Can the orbital angular momentum of u-quarks in the nucleon be accessed at HERMES?

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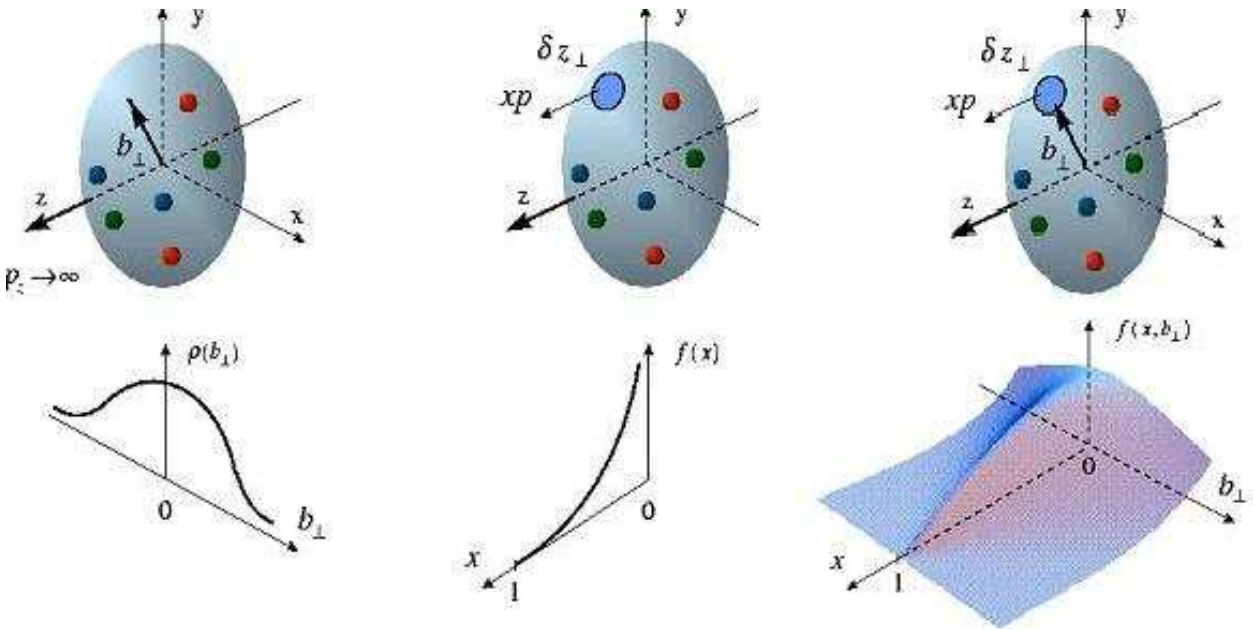
Spin Discussion , BNL, February 2006

- Generalized Parton Distributions (GPDs)
- Exclusive Production of Photons (DVCS)
- Exclusive Production of Vector Mesons
- Can the OAM of u-quarks in the N be accessed at HERMES?
  (F.E., W.-D. Nowak, A. Vinnikov, Z. Ye, accep. by EPJC, hep–ph/0506264)

GPDs: Parameterization of the Nucleon Structure

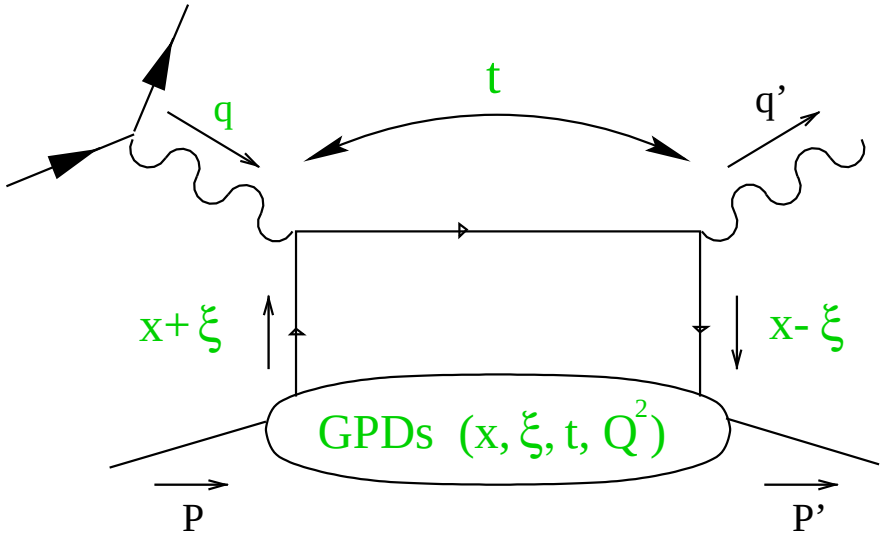


FF **PDF** **GPD**

- 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):

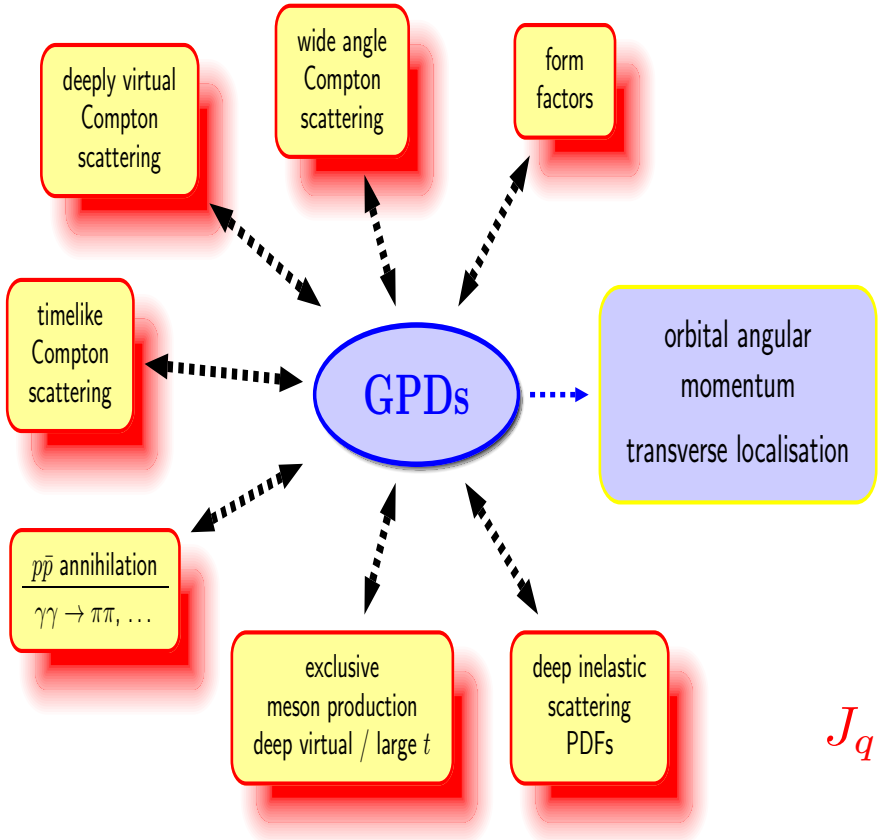


- Longitudinal momentum fractions:
  $x \in [-1, 1]$ (not accessible)
  $\xi \approx x_B/(2 - x_B)$
- $t = (q - q')^2$
  ($\gamma^* \to \gamma$ Momentum transfer)
- $Q^2 = -q^2$

$\Rightarrow$ 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:

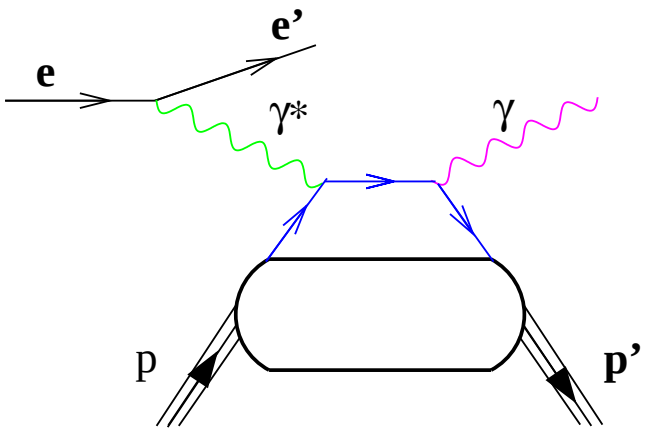
$$J_q = \lim_{t\to 0} \frac{1}{2} \int_{-1}^{1} dx\, x\, [H^q(x,\xi,t) + E^q(x,\xi,t)]$$

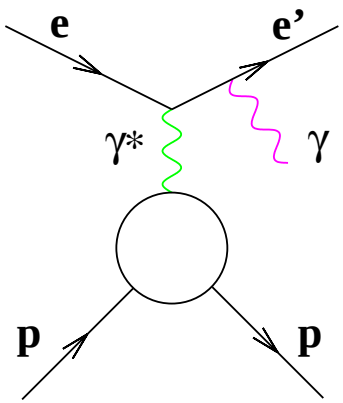
(Original) HERMES Motivation:

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

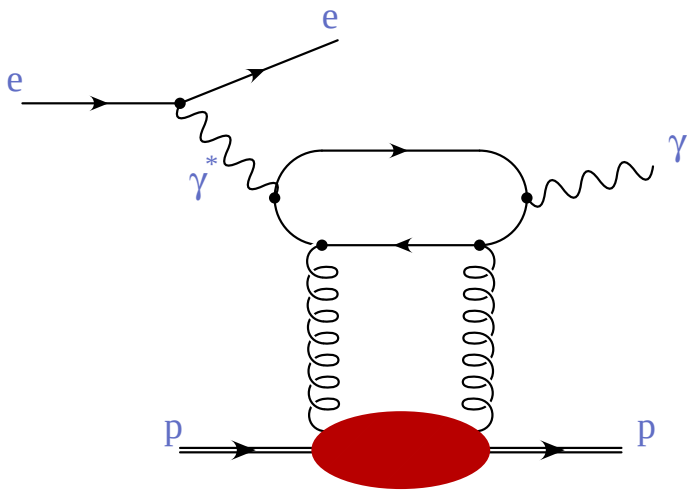
HowTo Access GPDs via DVCS?

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

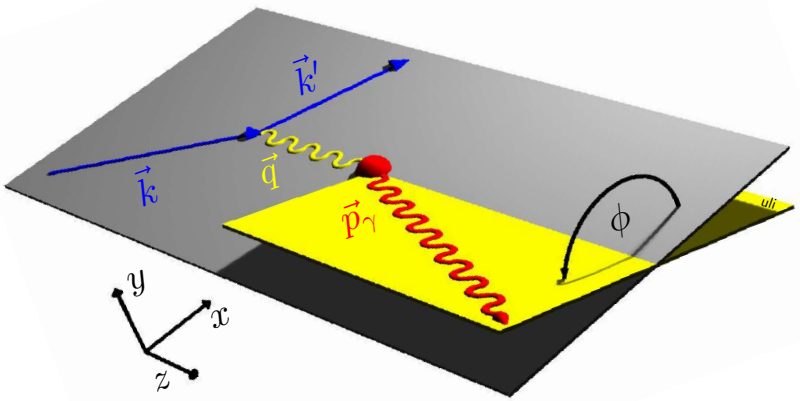
$$d\sigma \propto |\tau_{\mathrm{BH}}|^2 + \underbrace{(\tau^*_{\mathrm{DVCS}}\tau_{\mathrm{BH}} + \tau^*_{\mathrm{BH}}\tau_{\mathrm{DVCS}})}_{I} + |\tau_{\mathrm{DVCS}}|^2$$

$|\tau_{\mathrm{BH}}|^2$ 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:

$$\text{BSA}: \quad d\sigma(\overrightarrow{e^+}p) - d\sigma(\overleftarrow{e^+}p) \sim s_{1,unp}^I \sin(\phi) \sim \sin(\phi) \times \mathrm{Im}\, M_{unp}^{1,1}$$

$$\text{BCA}: \quad d\sigma(e^+p) - d\sigma(e^-p) \sim c_{1,unp}^I \cos(\phi) \sim \cos(\phi) \times \mathrm{Re}\, M_{unp}^{1,1}$$

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

Longitudinal Target–Spin Asymmetry (LTSA)

$$\text{LTSA}: \quad d\sigma(e^+\overleftarrow{p}) - d\sigma(e^+\overrightarrow{p}) \sim s_{1,LP}^I \sin(\phi) \sim \sin(\phi) \times \mathrm{Im}\, M_{LP}^{1,1}$$

(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

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

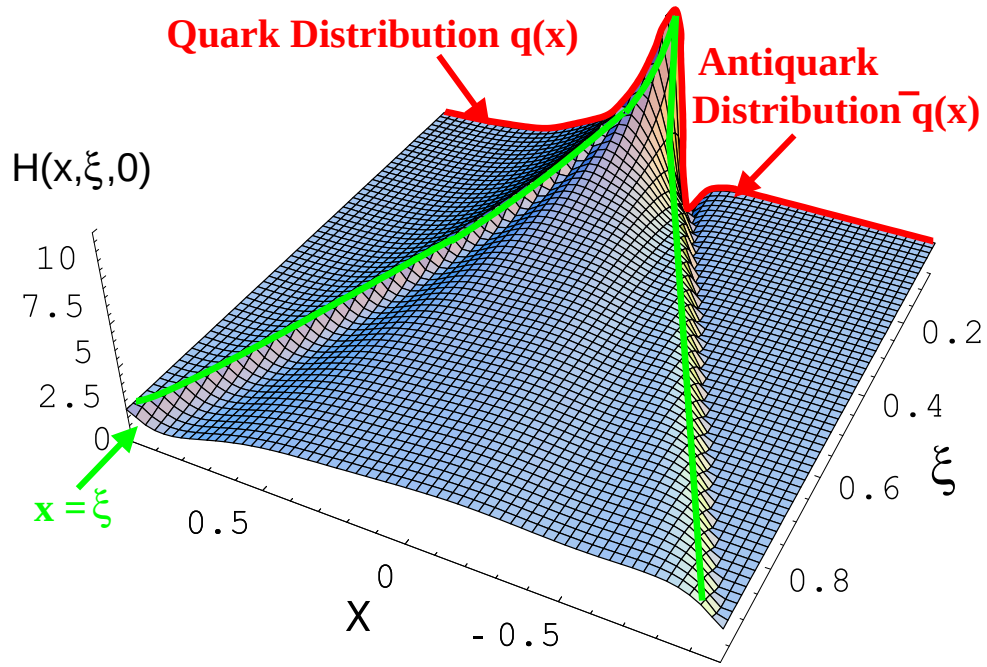
$$\mathrm{Re}\, H_1 \sim \sum_q e_q^2 \left[P \int_{-1}^{1} H^q(x,\xi,t) \left(\frac{1}{x-\xi} + \frac{1}{x+\xi} \right) dx \right]$$

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

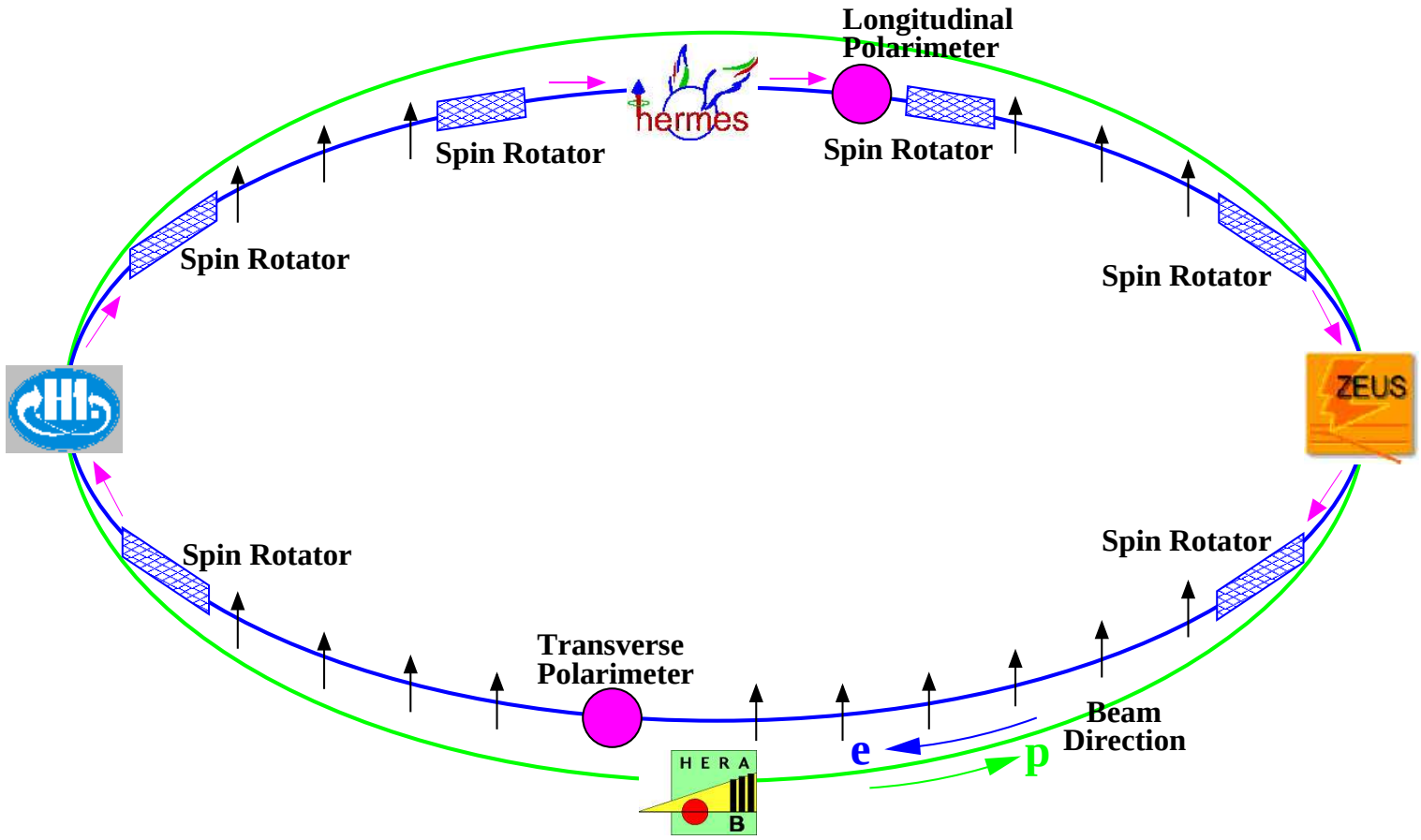


(Goeke, Polyakov, Vanderhaeghen, hep-ph/0106012)

Need both charges and polarized beam
$\Rightarrow$ HERA!!!

The HERA accelerator at DESY

The HERA Accelerator

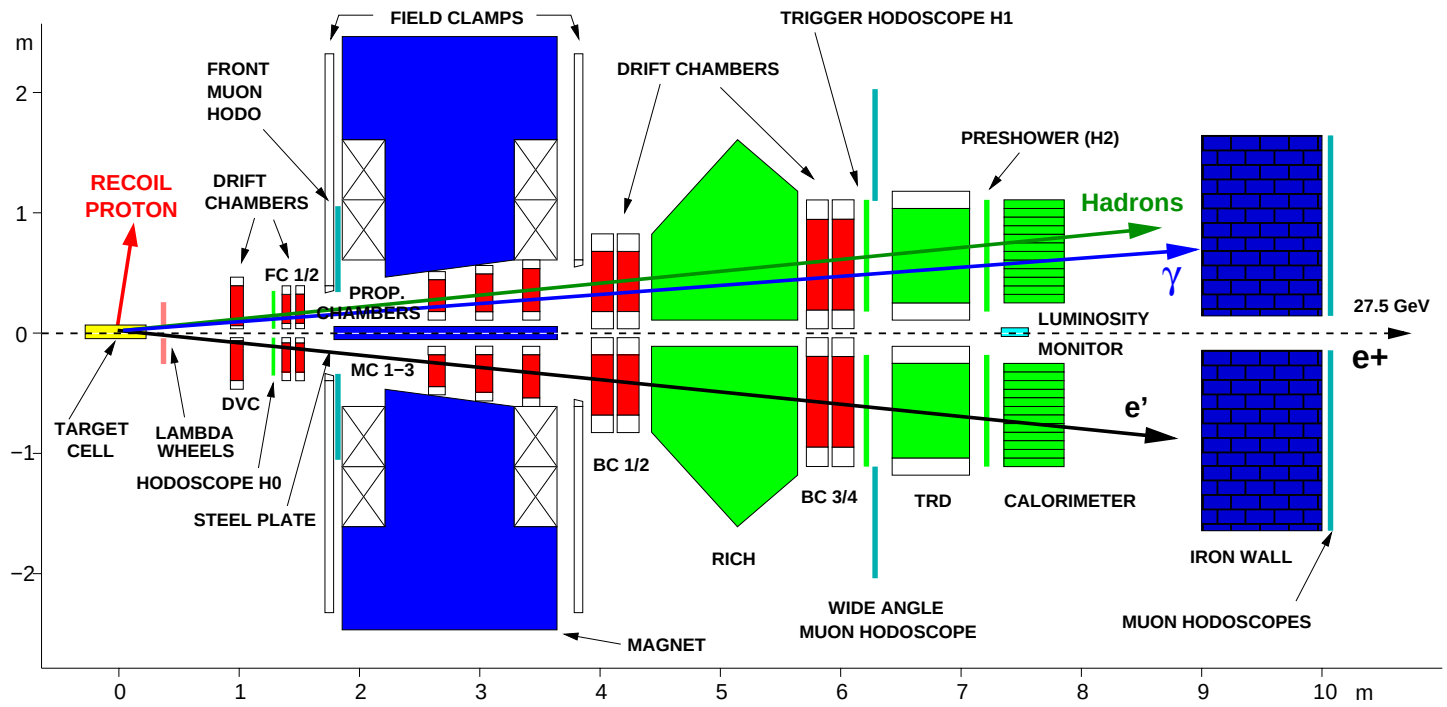


Beam: 27.6 GeV, e^+ or e^-, $\langle P \rangle \approx 55\%$

HERMES Event Selection

UNPOL.
GAS TARGETS:
H/D/NE/KR/..

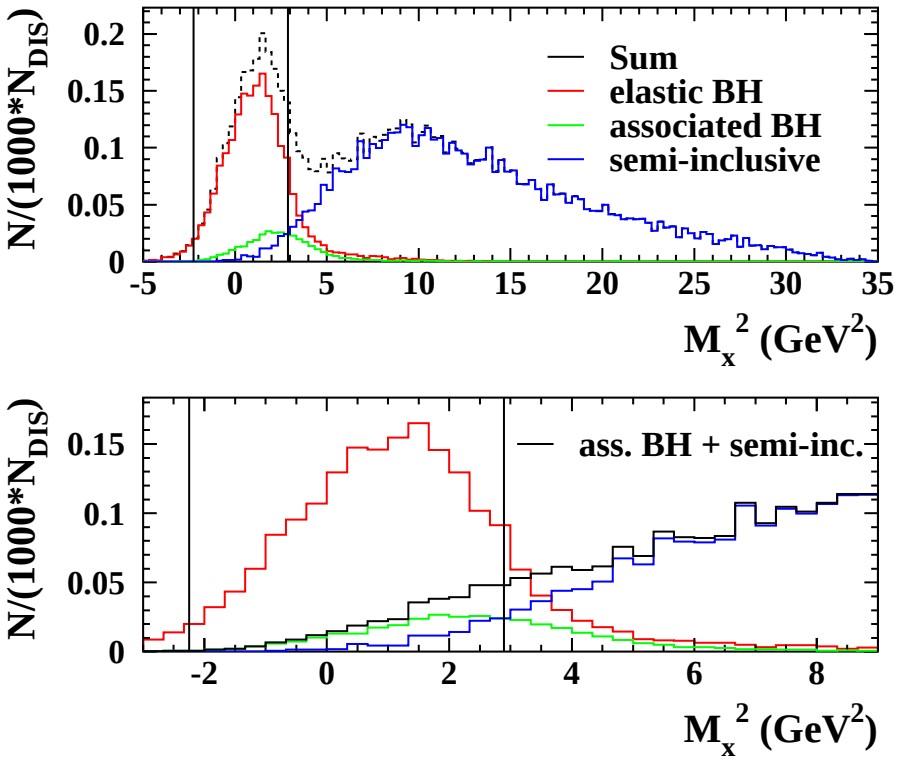
POL.
GAS TARGETS:
H/D



- EVENTS WITH EXACTLY ONE DIS-POSITRON/DIS-ELECTRON AND EXACTLY ONE TRACKLESS CLUSTER IN THE CALORIMETER (OR ONE ($\rho^0 \rightarrow$) $\pi^+\pi^-$ PAIR)
- CUTS ON SCATTERED LEPTON: $Q^2 > 1$ GeV^2, ...
- 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)!



Processes taken into account:

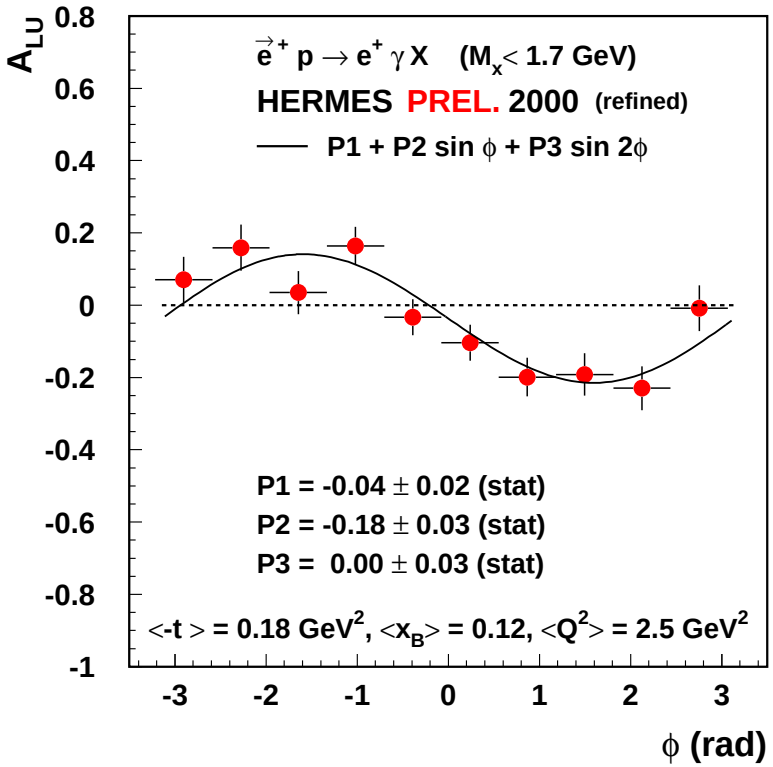
- elastic BH/DVCS ($e\,p \rightarrow e'\,p'\,\gamma$)
- associated BH/DVCS (mainly $e\,p \rightarrow e'\,\Delta^+\,\gamma$)
- semi–inclusive (mainly $e\,p \rightarrow e'\,\pi^0\,X$)

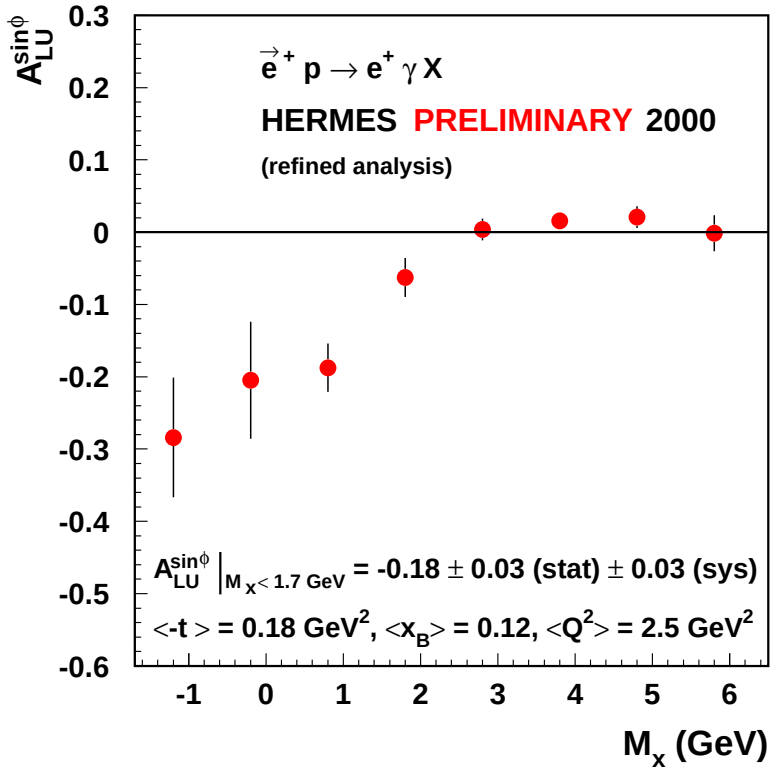
$\Rightarrow$ "Exclusive" bin (-1.5 $< M_x <$ 1.7 GeV)

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

Beam–Spin Asymmetry (BSA)

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





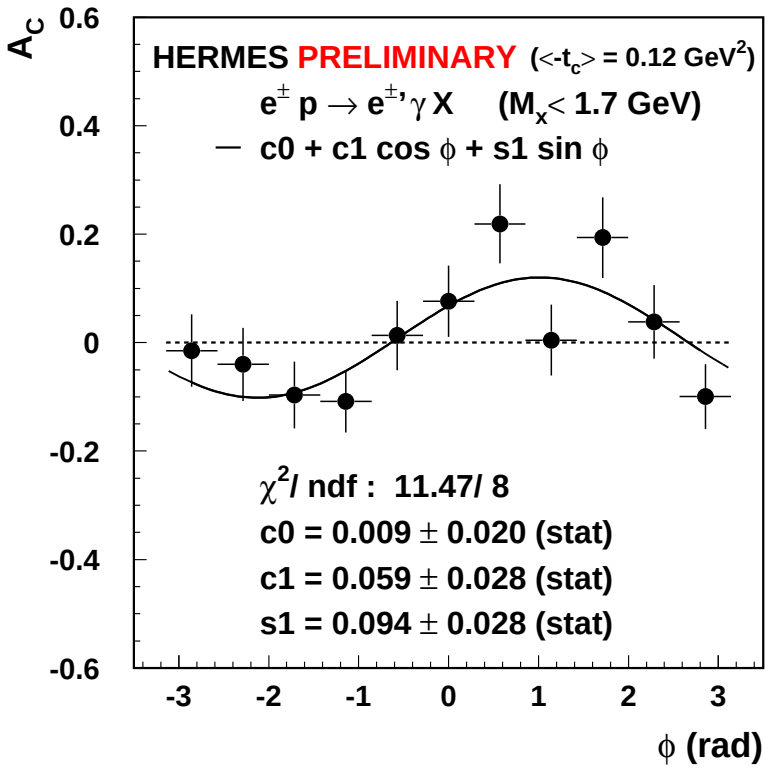
A_{LU} in exclusive bin: Expected $\sin(\phi)$ dependence $\Rightarrow \mathrm{Im}\, M^{1,1}_{unp}$

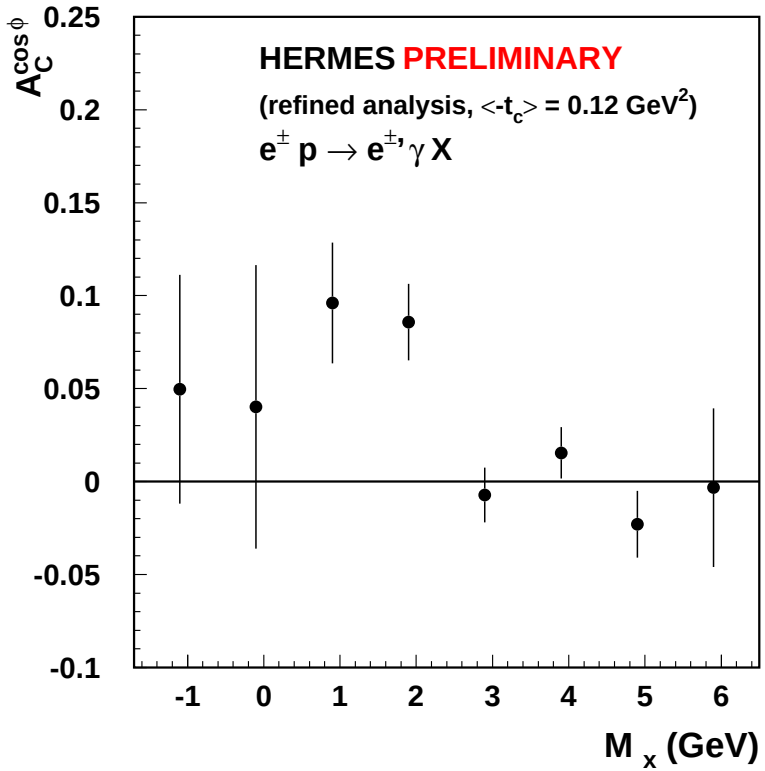
$\sin(\phi)$–Moment in non–exclusive region: small and slightly positive ($\to \pi^0$)

(Results from 1996/97 $\to$ PRL **87**, 182001 (2001))

Beam–Charge Asymmetry (BCA)

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



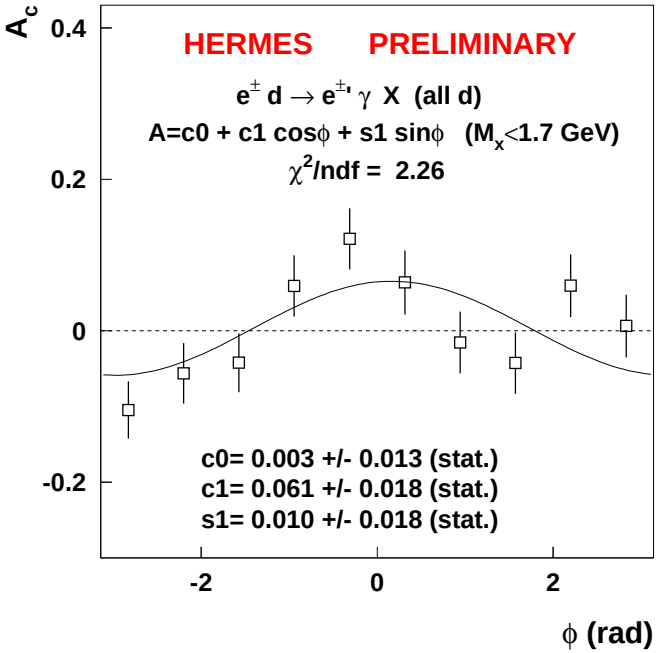


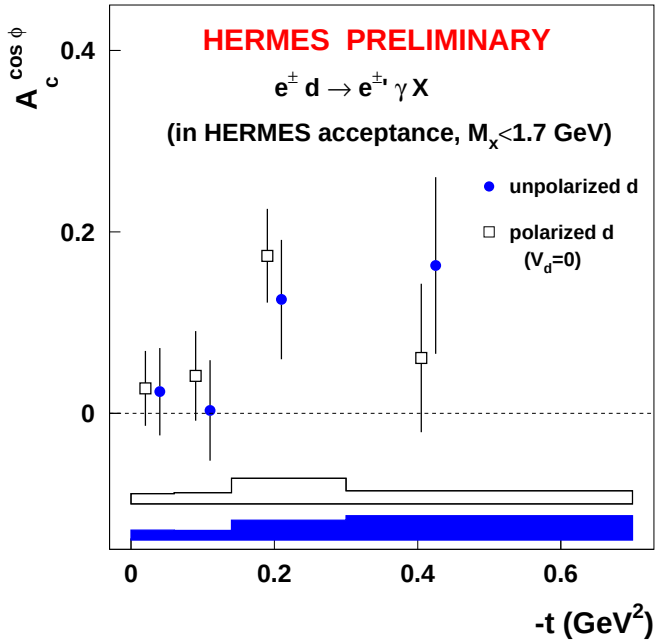
A_C in exclusive bin: Expected $\cos(\phi)$ dependence $\Rightarrow \mathrm{Re}\, M_{unp}^{1,1}$

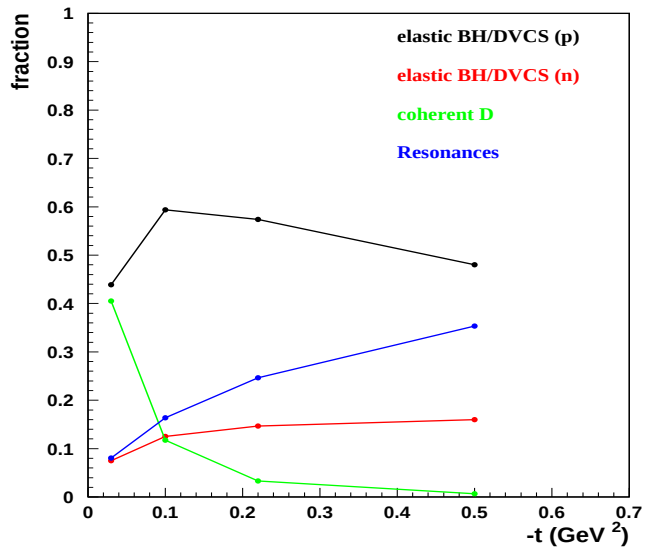
$\sin\phi$ due to polarized beam

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

Beam–Charge Asymmetry (BCA) on Deuterium

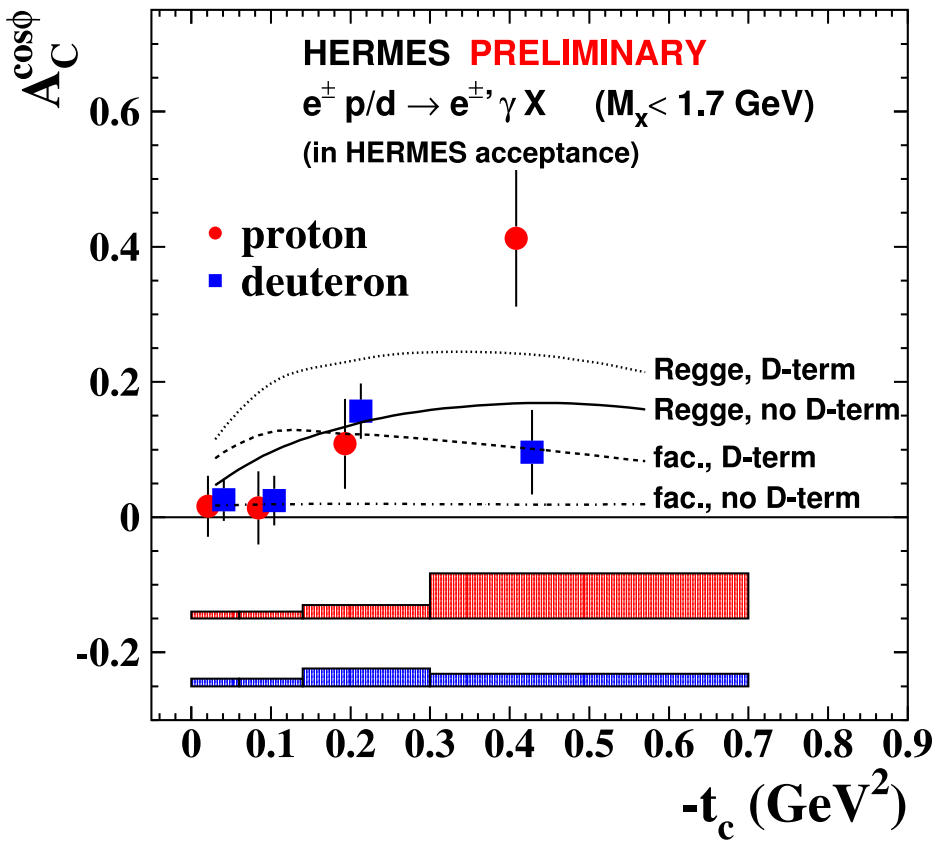






- $A_C^{\cos\phi}(d) \approx A_C^{\cos\phi}(p)$
- Spin-1 particle → 9 GPDs, but coherent production only ≈ 20%
- 40% coherent in first t-bin
  ⇒ no Tensor effect seen
  ⇒ Data can (indeed) be combined

Beam–Charge Asymmetry (BCA) versus t



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 (Vanderhaeghen et al.) calc. at average kinematic values per bin

Data averaged over x_B, Q^2 range $\rightarrow$ Model curves can change up to 20% (model dep.) when calc. at real events kinematics

tiny e^-p sample ($L \approx 10$ pb^{-1})

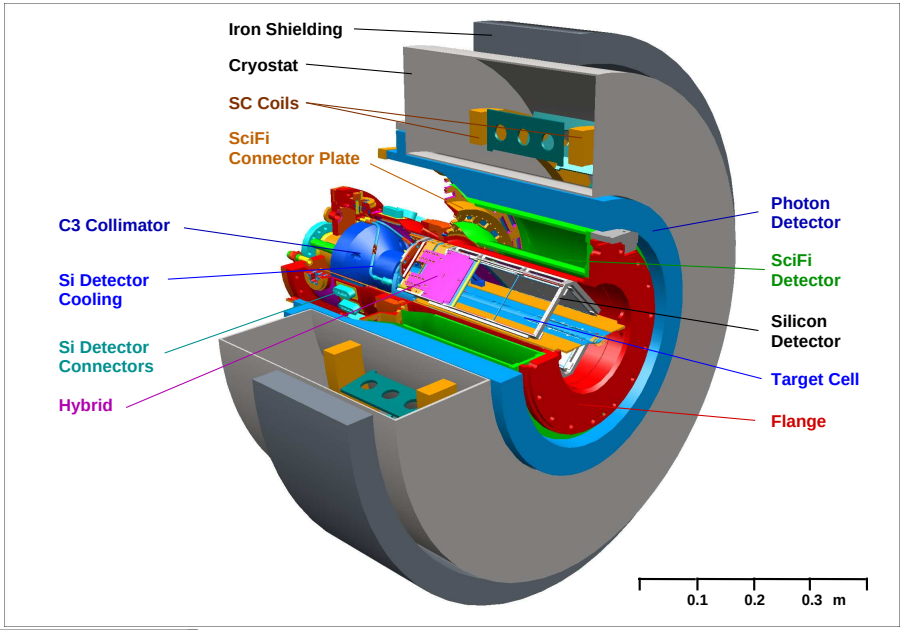
If multidimensional binning possible (Statistics !) or fast generator/lookup-table available

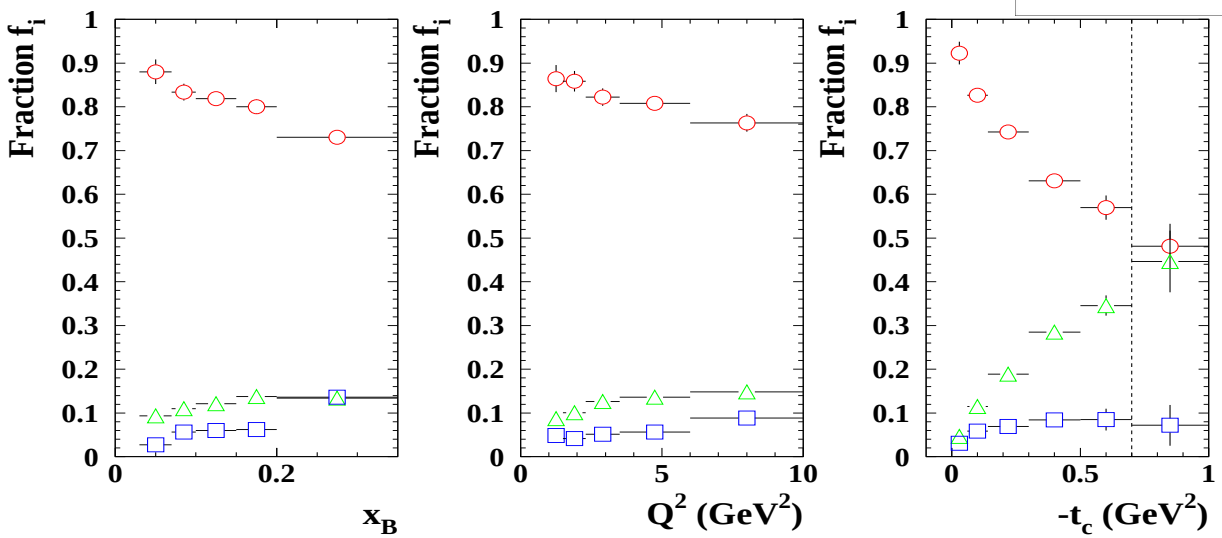
$\Rightarrow$ t–dependence of BCA has high sensitivity to GPD models!

More on H to come

Recoil Detector and unpol. Targets (2006/2007)

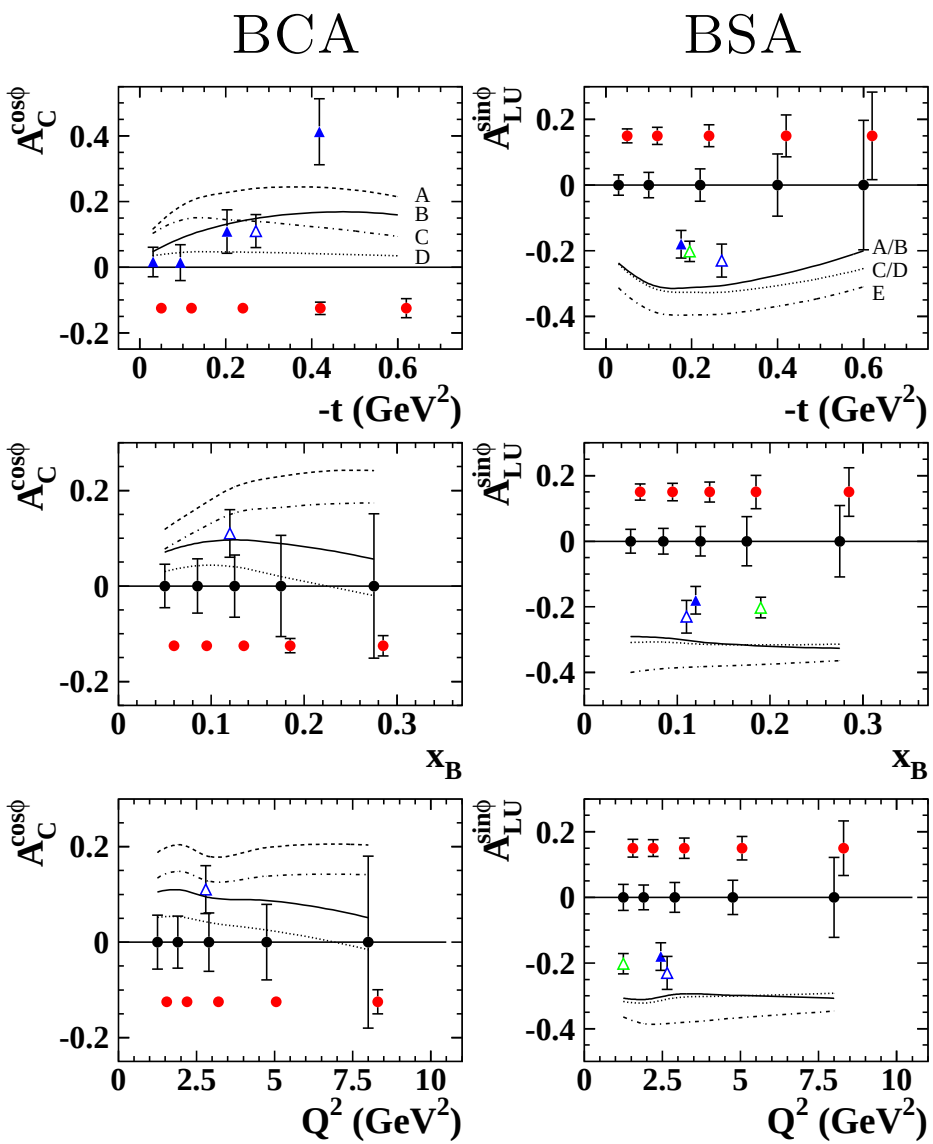
- ensures exclusivity of events
  - Semi–inclusive background 5% ⇒ ≪ 1%
  - Associated background 10% ⇒ ≈ 1%





⇒ Essential at larger $-t$ values

The GPD H, Summary and Outlook



△: HERMES prelim./published

△: CLAS, PRL, 2001 ($\times -1$)

● Hydrogen data (1996-2000), Analysis almost completed

● BCA: $1fb^{-1}\,e^+$ and $1fb^{-1}\,e^-$

● BSA: $1fb^{-1}\,e^+$, Pol. = 40%

(exp. 2006/2007 Recoil 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.

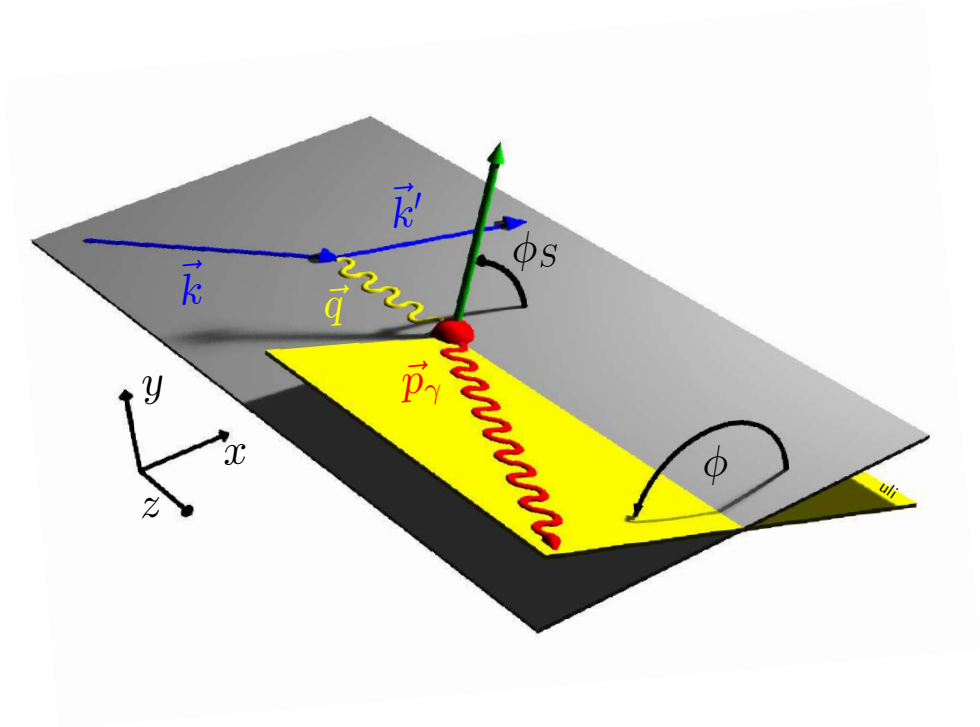
What about the GDP E ?

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 is always kinematically suppressed, except in:

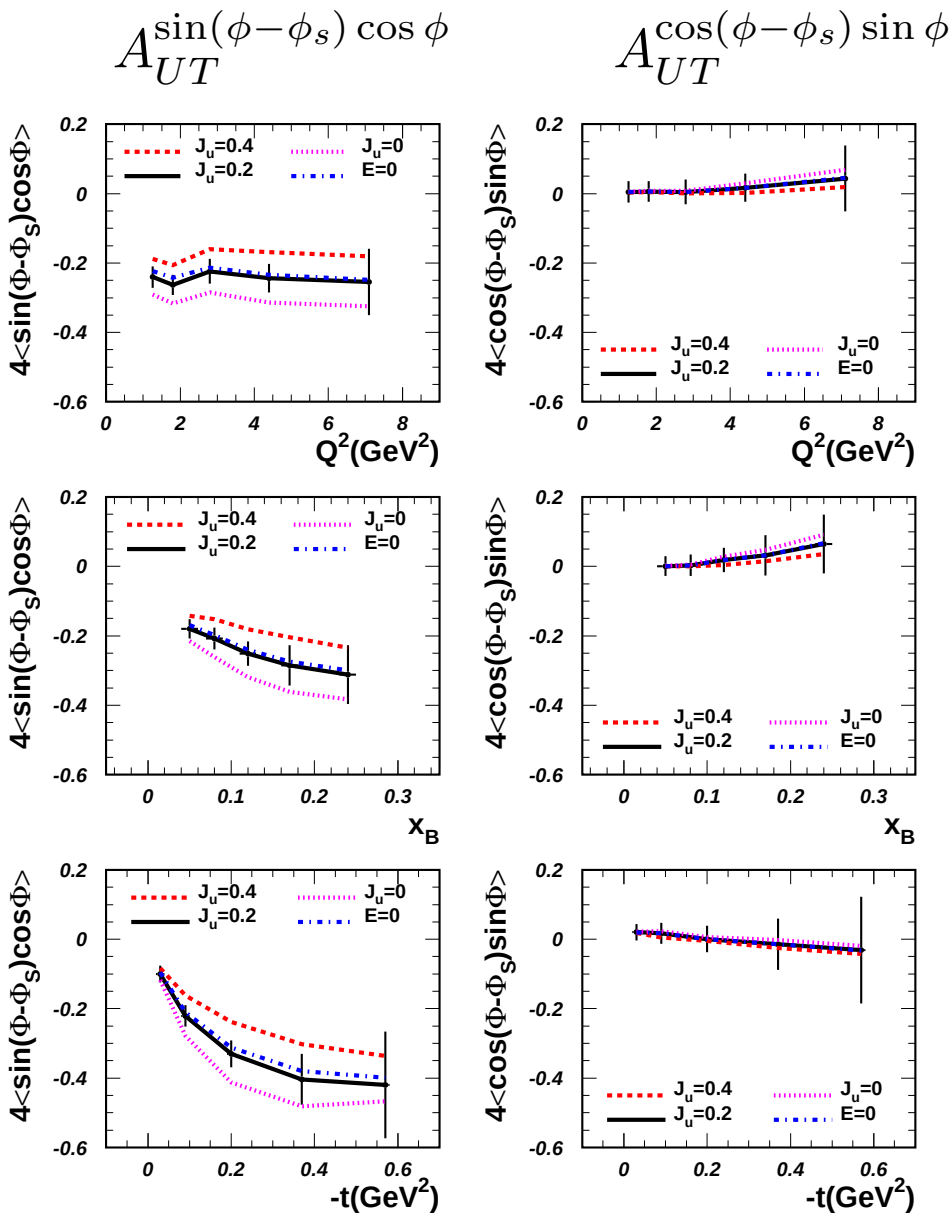
A_{UT}: unpolarized beam,
transversely pol. target



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

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

Can it? Projection for transverse Target-Spin Asy.



Assumed: 8 million DIS, Target Pol. 75%

Change model parameters only for E ($\rightarrow J_u$)

$\rightarrow$ only $A_{UT}^{\sin(\phi-\phi_s)\cos\phi}$ sensitive

After GPD H^u well known $\Rightarrow$

- E=0 "baseline" known
- some/many model par. are the same for H and E !?!

Surprise: $A_{UT}^{\sin(\phi-\phi_s)\cos\phi}$ largely independent on all model par. but J_u!

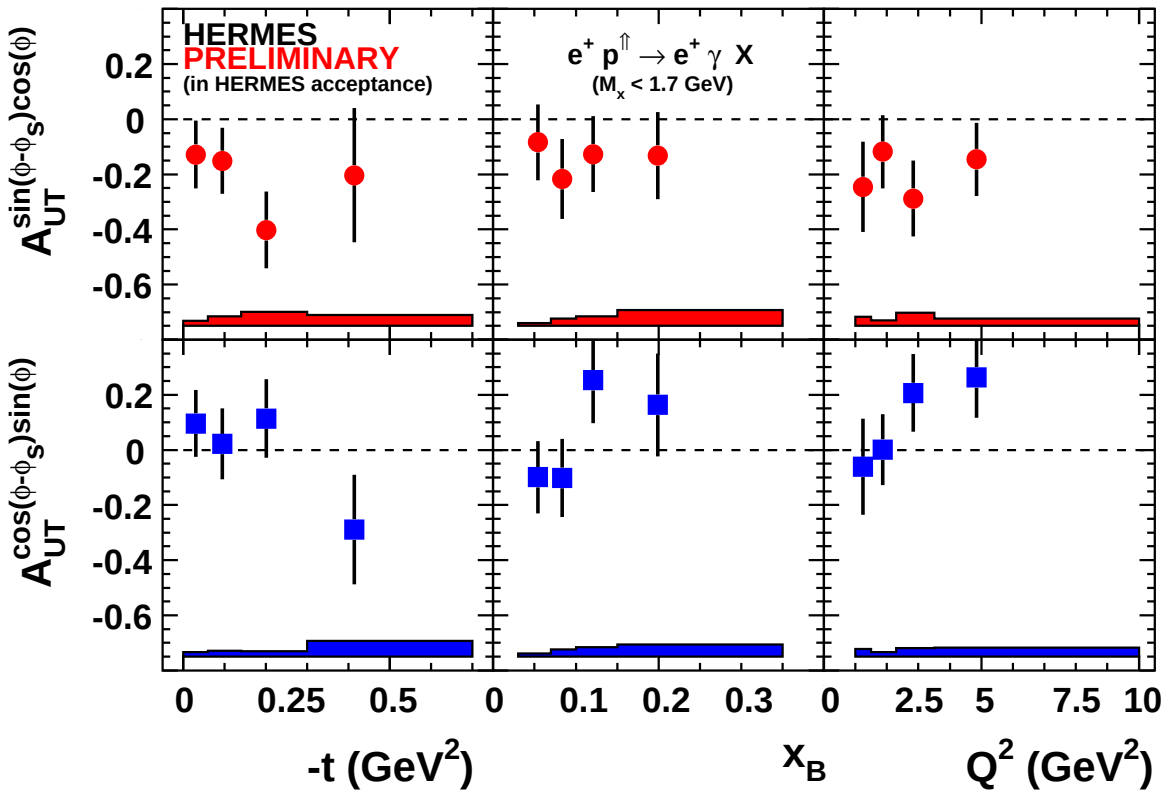
Models show same kin. dep.

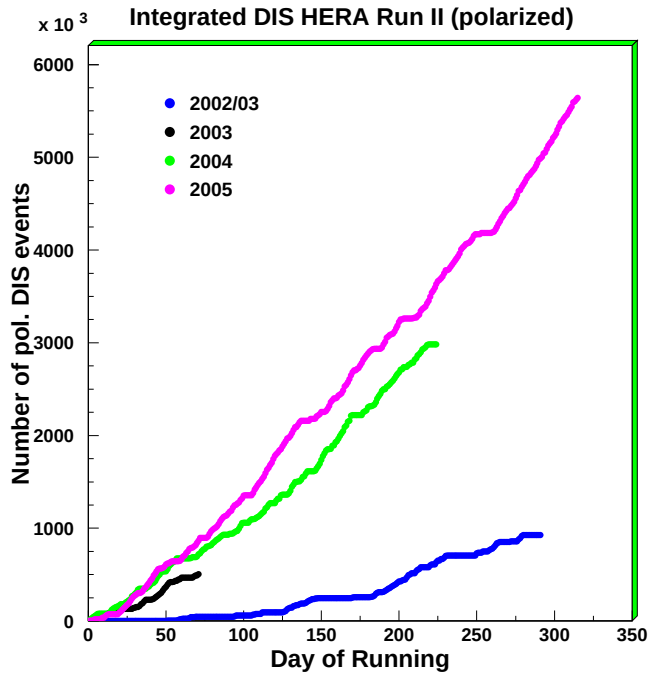
$\Rightarrow$ integrate over kinematics

$\Rightarrow$ 4σ difference (total exp unc.) between $J_u = 0.4$ and 0.0

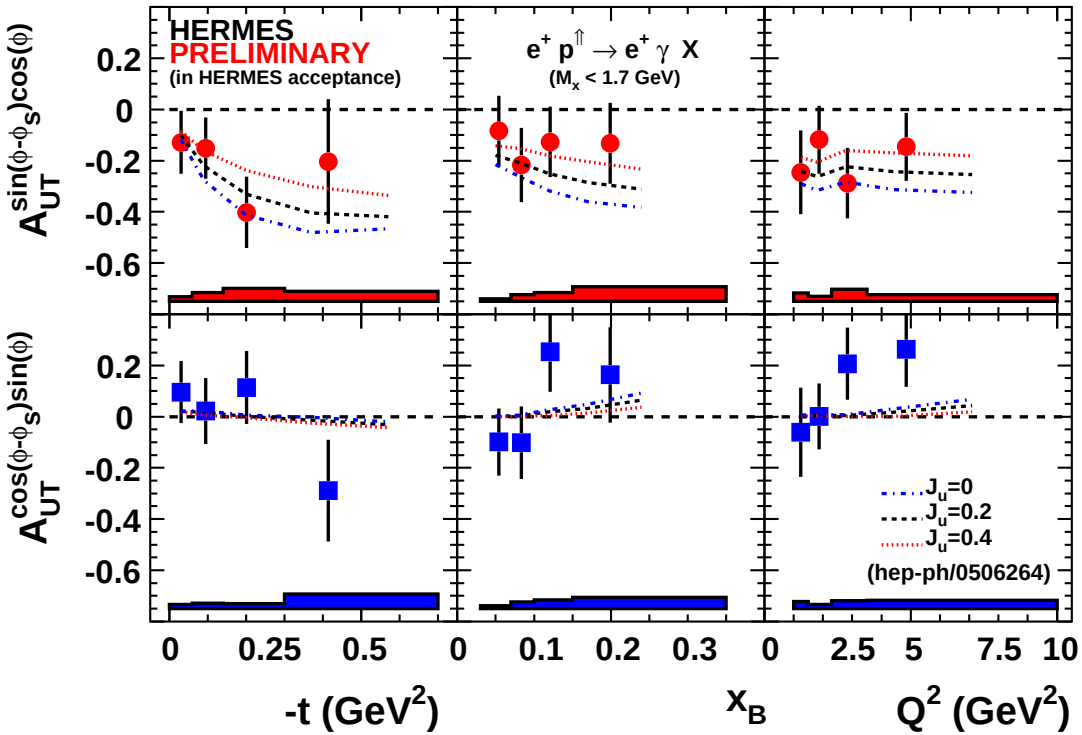
First result on DVCS TTSA!

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





DVCS TTSA compared to the Model Calculations!



$\Rightarrow$ First model dependent extraction of J_u!

preliminary: $J_u \approx 0.37 \pm 0.24$ (Assume $J_d = 0$, u-quark dominance)

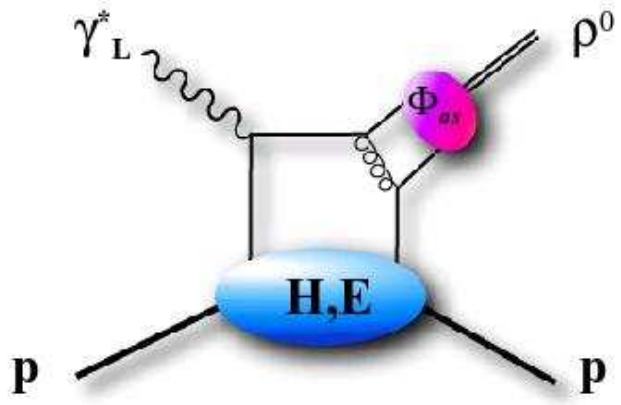
Recent Lattice QCD Results: $J_u = 0.37 \pm 0.06$, $J_d = -0.04 \pm 0.04$
(Goeckeler et al., PRL 92, 2004), similar results in other lattice calc.

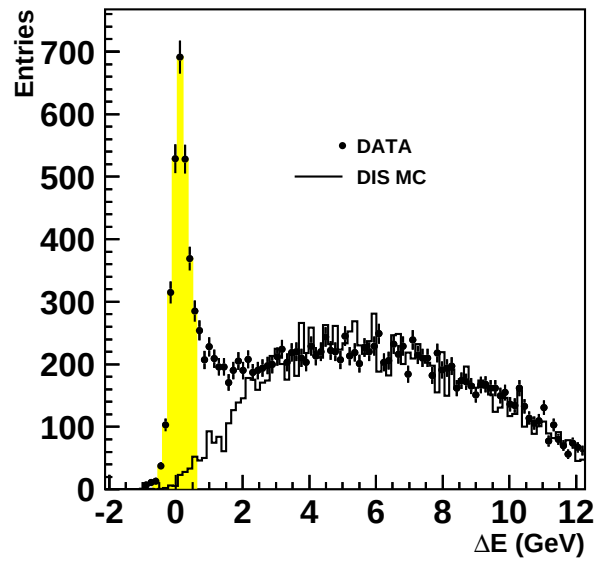
Work in Progress: No assumption on $J_d \to$ two-dim fit

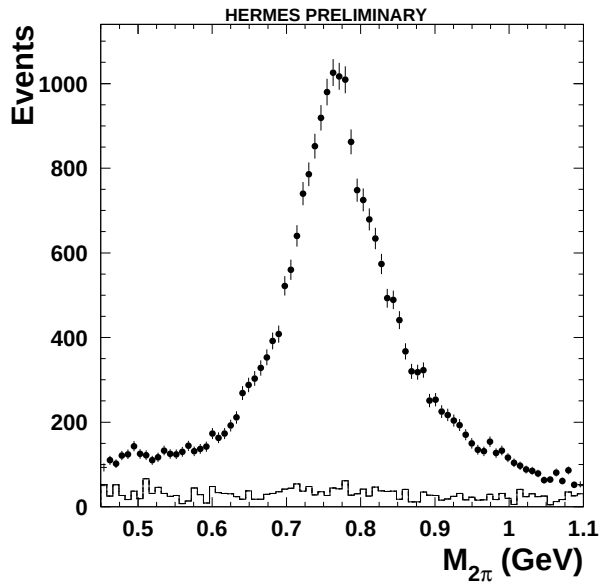
Exclusive Vector Meson Production

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

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





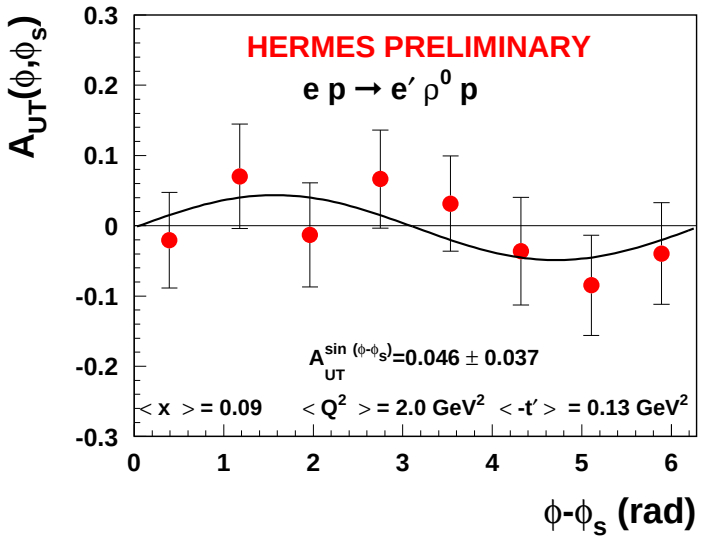


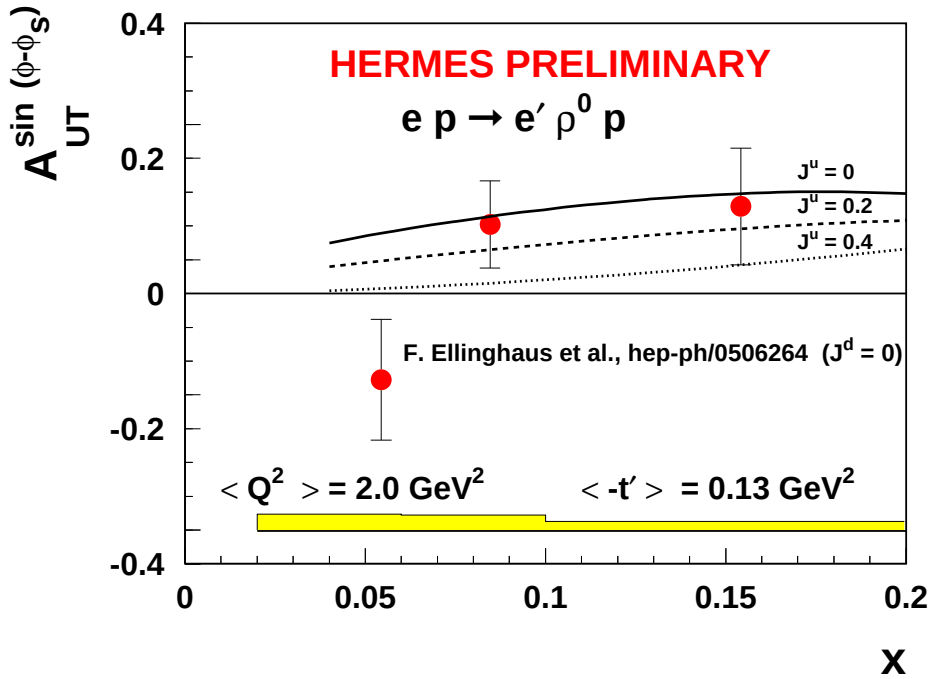
Event selection:

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

The GDP E in the transv. Target-Spin Asymmetry

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



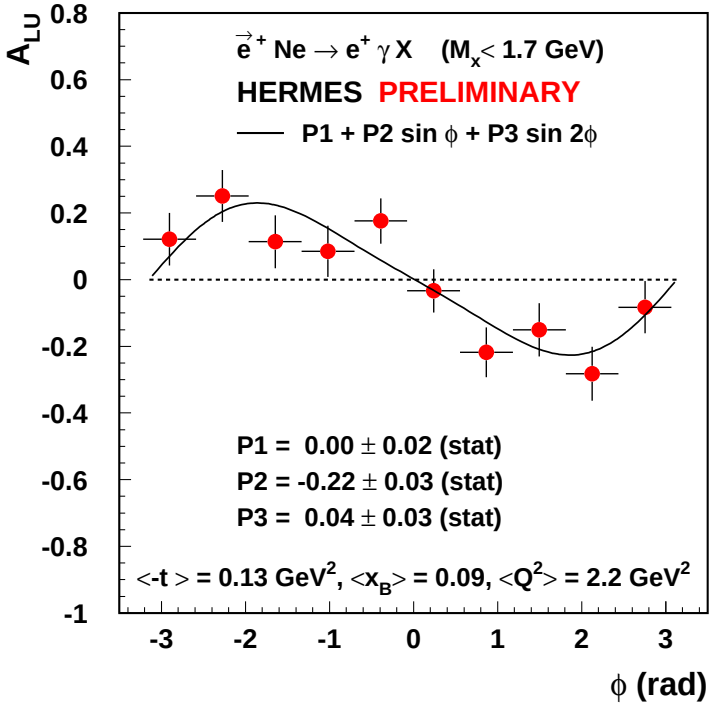


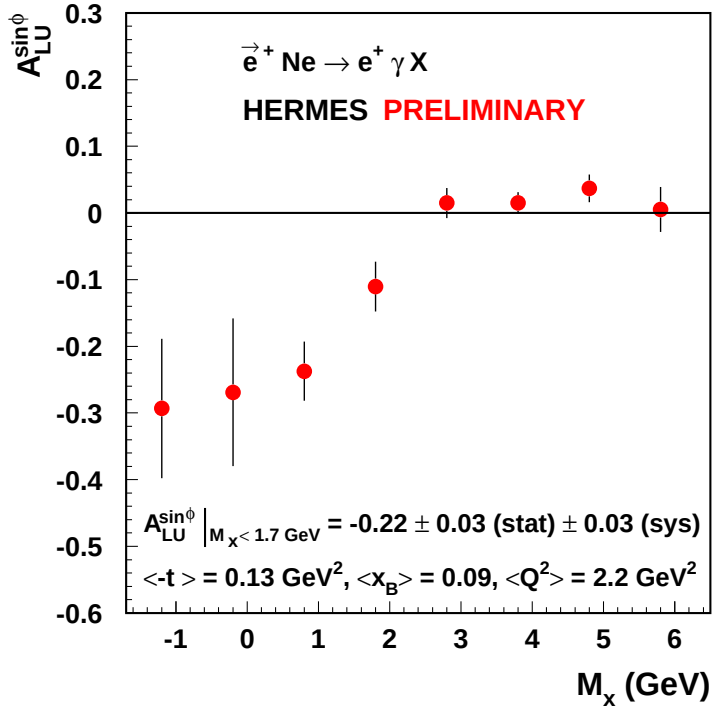
expected $\sin\phi$ behavior
(no L/T separation yet)

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

Investigate the internal structure of Nuclei





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

Goal: A-Dependence of BSA (H, D, Ne, Kr, Xe) and BCA (H, D, Kr, Xe). BSA results 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:
  $\rightarrow$ "map out" GPD H^u via DVCS Beam-Spin and Beam-Charge Asymmetry (Primary Goal $\leftrightarrow$ unpolarized target)
- BCA especially sensitive to model parameters.
- First (model dependent) extraction of J_u (preliminary, $J_u = 0.37 \pm 0.24$) in agreement with results from lattice QCD calc.
- Final statistics factor 2 higher, 2 dim-fit in progress, GPD H_u will be 'known' $\Rightarrow$ Significant constraint on J_u expected!