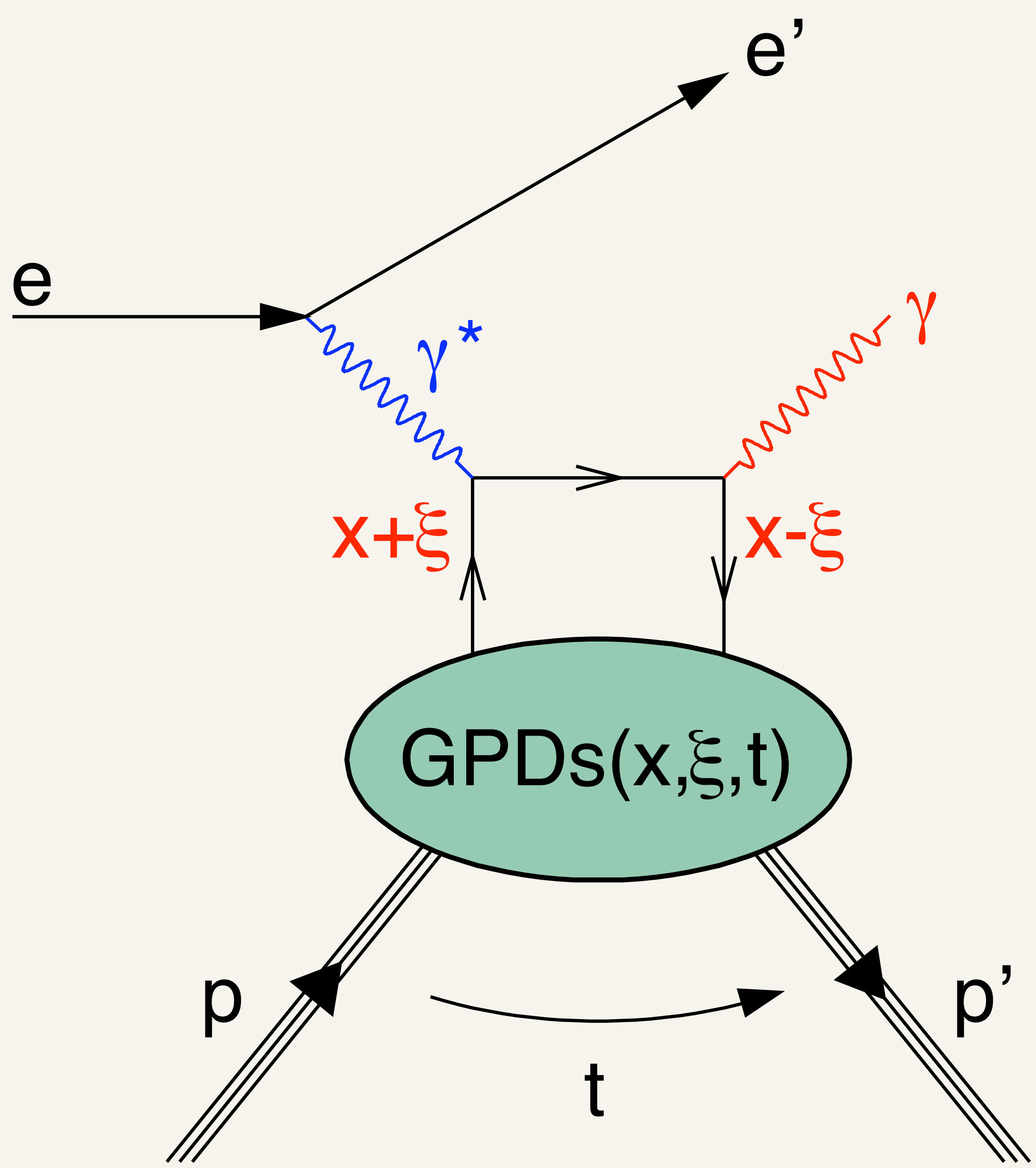
Deeply Virtual Compton Scattering

Caroline Riedl



what?

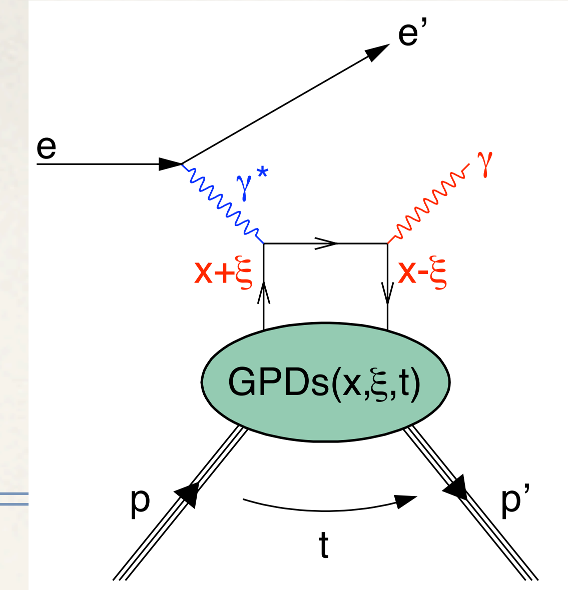
why?

where?

... and the future?

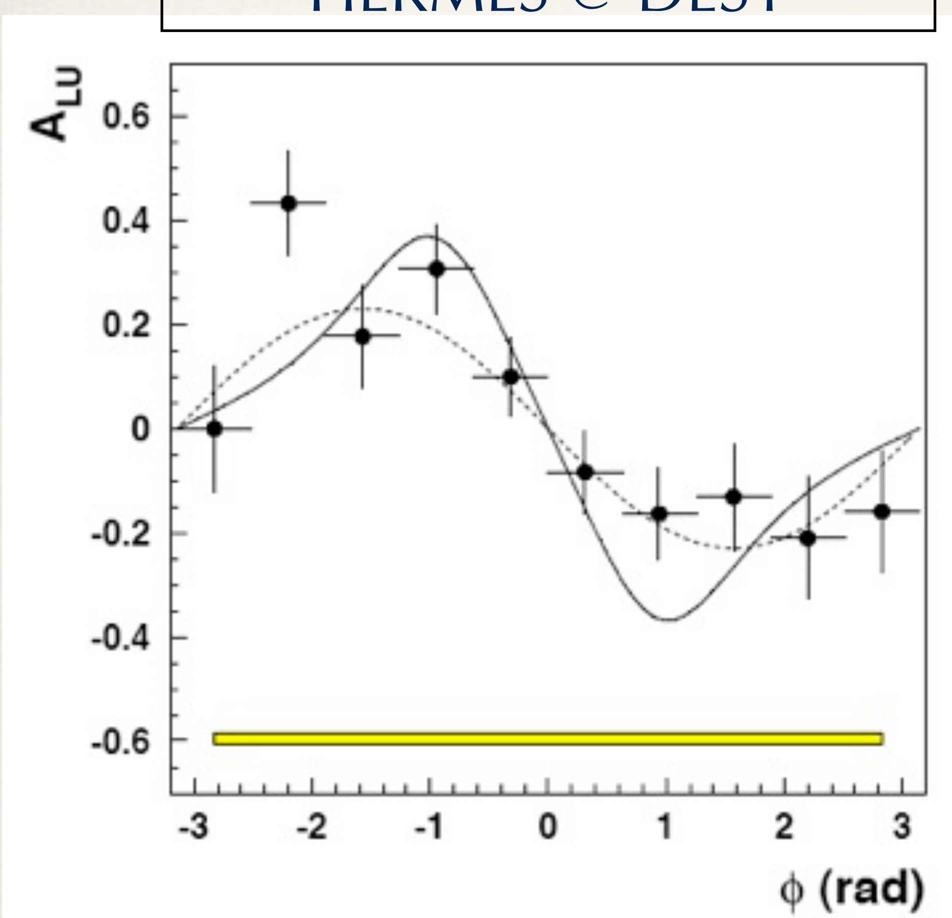
Meson-Nucleon Physics and the Structure of the Nucleon (MENU2010)
Williamsburg, 2.6.2010

Appetizer: first DVCS measurements in 2001



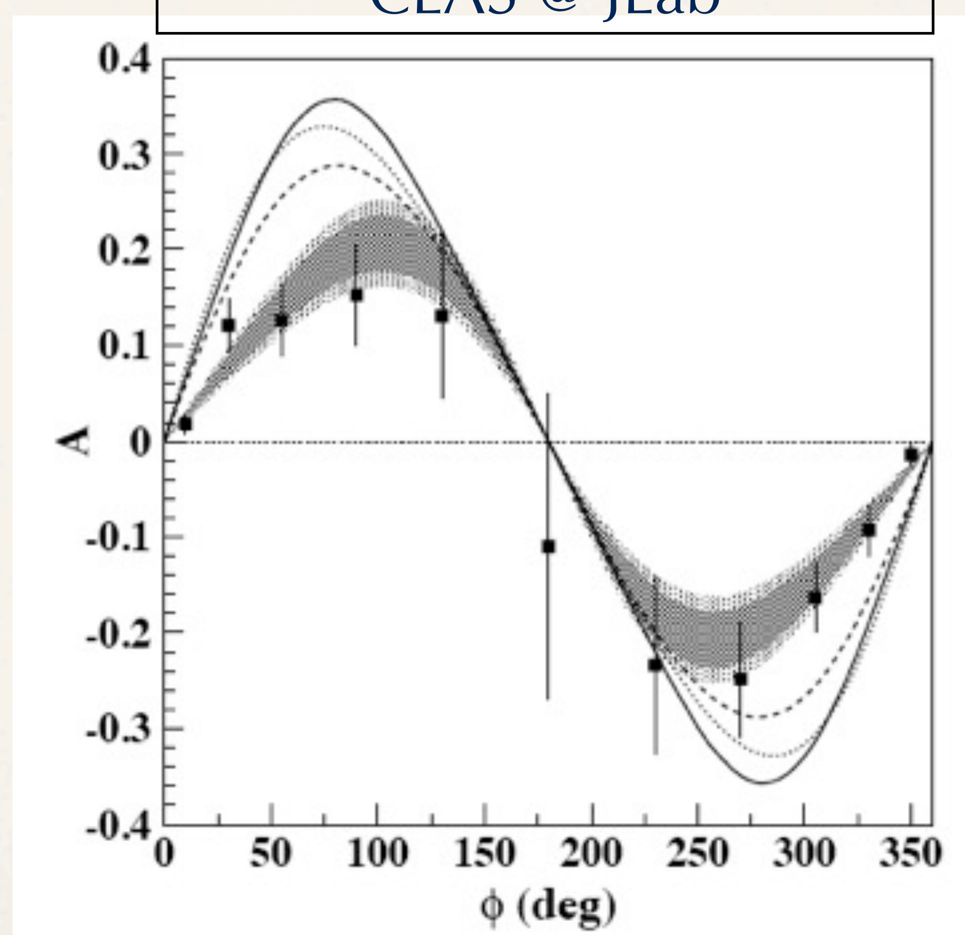
DVCS =hard electroproduction
of a real photon

HERMES @ DESY



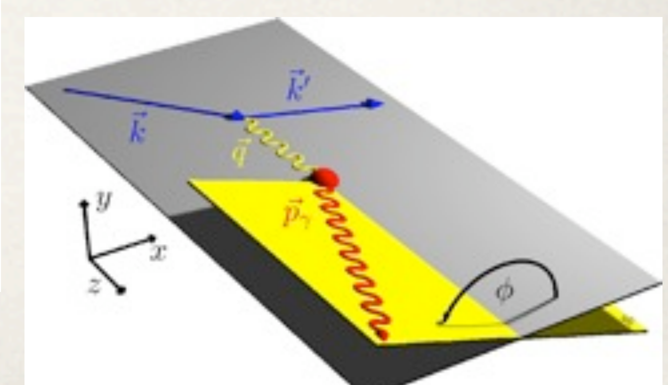
hep/ex:0106068
PRL **87** (2001) 182001

CLAS @ JLab

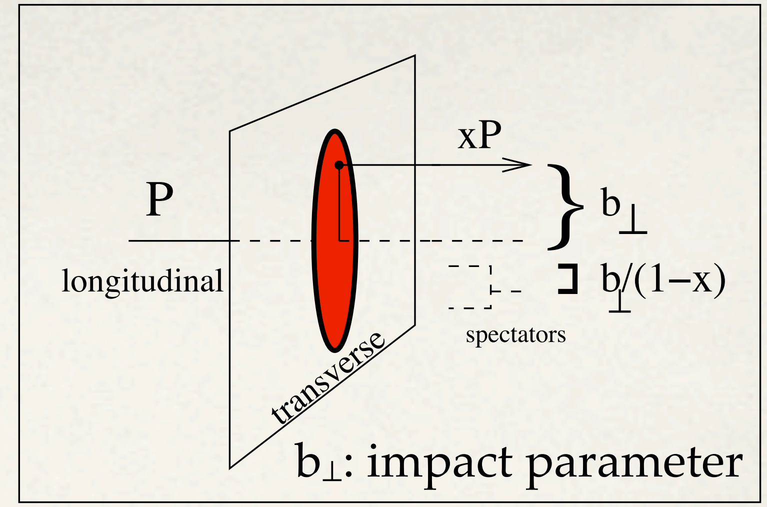


hep/ex:0107043
PRL **87** (2001) 182002

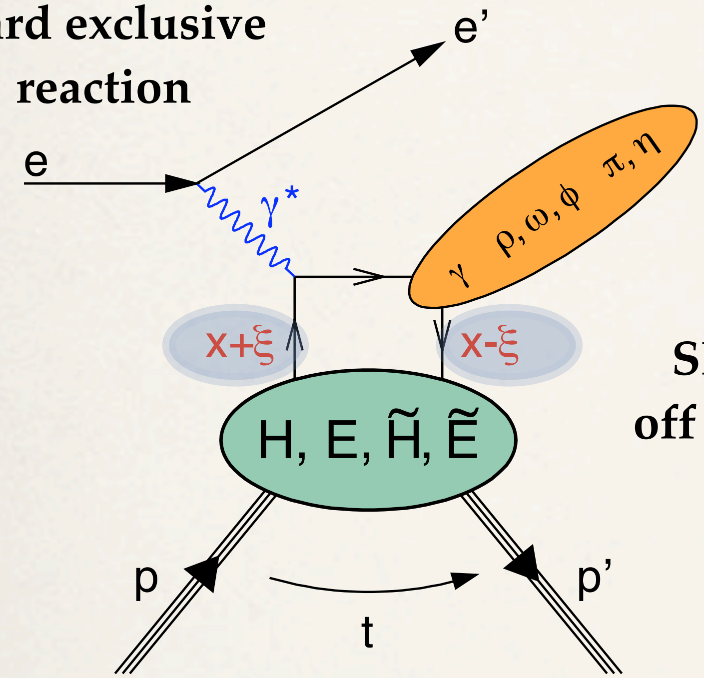
Observation of
azimuthal modulation
in
beam spin asymmetry!



Generalized Parton Distributions



Hard exclusive reaction



Skewing: ξ≠0
off forward limit

leading twist, quark chirality conserving, spin-1/2		
f(quark helicity) ☞	✘	✔
nucleon spin flip ☟	photon: $J^P=1^-$ (**DVCS**)	
✘	**H**	**H̃**
✔	**E**	**Ẽ**
	$J^P=1^-$ mesons	$J^P=0^-$ mesons

"Nucleon tomography"

- PDFs: longitudinal momentum

  forward limit ξ=0, t=0: $H^q(x,0,0) = q(x)$

- Form Factors: transverse position

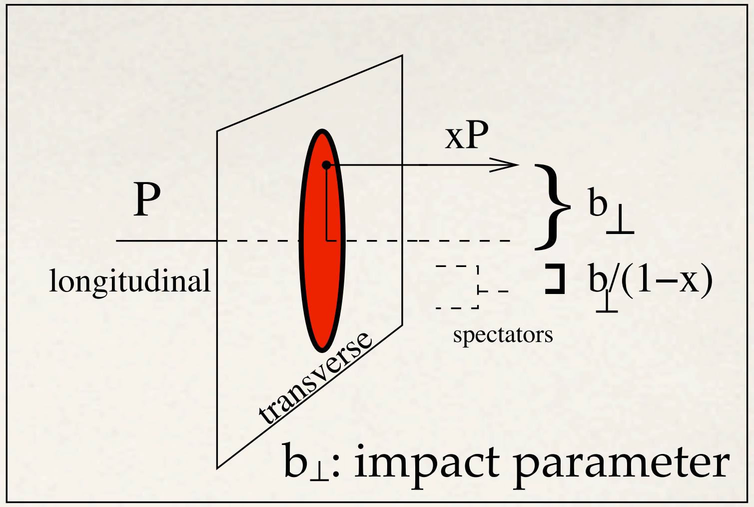
  moments of GPDs: $\int_{-1}^{1} dx H^q(x,\xi,t) = F_1^q(t)$

- Nucleonic Spin:
  total angular momentum

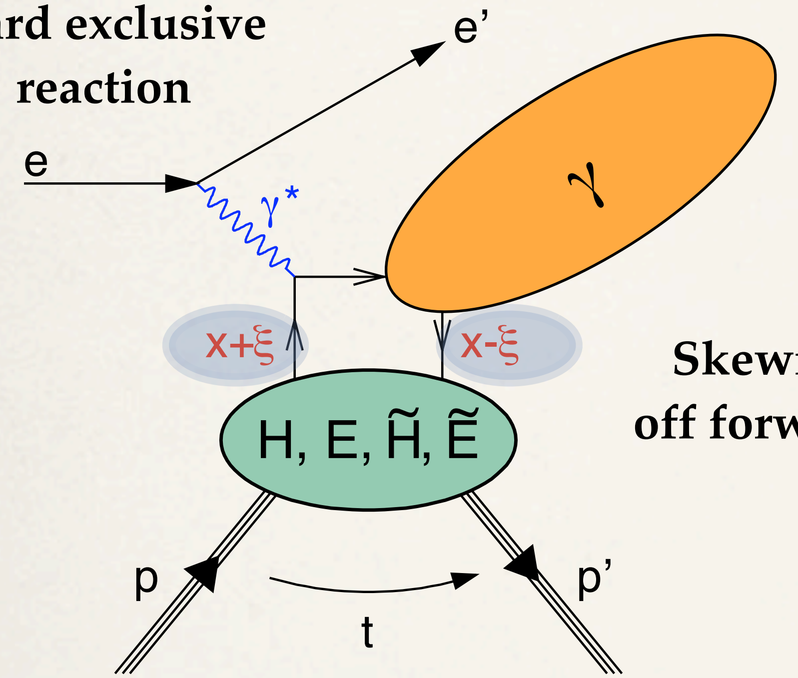
Ji relation:

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

Generalized Parton Distributions



Hard exclusive reaction



Skewing: ξ≠0
off forward limit

"Nucleon tomography"

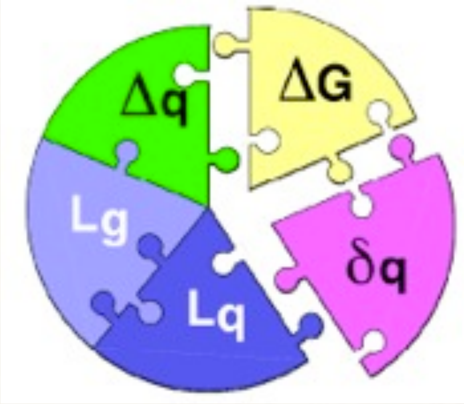
- PDFs: longitudinal momentum

  forward limit ξ=0, t=0: $H^{\rm q}(x,0,0) = q(x)$

- Form Factors: transverse position

  moments of GPDs: $\int_{-1}^{1} {\rm d}x H^{\rm q}(x,\xi,t) = F_1^{\rm q}(t)$

- Nucleonic Spin:
  total angular momentum



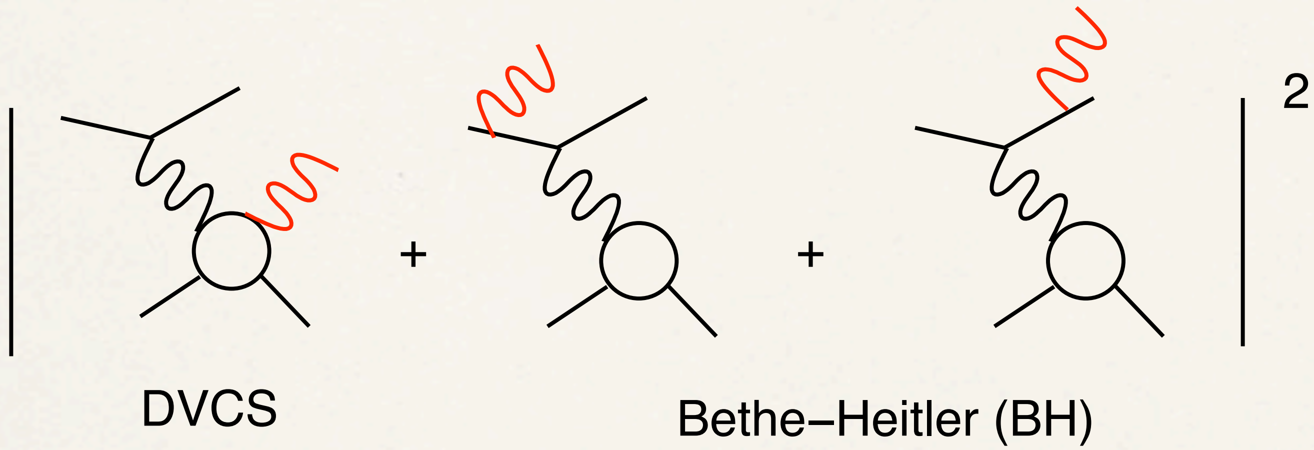
Ji relation:

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

leading twist, quark chirality conserving, spin-1/2		
f(quark helicity) ☞	✘	✔
nucleon spin flip ☟	photon: $J^P=1^-$ (**DVCS**)	
✘	**H**	**H̃**
✔	**E**	**Ẽ**
	$J^P=1^-$ mesons	$J^P=0^-$ mesons

Deeply Virtual Compton Scattering

$\sigma_{\gamma^*\gamma N} \sim$



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

DVCS-BH interference term $\mathcal{I}$

Collider:
$|\tau_{DVCS}|^2 \approx |\tau_{BH}|^2$

Fixed target:
$|\tau_{DVCS}|^2 \ll |\tau_{BH}|^2$

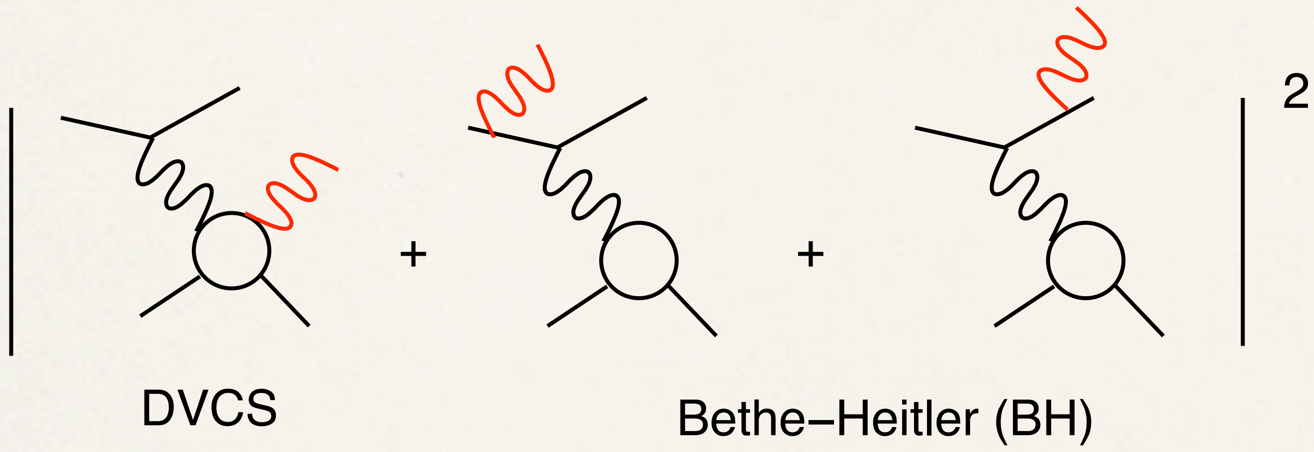
Exactly calculable in QED given the nucleon elastic form factors F_1 and F_2

Holographic principle:

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

Deeply Virtual Compton Scattering

$\sigma_{\gamma^*\gamma N} \sim$



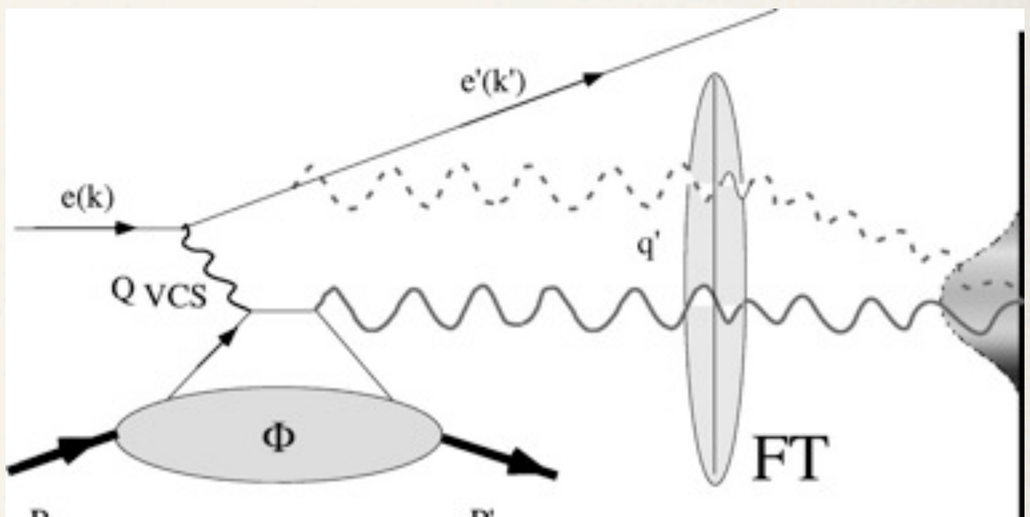
$= |\tau_{DVCS}|^2 + |\tau_{BH}|^2 + \tau_{DVCS}\tau_{BH}^* + \tau_{DVCS}^*\tau_{BH}$

DVCS-BH interference term $\mathcal{I}$

Collider:
$|\tau_{DVCS}|^2 \approx |\tau_{BH}|^2$

Fixed target:
$|\tau_{DVCS}|^2 \ll |\tau_{BH}|^2$

Exactly calculable in QED given the nucleon elastic form factors F_1 and F_2



Belitsky, Müller, hep-ph/0206306

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

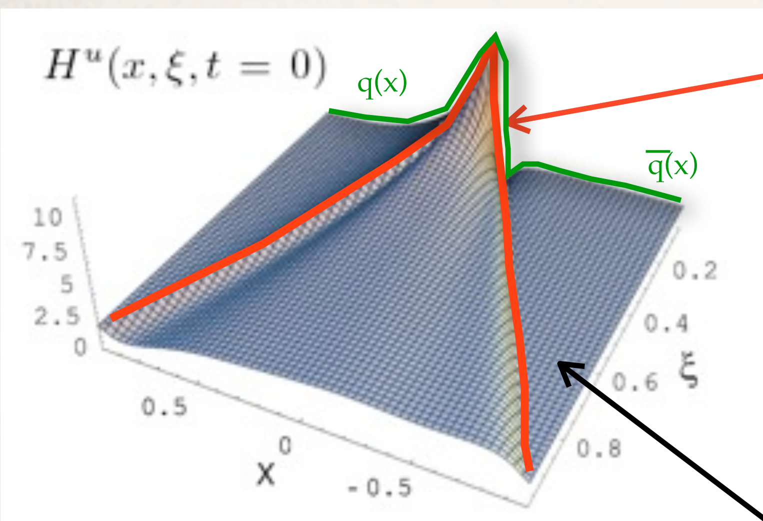
DVCS cross-section
in the valence quark region

- Hall-A at JLab, proton target (E00-110)

Differential cross section vs. azimuthal angle

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

GPDs: 2 orthogonal spaces probed simultaneously



Goeke, Polyakov, Vanderhaeghen, hep-ph/0106012

Helicity-dependent

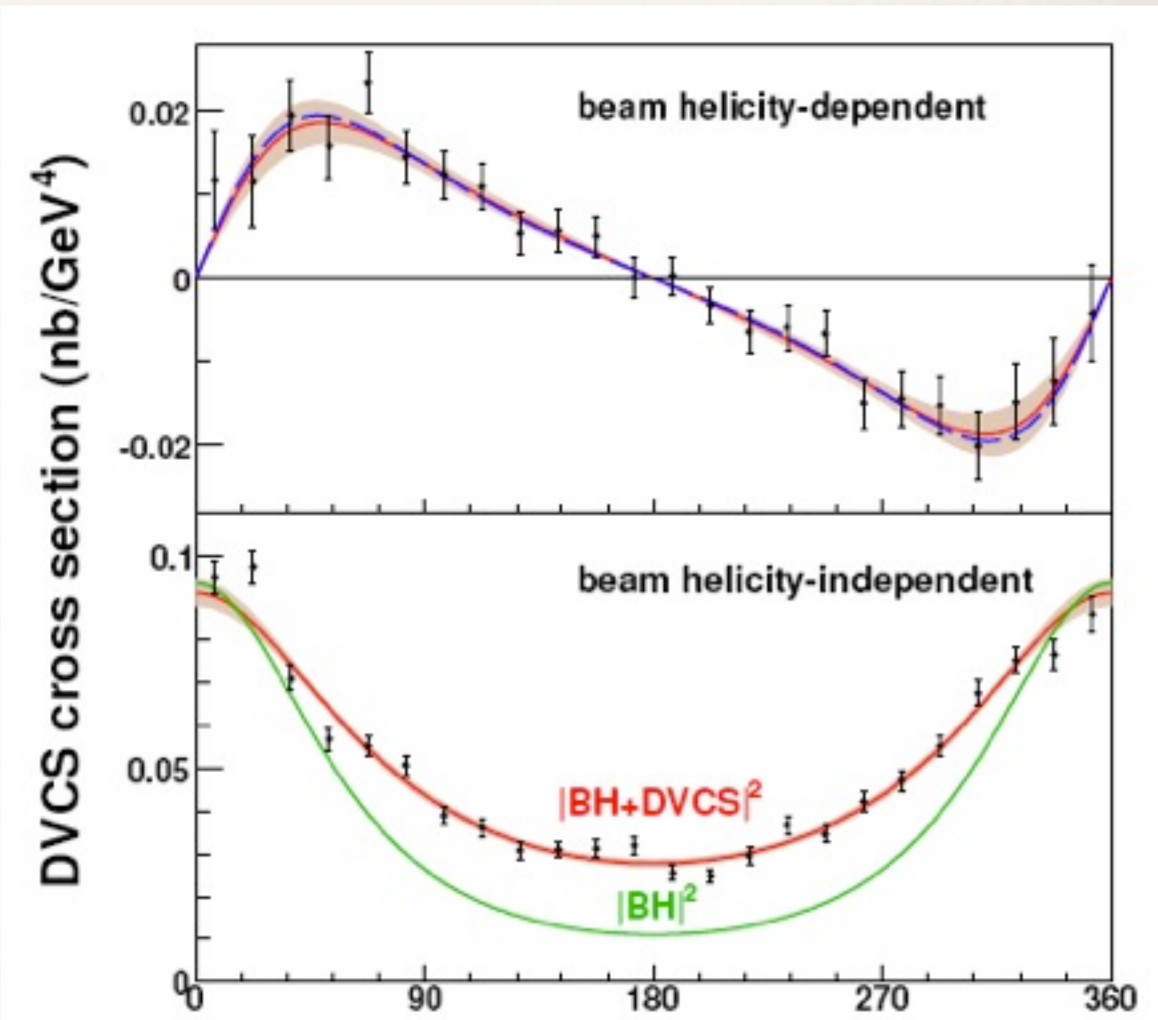
$\propto \mathcal{Im}(\ \mathcal{T}_{DVCS}\ )$

GPDs @ $x=\xi$

Helicity-independent

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

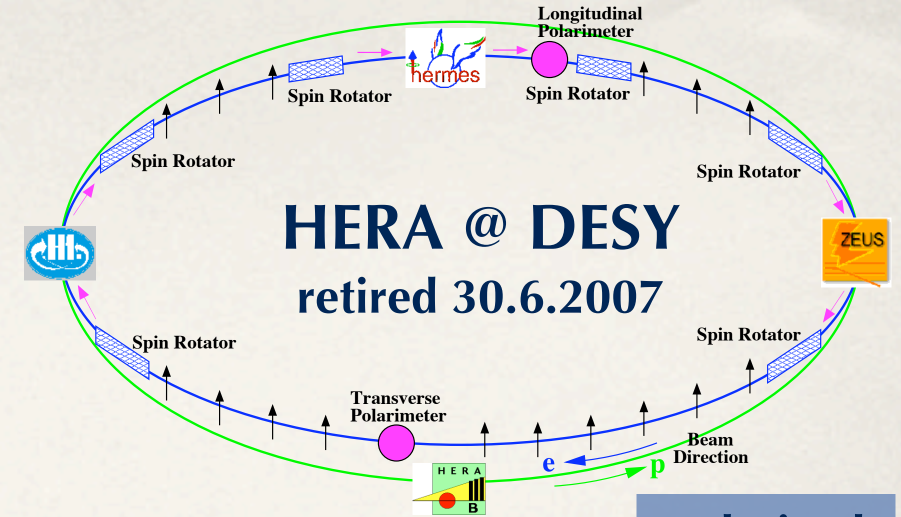
integral of GPDs over x



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

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

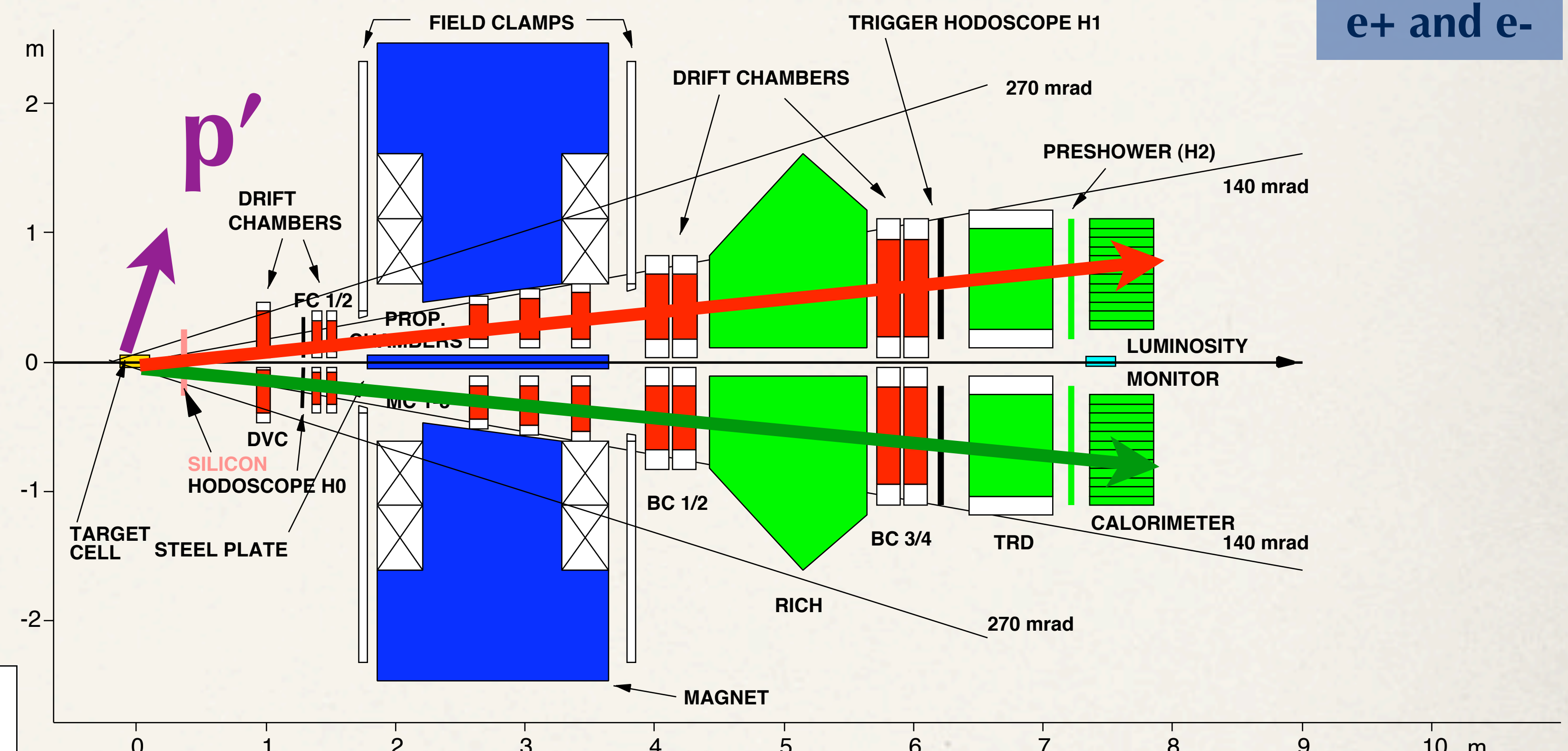
DVCS at HERMES 1996-2005

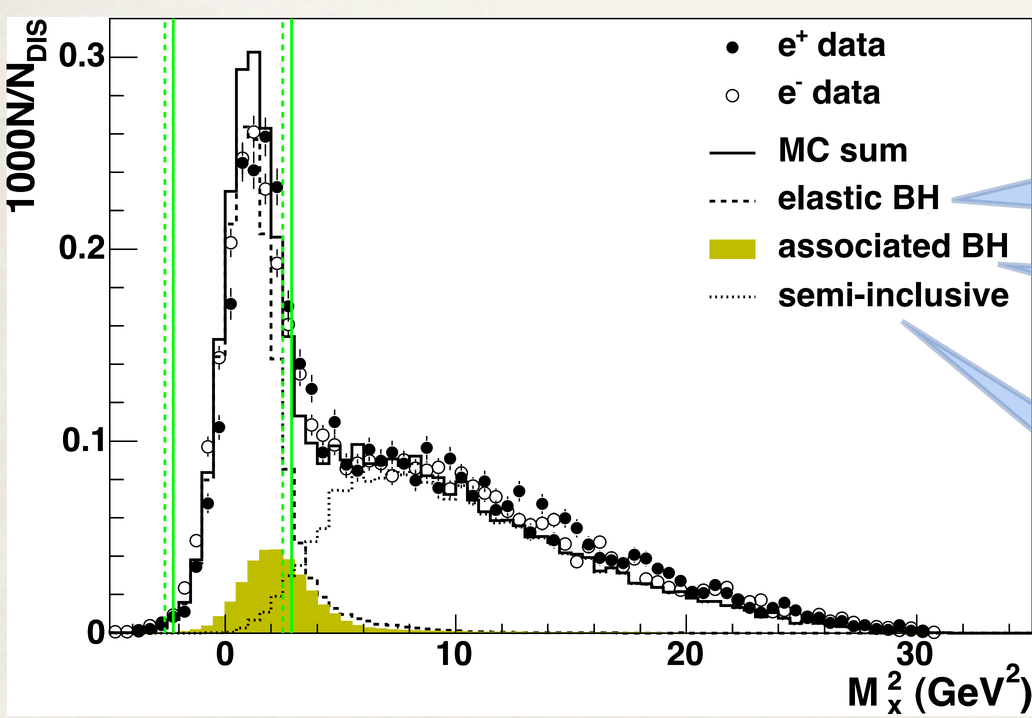


polarized e+ and e-

Detected particles:
electron and photon

Missing mass technique for
ep→eXγ
$M_X^2=(p+q-p_\gamma)^2$





X=p

resonant excitation: $X=\Delta^+$

$p\pi^0$ $n\pi^+$

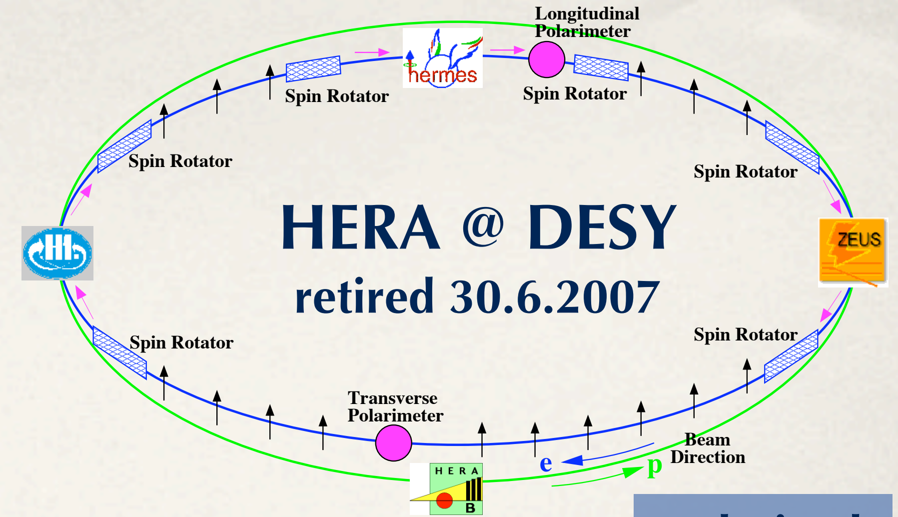
$X=\pi^0+\ldots$

hydrogen target:
400 pb^{-1}
thereof L-polarized:
50 pb^{-1}
and T-polarized:
170 pb^{-1}

unpolarized deuterium:
300 pb^{-1}
L-polarized deuterium:
200 pb^{-1}
+heavier nuclear targets

+ more unpolarized H and D data in 2006-2007

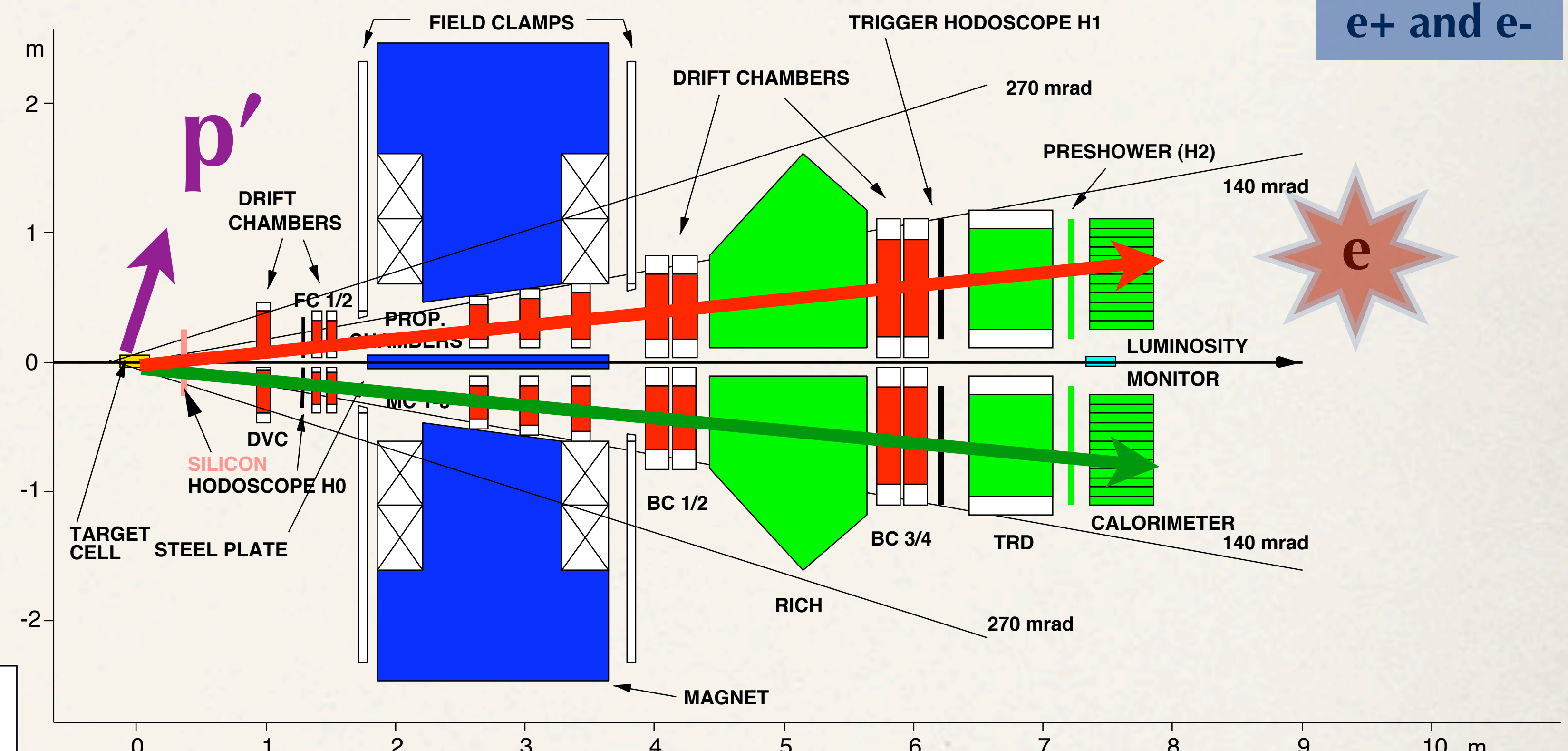
DVCS at HERMES 1996-2005



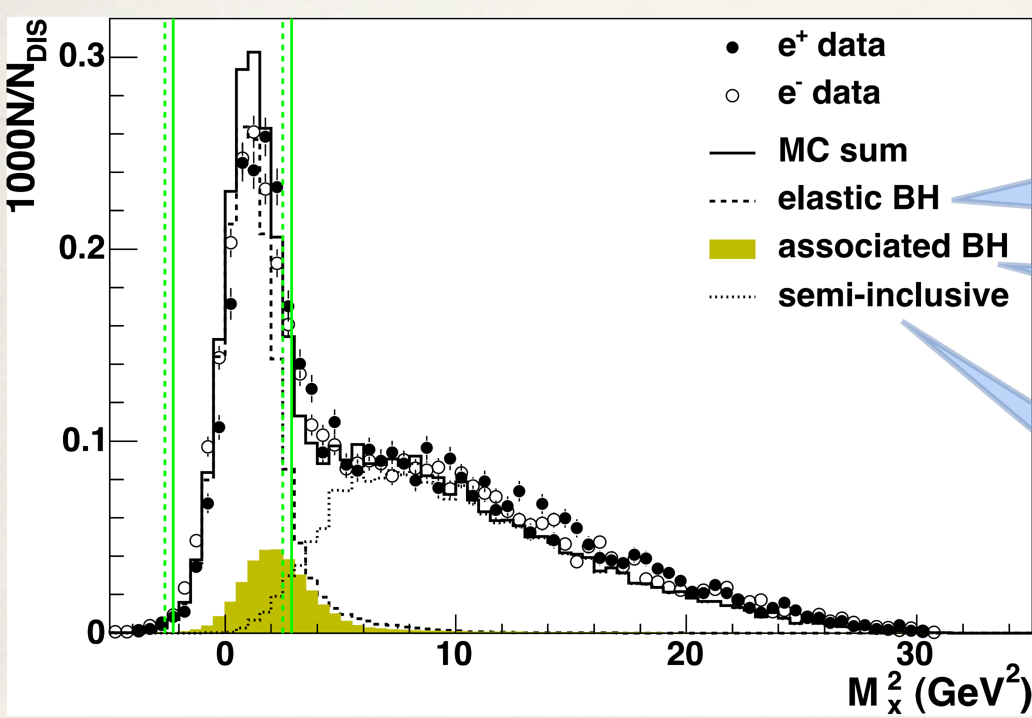
polarized e+ and e-

Detected particles:
electron and photon

Missing mass technique for
$ep \rightarrow eX\gamma$
$M_X^2=(p+q-p_\gamma)^2$



hydrogen target:
400 pb^{-1}
thereof L-polarized:
50 pb^{-1}
and T-polarized:
170 pb^{-1}



X=p

resonant excitation: $X=\Delta^+$

$p\pi^0$

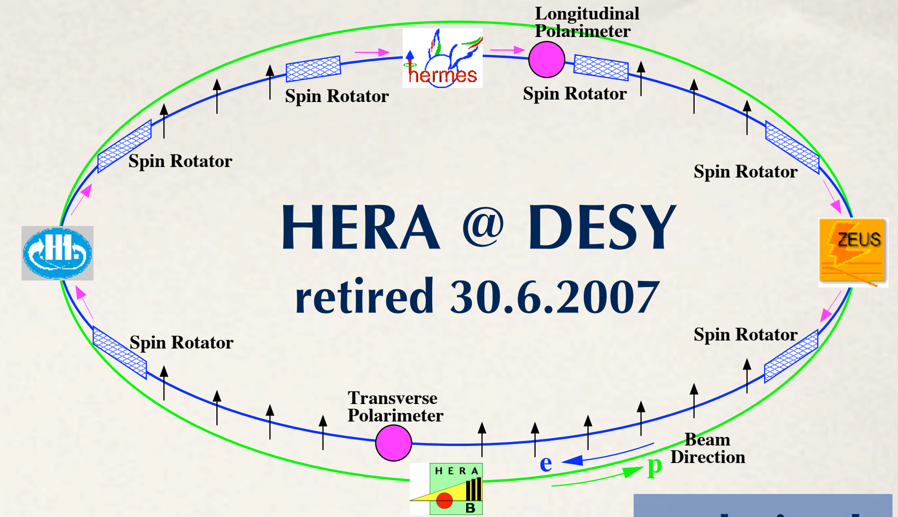
$n\pi^+$

$X=\pi^0+...$

+ more unpolarized H and D data in 2006-2007

unpolarized deuterium:
300 pb^{-1}
L-polarized deuterium:
200 pb^{-1}
+heavier nuclear targets

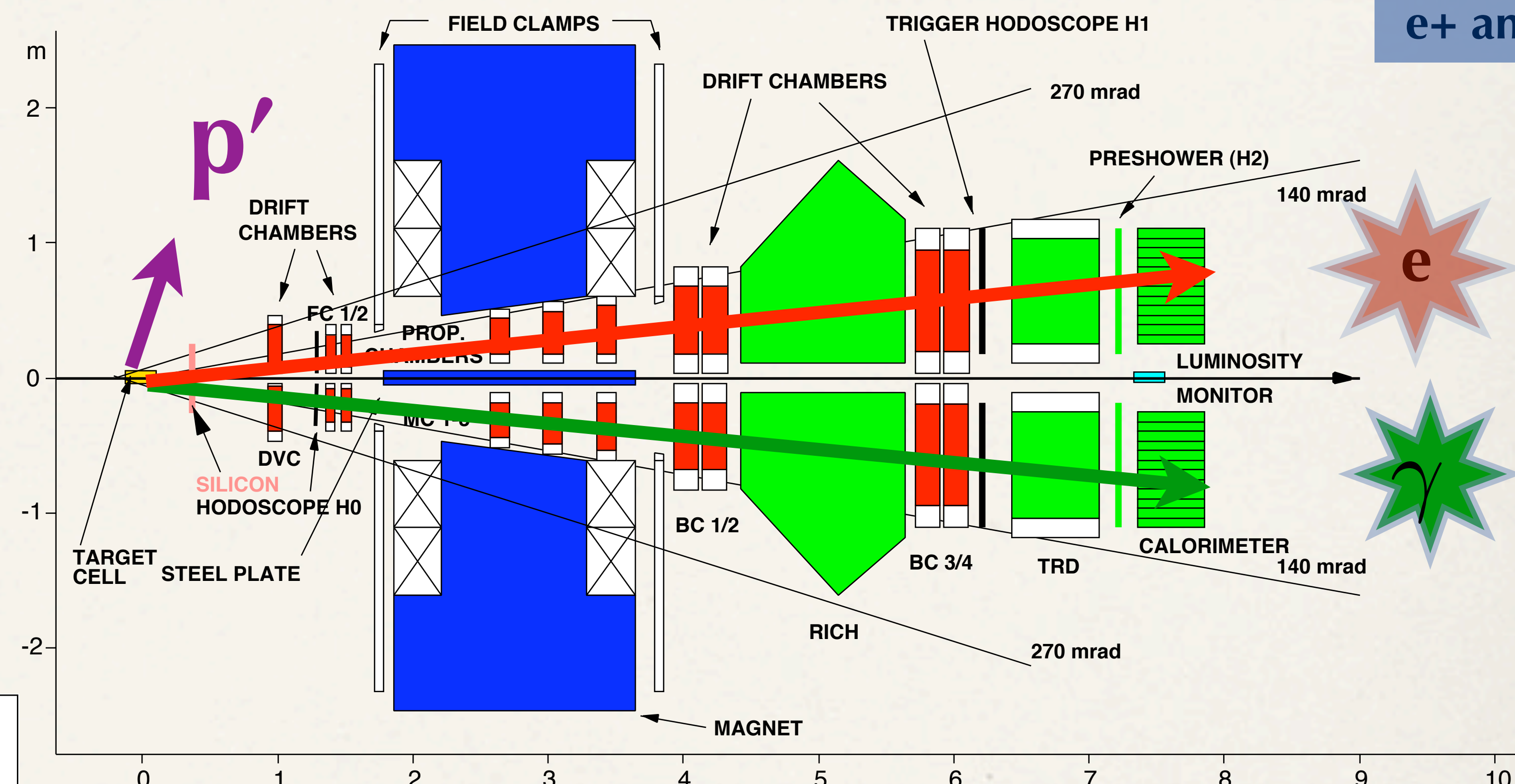
DVCS at HERMES 1996-2005

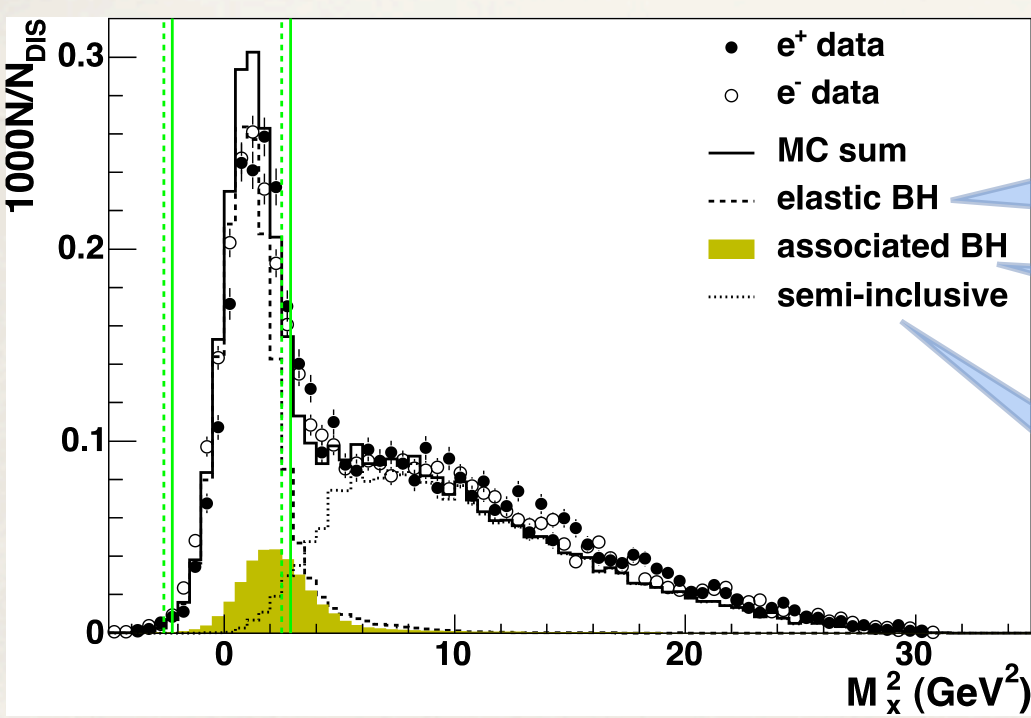


polarized e+ and e-

Detected particles:
electron and photon

Missing mass technique for
$ep \rightarrow eX\gamma$
$M_X^2=(p+q-p_\gamma)^2$





X=p

resonant excitation: $X=\Delta^+$

$p\pi^0$

$n\pi^+$

$X=\pi^0+\ldots$

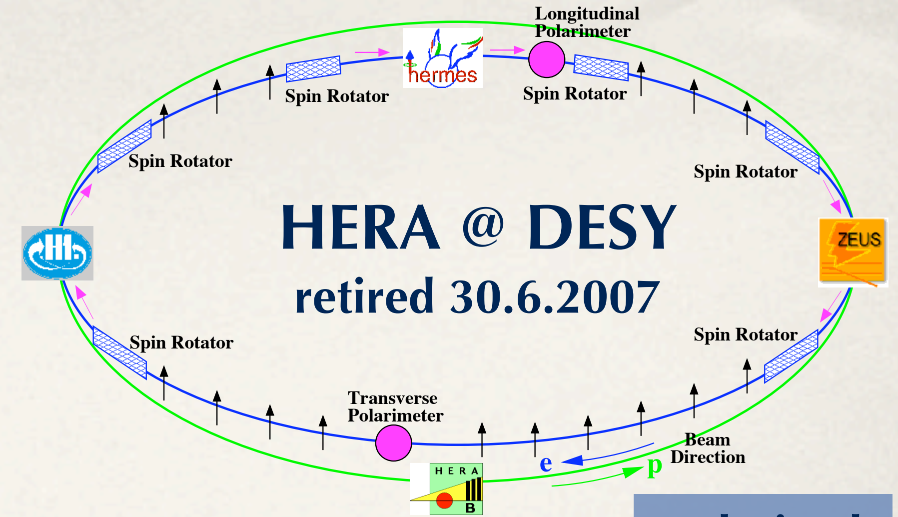
hydrogen target:
400 pb^{-1}
thereof L-polarized:
50 pb^{-1}
and T-polarized:
170 pb^{-1}

unpolarized deuterium:
300 pb^{-1}
L-polarized deuterium:
200 pb^{-1}
+heavier nuclear targets

+ more unpolarized H and D data in 2006-2007

DVCS at HERMES 1996-2005

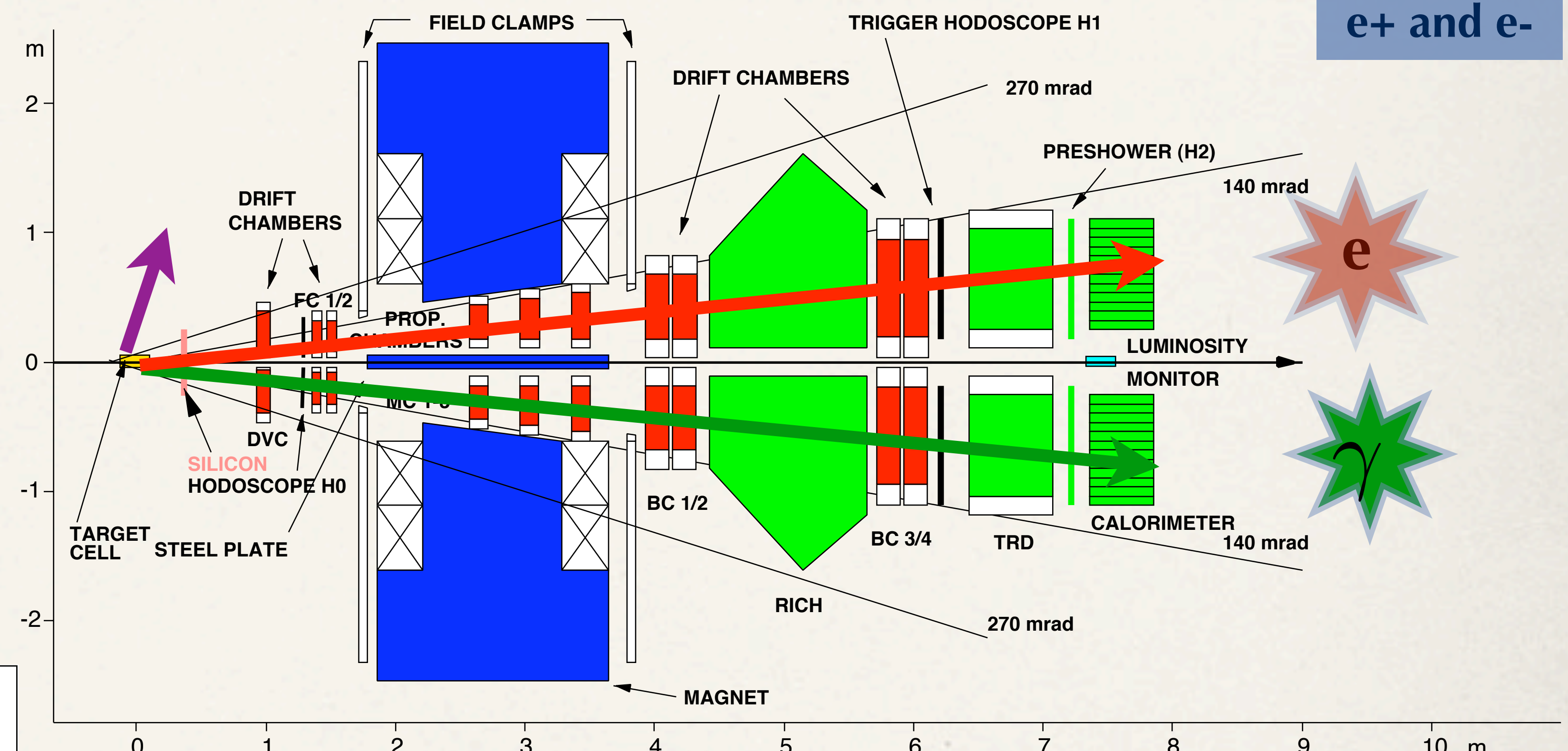
p′

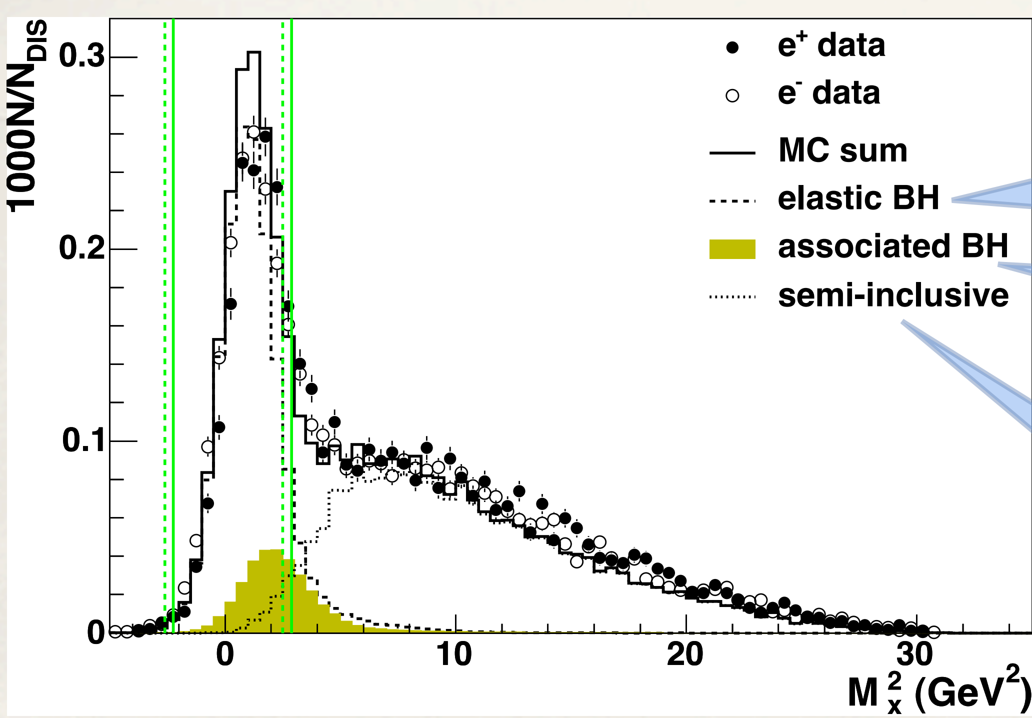


polarized e+ and e-

Detected particles:
electron and photon

Missing mass technique for
ep→eXγ
$M_X^2=(p+q-p_\gamma)^2$





X=p

resonant excitation: $X=\Delta^+$

$p\pi^0$

$n\pi^+$

$X=\pi^0+\ldots$

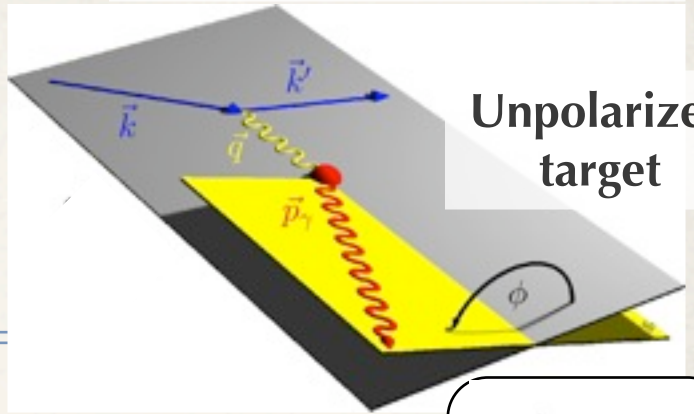
+ more unpolarized H and D data in 2006-2007

hydrogen target:
400 pb^{-1}
thereof L-polarized:
50 pb^{-1}
and T-polarized:
170 pb^{-1}

unpolarized deuterium:
300 pb^{-1}
L-polarized deuterium:
200 pb^{-1}
+heavier nuclear targets

Azimuthal Asymmetries in DVCS

Lepton beam with charge C_B and polarization P_B



$$\sigma_{\gamma\gamma^* N} = |\tau_{BH}|^2 + |\tau_{DVCS}|^2 + \mathcal{I}$$

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

$$|\mathcal{T}_{\mathrm{DVCS}}|^2 = K_{\mathrm{DVCS}} \left[\sum_{n=0}^{2} c_n^{\mathrm{DVCS}} \cos(n\phi) + P_B \sum_{n=1}^{1} s_n^{\mathrm{DVCS}} \sin(n\phi) \right]$$

$$\mathcal{I} = \frac{C_B K_{\mathcal{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left[\sum_{n=0}^{3} c_n^{\mathcal{I}} \cos(n\phi) + P_B \sum_{n=1}^{2} s_n^{\mathcal{I}} \sin(n\phi) \right]$$

Wanted: Fourier coefficients

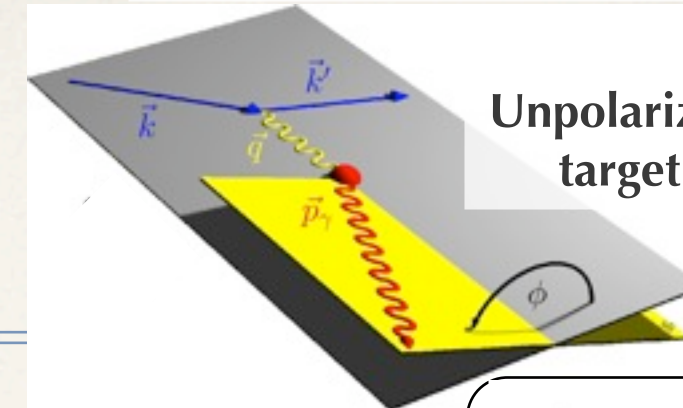
$\mathcal{A}_{LU}$

Beam Target

Azimuthal Asymmetries in DVCS

$\sigma_{\gamma\gamma^* N} = |\tau_{BH}|^2 + |\tau_{DVCS}|^2 + \mathcal{I}$

Lepton beam with charge C_B and polarization P_B



Unpolarized target

$\mathcal{A}_{LU}$: Beam, Target

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

$$|\mathcal{T}_{DVCS}|^2 = K_{DVCS} \left[\sum_{n=0}^{2} c_n^{DVCS} \cos(n\phi) + P_B \sum_{n=1}^{1} s_n^{DVCS} \sin(n\phi) \right]$$

$$\mathcal{I} = \frac{C_B K_{\mathcal{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left[\sum_{n=0}^{3} c_n^{\mathcal{I}} \cos(n\phi) + P_B \sum_{n=1}^{2} s_n^{\mathcal{I}} \sin(n\phi) \right]$$

Wanted: Fourier coefficients

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

Old approach at HERMES and CLAS: **single-charge** $\mathcal{A}_{LU}$

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

no separate access to $s_1^{\mathcal{I}}$ and s_1^{DVCS}

Beam-helicity asymmetries

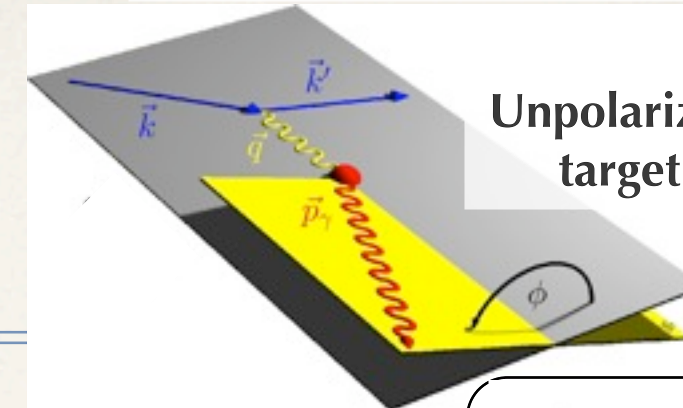
Beam-charge asymmetry

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

Azimuthal Asymmetries in DVCS

$$\sigma_{\gamma\gamma^* N} = |\tau_{BH}|^2 + |\tau_{DVCS}|^2 + \mathcal{I}$$

Lepton beam with charge C_B and polarization P_B



Unpolarized target

$\mathcal{A}_{LU}$

Beam Target

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

$$|\mathcal{T}_{DVCS}|^2 = K_{DVCS} \left[\sum_{n=0}^{2} c_n^{DVCS} \cos(n\phi) + P_B \sum_{n=1}^{1} s_n^{DVCS} \sin(n\phi) \right]$$

$$\mathcal{I} = \frac{C_B K_{\mathcal{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left[\sum_{n=0}^{3} c_n^{\mathcal{I}} \cos(n\phi) + P_B \sum_{n=1}^{2} s_n^{\mathcal{I}} \sin(n\phi) \right]$$

Wanted: Fourier coefficients

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

Old approach at HERMES and CLAS: **single-charge $\mathcal{A}_{LU}$**

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

no separate access to $s_1^{\mathcal{I}}$ and s_1^{DVCS}

Beam-helicity asymmetries

New approach at HERMES: $s_1^{\mathcal{I}}$ and s_1^{DVCS} can be disentangled

Need 2 beam charges!

Beam-charge asymmetry

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

Charge-average $\mathcal{A}_{LU}$:

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

Charge-difference $\mathcal{A}_{LU}$:

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

Azimuthal Asymmetries ⇒ GPDs

$$\mathcal{I} = \frac{C_B K_\mathcal{I}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left[\sum_{n=0}^{3} c_n^\mathcal{I} \cos(n\phi) + P_B \sum_{n=1}^{2} s_n^\mathcal{I} \sin(n\phi) \right]$$

At leading twist level (twist-2):

$$c_1^\mathcal{I} \propto \frac{\sqrt{-t}}{Q} \Re\mathrm{e} \left[\mathcal{C}_{\mathrm{unp}}^\mathcal{I} \right] \qquad s_1^\mathcal{I} \propto \frac{\sqrt{-t}}{Q} \Im\mathrm{m} \left[\mathcal{C}_{\mathrm{unp}}^\mathcal{I} \right]$$

$\mathcal{A}_{\mathrm{C}}$ $\mathcal{A}_{\mathrm{LU}}$

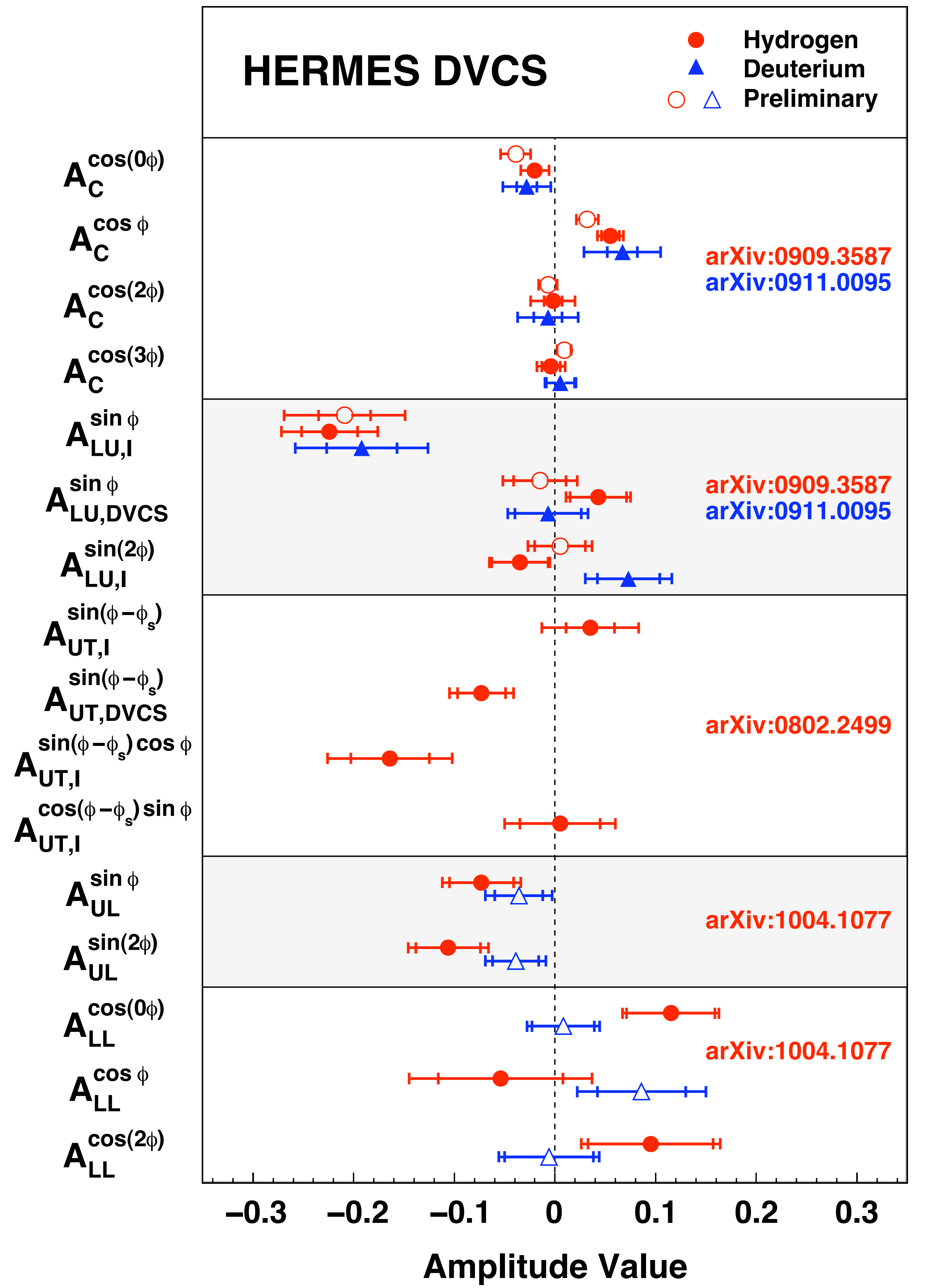
Compton Form Factors (CFFs):
$$\mathcal{F}(\xi, t) = \sum_q \int_{-1}^{1} \mathrm{d}x \; C_q^{\mp}(\xi, x) F^q(x, \xi, t)$$

twist-2 GPD

$$\mathcal{C}_{\mathrm{unp}}^\mathcal{I} = F_1 \mathcal{H} + \xi(F_1 + F_2)\widetilde{H} - \frac{t}{4M^2} F_2 \mathcal{E}$$

dominant for the proton

Linear combination of CFFs



Fourier Amplitudes

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

(A) Beam charge asymmetry:
GPD H

(B) Beam helicity asymmetry:
GPD H

(C) Transverse target spin asymmetry:
GPD E from proton target

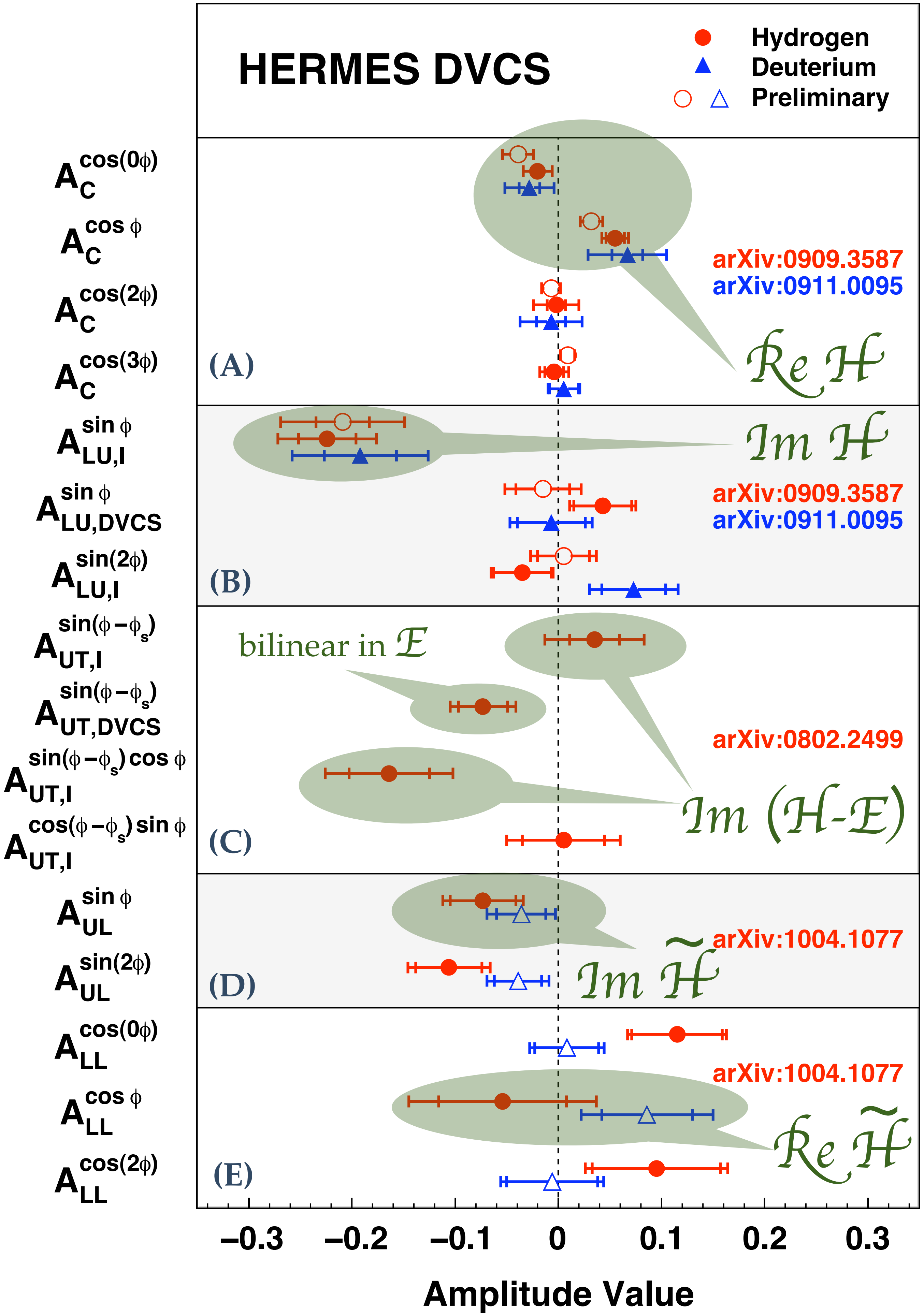
(D) Longitudinal target spin asymmetry:
GPD $\tilde{H}$

arXiv:1004.1077

(E) Double-spin asymmetry: **first measurement!**
GPD $\tilde{H}$

Fourier Amplitudes

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



(A) Beam charge asymmetry:
GPD H

(B) Beam helicity asymmetry:
GPD H

(C) Transverse target spin asymmetry:
GPD E from proton target

(D) Longitudinal target spin asymmetry:
GPD $\tilde{H}$

arXiv:1004.1077

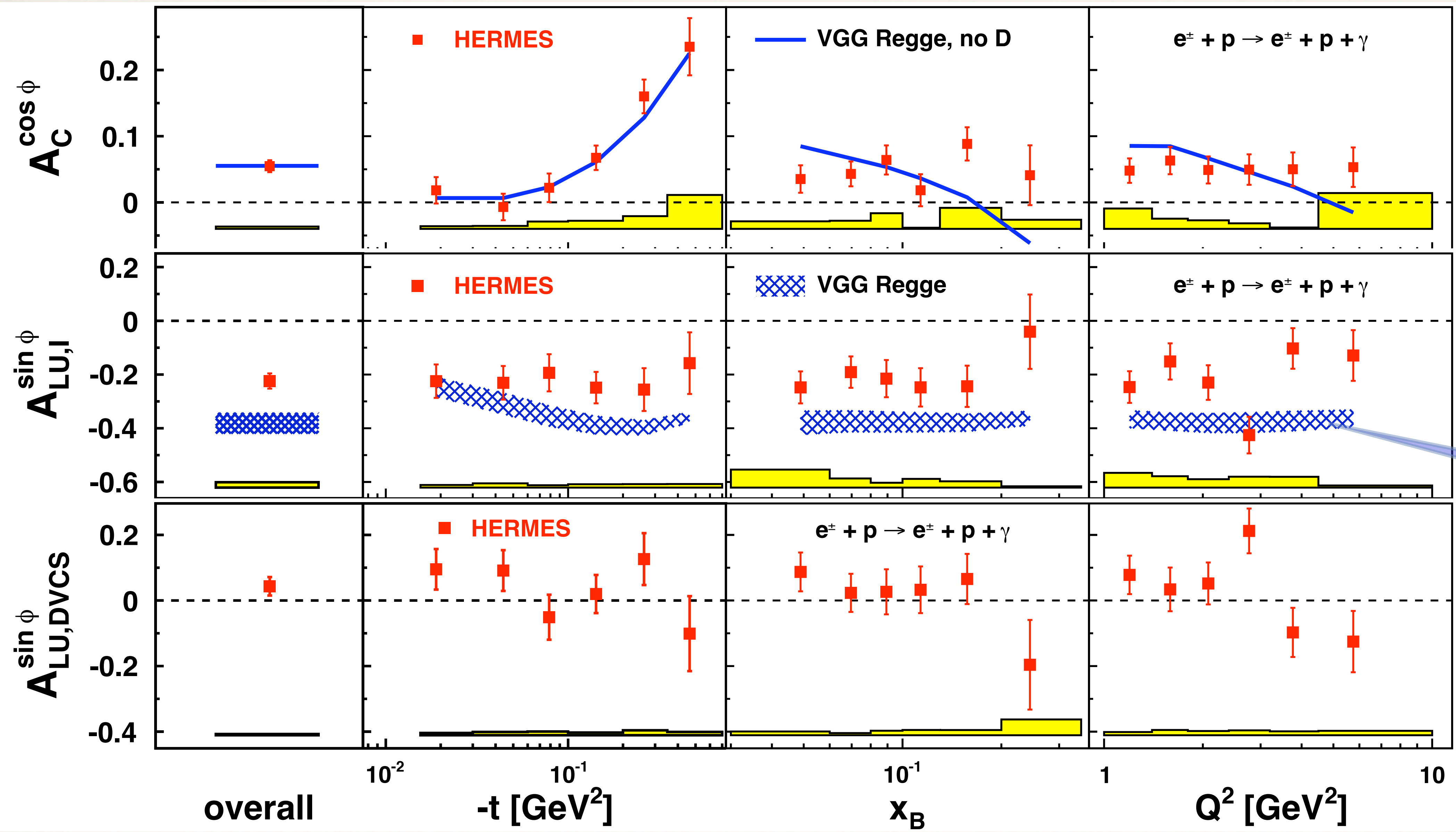
(E) Double-spin asymmetry: **first measurement!**
GPD $\tilde{H}$

HERMES

$\mathcal{A}_C$ & $\mathcal{A}_{LU}$ amplitudes

HERMES data 1996-2005
arXiv:0909.3587
JHEP 11 (2009) 083

Also available:
2-dim (x_B,t) binning



Beam-charge asymmetry

$\mathcal{R}e\,\mathcal{H}$

$\mathcal{I}m\,\mathcal{H}$

Beam-helicity asymmetry
sensitive to interference term

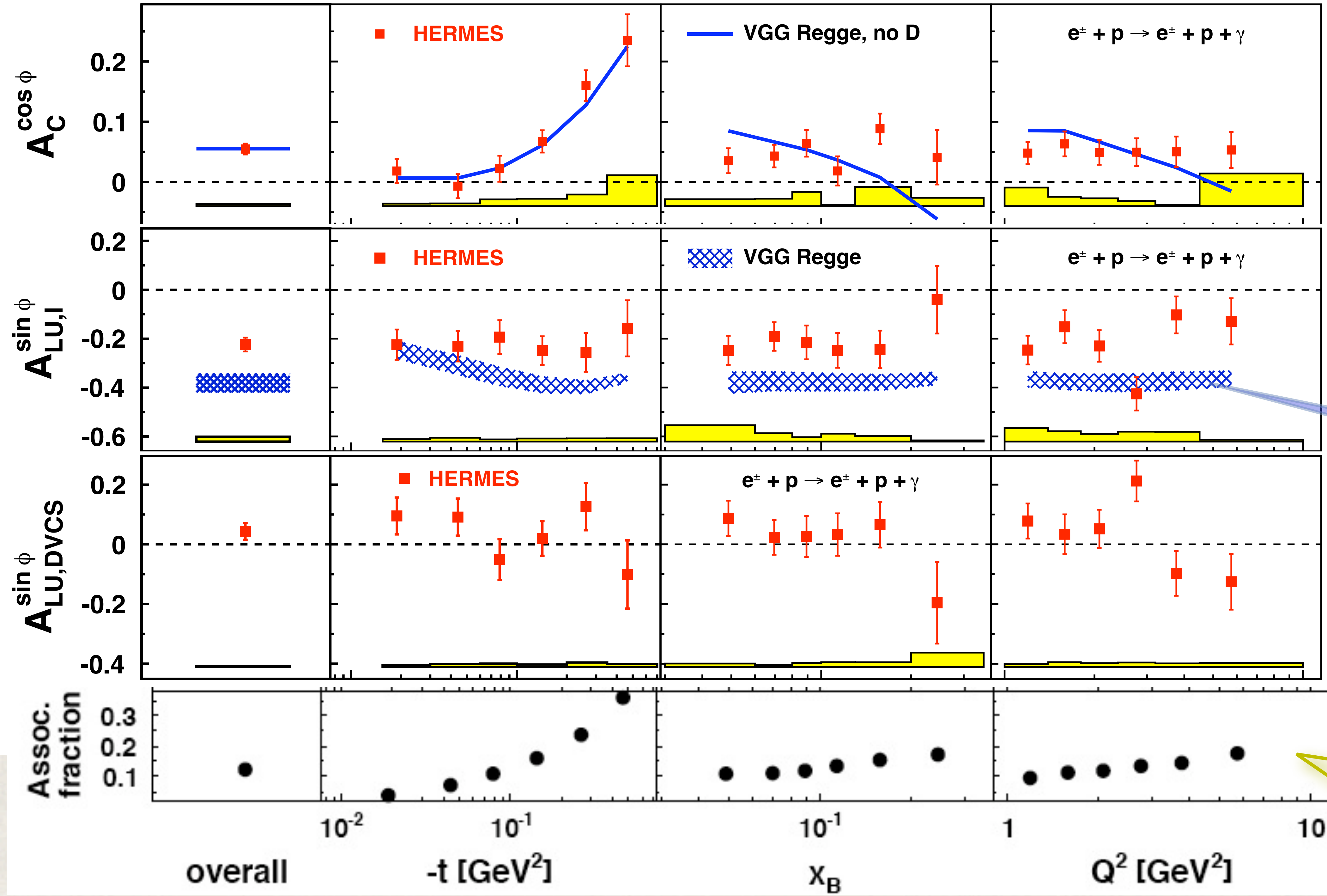
VGG:
Phys.Rev. **D60** (1999) 094017 and Prog.Nucl.Phys. **47** (2001) 401

Beam-helicity asymmetry
sensitive to DVCS² term

HERMES
$\mathcal{A}_C$ & $\mathcal{A}_{LU}$ amplitudes

HERMES data 1996-2005
arXiv:0909.3587
JHEP 11 (2009) 083

Also available:
2-dim (x_B,t) binning



Beam-charge asymmetry

Re H

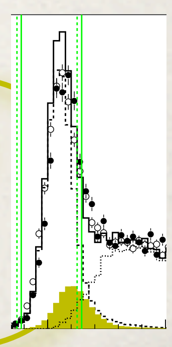
Im H

Beam-helicity asymmetry
sensitive to interference term

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

Beam-helicity asymmetry
sensitive to DVCS² term

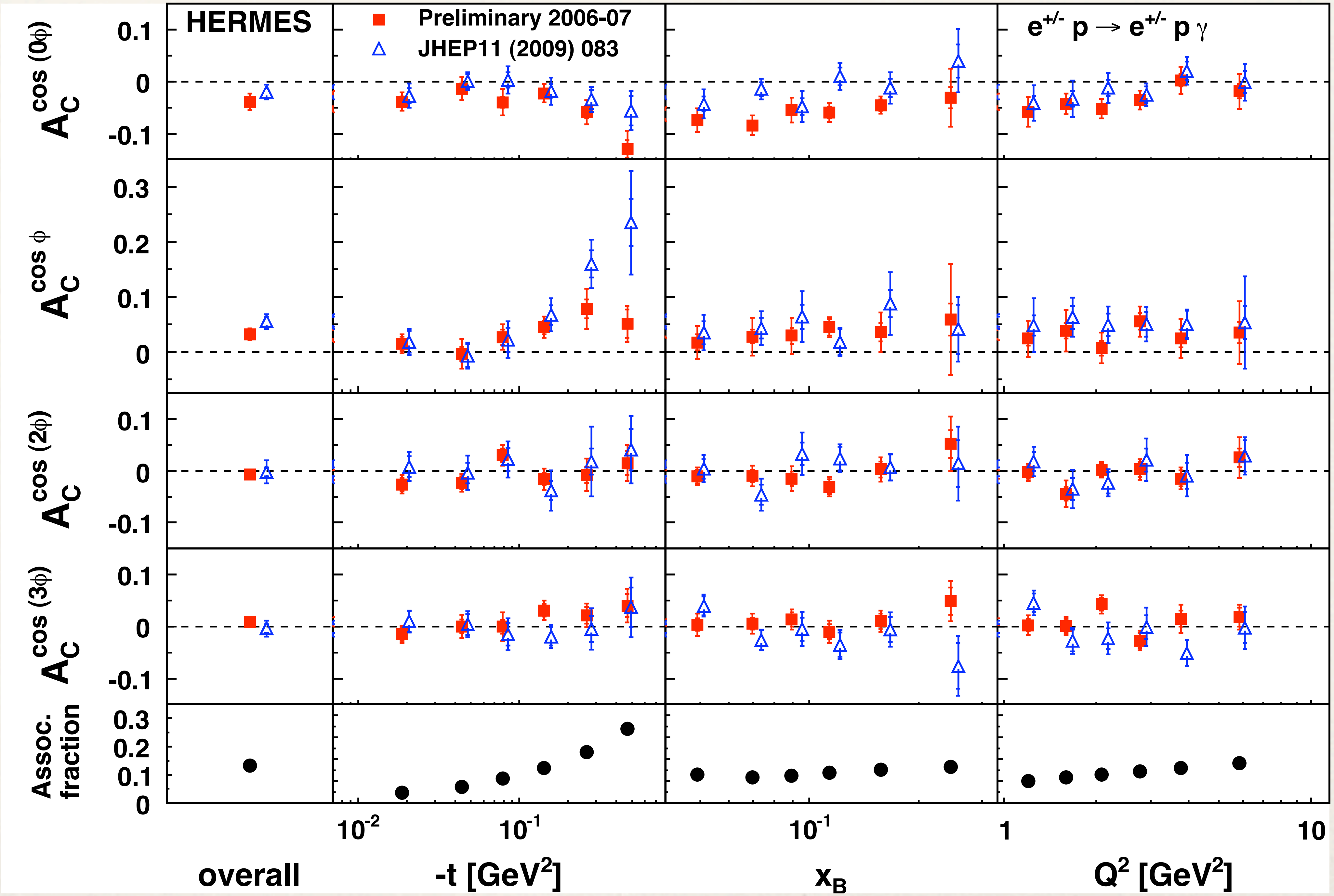
Fraction of resonant excitation



HERMES
$\mathcal{A}_C$ amplitudes: new data

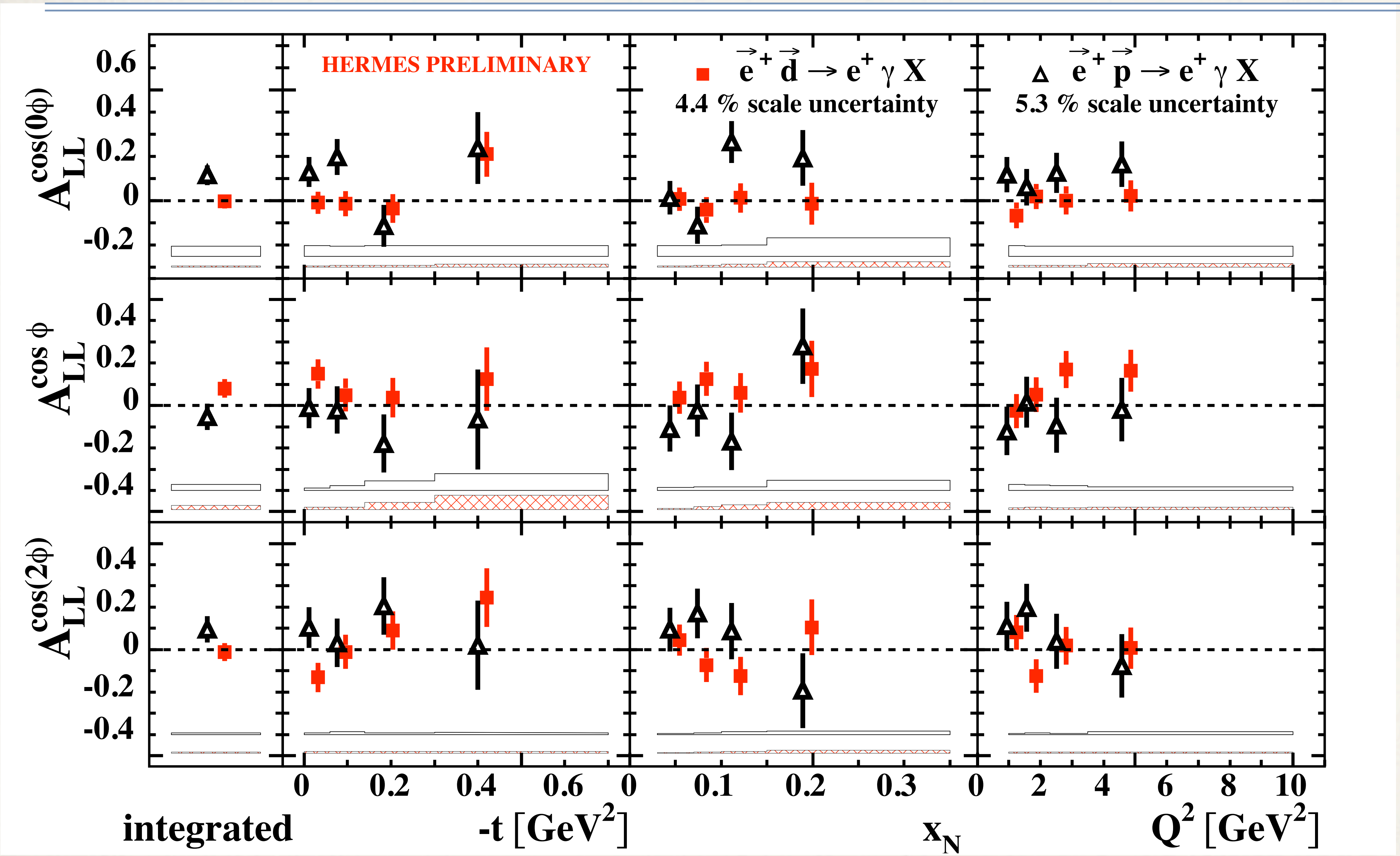
Huge 2006/2007 data set, **preliminary results**

hydrogen target: 1700 pb^{-1}

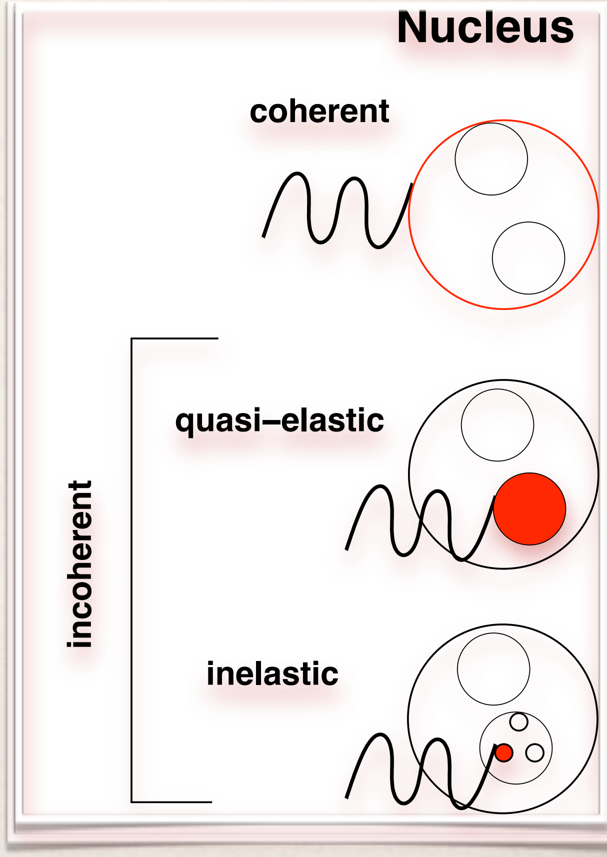


HERMES $\mathcal{A}_{LL}$ on hydrogen & deuterium

To be published in summer 2010

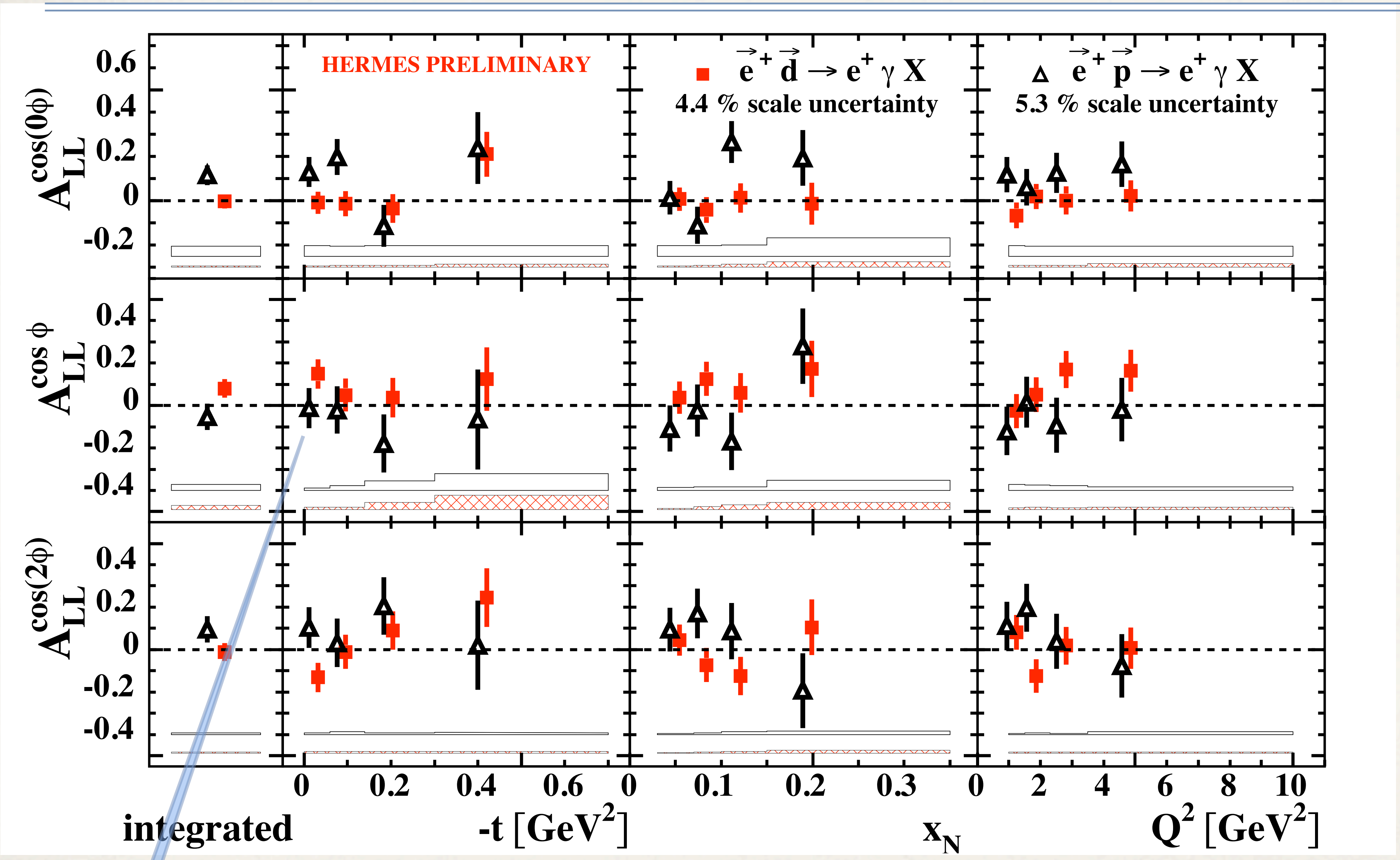


Coherent signature

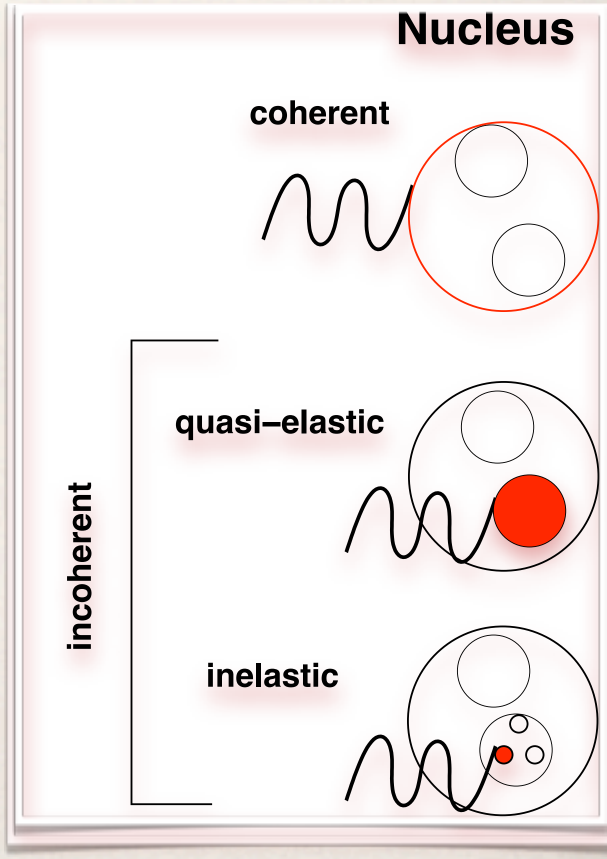


HERMES $\mathcal{A}_{LL}$ on hydrogen & deuterium

To be published in summer 2010



Coherent signature

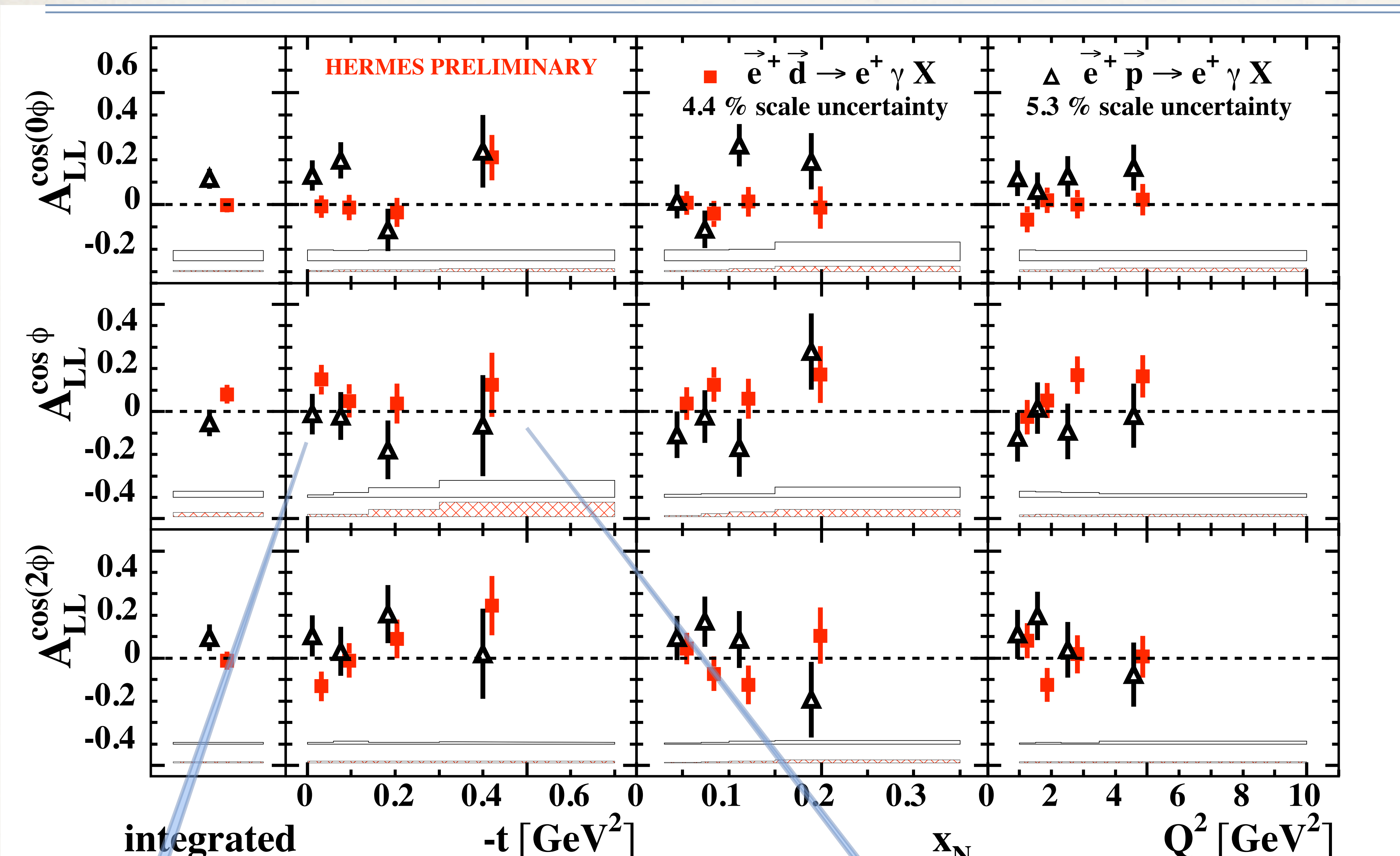


low t: coherent

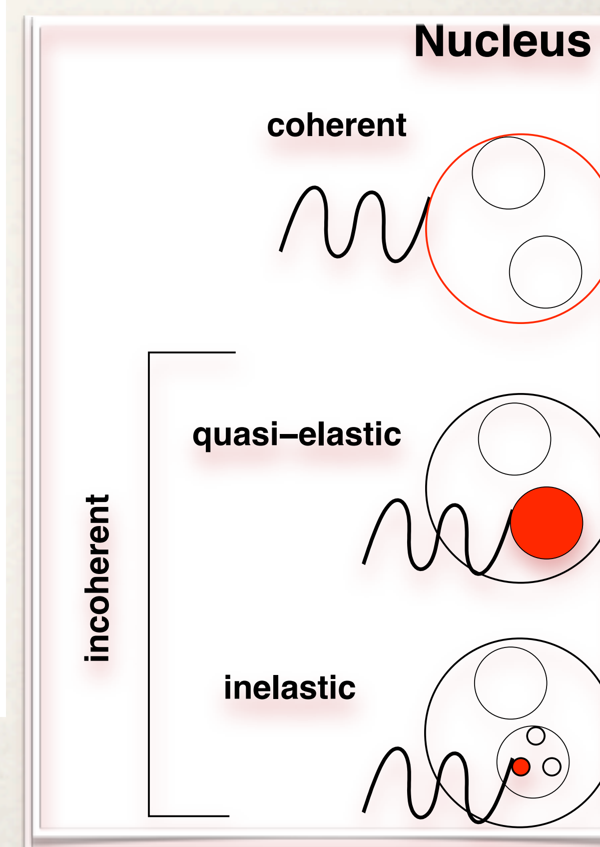
deuteron = spin-1 object, need 9 GPDs; $\widetilde{H}_1$

HERMES $\mathcal{A}_{LL}$ on hydrogen & deuterium

To be published in summer 2010



Coherent signature



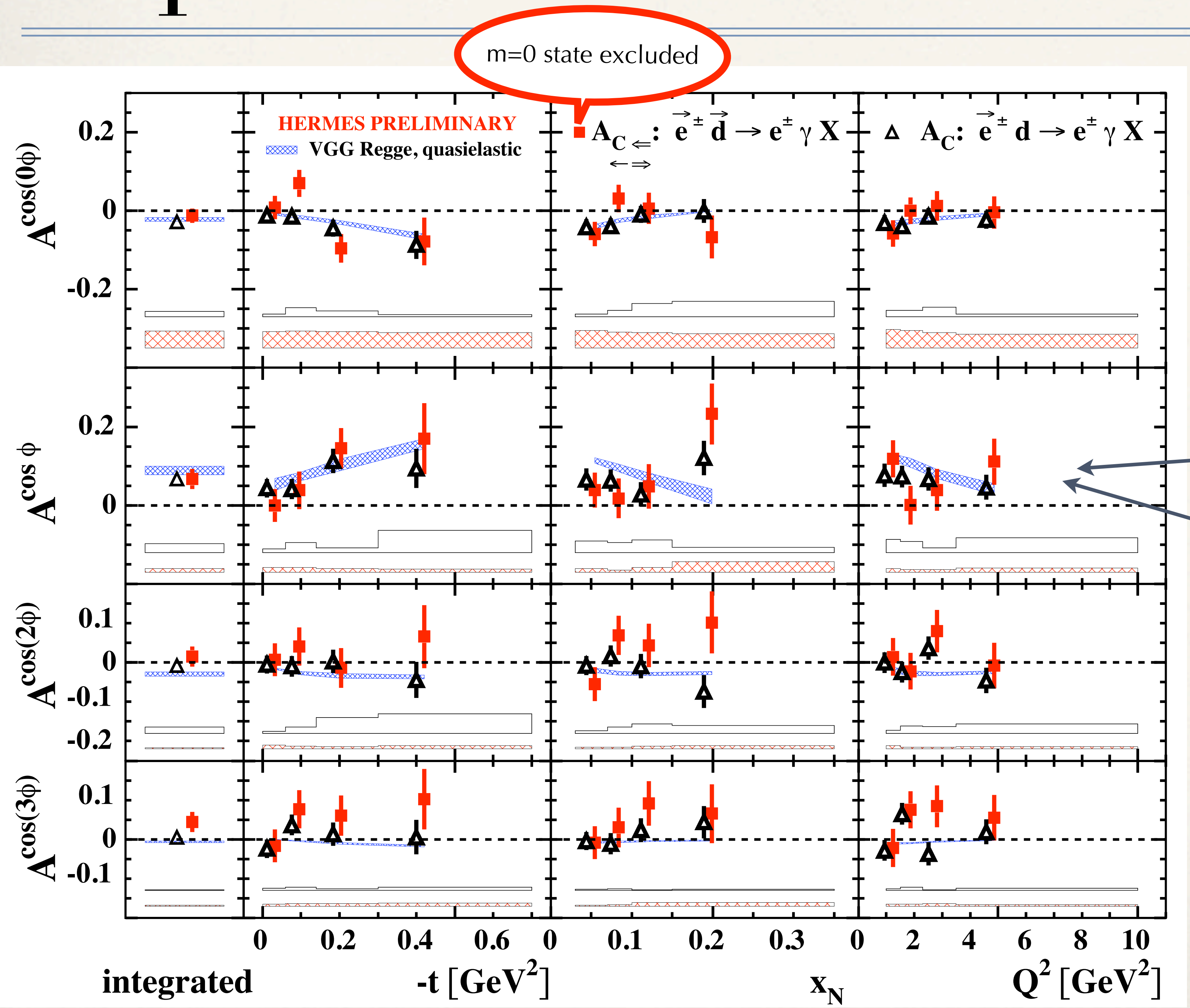
low t: coherent

deuteron = spin-1 object, need 9 GPDs; $\tilde{H}_1$

high t: incoherent

scatter off nucleon = spin1/2 object

HERMES $\mathcal{A}_C$ on polarized / unpolarized deuterium



spin 1 ☞ 3 spin projections m=-1,0,+1

Tensor signature

△ $\mathcal{R}e\ \mathcal{H}_1$

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

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

DVCS $\mathcal{A}_{LZZ}$ sinϕ amplitude:

0.074 ± 0.196 ± 0.022

(-t<0.06 GeV², 40% coherent)

HERMES preliminary

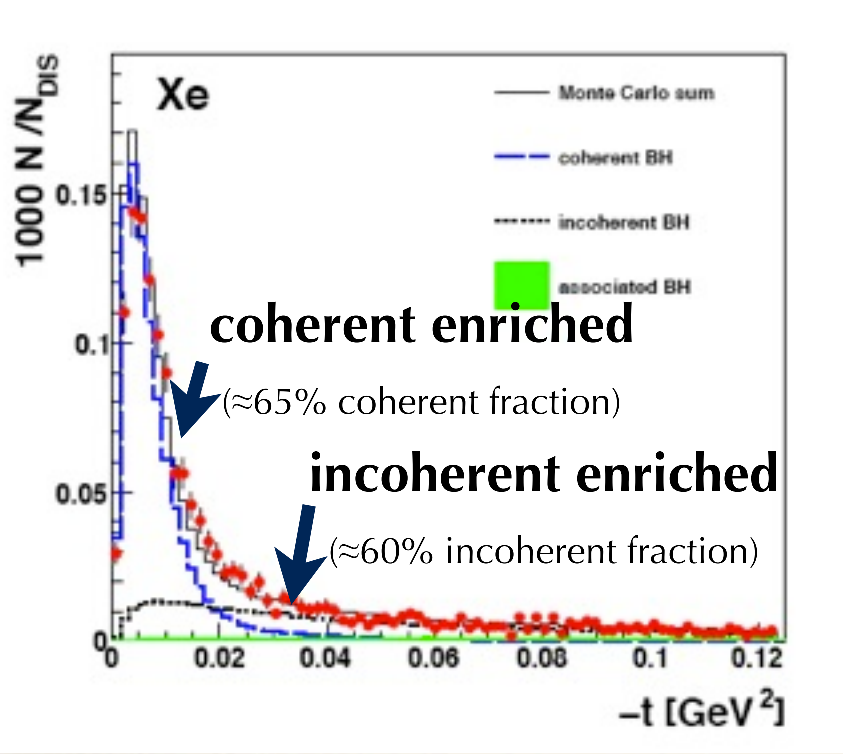
DVCS Nuclear Mass Dependence

HERMES arXiv:0911.0091,
Phys. Rev. C 81 (2010) 035202

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

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

DVCS Nuclear Mass Dependence



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

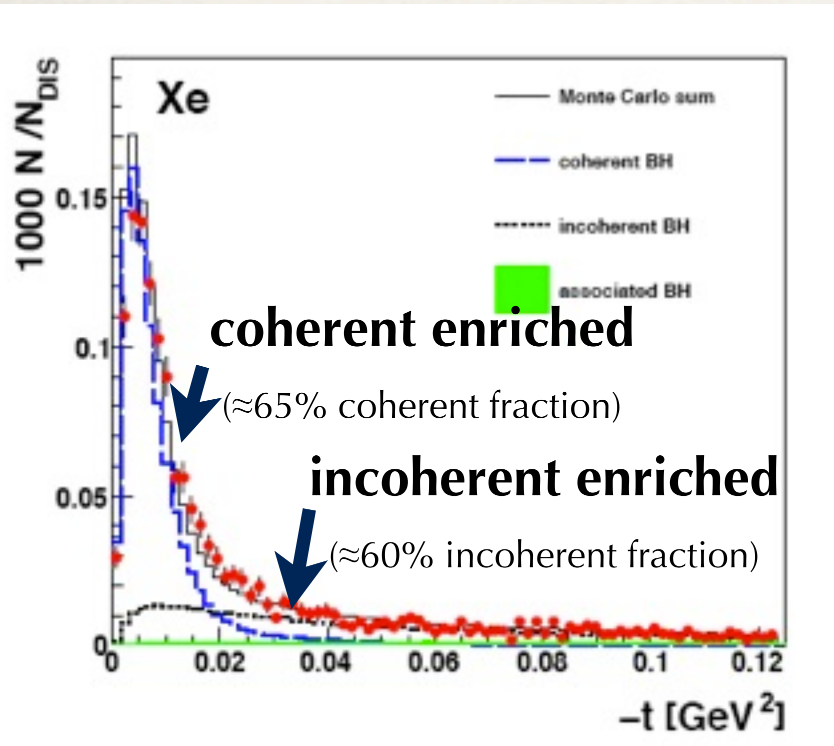
coherent / incoherent sample separation by t-cutoff

HERMES arXiv:0911.0091, Phys. Rev. C 81 (2010) 035202

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

DVCS Nuclear Mass Dependence

HERMES arXiv:0911.0091,
Phys. Rev. C 81 (2010) 035202



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

coherent / incoherent sample separation by t-cutoff

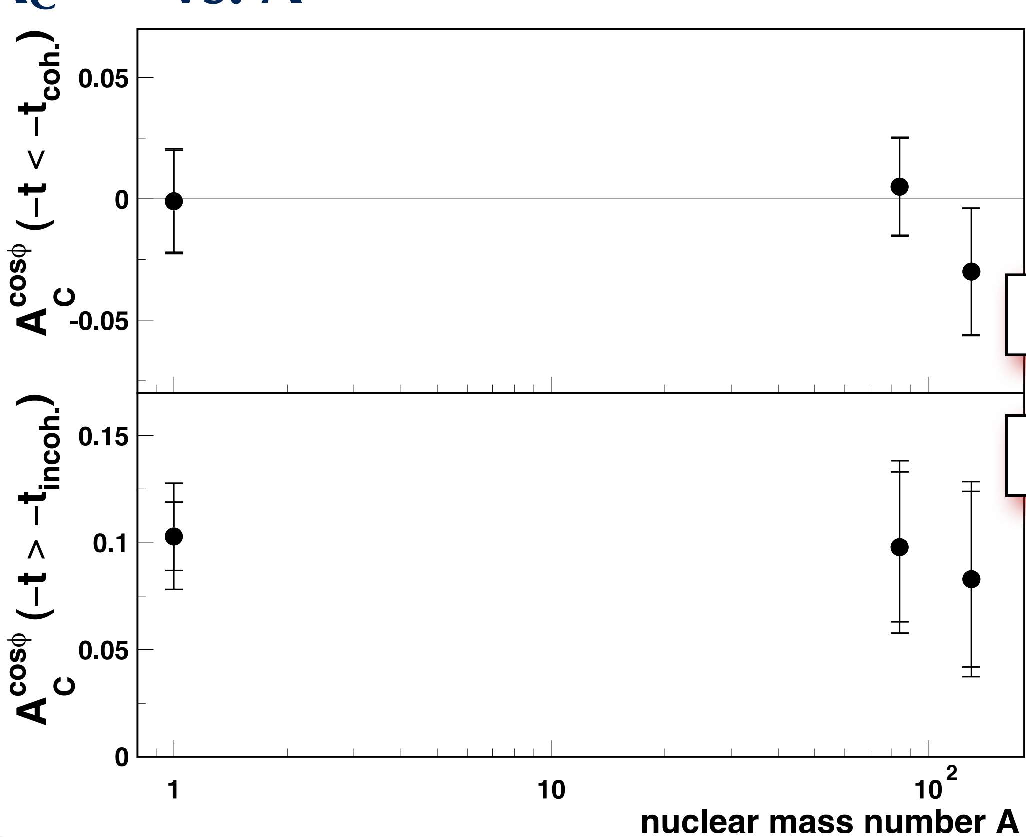
- How does the nuclear medium modify parton-parton correlations?
- How do nucleon properties change in the nuclear medium?
- Enhanced 'generalized EMC effect', rise of τ_{DVCS} with A?

Average $\mathcal{A}_{LU}^{A}$ / $\mathcal{A}_{LU}^{H}$:

coherent enriched: 0.91±0.19

incoherent enriched: 0.93±0.23

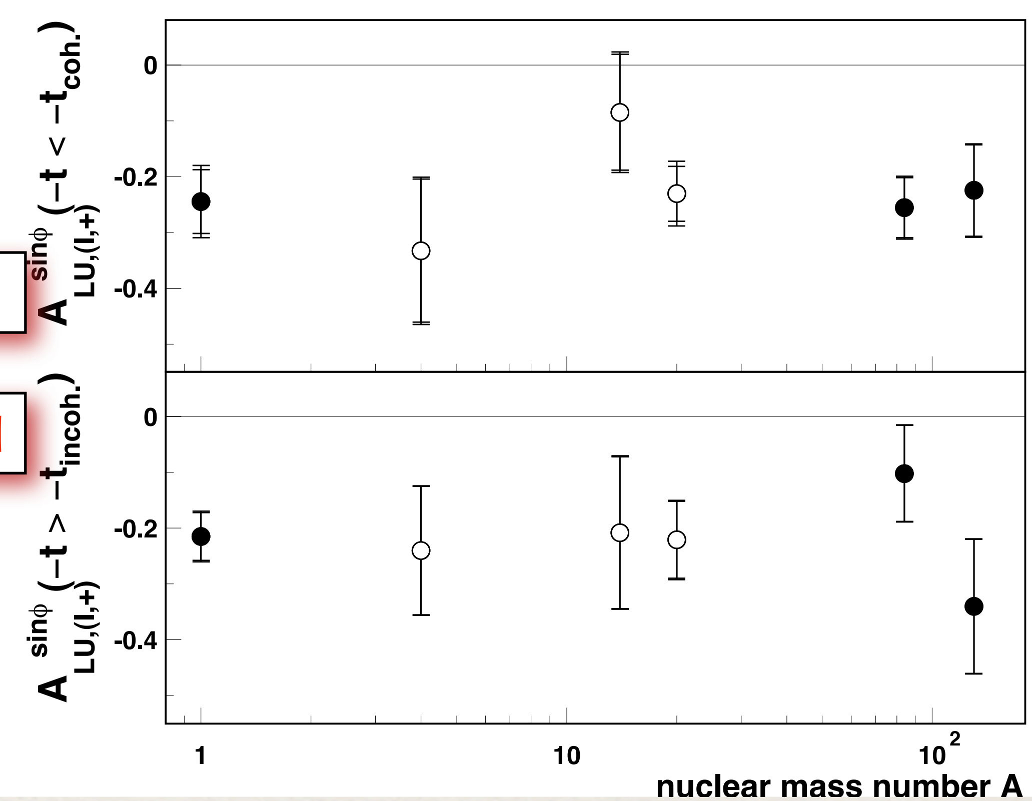
$A_C^{\cos\phi}$ vs. A



coherent enriched

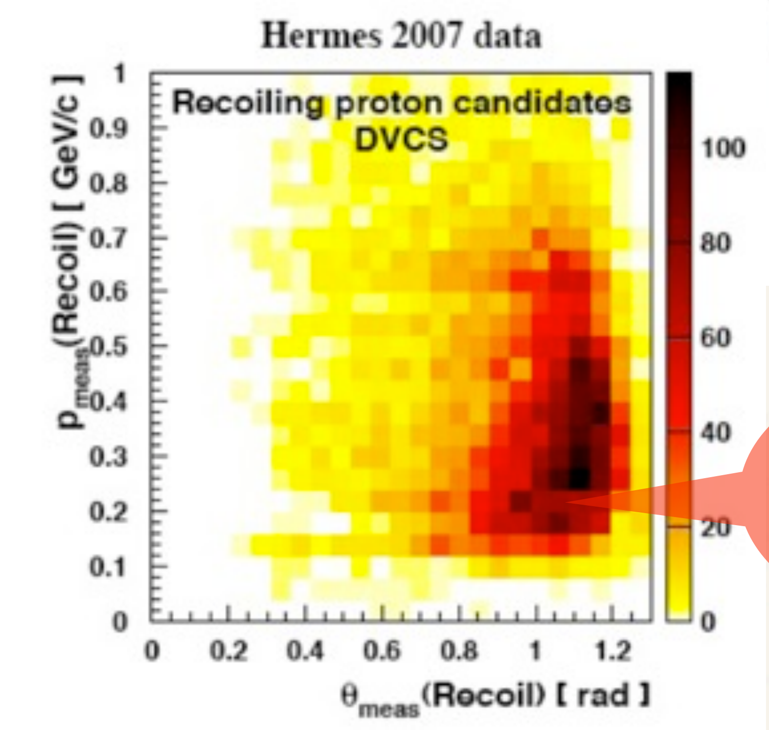
incoherent enriched

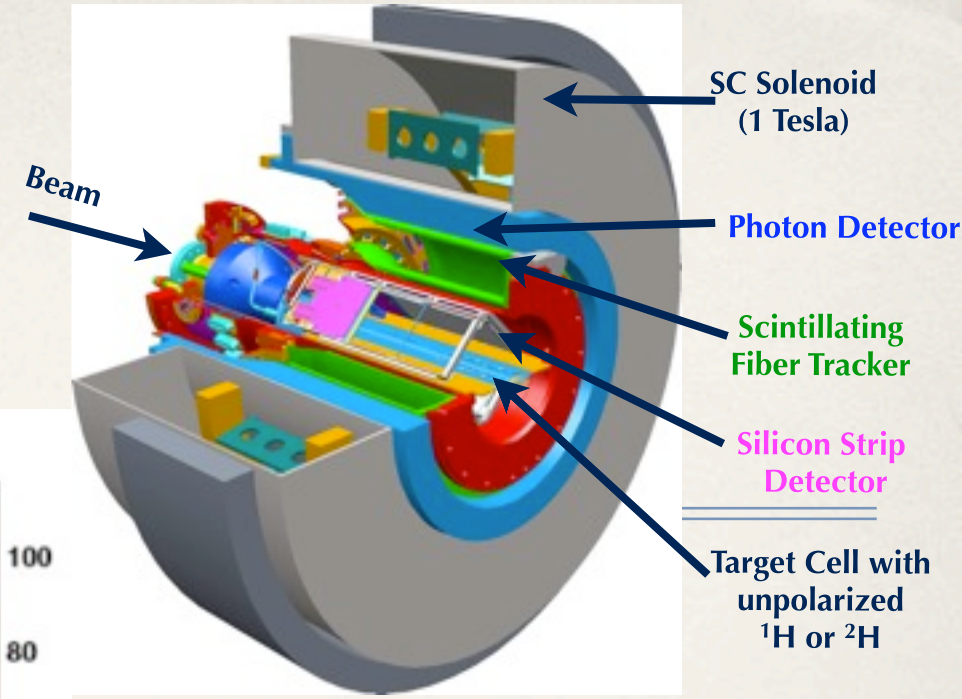
$A_{LU}^{\sin\phi}$ vs. A



HERMES Recoil Detector 2006/2007

- Purpose: to **tag exclusive events**

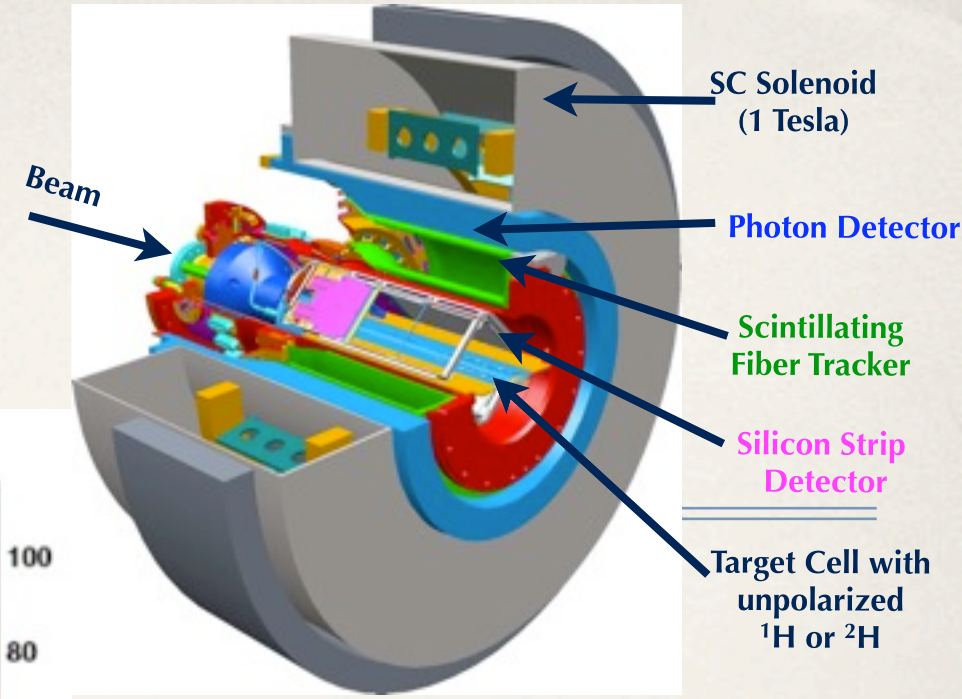




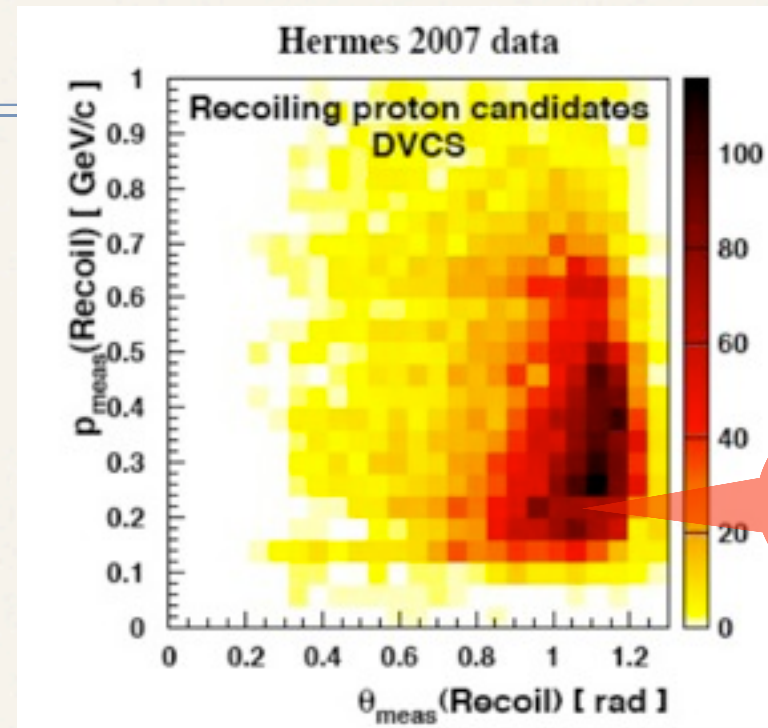
Azimuthal coverage: 76%

HERMES Recoil Detector 2006/2007

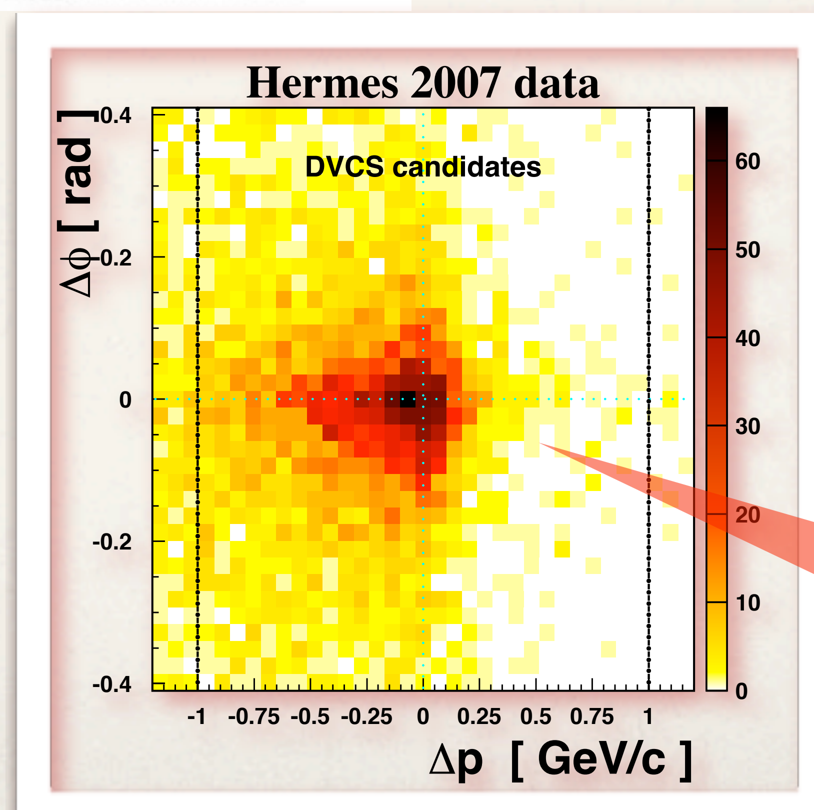
- Purpose: to **tag exclusive events**



Azimuthal coverage: 76%

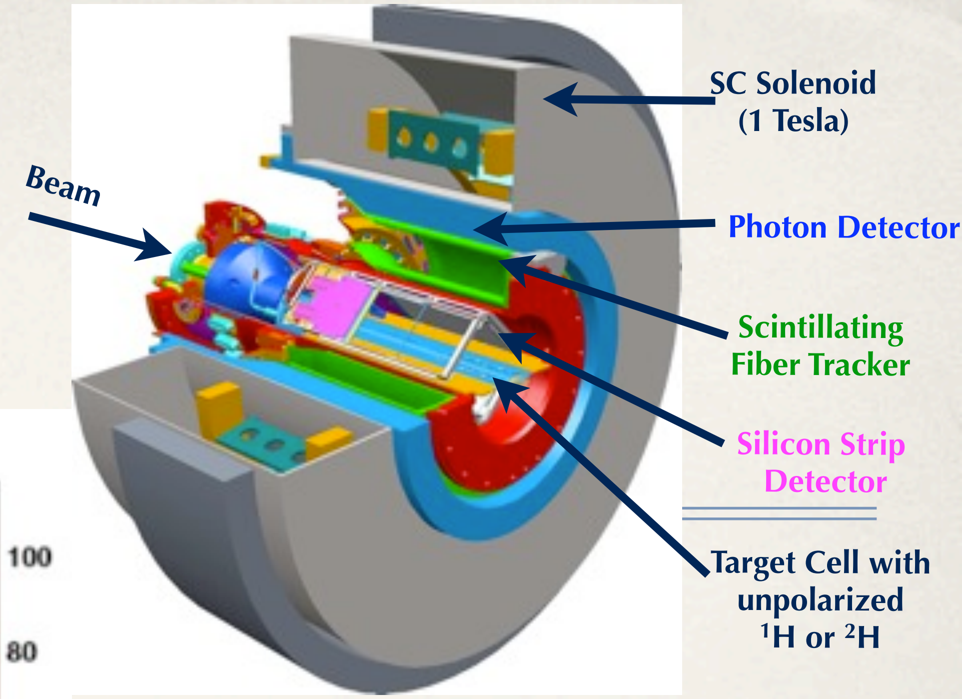


small momenta, large polar angles



missing azimuthal angle vs. missing momentum

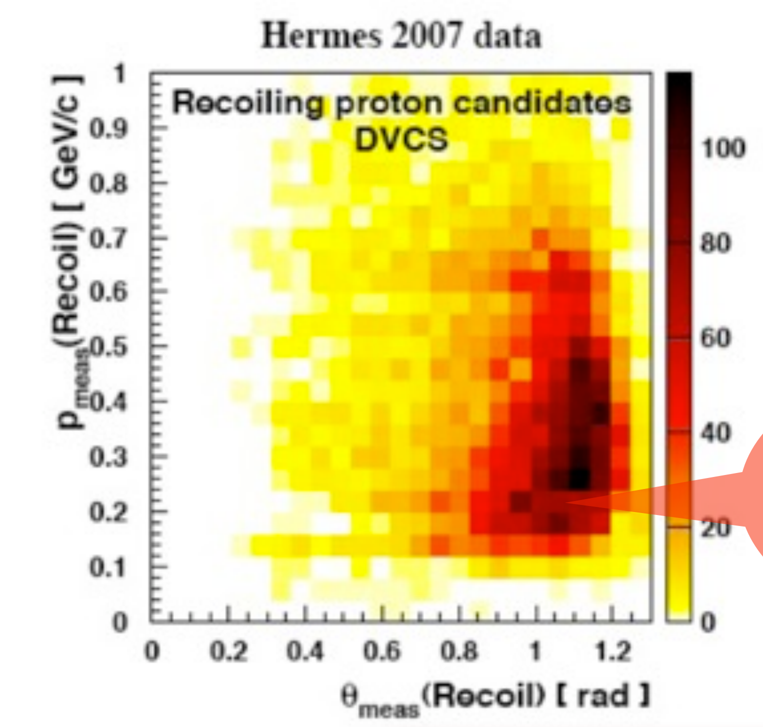
HERMES Recoil Detector 2006/2007



Azimuthal coverage: 76%

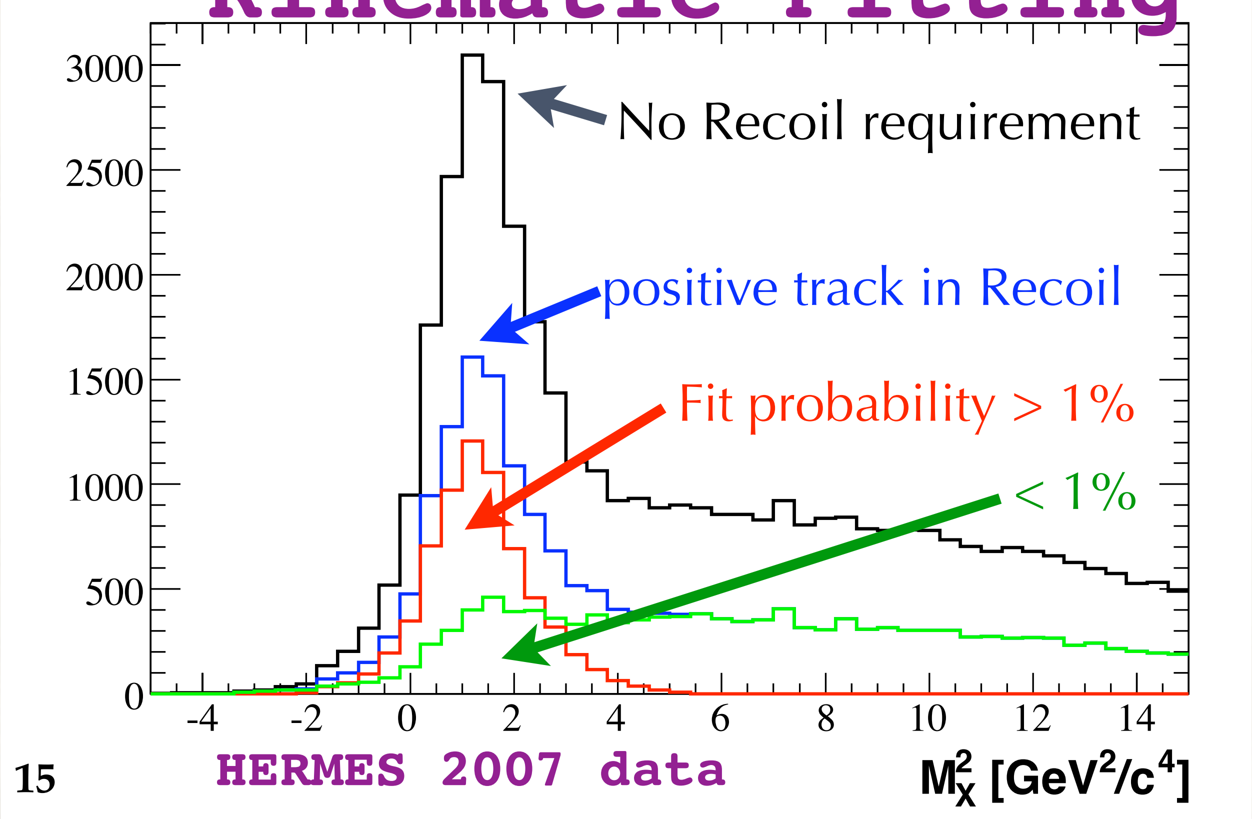
- Purpose: to **tag exclusive events**

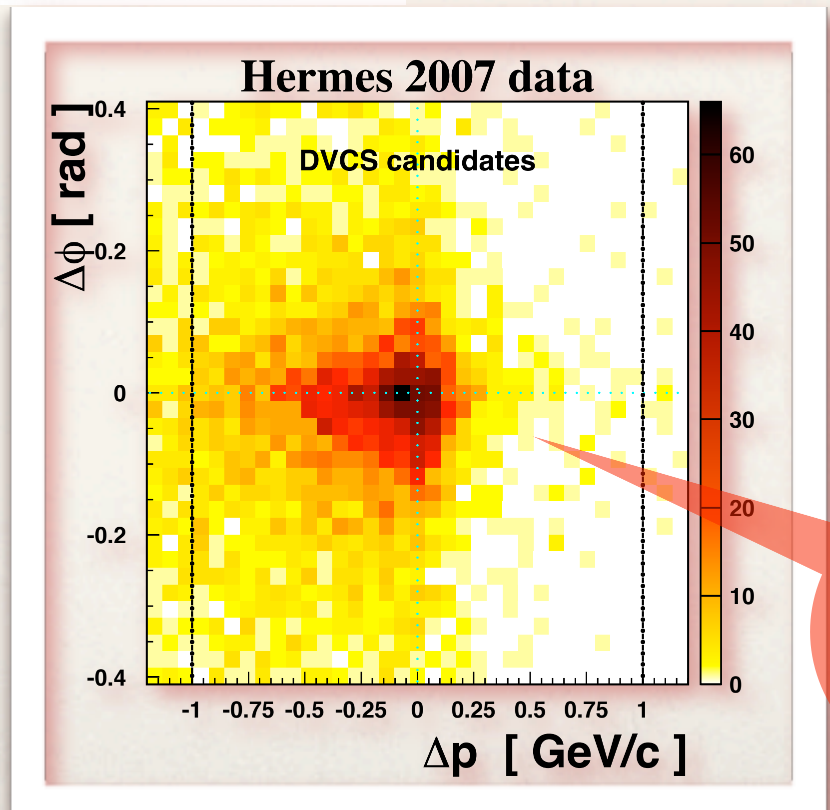
- Measure elastic asymmetry, try to separate resonant asymmetry ($\Delta^+ \rightarrow p\pi^0$)



small momenta, large polar angles

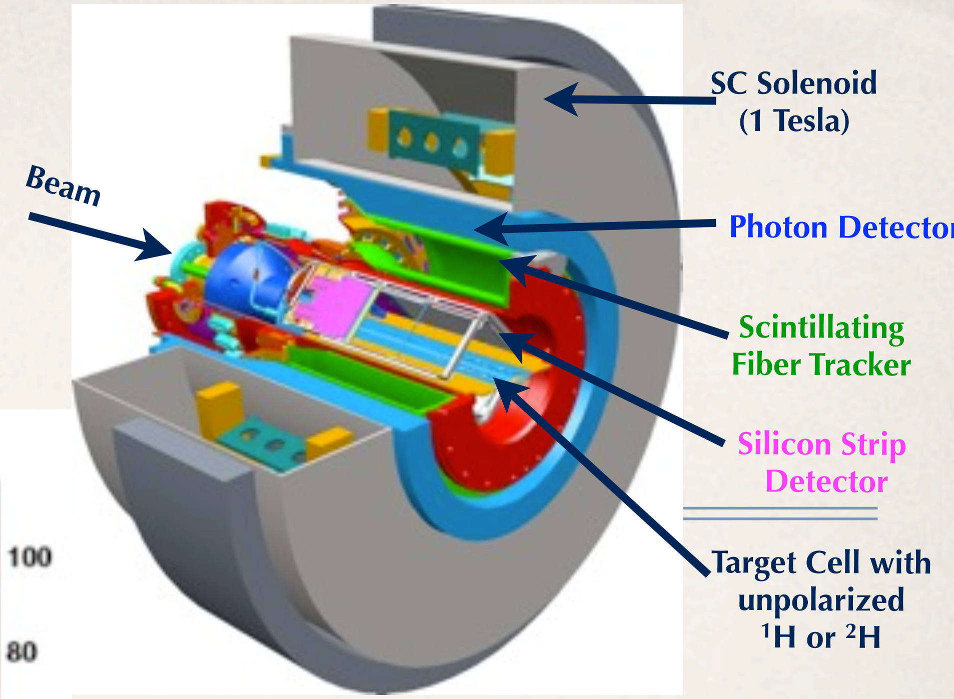
Kinematic Fitting





missing azimuthal angle vs. missing momentum

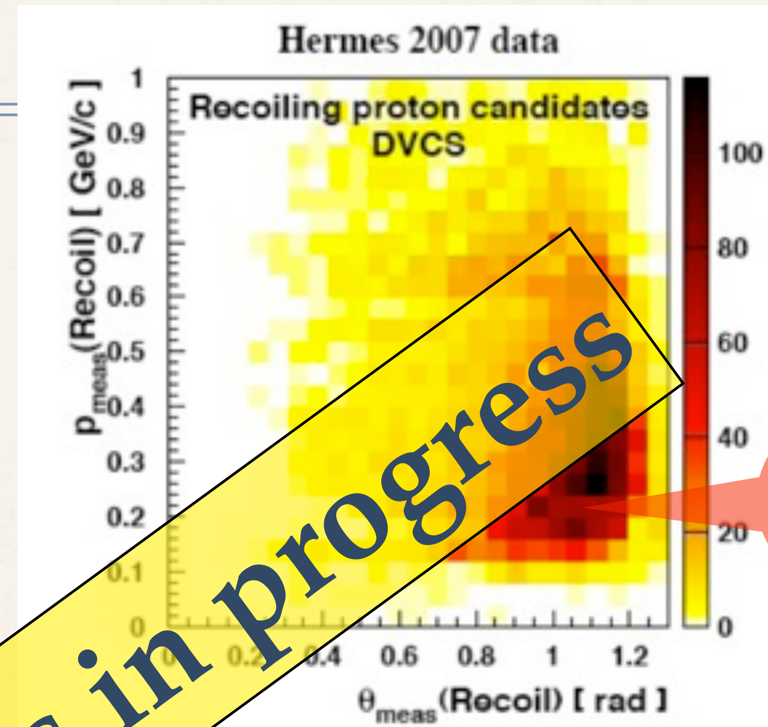
HERMES Recoil Detector 2006/2007



Azimuthal coverage: 76%

- Purpose: to **tag exclusive events**

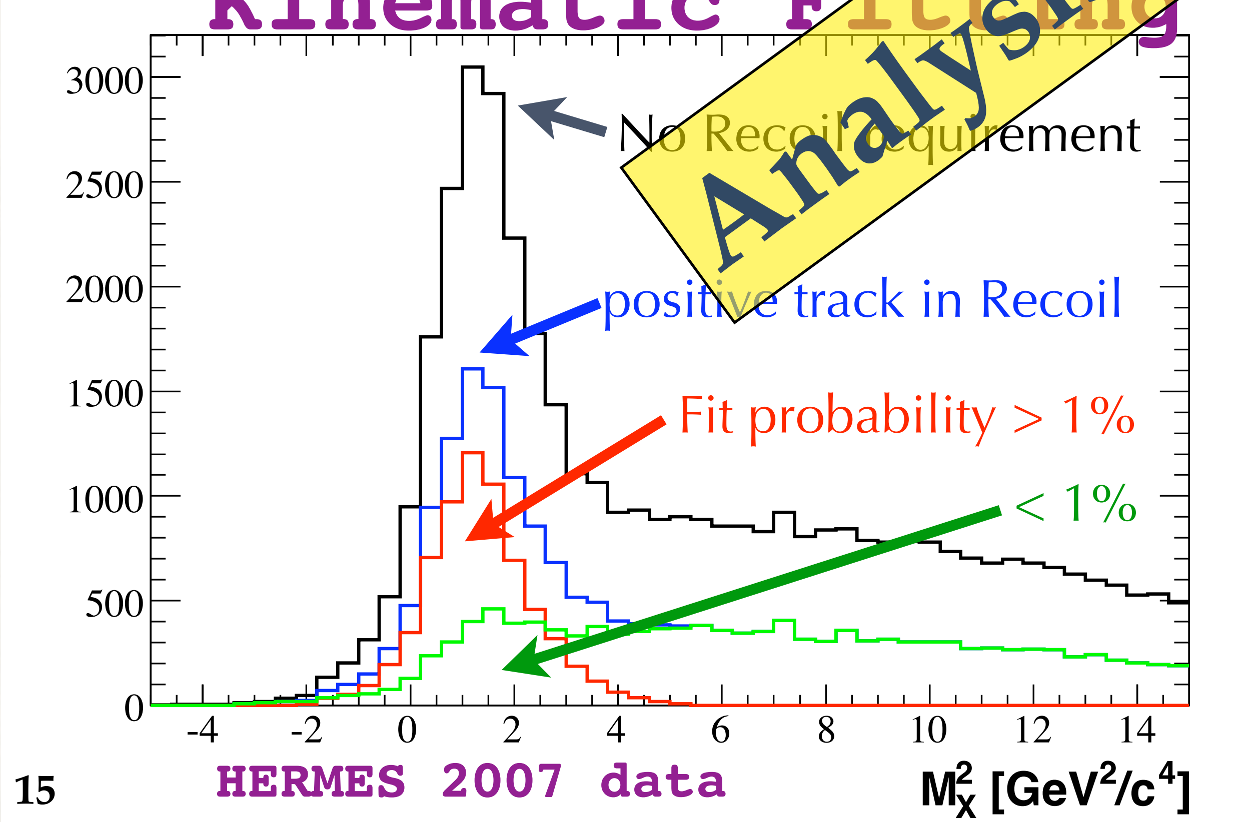
- Measure elastic asymmetry, try to separate resonant asymmetry ($\Delta^+ \rightarrow p\pi^0$)

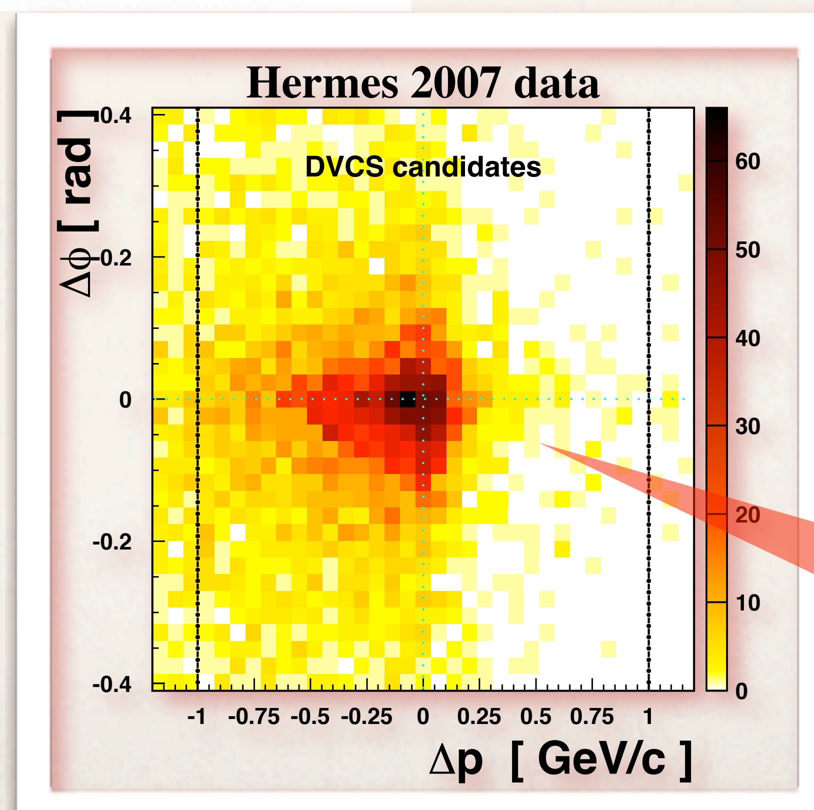


small momenta, large polar angles

Analysis in progress

Kinematic Fitting



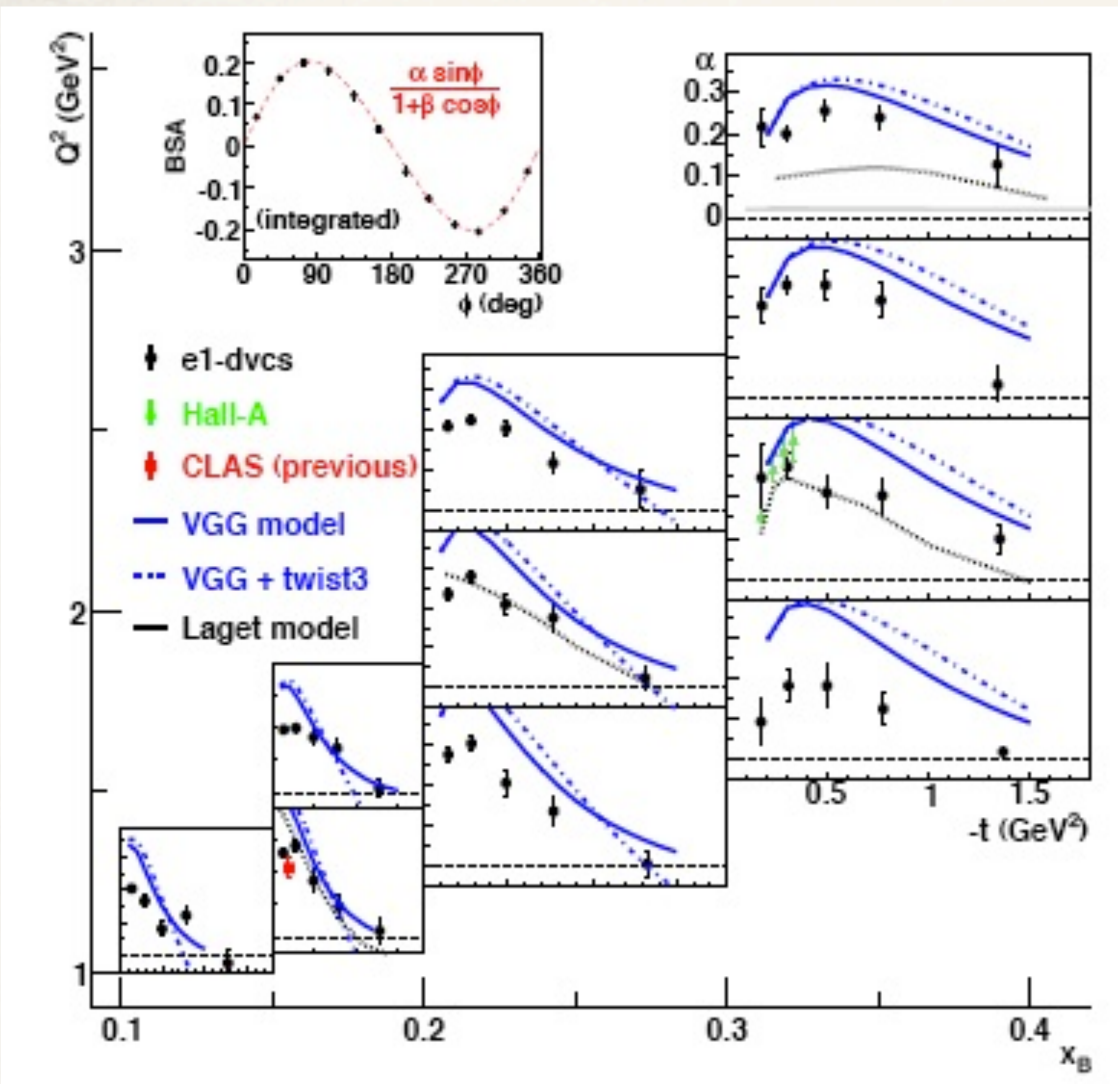


missing azimuthal angle vs. missing momentum

CLAS latest measurements

More details: see talk by Francois-Xavier Girod (5A)

Beam-spin asymmetry 2008



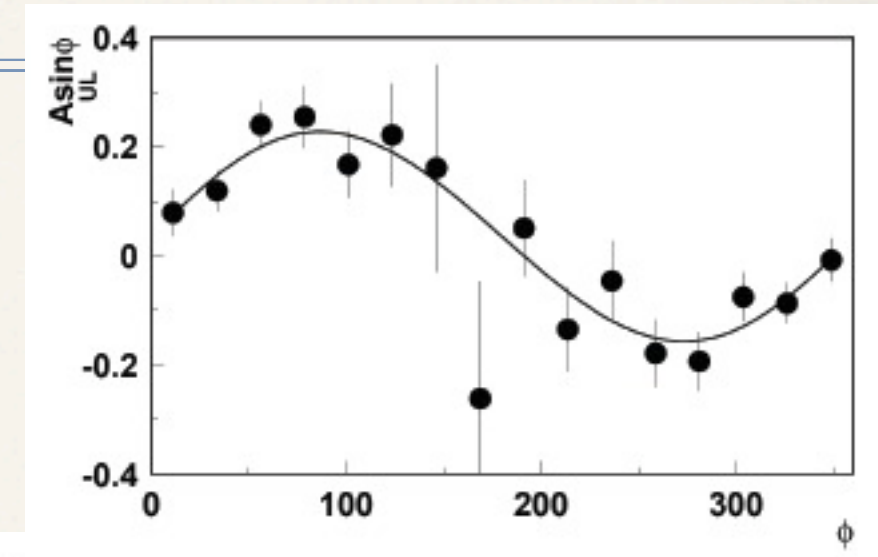
F.-X. G. *et al.*, PRL **100** (2008) 162002

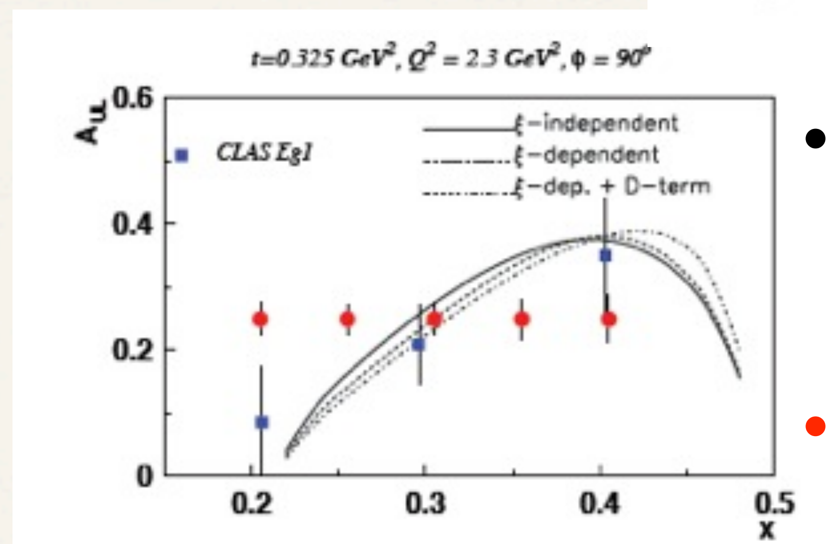
CLAS: $\langle Q^2 \rangle = 1.82$ GeV², $\langle x_B \rangle = 0.28$, $\langle -t \rangle = 0.31$ GeV²

See talk by Tanja Horn (5A)

Longitudinal target-spin asymmetry

20% of stat shown





- Dedicated run 2009 with inner calo for target- and double-spin asymmetry
- Results to be released

- Cross-section measurement: $\mathcal{R}e(\mathcal{T}_{DVCS})$
- Time-like Compton Scattering (double DVCS)

Access to the total angular momentum of quarks

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

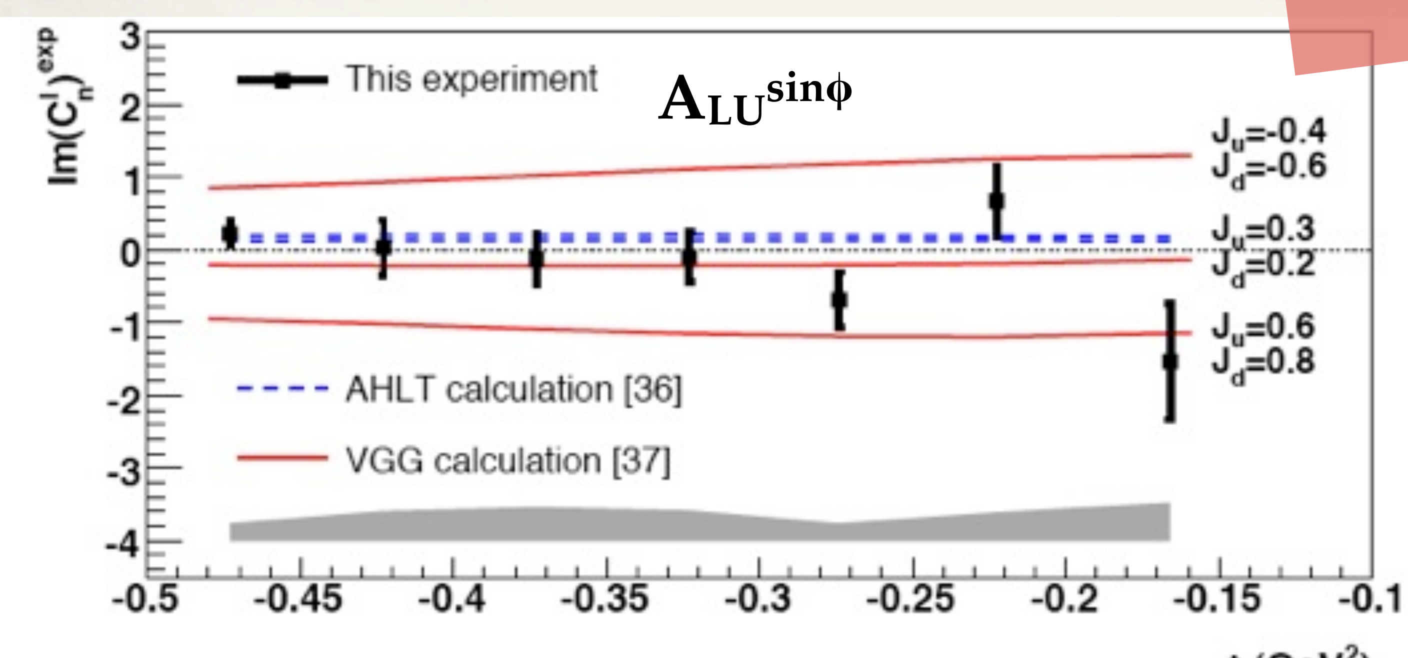
(A) HERMES: $\mathbf{ep^{\uparrow} \to ep\gamma}$

(B) Hall A: $\mathbf{\vec{e}^- n \to e^- n \, \gamma}$

dominant for the neutron

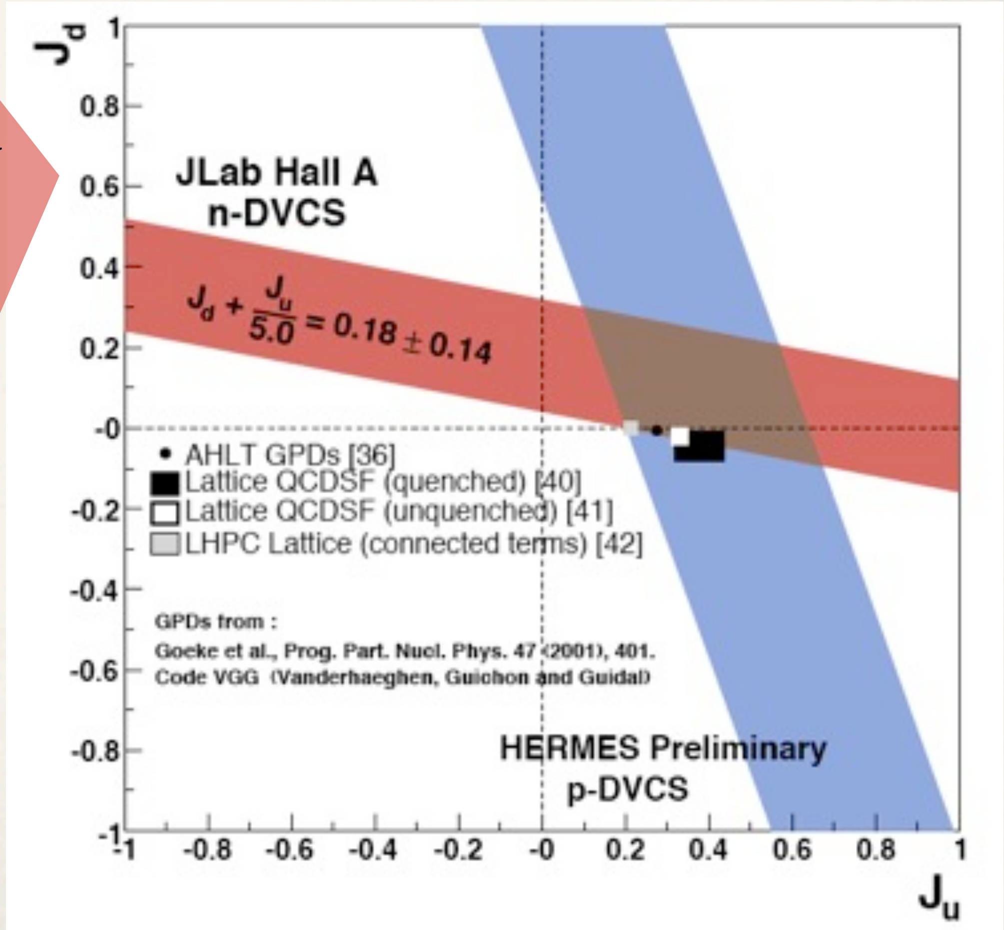
$$\mathcal{C}^{\mathcal{I}}_{\text{unp}} = F_1 \mathcal{H} + \xi (F_1 + F_2) \widetilde{H} - \frac{t}{4M^2} F_2 \mathcal{E}$$

- Hall A, deuteron target (E03-106)
- Quasi-elastic proton contribution subtracted from deuteron signal
- Beam-helicity asymmetry:



Hall-A arXiv:0709.0450

from sensitivity to J_q:



Access to the total angular momentum of quarks

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

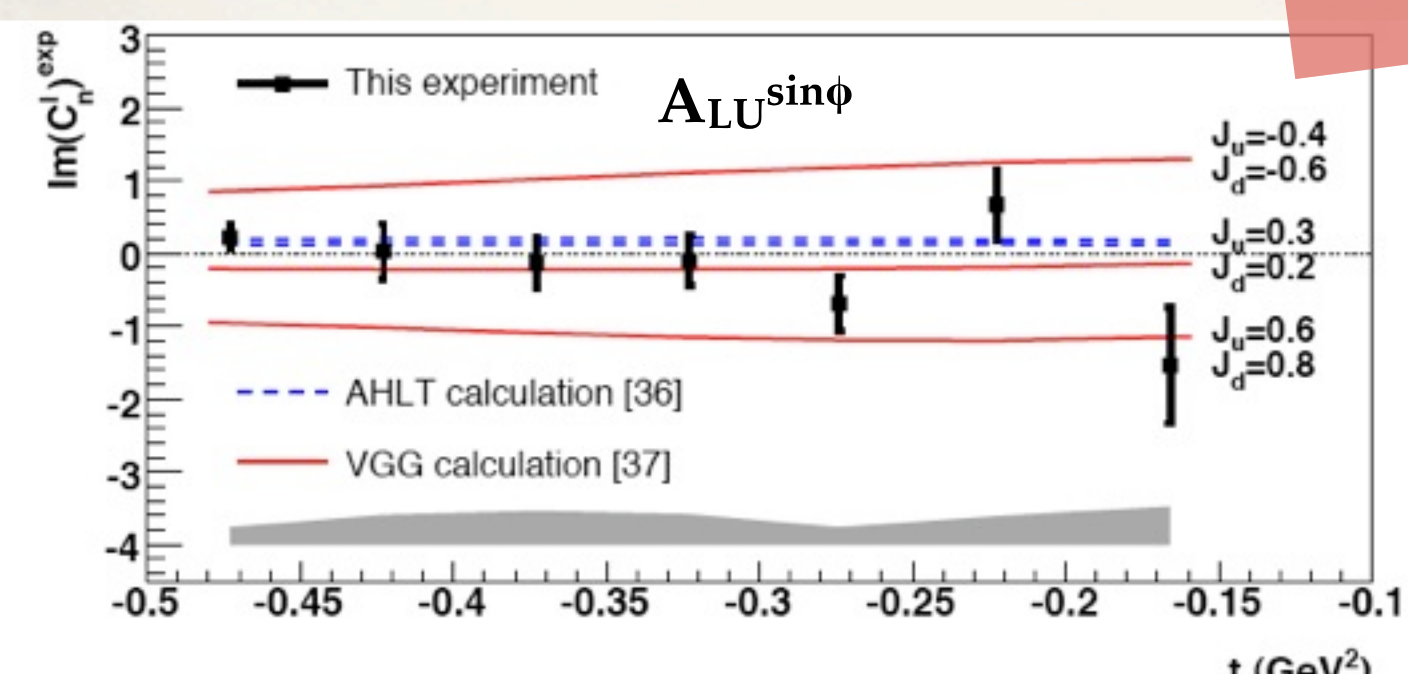
(A) HERMES: $ep^{\uparrow} \to ep\gamma$

(B) Hall A: $\vec{e}^- n \to e^- n\, \gamma$

dominant for the neutron

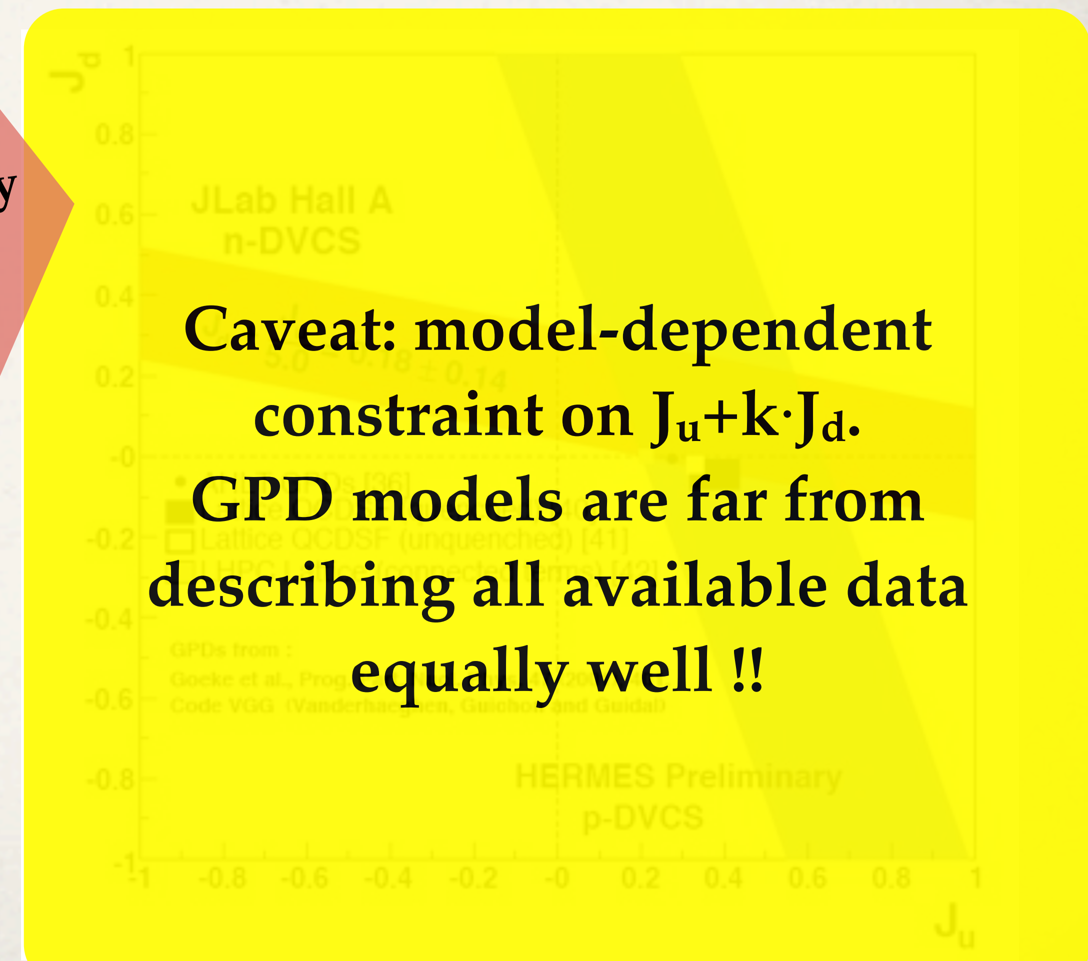
$$\mathcal{C}^{\mathcal{I}}_{\text{unp}} = F_1 \mathcal{H} + \xi (F_1 + F_2) \widetilde{H} - \frac{t}{4M^2} F_2 \mathcal{E}$$

- Hall A, deuteron target (E03-106)
- Quasi-elastic proton contribution subtracted from deuteron signal
- Beam-helicity asymmetry:



Hall-A arXiv:0709.0450

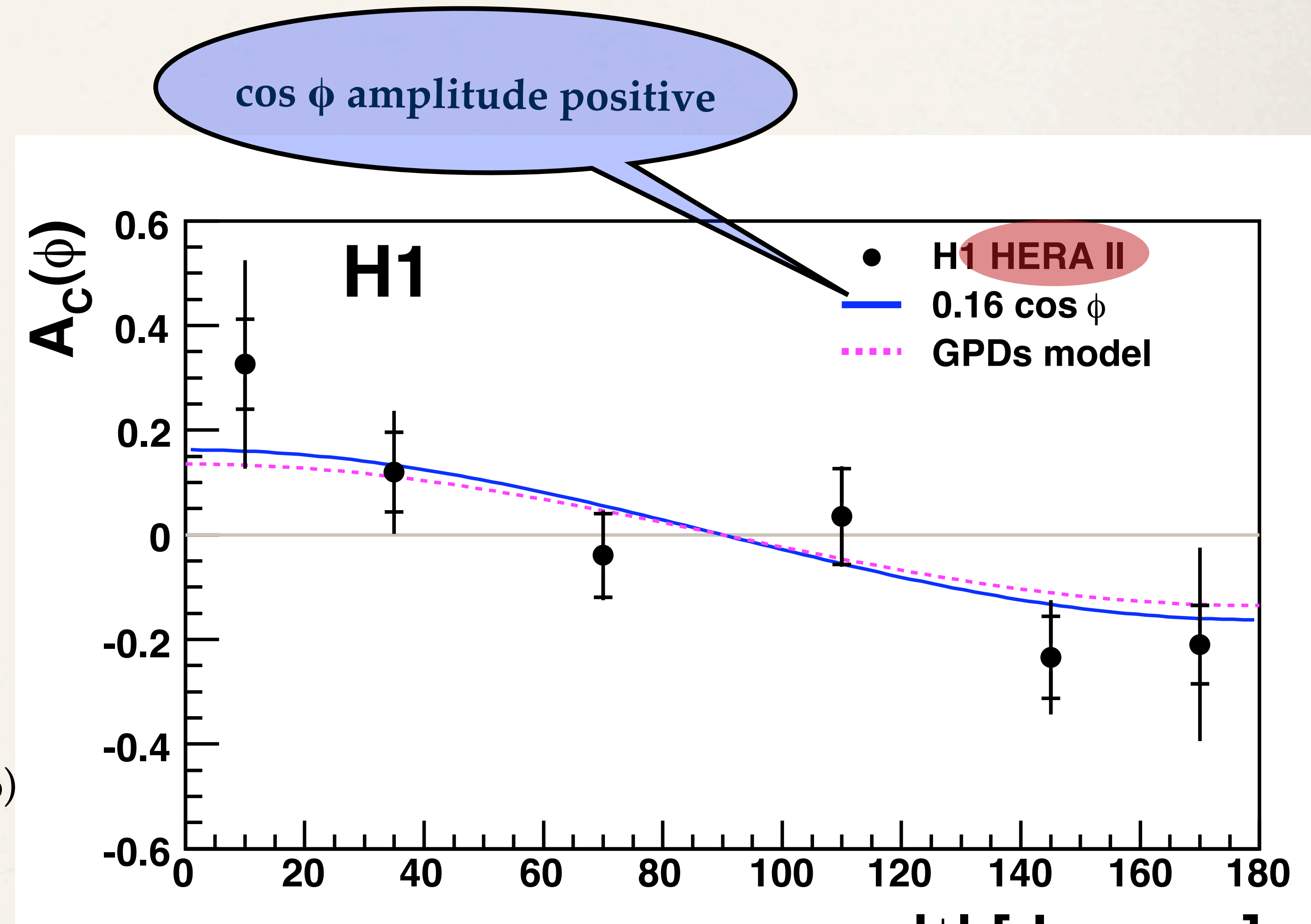
from sensitivity to J_q:



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

HERA / H1: Beam Charge Asymmetry

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



Phys.Lett.B681 (2009) 391

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

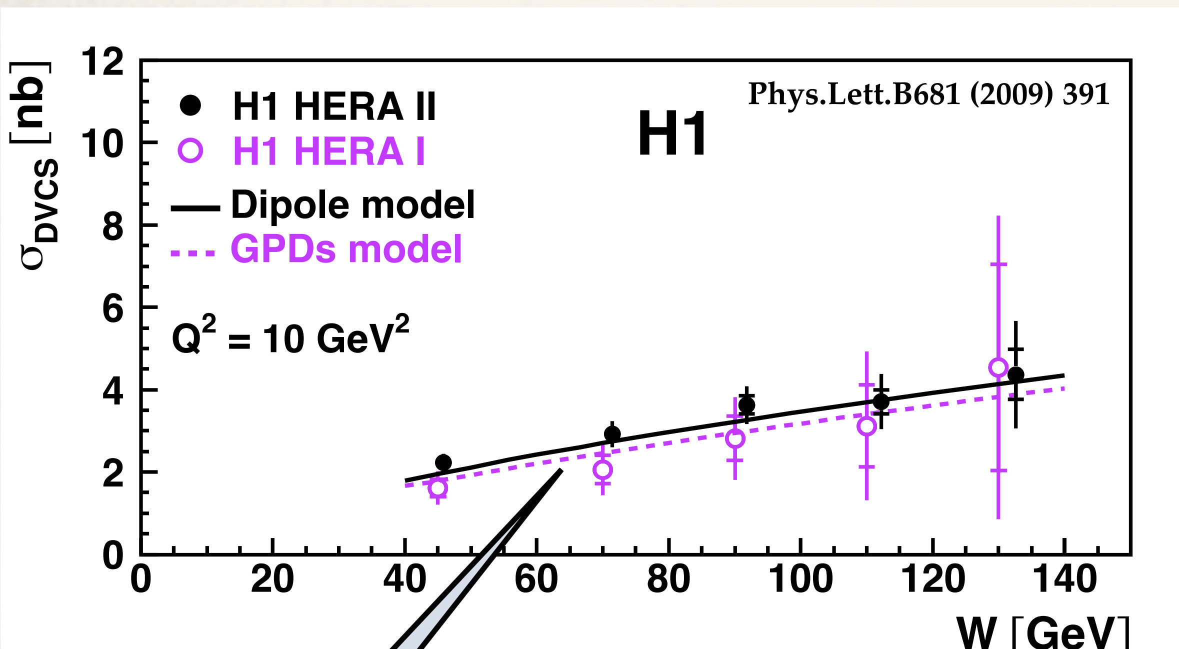
(if same ϕ convention is used as for H1, i.e. non-Trento)

- Ratio ϱ = **Re(τ_{DVCS}) / Im(τ_{DVCS})**
  - $\varrho=0.20 \pm 0.05(\text{stat}) \pm 0.08(\text{sys})$
  - In good agreement with theoretical calculation (dispersion relation)

HERA: cross-section
in the sea/glue region

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

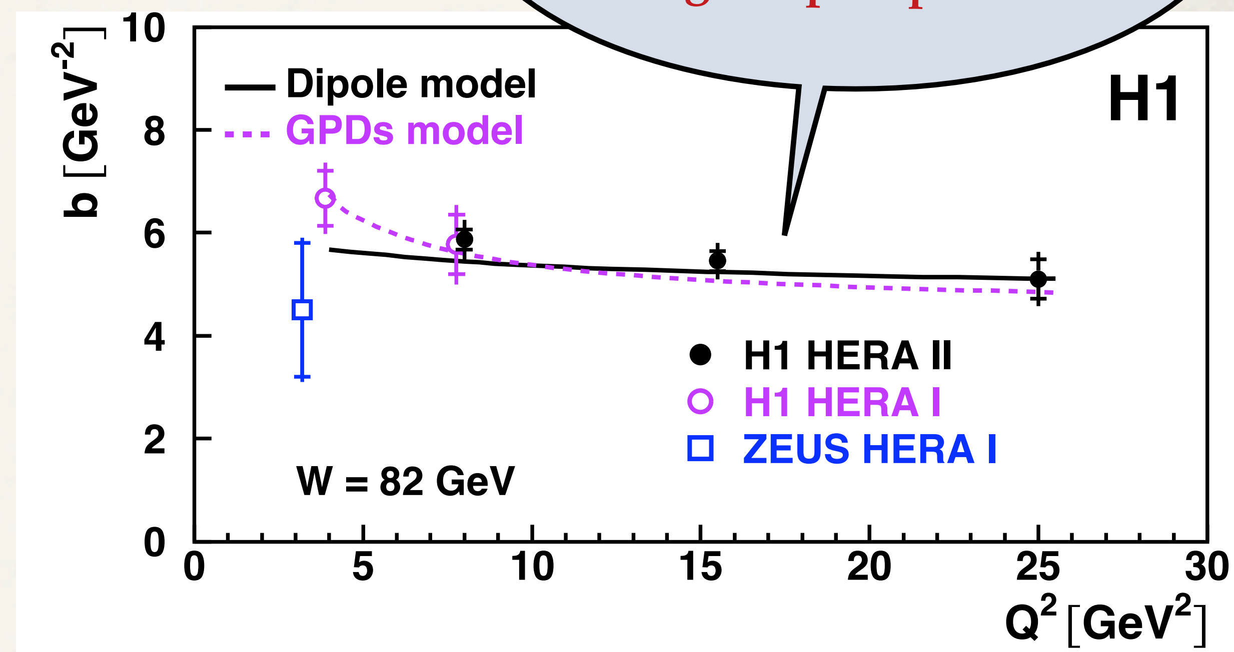
GPD model: K. Kumericki, D. Müller, fit to previous HERA meas.

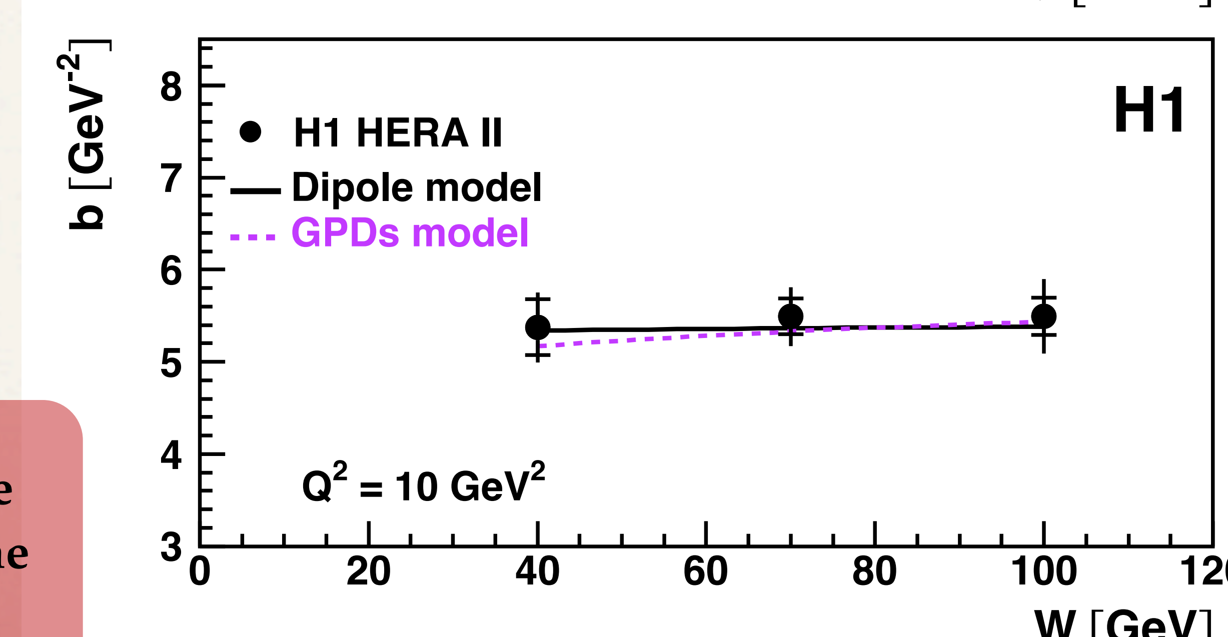


Steep W-dependence: $\sigma(W) \propto W^{\delta}$ with $\delta \approx 0.7$

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

t-slope: average impact parameter



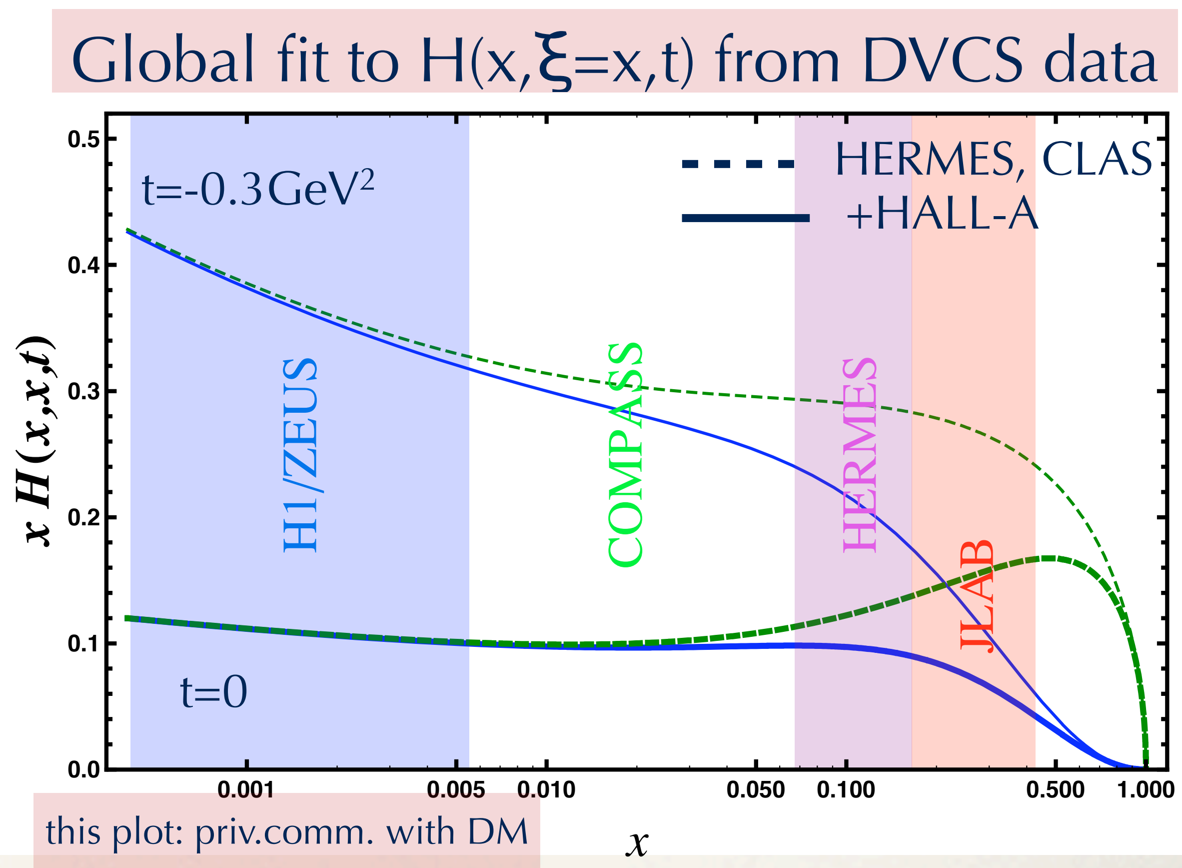


DVCS is hard process, gluons resolved!

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

ZEUS arXiv:0812.2517

Global analysis of DVCS data



- **Kresimir Kumericki & Dieter Müller**
  arXiv:0904.0458 [hep-ph]
  - Global fit to extract GPD H at cross-over line ξ=x
  - **HERMES** A_C, **CLAS** A_{LU} and **Hall A** x-section
  - Small-x behavior from **HERA collider** data

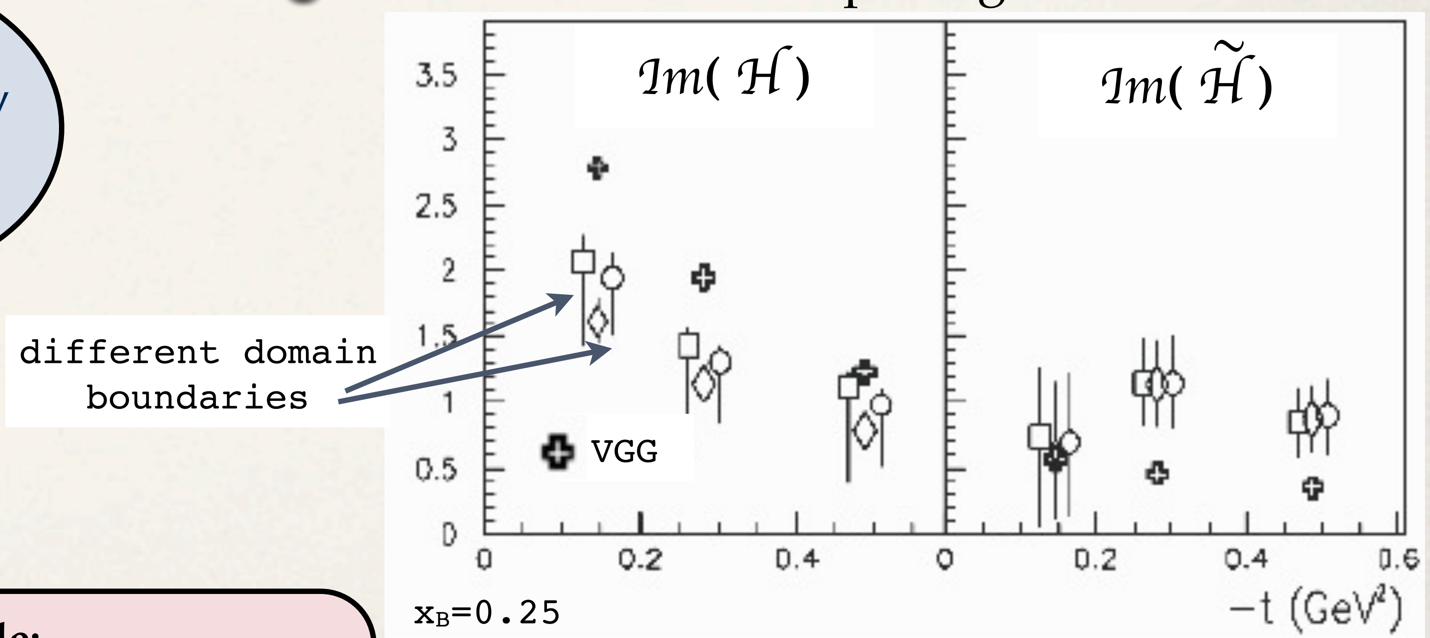
- **Herve Moutarde** PRD 79, 094021 (2009)
  - Global fit to extract *Re*(*H*) & *Im*(*H*)
  - **Hall A** x-section & **CLAS** A_{LU}
  - Small systematic uncertainties.

See next to next talk by Herve Moutarde

- **Michel Guidal & Herve Moutarde**
  EPJ A42, 71-78 (2009)
  - Model independent fit with *Re*(CFF) & *Im*(CFF) as ≈free parameters
  - **HERMES** A_C, A_{LU}, A_{UT} : 17 indep. observables

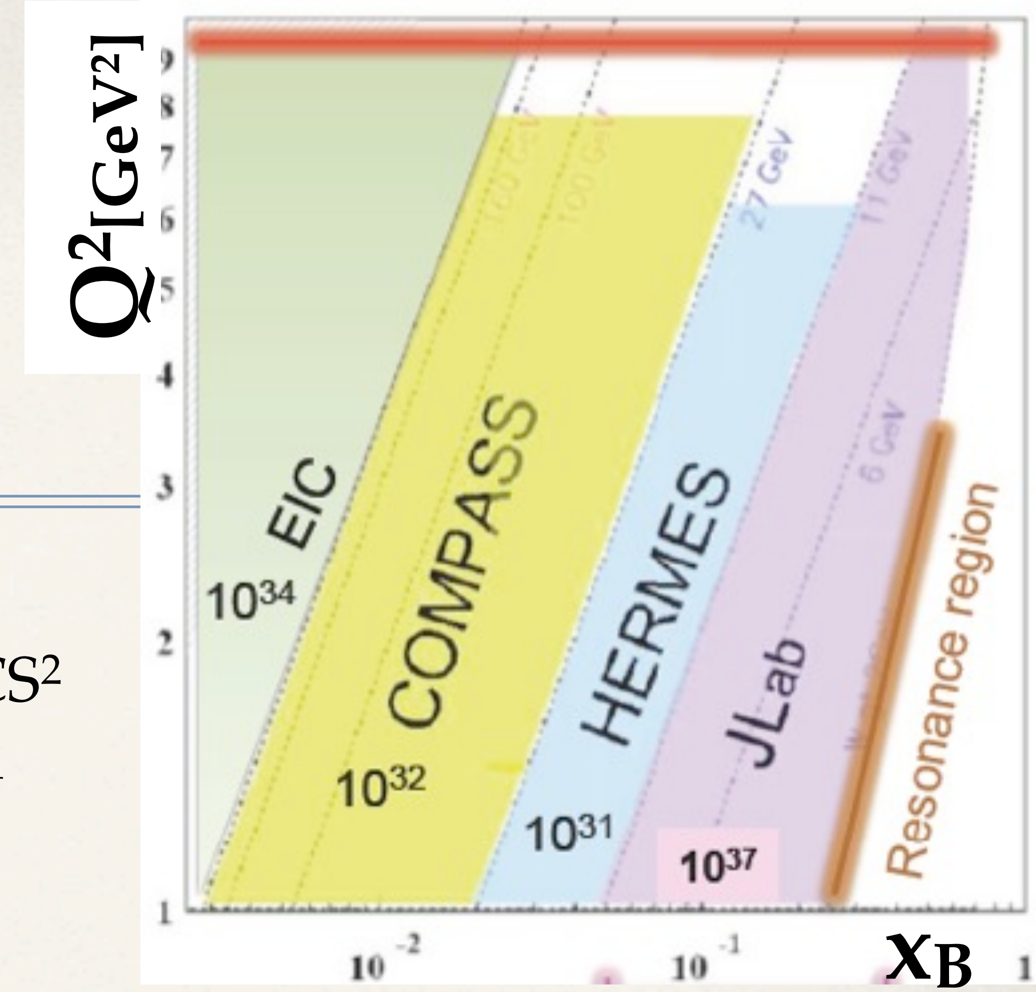
Desirable:
1.) More observables sensitive to different CFFs
2.) Measured at same average kinematics

- **Michel Guidal** PLB 689 (2010) 156
  - **CLAS** A_{LU} & $\mathbf{A_{UL}}$ (← important for convergence)
  - Price for model-indep.: large uncertainties



- **M. Guidal** arXiv:1005.4922, **HERMES** A_{UL} & A_{LL}

The Future of DVCS

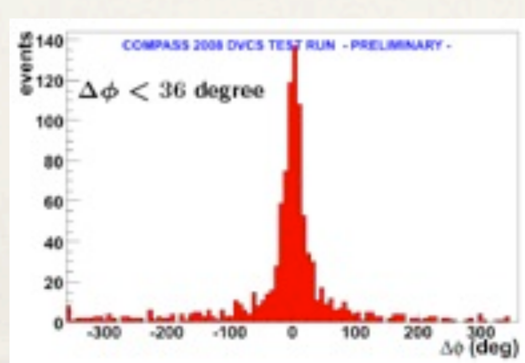


- JLab
  - Hall A (E07-007 @6GeV, fall 2010): Interference-DVCS² separation and Q2 dependence of total cross-section
  - CLAS: transversely polarized HD-Ice target (2012)
  - JLab 12 GeV upgrade: Q^2_{max} = 13...14 GeV², e⁺ beam

See talk by Robert McKeown (Friday plenary)

- COMPASS
  - 2008-09: ‘DVCS test runs’, small Recoil
  - 2012-15: GPD H, large Recoil
    beam-charge and -spin asys + x-section
  - 2015+ (?): GPD E,
    trans. pol. target

See next talk by Etienne Burtin



- Future Electron-Ion Collider

  ELIC @ JLab or eRHIC @ BNL:
  $\sqrt{s}$ = 20-70 GeV (HERMES: 7 GeV)
  ENC @ GSI: $\sqrt{s}$ = 40 GeV, ..

- Global analysis

Summary:
Deeply Virtual Compton Scattering

- DVCS is an interesting and clean signal
  - Access to GPDs & total angular momentum of quarks
  - Key role in understanding of strong interaction dynamics in DIS
- Measurements at different existing and future facilities complement each other in observables and phase space covered
- First global analyses started

Backup

HERMES A_{UL} & A_{LL} DVCS amplitudes

- Proton target polarization (→): ≈80%
- HERA e+ beam polarization (→): ≈50%
- Integrated luminosity: ≈50pb^{-1}

VGG

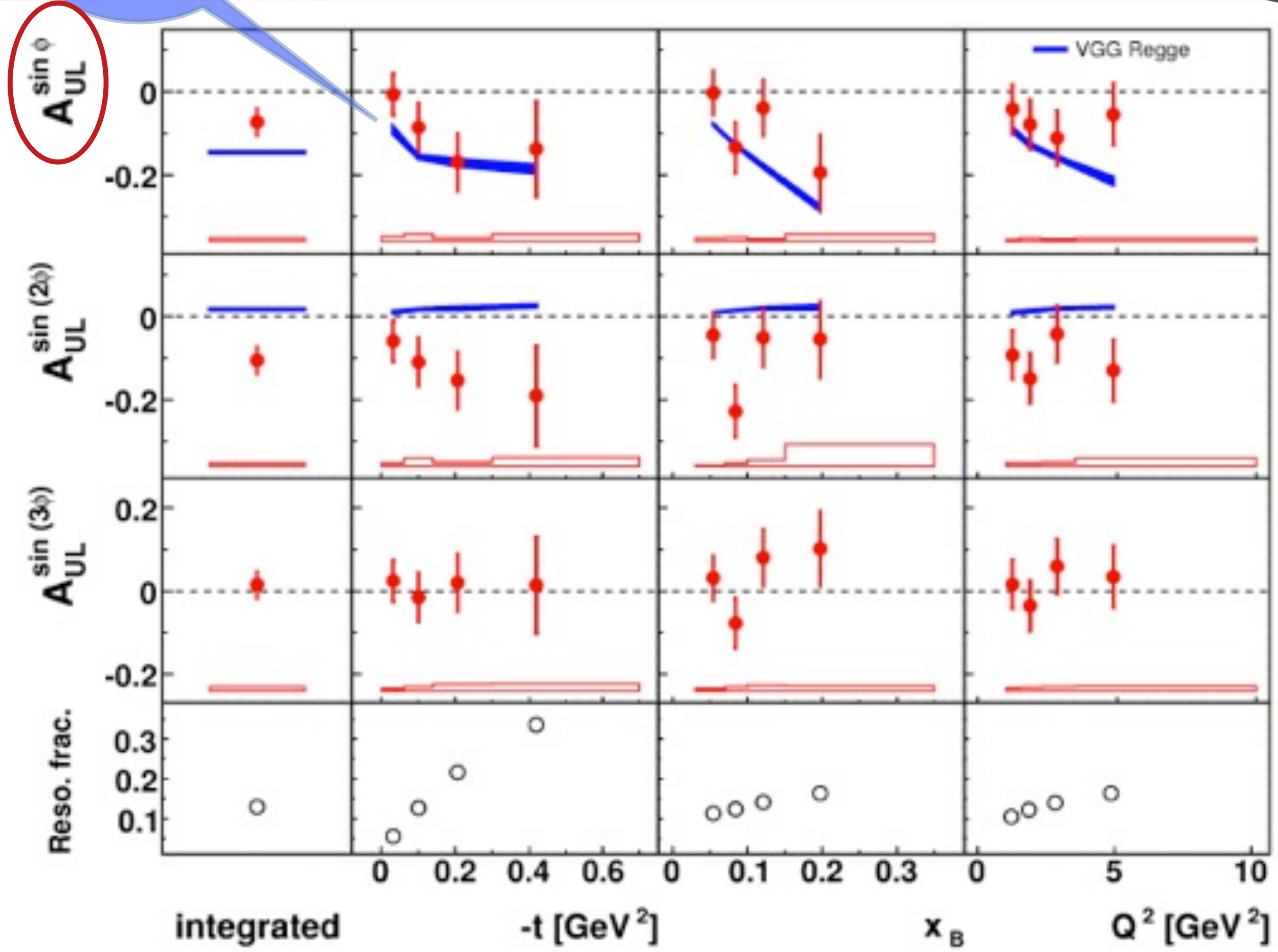
Target spin asymmetry

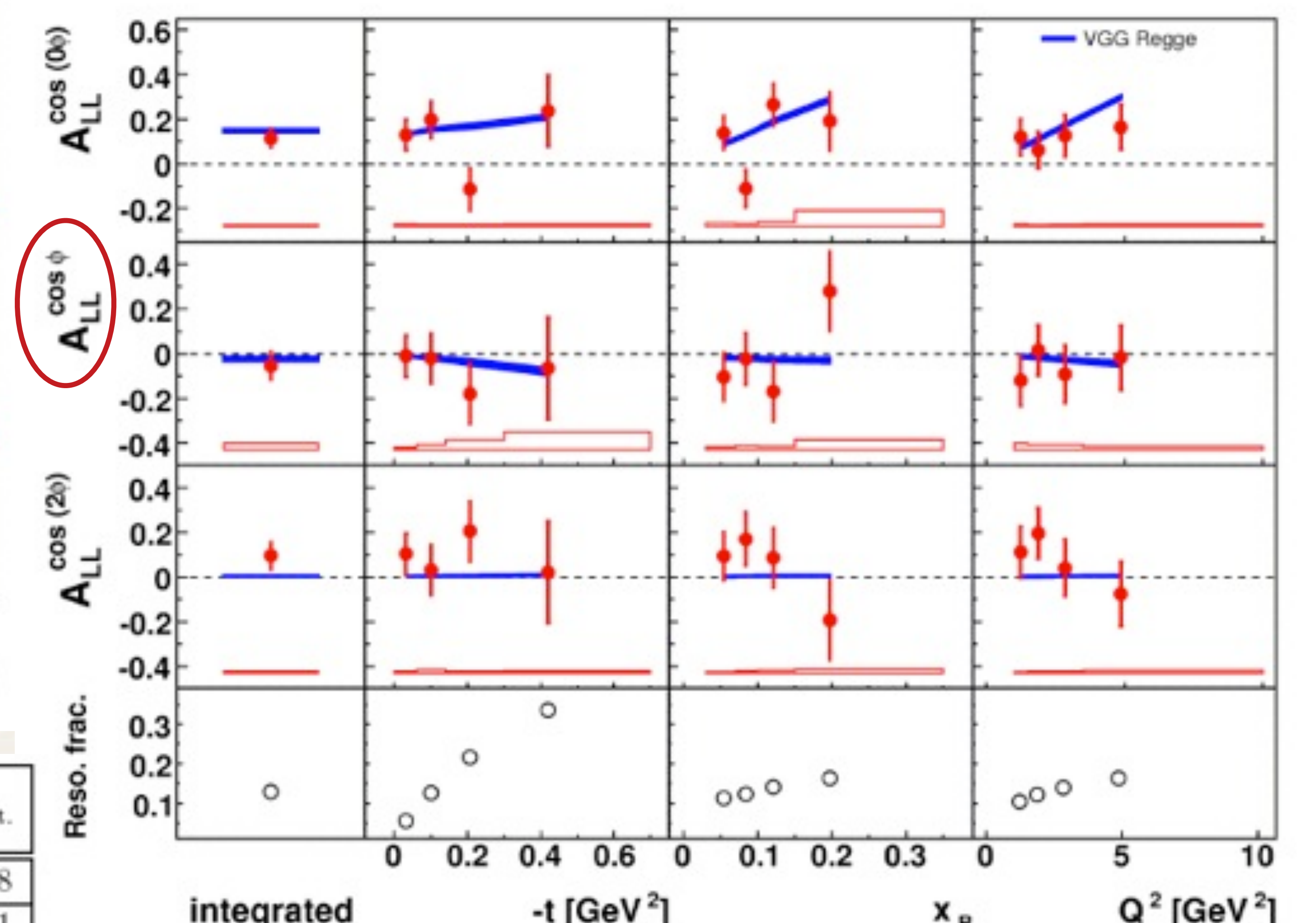
Sensitive to $Im\,\widetilde{H}$ / $Re\,\widetilde{H}$

HERMES arXiv:1004.0177, accepted by JHEP (2010)

First measurement!

Double spin asymmetry





Experiment	$\langle -t \rangle$ [GeV^2]	$\langle x_B \rangle$ -	$\langle Q^2 \rangle$ [GeV^2]	$A_{UL}^{\sin\phi} \pm \delta_{stat.} \pm \delta_{syst.}$	$A_{UL}^{\sin(2\phi)} \pm \delta_{stat.} \pm \delta_{syst.}$
HERMES	0.12	0.10	2.46	$-0.073 \pm 0.032 \pm 0.007$	$-0.106 \pm 0.032 \pm 0.008$
CLAS	0.31	0.28	1.82	$-0.252 \pm 0.042 \pm 0.020$	$-0.022 \pm 0.045 \pm 0.021$