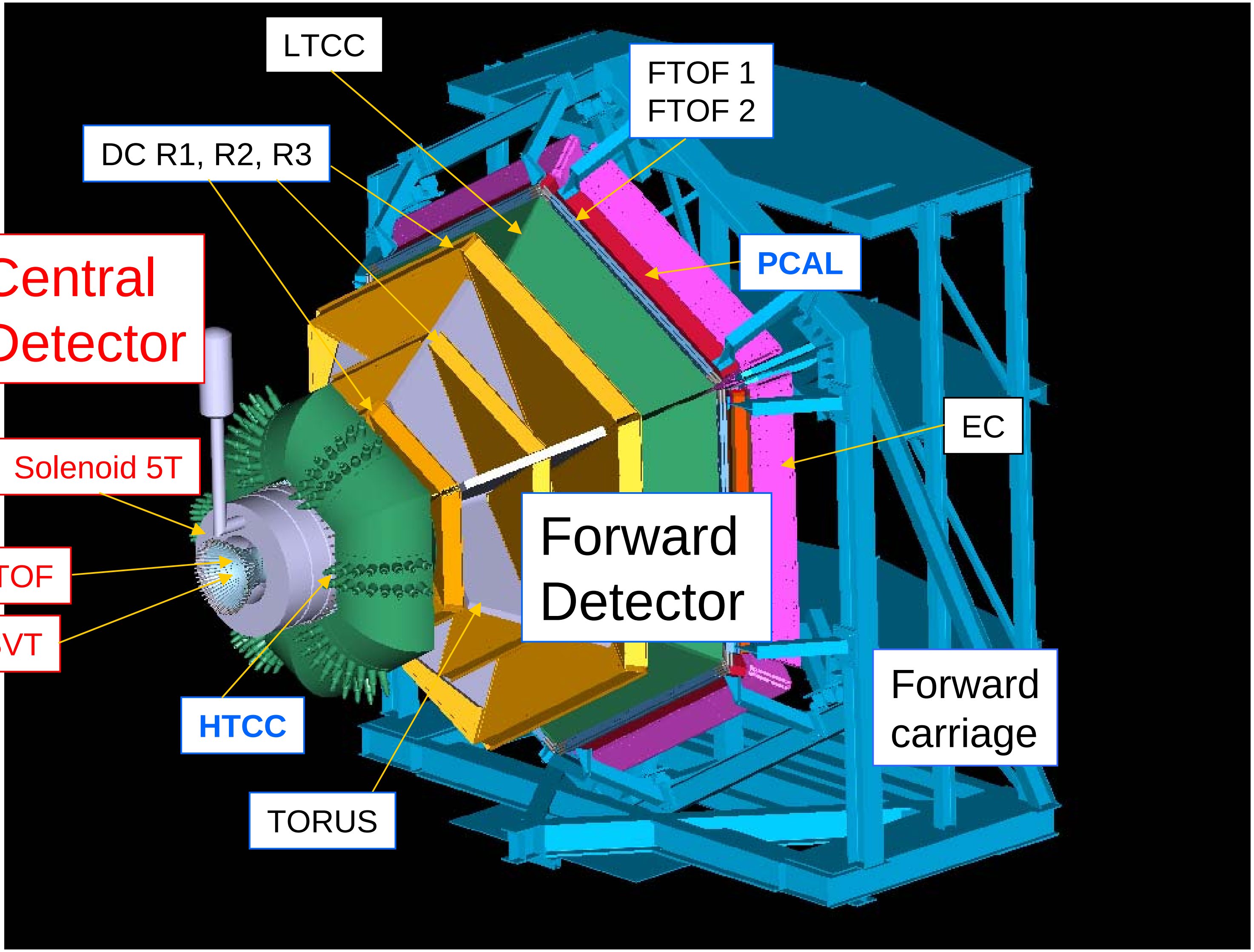
→ **Sea quarks (and gluons): overlap with HERMES & COMPASS**

→ **Extended Q^2 range for detailed scaling laws, and a must for DVMP**



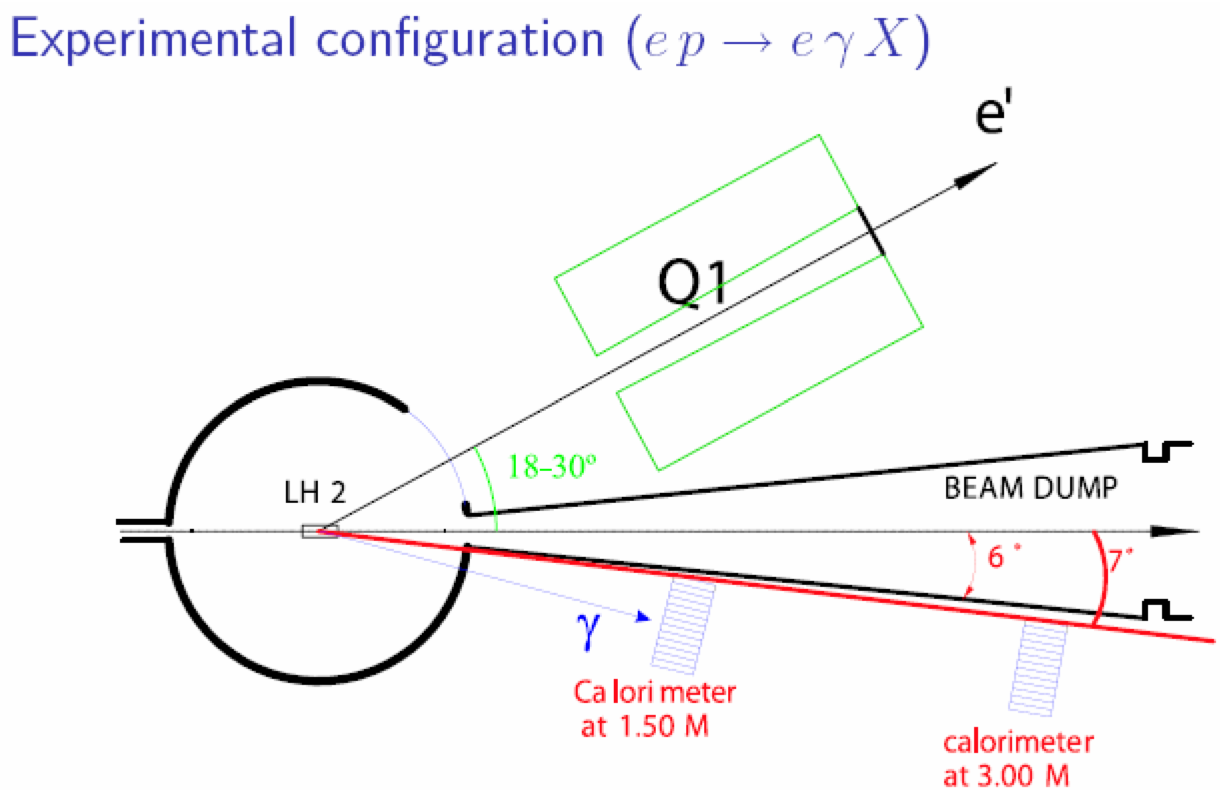
Increase luminosity tenfold to > 10^{35} $cm^{-2}s^{-1}$

CLAS12



Challenges: integration of (forward angle) inner calorimeter in tight space, radiation damage

Hall A



<u>Challenges</u>: accidentals and radiation damage, no redundant kinematical constraints

DVCS experiments at (or up to) 11 GeV

Polarized beam	*Target*	*Sensitive to GPD*	*Hall*
x	U	H possibly E at high t	A, B
-	L	H & $\tilde{H}$	B
-	T	E	B
x	n (d) U	E	A, B

Approved experiments

+ other ideas: positron beam → beam charge asymmetry ↔ H

measurement of proton recoil polarization ↔ H, $\tilde{H}$, E

+ DDVCS ?

DVCS and GPDs : beam spin asymmetry

(The imaginary part of the) DVCS-BH interference generates a

Beam-spin cross-section difference: $\Delta\sigma_{LU} = \left(\sigma^{+} - \sigma^{-}\right)/2 = \Gamma \cdot \left[s_1^I \sin\Phi + \ldots\right]$

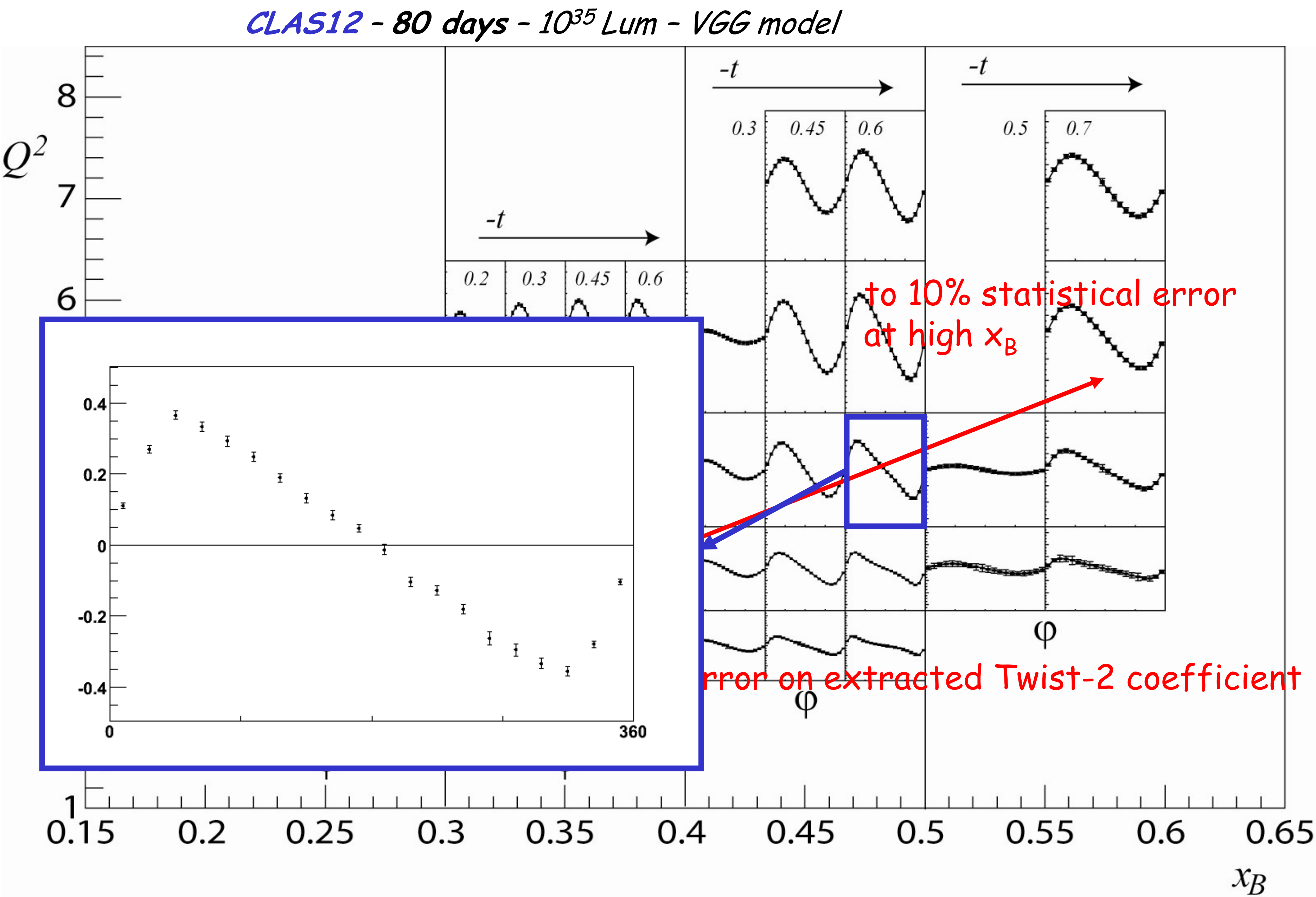
$$\boxed{s_1^I \propto \underline{F_1(t) \cdot \mathrm{H}} + \frac{x_B}{2 - x_B}\left[F_1(t) + F_2(t)\right] \cdot \widetilde{\mathrm{H}} - \frac{t}{4M^2} F_2(t) \cdot \mathrm{E}}$$

$$(\mathrm{H}, \widetilde{\mathrm{H}}, \mathrm{E}, \widetilde{\mathrm{E}}) = \pi \sum_q e_q^2 \left[GPD^q(\xi, \xi, t) \pm GPD^q(-\xi, \xi, t)\right]$$

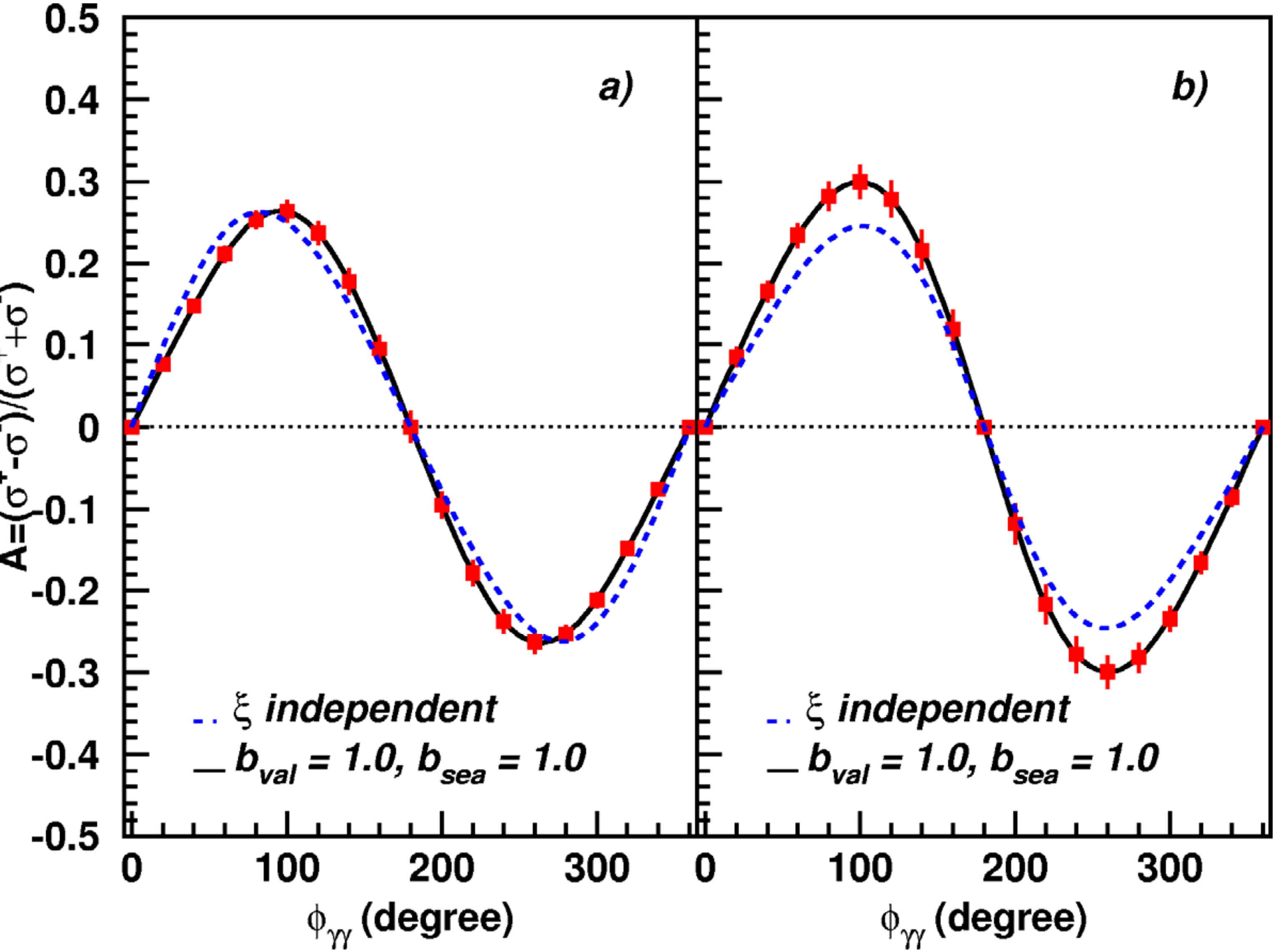
or an asymmetry: $\mathrm{A}_{LU} = \dfrac{\sigma^{+} - \sigma^{-}}{\sigma^{+} + \sigma^{-}}$

The sinusoidal behaviour is characteristic of the interference BH-DVCS

Beam Spin Asymmetry



DVCS/BH projected for CLAS12 at 11 GeV

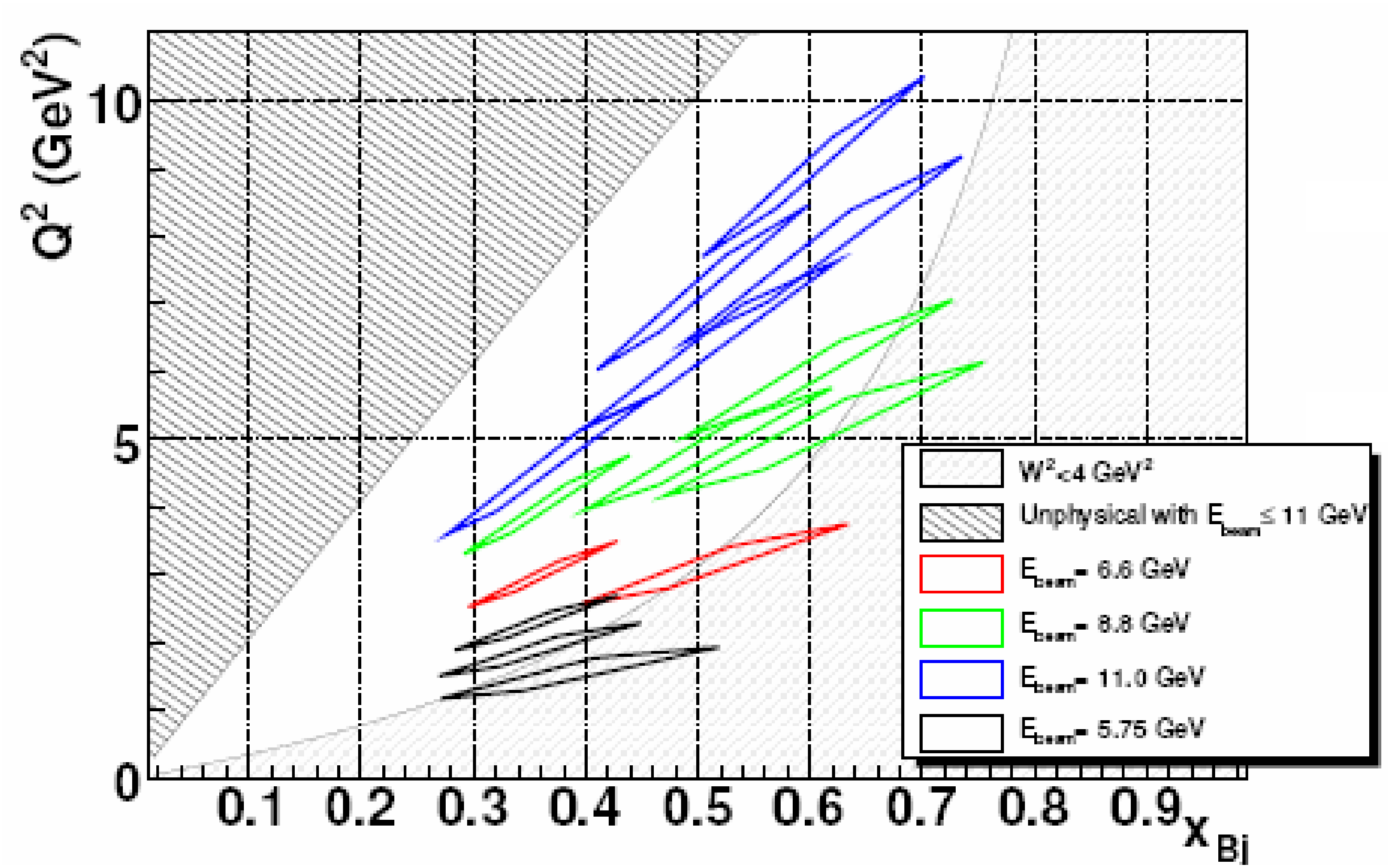


972 data points measured simultaneously

Q^2, x_B, t ranges measured simultaneously.

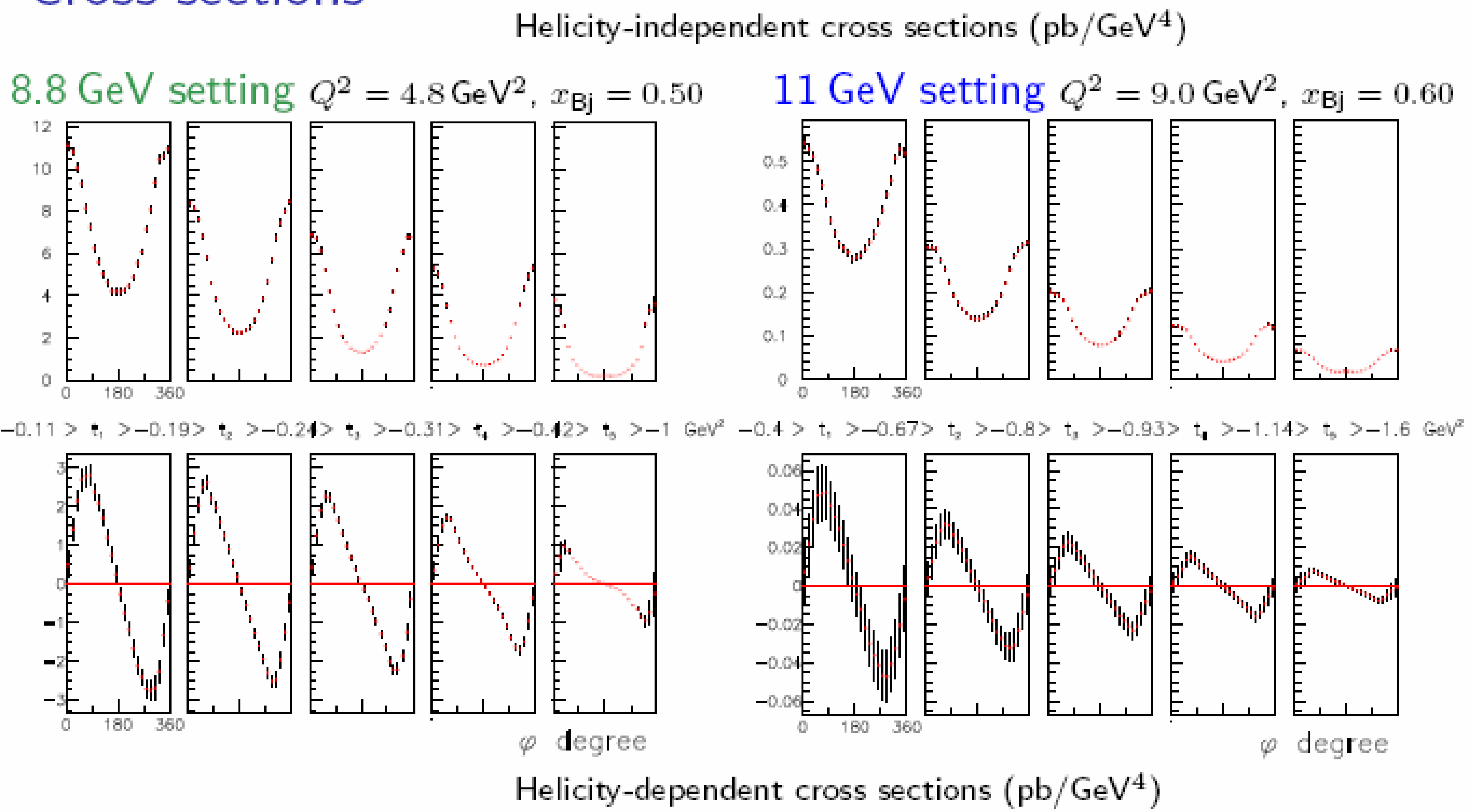
$A(Q^2,x_B,t)$
$\Delta\sigma_{LU}(Q^2,x_B,t)$
$\sigma(Q^2,x_B,t)$

DVCS/BH projected for Hall A



DVCS/BH projected for Hall A

Cross sections



Asymmetries and/or cross sections ?
A_{LU}, $\Delta\sigma_{LU}$, σ

An evidence: there is more information in numerator and denominator than in their ratio.

Need precise cross sections at selected kinematics to determine contributing terms, and to firmly anchor future fits.

Precise asymmetries over a wide kinematical range will constrain the kinematical dependences of all terms.

All the observables will contribute significantly to a future global fit.

DVCS Target Spin Asymmetries

$$A_{UL} \propto \underline{F_1 \cdot \widetilde{\mathrm{H}}} + \frac{x_B}{2-x_B}\left[F_1 + F_2\right]\cdot\left[\underline{\mathrm{H}} + \frac{x_B}{2}\mathrm{E}\right] - \frac{x_B}{2-x_B}\left[\frac{x_B}{2}F_1 + \frac{t}{4M^2}F_2\right]\cdot\widetilde{\mathrm{E}}$$

The contributions from H and $\tilde{H}$ are about equal

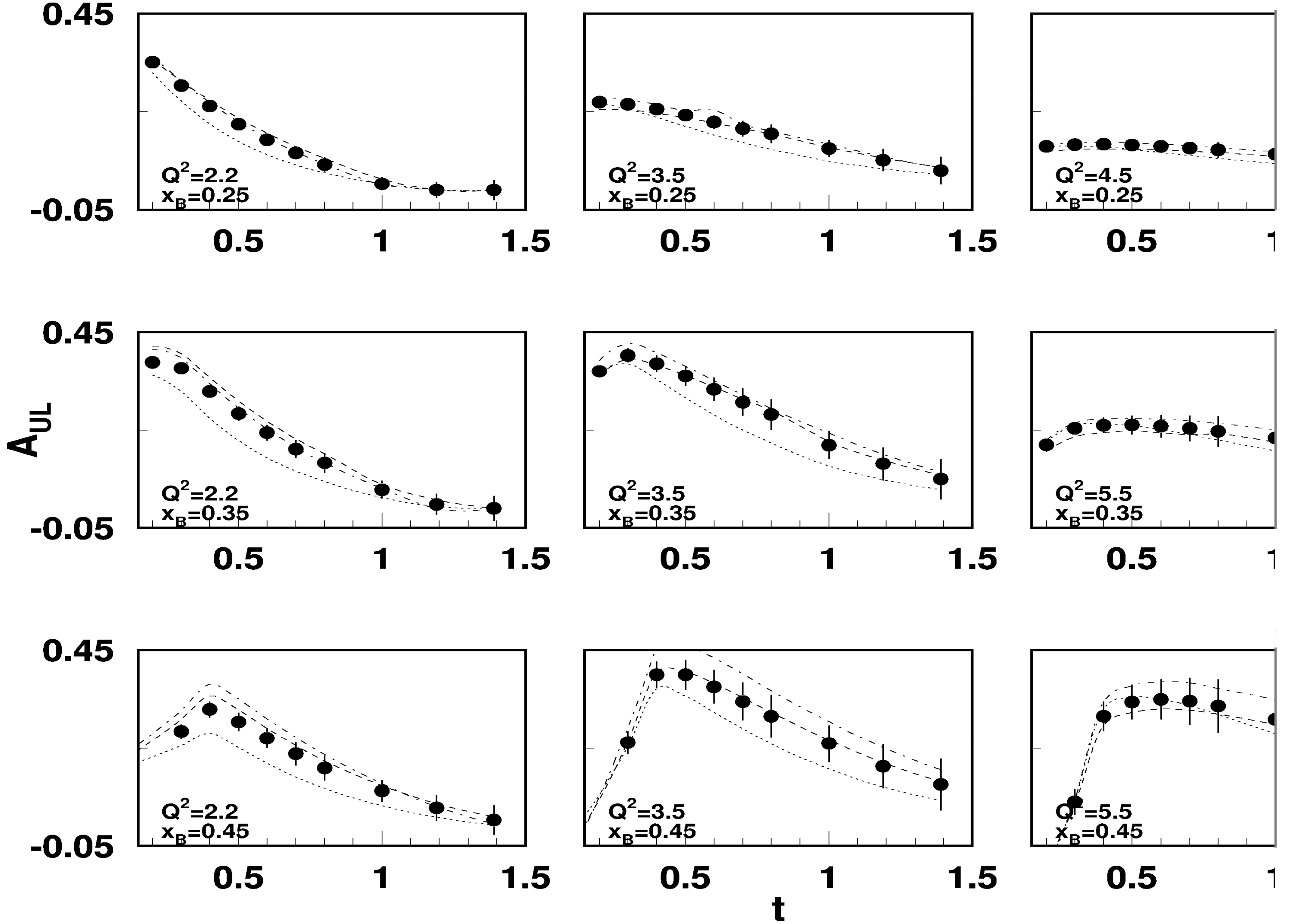
See CLAS data (S. Chen et al., PRL **97**, 262002).

$$A_{UT} \propto \frac{t}{2M^2}\left\{\underline{F_1 \cdot \mathrm{E}} - F_2 \cdot \mathrm{H}\right\} + x_B{}^2\left\{\cdots\right\}$$

Very sensitive to J (HERMES preliminary data).

CLAS studying the feasability of a transverse polarized target, NH_3 or HD (see also ρ production).

A_{UL}: Sensitivity to GPD models - sample of data points - CLAS12



CLAS12 - DVCS/BH Target Asymmetry

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

Transverse polarized target

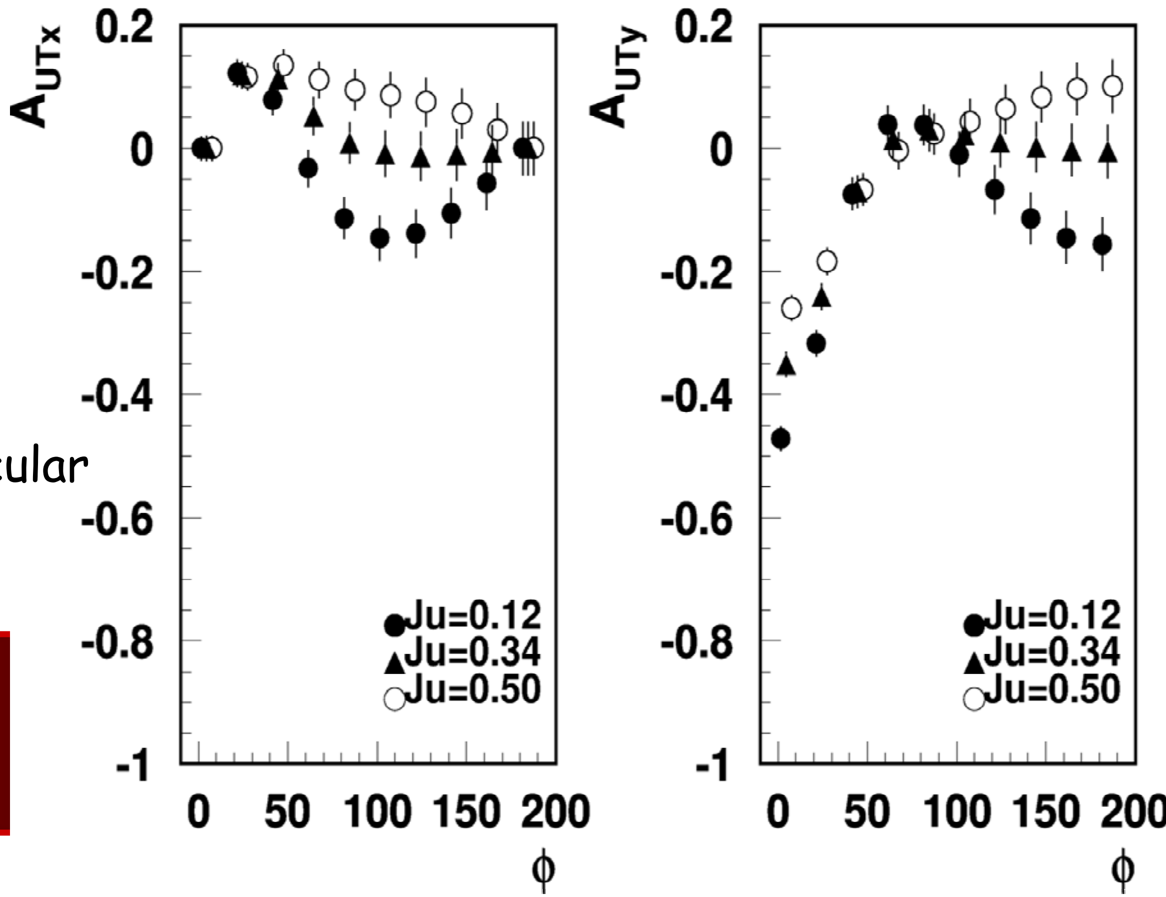
A_{UTx} Target polarization in the scattering plane

A_{UTy} Target polarized perpendicular to the scattering plane

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

Sample kinematics

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



DVCS on the neutron

Beam spin asymmetry

$$\Delta\sigma_{LU} = (\sigma^{+} - \sigma^{-})/2 = \Gamma \cdot \left[s_1^I \sin\Phi + \ldots \right]$$

$$\boxed{s_1^I \propto \underbrace{F_1(t)\cdot \mathrm{H}}_{\text{Main contribution for the proton}} + \frac{x_B}{2-x_B}\left[F_1(t)+F_2(t)\right]\cdot\widetilde{\mathrm{H}} - \underbrace{\frac{t}{4M^2}F_2(t)\cdot \mathrm{E}}_{\text{Main contribution for the neutron}}}$$

DVCS $\Delta\sigma_{LU}$ on the neutron shows (within a model) **sensitivity to** **<u>quark angular momentum J</u>**

Studies for CLAS12 just started

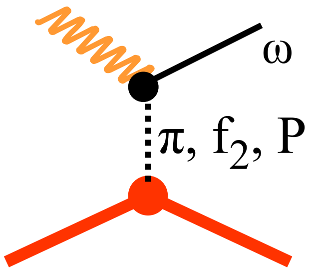
→ Add neutron detection in Central Detector

(modest efficiency)

→ Measure all three particles from e(n)→ enγ

Deeply virtual meson production: vector mesons ↔ H and E

Meson and Pomeron (or two-gluon) exchange …



ρ^0	(σ), f_2, P
ω	π, f_2, P
Φ	P

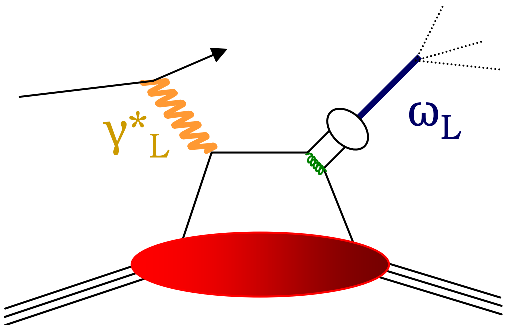
ω production shown to be dominated by π^0 exchange, for Q^2 up to 5 GeV^2

CLAS, EPJA **24** (2005)

… or scattering at the quark level ?

Flavor sensitivity of DVMP on the proton:

ρ^0	2u+d, 9g/4
ω	2u-d, 3g/4



ρ_L production in qualitative agreement with GPD calculations

HERMES, EPJC **17** (2002) **& CLAS**, PLB **605** (2005) + results to come soon

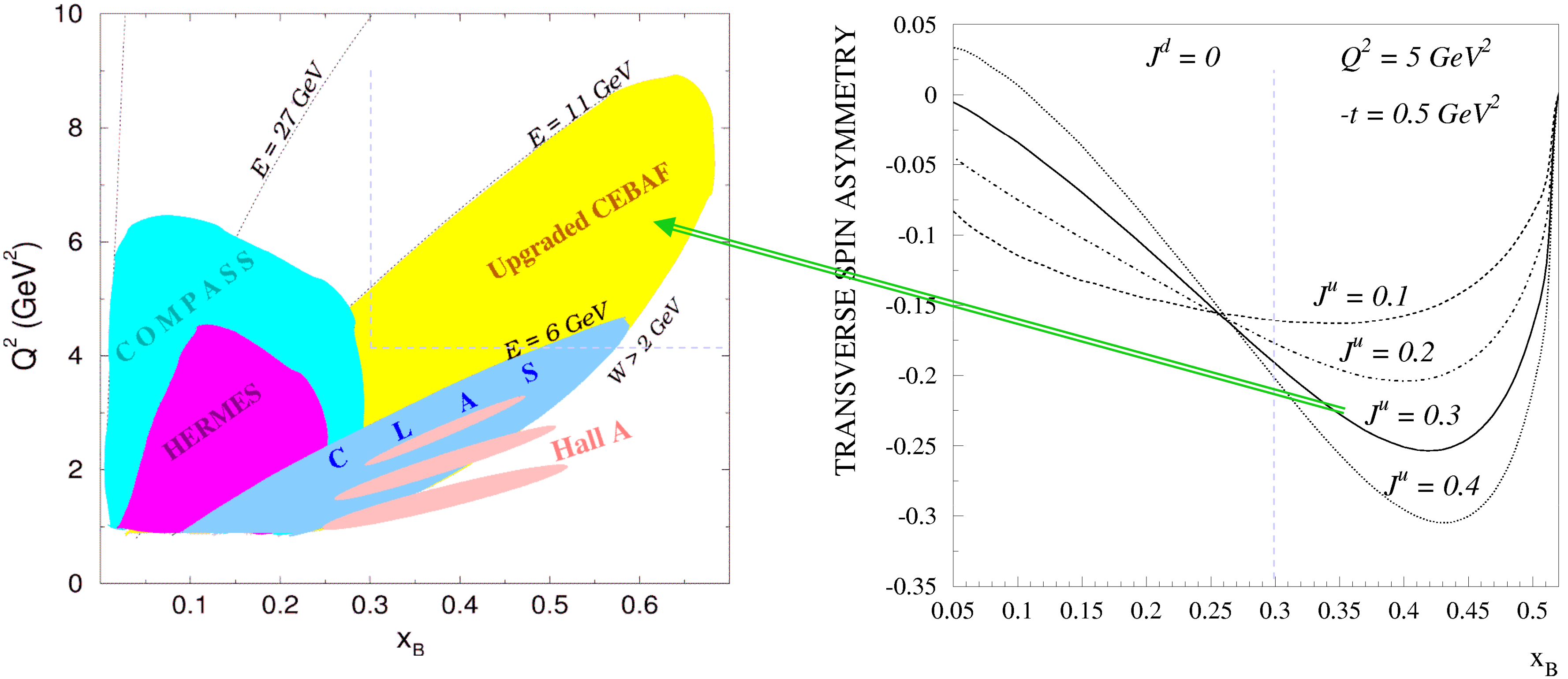
ρ^0/ω production with transverse polarized target

$$A_{UT} \propto \frac{\mathrm{Im}(\text{☟☜}^{*})}{|\text{☟}|^2\,(1-\xi^2) - |\text{☜}|^2\,(\xi^2 + t/4M^2) - 2\xi^2\,\mathrm{Re}(\text{☟☜}^{*})}$$

$$\text{☟}_{\rho} = \int_{-1}^{+1} \frac{dx}{\sqrt{2}} \left(e_u H^u - e_d H^d\right)\left[(x-\xi+i\varepsilon)^{-1} + (x+\xi-i\varepsilon)^{-1}\right]$$

Asymmetry depends linearly on the GPD *E*, which enters in Ji's sum rule. High x_B contribute significantly.

$\gamma_L^* + p \rightarrow \rho_L^0 + p$

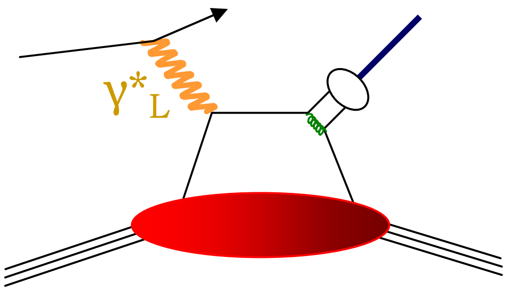


ω_L has similar sensitivity to proton quark spin

Deeply virtual meson production: pseudoscalar mesons ↔ $\tilde{H}$ and $\tilde{E}$

Flavor sensitivity of DVMP on the proton:

π^0	$2\Delta u + \Delta d$
η	$2\Delta u - \Delta d + 2\Delta s$
π^+	$\Delta u - \Delta d$



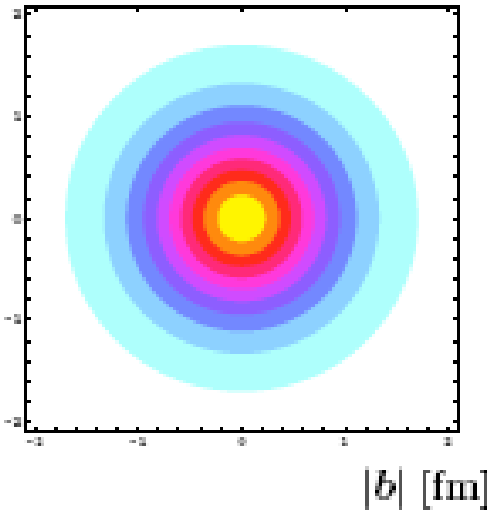
$$\frac{d\sigma_L}{dt} \propto \frac{1}{Q^4}\left[\frac{\alpha_S}{Q}\sum\iint\frac{\psi_M(z)}{z}\frac{1}{x\pm\xi-i\varepsilon}(a\tilde{H}+b\tilde{E})(x,\xi,t)dxdz\right]^2 \propto \frac{f(\xi,t)}{Q^6}$$

(Evidence from CLAS and Hall A at 6 GeV that σ_L does not dominate)

Nucleon Structure: the emerging picture

Gluons:

from an analysis of HERA data
($x \sim 10^{-3}$)



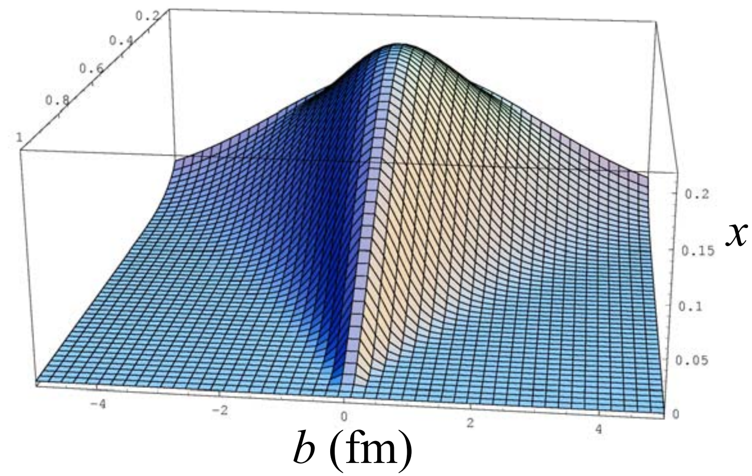
$$\left\langle b^2 \right\rangle^{\frac{1}{2}} \approx 0.85 \text{ fm}$$

(40-50% larger than proton charge radius)

D. Mueller, hep-ph/0605013

Quarks:

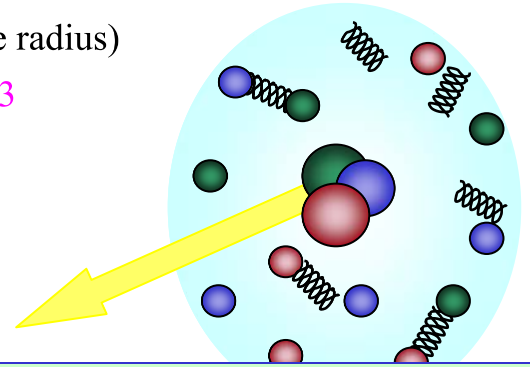
Qualitatively from lattice calculations and
from Regge inspired GPD parameterizations



$$H^q(x,0,t) = q_v(x) x^{-\alpha'_1(1-x)t}$$

M. Guidal et al., PRD **72** (2005)

QCDSF, PRL **92** (2004)



Differentiate the spatial distribution of valence quarks, sea quarks and gluons

Dedicated DVCS experiments

JLab / Hall A (p, n, $\Delta\sigma_{LU}$) **2004** **2009**

JLab / CLAS (p, A_{LU}, A_{UL}) **2005** **2008**

DESY/HERMES (p, A_{LU}, A_C) **2006-07**

CERN/COMPASS (p, A_C) **> 2011**

JLab / CLAS12 & Hall A **> 2013**

Will GSI/PANDA contribute ? **> 2015**

Some conclusions

- DVCS a very promising tool to measure GPDs: (virtual) Compton scattering at the quark level unravels the nucleon structure

- Need a general fitting routine (theory!), as is done with PDFs

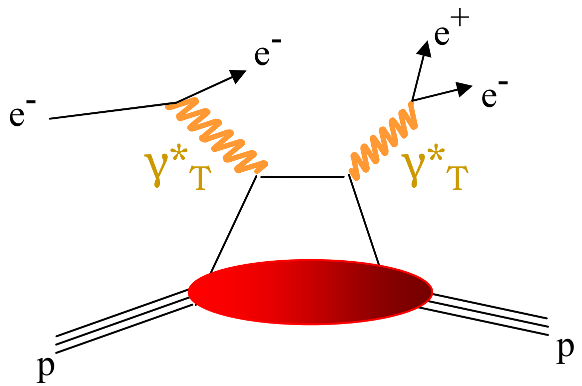
- DVMP more uncertain, but must be investigated

- CEBAF@12GeV has an ideal coverage in the valence quark sector (and some in the sea-quark sector)

- “Sister” distributions, such as TMDs, TDAs, will be investigated as well.

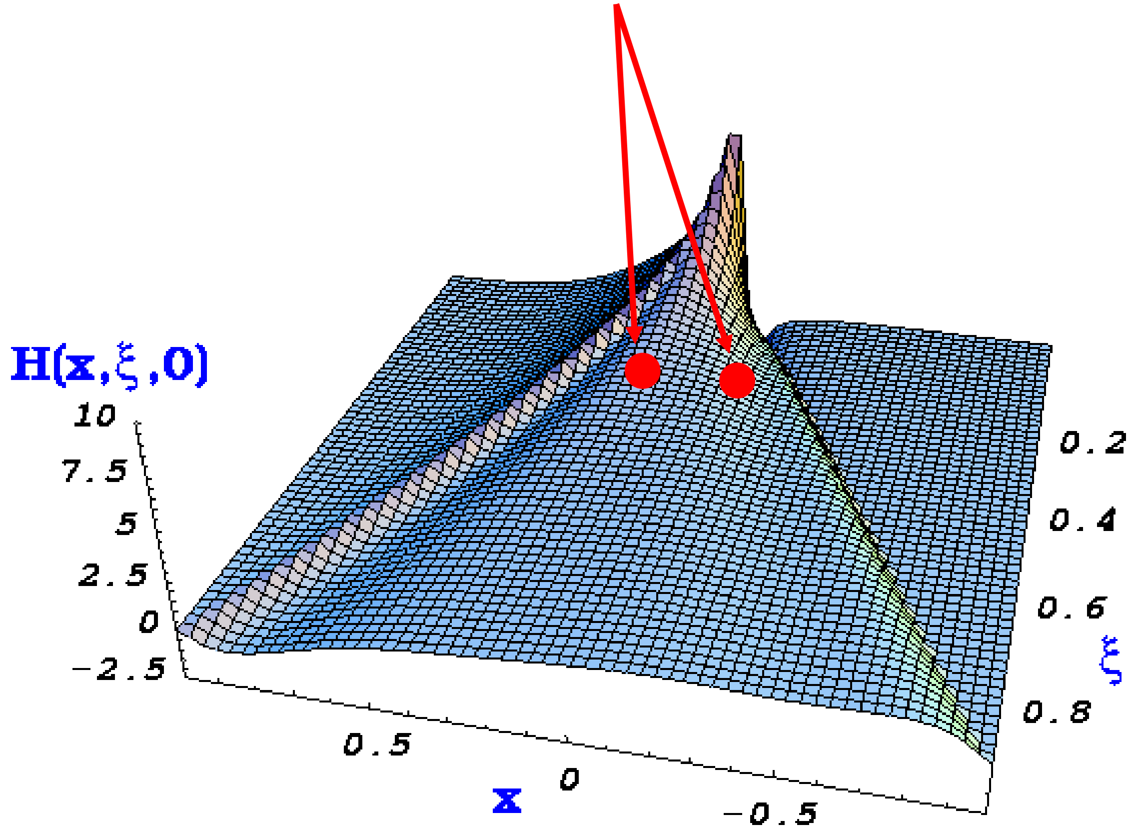
Additional slides

DDVCS
(Double Deeply Virtual Compton Scattering)



DDVCS-BH interference generates a **beam spin asymmetry** sensitive to

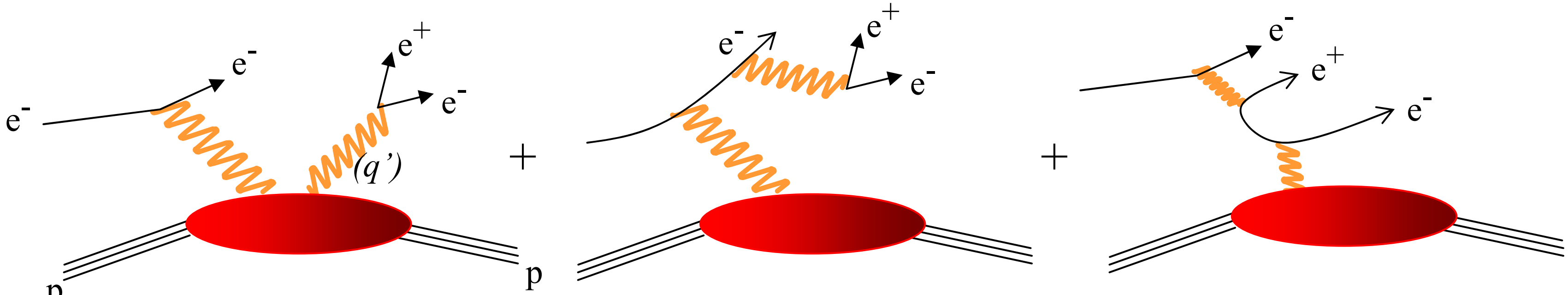
$$\mathrm{Im}\, T^{DDVCS} \sim H(\pm x(\xi, q'), \xi, t) + \ldots$$



The (continuously varying) virtuality of the outgoing photon allows to "tune" the kinematical point (x,ξ,t) at which the GPDs are sampled (with |**x** | < ξ).

M. Guidal & M. Vanderhaeghen, PRL 90
A. V. Belitsky & D. Müller, PRL 90

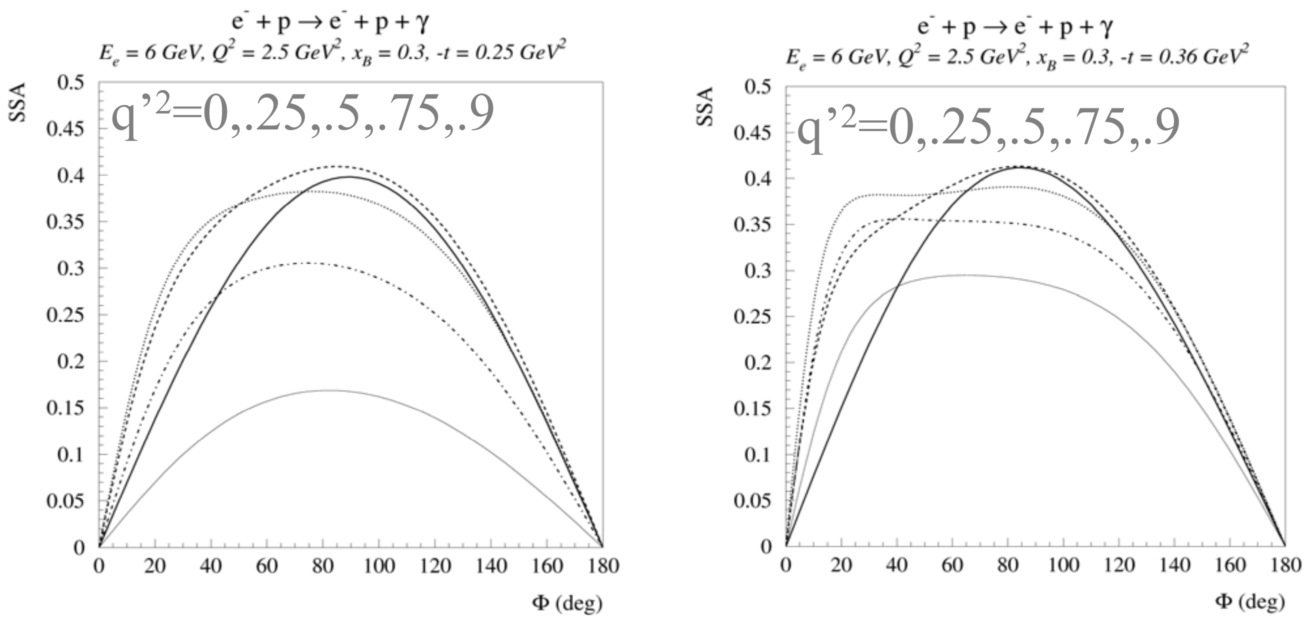
DDVCS: (integrated) beam spin asymmetry



DDVCS ***Bethe-Heitler***

interference leads to a <u>beam spin asymmetry</u>:

Calculations by Guidal and Vanderhaeghen

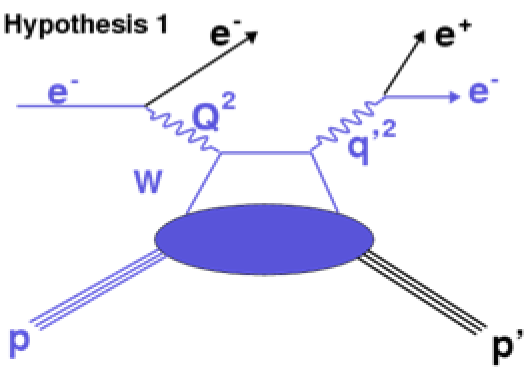


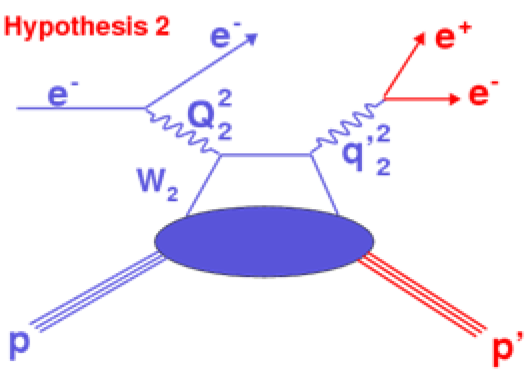
We made an implicit hypothesis !

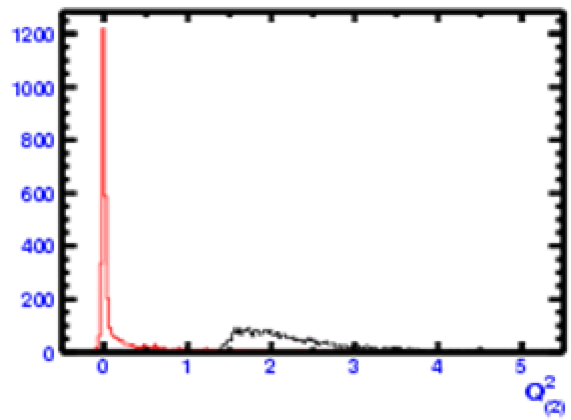
Why would the detected electron be the scattered one? It could be the $e^+ e^-$ one!

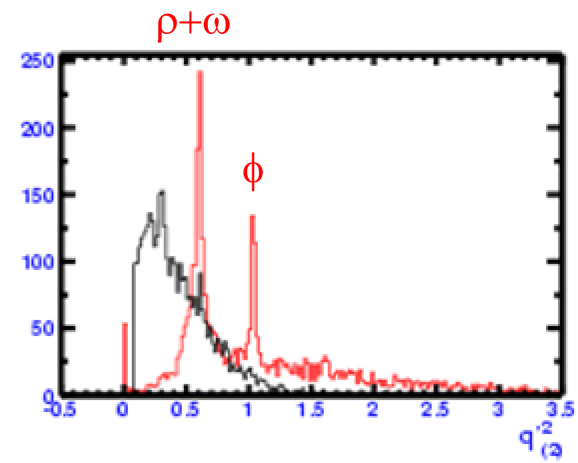
<u>Let us test both « hypothesis »:</u>

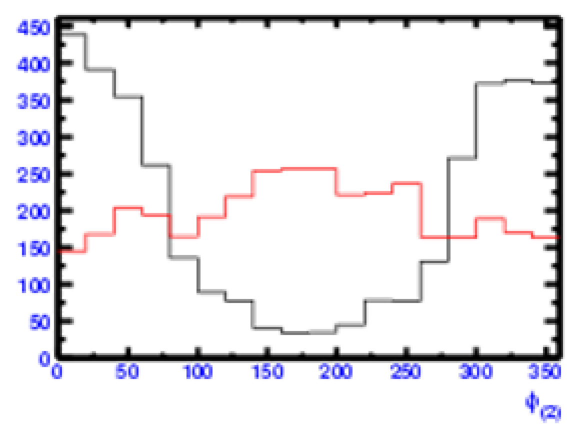
- Detected e^- is scattered electron
- Detected e^- is decay electron

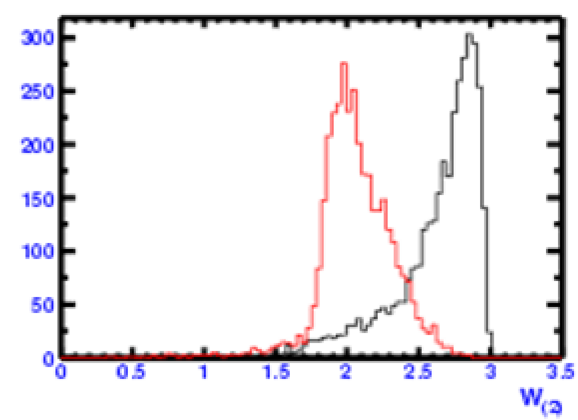












DDVCS: first observation of $ep \to epe^+e^-$

* **Positrons identified** among large background of positive pions

* **$ep \to epe^+e^-$ cleanly selected** (mostly) through missing mass $ep \to epe^+X$

* Φ distribution of outgoing γ^* and beam spin asymmetry extracted (integrated over γ^* virtuality)

but…

A problem for both experiment and theory:

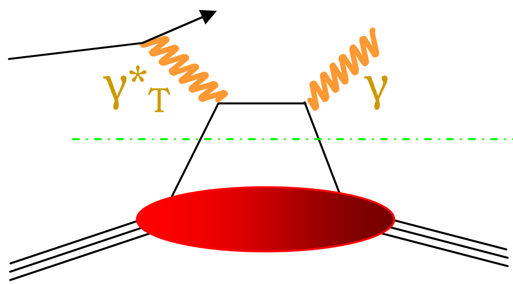
* 2 electrons in the final state → *antisymmetrisation* was not included in calculations,
→ define domain of validity for *exchange diagram*.

* data analysis was performed assuming two different hypotheses
either detected electron = scattered electron
or detected electron belongs to lepton pair from γ^*

Hyp. 2 seems the most valid → **quasi-real photoproduction of vector mesons**

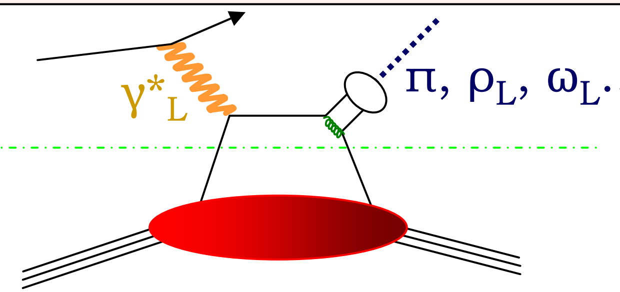
How to measure GPDs ?

Step 1: define observables sensitive to different GPDs (at leading order)



This is about done

Factorization theorems



DVCS (Virtual Compton)

- Sensitive to all H, E, $\tilde{H}$ and $\tilde{E}$
- Beam spin asymmetry → H(p) or E(n) at $x = \pm\xi$
- Target spin asymmetry → $\tilde{H}$ at $x = \pm\xi$,
- Beam charge asymmetry → H
- leading order (twist-2) contribution may dominate down to relatively low Q^2

-Cross sections:

BH/DVCS decreases when E increases

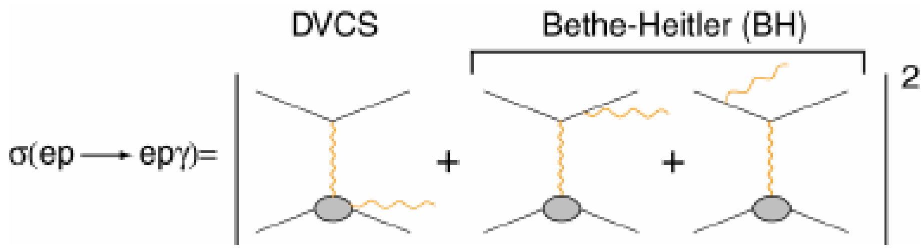
$\sigma(\mathrm{DVCS}) \sim 1/Q^4$

DVMP (Meson production)

- Pseudoscalar mesons → $\tilde{H}$, $\tilde{E}$
- Vector mesons → H, E *(the GPDs entering Ji's sum rule)*
- Different mesons → flavor decomposition of GPDs,
- Cross sections: necessary to extract σ_L ($\sim 1/Q^6$)
- Ratios $\sigma_L(\eta)/\sigma_L(\pi^0)$, $\sigma_L(\rho)/\sigma_L(\omega)$
- Asymmetries, e.g. with transverse polarized target $A_{UT}(\pi) \sim \tilde{H}\bullet\tilde{E}$, $A_{UT}(\rho) \sim H\bullet E$
- Such ratios and asymmetries less sensitive to higher-twist contributions.

DVCS/BH interference

3. Experimentally, DVCS is undistinguishable with Bethe-Heitler



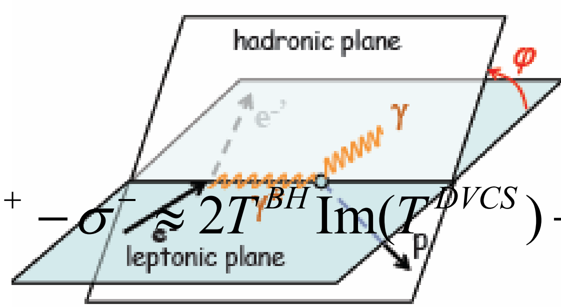
However, we know FF at low t and BH is fully calculable

Using a polarized beam on an unpolarized target, 2 observables can be measured:

$$\frac{d^4\sigma}{dx_B dQ^2 dt d\varphi} \approx \left|T^{BH}\right|^2 + 2T^{BH} \cdot \mathrm{Re}\left(T^{DVCS}\right) + \left|T^{DVCS}\right|^2$$

$$\frac{d^4\overrightarrow{\sigma} - d^4\overleftarrow{\sigma}}{dx_B dQ^2 dt d\varphi} \approx 2T^{BH} \cdot \mathrm{Im}\left(T^{DVCS}\right) + \left[\left|T^{\overrightarrow{DVCS}}\right|^2 - \left|T^{\overleftarrow{DVCS}}\right|^2\right]$$

At JLab energies, $|T^{DVCS}|^2$ is small



$$\sigma^+ - \sigma^- \approx 2T^{BH}\,\mathrm{Im}(T^{DVCS}) + \left|T_+^{DVCS}\right|^2 - \left|T_-^{DVCS}\right|^2$$

HERMES

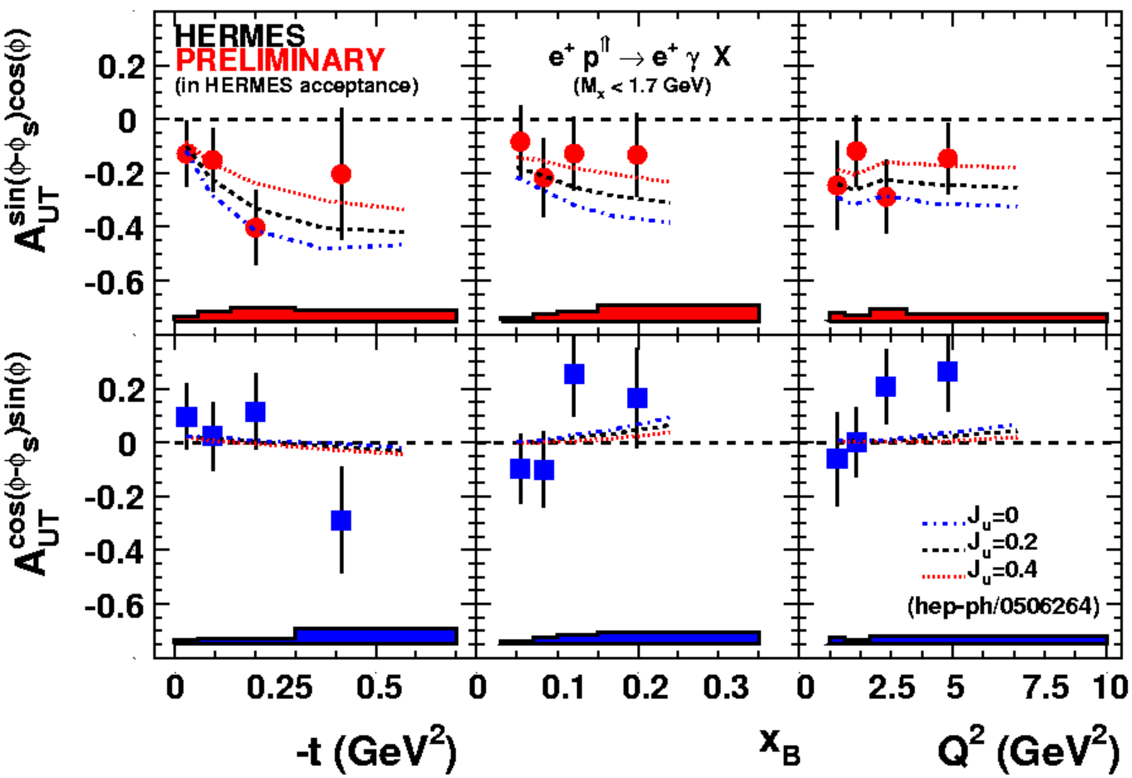
HERMES explored several different observables which have selective sensitivity to the 4 GPDs,

Beam Spin Asymmetry (A_{LU})

Beam Charge Asymmetry (A_C)

Target spin asymmetries (A_{UL} and A_{UT})

e.g. **preliminary results on** **<u>transverse target spin asymmetry</u> (A_{UT})**



$$\propto \frac{t}{2M^2}\left\{F_1 \cdot \mathrm{E} - F_2 \cdot \mathrm{H}\right\} + x_B{}^2\left\{\cdots\right\}$$

$$\propto \frac{t}{2M^2}\left\{F_2 \cdot \widetilde{\mathrm{H}} - 2x_B F_1 \cdot \widetilde{\mathrm{E}}\right\} + \left\{\cdots\right\}$$

(see F. Ellinghaus' talk)