Quark Orbital Angular Momentum and Exclusive Processes at HERMES

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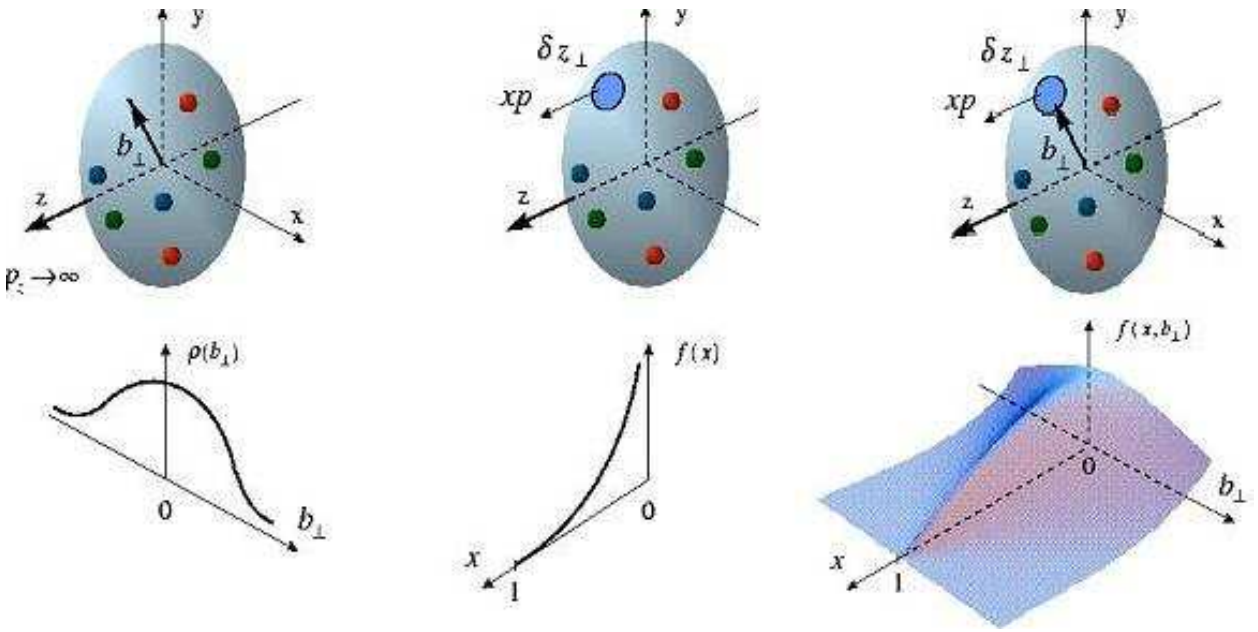
for the HERMES–Collaboration

Future Prospects in QCD at High Energy, BNL, USA, July 2006

- Generalized Parton Distributions (GPDs)
- Exclusive Production of Photons (DVCS) and Mesons
- HERMES Results
- First model dependent constraint on Quark Orbital Angular Momentum

GPDs: Parameterization of the Nucleon Structure

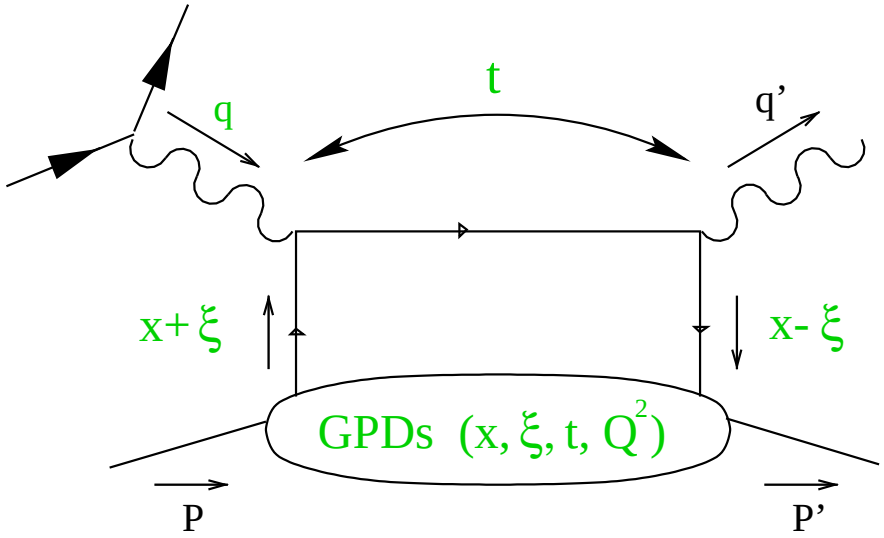


FF **PDF** **GPD**

- Form Factors → Transverse position ← Elastic scattering
- PDFs → Longitudinal momentum distribution ← DIS
- GPDs → Access to transverse position and longitudinal momentum distr. at the SAME time, 3-D picture ← Exclusive reactions

Generalized Parton Distributions (GPDs)

Simplest/cleanest hard exclusive process:
Deeply-virtual electroproduction of real photons: $e\,p \to e'\,p'\,\gamma$
Deeply-virtual Compton Scattering (DVCS):

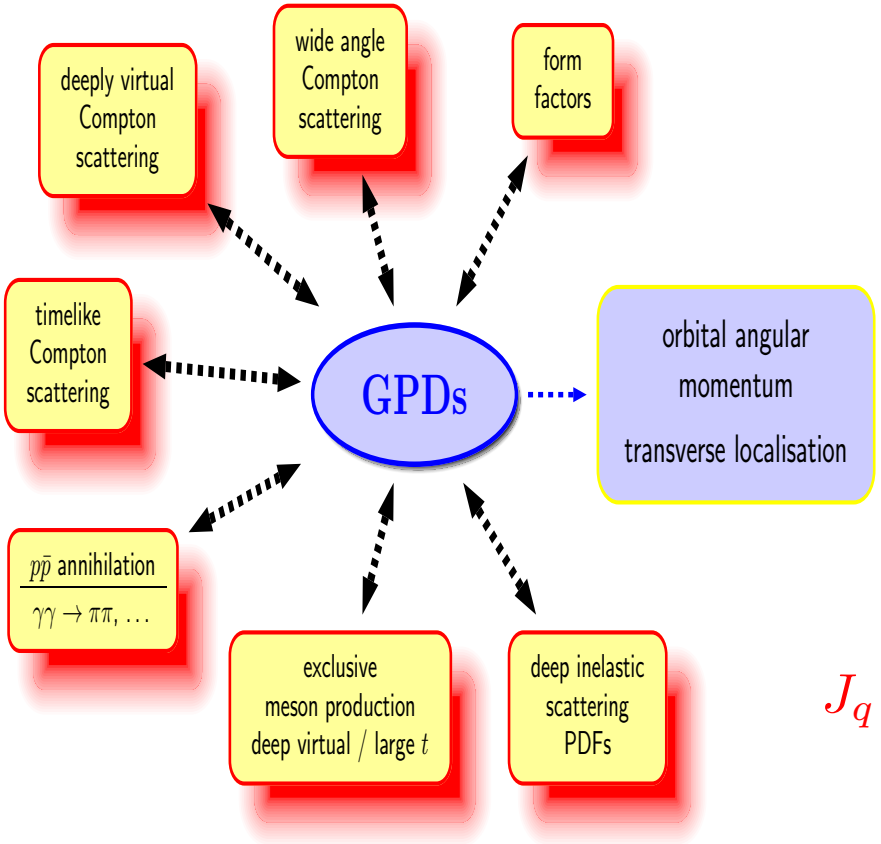


- Longitudinal momentum fractions:
  $x \in [-1, 1]$ (not accessible)
  $\xi \approx x_B/(2 - x_B)$
- $t = (q - q')^2$
  ($\gamma^* \to \gamma$ Momentum transfer)
- $Q^2 = -q^2$

$\Rightarrow$ Measurements as function of x_B, t, Q^2

DVCS: Access to all four GPDs H, $\widetilde{H}$, E, $\widetilde{E}$
Mesons: Access to H, E (VM) and $\widetilde{H}$, $\widetilde{E}$ (PS)

Overview GPDs



PDFs: GPDs in the limit $t \to 0$

$e.g.\ H(x,0,0) = q(x)$

FFs: First moments of GPDs

$e.g.\ \int_{-1}^{1} dx\, H(x,\xi,t) = F_1(t)$

Only known (quantitative) access to (total) Orbital angular momentum:

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

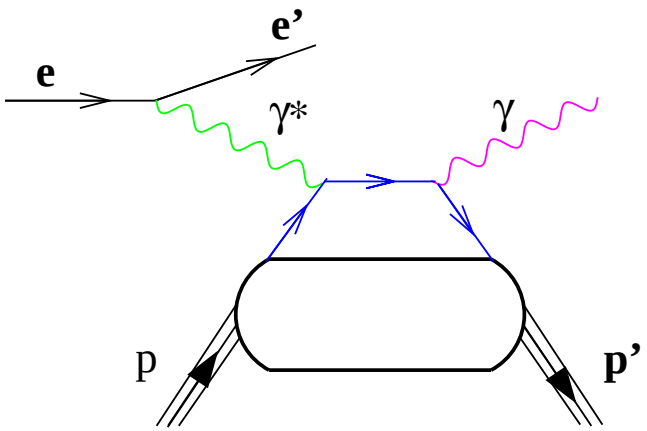
(X. Ji, 97)

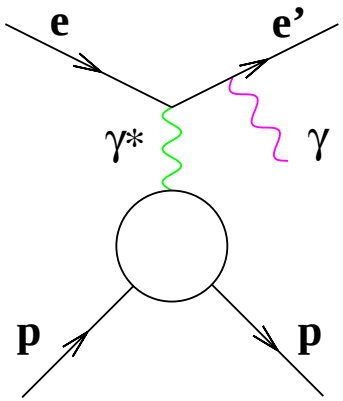
(Original) HERMES Motivation:

Nucleon (Long.) Spin Structure: $1/2 = \underbrace{1/2(\overbrace{\Delta u + \Delta d + \Delta s}^{\sim 30\%})}_{J_q=?} + \overbrace{L_q}^{?} + \overbrace{J_g}^{?}$

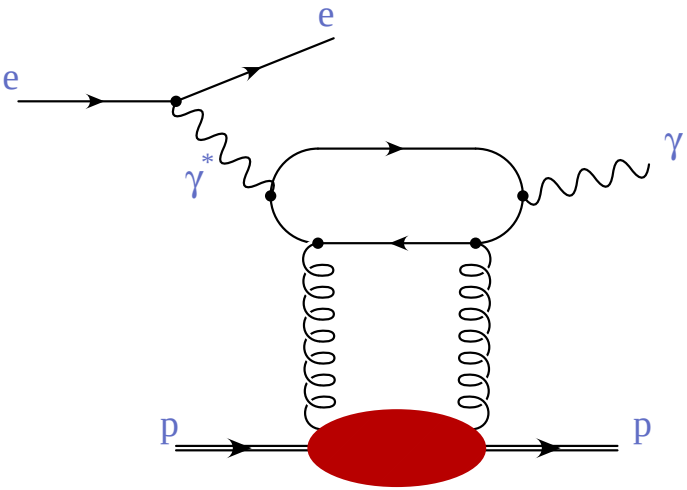
HowTo Access GPDs via DVCS?

DVCS final state $e + p \rightarrow e' + p' + \gamma$ is indistinguishable from the Bethe-Heitler Process (BH) $\rightarrow$ Amplitudes add coherently





Fixed-Target, Collider



Collider

Photon-Production cross section:

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

DVCS Measurements

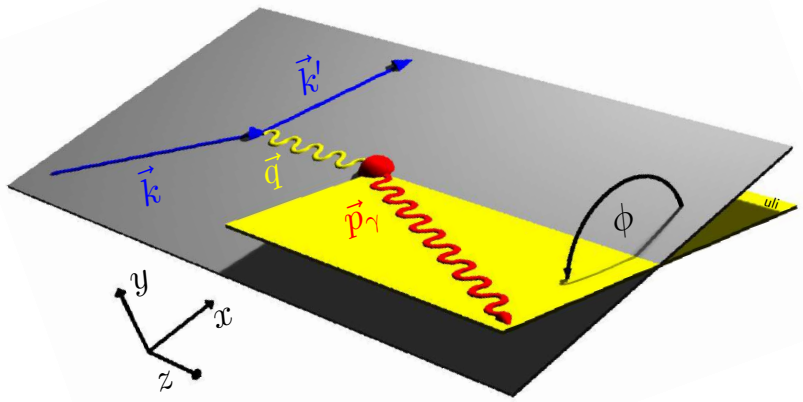
$$d\sigma \propto |\tau_{\mathrm{BH}}|^2 + \underbrace{(\tau^*_{\mathrm{DVCS}}\tau_{\mathrm{BH}} + \tau^*_{\mathrm{BH}}\tau_{\mathrm{DVCS}})}_{I} + |\tau_{\mathrm{DVCS}}|^2$$

$|\tau_{\mathrm{BH}}|^2$ calculable in QED with the knowledge of the form factors

$$I \propto \pm\left(c_0^I + \sum_{n=1}^{3} c_n^I \cos(n\phi) + \lambda \sum_{n=1}^{3} s_n^I \sin(n\phi)\right)$$

DVCS cross section (H1, Zeus):
Measurement integrated over ϕ
$\rightarrow I = 0$ (at Twist–2), subtract $|\tau_{\mathrm{BH}}|^2$
(GPDs enter in quadratic combinations)

Azimuthal asymmetries
(HERMES, JLab):
DVCS amplitudes directly accessible
via I $\Rightarrow$ Magnitude + Phase!!!
(GPDs enter in linear combinations)



Azimuthal Asymmetries

$$I \propto \pm(c_0^I + \sum_n [c_n^I \cos(n\phi) + \lambda s_n^I \sin(n\phi)])$$

Beam–Spin Asymmetry (BSA) and Beam–Charge Asymmetry (BCA) on unpolarized target:

$$\text{BSA}: \quad d\sigma(\overrightarrow{e^+}p) - d\sigma(\overleftarrow{e^+}p) \sim s^I_{1,unp} \sin(\phi) \sim \sin(\phi) \times \text{Im}\, M^{1,1}_{unp}$$

$$\text{BCA}: \quad d\sigma(e^+p) - d\sigma(e^-p) \sim c^I_{1,unp} \cos(\phi) \sim \cos(\phi) \times \text{Re}\, M^{1,1}_{unp}$$

(Higher Twist/Order $\rightarrow \cos 2\phi,\ \cos 3\phi,\ \sin 2\phi$)

Longitudinal Target–Spin Asymmetry (LTSA)

$$\text{LTSA}: \quad d\sigma(e^+\overleftarrow{p}) - d\sigma(e^+\overrightarrow{p}) \sim s^I_{1,LP} \sin(\phi) \sim \sin(\phi) \times \text{Im}\, M^{1,1}_{LP}$$

(Higher Twist/Order $\rightarrow \sin 2\phi,\ \sin 3\phi$)

From Amplitudes to GPDs

$M^{1,1}_{unp} = F_1(t)\, H_1(\xi,t) + \frac{x_B}{2-x_B}(F_1(t)+F_2(t))\, \widetilde{H}_1(\xi,t) - \frac{t}{4M^2} F_2(t)\, E_1(\xi,t)$

$\langle x_B \rangle$, $\langle -t \rangle \approx 0.1 \Rightarrow$ Compton Form-Factor H_1

$$\mathrm{Im}\, H_1 \sim -\pi \sum_q e_q^2 \left(H^q(\xi,\xi,t) - H^q(-\xi,\xi,t)\right)$$

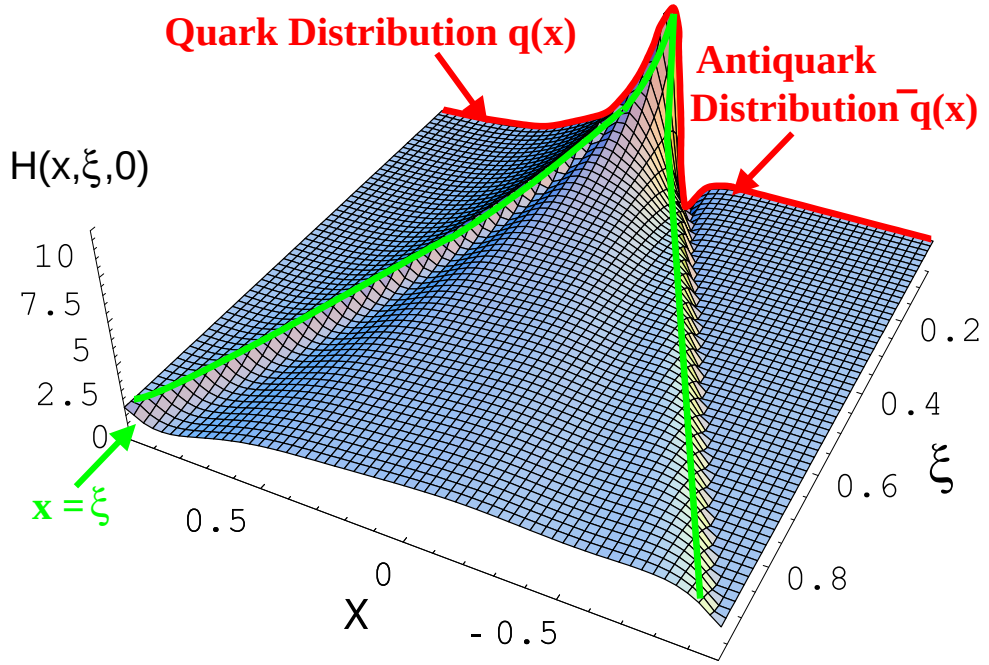
$$\mathrm{Re}\, H_1 \sim \sum_q e_q^2 \left[P \int_{-1}^{1} H^q(x,\xi,t) \left(\frac{1}{x-\xi} + \frac{1}{x+\xi} \right) dx \right]$$

BSA: $\mathrm{Im}\, M^{1,1}_{unp}$ mainly accesses the GPD $H^q(x,\xi,t)$ at $x = \xi \Rightarrow$ measures $H^q(\xi,\xi,t)$

BCA: $\mathrm{Re}\, M^{1,1}_{unp}$ contains full x–dependence of the GPD $H^q(x,\xi,t)$, x is not accessible $\Rightarrow$
GPD Model $\rightarrow$ Observables $\leftarrow$ Measurement

A GPD Model

Use relations to Nucleon Structure (PDFs, ...) to model GPDs

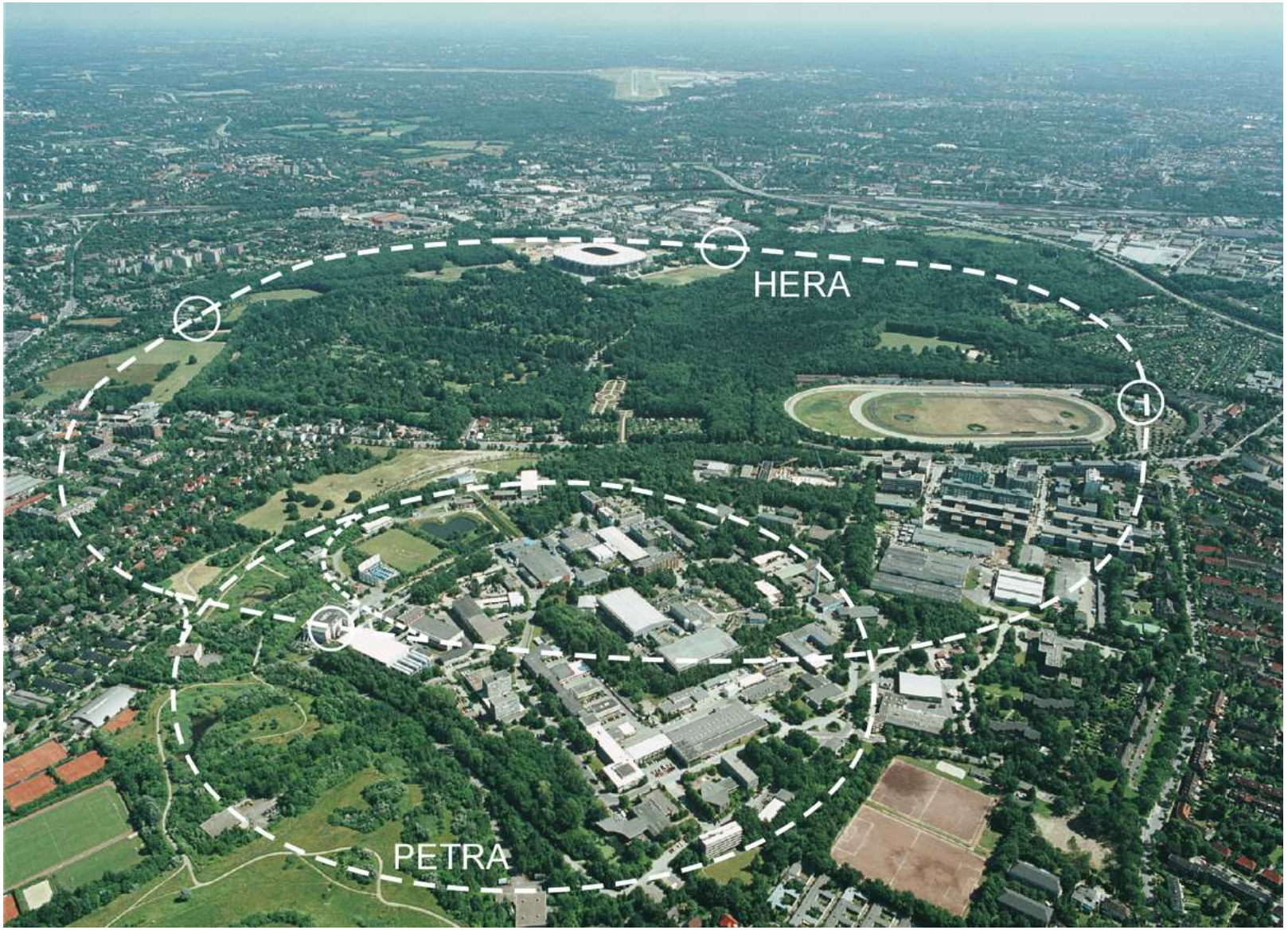


(Goeke, Polyakov, Vanderhaeghen, hep-ph/0106012)

Need both lepton charges and polarized "beam" and "target"

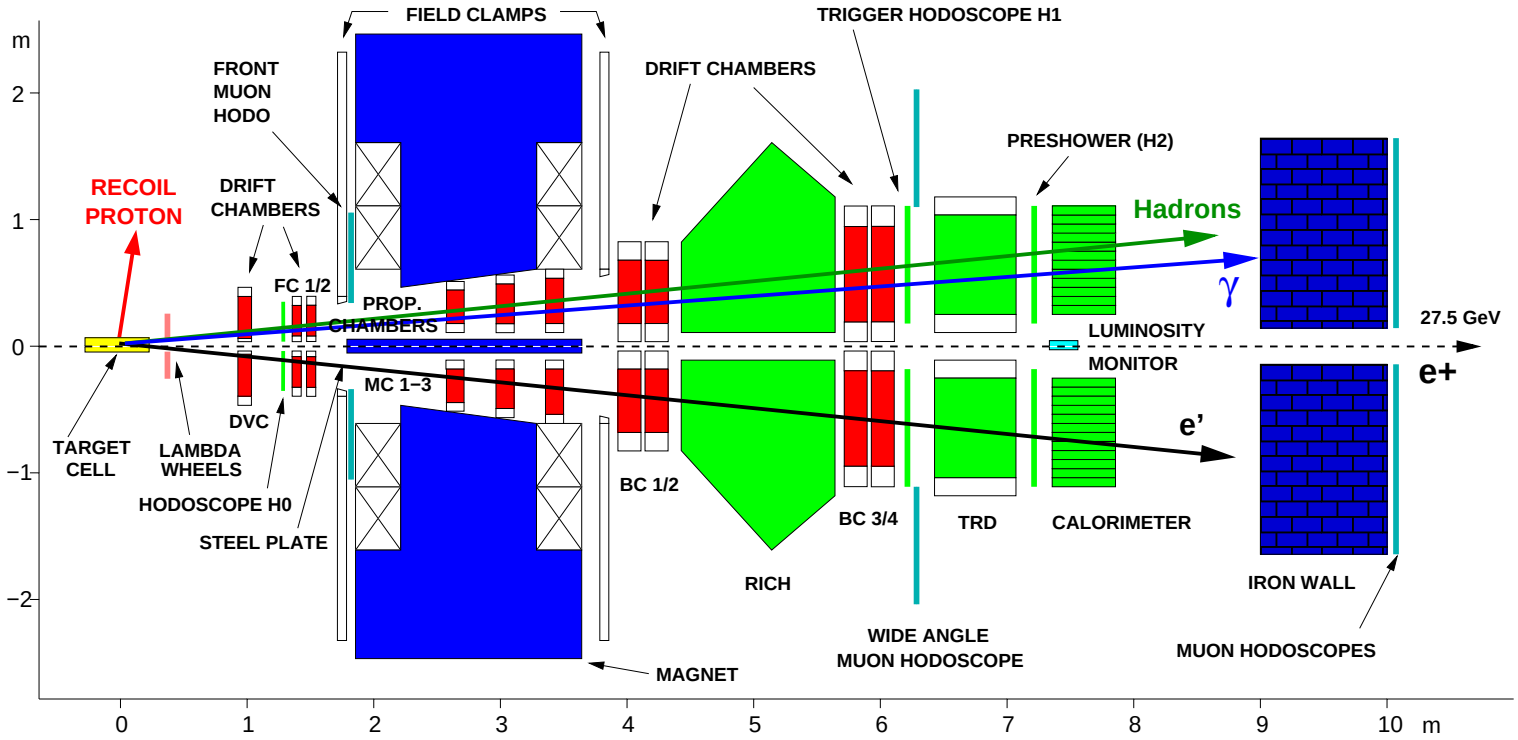
$\Rightarrow$ ...

The HERA accelerator at DESY (HAMBURG)



HERMES Event Selection

HERA Beam: 27.6 GeV, e^+ and e^-, $\langle P \rangle \approx 35 - 55\%$

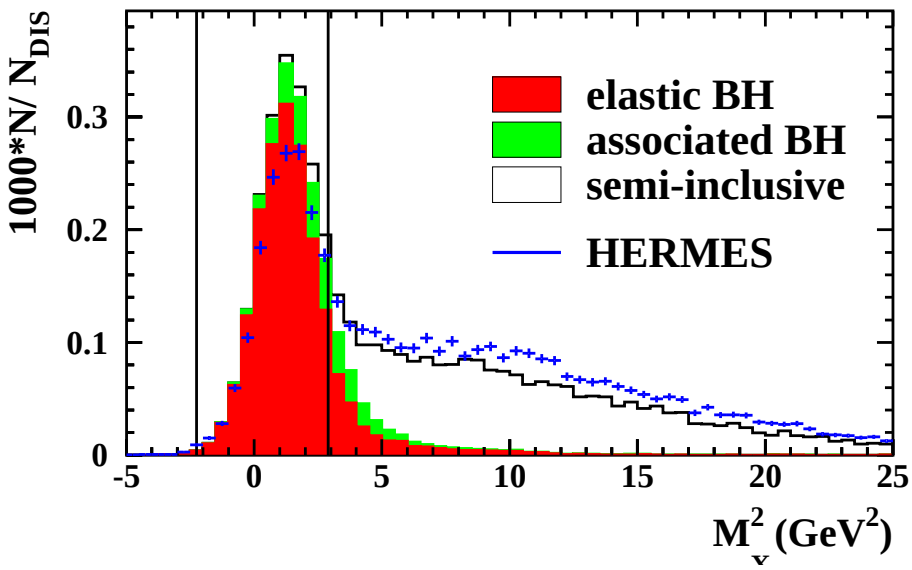


Events with exactly one DIS-positron/DIS-electron and exactly one photon in the calorimeter (or one $(\rho^0 \rightarrow)\ \pi^+\pi^-$ pair)

No recoil detection (yet) $\Rightarrow$ Exclusivity via ...

Exclusivity for DVCS via Missing Mass

$M_x^2 \equiv (q + p - p_\gamma)^2 \Rightarrow$ MC for background and cuts ($\rightarrow$ resolution)!



- elastic BH $(e\,p \rightarrow e'\,p'\,\gamma)$
- associated BH (mainly $e\,p \rightarrow e'\,\Delta^+\,\gamma$)
- semi–inclusive (mainly $e\,p \rightarrow e'\,\pi^0\,X$)
- exclusive π^0 $(e\,p \rightarrow e'\,\pi^0)$ not shown (small)

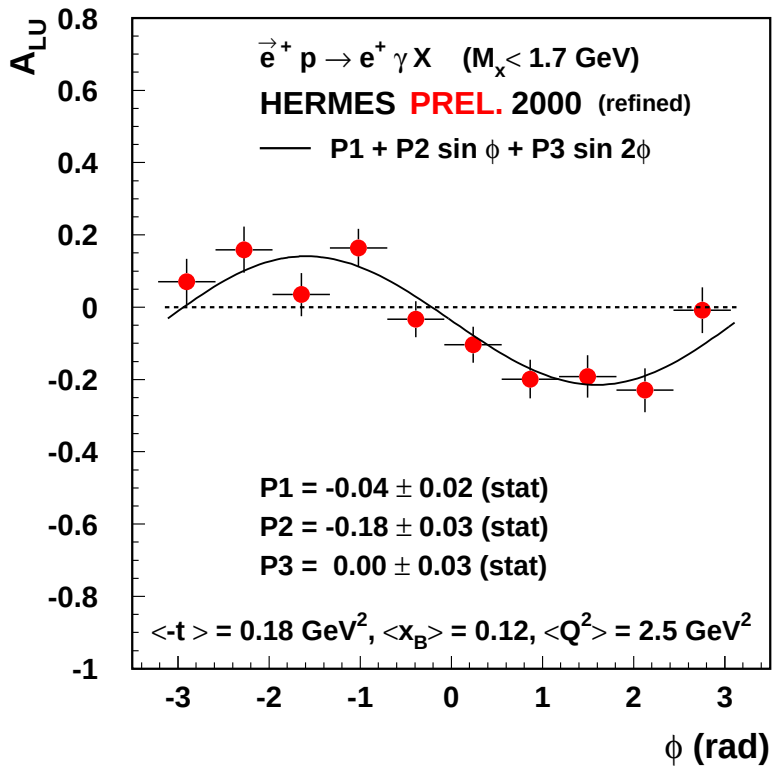
Not simulated: DVCS process (DVCS c.s. "unknown", DVCS << BH) +Radiative corrections to BH ($\rightarrow$ excl. peak overestimated, BG underestimated)

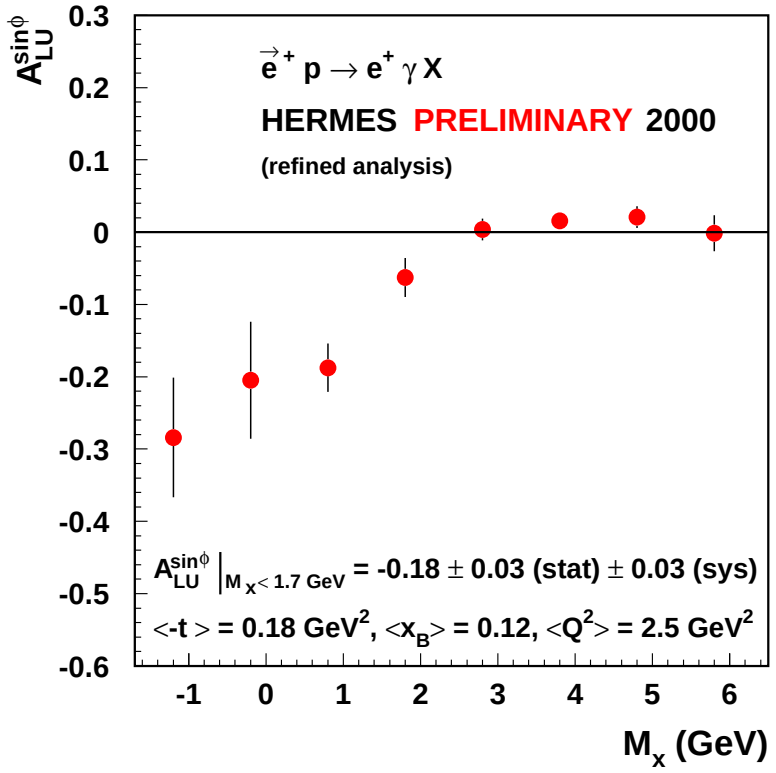
$\Rightarrow$ "Exclusive" bin (-1.5 < M_x < 1.7 GeV)

$\Rightarrow$ Overall background contribution $\approx 15\%$

Beam–Spin Asymmetry (BSA)

$$A_{\mathrm{LU}}(\phi) = \frac{1}{<|P_b|>} \frac{\overrightarrow{N}(\phi) - \overleftarrow{N}(\phi)}{\overrightarrow{N}(\phi) + \overleftarrow{N}(\phi)}$$





A_{LU} in exclusive bin: Expected $\sin(\phi)$ dependence $\Rightarrow \mathrm{Im}\, M_{unp}^{1,1}$

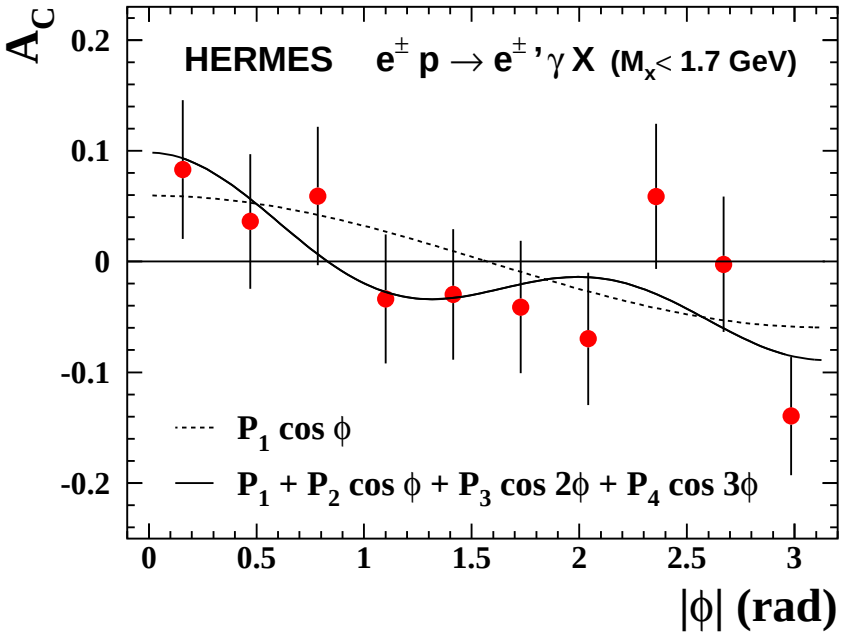
$\sin(\phi)$–Moment in non–exclusive region: small and slightly positive $(\rightarrow \pi^0)$

(Results from 1996/97 → PRL **87**, 182001 (2001))

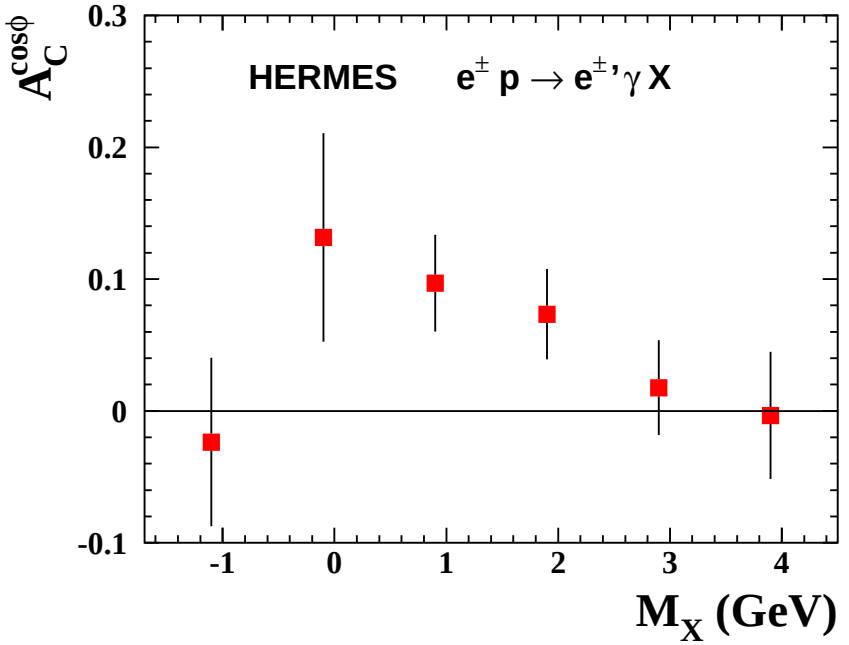
BCA: Beam–Charge Asymmetry *(hep-ex/0605108, subm. to PRL)*

$$A_C(\phi) = \frac{N^+(\phi)-N^-(\phi)}{N^+(\phi)+N^-(\phi)} \propto I \propto \pm(c_0^I + \sum_{n=1}^{3} c_n^I \cos(n\phi) + \lambda \sum_{n=1}^{2} s_n^I \sin(n\phi))$$

⇒ Calculate "symmetrized" BCA ($\phi \to |\phi|$) to get rid of all $\sin(\phi)$–dependences due to polarized beam.

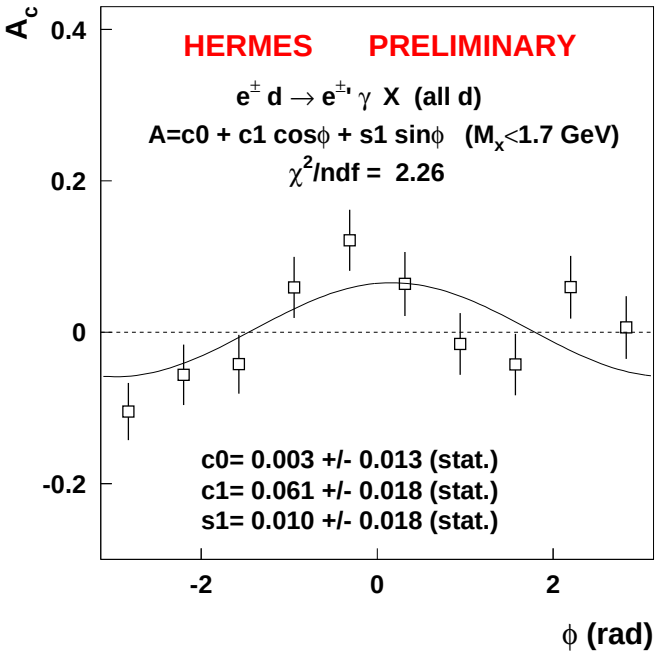


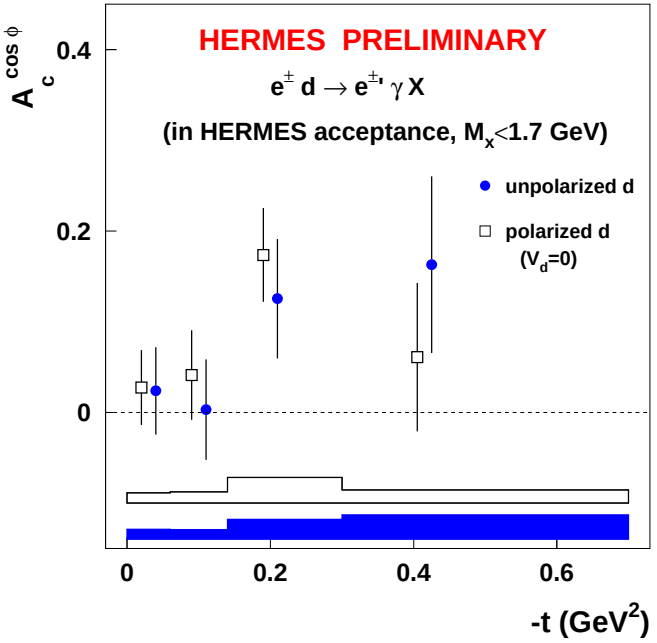
A_C in exclusive bin: Expected $\cos(\phi)$ dependence ⇒ $\mathrm{Re}\, M_{unp}^{1,1}$

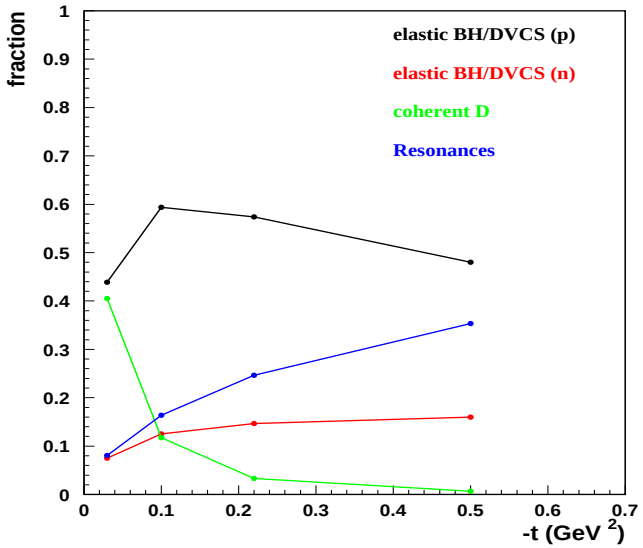


$\cos(\phi)$–Moments zero at higher missing mass

BCA: Beam–Charge Asymmetry cont'd

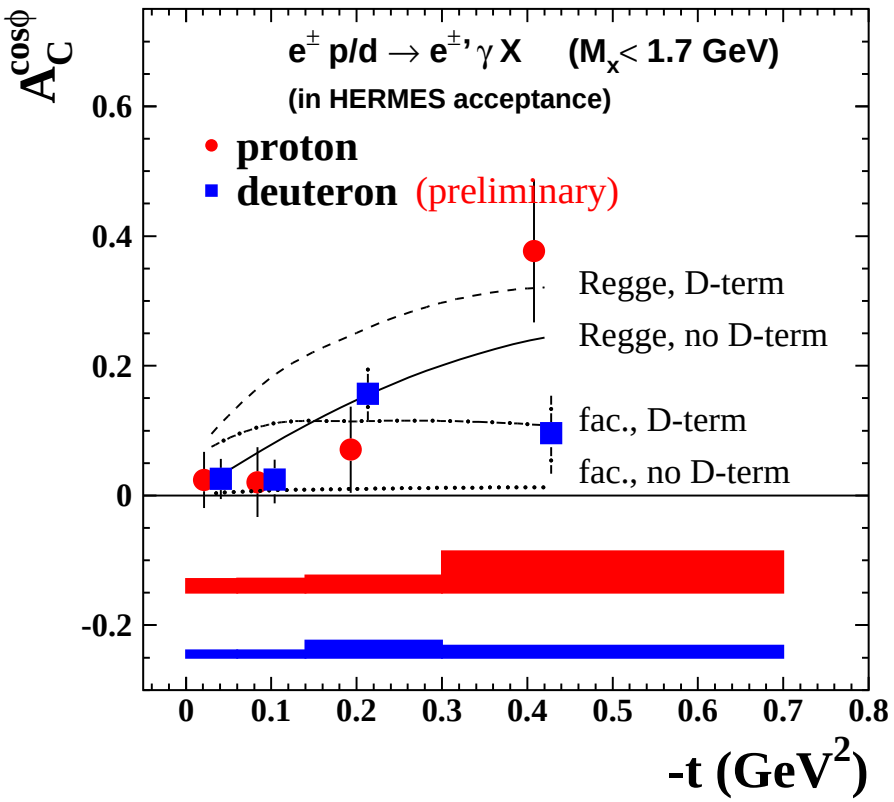






- $A_C^{\cos\phi}(d) \approx A_C^{\cos\phi}(p)$
- Spin-1 particle $\rightarrow$ 9 GPDs, but coherent production only $\approx 20\%$
- 40% coherent in first t-bin
  $\Rightarrow$ no Tensor effect seen
  $\Rightarrow$ Data can (indeed) be combined

Beam–Charge Asymmetry (BCA) versus $-t$



DVCS on deuterium:

Coherent production on D only in first t-bin ($\approx 40\%$)

$\Rightarrow$ No effect seen

$\rightarrow \approx$ p-target

Possible difference in last bin ($\rightarrow$ neutron)

GPD Model calc. at average kinematic values per bin
(code by Vanderhaeghen, Guichon, Guidal)

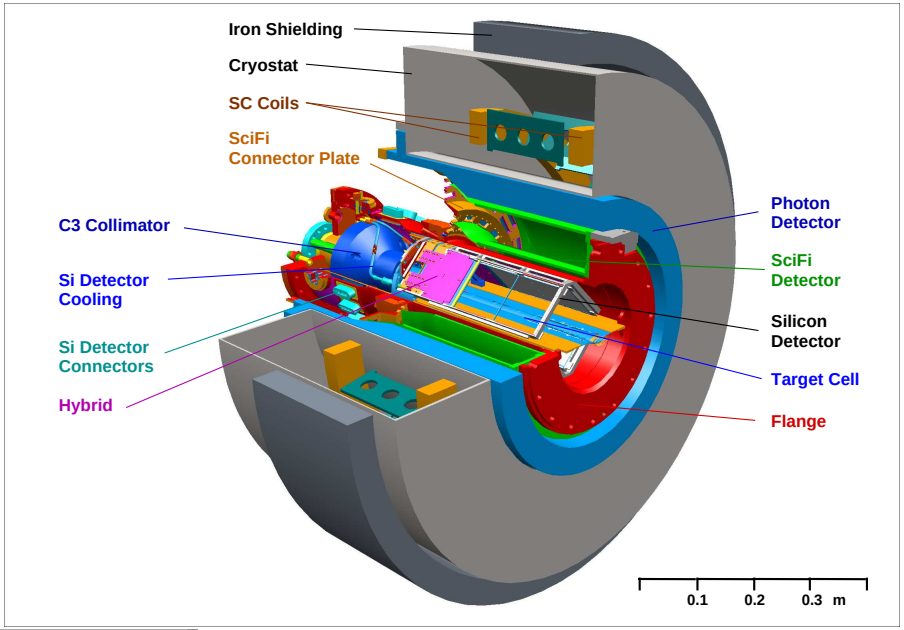
tiny e^-p sample ($L \approx 10$ pb^{-1}) $\Rightarrow$ Regge+D-Term disfavored

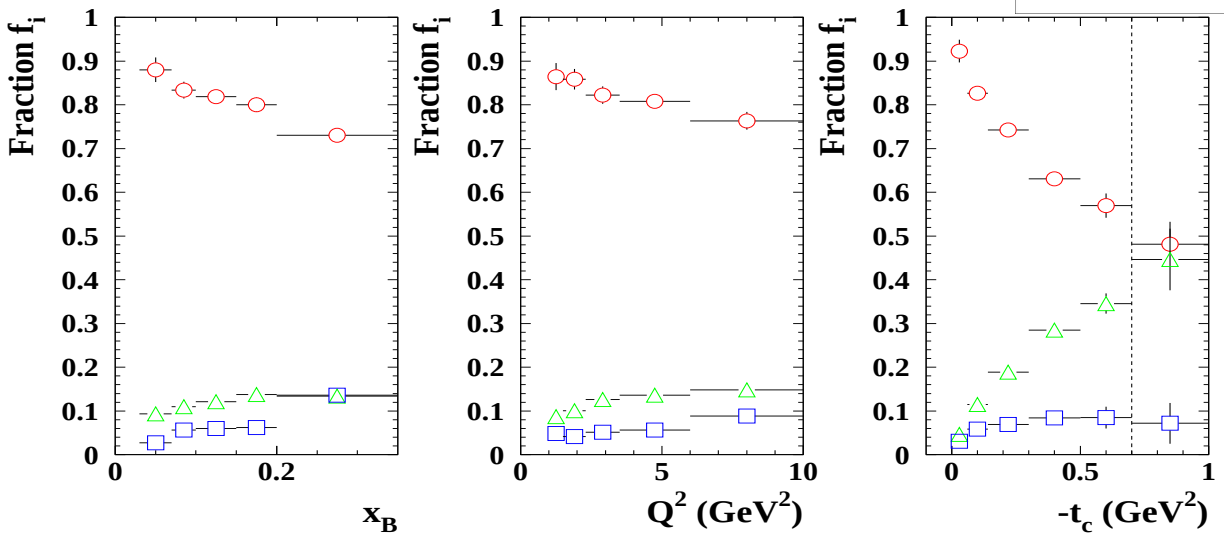
$\Rightarrow$ t–dependence of BCA has high sensitivity to GPD models!

More on H to come

Recoil Detector and unpol. Targets (2006/2007)

- ensures exclusivity of events
  - Semi–inclusive background 5% $\Rightarrow \ll 1\%$
  - Associated background 10% $\Rightarrow \approx 1\%$



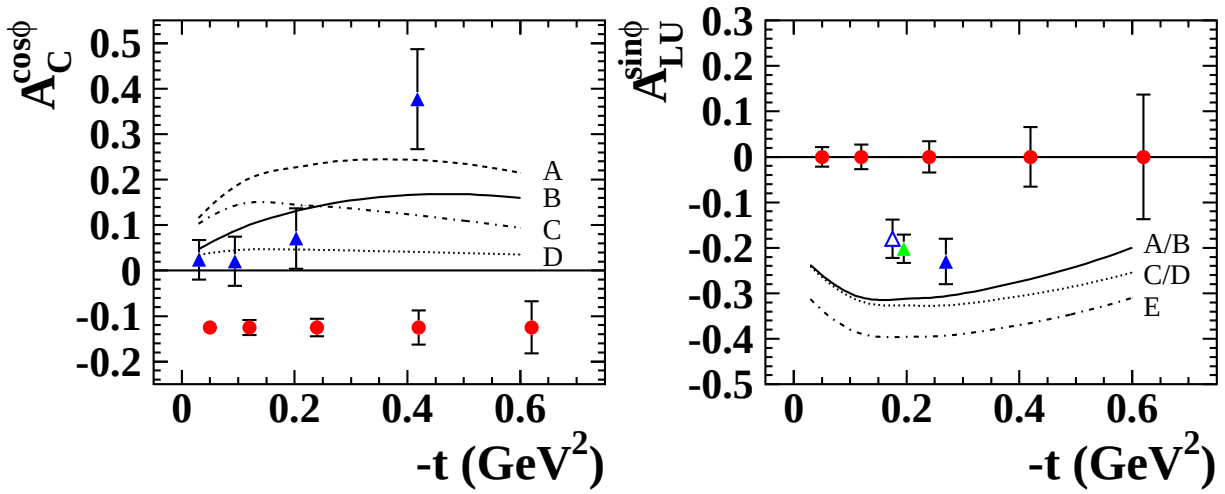


$\Rightarrow$ Essential at larger $-t$ values

The GPD H, Summary and Outlook

BCA

BSA



△: HERMES prelim./published

△: CLAS, PRL, 2001 $(\times -1)$

●: $1 fb^{-1}\, e^+$ and $0.25 fb^{-1}\, e^-$, Pol. $= 35\%$ (exp. 2002-2007 data)

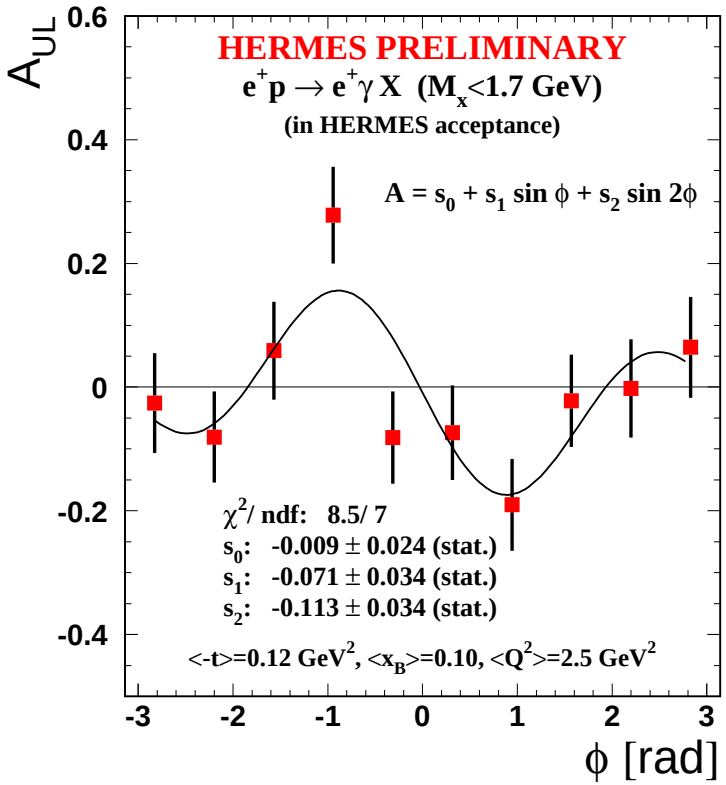
BCA: high sensitivity to t-dependence (fact./Regge) and D-term

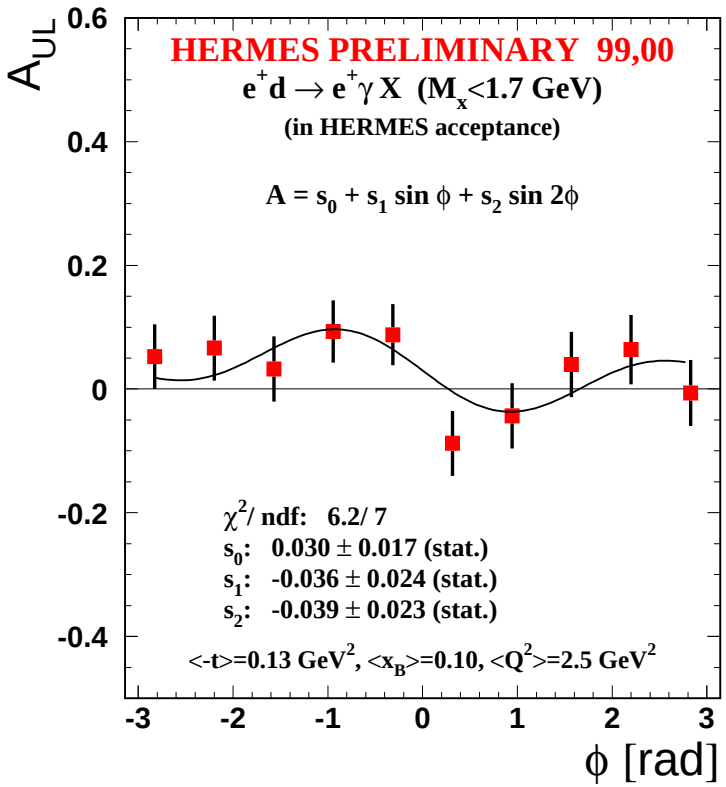
BSA: highest sensitivity to b_s parameter in profile function

Possibility to "map out" GPD H^u in the final two HERA years.

The GPD $\widetilde{H}$, Long. Target–Spin Asymmetry (LTSA)

$$A_{\rm UL}(\phi) = \frac{1}{<|P_T|>} \frac{\overleftarrow{N}(\phi) - \overrightarrow{N}(\phi)}{\overleftarrow{N}(\phi) + \overrightarrow{N}(\phi)} \propto \sin\phi \times Im\widetilde{H}_1$$

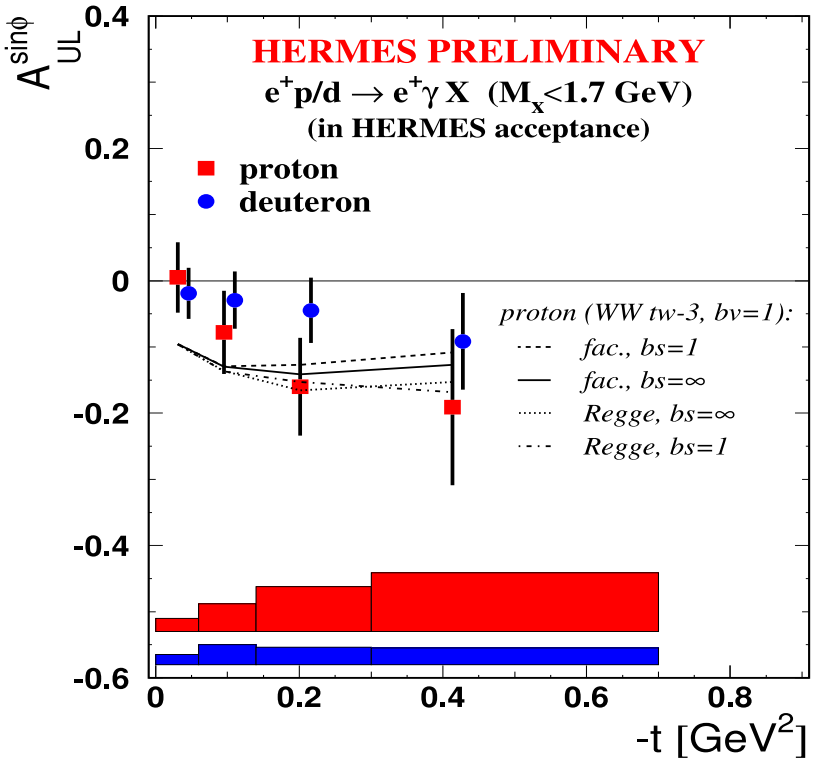


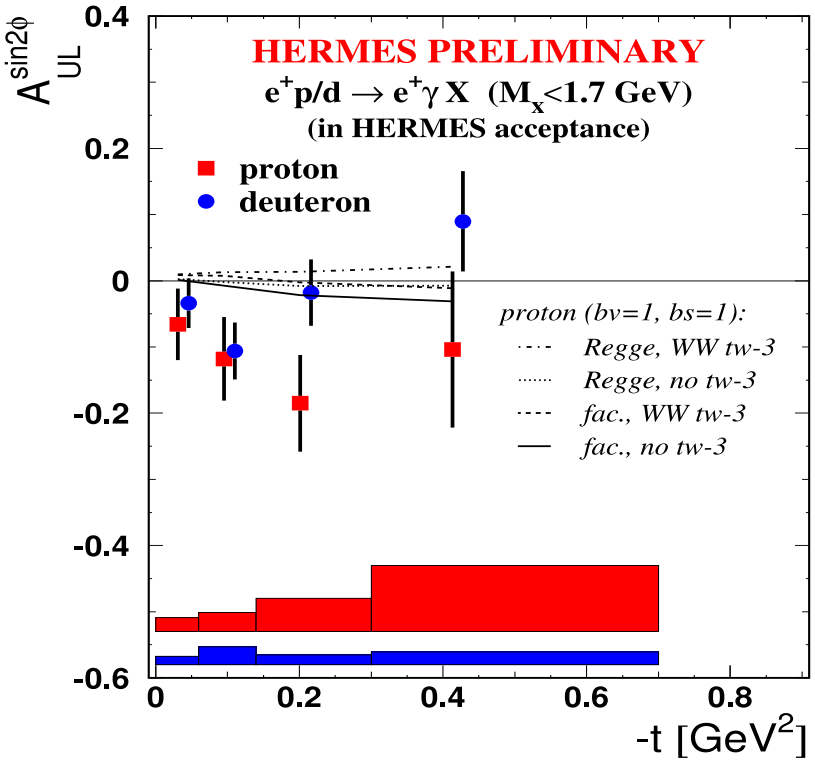


$A_{\rm UL}(\overrightarrow{p})$ in exclusive bin:
Expected $\sin(\phi)$ dep. $\Rightarrow$ GPD $\widetilde{H}$,
Unexpected $\sin(2\phi)$ dependence

$A_{\rm UL}(\overrightarrow{d})$ in exclusive bin:
$\Rightarrow$ consistent with zero

The GPD $\tilde{H}$, Long. Target–Spin Asymmetry (LTSA)





- No effect seen from 40% coherent contribution in first bin
- Difference at higher $-t$
  $\Rightarrow$ Different asymmetry on the neutron when comp. to proton
- $A_{UL}^{\sin 2\phi} \Rightarrow$ Difference due to missing qGq twist-3 in the models?
  $A_{UL}^{\sin 2\phi} \Rightarrow$ Difference due to large $\sin 2\phi$ (while $\sin\phi$ is small) in π^0 background (CLAS, hep–ex/0605012)?

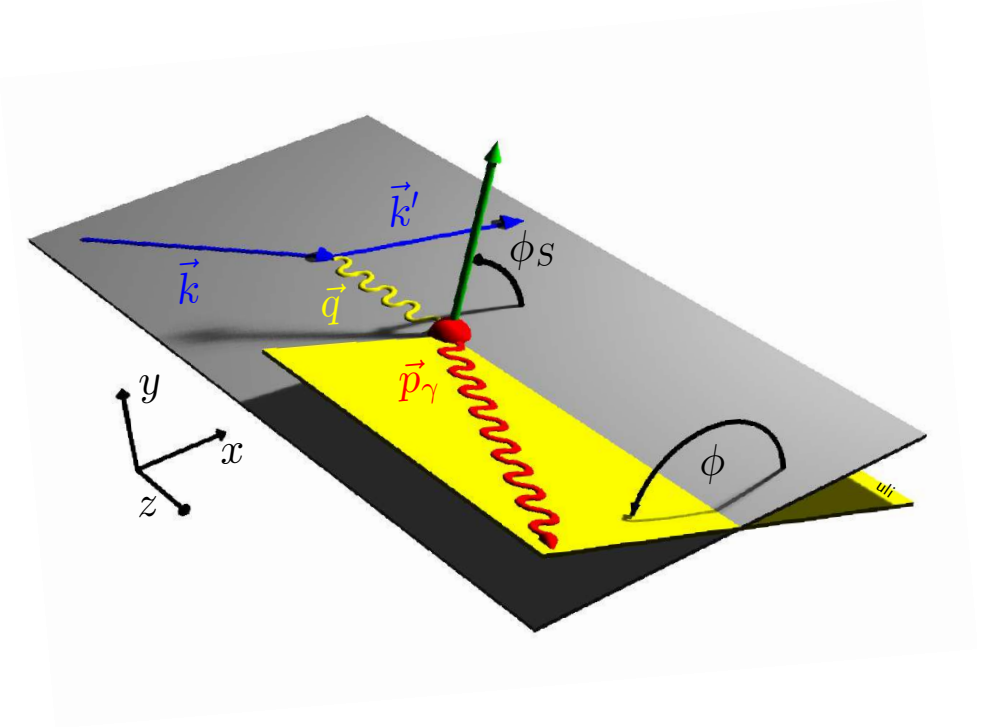
What about the GDP E ?

Remember:

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

GPD E (on p target) is always kinematically suppressed, except in:

A_{UT}: unpolarized beam, transversely pol. target

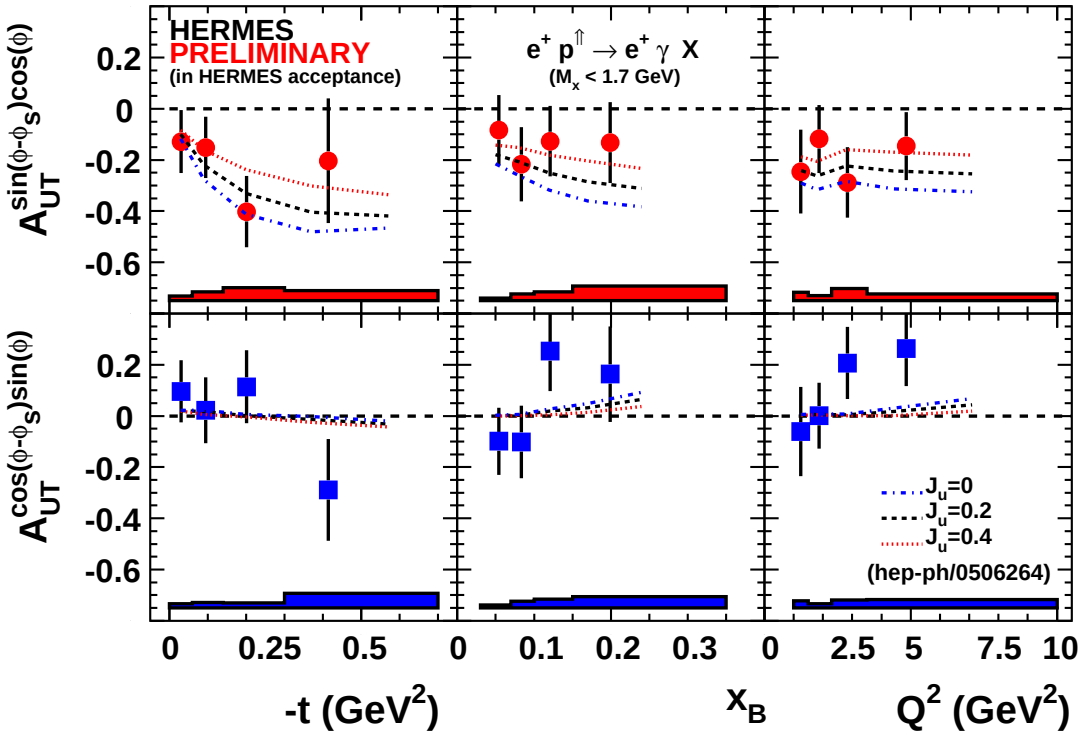


$$A_{UT}(\phi,\phi_s) = \frac{1}{|P_T|} \cdot \frac{d\sigma^{\Uparrow}(\phi,\phi_s) - d\sigma^{\Downarrow}(\phi,\phi'_s)}{d\sigma^{\Uparrow}(\phi,\phi_s) + d\sigma^{\Downarrow}(\phi,\phi'_s)}$$

$$\propto \mathrm{Im}[F_2\mathcal{H} - F_1\mathcal{E}] \cdot \sin(\phi-\phi_S)\cos\phi + \mathrm{Im}[F_2\widetilde{\mathcal{H}} - F_1\xi\widetilde{\mathcal{E}}] \cdot \cos(\phi-\phi_S)\sin\phi$$

DVCS TTSA compared to the Model Calculations!

Data taking with transverse Hydrogen target finished
≈ 10 million on tape, half the data (2002-2004) analyzed

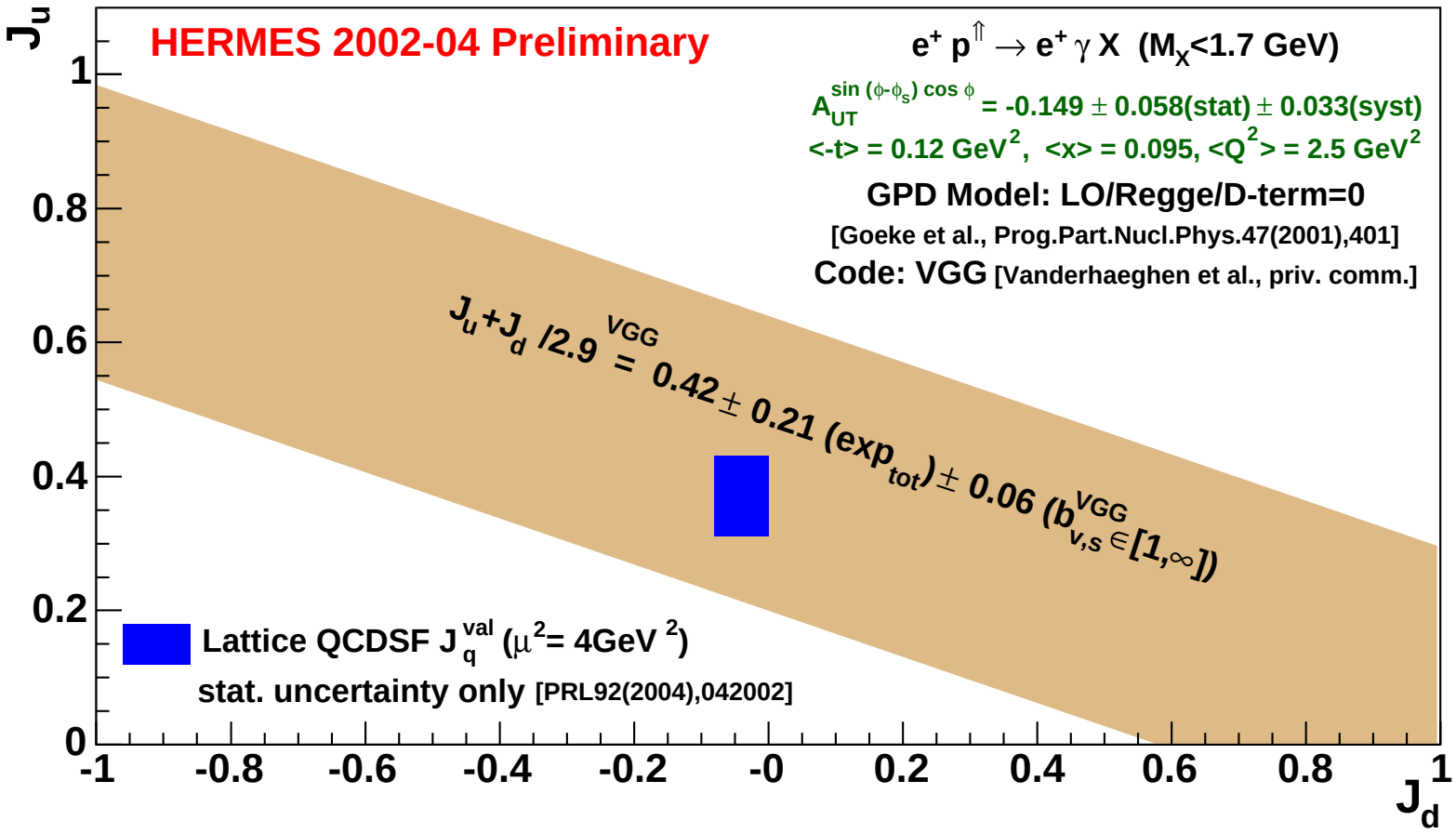


$A_{UT}^{\sin(\phi-\phi_s)\cos\phi}$ largely INDEPENDENT on all model parameters but J_u

(F.E., Nowak, Vinnikov, Ye, hep-ph/0506264)

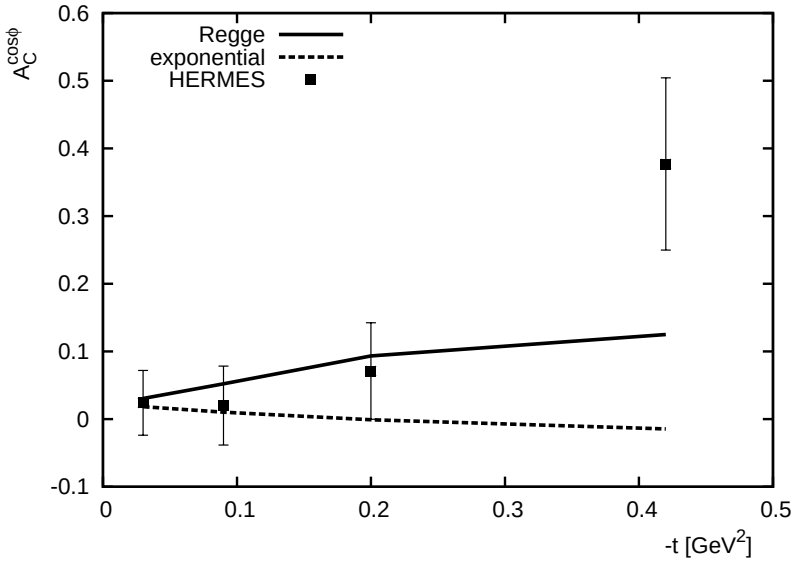
⇒ First model dependent extraction of J_u possible!

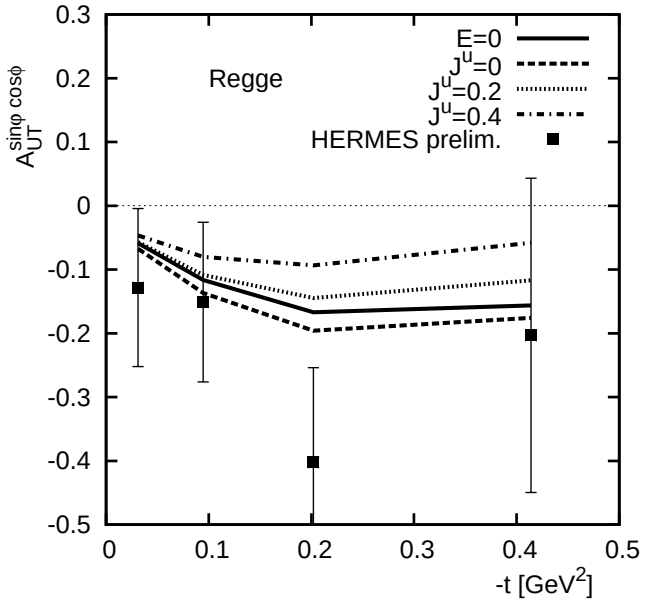
First Constraint on Angular Momentum !

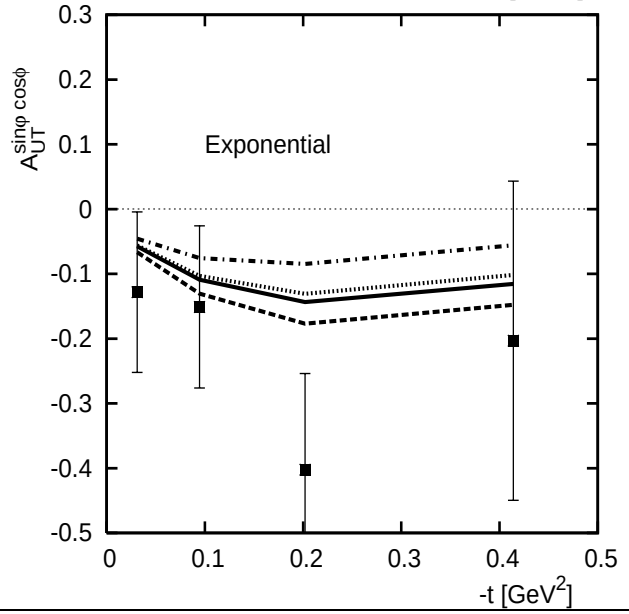


$\Rightarrow$ First model dependent constraint on total quark angular momentum J_u, J_d.

Latest model calculation ...





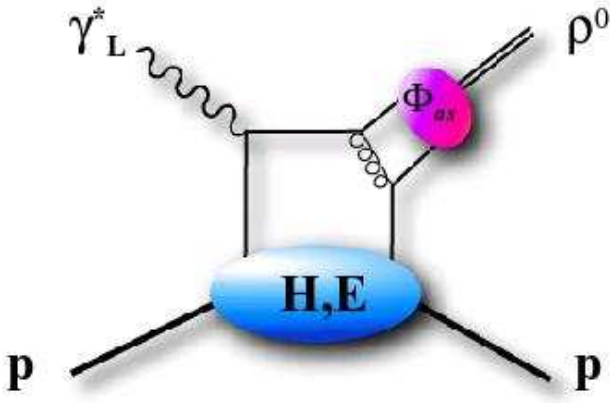


- The models (Guzey/Teckentrup, hep–ph/0607099) are in agreement with "all" other DVCS data:
  → Cross section measurements by H1/ZEUS
  → Published BSA measurements by HERMES/CLAS

Exclusive Vector Meson Production

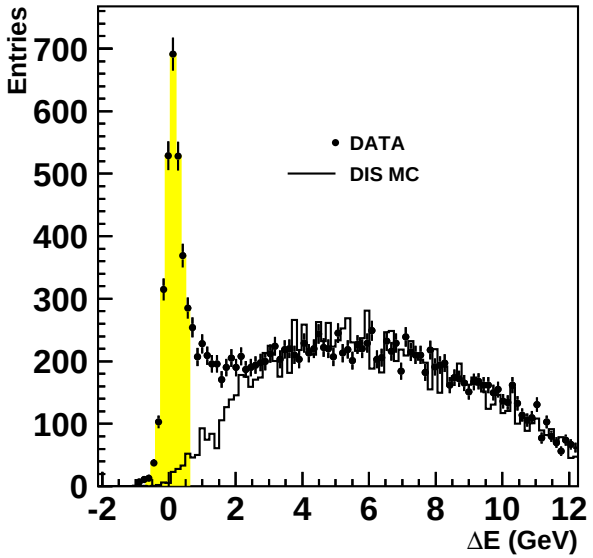
The (only) other (promising) access to E (J) (on a p target): A_{UT} in exclusive ρ^0 production:

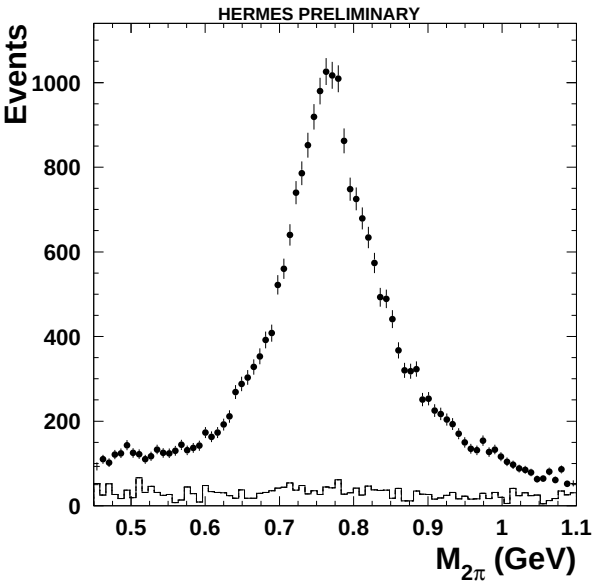
$$e\,p \rightarrow e\,p\,\rho^0$$



Event selection:

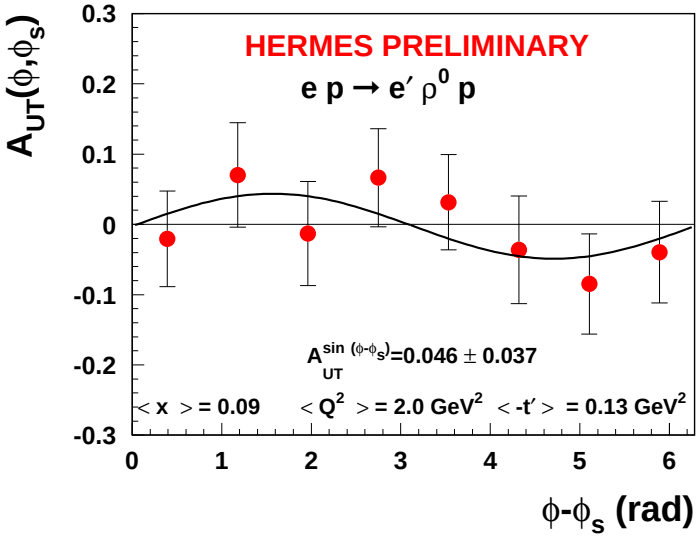
- $\rho^0 \rightarrow \pi^+\pi^-$,
- No recoil detection
- $\rightarrow$ missing energy

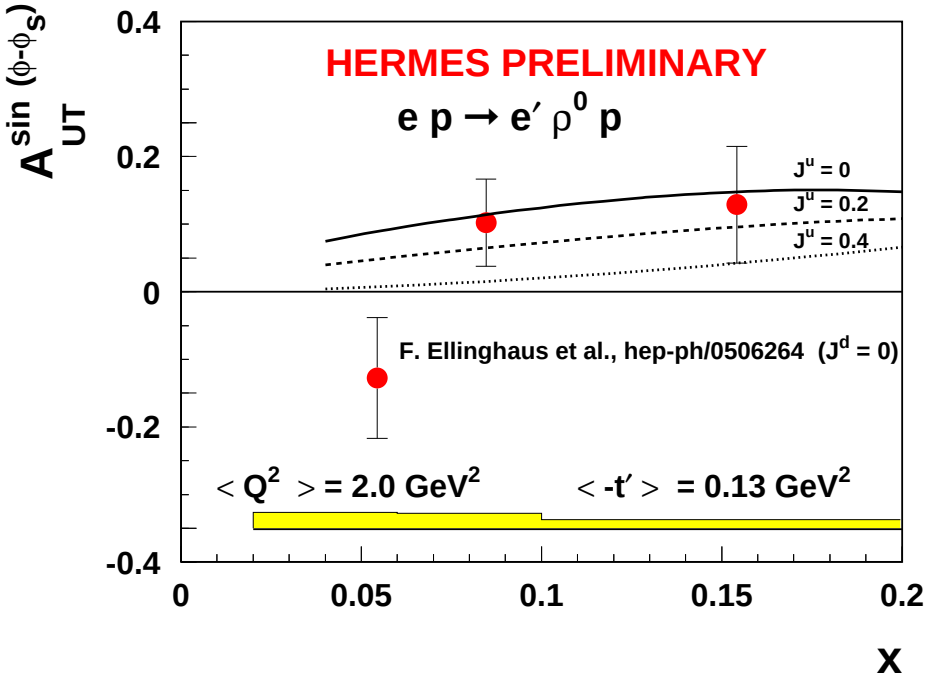




The GDP E in the transv. Target-Spin Asymmetry

$$A_{UT}(\phi,\phi_s) = \frac{1}{|P_T|}\cdot\frac{d\sigma^{\Uparrow}(\phi,\phi_s)-d\sigma^{\Downarrow}(\phi,\phi_s)}{d\sigma^{\Uparrow}(\phi,\phi_s)+d\sigma^{\Downarrow}(\phi,\phi_s)} \propto H\,E\cdot\sin(\phi-\phi_S)$$





EXPECTED $\sin\phi$ BEHAVIOR

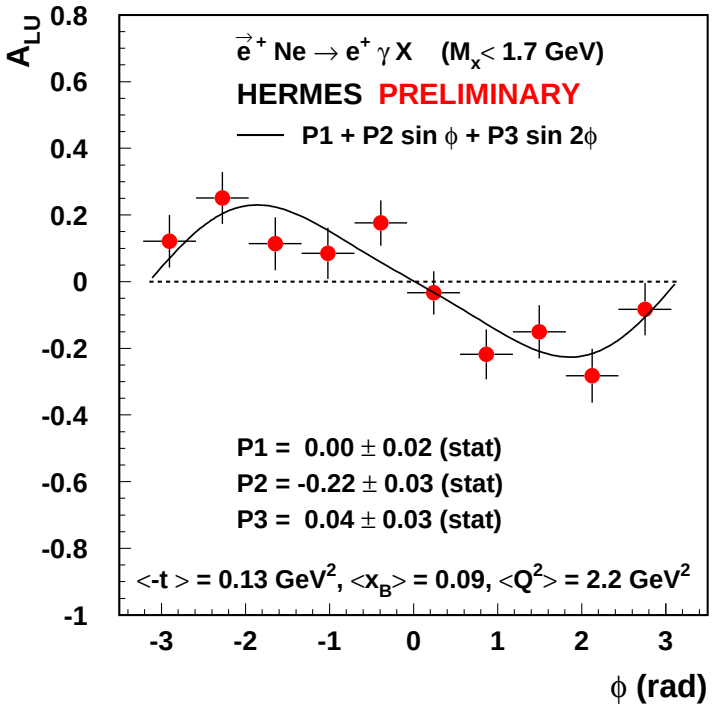
AGREEMENT WITH THEORETICAL CALCULATION.

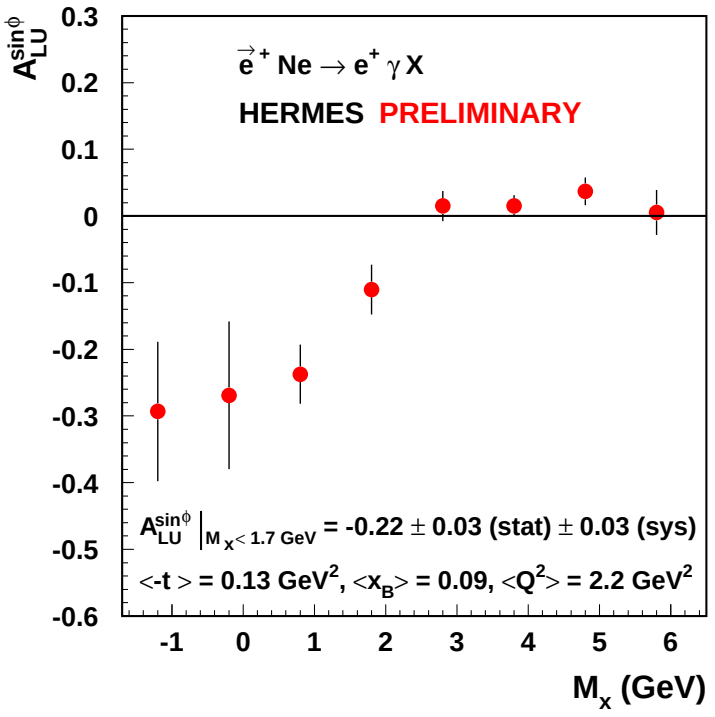
(CALCULATION/FACTORIZATION PROOF FOR LONGITUDINAL PHOTONS ONLY)

AGAIN: SAME SIZE DATA SET TO COME, A_{UT}^{ρ} LESS SENSITIVE TO J_u WHEN COMPARED TO A_{UT}^{DVCS} $\rightarrow$ PROVIDE ADDITIONAL CONSTRAINTS

REMARK: Q^2 MIGHT BE TOO SMALL $\Rightarrow$ *EIC*

Investigate the internal structure of Nuclei





DVCS on Neon (hep-ex/0212019) triggered first calculations for DVCS on Nuclei (Kirchner, Müller, hep-ph/0302007, Guzey, Strikman, hep-ph/0301216, ...)

A-dependence of BSA (H, D, 4He, N, Ne, Kr, Xe) separately for coherent and incoherent production coming very soon!

Summary

- Hard exclusive processes probe GPDs
  Results so far in general agreement with basic models and assumptions.

- 2006/2007 data taking (+Recoil Detector) devoted to exclusive reactions:
  → "map out" GPD H^u via DVCS Beam-Spin and Beam-Charge Asymmetry

- DVCS on transverse polarized target:
  First model dependent constraint on the total angular momentum of u-quarks (J_u) and d-quarks (J_d) in the nucleon.

- Final remark: Orbital angular momentum sum rule needs $t \to 0$
  Hermes measurements on GPD E at "small" t will not be precise
  JLab@12 will yield precision measurements at "large" t

$\Rightarrow$ EIC