Deeply Virtual Compton Scattering at HERMES – an Overview

Caroline K. Riedl

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

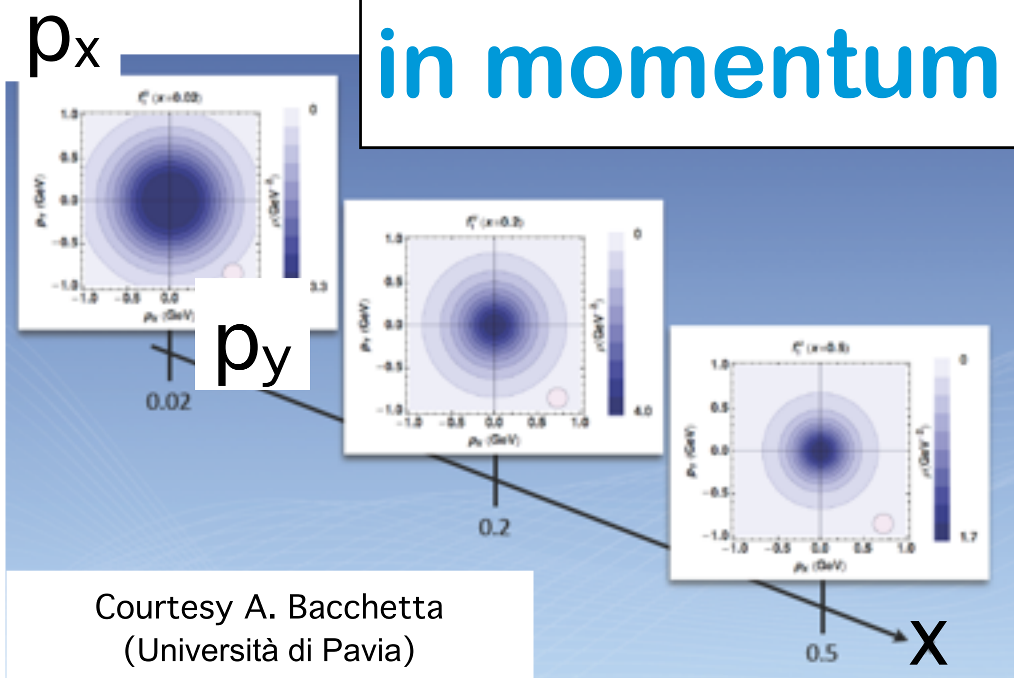
CEA-Saclay
March 27, 2013

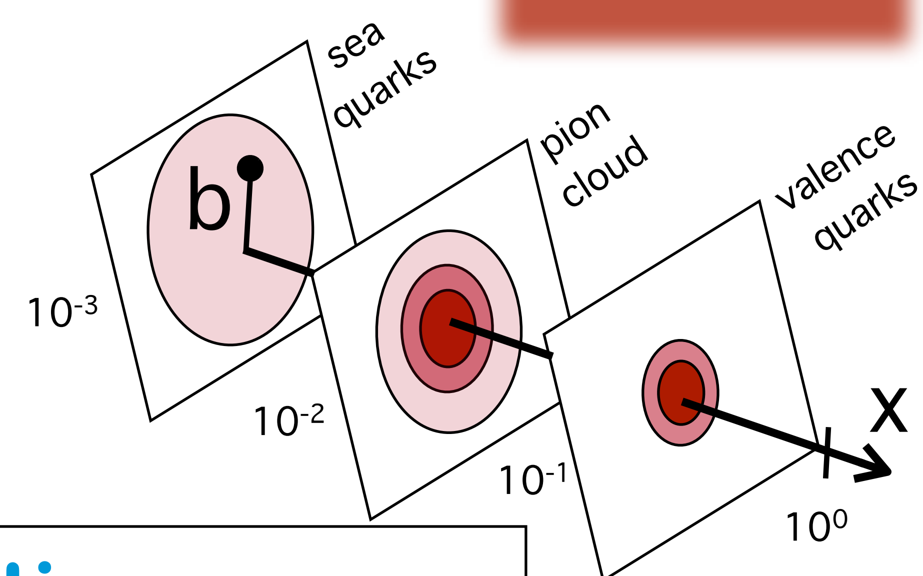
Outline: DVCS @ HERMES

- Setting the scene
- Results on the proton target
- Results using recoil-proton detection
- Results on targets heavier than the proton

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

DVCS as Laboratory for Probing Hadrons

1. Access to Generalized Parton Distributions

☛ "Nucleon Tomography"

☛ Global analysis

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

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

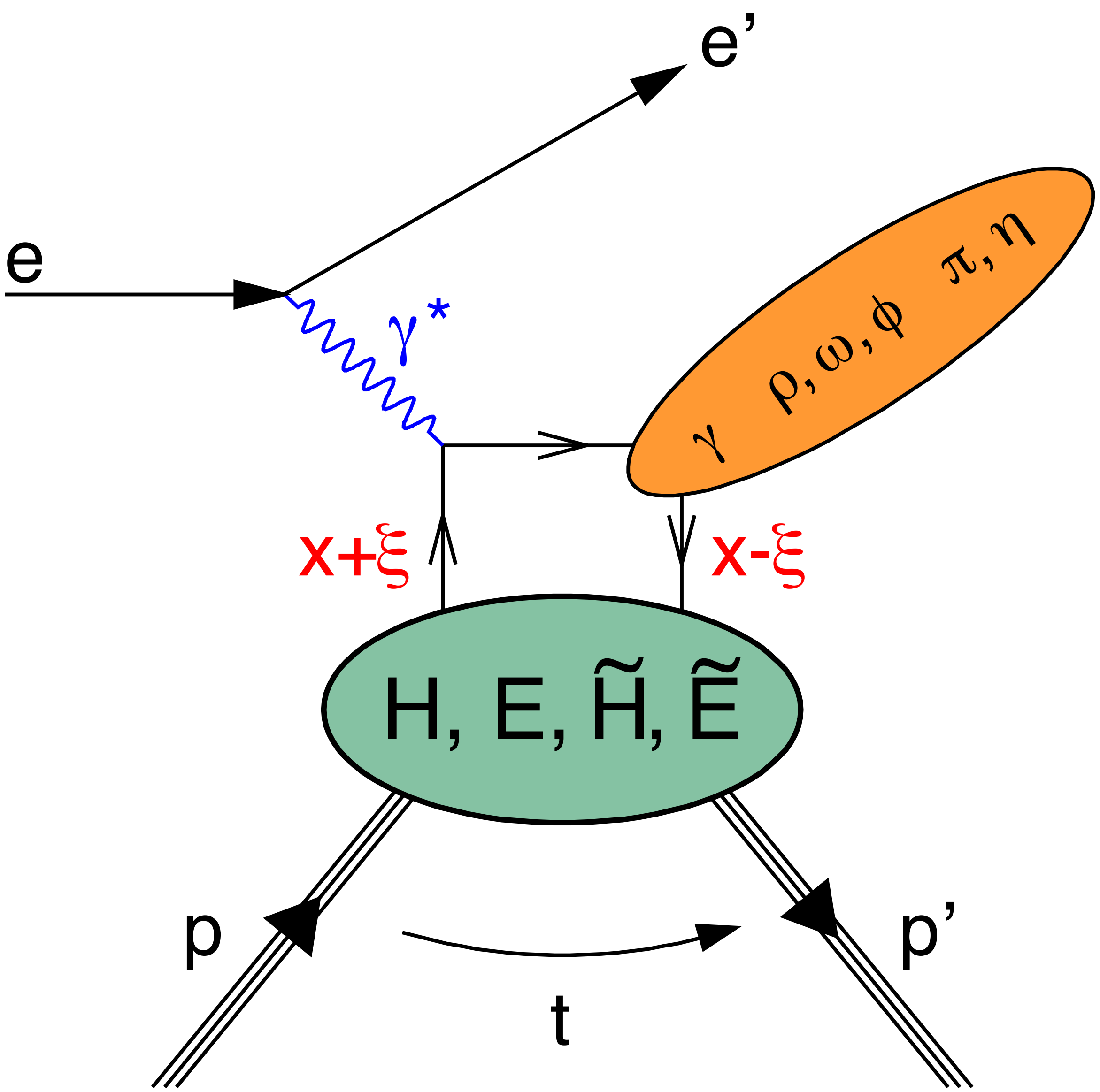
-Ji, PRL 78 (1997) 610-

3. DVCS on hadrons other than the nucleon

Spin-1: tensor and coherent signatures?

How does the nuclear environment modify the DVCS amplitude?

Hard Exclusive Reactions and GPDs



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	$\widetilde{E}$	$\widetilde{H}$

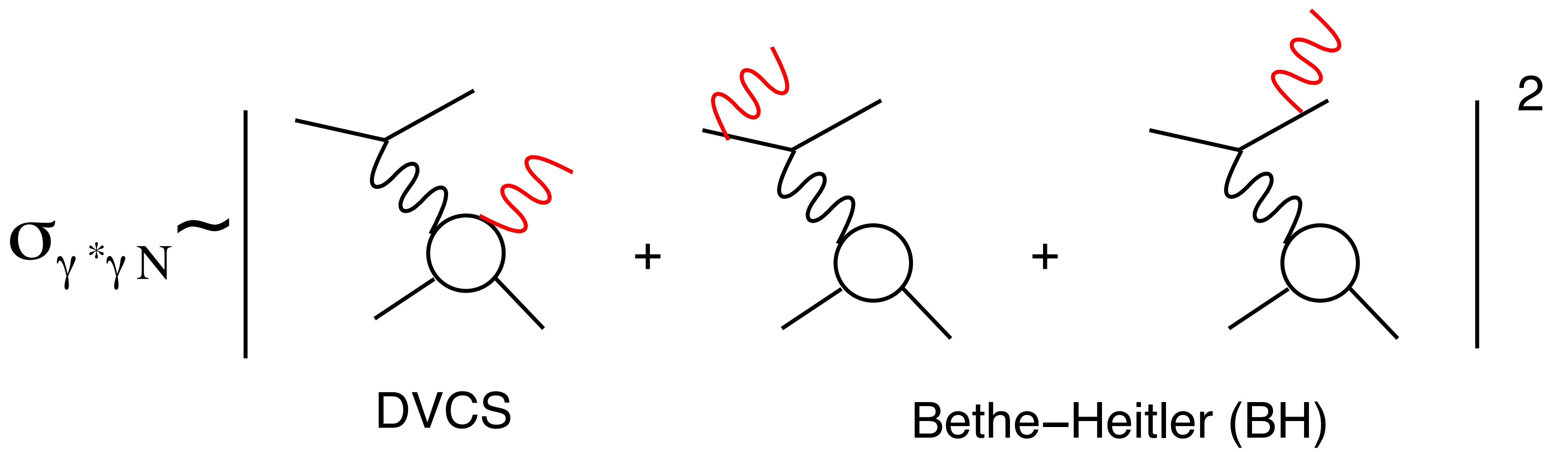
forward limit $\xi \rightarrow 0, t \rightarrow 0$

$H \rightarrow q^+ + q^-$

$\widetilde{H} \rightarrow q^+ - q^-$

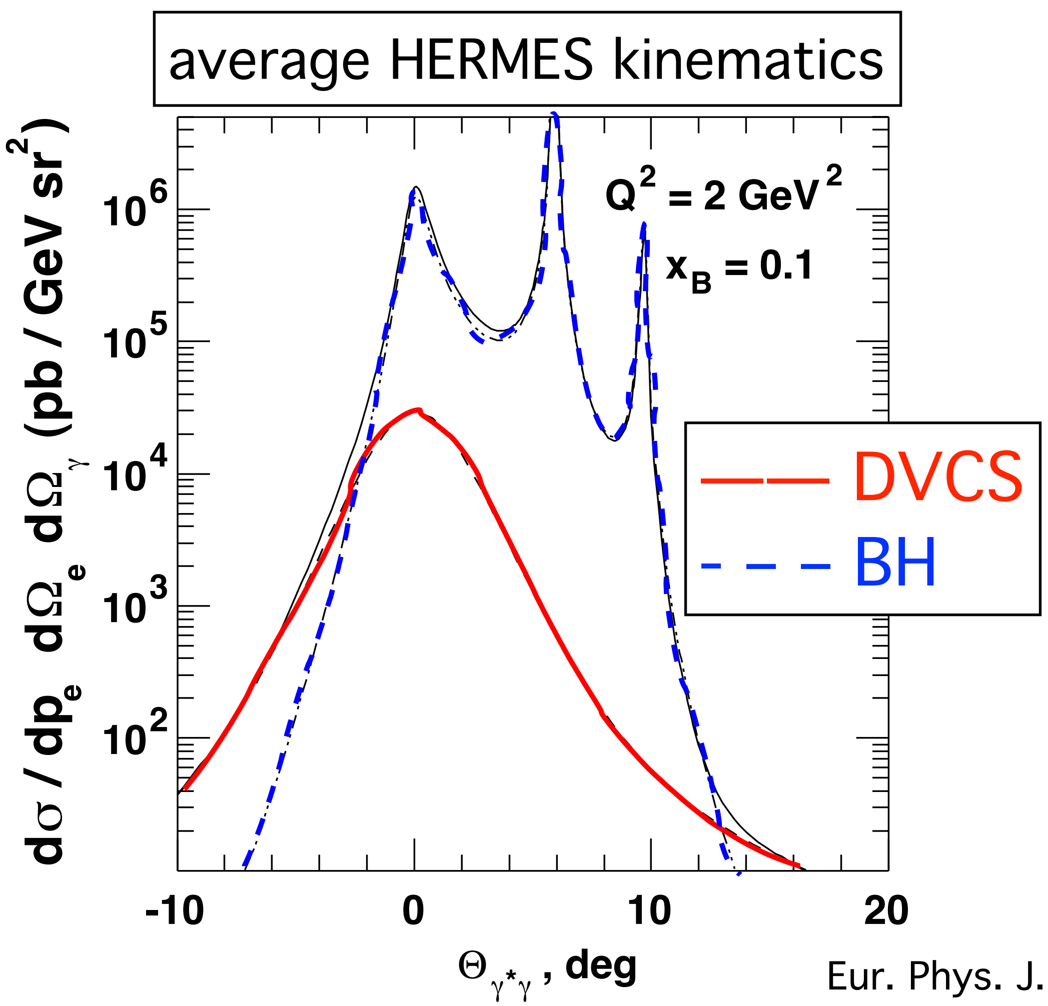
- x, ξ : longitudinal momentum fractions of probed quark
- t : squared 4-momentum transfer to target
- DVCS: Deeply Virtual Compton Scattering = electroproduction of a real photon

Deeply Virtual Compton Scattering



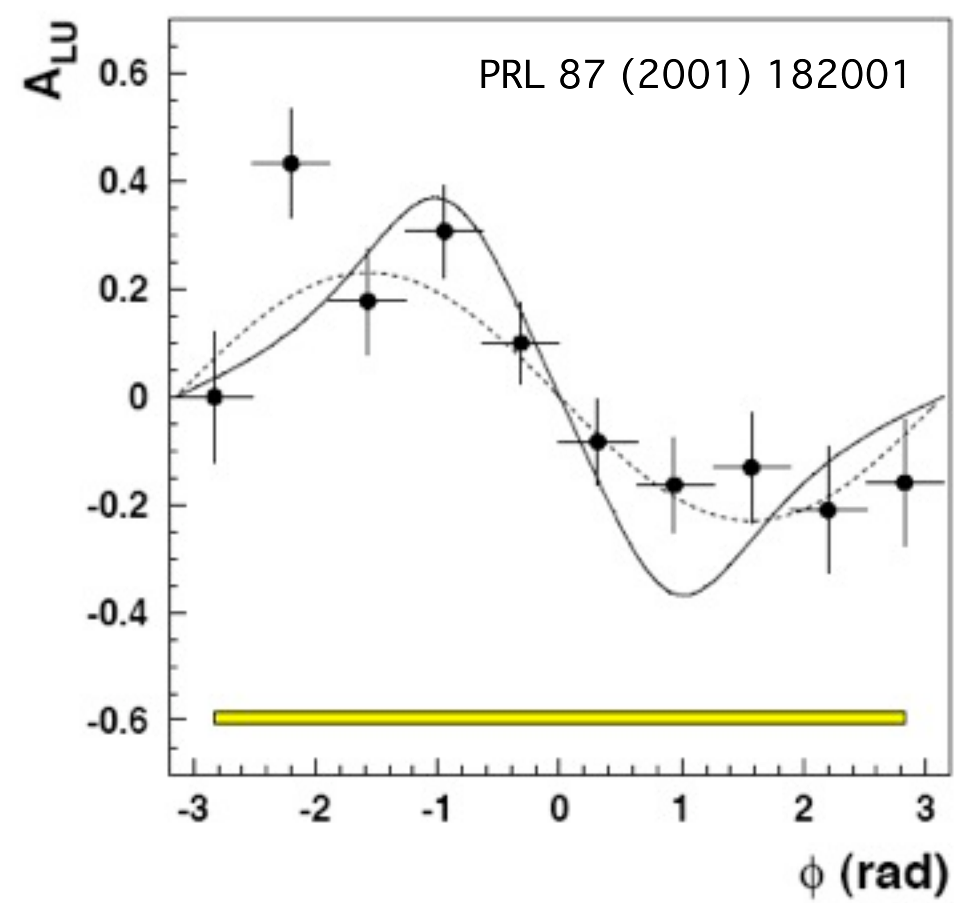
$= |\tau_{DVCS}|^2 + |\tau_{BH}|^2 + (\tau_{DVCS}\tau_{BH}^* + \tau_{DVCS}^*\tau_{BH})$

DVCS-BH interference term



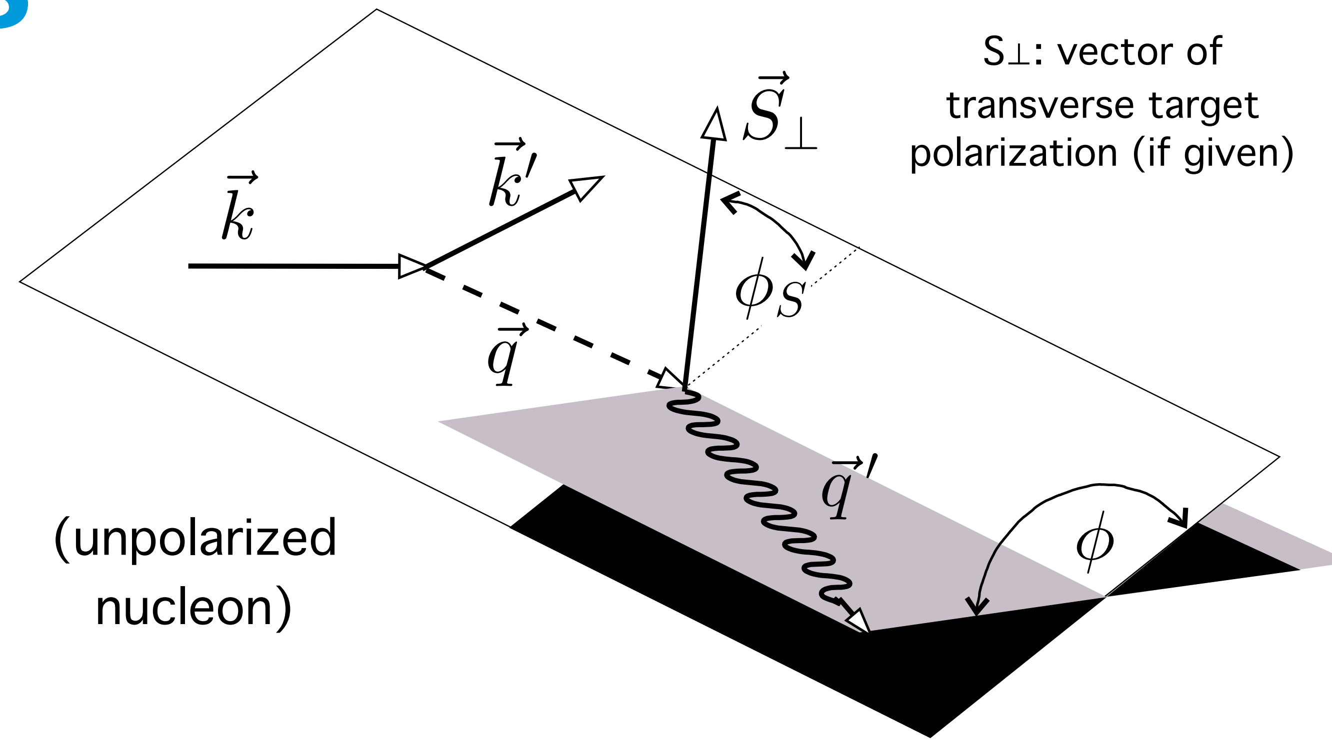
Eur. Phys. J. C 23 (2002) 455 [hep-ph/018077]

early HERMES measurement



Harmonic Analysis

lepton beam k with
charge C_B and helicity P_B



S⊥: vector of transverse target polarization (if given)

(unpolarized nucleon)

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

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

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

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

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

Beam-charge asymmetry

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

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

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}:

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

Azimuthal Asymmetries and GPDs

$\mathcal{A}_{\mathrm{LU}}$
Beam Target

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

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

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

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.

Longitudinal target-spin asymmetry

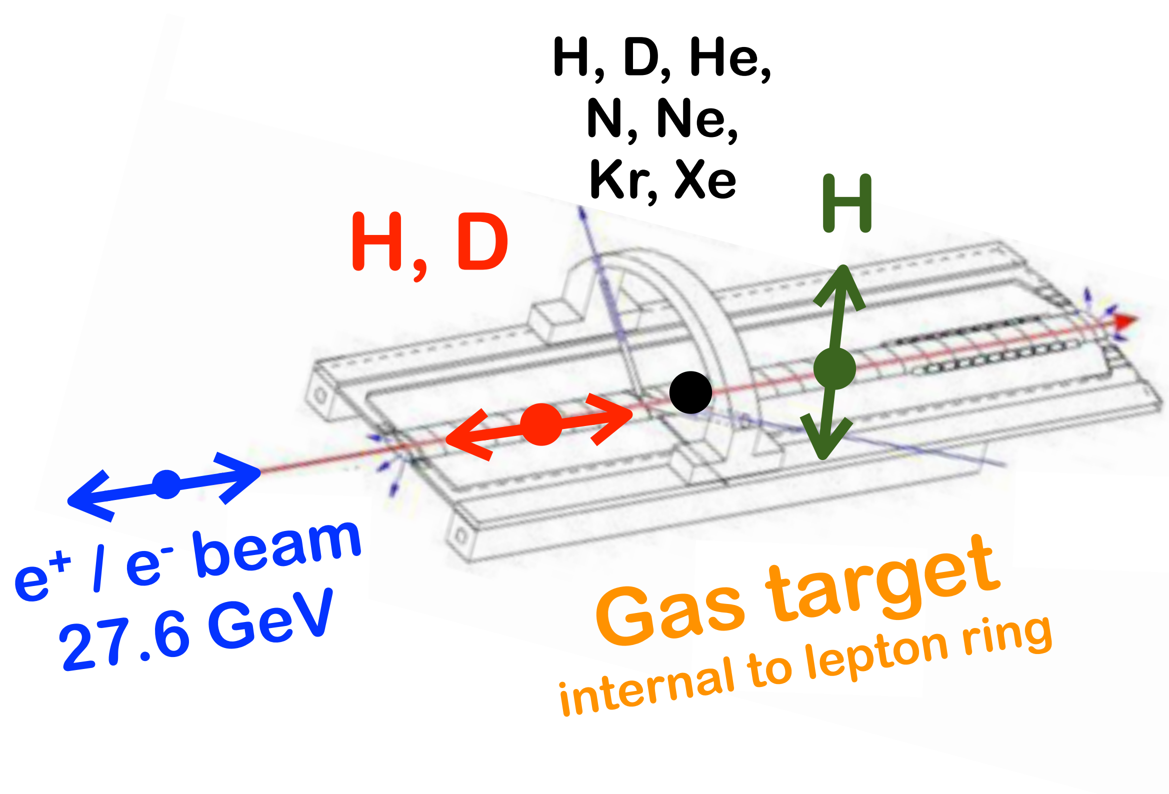
$$\mathcal{A}_{\mathrm{UL}}(\phi, e_\ell) \equiv \frac{[\sigma^{\leftarrow\Rightarrow}(\phi, e_\ell) + \sigma^{\rightarrow\Rightarrow}(\phi, e_\ell)] - [\sigma^{\leftarrow\Leftarrow}(\phi, e_\ell) + \sigma^{\rightarrow\Leftarrow}(\phi, e_\ell)]}{[\sigma^{\leftarrow\Rightarrow}(\phi, e_\ell) + \sigma^{\rightarrow\Rightarrow}(\phi,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

Double-spin (LL) asymmetry

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

HERMES

HERA @ DESY retired 30.6.2007

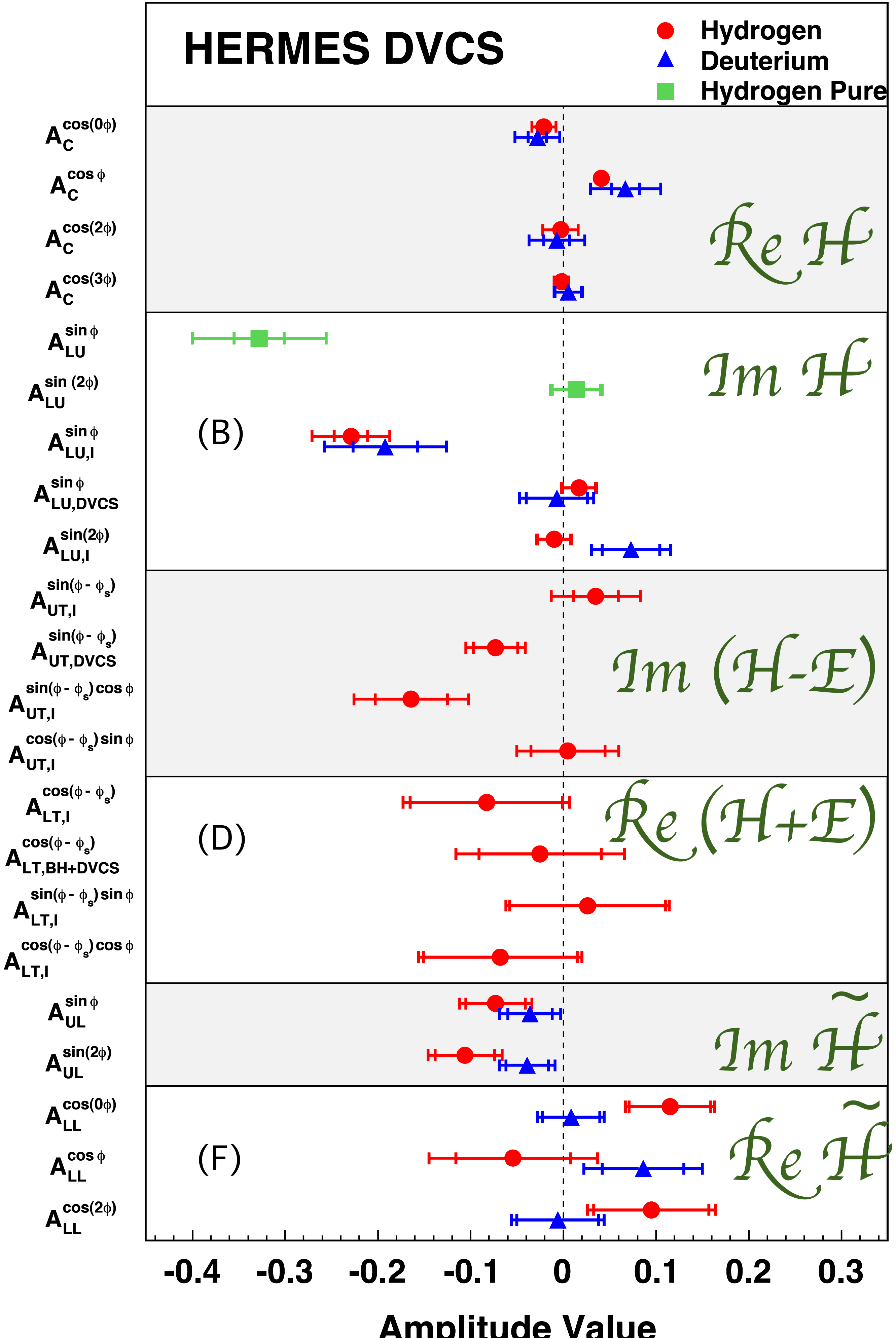


Results on the proton target

- ☛ Proton target with longitudinal (50 /pb) & transverse polarization (150 /pb); unpolarized (1200 /pb, thereof 670 /pb with fully operational recoil detector)

- ☛ Deuteron target with longitudinal polarization (200 /pb); unpolarized (800 /pb)

- ☛ Nuclear Targets: He, N, Ne, Kr, Xe (300 /pb)



DVCS 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]

Unique & complete set

Variety highly welcome by global fitters

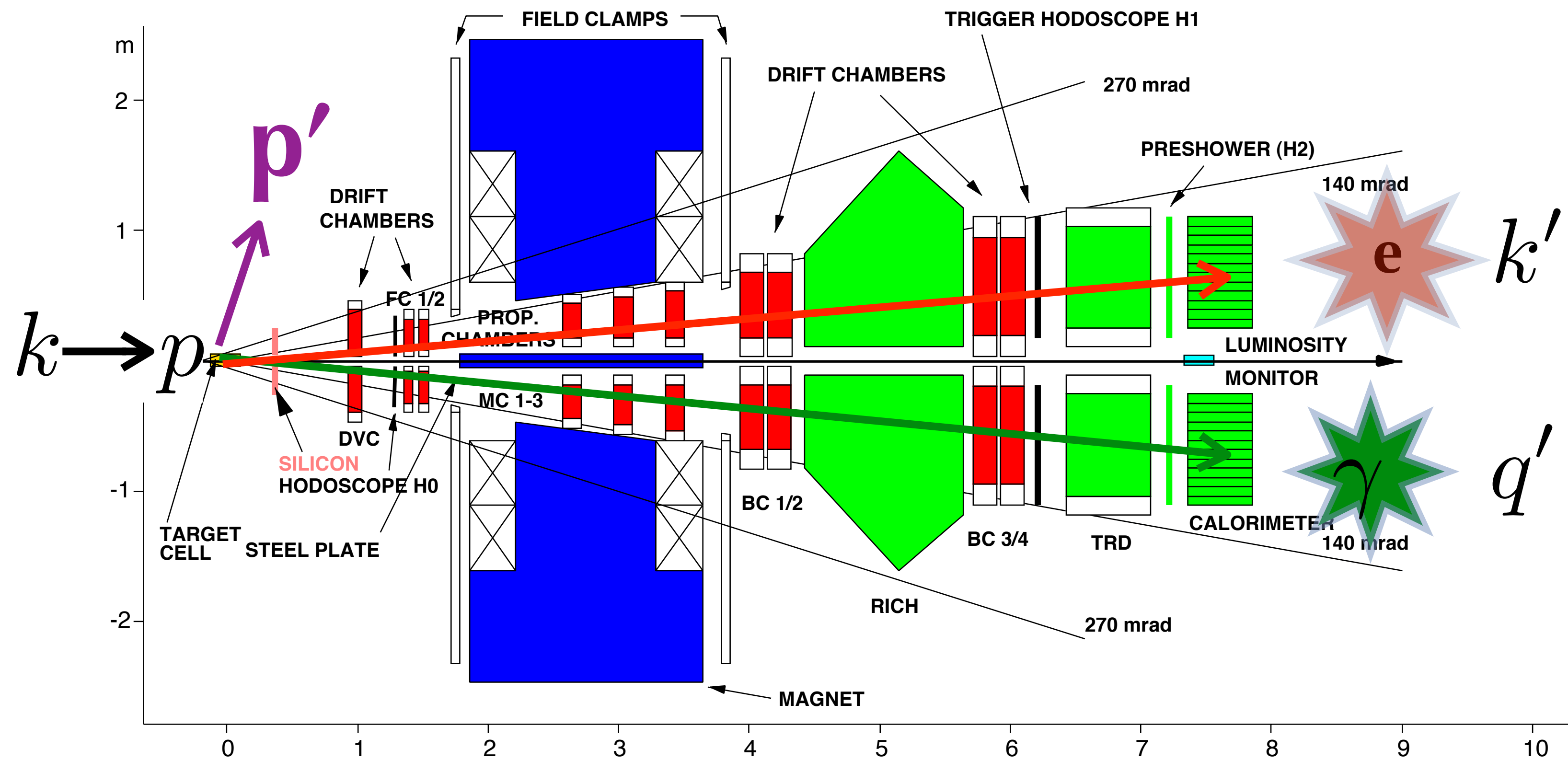
(E) Longitudinal target-spin asymmetry:
GPD H~
[JHEP 06 (2010) 019 - Nucl. Phys. B 842 (2011) 265–298]

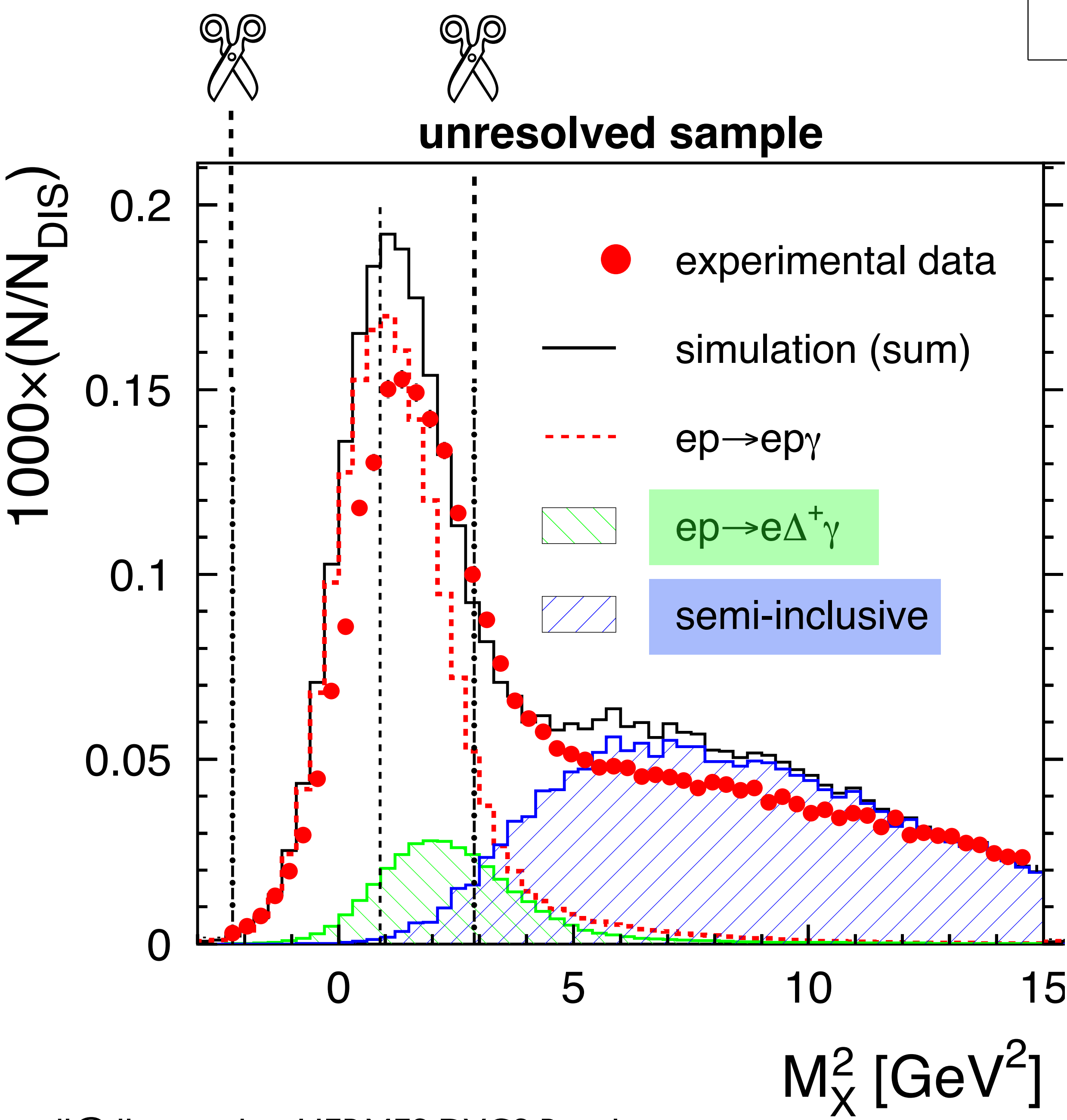
(F) Double-spin (LL) asymmetry:
GPD H~
[JHEP 06 (2010) 019 - Nucl. Phys. B 842 (2011) 265–298]

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

"Traditional" DVCS Analysis

"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%

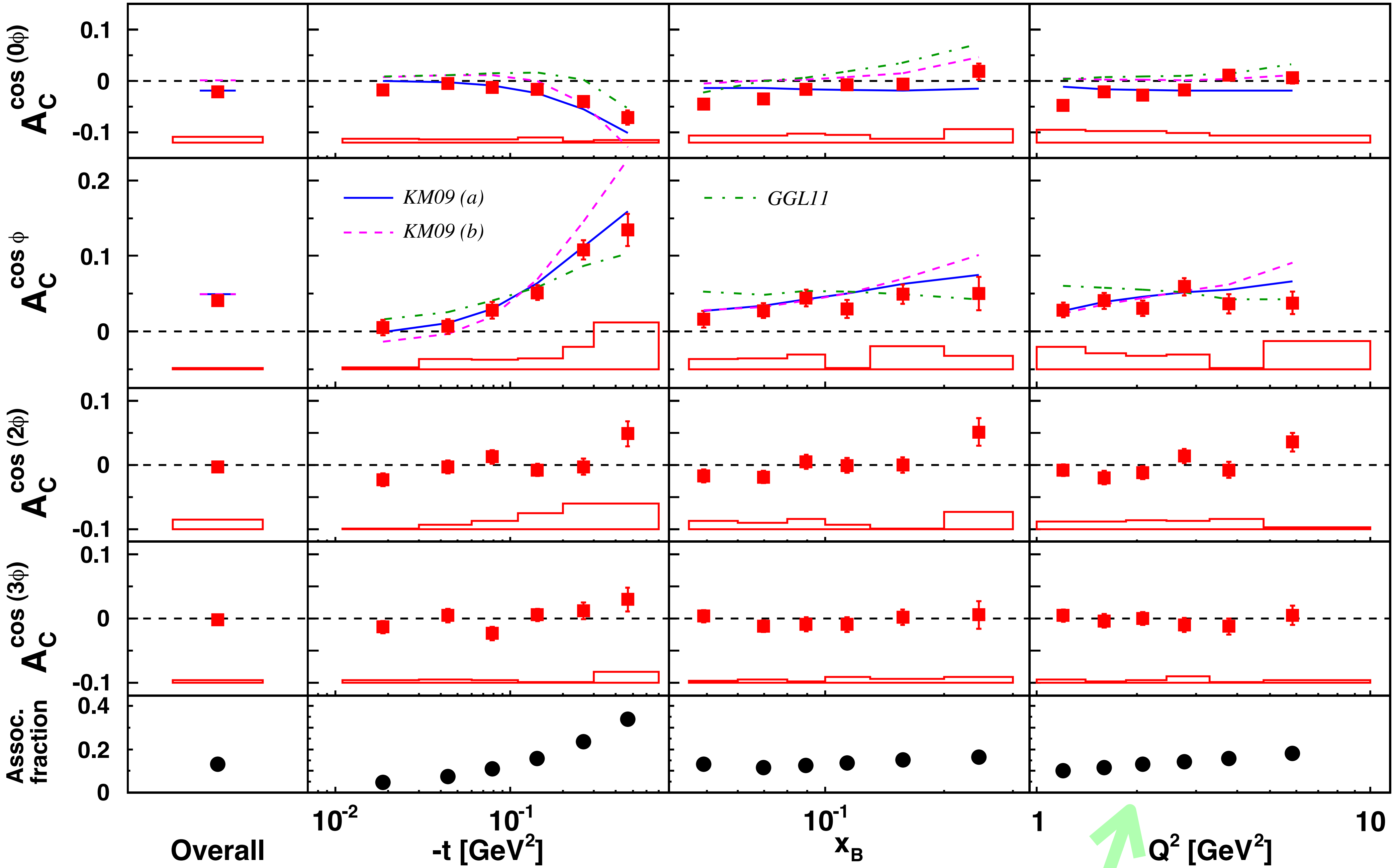
✘ Unresolved for associated production

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

Beam-Charge Asymmetry

GPD H

All 1996–2007 proton data



☆ 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 [arXiv:0904.0458]

☆ GGL11

Model calculation

G. Goldstein, J. Hernandez and S. Liuti, Phys. Rev. D 84 034007 (2011) [arxiv:1012.3776]

Associated fraction $ep \to e\Delta^+\gamma$

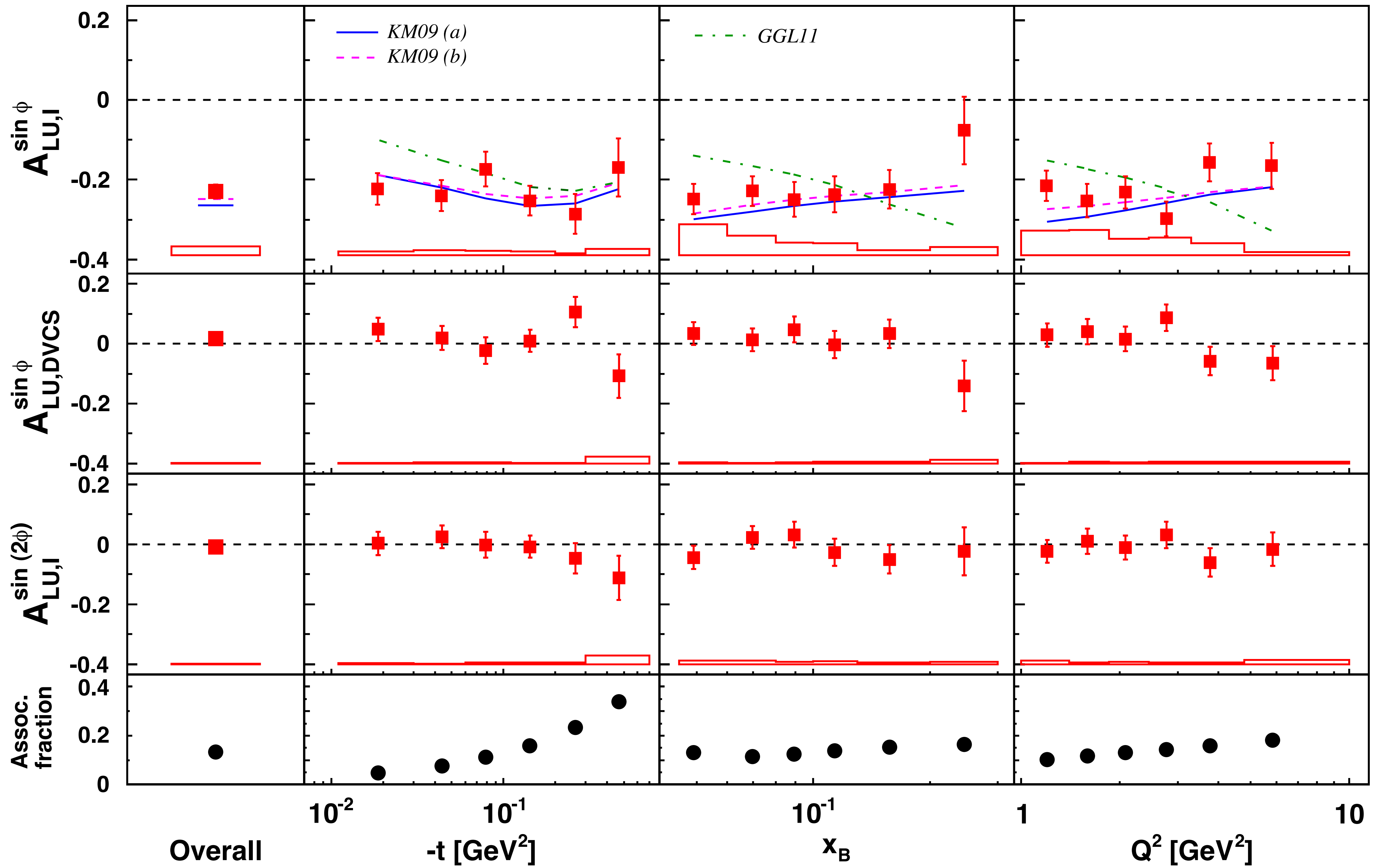
(from MC simulation)

JHEP 07 (2012) 032

GPD H

Beam-Helicity Asymmetry

All 1996–2007 proton data

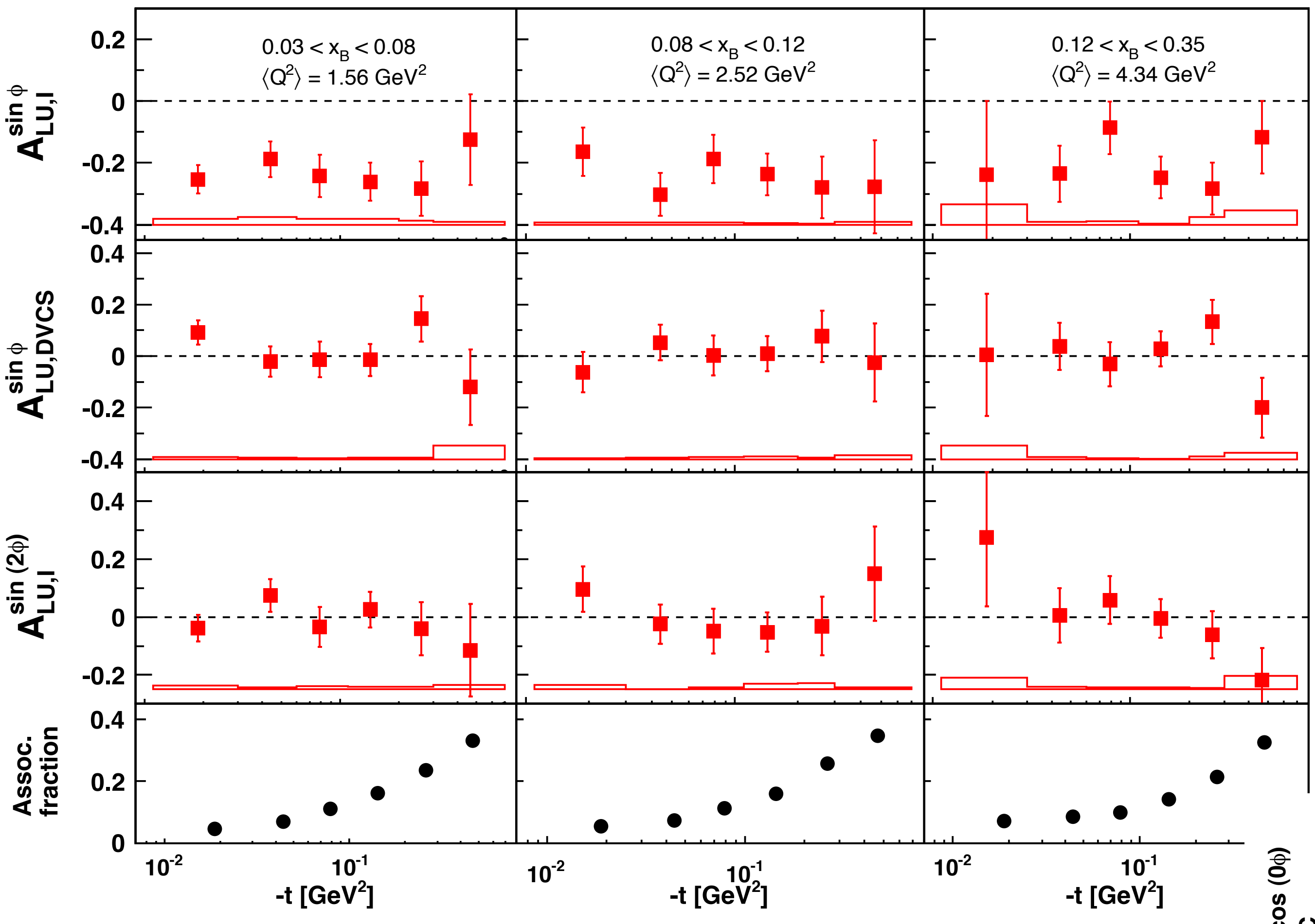


JHEP 07 (2012) 032

GPD H

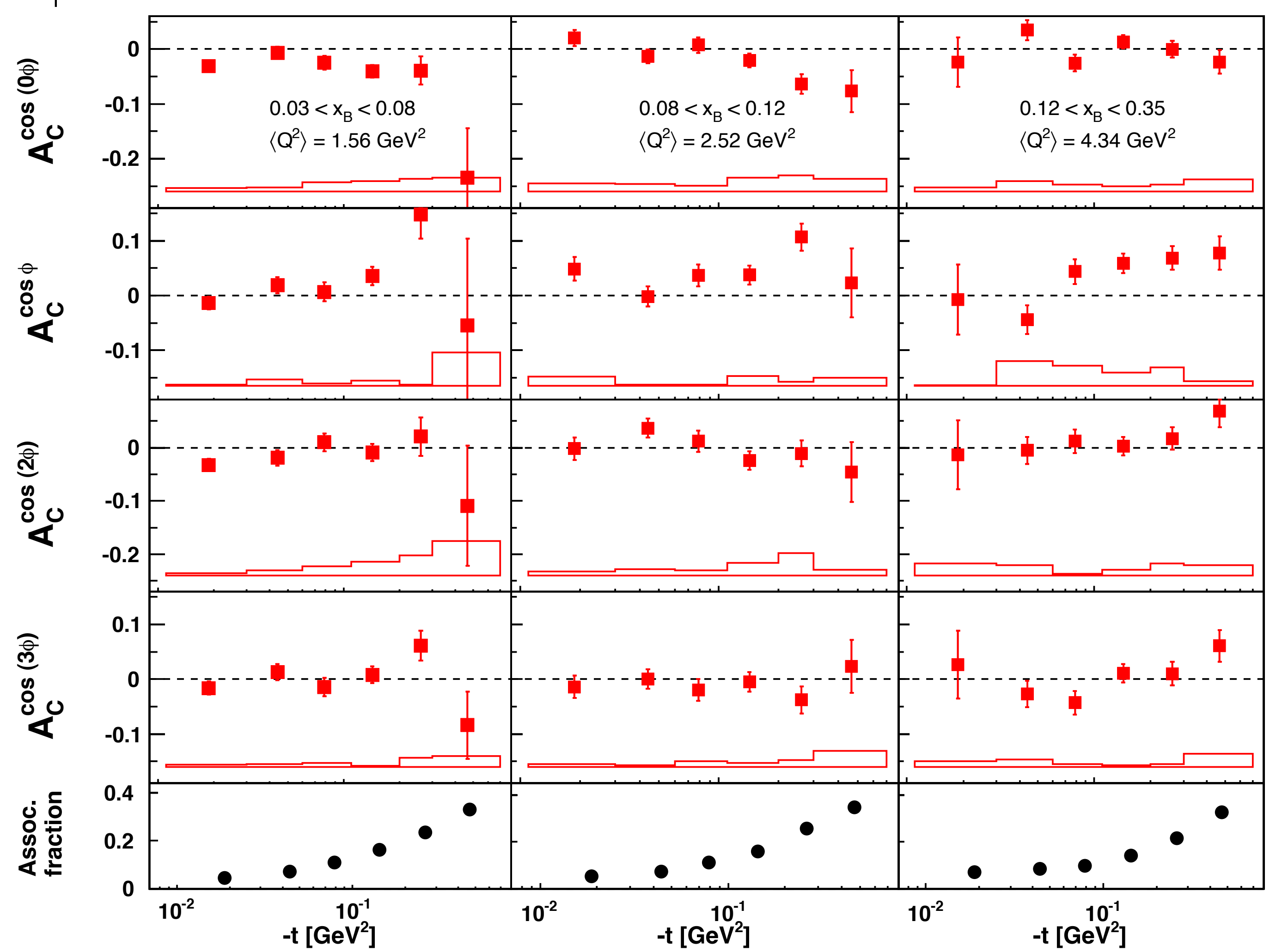
2-Dimensional (-t, Q^2) Binning

All 1996–2007 proton data



beam-helicity asymmetry

beam-charge asymmetry



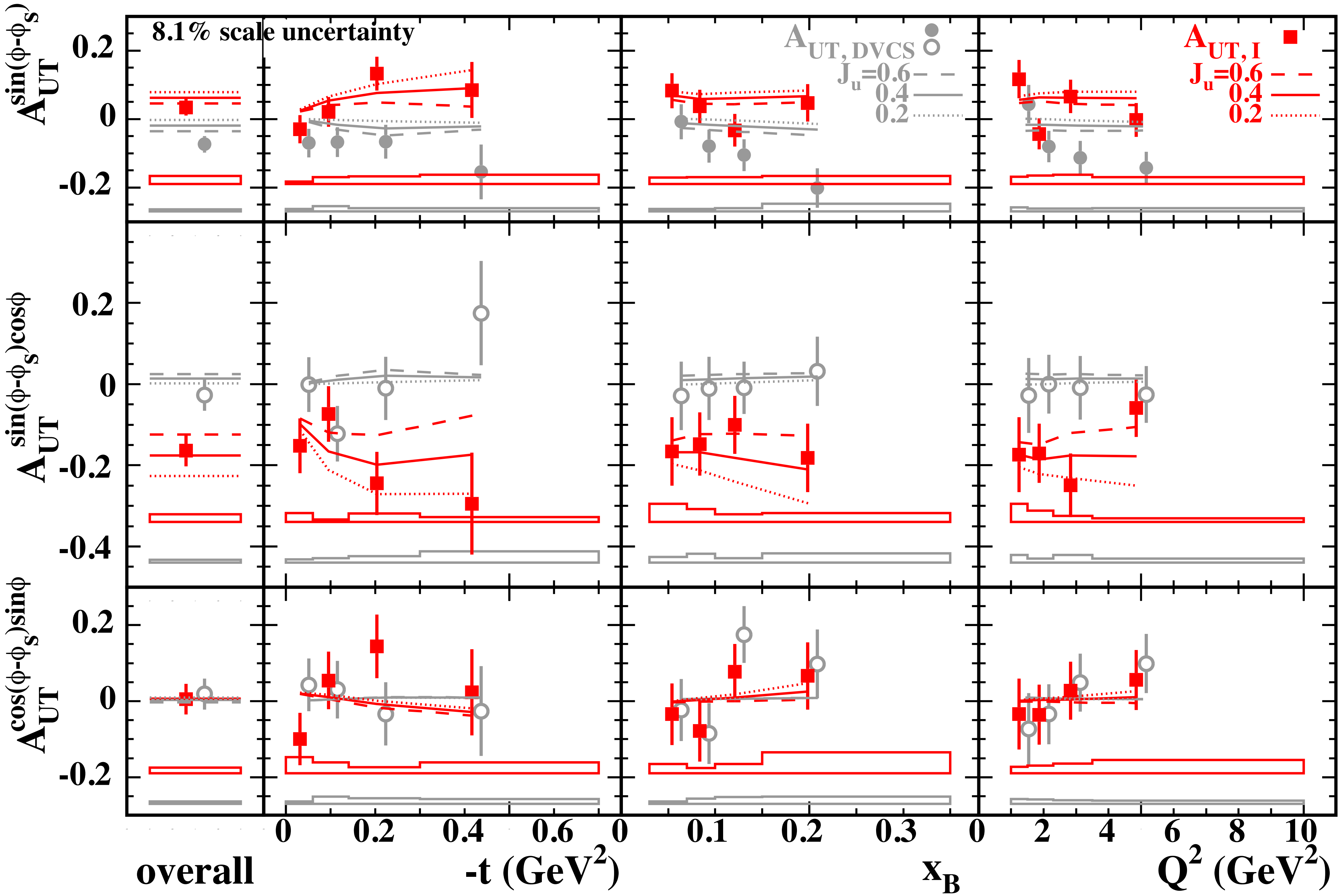
1D results also available in "traditional binning" with 4 bins (→ global fits)

JHEP 07 (2012) 032

GPD E

Transverse Target-Spin Asymmetry

2002–2005 transversely polarized proton data



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

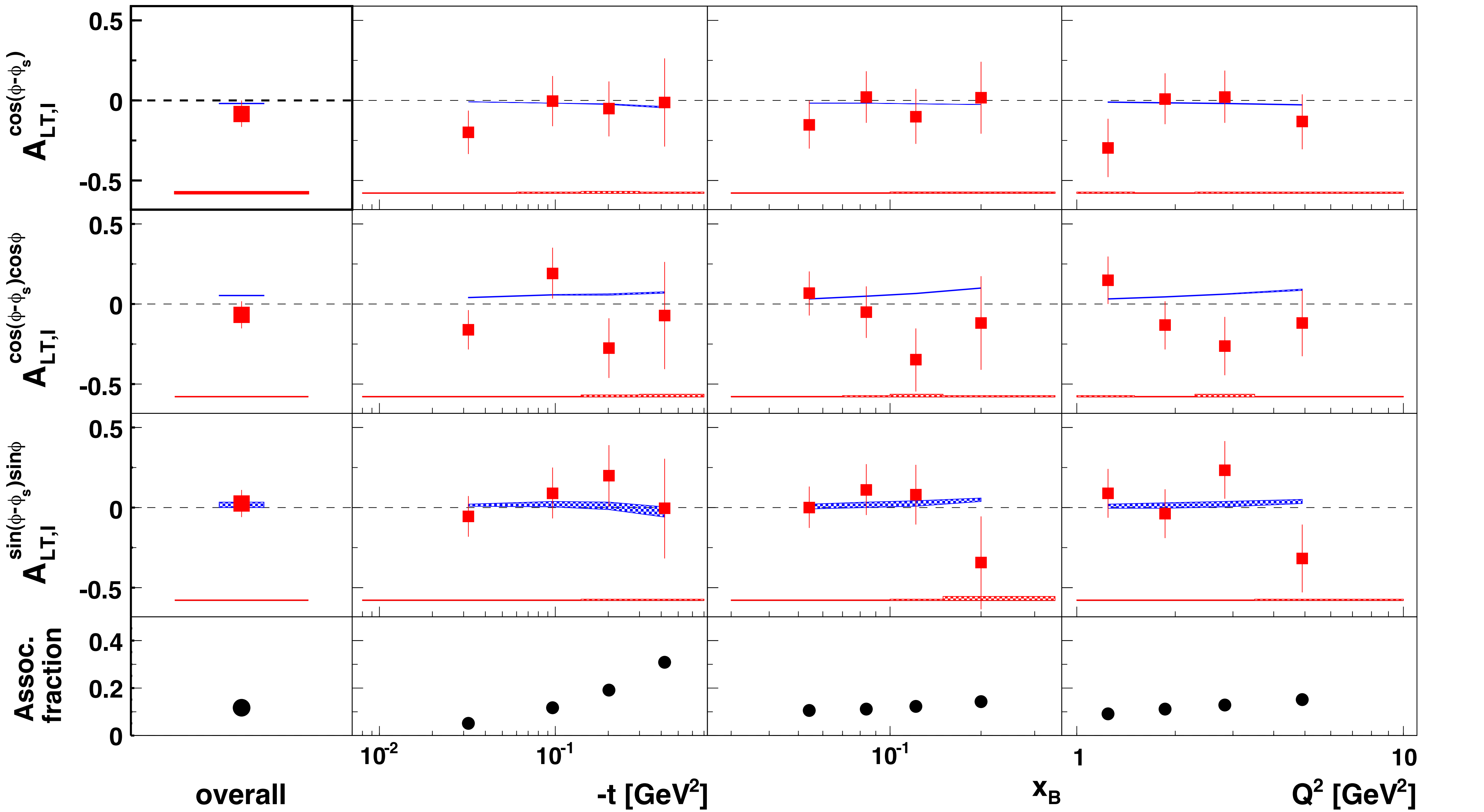
JHEP 06 (2008) 066

GPD E

Double-Spin (LT) Asymmetry

2002–2005 transversely polarized proton data

Charge-difference



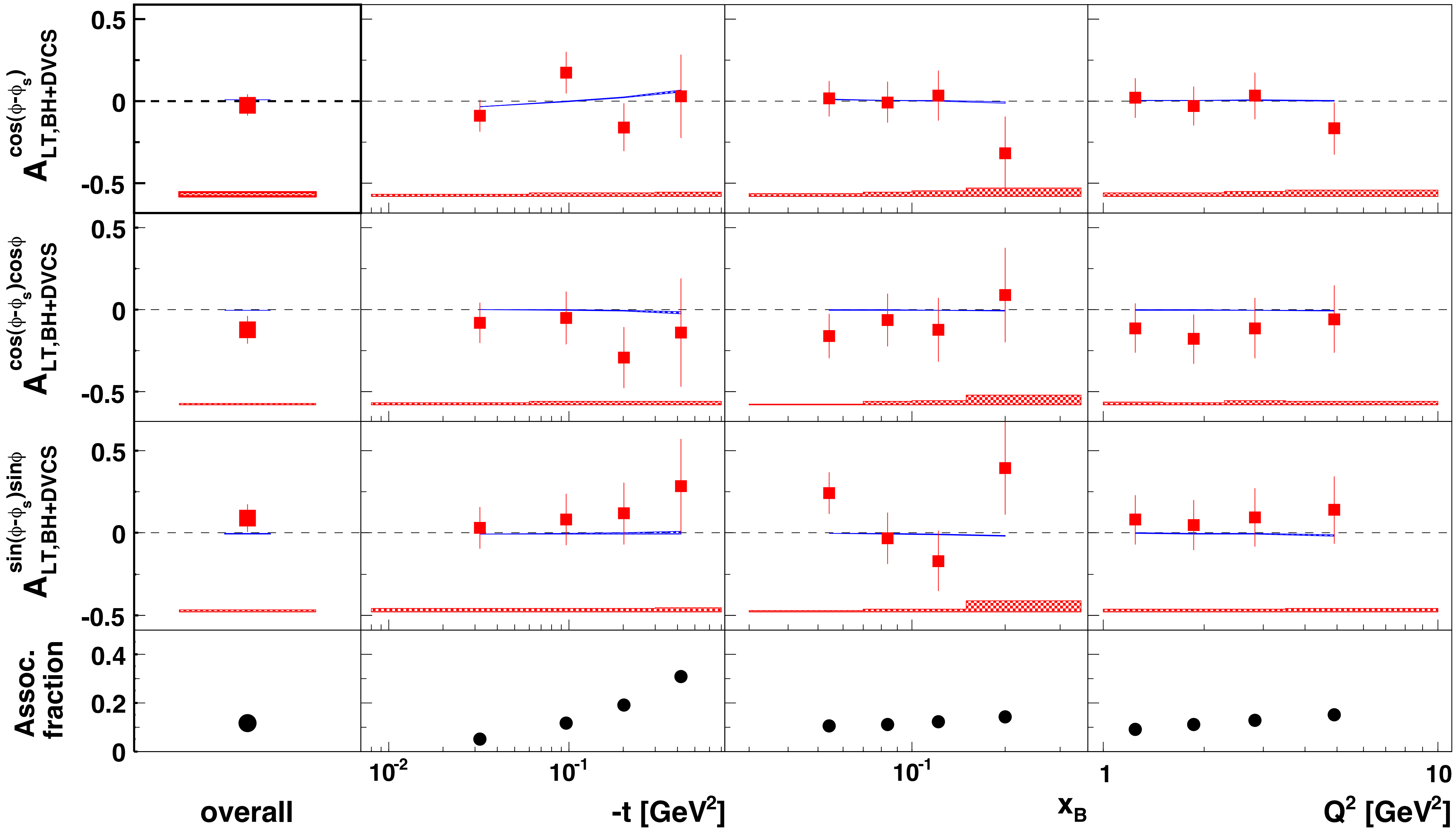
Phys. Lett. B 704 (2011) 15-23

GPD E

Double-Spin (LT) Asymmetry

Charge-averaged

2002–2005 transversely polarized proton data



Phys. Lett. B 704 (2011) 15-23

Total angular momentum of quarks

Nucleon spin $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_g$

Ji sum rule for the nucleon

-Ji, PRL 78 (1997) 610-

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

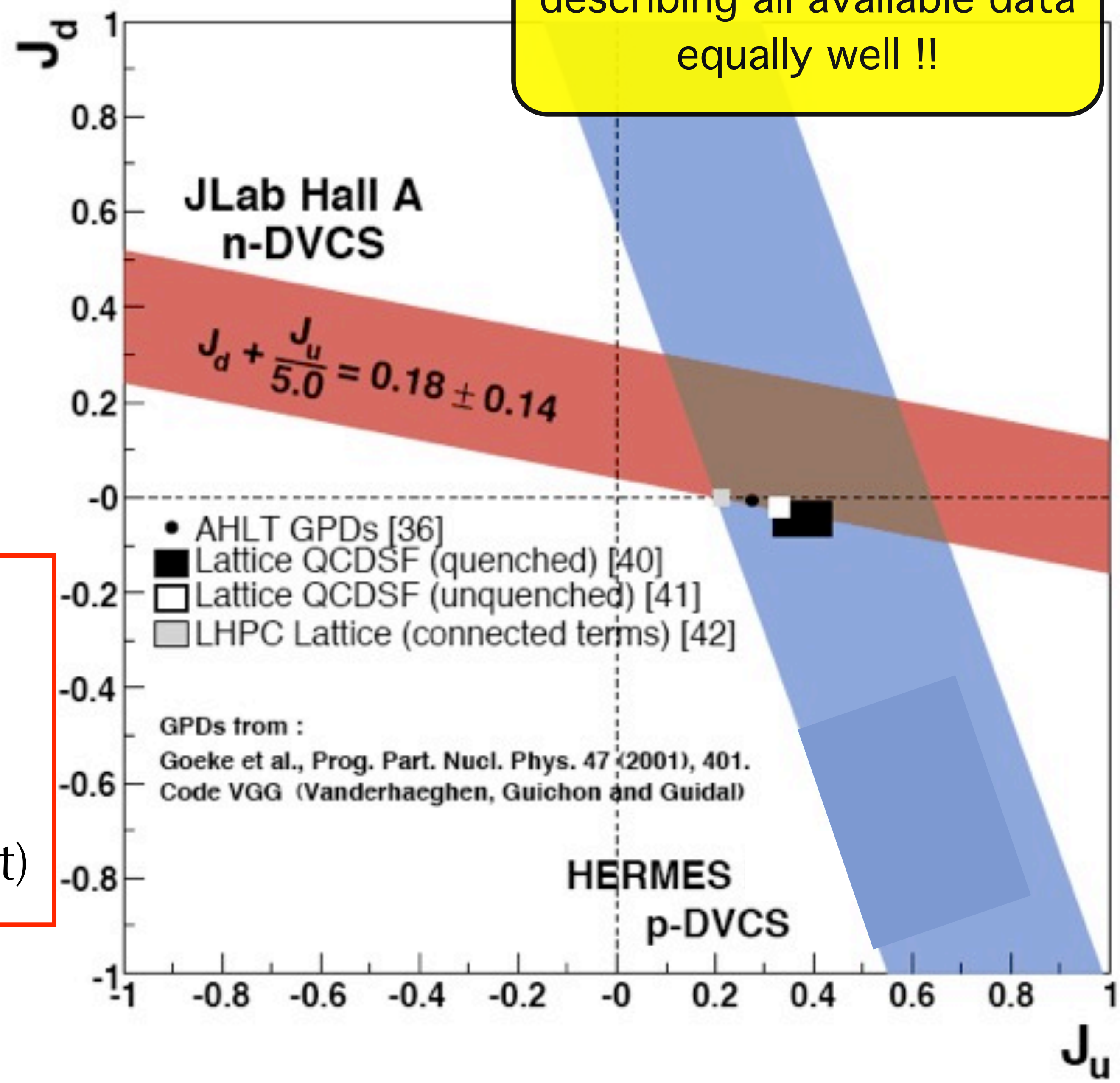
HERMES + CLAS measurements & sensitivity to J_q:

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

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

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

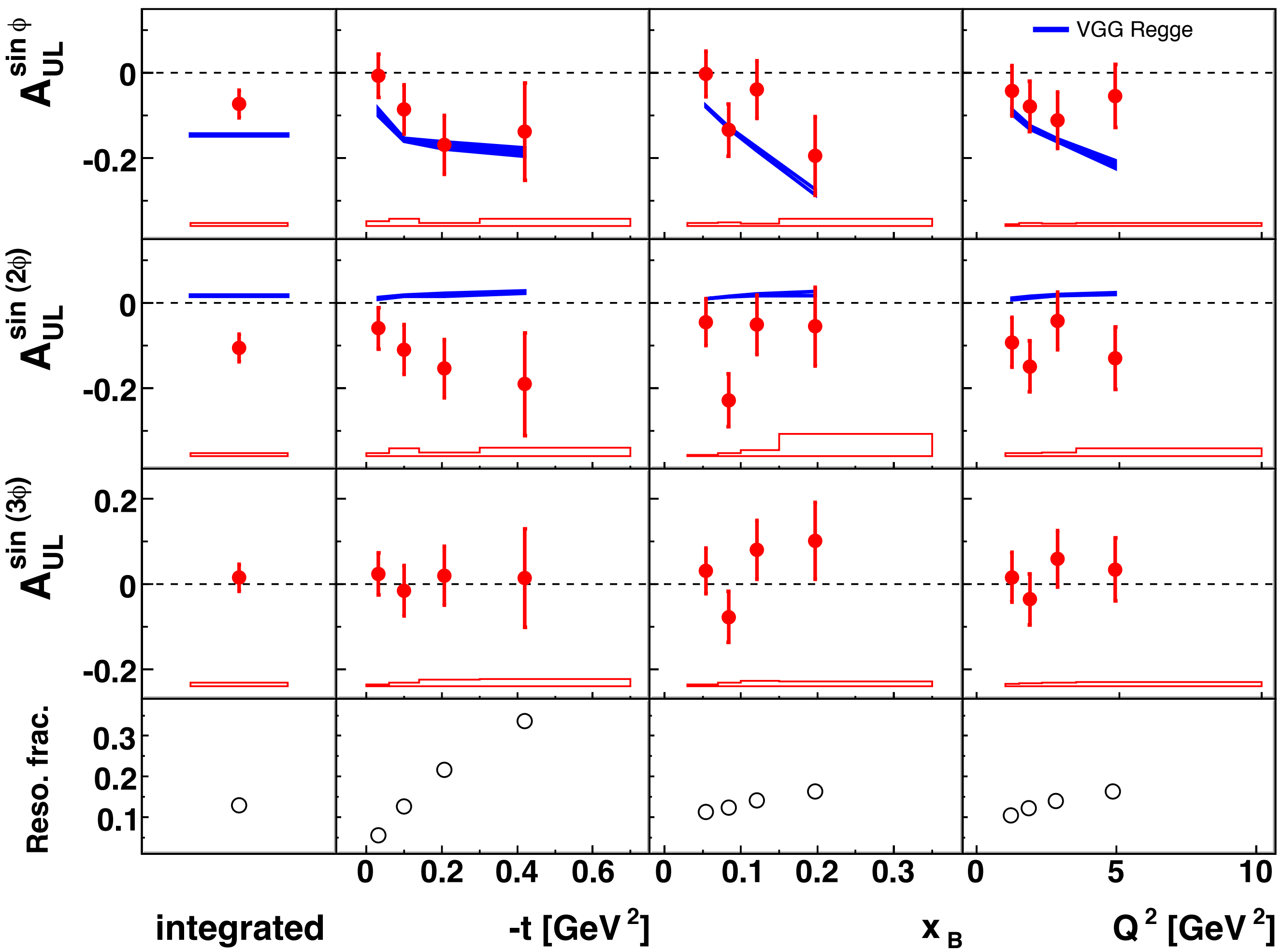
Caveat: model-dependent constraint on $J_u + k \cdot J_d$. GPD models are far from describing all available data equally well !!



GPD H~

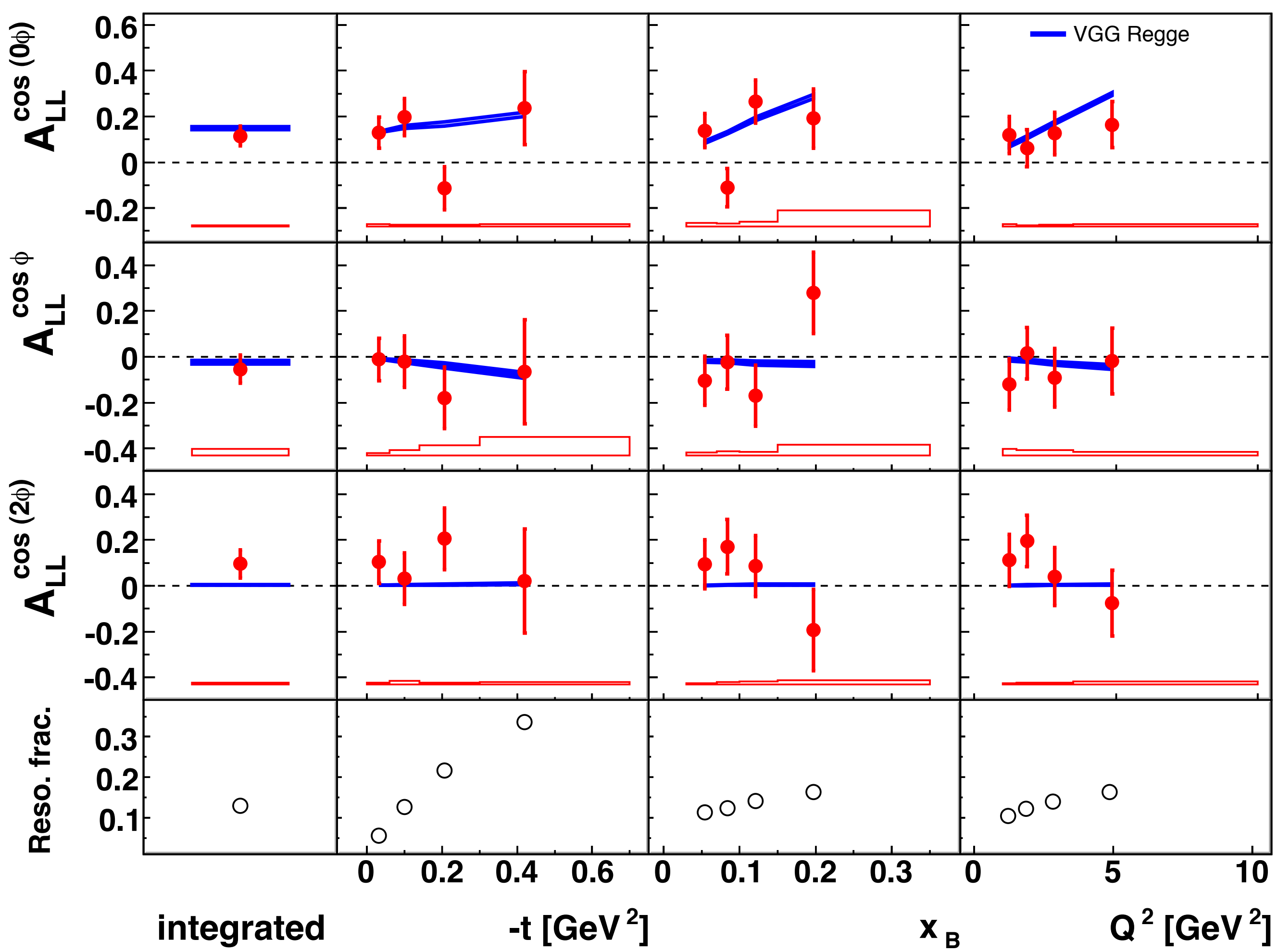
Longitudinal Target-Spin Asymmetry

target-spin asymmetry



1996/1997 longitudinally polarized proton data

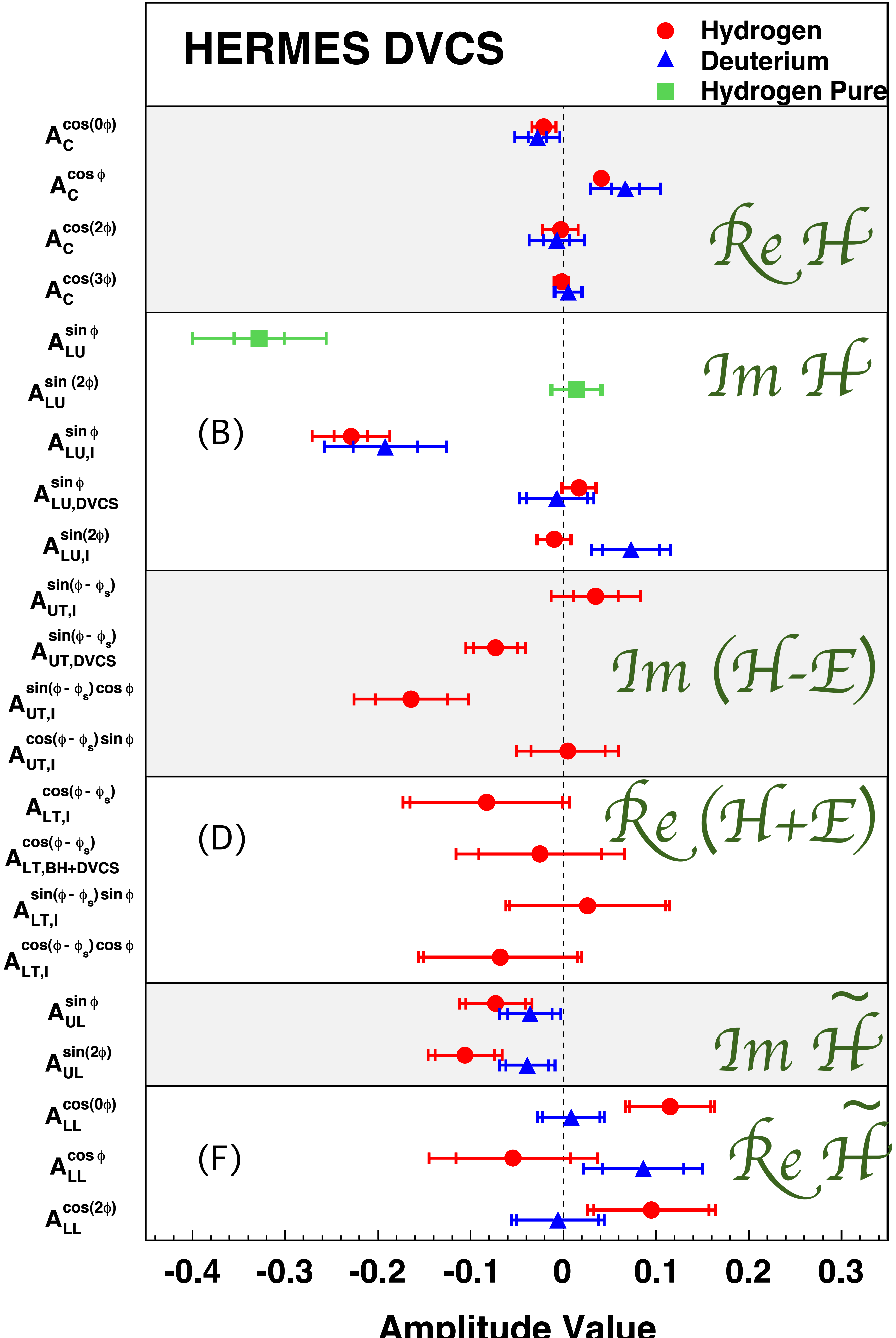
double-spin (LL) asymmetry



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

JHEP 06 (2010) 019

DVCS 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]

Unique & complete set

Variety highly welcome by global fitters

(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]

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

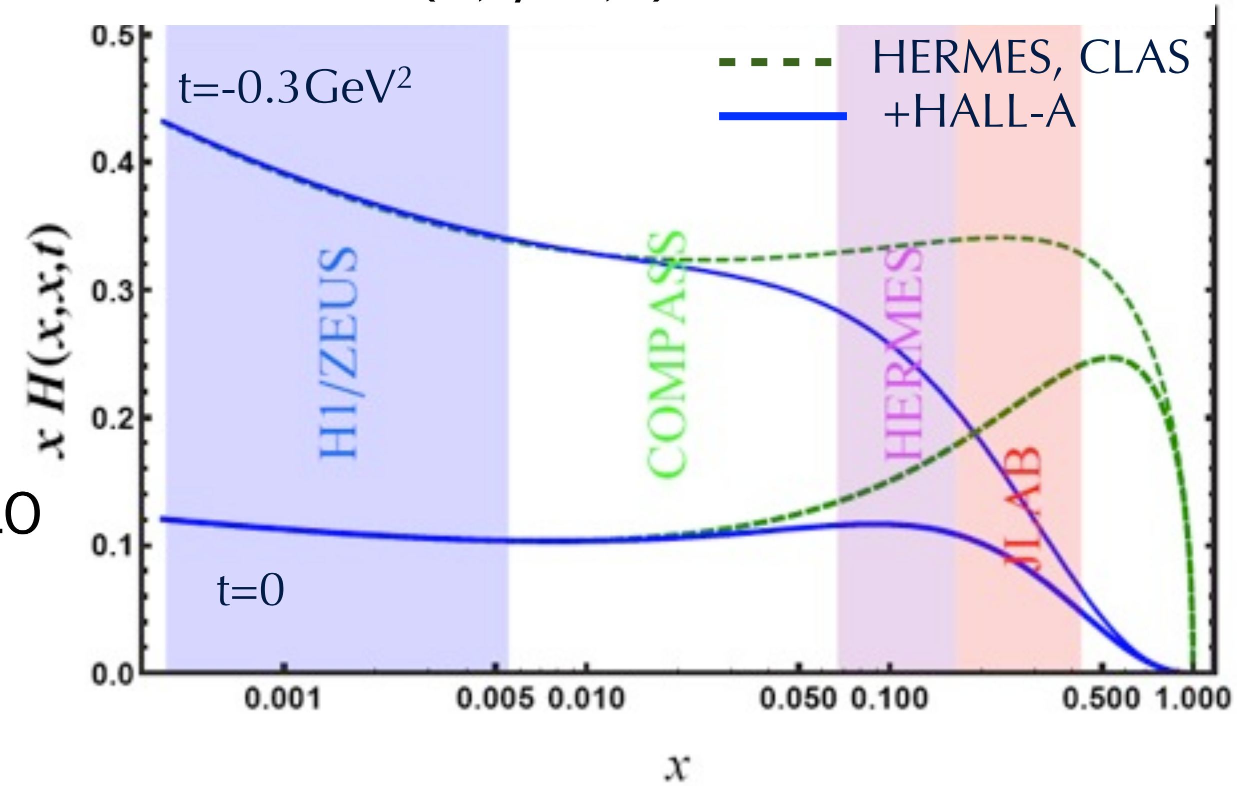
Global analysis of DVCS data

Kresimir Kumericki & Dieter Müller
Nucl. Phys. B841 (2010) 1-58

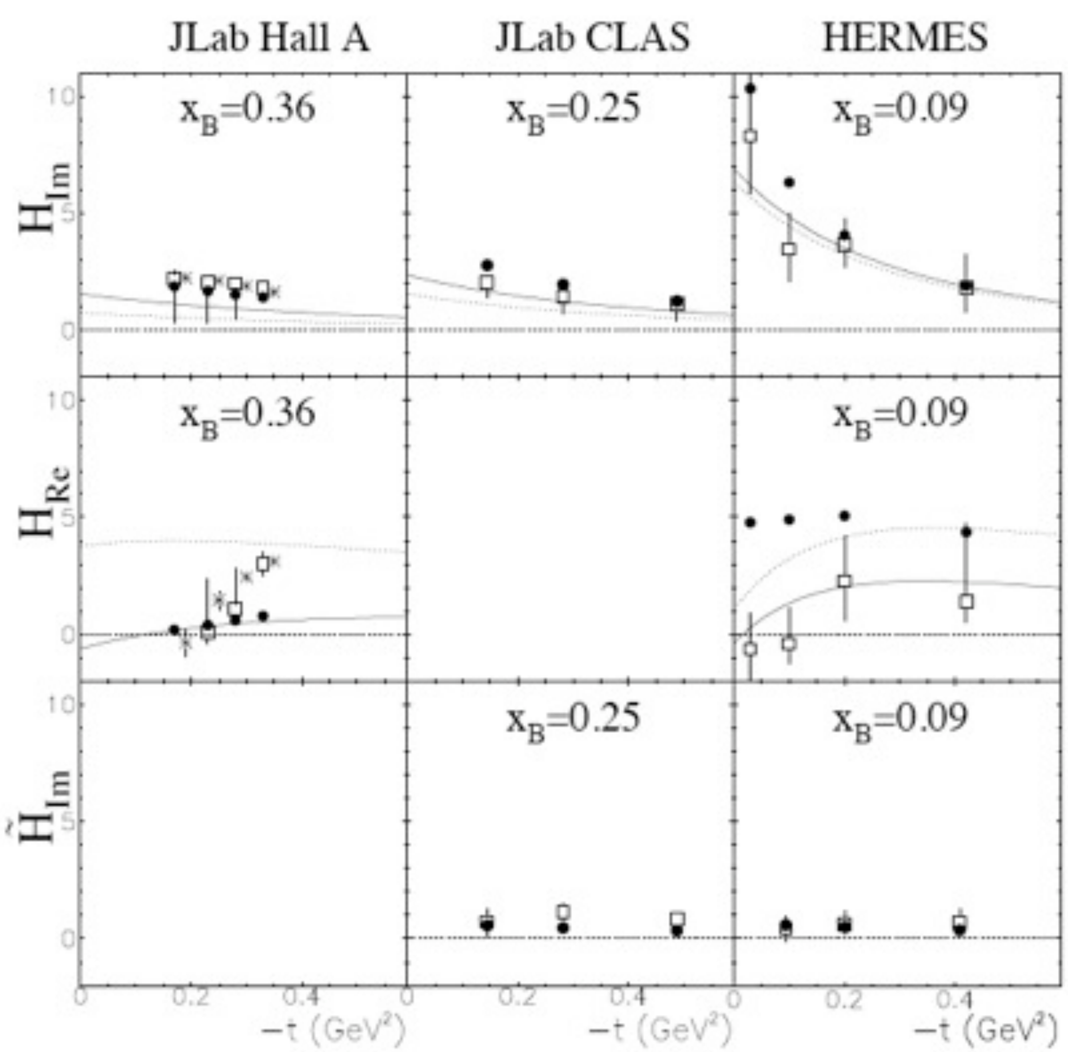
- Global fit to extract GPD H at cross-over line ξ=x. NNLO
- HERMES A_C, CLAS A_{LU} and Hall A x-section.
- Small-x behavior from HERA collider data.

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 Re(H) & Im(H)
  - Hall A x-section & CLAS A_{LU}
- Michel 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

Results using recoil-proton detection

The HERMES Recoil Detector

2006/2007 unpolarized proton and deuteron data

purpose: tagging of exclusive events

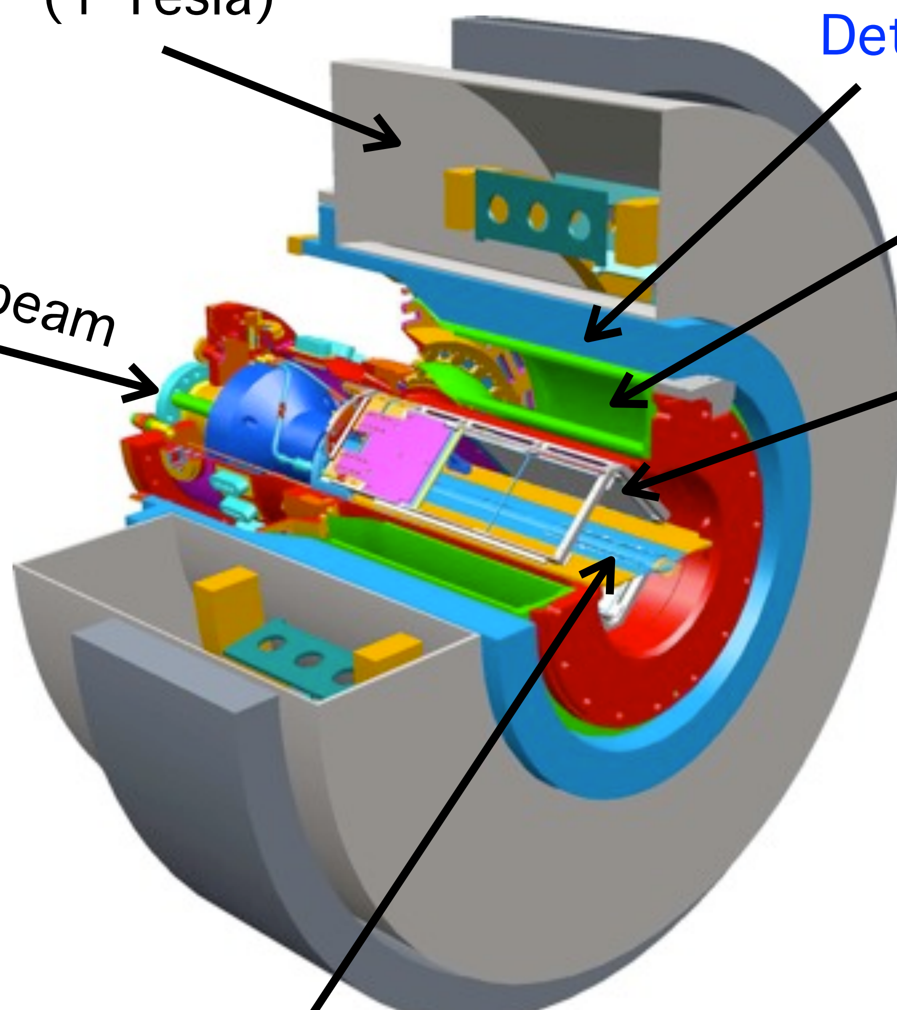
SC Solenoid (1 Tesla)

beam

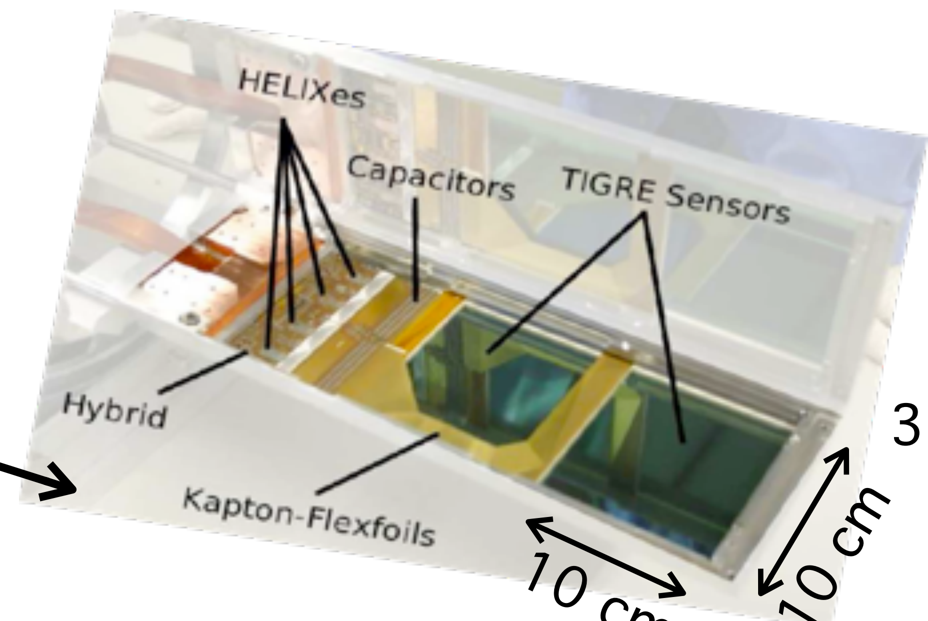
Photon Detector PD

Scintillating Fiber Tracker SFT

Silicon Strip Detector SSD



Target Cell

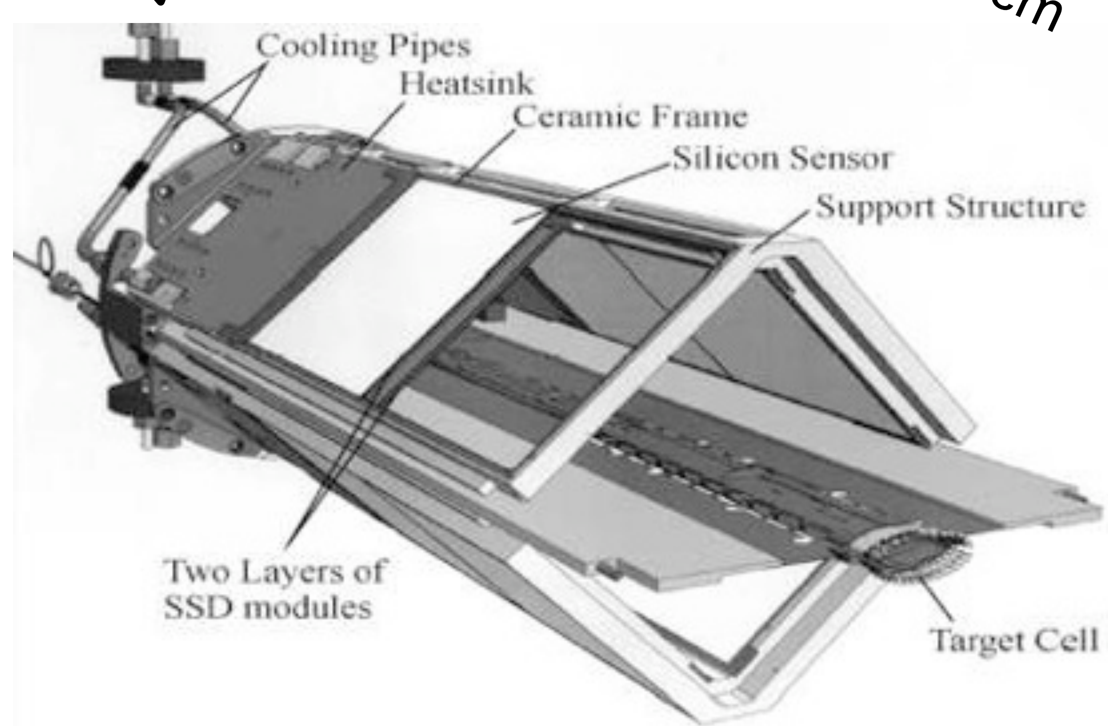


10 cm

10 cm

x2 x4

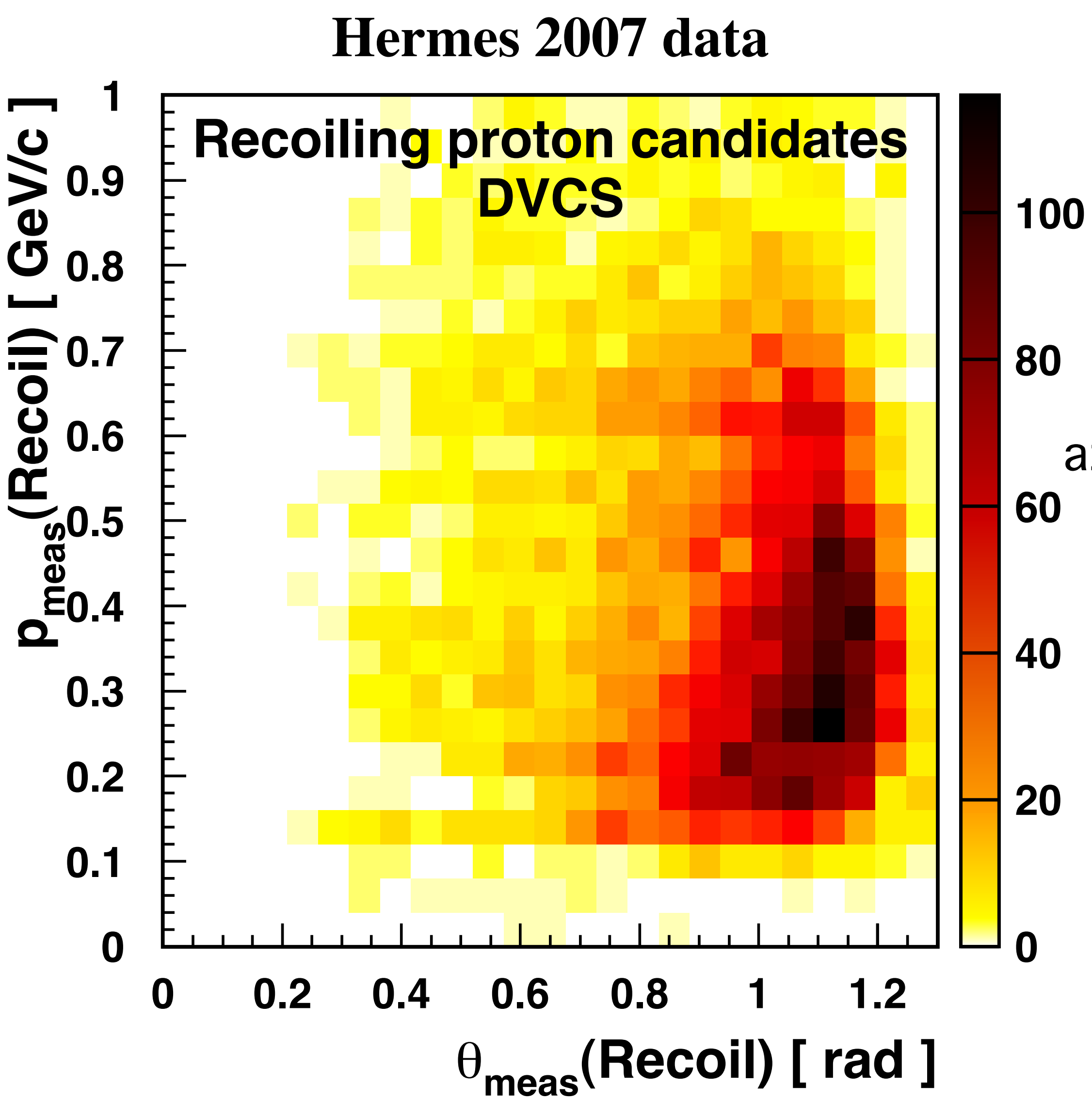
300 μm thick

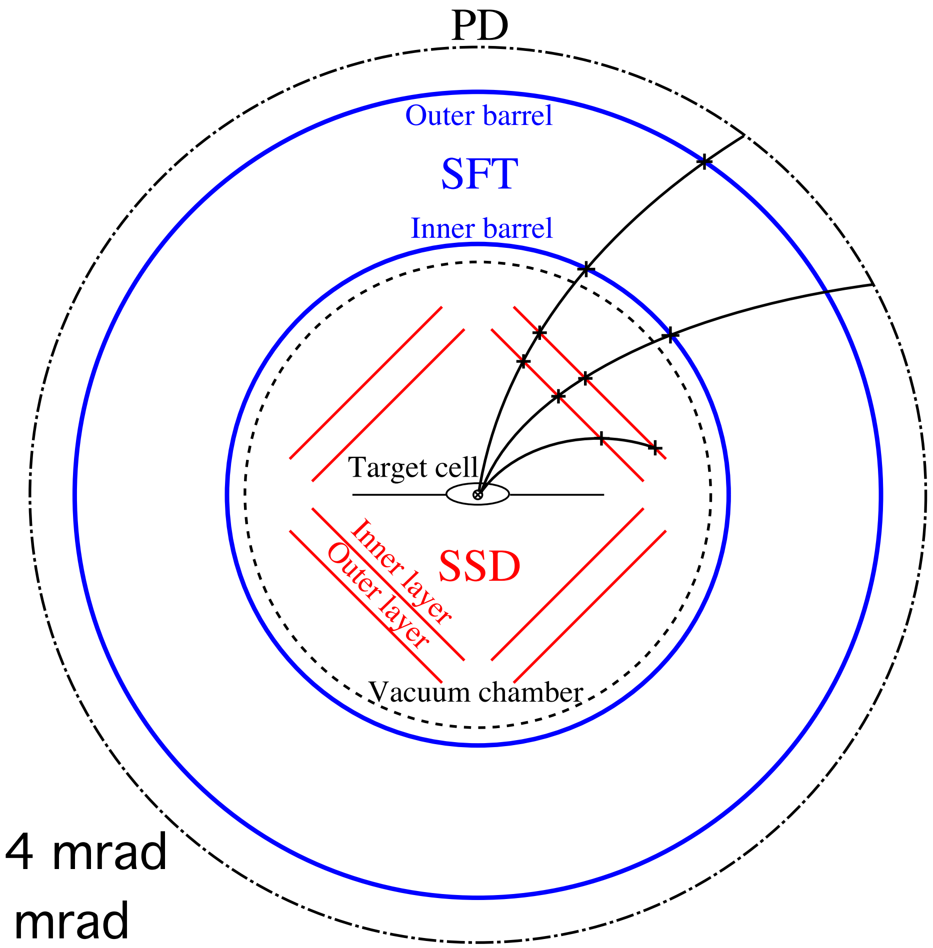


arXiv:1302.6092, submitted to JINST

Track Reconstruction

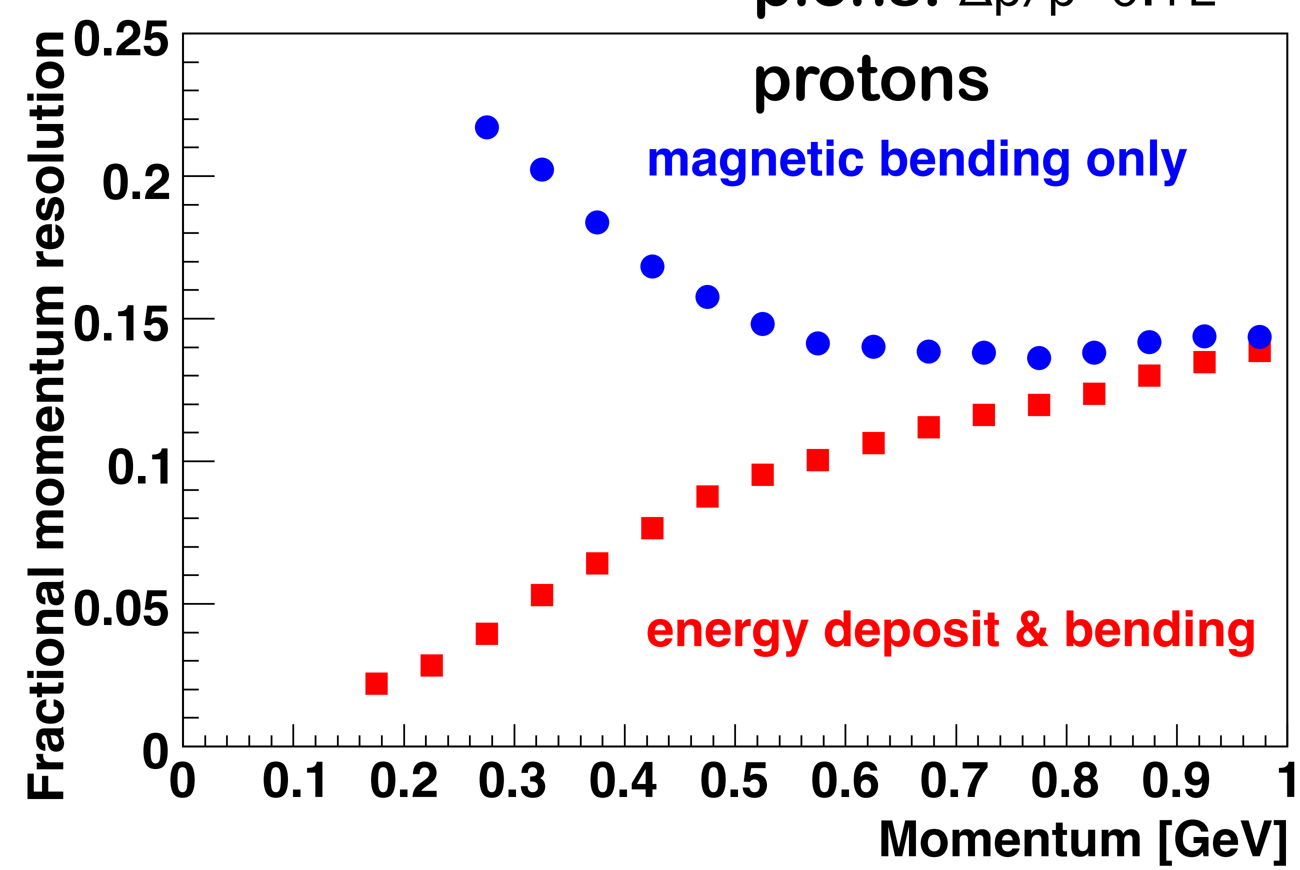
with recoil detector





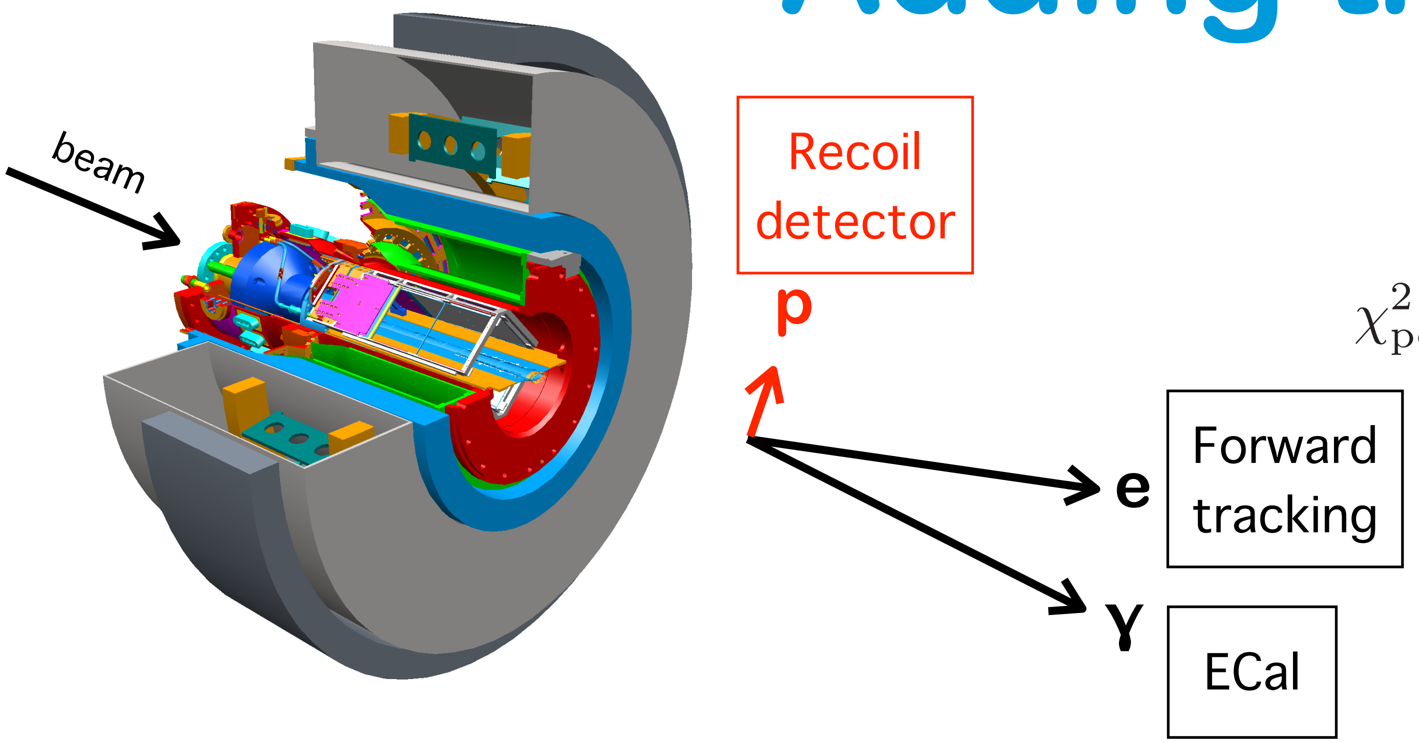
azimuthal-angle resolution: 4 mrad
polar-angle resolution: 10 mrad
(for p>0.5 GeV)

pions: Δp/p=0.12



Momentum reconstruction down to 125 MeV (protons).
Want as low -t as possible!
(corresponds to -t=0.016 GeV^2)

Adding the Recoil Proton



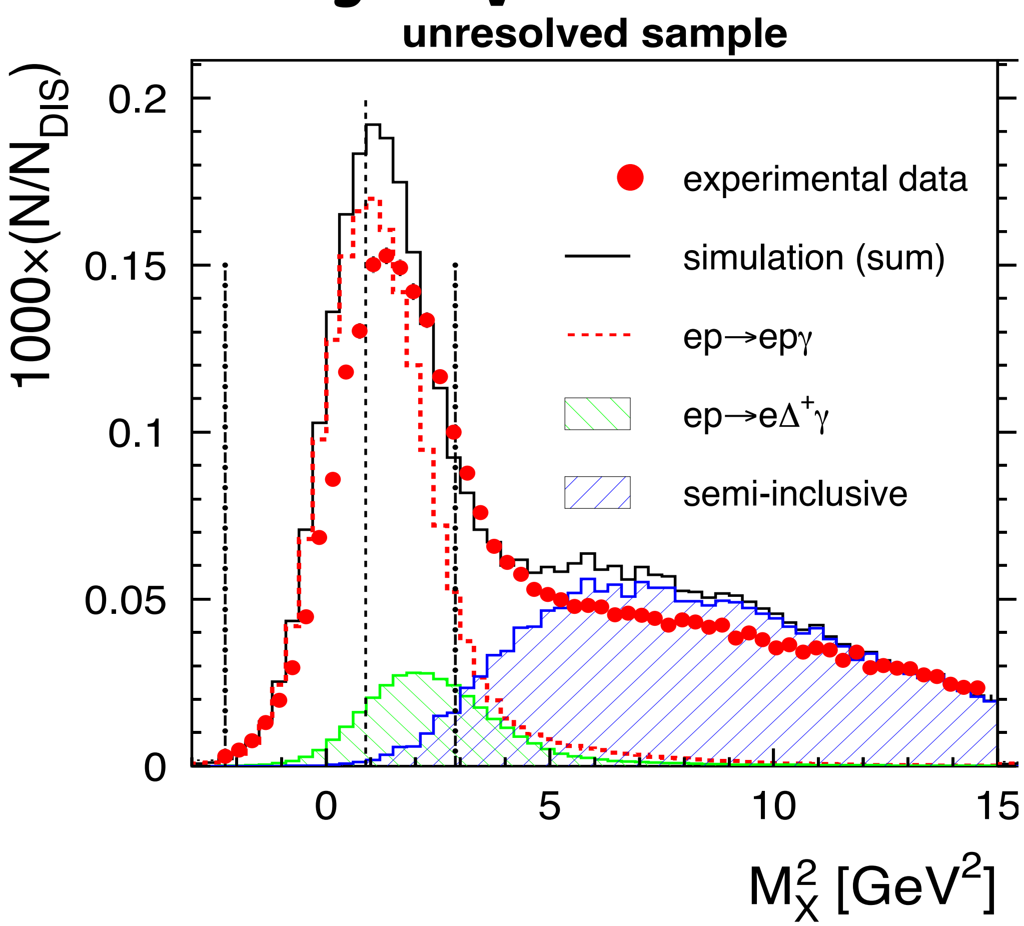
Kinematic event fitting

$$\chi^2_{\text{pen}} = \sum_{i=1}^{9} \frac{(r_i^{\text{fit}} - r_i^{\text{meas}})^2}{\sigma_i^2} + T \cdot \sum_{j=1}^{4} \frac{\left[f_j(r_1^{\text{fit}}, \ldots, r_9^{\text{fit}})\right]^2}{(\sigma_j^f)^2}$$

f_j: 4 constraints of 4-momentum conservation & assuming proton mass

Hypothesis: ep→epγ event
⇒ require: $\chi^2 < 13.7$

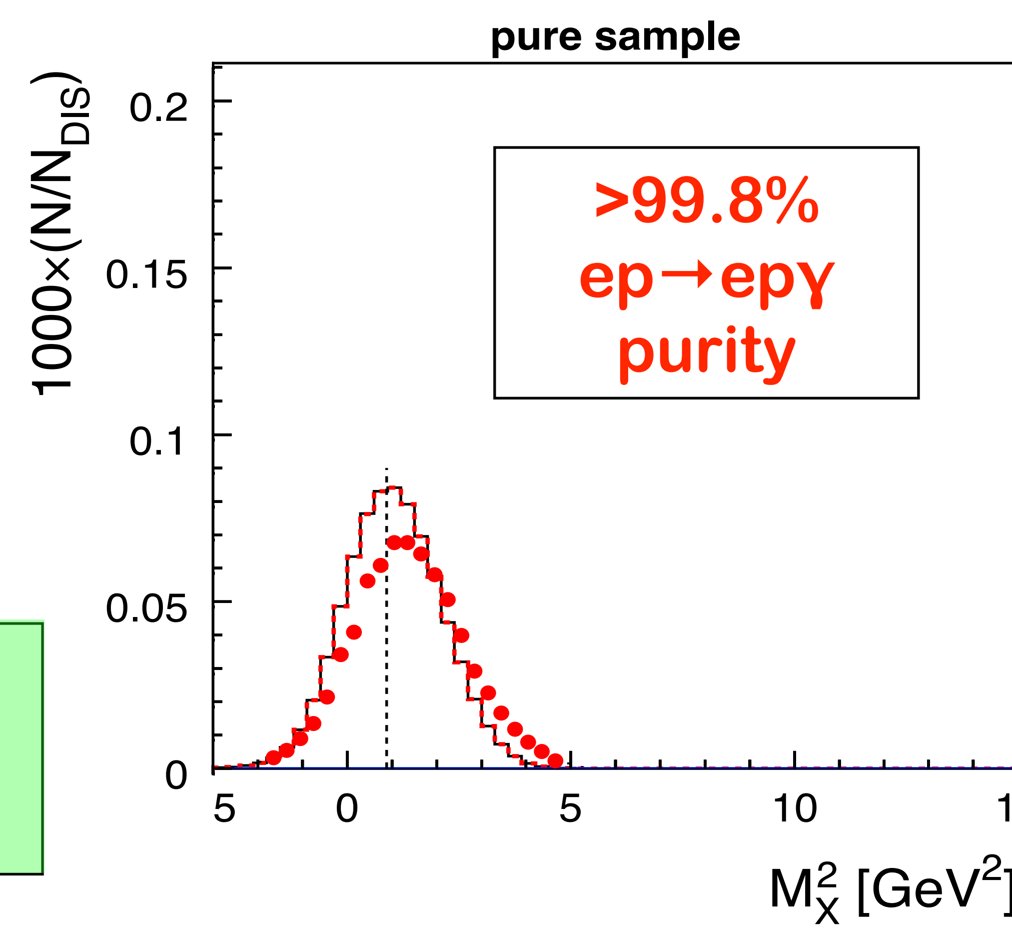
Only eγ detection



unresolved for Δ⁺

~88% ep→epγ purity

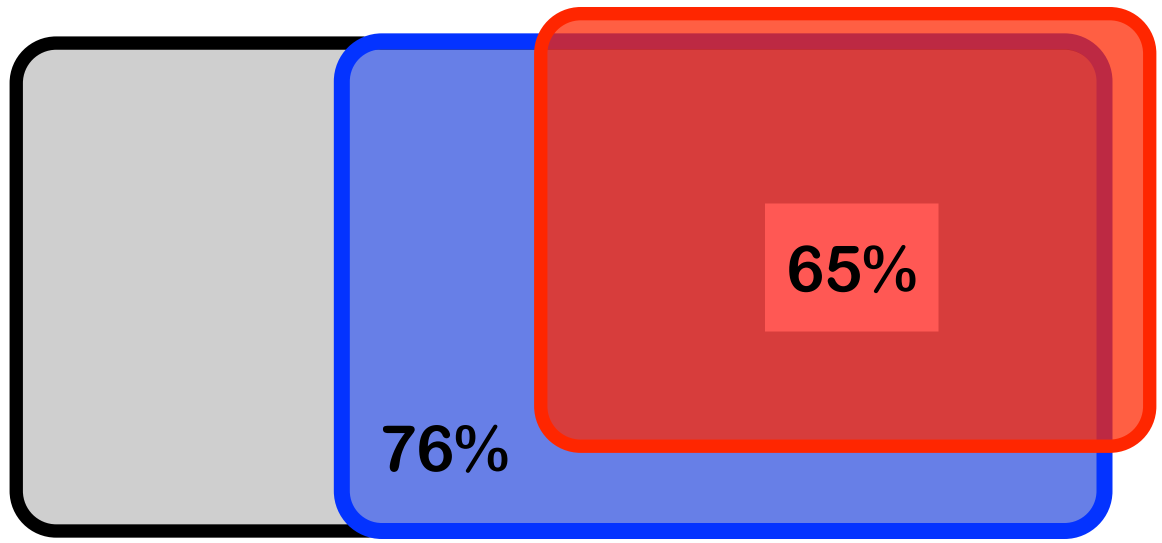
epγ detection



>99.8% ep→epγ purity

Unresolved Reference Sample

Disentangling the effects of recoil-detector acceptance and purification



<u>Loss</u> due to
- lower-mom. threshold
- Φ-gaps of SSD

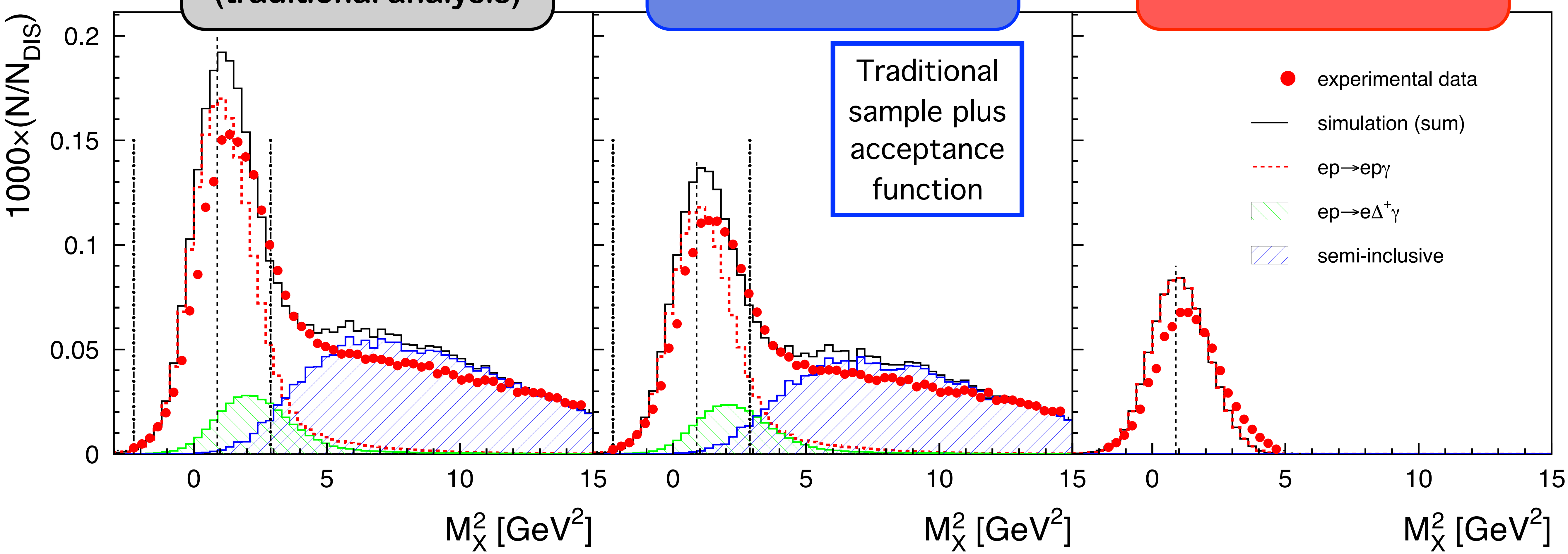
<u>Deficit</u> due to
- removal of background
- inefficiencies of χ^2 cut
- recoil-det. ineffciencies

Unresolved sample (traditional analysis)

Unresolved-reference

Pure sample

Traditional sample plus acceptance function



Available Statistics

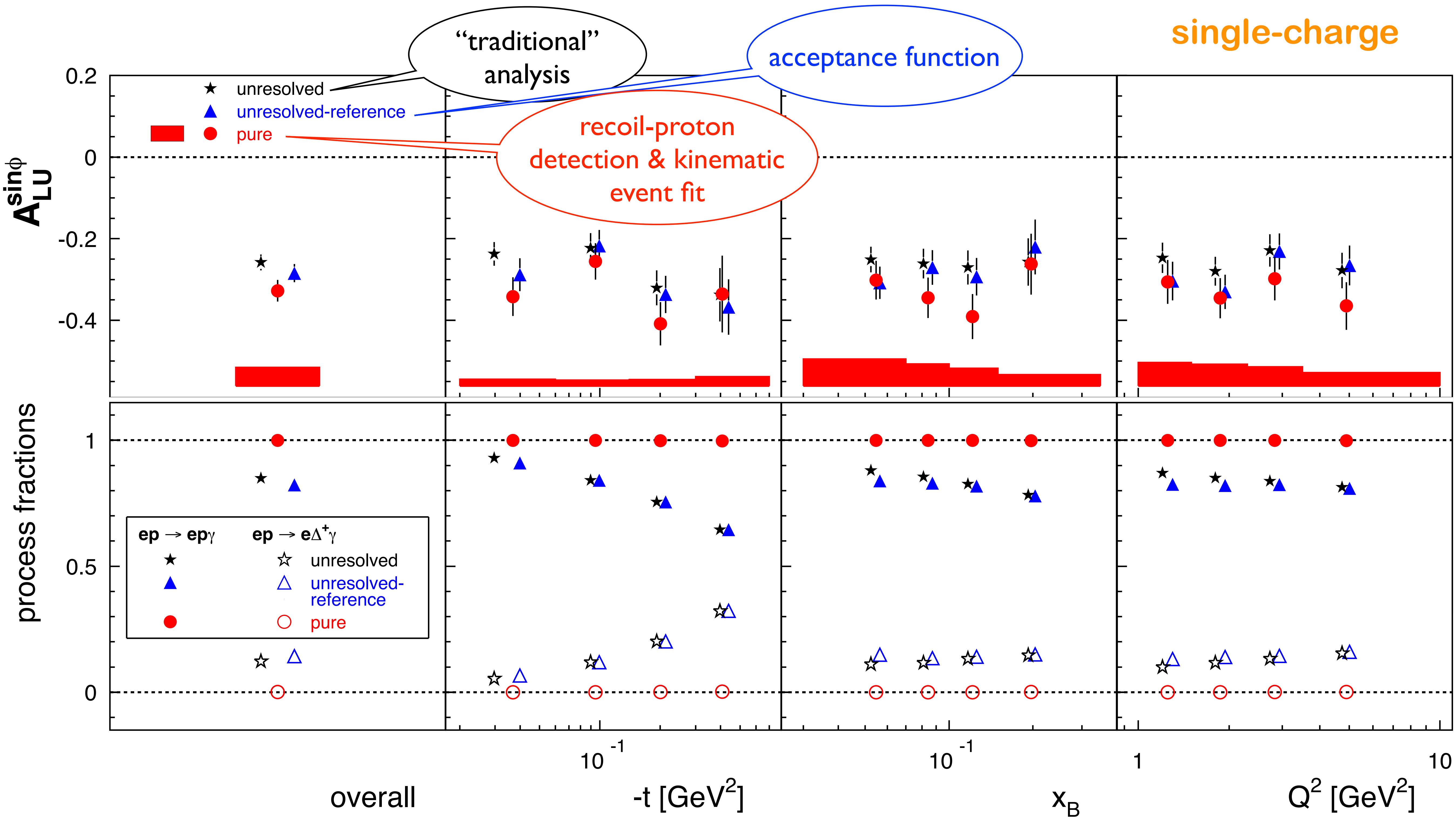
	$P_\ell > 0$	$P_\ell < 0$	total
integrated luminosity	$430\,\text{pb}^{-1}$	$240\,\text{pb}^{-1}$	$670\,\text{pb}^{-1}$
DIS events $(/10^6)$	15.8	8.7	24.5
unresolved	23000	12300	35300
unresolved-reference	17000	9200	26200
pure	11000	6000	17000
$\langle P_\ell \rangle$	0.402	-0.394	$\langle \lvert P_\ell \rvert \rangle$=0.399

Beam-Helicity Asymmetry with Recoil-Proton Detection

GPD H

2006/2007 proton data

single-charge



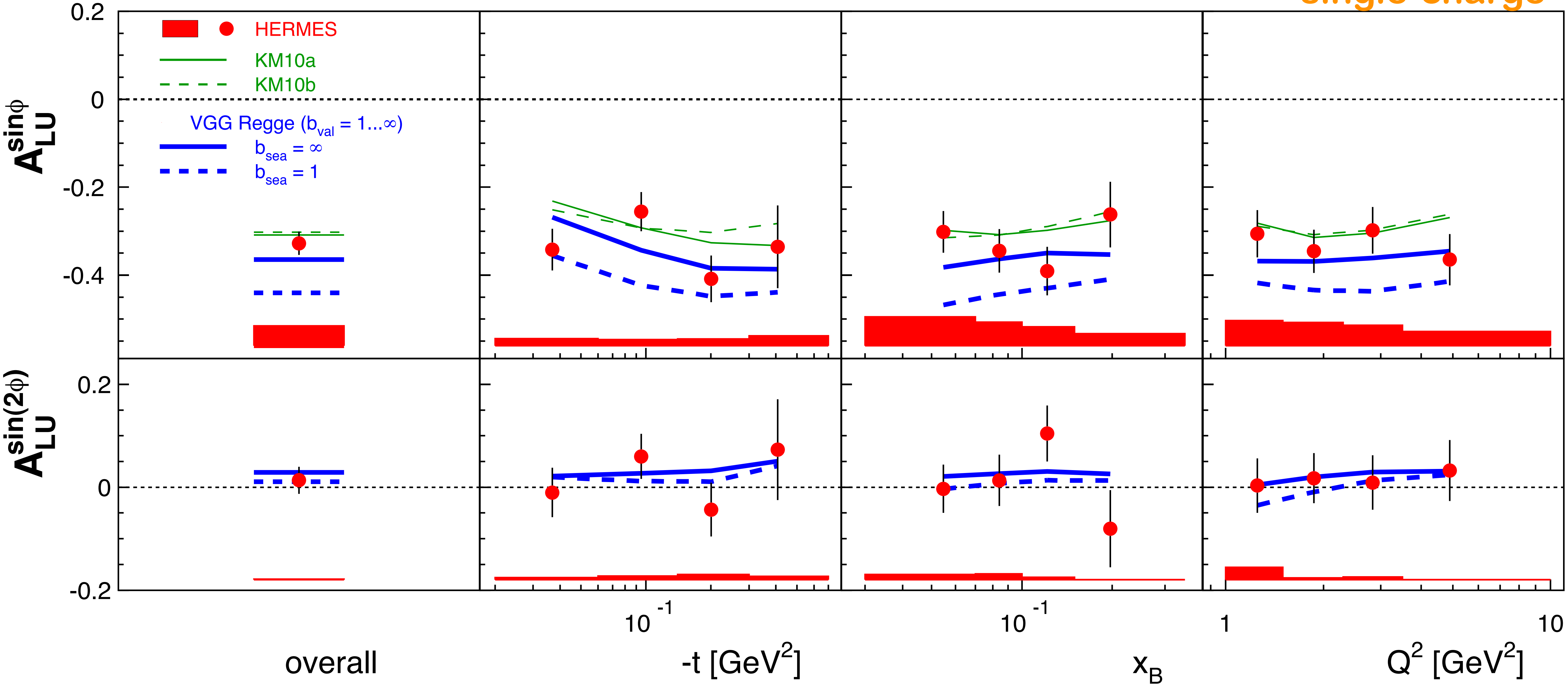
JHEP 10 (2012) 042

Beam-Helicity Asymmetry with Recoil-Proton Detection

GPD H

2006/2007 proton data

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

JHEP 10 (2012) 042

Associated Electroproduction of Real Photons

$ep \to e\gamma(\pi N)$ in the Δ-resonance region

- The charged particle of (πN) reconstructed by the recoil detector.
- Kinematic event fitting under the hypotheses:
  - $ep \to e\gamma\pi^0 p$: neutral-pion mass as constraint plus identified p in recoil detector
  - $ep \to e\gamma\pi^+ n$: neutron mass as constraint plus identified π^+ in recoil detector
  - $\Delta^+(1232)$ mass as constraint
- Reject "pure" $ep \to ep\gamma$ events

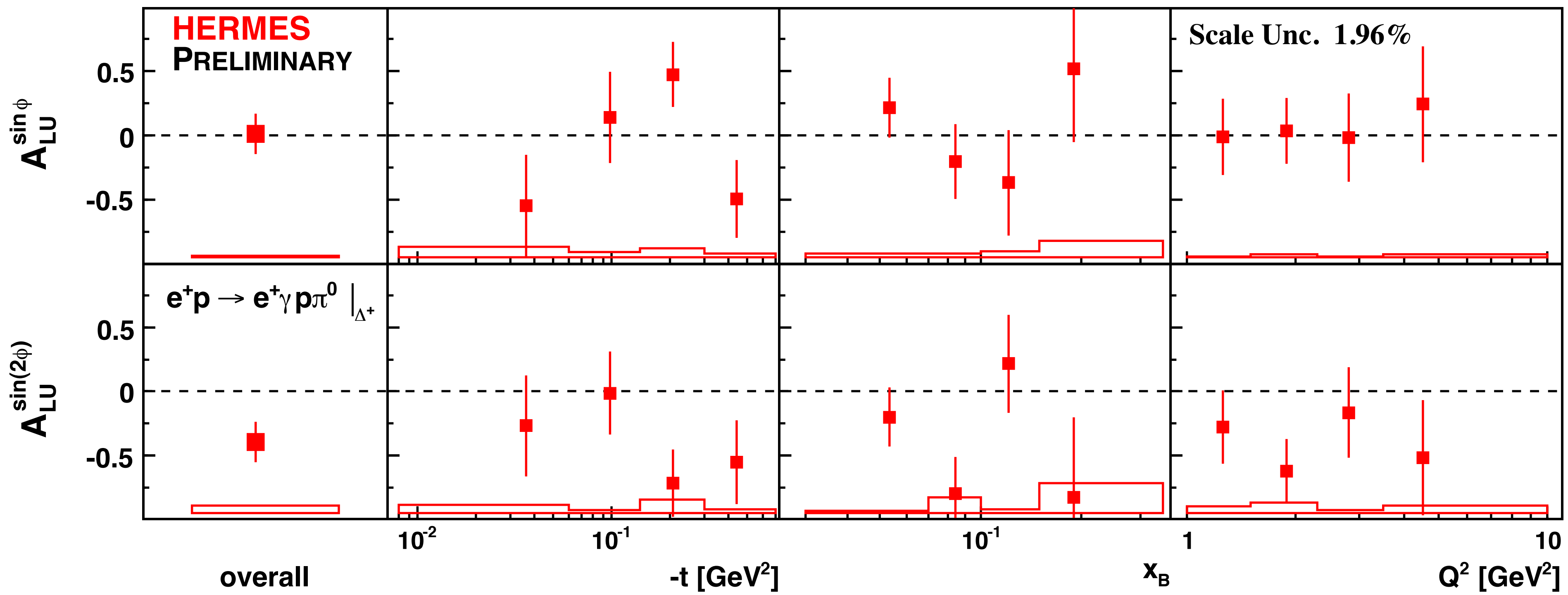
corrected for

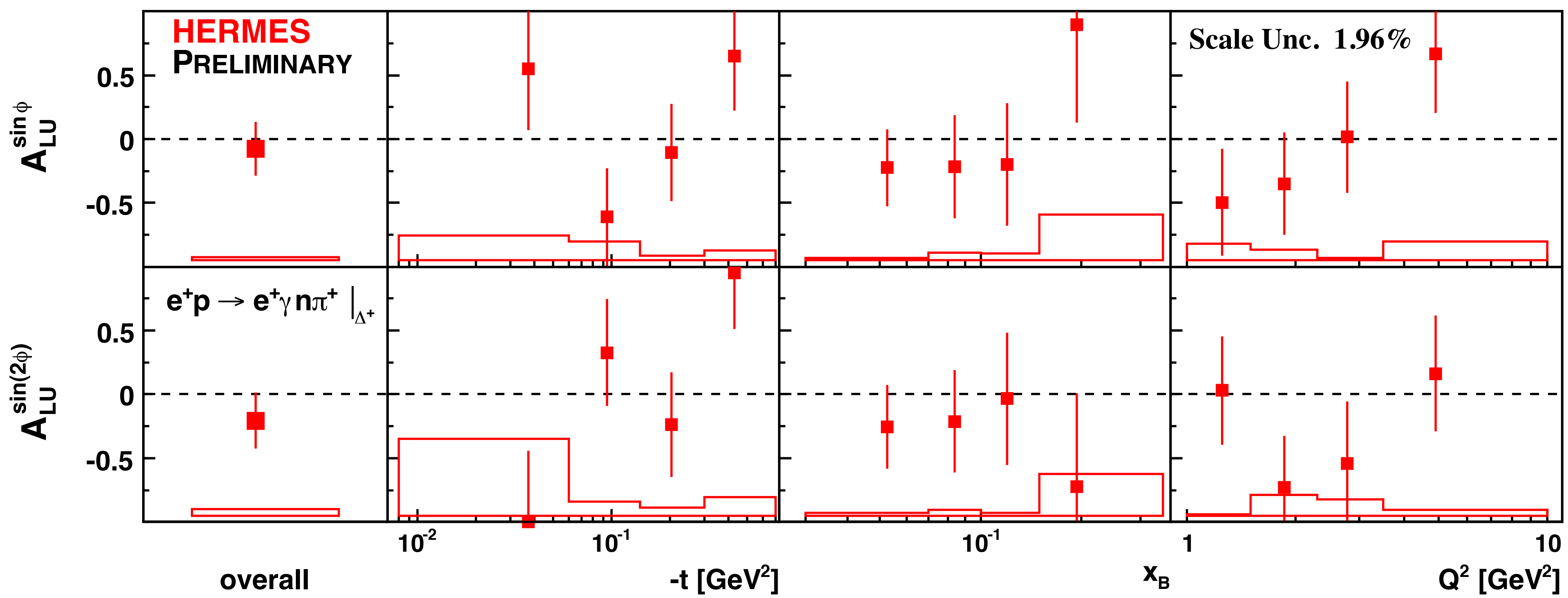
corrected for

Kinematic bin	$ep \to e\gamma\pi^0 p$ (%)	$ep \to e\gamma p$ (%)	SIDIS (%)	
Overall	85.7 ± 1.8	1.1 ± 0.1	13.2 ± 1.9	variation 5-26%
Kinematic bin	$ep \to e\gamma\pi^+ n$ (%)	$ep \to e\gamma p$ (%)	SIDIS (%)	
Overall	75.6 ± 2.6	0.1 ± 0.1	24.4 ± 3.4	variation 9-43%

preliminary analysis

Beam-Helicity Asymmetry in ep→eγ(πN)





2006/2007 proton data

☛ This result is consistent with the slight increase of the beam-helicity asymmetry amplitude for the pure sample.

☛ Associated process acts as small dilution in the asymmetries for the unresolved sample.

☛ Only existing model prediction for sinϕ amplitude:
$\pi^0 p$: -0.15
$\pi^+ n$: -0.10

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

preliminary analysis

Results on targets heavier than the proton

☛ Proton target with longitudinal (50 /pb) & transverse polarization (150 /pb); unpolarized (1200 /pb, thereof 670 /pb with fully operational recoil detector)

☛ Deuteron target with longitudinal polarization (200 /pb); unpolarized (800 /pb)

☛ Nuclear Targets: He, N, Ne, Kr, Xe (300 /pb)

Deuteron Target

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

H_5 → $b_1(x)$ tensor structure function

- ☛ 9 chiral-even quark GPDs at leading twist
- ☛ H_3, H_5 associated with 5% D-wave component of deuteron wave function

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	$\tilde{E}$	$\tilde{H}$

H → $q^+ + q^-$

$\tilde{H}$ → $q^+ - q^-$

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

Longitudinally polarized deuteron

- ➳ Vector polarization $P_z \approx 0.85$
- ➳ Tensor polarization $P_{zz} \approx 0.83$
- ➳ Dedicated data set with
  with $P_{zz} = -1.656$ && $P_z \approx 0$

$$P_z = \frac{n^+ - n^-}{n^+ + n^- + n^0}$$

$$P_{zz} = \frac{n^+ + n^- - 2n^0}{n^+ + n^- + n^0}$$

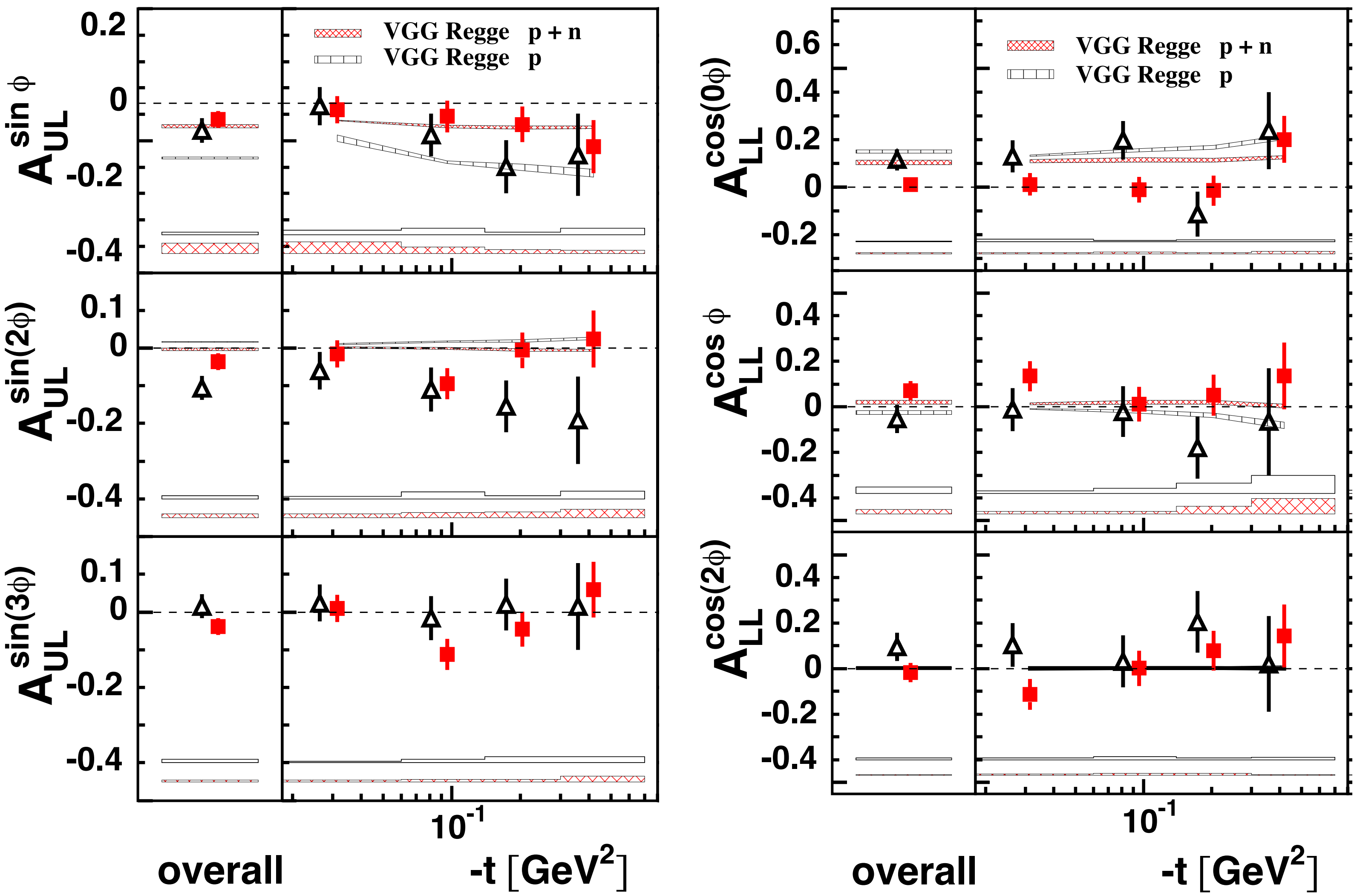
Spin-1 particle with Λ=-1,0,+1

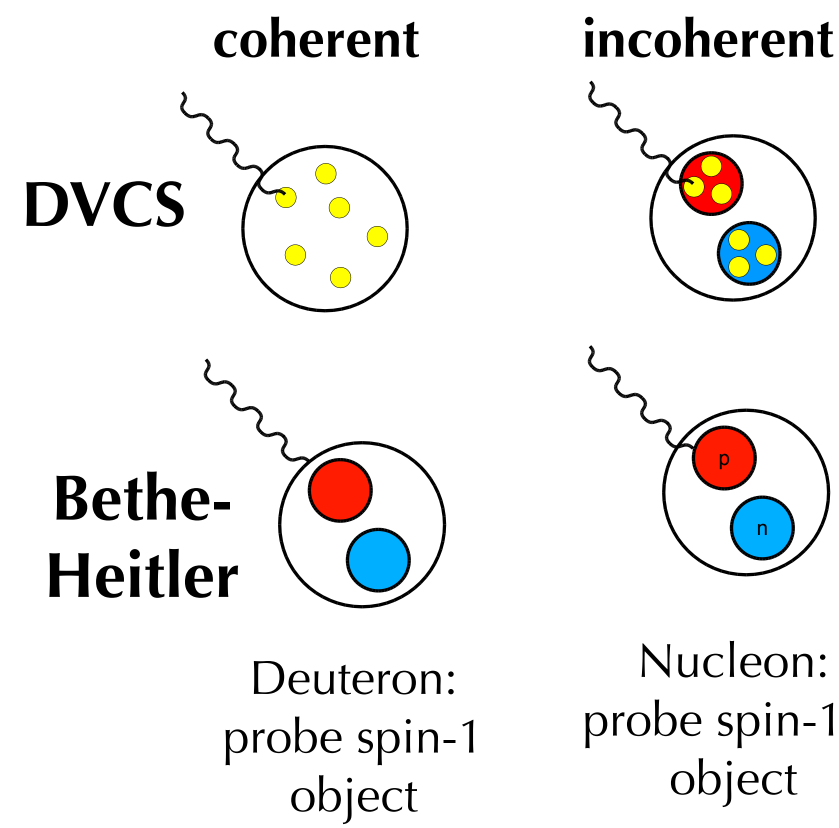
GPD H_1~

Target-Spin Asymmetry on p and d

Search for coherent signature

1998–2000 longitudinally polarized deuteron data





□ **Proton:**

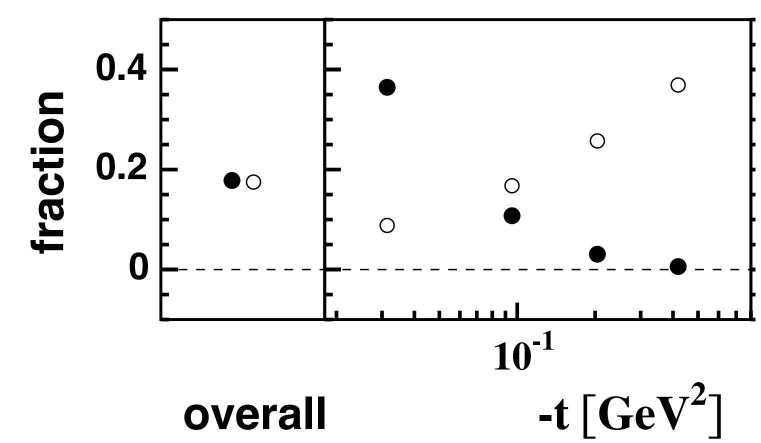
$\mathcal{R}e(\widetilde{\mathcal{H}})$ (incoherent)

■ **Deuteron:**

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

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

● coherent fraction
o resonant fraction



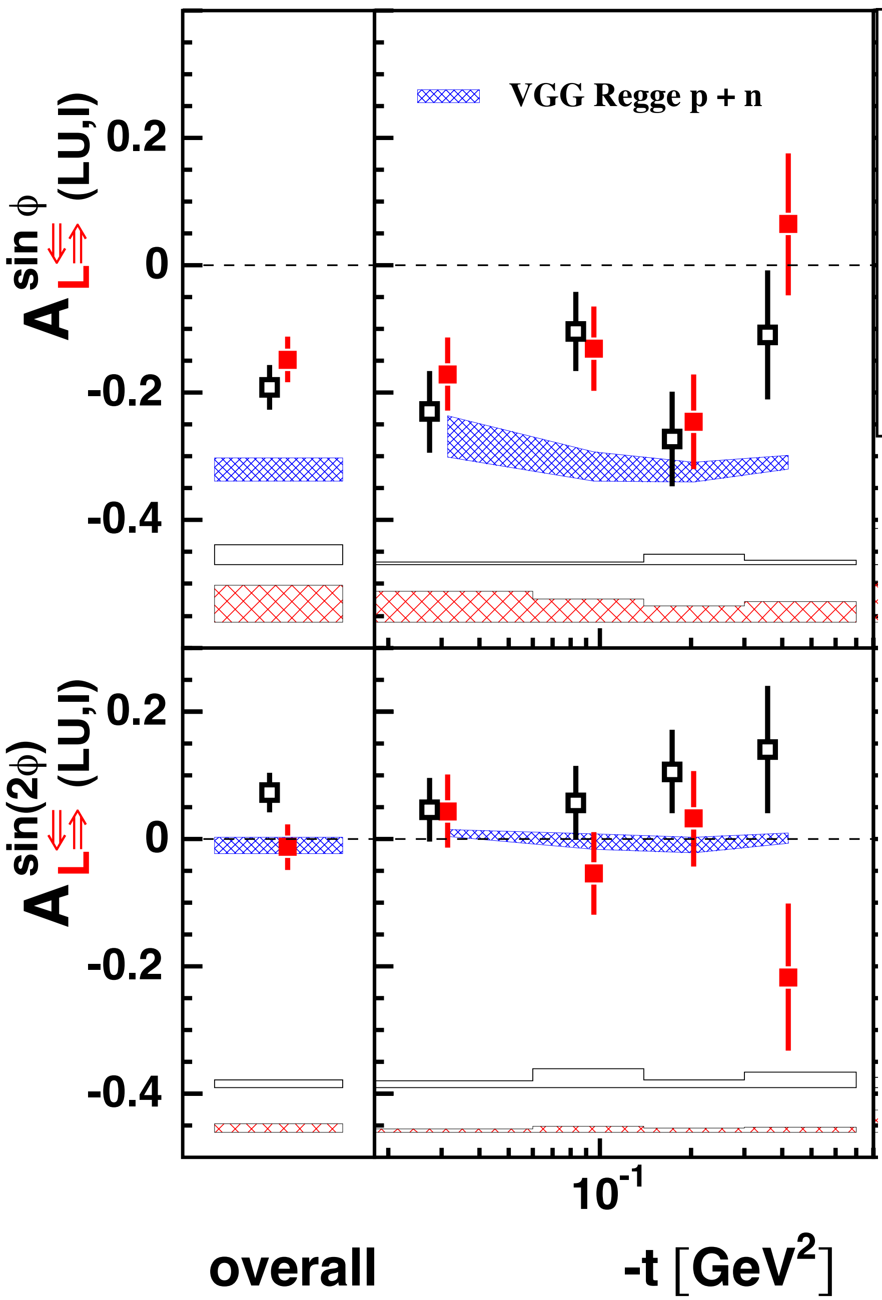
Nucl. Phys. B 842 (2011) 265-298

GPDs H1, H_5

Beam-Helicity Asymmetry on p and d

Search for tensor signature

1998–2000 longitudinally polarized deuteron data



□ unpolarized: Re(H_1)

■ tensor-polarized (P_{zz}=0.827): Re(H_1-⅓H_5)

for coherent scattering at low values of -t

$\mathcal{H}_5$ ≡ tensor structure function in the forward limit

DVCS A_{LZZ} (tensor asymmetry) sinϕ amplitude:

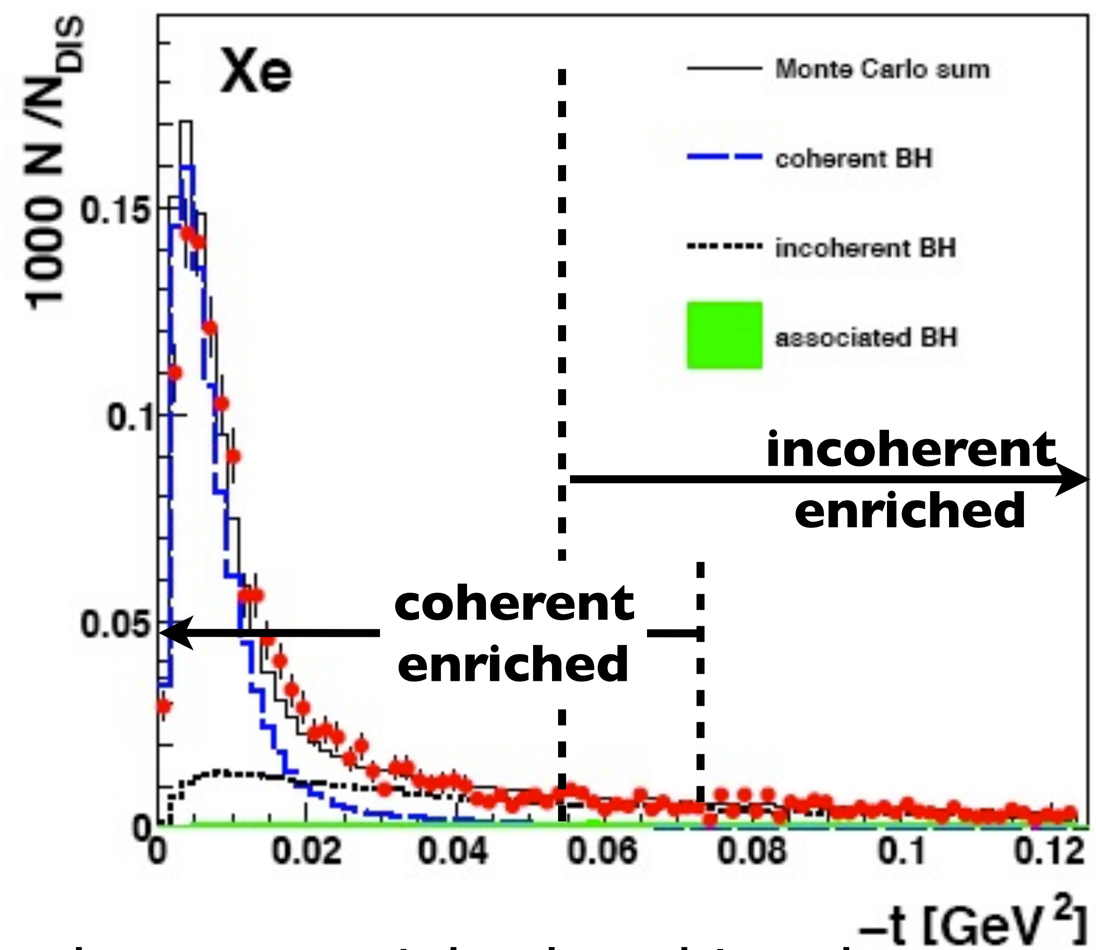
0.074 ± 0.196 ± 0.022

(-t<0.06 GeV^2, 40% coherent)

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

Nuclear Data Sets

Target	Spin	L (pb^{-1})
^{1}H	1/2	227
He	0	32
N	1	51
Ne	0	86
Kr	0	77
Xe	0, 1/2, 3/2	47



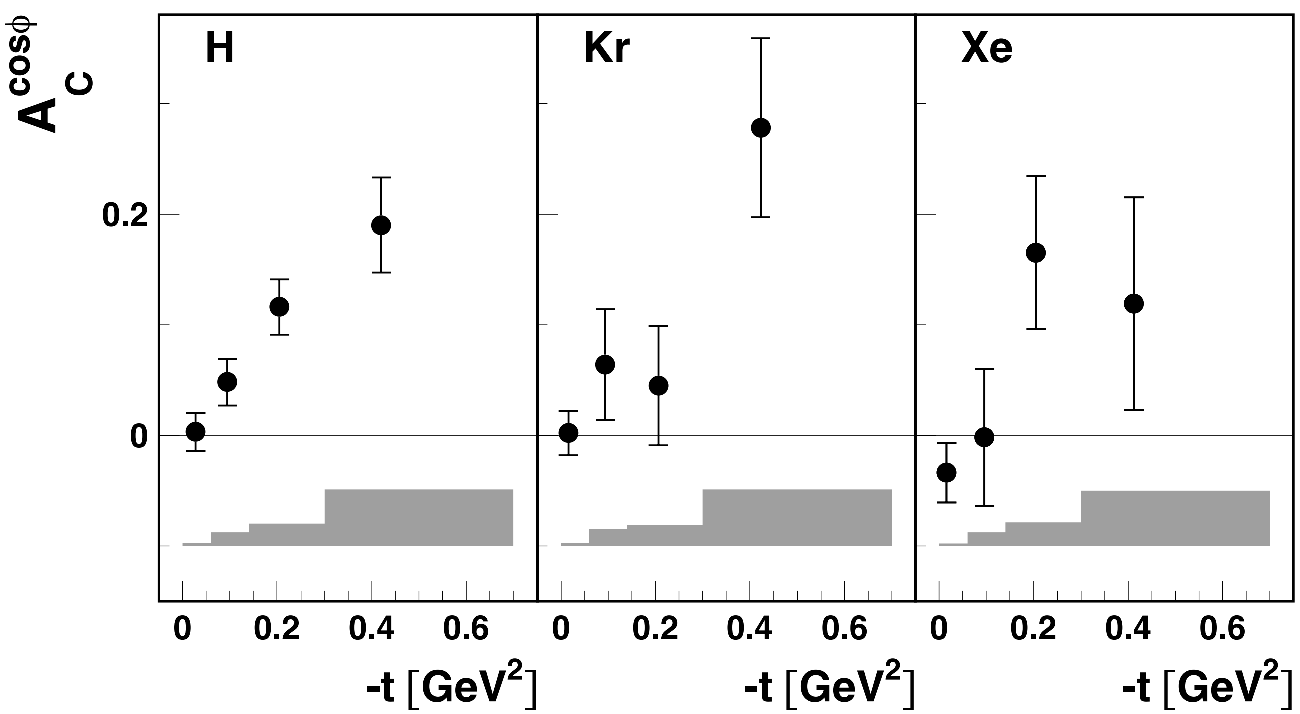
Heavy target data taken at the end of each HERA fill ("high density runs")

- Separation of coherent-enriched and incoherent-enriched data samples by t-cutoff such that ≈same average kinematics for each target.
- Coherent enriched samples: ≈65% coherent fraction
- Incoherent enriched samples: ≈60% incoherent fraction

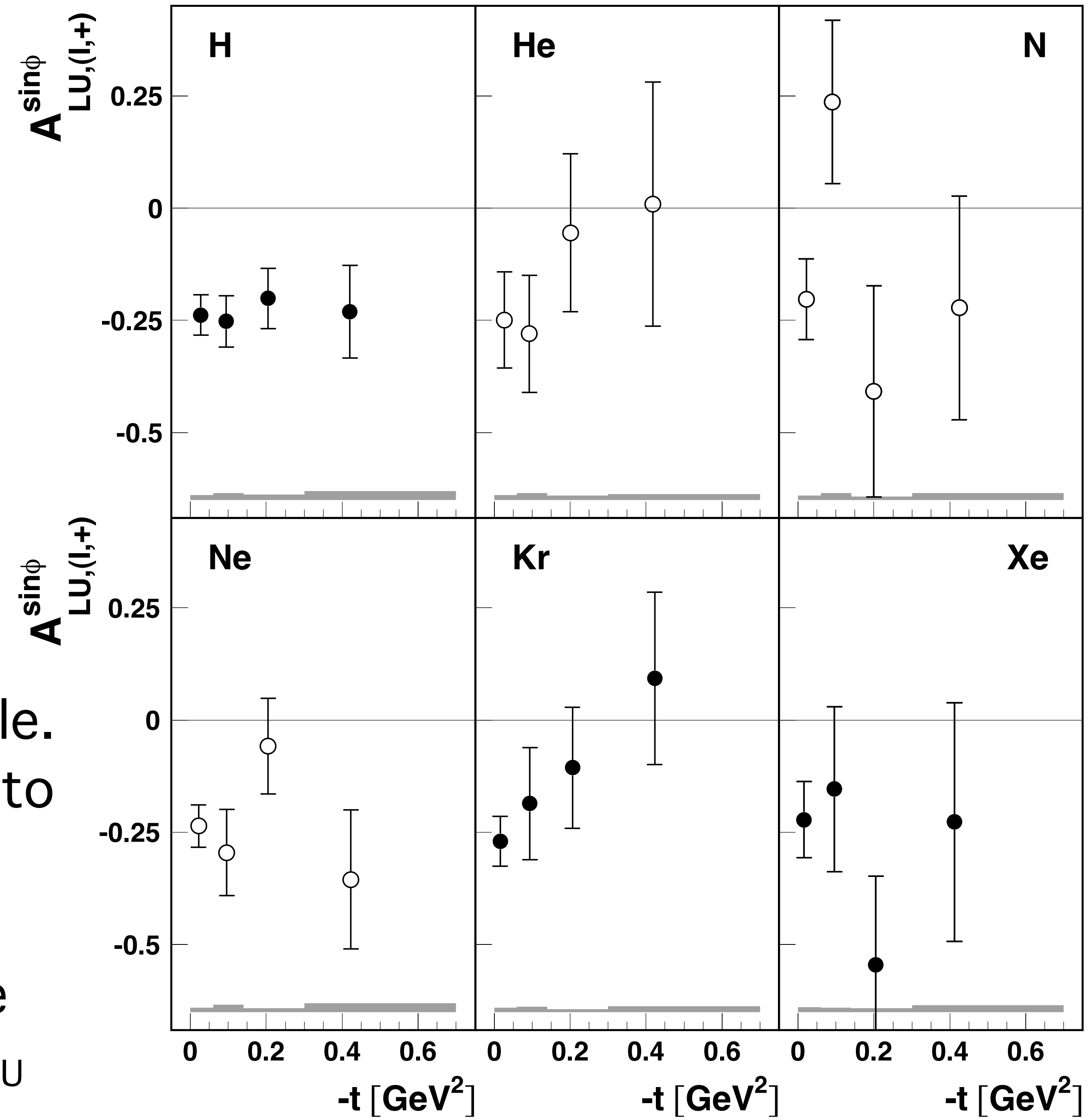
DVCS Asymmetries on Nuclei

1996–2005 nuclear data

Beam-charge asymmetry



Beam-helicity asymmetry



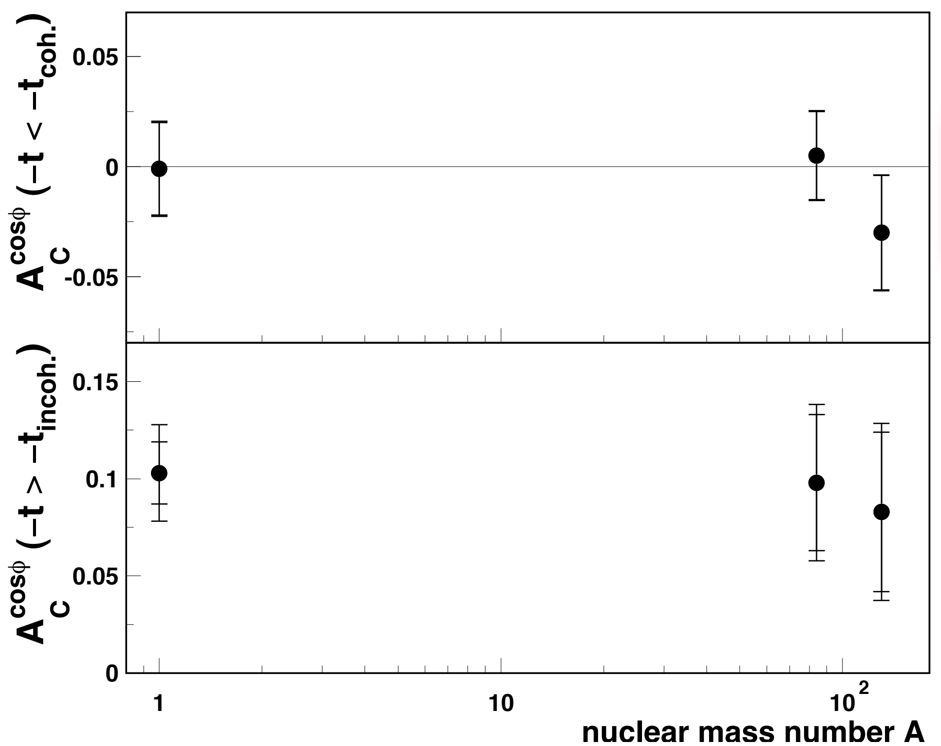
- Targets with 2 beam charges available. A_C and charge-difference A_{LU} sensitive to DVCS-BH interference term

○ Targets with only one beam charge available. No A_C and single-charge A_{LU} with entangled s_1 coefficients

Phys. Rev. C 81 (2010) 035202

DVCS Nuclear Mass Dependence

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

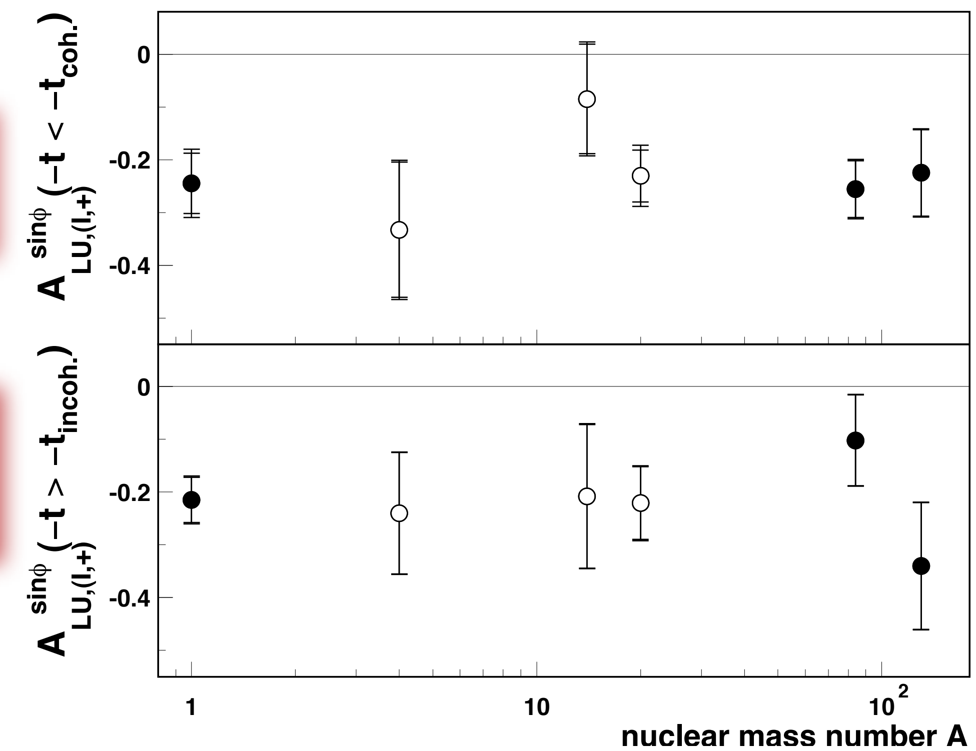


coherent enriched

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 ^1H

- How does the nuclear medium modify parton-parton correlations?
- How do the nucleon properties change in the nuclear medium?
- Is there an enhanced 'generalized EMC effect', which could be revealed through the rise if τ_{DVCS} with A?

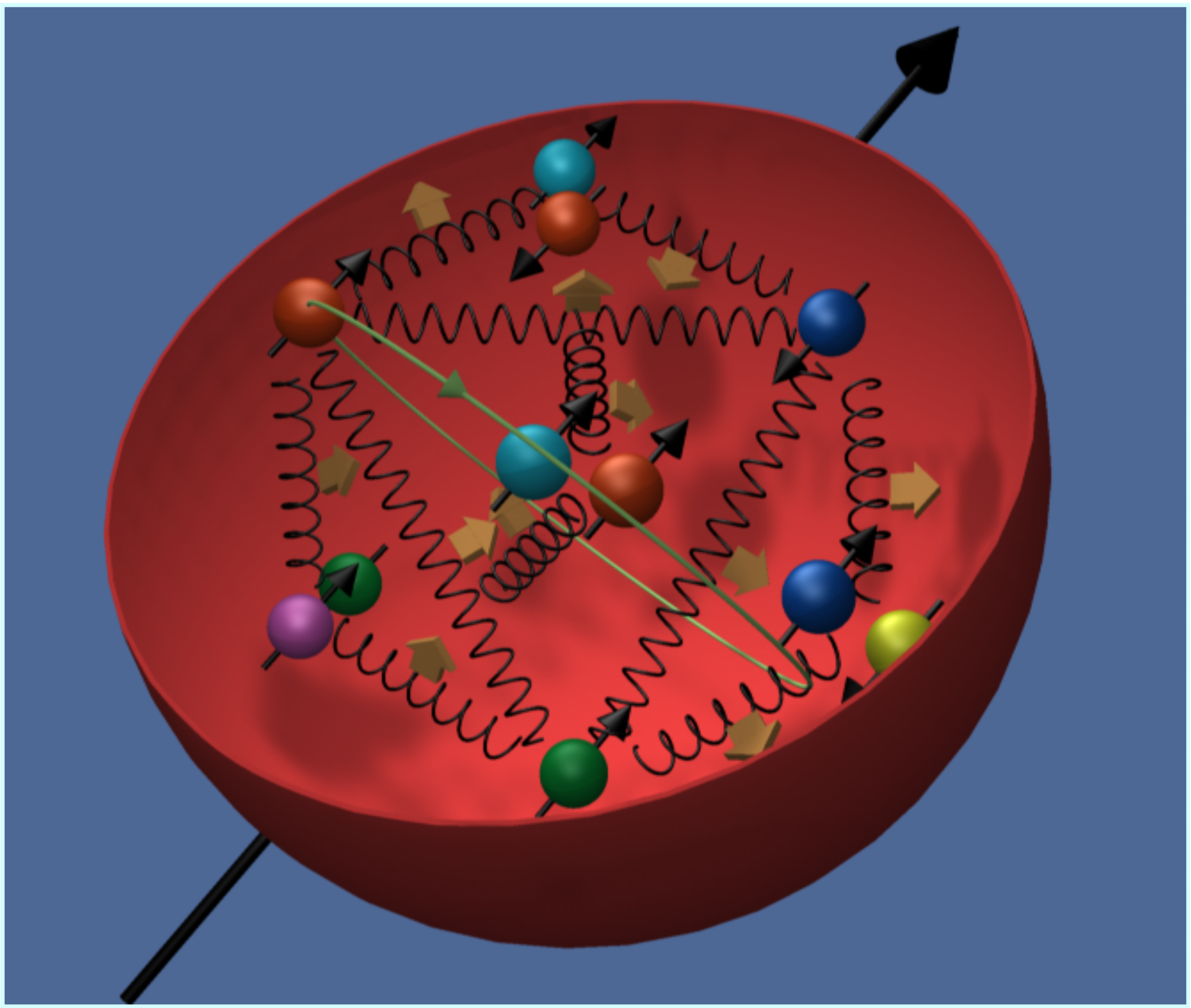
Phys. Rev. C 81 (2010) 035202

Summary: DVCS at hermes

- Results on the proton, the deuteron and nuclear targets.
- Complete and so far unique set of azimuthal asymmetry amplitudes with respect to beam charge, beam helicity and longitudinal / transverse target polarization.
- Unpolarized data allows access to GPD H;
  beam charge projects real part of CFF related to H;
  beam helicity its imaginary part.
  Polarized data allows access to GPDs H~ and E.
- Heavier targets allow searches for coherent and tensor signatures.
- DVCS at HERMES possible without recoil detector; contamination by associated DVCS can only be separated with full event reconstruction using recoil-detector data.

Backup

The Spin of the Nucleon



"Spin Puzzle"

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

quark spin
$\Delta\Sigma \approx 1/3$

quark orbital angular momentum

?!

gluon spin
[very small]
and orbital angular momentum

Dynamic Hologram of the Nucleon

$W(x, b_\perp, k_\perp)$

probability of finding a quark with certain polarization, position and momentum

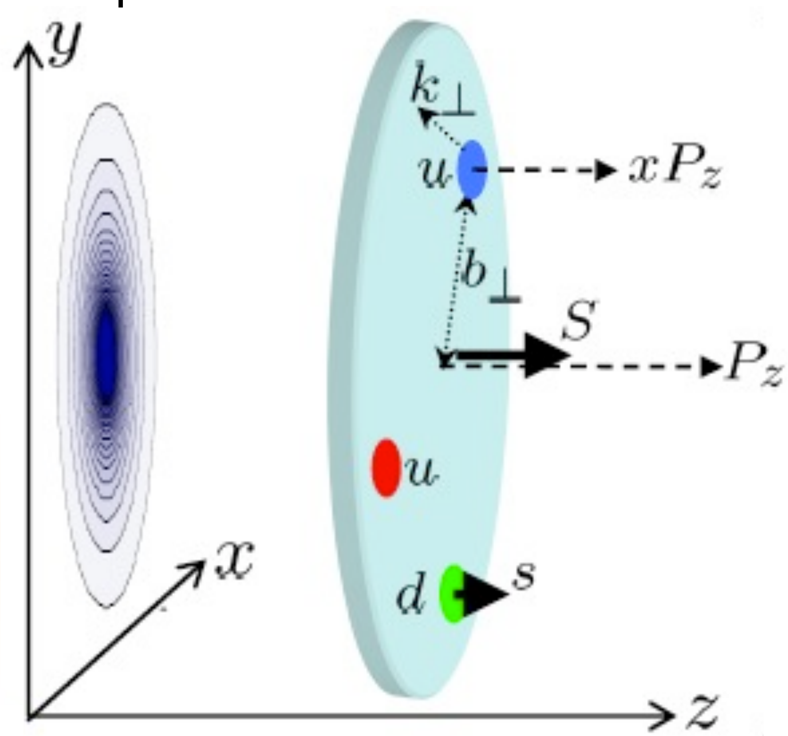
Correlation between **spin** and **transverse momentum** ?

TMDs:

Transverse Momentum dependent PDFs

$f(x, k_\perp)$

3D in momentum space



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

GPDs:

Generalized Parton Distributions

$H(x, b_\perp)$

$\updownarrow$ FT

$H(x, \xi, t)$

3D in coordinate space

$k_\perp$-integration

$\xi=0,\ t=0$

PDFs q(x):

Parton Distribution Functions

1D

semi-inclusive measurements

inclusive measurements

exclusive measurements

Wigner phase-space distributions

[X. Ji, PRL 2003; A. Belitsky, X. Ji, F. Yuan, PRD 2004]

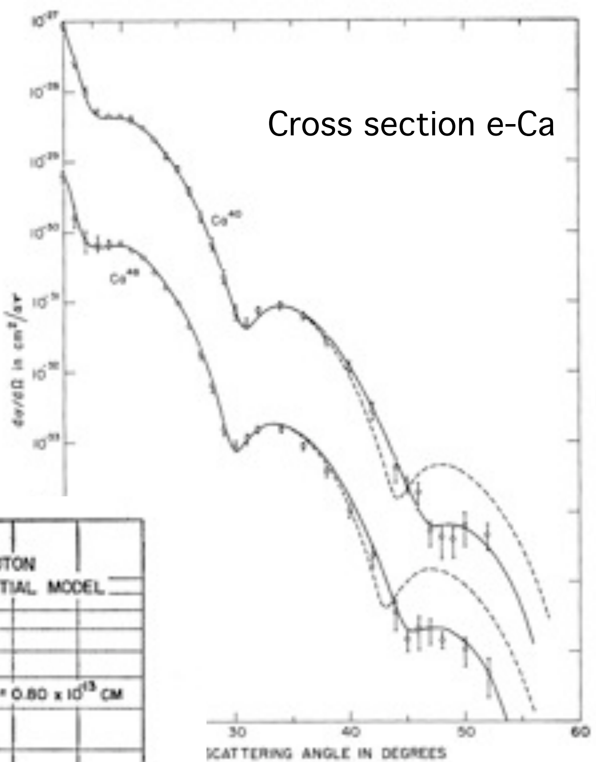
"mother distributions"

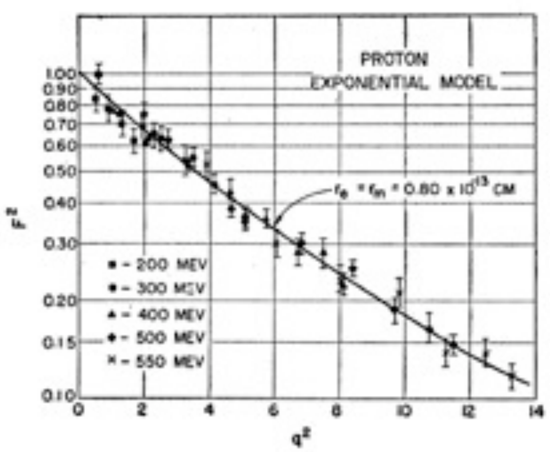
[Meissner, Metz, Schlegel, JHEP 0908:056, 2009]

Nucleon Tomography

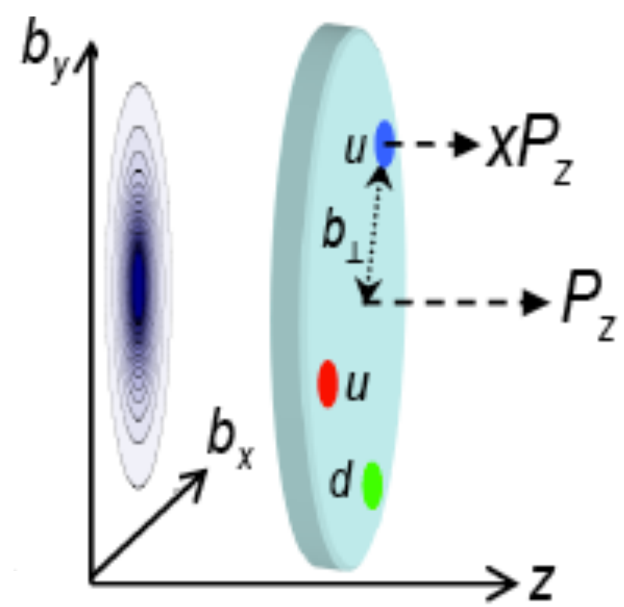
Form Factors

from elastic scattering

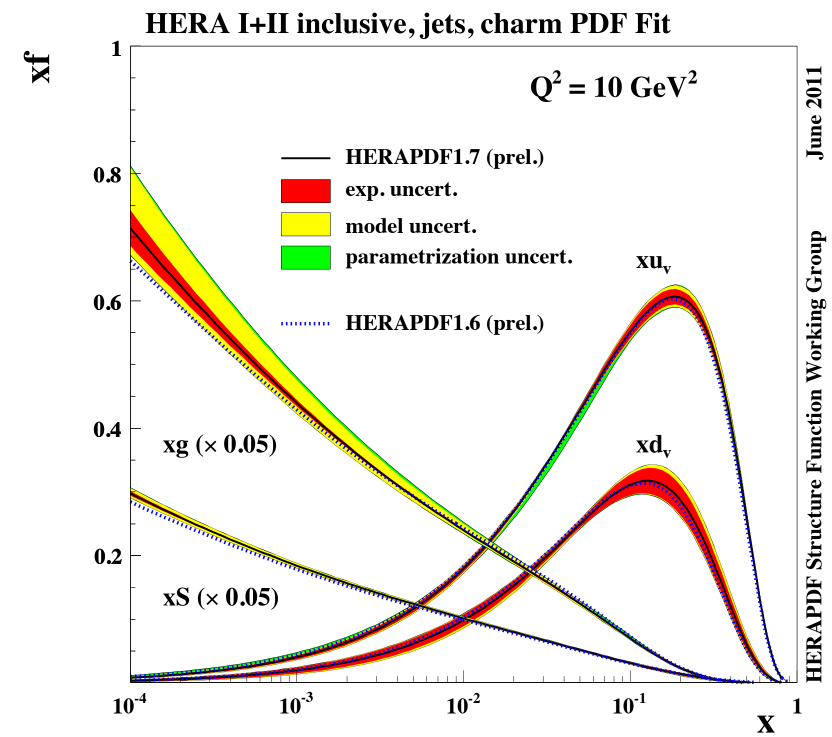




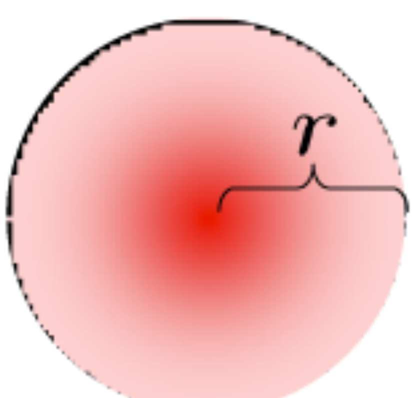
Generalized Parton Distributions

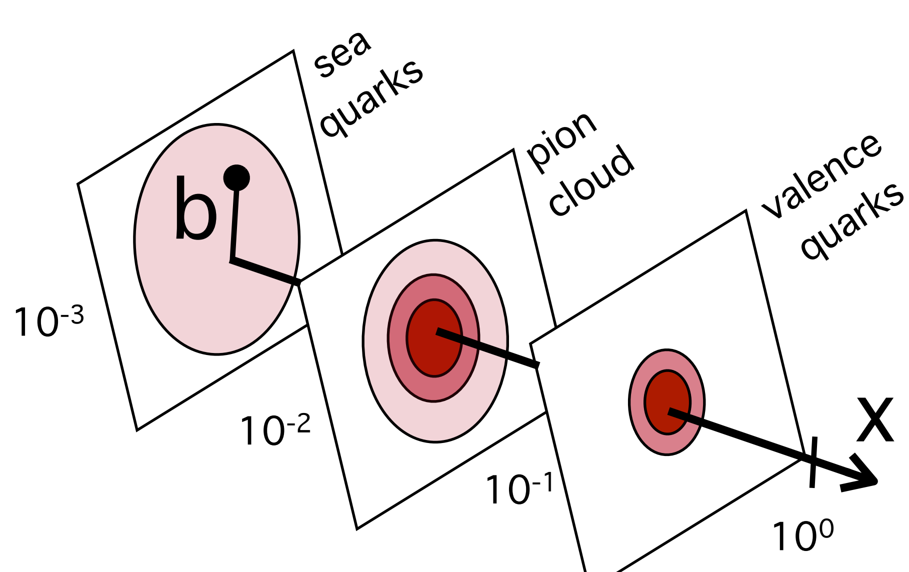


Parton Distribution Functions from inclusive deep-inelastic scattering

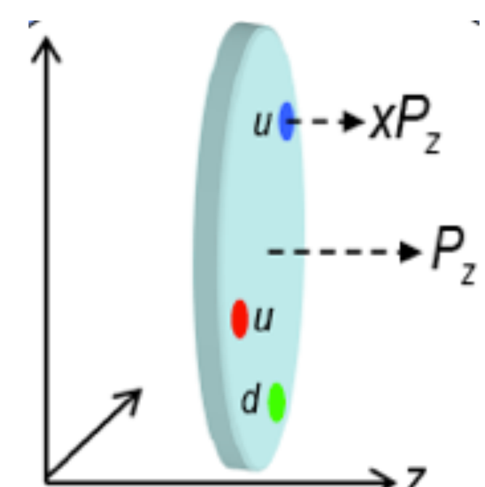


transverse position





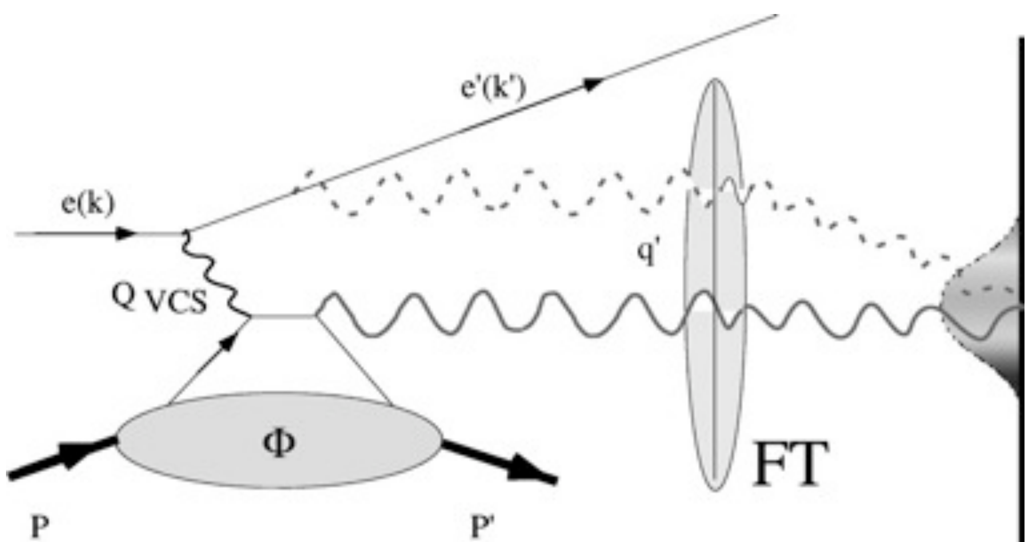
longitudinal momentum



HERAPDF1.7 NLO (Preliminary): H1prelim-11-143,ZEUS-prel-11-010

Illustrations: Ph. Hägler (TUM)

Holographic principle in DVCS



Belitsky, Müller, hep-ph/0206306

- BH reference amplitude magnifies DVCS
- Measure magnitude A and phase φ of DVCS amplitude $\tau_{DVCS}=Ae^{i\varphi}$

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:

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

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

⇓

Compton Form Factors:

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

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

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

Correction for neutral pions

- Correct unresolved samples.
- No correction for the pure sample since assumed to be free from pions.
- Reconstruct 2-photon asymmetry amplitudes A_{semi} from real data.
- Determine sidis fraction f_{semi} and f_{excl} from MC.
- Correct A_{meas} in each bin:

$$0 \pm \frac{2}{\sqrt{12}}$$

$$A_{\mathrm{final}} = \frac{A_{\mathrm{meas}} - f_{\mathrm{semi}} A_{\mathrm{semi}} - f_{\mathrm{excl}} A_{\mathrm{excl}}}{1 - f_{\mathrm{semi}} - f_{\mathrm{excl}}}$$

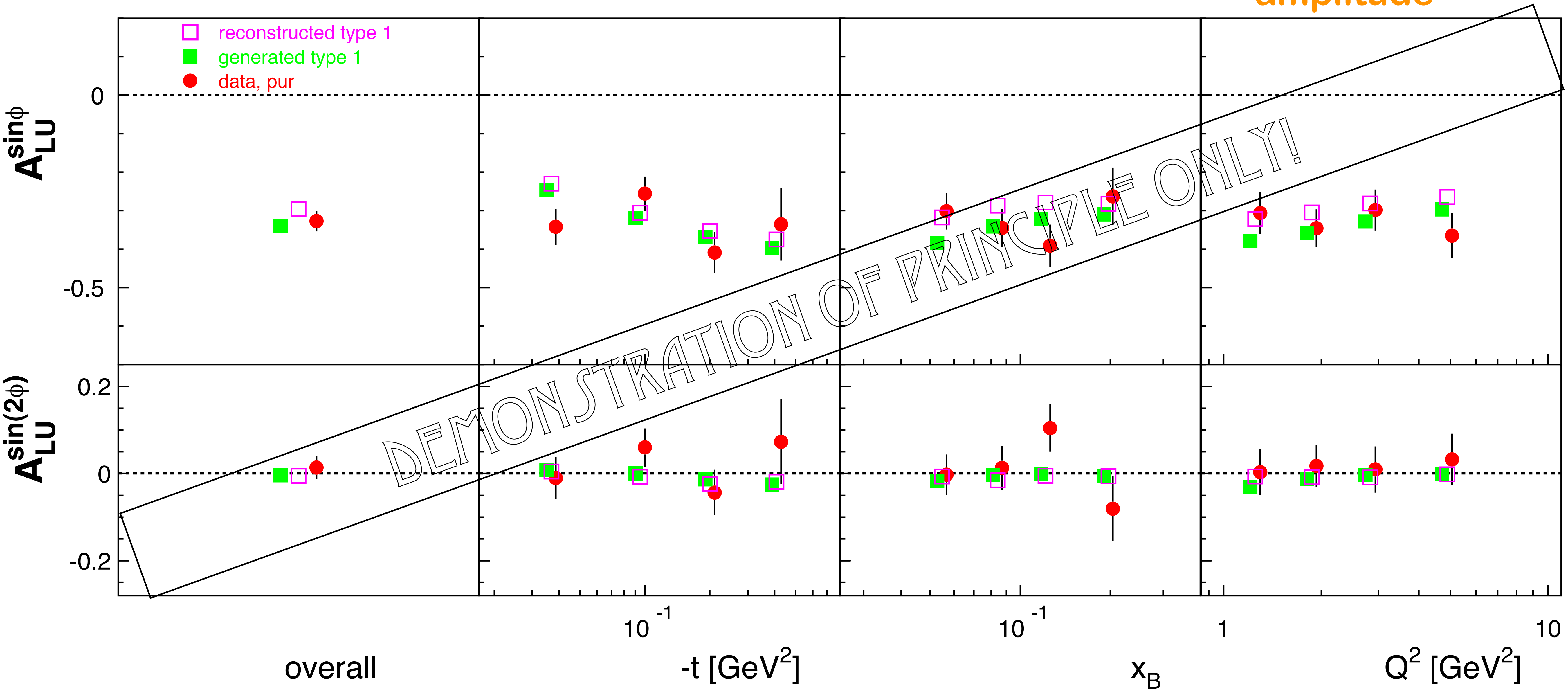
- Propagate statistical uncertainty and correct (increase) δA_{meas} for removal of events.
- Systematic uncertainty:

$$\delta A^{\mathrm{bg}}_{\mathrm{syst.}} = \frac{1}{2} |A_{\mathrm{final}} - A_{\mathrm{meas}}|$$

Example for “all-in-one” systematic uncertainty: VGG variant 1

Effects from smearing, finite bin width and acceptance (for some data samples, also alignment)

Sys = generated minus reconstructed amplitude



VGG model

M. Vanderhaeghen, P.A.M.Guichon and M. Guidal, *Deeply virtual electroproduction of photons and mesons on the nucleon: leading order amplitudes and power corrections, Phys. Rev. D60 (1999) 094017*, **arXiv:hep-ph/9905372**

K. Goeke, M.V. Polyakov and M. Vanderhaeghen, *Hard exclusive reactions and the structure of hadrons, Prog. Nucl. Phys. 47 (2001) 401-515*, **arXiv:hep-ph/0106012**

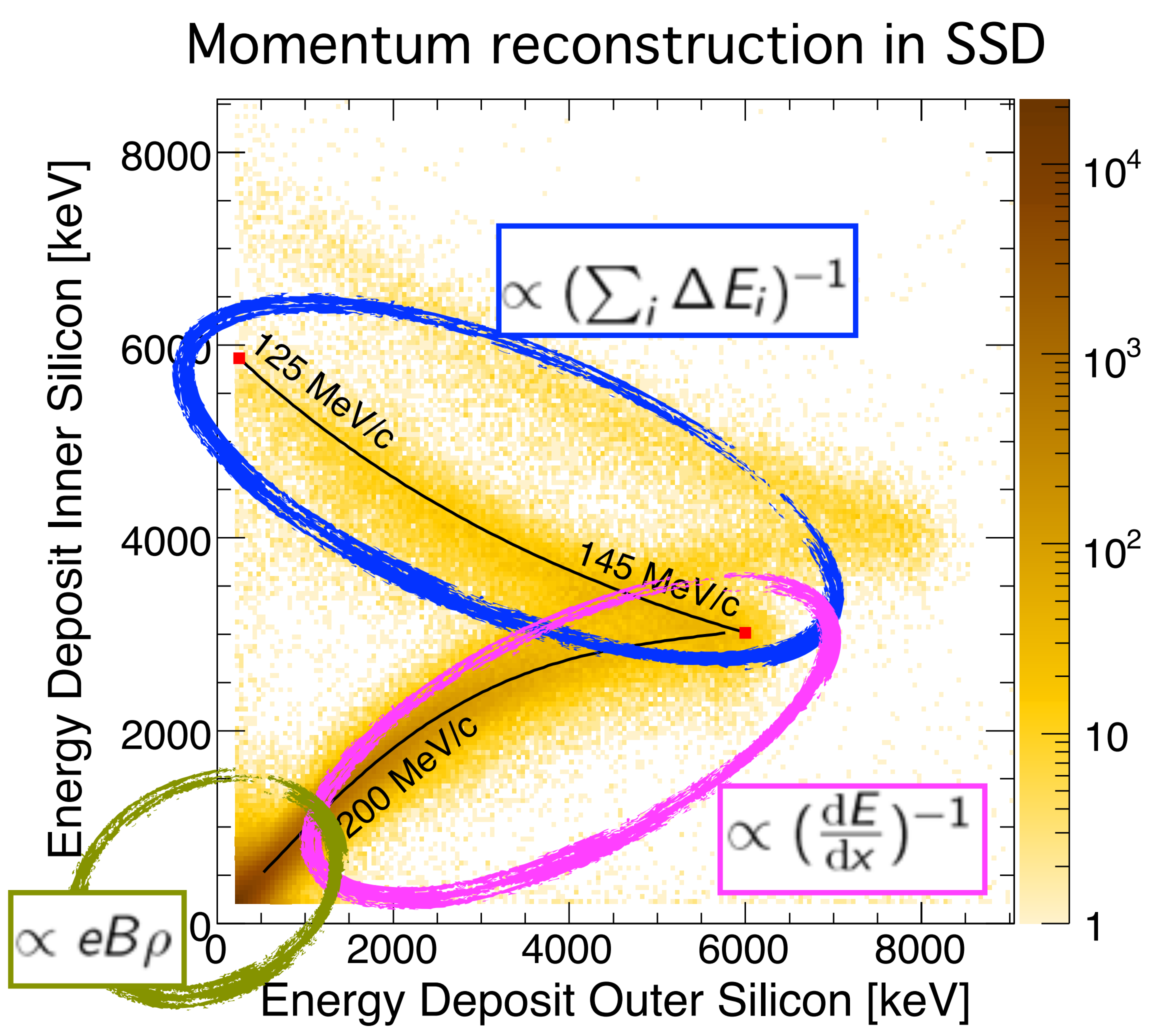
- Based on double distributions. Factorized or Regge ansatz.
  With or w/o D-term. Variable skewness parameters b_{val} and b_{sea}.

- Used to display model curves: stand-alone VGG code.
  At HERMES available in two versions: the original one from Vanderhaeghen “VGG01” and a later one from Guidal “VGG05”.
  Width of model band comes from variation of b_{val} and b_{sea}

- Used for systematics: “leading-order type” only (no twist 3 [?])
  ☛ Reconstruction with HERMES gmcDVCS MC. Models 1–5.
  ☛ Generation with “qplot” code, which contains “fast VGG” models 1–5

V. A. Korotkov, W.-D. Nowak, *Future Measurements of Deeply Virtual Compton Scattering at Hermes*, **arXiv:hep-ph/018077**

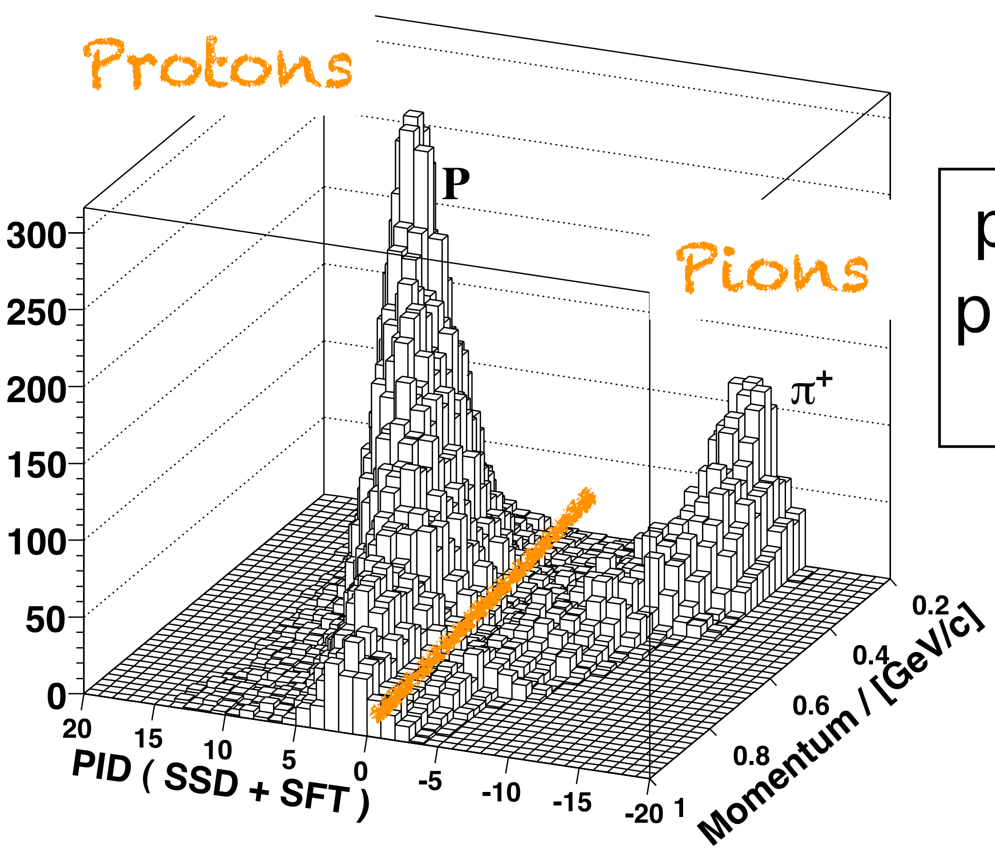
Momentum reconstruction with the recoil detector



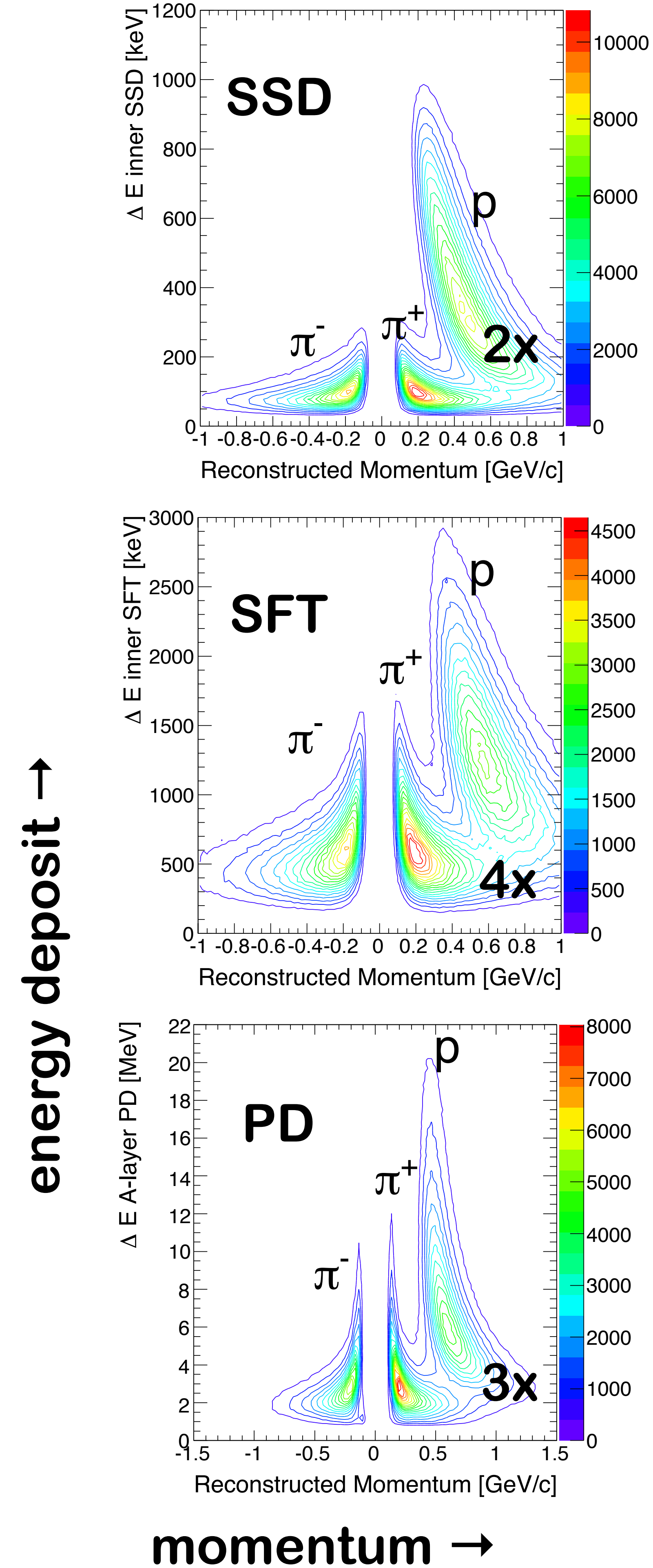
Proton / Pion Separation

Combine up to 9 layers to determine log-likelihood PID value:

$$\mathrm{PID} \equiv \log \frac{\mathcal{P}(\Delta E|\mathrm{proton}, p)}{\mathcal{P}(\Delta E|\mathrm{pion}, p)}$$

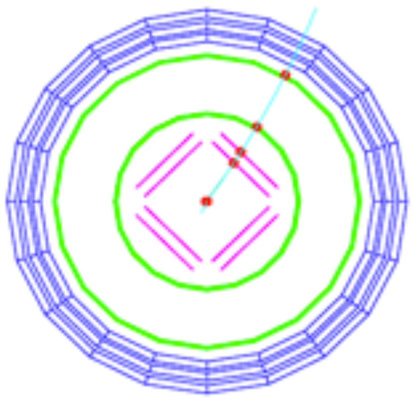


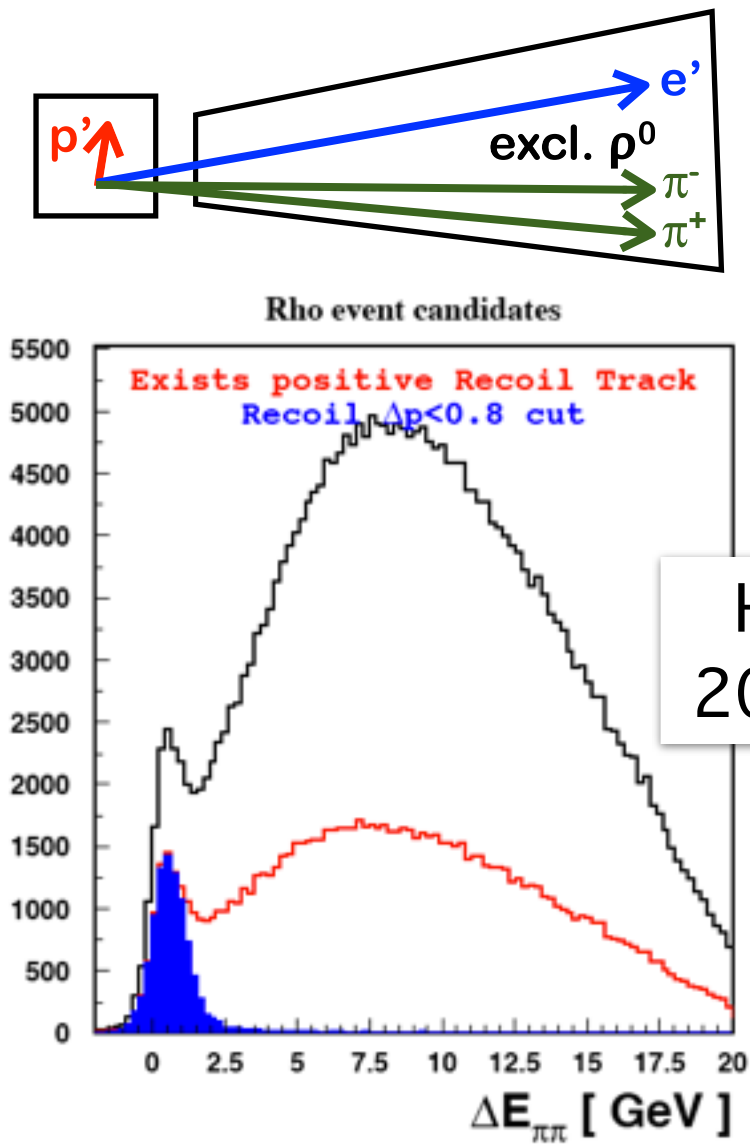
p<450 MeV/c, PIDcut=0:
pion contamination ≈0.1%
proton efficiency >99%

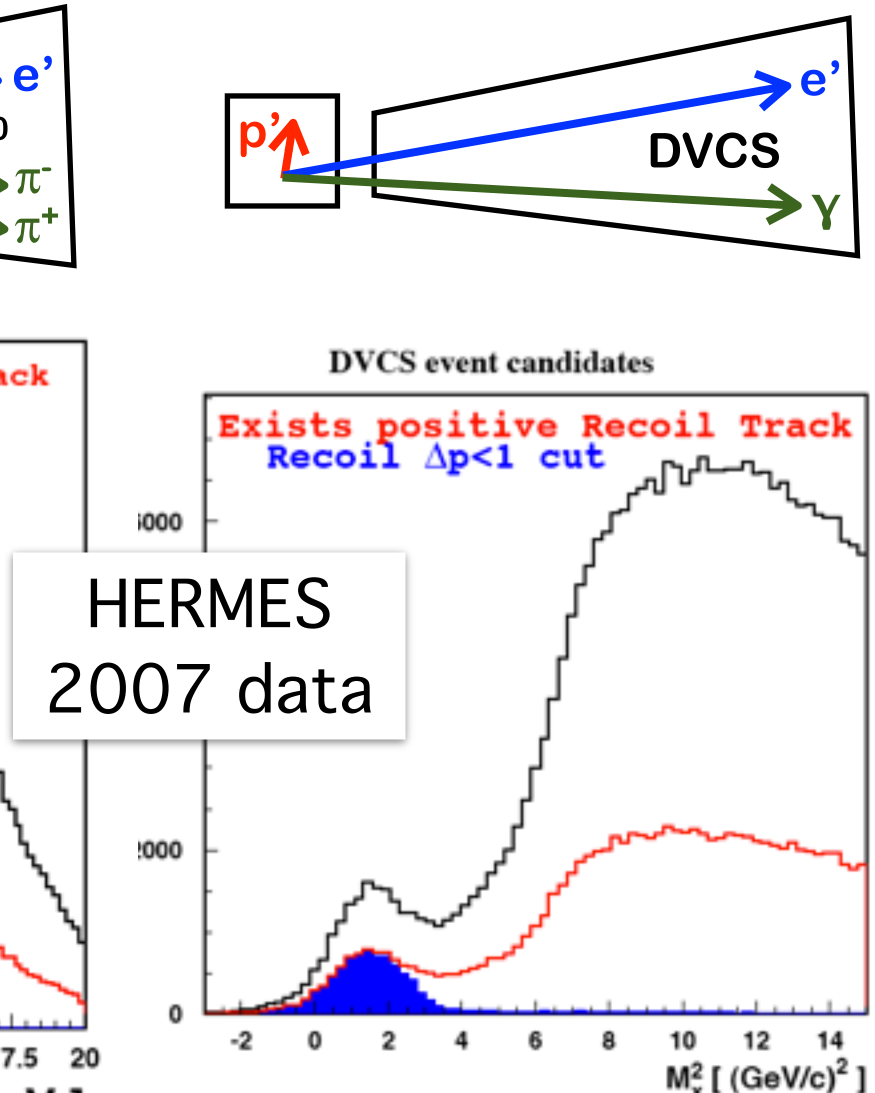


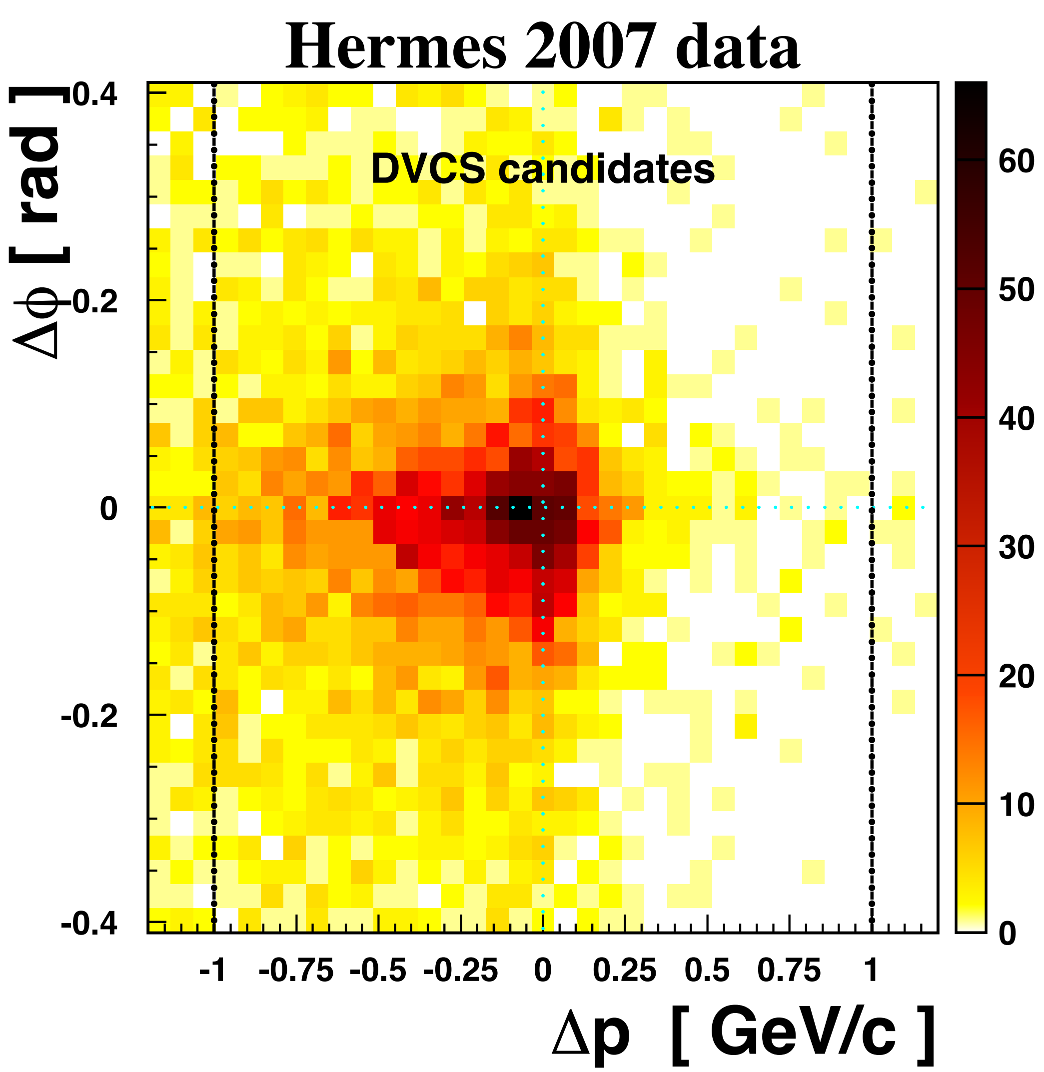
Commissioning of Recoil Analysis

- Reconstruct e and γ in the traditional way
- Calculate expected kinematics K_{exp} of recoil proton from e & γ kinematics
- Measure kinematics K_{meas} of recoil proton
- <u>Missing kinematics:</u> $\Delta K = K_{meas} - K_{exp}$





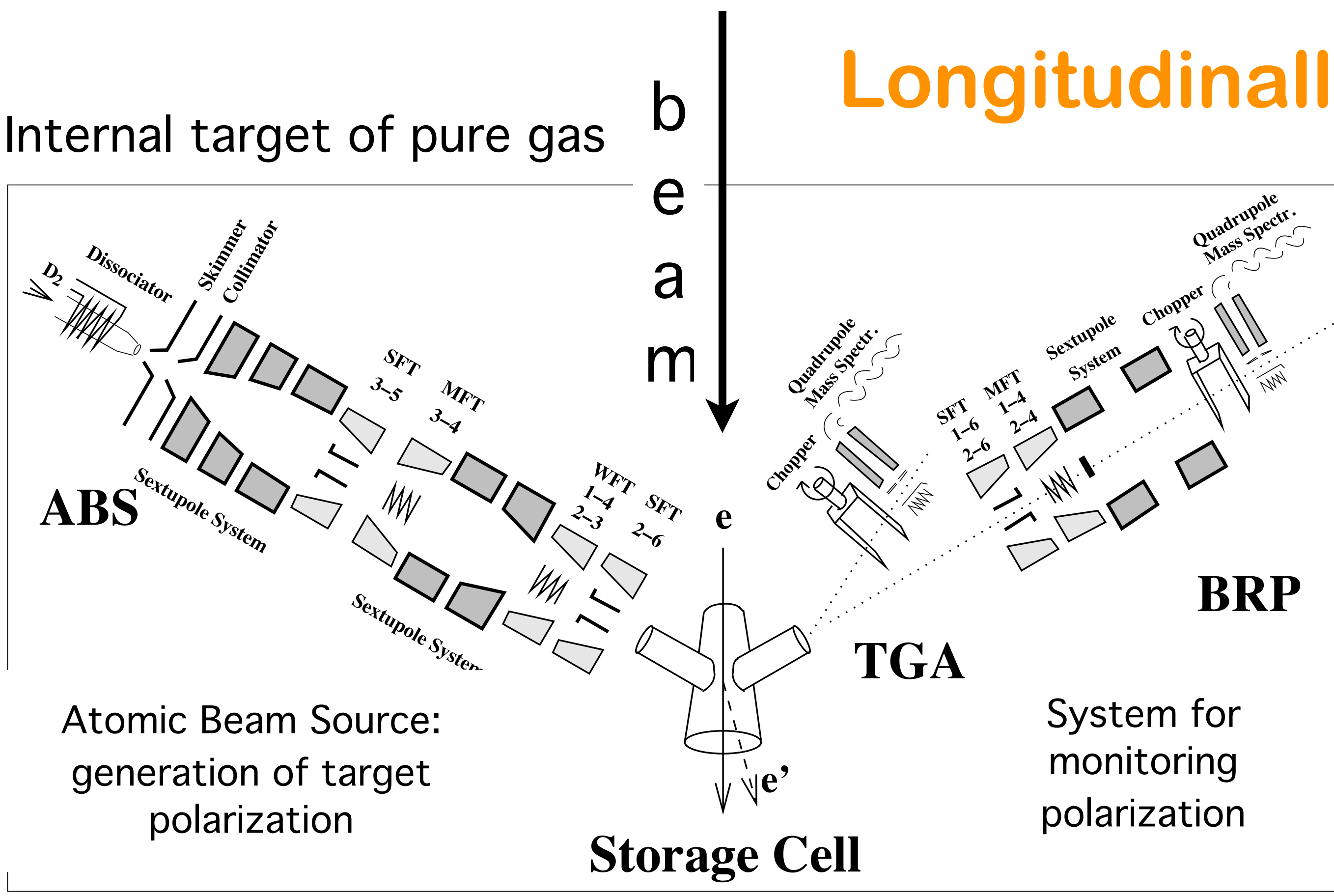




HERMES polarized target

Internal target of pure gas

Longitudinally polarized deuteron



EML method for amplitude extraction

$$\underline{-\log \mathcal{L}_{\mathrm{EML}}} = -\sum_{i=1}^{N} \log(1 + P_i \mathcal{A}_{\mathrm{LU},i}(\phi)) + \mathcal{N}$$

Normalization

Quantity to minimize

$$\mathcal{A}_{\mathrm{LU}} = A_{\mathrm{LU}}^{\cos(0\phi)} + A_{\mathrm{LU}}^{\sin\phi} \sin\phi + A_{\mathrm{LU}}^{\sin(2\phi)} \sin(2\phi)$$

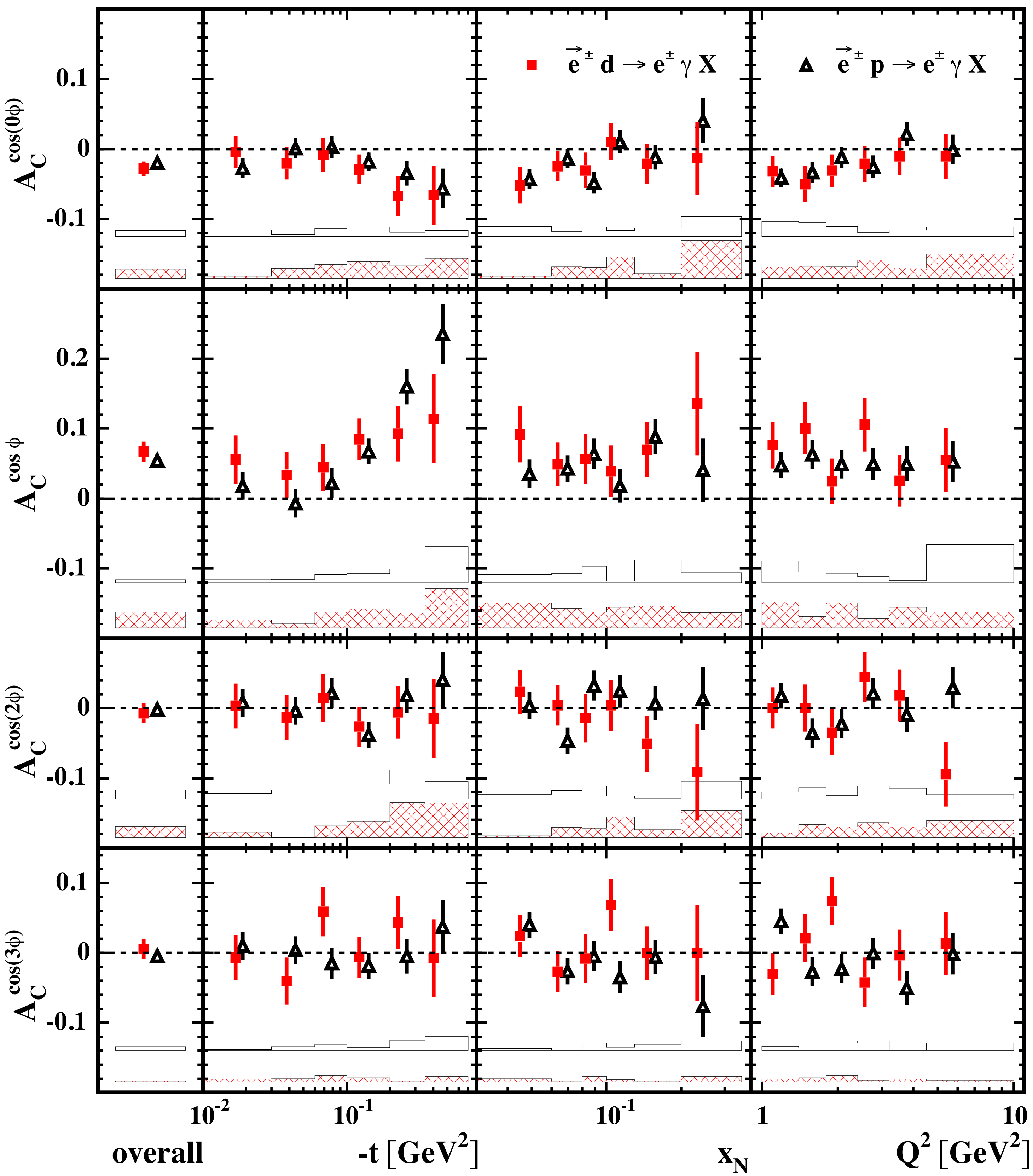
$$\mathcal{N} = \frac{L}{L_{P_\rightarrow}} \frac{\sum_{i,P_\rightarrow} (1 + \langle P \rangle \mathcal{A}_{\mathrm{LU},i}(\phi))}{1 - \frac{\langle P_\rightarrow \rangle}{\langle P_\leftarrow \rangle}} + \frac{L}{L_{P_\leftarrow}} \frac{\sum_{i,P_\leftarrow} (1 + \langle P \rangle \mathcal{A}_{\mathrm{LU},i}(\phi))}{1 - \frac{\langle P_\leftarrow \rangle}{\langle P_\rightarrow \rangle}}$$

→←: beam helicity +1/ -1,
P_i: beam polarization for event i

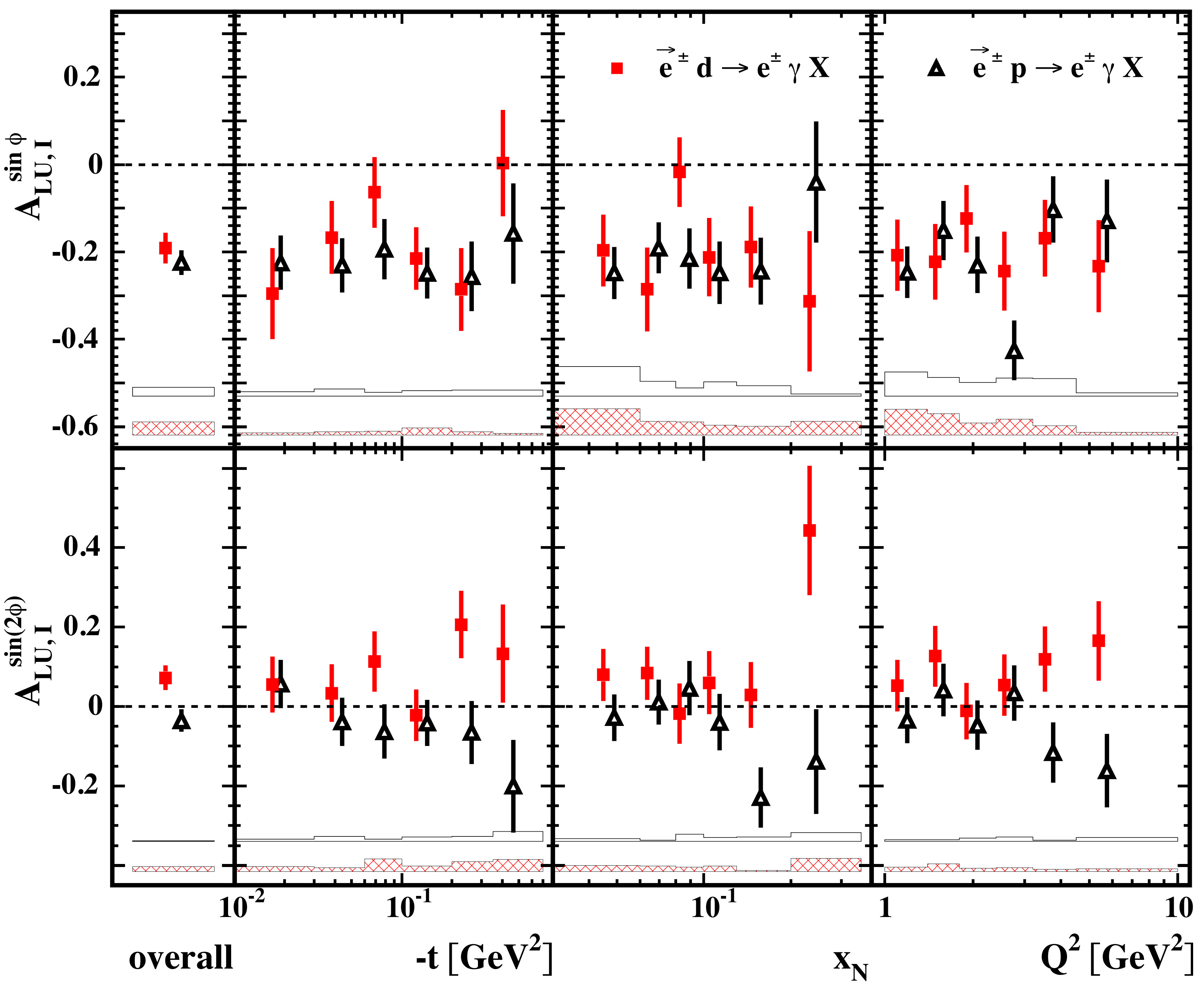
<P>: effective beam polarization

$A_{LU}^{\cos(0\phi)}$: test of normalization, should be compatible with zero for beam-helicity asymmetry

Beam-Charge Asymmetry on p and d



Beam-Helicity Asymmetry on p and d

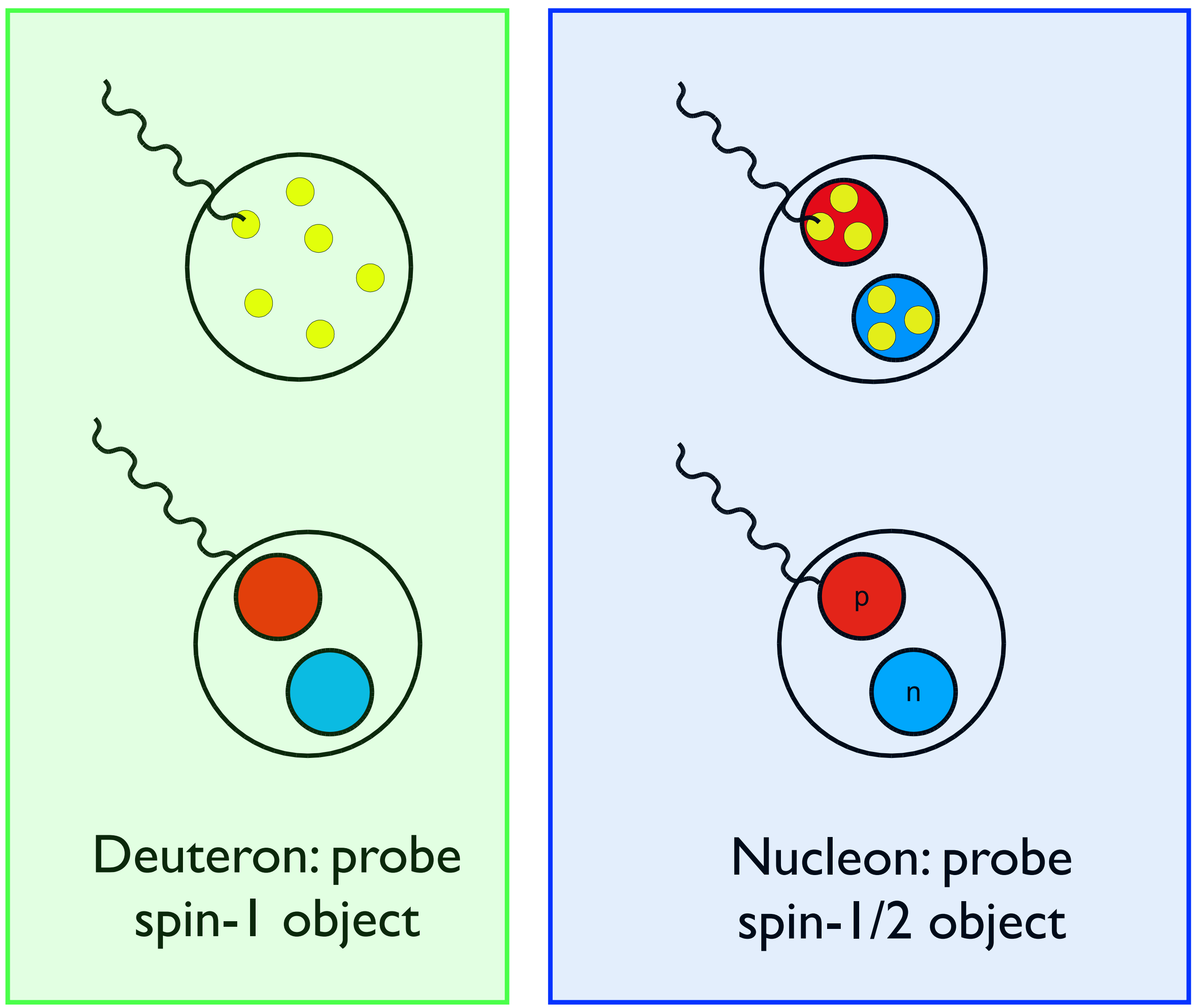


Coherent vs. incoherent

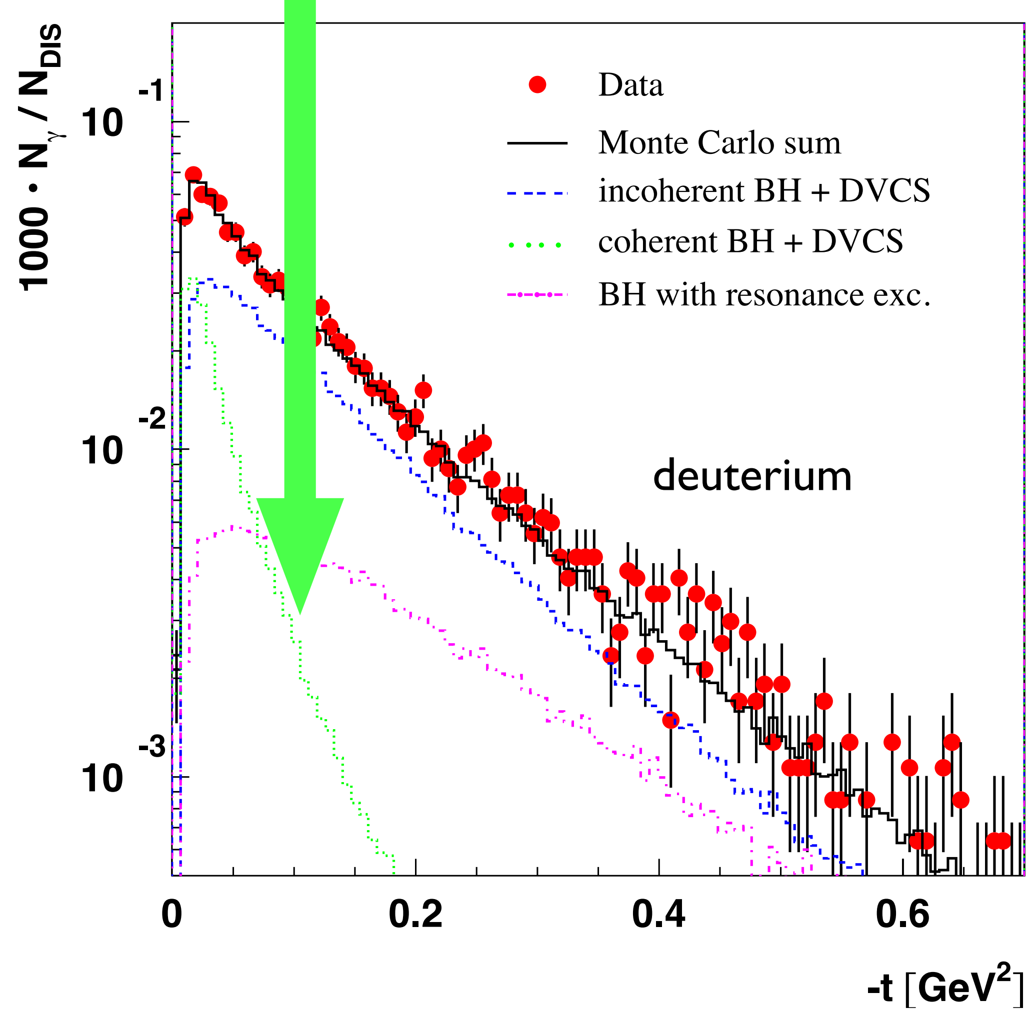
$eA \rightarrow eA\gamma$ $eA \rightarrow e(A-1)N\gamma$

DVCS

Bethe-Heitler



Coherent contribution rapidly decreasing with -t



BH (proton) » BH (neutron)
due to elastic electric form factor

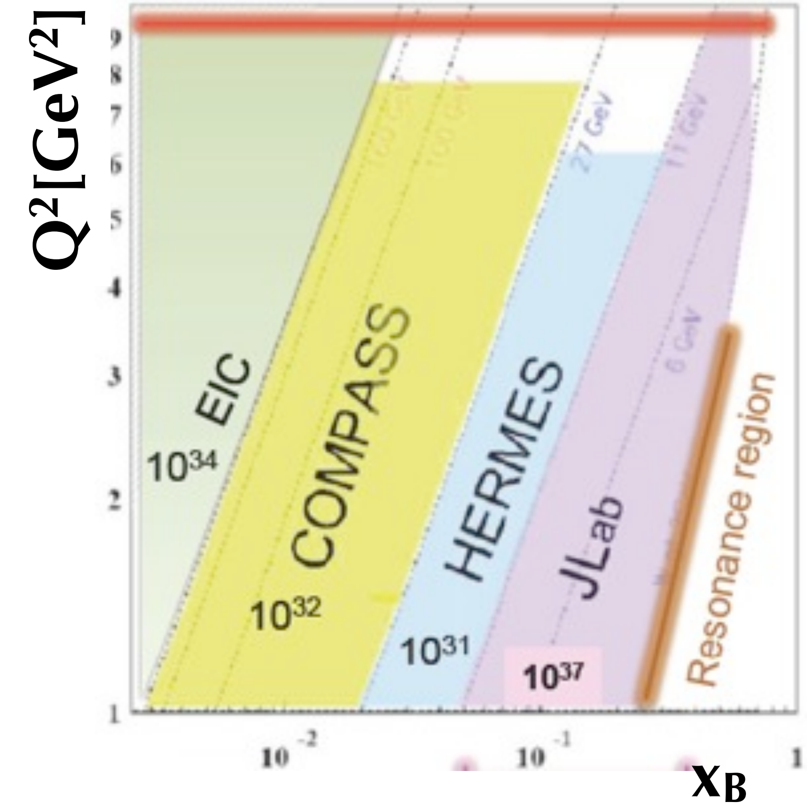
Asymmetries on polarized deuterons

		Lepton charge			Target population (deuterons)					Beam helicity			
					$\Lambda=+1$		$\Lambda=-1$		$\Lambda=0$	$\lambda=+1$		$\lambda=-1$	Coherent
		+1		−1	$\Rightarrow$		$\Leftarrow$		0	$\rightarrow$		$\leftarrow$	sensitivity
Single-charge	$\mathcal{A}_{\mathrm{L}\leftrightarrows}$	■			■	+	■			■	−	■	$\Im\mathrm{m}(\mathcal{H}_1,\mathcal{H}_5)$
	$\mathcal{A}_{\mathrm{UL}}$	■			■	−	■			■	+	■	$\Im\mathrm{m}(\widetilde{\mathcal{H}}_1)$
	$\mathcal{A}_{\mathrm{LL}}$	■			■	−	■			■	−	■	(BH)
	$\mathcal{A}_{\mathrm{Lzz}}$	■			■	+	■	−	■	■	−	■	$\Im\mathrm{m}(\mathcal{H}_5)$
Single-helicity	$\mathcal{A}_{\mathrm{C}\overset{\Leftarrow}{\leftrightarrow\Rightarrow}}$	■	−	■	■	+	■					■	$\Im\mathrm{m}/\Re\mathrm{e}(\mathcal{H}_1,\mathcal{H}_5)$
	$\mathcal{A}_{\overset{0}{\leftrightarrow}\mathrm{L}}$	■	+	■	■	−	■					■	(BH)
	$\mathcal{A}_{\overset{\mathrm{C}}{\leftrightarrow}\mathrm{L}}$	■	−	■	■	−	■					■	$\Im\mathrm{m}/\Re\mathrm{e}(\widetilde{\mathcal{H}}_1)$

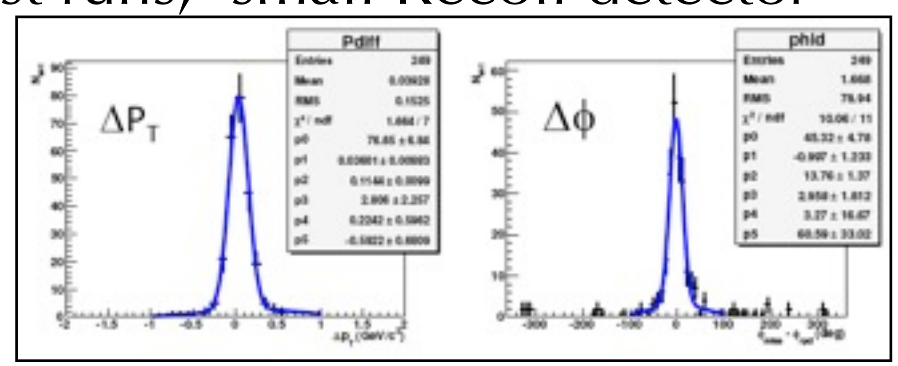
■ HERMES data set available

Not all combinations of beam-charge and beam-helicity available!

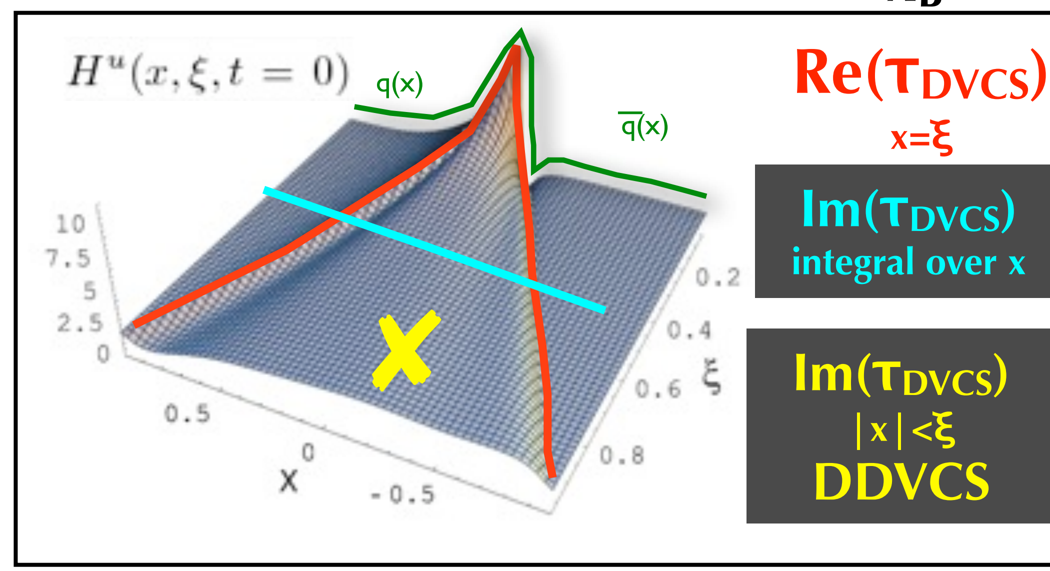
The Future of DVCS



- **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**
  - 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



- Future **Electron-Ion Collider**

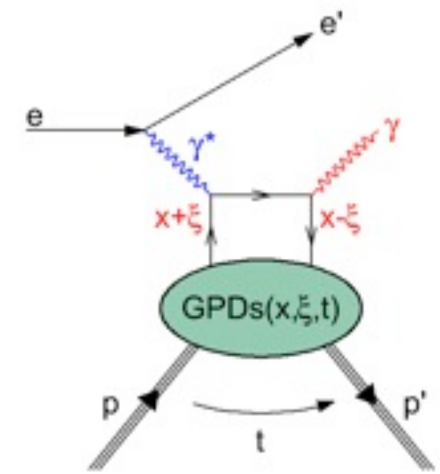
  ELIC @ JLab or eRHIC @ BNL: $\sqrt{s}$ = 20-70 GeV

  (HERMES: 7 GeV)

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

- LHeC

DVCS measurements
over the years



2001
- **H1 @ DESY** cross-section
- **HERMES @ DESY** BSA
- **CLAS @ JLab** BSA

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

2006
- HERMES BCA
- CLAS LTSA
- **Hall A @ JLab** cross-section (p,n)

2007
- CLAS BSA

2008
- HERMES TTSA

2009
- H1 BCA

2010
- HERMES pol-H, -D; nuclear

2011
- HERMES results with recoil and entire data set 1996-2007

> 2013
- **COMPASS @ CERN:** program with Recoil
- CLAS Tpol target
- **JLab 12**
- **EIC**

time →

List does not claim to be exhaustive.