Delia Hasch

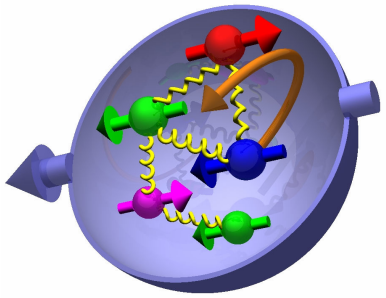
INFN Frascati

review of DVCS measurements

- **a brief introduction**
- **DVCS: from low to high x :**
  cross sections and asymmetries
  (selected results)
- **DVCS on nuclei**
- **conclusion & perspectives**

workshop on GPDs@COMPASS, CERN, March 04, 2010

GPDs and the spin puzzle



nucleon spin:

$$s_z^n = \frac{1}{2} = \frac{1}{2} \sum_q \Delta q + L_z^q + \Delta G + L_z^g = J_q + J_g$$

≈30% ≈zero

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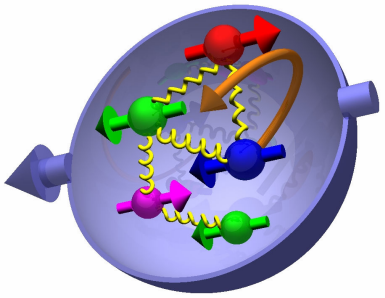

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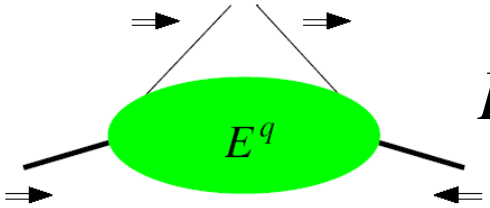
[X. Ji, 1997]

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



$E^q \neq 0$ *requires* orbital angular momentum

proton helicity flipped but quark helicity conserved

nucleon tomography

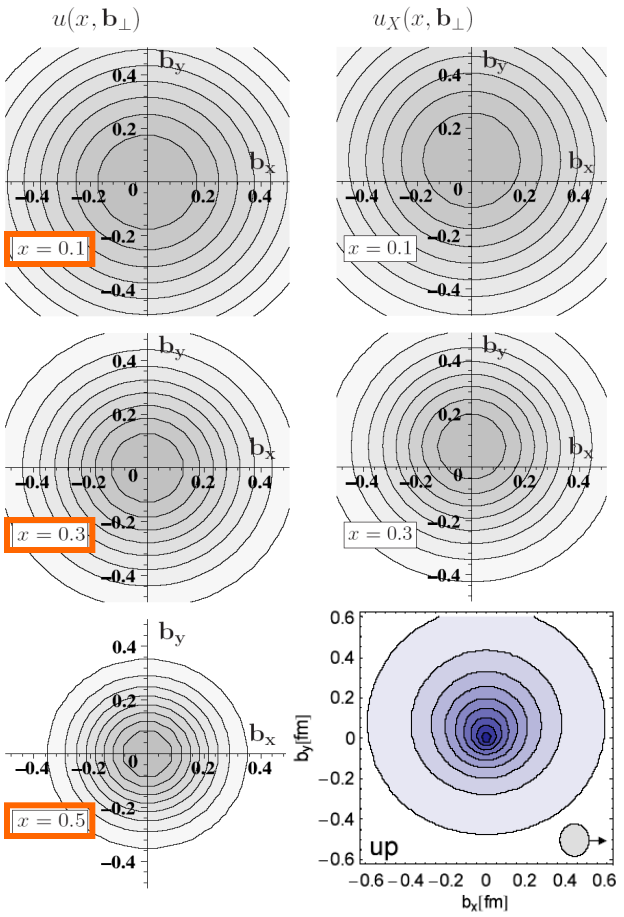
[M. Burkardt, M. Diehl 2002]

FT (GPD) : momentum space → impact parameter space:

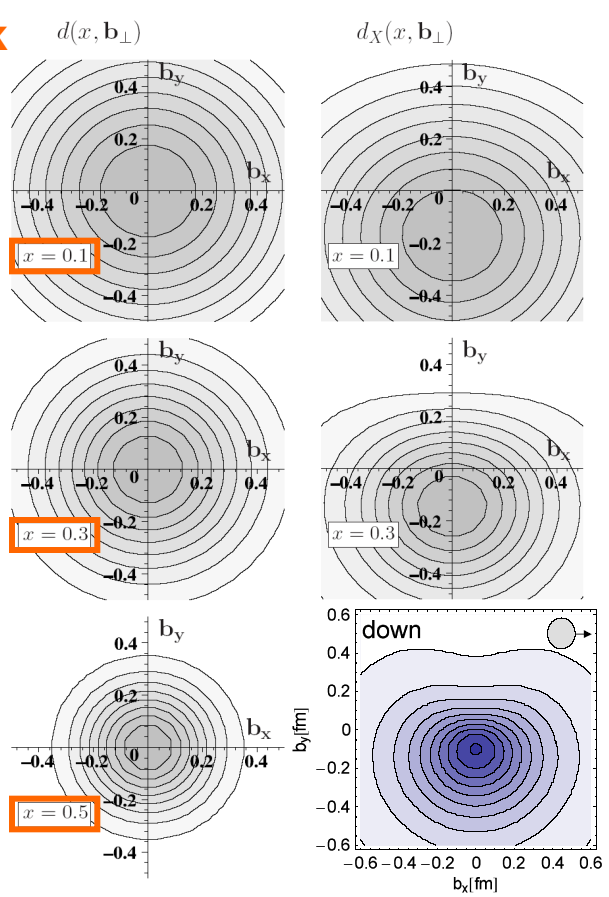
probing partons with specified long. momentum @transverse position $\mathbf{b}_\perp$

polarised nucleon: *spin-orbit correlations*

u-quark

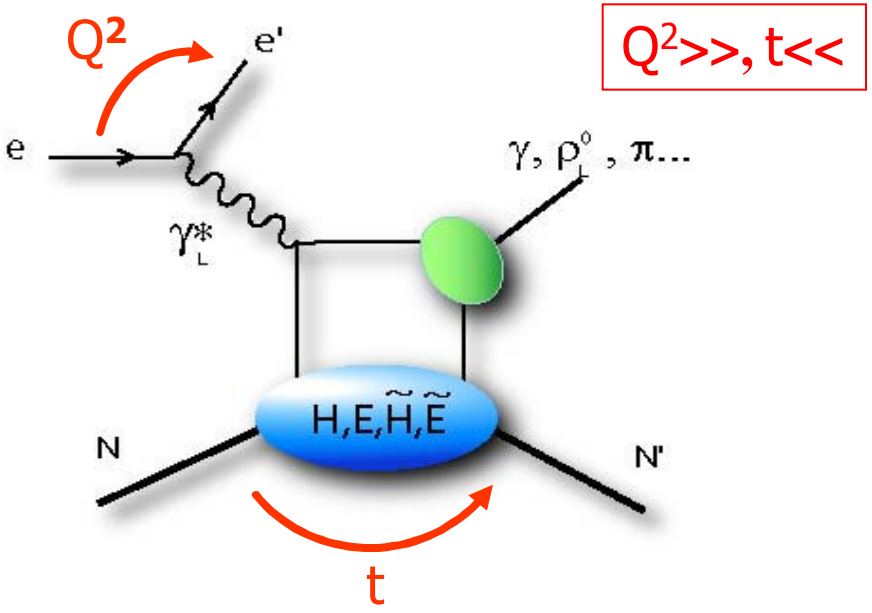


d-quark



from lattice

the ideal experiment for measuring hard exclusive processes



the ideal experiment for measuring hard exclusive processes

- high+variable beam energy
  - → hard regime
  - → wide kinematic range
- high luminosity
  - → small cross sections
  - → measure in 3 kinematic variables simultanously
- complete event reconstruction
  - → ensure exclusivity

… doesn't exist (yet)…

experimental prerequisites

- polarised 27GeV e+/e-
- unpolarised 920 GeV p
- ≈full event reconstruction

- polarised 27GeV e+/e-
- long.+transv. polarised p, d targets
  unpolarised nuclear targets
- missing mass/energy technique
- 2006/7: data with recoil detector

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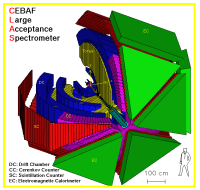
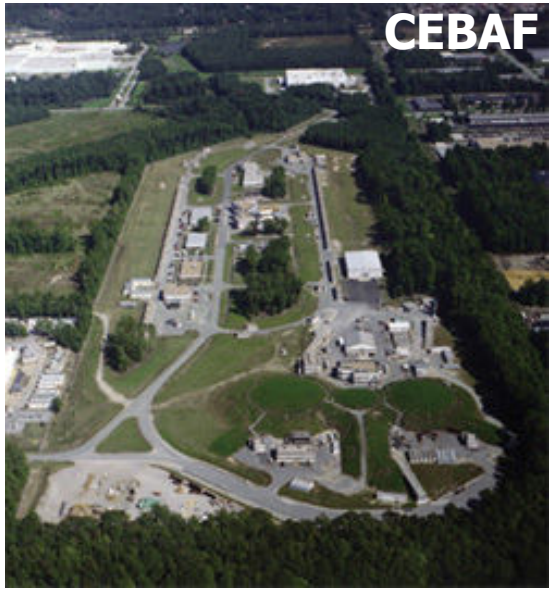
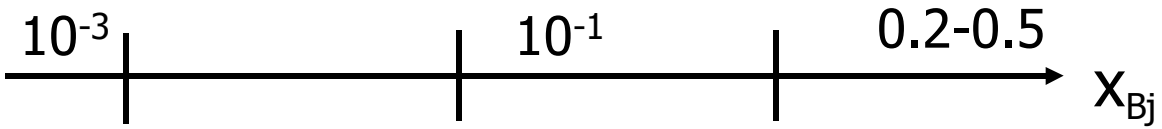


- highly polarised continuous up to 6GeV e-
- long. polarised effective p and n targets
- missing mass/energy technique



small → high x



HERA-collider

$10^{-4} < x_B < 0.02$

sea quarks & gluons

HERMES / JLab

$0.02 < x_B < 0.4$ $0.1 < x_B < 0.6$

(valence) quarks

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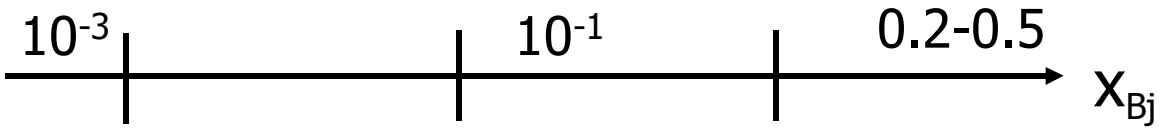

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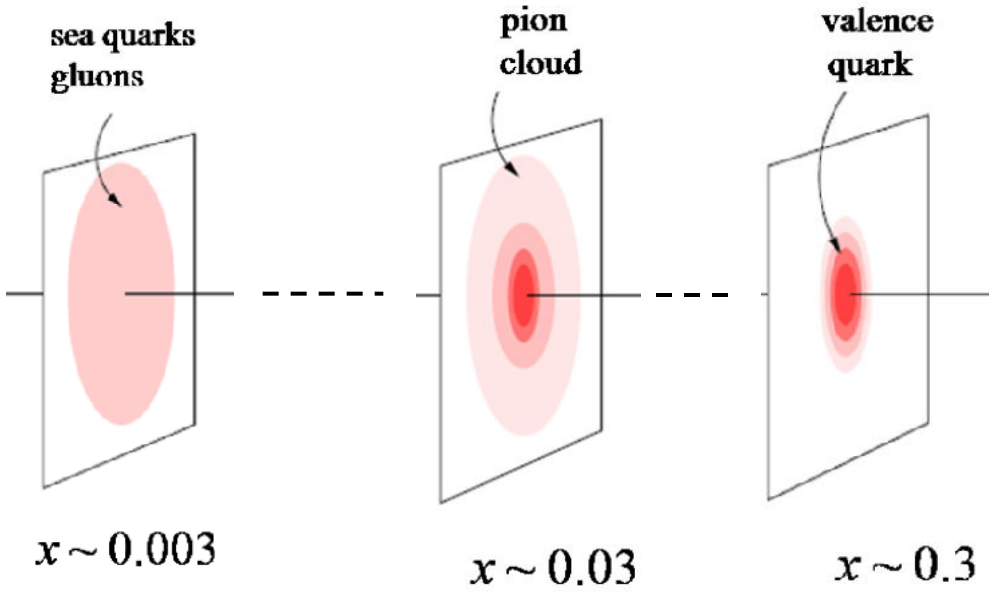
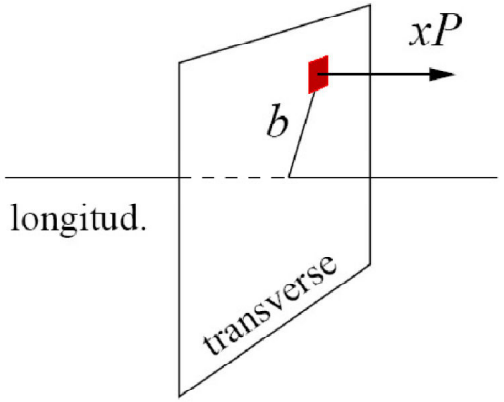


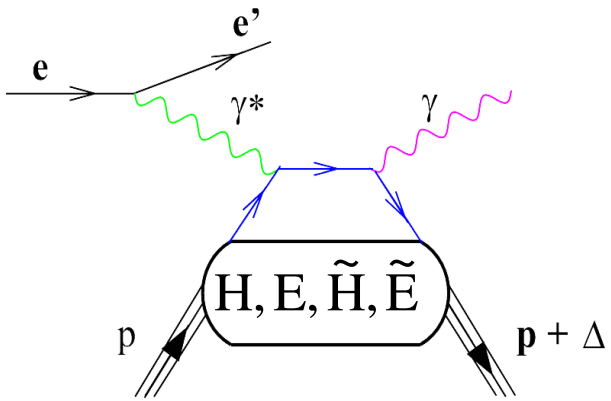


[C. Weiss]

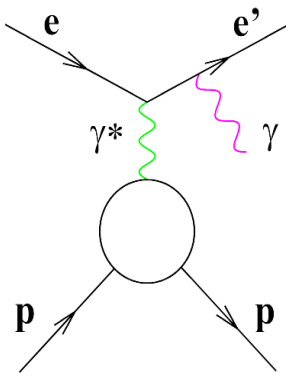
see talk by L. Schoeffel

deeply virtual compton scattering

DVCS



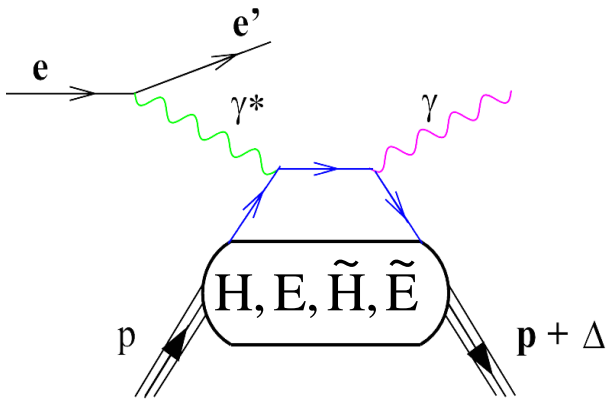
Bethe-Heitler



$$d\sigma \propto |\tau_{BH}|^2 + |\tau_{DVCS}|^2 + (\tau^*_{BH}\tau_{DVCS} + \tau^*_{DVCS}\tau_{BH})$$

deeply virtual compton scattering

DVCS



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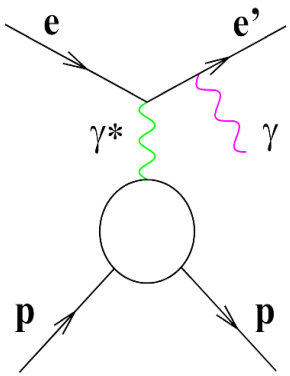


@H1/Zeus:

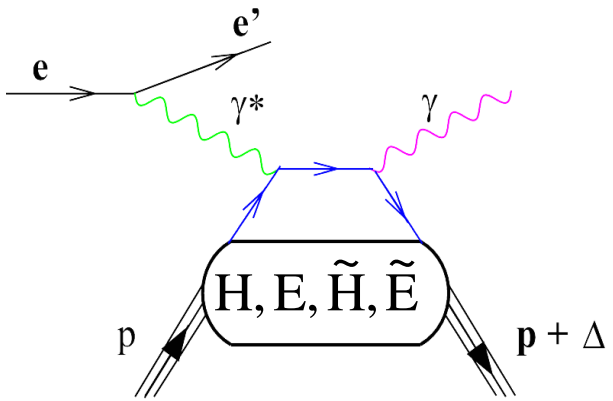
DVCS ≈ Bethe-Heitler

$$d\sigma \propto |\tau_{BH}|^2 + |\tau_{DVCS}|^2$$

→ bilinear in GPDs

deeply virtual compton scattering

DVCS



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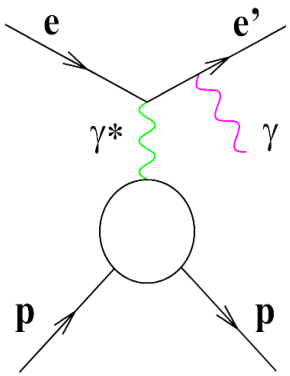

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@HERMES, JLab:

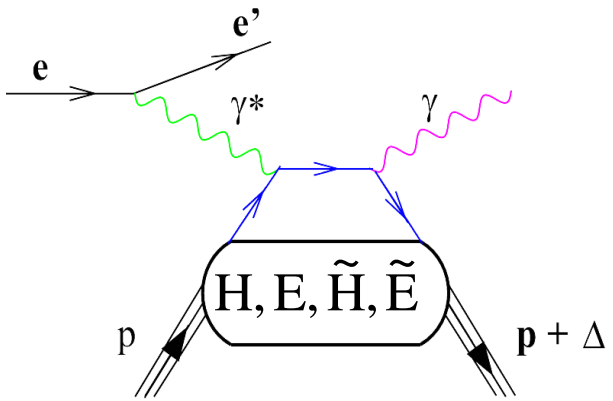
DVCS << Bethe-Heitler

$$d\sigma \propto |\tau_{BH}|^2 + \text{(shaded)} + (\tau^*_{BH}\tau_{DVCS} + \tau^*_{DVCS}\tau_{BH})$$

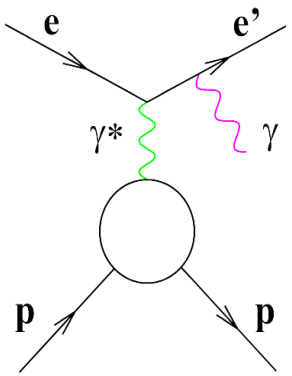
→ bilinear in GPDs → linear in GPDs

deeply virtual compton scattering

DVCS



Bethe-Heitler



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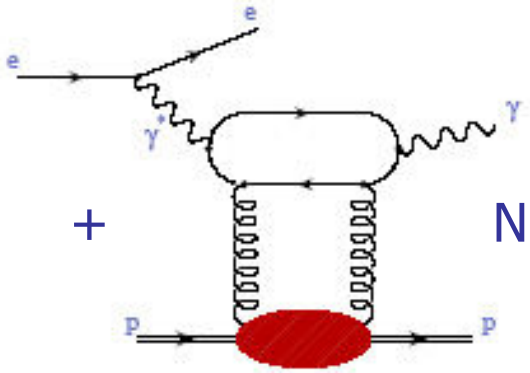
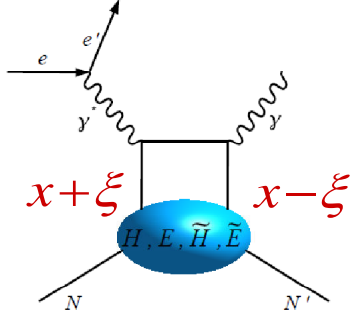
H1/Zeus: LO sea quark +



NLO gluon contribution

DVCS & GPDs: caveats



$$T_{\mu\nu} = \left[\mathcal{H}, \mathcal{E}, \widetilde{\mathcal{H}}, \widetilde{\mathcal{E}}\right](\xi, t, Q^2), \qquad \mathcal{F}(\xi, t, Q^2) = \int_{-1}^{1} dx\, C^{-}(\xi, x)\, F(x, \xi, t, Q^2),$$

- x is mute variable (integrated over):
  → apart from cross-over trajectory (ξ=x) GPDs not directly accessible
- extrapolation t → 0 is model dependent

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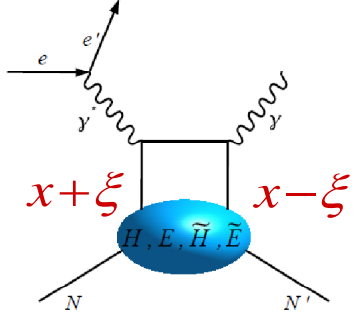

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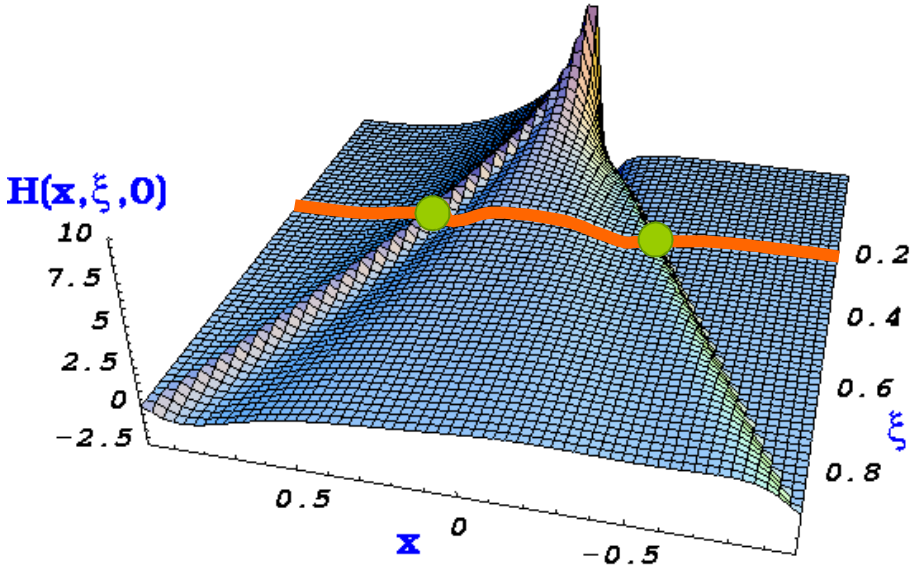
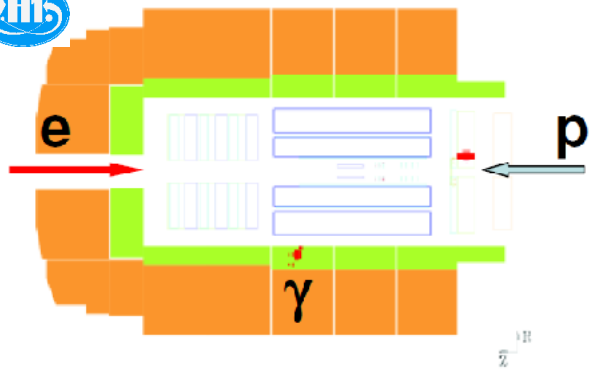


cross sections & beam-charge asymmetry ~ Re(T^{DVCS})

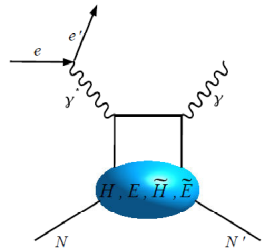
beam or target-spin asymmetries ~ Im(T^{DVCS})

selecting exclusive events

$$e + N \rightarrow e' + N' + \gamma$$



exclusivity

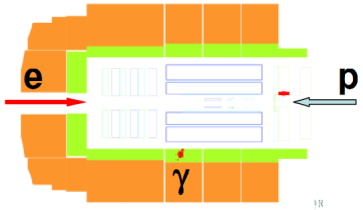


≈ 4π acceptance for e and γ

→ p escapes in beam pipe

ZEUS

LPS: p tagged sample



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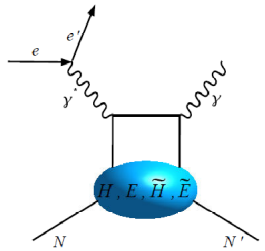

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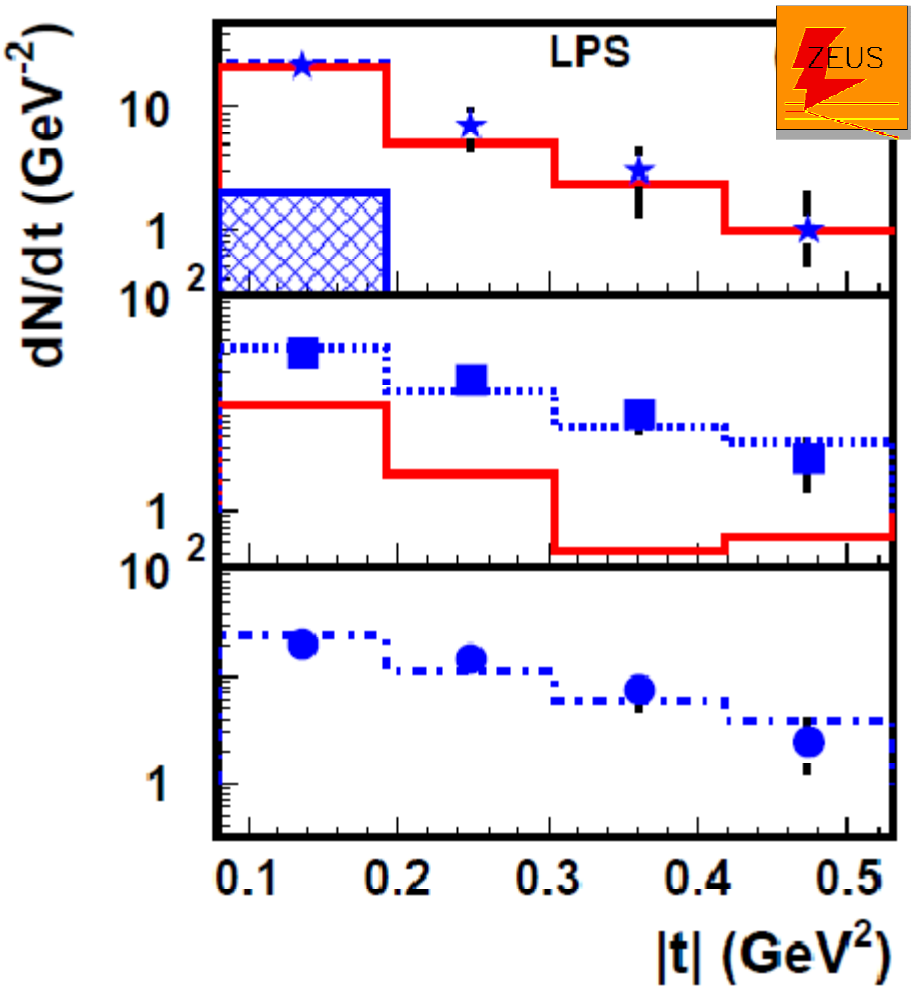


e-sample: BH control sample

e^+e^-, J/Ψ bg sample

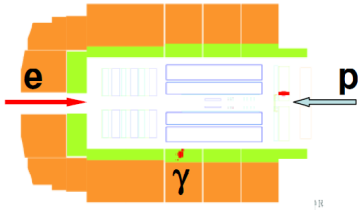
BH+e^+e^-+J/ψ

BH

γ-sample: BH + DVCS

BH

BH+FFS (DVCS)



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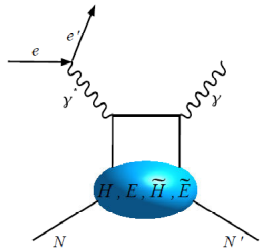

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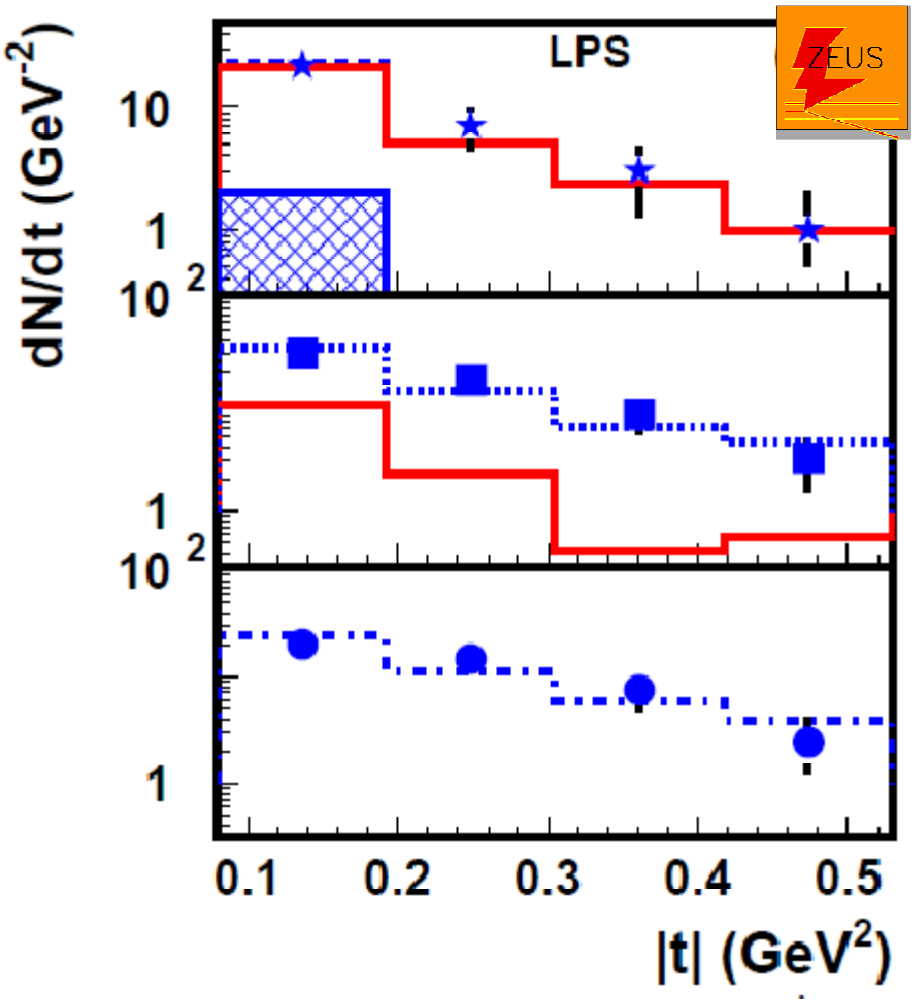

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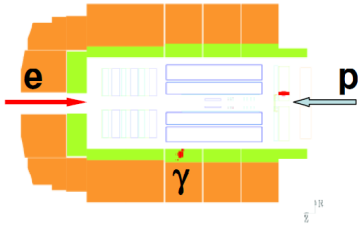
BH+FFS (DVCS)

(BH + DVCS) – BH

FFS (DVCS)



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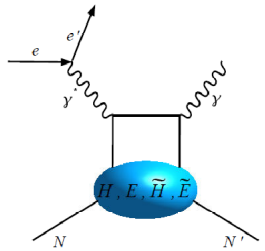
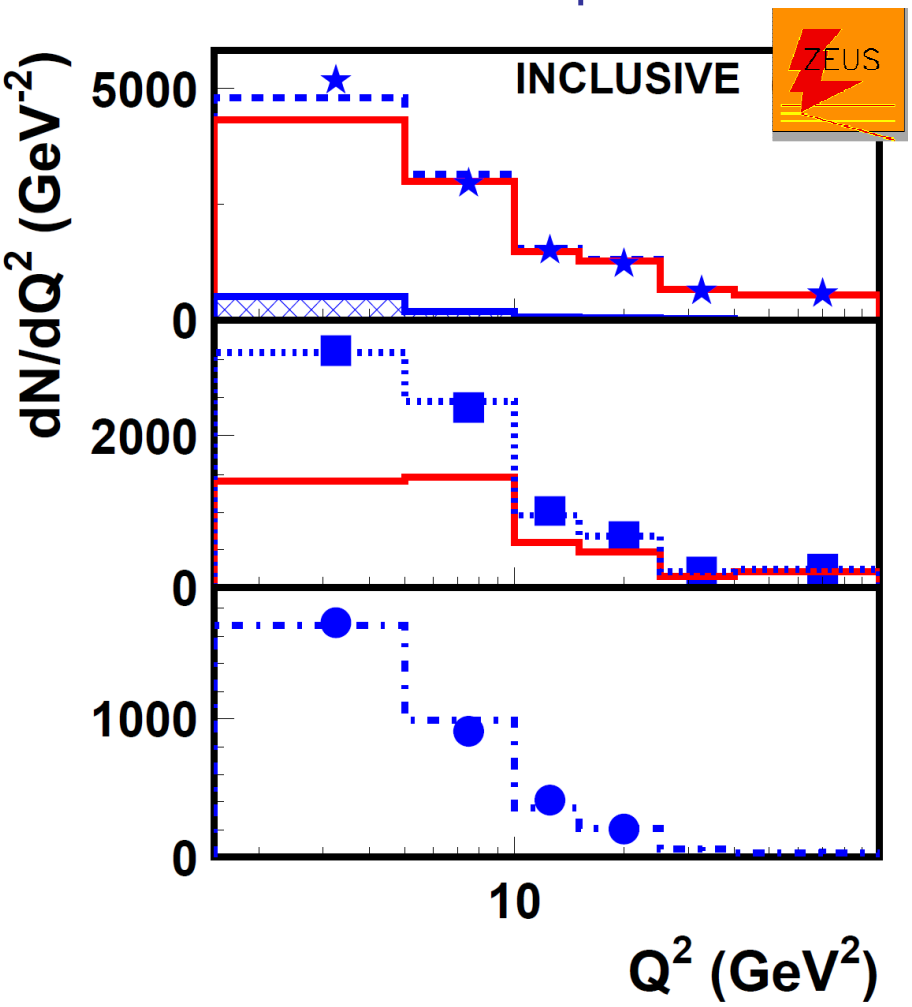


full data sample



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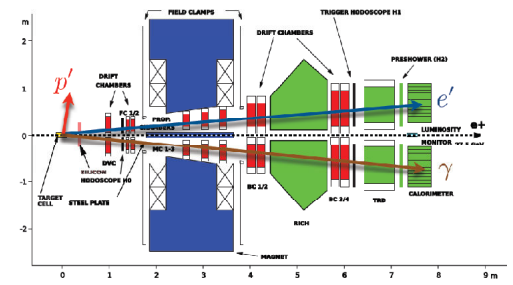
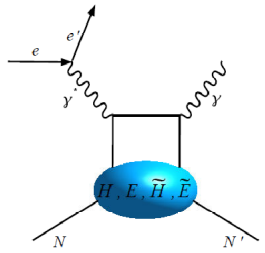
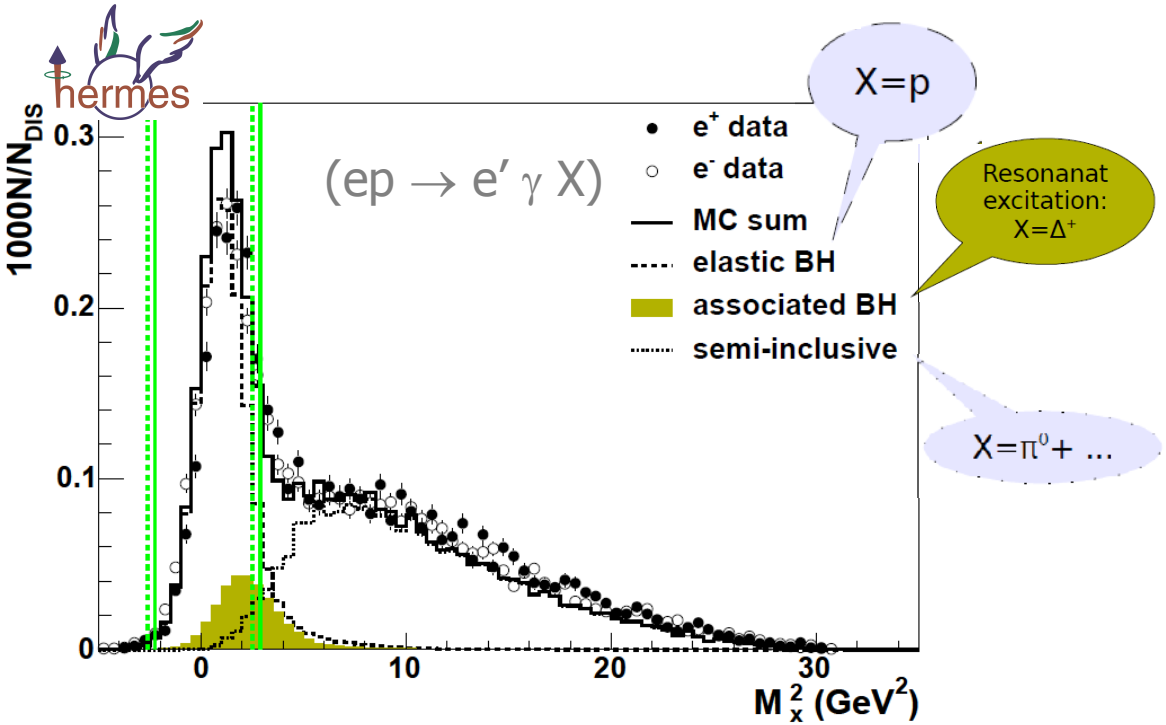


exclusivity

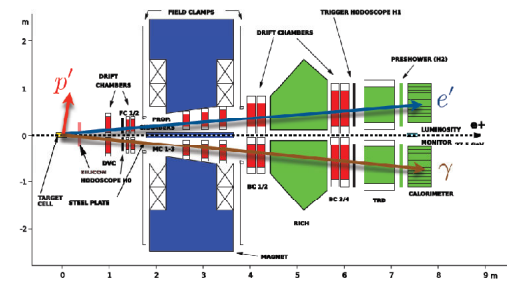
via missing mass / energy





part of the signal

subtracted
very well understood



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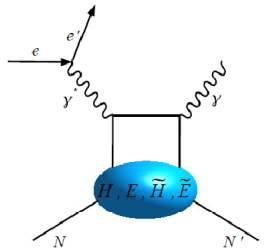
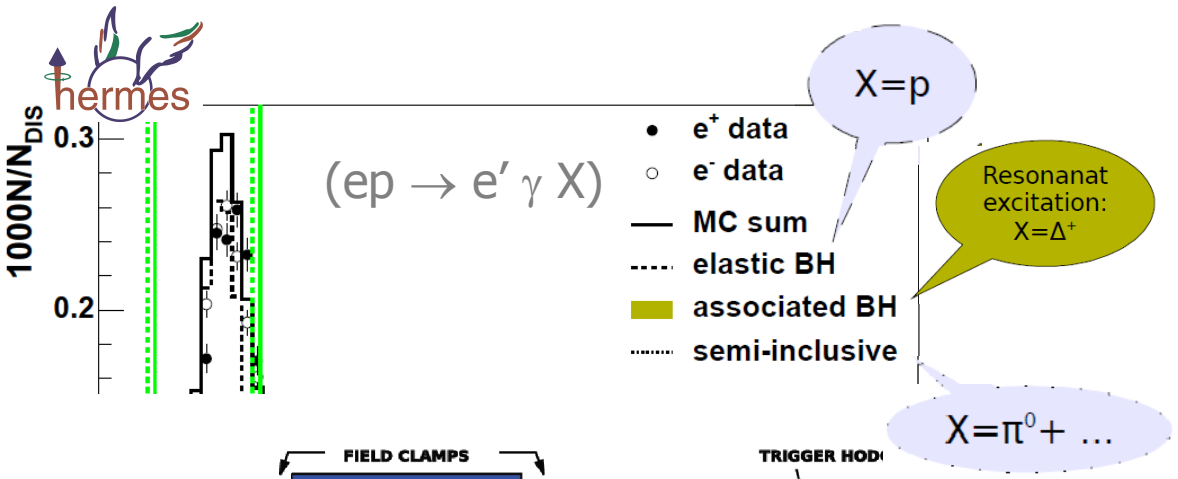




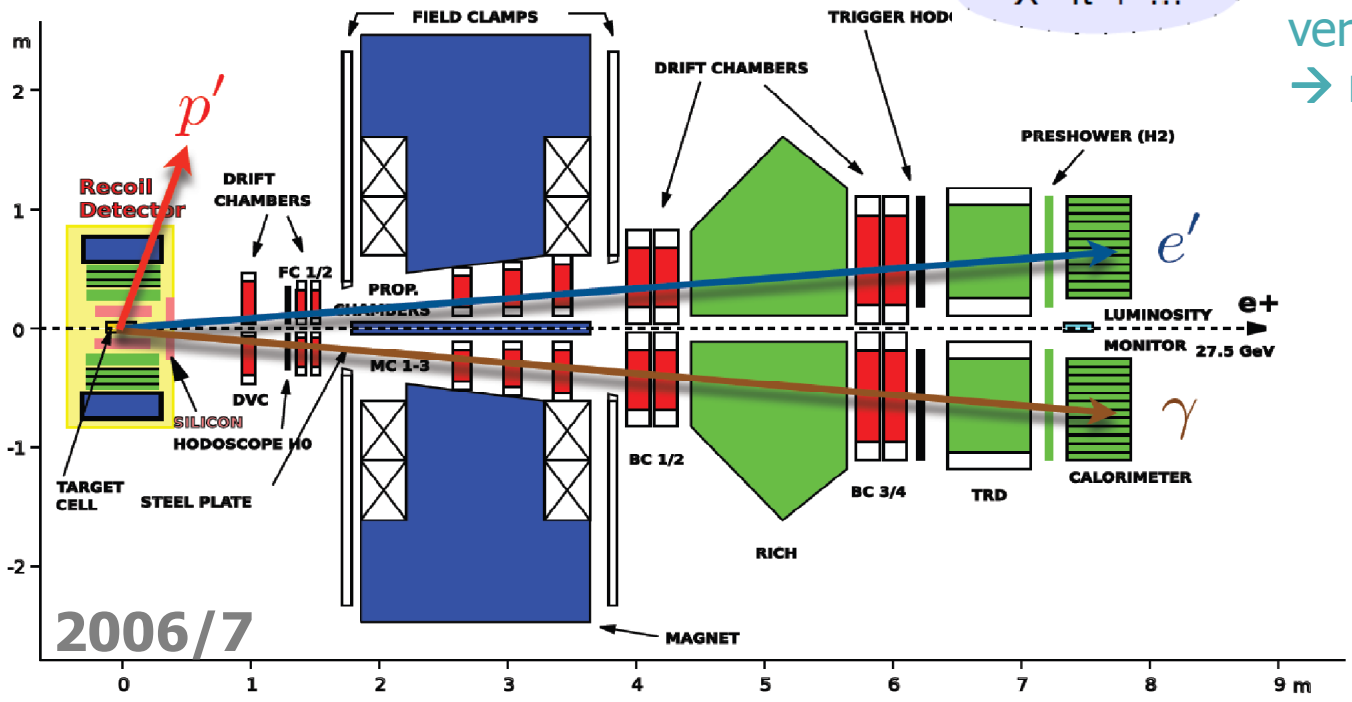
part of the signal

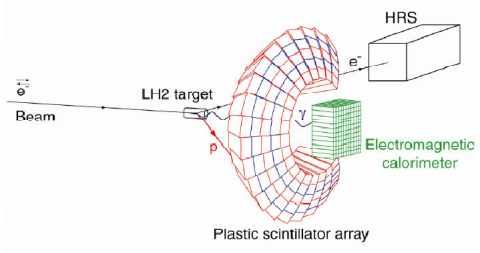
→ Δ^+ **ID:** transition GPDs

subtracted

very well understood

→ **reference samples**





exclusivity

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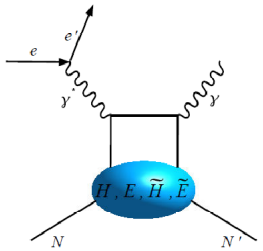
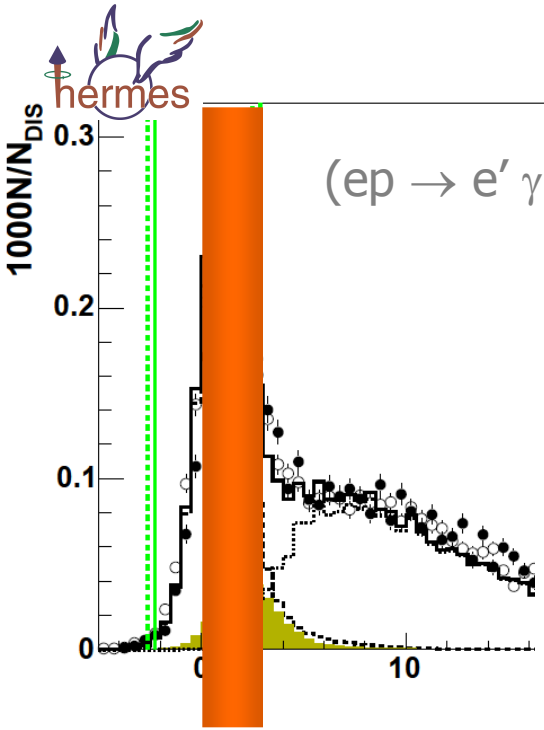
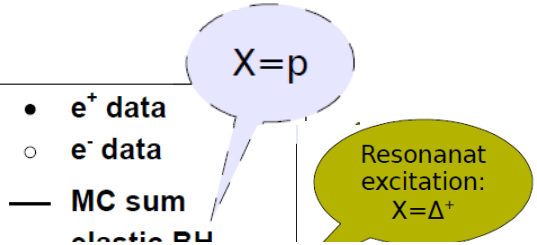


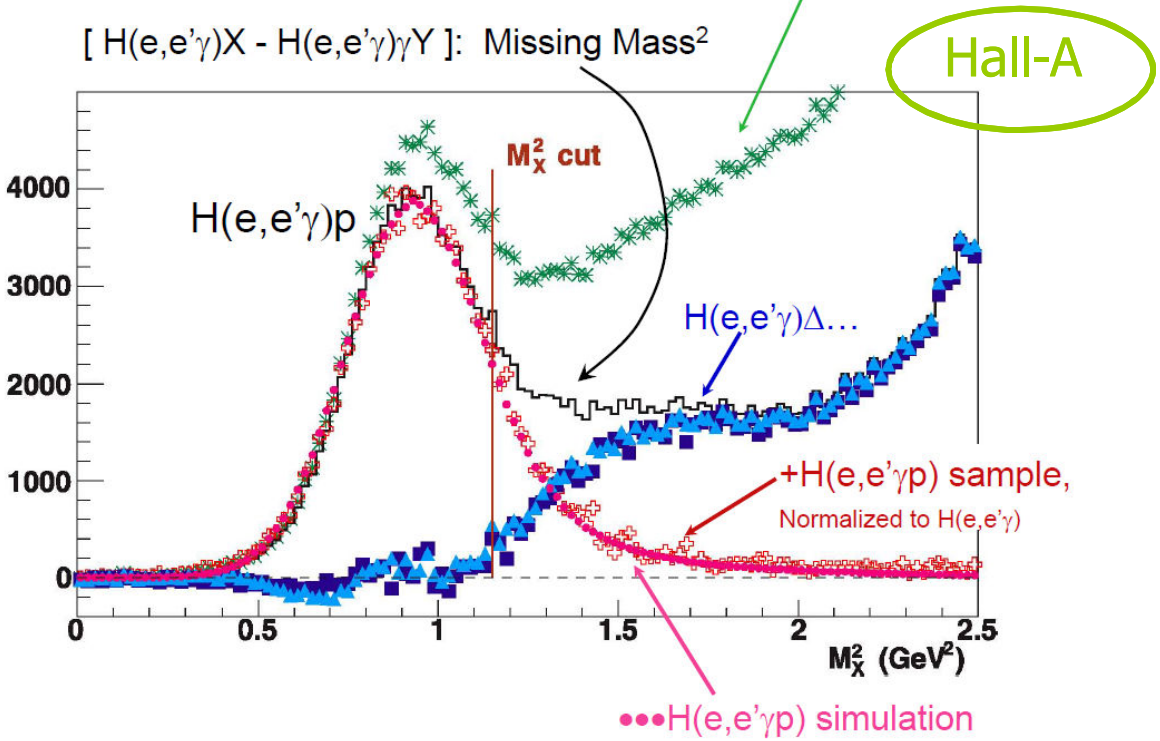


$(ep \rightarrow e' \gamma X)$



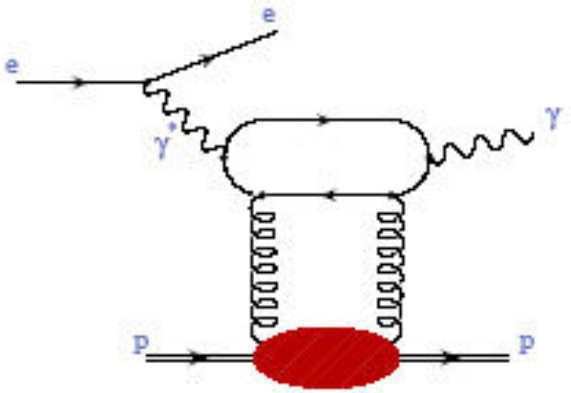
part of the signal

Raw H(e,e'γ)X Missing Mass² (after accidental subtraction).



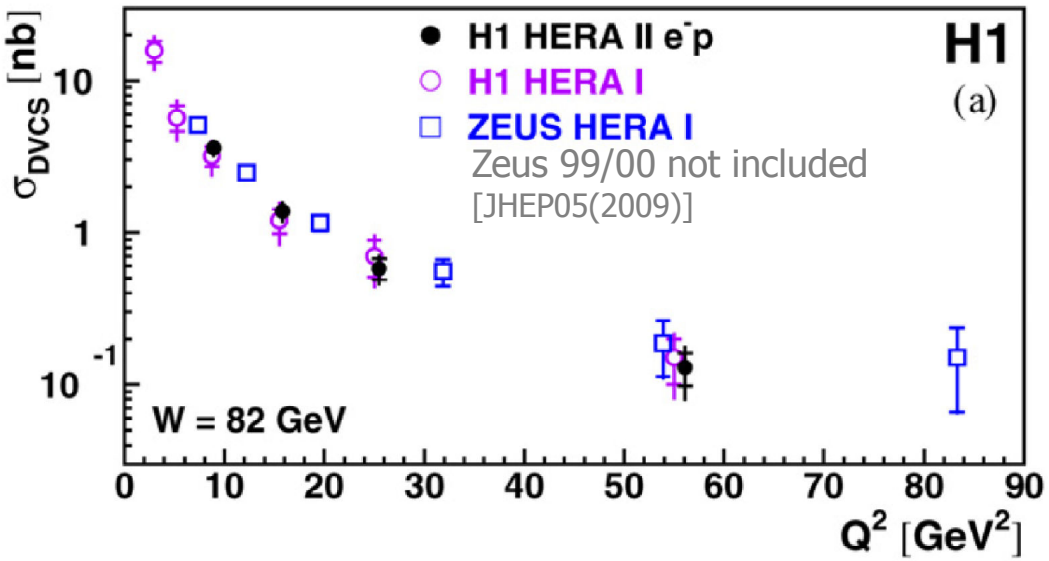
DVCS cross sections

$$d\sigma \propto |\tau_{BH}|^2 + |\tau_{DVCS}|^2$$

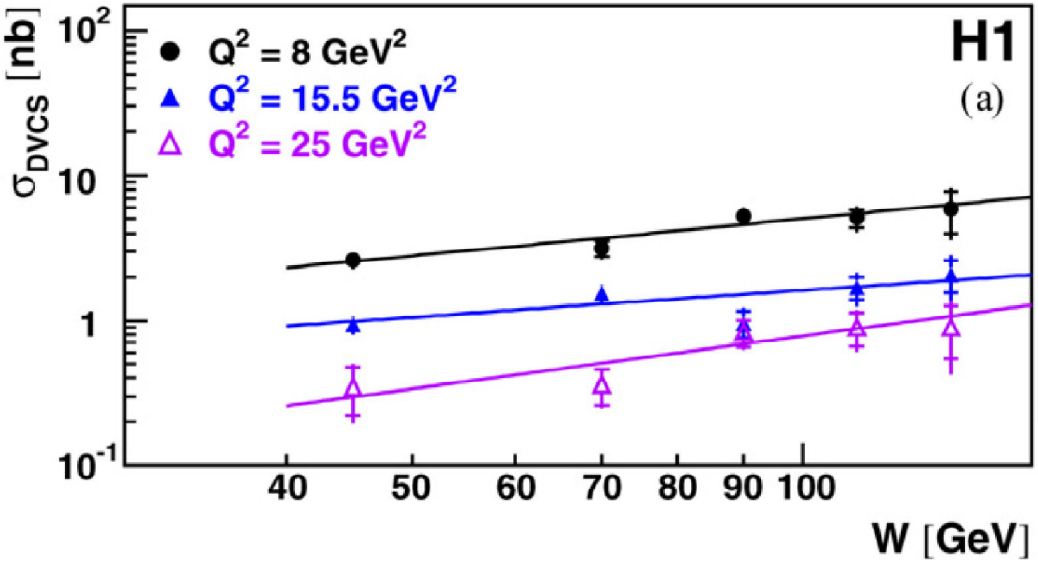


DVCS cross section

[PLB659(2008)]



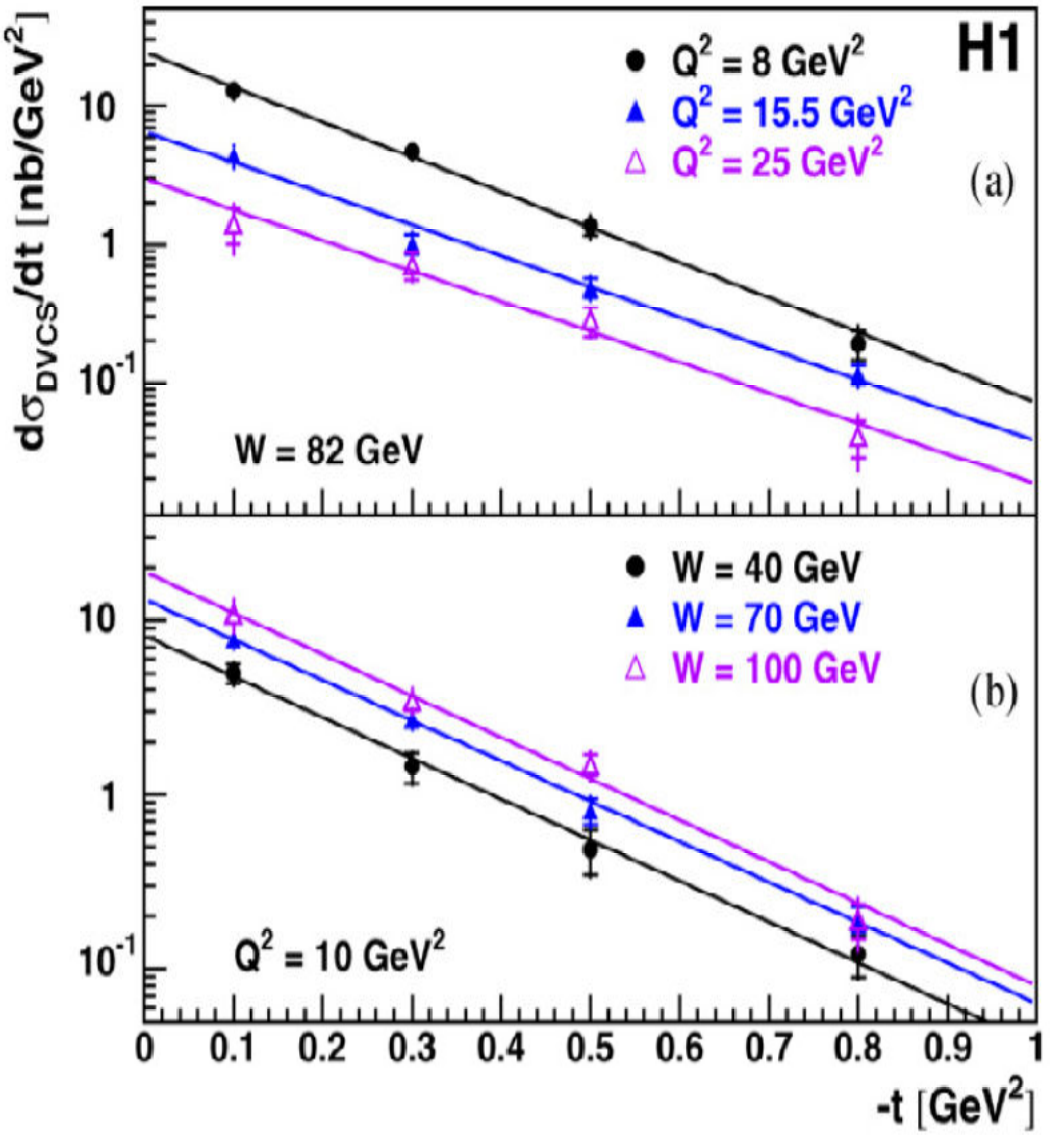
Q^2 range : 1 – 10^2 GeV^2



steep rise with W
→ hard process

DVCS cross section

[PLB659(2008)]



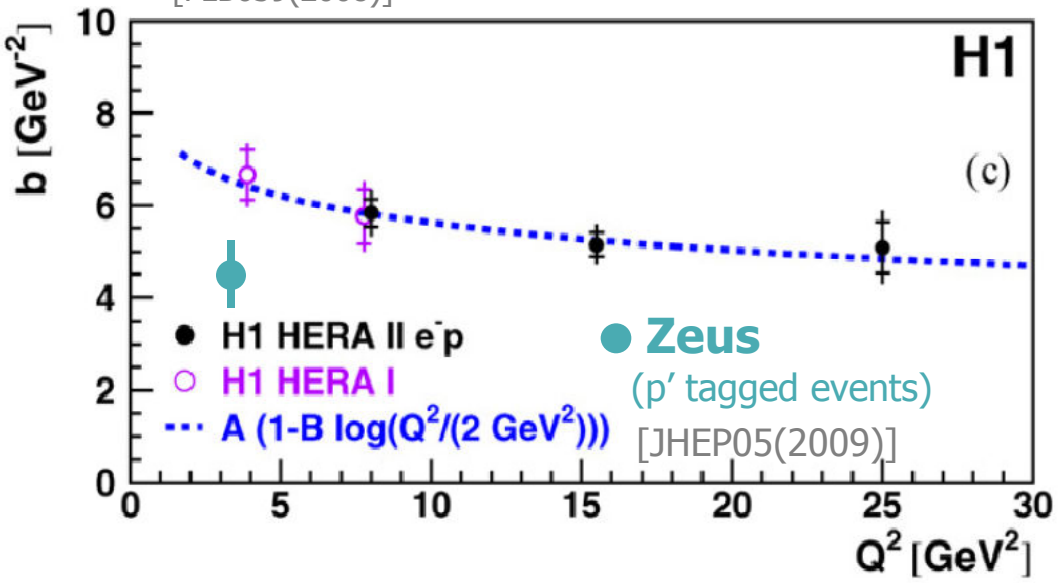
→ measurement of t–slope:

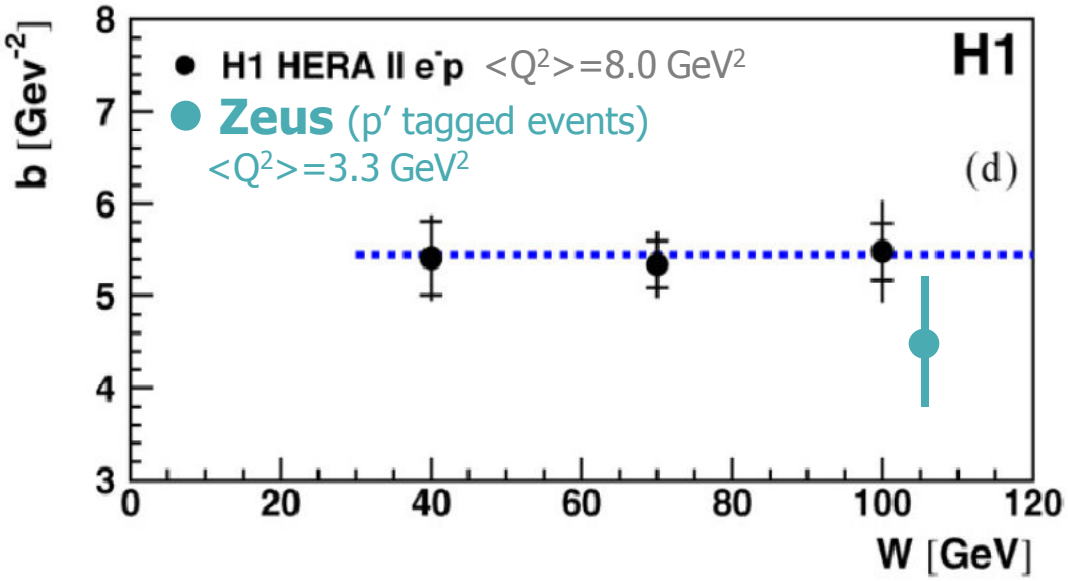
$$\frac{d\sigma}{dt} \propto e^{-b|t|}$$

provides absolute normalisation

DVCS cross section

[PLB659(2008)]





→ measurement of *t* –slope:

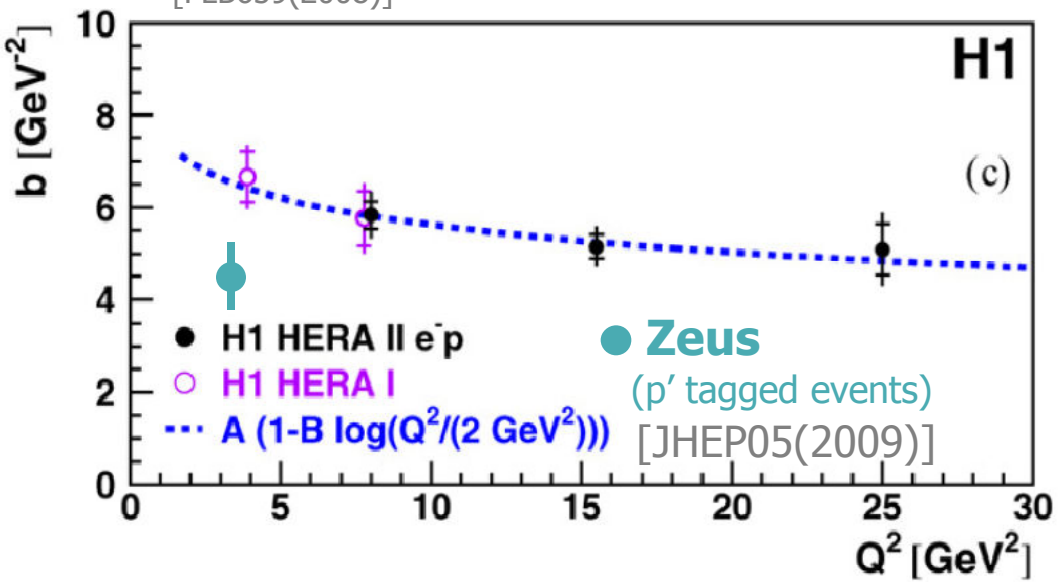
$$\frac{d\sigma}{dt} \propto e^{-b|t|}$$

provides absolute normalisation

→ universality of slope parameter:
point-like configurations dominate

DVCS cross section

[PLB659(2008)]



→ measurement of t–slope:

$$\frac{d\sigma}{dt} \propto e^{-b|t|}$$

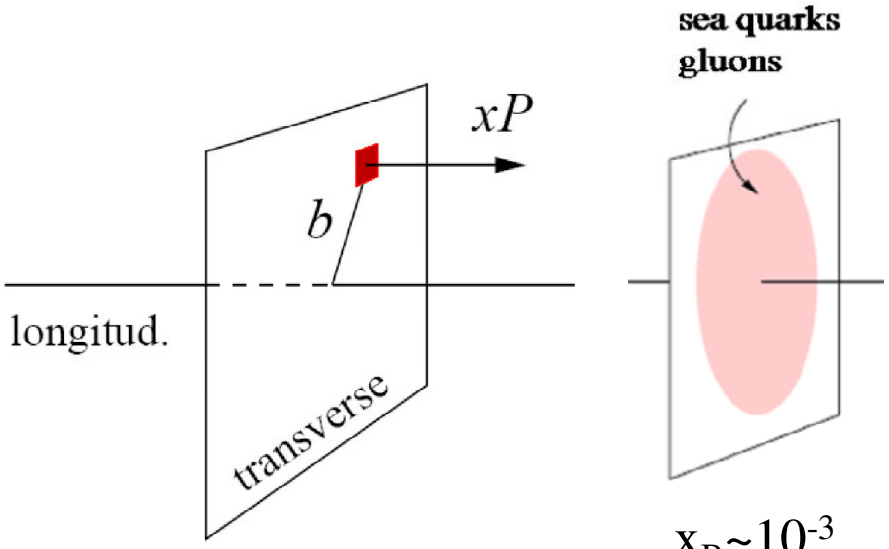
provides absolute normalisation

→ universality of slope parameter:
point-like configurations dominate

***b* → average impact parameter:**

$$\sqrt{\langle r_T^2 \rangle} = (0.65 \pm 0.02)\,\text{fm}$$

@ $x_B = 10^{-3}$



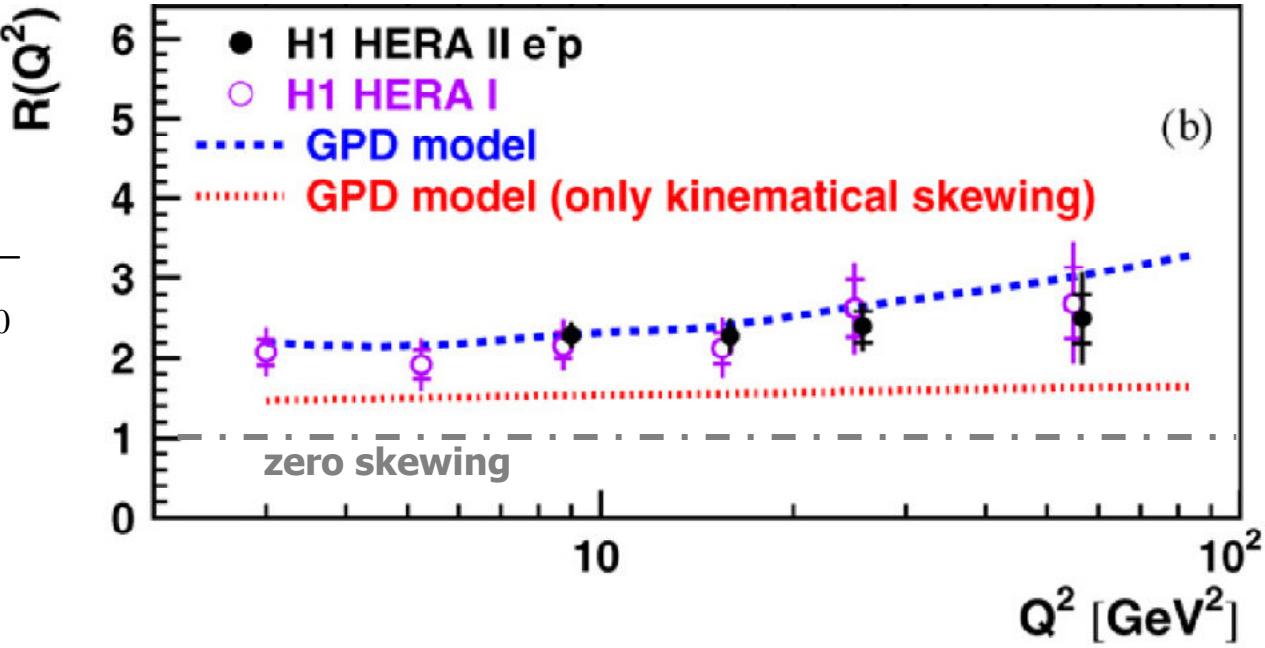
$x_B \sim 10^{-3}$

DVCS cross section

quantifying the skewing

$$R = \frac{\text{Im } A(\gamma^* p \to \gamma p)_{t=0}}{\text{Im } A(\gamma^* p \to \gamma^* p)_{t=0}}$$

LO: R = GPD / PDF



→ skewing due to Q^2 evolution of GPDs

DVCS @small x - outlook

- more HERA II data to come:

  H1: 2007

  Zeus: so far HERA I only

- combined H1 & ZEUS analysis (?)

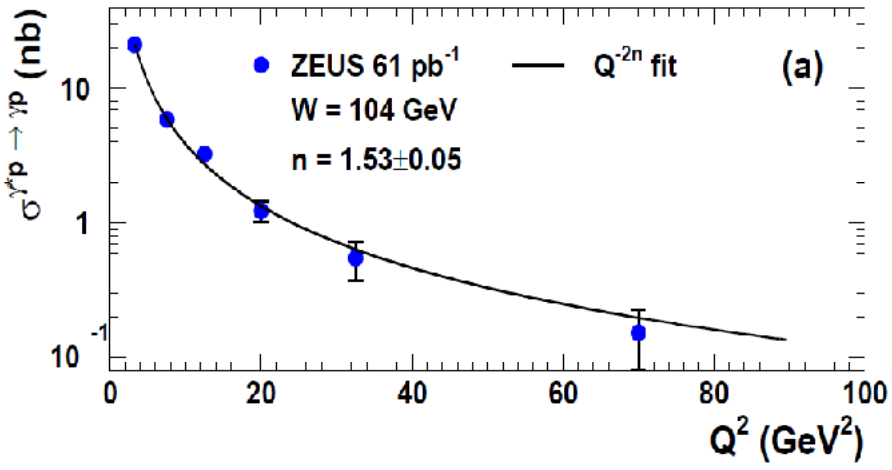
- beam-charge asymmetry @small x :

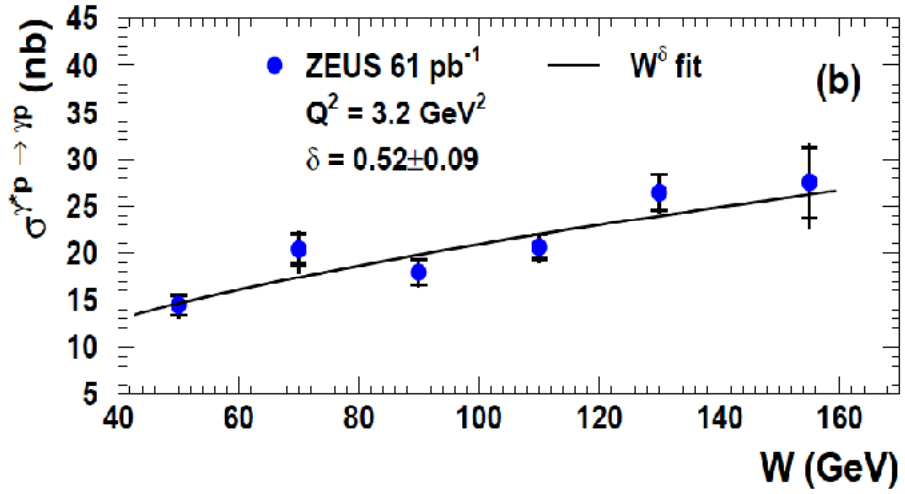
  → access to interference term

  first result from HERA II … very limited by statistics

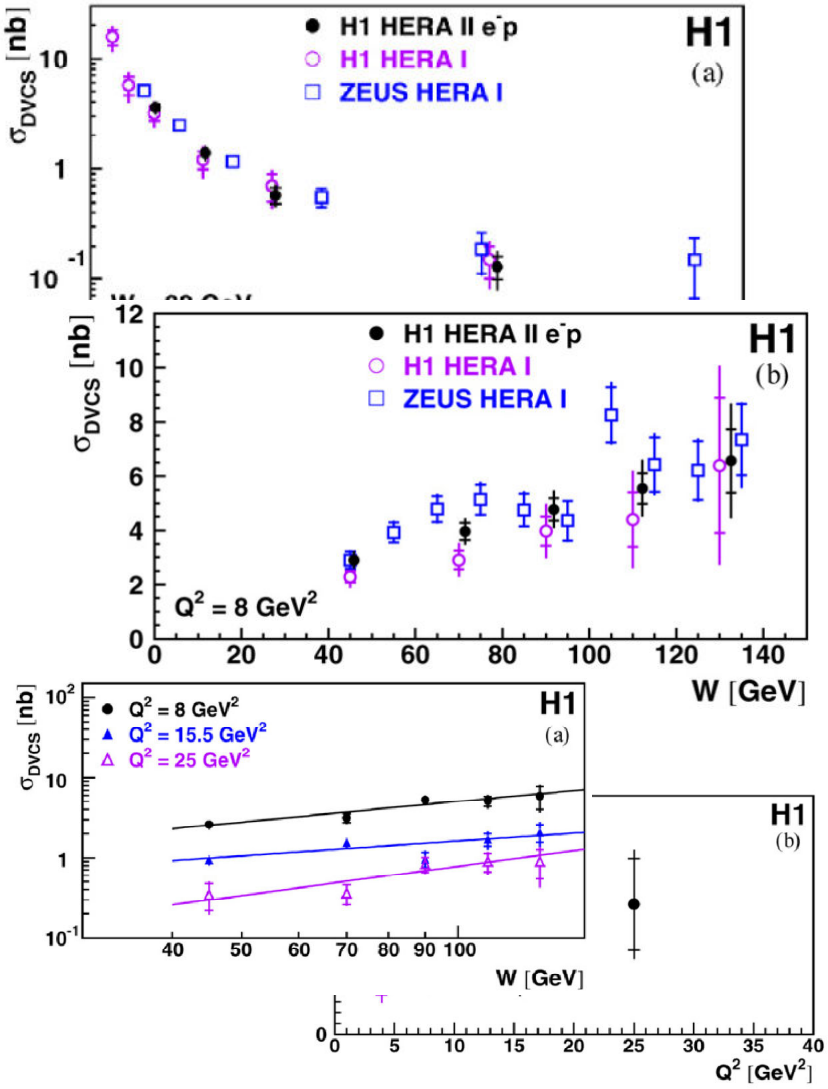
template

Zeus jhep2009:

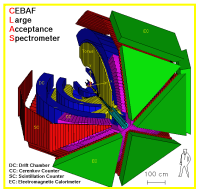




H1 2008:



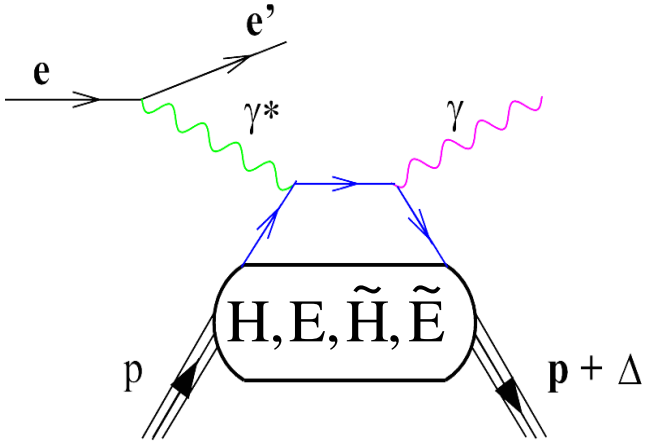
Hall-A



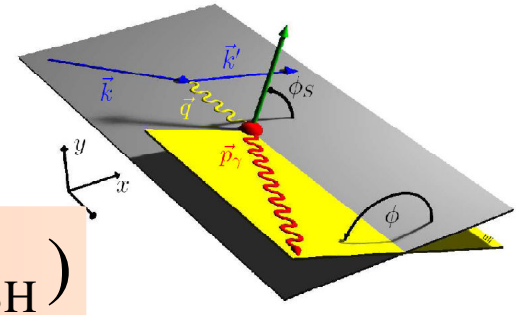
hermes

DVCS interference term

$$d\sigma \propto |\tau_{BH}|^2 + \text{(shaded)} + (\tau^*_{BH}\tau_{DVCS} + \tau^*_{DVCS}\tau_{BH})$$



DVCS interference term



$$d\sigma \propto |\tau_{BH}|^2 + |\tau_{DVCS}|^2 + (\tau^*_{BH}\tau_{DVCS} + \tau^*_{DVCS}\tau_{BH})$$

$I \sim \Delta\sigma$

→ different charges: e^+ e^- *(only @HERA!):*

$$\Delta\sigma_C \sim \cos\phi \cdot \mathrm{Re}\{ \mathbf{H} + \xi\tilde{\mathbf{H}} + \ldots \}$$

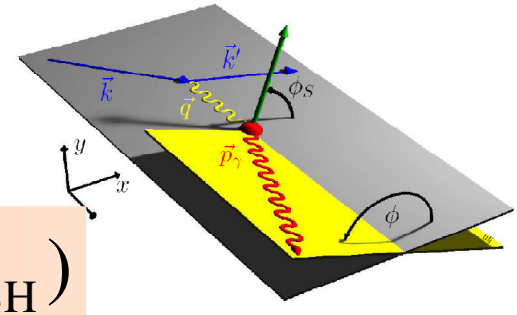
→polarisation observables:

$\Delta\sigma_{UT}$

beam	target
U, L	U, L, T

Unpolarised
Longitudinally
Transversely polarised

DVCS interference term



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→ different charges: e^+ e^- *(only @HERA!):*

$$\Delta\sigma_C \sim \cos\phi \cdot \mathrm{Re}\{ \mathbf{H} + \xi\widetilde{\mathbf{H}} + \dots \} \Rightarrow H$$

→polarisation observables:

$$\Delta\sigma_{LU} \sim \sin\phi \cdot \mathrm{Im}\{\mathbf{H} + \xi\widetilde{\mathbf{H}} + k\mathbf{E}\} \Rightarrow H$$

$$\Delta\sigma_{UL} \sim \sin\phi \cdot \mathrm{Im}\{\widetilde{\mathbf{H}} + \xi\mathbf{H} + \dots\} \Rightarrow \widetilde{H}$$

$$\Delta\sigma_{UT} \sim \sin(\phi-\phi_S)\cos\phi \cdot \mathrm{Im}\{k(\mathbf{H} - \mathbf{E}) + \dots\} \Rightarrow H, E$$

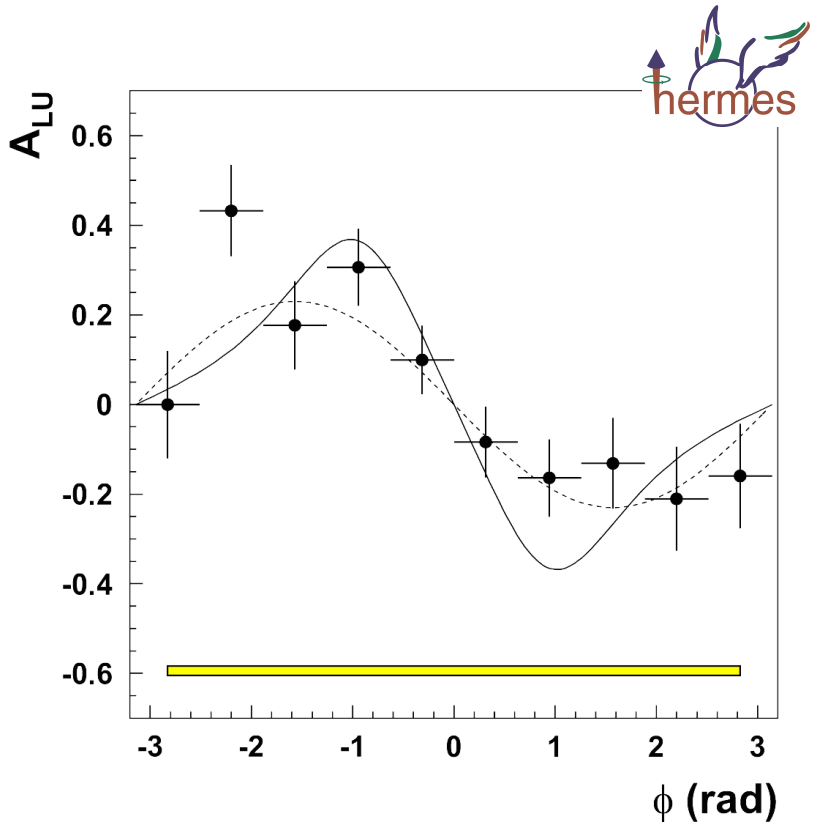
$\xi = x_B/(2-x_B)$, $k = t/4M^2$

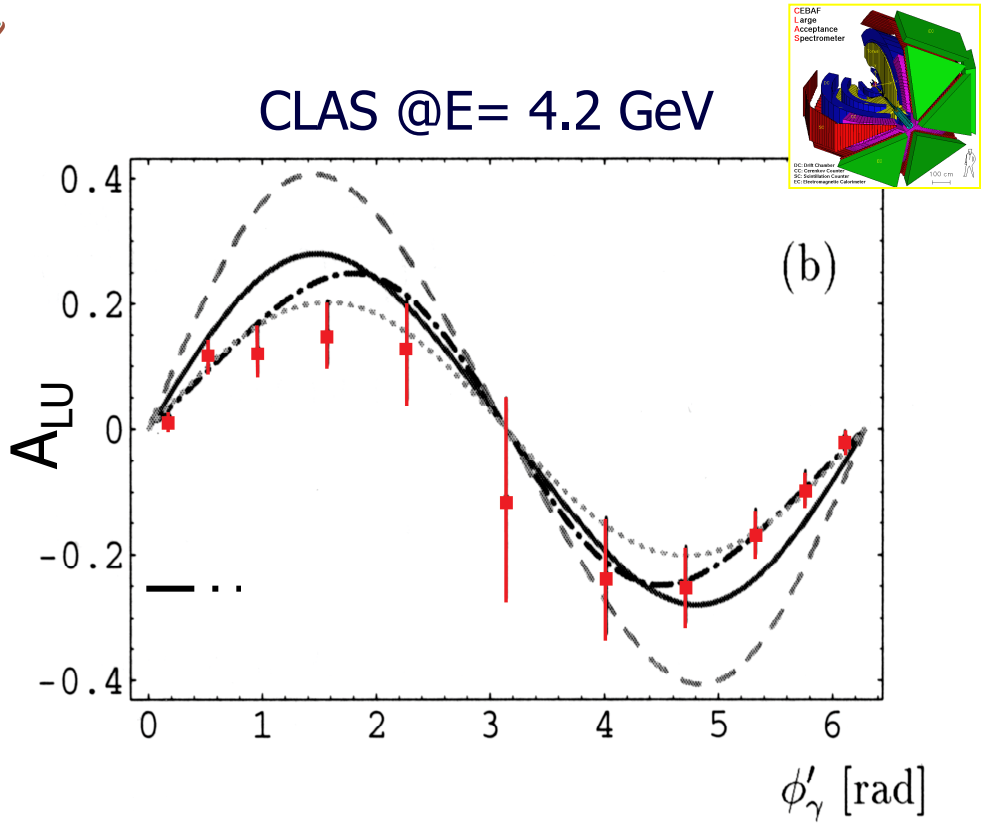
kinematically suppressed
@HERMES and JLab energies

first DVCS signals: A_{LU}

-- from interference term --

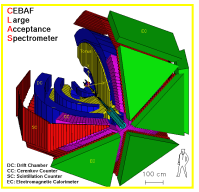
[PRL87(2001)]



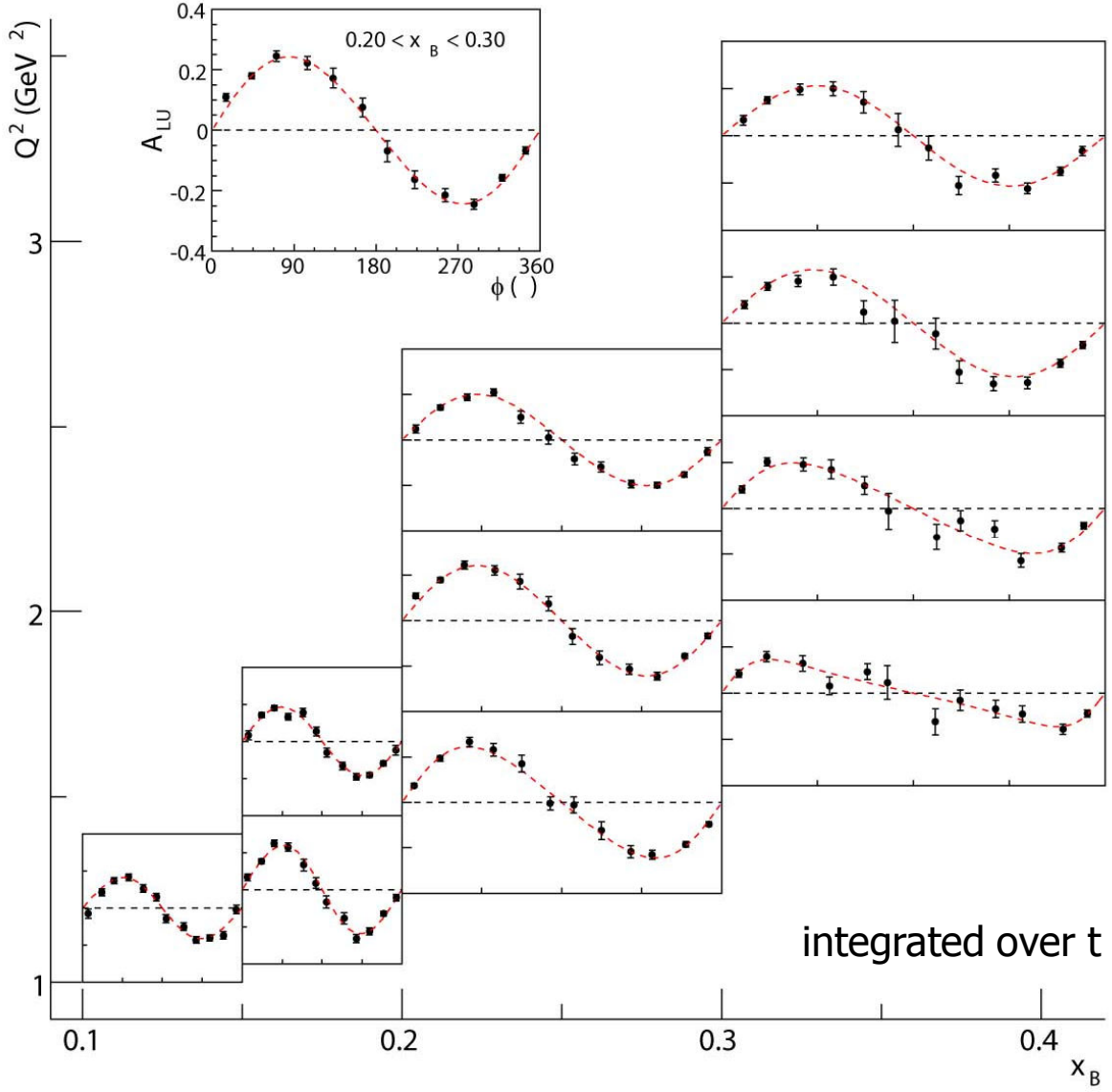


→ sinϕ dependence indicates dominance of handbag contribution

call for high statistics



JLab: E1-DVCS beam-spin asymmetry [PRL100(2008)]

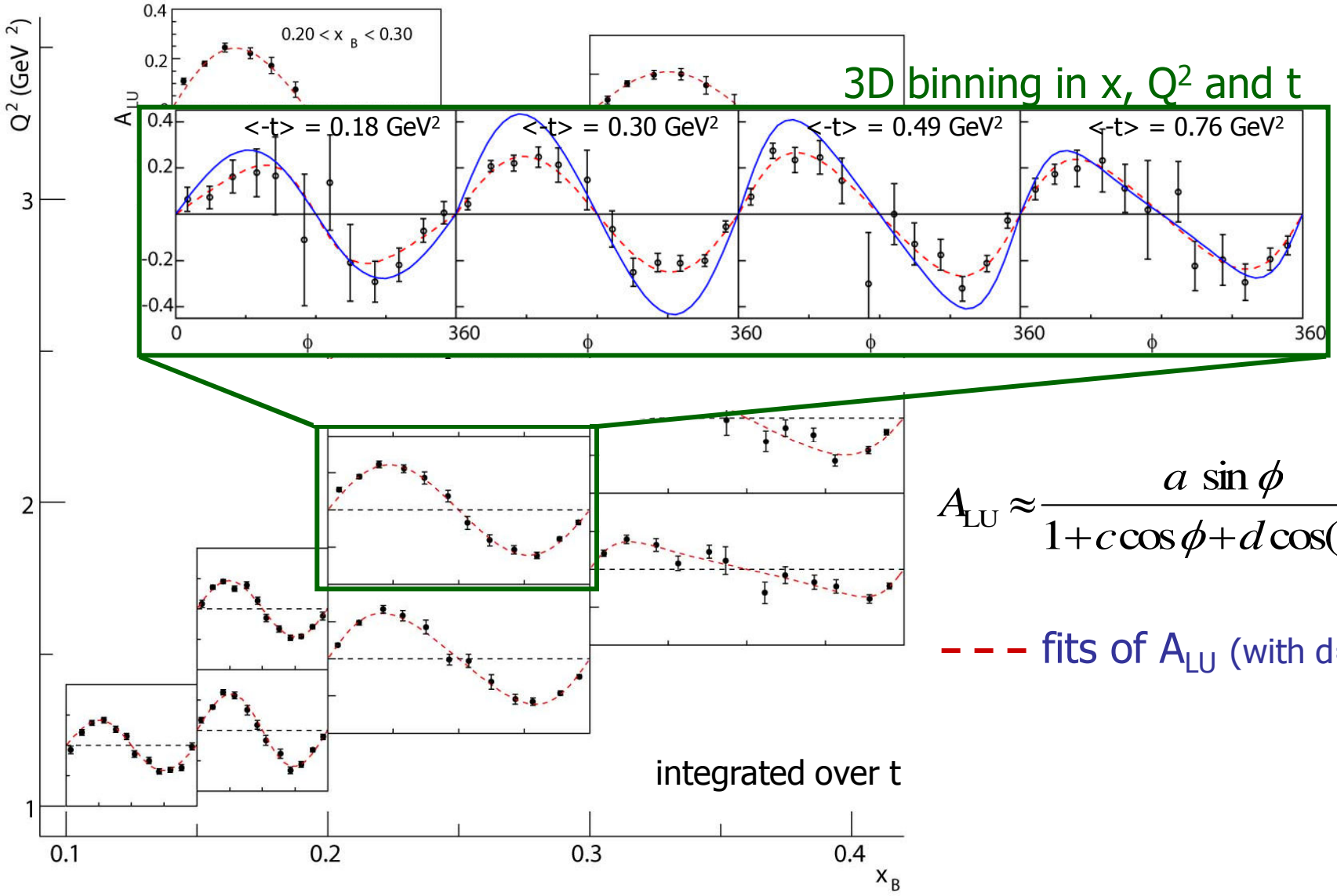


$$A_{LU} \approx \frac{a \sin\phi}{1 + c\cos\phi + d\cos(2\phi)}$$

– – – fits of A_{LU} (with d=0)

call for high statistics

JLab: E1-DVCS beam-spin asymmetry [PRL100(2008)]



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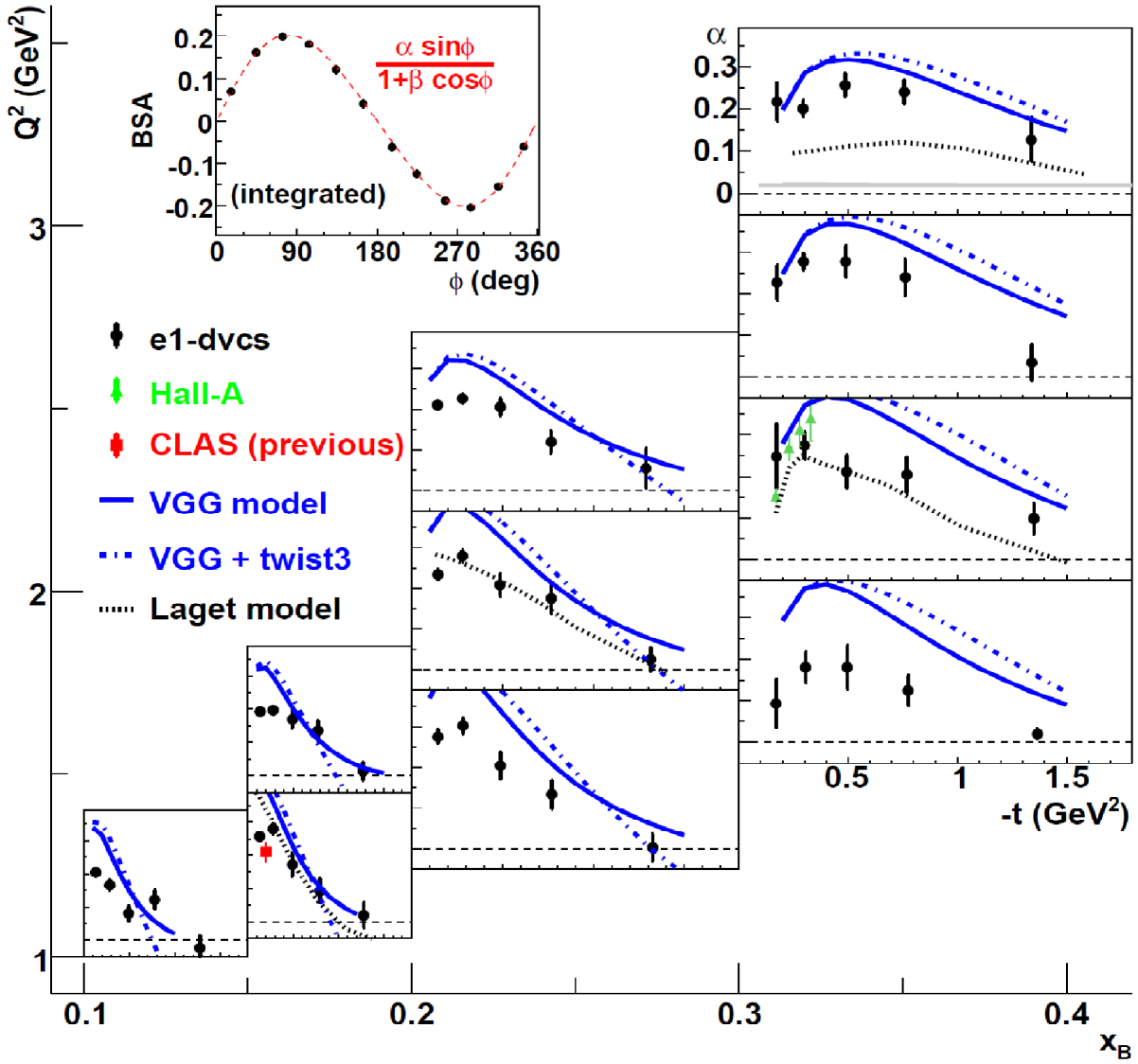
JLab: E1-DVCS beam-spin asymmetry [PRL100(2008)]



$\alpha \sim \mathrm{Im}[F_1 H]$

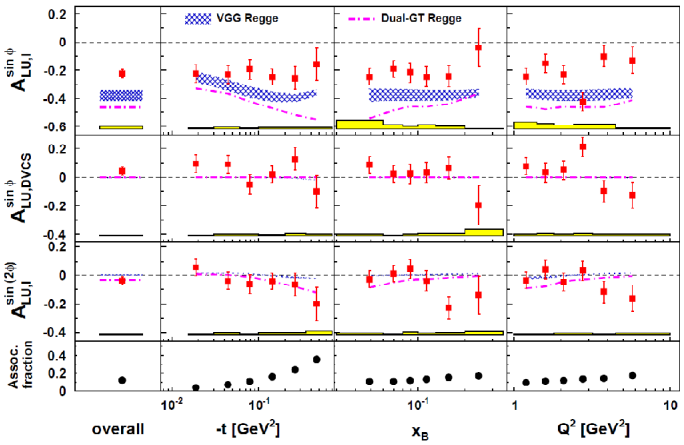
call for new analysis methods

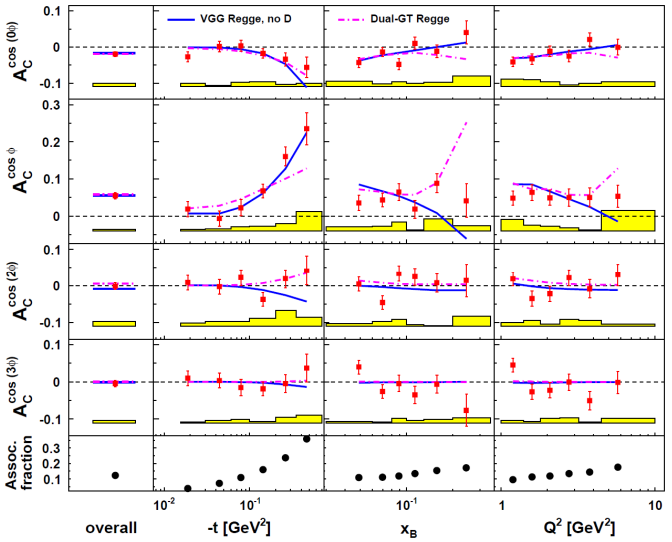
HERMES: combined analysis of charge & polarisation dependent data

→ separation of interference term + DVCS² amplitude

$$\sigma_{LU}(\phi; P_l, e_l) = \sigma_{UU}(\phi) \cdot \{1 + P_l A_{LU}^{DVCS}(\phi) + e_l P_l A_{LU}^{\mathcal{I}}(\phi) + e_l A_C(\phi)\}$$

$$s_1^{DVCS} sin(\phi) \qquad \sum_{n=1}^{2} s_n^I sin(n\phi) \qquad \sum_{n=0}^{3} c_n^I cos(n\phi)$$





call for new analysis methods

HERMES: combined analysis of charge & polarisation dependent data

→ separation of interference term + DVCS² amplitude

'classical' single-charge asymmetry:

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

$$= \frac{1}{D(\phi)} \cdot \left[-e\ell \frac{K_{\mathrm{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left[\sum_{n=1}^{2} s_n^{\mathrm{I}} \sin(n\phi) \right] + \frac{1}{Q^2} s_1^{\mathrm{DVCS}} \sin\phi \right]$$

call for new analysis methods

HERMES: combined analysis of charge & polarisation dependent data

→ separation of interference term + DVCS² amplitude

'classical' single-charge asymmetry:

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

$$= \frac{1}{D(\phi)} \cdot \left[-e\ell \frac{K_I}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left[\sum_{n=1}^{2} s_n^I \sin(n\phi) \right] + \frac{1}{Q^2} s_1^{DVCS} \sin\phi \right]$$

- charge difference asymmetry:

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

- charge average asymmetry:

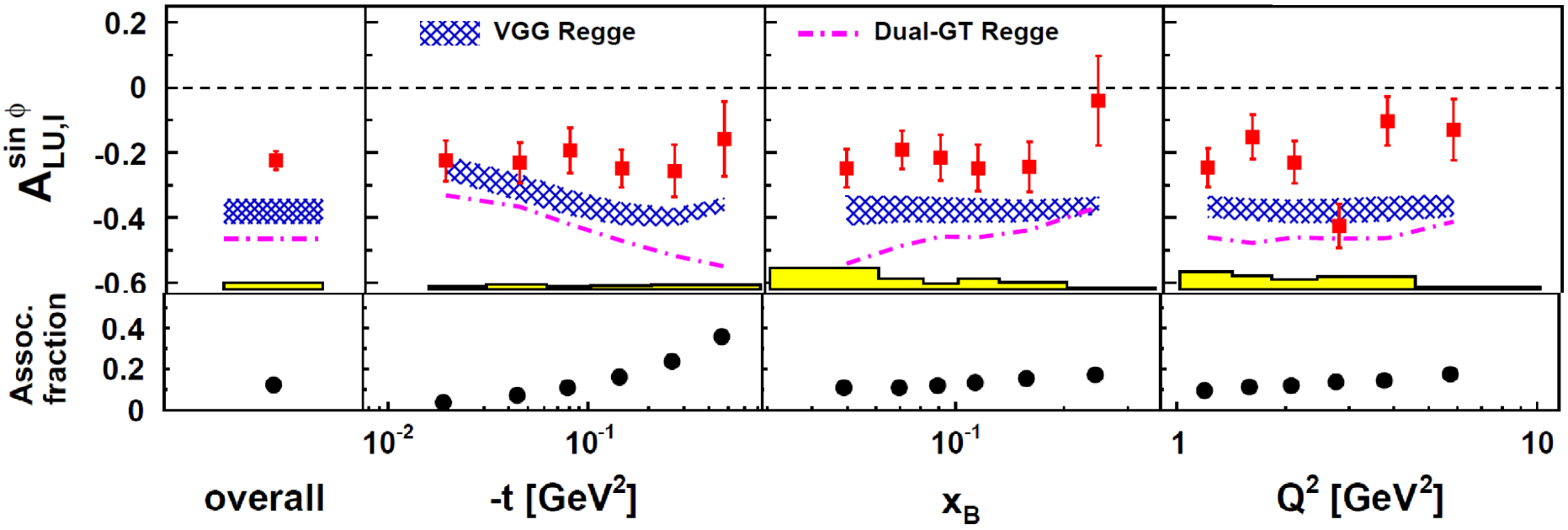
$$\mathcal{A}_{LU}^{DVCS}(\phi) \equiv \frac{(d\sigma^{+\rightarrow} - d\sigma^{+\leftarrow}) + (d\sigma^{-\rightarrow} - d\sigma^{-\leftarrow})}{(d\sigma^{+\rightarrow} + d\sigma^{+\leftarrow}) + (d\sigma^{-\rightarrow} + d\sigma^{-\leftarrow})}$$

call for new analysis methods

HERMES: combined analysis of charge & polarisation dependent data

→ separation of interference term + DVCS² amplitude

beam *spin* asymmetry: [JHEP11(2009)] $\propto F_1 \mathrm{Im}\mathcal{H}$



GPD models: VGG regge-ansatz for t-dependence

bands obtained by varying input parameters b_{val} & b_{sea} between 1 and ∞

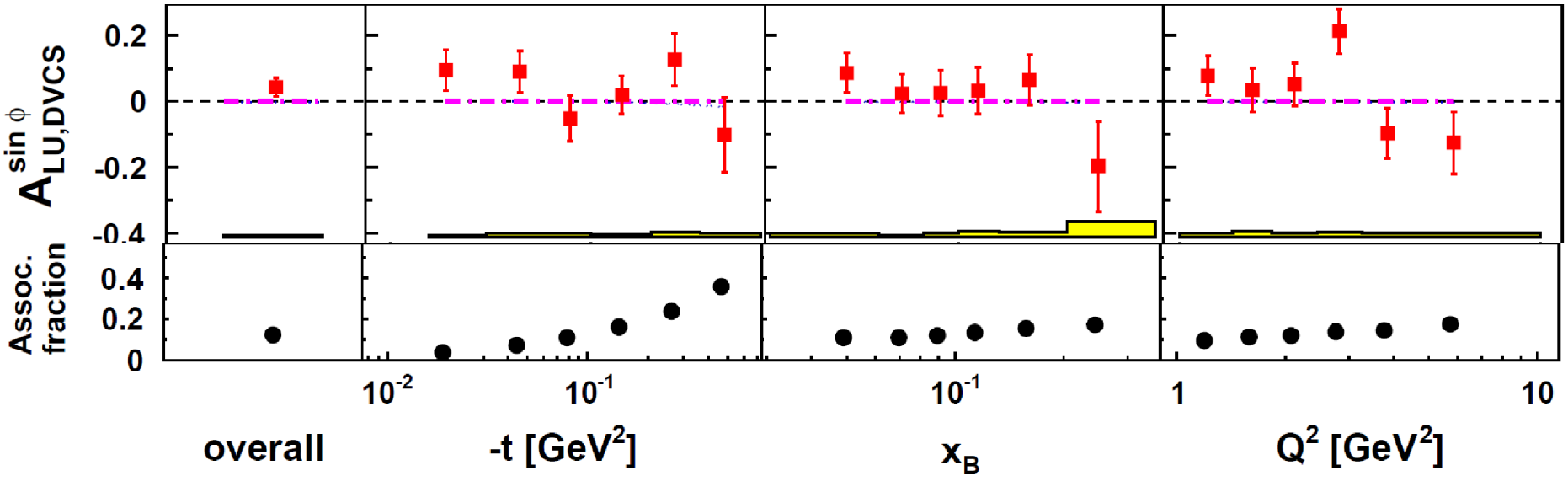
Dual-GT regge-ansatz for t-dependence

call for new analysis methods

HERMES: combined analysis of charge & polarisation dependent data

→ separation of interference term + DVCS² amplitude

beam *spin* asymmetry: [JHEP11(2009)]



→ contribution from DVCS² term small

Dual-GT regge-ansatz for t-dependence

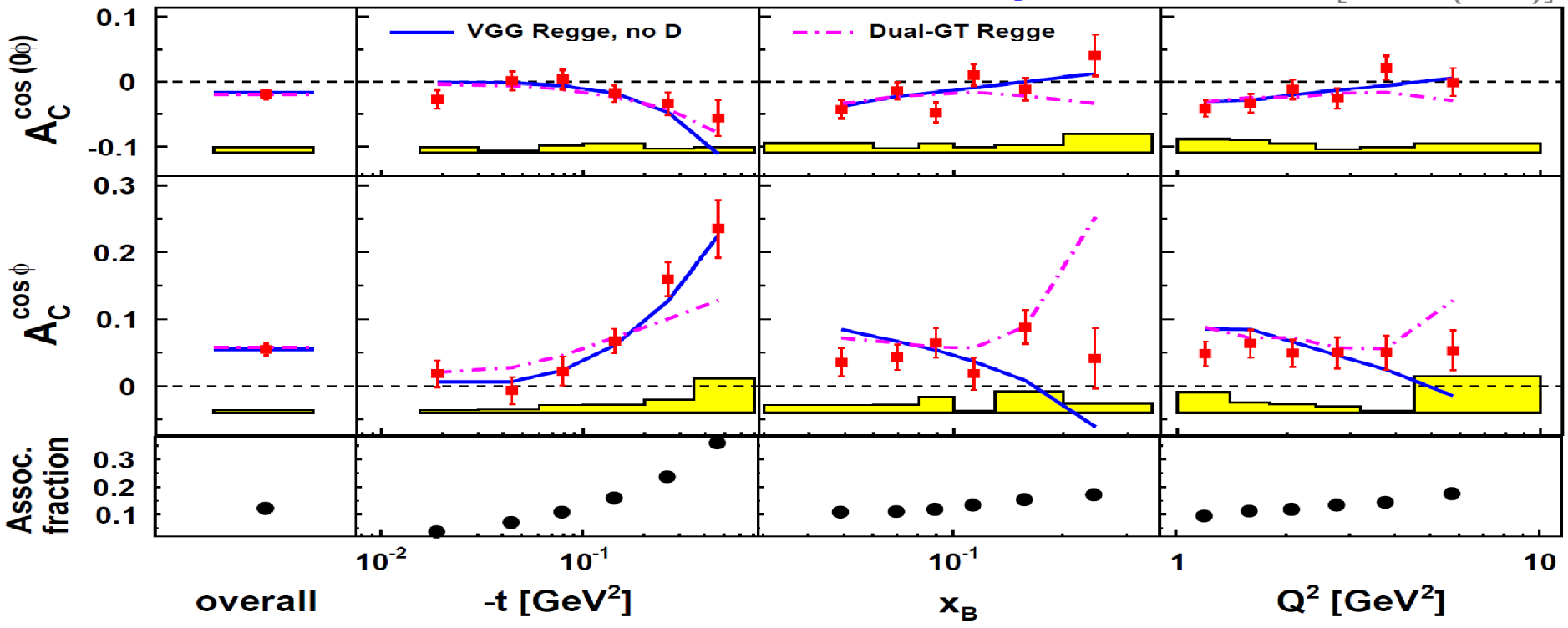
call for new analysis methods

HERMES: combined analysis of charge & polarisation dependent data

→ **beam charge asymmetry**

$$A_C^{\cos\phi} \propto F_1 \mathrm{Re}\mathcal{H} \qquad A_C^{\cos 0\phi} \propto -\frac{t}{Q} A_C^{\cos\phi}$$

[JHEP11(2009)]



GPD models: VGG regge-ansatz for t-dependence, **no D-term**

Dual-GT regge-ansatz for t-dependence

Hall-A

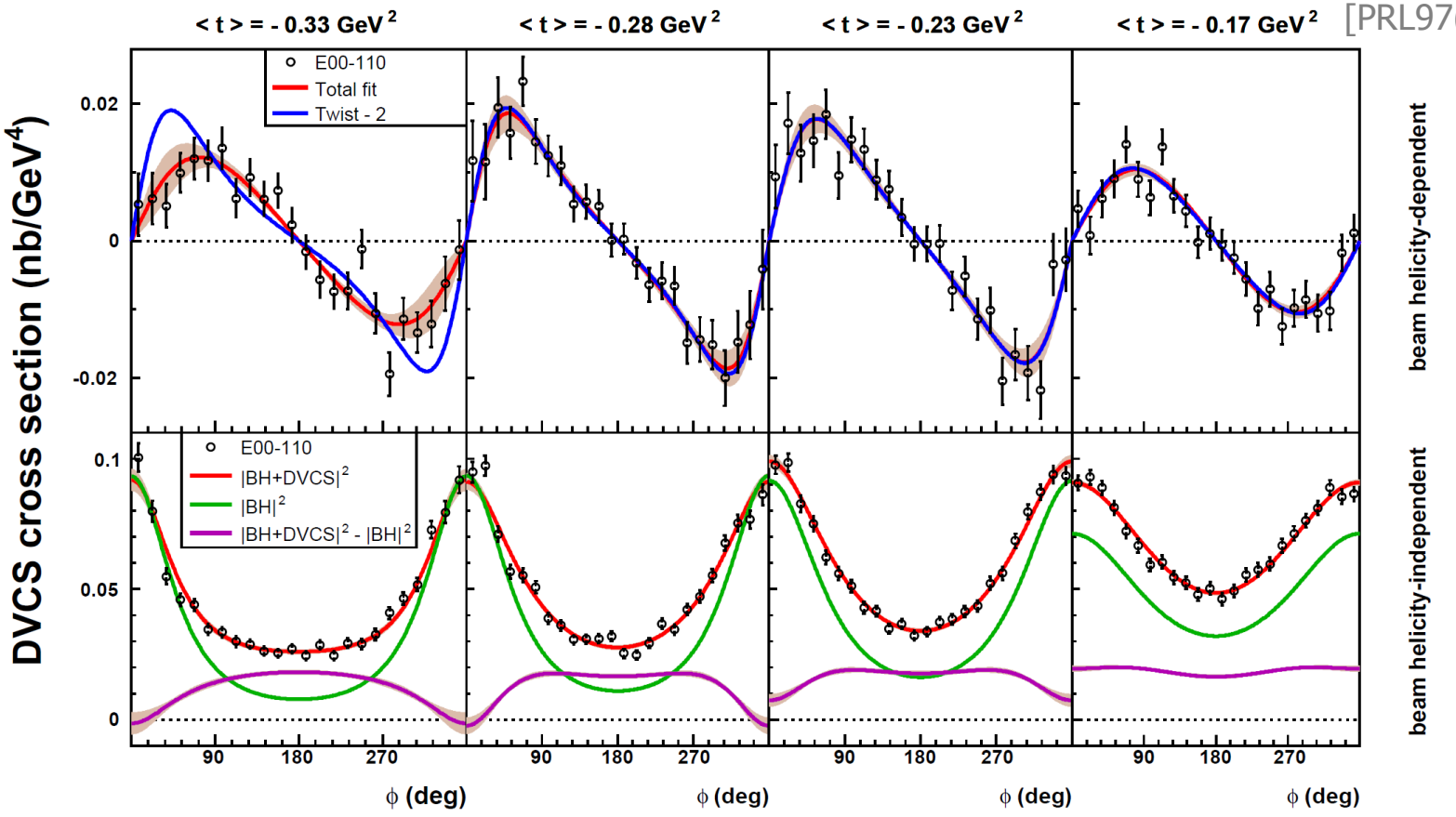
call for high precision data

Hall-A: DVCS cross section from interference term

Hall-A

call for high precision data

Hall-A: DVCS cross section from interference term



[PRL97(2006)]

Hall-A

call for high precision data

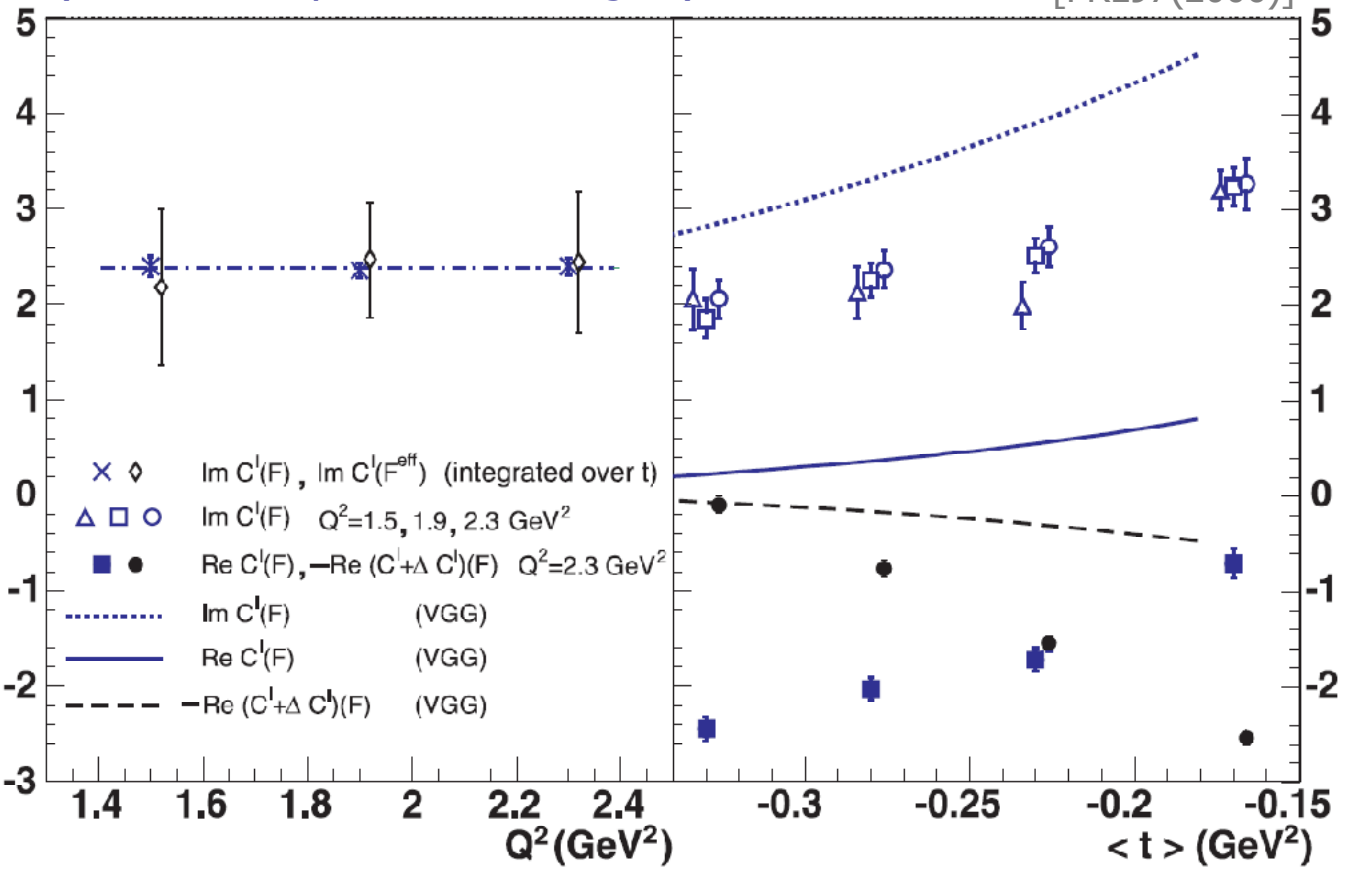
Hall-A: DVCS cross section from interference term

→ Q^2 dependence of DVCS coeff.:

dominance of tw-2 contribution (*handbag diagram*)

(however, very limited Q^2 range…)

[PRL97(2006)]



a word about 'user friendly' GPD models

VGG: [Vanderhaegen, Guichon, Guidal 1999]

- double distributions ; factorised or regge-inspired t-dependence
- D-term to restore full polynomiality
- skweness depending on free parameters b_{val} & b_{sea}
- includes tw-3 (WW approx)

Dual: [Guzey, Teckentrup 2006, 2009]

- GPDs based on infinite sum of t channel resonances (minimal: truncated k=[0,2])
- factorised or regge-inspired t-dependence
- tw-2 only

a word about 'user friendly' GPD models

VGG: [Vanderhaegen, Guichon, Guidal 1999]

- double distributions ; factorised
- D-term to restore full polynomi
- skweness depending on free p
- includes tw-3 (WW approx)

→ describes well A_C, $A_{UT,L}$ and A_{LL} data
→ fails for A_{LU}
→ A_c favours 'no D-term' ← contradicts χQSM & lattice results

Dual: [Guzey, Teckentrup 2006, 2009]

- GPDs based on infinite sum of
- factorised or regge-inspired t-
- tw-2 only

→ describes well kine dependence of charge]) and spin asymmetries
→ after correction in calculation: magnitude off by factor 2-4

→ call for new,
more sophisticated parametrisations of GPDs & new approaches

… on the way: - generalisation of Mellin transform technique & dispersion relations
- 'model independent fitter'

see talk by D. Muller

…

…nevertheless: first attempts to constrain J_q

observables sensitive to E:

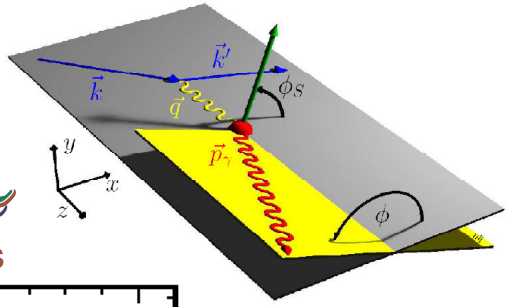
(J_q input parameter in ansatz for E)

$$J_q = \frac{1}{2}\int_{-1}^{1} x dx \left(H^q + E^q\right)$$

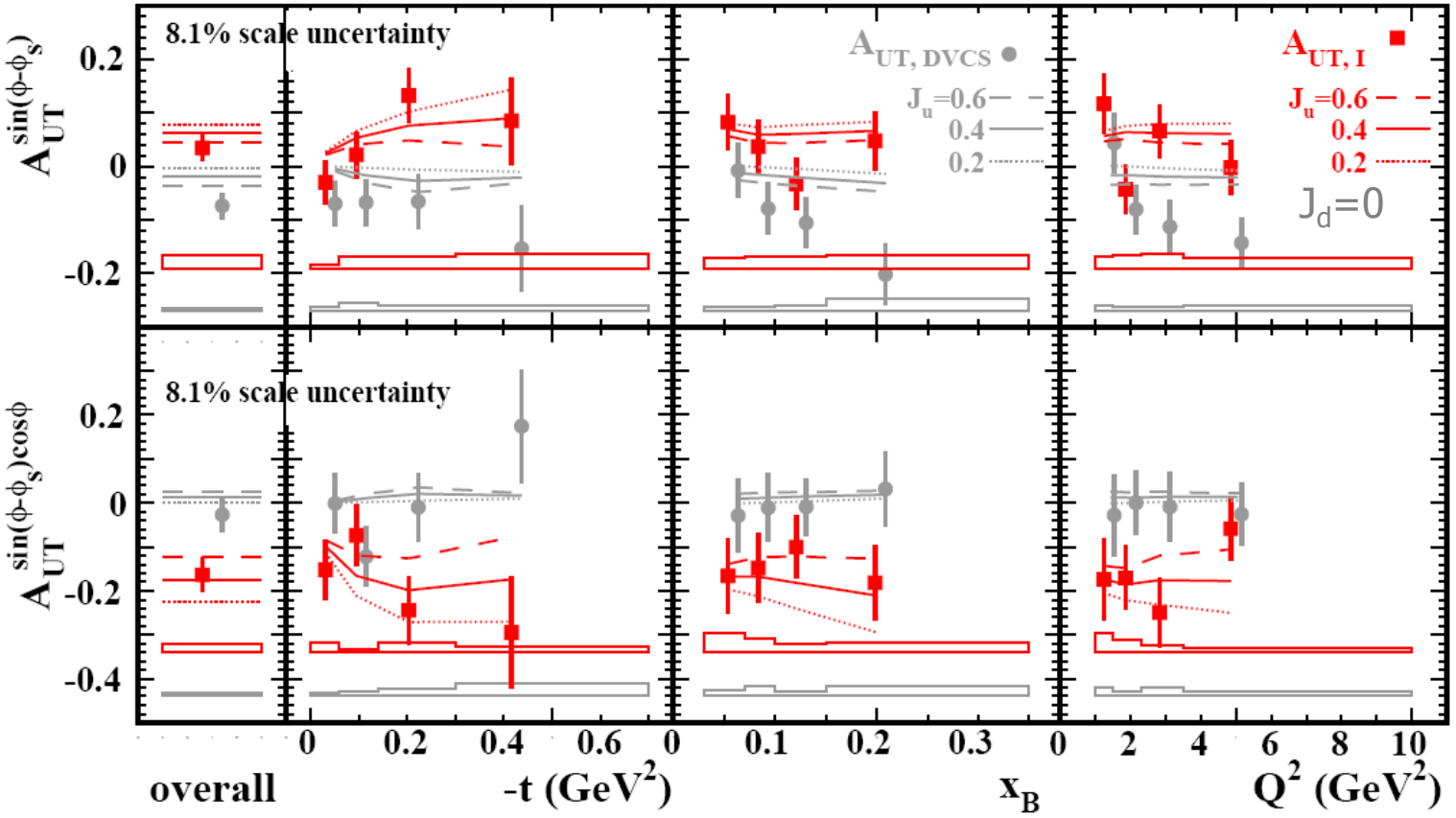
- DVCS A_{UT} : HERMES
- **n**DVCS A_{LU} : Hall A
- ρ^0 A_{UT} : HERMES

…nevertheless: first attempts to constrain J_q

J_q input parameter in ansatz for E:



[JHEP06(2008)] hermes



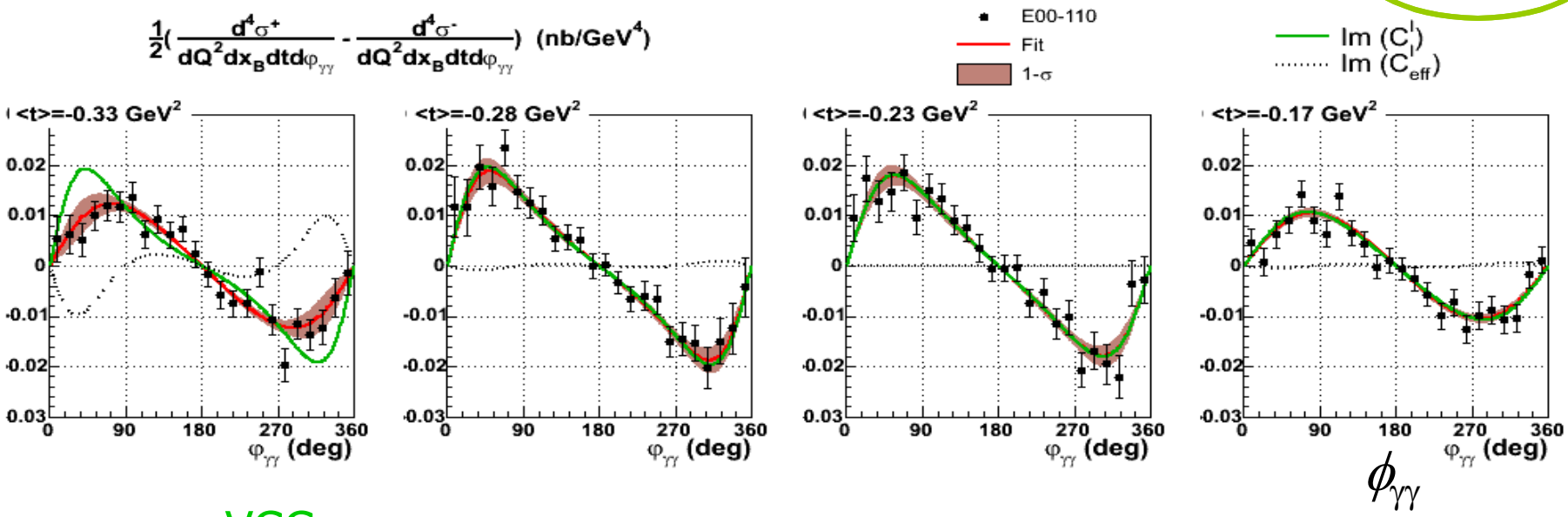
[VGG]

…nevertheless: first attempts to constrain J_q

J_q input parameter in ansatz for E:

difference of polarised cross sections on p&D → **n**DVCS: [PRL99(2007)]

Hall-A



VGG

nDVCS: enhanced sensitivity to GPD *E*

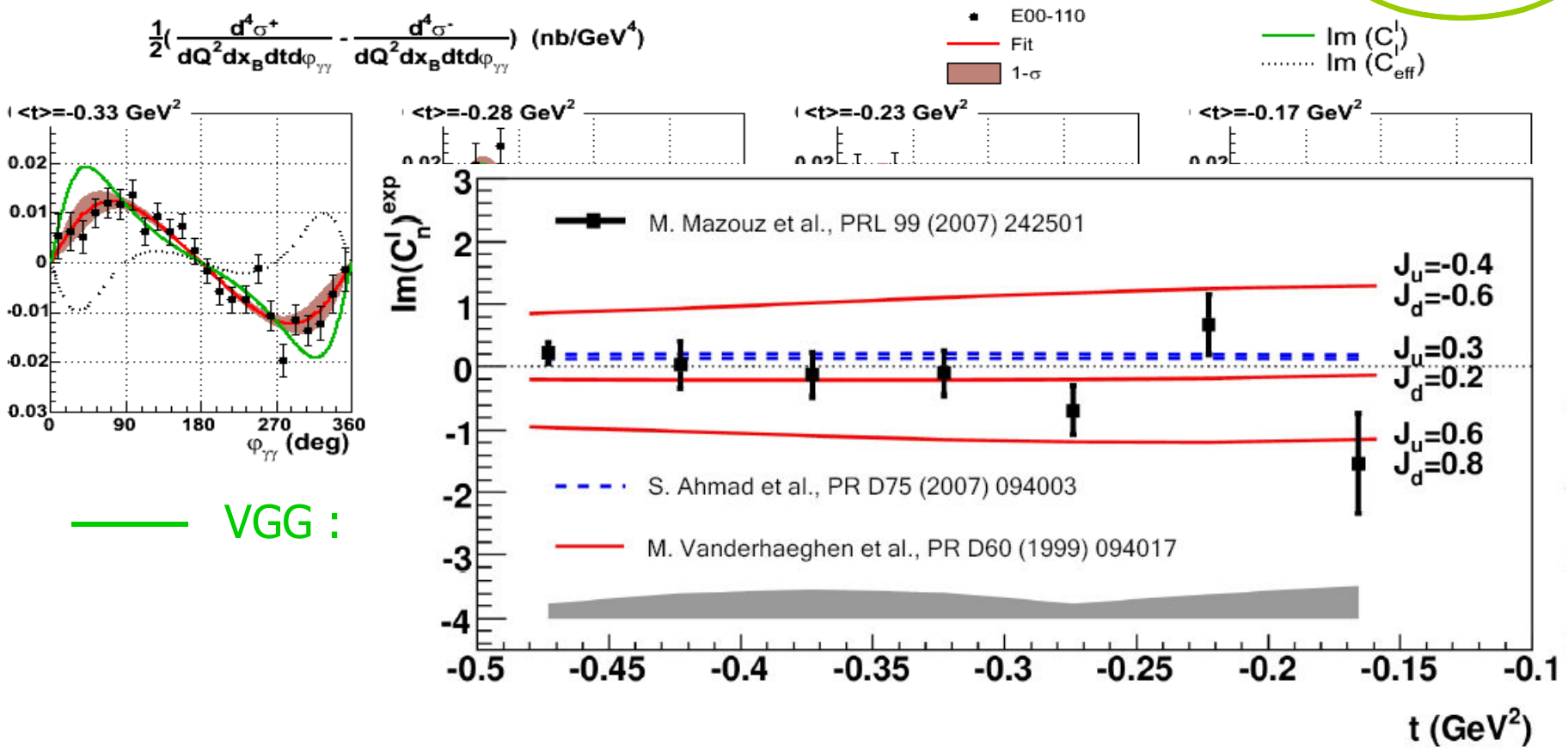
→ to J_q

…nevertheless: first attempts to constrain J_q

J_q input parameter in ansatz for E:

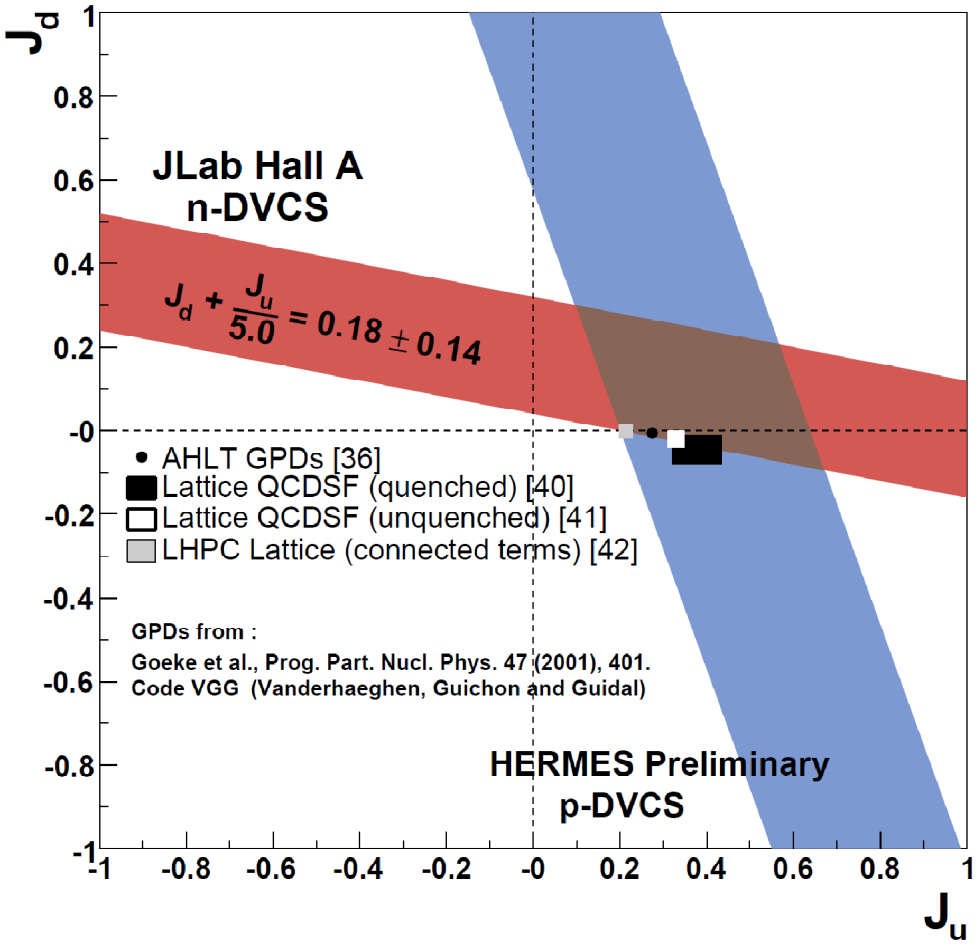
difference of polarised cross sections on p&D → **n**DVCS: [PRL99(2007)]

Hall-A



…nevertheless: first attempts to constrain J_q

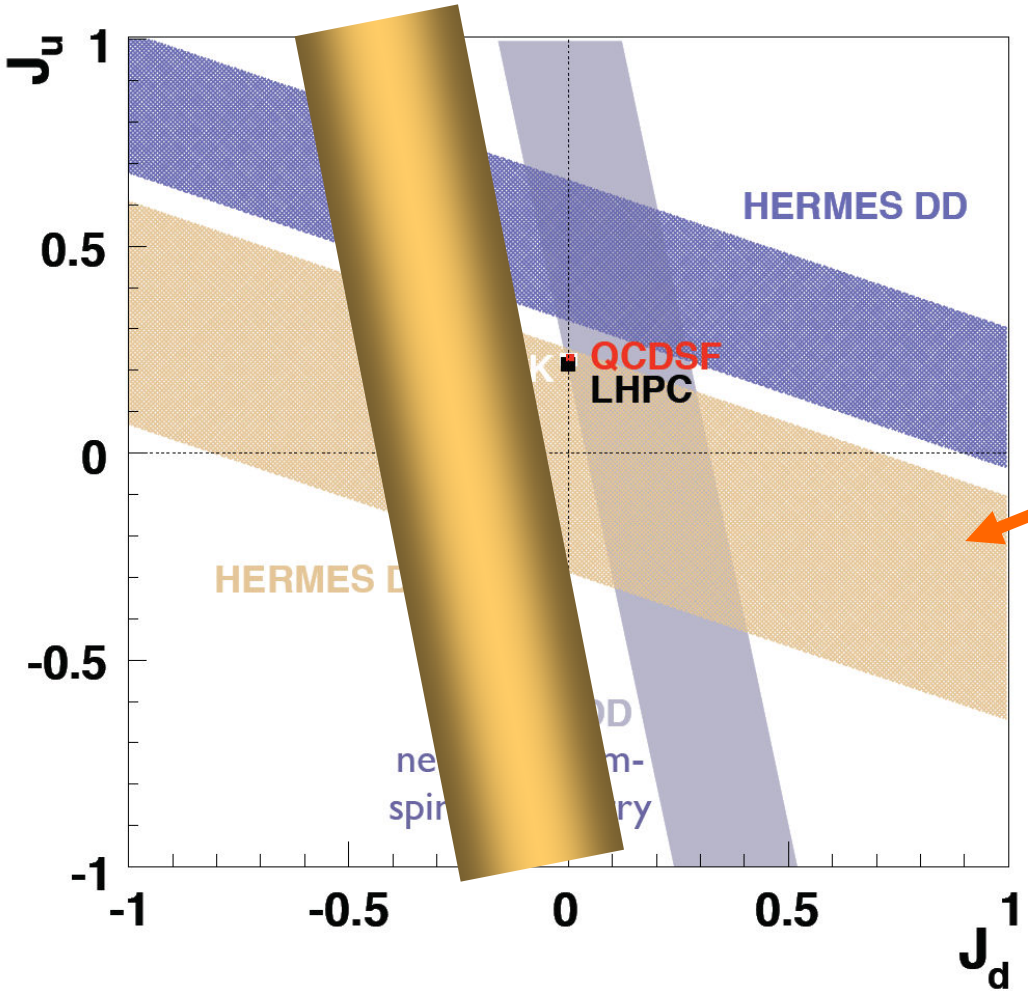
J_q input parameter in ansatz for E:



→ highly model dependent extraction:

…nevertheless: first attempts to constrain J_q

J_q input parameter in ansatz for E:

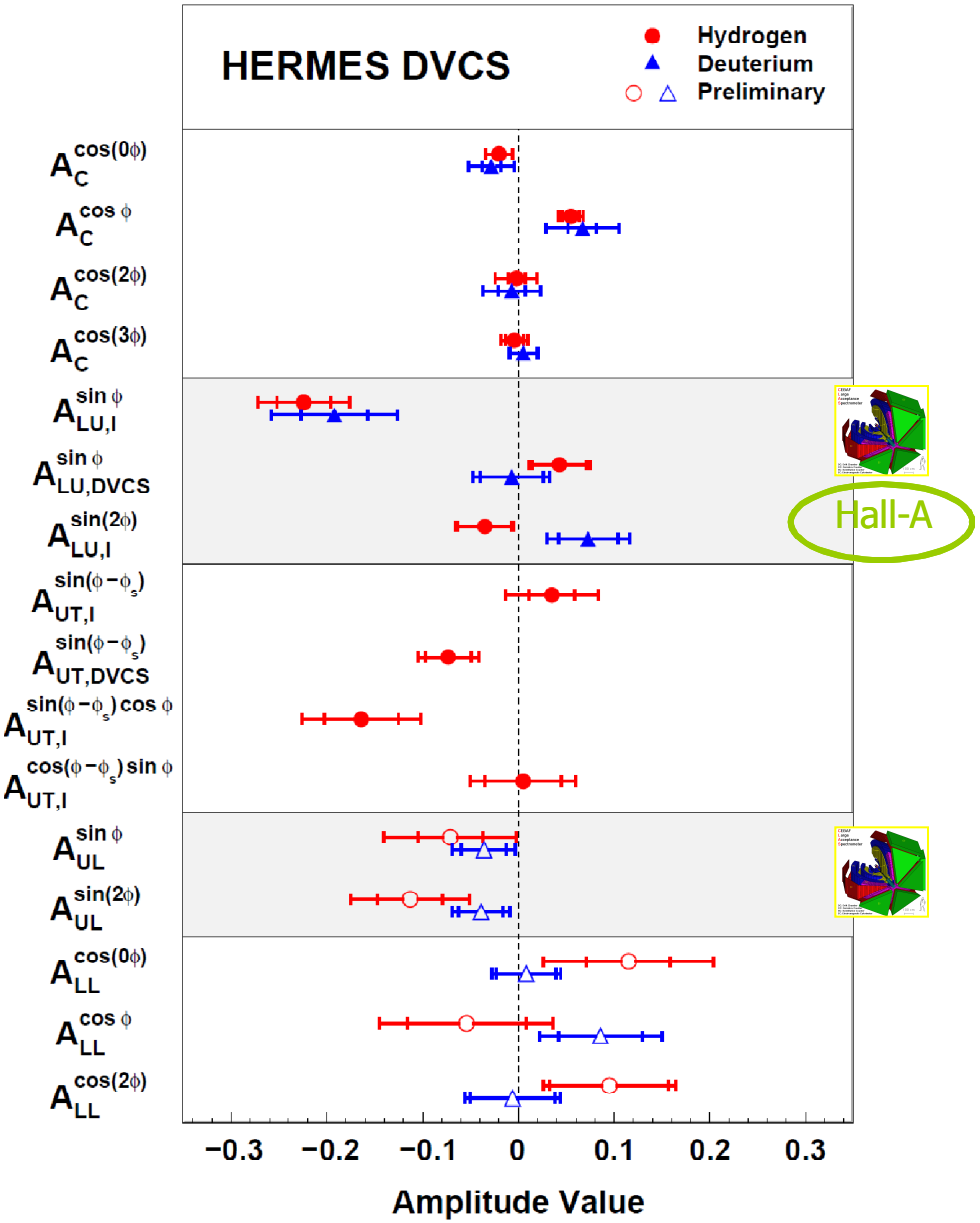


→ highly model dependent extraction: 'all' values possible…

NOTE: **uncorrected** Dual !

→ data are free to be re-used at any time with new models ☺

DVCS @large x - summary



Hall-A

→ beam charge asymmetry

$\mathrm{Re}\mathcal{H}$

→ beam spin asymmetry

$\mathrm{Im}\mathcal{H}$

→ transverse target spin asymm.

$\mathrm{Im}(\mathcal{H}\,\mathcal{E})$

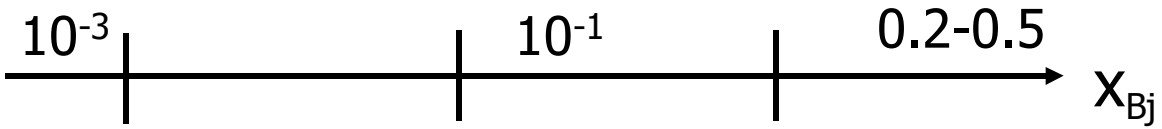
→ longitudinal target spin asymm.

$\mathrm{Im}\tilde{\mathcal{H}}$

→ double spin asymmetry

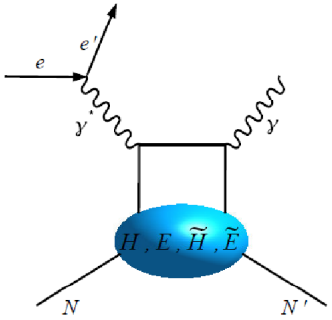
$\mathrm{Re}\tilde{\mathcal{H}}$

conclusions



HERA-collider
sea quarks & gluons

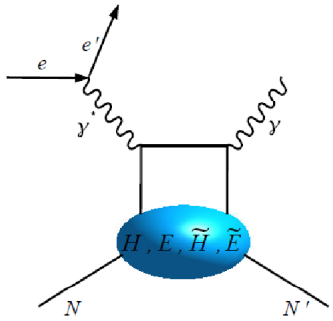
HERMES / JLab
(valence) quarks

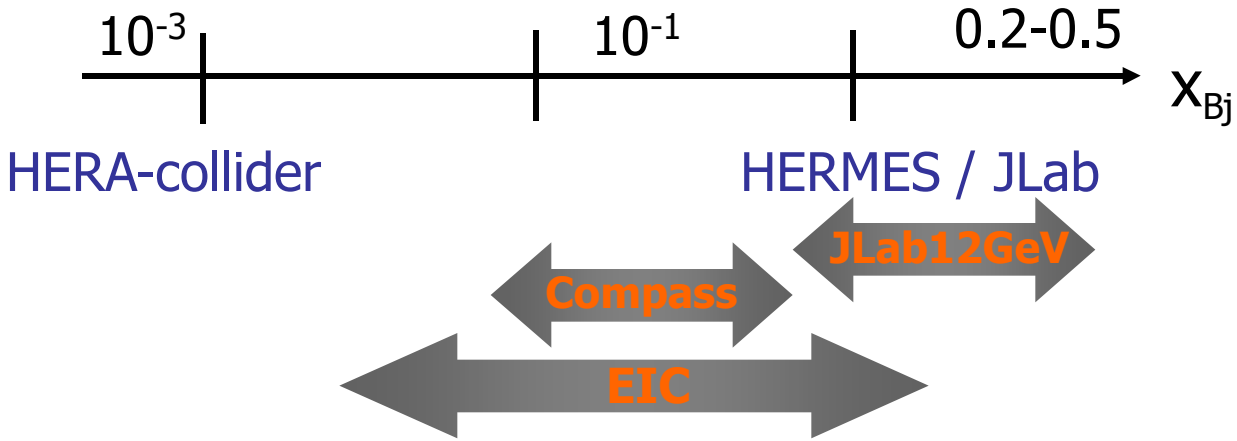


- increasing amount and precision of experimental data
- large "flow" of new data expected soon:
  - → JLab dedicated experiments
  - → HERMES data with recoil

⇒ multi-D analysis & results

conclusions





- increasing amount and precision of experimental data
- large "flow" of new data expected soon: **& bright future**
  - → JLab dedicated experiments, **JLab12GeV**
  - → HERMES data with recoil
  - → **COMPASS with recoil**
  - → **EIC**

⇒ prior to any conclusion about GPDs from data: call for new, more sophisticated parametrisations and approaches

outlook - I

→H1/ZEUS: more statistics from HERA II running

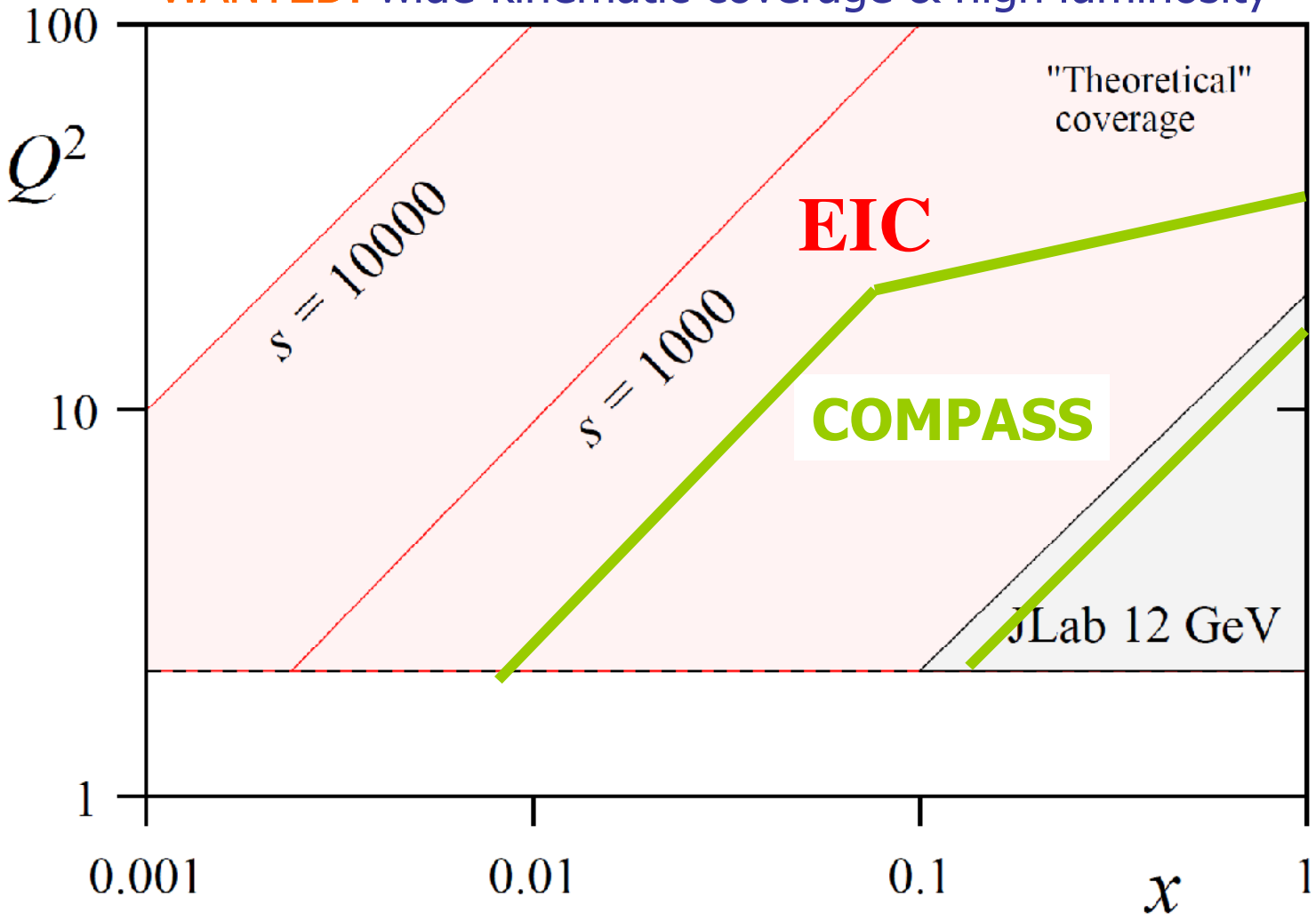
→HERMES: beam charge & spin asymmetries with improved statistics
separation of associated prod. with recoil info

→CLAS: - longitudinal target spin asymmetry
- beam spin asymmetry with ^{4}He
- **prove of principle for transverse HD target**
- **CLAS12**

→HallA: - (helicity dependent) cross sections for p&d @diff. beam energy
→ Rosenbluth-like separation of DVCS^2 – $\mathcal{I}$ terms, scaling tests
- **HallA @JLab12**

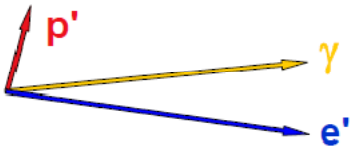
outlook - II

WANTED: wide kinematic coverage & high luminosity



[C. Weiss]

backup

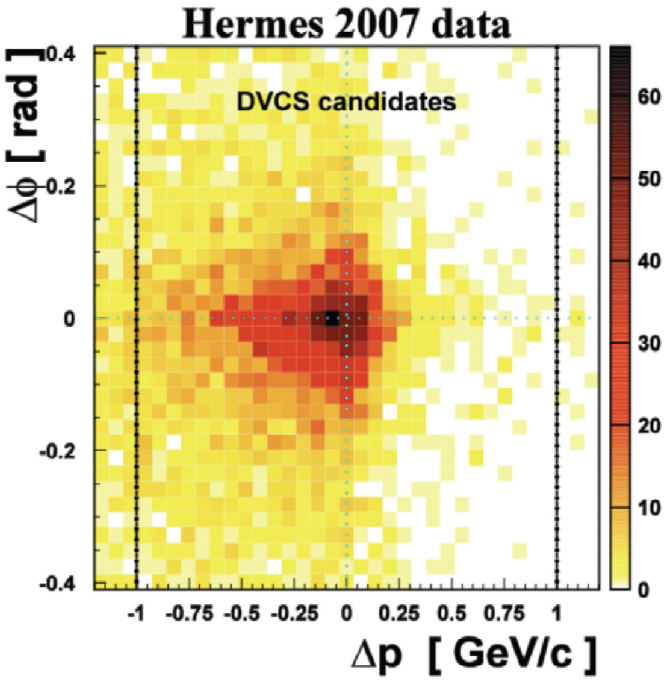


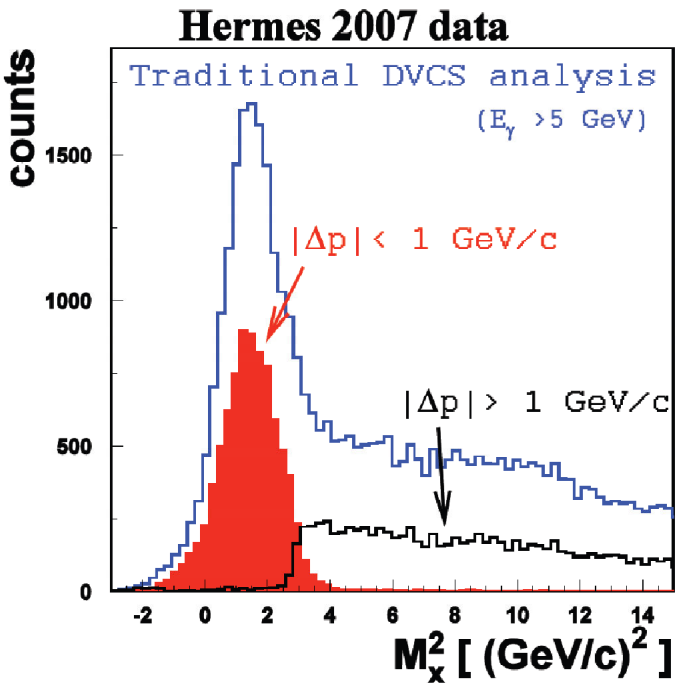
DVCS with recoil

- „Classic“ style HERMES DVCS analysis
  - Exactly one lepton and one photon detected in spectrometer

} DVCS candidate event

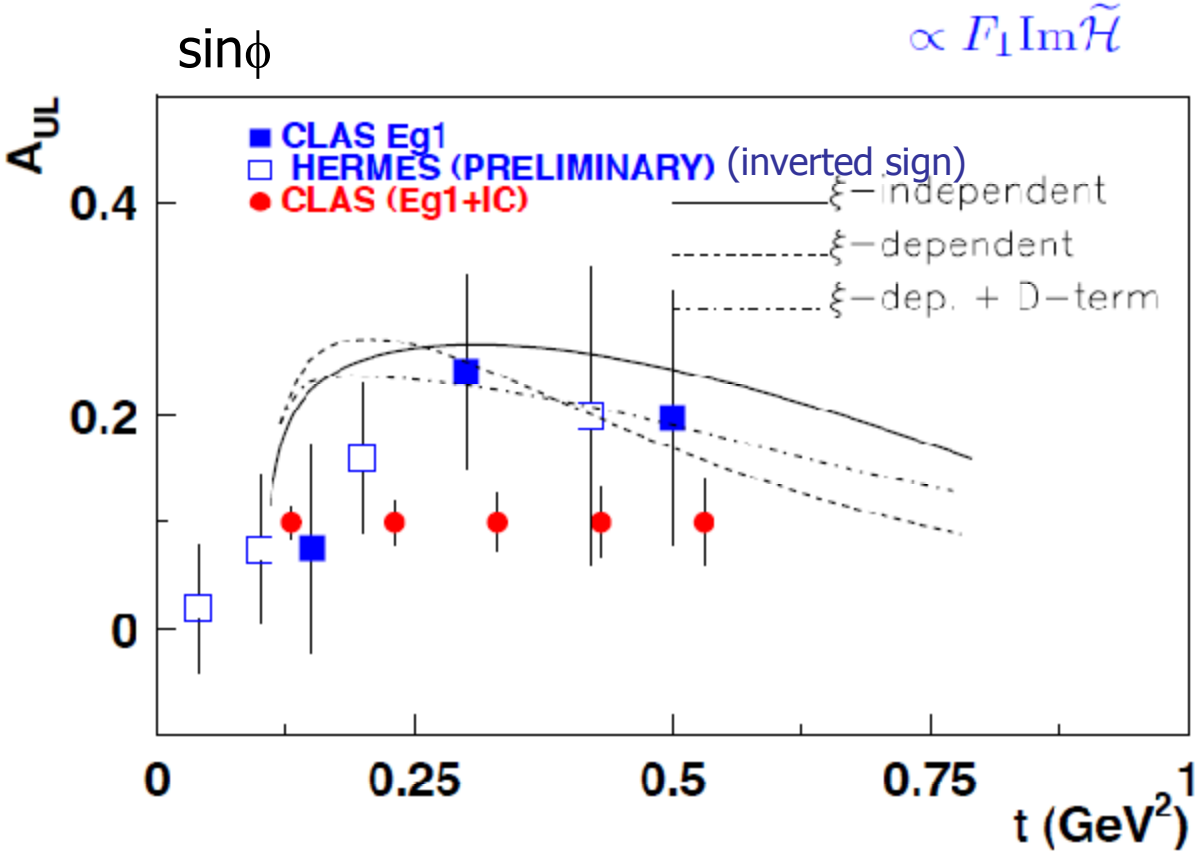
- Calculate kinematics of recoiling proton
- Look for a correlated track in recoil detector
  - $\Delta\phi = \phi_{measured} - \phi_{calculated}$
  - $\Delta p = p_{measured} - p_{calculated}$





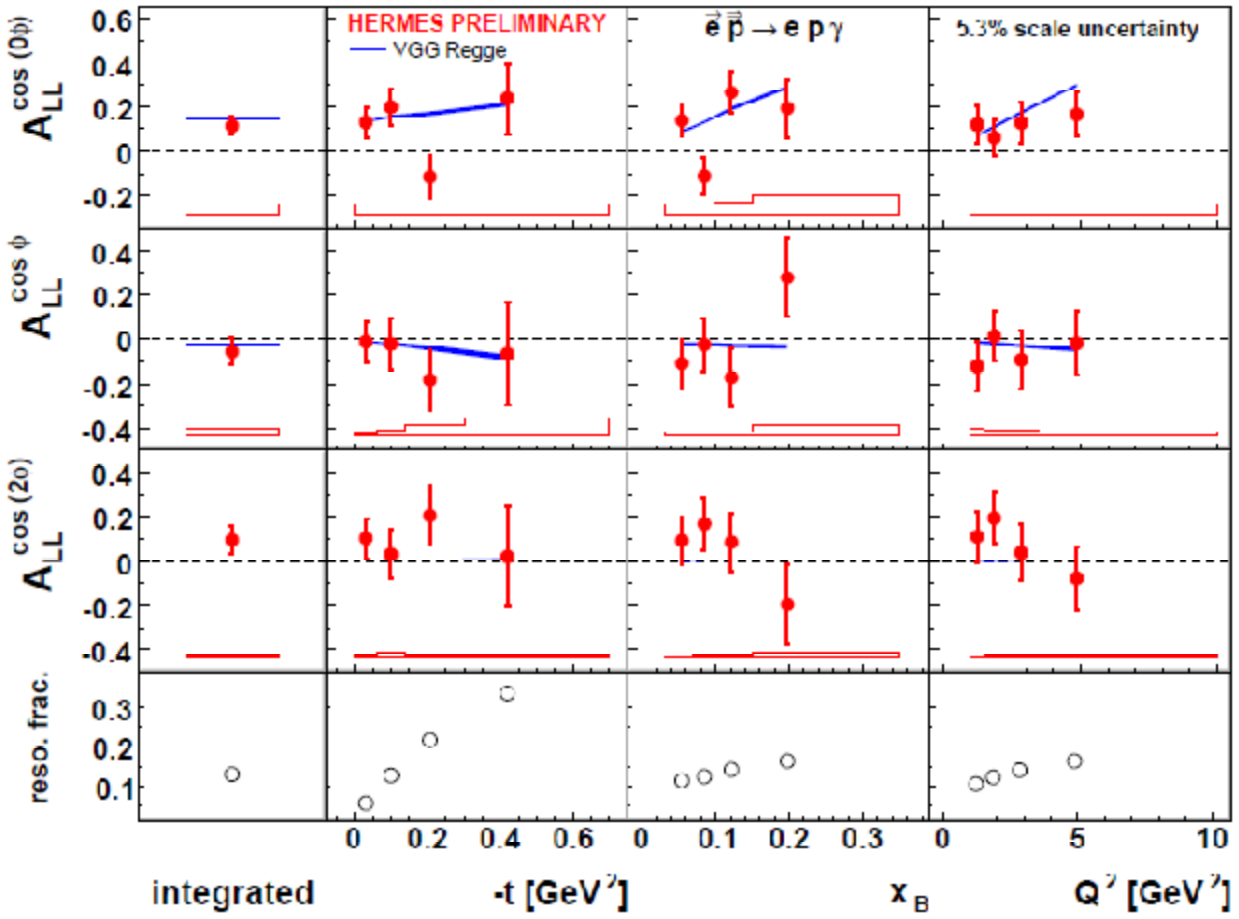
long. target spin asymmetry

$\propto F_1 \mathrm{Im}\widetilde{\mathcal{H}}$



double spin asymmetry

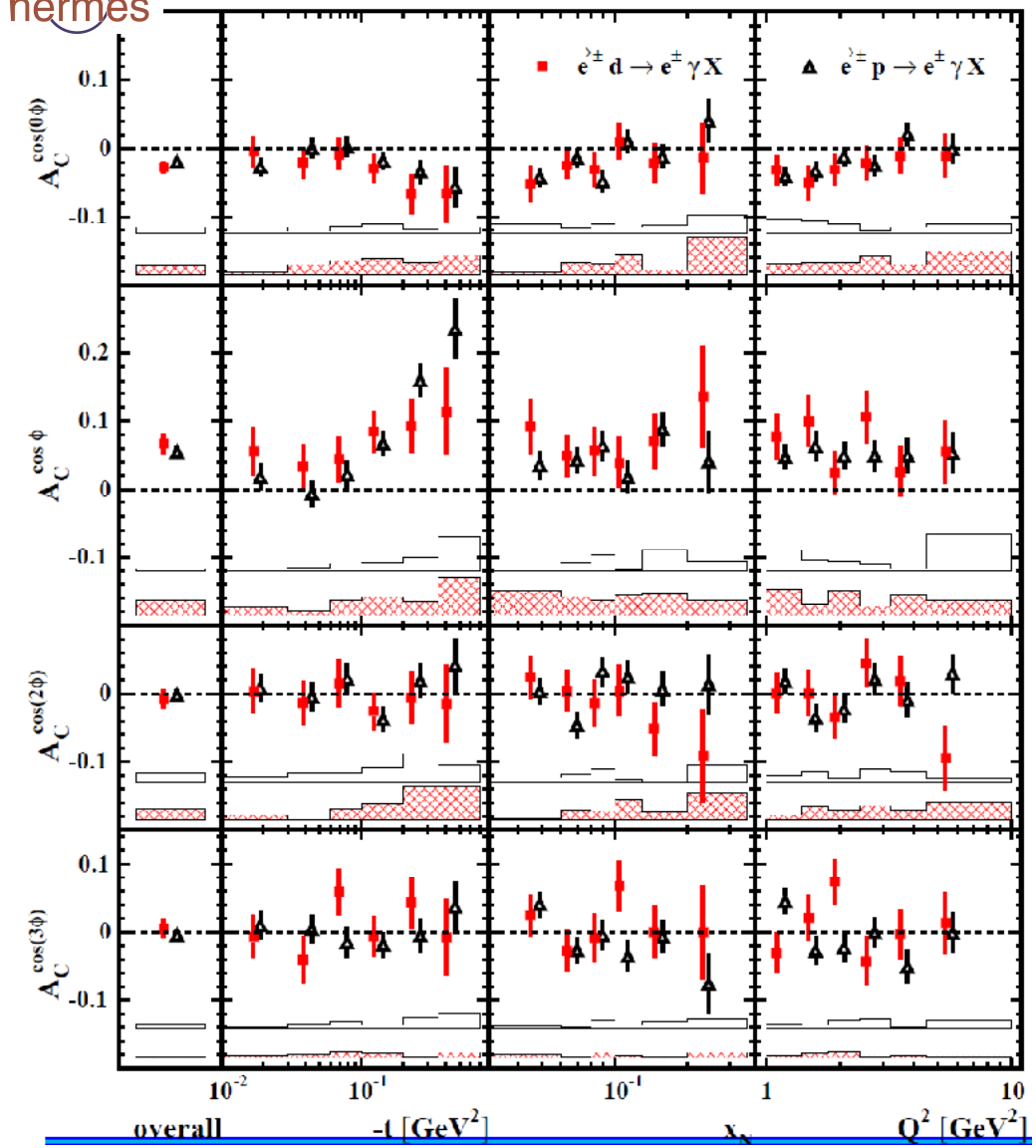
$$\mathcal{A}_{LL}(\phi) \propto \sum_{0}^{2} A_{LL}^{\cos(n\phi)} \cos(n\phi) \propto \sum_{n=0}^{2} c_n^{\mathrm{I}}, c_n^{\mathrm{DVCS}}$$



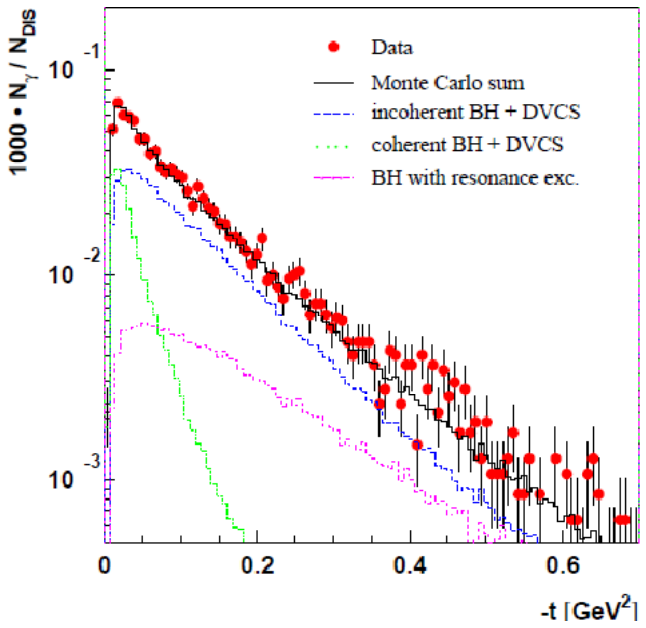
$\propto F_1 \mathrm{Re}\widetilde{\mathcal{H}}$

deuterium BCA

spin-1 targets described by 9 GPDs:
$I\!I_1^q, I\!I_2^q, I\!I_3^q, I\!I_4^q, I\!I_5^q, \tilde{I\!I}_1^q, \tilde{I\!I}_2^q, \tilde{I\!I}_3^q, \tilde{I\!I}_4^q$



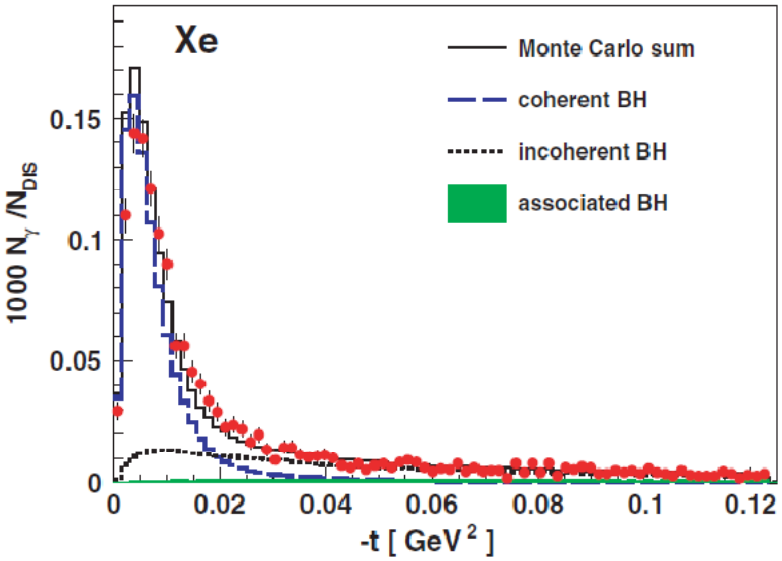
- d and p results consistent
- small values of $-t$: differences due to coherent contribution
- larger values of $-t$: differences due to neutron contribution



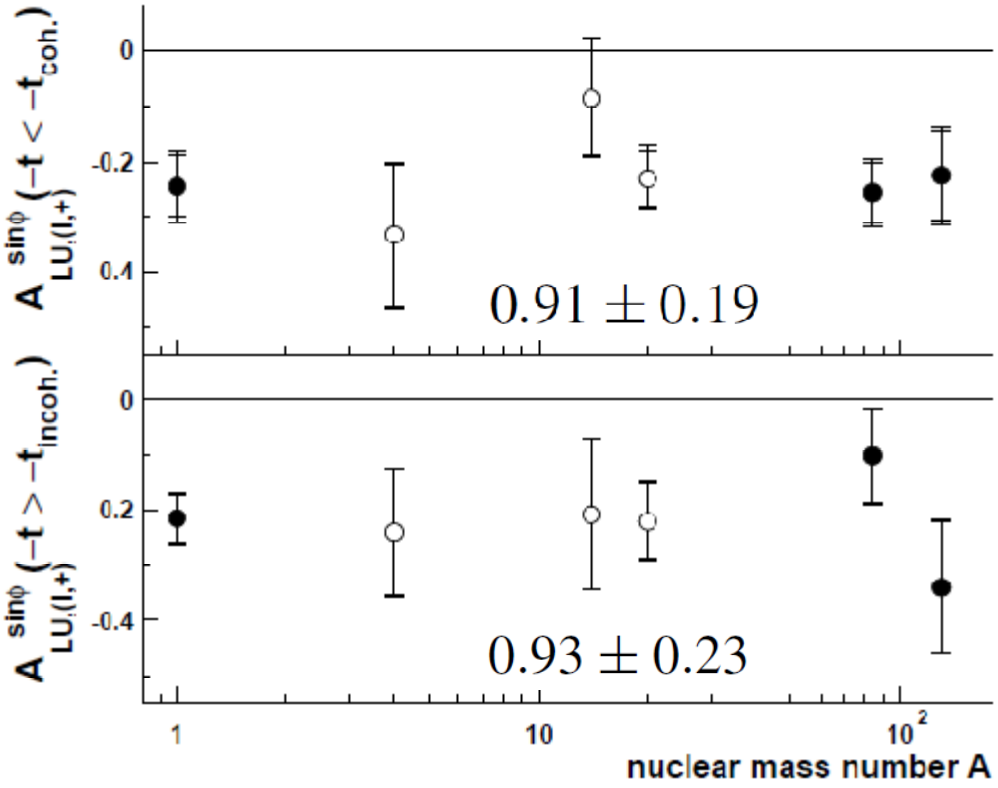
nuclear DVCS

nuclear targets: He, N, Ne, Kr, Xe

[PRC-in print]



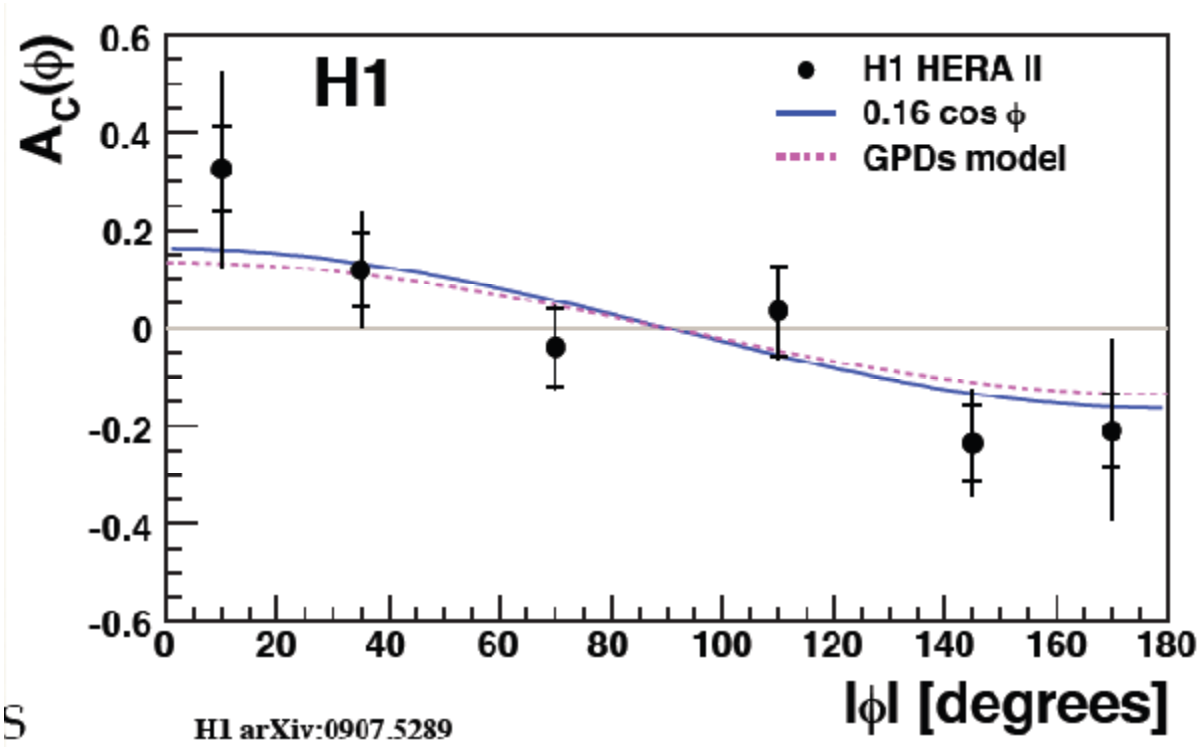
A	t threshold (GeV^2)	$\langle t \rangle$ (GeV^2)	$\langle x_B \rangle$	$\langle Q^2 \rangle$ (GeV^2)	% of coh.	% of assoc.
H	$-t < 0.033$	−0.018	0.070	1.81	–	4
He	$-t < 0.036$	−0.018	0.072	1.83	34	4
N	$-t < 0.043$	−0.018	0.068	1.73	66	3
Ne	$-t < 0.044$	−0.018	0.068	1.74	68	3
Kr	$-t < 0.070$	−0.018	0.064	1.63	69	3
Xe	$-t < 0.078$	−0.018	0.062	1.60	66	4



$$R_{LU} = A^{\sin\phi}_{LU,(I,+),A} / A^{\sin\phi}_{LU,I,H}$$

BCA @small x

information about GPDs @amplitude level



[note: ϕ definition opposite to HERMES Trento convention]