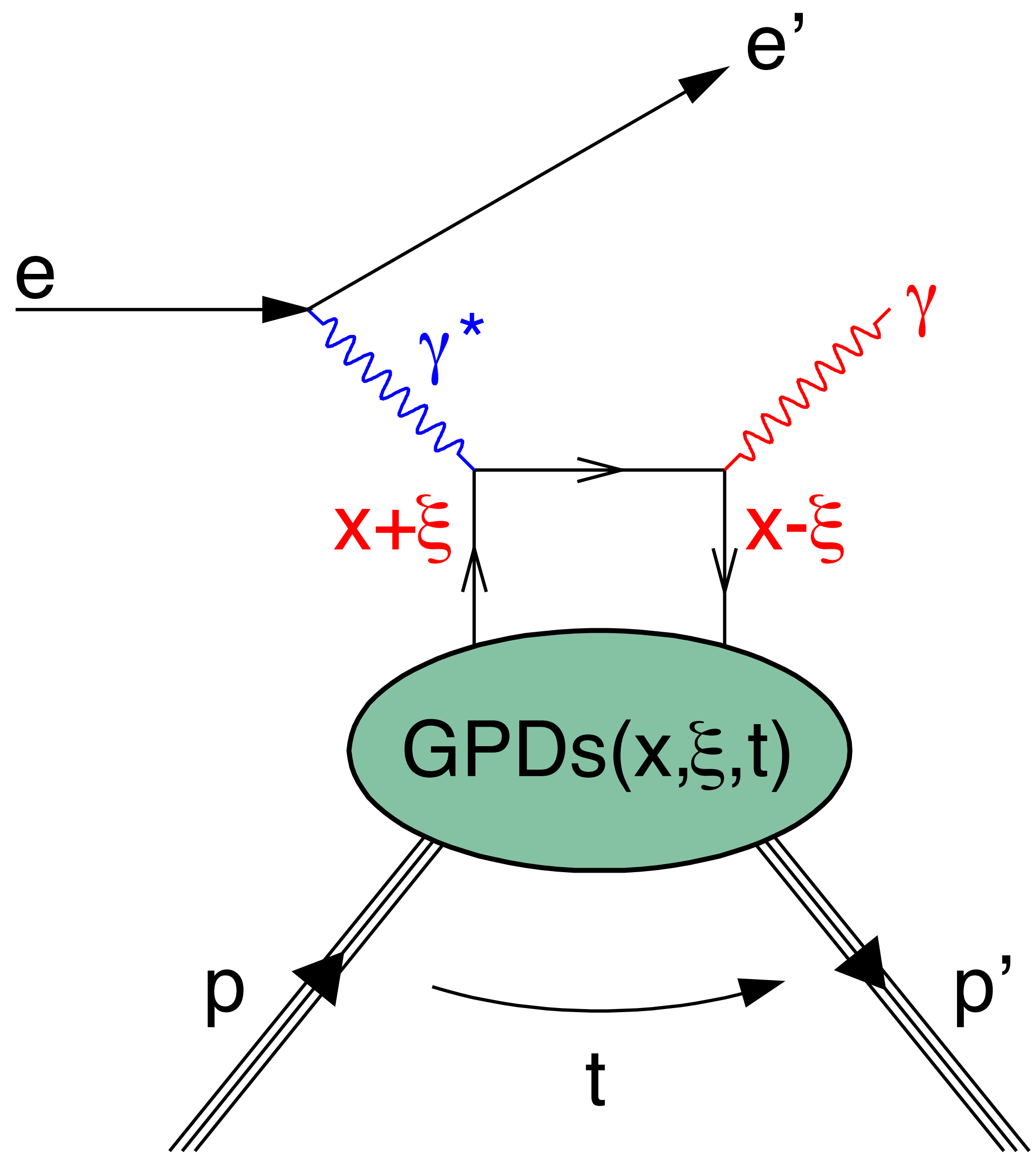
DVCS Measurements - Past and Future

- Setting the scene
- The past and the present
- Global analysis
- The future



Caroline K. Riedl

ILLINOIS
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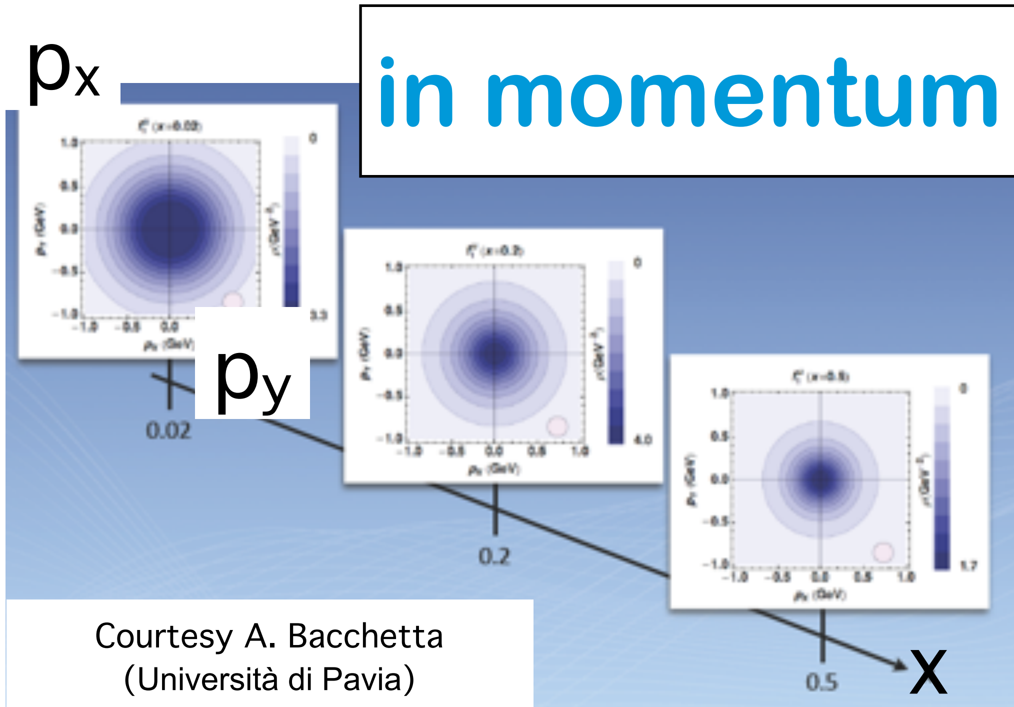
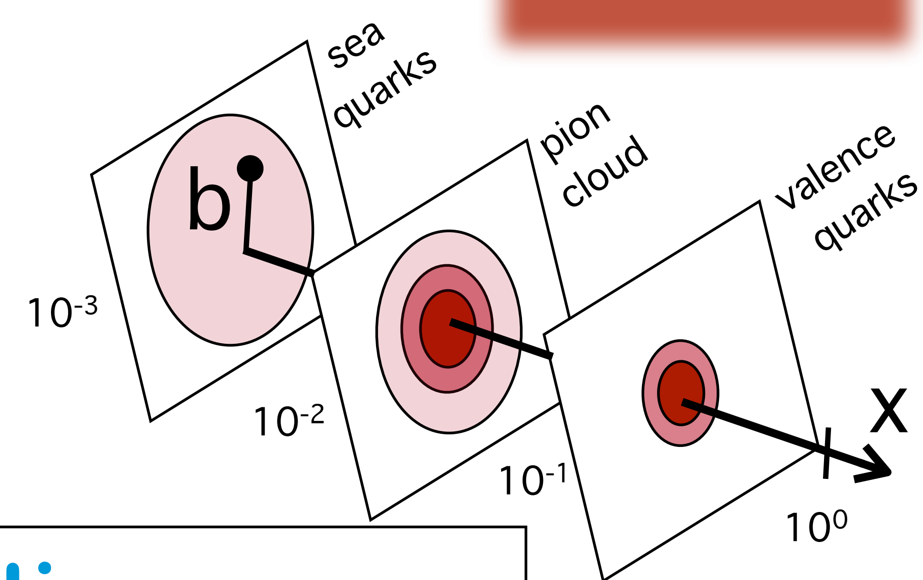
5th Workshop of the APS Topical Group on Hadronic Physics (GHP 2013)
Denver, April 11, 2013

Nucleon Tomography

in momentum space





in position space

Correlation between **spin** and **transverse momentum** ?

Correlation between **longitudinal momentum** and **transverse position** ?

Transverse Momentum dependent PDFs

TMDs
$f(x,k_\perp)$

GPDs
$H(x,b_\perp)$
$\leftrightarrow$ FT $\leftrightarrow$ $H(x,\xi,t)$

Generalized Parton Distributions

$k_\perp$-integration

PDFs q(x), 1D:
Parton Distribution Functions

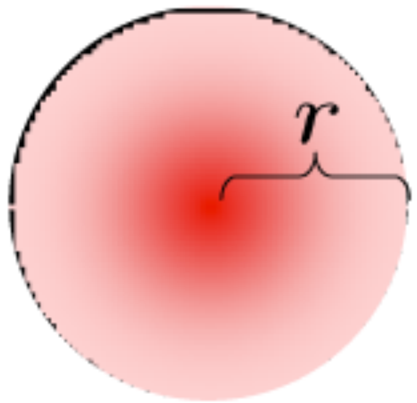
$\xi=0, t=0$

semi-inclusive measurements

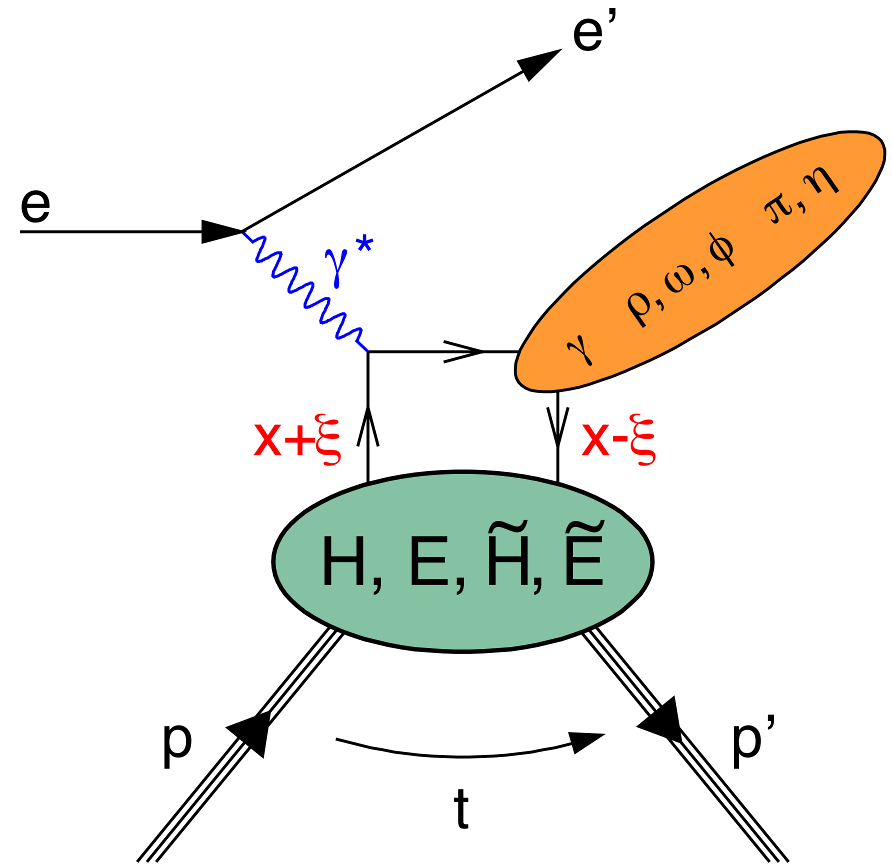
inclusive measurements

exclusive measurements

Nucleon tomography with GPDs

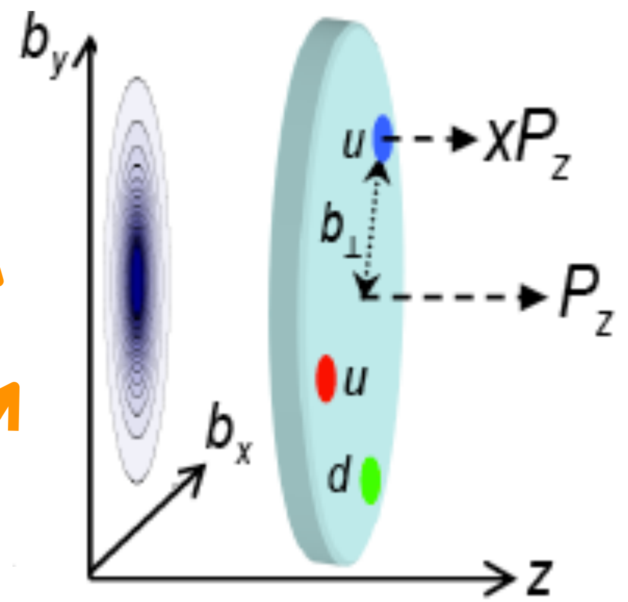


Generalized Parton Distributions

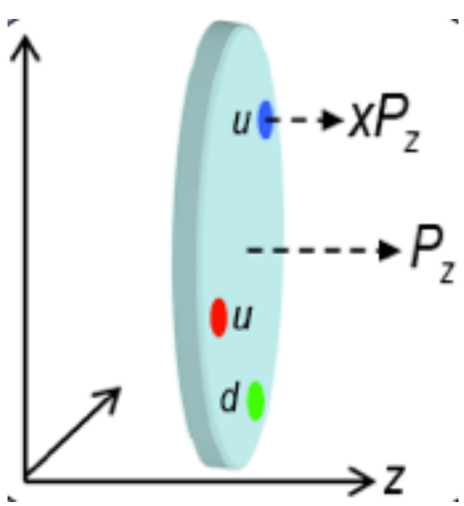


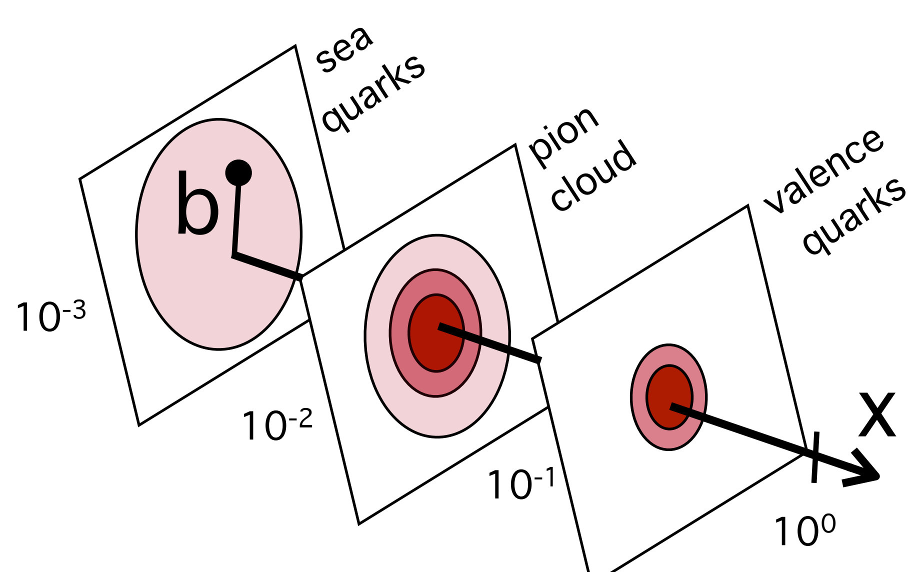
Form Factors: transverse parton positions

Parton Distribution Functions: longitudinal momentum



- **x, ξ :** longitudinal momentum fractions of probed quark
- **t :** 4-momentum^2 transfer to target
- **DVCS: Deeply Virtual Compton Scattering** = electroproduction of a real photon





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	Ẽ	H̃

H → $q^+ + q^-$

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

H̃ → $q^+ - q^-$

Illustrations: Ph. Hägler (TUM)

DVCS as laboratory for probing hadrons

1. Access to Generalized Parton Distributions

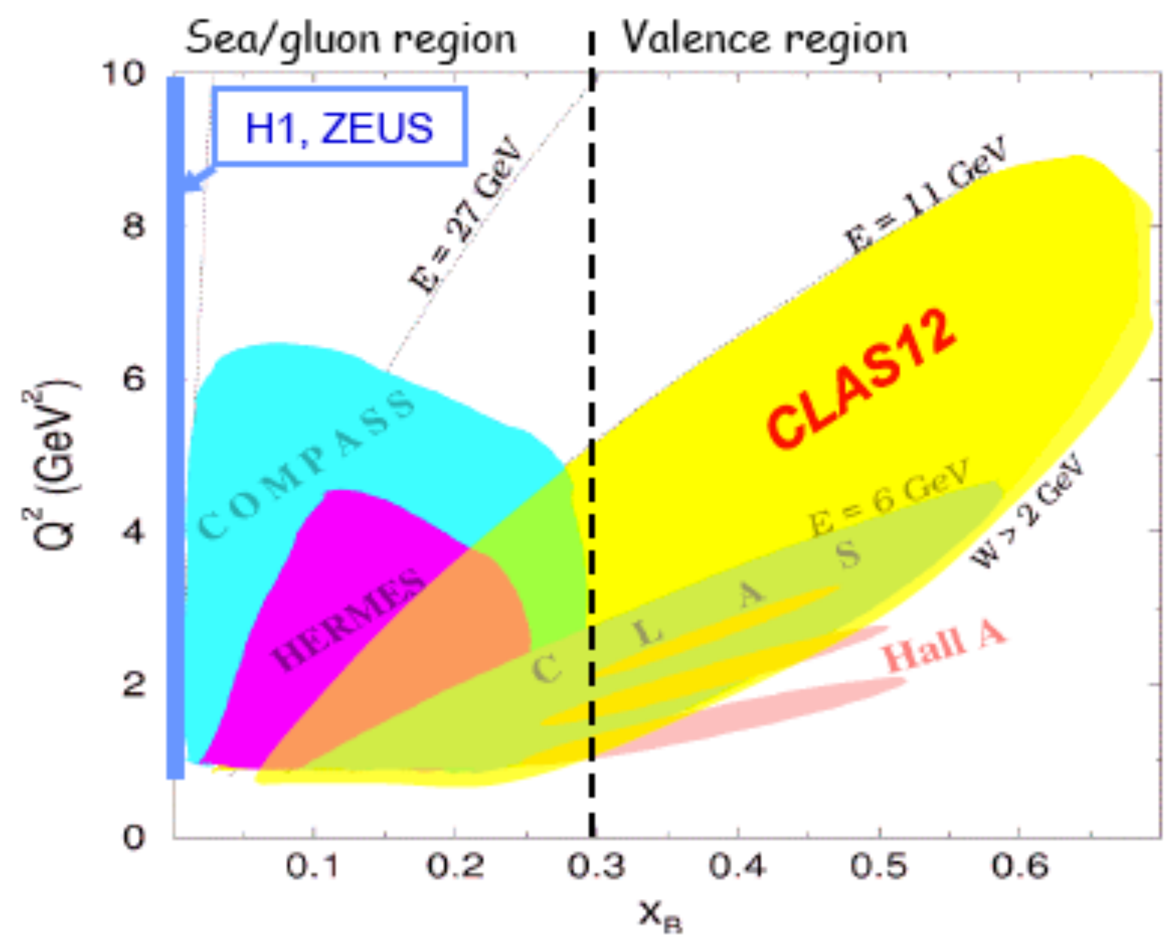
"Nucleon Tomography"

Global analysis requires measurements

☛ of cross-sections and

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

☛ preferably covering wide kinematic range



2. Access to total angular momentum of quarks through Ji sum rule

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

-Ji, PRL 78 (1997) 610-

3. DVCS on hadrons other than the nucleon

Spin-1: tensor and coherent signatures?

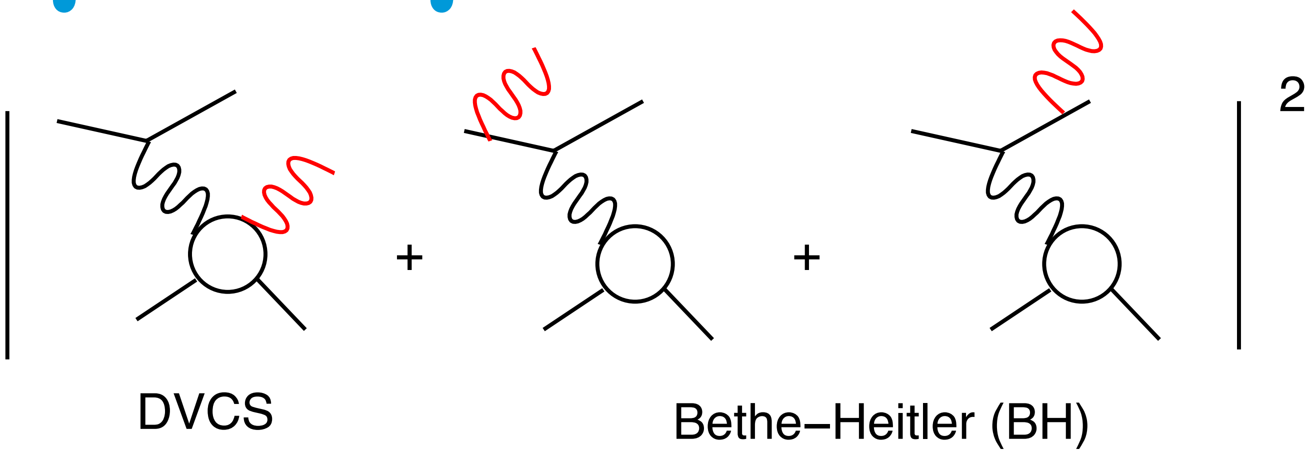
How does the nuclear environment modify the DVCS amplitude?

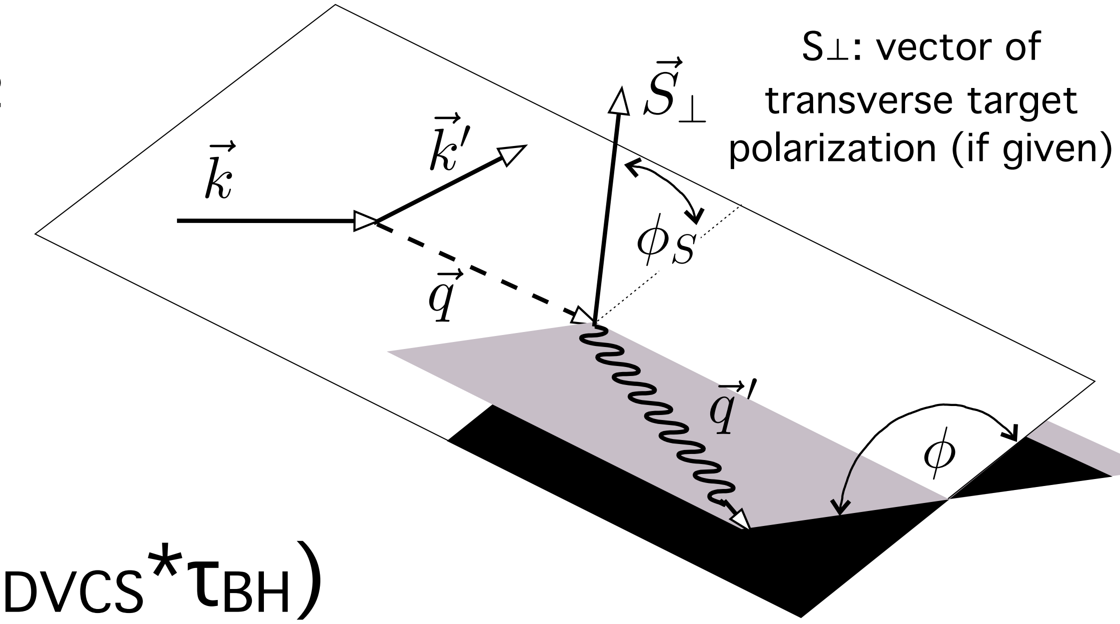
See also talk by Lekha Adhikari Wednesday afternoon, "Distribution of Angular Momentum in the Transverse Plane"

The $\gamma^*N \rightarrow \gamma N$ cross section

lepton beam k with
charge C_B and helicity P_B

$\sigma_{\gamma^*\gamma N} \sim \left| \quad + \quad + \quad \right|^2$





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

DVCS-BH interference term

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}

All 3 contributions can be written as harmonic series wrt ϕ (and ϕ_S)

Measure azimuthal asymmetries...:

$$\sigma(\phi; P_B, C_B) = \sigma_{UU}(\phi) \cdot [1 + P_B \mathcal{A}_{LU}^{DVCS}(\phi) + C_B P_B \mathcal{A}_{LU}^{\mathcal{I}}(\phi) + C_B \mathcal{A}_C(\phi)]$$

... or measure
helicity-dependent cross section,
$\Delta\sigma = \sigma(\rightarrow) - \sigma(\leftarrow)$
and
helicity-independent cross section,
$\Sigma\sigma = \sigma(\rightarrow) + \sigma(\leftarrow)$

Holographic principle Belitsky, Müller, hep-ph/0206306

- BH reference amplitude magnifies DVCS
- Measure magnitude A (**real part**) and phase φ (**imaginary part**) of DVCS amplitude $\tau_{DVCS} = Ae^{i\varphi}$

Parameterization of observables in terms of GPDs / CFFs

Harmonic analysis
of DVCS data with respect to beam helicity, beam charge, and/or target polarization

⇓

Compton Form Factors: twist-2 GPD

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

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

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

☞ unpolarized target: Best access

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

dominant for the proton ($\mathcal{H}$) — dominant for the neutron ($\mathcal{E}$)

☞ 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:

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

Facilities with results available

Jefferson Laboratory

polarized
e⁻ beam

electrons: 6 GeV

e-beam on fixed target

Hall A JLab

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

<u>detected particles:</u>
eγ

CLAS

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

<u>detected particles:</u>
no Inner Calo: ep or epγ
with Inner Calo: epγ

HERA

self-polarized electron beam

2 lepton beam charges: electrons and positrons

electrons: 30 GeV
protons: 920 GeV

hermes

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

H1 / ZEUS

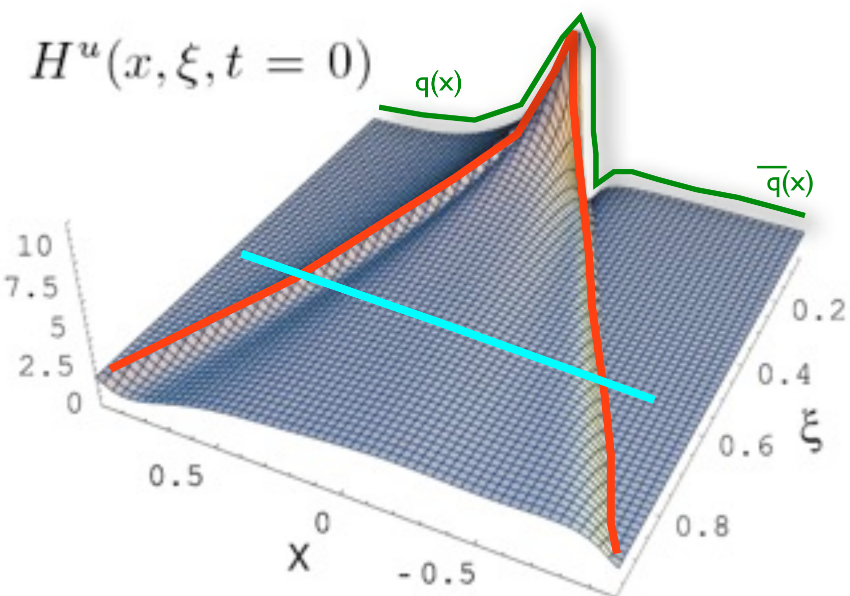
ep-collider
(unpolarized protons)

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

energy

GPD H
x-section

Hall A (E00-110): cross section in the valence quark region



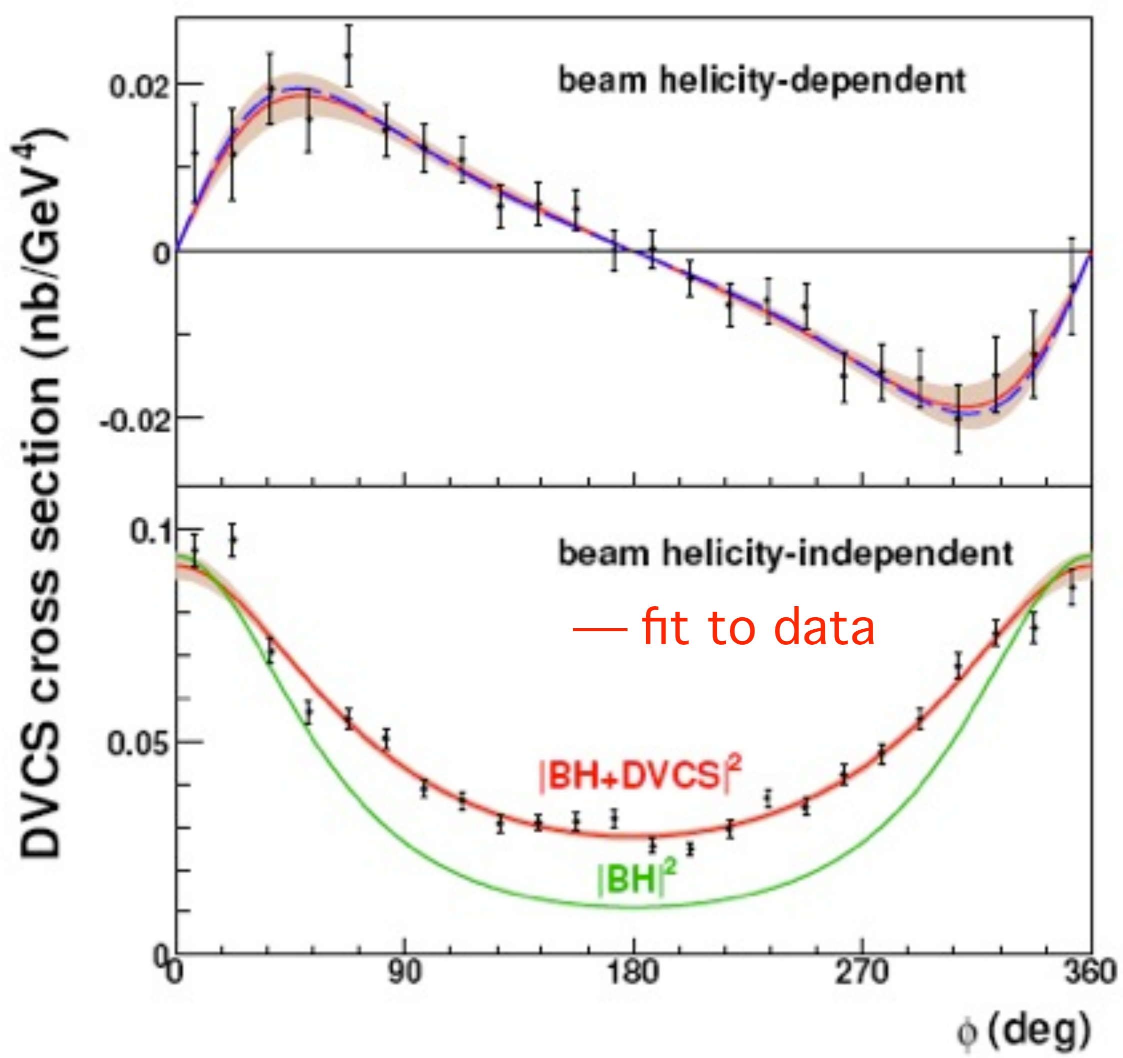
Goeke, Polyakov, Vanderhaeghen, hep-ph/0106012

$\Delta\sigma$
helicity-dependent
➥ Im(τ_{DVCS})
GPDs @ $x=\xi$

$\Sigma\sigma$
helicity-independent
➥Re(τ_{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

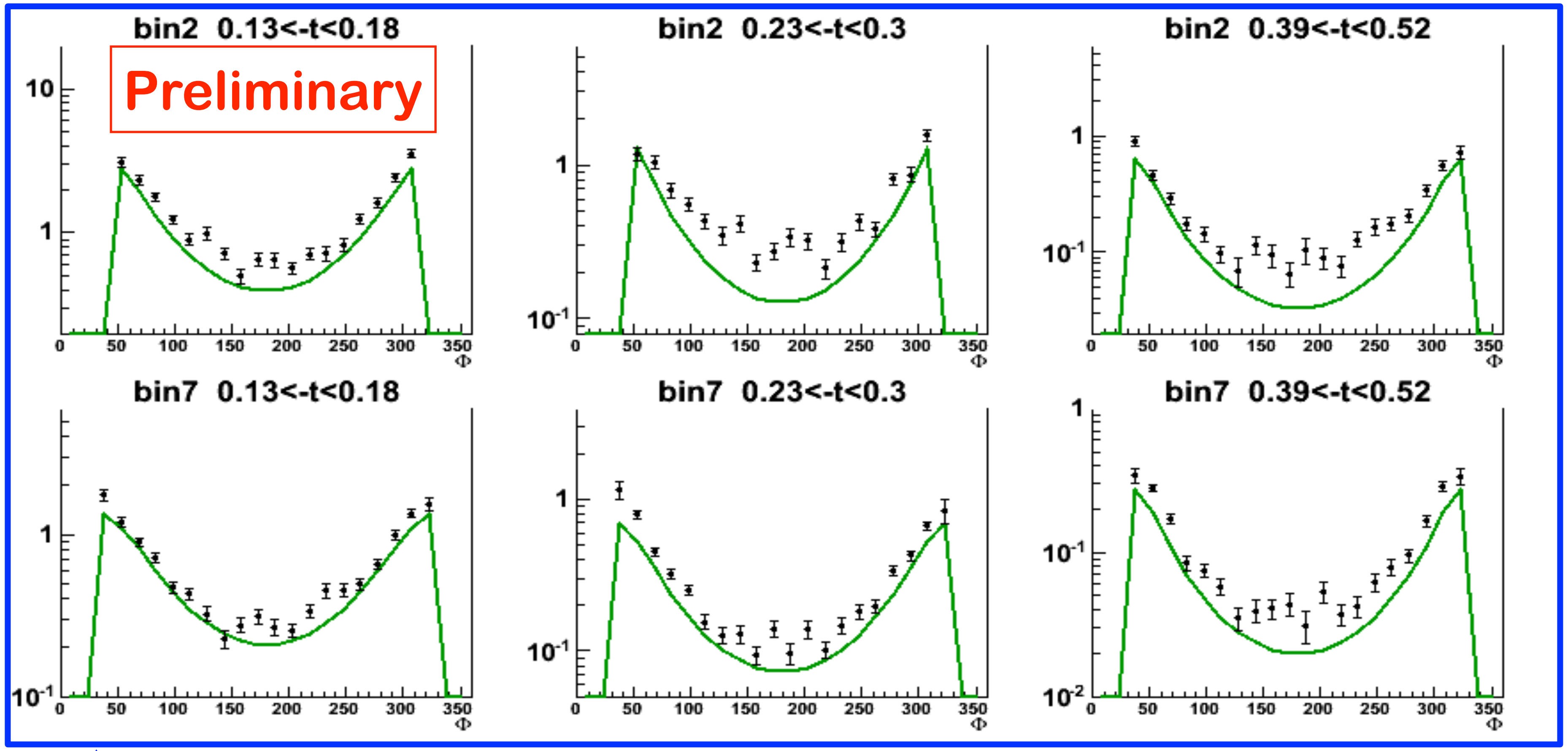


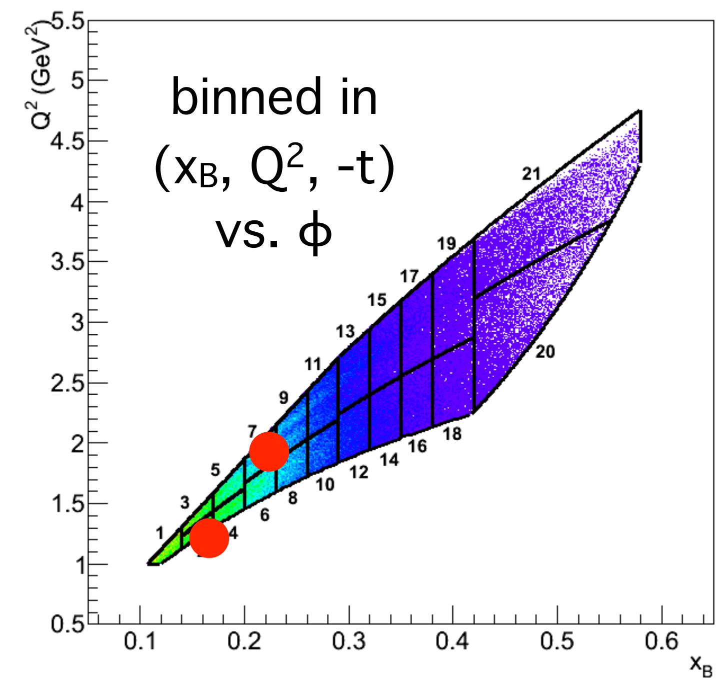
- Twist-2 (“handbag”) dominance
  - ☛ GPDs accessible at moderate Q^2.
- No Q^2 dependence of Im(I) over 1.5, 1.9 and 2.3 GeV^2
  - ☛ Indication of perturbative QCD scaling behavior.

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

CLAS (e1-dvcs): cross section

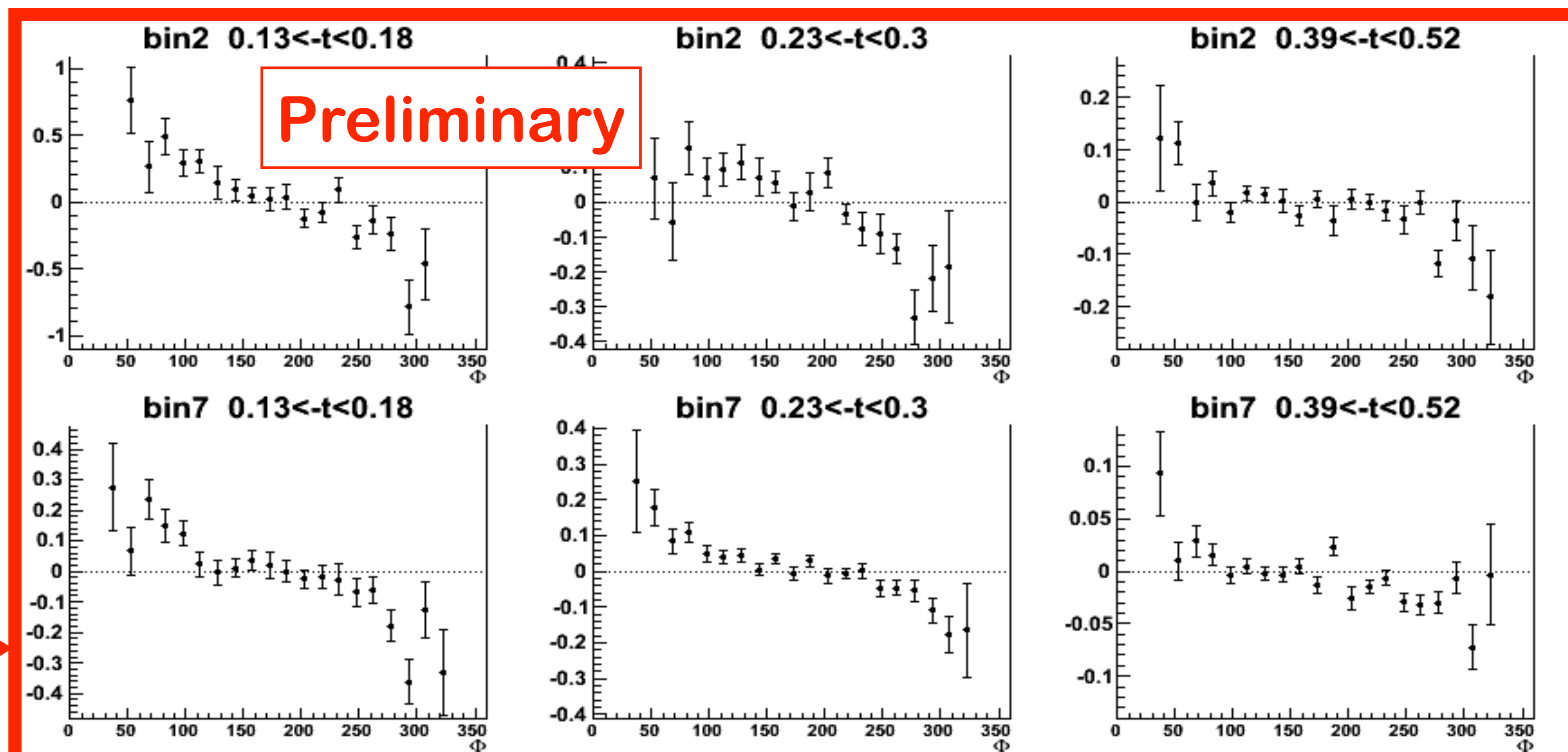
GPD H
x-section





Bethe-Heitler

$\Sigma\sigma$
➥Re(τ_{DVCS})



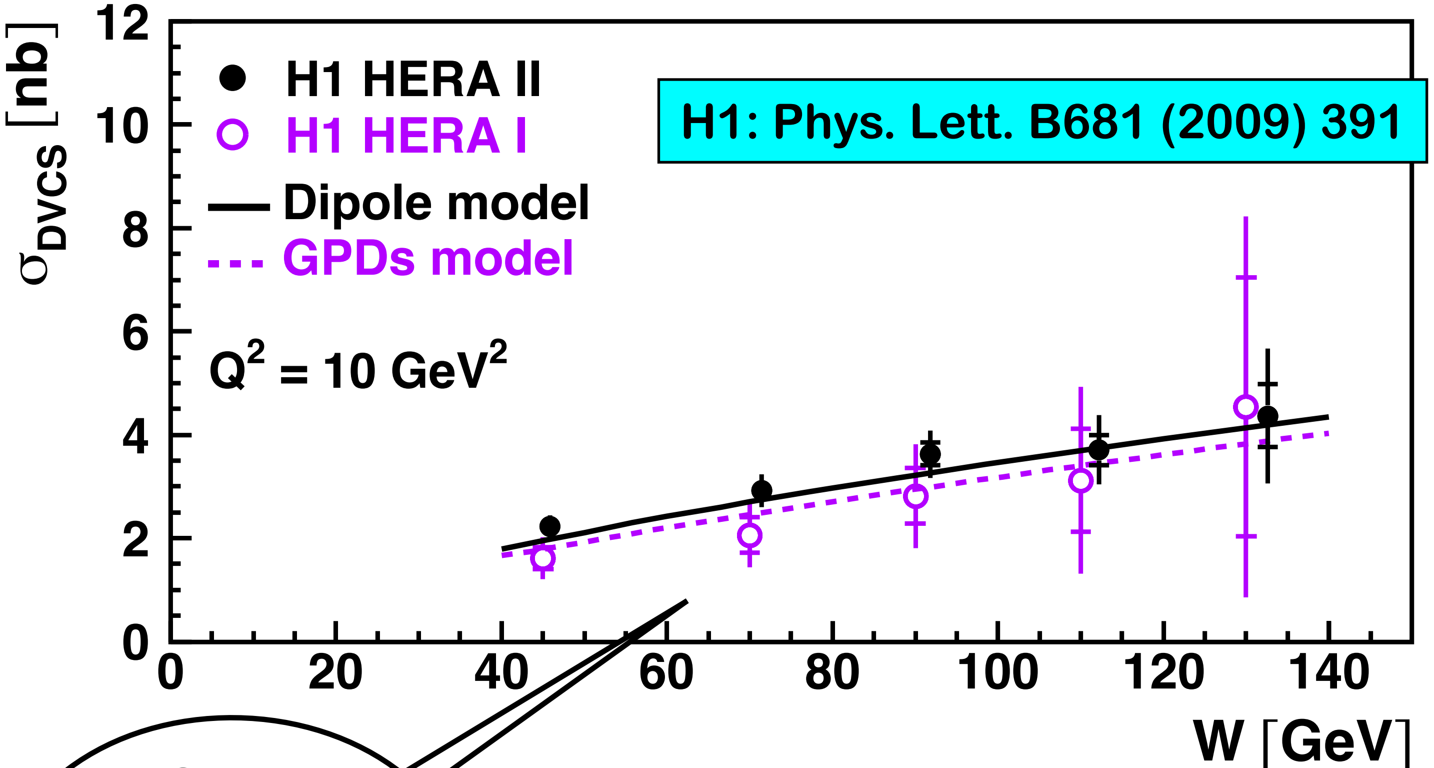
CLAS: preliminary analysis

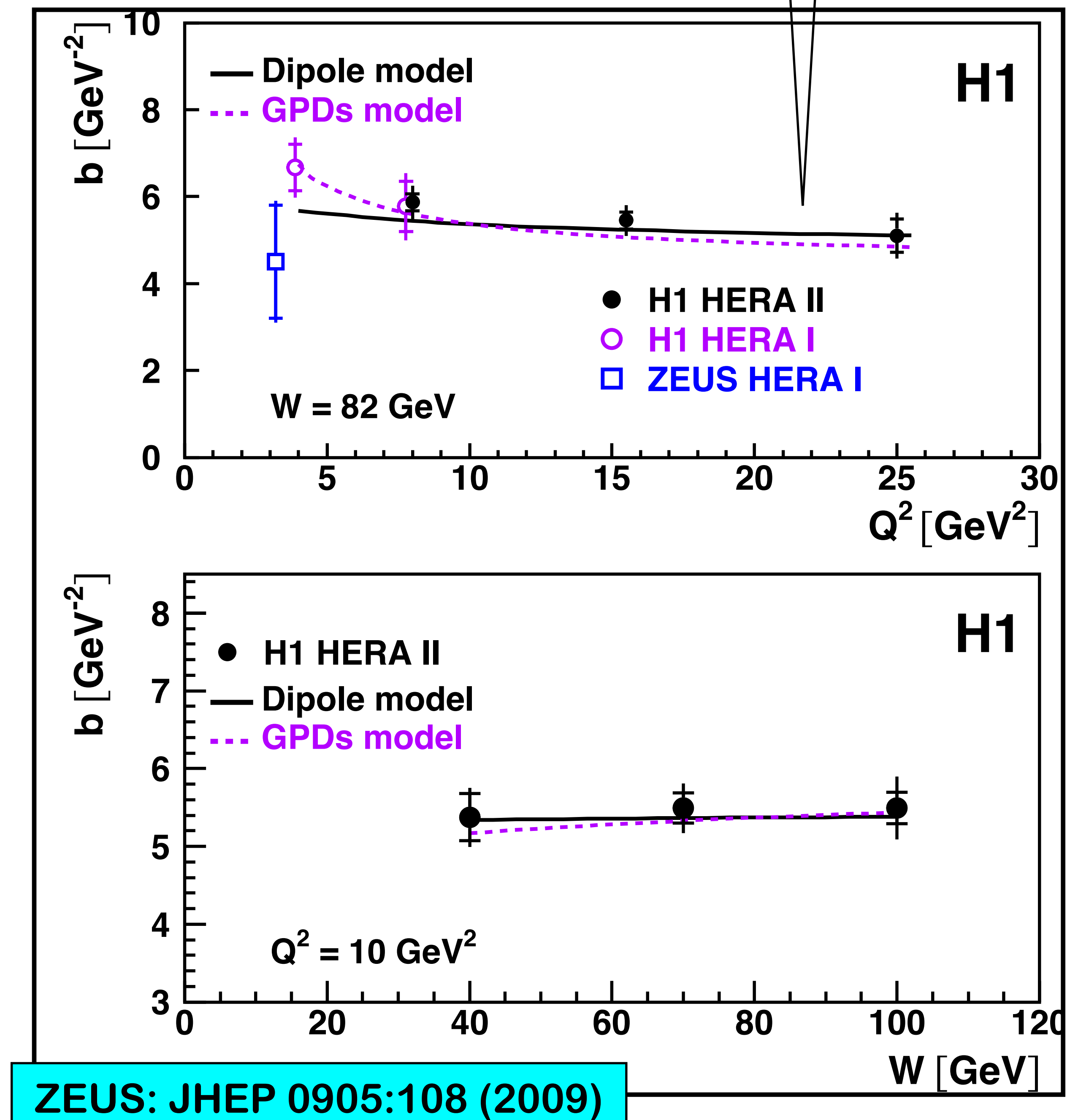
$\Delta\sigma$
➥ Im(τ_{DVCS})

GPD H
x-section

HERA (H1 and ZEUS): cross section in the sea/glue region

Ansatz: dσ/dt∝exp(-b|t|)
t-slope:
average impact parameter





Steep W-dependence:
σ(W)∝W$^{\delta}$
with δ≈0.7

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

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

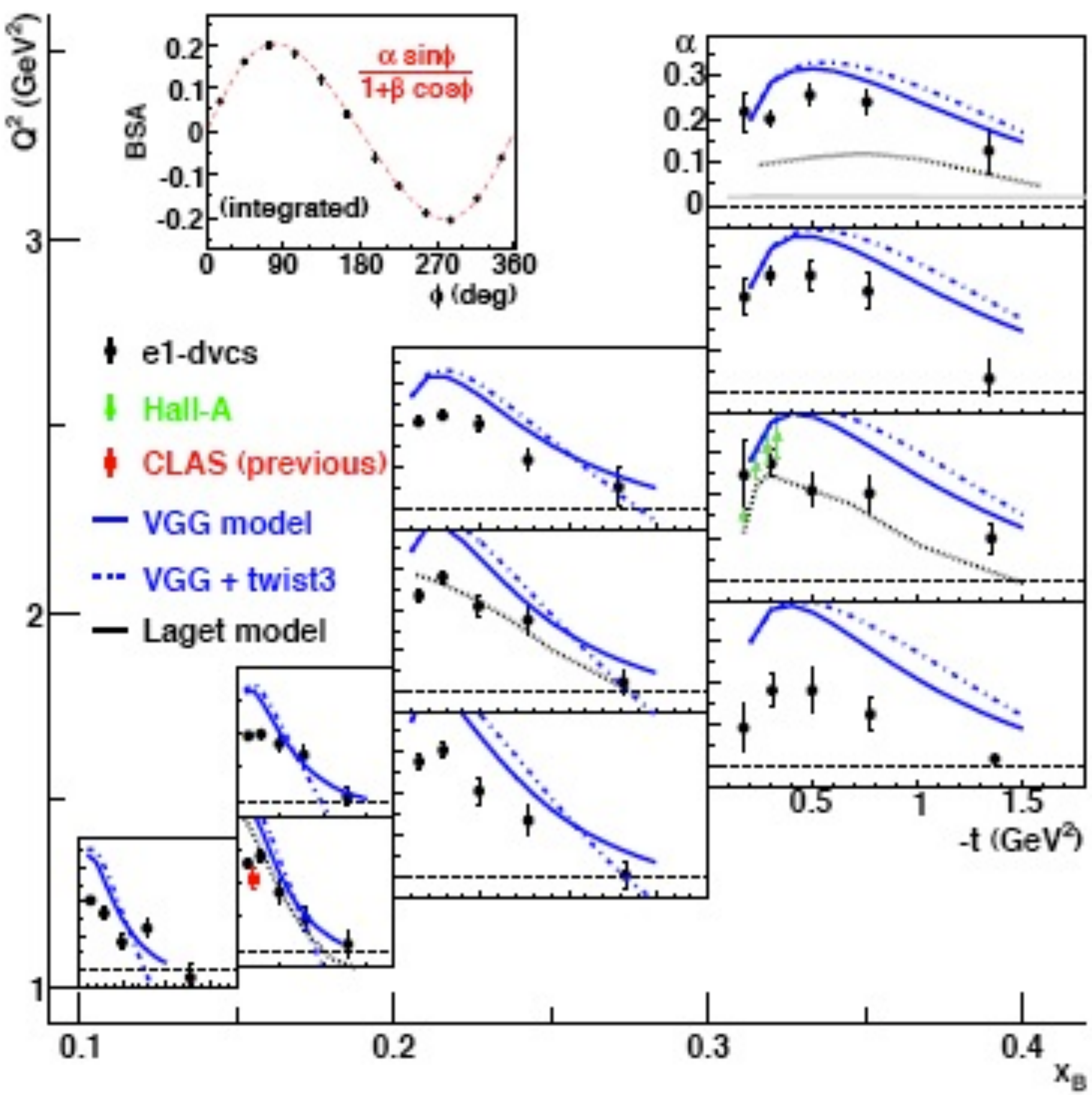
DVCS is hard process, gluons resolved!

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

GPD H
$Im(\tau_{DVCS})$
BSA

CLAS (e1-dvcs): beam-helicity asymmetry

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



- Data taken with inner eletromagnetic calorimeter for the detection of the BH/DVCS photon
- VGG Model overshoots data.

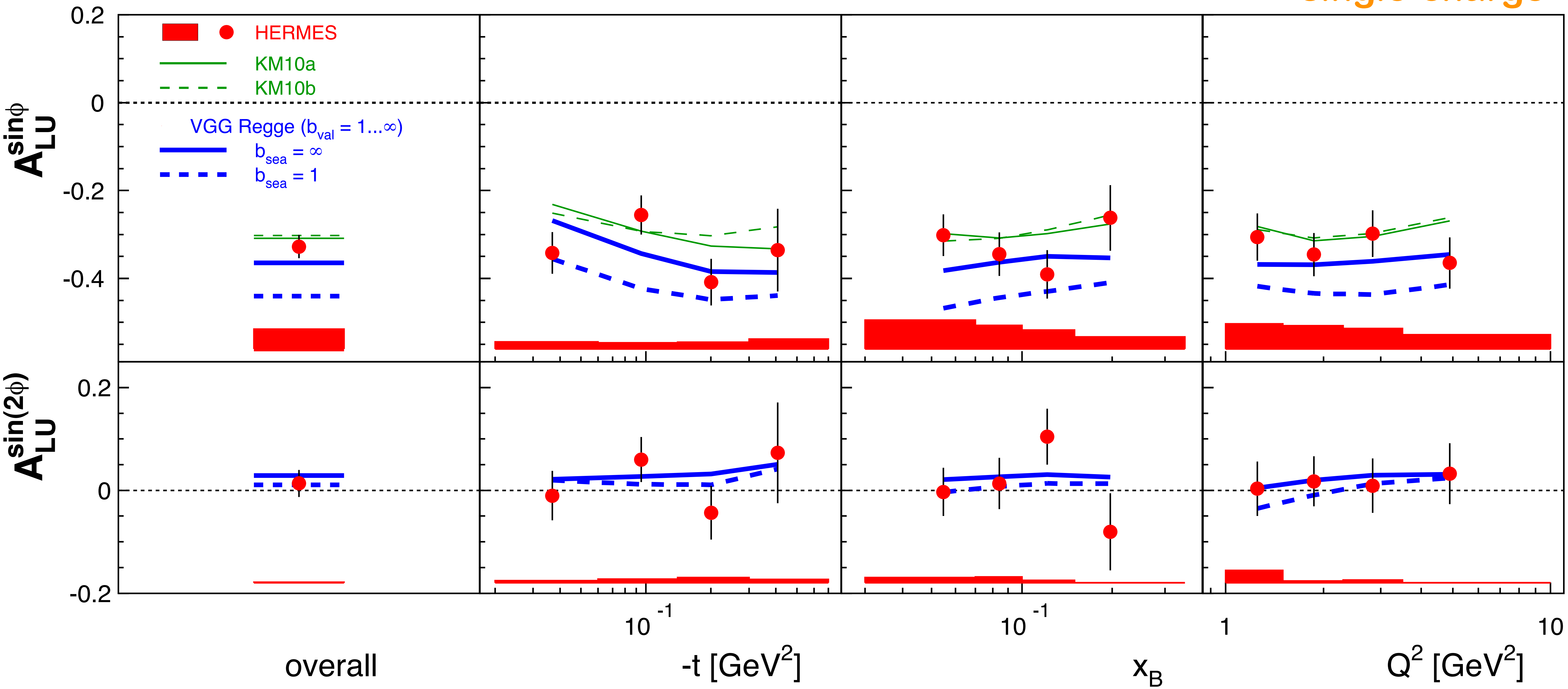
GPD model calculation
"VGG" (Vanderhaeghen, Guidal, Guichon):
Phys. Rev. D60 (1999) 094017 and
Prog. Nucl. Phys. 47 (2001) 401

CLAS: PRL 100 (2008) 162002

HERMES (with recoil proton): beam-helicity asymmetry

GPD H
$Im(\mathcal{T}_{DVCS})$
BSA

single-charge



Global fit of world data
JLab, HERMES and HERA,
dashed excludes JLab Hall A cross section
K. Kumericki and D. Müller, Nucl. Phys. B 841 (2010) 1

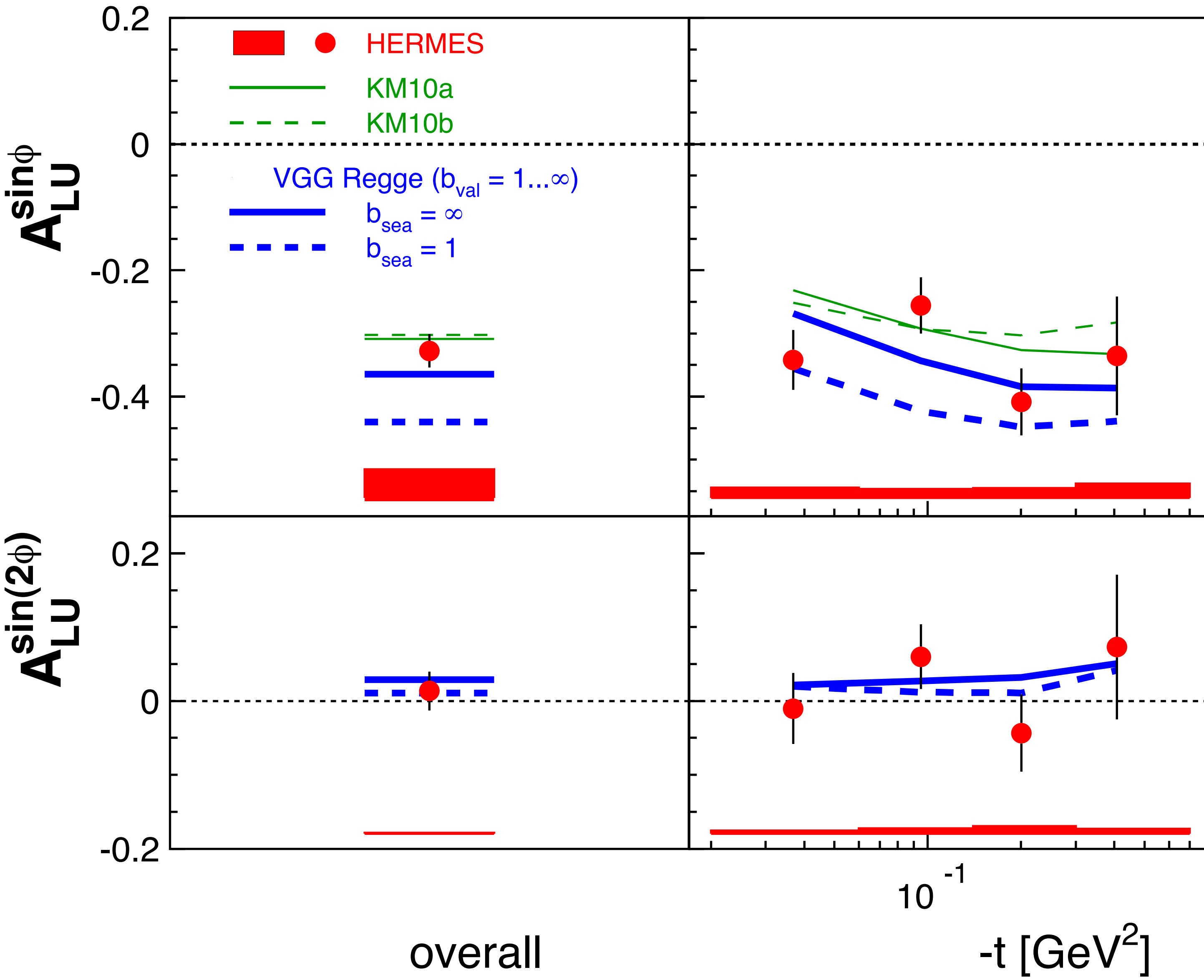
GPD model calculation "VGG Regge"
Phys.Rev. D60 (1999) 094017 and Prog.Nucl.Phys. 47 (2001) 401

HERMES: JHEP 10 (2012) 042

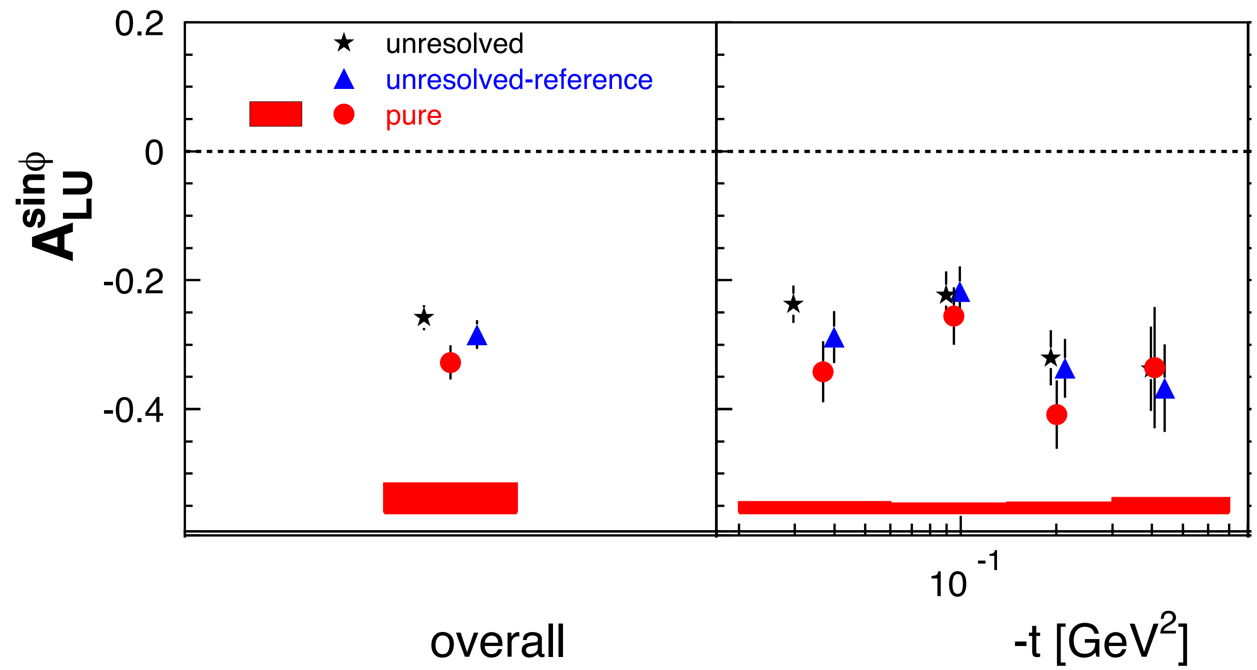
HERMES (with recoil proton): beam-helicity asymmetry

GPD H
Im($\mathcal{T}_{DVCS}$)
BSA

single-charge



- epγ detection: >99.8% purity of ep→ epγ
- ★ eγ detection: sample unresolved for 12% resonant production, e.g. ep→ e$\Delta^+\gamma$
- ▲ eγ detection in recoil acceptance (reference)



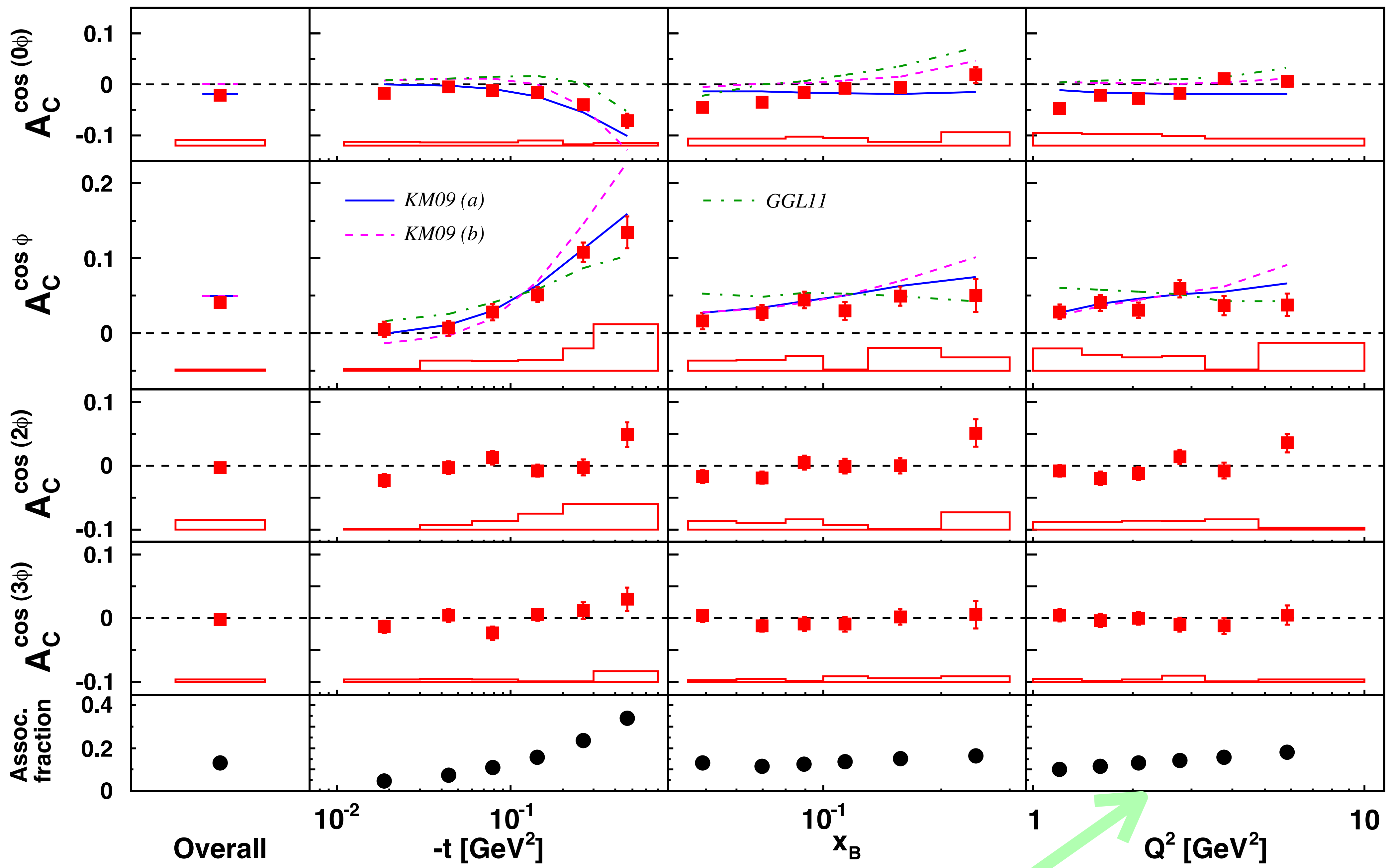
Global fit of world data
JLab, HERMES and HERA,
dashed excludes JLab Hall A cross section
K. Kumericki and D. Müller, Nucl. Phys. B 841 (2010) 1

GPD model calculation "VGG Regge"
Phys.Rev. D60 (1999) 094017 and Prog.Nucl.Phys. 47 (2001) 401

HERMES: JHEP 10 (2012) 042

HERMES: beam-charge asymmetry

GPD H
Re(τ_{DVCS})
BCA



☆ KM10
Global fit
including data from JLab, HERMES and HERA colliders
(dashed excludes JLab Hall A cross section)
K. Kumericki and D. Müller, Nucl. Phys. B 841 (2010) 1

☆ GGL11
Model calculation
G. Goldstein, J. Hernandez and S. Liuti, Phys. Rev. D 84 034007 (2011)

All 1996–2007 proton data.
No recoil-proton detection

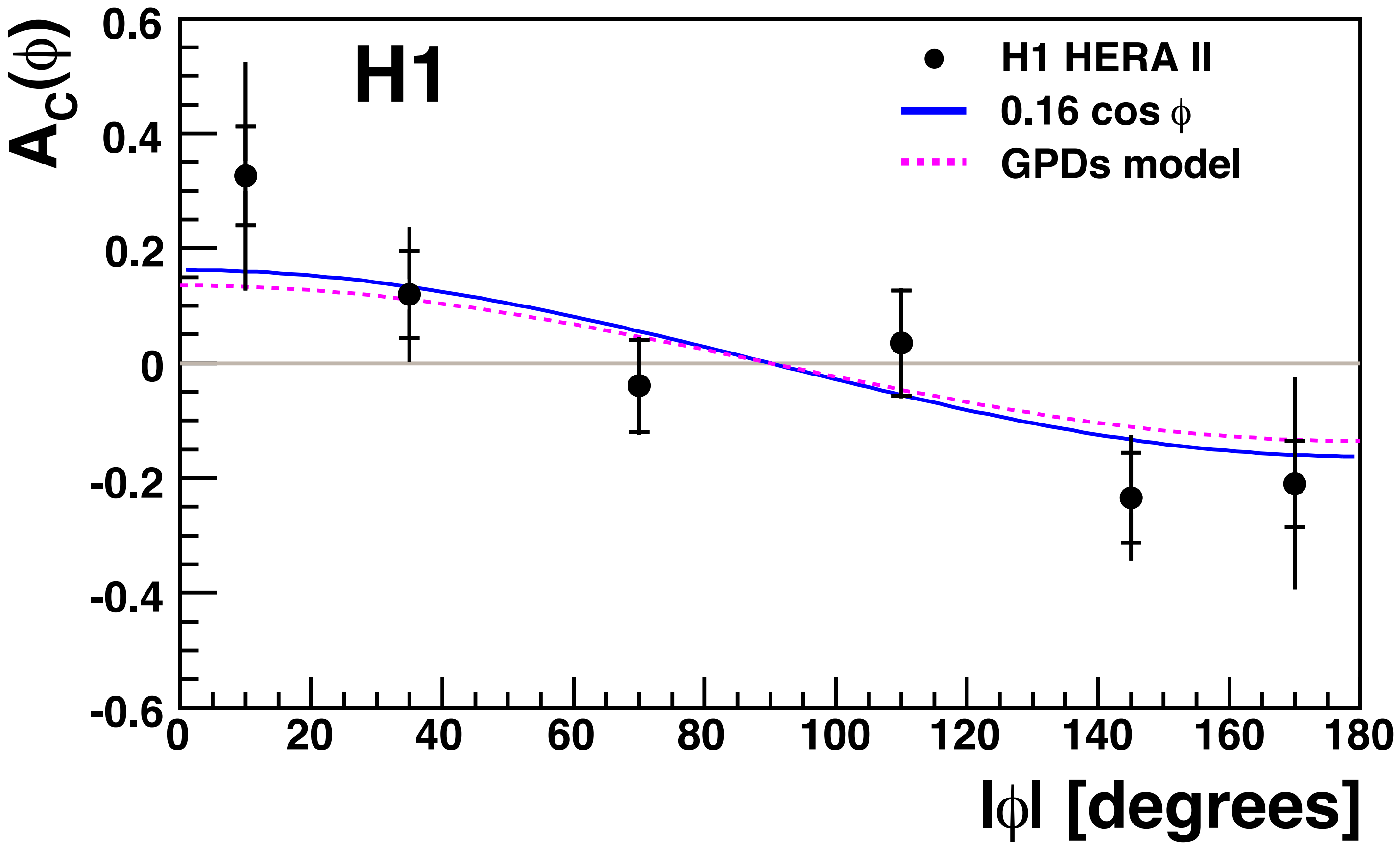
Associated fraction $ep \rightarrow e\Delta^+\gamma$
(from MC simulation)

HERMES: JHEP 07 (2012) 032

H1: beam-charge asymmetry

GPD H
Re(τ_{DVCS})
BCA

- First and only measurement at collider
  - low $x_B = 10^{-4} \ldots 10^{-2}$
  - $6.5 < Q^2 < 80$ GeV^2
  - $30 < W < 140$ GeV
  - $|t| < 1$ GeV^2



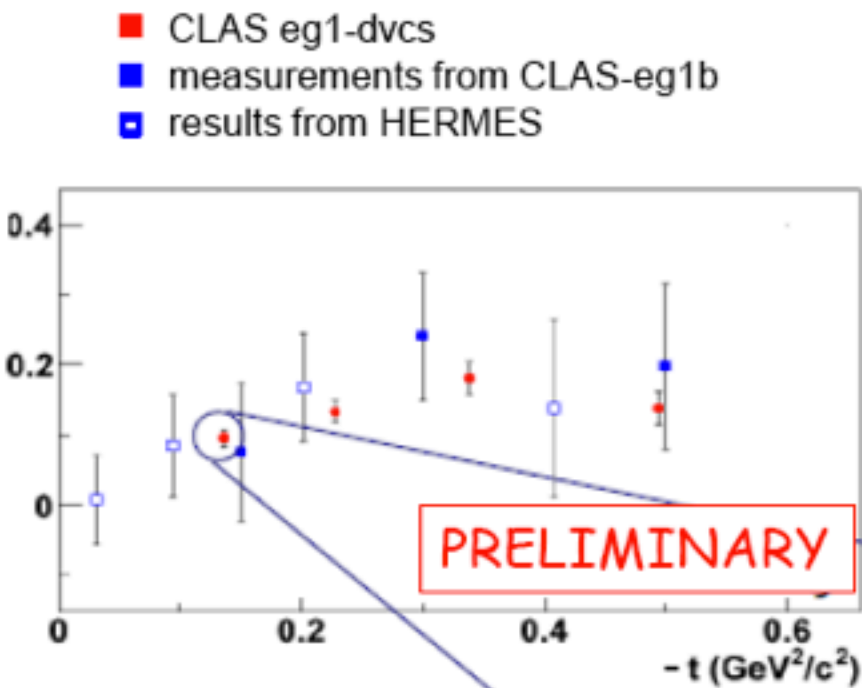
- Observation
  - Re(τ_{DVCS}) > 0 for HERA (small x)
  - Re(τ_{DVCS}) < 0 for HERMES (larger x)

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

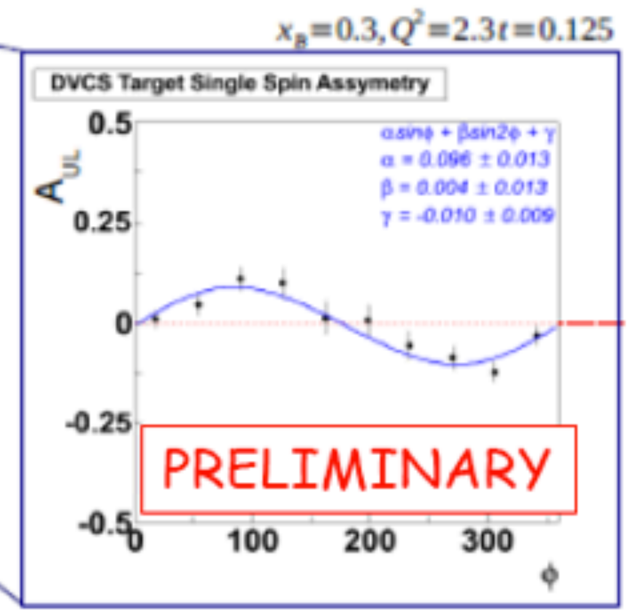
H1: Phys. Lett. B681 (2009) 391

CLAS (eg1-dvcs) and HERMES: longitudinal target-spin asymmetry

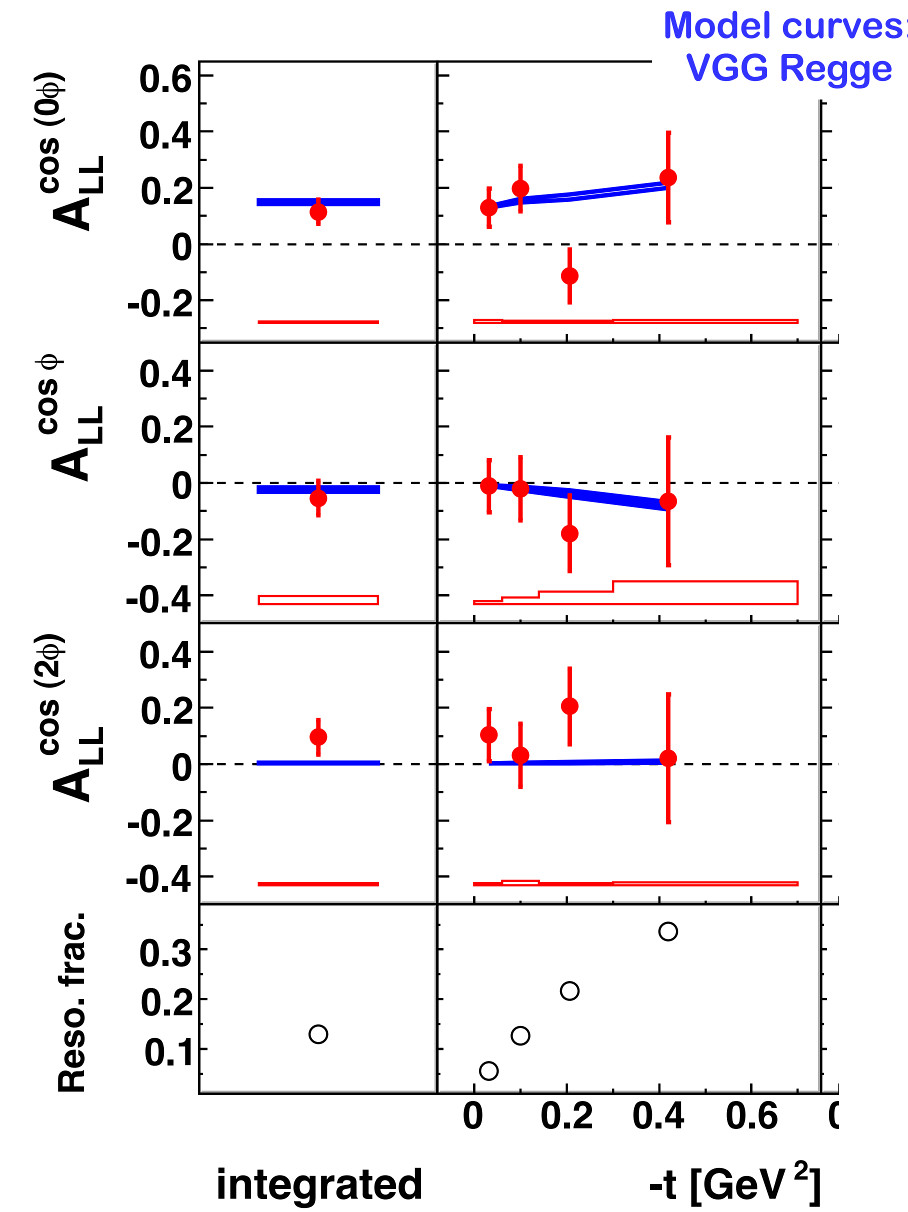
GPD H ~ LTSA



CLAS [prelim.] target-spin UL asymmetry
(no π^0 correction yet)



HERMES double-spin LL asymmetry



- ☛ eg1b-dvcs publication:

CLAS PRL 97, 072002 (2006)

- ☛ eg1-dvcs:
dedicated run 2009 with inner calo

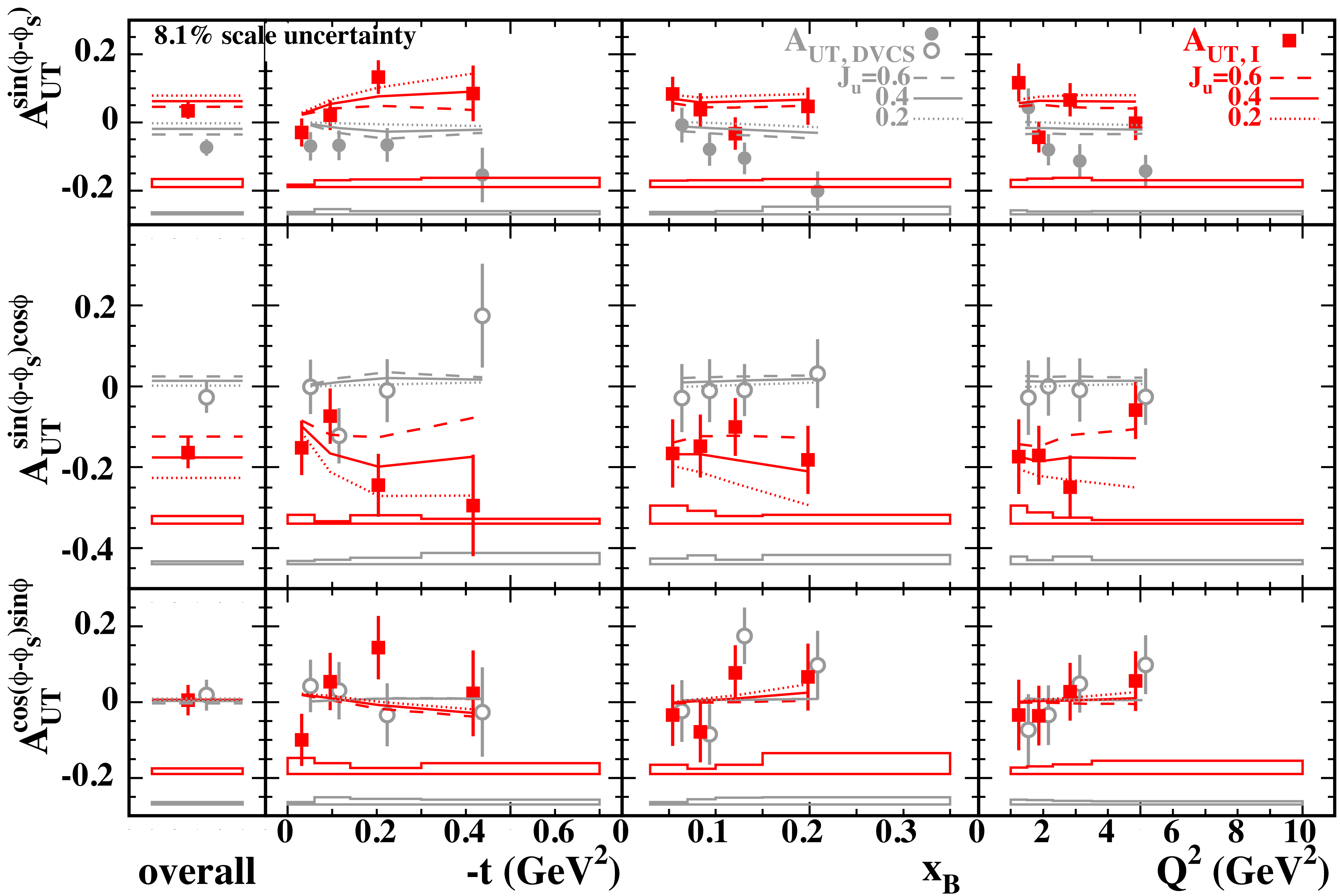
CLAS preliminary analysis

More details: see talk by Andrey Kim on Wednesday afternoon: "Deeply Virtual Exclusive Production on a Longitudinally Polarized Proton with CLAS"

HERMES: JHEP 06 (2010) 019

HERMES: transverse target-spin asymmetry

GPD E



Model curves: VGG Regge, no D-term

3 different values for J_u fixed J_d=0

Eur. Phys. J C46 (2006) 729

HERMES: JHEP 06 (2008) 066

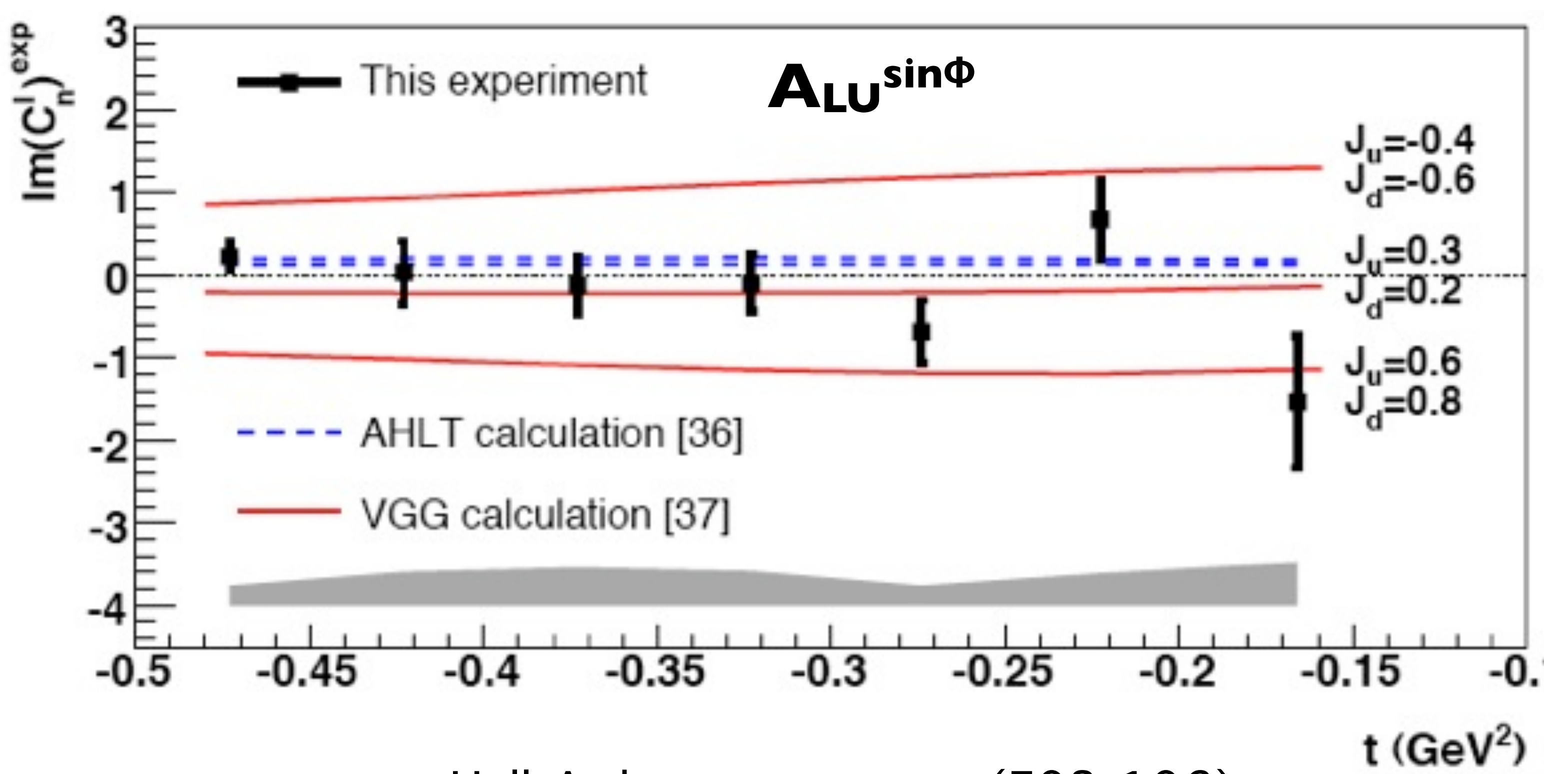
Hall A (E03-106): beam-helicity asymmetry on the neutron

GPD E

Sensitivity to GPD E

(A) HERMES: **ep$^{\uparrow}$ → epγ** :
$\mathcal{H}$-$\mathcal{E}$ (transversely polarized target)

(B) Hall A: **$\vec{e}^{-}$ n → e^{-} n γ** :
$\mathcal{E}$ dominant for the neutron
(unpolarized target)



Hall-A deuteron target (E03-106)

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

Nucleon spin

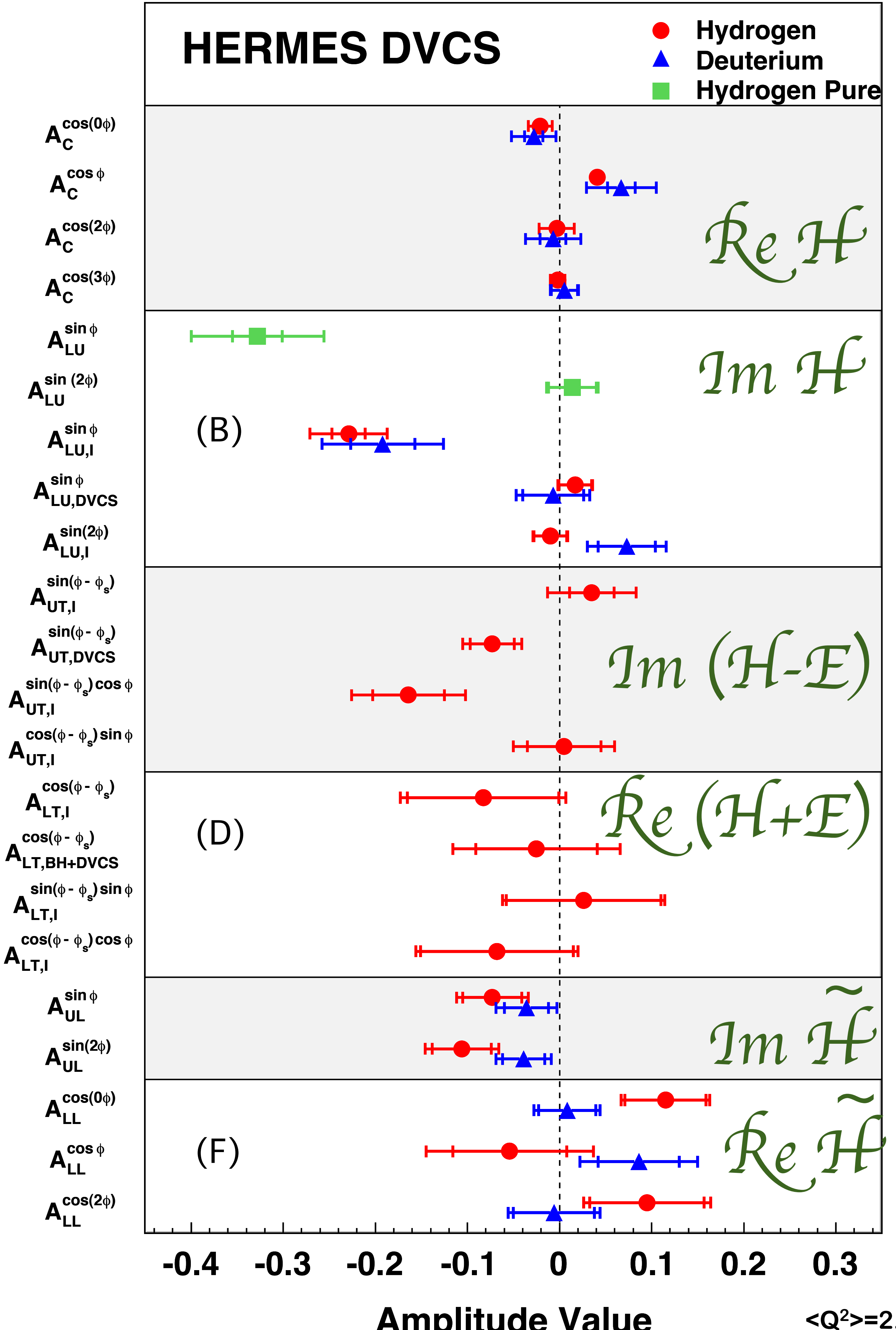
$$\tfrac{1}{2} = \tfrac{1}{2}\Delta\Sigma + L_q + J_g$$

Ji sum rule for the nucleon

-Ji, PRL 78 (1997) 610-

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

Through these measurements, we can in principle learn something about the total angular momentum of quarks in the nucleon.



HERMES amplitudes

(A) Beam-charge asymmetry:
GPD H
[JHEP 07 (2012) 032 – Nucl. Phys. B 829 (2010) 1–27]

(B) Beam-helicity asymmetry:
GPD H
[JHEP 07 (2012) 032 – Nucl. Phys. B 829 (2010) 1–27 - JHEP10 (2012) 042]

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

(D) Double-Spin (LT) asymmetry: GPD E
[Phys. Lett. B 704 (2011) 15–23]

(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]

Unique & complete set

Variety highly welcome by global fitters

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

Global analysis of DVCS data

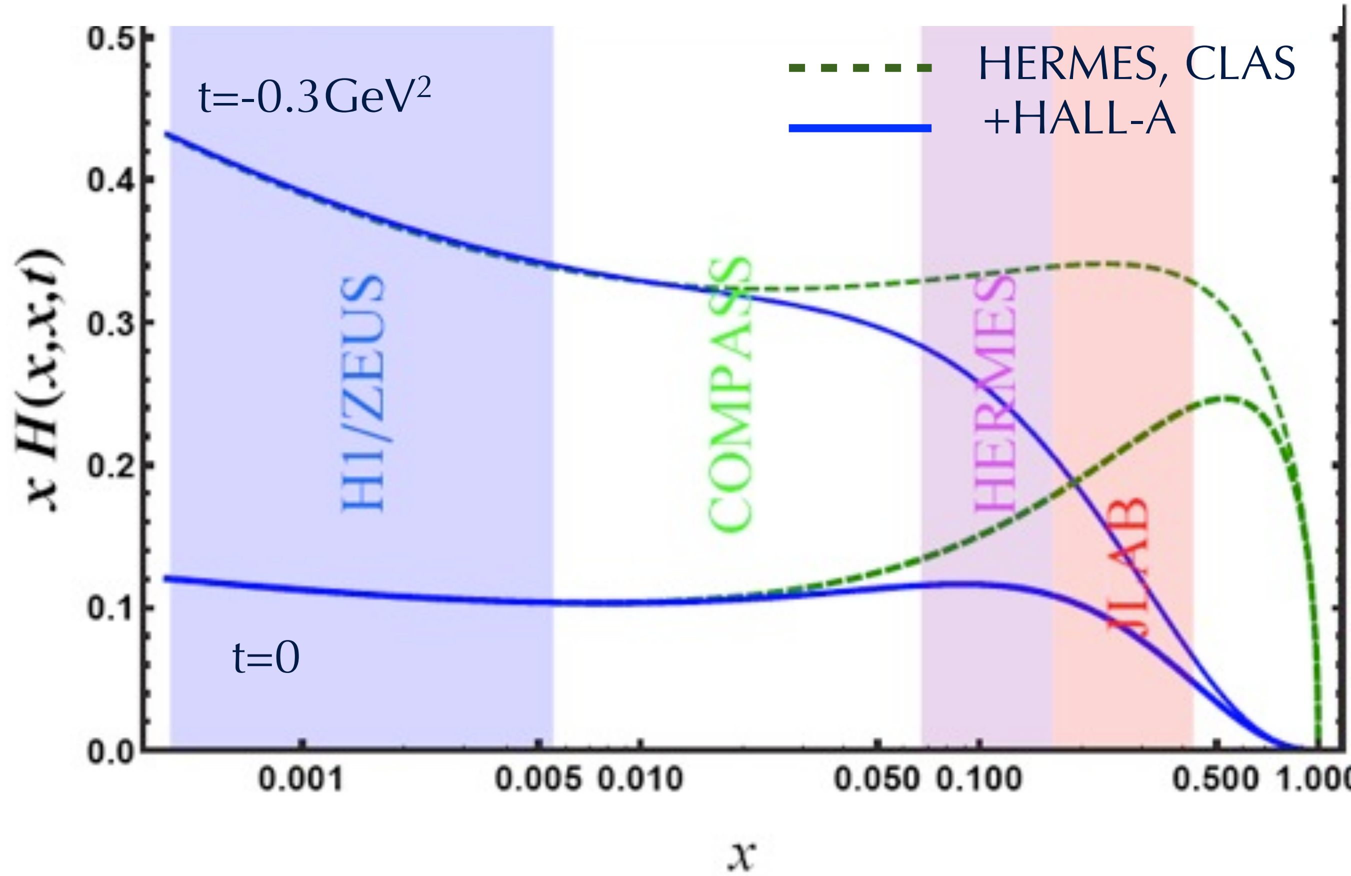
(a selection)

K. Kumericki and D. Müller (KM) **GPD H**

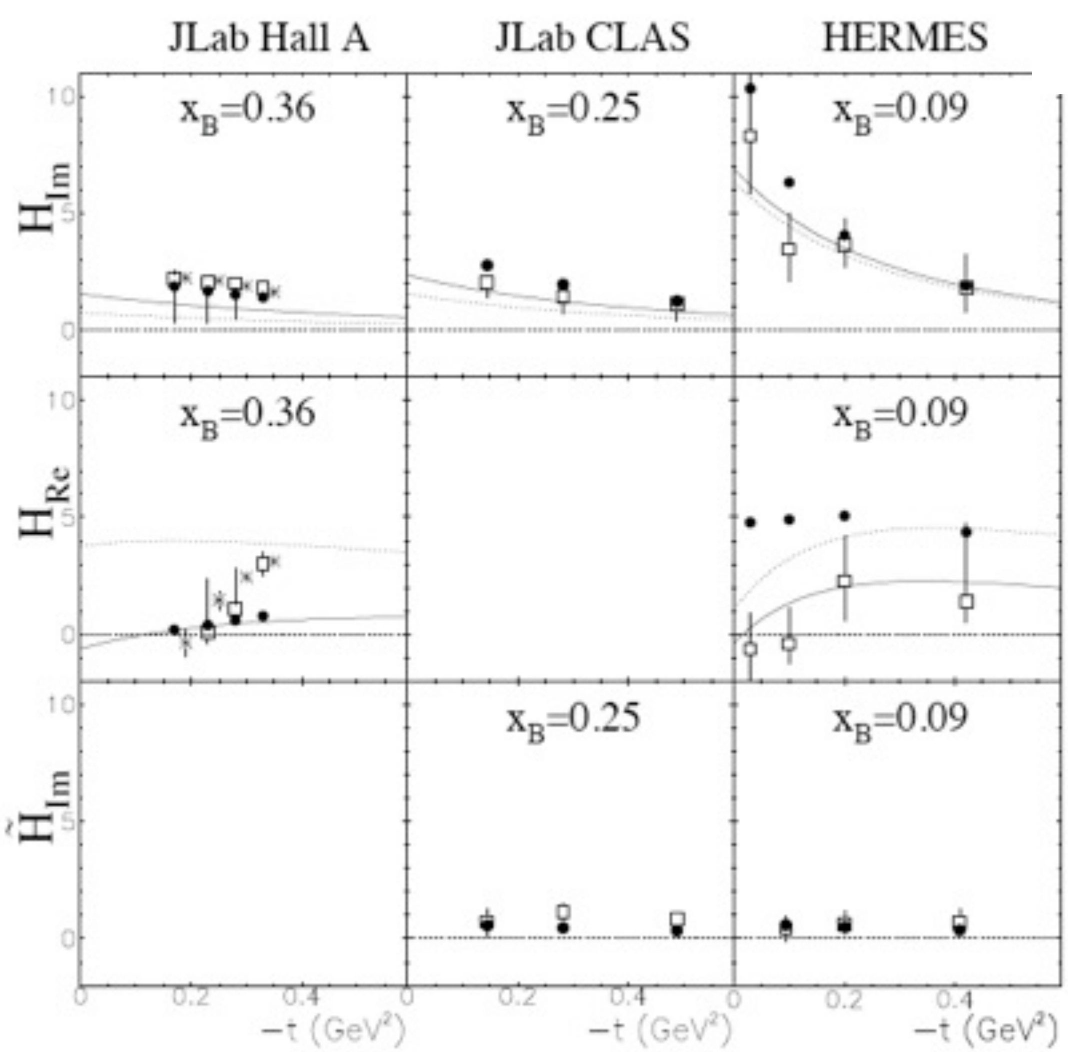
Nucl. Phys. B841 (2010) 1-58

- Global fit to extract GPD H at ξ=x. NNLO
- HERMES A_C , CLAS A_{LU} and Hall A x-section.
- Small-x behavior from HERA collider data.

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

H. Moutarde **PRD 79, 094021 (2009)**

- Global fit to extract Re(H) & Im(H)
- Hall A x-section & CLAS A_{LU}

M. Guidal **arXiv:1011.4195**

- Model-independent fit of Re(CFF) & Im(CFF)
- HERMES A_C, A_{LU}, A_{UT}, A_{UL}, A_{LL}; CLAS A_{LU}, A_{UL}; Hall A x-section

Compton Form Factors

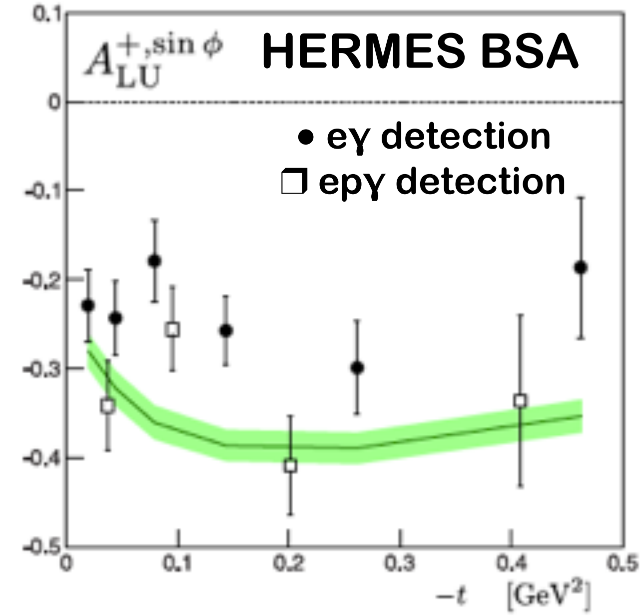
K. Kumericki, D. Müller, A. Schäfer
arXiv:1106.2808

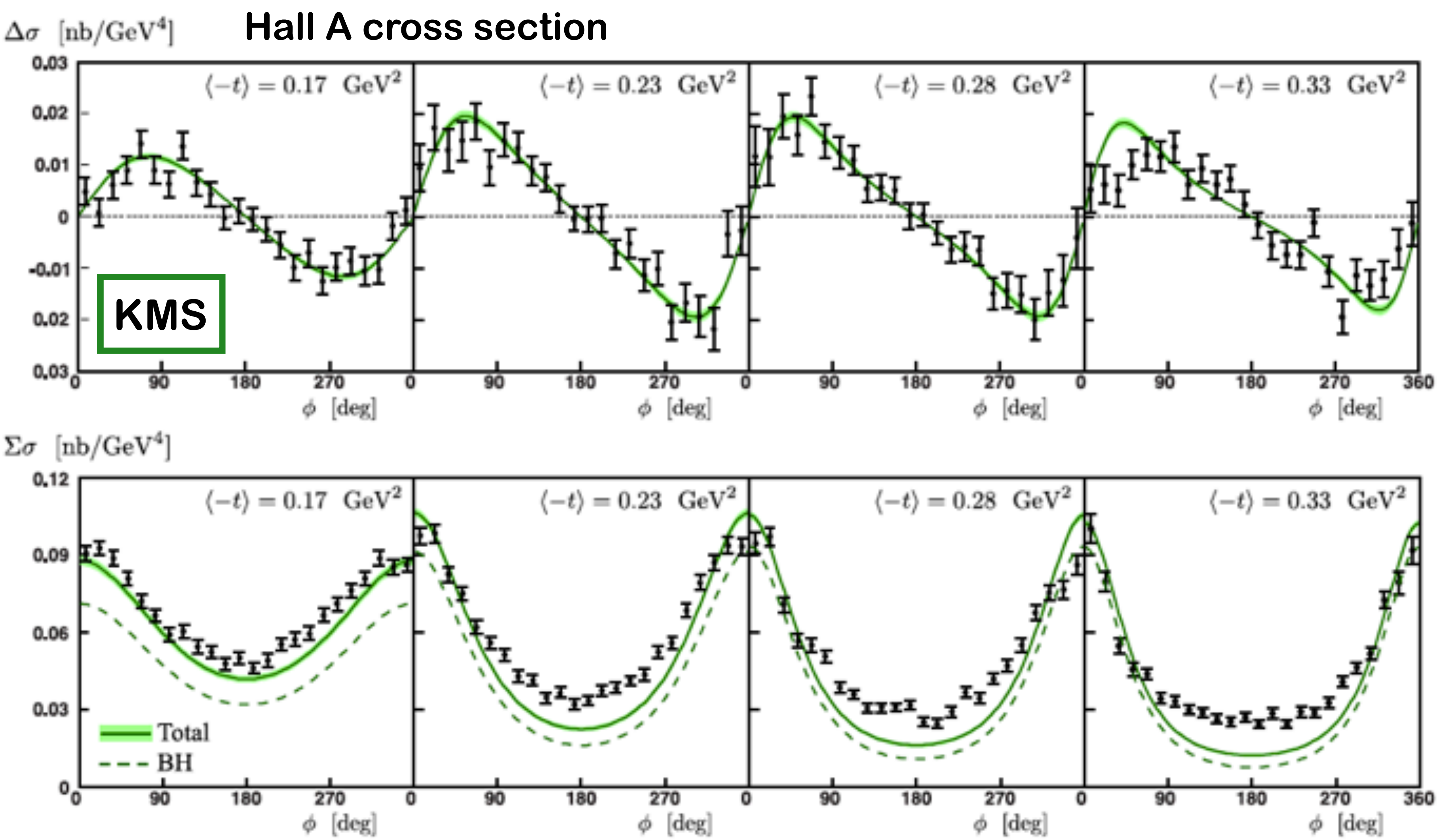
- Neural-network generated, model-independent parameterizations of CFFs
- Facilitates error propagation from data

Check of GPD universality

P. Kroll, H. Moutarde and F. Sabatié (KMS) arXiv:1210.6975

- Use hard-exclusive meson (DVMP) data, FF and PDFs to constrain GPD parameters (LO, LT): GK model
- Compare to DVCS observables - good for HERA and HERMES, fair for JLab





Unpolarized x-section Σσ = important normalization factor for asymmetries. Also:

☹ VGG model

☹ GK (Goloskokov-Kroll) model

☹ Minimal (i.e. forward) dual model (→ Polyakov and Vanderhaeghen)

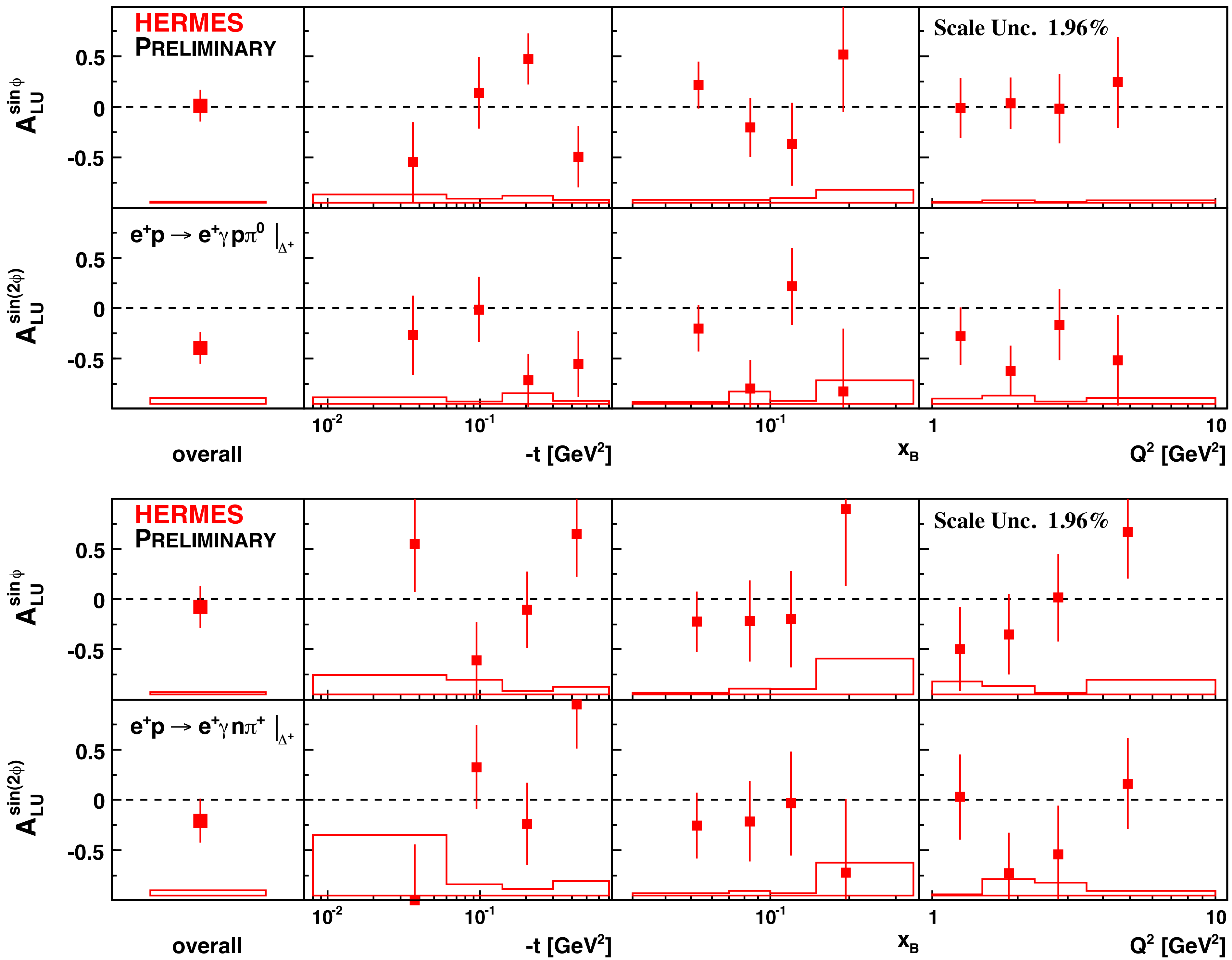
☺ KM model, though needs large H~.

Polarized x-section, and in general imaginary part of τ(DVCS) known better.

Recent review article:
M. Guidal, H. Moutarde, M. Vanderhaeghen: Generalized Parton Distributions in the valence region from Deeply Virtual Compton Scattering, arxiv.org:1303.6600

HERMES: beam-helicity asymmetry

in ep→eγ(πN) in the Δ-resonance region



- ☛ The charged particle of (πN) reconstructed by the recoil detector.
- ☛ This result is consistent with the slight increase of the beam-helicity asymmetry amplitude with recoil proton.
- ☛ Associated process acts as small dilution in the asymmetries for the unresolved sample.
- ☛ Only existing model prediction for sinϕ amplitude: π^0p: -0.15, π^+n: -0.10

P.A.M. Guichon, L. Mossé, M. Vanderhaeghen: Pion production in deeply virtual Compton scattering, Phys. Rev. D68, 034018 (2003).

HERMES: preliminary analysis

HERMES: DVCS on hadrons other than the proton

Coherent and tensor signatures; nuclear medium

HERMES: Nucl. Phys. B 842 (2011) 265-298

longitudinally polarized deuterium

GPD $\tilde{H}_1$

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

GPD $\tilde{H}_5$

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

GPD H_A

CLAS [eg6]:
coherent DVCS
on ^{4}He, spin 0

HERMES: DVCS on hadrons other than the proton

Coherent and tensor signatures; nuclear medium

HERMES: Nucl. Phys. B 842 (2011) 265-298

longitudinally polarized deuterium

GPD H_1~

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

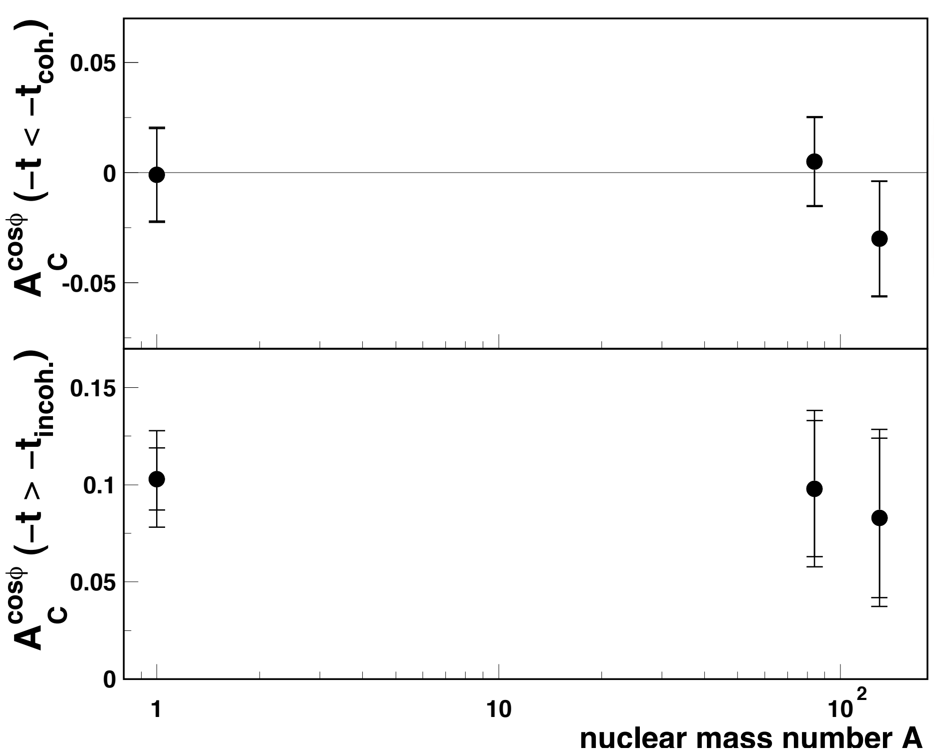
GPD H_5~

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

GPD H_A

CLAS [eg6]: **coherent DVCS** on ^{4}He, spin 0

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

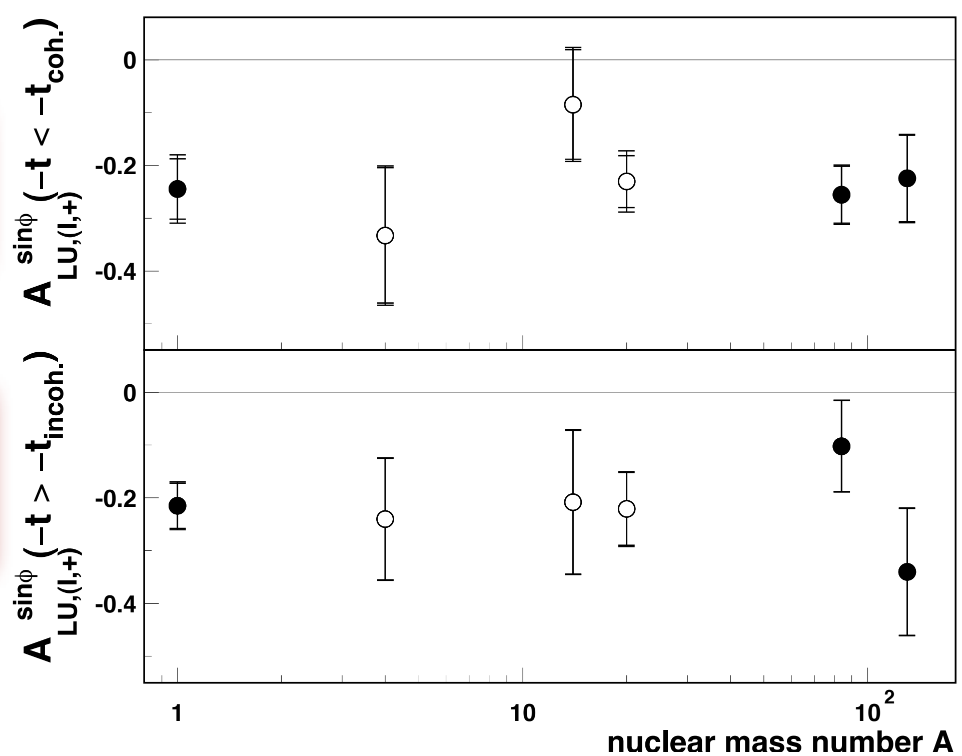


coherent enriched

incoherent enriched

Beam-charge asymmetry

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



Beam-helicity asymmetry

Average A_{LU}^A / A_{LU}^H:

0.91±0.19
0.93±0.23

Normalization to hydrogen ^{1}H

HERMES: Phys. Rev. C 81 (2010) 035202

The future of DVCS

JLab12

☛ Hall A: DVCS on the proton (E12–06–114).

Scaling tests of x-section; separation of Re and Im parts of τ DVCS; E=6.6, 8.8, 11 GeV.

E07–007 for p, E08–025 for n ran successfully in 2010 with 12GeV-equipment. Rosenbluth analysis ongoing.

☛ CLAS12: A_{LU}, A_{UL}, A_{UT} and A_{LT} on the proton and A_{LU} on the neutron.

Transversely polarized HD-Ice target. Timelike Compton Scattering; DDVCS?

More details: see talk by Stepan Stepanyan on Wednesday afternoon: “The CLAS12 Physics Program”

COMPASS

☛ Phase 1: 2015/16: GPD H, large recoil detector: separation of Re and Im parts of τ(DVCS) by using two different combinations of beam charge and helicity; t-slope.

☛ Phase 2: 2018 (?): GPD E: transversely polarized target.

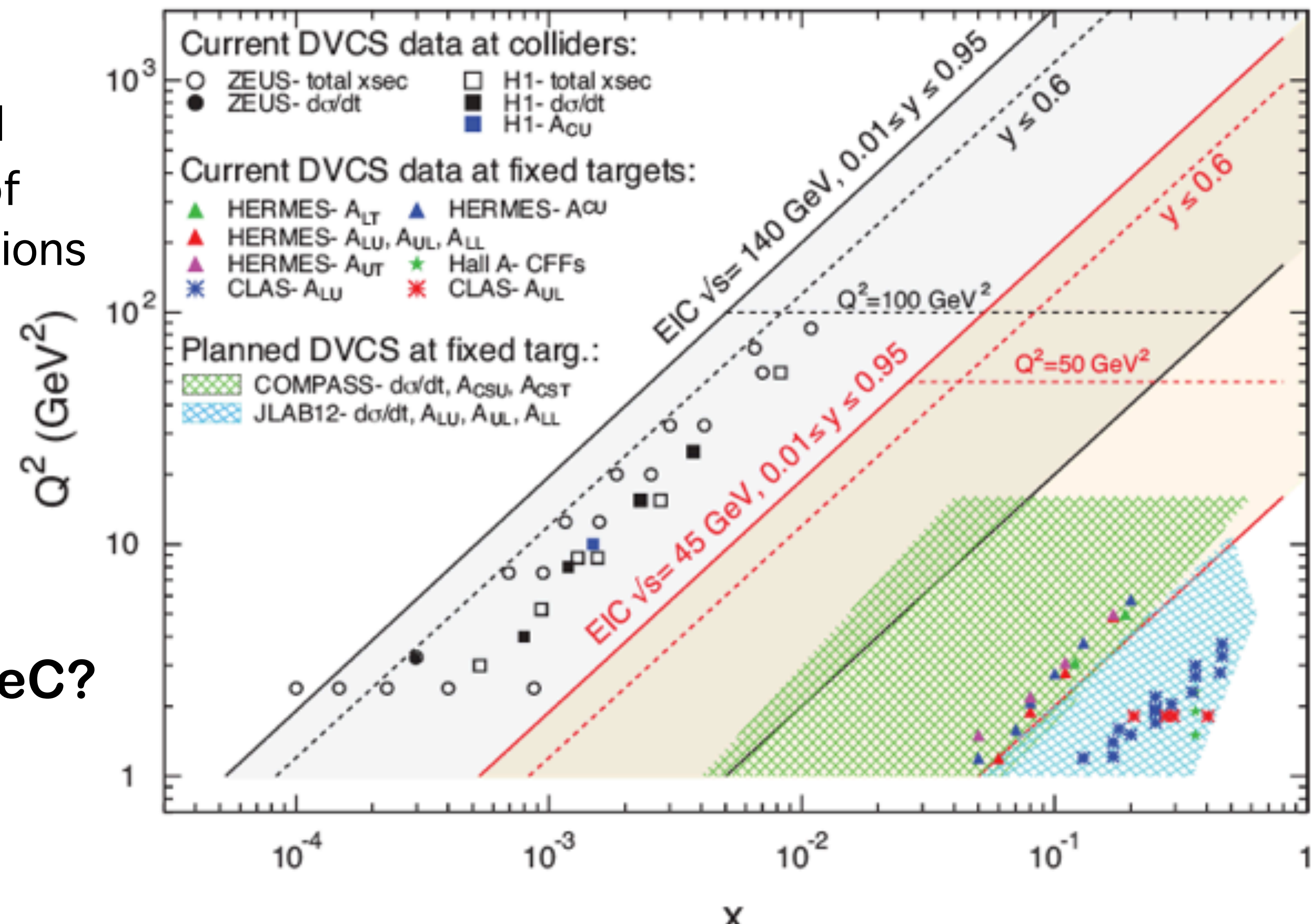
Future Electron-Ion Collider (2025+)

LHeC?

☛ ELIC @ JLab or eRHIC @ BNL:

$\sqrt{s}$ = 20-70 GeV

☛ ENC @ GSI: $\sqrt{s}$ = 40 GeV, ...



"Deeply Virtual Compton Scattering at a Proposed High-Luminosity Electron-Ion Collider", E.-C. Aschenauer, S. Fazio, K. Kumericki and D. Mueller, arXiv:1304.0077

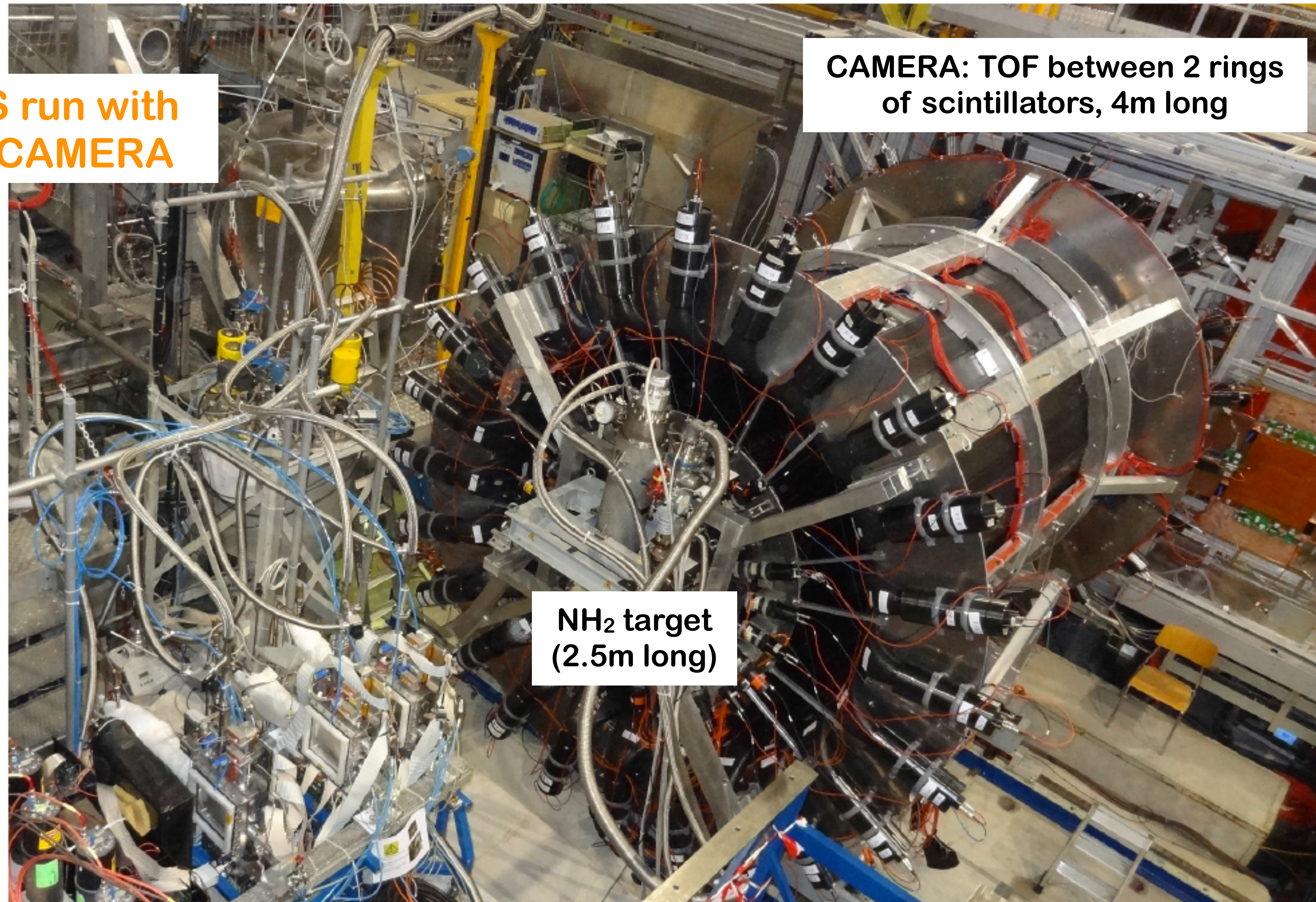
See also talk by Oleg Eyser Wednesday afternoon: “Future Opportunities at an Electron-Ion Collider”

COMPASS CAMERA

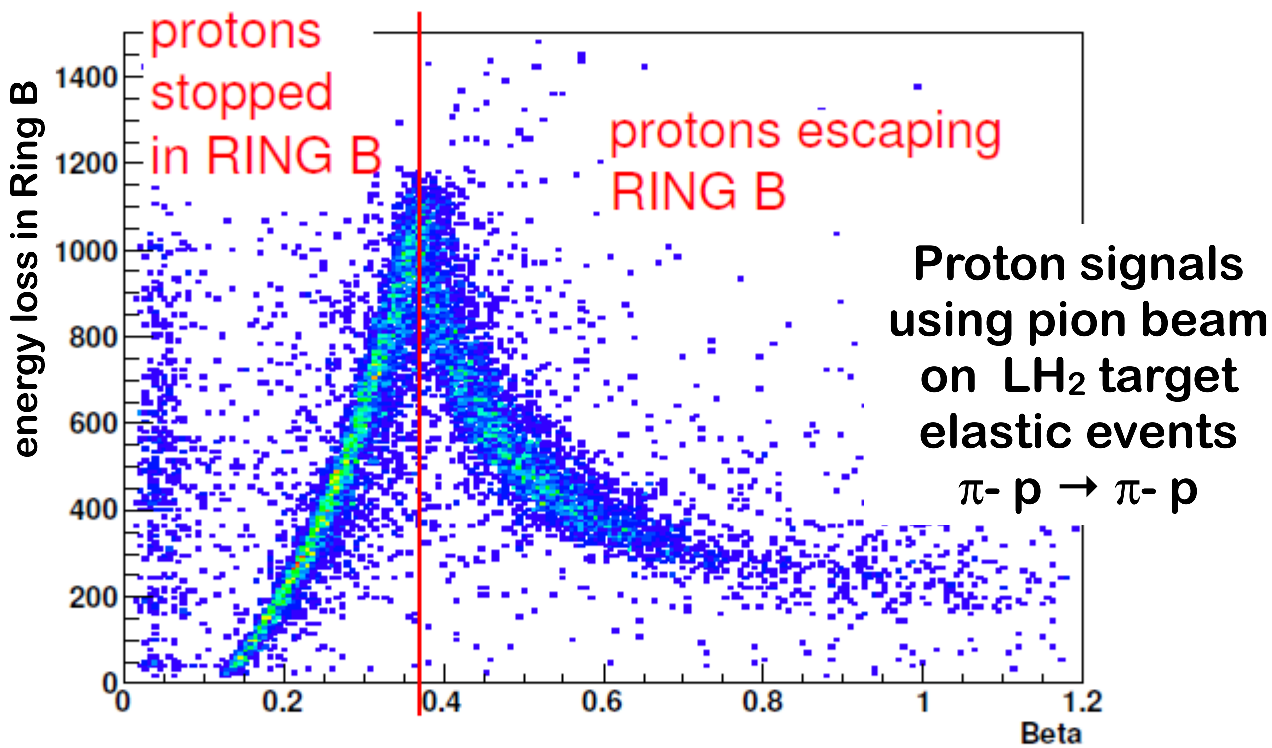
2008/09: DVCS test runs with
small recoil detector (not shown)

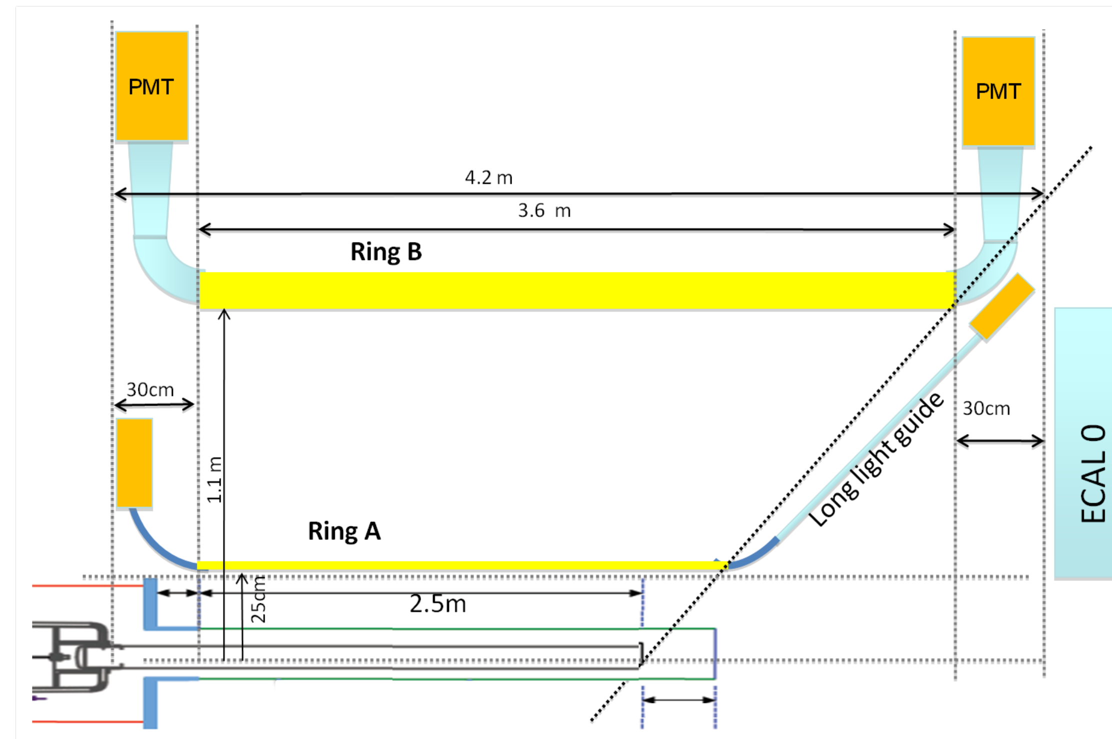
2012: first DVCS run with recoil detector CAMERA

- Detection of recoil proton
- First DVCS run Sept 26 until Dec. 2012



COMPASS: DVCS "Phase 1"





- First test run with large recoil detector end of 2012.
- Dedicated 2 years of data taking 2015/2016 with 160 GeV longitudinally polarized muon beam (μ+← and μ-→).
- t-slope on ϕ-integrated helicity-independent cross section.
- Helicity-independent x-section: σ(μ+←) + σ(μ-→), Re(CFF-H).
- Helicity-dependent x-section: σ(μ+←) – σ(μ-→), Im(CFF-H).

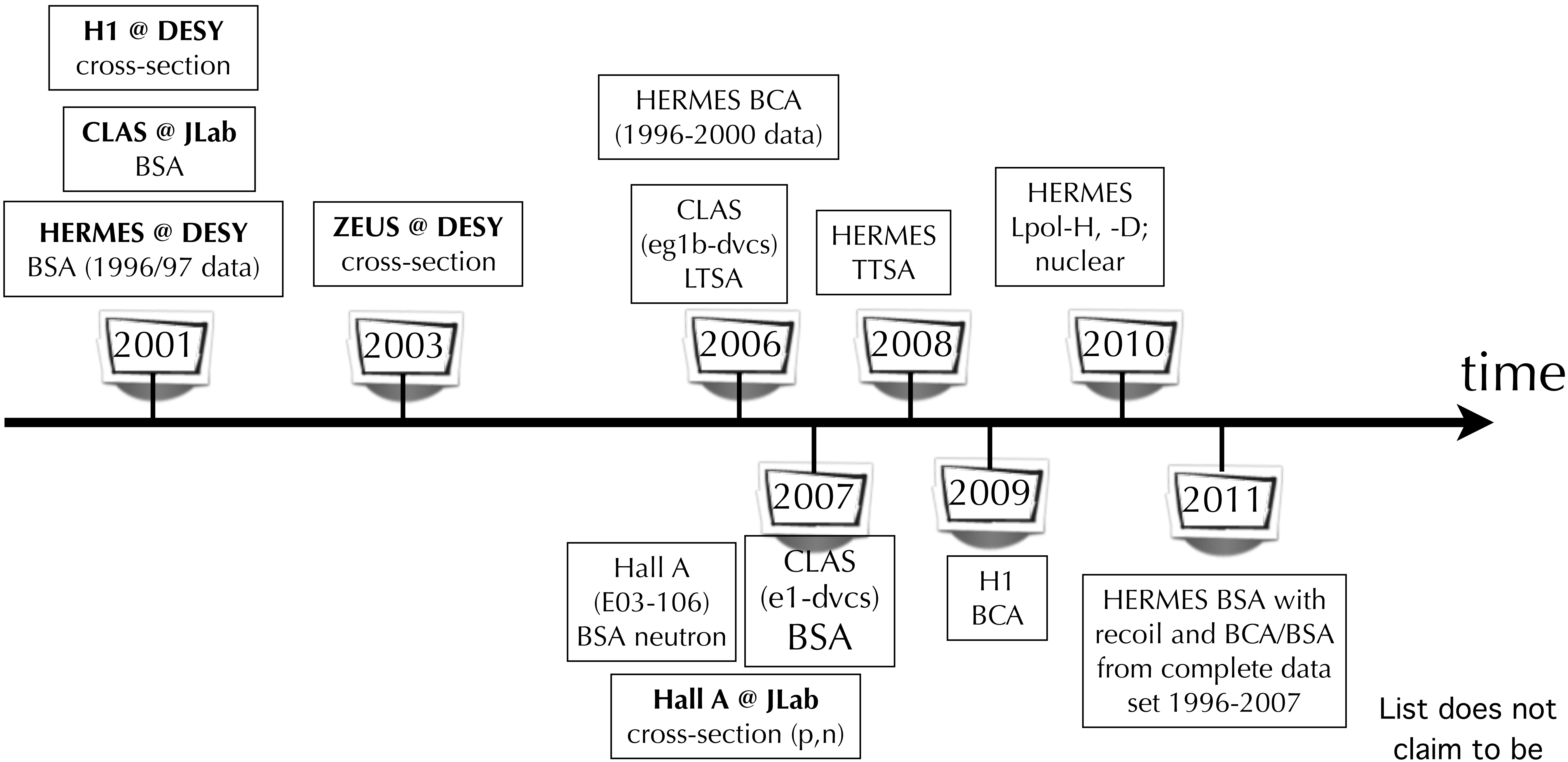
Transverse imaging

GPD H

DVCS evolution over the years

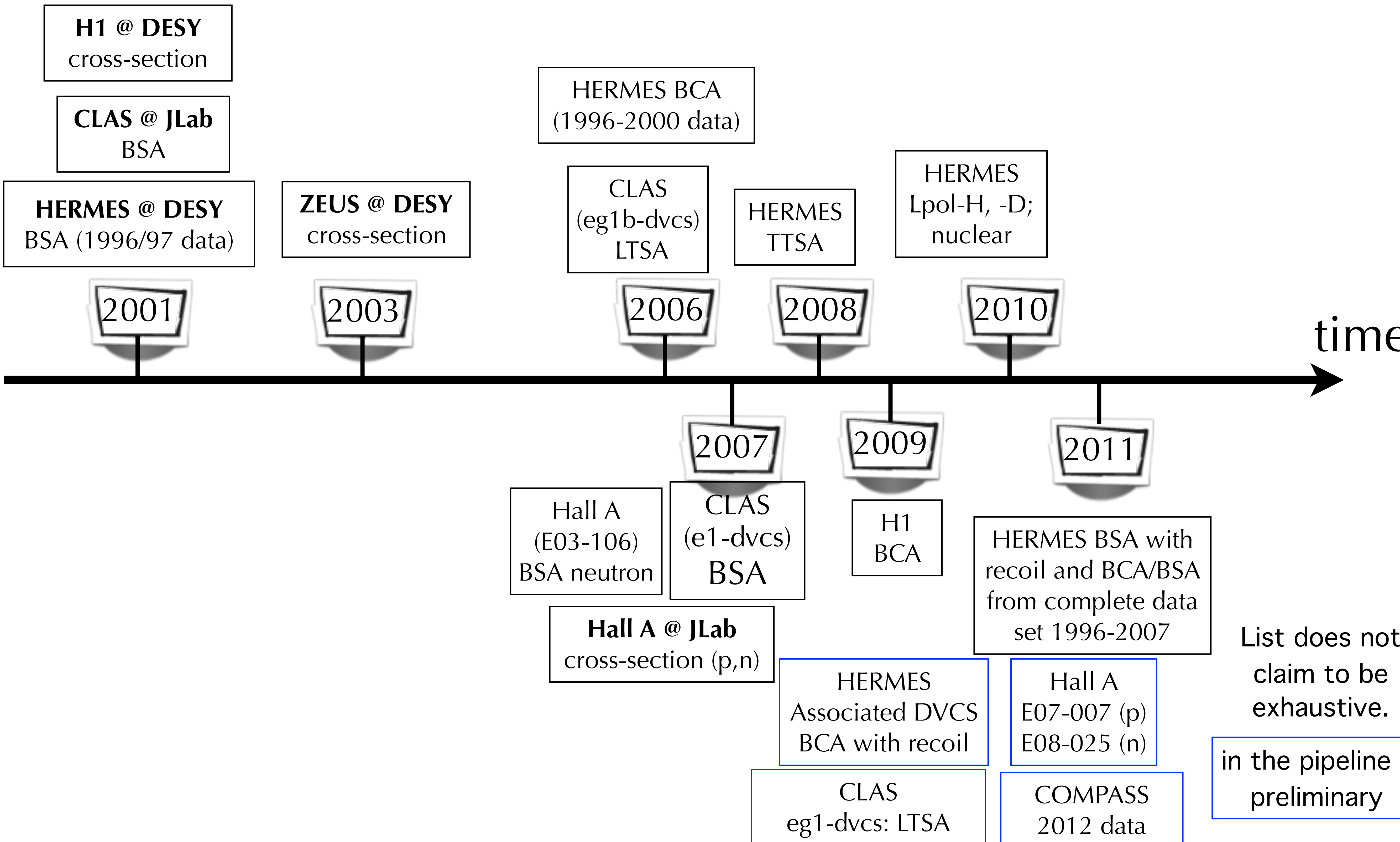
List does not claim to be exhaustive.

DVCS evolution over the years



List does not claim to be exhaustive.

DVCS evolution over the years



List does not claim to be exhaustive.

in the pipeline / preliminary

DVCS evolution over the years

2001
- **H1 @ DESY** cross-section
- **CLAS @ JLab** BSA
- **HERMES @ DESY** BSA (1996/97 data)

2003
- **ZEUS @ DESY** cross-section

2006
- HERMES BCA (1996-2000 data)
- CLAS (eg1b-dvcs) LTSA

2007
- Hall A (E03-106) BSA neutron
- CLAS (e1-dvcs) BSA
- **Hall A @ JLab** cross-section (p,n)

2008
- HERMES TTSA

2009
- H1 BCA

2010
- HERMES Lpol-H, -D; nuclear

2011
- HERMES BSA with recoil and BCA/BSA from complete data set 1996-2007

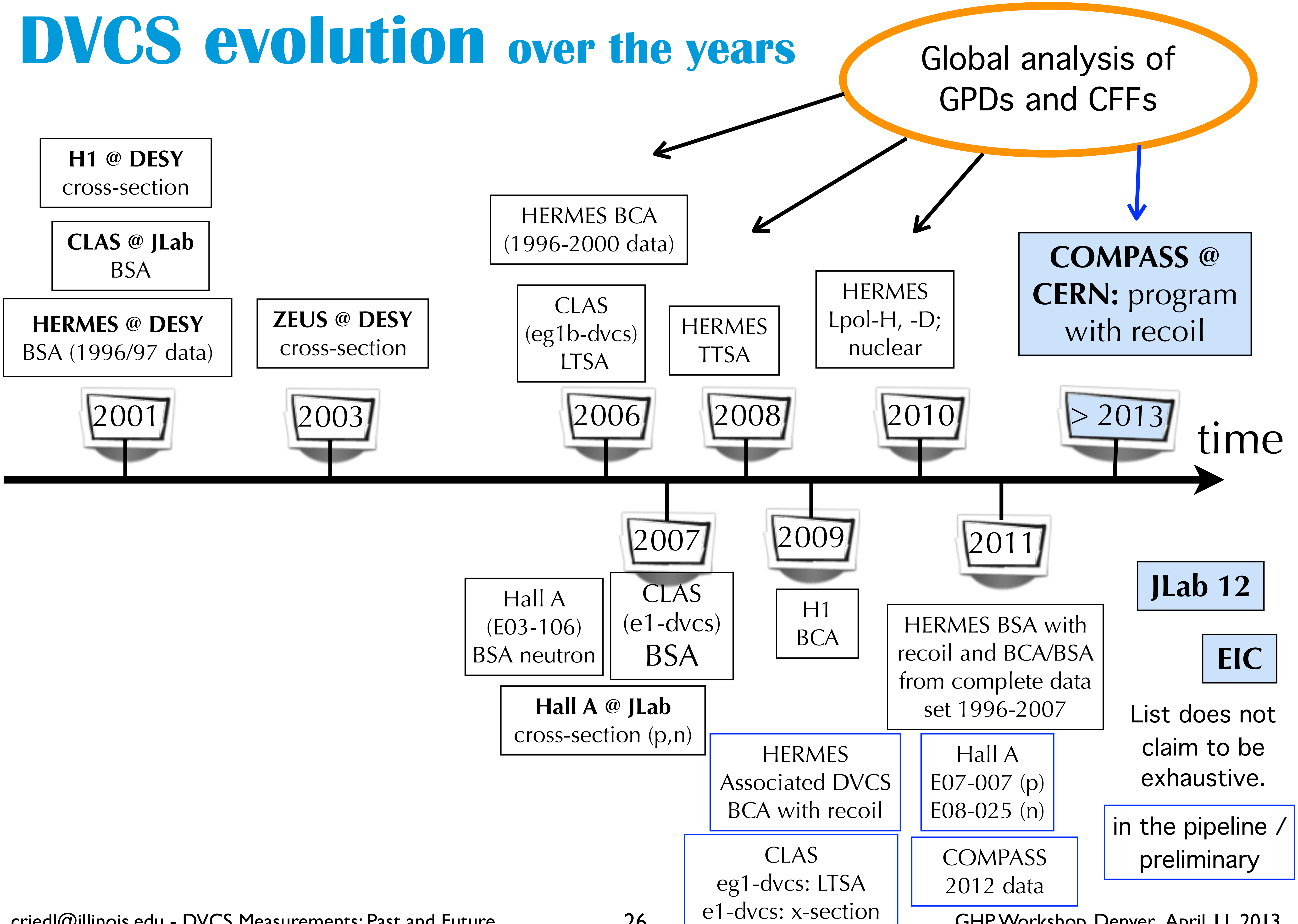
> 2013
- **COMPASS @ CERN:** program with recoil
- **JLab 12**
- **EIC**

time

In the pipeline / preliminary:
- HERMES Associated DVCS BCA with recoil
- CLAS eg1-dvcs: LTSA e1-dvcs: x-section
- Hall A E07-007 (p) E08-025 (n)
- COMPASS 2012 data

List does not claim to be exhaustive.

DVCS evolution over the years



DVCS evolution over the years

Global analysis of GPDs and CFFs

H1 @ DESY cross-section

CLAS @ JLab BSA

HERMES @ DESY BSA (1996/97 data)

2001

ZEUS @ DESY cross-section

2003

HERMES BCA (1996-2000 data)

CLAS (eg1b-dvcs) LTSA

2006

Hall A (E03-106) BSA neutron

CLAS (e1-dvcs) BSA

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

2007

HERMES TTSA

2008

H1 BCA

2009

HERMES Lpol-H, -D; nuclear

2010

HERMES BSA with recoil and BCA/BSA from complete data set 1996-2007

2011

COMPASS @ CERN: program with recoil

> 2013

time

JLab 12

EIC

HERMES Associated DVCS BCA with recoil

Hall A E07-007 (p) E08-025 (n)

CLAS eg1-dvcs: LTSA e1-dvcs: x-section

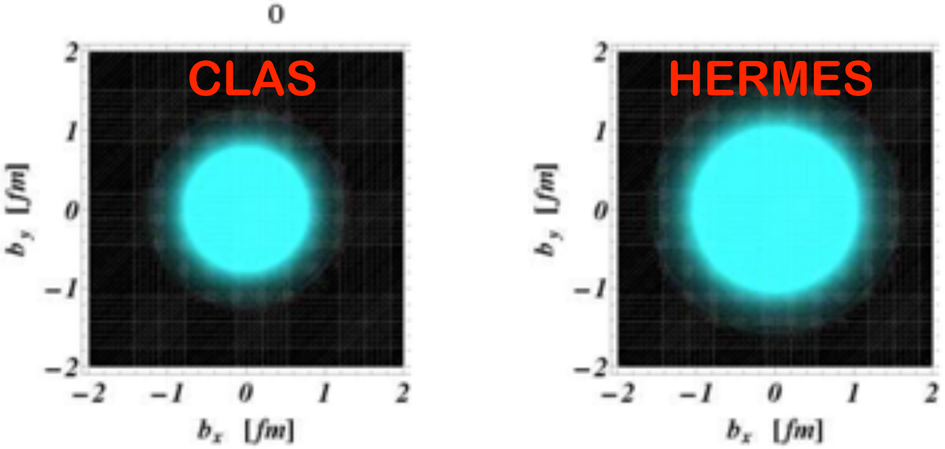
COMPASS 2012 data

List does not claim to be exhaustive.

in the pipeline / preliminary

From CFFs to spatial charge densities

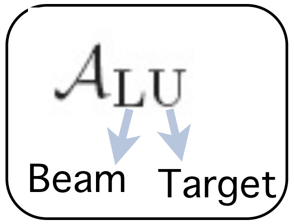
$$H(x, b_\perp) = \int_0^\infty \frac{d\Delta_\perp}{2\pi} \Delta_\perp \, J_0(b_\perp \Delta_\perp) \, H(x, 0, -\Delta_\perp^2)$$



M. Guidal, H. Moutarde, M. Vanderhaeghen, arxiv.org:1303.6600

Backup

Azimuthal asymmetries and GPDs



Single-charge beam-helicity asymmetry

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

no separate access to s_1^{I} and s_1^{DVCS}

Beam-helicity asymmetries with 2 beam charges

Charge-average	Charge-difference
$\mathcal{A}_{\mathrm{LU}}$	$\mathcal{A}_{\mathrm{LU}}$

s_1^{DVCS} and s_1^{I} can be disentangled

Beam-charge asymmetry

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

Transverse target-spin asymmetry $\mathcal{A}_{\mathrm{UT}}^{\mathrm{DVCS}}(\phi,\phi_S)$ $\mathcal{A}_{\mathrm{UT}}^{\mathrm{I}}(\phi,\phi_S)$

Double-spin (LT) asymmetry $\mathcal{A}_{\mathrm{LT}}^{\mathrm{I}}(\phi,\phi_S)$ $\mathcal{A}_{\mathrm{LT}}^{\mathrm{BH+DVCS}}(\phi,\phi_S)$

Longitudinal target-spin asymmetry

$$\mathcal{A}_{\mathrm{UL}}(\phi,e_\ell) \equiv \frac{[\sigma^{\leftarrow\Rightarrow}(\phi,e_\ell)+\sigma^{\rightarrow\Rightarrow}(\phi,e_\ell)] - [\sigma^{\leftarrow\Leftarrow}(\phi,e_\ell)+\sigma^{\rightarrow\Leftarrow}(\phi,e_\ell)]}{[\sigma^{\leftarrow\Rightarrow}(\phi,e_\ell)+\sigma^{\rightarrow\Rightarrow}(\phi,e_\ell)] + [\sigma^{\leftarrow\Leftarrow}(\phi,e_\ell)+\sigma^{\rightarrow\Leftarrow}(\phi,e_\ell)]}$$

Double-spin (LL) asymmetry

$$\mathcal{A}_{\mathrm{LL}}(\phi,e_\ell) \equiv \frac{[\sigma^{\rightarrow\Rightarrow}(\phi,e_\ell)+\sigma^{\leftarrow\Leftarrow}(\phi,e_\ell)] - [\sigma^{\leftarrow\Rightarrow}(\phi,e_\ell)+\sigma^{\rightarrow\Leftarrow}(\phi,e_\ell)]}{[\sigma^{\rightarrow\Rightarrow}(\phi,e_\ell)+\sigma^{\leftarrow\Leftarrow}(\phi,e_\ell)] + [\sigma^{\leftarrow\Rightarrow}(\phi,e_\ell)+\sigma^{\rightarrow\Leftarrow}(\phi,e_\ell)]}$$

Compton Form Factors (CFFs)

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

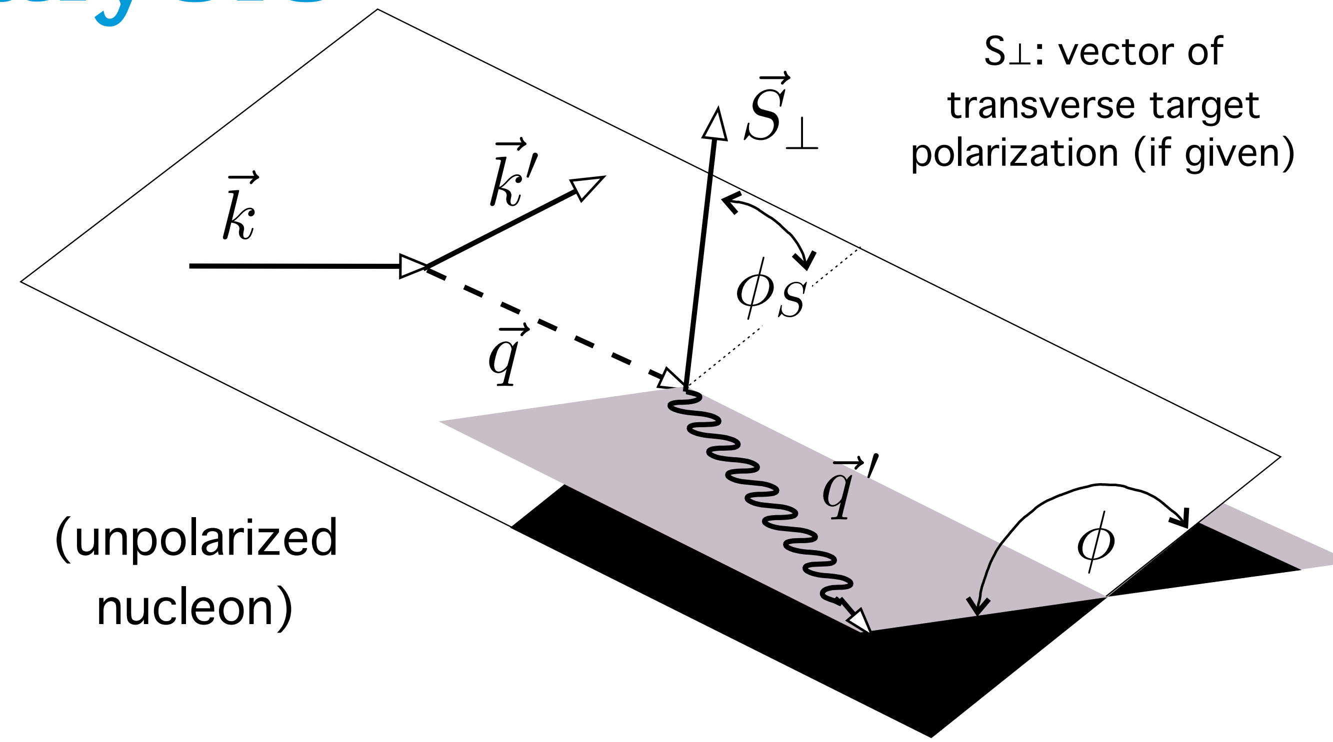
twist-2 GPD

- ☛ Measure asymmetry
- ☛ Extract its azimuthal moments (extended Maximum Likelihood Fit)
- ☛ Those azimuthal asymmetry amplitudes are related to certain linear or bi-linear combinations of CFFs.

Harmonic analysis

lepton beam k with
charge C_B and helicity P_B

$S_\perp$: vector of transverse target polarization (if given)



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

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

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

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

Old approach at HERMES and CLAS: single-charge A_{LU}

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

no separate access to s_1^{I} and s_1^{DVCS}

Beam-helicity asymmetries

Approach at HERMES:
s_1^{I} and s_1^{DVCS} can be disentangled
Need 2 beam charges!

Beam-charge asymmetry

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

Charge-average A_{LU}:

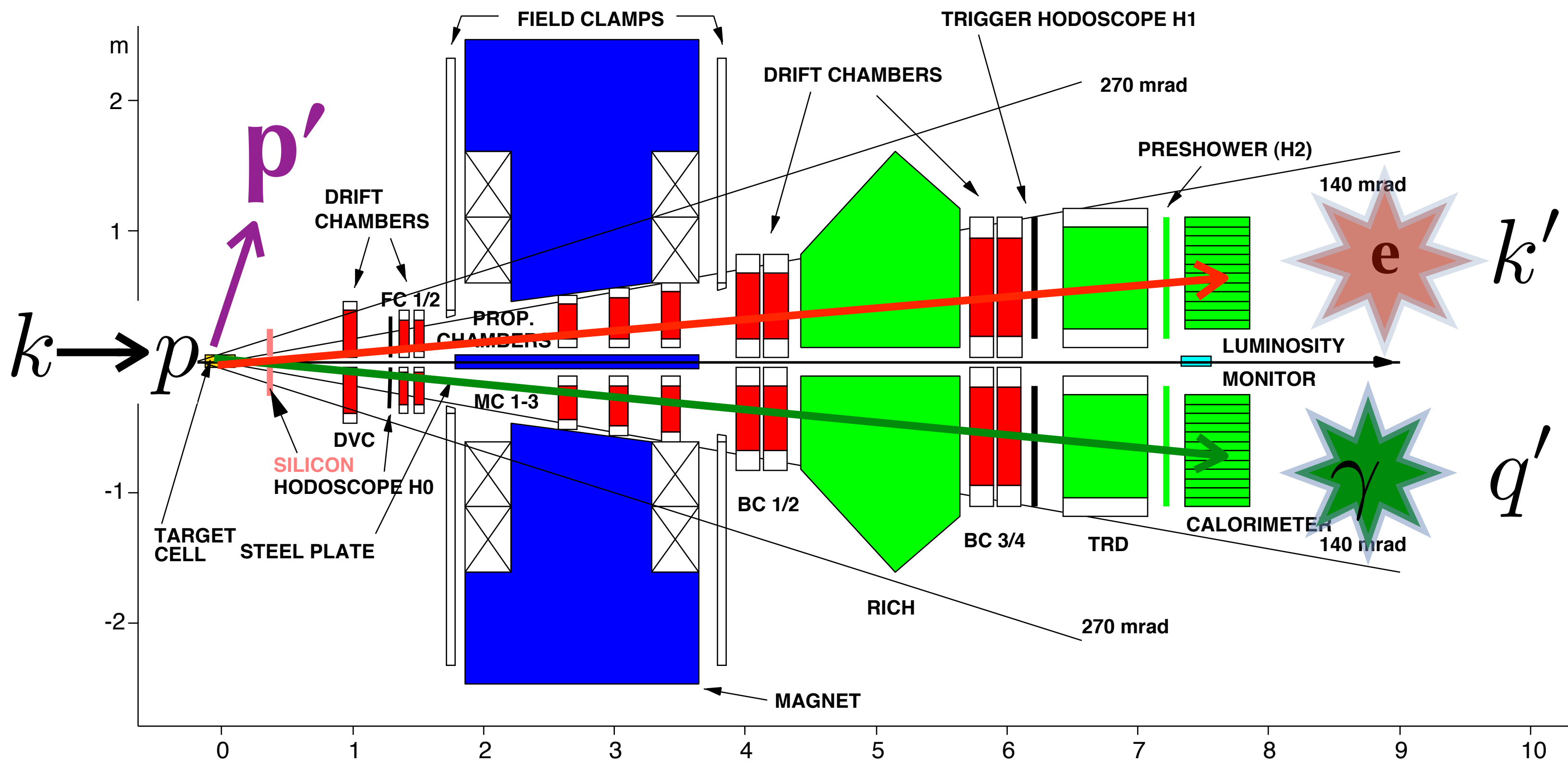
$$\mathcal{A}_{\rm LU}^{\rm DVCS}(\phi) \equiv \frac{(d\sigma^{+\rightarrow} - d\sigma^{+\leftarrow}) + (d\sigma^{-\rightarrow} - d\sigma^{-\leftarrow})}{(d\sigma^{+\rightarrow} + d\sigma^{+\leftarrow}) + (d\sigma^{-\rightarrow} + d\sigma^{-\leftarrow})}$$

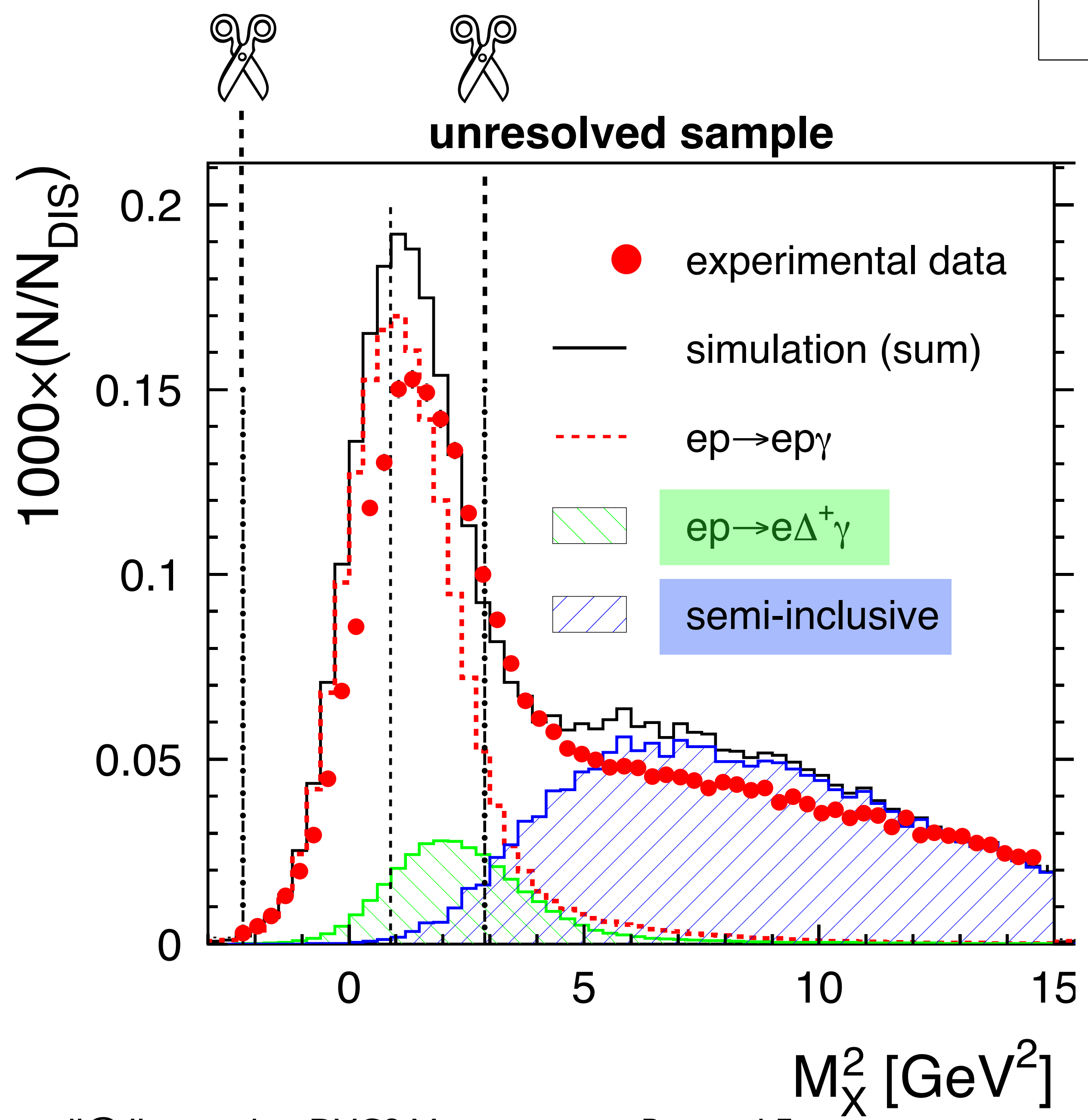
Charge-difference A_{LU}:

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

"Traditional" DVCS Analysis at HERMES

"exclusive region" in (missing mass)^2





- No other charged tracks reconstructed
- No other untracked clusters in the calorimeter

Missing-mass technique

$$M_X^2 = (k + p - k' - q')^2$$

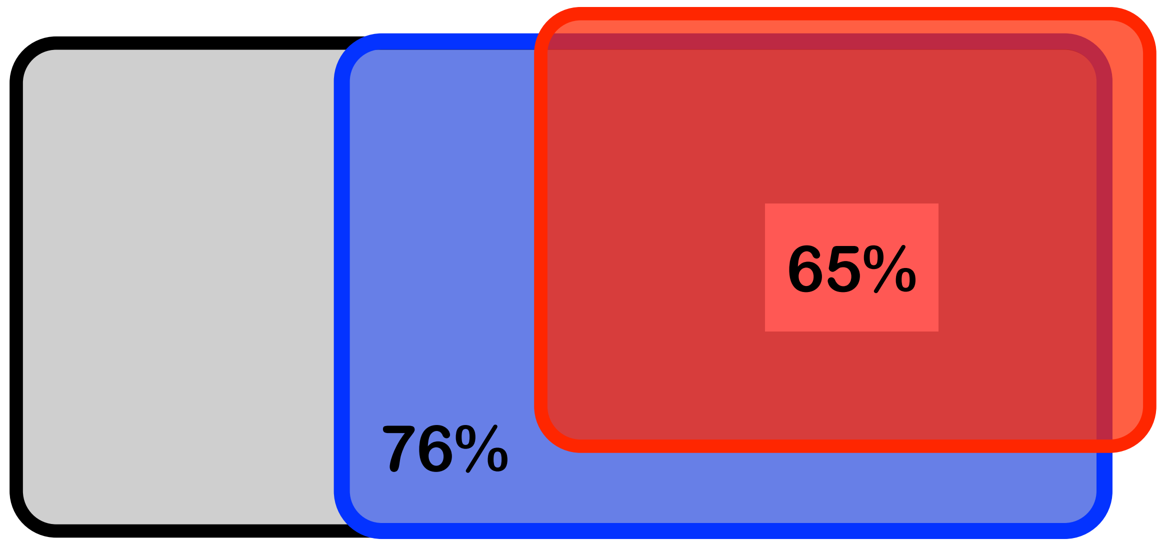
ep ➔ eXγ sample (about 12%)

✘ Unresolved for associated production

✔ Semi-inclusive neutral pion production corrected for (about 3%)

HERMES: unresolved reference sample

Disentangling the effects of recoil-detector acceptance and purification



Loss due to
- lower-mom. threshold
- Φ-gaps of SSD

Deficit due to
- removal of background
- inefficiencies of χ^2 cut
- recoil-det. ineffciencies