Deeply Virtual Compton Scattering experiments

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CEA Saclay

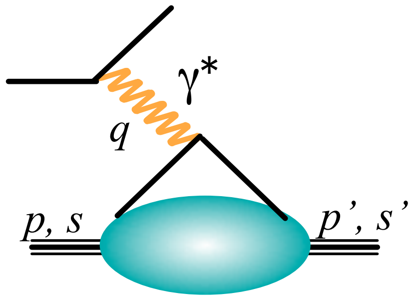
hard photon & meson production workshop

European Centre for Theoretical studies
Trento, Italy
10th-15th October

- Short introduction to GPDs
- DVCS as a tool to extract GPDs
- From the first DVCS observations
- to the last JLab and HERMES results
- Future DVCS measurements
- Conclusion

The electromagnetic probe for the nucleon structure

Local, *Off-diagonal*



Elastic scattering

Hofstadter (1958)

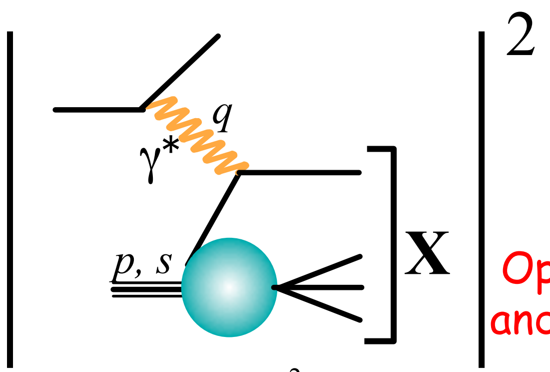
$$\langle p's' | \overline{\psi}(0)\gamma^{\mu}\psi(0) | ps \rangle \rightarrow G_M, G_E$$

$$\langle p's' | \overline{\psi}(0)\gamma^{\mu}\gamma^{5}\psi(0) | ps \rangle \rightarrow G_A, G_P$$

Non-local, Diagonal

Deep Inelastic Scattering

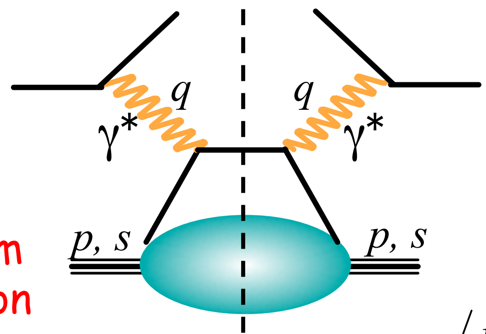
Taylor et al. (1969)



$$x_B = \frac{Q^2}{2p.q}$$

$\propto \; Im$

Optical theorem
and factorization



Forward Compton
Amplitude

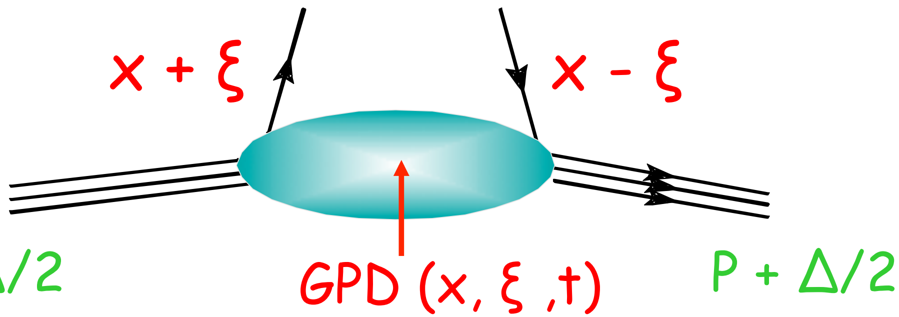
$$\langle ps | \overline{\psi}(-y/2)\gamma^{\mu}\psi(y/2) | ps \rangle \rightarrow F_2$$

$$\langle ps | \overline{\psi}(-y/2)\gamma^{\mu}\gamma^{5}\psi(y/2) | ps \rangle \rightarrow g_1$$

A natural extension: non-local, off-diagonal matrix elements

Mueller

(1995)



(x + ξ) and (x - ξ) : longitudinal momentum fractions of quarks

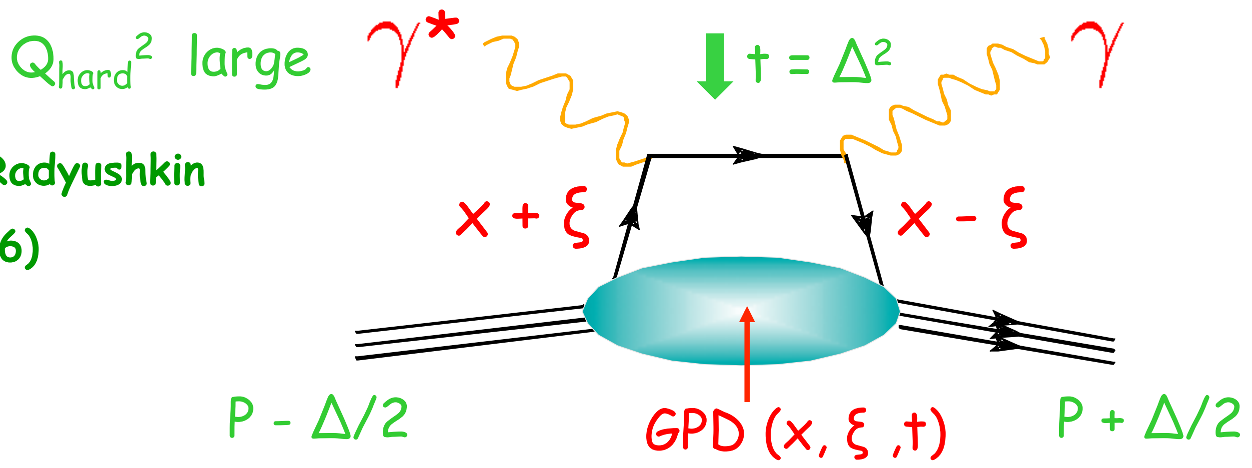
The structure of the nucleon can be described by
4 Generalized Parton Distributions :

Vector : $H(x, \xi, t)$ Axial-Vector : $\tilde{H}(x, \xi, t)$

Tensor : $E(x, \xi, t)$ Pseudoscalar : $\tilde{E}(x, \xi, t)$

And its golden process : Deeply Virtual Compton Scattering

Ji, Radyushkin (1996)



low −t process : $-t \ll Q_{hard}^2$

$(x + \xi)$ and $(x - \xi)$: longitudinal momentum fractions of quarks

at large Q^2 : QCD factorization theorem ➡ hard exclusive processes can be described by 4 Generalized Parton Distributions:

Vector : $H(x, \xi, t)$ Axial-Vector : $\tilde{H}(x, \xi, t)$

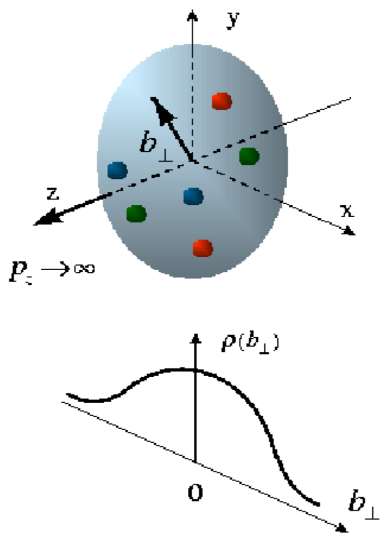
Tensor : $E(x, \xi, t)$ Pseudoscalar : $\tilde{E}(x, \xi, t)$

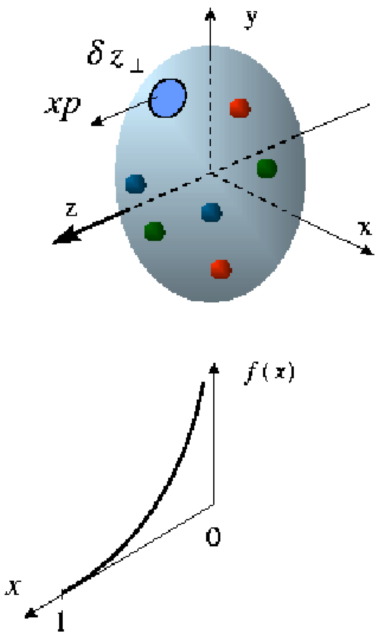
Why Generalized Parton Distributions are the way to go !

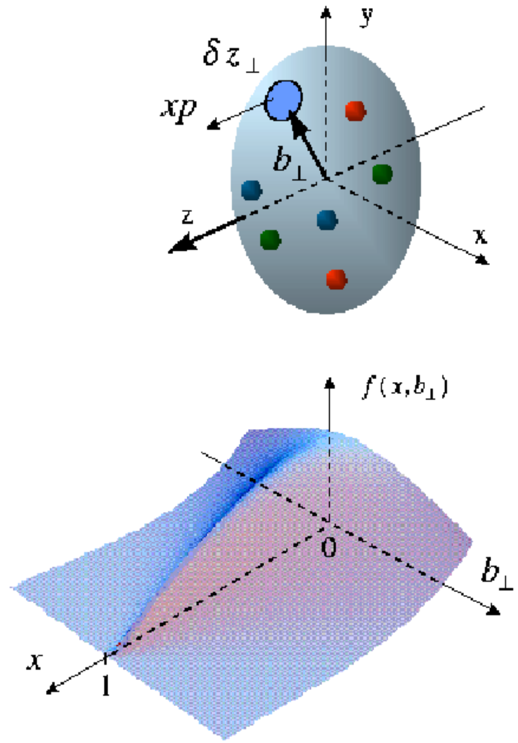
GPDs yield 3-dim quark structure of the nucleon

Burkardt (2000, 2003)

Belitsky, Ji, Yuan (2003)







Elastic Scattering

transverse quark **distribution** in coordinate space

DIS

longitudinal quark **distribution** in momentum space

DES (GPDs)

fully-correlated quark distribution in both coordinate and momentum space

Properties, applications

They contain what we know already through sum rules and kinematical limits: Form Factors, parton distributions

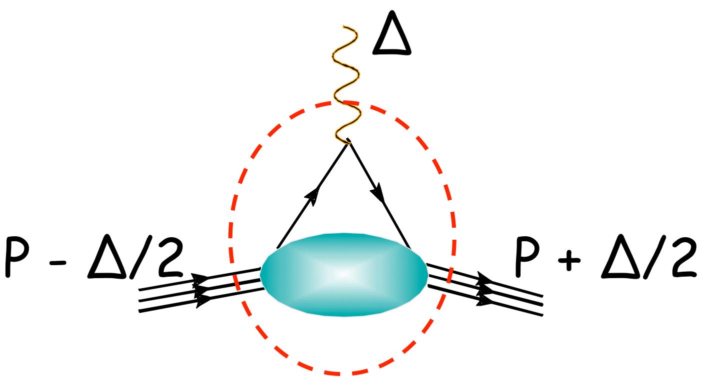
- forward limit : ordinary parton distributions

$$H^q(x, \xi = 0, t = 0) = q(x) \quad \text{unpolarized quark distributions}$$

$$\tilde{H}^q(x, \xi = 0, t = 0) = \Delta q(x) \quad \text{polarized quark distributions}$$

E^q , $\tilde{E}^q$: do NOT appear in DIS ... new information

- first moments : nucleon electroweak form factors



ξ-independence : Lorentz invariance

$$\int_{-1}^{1} dx\, H^q(x, \xi, t) = F_1^q(t) \quad \text{Dirac}$$

$$\int_{-1}^{1} dx\, E^q(x, \xi, t) = F_2^q(t) \quad \text{Pauli}$$

$$\int_{-1}^{1} dx\, \tilde{H}^q(x, \xi, t) = G_A^q(t) \quad \text{axial}$$

$$\int_{-1}^{1} dx\, \tilde{E}^q(x, \xi, t) = G_P^q(t) \quad \text{pseudo-scalar}$$

Properties, applications

- They contain what we know already through sum rules and kinematical limits: Form Factors, parton distributions

- Through the space-momentum correlation, they give access to the Orbital Angular Momentum (OAM) carried by partons inside the nucleon : Finally an end to the spin crisis ?

Ji's sum rule :

$$J^q = \frac{1}{2}\Delta\Sigma + L^q = \lim_{t \to 0} \frac{1}{2} \int_{-1}^{1} x dx \left[H^q(x,\xi,t) + E^q(x,\xi,t) \right]$$

Related to momentum fraction carried by quarks (H^q)

Best accessible using transverse polarized target, but also neutron DVCS (E^q)

Moments of GPDs are calculable in Lattice QCD. Lowest moments have already been computed for valence quarks (Goeckeler)

Properties, applications

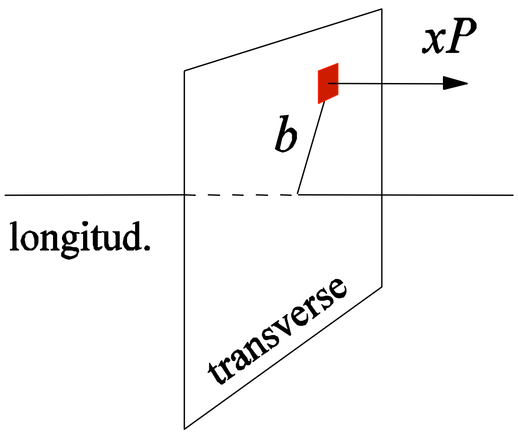
- They contain what we know already through sum rules and kinematical limits: Form Factors, parton distributions

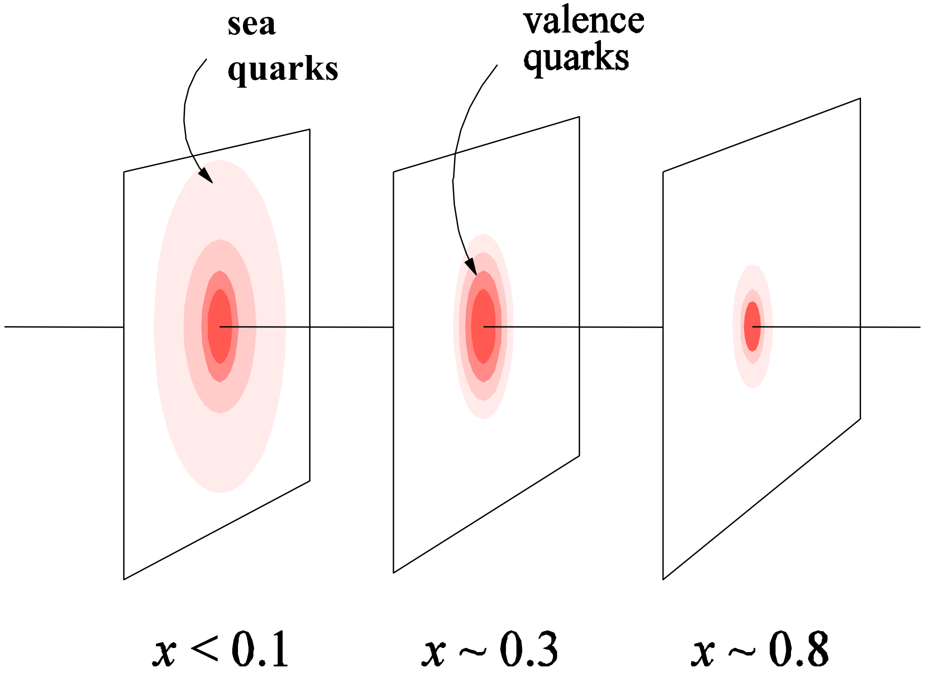
- Through the space-momentum correlation, they give access to the
  Ang
  nucl

M. Burkardt, M. Diehl (2002)

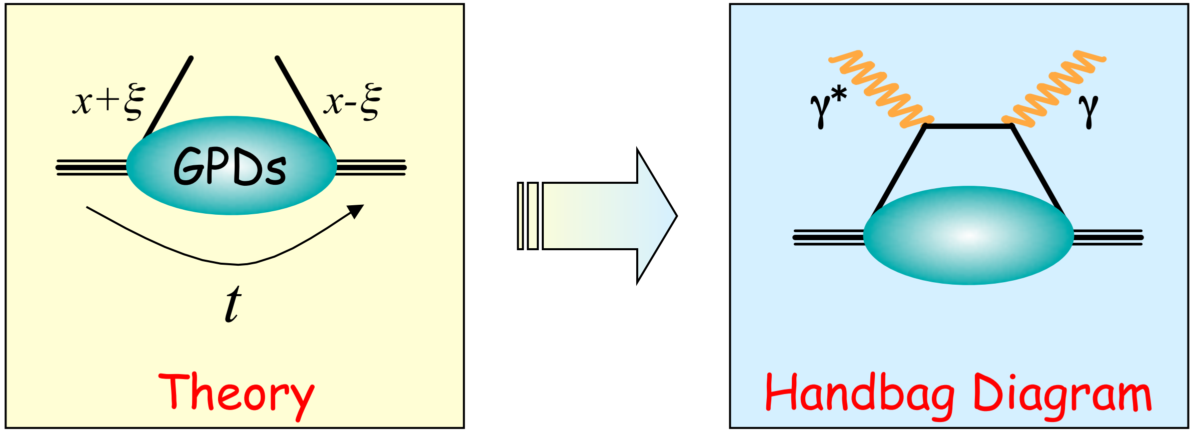
$$H^q(x, \mathbf{b}_\perp) = \int \frac{d^2\boldsymbol{\Delta}_\perp}{(2\pi)^2}\, e^{i\mathbf{b}_\perp \cdot \boldsymbol{\Delta}_\perp}\, H^q(x, \xi = 0, -\boldsymbol{\Delta}_\perp{}^2)$$

- e





GPDs from Theory to Experiment



2. The GPDs enter the DVCS amplitude as an integral over x:

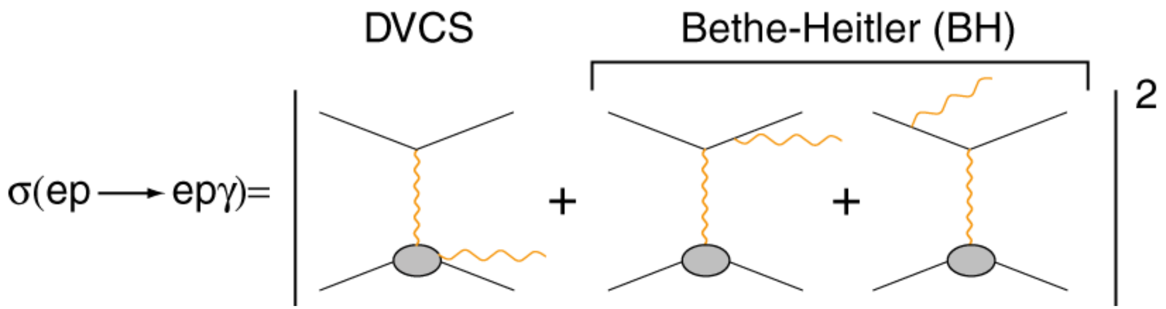
- GPDs appear in the real part through a PP integral over x
- GPDs appear in the imaginary part but at the line x=ξ

$$T^{DVCS} = \int_{-1}^{+1} \frac{GPD(x,\xi,t)}{x-\xi+i\varepsilon} dx \quad + \quad \cdots$$

$$= P\int_{-1}^{+1} \frac{GPD(x,\xi,t)}{x-\xi} dx \quad - \quad i\pi GPD(x=\xi,\xi,t) \quad + \quad \cdots$$

Experimental observables linked to GPDs

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:

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

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

At low energy,
$|T^{DVCS}|^2$ supposed small

Ji, Kroll, Guichon, Diehl, Pire, …

Into the harmonic structure of DVCS

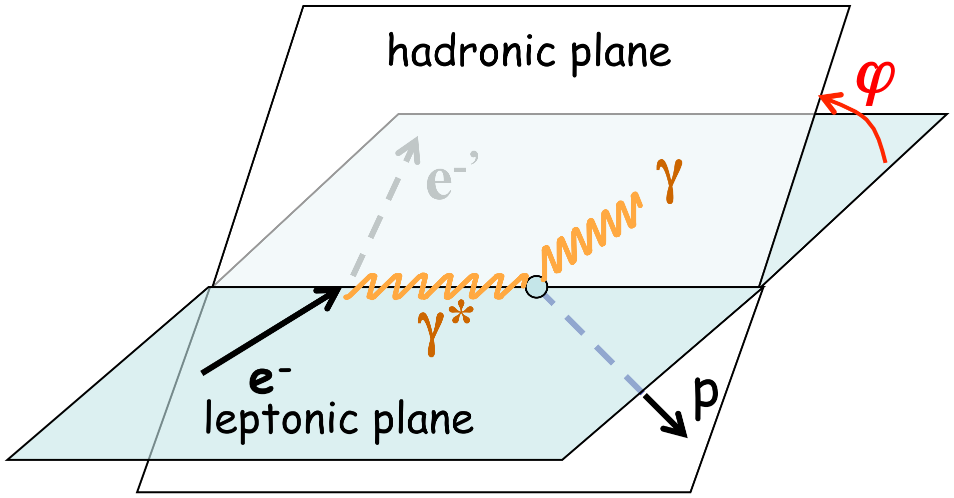
$$\frac{d^4\sigma}{dx_B dQ^2 dt d\varphi} = \frac{1}{P_1(\varphi)P_2(\varphi)}\Gamma_1(x_B,Q^2,t)\left\{c_0^{BH} + c_1^{BH}\cos\varphi + c_2^{BH}\cos 2\varphi\right\}$$

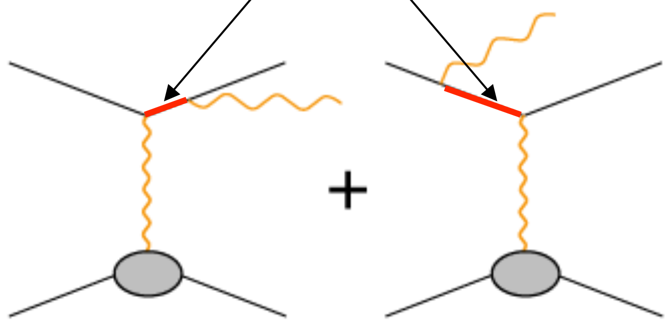
$|T^{BH}|^2$

$$+ \frac{1}{P_1(\varphi)P_2(\varphi)}\Gamma_2(x_B,Q^2,t)\left\{c_0^I + c_1^I\cos\varphi + c_2^I\cos 2\varphi + c_3^I\cos 3\varphi\right\}$$

$$\frac{d^4\overrightarrow{\sigma} - d^4\overleftarrow{\sigma}}{dx_B dQ^2 dt d\varphi} = \frac{\Gamma(x_B,Q^2,t)}{P_1(\varphi)P_2(\varphi)}\left\{s_1^I\sin\varphi + s_2^I\sin 2\varphi\right\}$$

Interference term



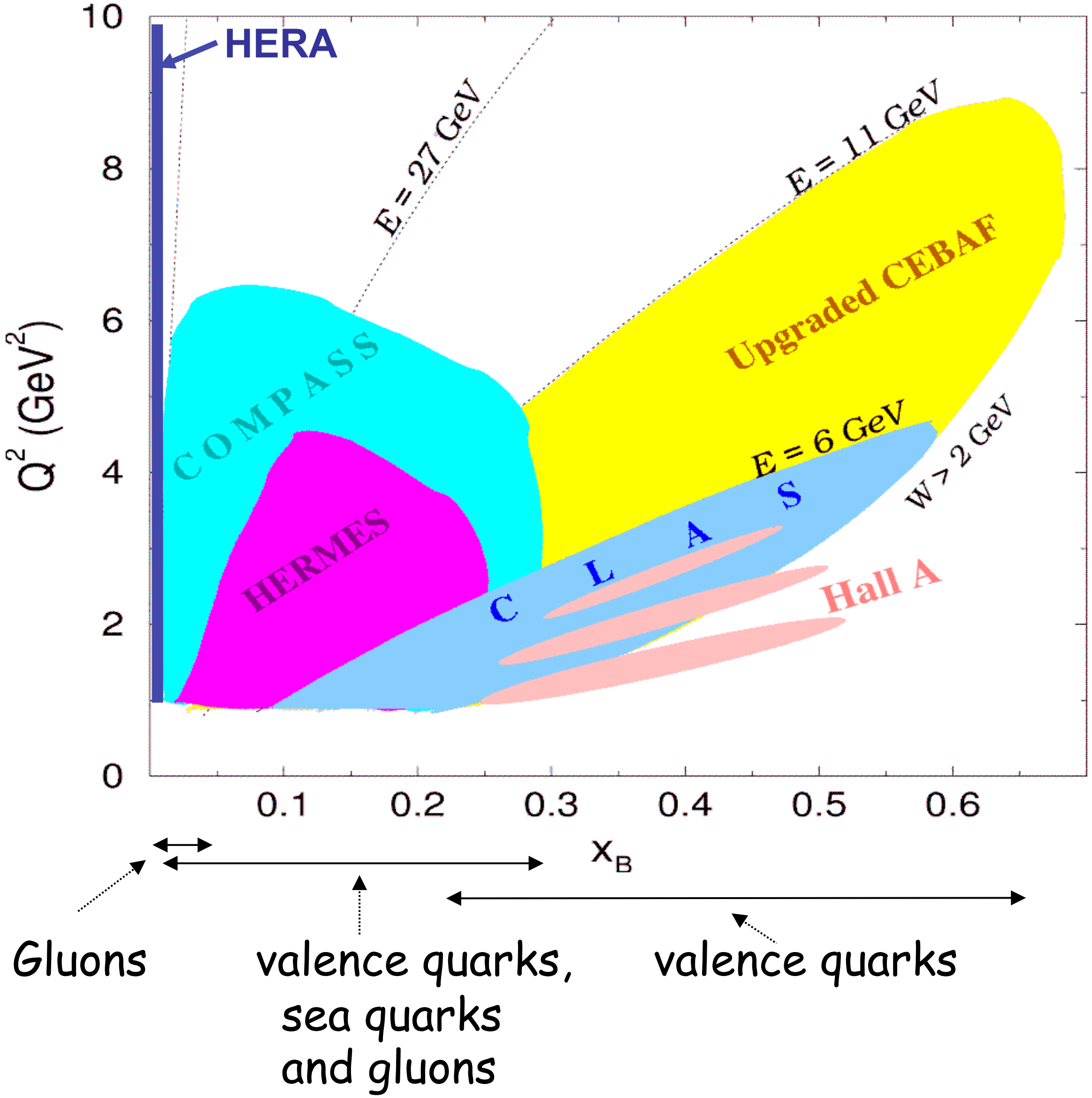


$$\frac{1}{P_1(\varphi)P_2(\varphi)}$$

BH propagators φ dependence

Belitsky, Mueller, Kirchner

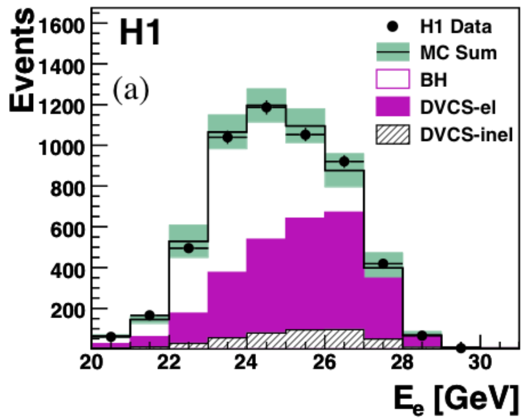
DVCS experiments and proposals worldwide

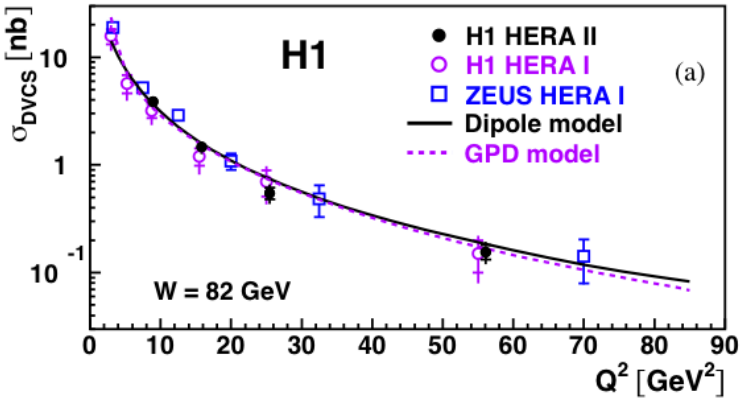


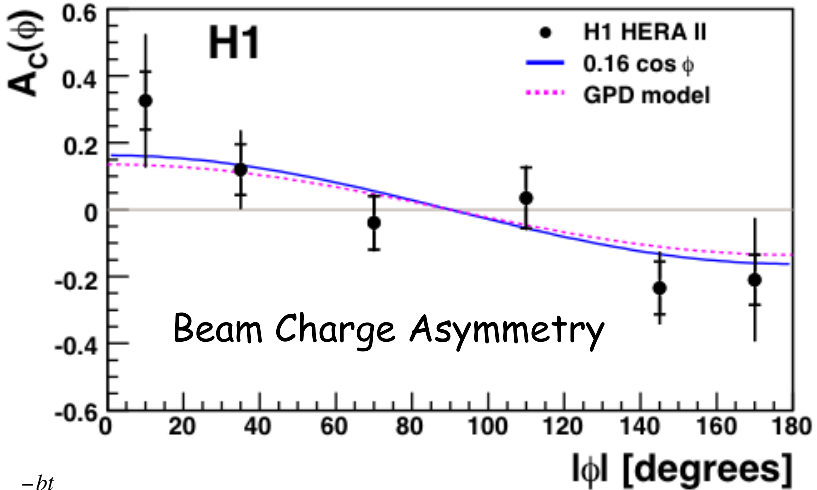
HERA data

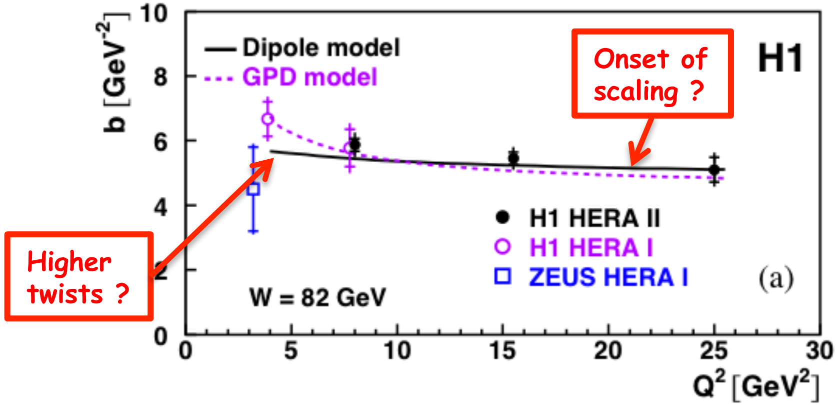
- Good Monte Carlo description using BH and DVCS contributions

- Negligible Interference contribution when integrated over ϕ









$$\frac{d\sigma_{DVCS}}{dt} \propto e^{-bt}$$

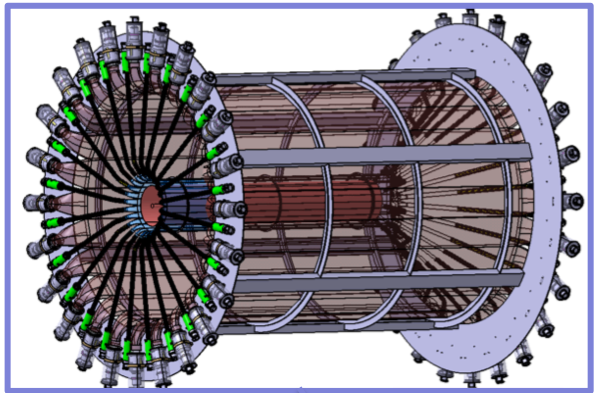
$$b = 5.41 \pm 0.14 \pm 0.31\ \mathrm{GeV}^{-2}$$

$$\sqrt{< r_T^2 >} \approx 0.64\ \mathrm{fm}$$

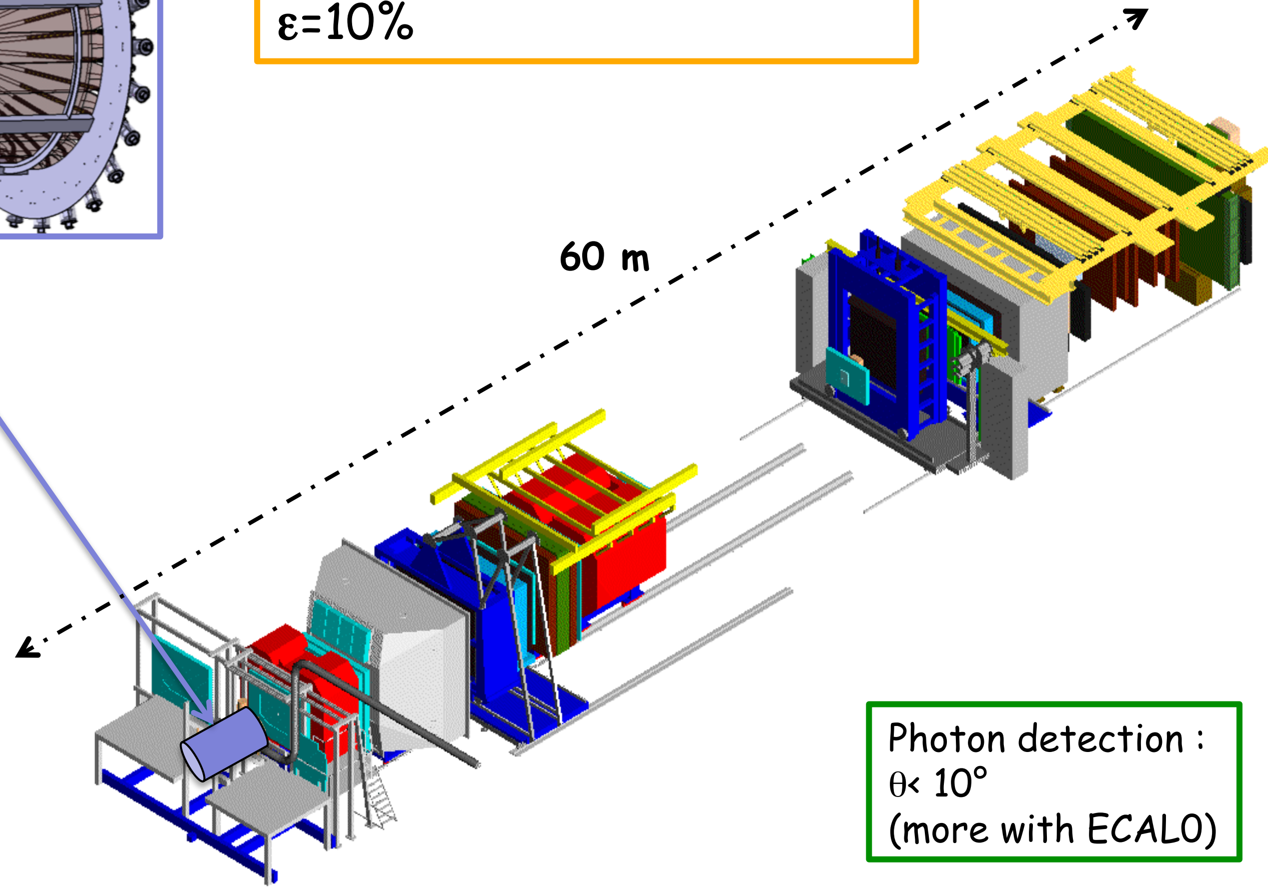
mostly gluons at x~10^{-3}

Presentation by L. Schoeffel

COMPASS DVCS setup



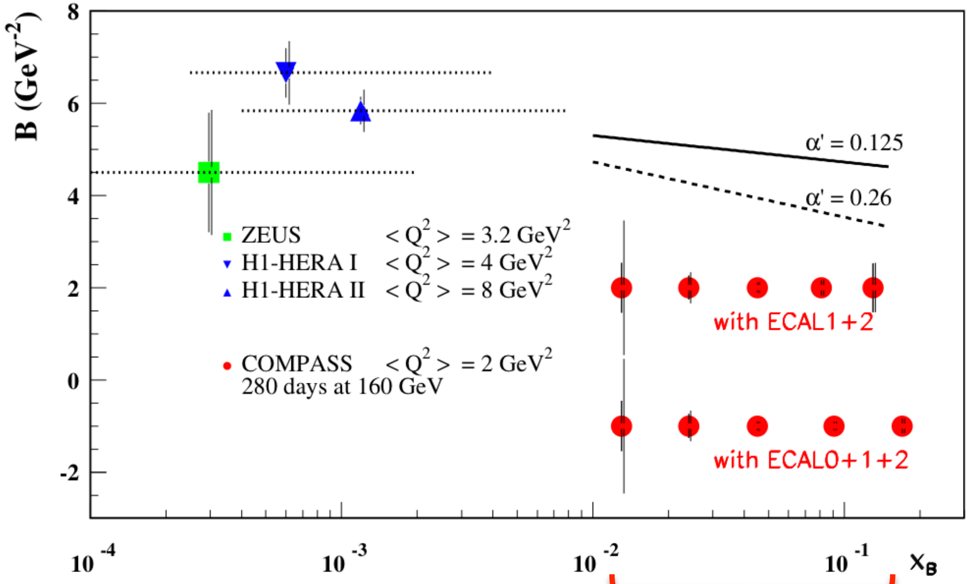
160 GeV muon beam
2 years of planned run time
$L = 1222\ fb^{-1}$
$\varepsilon = 10\%$



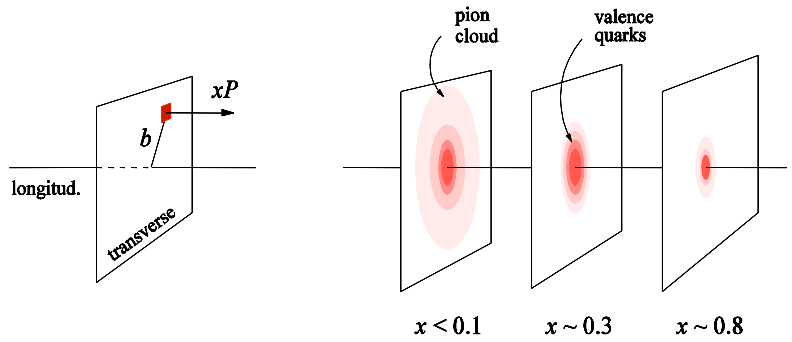
Photon detection :
$\theta < 10°$
(more with ECAL0)

2.5m LH2 target
4m-long Recoil Proton Detector
(potential transversely polarized target later on)

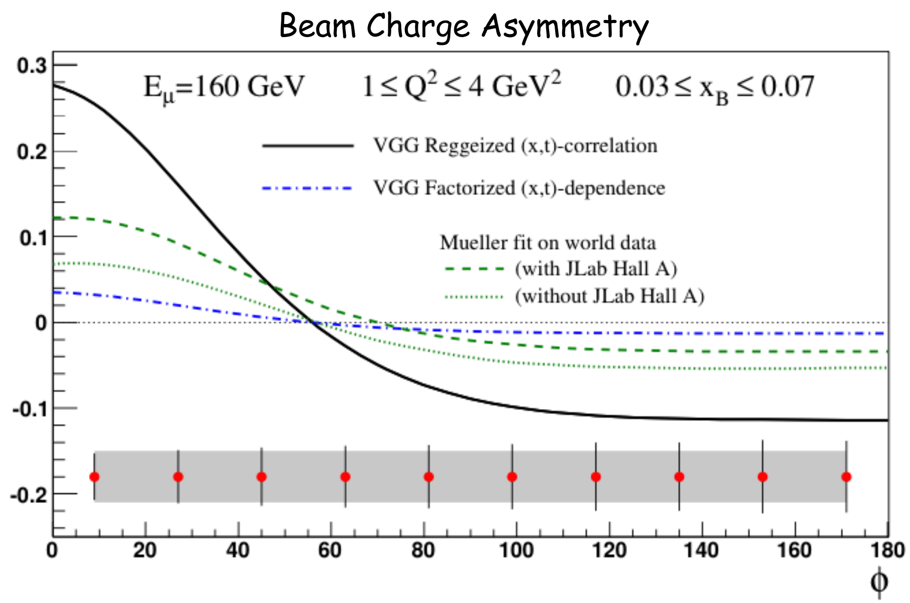
COMPASS DVCS proposal



Expectation (Gribov) :
$< b^2 > \propto \alpha' \log(1/x)$



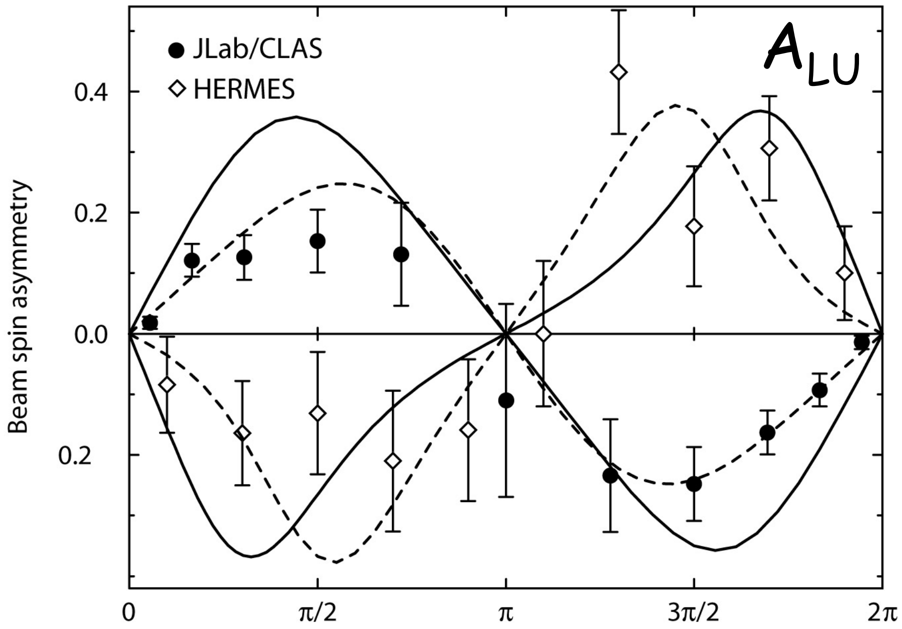
from gluons & sea quarks towards valence quarks

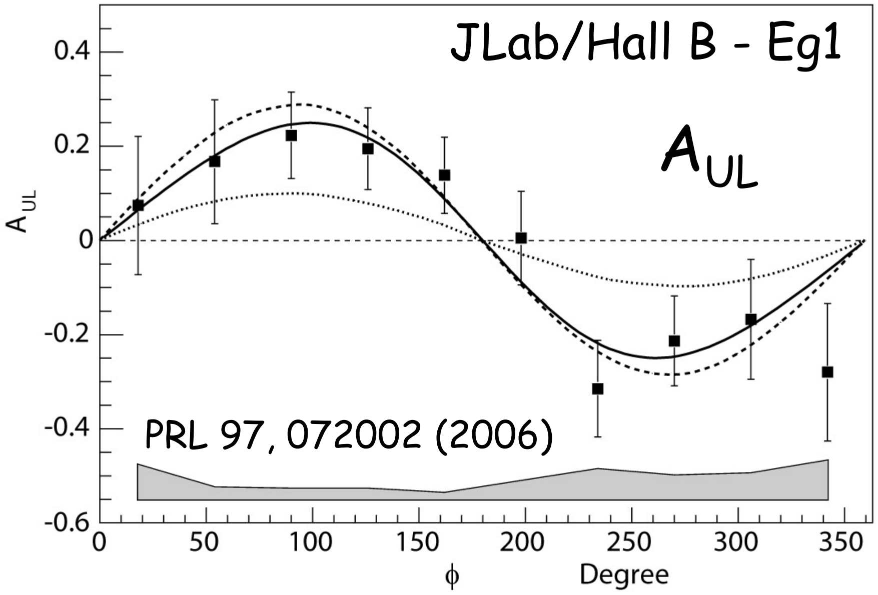


Presentation by H. Fischer

CLAS & HERMES : Pioneering results on A_{LU} and A_{UL}

JLab/Hall B - E1 & HERMES





CLAS: PRL 87, 182002 (2001)
HERMES: PRL 87, 182001 (2001)

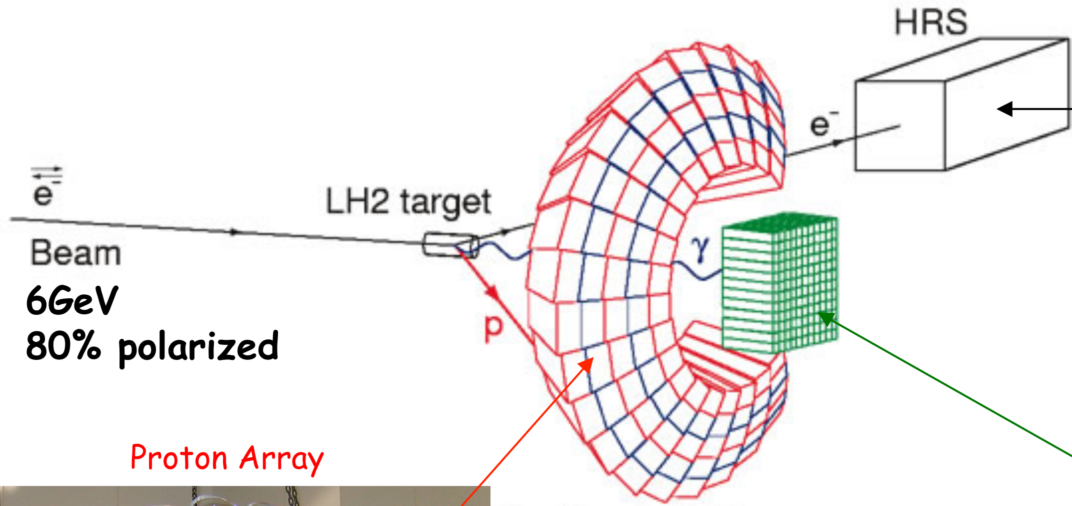
Both results show, with a limited statistics, a sin φ behavior (necessary condition for handbag dominance)

In the A_{LU} result, DD models (VGG) tend to over-estimate the data

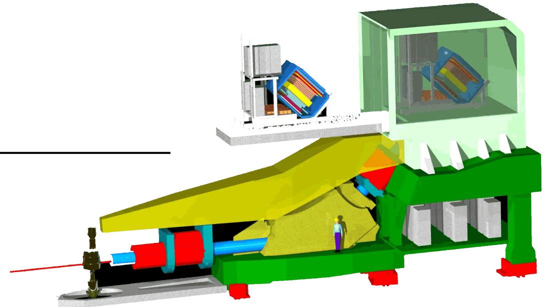
DVCS experiments at 6 GeV in the Jefferson Lab Hall A

E00-110 and E03-106

Two pioneering high precision experiments (p and n)

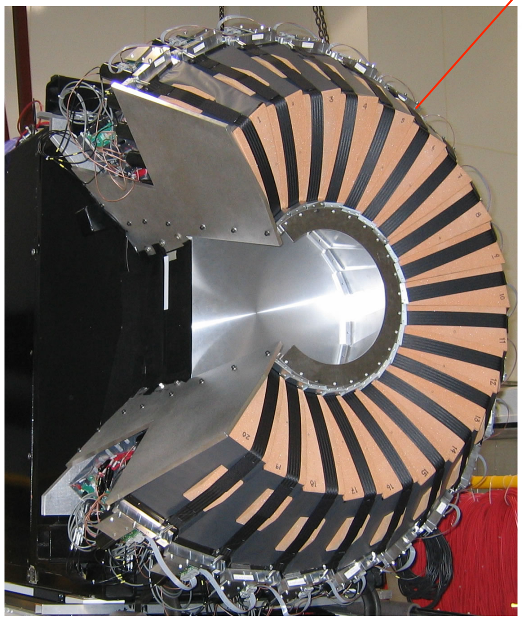


6GeV
80% polarized



HRS spectrometer in Hall A

Proton Array



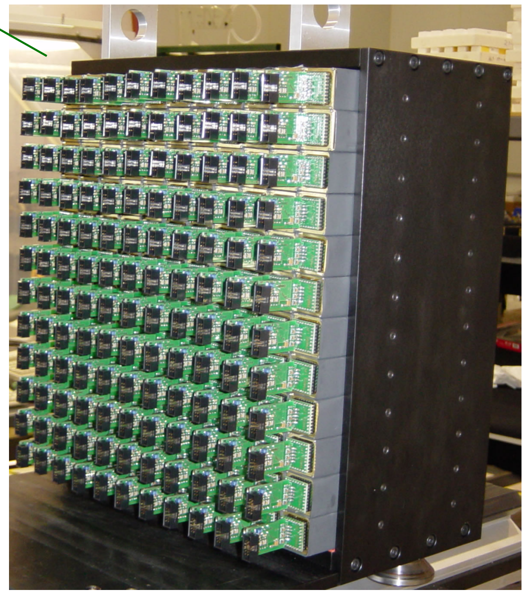
50 days of beam time in the fall 2004, at 2.5μA

L=13300 fb^{-1}

3 kinematic settings :

Kin	Q^2 (GeV^2)	x_B	θ_{γ^*} (deg.)	W (GeV)
1	**1.5**	0.36	**22.3**	1.9
2	**1.9**	0.36	**18.3**	2.0
3	**2.3**	0.36	**14.8**	2.2

Electromagnetic Calorimeter

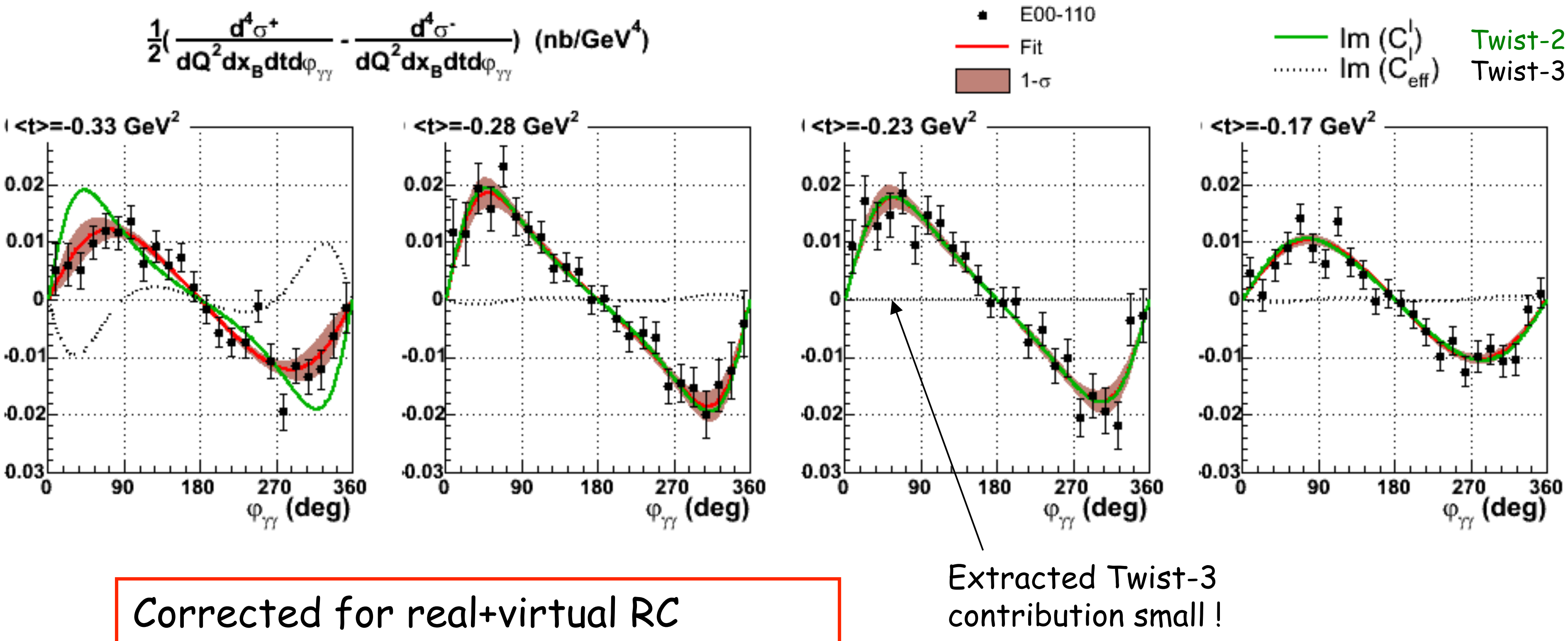


Difference of cross-sections

PRL97, 262002 (2006)

$\langle Q^2 \rangle = 2.3\ \mathrm{GeV}^2$

$\langle x_B \rangle = 0.36$

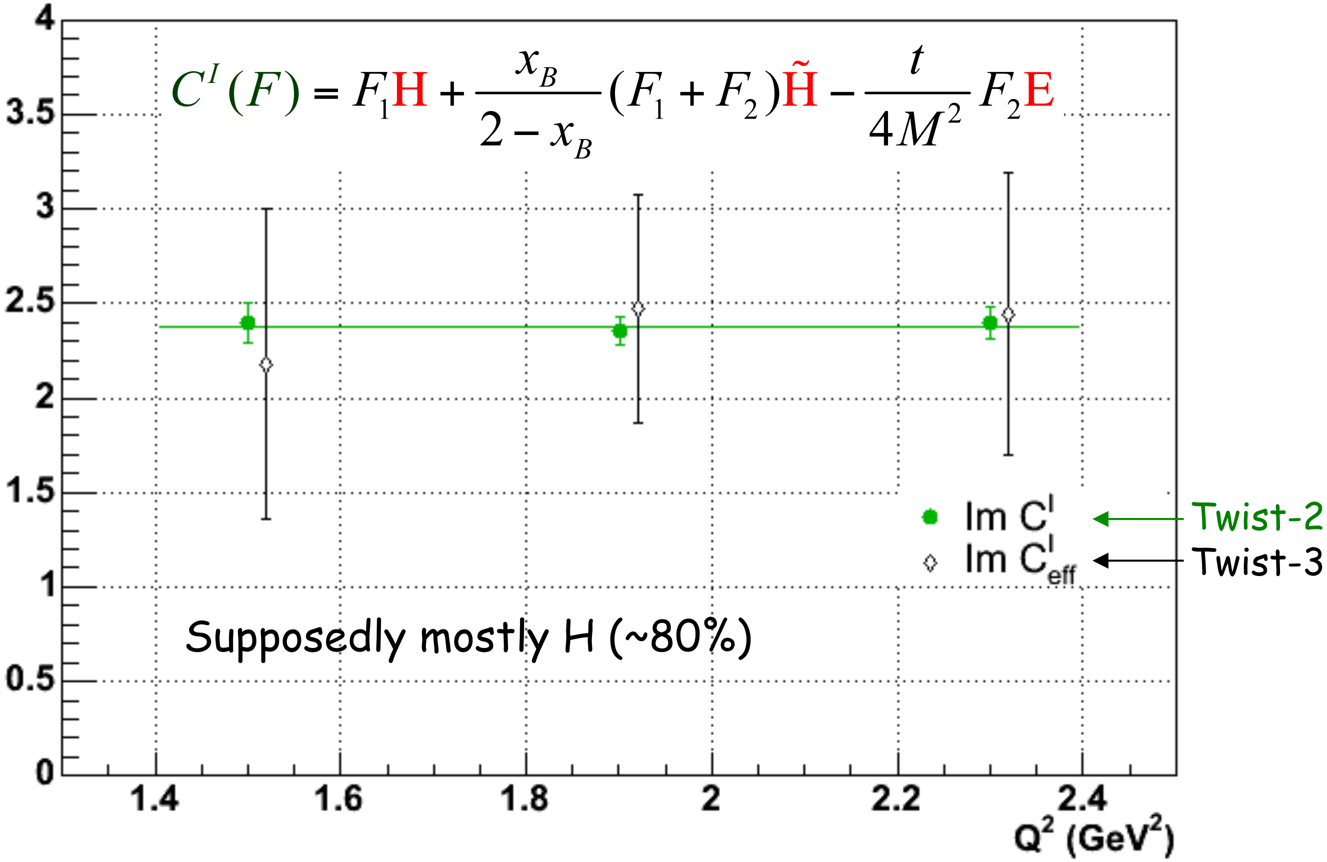


Corrected for real+virtual RC
Corrected for efficiency
Corrected for acceptance
Corrected for resolution effects
Checked elastic cross-section @ ~1%

Q^2 dependence and test of scaling

PRL97, 262002 (2006)

$\langle -t \rangle = 0.26$ GeV^2, $\langle x_B \rangle = 0.36$



No Q^2 dependence using BMK separation:
strong indication for scaling behavior and handbag dominance

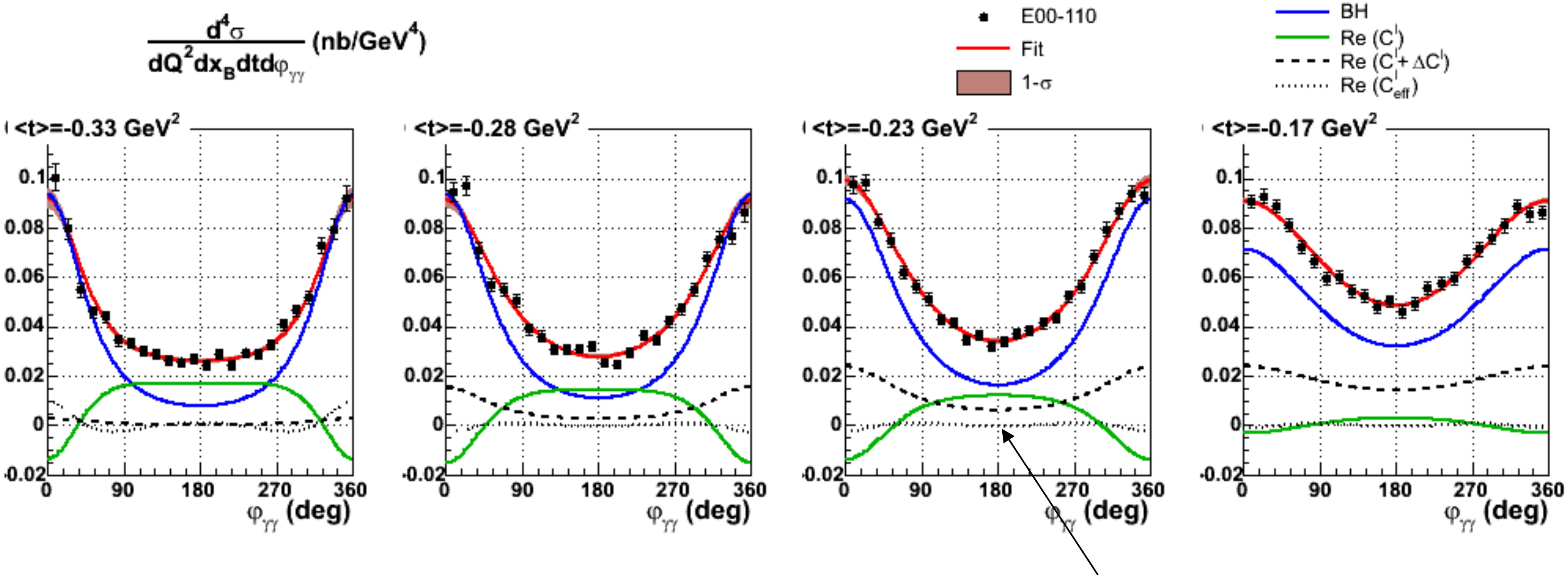
Twist 4+ contributions are smaller than 10%

Total cross-section

PRL97, 262002 (2006)

$$\langle Q^2 \rangle = 2.3\ \text{GeV}^2$$

$$\langle x_B \rangle = 0.36$$

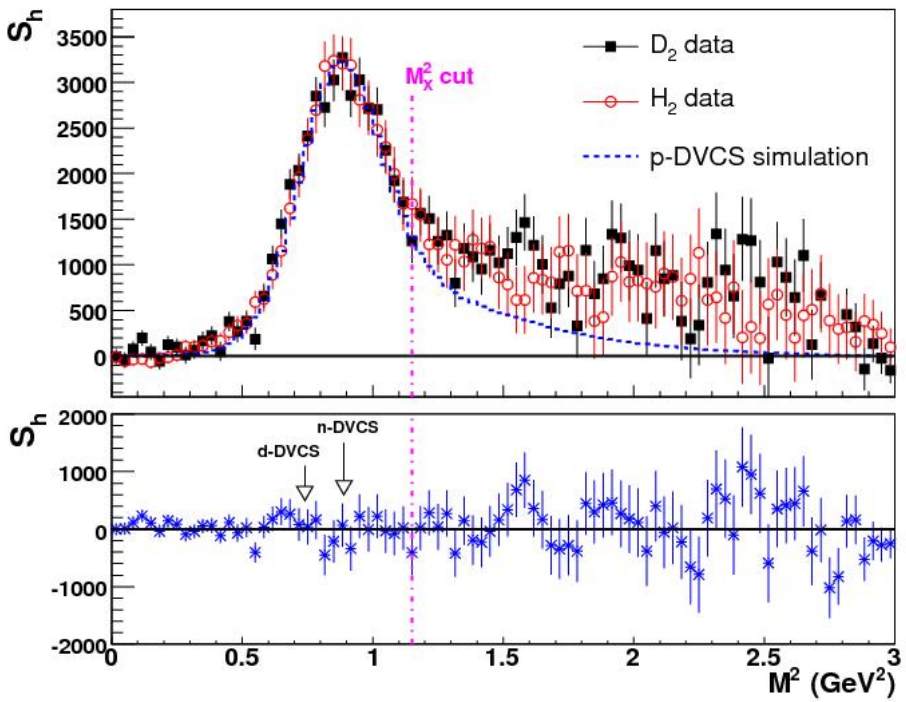


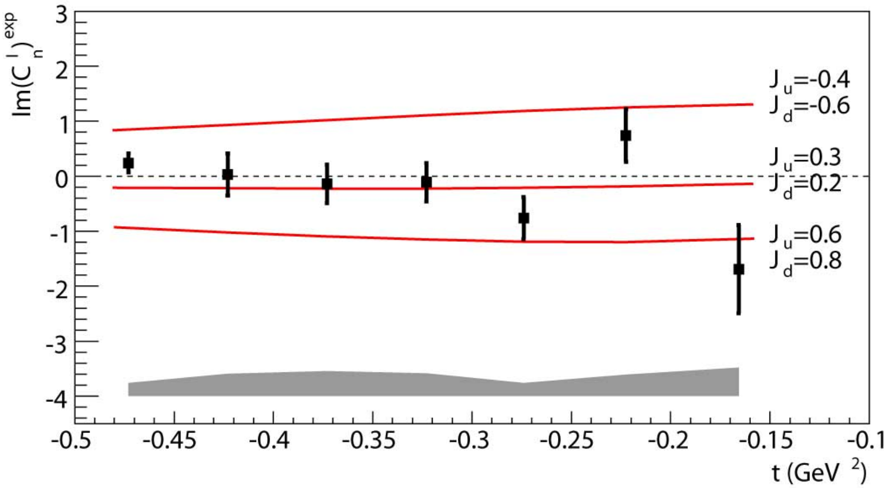
Corrected for real+virtual RC
Corrected for efficiency
Corrected for acceptance
Corrected for resolution effects

but impossible to disentangle DVCS^2 from the interference term !

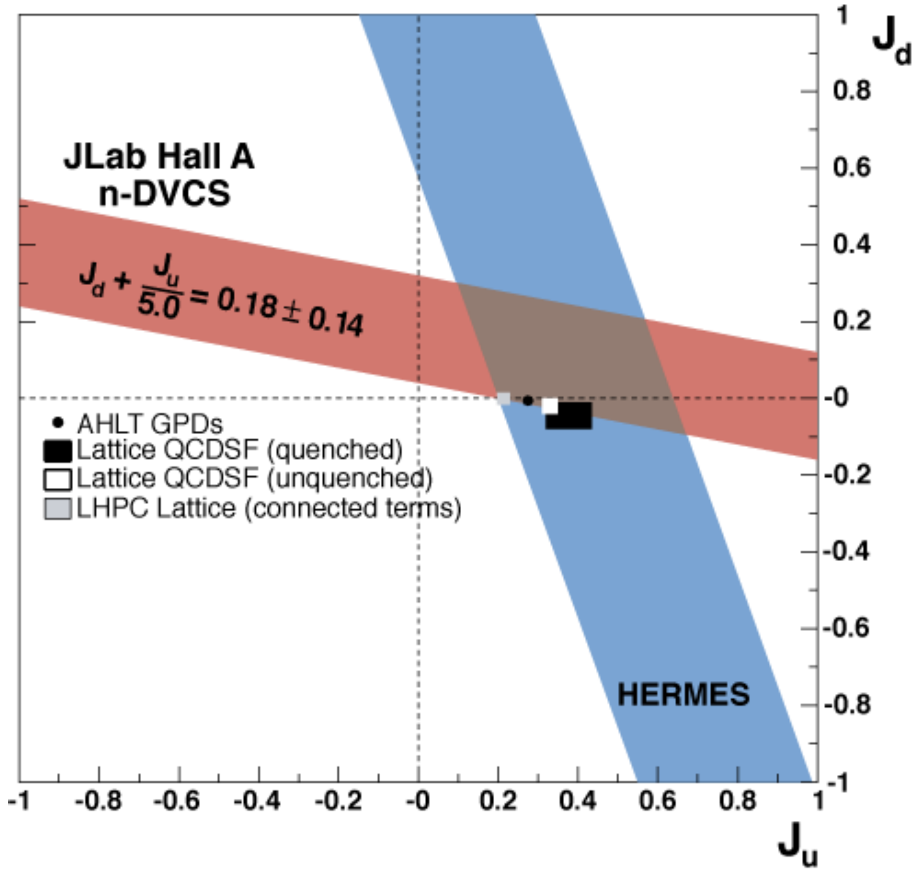
DVCS on the neutron in JLab/Hall A: E03-106

LD_2 target
24000 fb-1
x_B=0.36, Q^2=1.9 GeV^2



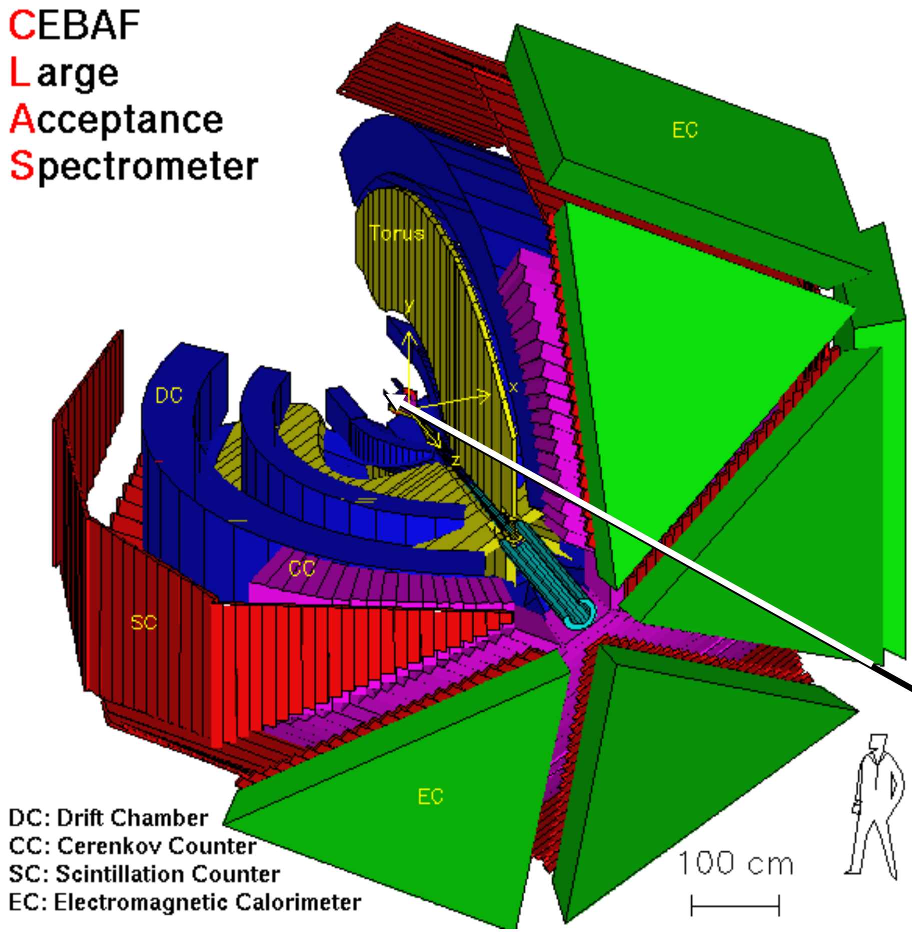


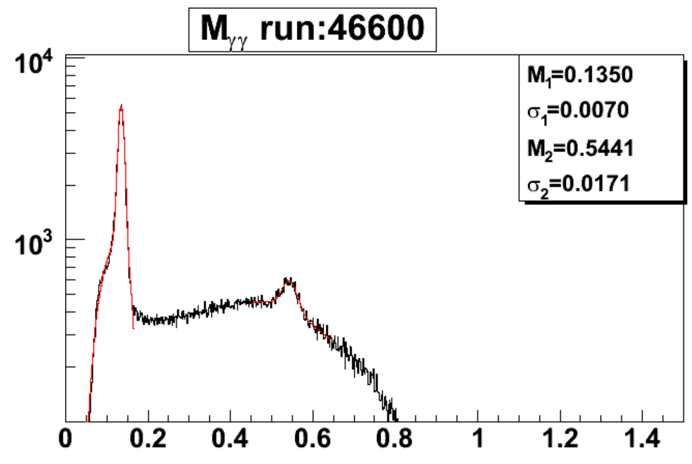
MODEL-DEPENDENT
Ju-Jd extraction



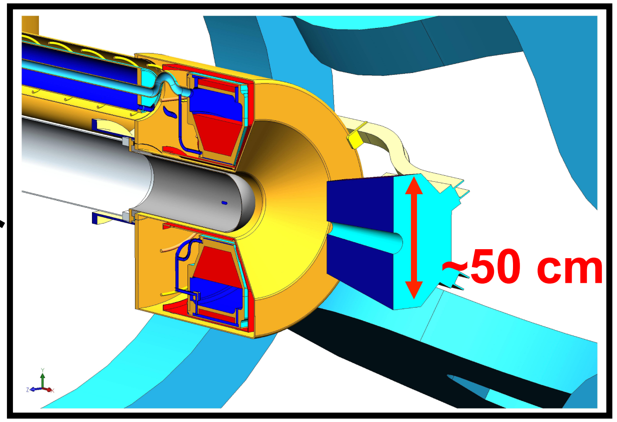
E1-DVCS with CLAS : a dedicated DVCS experiment in Hall B

Beam energy: ~5.8 GeV
Beam Polarization: 75-85%
Integ. Luminosity: 45 fb^{-1}
2nd half of data under analysis

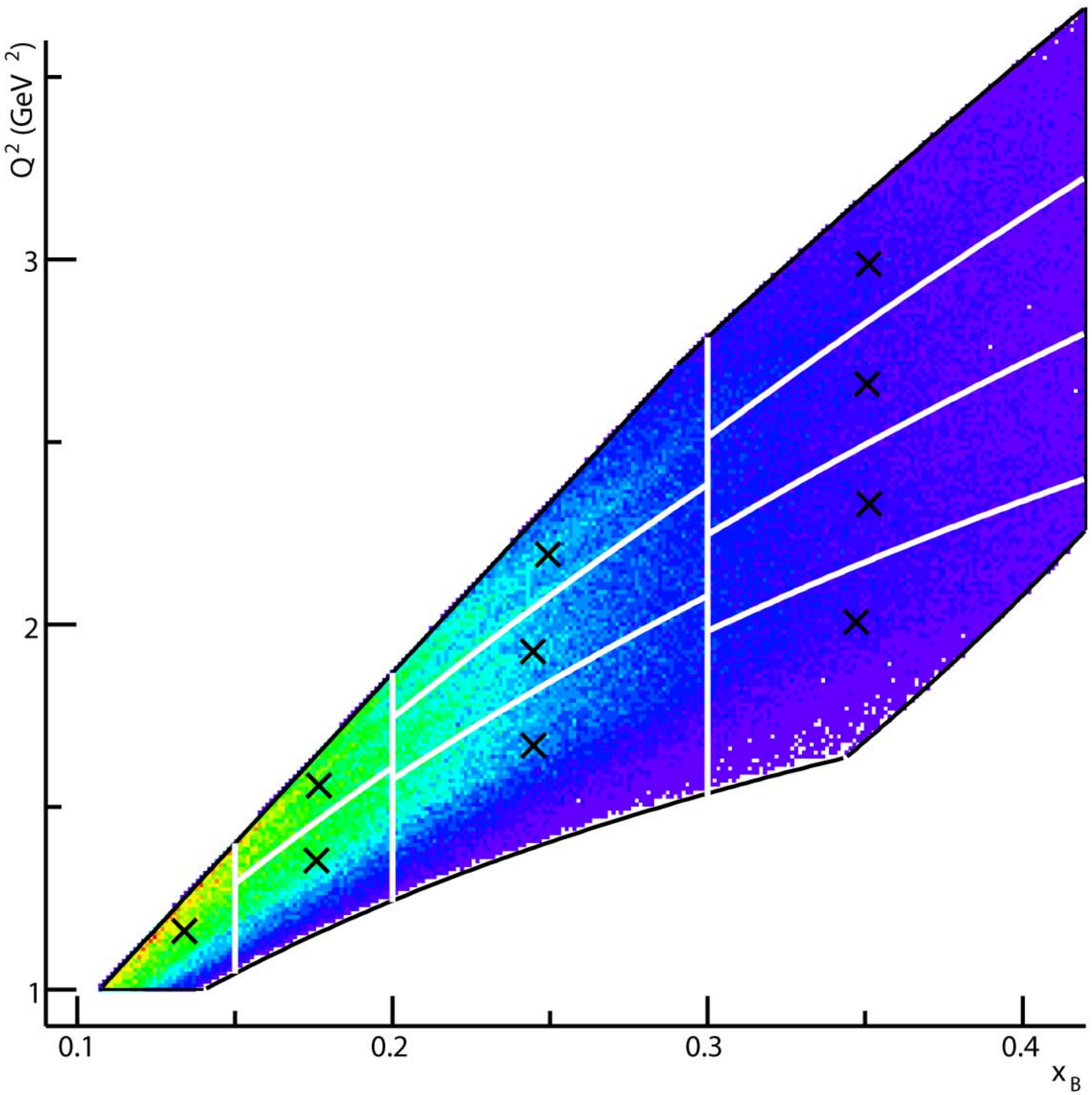




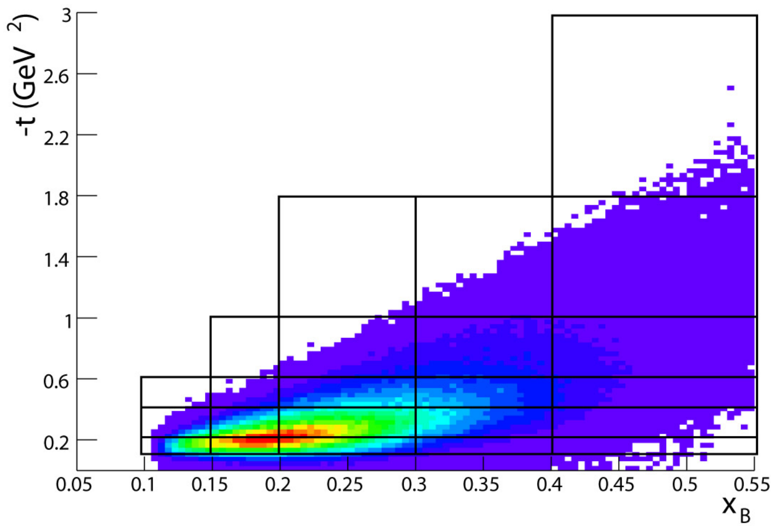
Inner Calorimeter
+ Moller shielding solenoid



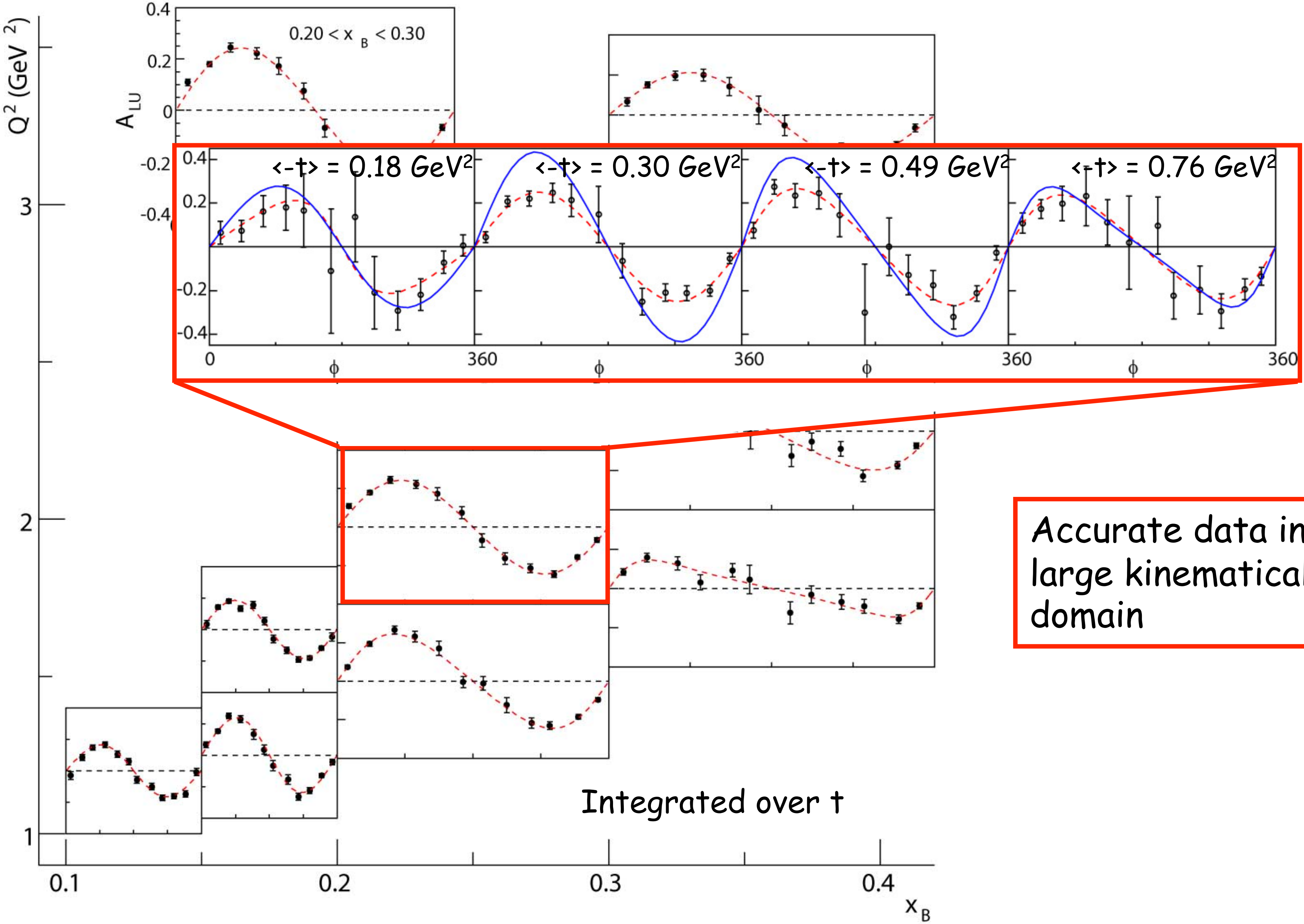
E1-DVCS kinematical coverage and binning



$W^2 > 4\ GeV^2$
$Q^2 > 1\ GeV^2$



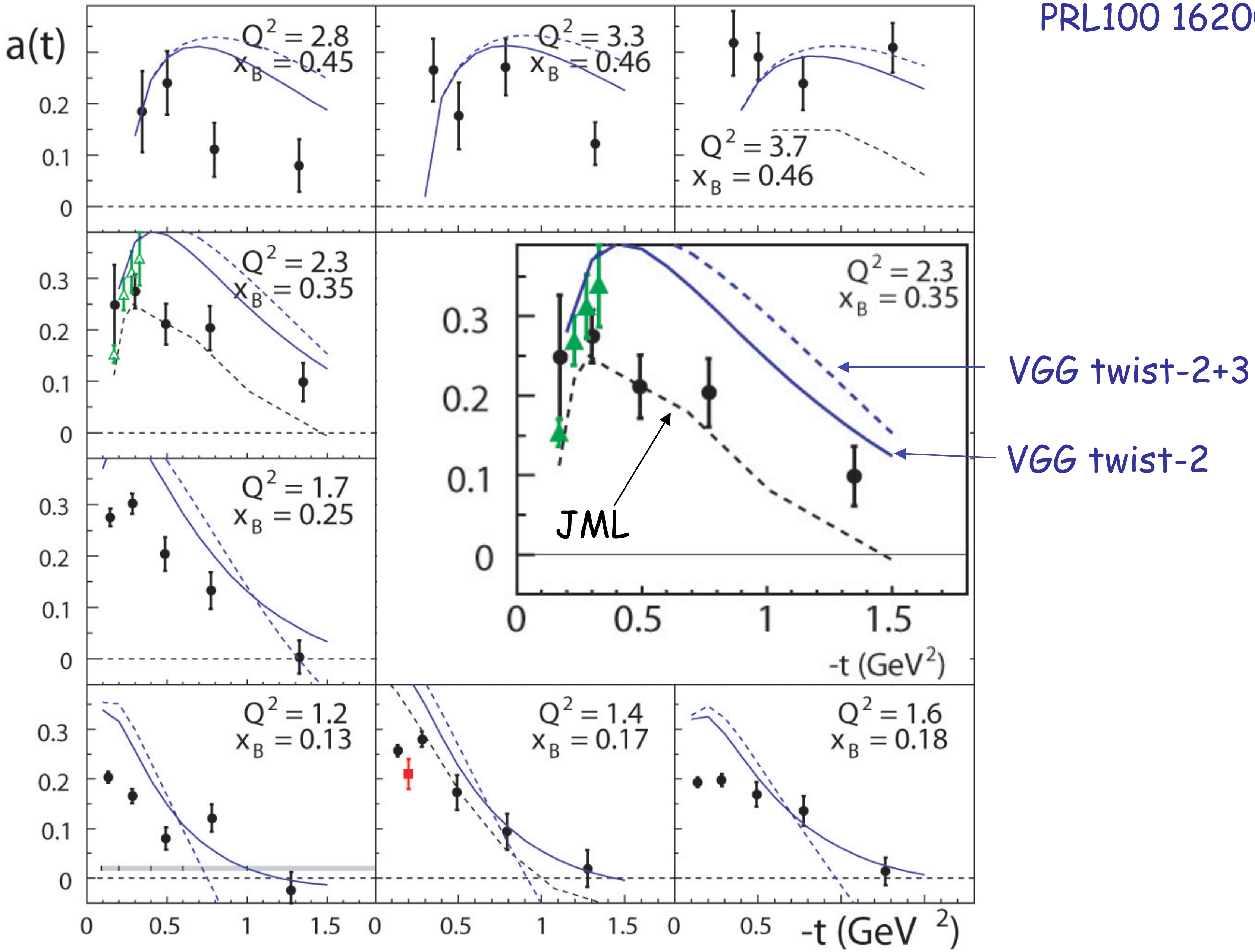
E1-DVCS : Asymmetry as a function of x_B and Q^2



Accurate data in a large kinematical domain

E1-DVCS : $A_{LU}(90°)$ as a function of $-t$ + models

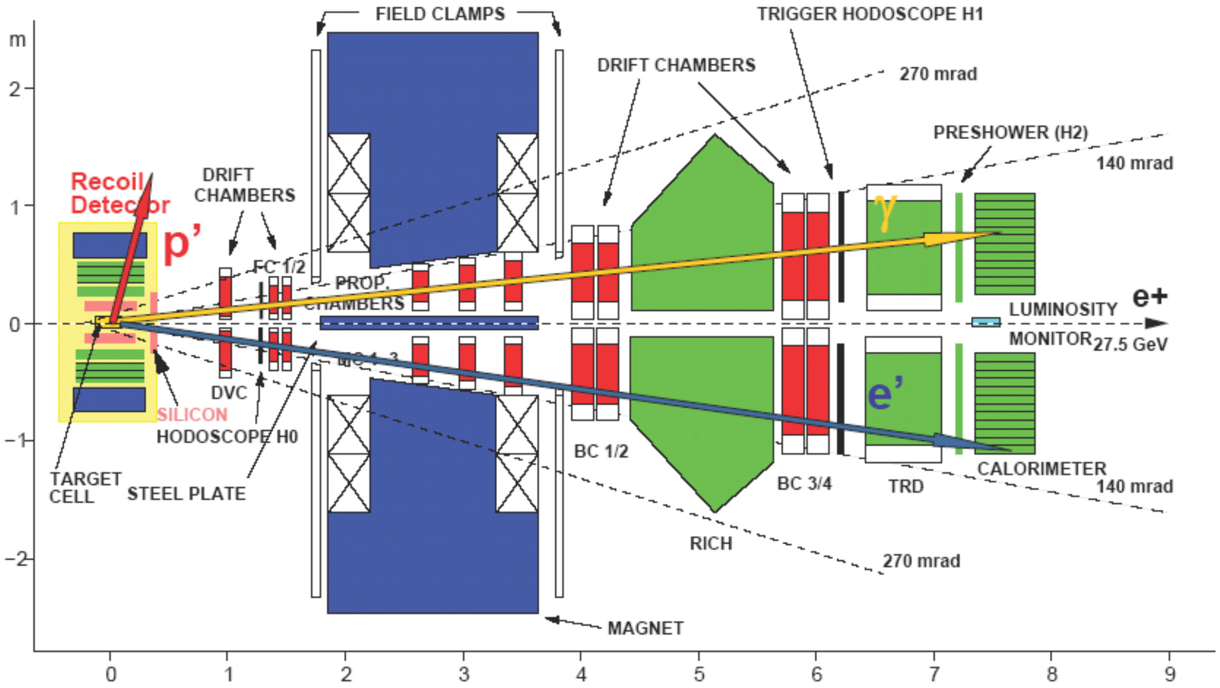
PRL100 162002, 2008



HERMES

HERMES has a very broad coverage of observables with:

- Beam Charge (e^+ and e^- beams)
- Beam spin direction (both beam helicities)
- Target spin direction (parallel, transverse, unpolarized)
- Different targets (H, D, He, N, Ne, Kr, Xe)
- *Recoil and spectator proton detection (results soon ?)*



Interesting aspect : reversing both beam charge and spin

charge spin

Asymmetry of interference term

$$\mathcal{A}^{\mathrm{I}}_{\mathrm{LU}}(\phi) \equiv \frac{(d\sigma^{+\rightarrow} - d\sigma^{+\leftarrow}) \ominus (d\sigma^{-\rightarrow} - d\sigma^{-\leftarrow})}{(d\sigma^{+\rightarrow} + d\sigma^{+\leftarrow}) + (d\sigma^{-\rightarrow} + d\sigma^{-\leftarrow})}$$

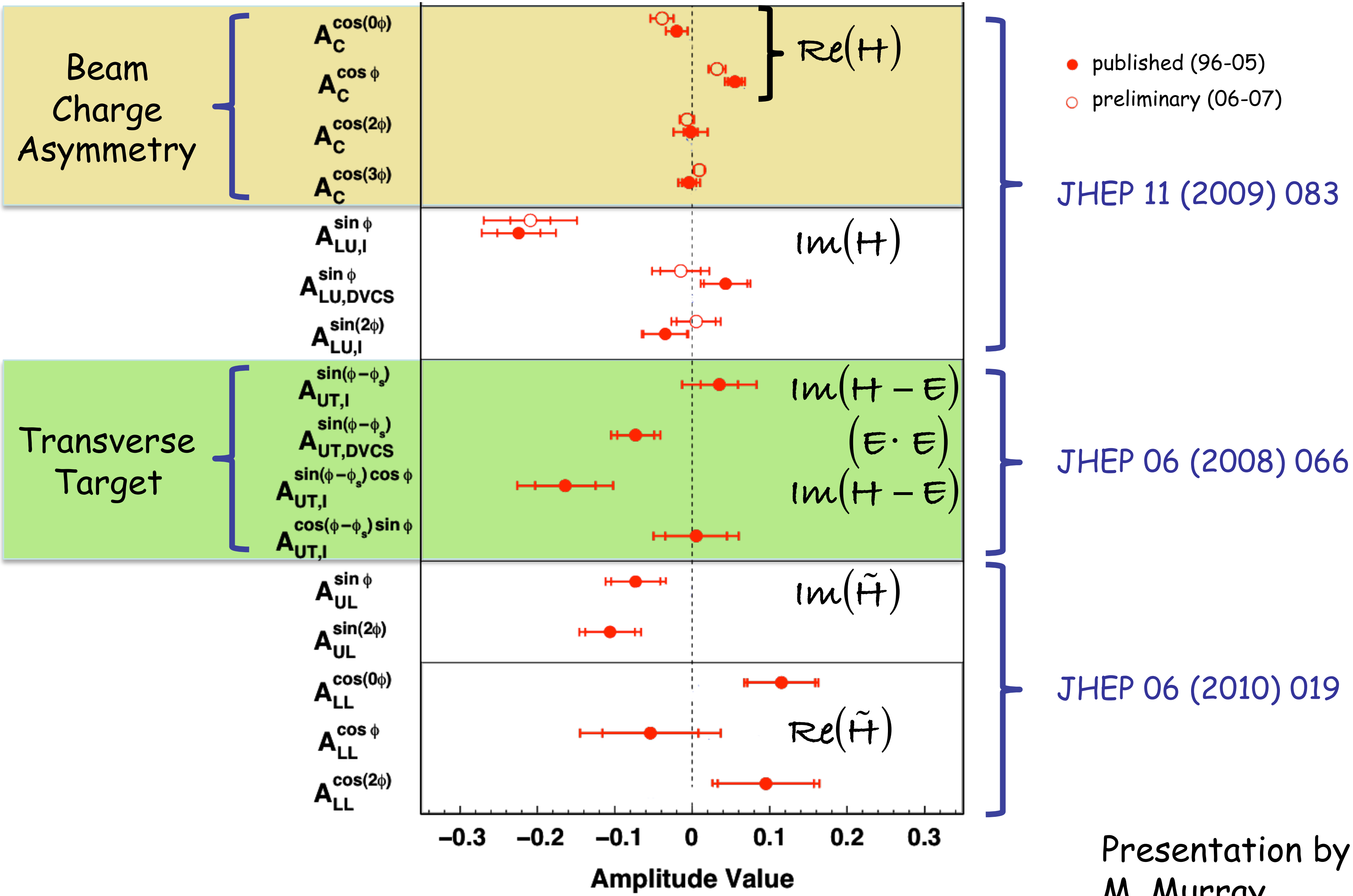
$$= \frac{-\frac{K_{\mathrm{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left[\sum_{n=1}^{2} s_n^{\mathrm{I}} \sin(n\phi)\right]}{\frac{K_{\mathrm{BH}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \sum_{n=0}^{2} c_n^{\mathrm{BH}} \cos(n\phi) + \frac{1}{Q^2} \sum_{n=0}^{2} c_n^{\mathrm{DVCS}} \cos(n\phi)}$$

Cancels terms proportional to BH

Asymmetry of DVCS

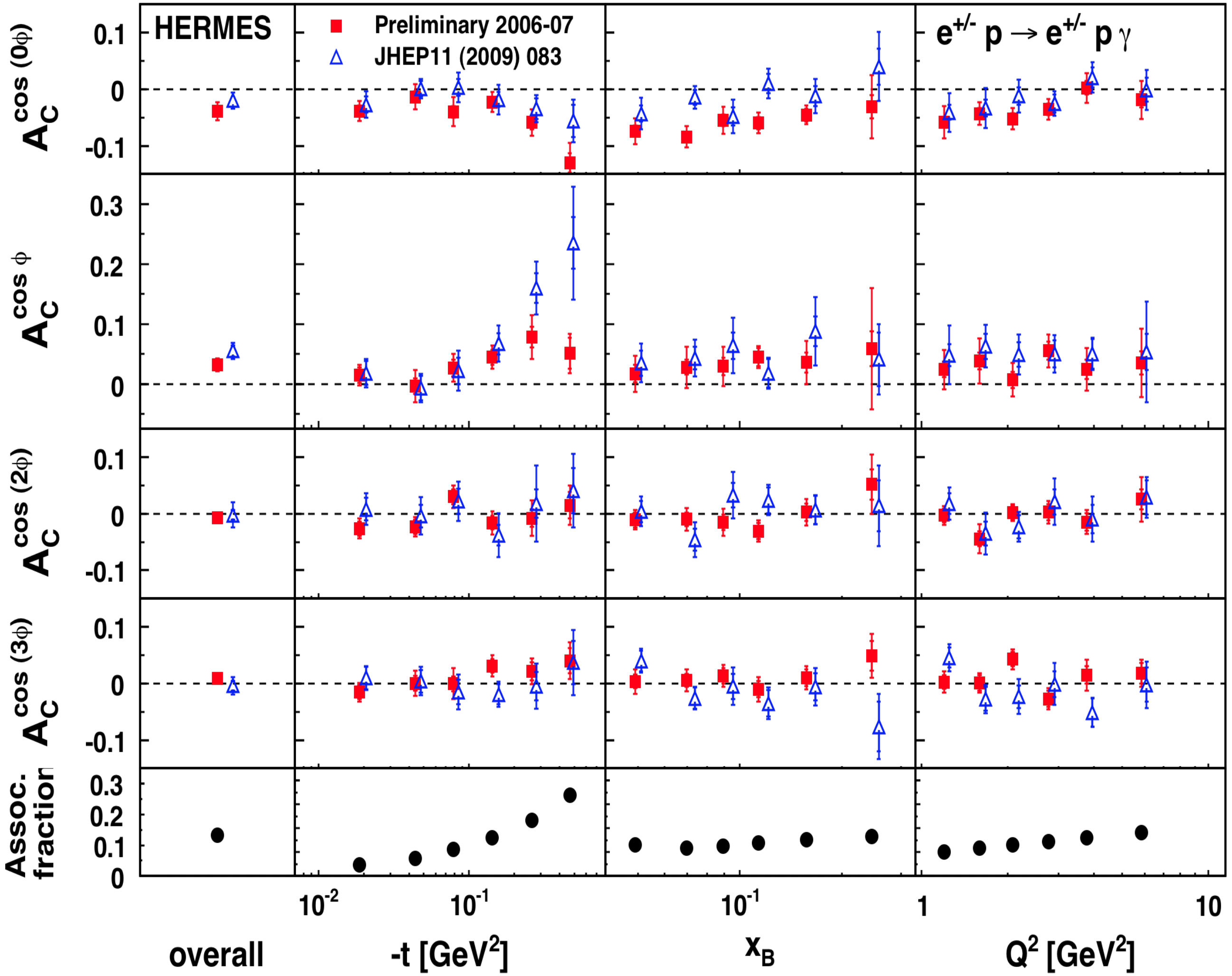
$$\mathcal{A}^{\mathrm{DVCS}}_{\mathrm{LU}}(\phi) \equiv \frac{(d\sigma^{+\rightarrow} - d\sigma^{+\leftarrow}) \oplus (d\sigma^{-\rightarrow} - d\sigma^{-\leftarrow})}{(d\sigma^{+\rightarrow} + d\sigma^{+\leftarrow}) + (d\sigma^{-\rightarrow} + d\sigma^{-\leftarrow})}$$

HERMES proton measurements



Presentation by M. Murray

HERMES Beam Charge Asymmetries



Sensitive to:

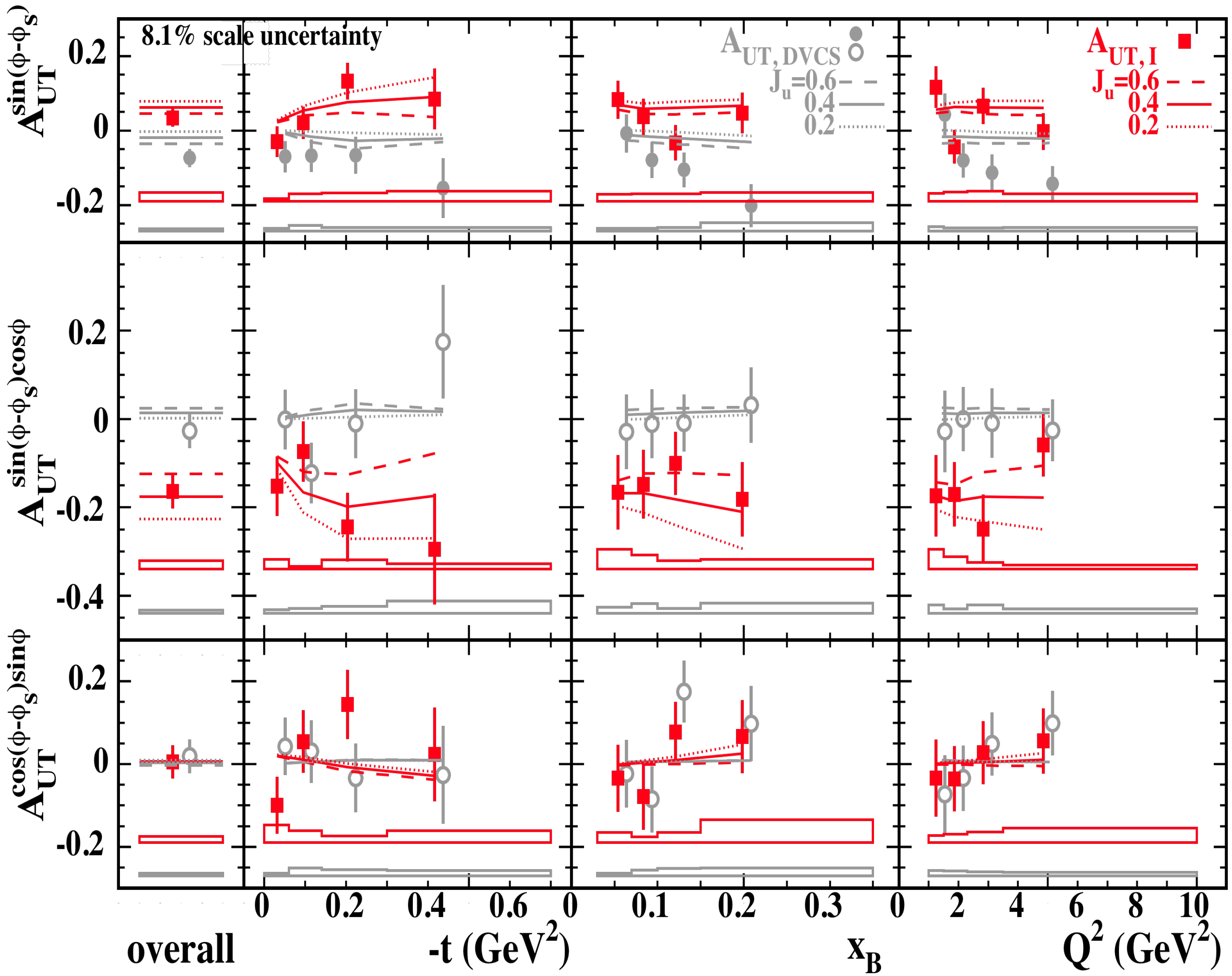
Re(H)

twist-3 GPDs

gluon helicity-flip GPDs

fraction of ep→eΔ γ

HERMES Transverse Target Spin Asymmetries



Sensitive to:

$Im(H - E)$

$(E \cdot E)$

$Im(\tilde{H} - \tilde{E})$

Understanding the data and fitting GPDs

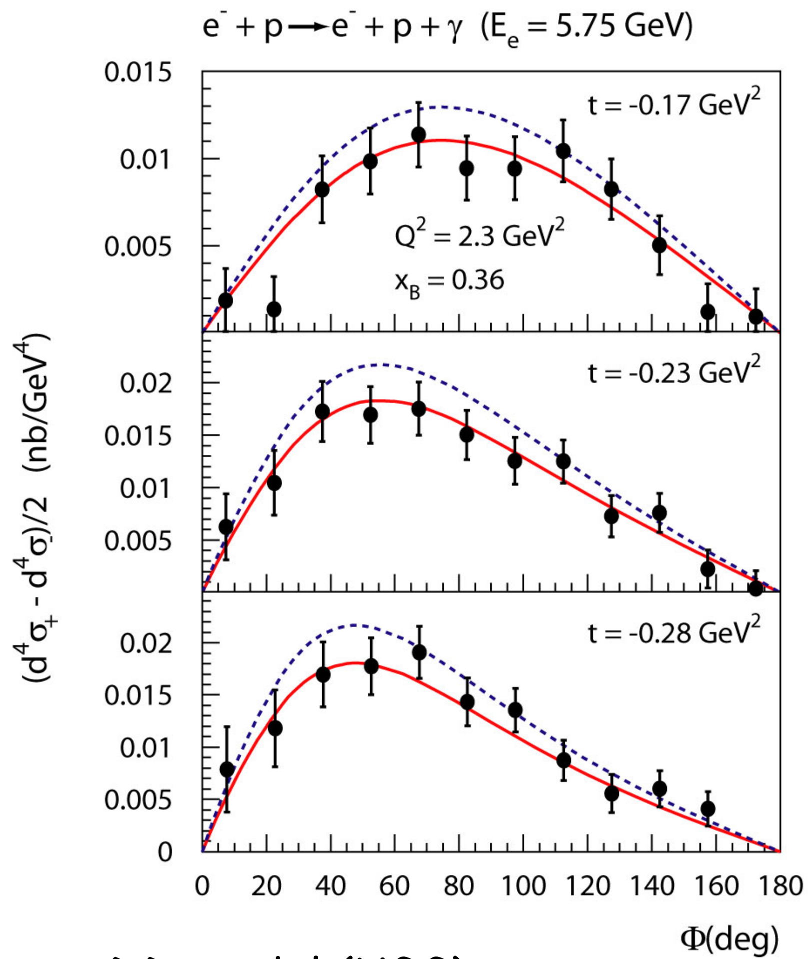
A few interesting attempts to understand the data in terms of GPDs:

- (minimal) Dual Model
- Local fits of Compton Form Factors
- Global fits using Dual Model
- « Dispersion relations » global fits
- … (not exhaustive)

More information? don't miss the following talks:
Moutarde, Kumericky, Semenov, Goldstein, Liuti

Minimal dual model (*i.e.* forward model) of DVCS data

Difference of cross sections (imaginary part of interference term)



Polyakov, Vanderhaeghen

Data are well described by minimal dual model: *Small* geniune non-forward effects !

DD model (VGG)

Minimal dual model

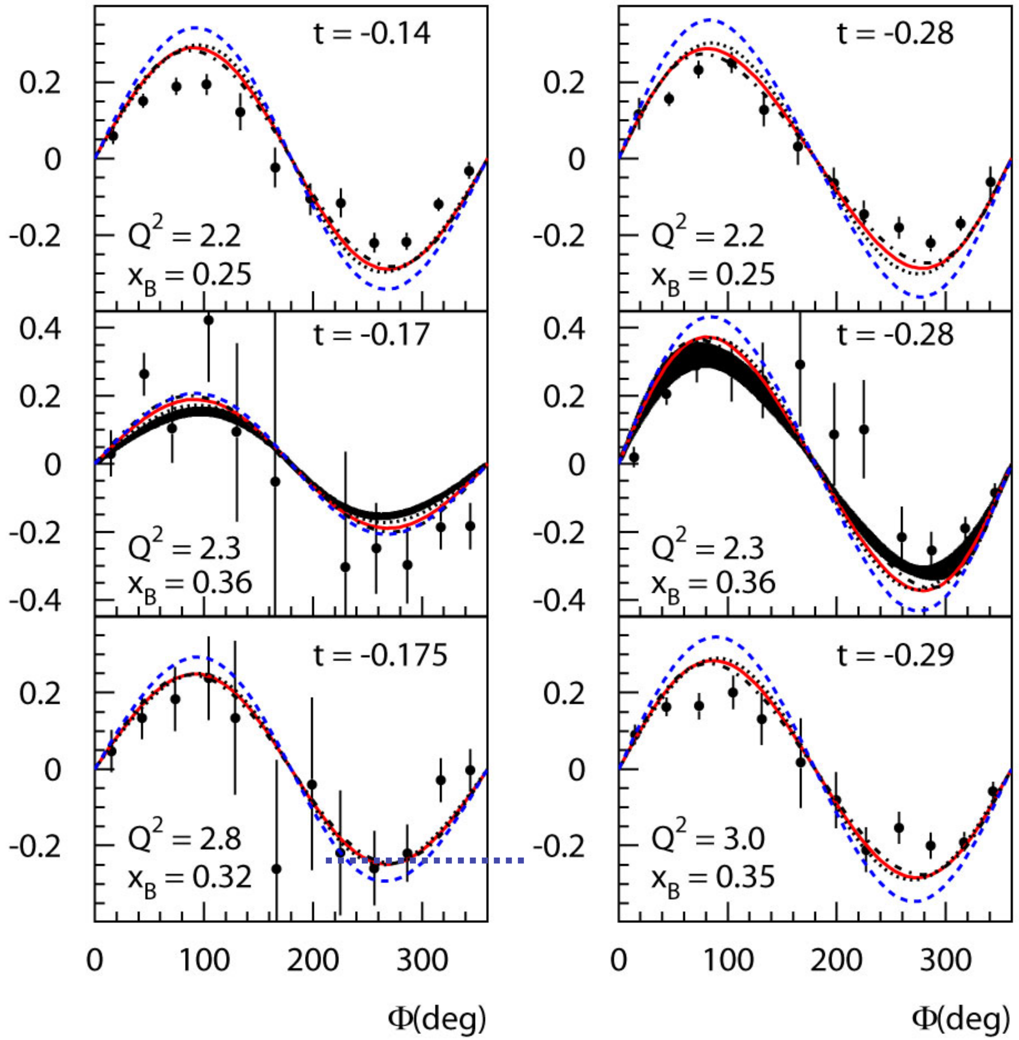
Data: Hall A polarized cross section data at Q^2=2.3 GeV^2

Minimal dual model (2)

DD model (VGG)
Minimal dual model

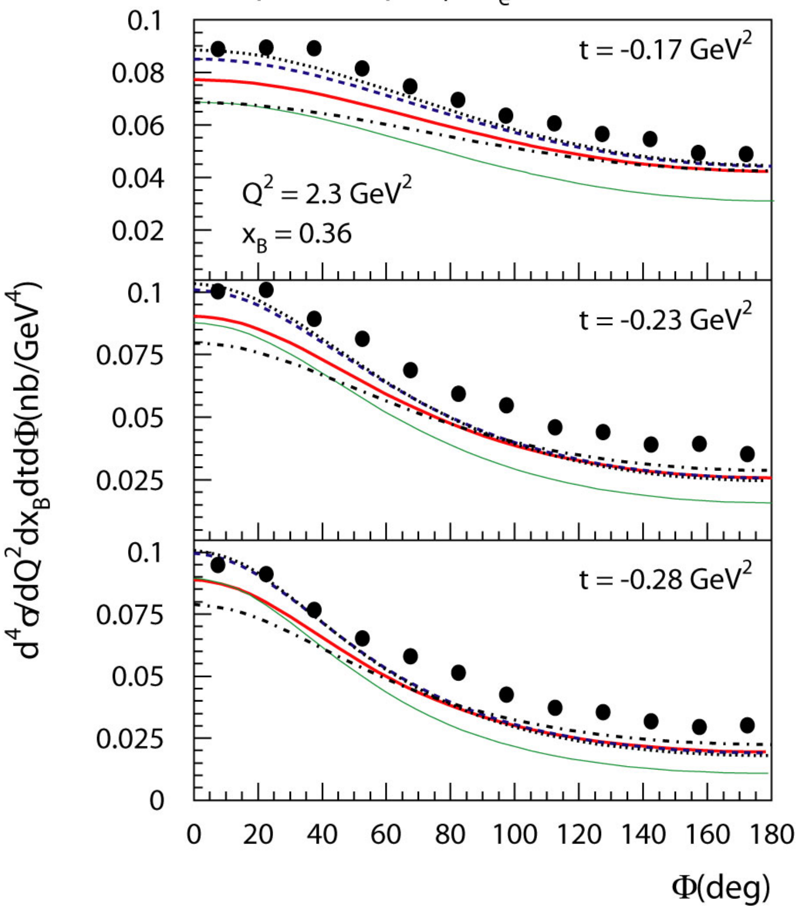
Beam Spin Asymmetries
(Hall B data)

$e^- + p \longrightarrow e^- + p + \gamma$ $(E_e = 5.77\ \text{GeV})$



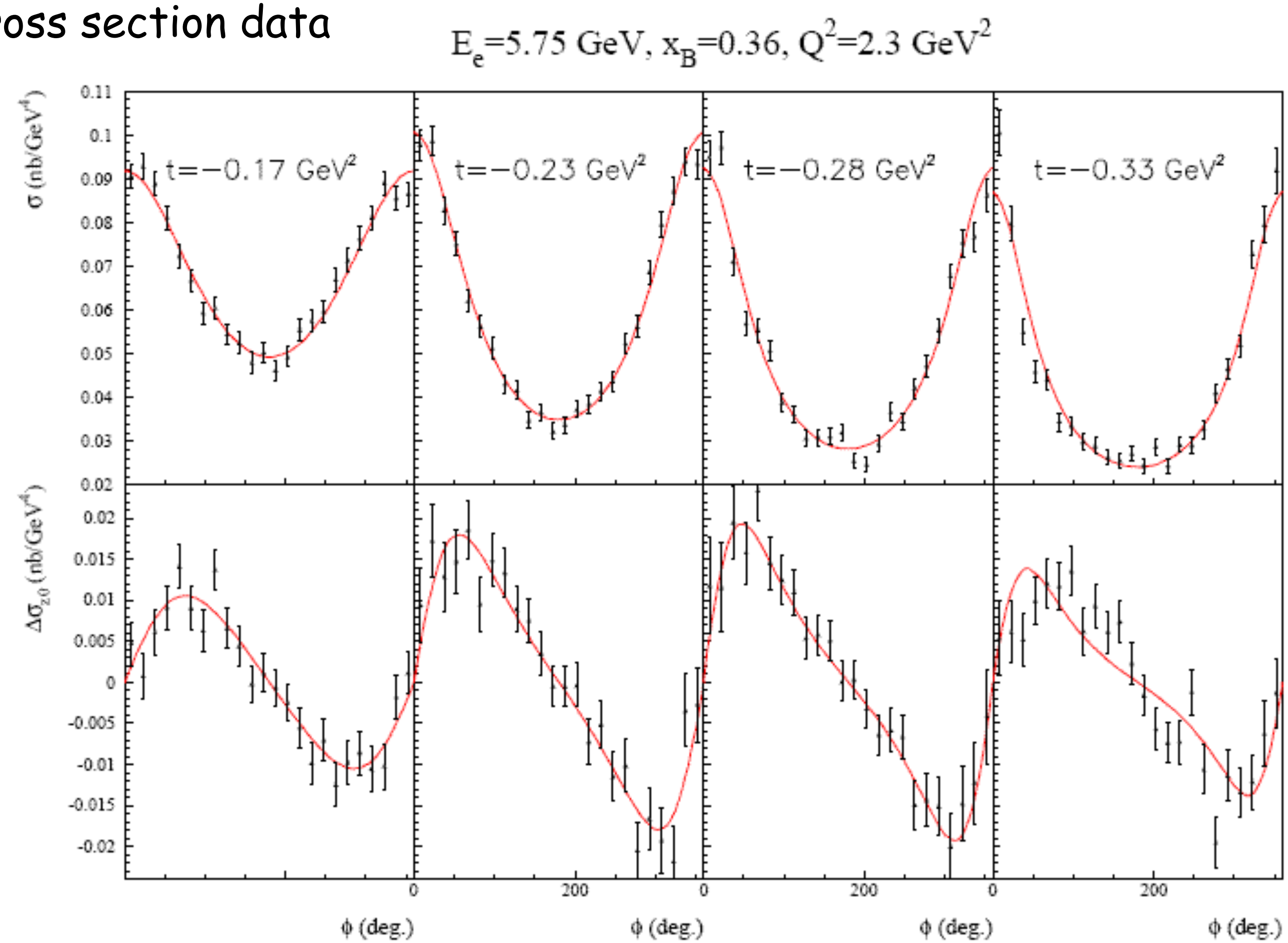
Total cross sections
(Hall A data)

$e^- + p \longrightarrow e^- + p + \gamma$ $(E_e = 5.75\ \text{GeV})$



Compton Form Factor fits (local fits)

Hall A cross section data

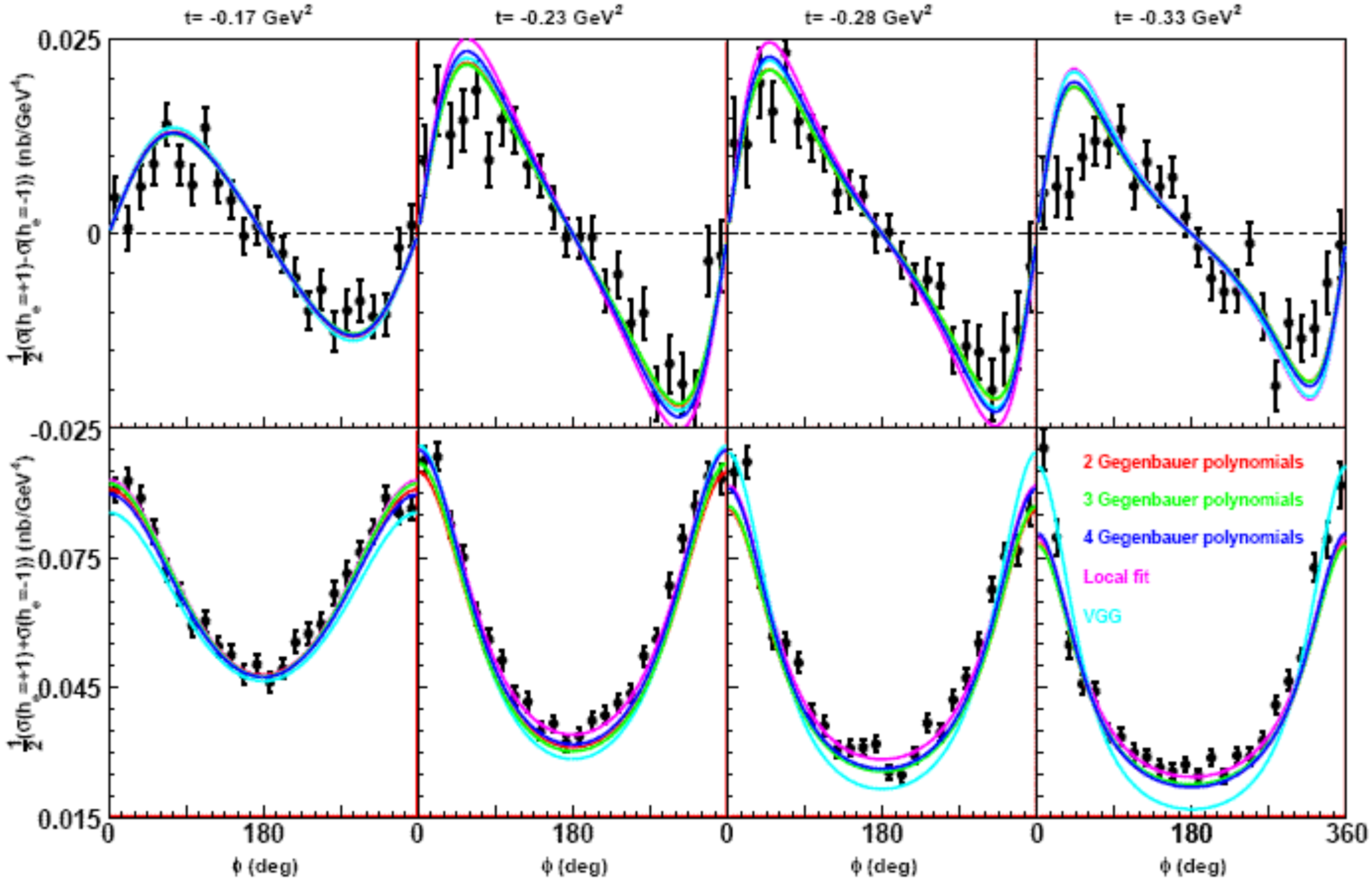


Includes H, $\tilde{H}$ and E

M. Guidal

Compton Form Factor (local) or dual model global fits (H only)

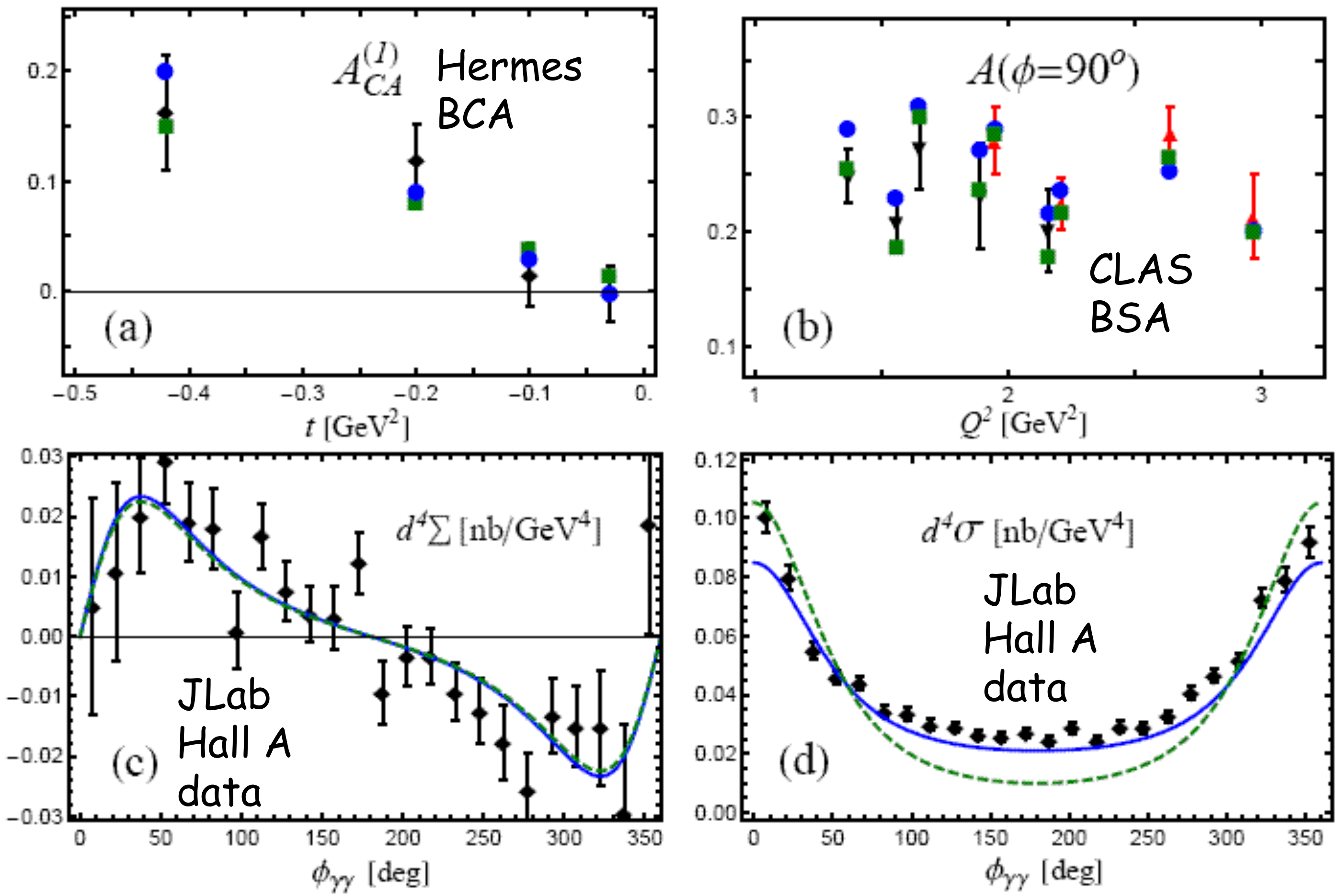
Hall A cross section data



Presentation by
H. Moutarde

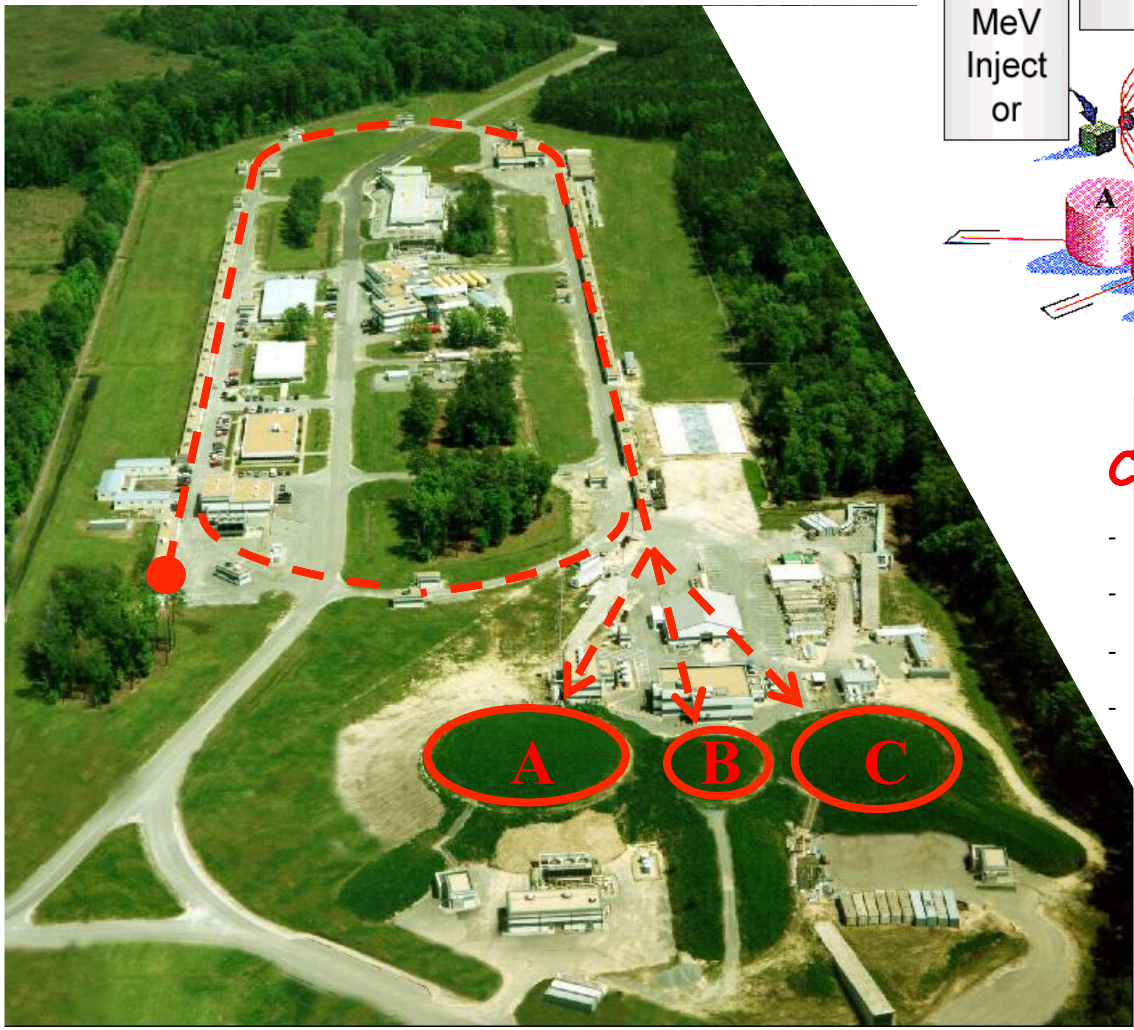
Dispersion relation fits of DVCS data

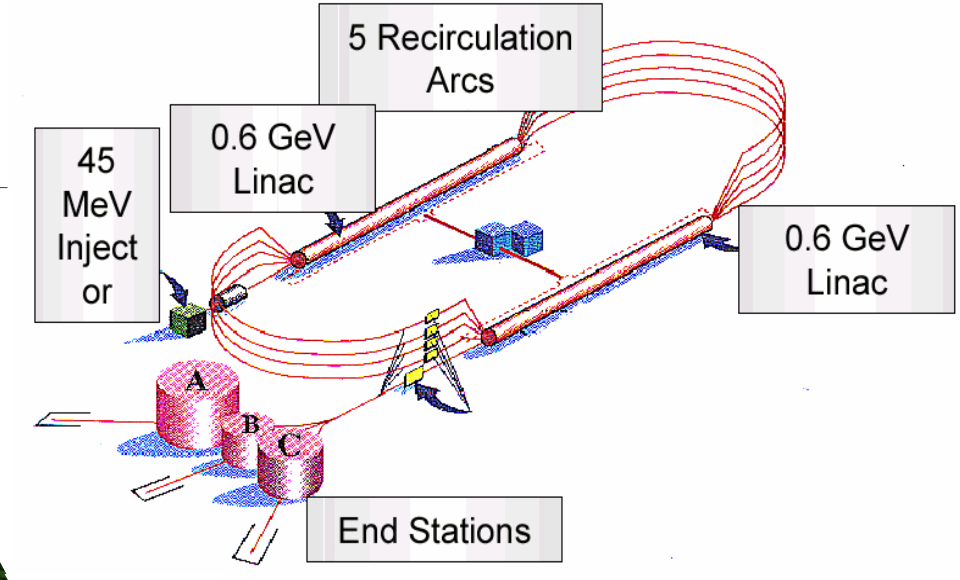
Presentation by
K. Kumericky



Fit of H1/ZEUS+CLAS+Hermes with only H
+Hall A and H + $\tilde{H}$

Jefferson Lab today

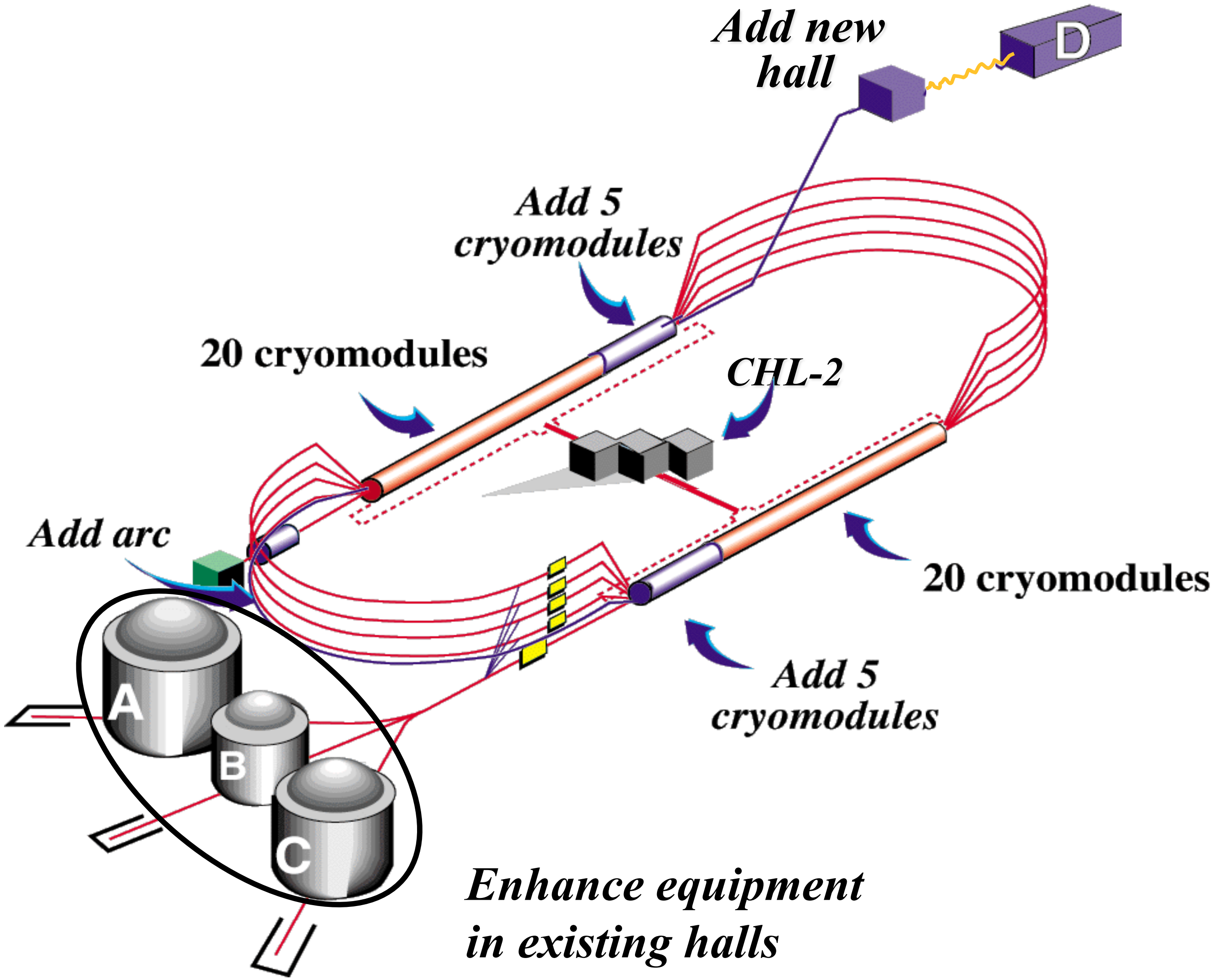




Continuous electron beam

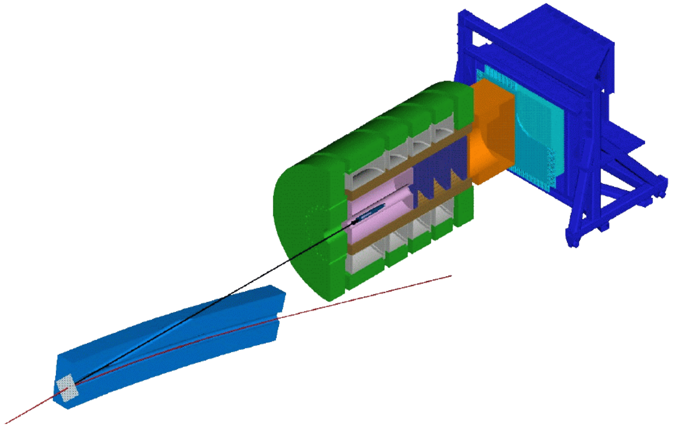
- Energy from 0.8 to 6 GeV
- Duty factor 100%
- Beam polar ~85%
- Delivers 3 halls simultaneously

Upgrading JLab from 6 to 12 GeV



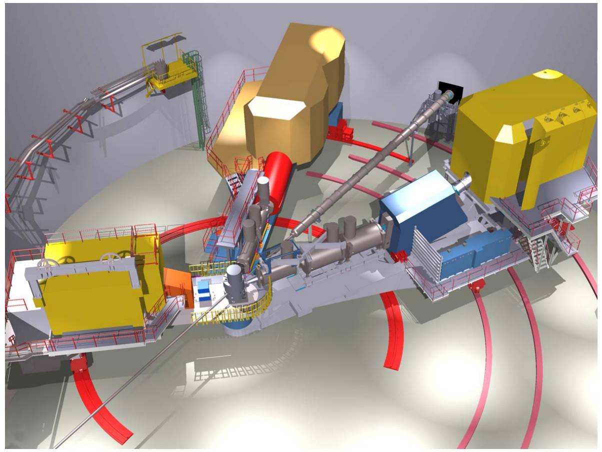
New equipments for 11-12 GeV beam

D



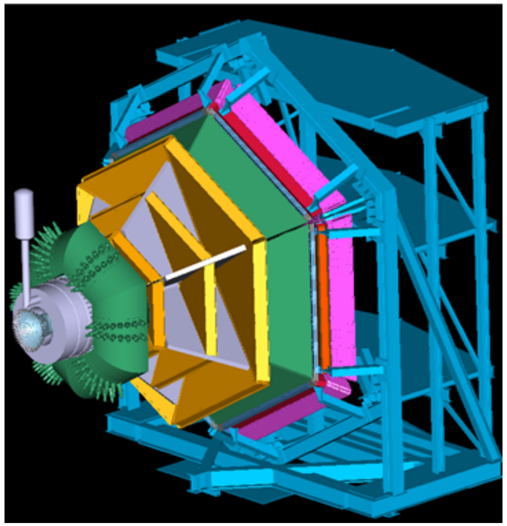
9 GeV tagged polarized photons
and a 4π hermetic detector

C



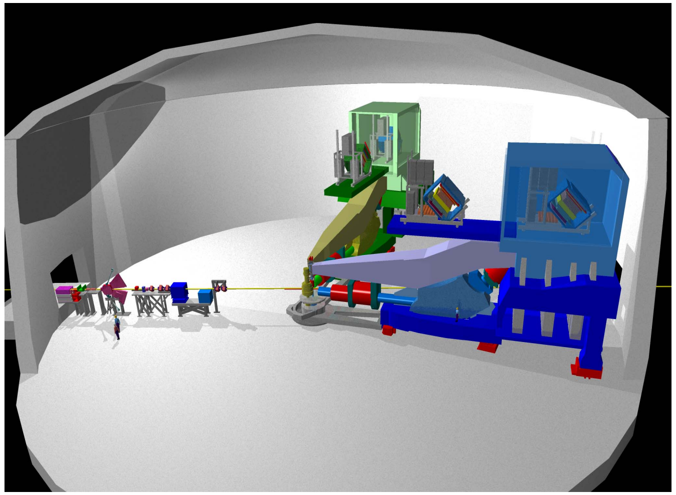
Super High Momentum Spectrometer (SHMS)
at high luminosity and forward angles

B



CLAS12 with new detectors and
higher luminosity (10^{35} /cm^2-s)

A

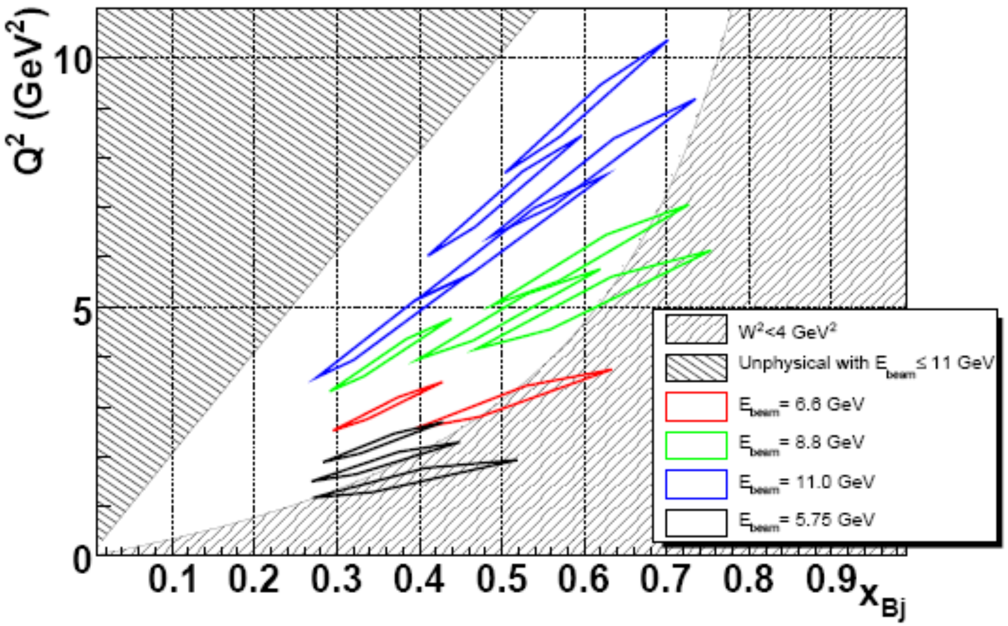


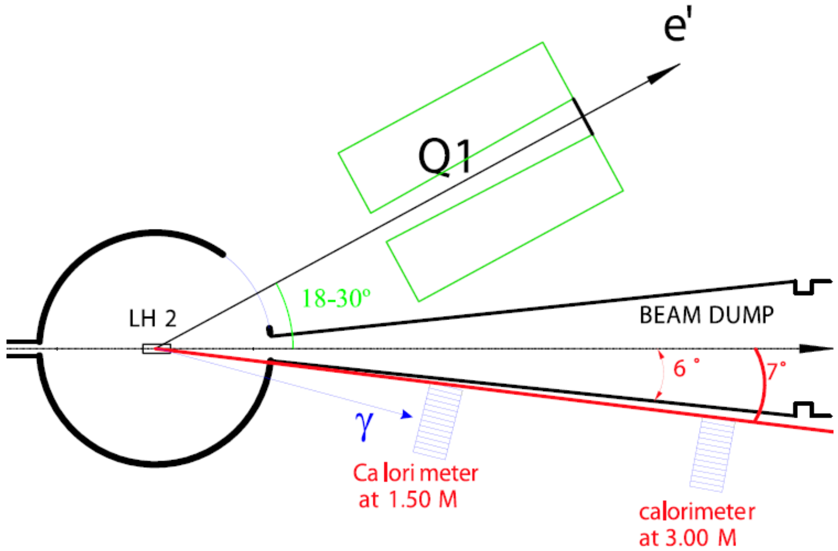
High Resolution Spectrometer (HRS) Pair,
and specialized large installation experiments

Extension of the Hall A experiments

- **88 days on H target (BSA)**
- **L ≈ 4x10^{37} /cm^2/s @ 6.6, 8.8 and 11 GeV**

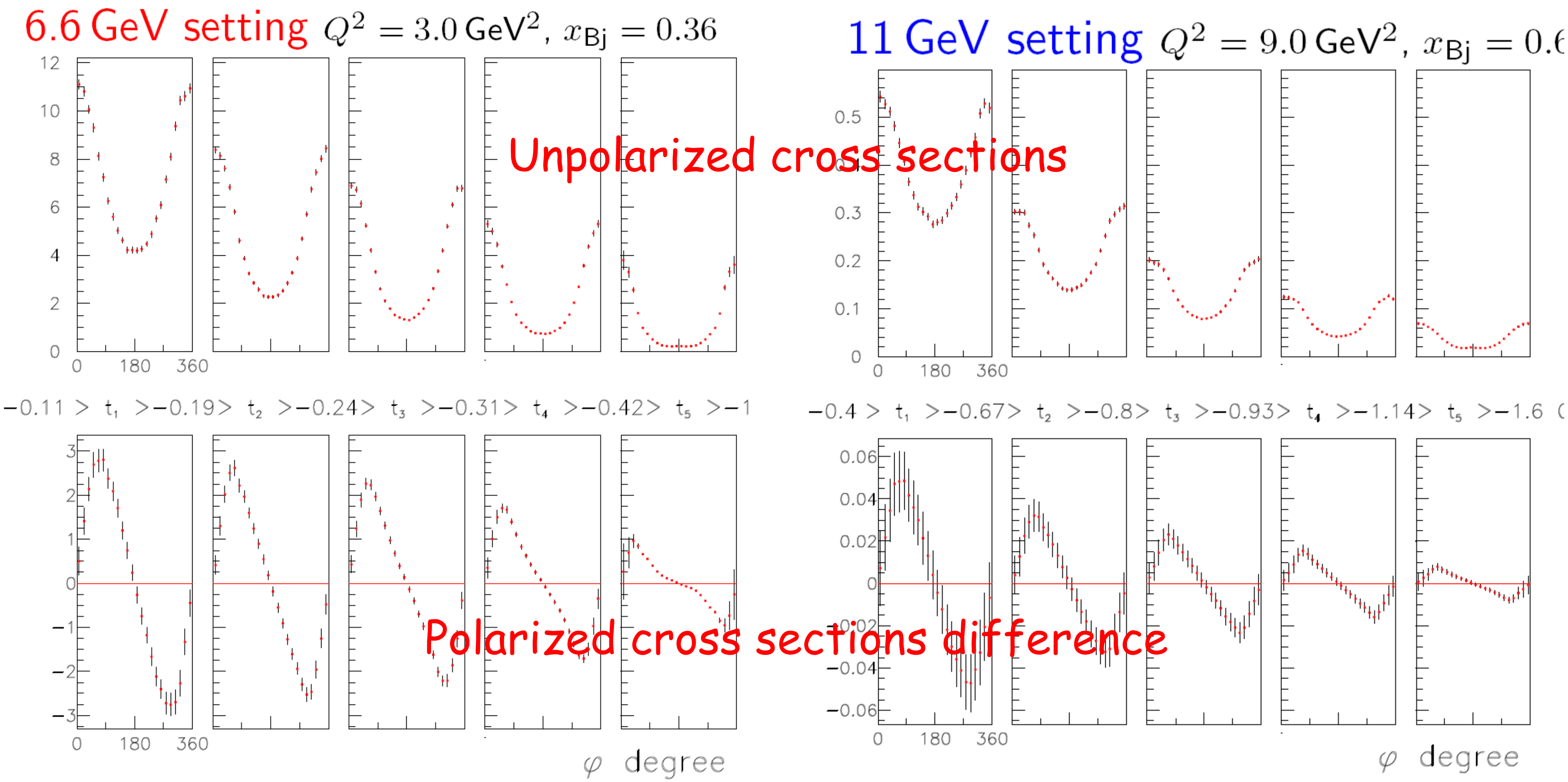
Exclusivity ensured
by high resolution





- DVCS^2, twist-2, twist-3 separation
- Test of factorization at different x_B

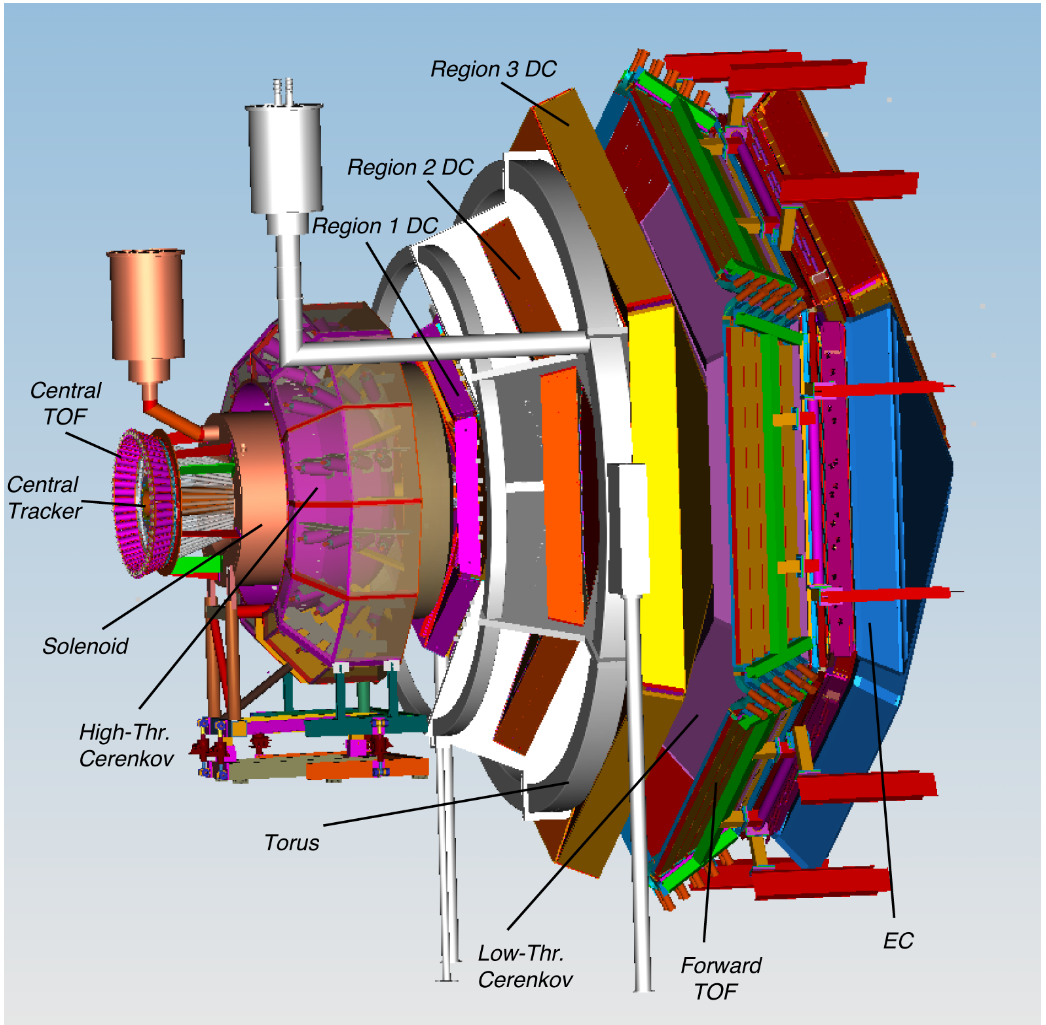
Expected accuracy (only a few bins)



→ Access the real and imaginary parts of T^{DVCS} separately

Experimental Setup and proposed experiments at 11 GeV

Use of base CLAS12 equipment,

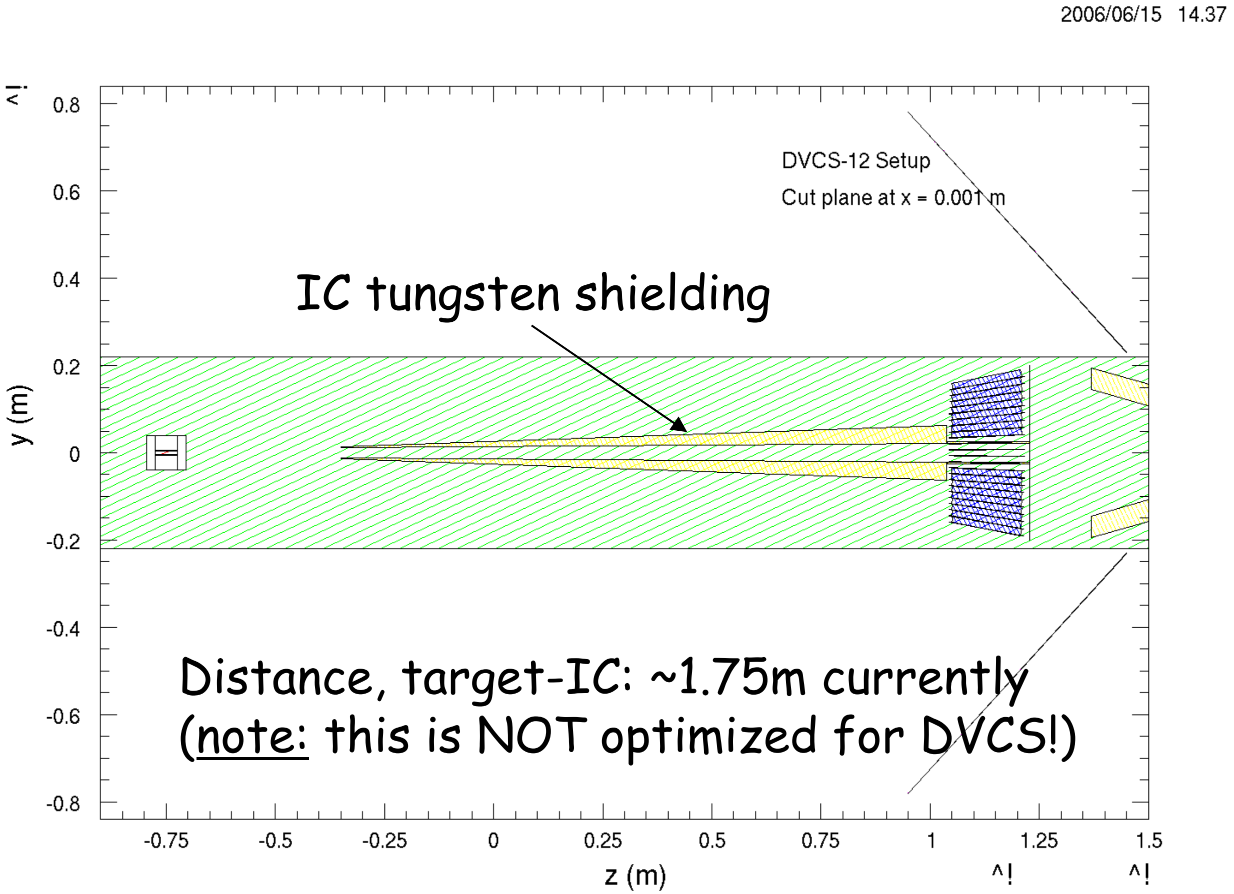


Detection of the full (e,p,γ) final state

Perform 2 experiments for the extraction of the BSA and the TSA

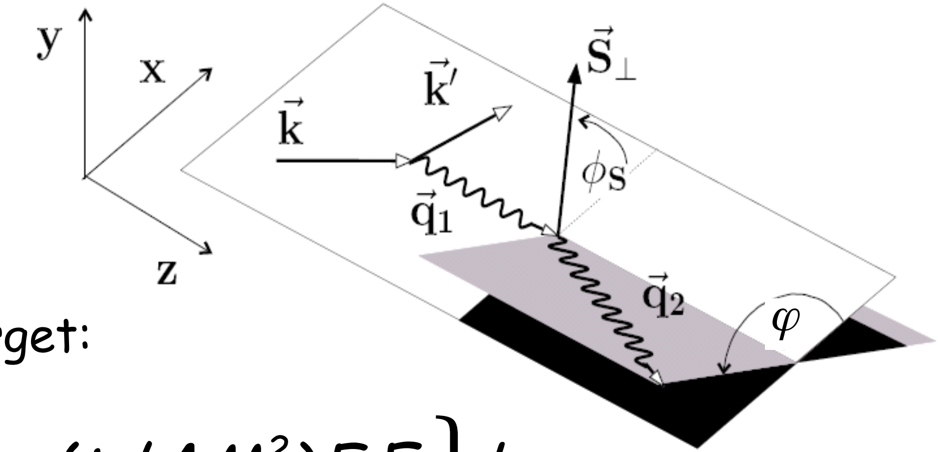
Experimental Setup and proposed experiments at 11 GeV

Use of base CLAS12 equipment, including Inner Calorimeter (IC)



Detection of the full (e,p,γ) final state
Perform 2 experiments for the extraction of the BSA and the TSA

Measuring DVCS using all polarization settings !



CLAS12 will have access to beam and target polarizations (both L and T)

With polarized beam and unpolarized target:

$$\Delta\sigma_{LU} \sim \sin\varphi \left\{ F_1 H + \xi(F_1 + F_2)\tilde{H} + (t/4M^2)F_2 E \right\} d\varphi$$

With unpolarized beam and Longitudinally polarized target:

$$\Delta\sigma_{LU} \sim \sin\varphi \left\{ F_1 \tilde{H} + \xi(F_1 + F_2)H + (t/4M^2)F_2 E \right\} d\varphi$$

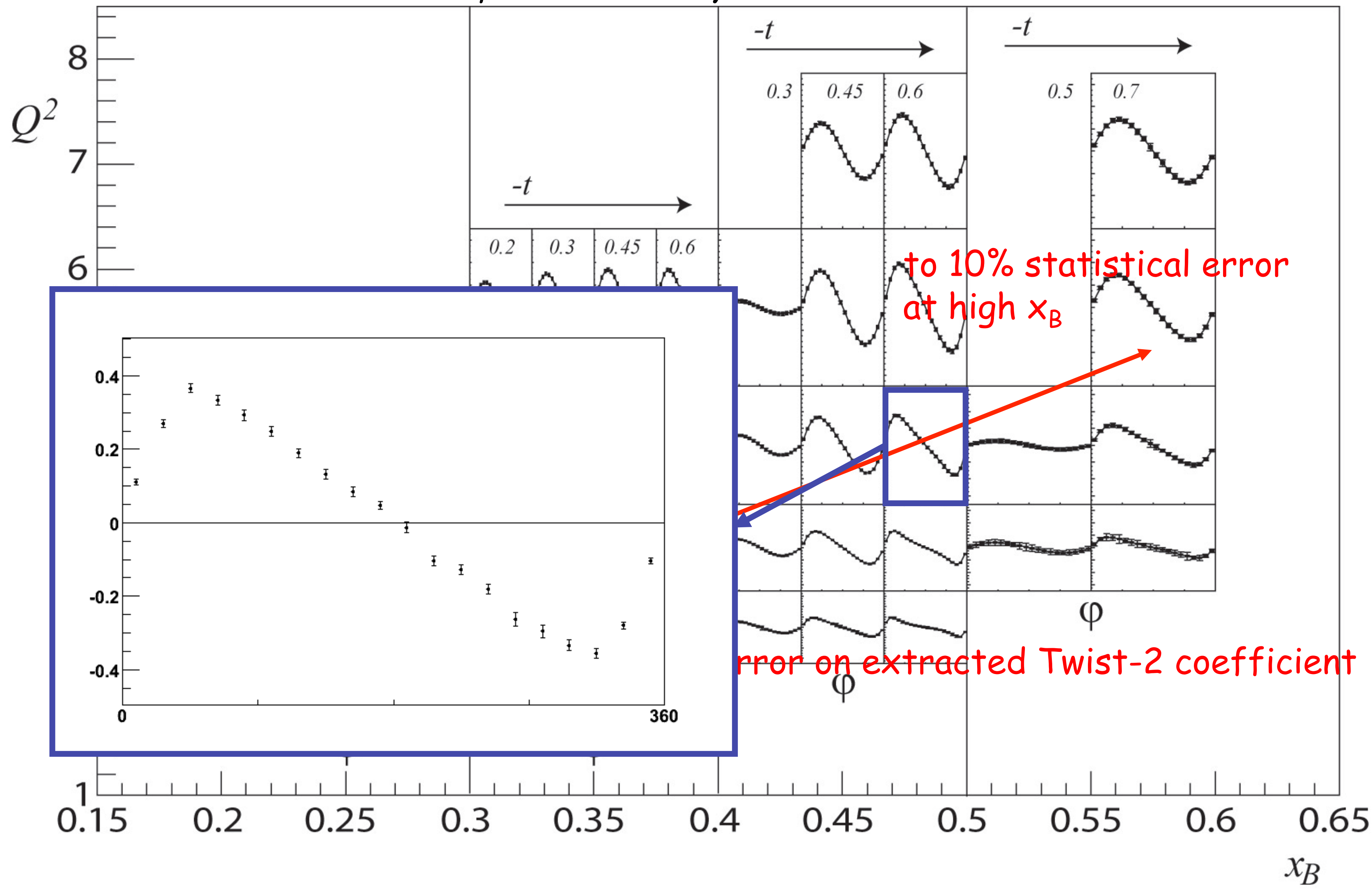
With unpolarized beam and Transversely polarized target:

$$\Delta\sigma_{UT} \sim \cos\varphi \sin(\phi_S - \varphi) \left\{ (t/4M^2)F_2 H - (t/4M^2)F_1 E + \ldots \right\} d\varphi$$

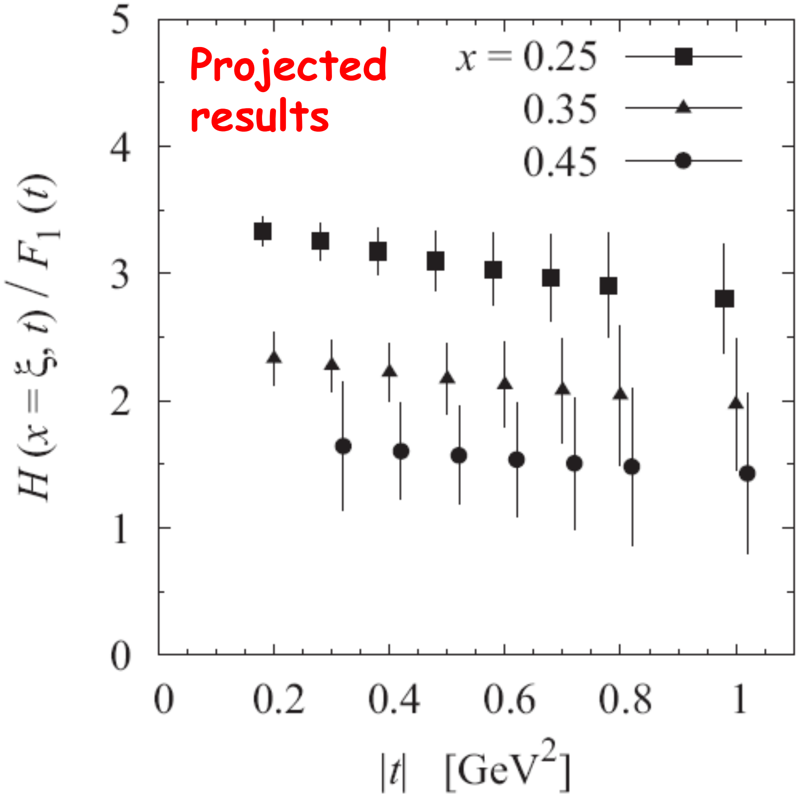
Depending on the experiment, measurement of $\Delta\sigma$ and σ or $A = \dfrac{\Delta\sigma}{2\sigma}$

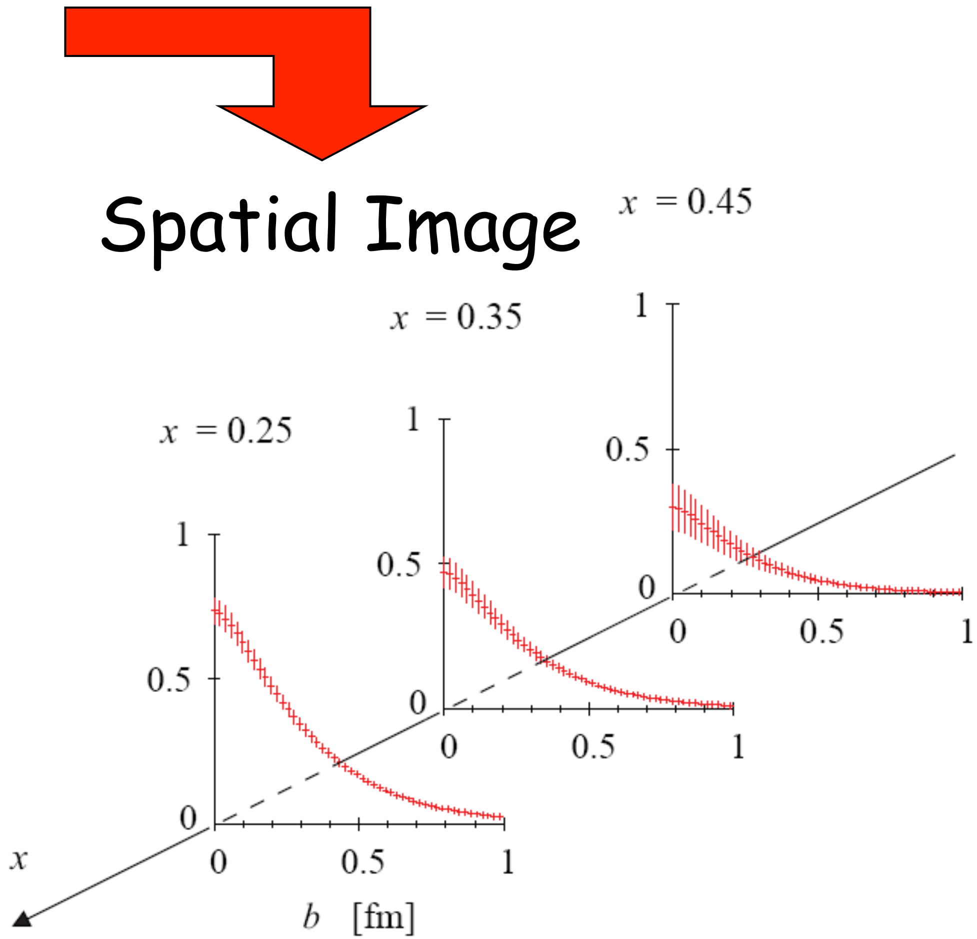
One example : Beam Spin Asymmetry

*IC in standard position – **80 days** – 10^35 Lum – VGG model*



Extraction of the GPD H(x=ξ) from projected CLAS12 data





Conclusion and Outlook

- A large set of data from HERA, HERMES, JLab Hall A/B

- More data to come soon from HERMES (recoil detector), CLAS (2nd part of e1dvcs experiment and Longitudinal + Transverse Target data), Hall A (full separation of cross section at 6 GeV)

- Even more data later on : COMPASS, CLAS12

- A few groups are working hard on ways to parametrize and extract GPDs from these data and show promising results and progress

The 3D pictures of the nucleon are not so far ahead, stay tuned !