Exclusive Reactions at HERMES

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for the HERMES–Collaboration

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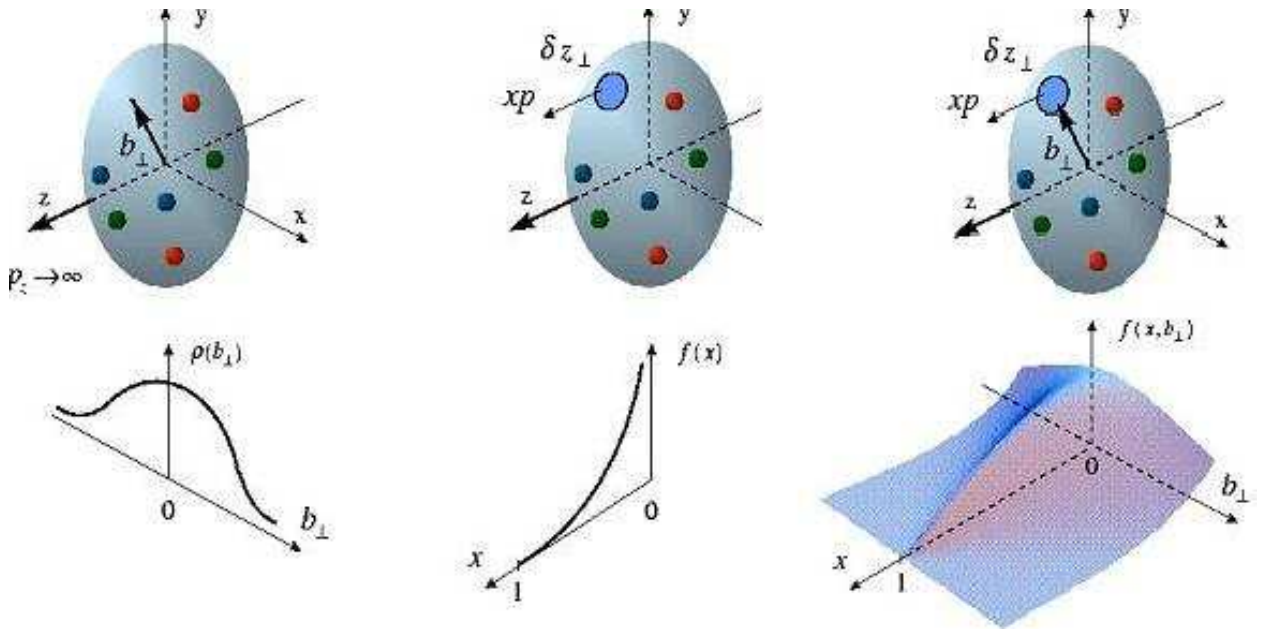
- Exclusive Physics and Generalized Parton Distributions (GPDs)
- Exclusive Photons (→ Azimuthal Asymmetries)
- Exclusive Vector Mesons (→ Transv. Target-Spin Asymmetry)
- Exclusive Pseudo-Scalar Mesons (→ Factorisation)
- Exclusive Reactions on Nuclei
- Summary and Outlook

GPDs: Parameterization of the Nucleon Structure

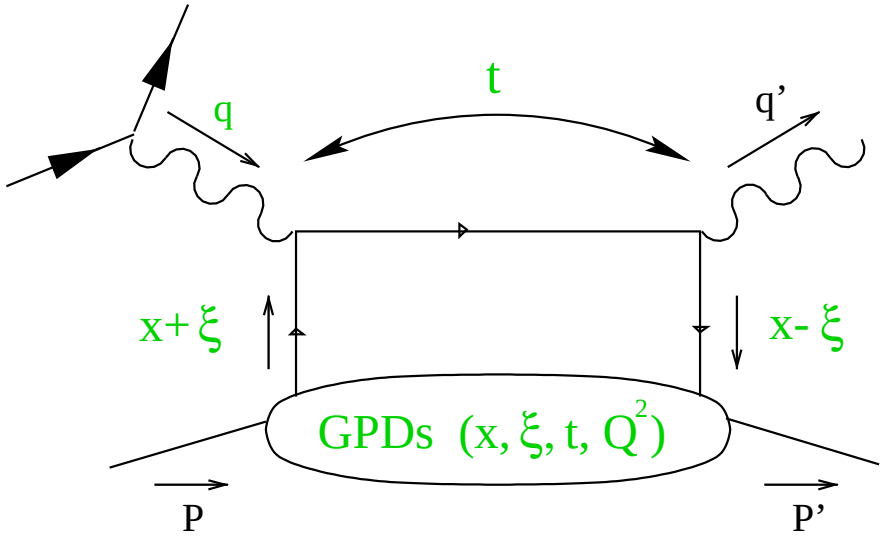


FF **PDF** **GPD**

- 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):

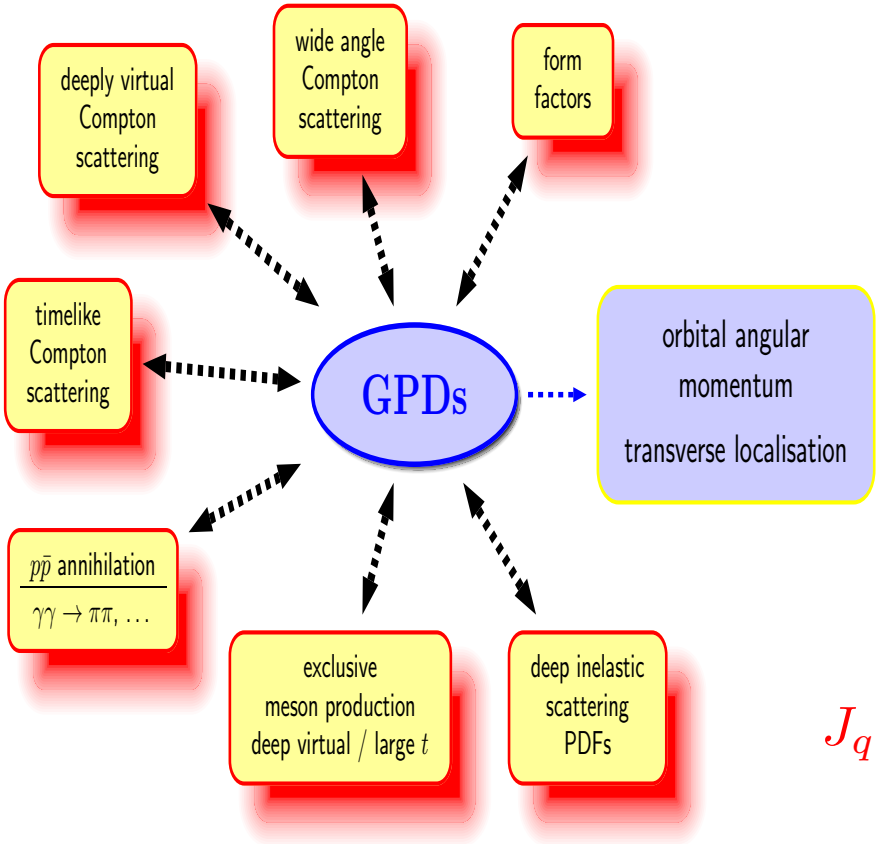


- Longitudinal momentum fractions:
  $x \in [-1, 1]$ (not accessible)
  $\xi \approx x_B/(2 - x_B)$
- $t = (q - q')^2$
  ($\gamma^* \to \gamma$ Momentum transfer)
- $Q^2 = -q^2$

$\Rightarrow$ 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:

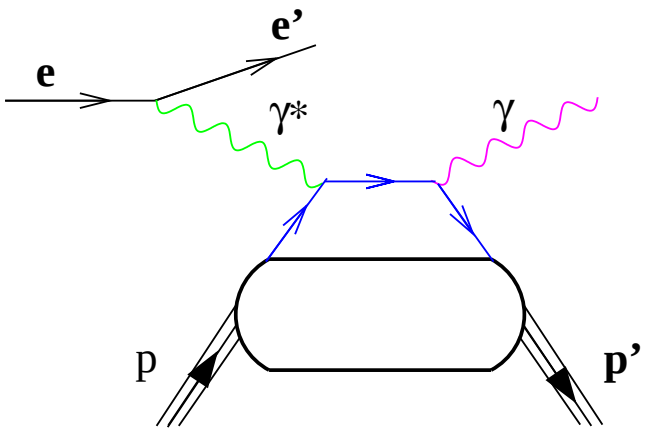
$$J_q = \lim_{t\to 0} \frac{1}{2} \int_{-1}^{1} dx\, x\, [H^q(x,\xi,t) + E^q(x,\xi,t)]$$

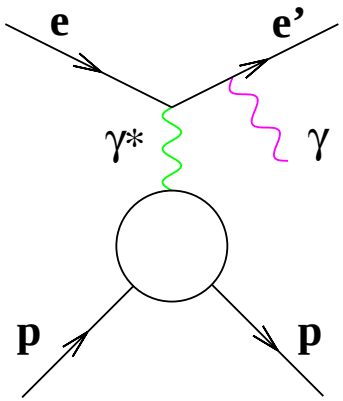
(Original) HERMES Motivation:

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

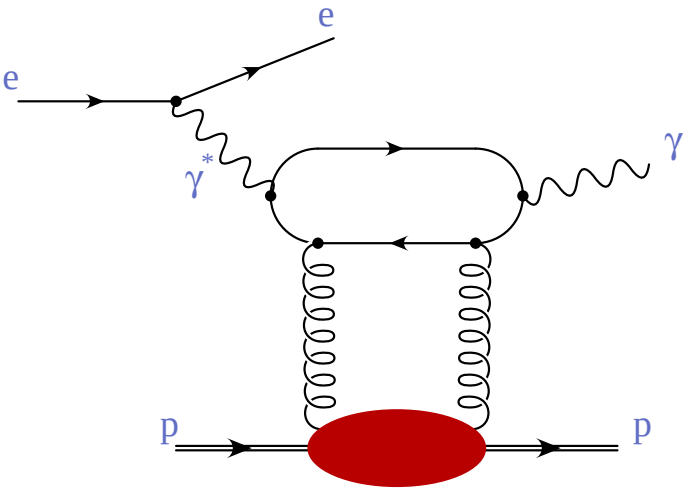
HowTo Access GPDs via DVCS?

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

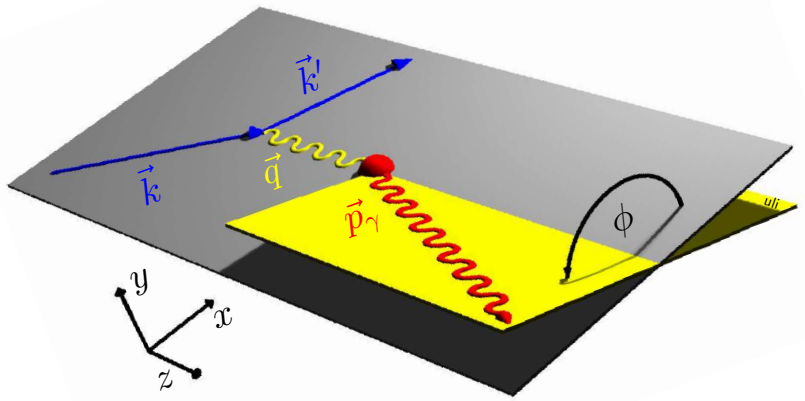
$$d\sigma \propto |\tau_{\mathrm{BH}}|^2 + \underbrace{(\tau^*_{\mathrm{DVCS}}\tau_{\mathrm{BH}} + \tau^*_{\mathrm{BH}}\tau_{\mathrm{DVCS}})}_{I} + |\tau_{\mathrm{DVCS}}|^2$$

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

Azimuthal asymmetries:
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

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

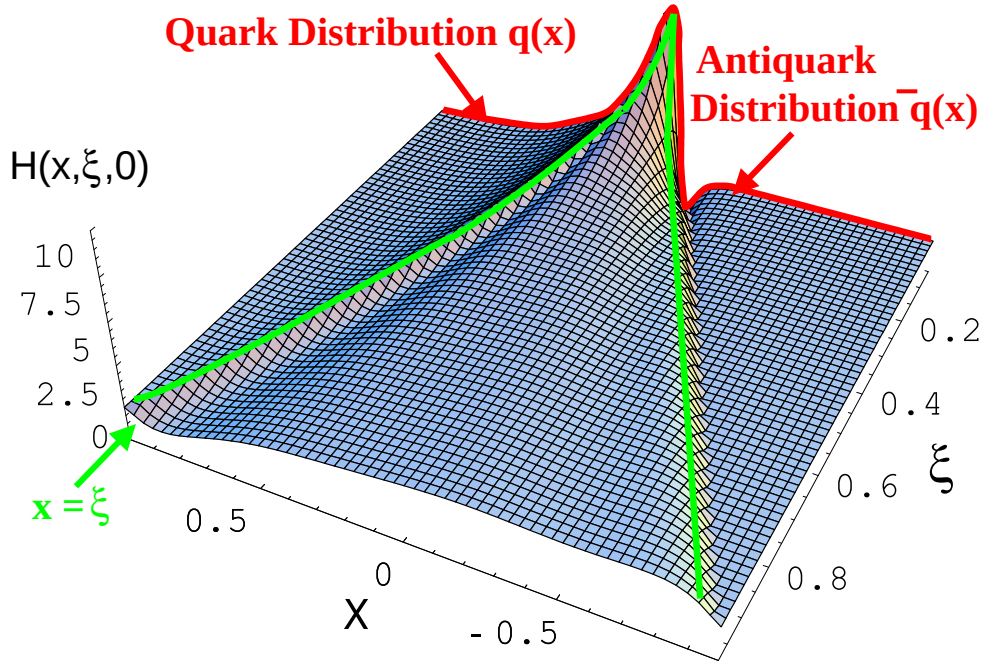
$$\mathrm{Re}\, H_1 \sim \sum_q e_q^2 \left[P \int_{-1}^{1} H^q(x,\xi,t) \left(\frac{1}{x-\xi} + \frac{1}{x+\xi} \right) dx \right]$$

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 charges and polarized beam
⇒ HERA!!!

HERMES Event Selection

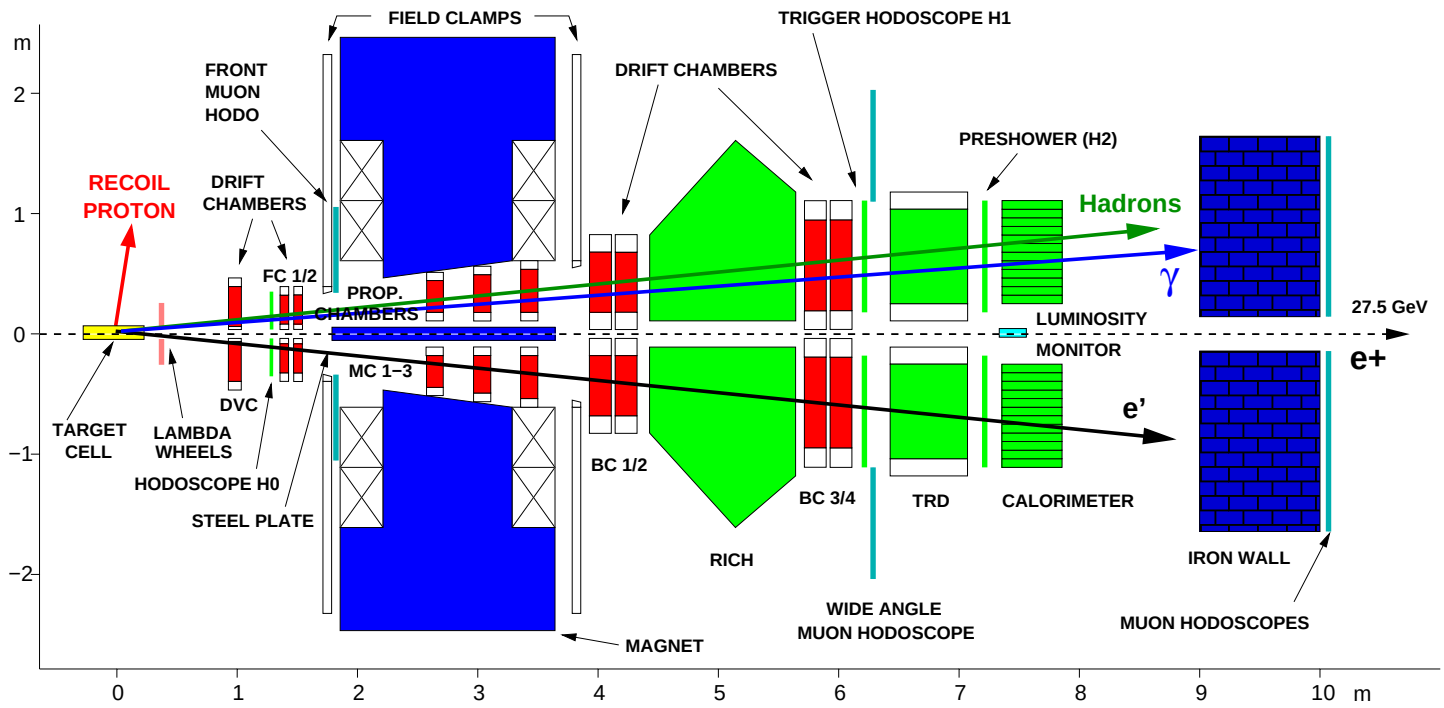
Gas Targets:
H/D/Ne/Kr/..

Beam:

27.6 GeV

e^+ and e^-

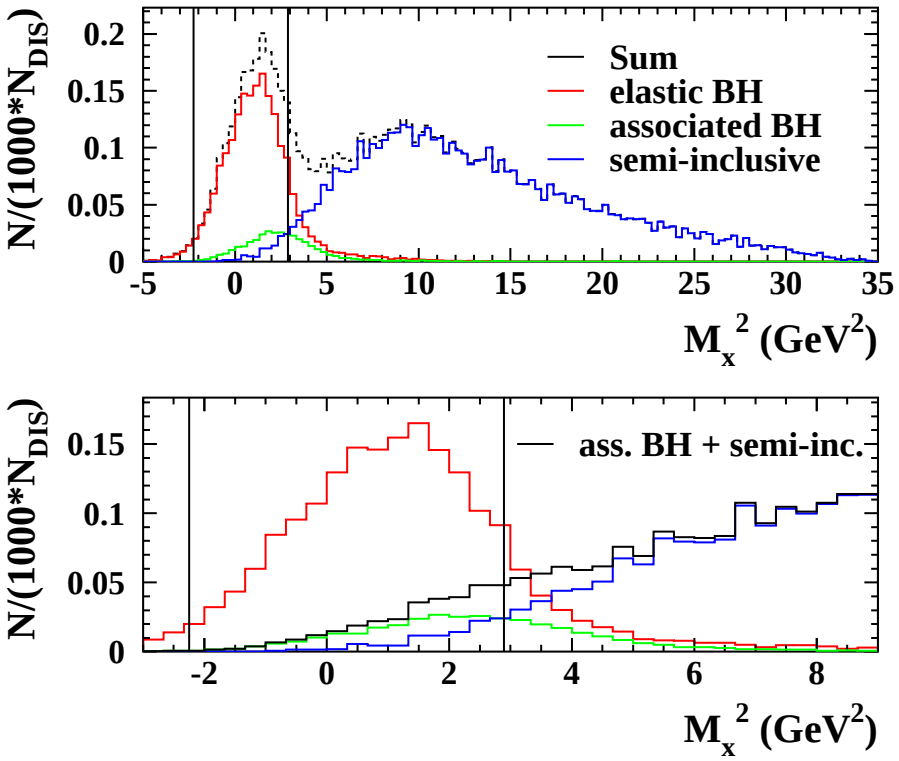
$\langle P \rangle \approx 55\%$



- Events with exactly one DIS-positron/DIS-electron and exactly one trackless cluster in the calorimeter (or one identified π^+ 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:

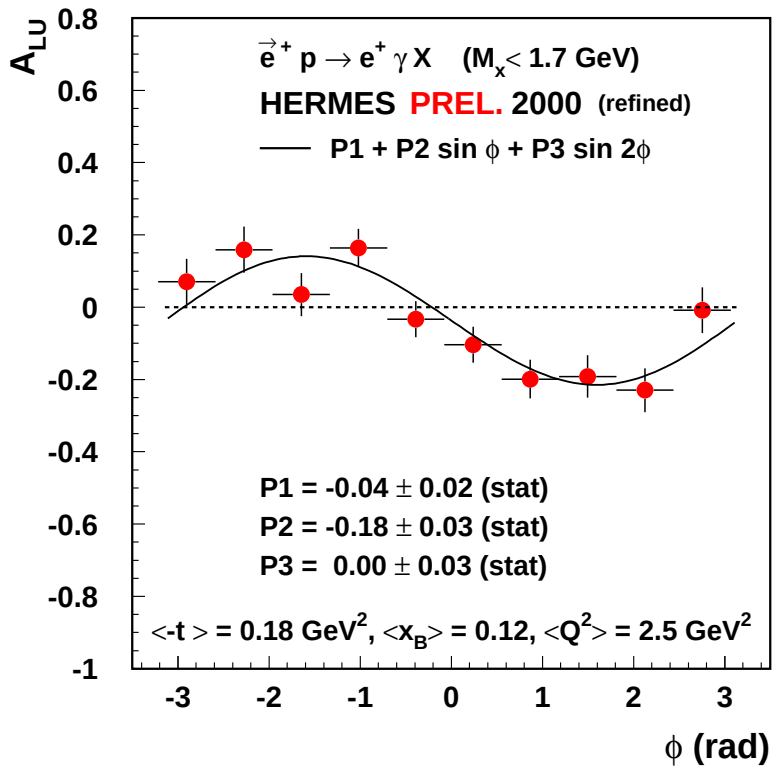
- elastic BH/DVCS ($e\,p \rightarrow e'\,p'\,\gamma$)
- associated BH/DVCS (mainly $e\,p \rightarrow e'\,\Delta^+\,\gamma$)
- semi–inclusive (mainly $e\,p \rightarrow e'\,\pi^0\,X$)

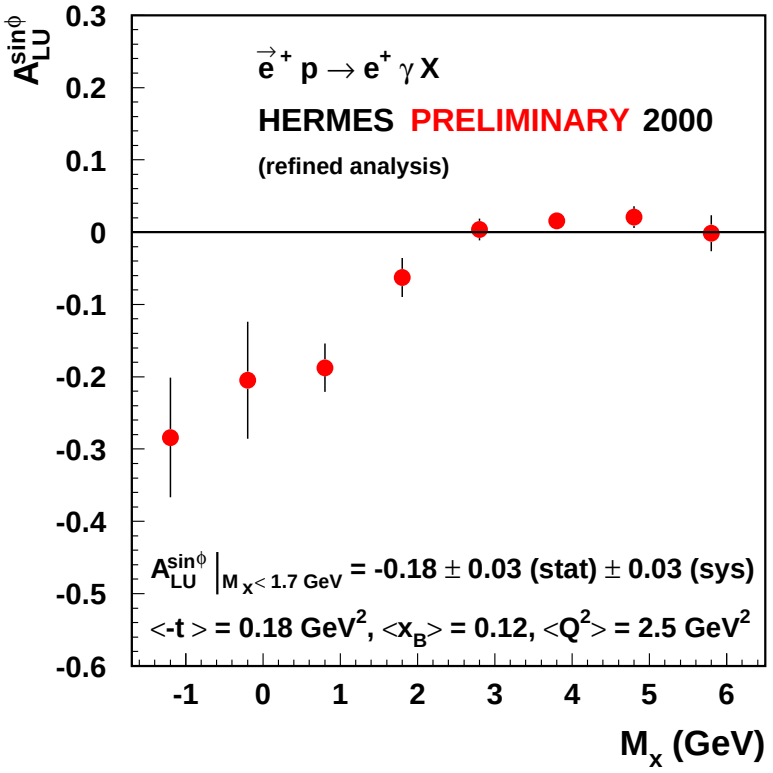
$\Rightarrow$ "Exclusive" bin (-1.5 $< M_x <$ 1.7 GeV)

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

Beam–Spin Asymmetry (BSA)

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





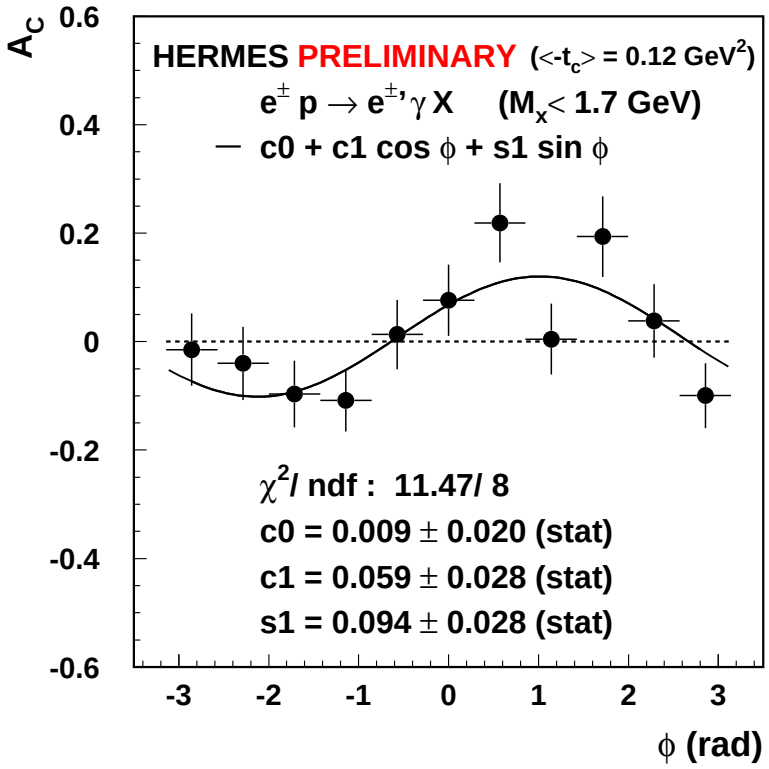
A_{LU} in exclusive bin: Expected $\sin(\phi)$ dependence $\Rightarrow \mathrm{Im}\, M_{unp}^{1,1}$

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

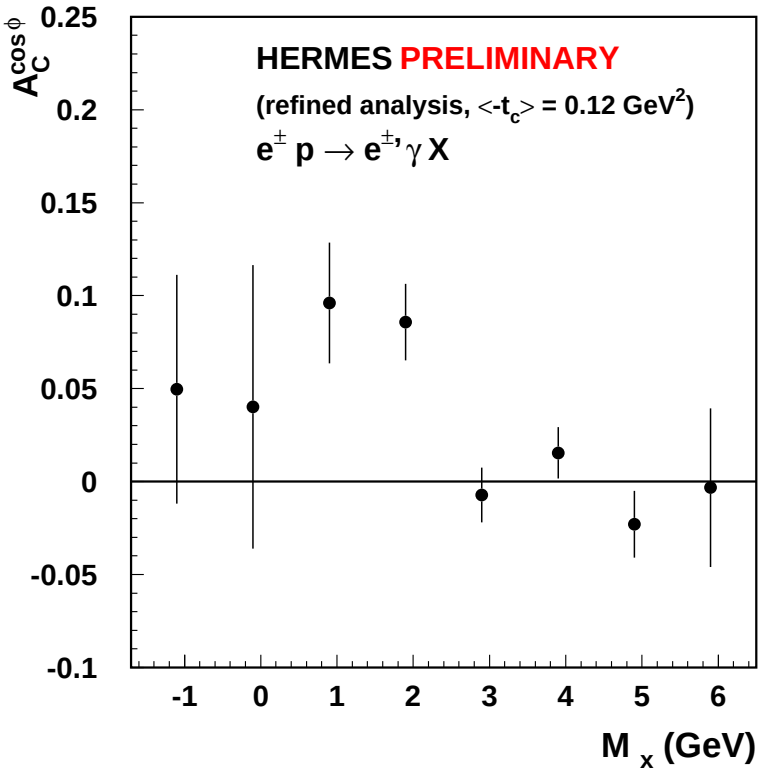
(Results from 1996/97 → PRL **87**, 182001 (2001))

Beam–Charge Asymmetry (BCA)

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

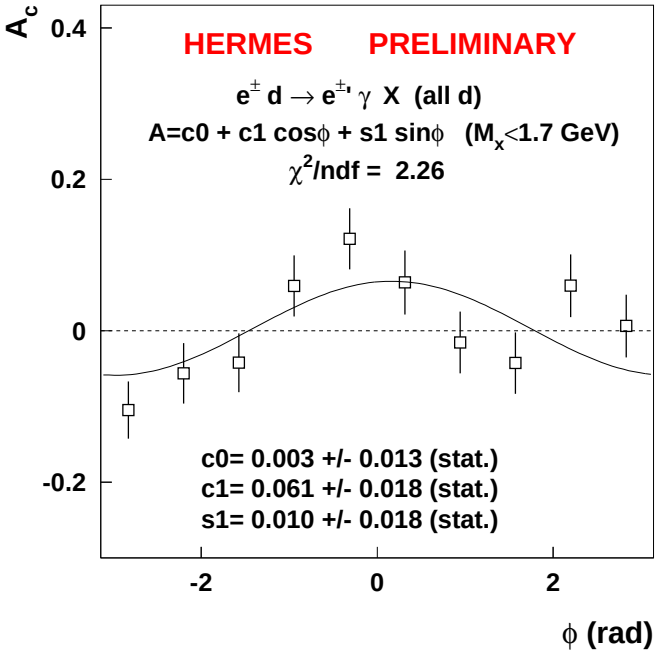


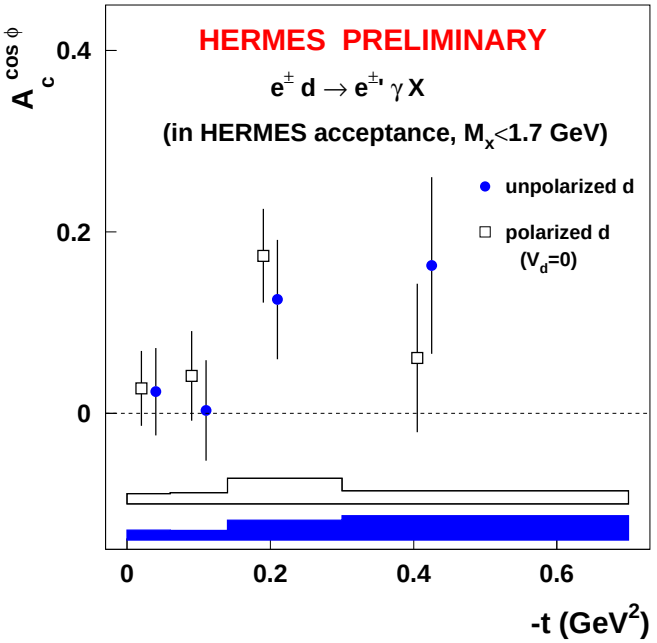
A_C in exclusive bin: Expected $\cos(\phi)$ dependence $\Rightarrow \mathrm{Re}\, M_{unp}^{1,1}$ $\sin\phi$ due to polarized beam

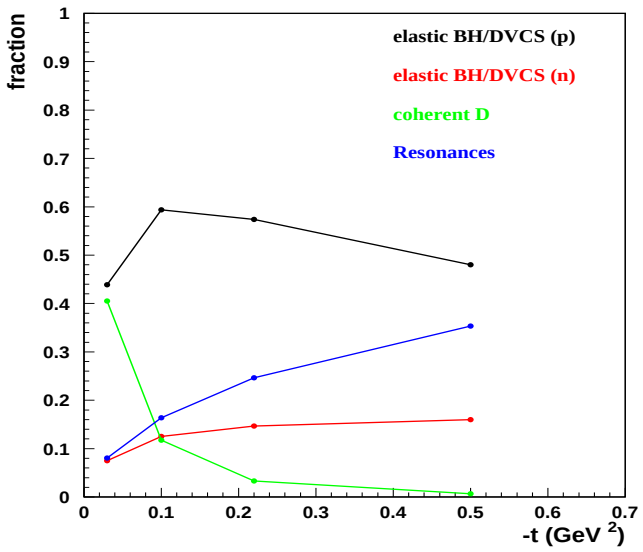


$\cos(\phi)$–Moments zero at higher missing mass

Beam–Charge Asymmetry (BCA) on Deuterium

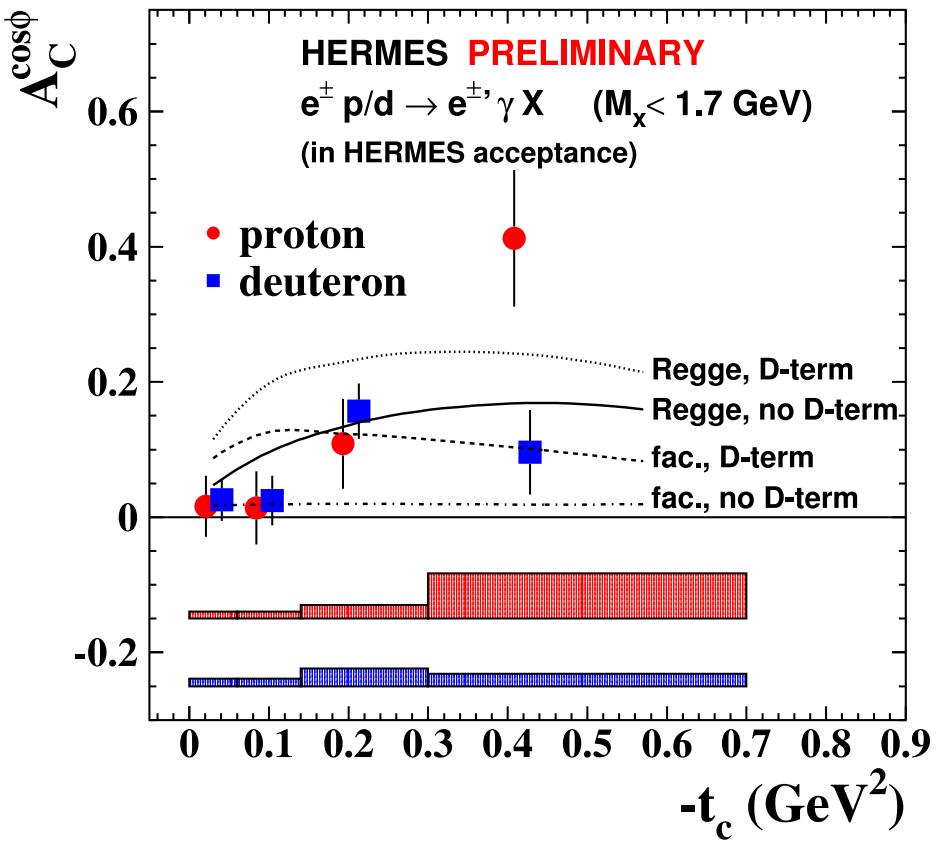






- $A_C^{\cos\phi}(d) \approx A_C^{\cos\phi}(p)$
- Spin-1 particle $\rightarrow$ 9 GPDs, but coherent production only $\approx 20\%$
- 40% coherent in first t-bin
  $\Rightarrow$ no Tensor effect seen
  $\Rightarrow$ Data can (indeed) be combined

Beam–Charge Asymmetry (BCA) versus t



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})

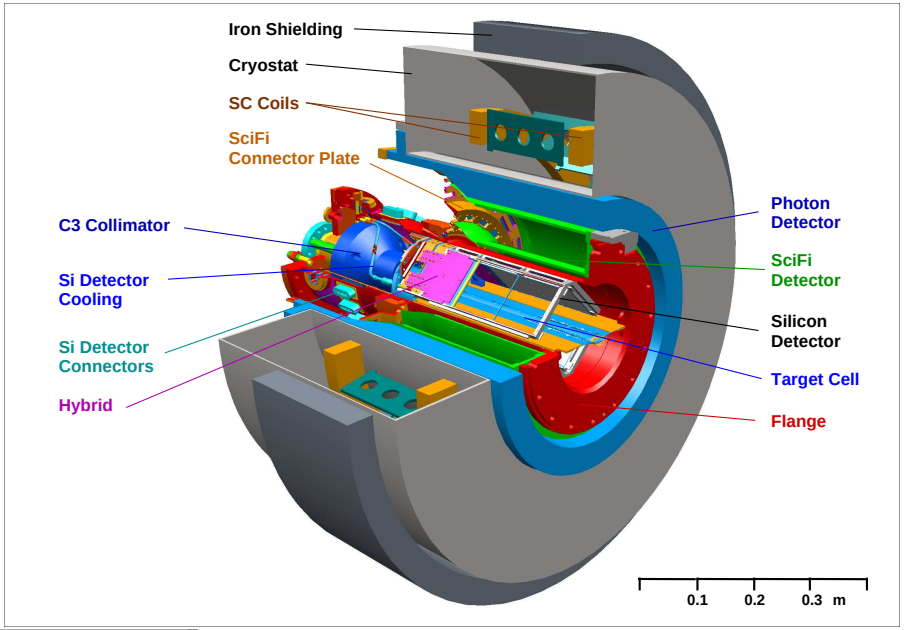
If multidimensional binning possible (Statistics !) or fast generator/lookup-table available

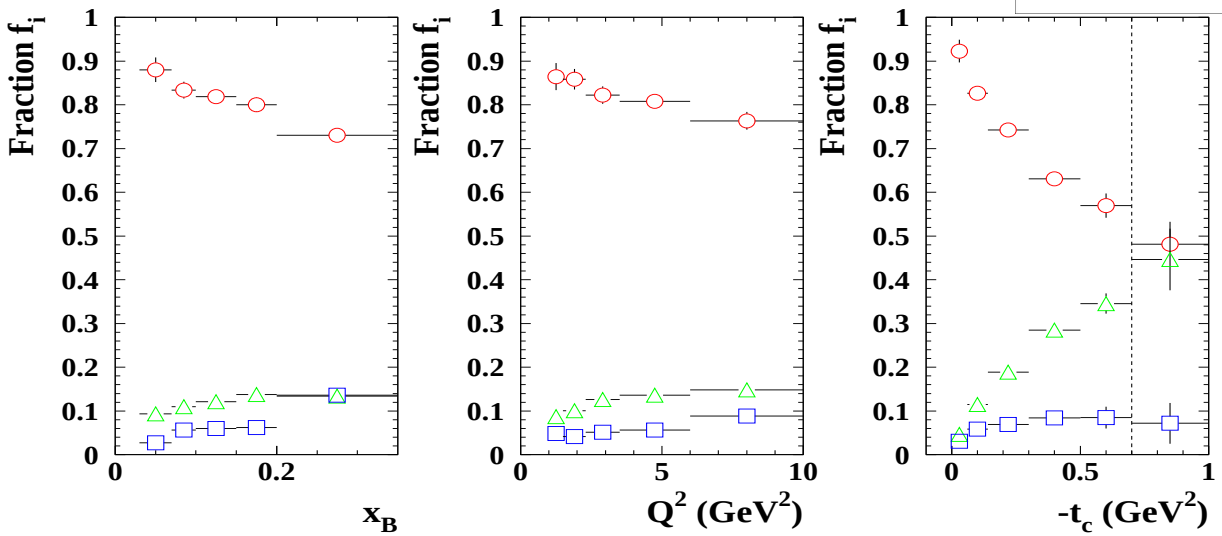
$\Rightarrow$ t–dependence of BCA has high sensitivity to GPD models!

More on H to come

Recoil Detector and unpol. Targets (2006/2007)

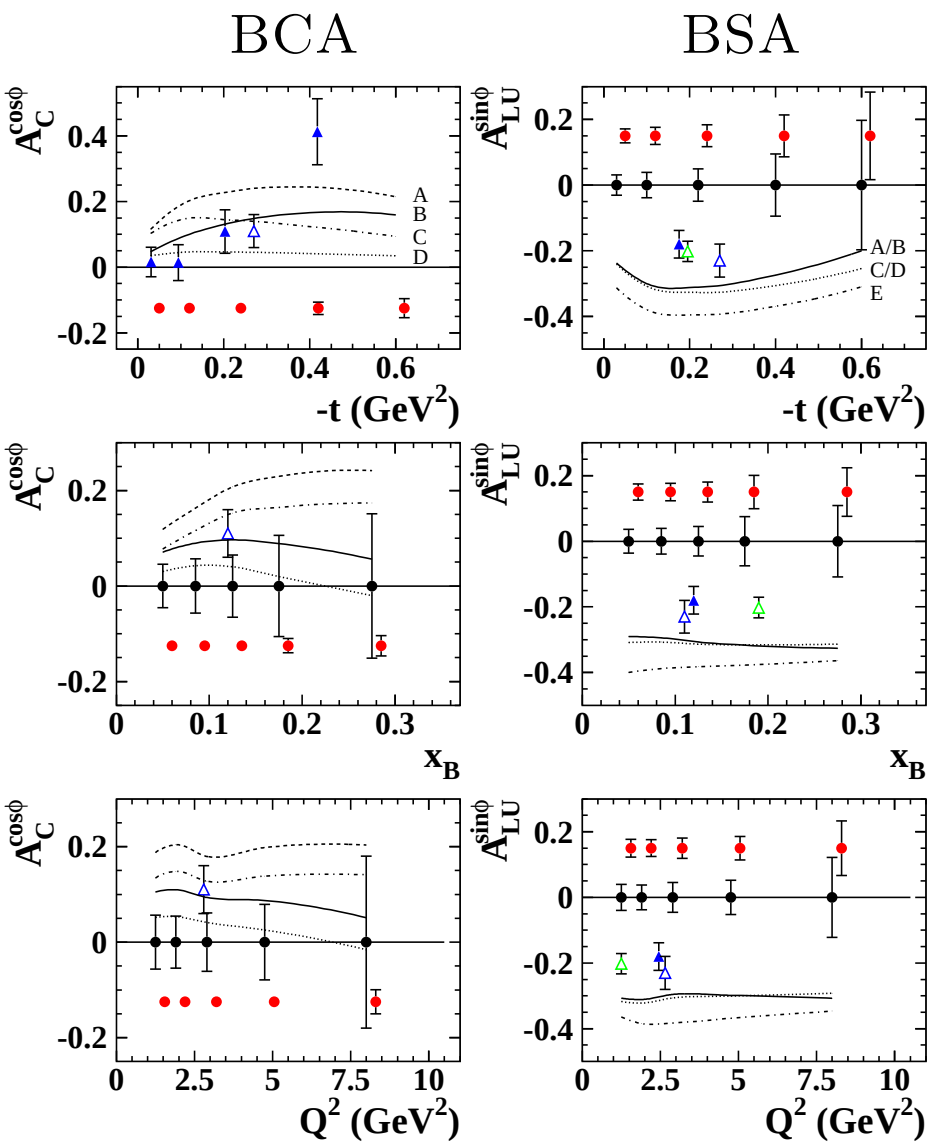
- ensures exclusivity of events
  - Semi–inclusive background 5% $\Rightarrow \ll 1\%$
  - Associated background 10% $\Rightarrow \approx 1\%$





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

● BSA: $1 fb^{-1}\, e^+$, Pol. $= 40\%$

(exp. 2006/2007 Recoil data)

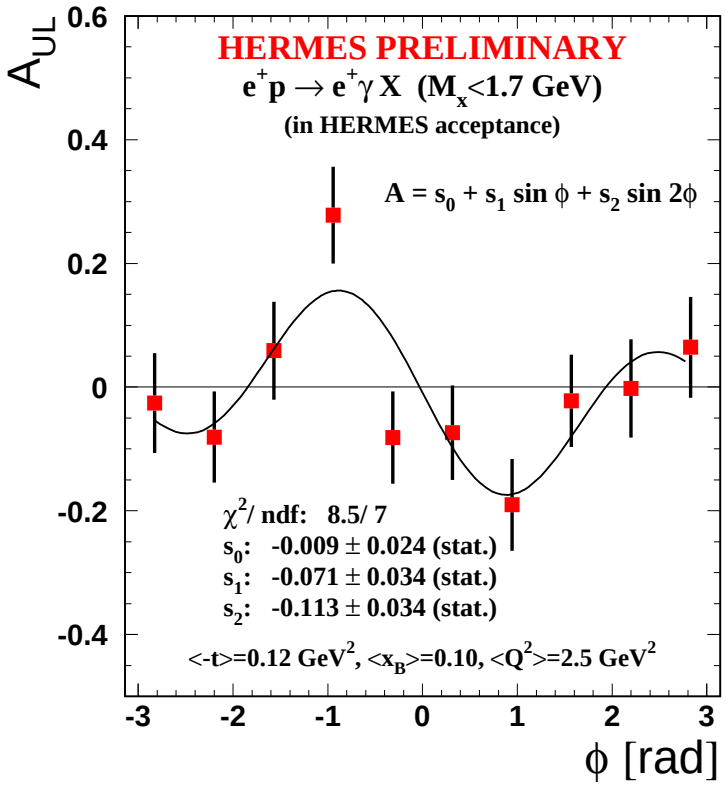
BCA: high sensitivity to t-dependence (fact./Regge) and D-term

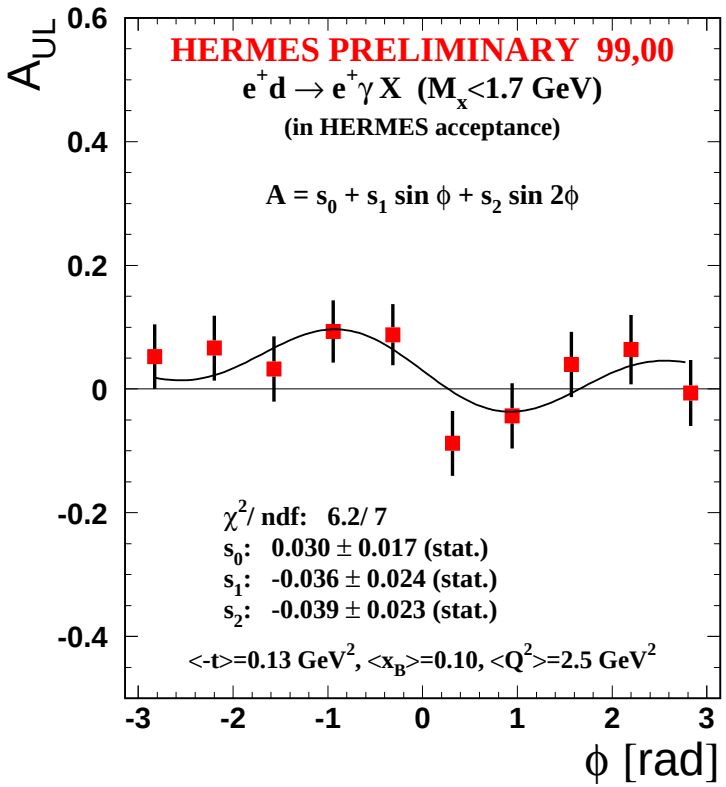
BSA: highest sensitivity to b_s parameter in profile function

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

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

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

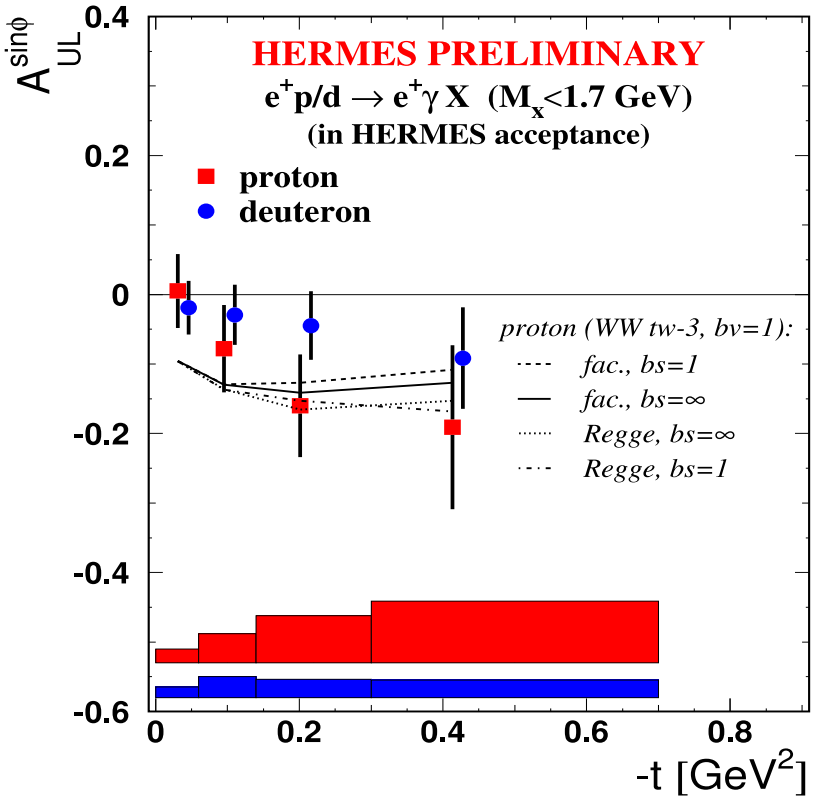


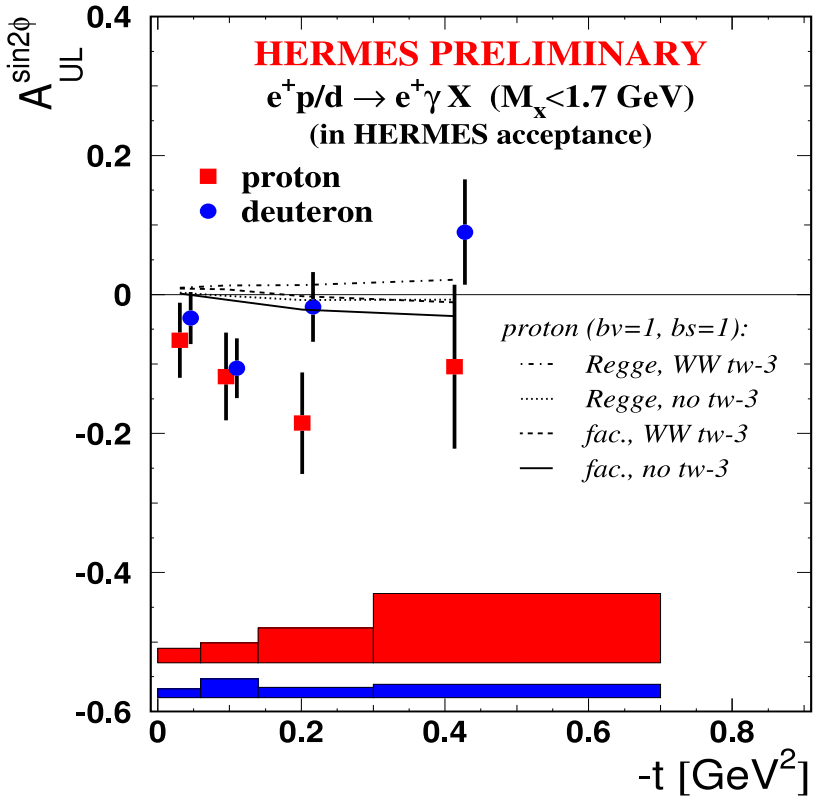


$A_{\mathrm{UL}}(\overrightarrow{p})$ in exclusive bin:
Expected $\sin(\phi)$ dep. $\Rightarrow$ GPD $\widetilde{H}$,
Unexpected $\sin(2\phi)$ dependence

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

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



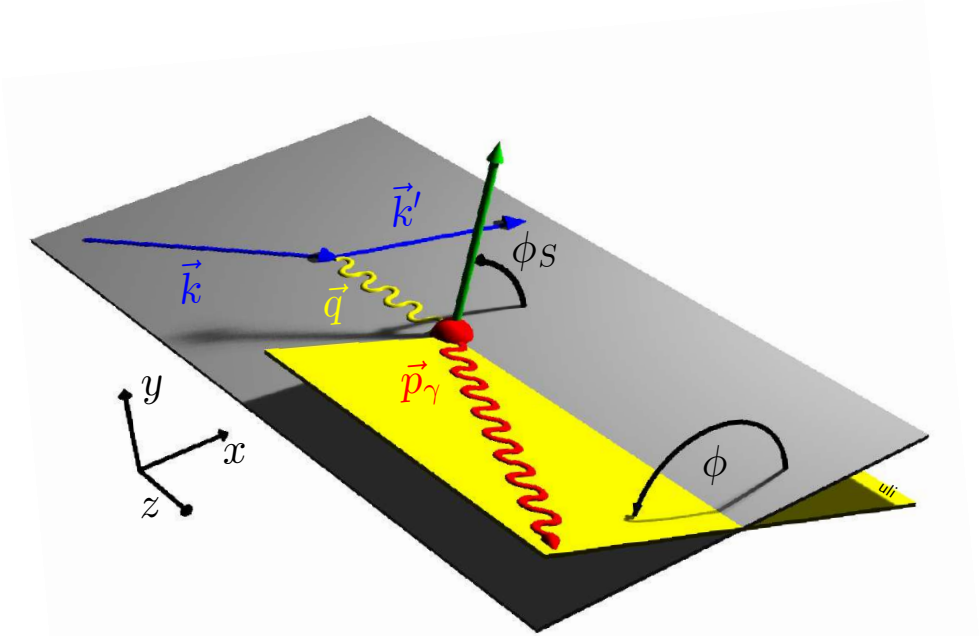


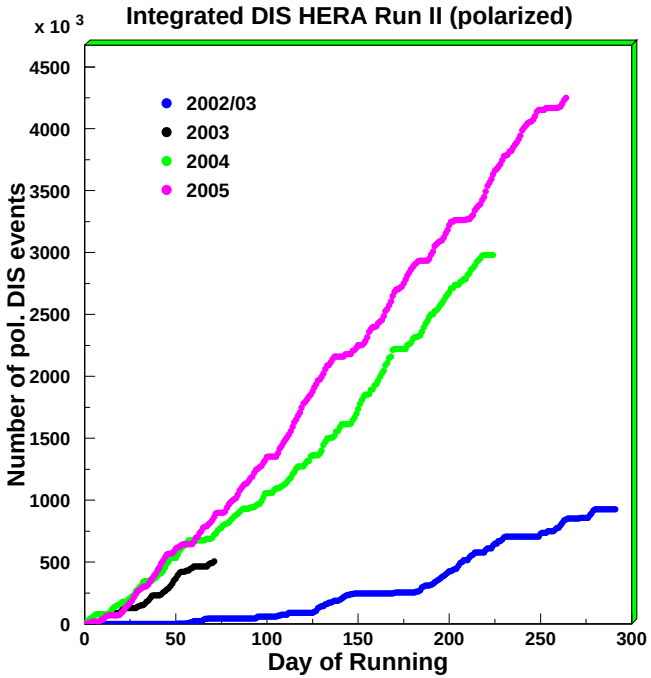
- No effect seen from 40% coherent contribution in first bin
- Difference at higher $-t$
  $\Rightarrow$ Different asymmetry on the neutron when comp. to proton
- $A_{UL}^{\sin 2\phi} \Rightarrow$ Difference due to missing qGq twist-3 in the models?

What about the GDP E ?

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

Data taking with transverse Hydrogen target until Nov. ...
$\approx$ 8 million on tape



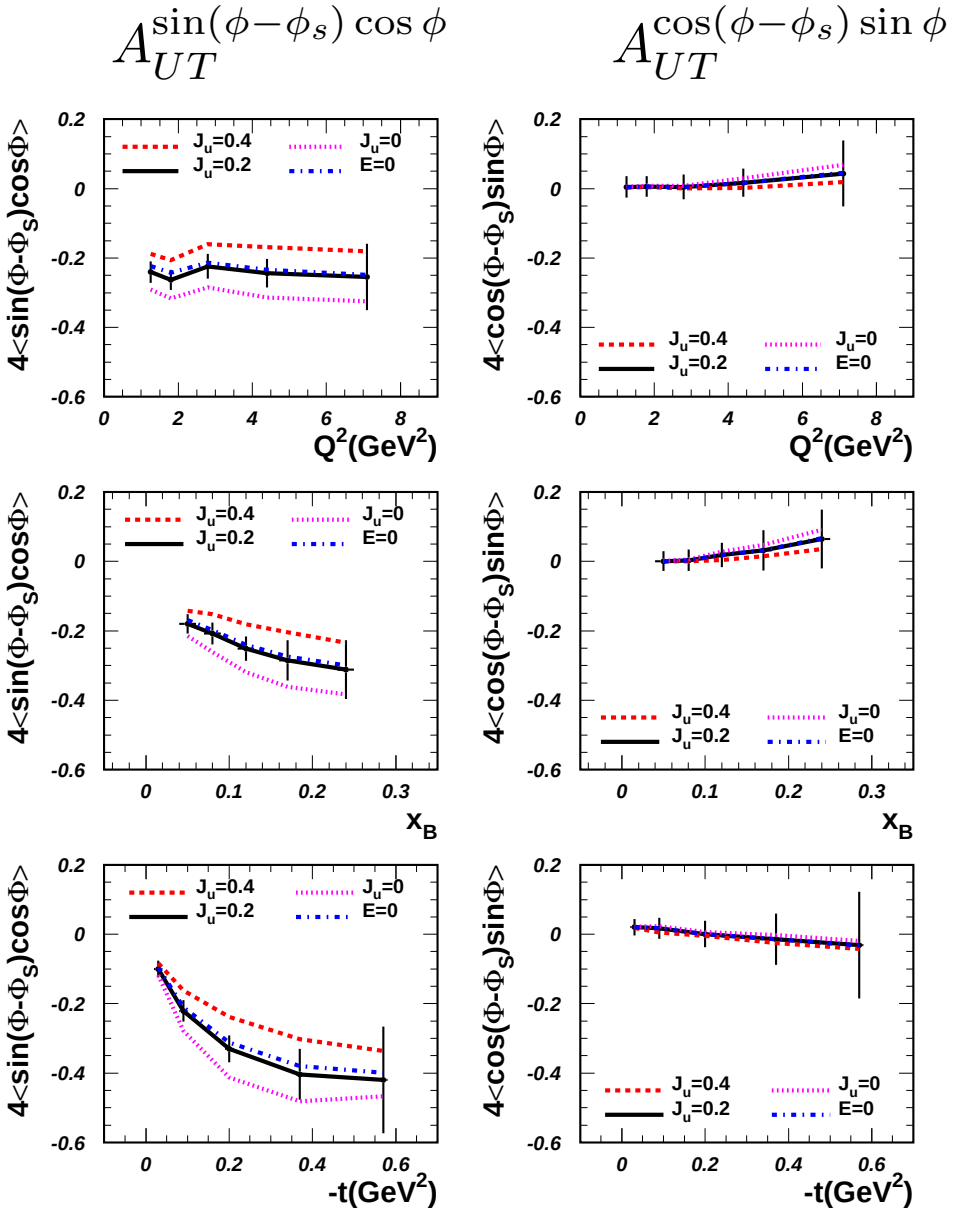


$$A_{UT}(\phi, \phi_s)$$

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

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

Projection for transverse Target-Spin Asymmetry



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 $\Rightarrow$

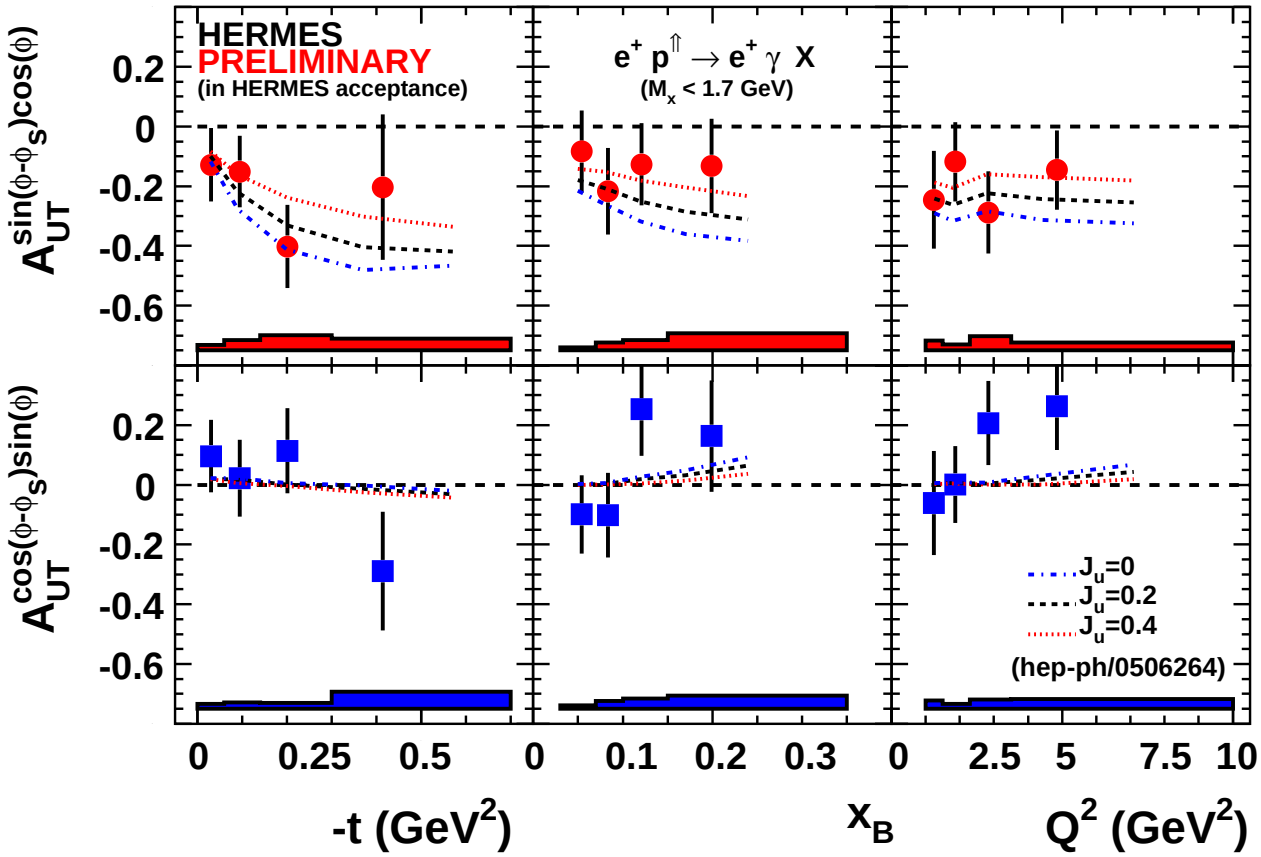
- E=0 "baseline" known
- some/many model parameters are the same for H and E ?!?

Models show same kinematic dependences
$\Rightarrow$ integrate over kinematics

8 million DIS,
Target Pol. = 75% $\Rightarrow$
4σ difference (total exp unc.) between $J_u = 0.4$ and 0.0

Latest News: First result on DVCS TTSA!

Based on data taken 2002-2004



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

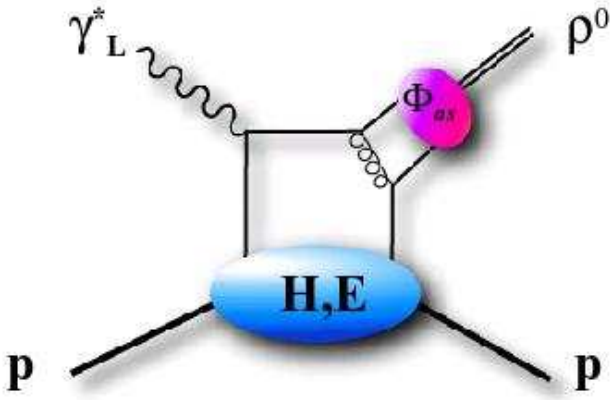
(F.E., Nowak, Vinnikov, Ye, hep-ph/0506264)

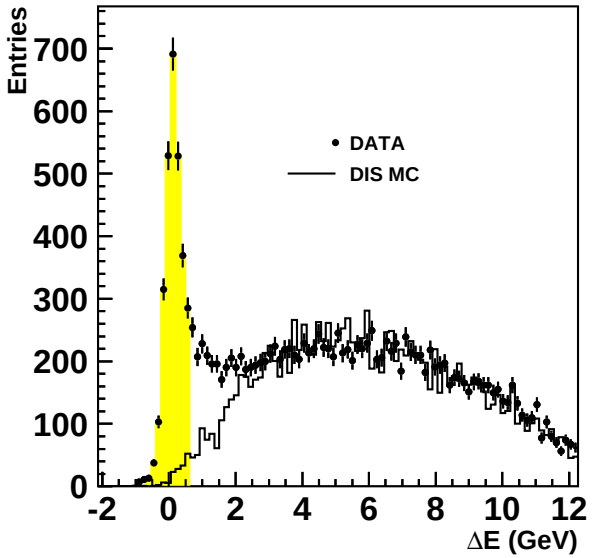
$\Rightarrow$ First model dependent extraction of J_u possible!

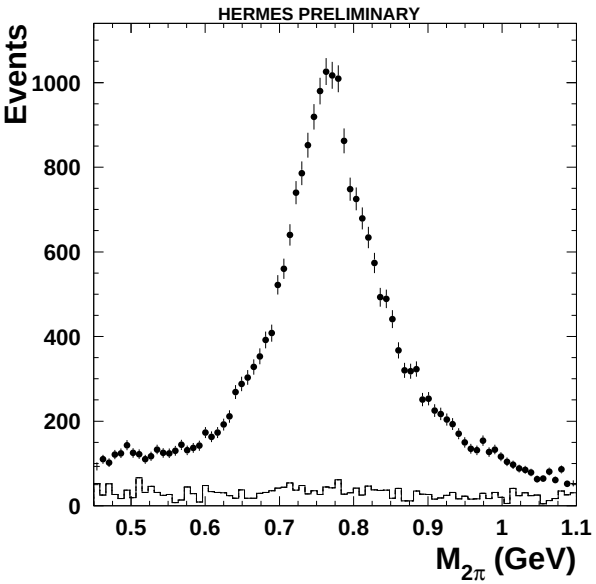
Exclusive Vector Meson Production

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

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





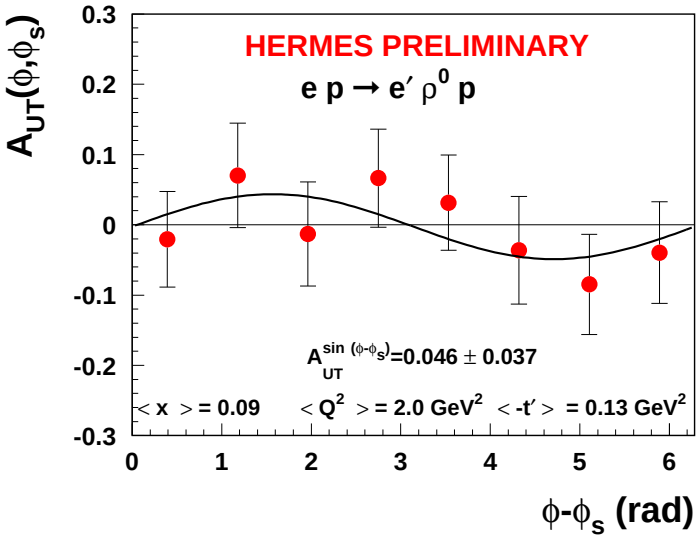


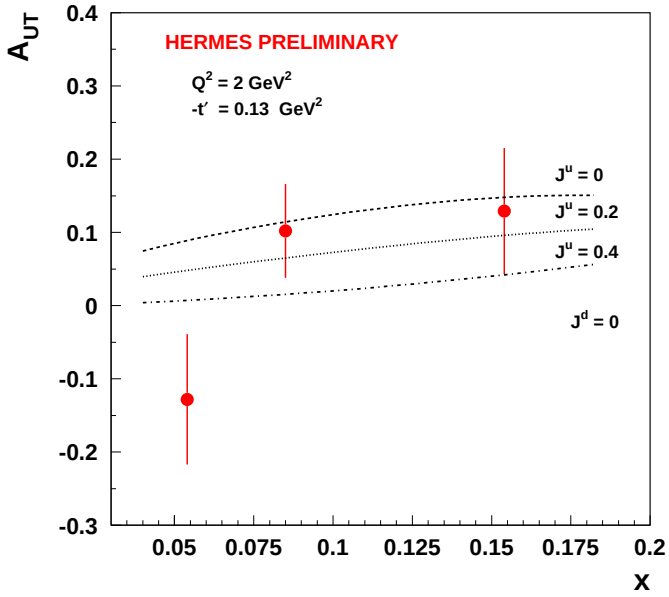
Event selection:

- $\rho^0 \to \pi^+\pi^-$,
- No recoil detection
- $\to$ 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)

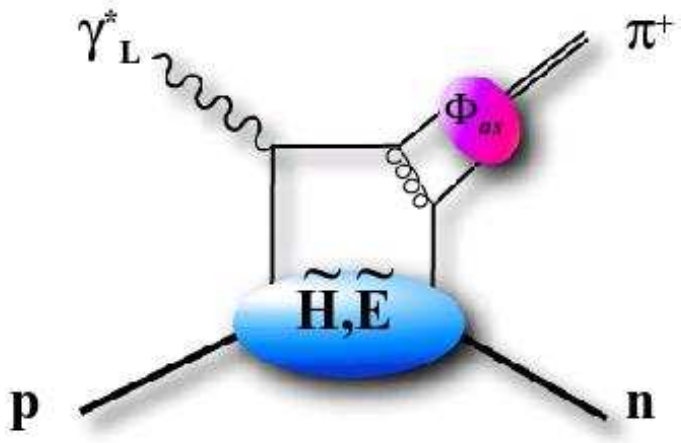
AGREEMENT WITH THEORETICAL CALCULATIONS (F.E., NOWAK, VINNIKOV, YE, HEP-PH/0506264)

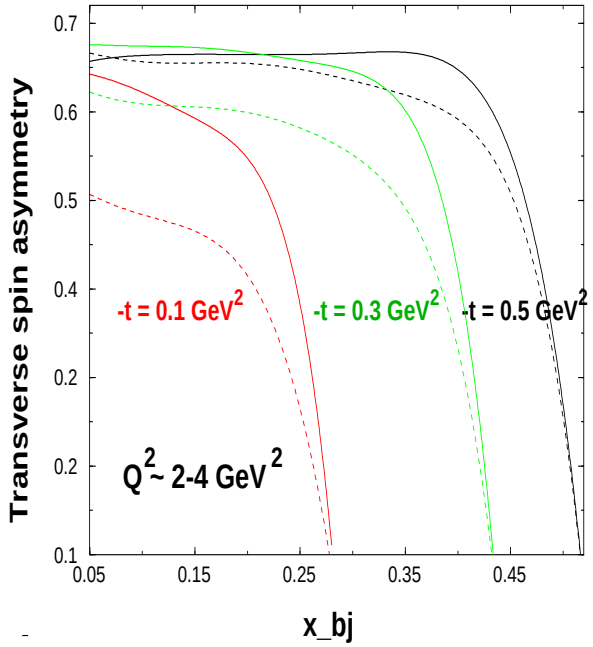
AGAIN: SAME SIZE DATA SET TO COME, A_{UT}^{ρ} LESS SENSITIVE TO J_u WHEN COMPARED TO A_{UT}^{DVCS} $\rightarrow$ PROVIDE ADDITIONAL CONSTRAINTS

Exclusive Pseudo-Scalar Meson Production

Access to $\widetilde{H}$ and $\widetilde{E}$
Exclusive π^+ production:

$$e\,p \rightarrow e\,n\,\pi^+$$





Frankfurt, Pobylitsa, Polyakov, Strikman, PRD 60 (1999)

Most sensitive to $\widetilde{E}$:
$A_{UT} \propto |S_T| sin(\phi - \phi_s)) \widetilde{H}\widetilde{E}$

- Huge asymmetries predicted
- Also sensitive to different distribution amplitudes

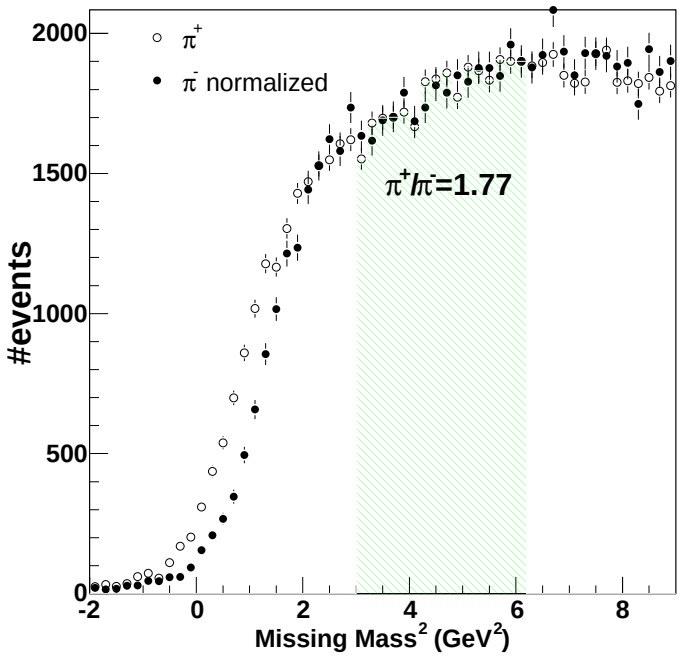
TTSA not yet available (small stat., 'wait' until November)
...but does factorisation at all hold at these 'low' Q^2?

Exclusivity of $e\,p \to e\,\pi^+\,n$

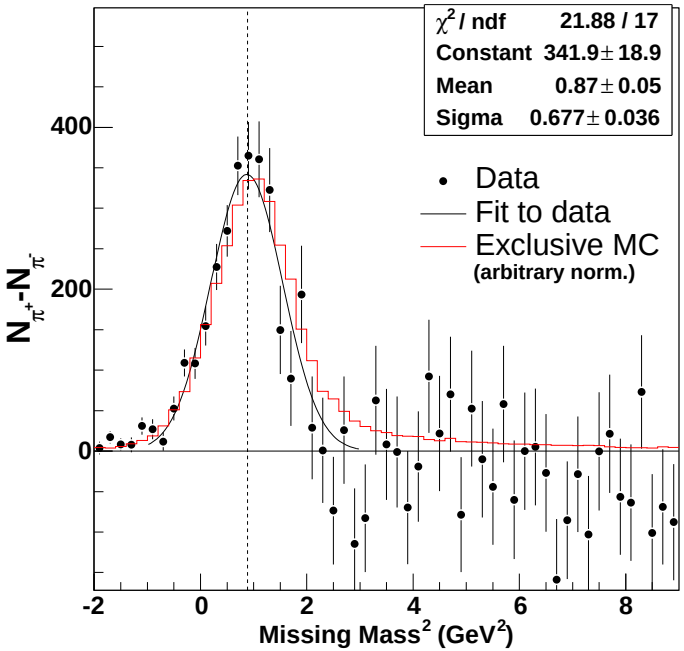
No neutron detection, large (fragmentation) background:

Exclusivity via $M_x^2 = (P_p + P_e - P'_e - P_\pi)^2$ and ...

$e\,p \to e\,\pi\,X$



$e\,p \to e\,\pi^+\,n$



... subtraction of pi- yield $\Rightarrow$

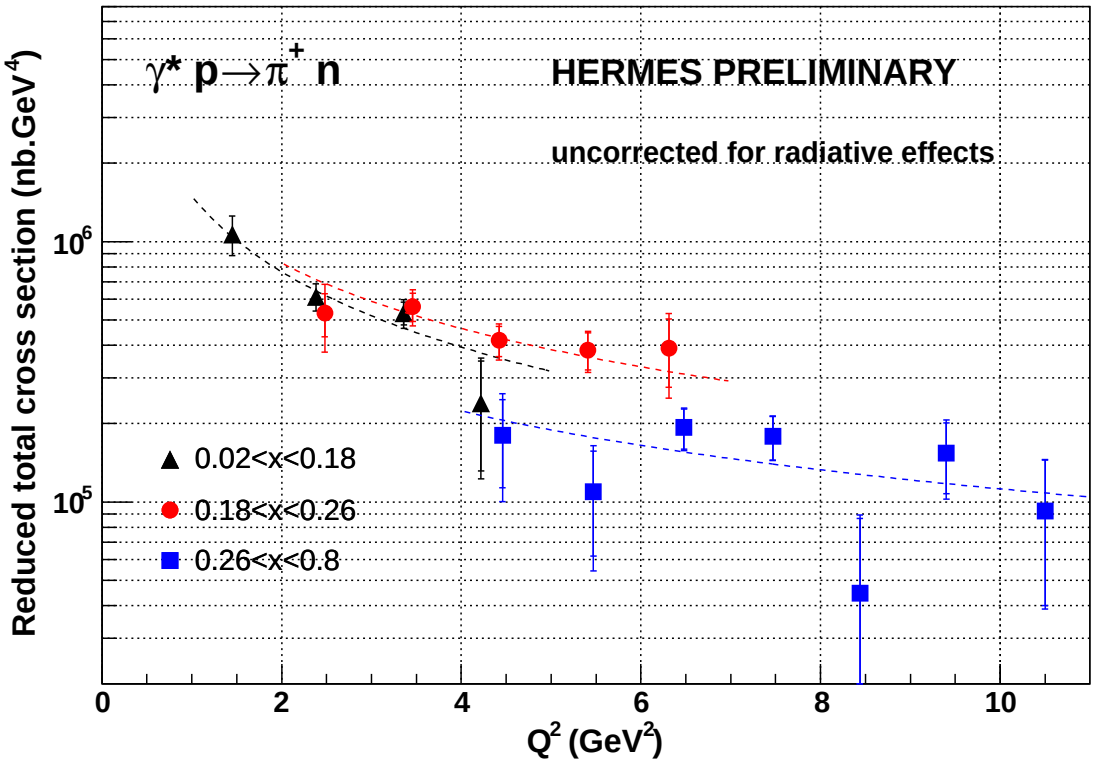
Exclusive peak at $M_x^2 = M_n^2$

Excl. MC based on GPD model by VGG (Vanderhaeghen, Guichon, Guidal, PRD 60, 1999)

Factorization at 'low' Q^2

Factorization theorem: $\sigma_L \to 1/Q^6$ at fixed x_B, t

σ_T suppressed by $1/Q^2 \to \sigma_L$ domiates for 'large' Q^2



$$\sigma_{tot} = \overbrace{f(x_B, Q^2)}^{\propto 1/Q^4} \cdot \sigma_{reduced}$$

fit to $1/Q^p$:

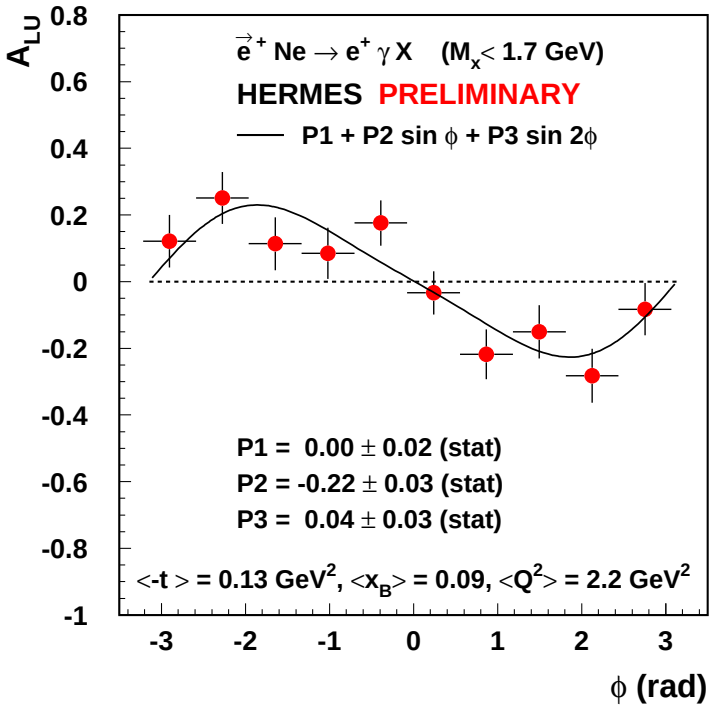
$p = 1.9 \pm 0.5$

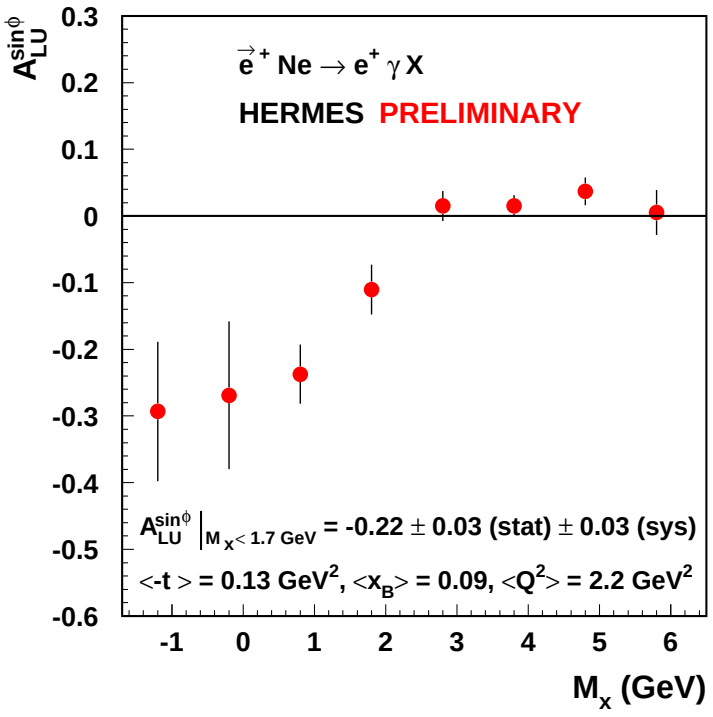
$p = 1.7 \pm 0.6$

$p = 1.5 \pm 1.0$

$\Rightarrow$ Q^2 dependence of cross section in agreement with expectation from factorization

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) by middle of next year!

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 (Primary Goal ↔ unpolarized target)
- BCA especially sensitive to model parameters (HERA!!!)
- First (model dependent) extraction of J_u possible.