The Abdus Salam
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1942-48

Sixth International Conference on Perspectives in Hadronic Physics

12 - 16 May 2008

Deeply virtual Compton scattering and CLAS12.

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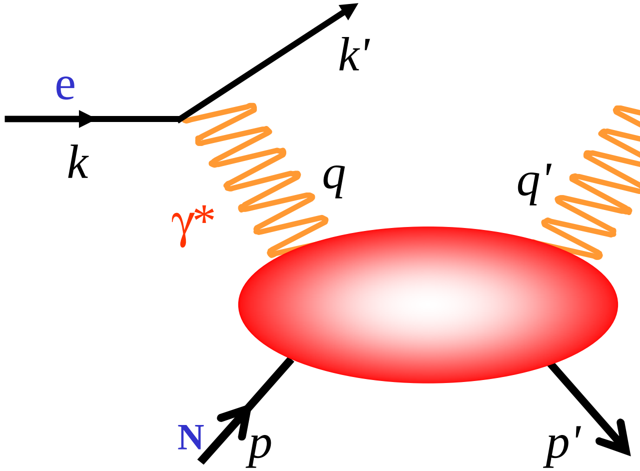
SPhN/Saclay
France

Nucleon structure studies via deeply virtual exclusive reactions at Jefferson Lab

(1)



Exclusive ep→epγ

and also

ep→epρ, epπ, …

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

DVCS and DVMP are the key reactions

to determine

Generalized Parton Distributions (GPDs)

experimentally.

At JLab

Preliminary rounds 1999-2006

First dedicated experiments 2004-2005

Second generation 2008-2011

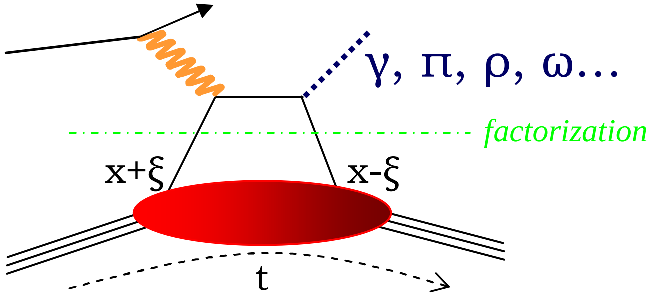
Final rounds from 2013 (12 GeV upgrade)

Classification of nucleon (chiral-even) GPDs

For each quark flavor and for gluons:

Legend *Forward limit* **GPD** *Operator at nucleon level* *Corresponding form factor*		*Operator at quark level*
$q(x)$ **H** *Vector* $F_1(t)$	– **E** *Tensor* $F_2(t)$	*Vector* $\gamma^{-}_{\alpha\beta}$ **Quark helicity independent (or « unpolarized ») GPDs**
$\Delta q(x)$ **$\tilde{\mathrm{H}}$** *Pseudo-vector* $g_A(t)$	– **$\tilde{\mathrm{E}}$** *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**	

GPD: relation with observables & sum rules



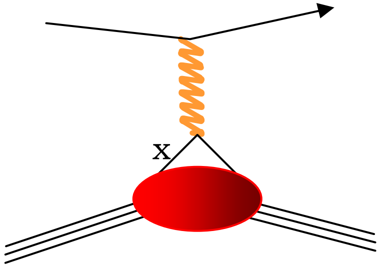
Observables are integrals, in x, of GPDs

Lattice QCD (moments)
Models
Parameterizations

Deconvolution

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

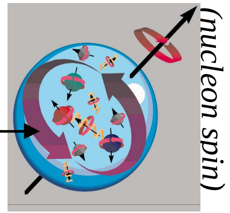
Elastic form factors



$\int H(x,\xi,t)dx = F(t)$ $(\forall\ \xi)$

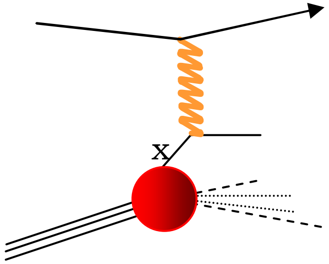
Ji's sum rule

$2J_q = \int x(H+E)(x,\xi,0)dx$



$$\frac{1}{2} = \overbrace{\left(\frac{1}{2}\Delta\Sigma + L_q\right)} + \left(\Delta G + L_g\right)$$

"Ordinary" parton distributions

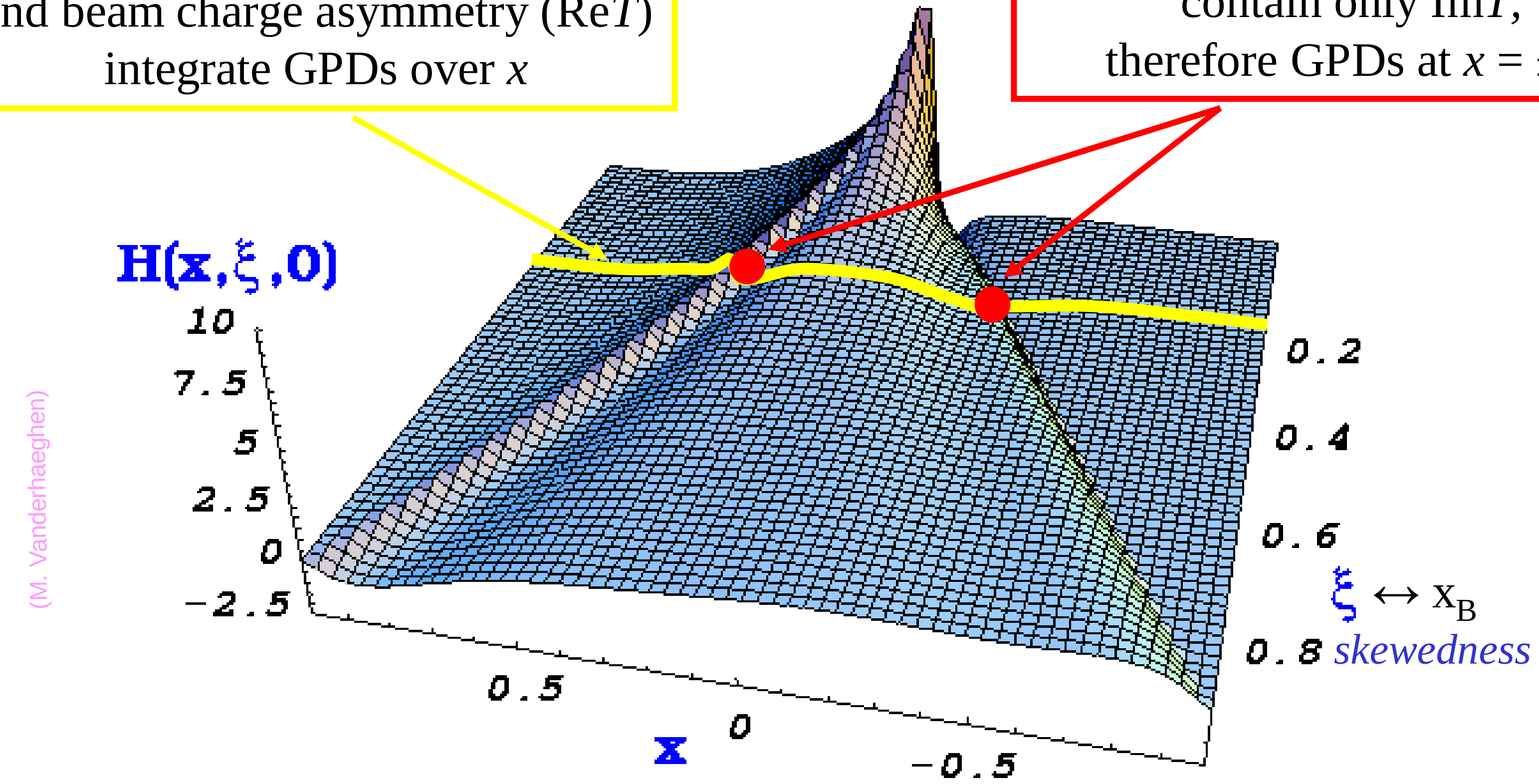


$H(x,0,0) = q(x)$,
$\tilde{H}(x,0,0) = \Delta q(x)$

GPD and DVCS

(at leading order:)

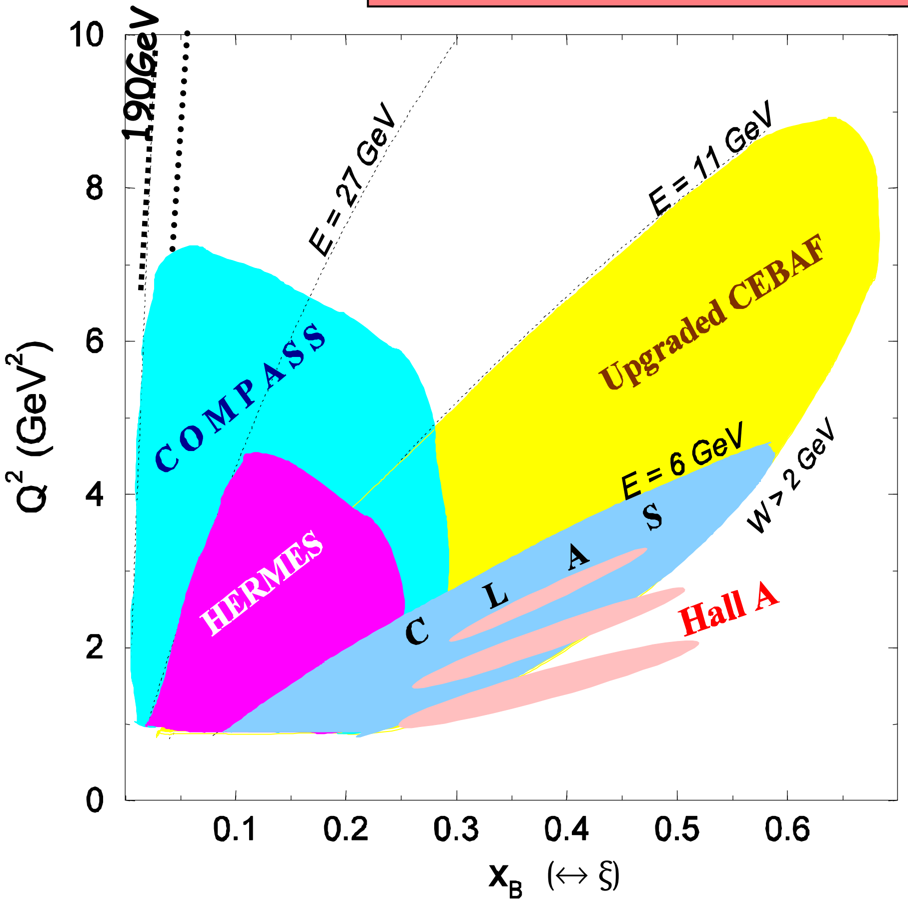
$$T \sim \int_{-1}^{+1} \frac{H(x,\xi,t)}{x\pm\xi-i\varepsilon}\,dx + \ldots \sim \mathcal{P}\int_{-1}^{+1}\frac{H(x,\xi,t)}{x\pm\xi}\,dx - i\pi H(\pm\xi,\xi,t)+\ldots$$



Cross-section measurement
and beam charge asymmetry (Re*T*)
integrate GPDs over *x*

Beam or target spin asymmetries
contain only Im*T*,
therefore GPDs at *x* = ±ξ

DVCS experiments in the world



Complementary experiments
explore all the components
of the nucleon structure.

$0.0001 < x_B < 0.01$
(mostly) Gluons
H1 and ZEUS

PL B517 (2001)
PL B573 (2003)
EPJC 44 (2005)
PL B659 (2008)

Quarks and Gluons

Hermes

PRL 87 (2001)
PRD 75 (2007)
arXiv:0802.2499

COMPASS

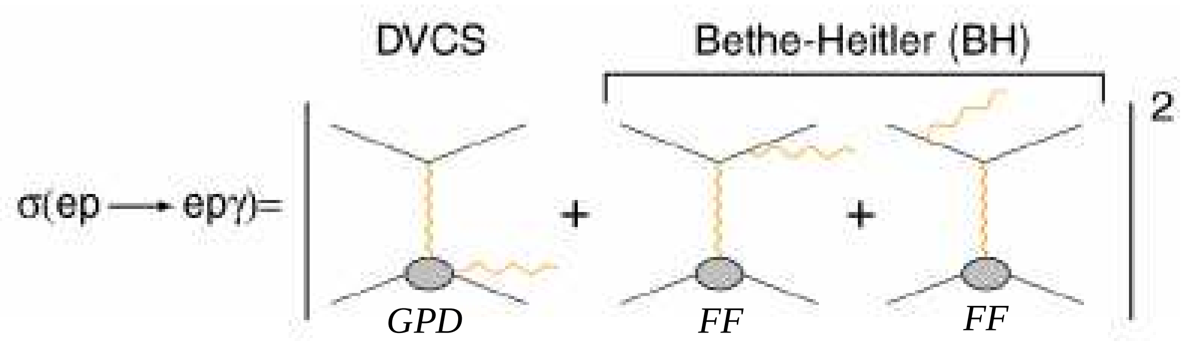
Valence quarks

JLab

PRL 87 (2001)
PRL 97 (2006)
PRL 97 (2006)
PRL 99 (2007)
PRL 100 (2008)

DVCS/BH interference

DVCS and Bethe-Heitler processes result in the same final state

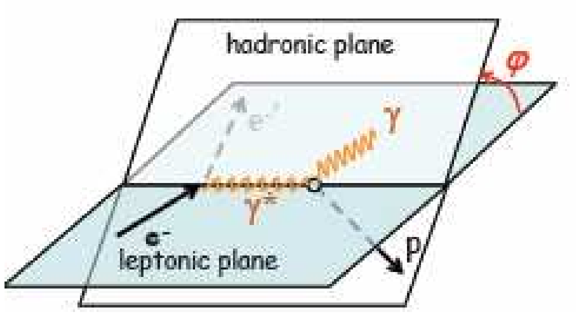


BH is calculable in QED, in function of nucleon FF, well known at low *t*

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

In spin (or beam charge) cross section differences,

σ^{BH} cancels out



DVCS and GPDs : (some) sensitive observables

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

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

$$A = \underline{F_1(t)\cdot\mathrm{H}} + \frac{x_B}{2-x_B}\left[F_1(t)+F_2(t)\right]\cdot\tilde{\mathrm{H}} - \frac{t}{4M^2}F_2(t)\cdot\mathrm{E}$$

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

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

And likewise **target spin cross section differences or asymmetries**:
either *longitudinal*

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

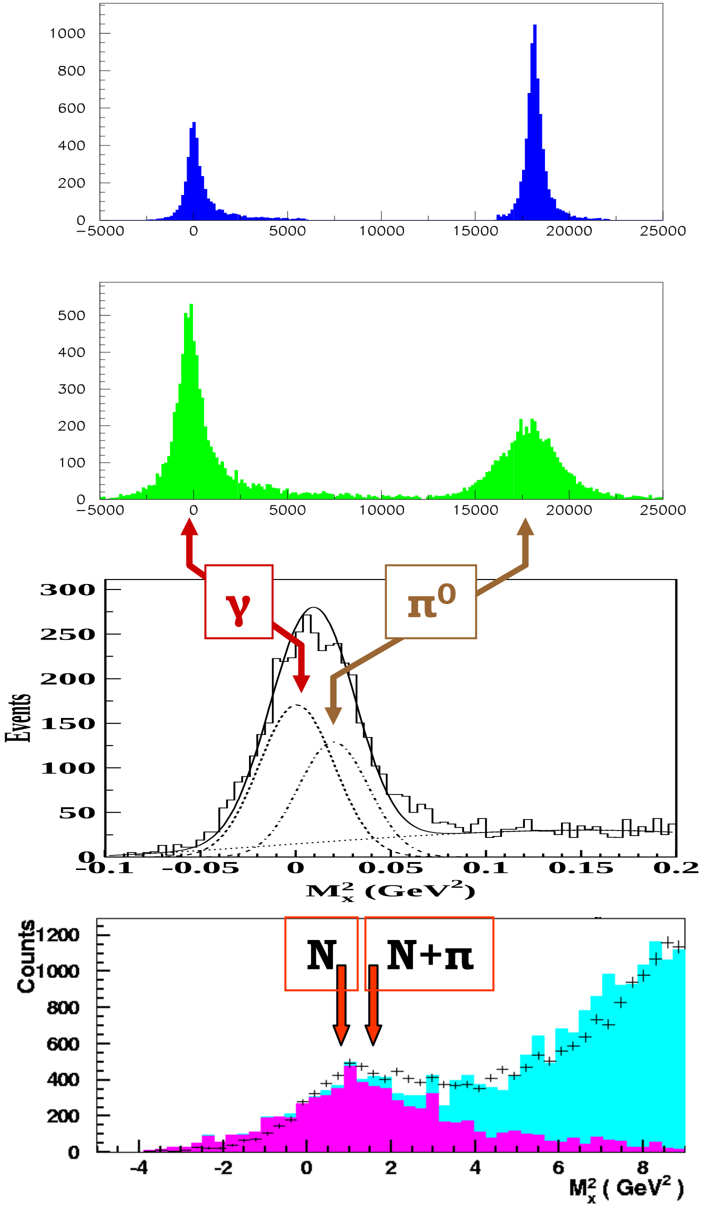
or *transverse*:

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

The sinusoidal behaviour is characteristic of the interference BH-DVCS

DVCS: an experimental challenge

Missing mass M_X^2



ep → epX
MAMI 850
MeV

ep → epX
Hall A
4 GeV

ep → epX
CLAS
4.2 GeV

ep → eγX
HERMES
28 GeV

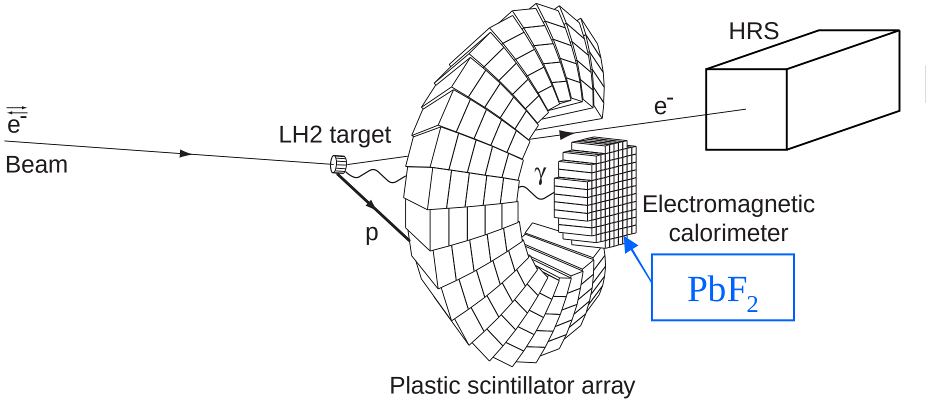
→ Require :

Exclusivity
- → resolution
- → redundant constraints

High Q^2
- → luminosity × acceptance

First dedicated DVCS experiments: JLab

Hall A



Dedicated, high statistics, DVCS experiments

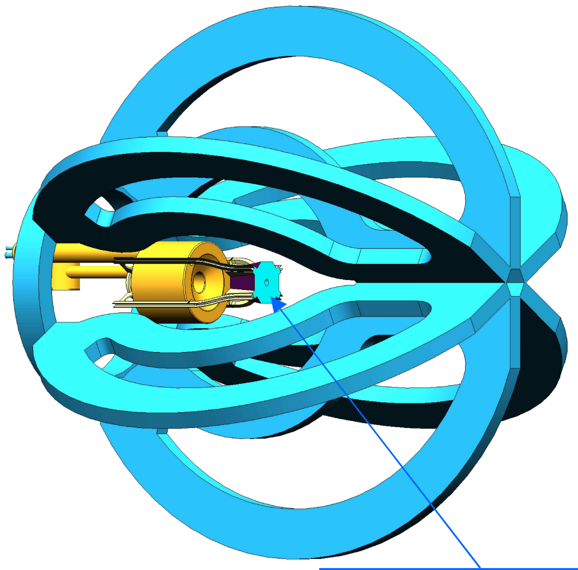
⟶ Virtual Compton scattering at the quark level

⟶ If scaling laws are observed (up to $Q^2 \sim 5$ GeV^2),
or deviations thereof understood,
first significant measurement of GPDs.

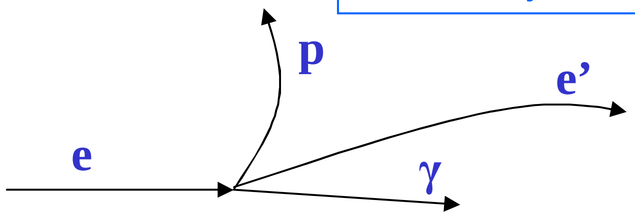
⟶ Large kinematical coverage in x_B and t
leads to 3D-picture of the nucleon

CLAS

Calorimetrer and supraconducting magnet
within CLAS torus

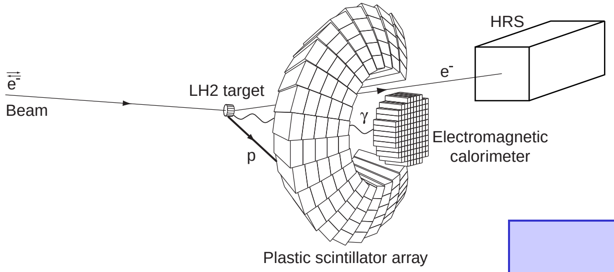


$PbWO_4$ crystals
read-out by APDs



DVCS: (close to) full exclusivity achieved at JLab

Exclusivity
→ resolution
→ redundant constraints
High Q^2
→ luminosity × acceptance



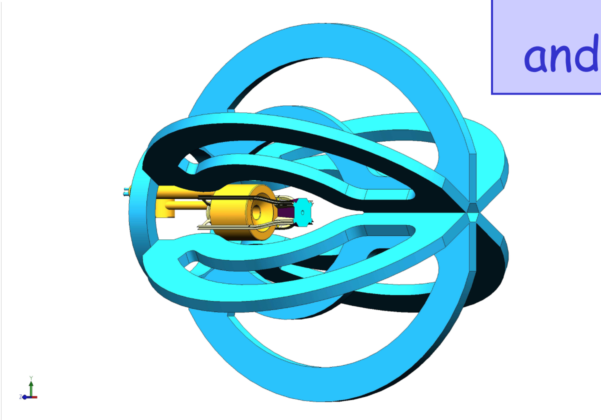
10^{37} $cm^{-2}s^{-1}$ / 5 msr (e)

ep → eγX
Hall A
5.75 GeV

In both cases,

background is small (mostly from $ep \rightarrow ep\pi^0$)

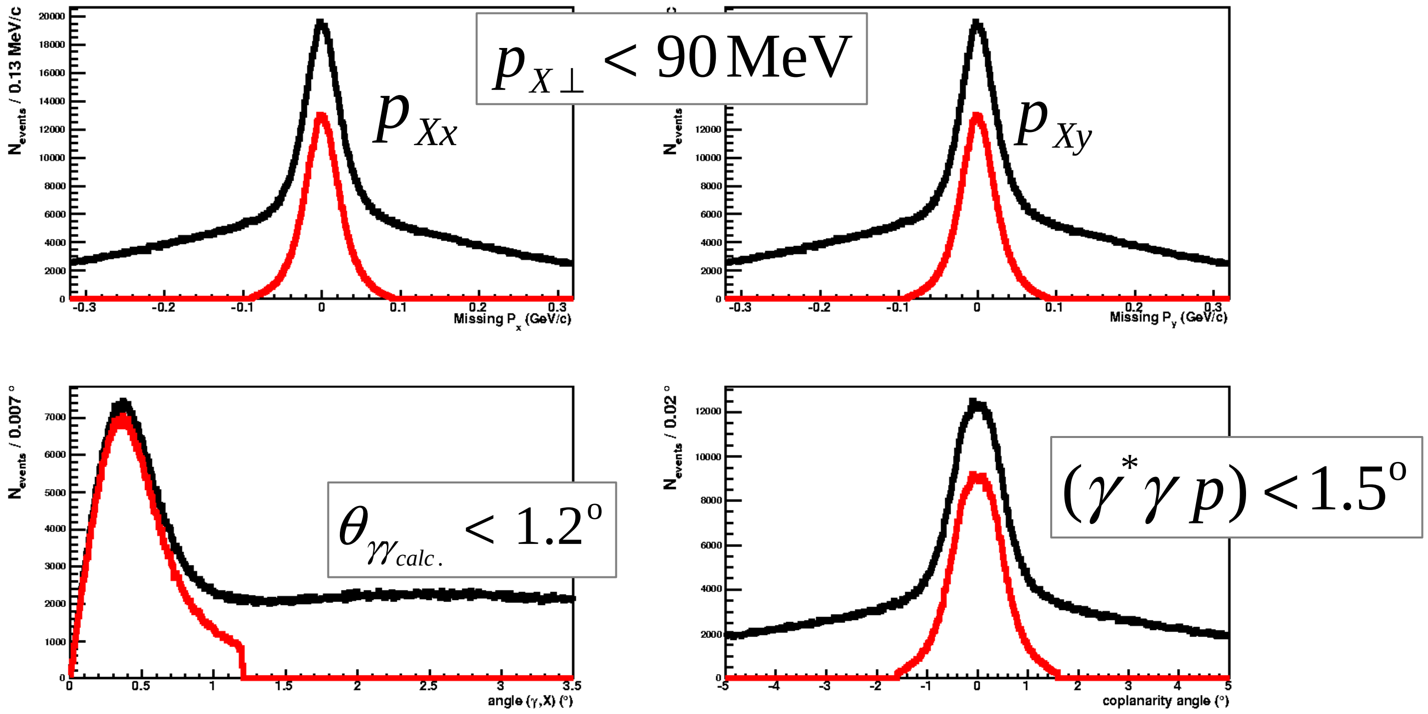
and estimated in a model-independent fashion



2.10^{34} $cm^{-2}s^{-1}$ / ~ 2 sr (e/p)

ep → epγ
CLAS
5.75 GeV

Event selection in CLAS/DVCS (ep→epγX)



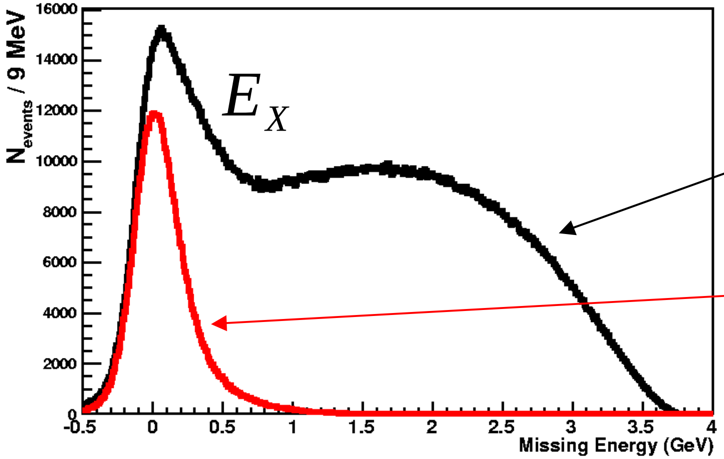
p_{Xx}

$p_{X\perp} < 90\,\mathrm{MeV}$

p_{Xy}

$\theta_{\gamma\gamma_{calc.}} < 1.2^{\mathrm{o}}$

$(\gamma^{*}\gamma\, p) < 1.5^{\mathrm{o}}$



E_X

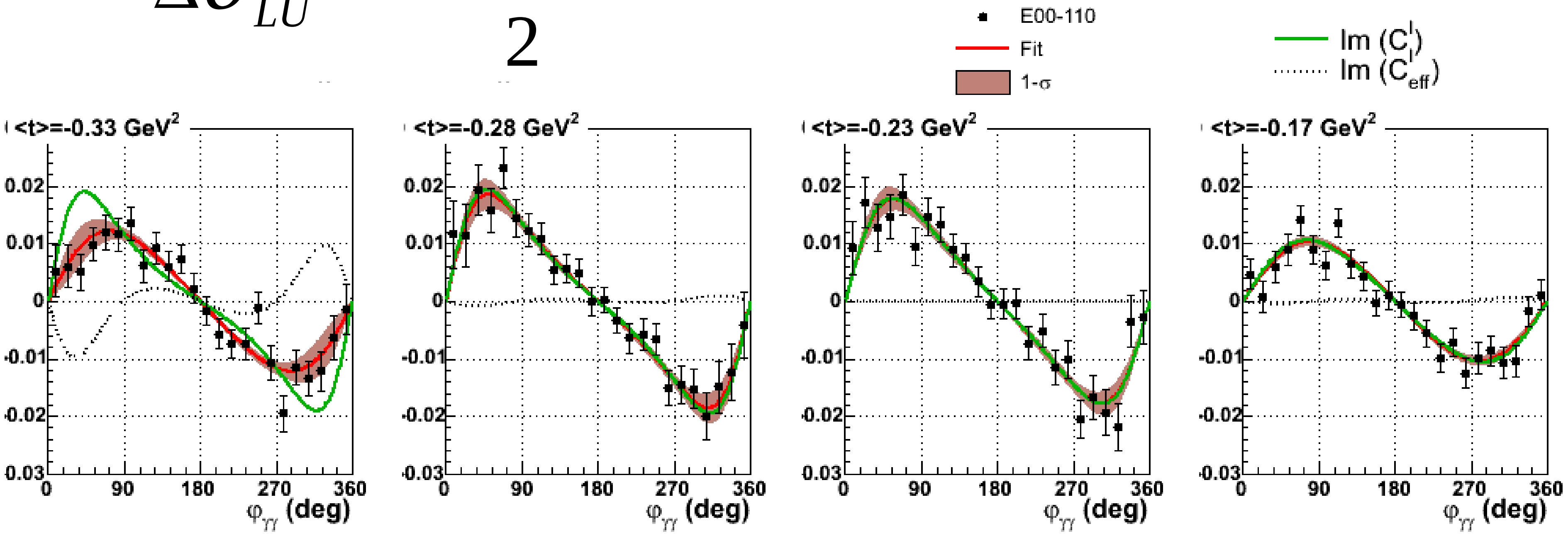
All epγX events

After kinematical cuts given above

→ **cleanest « DVCS » peak ever**

Hall A results on $\Delta\sigma_{LU}$ (ep → epγ): an unprecedented precision

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

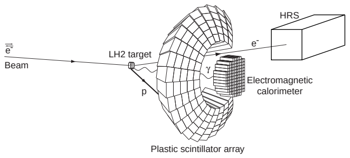


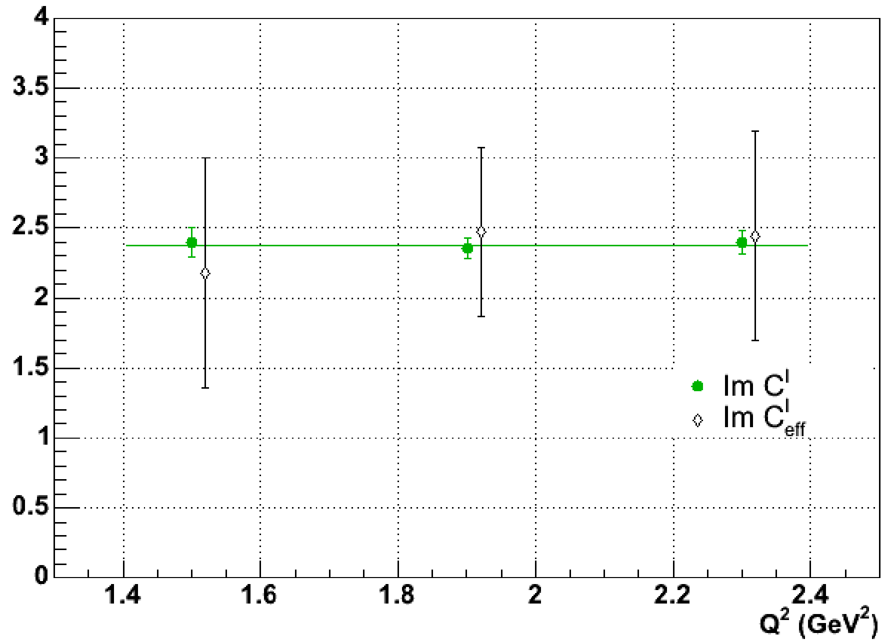
C. Muñoz Camacho *et al*. (Hall A), PRL **97** (2006)

Hall A results : an unprecedented precision

$$\frac{\sigma^{+} - \sigma^{-}}{2} = \Gamma \cdot \left[A \sin\Phi + \frac{\lambda}{Q} B \sin 2\Phi + \ldots \right]$$

For fixed x_B and *t*, ***A*** and ***B*** are found independent of Q^2:





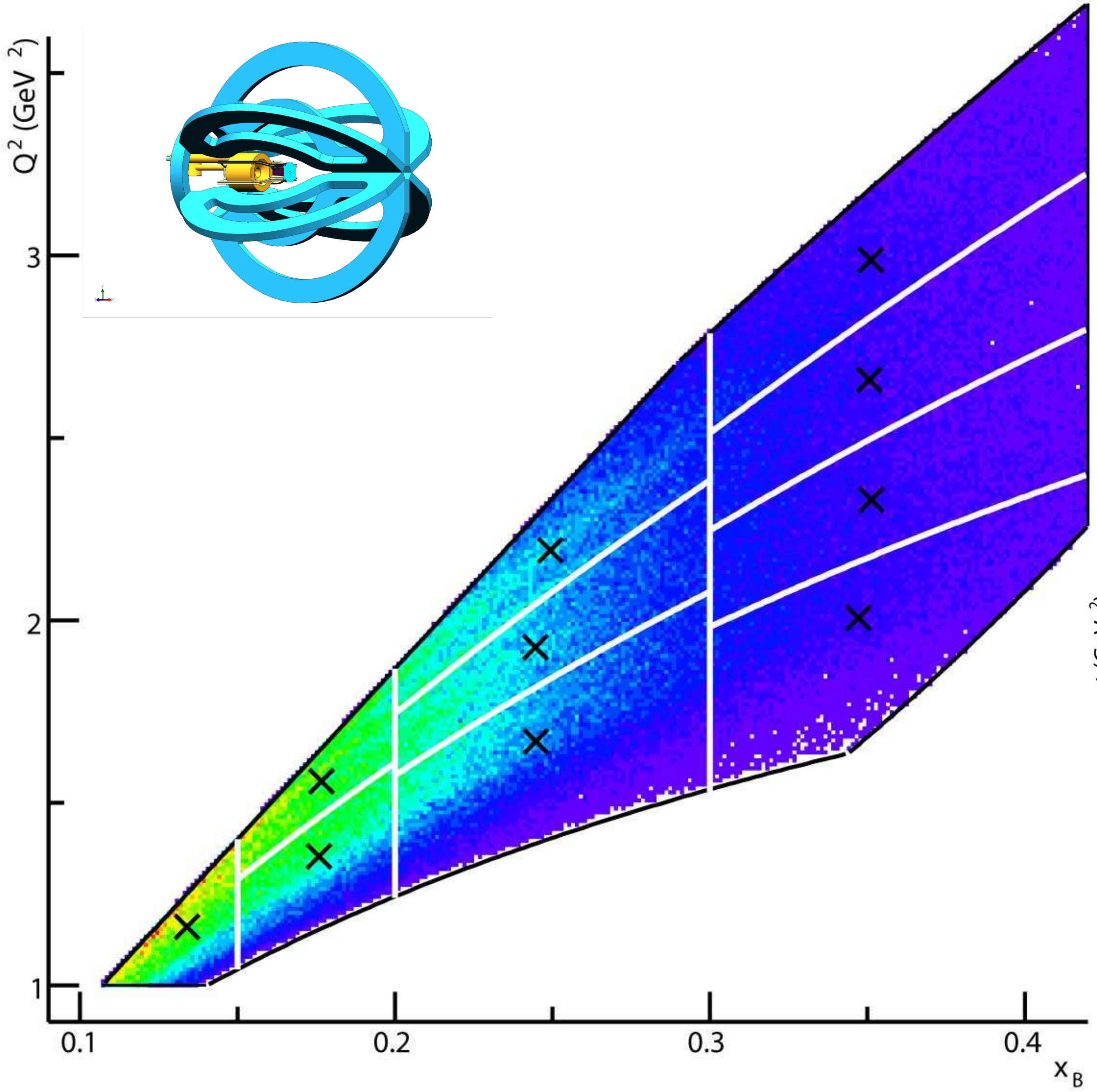
➡ This is the first direct indication of scaling in DVCS !

➡ Compton scattering is occurring at the quark level !

➡ Purely experimental extraction of GPDs can really start !

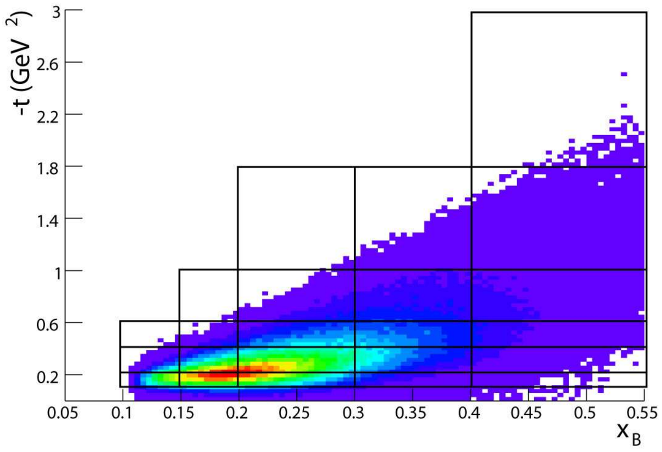
C. Muñoz Camacho *et al*. (Hall A), PRL **97** (2006)

CLAS: an unprecedented kinematic coverage

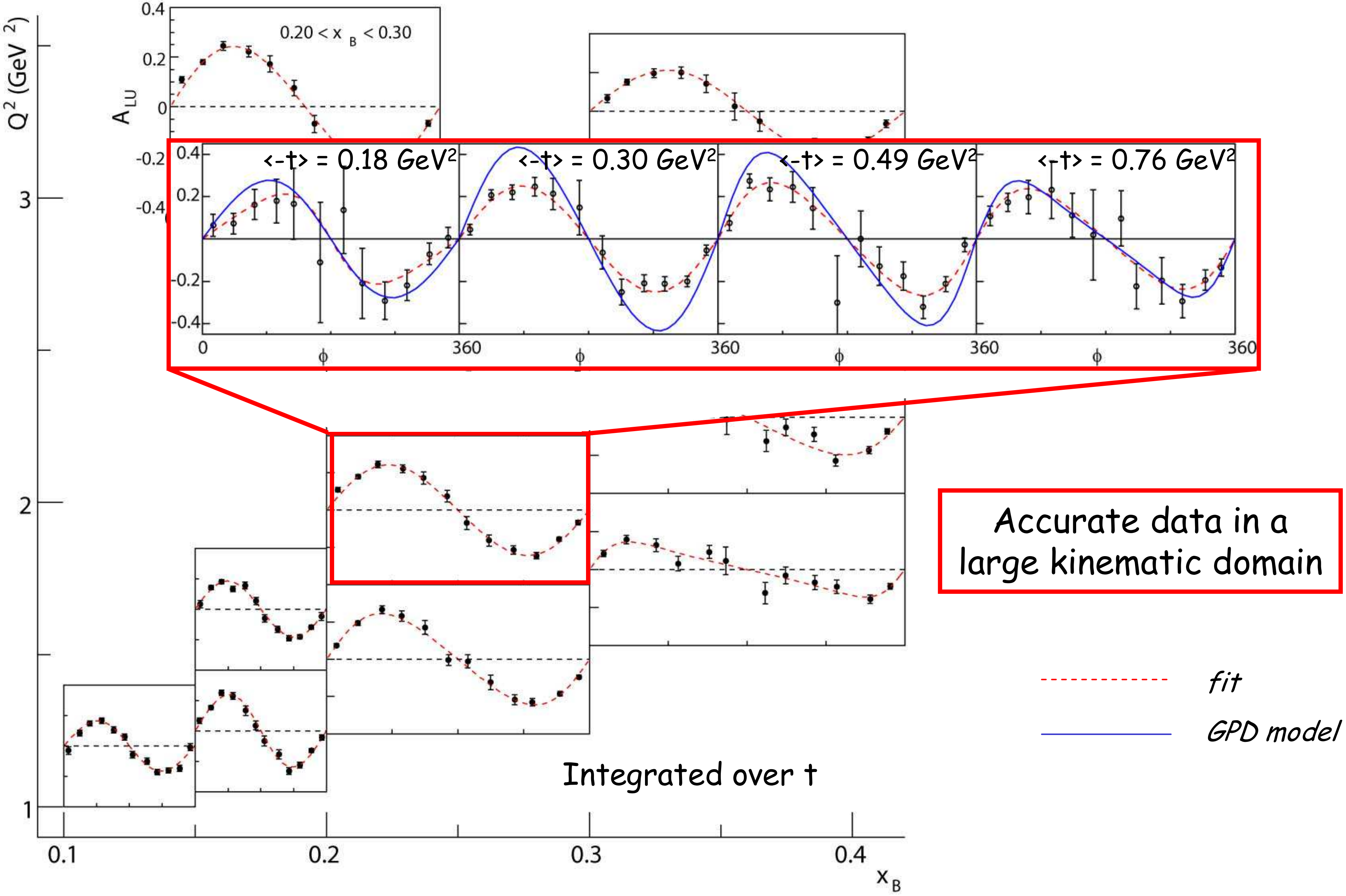


$W > 2$ GeV
$Q^2 > 1$ GeV^2

+ 3 high-x_B / high-Q^2 bins
not shown



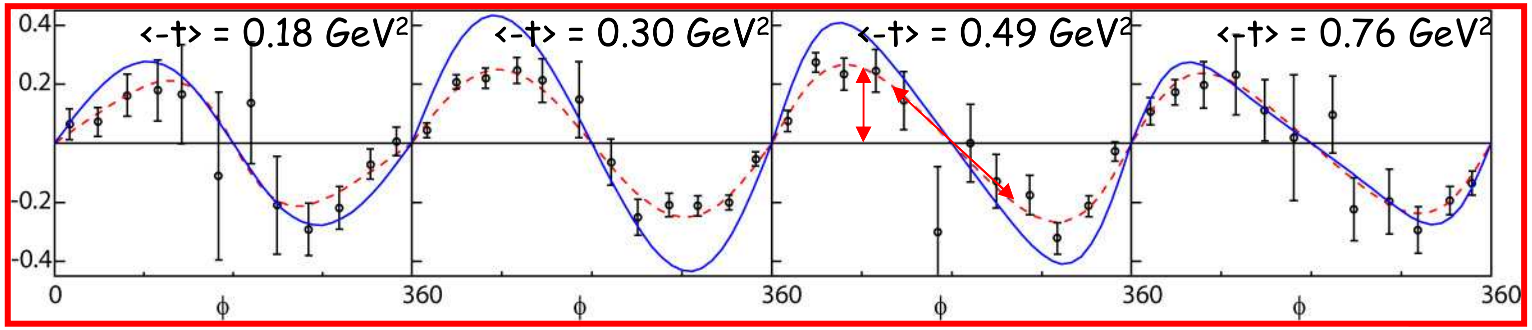
CLAS: beam-spin asymmetry binned in all 4 variables



Accurate data in a large kinematic domain

Integrated over t

CLAS beam-spin asymmetries



In all bins, Φ dependence compatible with leading-twist expectation

$$A_{LU} = \frac{a \sin\phi}{1 + c\cos\phi + d\cos 2\phi}$$

with d negligibly small

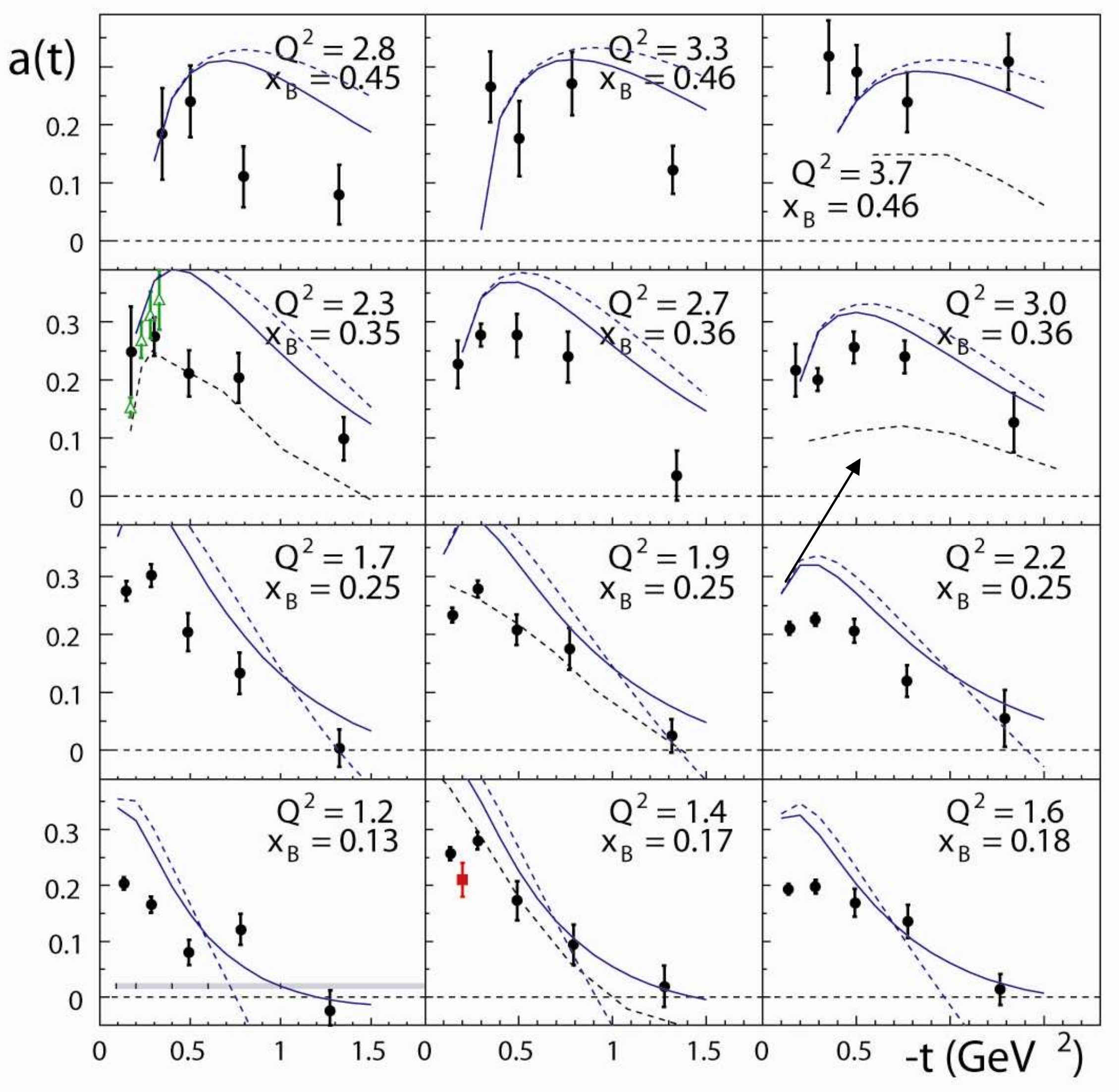
$a \approx A_{LU}(90°)$ is mostly sensitive to Im(DVCS) $\rightarrow H(\xi,\xi,t)$

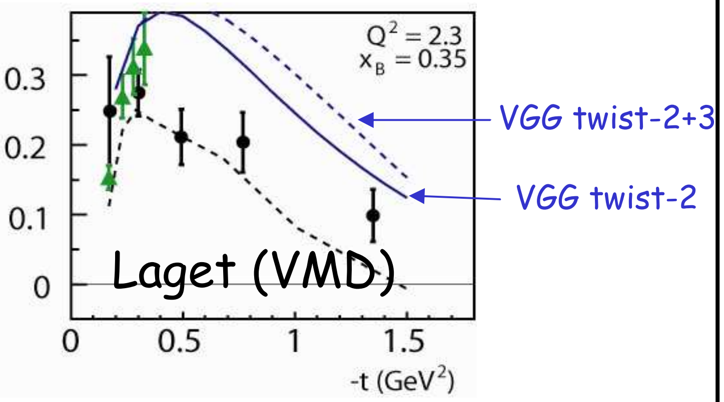
c has additional sensitivity to Re(DVCS)

(but such an analysis has to await new formalism under construction)

F.X. Girod *et al*. (CLAS), PRL **100** (2008)

CLAS: a = $A_{LU}(90°)$ as a function of t





F.X. Girod *et al*. (CLAS), PRL **100** (2008)

Comments on GPD parameterizations

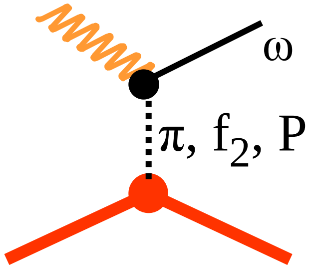
- Double-distributions are not able to reproduce the new precise JLab data. Is the functional form not adequate ? Are there still higher-twist contributions to the unpolarized cross section ?

- A dual representation is being revived (Polyakov & Vanderhaeghen, arXiv:0803.1271). With simplifying assumptions (dominance of GPD H and truncation of infinite series of t-channel exchanges to first – forward-like – term), it gives an adequate description of the same data. Is this accidental or really giving the main physical picture ? If the latter is true, it gives direct access to $H(x,0,t)$ and to the 2D-imaging of the quarks inside the nucleon.

- A reliable and practical parameterization is needed before performing general fits of world data. This future is within reach…

Deeply virtual meson production: vector mesons

Meson and Pomeron (or two-gluon) exchange …



ρ^0	(σ), f$_2$, P
ω	π, f$_2$, P
Φ	P

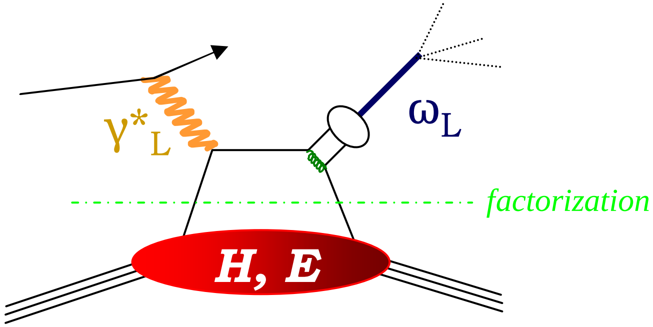
ω production shown to be dominated by π^0 exchange, for Q^2 up to 5 GeV^2

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
Φ	s, g
ρ^+	u-d



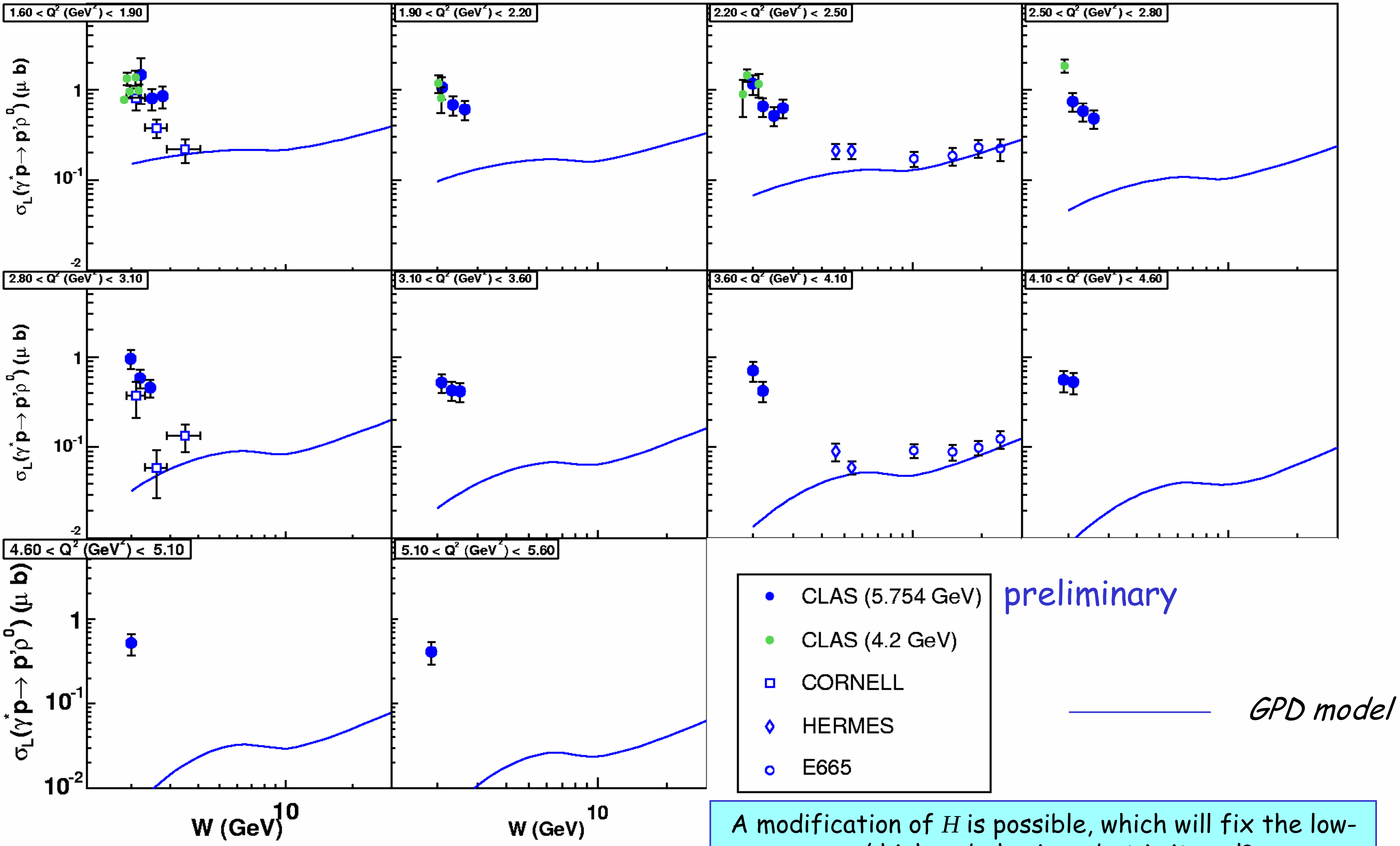
$$\frac{d\sigma_L}{dt} \propto \frac{1}{Q^4}\left[\frac{\alpha_S}{Q}\sum\iint\frac{\psi_M(z)}{z}\,\frac{1}{x\pm\xi\mp i\varepsilon}(aH+bE)(x,\xi,t)\,dxdz\right]^2 \propto \frac{f(\xi,t)}{Q^6}$$

ρ_L production : a theoretical prejudice more in favor of handbag diagram dominance.

HERMES, EPJC **17** (2002) **& CLAS**, PLB **605** (2005) + preliminary results

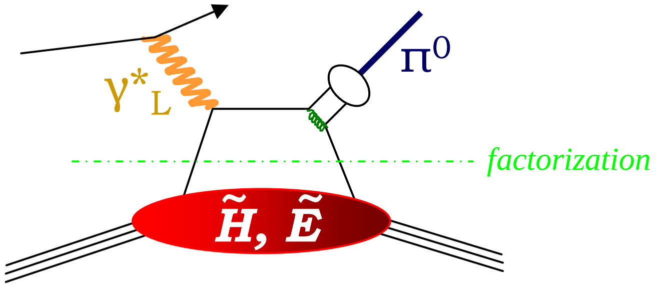
Deeply virtual meson production: ρ

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



A modification of H is possible, which will fix the low-W / high-x_B behaviour, but is it real?

Deeply virtual meson production: pseudoscalar mesons



See next talk

for new results

from Hall A and CLAS

on π^0 production

… and much more to come

More DVCS experiments at JLab / 6 GeV

2008: doubling the statistics for BSA (A_{LU}) at **CLAS** H

2009: **CLAS**/LTSA (A_{UL}) experiment $\tilde{H}$
(longitudinally polarized target + inner calorimeter)

2010: **Hall A** experiment at lower energy for « Rosenbluth-like » separation of terms entering the DVCS cross section. H

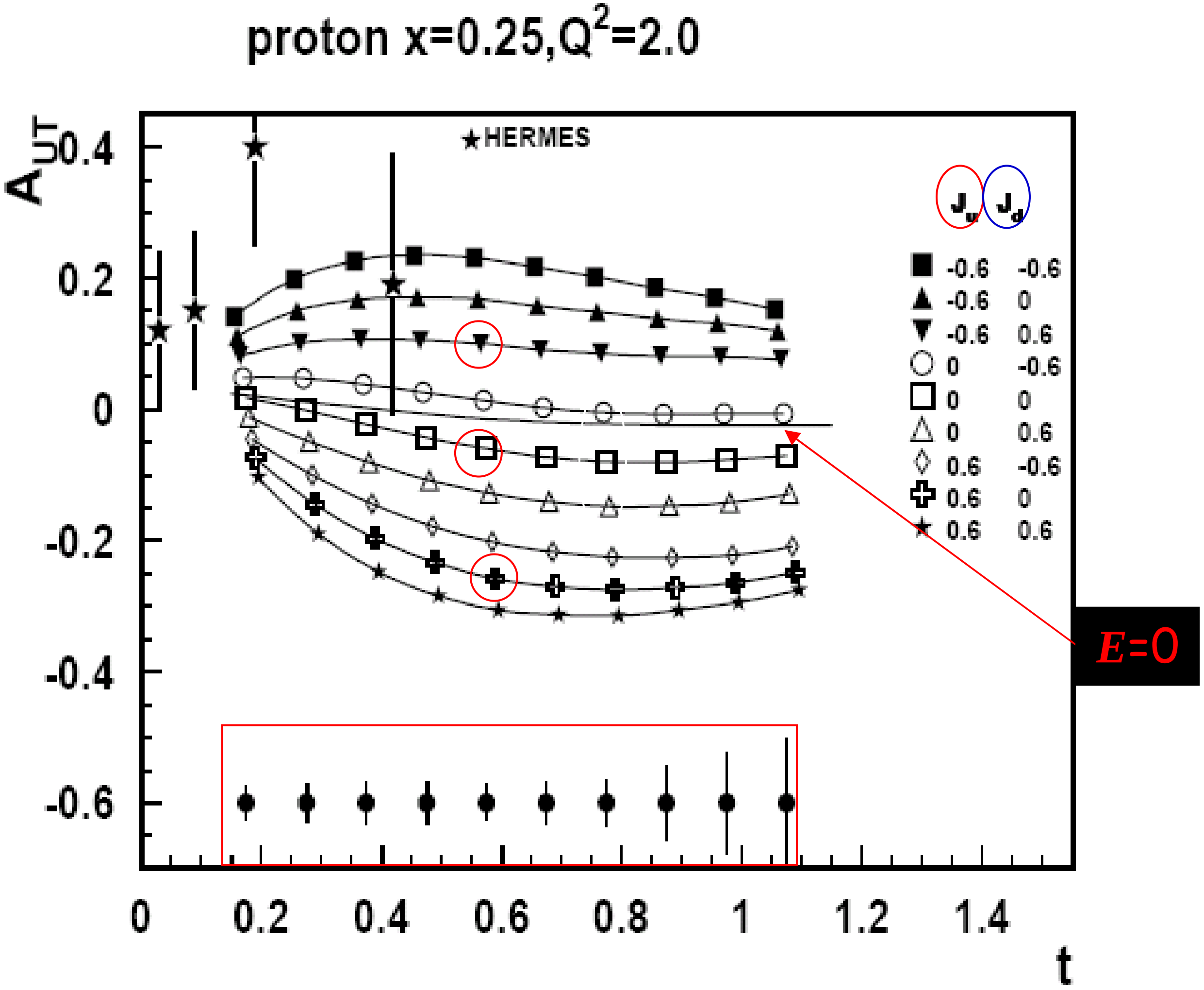
2011: **CLAS**/TTSA (A_{UT}) experiment E
(transversely polarized target – possibly HD)

CLAS: Sensitivity of A_{UT} to GPD E

Anticipated results from CLAS at 6 GeV

Technical challenge:

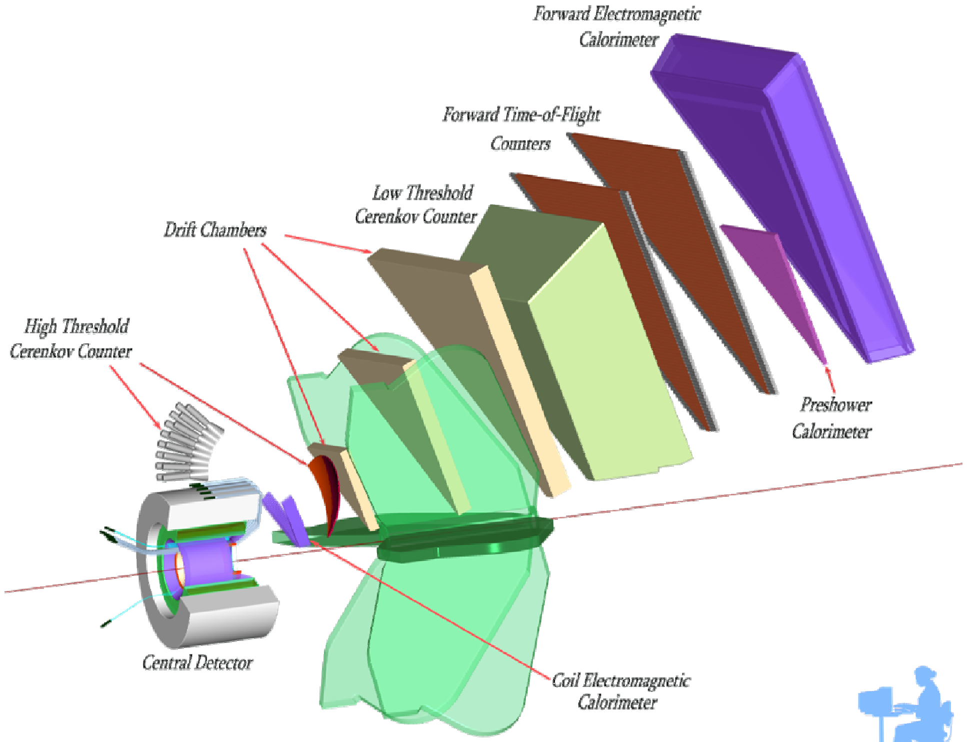
use of polarized HD with electron beam



E=0

Transverse asymmetry is large and has strong sensitivity to GPD-*E* and thus to the quark angular momentum contributions.

JLab @ 12 GeV: CLAS12



Study of quark dynamics

within the nucleon.

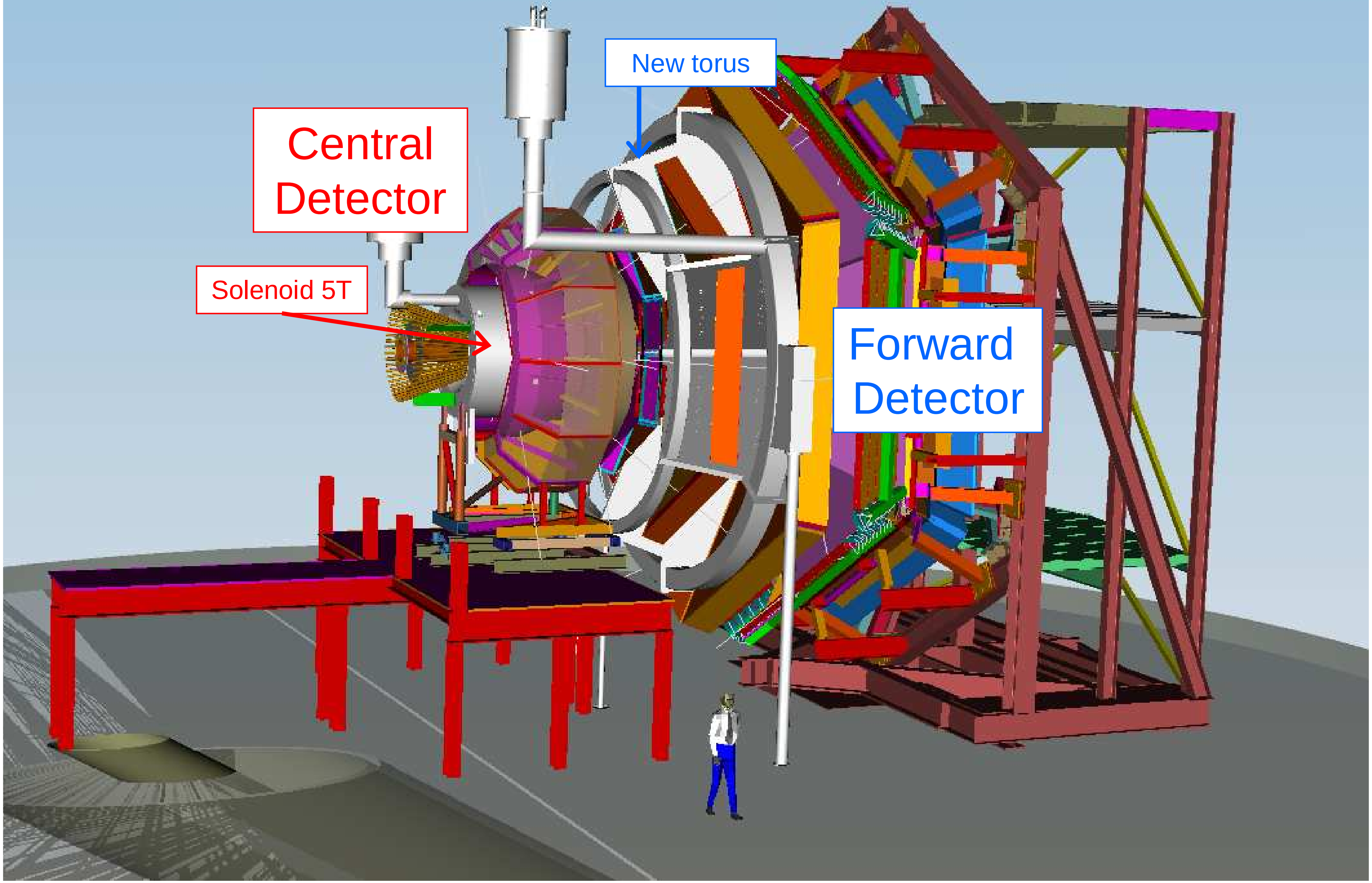
Measurement of GPDs

(+ quark angular

momentum)

First beam in 2014

CLAS12 - Detector



Central Detector

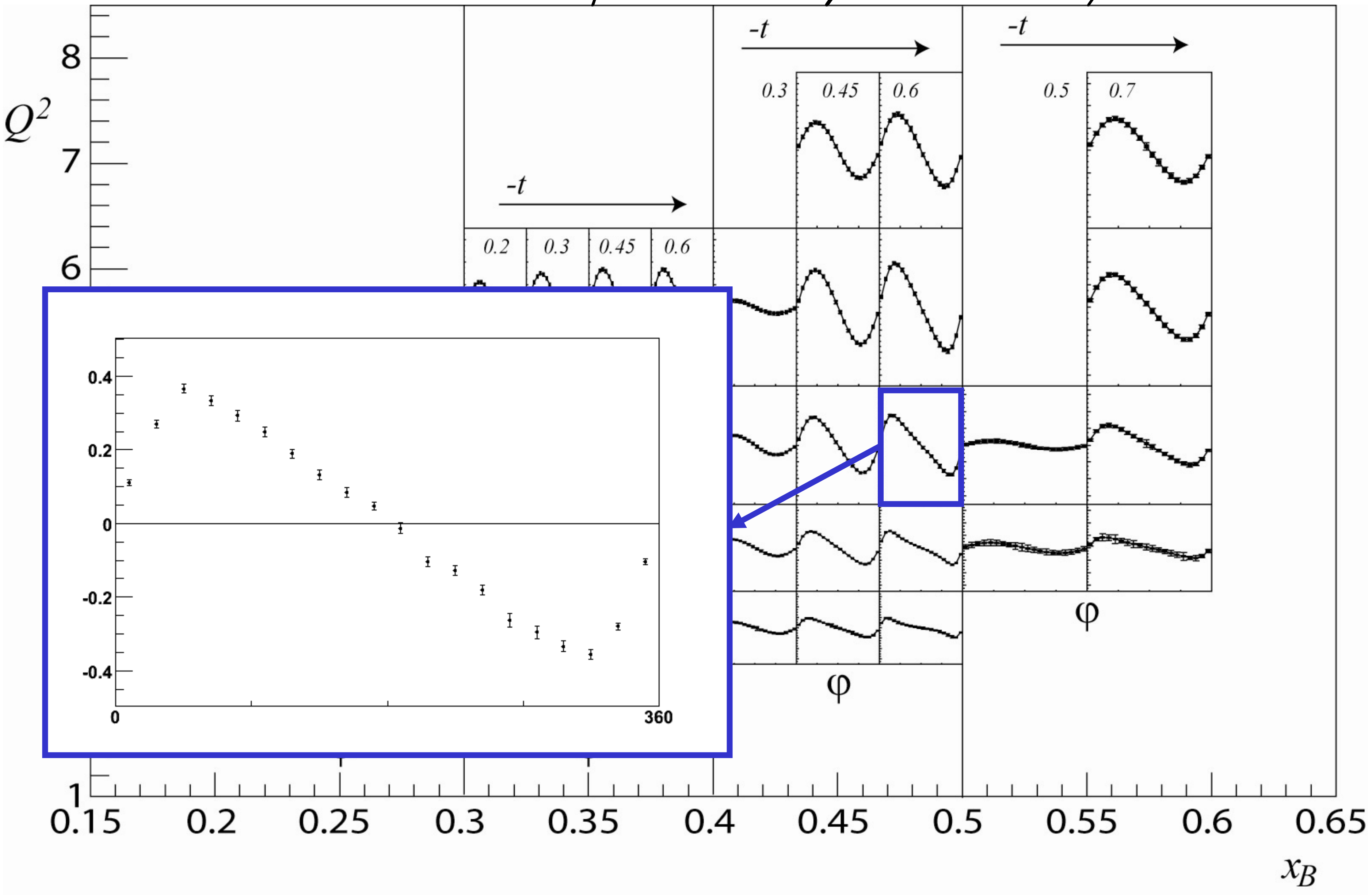
New torus

Solenoid 5T

Forward Detector

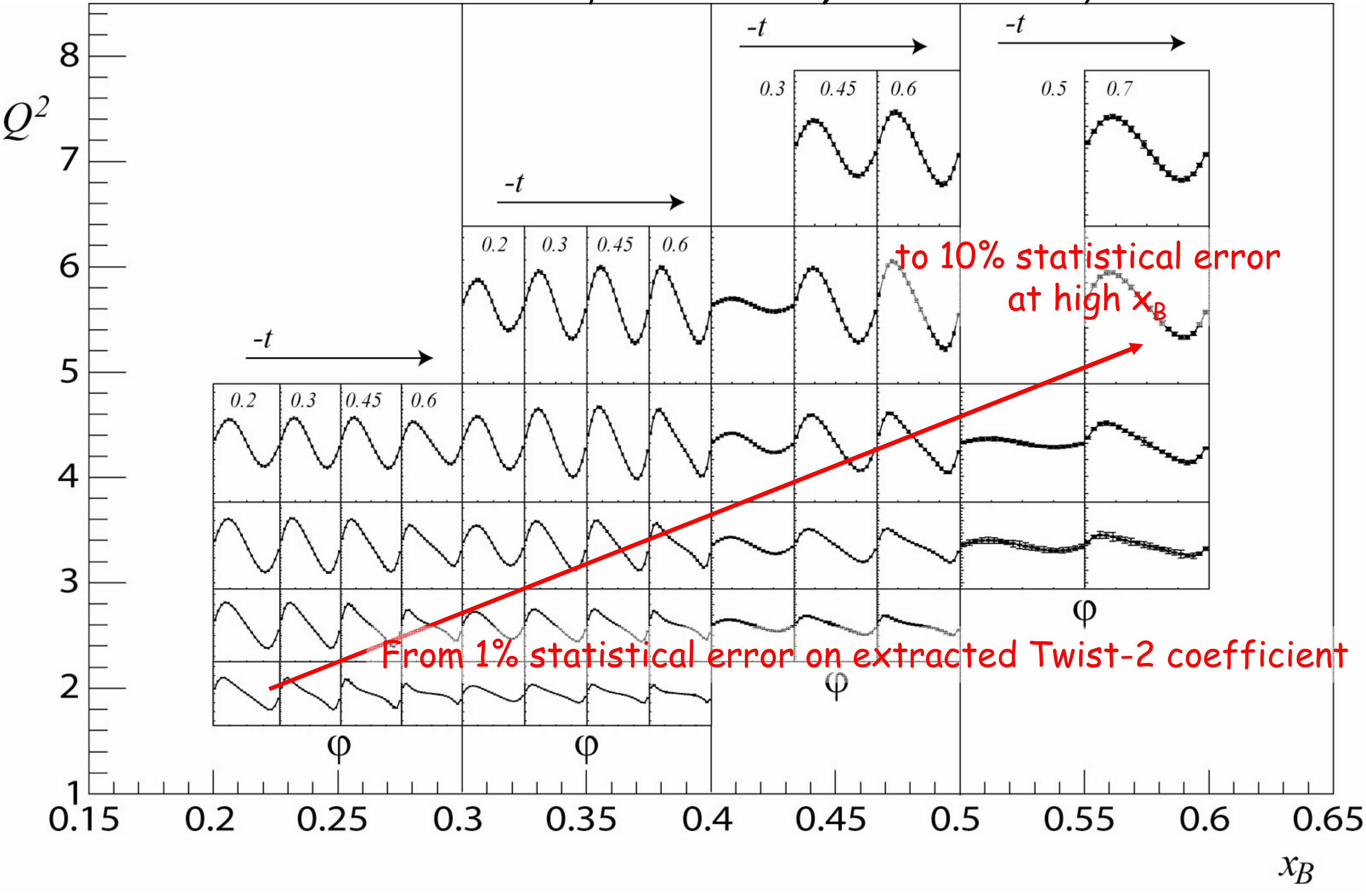
CLAS12: Beam-spin asymmetries

*Inner Calorimeter in standard position – **80 days** – 10^{35} luminosity – VGG model*



CLAS12: Beam-spin asymmetries

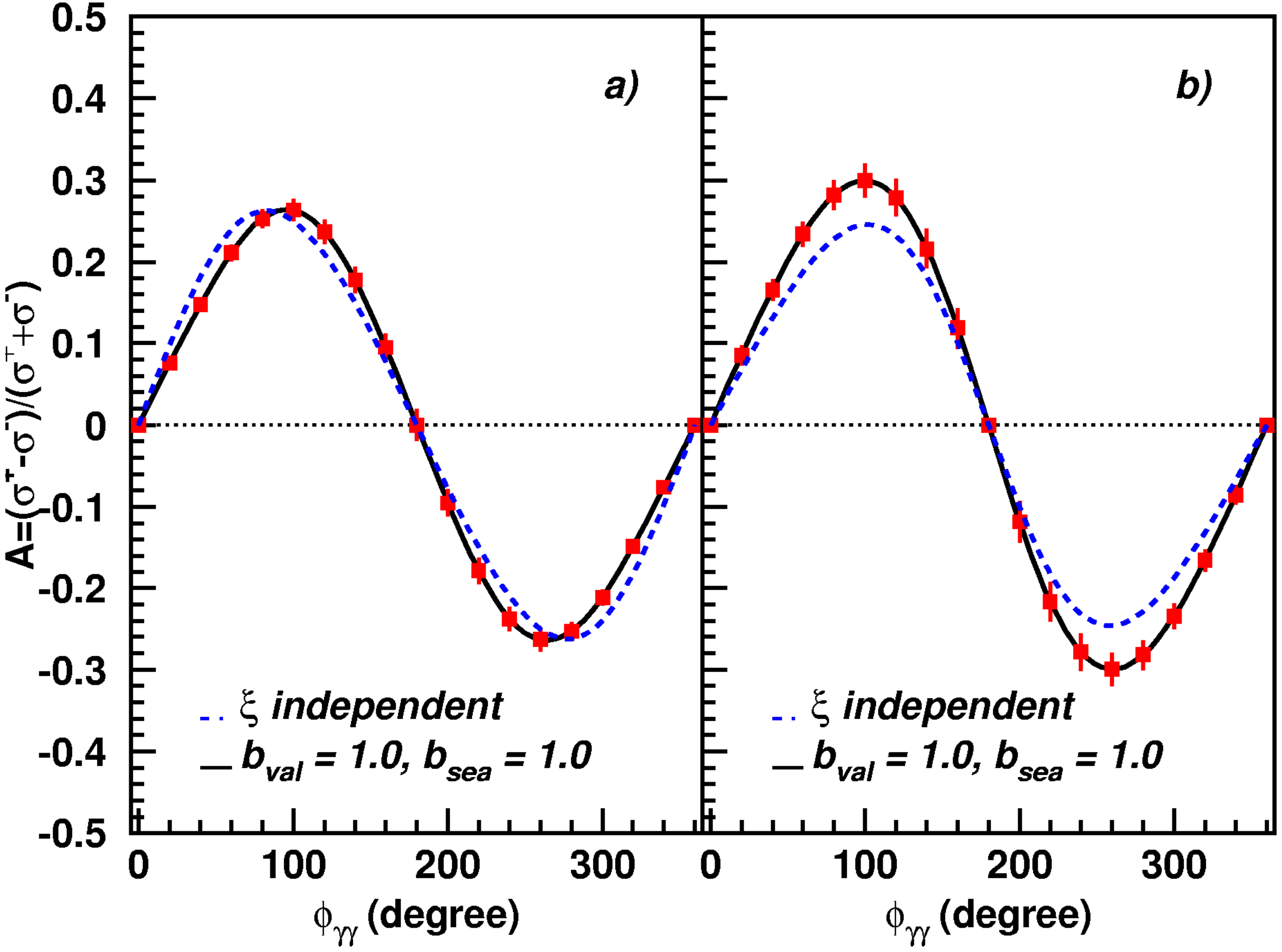
*Inner Calorimeter in standard position – **80 days** – 10^{35} luminosity – VGG model*



to 10% statistical error at high x_B

From 1% statistical error on extracted Twist-2 coefficient

CLAS12: Beam-spin asymmetries

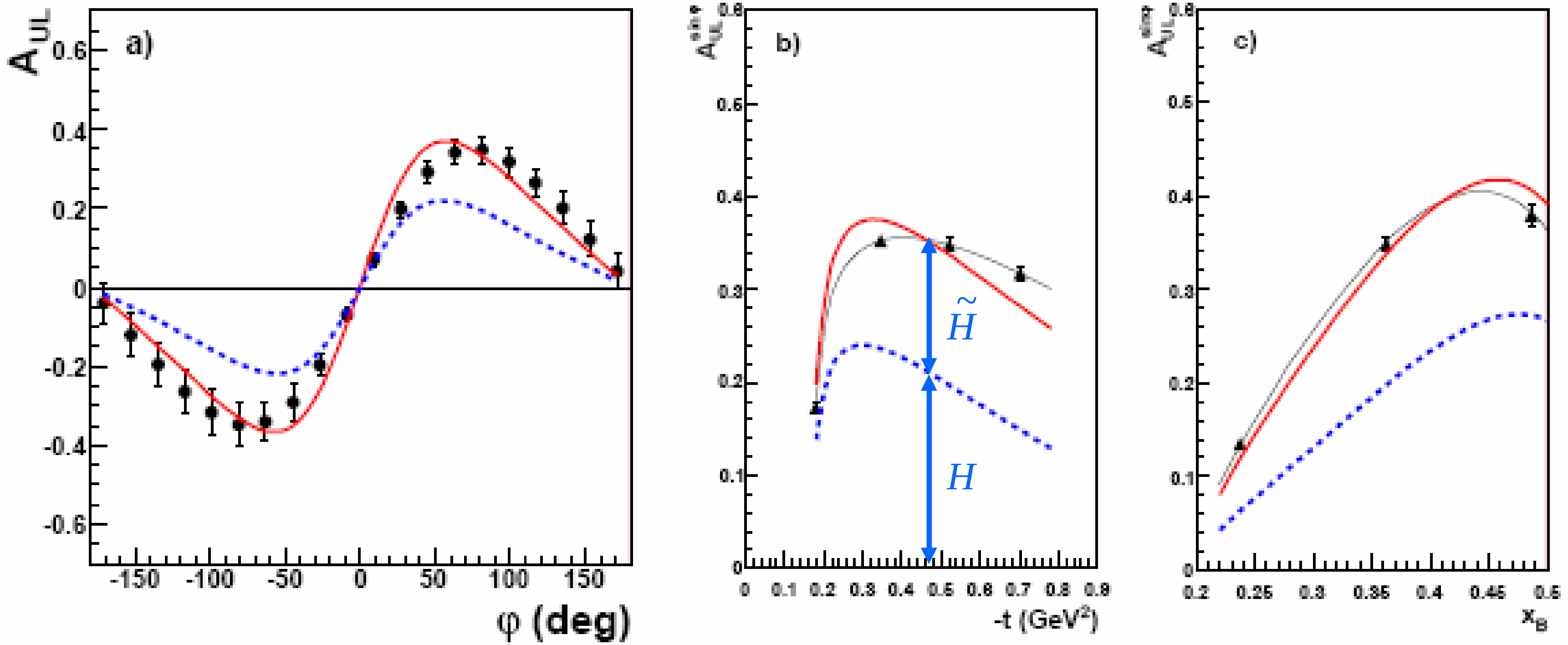


972 data points measured simultaneously

Q^2, x_B, t ranges measured simultaneously.

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

CLAS12: Target-spin asymmetries



Longitudinal target spin asymmetry,

with uncertainty projected for 11 GeV

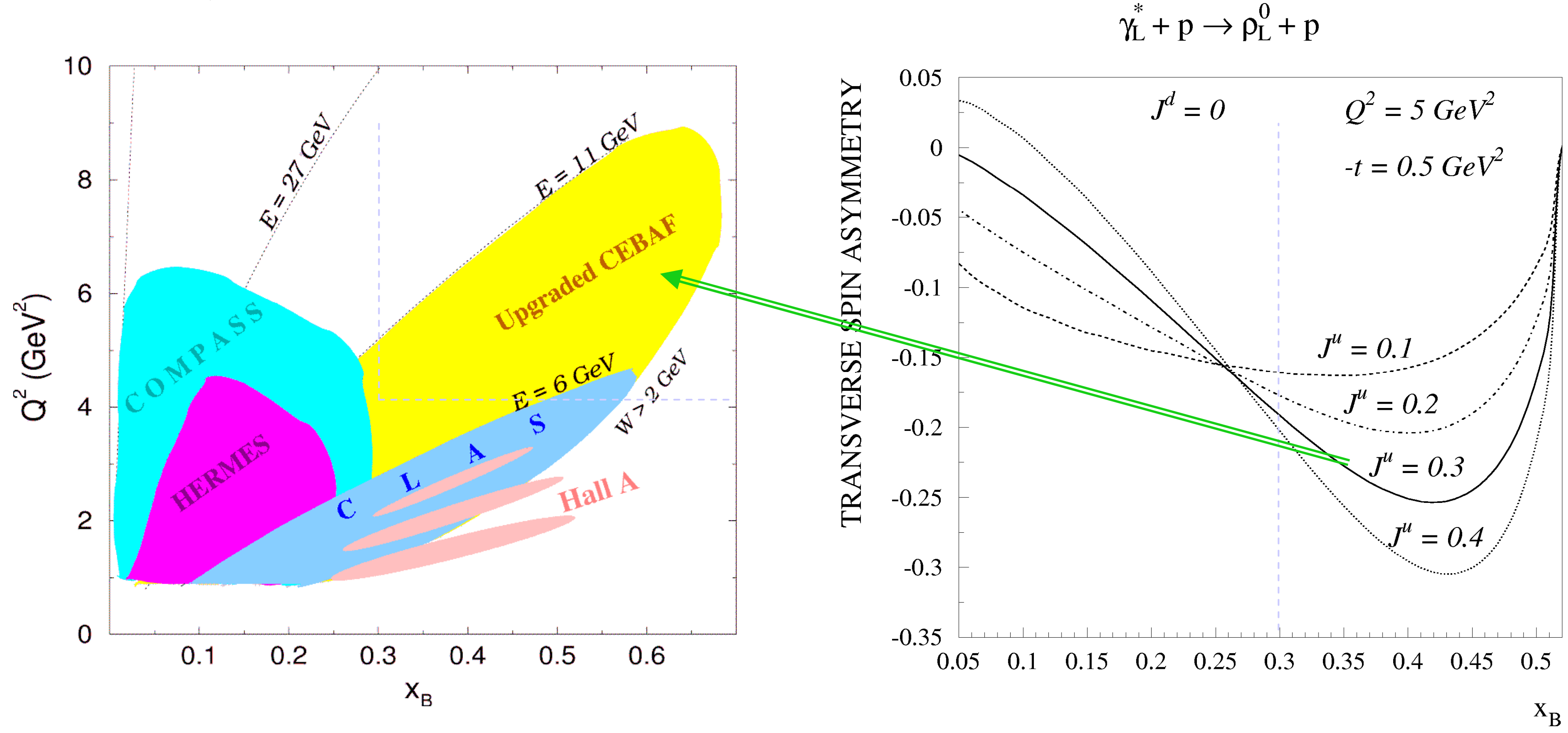
(approved experiment).

ρ^0/ω production with transverse polarized target

$$A_{UT} \propto \frac{\mathrm{Im}(\mathcal{H}_\rho \mathcal{E}_\rho^*)}{\left|\mathcal{H}_\rho\right|^2(1-\xi^2) - \left|\mathcal{E}_\rho\right|^2(\xi^2 + t/4M^2) - 2\xi^2\,\mathrm{Re}(\mathcal{H}_\rho \mathcal{E}_\rho^*)}$$

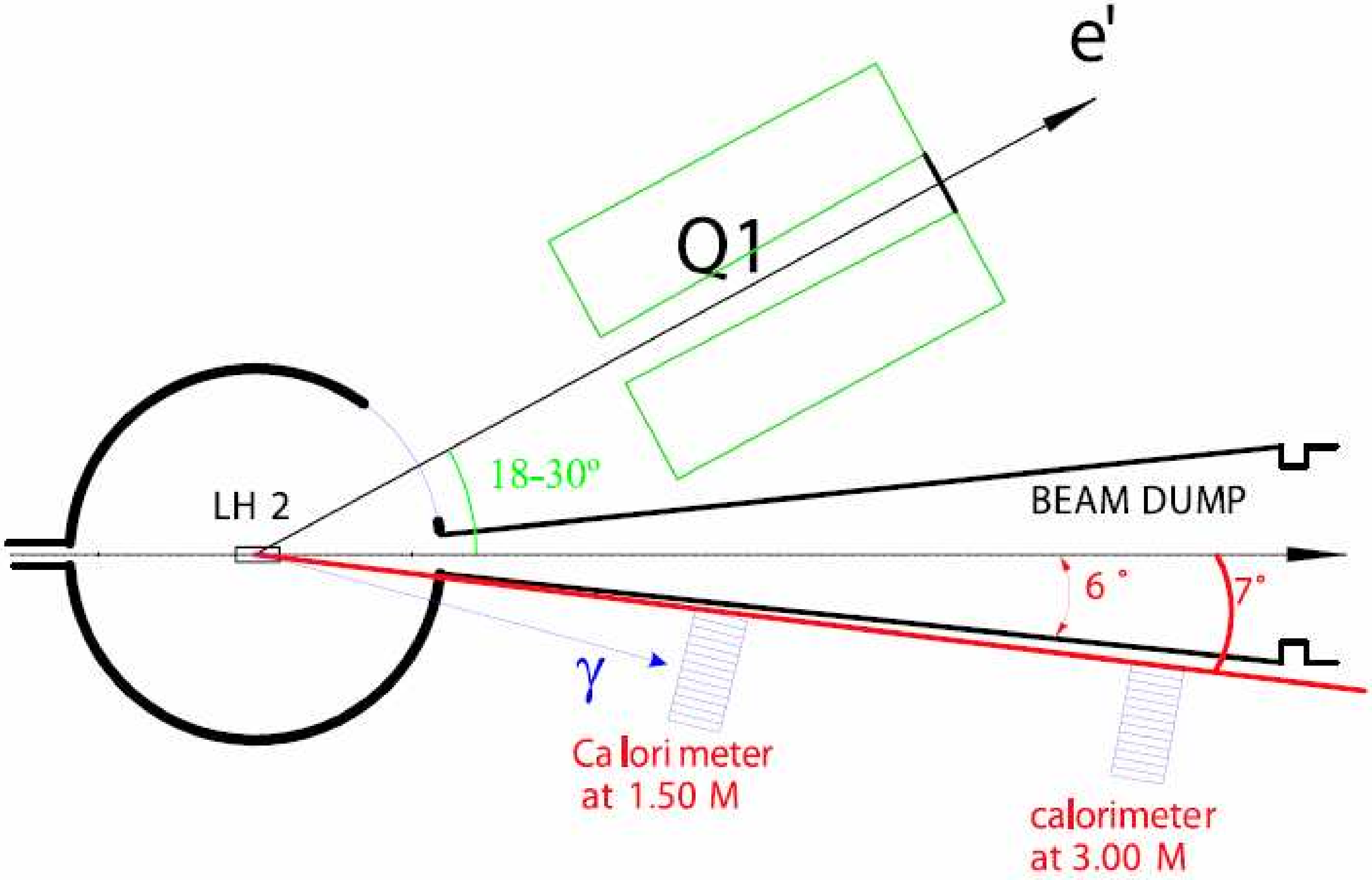
$$\mathcal{H}_\rho = \int_{-1}^{+1} \frac{dx}{\sqrt{2}} \left(e_u H^u - e_d H^d\right)\left[(x-\xi+i\varepsilon)^{-1} + (x+\xi-i\varepsilon)^{-1}\right]$$

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


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

JLab @ 6.6 - 11 GeV: Hall A

Experimental configuration ($e\,p \to e\,\gamma\,X$)



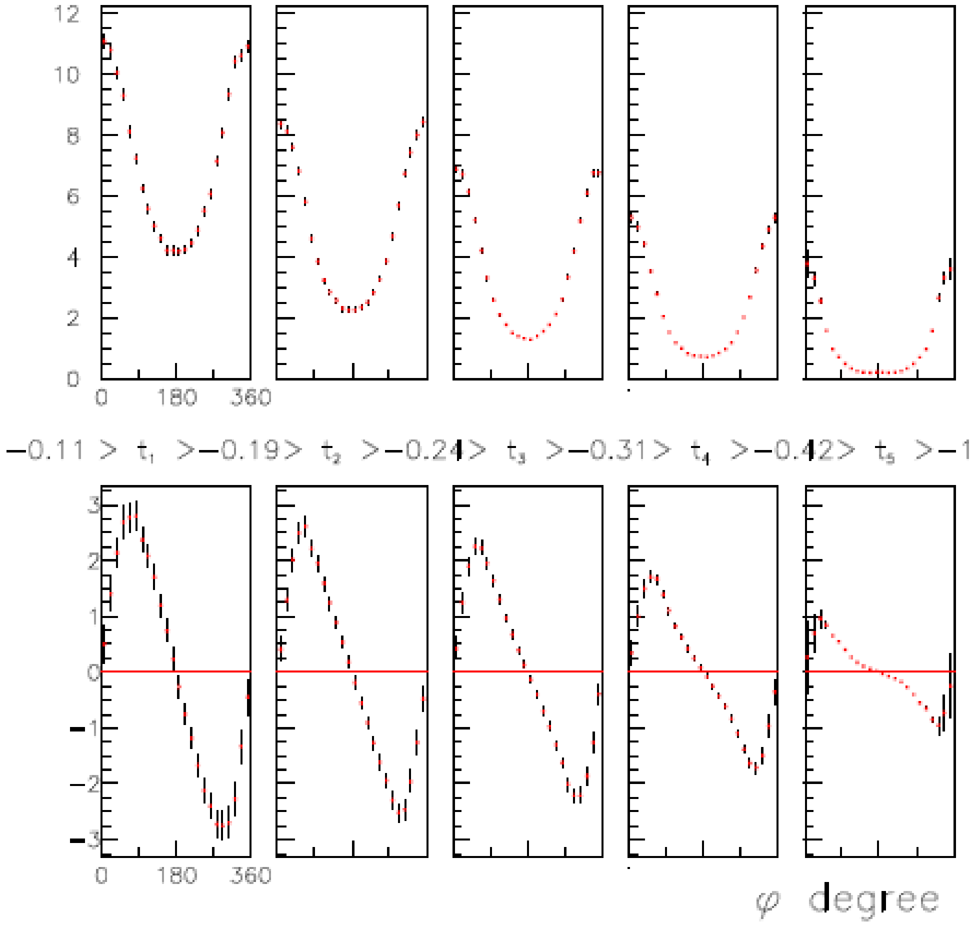
JLab @ 6.6 - 11 GeV: Hall A

Cross sections

- 250k events/setting or 40k events per $t-$bin

Helicity-independent cross sections (pb/GeV^4)

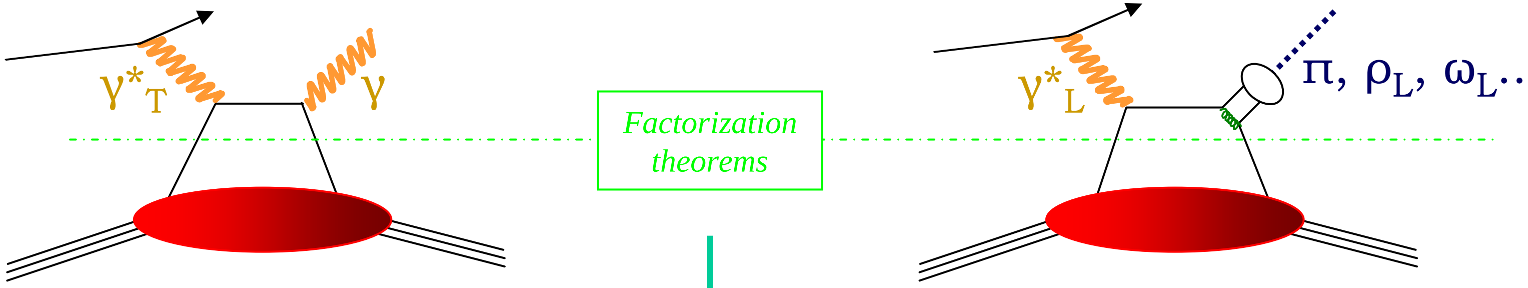
6.6 GeV setting $Q^2 = 3.0\,\text{GeV}^2$, $x_{\text{Bj}} = 0.36$



Helicity-dependent cross sections (pb/GeV^4)

How to measure GPD's?

Summary of observables to be mapped out



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 (long.) → $\tilde{H}$ at $x = \pm\xi$,
- Target spin asymmetry (transv.) → also E
- Beam charge asymmetry → H
- leading order (twist-2) contribution dominates down to relatively low Q^2

-Cross sections:

BH/DVCS decreases when E increases

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.

Conclusion & perspectives

JLab, with high luminosity and/or high-acceptance detectors,
is well equiped for the studies of (rare) deeply exclusive reactions

At **6 GeV**, successful first dedicated experiments and more to come !

The **12 GeV upgrade** will significantly increase the coverage
in x_B (both low and high) and Q^2

DVCS: several observables already explored will be « nailed down »
with considerable detail

DVMP: the dominance of leading-order diagram (handbag)
still to be found/established → 12 GeV crucial

In parallel, **theoretical progress** in

- the physical interpretation of GPDs
- the calculation of GPD moments using lattice QCD
- finding suitable parameterizations of GPDs
to perform global fits to the data

Additional slides

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

GPD evolution

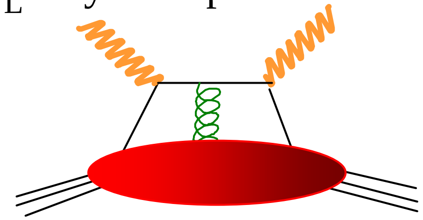
Dependence on factorization scale μ :

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

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)

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

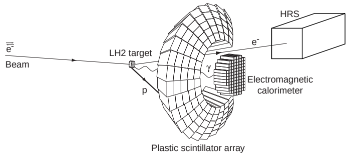
- Other twist-4 ……

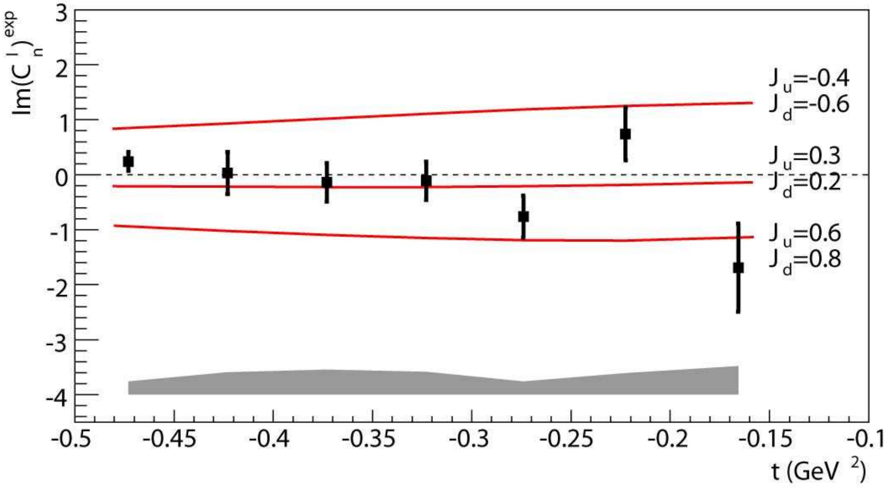
DVCS on the neutron (JLab/Hall A)

Beam spin asymmetry

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

$$\boxed{A = \underbrace{F_1(t)\cdot \mathrm{H}}_{\text{Main contribution for the proton}} + \frac{x_B}{2-x_B}[F_1(t)+F_2(t)]\cdot\tilde{\mathrm{H}} - \underbrace{\frac{t}{4M^2}F_2(t)\cdot \mathrm{E}}_{\text{Main contribution for the neutron}}}$$



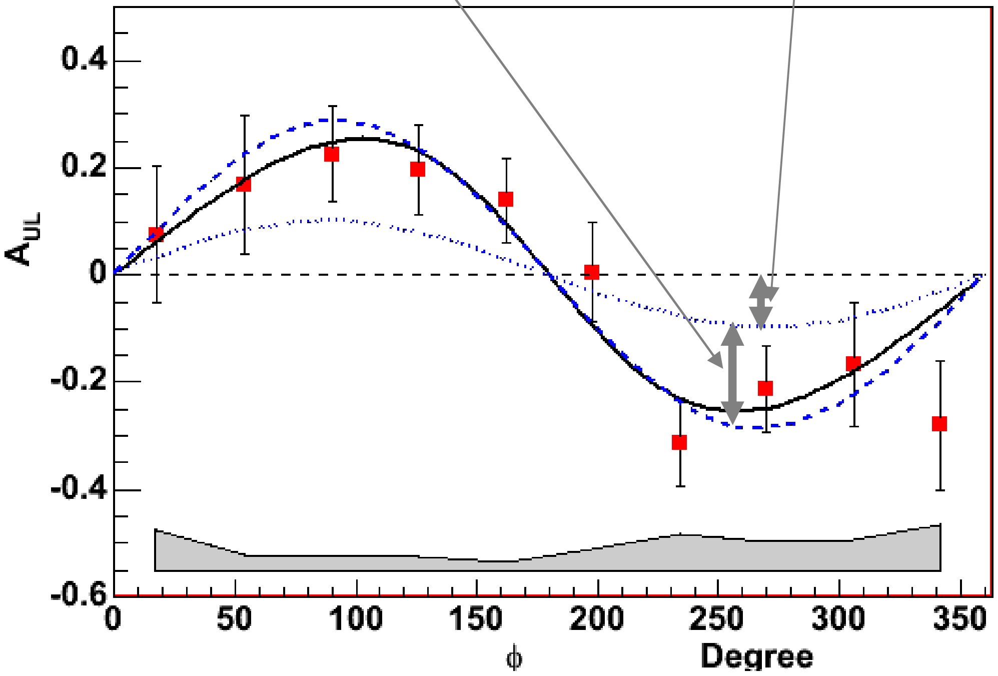


DVCS $\Delta\sigma_{LU}$ on the neutron shows (within a model) **sensitivity to**
<u>quark angular momentum J</u>

M. Mazouz *et al*. (Hall A), PRL **99** (2007)

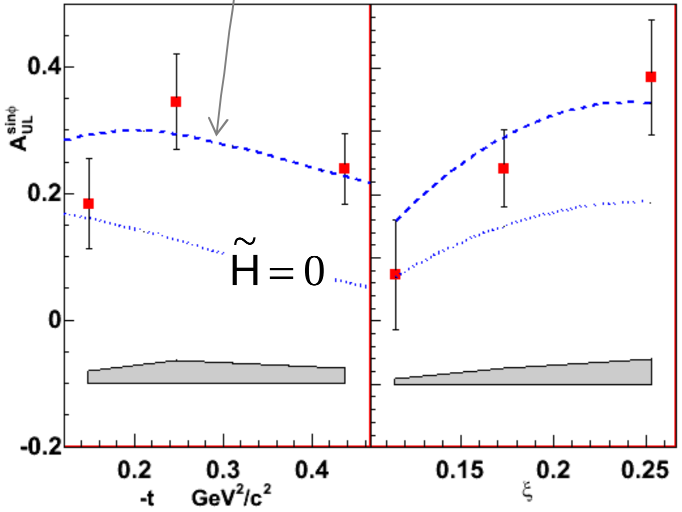
DVCS Target Spin Asymmetry from CLAS

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



ep → epγ on longitudinally polarized NH_3 target

Full GPD model,
(VGG, PRD **60** (1999))



S. Chen *et al.* (CLAS), PRL **97** (2006)

HERMES

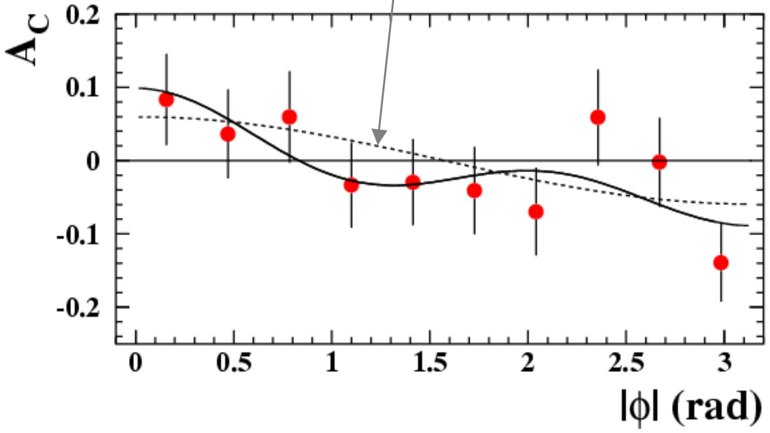
Explored several observables which have selective sensitivity to the 4 GPDs:

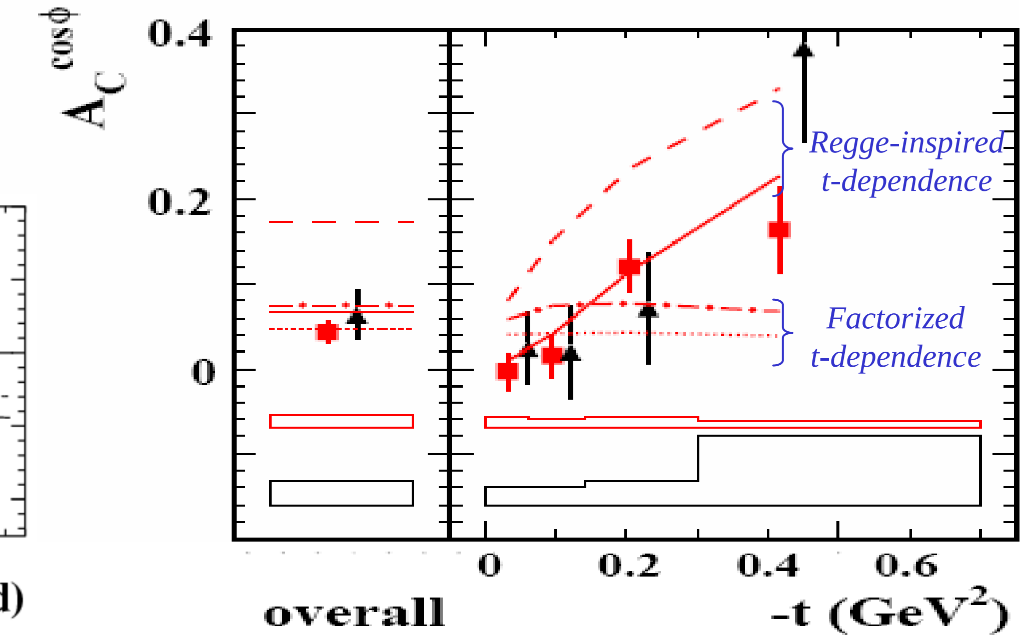
Beam Spin Asymmetry (A_{LU})

Target Spin Asymmetries (A_{UL} and A_{UT})

Beam Charge Asymmetry (A_C)

$$A_C \propto F_1\left\{\cos\phi\cdot\mathcal{P}\int_{-1}^{+1}H(x,\xi,t)\left[(x-\xi)^{-1}+(x+\xi)^{-1}\right]dx+aP_l\sin\phi\cdot\mathrm{H}\right\}+\dots$$





Regge-inspired t-dependence

Factorized t-dependence

A. Airapetian et al. (HERMES), hep-ex/0802.2499

HERMES

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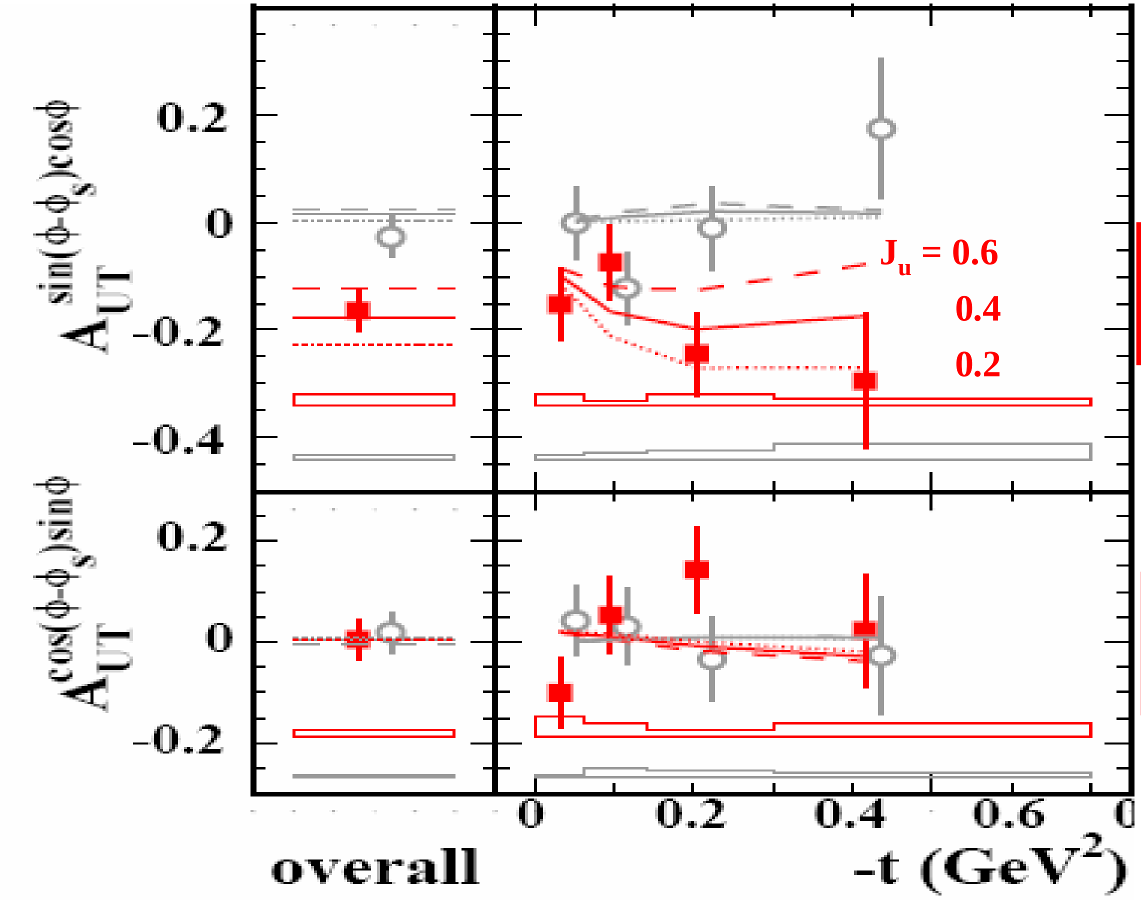
Beam Charge Asymmetry (A_C)



Red squares from DVCS-BH interference terms:

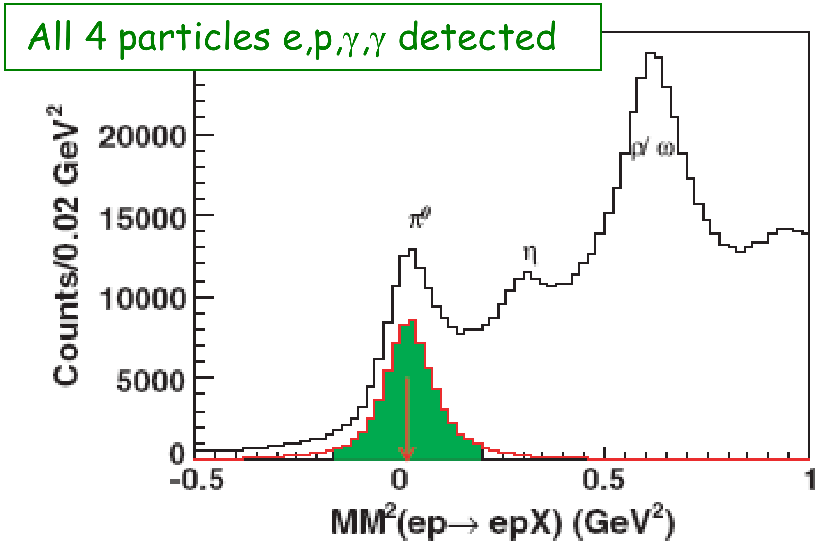
$$\propto \frac{t}{2M^2}\{F_1 \cdot E - F_2 \cdot H\} + x_B^{\,2}\{\cdots\}$$

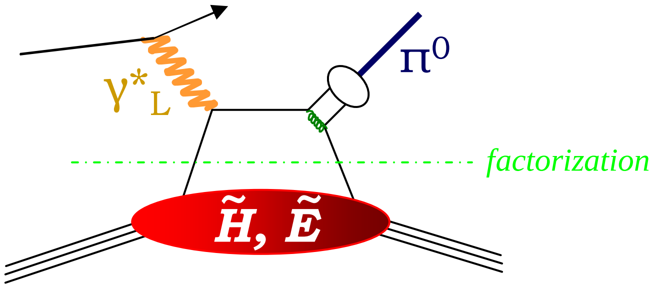
$$\propto \frac{t}{2M^2}\{F_2 \cdot \tilde{H} - 2x_B F_1 \cdot \tilde{E}\} + \{\cdots\}$$

A. Airapetian et al. (HERMES), arXiv:0802.2499

Deeply virtual meson production: CLAS/π^0

All 4 particles e,p,γ,γ detected

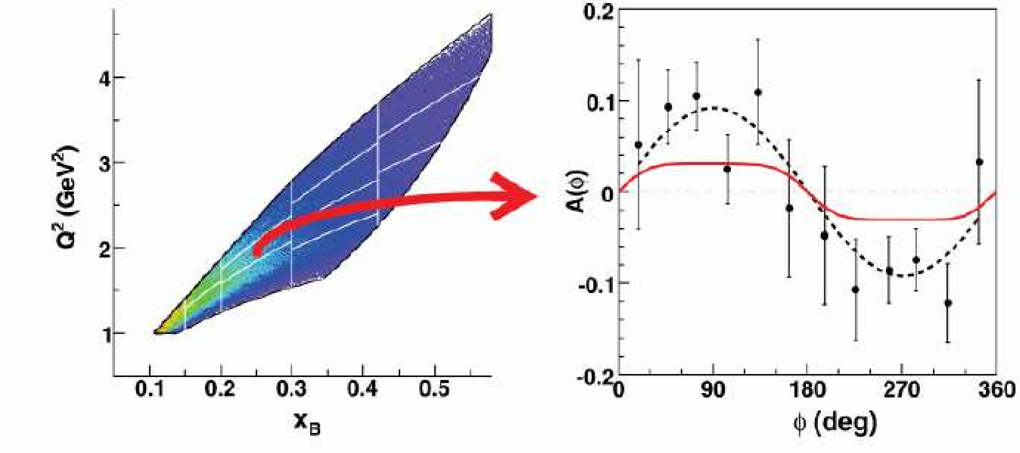


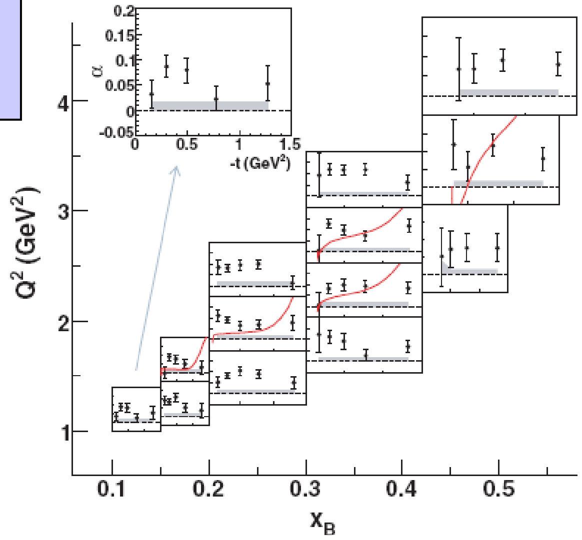


BSA in this case is a sign of a non-zero L/T interference

Handbag diagram might not be dominant

Hall A data (see C. Muñoz Camacho's talk) indicates that cross section is much higher than anticipated in GPD model and contains significant contributions from transverse amplitudes.





R. De Masi *et al.* (CLAS), PRC **77** (2008)

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: $<\sin\Phi> \sim 1/Q$, $<\sin 2\Phi> \sim 1/Q^2$

OK as of ~ 2 GeV²

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

- theoretical expectation: scaling at higher Q^2
- may have to await CEBAF@12GeV

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

JLab (Hall A & CLAS) dedicated DVCS experiments represent a quantitative and qualitative jump

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

Except for specific cases (access to imaginary part of DVCS amplitude and/or use of DDVCS),

the observables are convolutions of the Generalized Parton Distributions.

In theory, an infinite set of data is needed to deconvolute the observables.

In practice, there are several ways to use a finite set of data

(including all finite Q^2 corrections in the formalism)

- Comparison of given GPD model with experiment,
- Fit of parameterized GPDs with constraints:

forward limit, elastic form factors, polynomiality, positivity bounds,

- GPDs given by sums over *t*-channel exchanges, like a partial wave expansion,
- Inverse transformations (see e.g. Teryaev on Radon tomography)
- and **more to come**

Determining GPDs: DVCS or Lattice QCD ?

Experiment

→ extract/check LO/twist-2 contributions (hopefully dominant),

→ use several observables to extract different linear combinations of GPDs, including different flavor combinations,

→ « deconvolution » or fit with adequate parameterisation(s) of GPDs.

Lattice

→ calculate GPD moments n = 0, 1, 2 (and more ??),

→ check for fermion discretisation scheme, extrapolations, « elusive » disconnected diagrams,

→ parameterise and extrapolate moments for all values of n,

→ get GPD from inversion from infinite set of moments.

Lattice has the lead… but
(dixit C.M.)
experiment is, at the end of the day, what
validates our knowledge