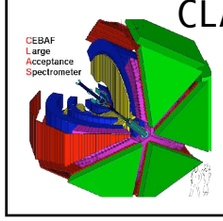
Review of experimental results on DVCS

Hall A
JLab

CLAS

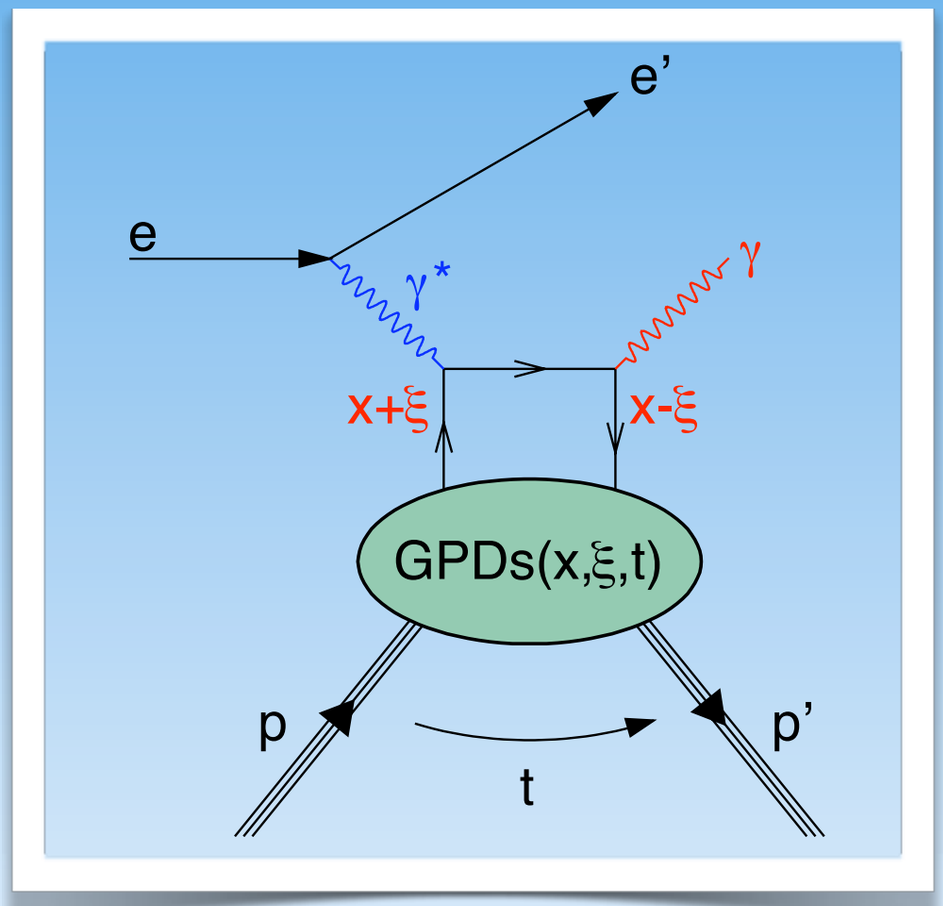


hermes

COMPASS

H1

ZEUS



what?

why?

where?

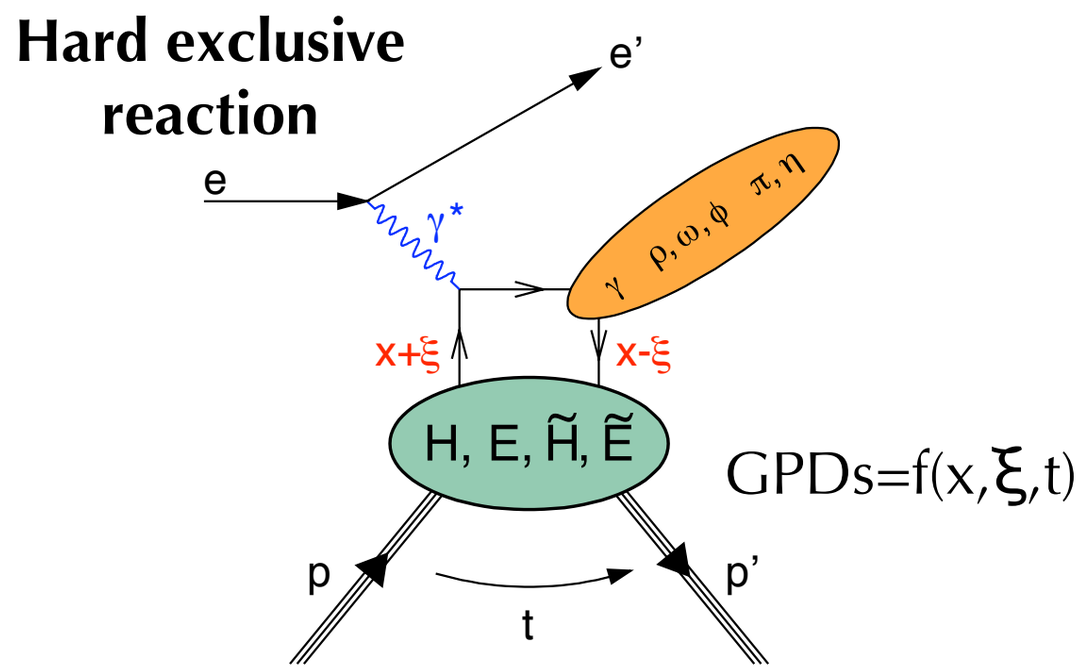
... and the future?

Caroline Riedl

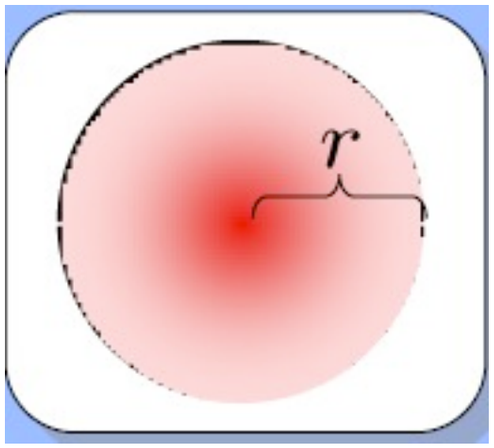
DESY

PHOTON 2011 - Spa, Belgium - May 22-27, 2011

Generalized Parton Distributions

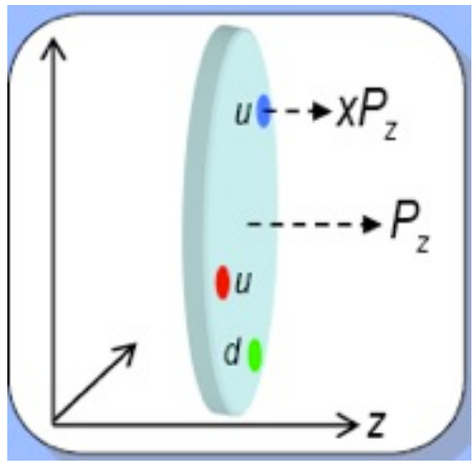


Elastic Form Factors



transverse position of partons

Parton Distribution Functions (PDFs)



longitudinal momentum of partons

DVCS = hard electroproduction of a real photon

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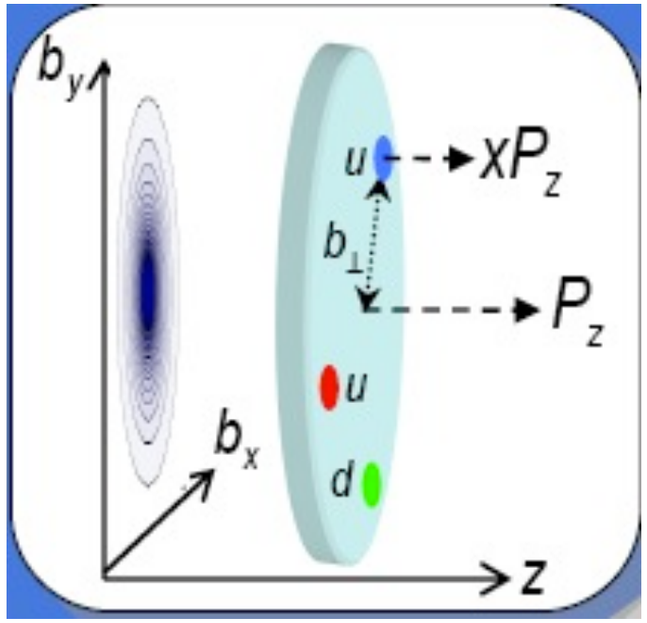
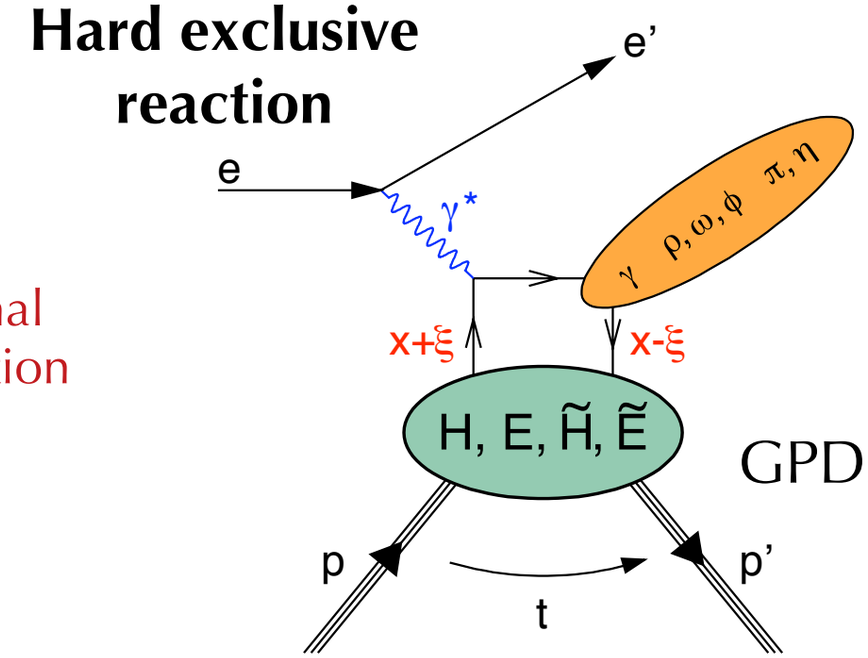


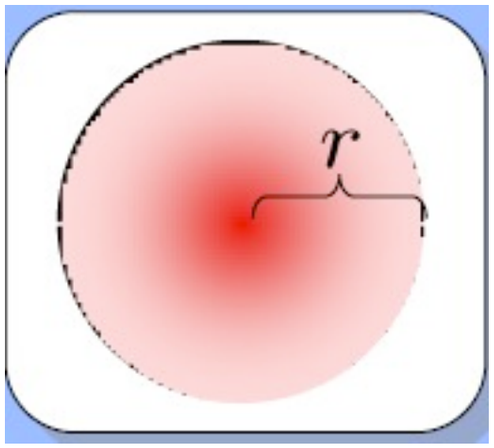
Nucleon Tomography



GPDs=f(x,ξ,t)

correlation between longitudinal momentum and transverse position

Elastic Form Factors



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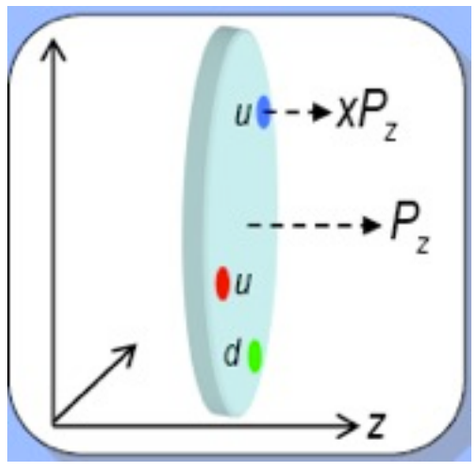

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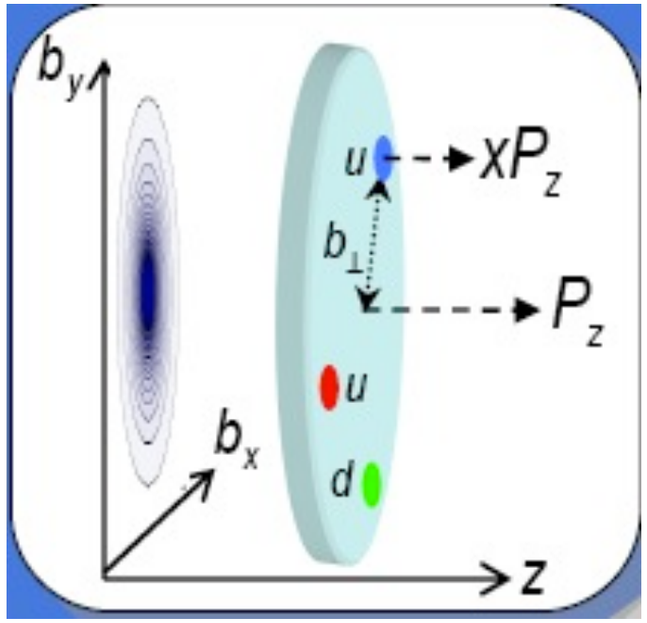

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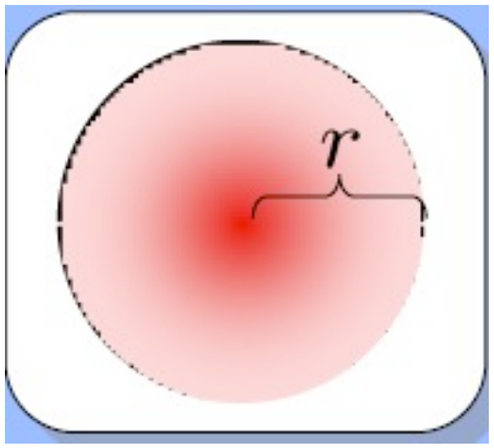

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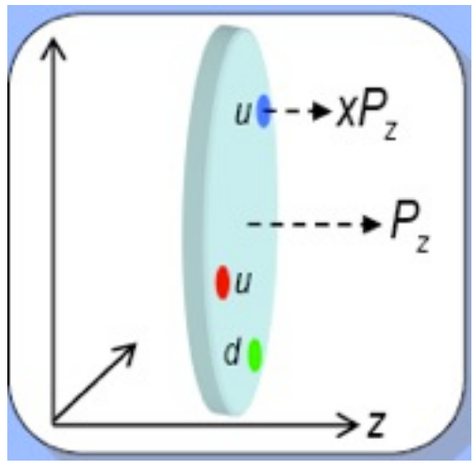
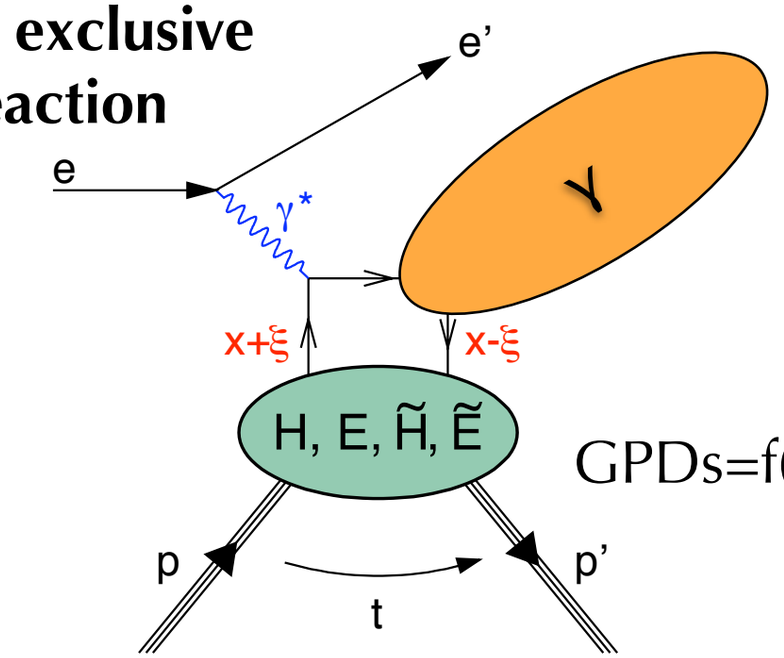


longitudinal momentum of partons

Hard exclusive reaction



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Mesons: see talk by M. Guidal

DVCS = hard electroproduction of a real photon

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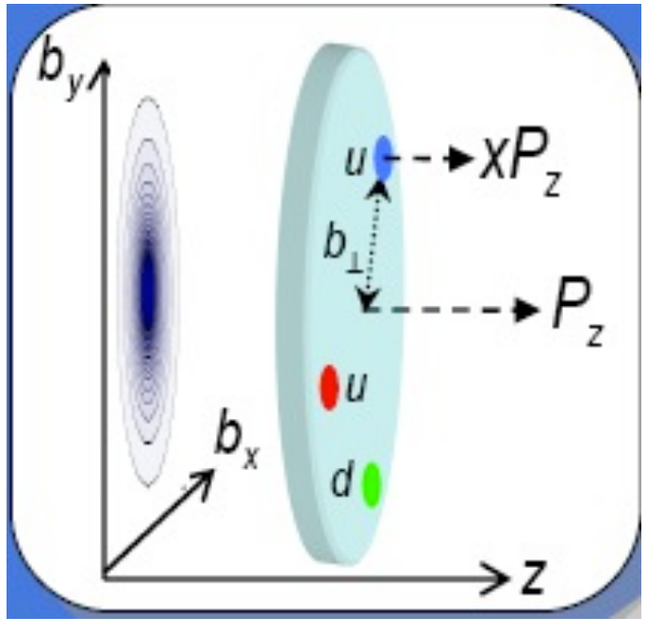

More details on GPDs: see talk by B. Pire

Nucleon Tomography

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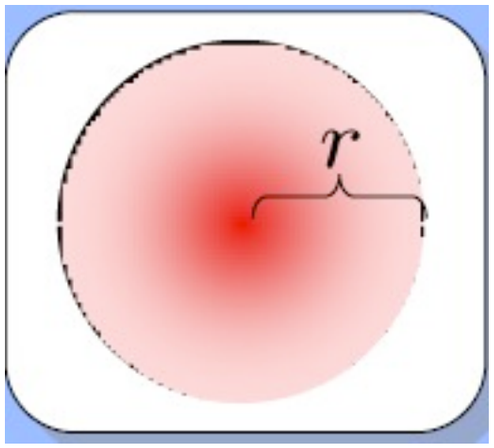

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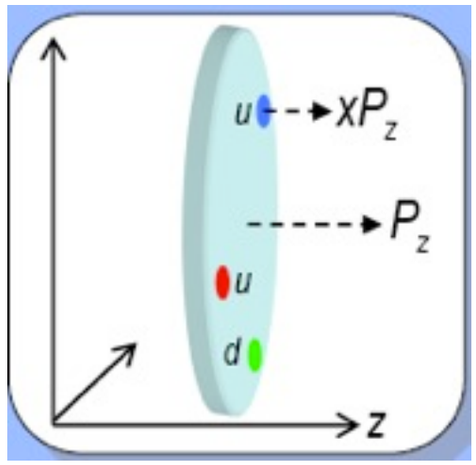

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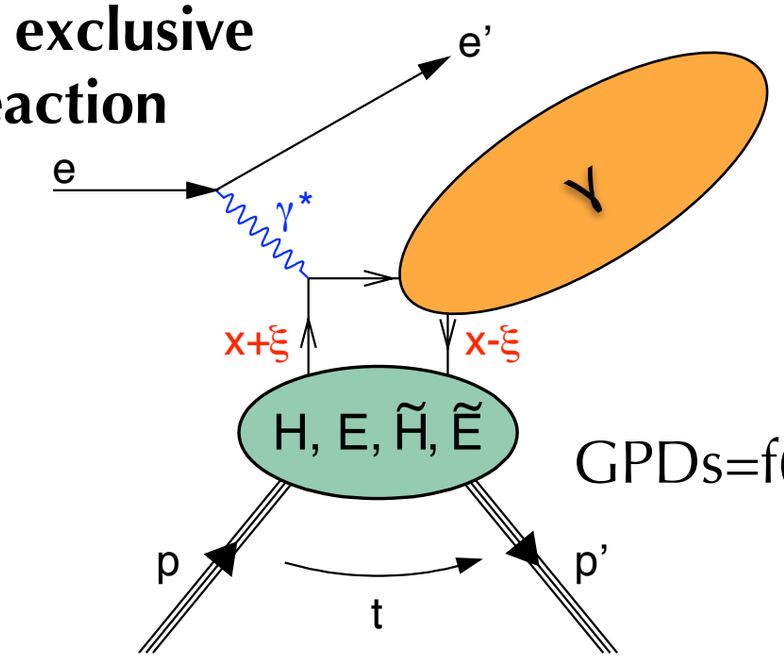

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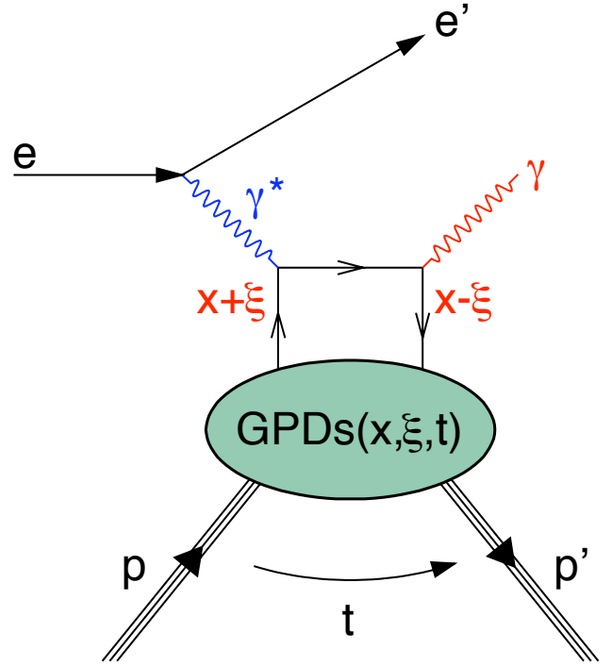
DVCS as laboratory for probing hadrons



I.

Global analysis of GPDs

requires measurements

☛ of cross-sections and

☛ of azimuthal asymmetries related to beam charge, beam helicity, target polarization

☛ preferably covering wide kinematic range

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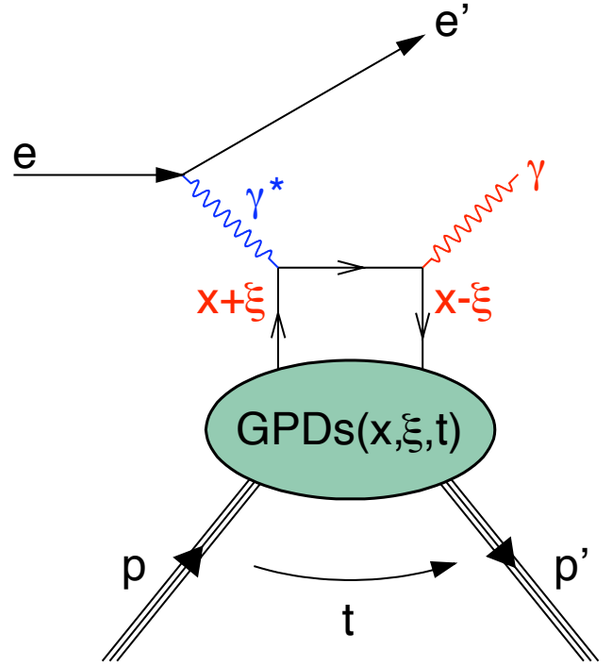

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4 chiral-even quark **GPDs** at leading twist

Spin-½	flips nucleon helicity	conserves nucleon helicity
does not depend on quark helicity	E	H
depends on quark helicity	$\tilde{E}$	$\tilde{H}$

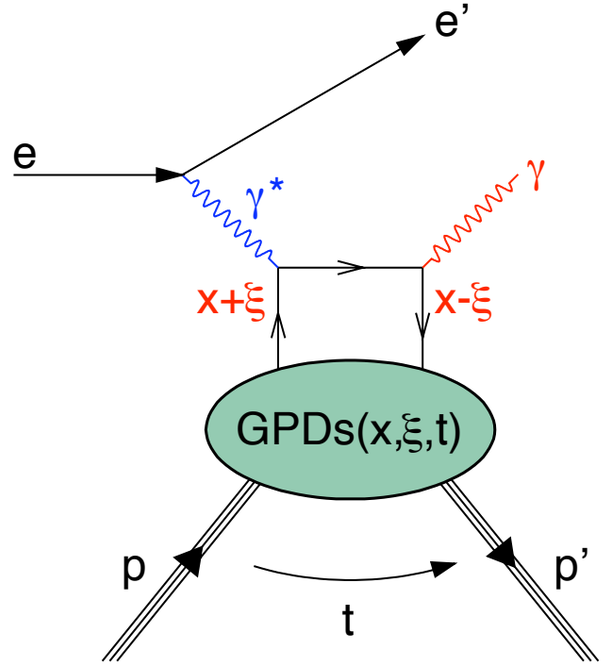
forward limit $\xi \to 0, t \to 0$

2.

H → q(x)

$\tilde{H}$ → Δq(x)

DVCS as laboratory for probing hadrons



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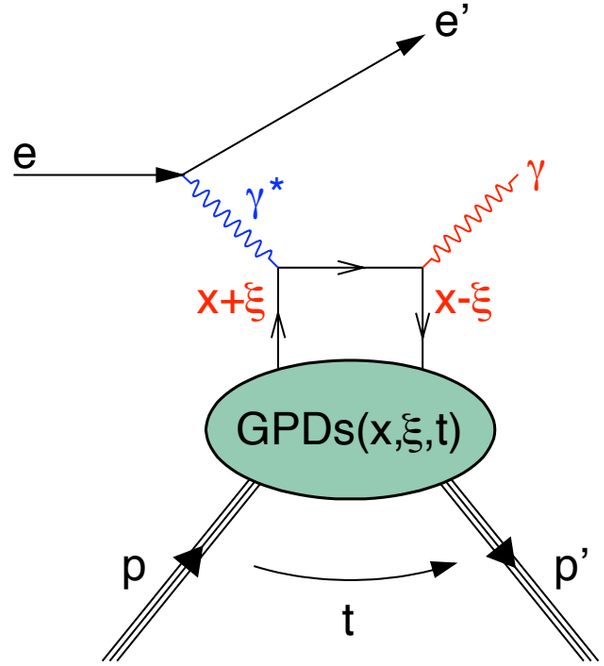
Spin-1	$H_1, H_2, H_3, H_4, H_5, \tilde{H}_1, \tilde{H}_2, \tilde{H}_3, \tilde{H}_4$

9 chiral-even quark GPDs at leading twist

Tensor signature? Coherent signature?

DVCS as laboratory for probing hadrons



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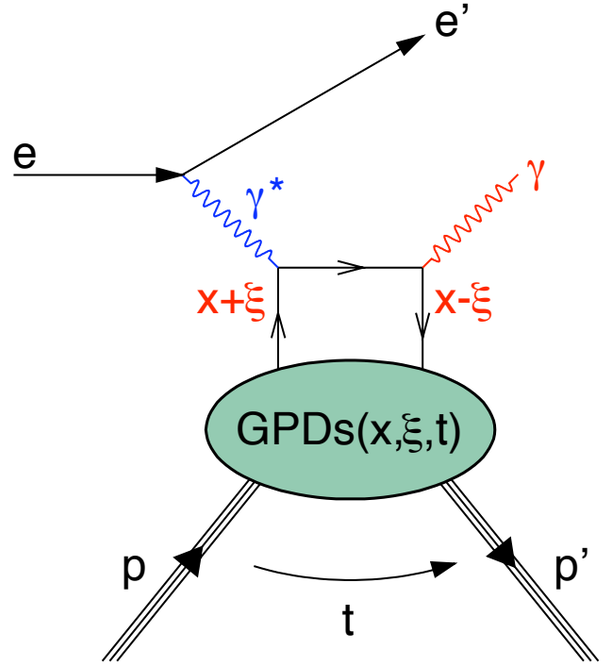
3.

Access to **total angular momentum of quarks** through Ji sum rule

$$J_q = \frac{1}{2}\lim_{t\to 0}\int_{-1}^{1} dx\, x\,[H^q(x,\xi,t) + E^q(x,\xi,t)]$$

DVCS as laboratory for probing hadrons



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Tensor signature? Coherent signature?

4. How does the **nuclear environment** modify the DVCS amplitude?

Fourier decomposition

of the γ*N→γN x-section

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Cross-section

$$\sigma_{\gamma^*\gamma N} \sim \left| \text{DVCS} + \text{Bethe–Heitler (BH)} \right|^2$$

$$= |\tau_{DVCS}|^2 + |\tau_{BH}|^2 + (\tau_{DVCS}\tau_{BH}^* + \tau_{DVCS}^*\tau_{BH})$$

high energy: $|\tau_{DVCS}|^2 \approx |\tau_{BH}|^2$
low energy: $|\tau_{DVCS}|^2 \ll |\tau_{BH}|^2$

Exactly calculable in QED given nucleon elastic form factors

Amplifies contribution of τ_{DVCS}

DVCS-BH interference term

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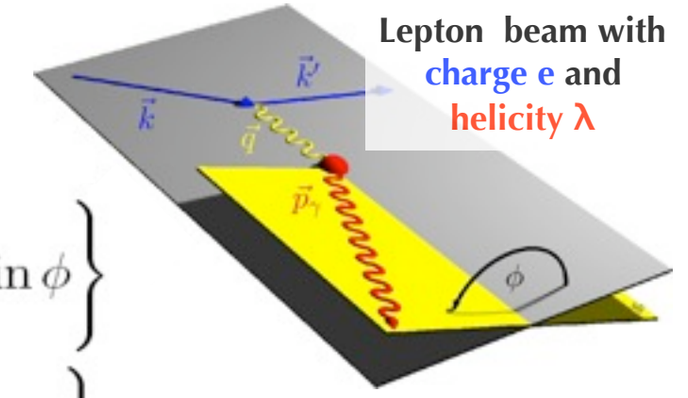
2. Harmonic expansion

Unpolarized nucleon
Case of polarized nucleon is more complicated!

$$|\tau_{\rm BH}|^2 = \frac{K_{\rm BH}}{\mathcal{P}_1(\phi)\,\mathcal{P}_2(\phi)} \left\{ \sum_{n=0}^{2} c_n^{\rm BH} \cos(n\phi) \right\}$$

$$|\tau_{\rm DVCS}|^2 = \frac{1}{Q^2} \left\{ \sum_{n=0}^{2} c_n^{\rm DVCS} \cos(n\phi) + \lambda\, s_1^{\rm DVCS} \sin\phi \right\}$$

$$\mathrm{I} = \frac{-e_\ell\, K_{\rm I}}{\mathcal{P}_1(\phi)\,\mathcal{P}_2(\phi)} \left\{ \sum_{n=0}^{3} c_n^{\rm I} \cos(n\phi) + \sum_{n=1}^{2} \lambda\, s_n^{\rm I} \sin(n\phi) \right\}$$



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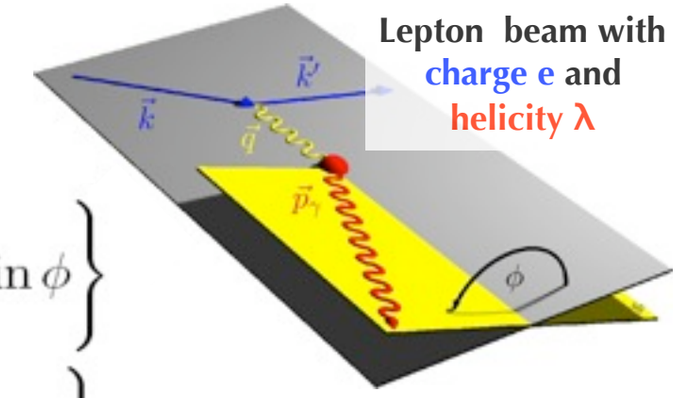

3. Express cross-section in terms of azimuthal asymmetries

$$\sigma(\phi; P_\ell, e_\ell) = \sigma_{\rm UU}(\phi) \times \left[1 + P_\ell \mathcal{A}_{\rm LU}^{\rm DVCS}(\phi) + e_\ell P_\ell \mathcal{A}_{\rm LU}^{\rm I}(\phi) + e_\ell \mathcal{A}_{\rm C}(\phi)\right]$$

$\mathcal{A}_{LU}$ — Beam, Target

Parameterization of observables in terms of GPDs

Harmonic analysis:
measure azimuthal asymmetries in DVCS with respect to beam helicity, beam charge, and/or target polarization

Compton Form Factors:

$$\mathcal{F}(\xi,t) = \sum_q \int_{-1}^{1} \mathrm{d}x \; C_q^{\mp}(\xi,x) F^q(x,\xi,t)$$

Parameterization of observables in terms of GPDs

Best access

☞ unpolarized target:

$$F_1\mathcal{H} + \frac{x_B}{2-x_B}(F_1+F_2)\widetilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}$$

dominant for the proton

dominant for the neutron

☞ longitudinally polarized target:

$$\frac{x_B}{2-x_B}(F_1+F_2)\left(\mathcal{H}+\frac{x_B}{2}\mathcal{E}\right) + F_1\widetilde{\mathcal{H}} - \frac{x_B}{2-x_B}\left(\frac{x_B}{2}F_1+\frac{t}{4M^2}F_2\right)\widetilde{\mathcal{E}}$$

☞ transversely polarized target:

$$\frac{t}{4M^2}\left[(2-x_B)F_1\mathcal{E} - 4\frac{1-x_B}{2-x_B}F_2\mathcal{H}\right]$$

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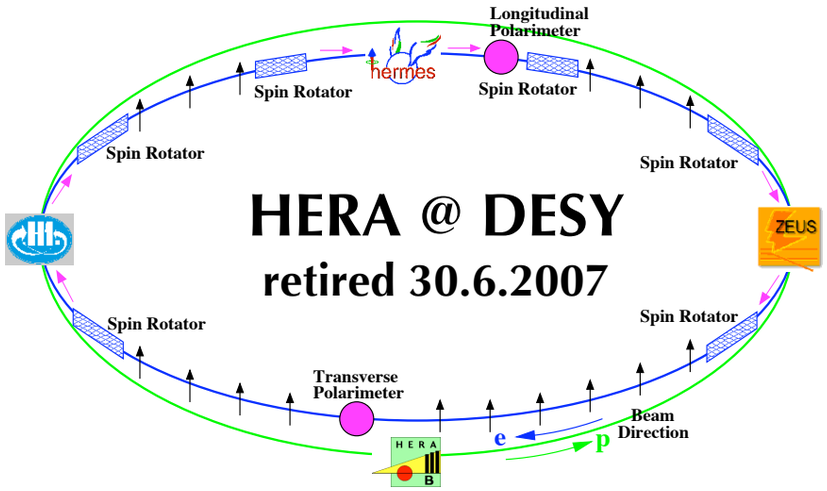
Cross-section measurement
(collider example): integration over Φ

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t}(W,t,Q^2) \approx \frac{4\pi\alpha^2}{Q^4}\frac{W^2\xi^2}{W^2+Q^2}\left[|\mathcal{H}|^2 - \frac{t}{4M^2}|\mathcal{E}|^2\right](\xi,t,Q^2)$$

DVCS at HERA



self-polarized electron beam

2 lepton beam charges: electrons and positrons

electrons: 30 GeV
protons: 920 GeV

low energy

e-beam on fixed pure gas target

- unpolarized p, d; He, N, Ne, Kr, Xe
- longitudinally polarized p, d
- transversely polarized p

<u>detected particles:</u>
no Recoil: eγ
with Recoil: epγ

hermes

H1

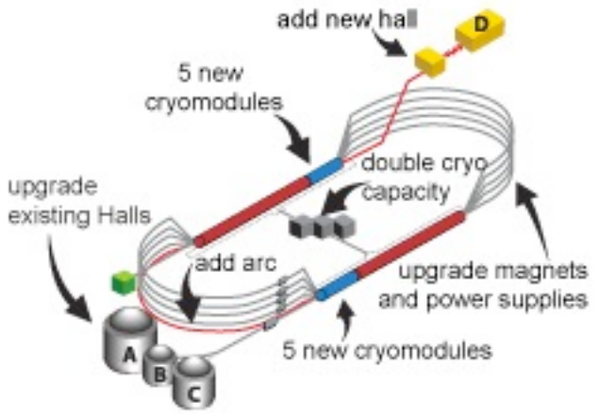
ZEUS

ep-collider
(unpolarized protons)

<u>detected particles:</u>
eγ + forward veto
ZEUS subsamle: epγ

high energy

DVCS at Jefferson Lab



polarized
e^- beam

electrons: 6 GeV

e-beam on
fixed target

Hall A
JLab

Targets:
- unpolarized p [E00-110]
- unpolarized d (→ n) [E03-106]

detected particles:
eγ

CLAS
CEBAF Large Acceptance Spectrometer

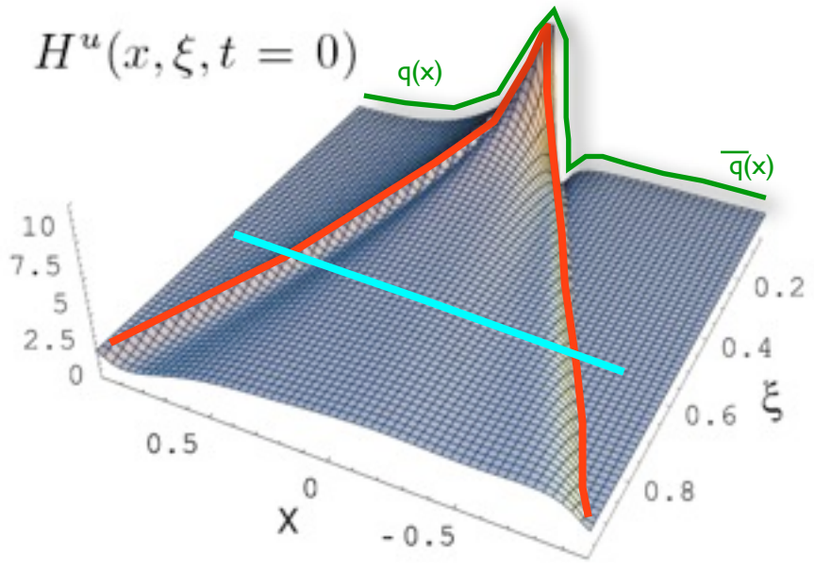
Targets:
- unpolarized p
- longitudinally polarized p
- ^{4}He

detected particles:
no Inner Calo: ep or epγ
with Inner Calo: epγ

+ future

DVCS cross-section in the valence quark region

Hall-A at JLab
proton target [E00-110]



Goeke, Polyakov, Vanderhaeghen,
hep-ph/0106012

Helicity-dependent

$\propto \mathrm{Im}(\mathcal{T}_{DVCS})$

GPDs @ $x=\xi$

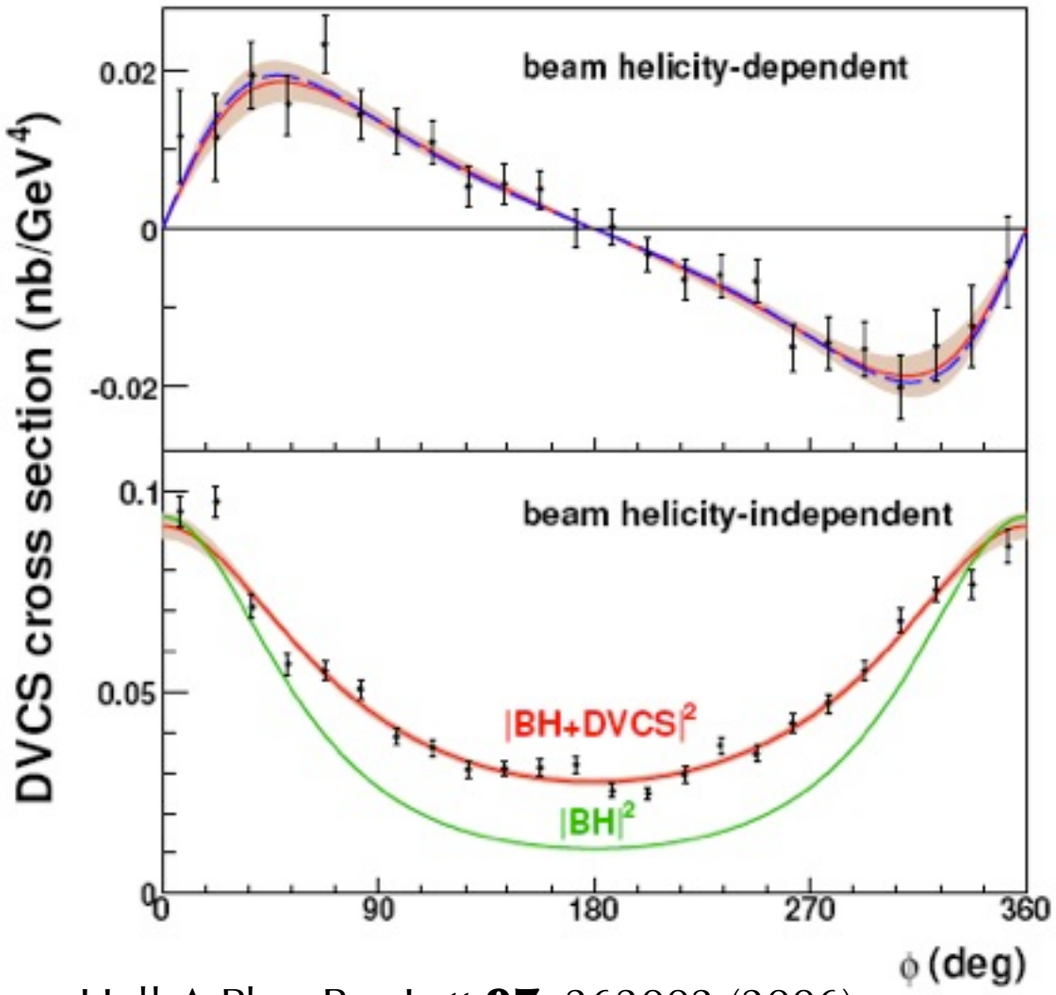
Helicity-independent

$\propto \mathrm{Re}(\mathcal{T}_{DVCS})$

integral of GPDs over x

Differential cross section vs. azimuthal angle

Bin: $\langle x_B\rangle$=0.36, $\langle Q^2\rangle$=2.3 GeV^2, $\langle t\rangle$=-0.28 GeV^2



Hall-A Phys.Rev.Lett.**97**, 262002 (2006)

- Twist-2 dominance: GPDs accessible at moderate Q^2
- No Q^2 dependence of $\mathrm{Im}(\mathcal{I})$
  - Indication of perturbative QCD scaling at Q^2=2 GeV^2

HERA: DVCS cross-section in the sea/glue region

GPD H
x-section

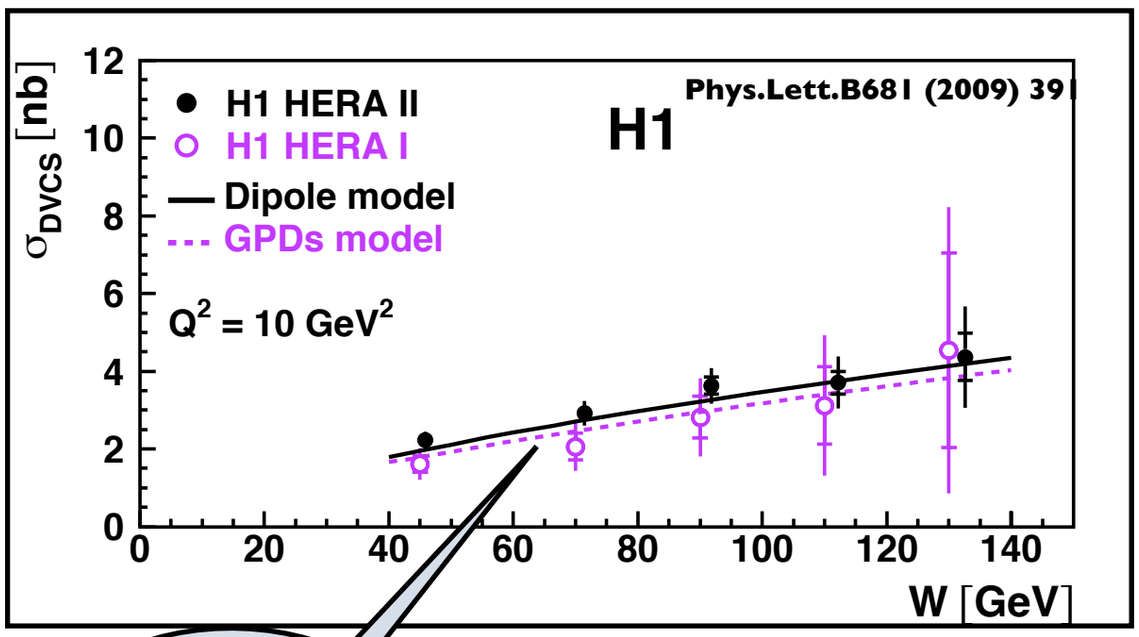
Ansatz:

$d\sigma/dt \propto \exp(-b|t|)$

t-slope:
average impact parameter

Dipole model: C. Marquet, R. Peschanski, G. Soyez, hep-ph/0702171

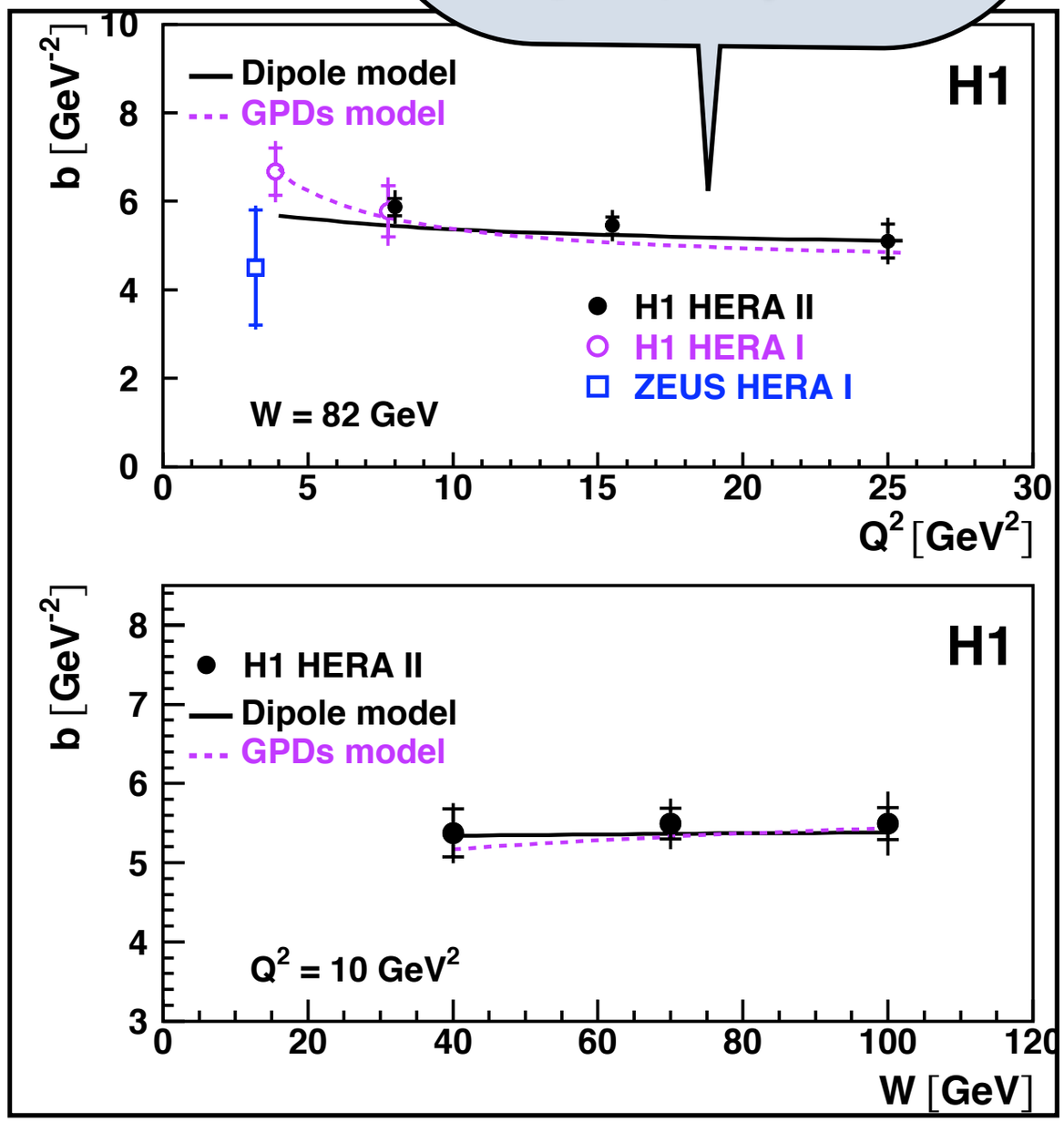
GPD model: K. Kumericki, D. Müller, fit to previous HERA meas.



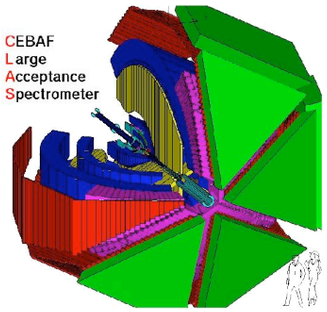
Steep W-dependence:
$\sigma(W) \propto W^{\delta}$
with $\delta \approx 0.7$

DVCS is hard process, gluons resolved!

Description of transverse extension of partons in the proton!
$\sqrt{\langle r_T^2 \rangle} = (0.65 \pm 0.02)$fm @ $x_B = 10^{-3}$



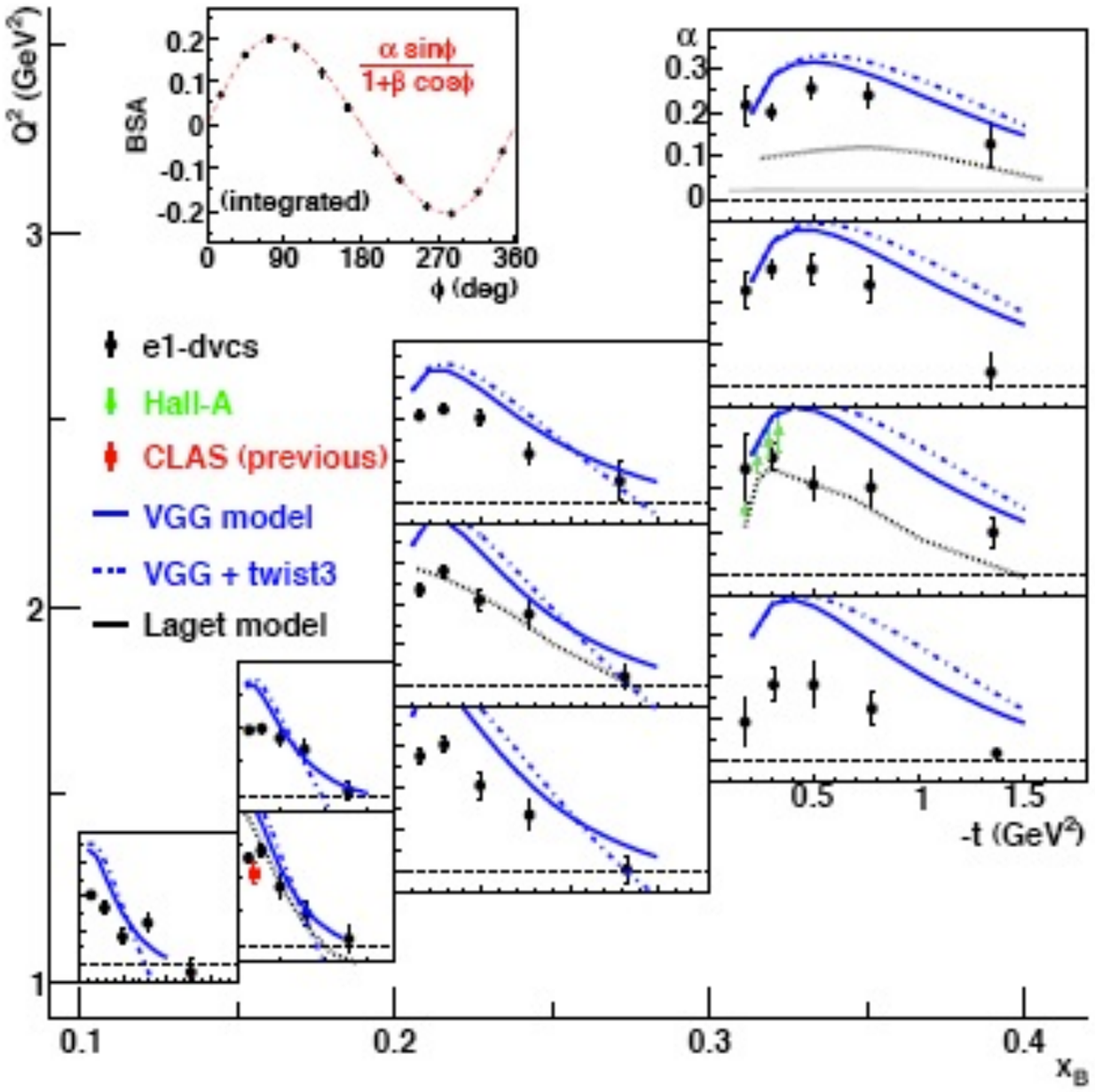
ZEUS arXiv:0812.2517



CLAS beam-helicity asymmetry

GPD H
Im(τ_{DVCS})
BSA

CLAS: $\langle Q^2 \rangle$=1.82 GeV^2, $\langle x_B \rangle$=0.28, $\langle -t \rangle$=0.31 GeV^2



F.-X. G. *et al.*, PRL **100** (2008) 162002

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

- **Model** overshoots data.
- Effect also observed for HERMES data.

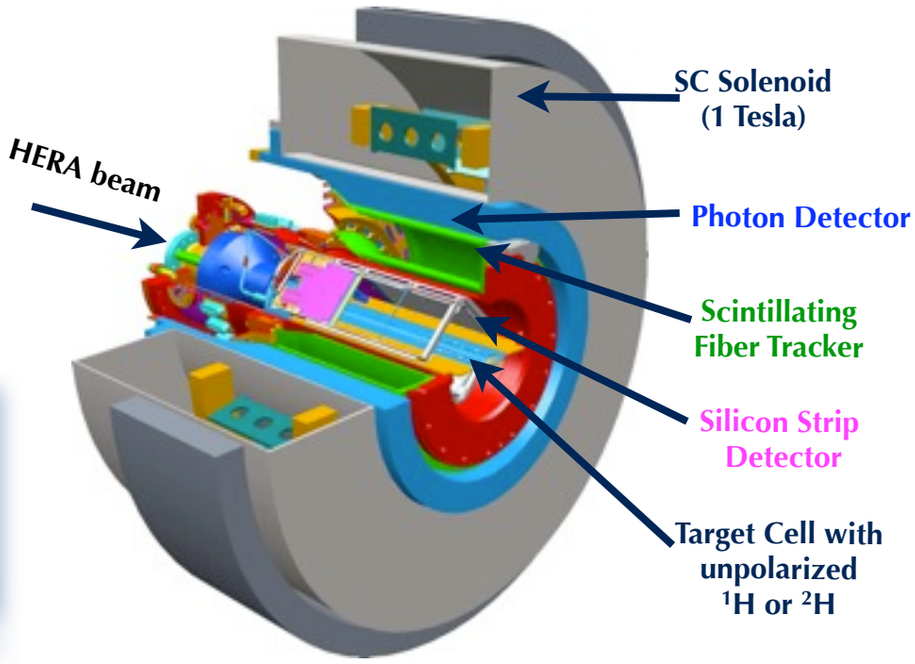
Data taken with
Inner Calorimeter

VGG model calculations:
Phys.Rev. D60 (1999) 094017 and
Prog.Nucl.Phys. 47 (2001) 401

Recoil Detector

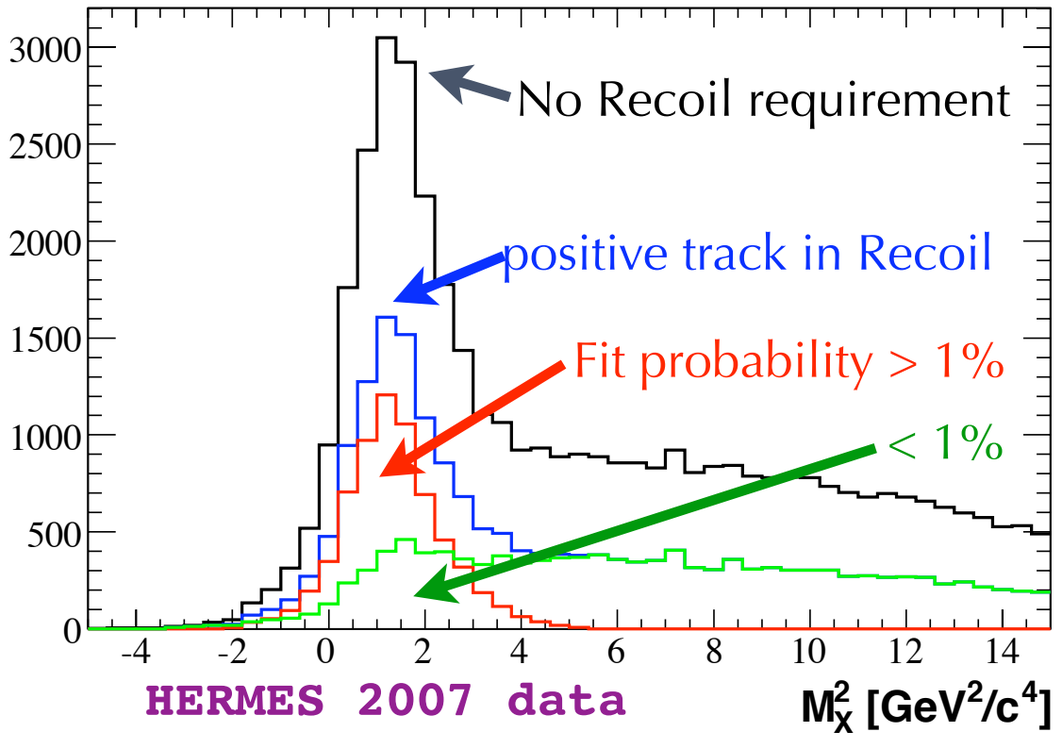
2006/2007

Tag DVCS events by detecting the **recoiling proton** in coincidence with scattered beam **lepton** and real **photon**



Azimuthal coverage: 76%
Targets: unpol. H and D

Kinematic Event Fitting



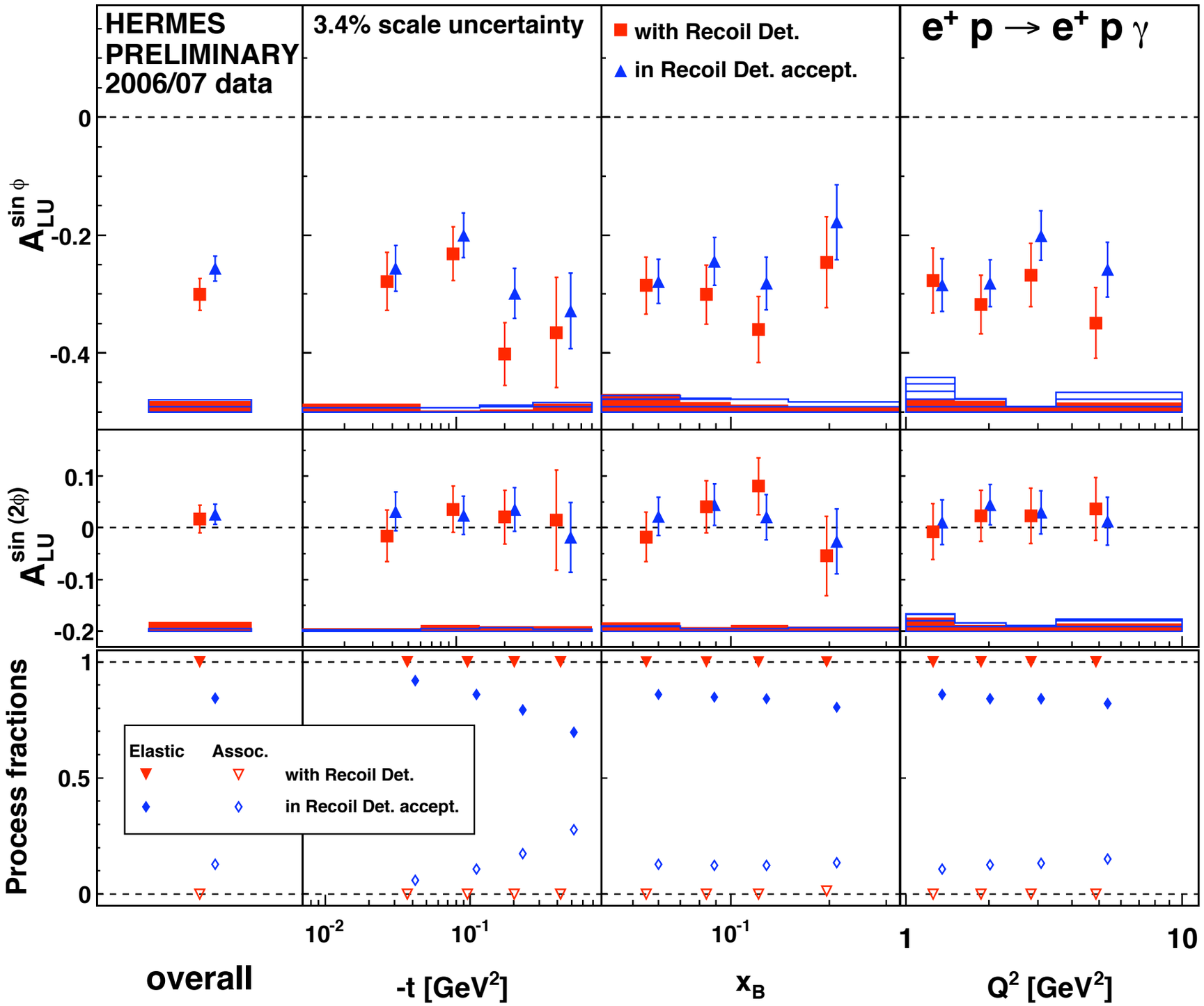
No Recoil:
12% resonant production $ep \rightarrow e\Delta^{+}\gamma$
2.5% semi-inclusive production $ep \rightarrow eX\pi^{0}$

With Recoil:
$ep \rightarrow ep\gamma$ with >99.9% purity

HERMES Recoil analysis

Beam-helicity asymmetry

GPD H
Im(τ_{DVCS})
BSA



HERMES: $\langle Q^2\rangle$=2.46 GeV², $\langle x_B\rangle$=0.10, $\langle -t\rangle$=0.12 GeV²

- Indication of A(ep→epγ) > A(no Recoil).
- Extraction of A(resonant) subject of an ongoing dedicated analysis.

HERMES Recoil analysis

Beam-helicity asymmetry

GPD H
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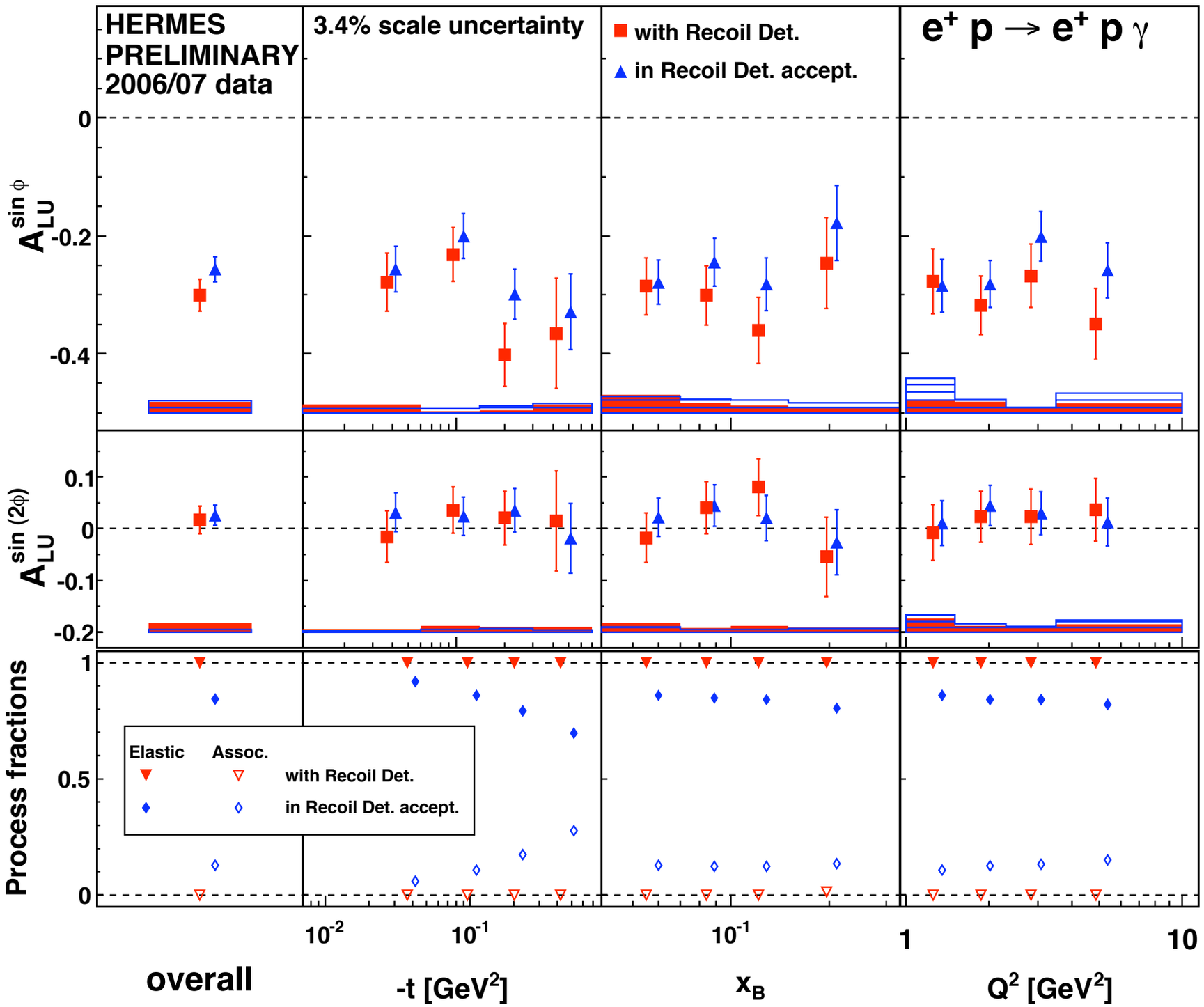


HERMES: $\langle Q^2\rangle$=2.46 GeV^2, $\langle x_B\rangle$=0.10, $\langle -t\rangle$=0.12 GeV^2

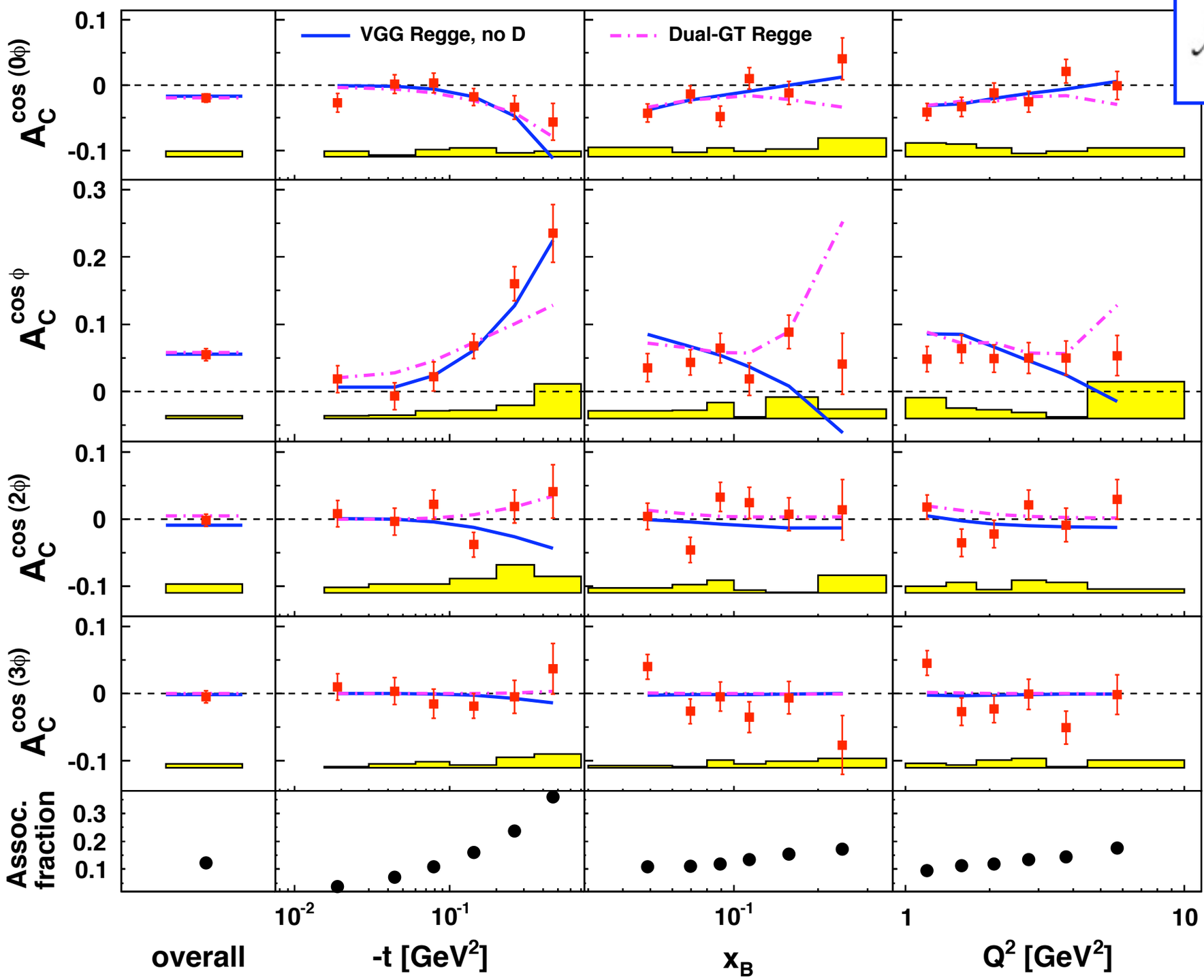
- Indication of A(ep→epγ) > A(no Recoil).
- Extraction of A(resonant) subject of an ongoing dedicated analysis.

CLAS: Resonant beam-helicity asymmetry in ep→eNπγ (Δ^+ region): feasibility demonstrated

Beam-charge asymmetry

GPD H
$\mathrm{Re}(\mathcal{T}_{DVCS})$
BCA

JHEP 11 (2009) 083



$$\mathcal{A}_C(\phi) \equiv \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-}$$

VGG Regge
Phys.Rev. D60 (1999) 094017 and
Prog.Nucl.Phys. 47 (2001) 401
b_{val} = infinity
b_{sea} = 1
D-term = 0
☞ good description of BCA data

Dual-GT Regge
Phys.Rev.D74 (2006) 054027 and
Phys.Rev.D79 (2009) 017501

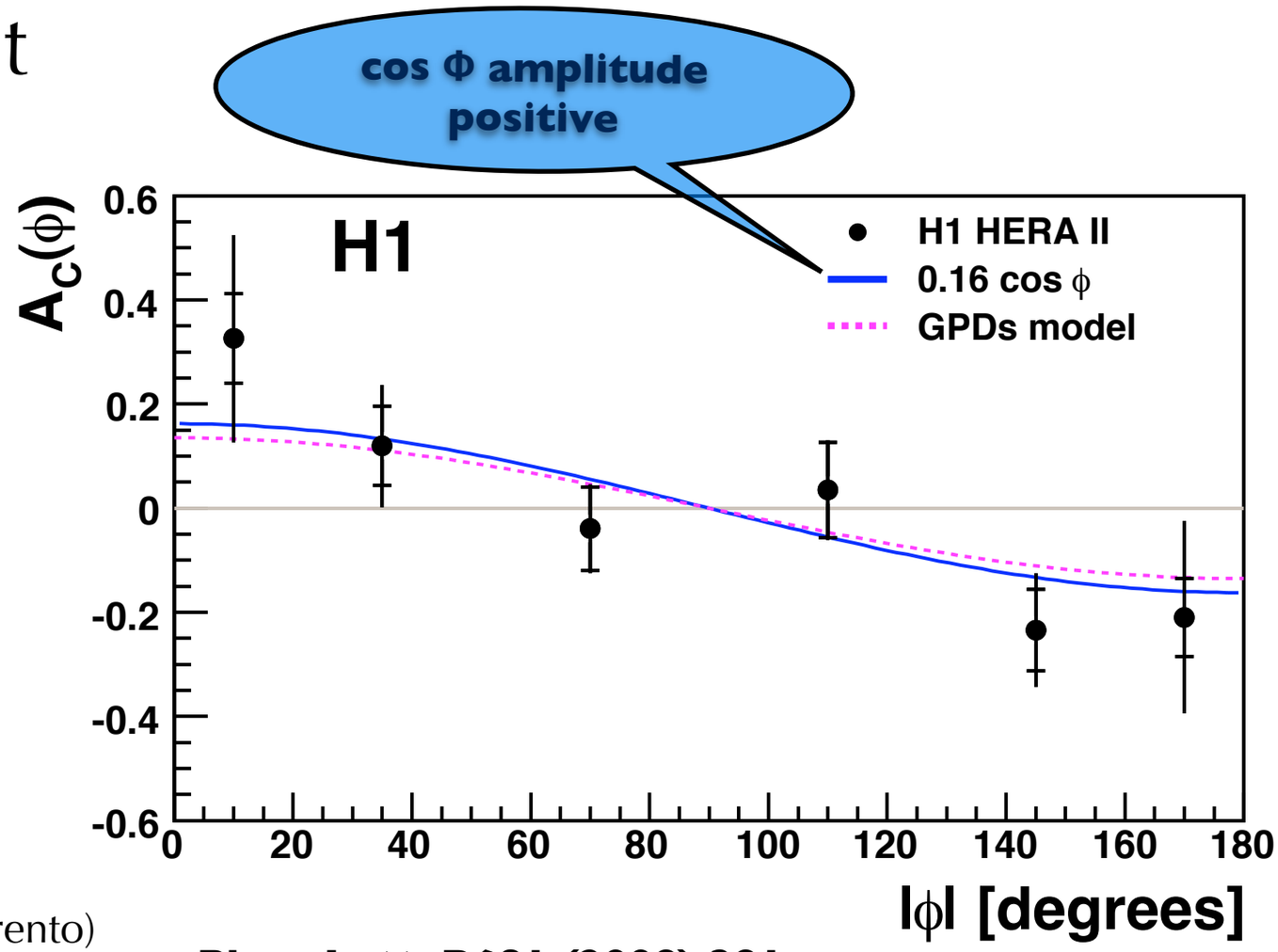
☞ both models overshoot BSA data

Beam-charge asymmetry

GPD H
$\mathrm{Re}(\tau_{DVCS})$
BCA

- First and only measurement at collider
  - low $x_B=10^{-4}...10^{-2}$
  - $6.5 < Q^2 < 80$ GeV^2
  - $30 < W < 140$ GeV
  - $|t|<1$ GeV^2
- Observation
  - **$\mathrm{Re}(\tau_{DVCS}) > 0$** for HERA (small x)
  - **$\mathrm{Re}(\tau_{DVCS}) < 0$** for HERMES (larger x)

    (if same Φ-convention is used as for H1, i.e. non-Trento)
- $\rho = \mathbf{Re}(\tau_{DVCS}) / \mathbf{Im}(\tau_{DVCS})$
  - $\rho=0.20 \pm 0.05(\mathrm{stat}) \pm 0.08(\mathrm{sys})$
  - In good agreement with theoretical calculation (dispersion relation)

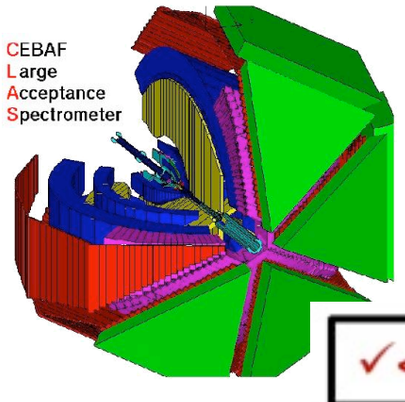


Phys. Lett. B681 (2009) 391

Longitudinal target-spin asymmetry

GPD H ~ LTSA

$$\mathcal{A}_{\mathrm{UL}} = \frac{d\sigma^{\Rightarrow} - d\sigma^{\Leftarrow}}{d\sigma^{\Rightarrow} + d\sigma^{\Leftarrow}}$$

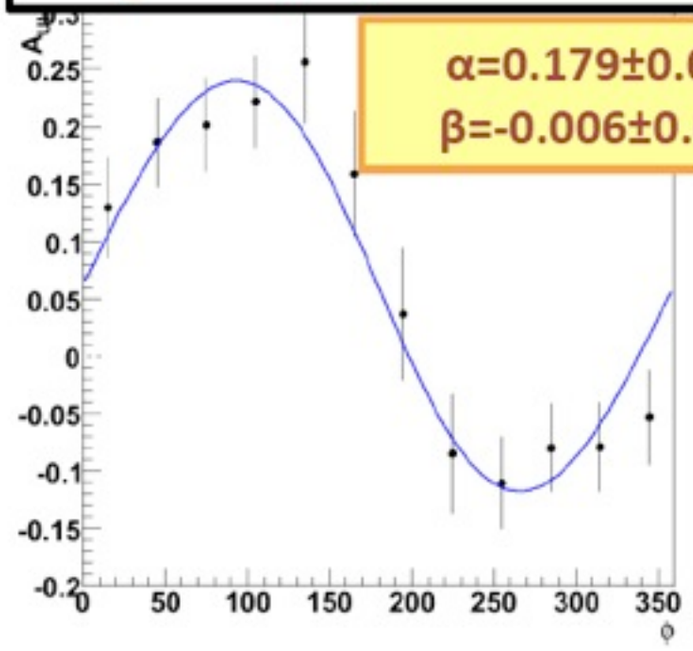


CLAS [2011 preliminary] target-spin asymmetry

✓$\langle x_B \rangle \approx 0.21$, $\langle Q^2 \rangle \approx 2.15\,\mathrm{GeV}^2$

$\alpha = 0.179 \pm 0.017$

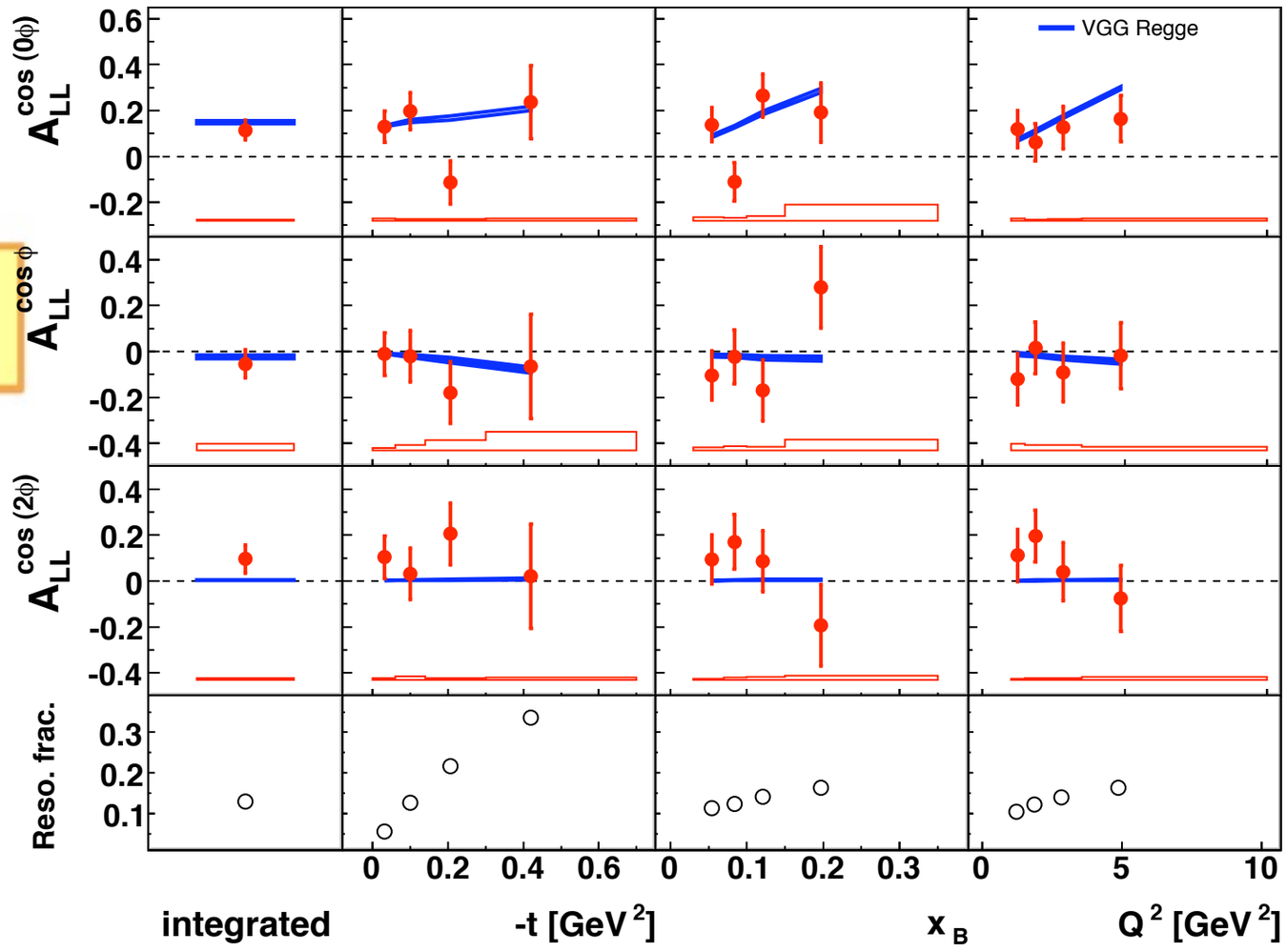
$\beta = -0.006 \pm 0.018$



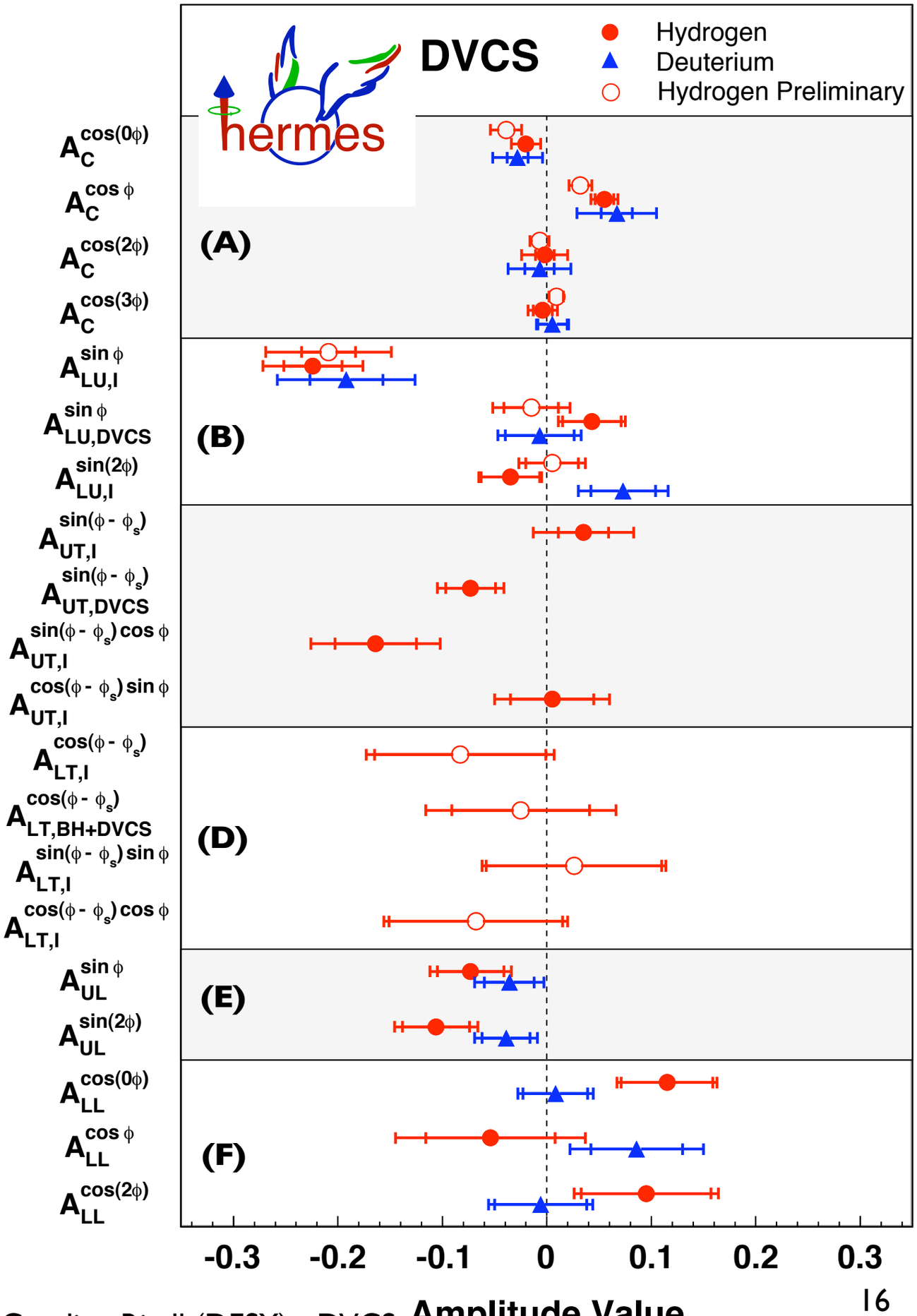
EG1-dvcs: dedicated run 2009 with Inner Calo

1st publication: CLAS PRL 97, 072002 (2006)

hermes Double-spin LL asymmetry



HERMES JHEP 06 (2010) 019



Fourier Amplitudes

Unique & complete set of asymmetries

(A) Beam-charge asymmetry:
GPD H [JHEP 11 (2009) 083 - Nucl. Phys. B 829 (2010) 1-27]

(B) Beam-helicity asymmetry:
GPD H [JHEP 11 (2009) 083 - Nucl. Phys. B 829 (2010) 1-27]

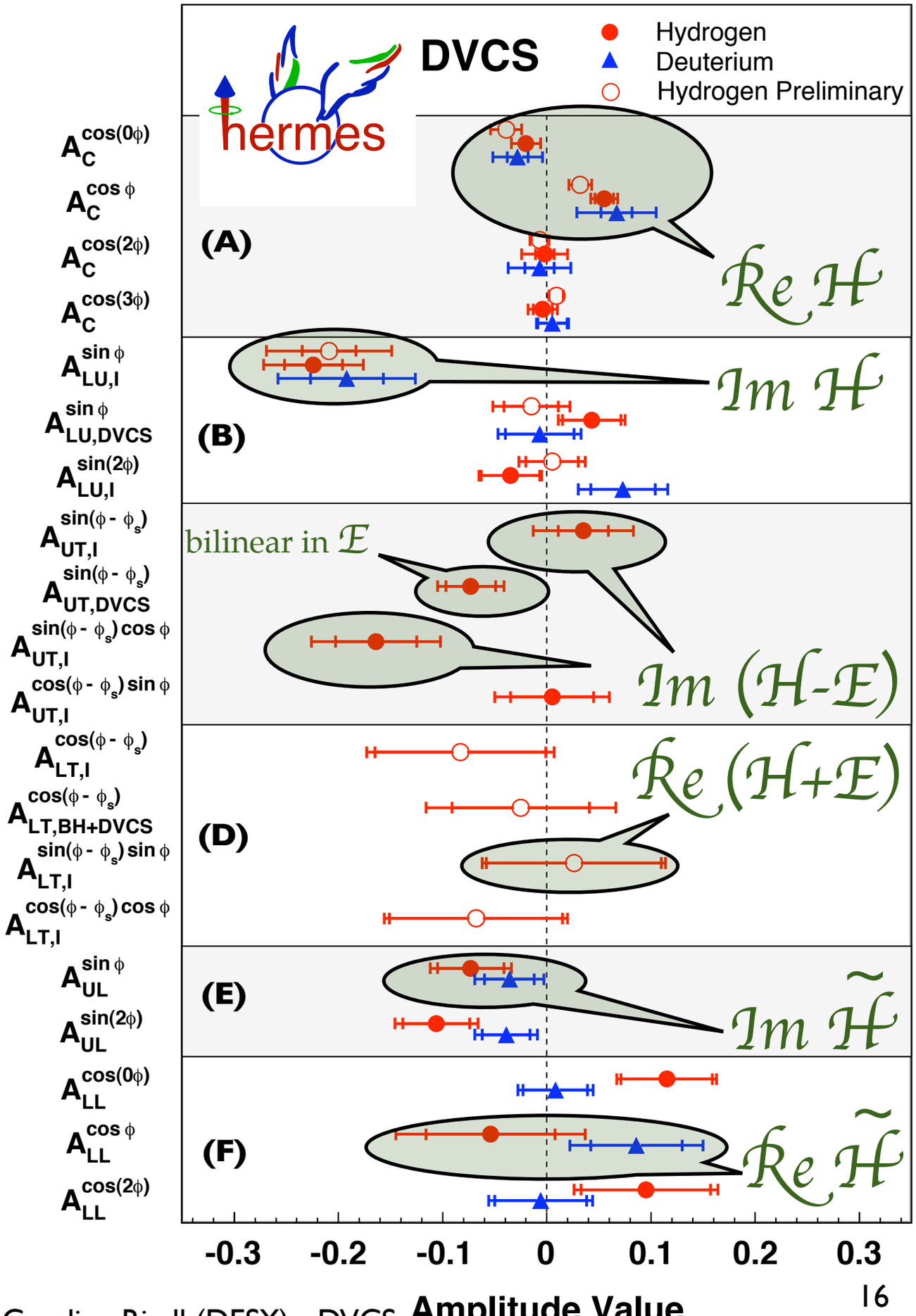
(C) Transverse target-spin asymmetry:
GPD E from proton target [JHEP 06 (2008) 066]

(D) Double-Spin (LT) asymmetry:
GPD E [to be published 2011]

(E) Longitudinal target-spin asymmetry:
GPD H~ [JHEP 06 (2010) 019 - Nucl. Phys. B 842 (2011) 265-298]

(F) Double-spin (LL) asymmetry:
GPD H [JHEP 06 (2010) 019 - Nucl. Phys. B 842 (2011) 265-298]

HERMES: $\langle Q^2\rangle = 2.46$ GeV^2, $\langle x_B\rangle = 0.10$, $\langle -t\rangle = 0.12$ GeV^2



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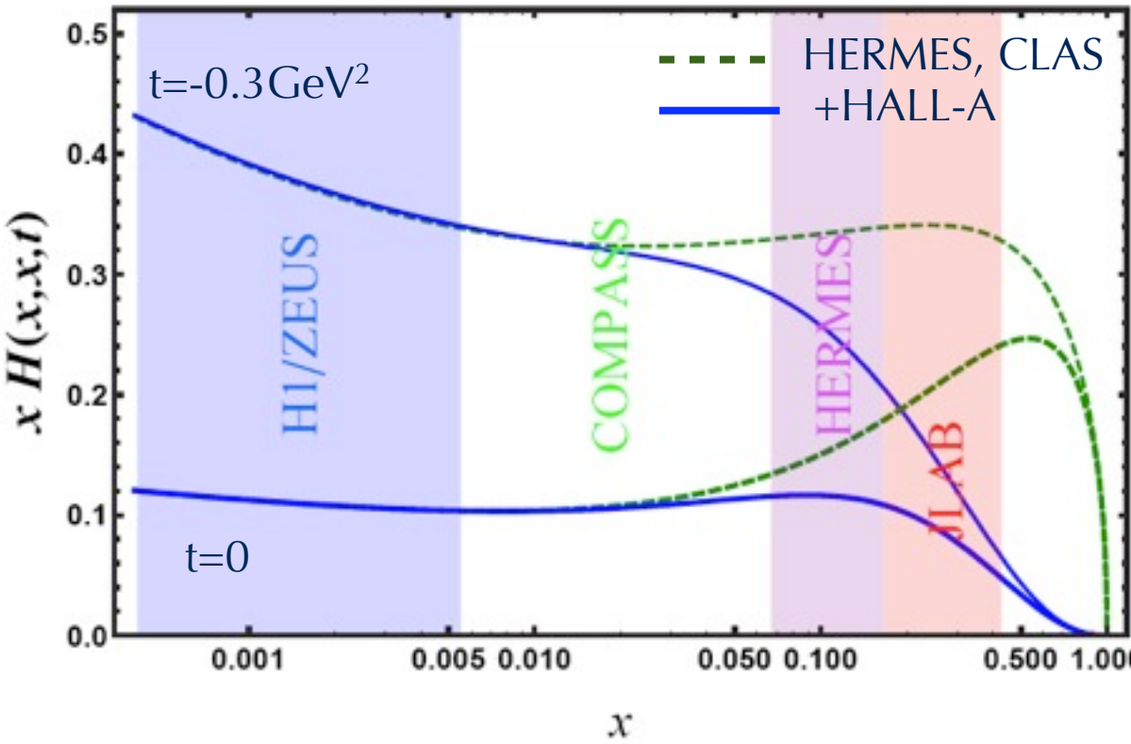
Global analysis of DVCS data

- **Kresimir Kumericki & Dieter Müller**
  Nucl. Phys. **B**841 (2010) 1-58
  - Global fit to extract GPD H at cross-over line ξ=x. NNLO
  - **HERMES** A_C , **CLAS** A_{LU} and **Hall A** x-section.
  - Small-x behavior from **HERA collider** data.

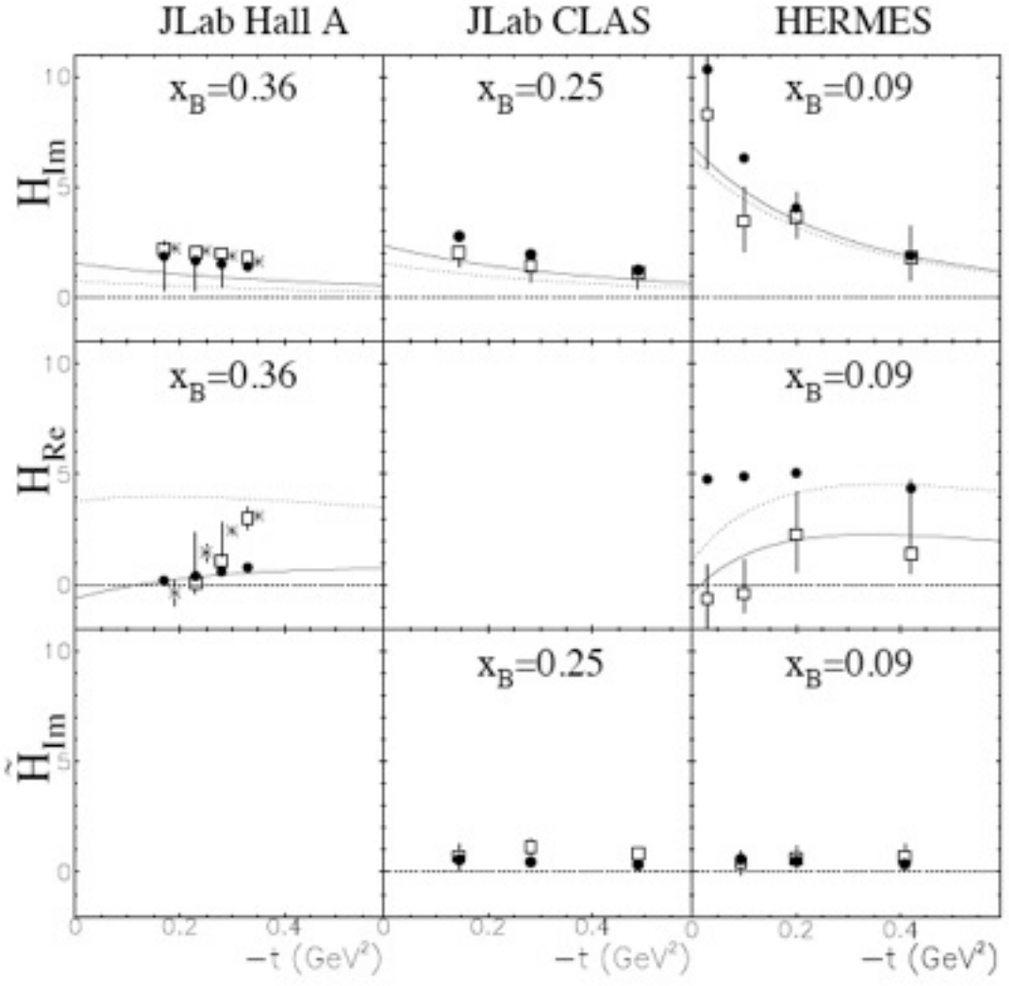
See talk by K. Kumericki

GPD H

Global fit to H(x,ξ=x,t) from DVCS data



Desirable: As many observables as possible sensitive to different CFFs



❑ Guidal
✳ Moutarde
— Müller/ Kumericki
• VGG

Compton Form Factors

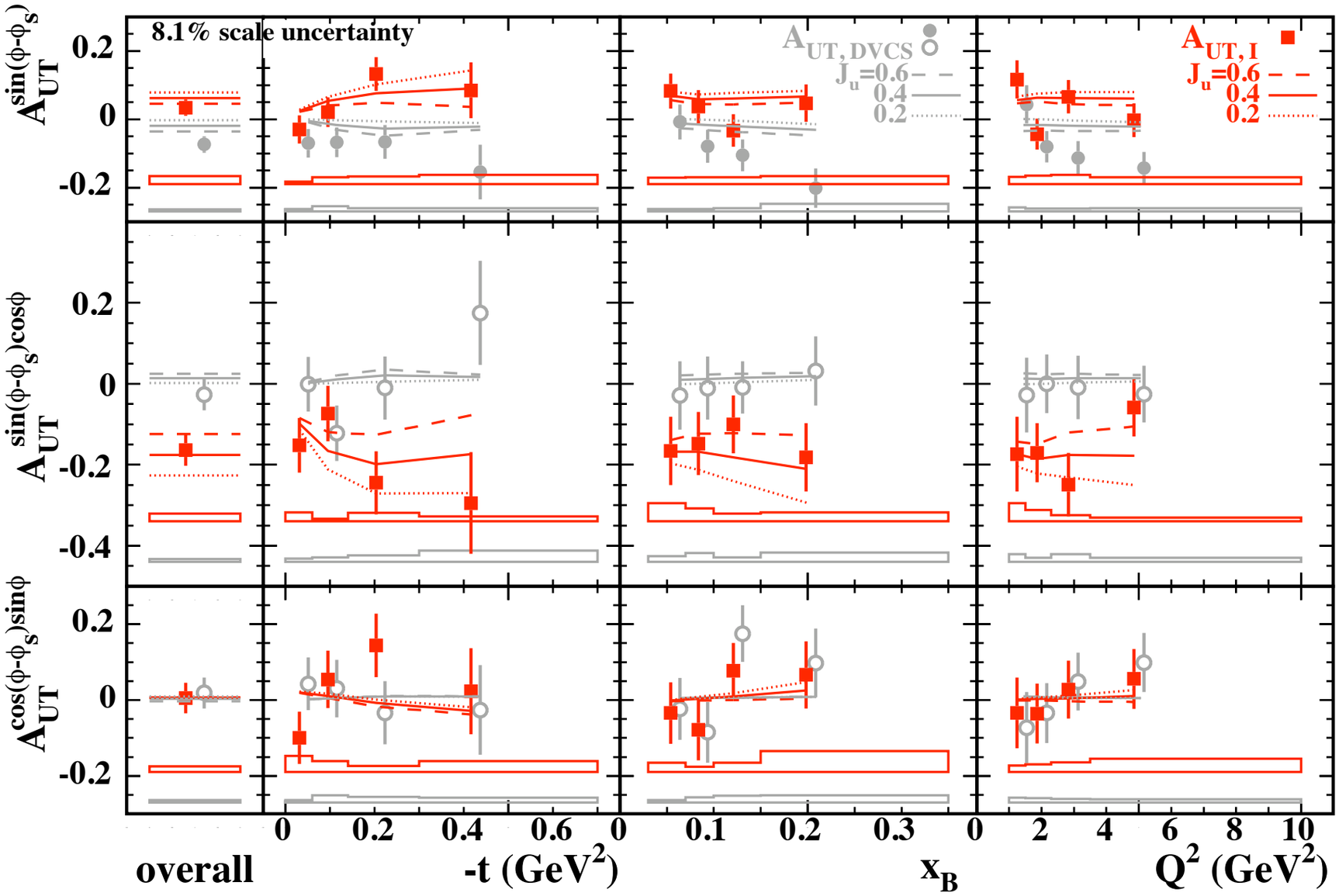
- **Herve Moutarde** PRD 79, 094021 (2009)
  - Global fit to extract $\mathcal{Re}(\mathcal{H})$ **&** $\mathcal{Im}(\mathcal{H})$
  - **Hall A** x-section & **CLAS** A_{LU}

- **Michel Guidal** arXiv:1011.4195
  - Model-independent fit of $\mathcal{Re}$(CFF) & $\mathcal{Im}$(CFF)
  - **HERMES:** $A_C, A_{LU}, A_{UT}, A_{UL}, A_{LL}$
  - **CLAS:** A_{LU}, A_{UL}
  - **Hall A:** x-section

Transverse target-spin asymmetry

GPD E
TTSA, BSA

JHEP 06 (2008) 066



Model curves:
VGG Regge, no D-term
3 different values for J_u
fixed J_d=0
Eur. Phys. J C46 (2006) 729

(A) HERMES: $\mathbf{ep^{\uparrow} \rightarrow ep\gamma}$: $\mathcal{H}$-$\mathcal{E}$ (transversely polarized target)

(B) Hall A: $\vec{\mathbf{e}}^{-}\mathbf{n} \rightarrow \mathbf{e}^{-}\mathbf{n}\,\boldsymbol{\gamma}$: $\mathcal{E}$ dominant for the neutron (unpolarized target)

Total angular momentum of quarks

Ji sum rule for the nucleon

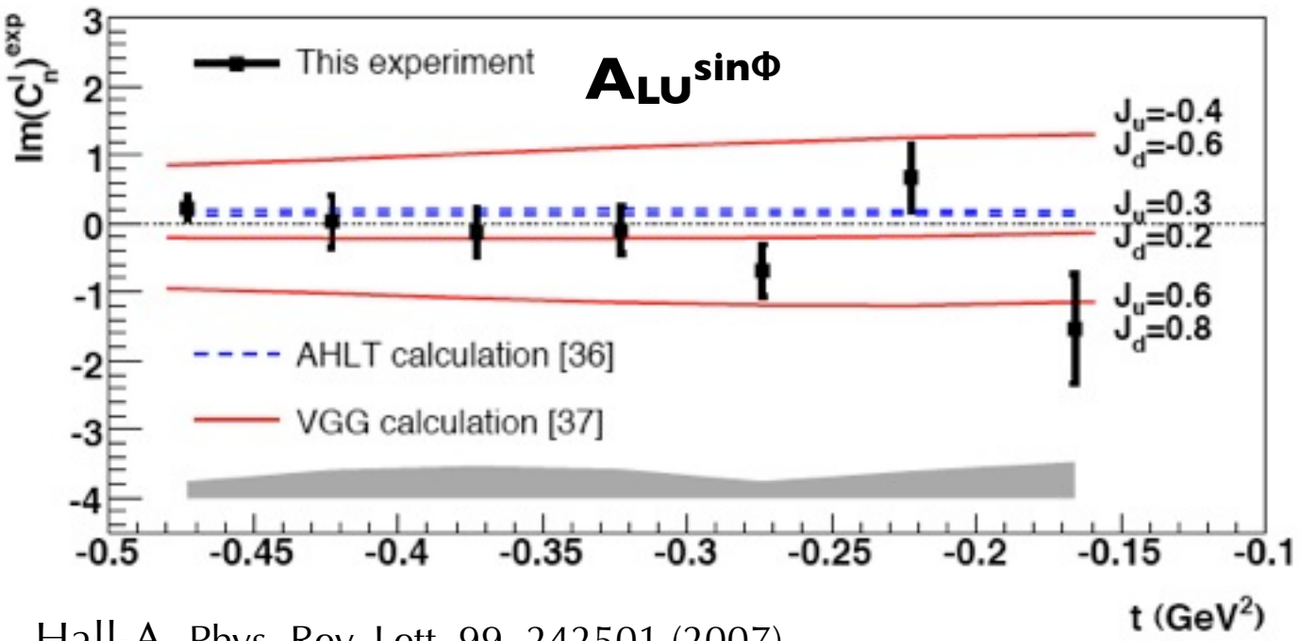
-Ji, PRL 78 (1997) 610-

$$J_q = \frac{1}{2}\lim_{t\to 0}\int_{-1}^{1} \mathrm{d}x\; x\,[H^q(x,\xi,t) + E^q(x,\xi,t)]$$

Nucleon spin

½ = ½ΔΣ + L_q + J_g

- Hall A / JLab, deuteron target (E03-106).
- Quasi-elastic proton contribution subtracted from deuteron signal.
- Beam-helicity asymmetry on the neutron:



Hall-A Phys. Rev. Lett. 99, 242501 (2007)

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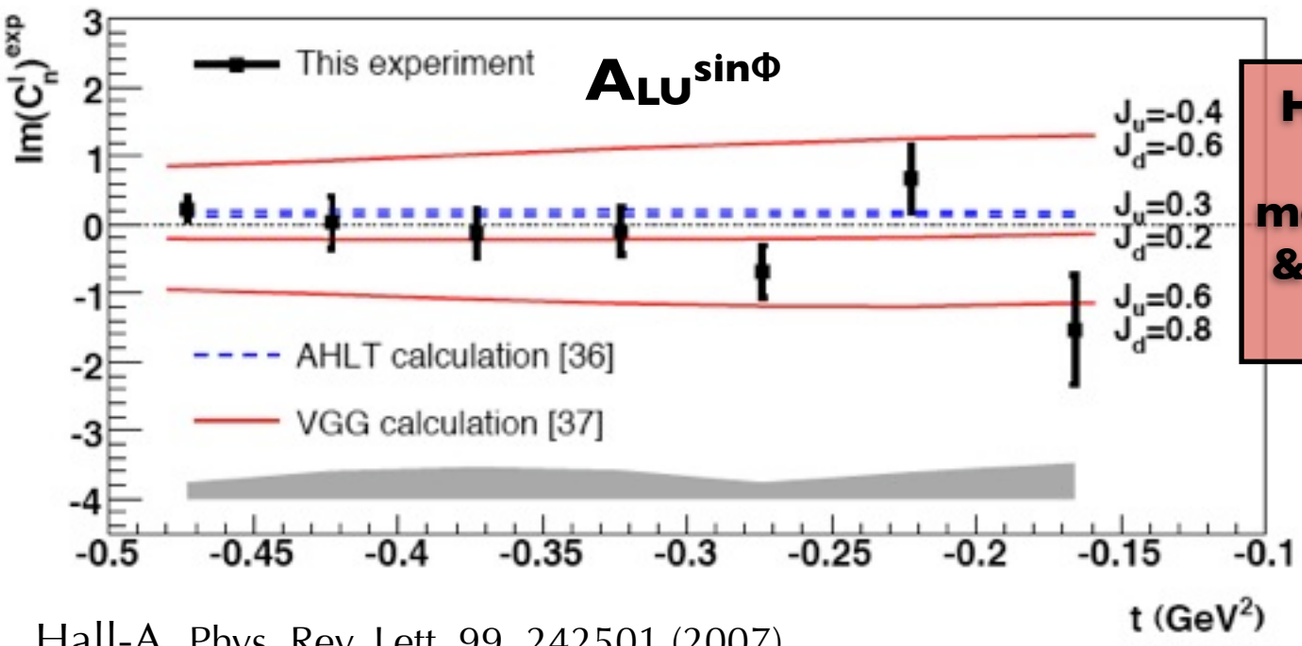
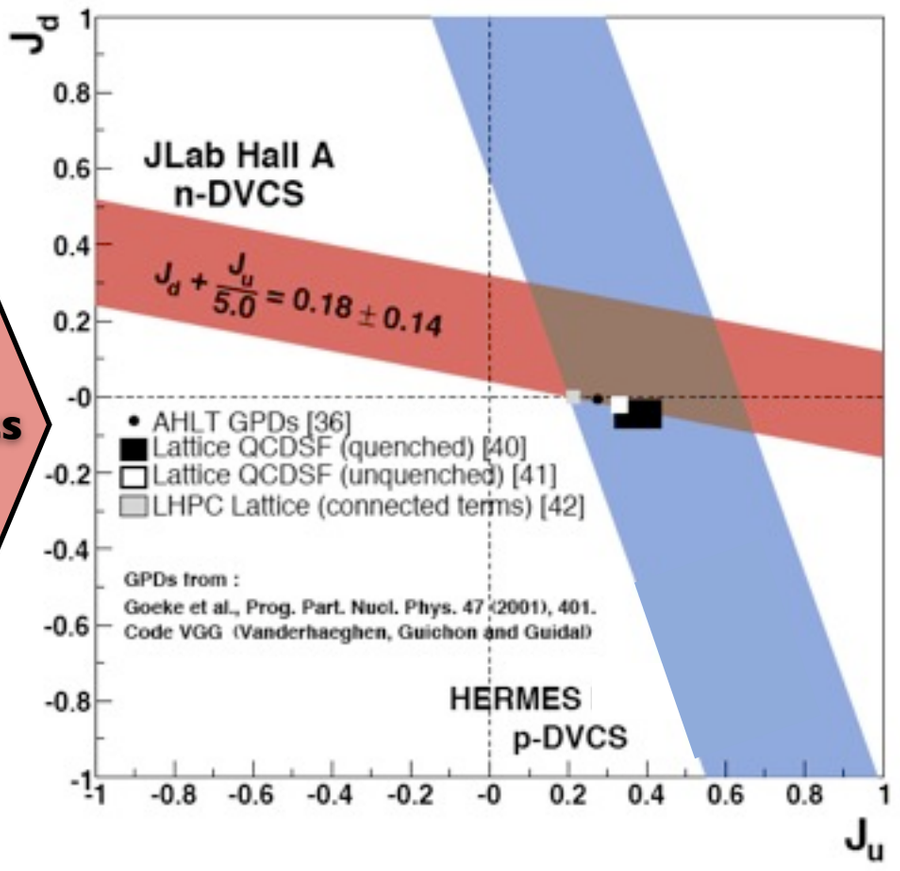


HERMES + CLAS measurements & sensitivity to J_q:



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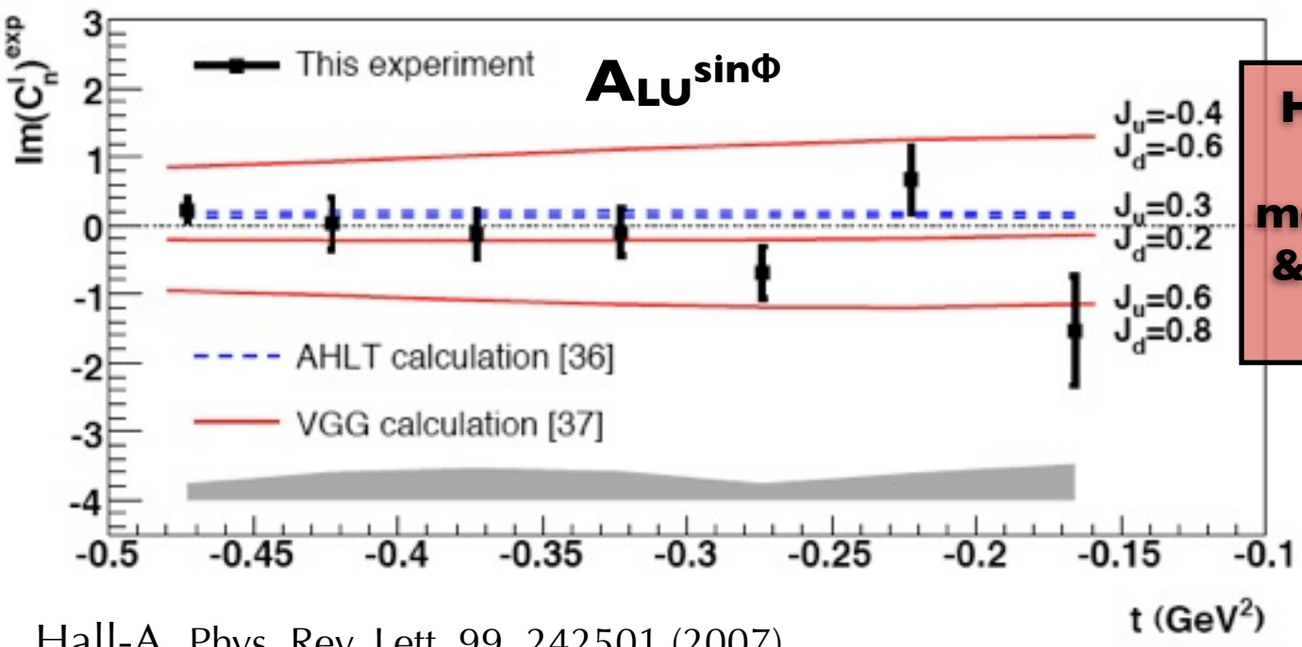


Hall-A Phys. Rev. Lett. 99, 242501 (2007)

HERMES + CLAS measureme & sensitivit to J_q:

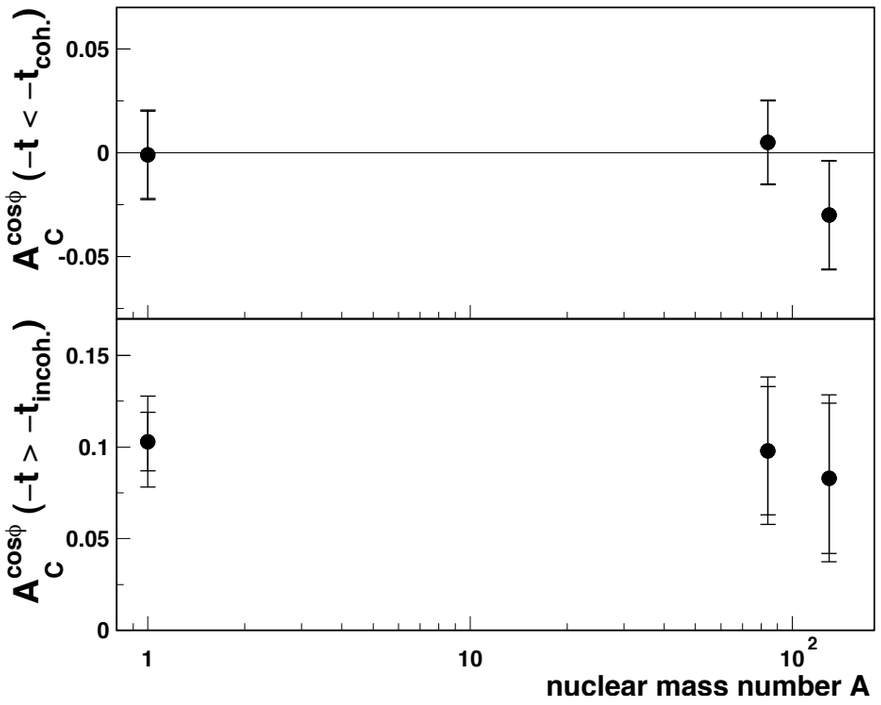
Caveat: model-dependent constraint on J_u+k·J_d.
GPD models are far from describing all available data equally well !!

DVCS nuclear effects

Nuclear medium

Phys. Rev. C 81 (2010) 035202

$A_C^{\cos\phi}$ vs. A

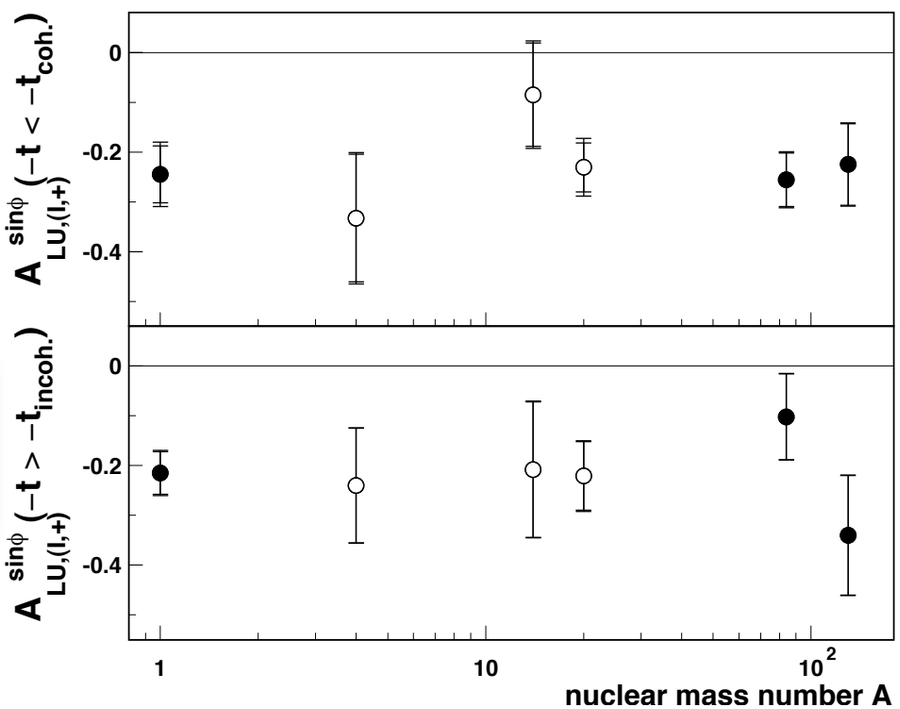


Beam-charge asymmetry

coherent enriched

incoherent enriched

$A_{LU}^{\sin\phi}$ vs. A



Beam-helicity asymmetry

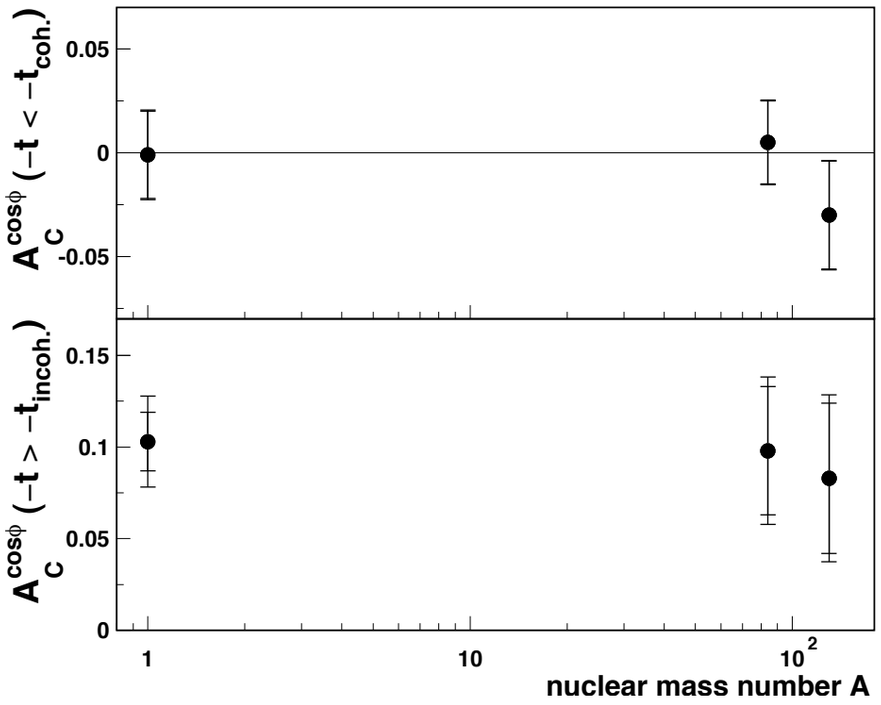
Average A_{LU}^A / A_{LU}^H:
0.91±0.19
0.93±0.23

- How does the nuclear medium modify parton-parton correlations?
- How do nucleon properties change in the nuclear medium?
- Enhanced 'generalized EMC effect', rise of T_{DVCS} with A?

DVCS nuclear effects

Phys. Rev. C 81 (2010) 035202

$A_C^{\cos\phi}$ vs. A



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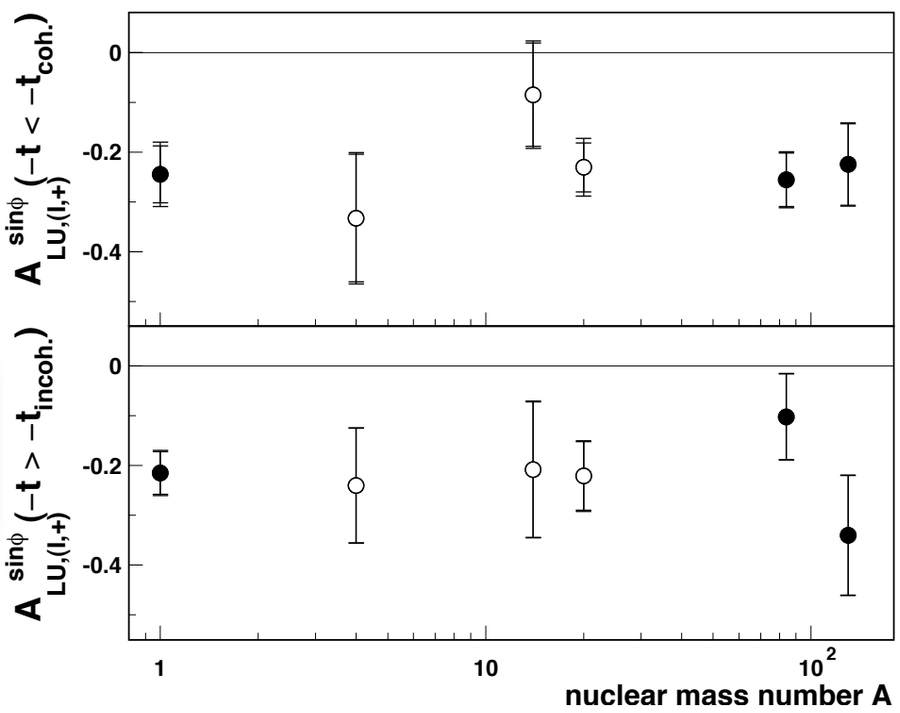

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GPD H_1~

HERMES: Search for **coherent signature** on polarized d, spin 1

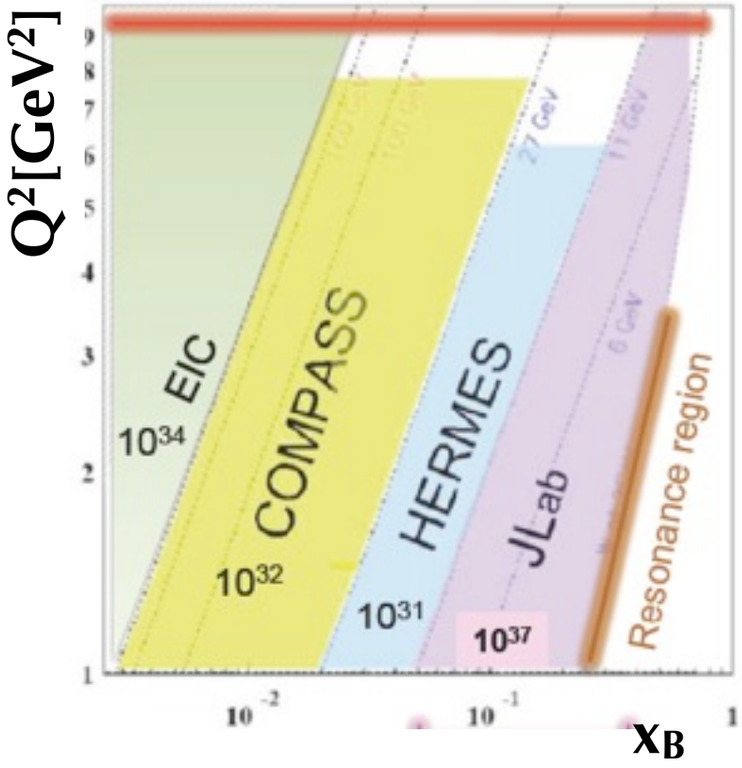
GPD H_5~

HERMES: Search for **tensor signature** on tensor-polarized d, spin 1

GPD H_A

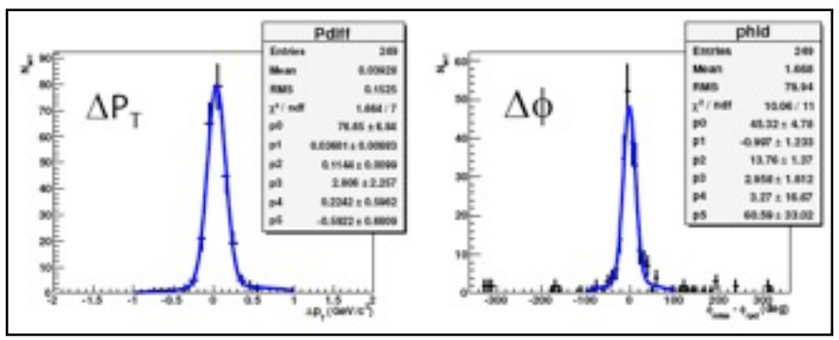
CLAS [EG6]: **coherent DVCS** on ^{4}He, spin 0

The Future of DVCS



- **Jefferson Laboratory**
  - Hall A (E07-007 for p, E08-025 for n): Interference-DVCS^2 separation and Q^2-dependence of total cross-section (2010)
  - CLAS: transversely polarized HD-Ice target (2012)
  - JLab 12 GeV upgrade: Q^2_{max} = 13…14 GeV^2, e^+ beam
- COMPASS @ **CERN**

  See talk by A. Ferrero
  - 2008-09: DVCS test runs, small Recoil detector
  - 2012-15: GPD H,

    large Recoil detector: beam-charge and -spin asys + x-section
  - 2015+ (?): GPD E,
    transversely polarized target

The Future of DVCS

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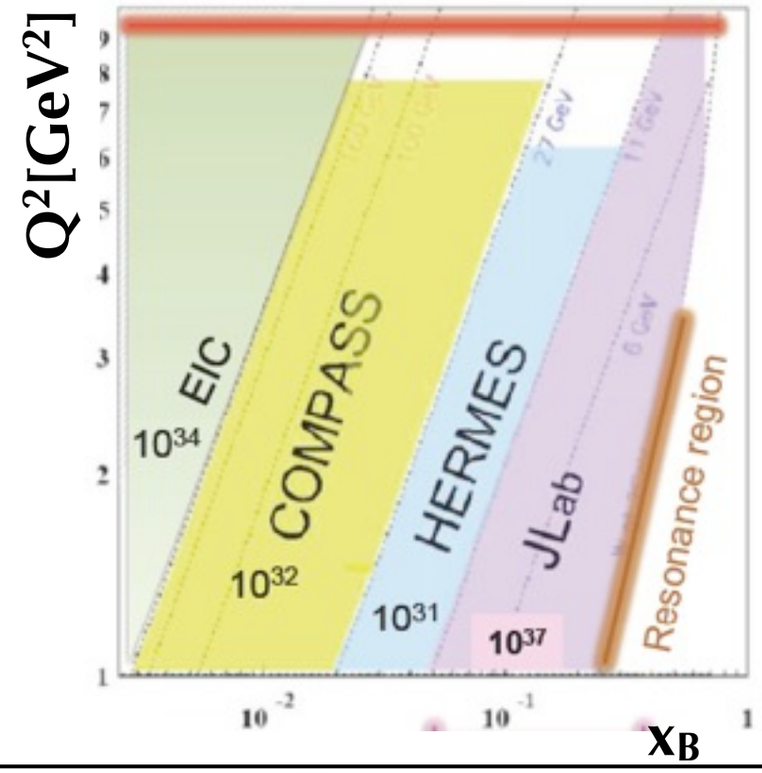

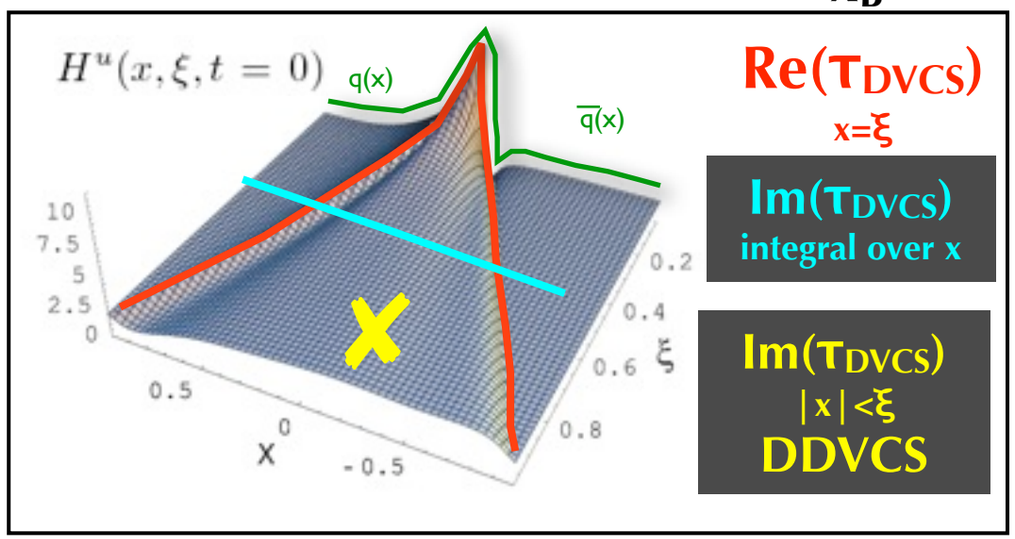

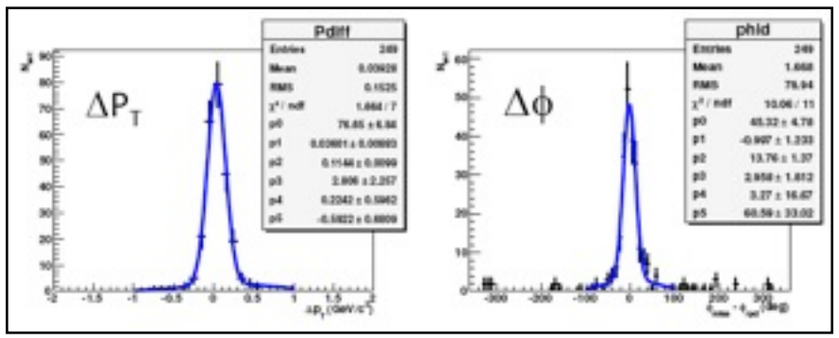

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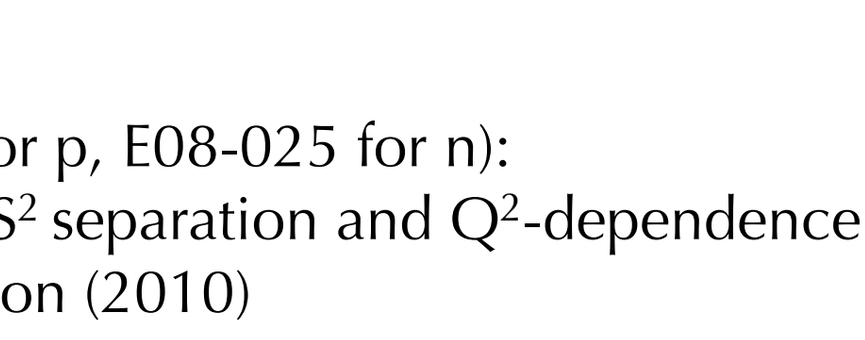
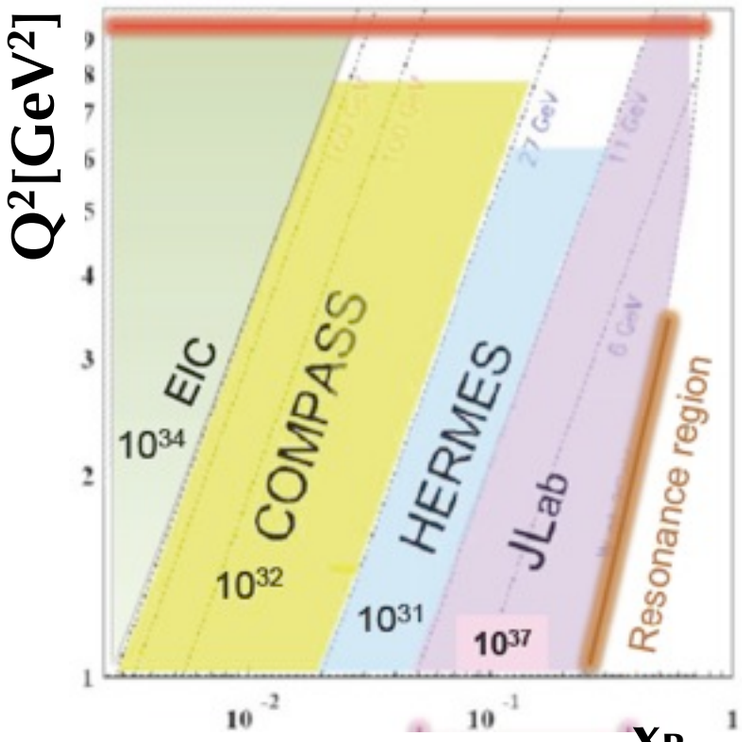
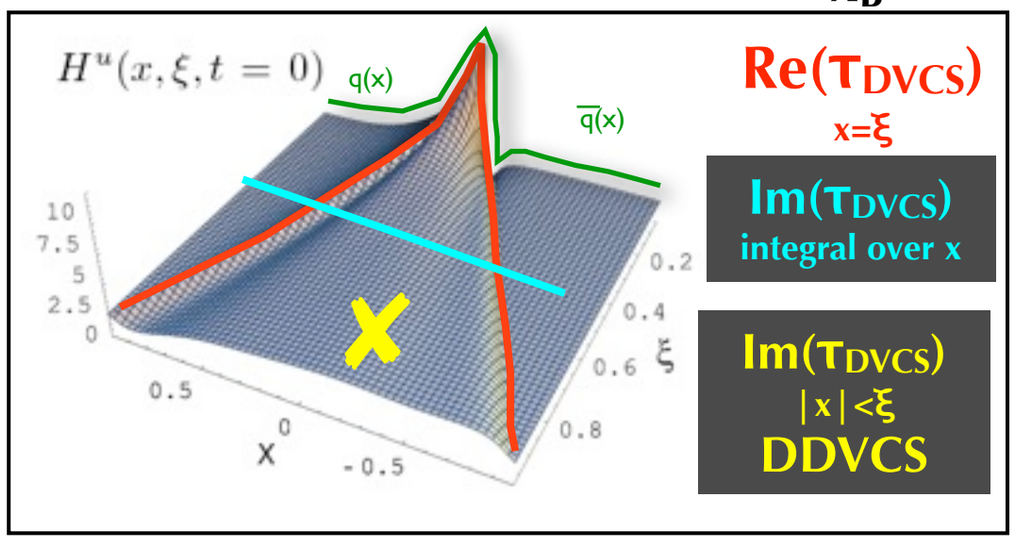


  - 2015+ (?): GPD E, transversely polarized target





- Future **Electron-Ion Collider**

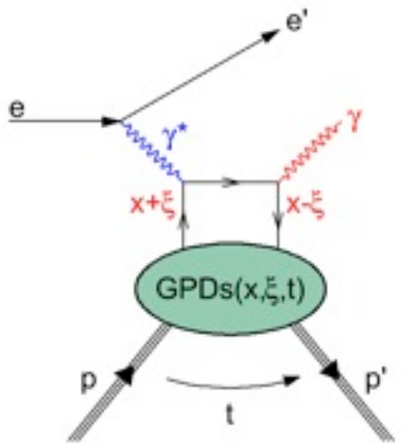
  ELIC @ JLab or eRHIC @ BNL:
  $\sqrt{s}$ = 20-70 GeV
  (HERMES: 7 GeV)

  ENC @ GSI: $\sqrt{s}$ = 40 GeV, ...

See talk by T. Schoerner-Sadenius

- LHeC

DVCS measurements
over the years



H1 @ DESY
cross-section

ZEUS @ DESY
cross-section

2001

2003

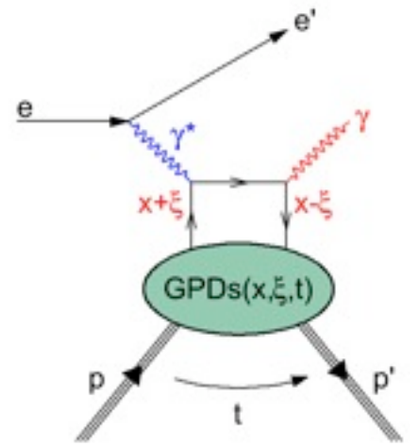
time

HERMES @ DESY
BSA

CLAS @ JLab
BSA

List does not claim to be exhaustive.

DVCS measurements
over the years



H1 @ DESY
cross-section
2001

ZEUS @ DESY
cross-section
2003

HERMES
BCA

CLAS
LTSA
2006

HERMES
TTSA
2008

HERMES
pol-H, -D;
nuclear
2010

time

HERMES @ DESY
BSA

CLAS @ JLab
BSA

2007
CLAS
BSA

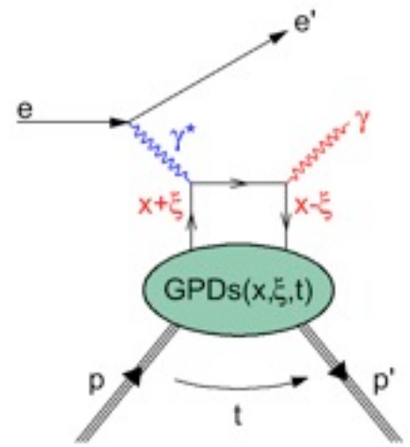
Hall A @ JLab
cross-section
(p,n)

2009
H1
BCA

2011
HERMES
results with
Recoil

List does not claim
to be exhaustive.

DVCS measurements
over the years



H1 @ DESY cross-section — 2001

ZEUS @ DESY cross-section — 2003

HERMES BCA; CLAS LTSA — 2006

HERMES TTSA — 2008

HERMES pol-H, -D; nuclear — 2010

COMPASS @ CERN: program with Recoil — > 2011

time

HERMES @ DESY BSA

CLAS @ JLab BSA

2007: CLAS BSA; **Hall A @ JLab** cross-section (p,n)

2009: H1 BCA

2011: HERMES results with Recoil

CLAS Tpol target

JLab 12

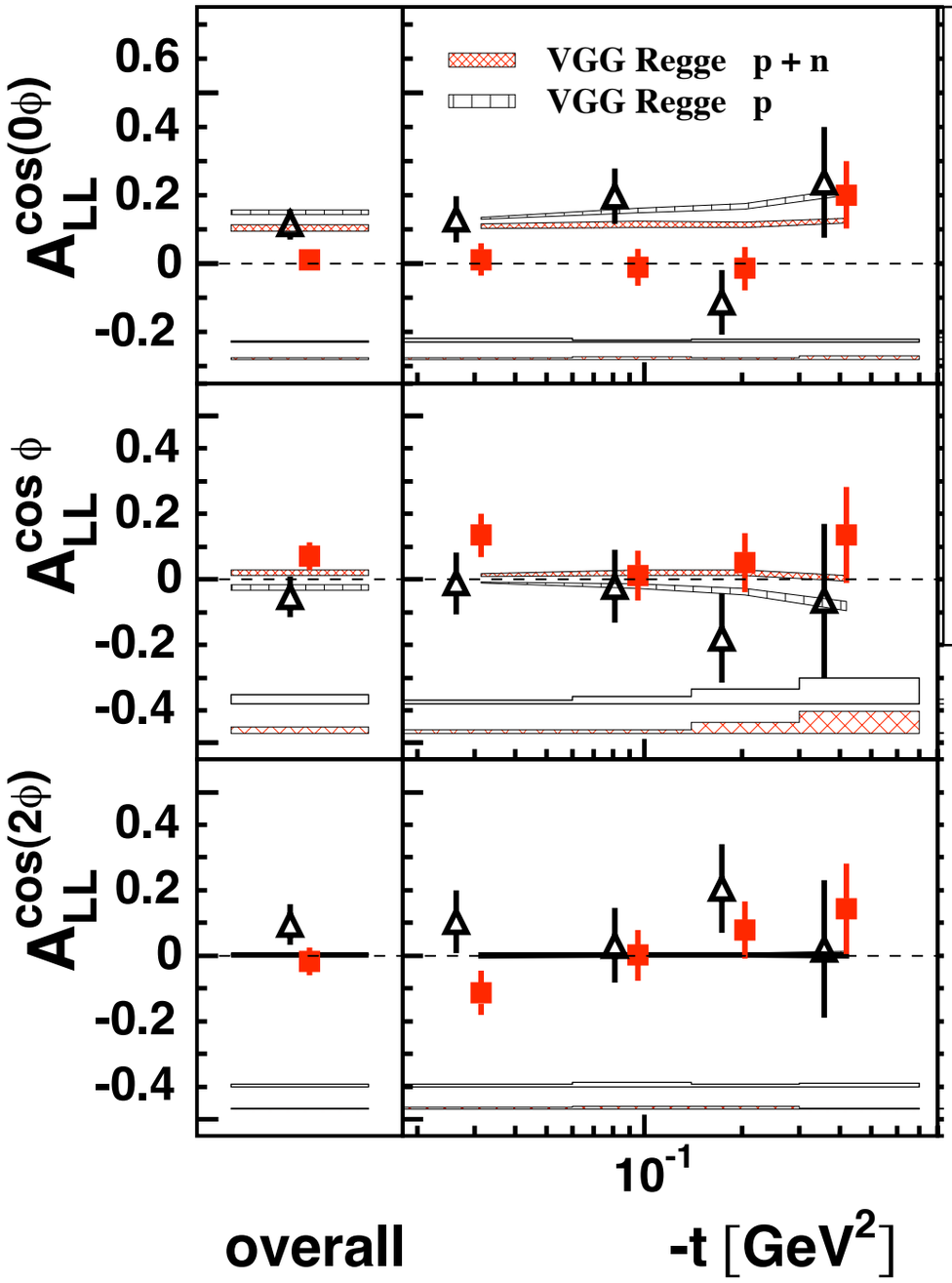
EIC

List does not claim to be exhaustive.

DVCS double-spin LL asymmetry

GPD H_1~

Search for coherent signature



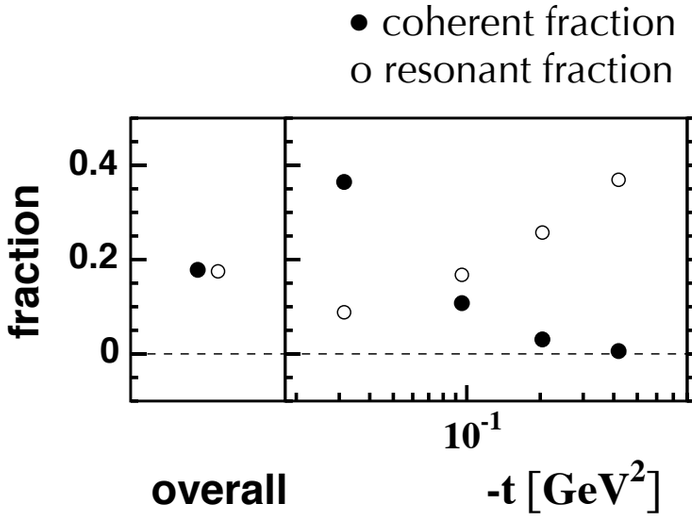
□ **Proton:**

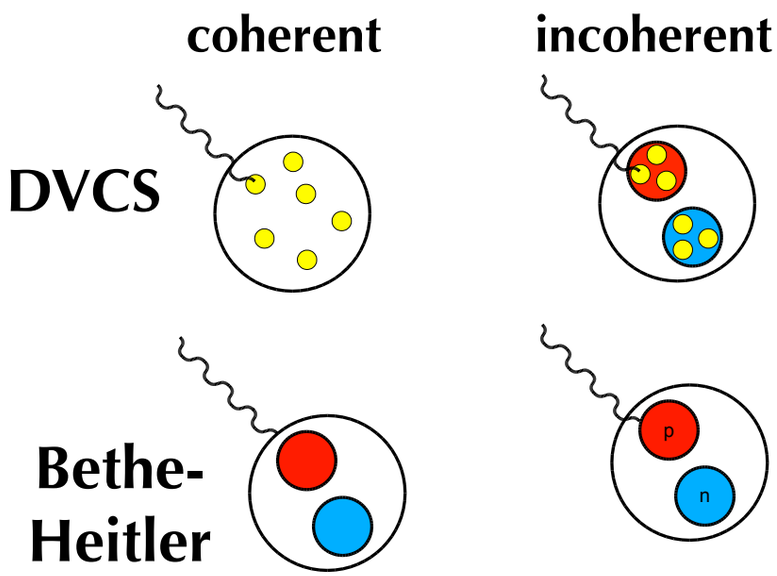
$\mathcal{R}e(\tilde{H})$ (incoherent)

■ **Deuteron:**

$\mathcal{R}e(\tilde{H}_1)$ (coherent @low -t)

$\mathcal{R}e(\tilde{H})$ (incoherent @larger -t)





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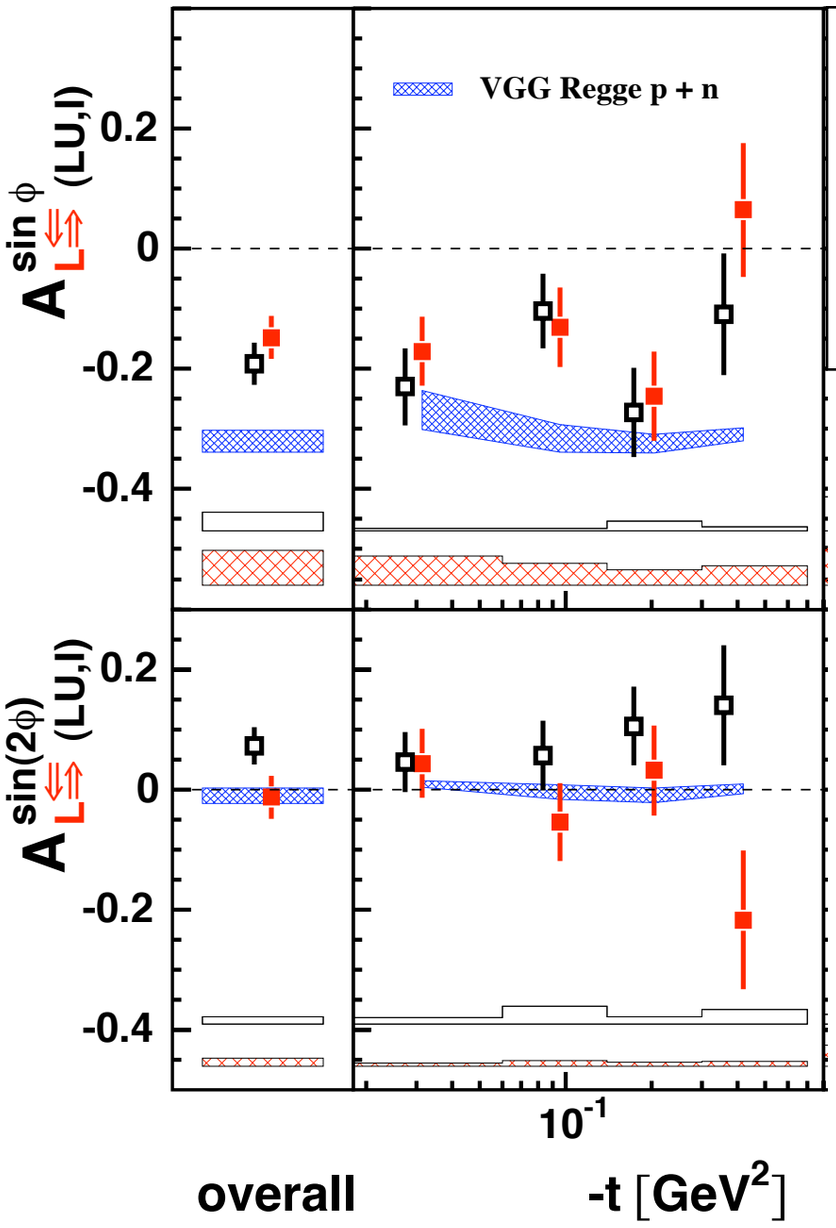
GPD H_5~

DVCS beam-helicity asymmetry on the deuteron

Search for tensor signature



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□ **unpolarized:** $\mathcal{R}e(\mathcal{H}_1)$

■ **tensor-polarized (P_{zz}=0.827):**

$\mathcal{R}e(\mathcal{H}_1 - \frac{1}{3}\mathcal{H}_5)$

for coherent scattering at low values of -t

$\mathcal{H}_5$

≡ tensor structure function in the forward limit

DVCS $\mathcal{A}_{LZZ}$ (tensor asymmetry) sinϕ amplitude:

$0.074 \pm 0.196 \pm 0.022$

(-t<0.06 GeV², 40% coherent)