Quark Orbital Angular Momentum and Exclusive Processes at HERMES

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for the HERMES–Collaboration

CIPANP, Puerto Rico, May 2006

- Generalized Parton Distributions (GPDs)

- Exclusive Production of Photons (DVCS) and Mesons

- HERMES Results

- First model dependent constraint on Quark Orbital Angular Momentum

FF **PDF** **GPD**
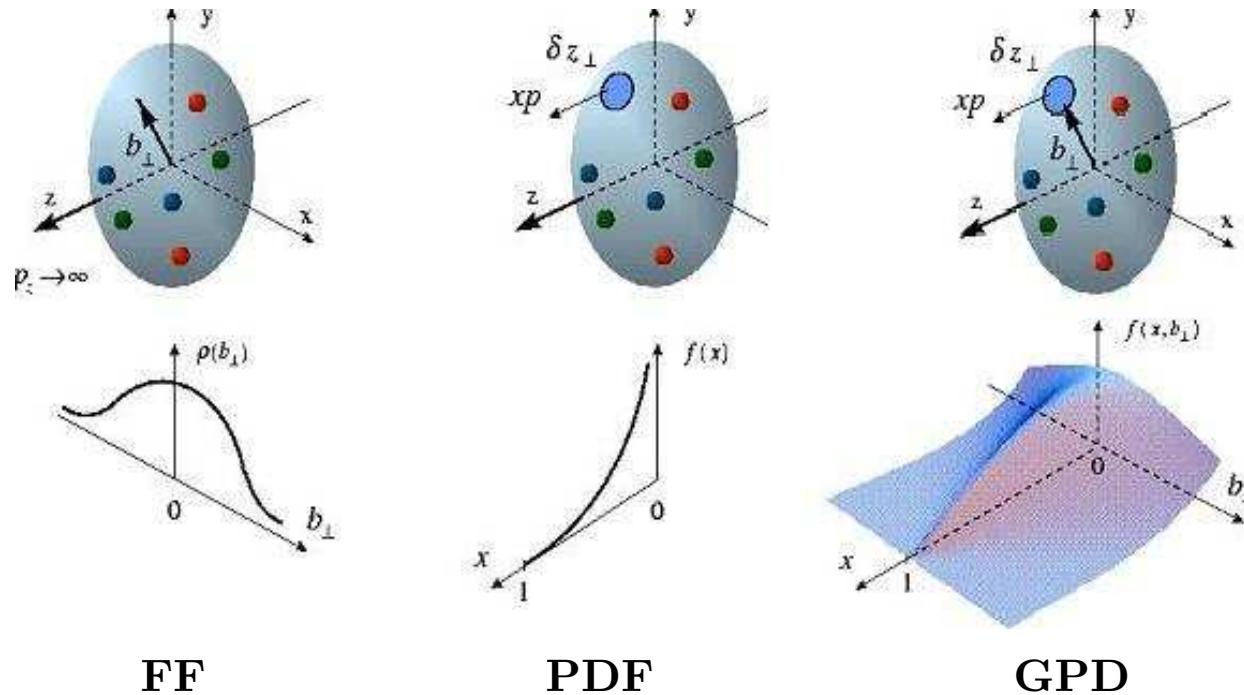
- Form Factors → Transverse position ← Elastic scattering

- 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):
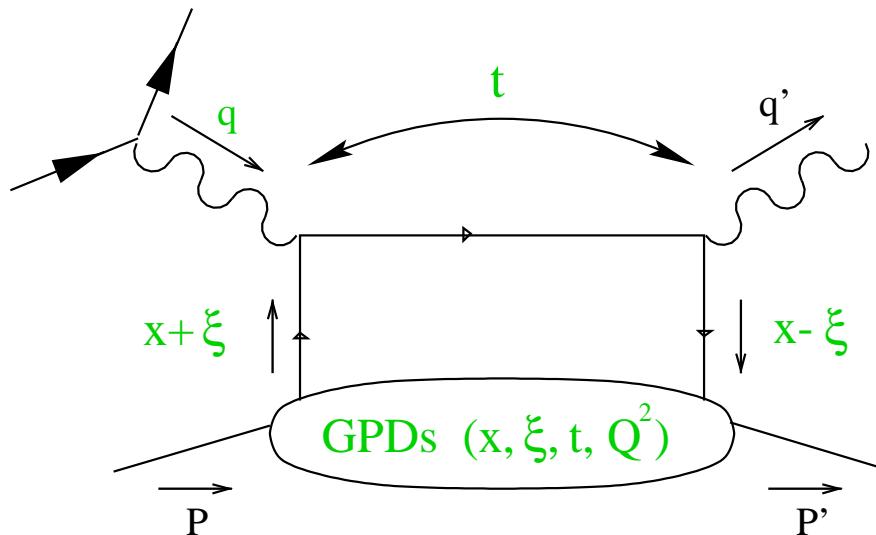
- LONGITUDINAL MOMENTUM FRACTIONS:
  $x \in [-1, 1]$ (NOT ACCESSIBLE)
  $\xi \approx x_B/(2 - x_B)$

- $t = (q - q')^2$
  ($\gamma^* \to \gamma$ 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)
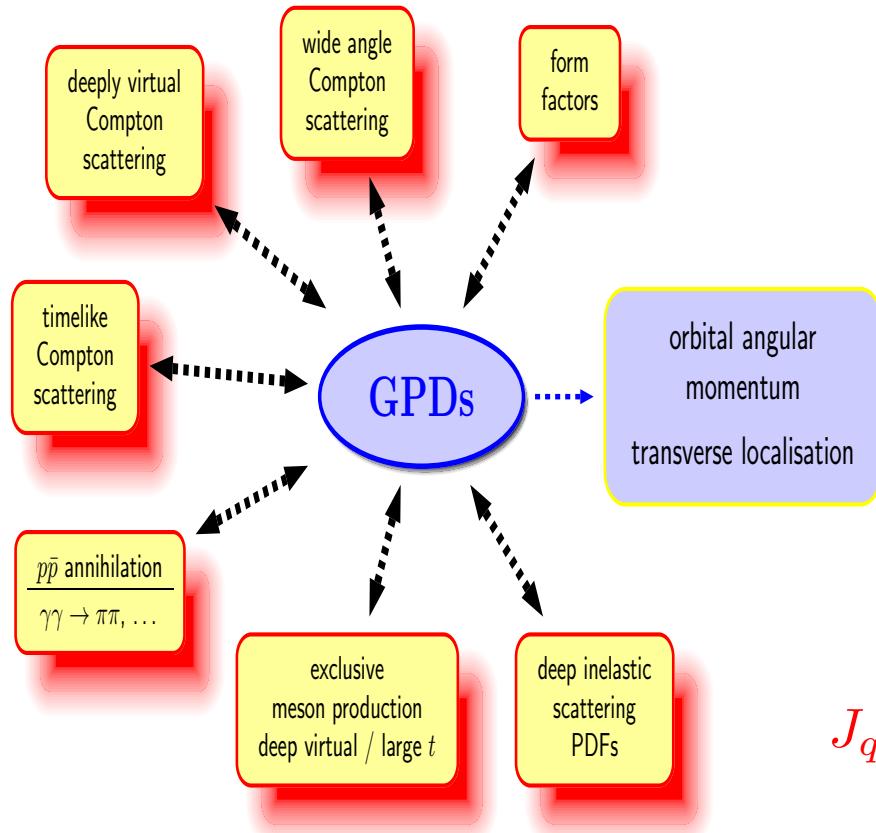
PDFs: GPDs IN THE LIMIT $t \to 0$
$$e.g.\, H(x,0,0) = q(x)$$

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:

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

Diagram boxes: deeply virtual Compton scattering; wide angle Compton scattering; form factors; timelike Compton scattering; GPDs; orbital angular momentum / transverse localisation; $p\bar{p}$ annihilation, $\gamma\gamma \to \pi\pi, \dots$; exclusive meson production deep virtual / large t; deep inelastic scattering PDFs

(ORIGINAL) HERMES MOTIVATION:

NUCLEON (LONG.) SPIN STRUCTURE: $1/2 = \underbrace{\underbrace{1/2(\Delta u + \Delta d + \Delta s)}_{\sim 30\%} + \overbrace{L_q}^{?}}_{J_q=?} + \overbrace{J_g}^{?}$

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
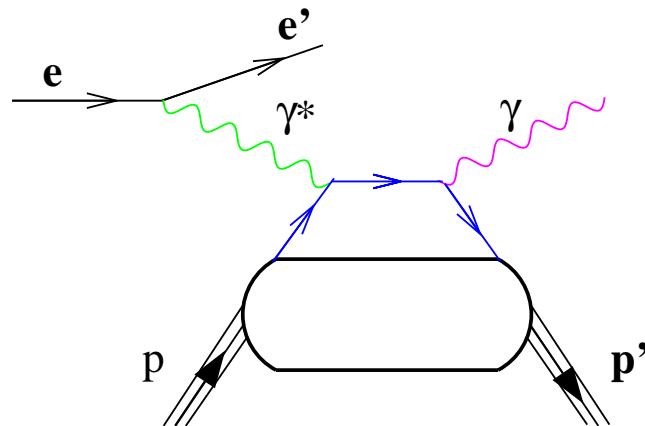
FIXED-TARGET, COLLIDER   COLLIDER
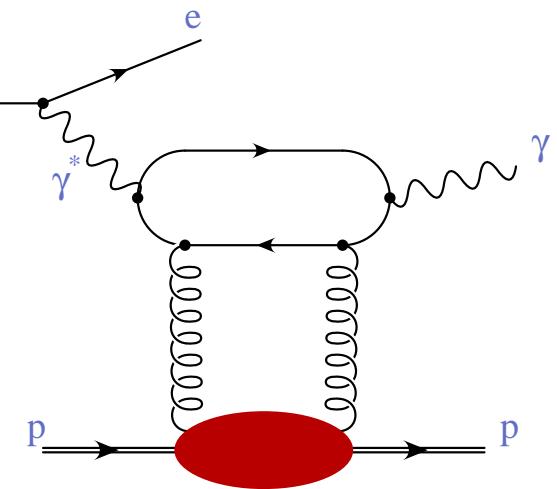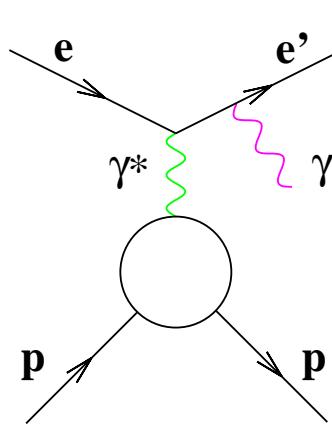
Photon-Production cross section:

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

DVCS Measurements

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

$\left|\tau_{\text{BH}}\right|^2$ 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 $\left|\tau_{\text{BH}}\right|^2$
(GPDS ENTER IN QUADRATIC COMBINATIONS)

AZIMUTHAL ASYMMETRIES
(HERMES, JLAB):
DVCS AMPLITUDES DIRECTLY ACCESSIBLE
VIA $I \Rightarrow$ MAGNITUDE + PHASE!!!
(GPDS ENTER IN LINEAR COMBINATIONS)
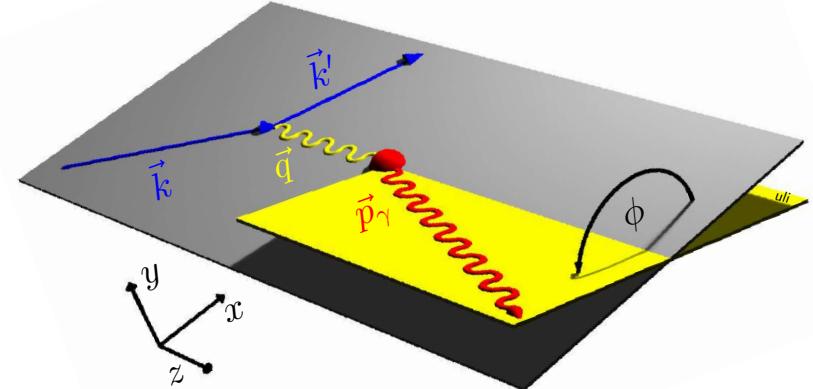
AZIMUTHAL ASYMMETRIES

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

BEAM–SPIN ASYMMETRY (BSA) AND BEAM–CHARGE ASYMMETRY (BCA)
ON UNPOLARIZED TARGET:

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

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

(HIGHER TWIST/ORDER $\rightarrow \cos 2\phi,\ \cos 3\phi,\ \sin 2\phi$)

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

$\langle x_B \rangle,\ \langle -t \rangle \approx 0.1 \Rightarrow$ COMPTON FORM-FACTOR $H_1 \Rightarrow$ GPD H

NEED BOTH CHARGES AND POLARIZED BEAM
$\Rightarrow$ HERA!!!

THE HERA ACCELERATOR AT DESY (HAMBURG)
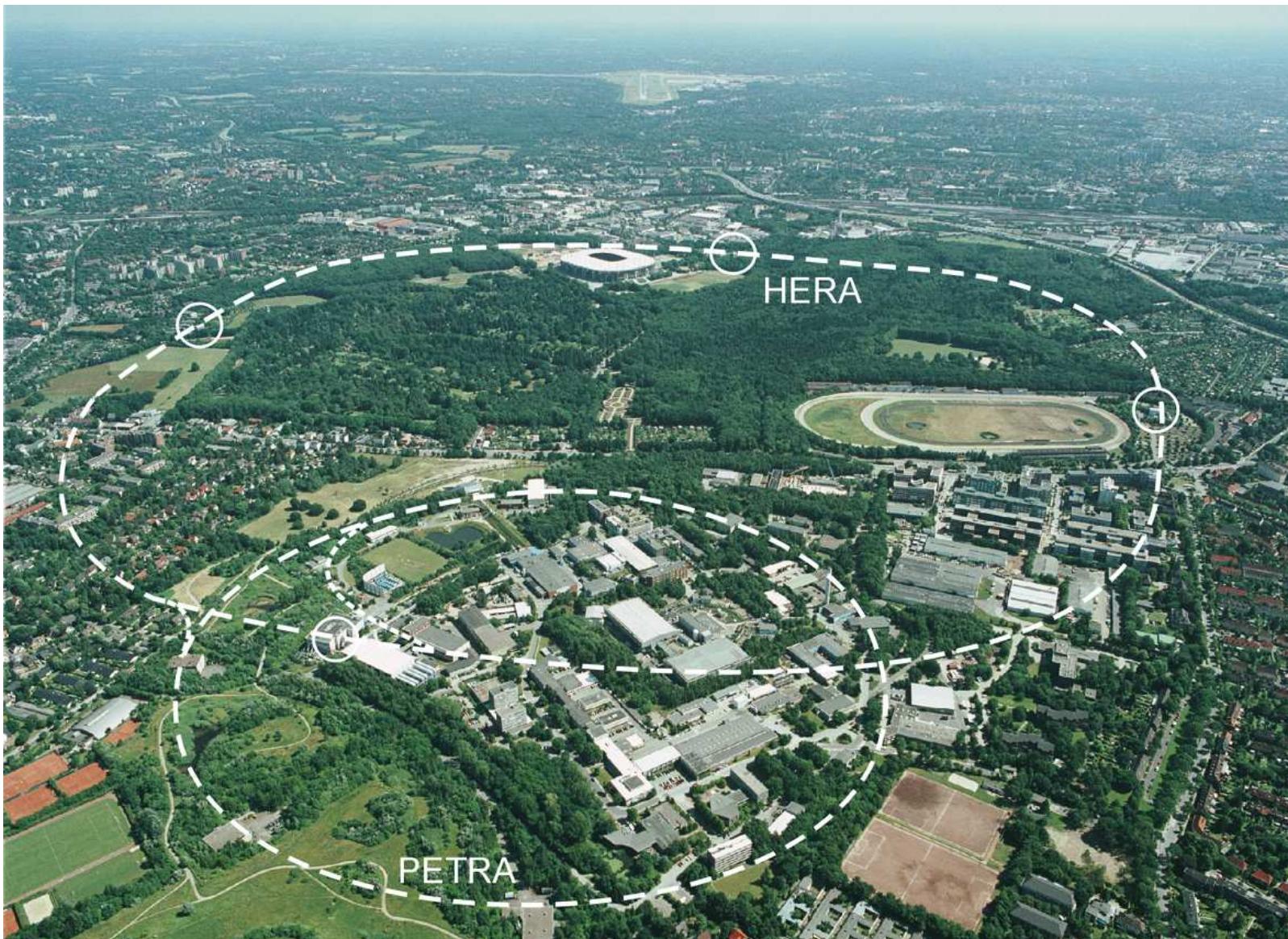
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HERA BEAM: 27.6 GEV, e^+ AND e^-, $\langle P \rangle \approx 35 - 55\%$
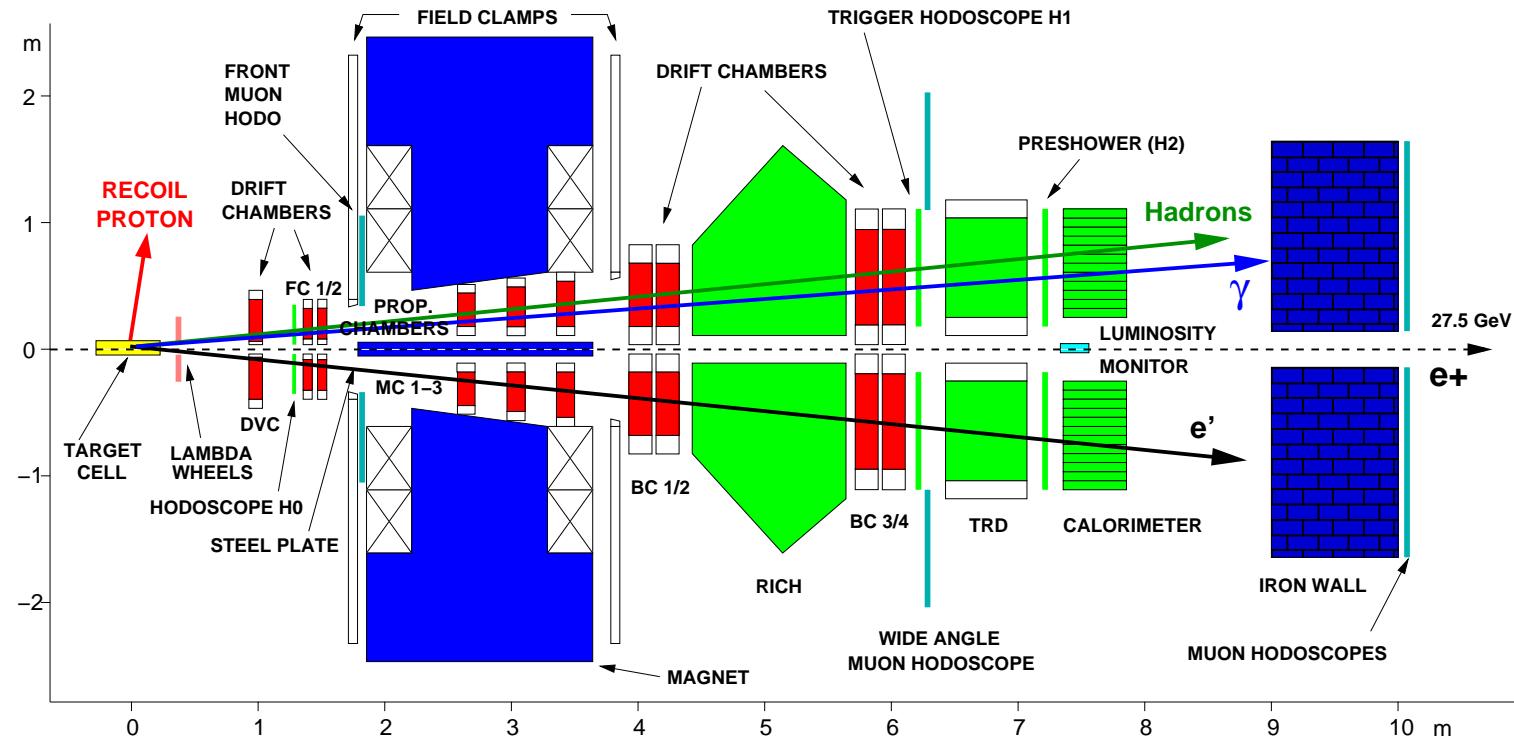

EVENTS WITH EXACTLY ONE DIS-POSITRON/DIS-ELECTRON AND EXACTLY ONE PHOTON IN THE CALORIMETER (OR ONE $(\rho^0 \to)$ $\pi^+\pi^-$ PAIR)

NO RECOIL DETECTION (YET) $\Rightarrow$ EXCLUSIVITY VIA ...

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$$M_x^2 \equiv (q + p - p_\gamma)^2 \Rightarrow \text{MC} \text{ for background and cuts } (\to \text{resolution})!$$
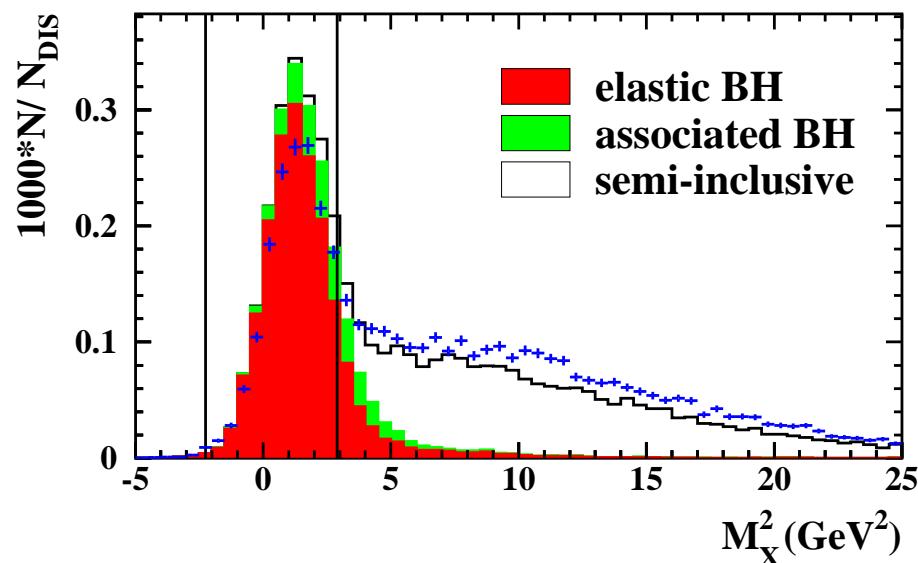
- ELASTIC BH $(e\, p \to e'\, p'\, \gamma)$

- ASSOCIATED BH
  (MAINLY $e\, p \to e'\, \Delta^+\, \gamma$)

- SEMI−INCLUSIVE
  (MAINLY $e\, p \to e'\, \pi^0\, X$)

- EXCLUSIVE π^0 $(e\, p \to e'\, \pi^0)$
  NOT SHOWN (SMALL)

NOT SIMULATED: DVCS PROCESS (DVCS C.S. "UNKNOWN", DVCS << BH) +RADIATIVE CORRECTIONS TO BH ($\to$ EXCL. PEAK OVERESTIMATED, BG UNDERESTIMATED)

$\Rightarrow$ "EXCLUSIVE" BIN $(-1.5 < M_x < 1.7 \text{ GeV})$

$\Rightarrow$ OVERALL BACKGROUND CONTRIBUTION $\approx 15\%$

Beam–Spin Asymmetry (BSA)

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

Left plot:

$\vec{e}^+ p \to e^+ \gamma X$ ($M_x < 1.7$ GeV)

HERMES **PREL.** 2000 (refined)

—— P1 + P2 sin ϕ + P3 sin 2ϕ

P1 = -0.04 ± 0.02 (stat)
P2 = -0.18 ± 0.03 (stat)
P3 = 0.00 ± 0.03 (stat)

$<-t> = 0.18$ GeV^2, $<x_B> = 0.12$, $<Q^2> = 2.5$ GeV^2

ϕ (rad)

Right plot:

$\vec{e}^+ p \to e^+ \gamma X$

HERMES **PRELIMINARY** 2000

(refined analysis)

$A_{\mathrm{LU}}^{\sin\phi} \big|_{M_x < 1.7 \,\mathrm{GeV}} = -0.18 \pm 0.03$ (stat) ± 0.03 (sys)

$<-t> = 0.18$ GeV^2, $<x_B> = 0.12$, $<Q^2> = 2.5$ GeV^2

M_x (GeV)
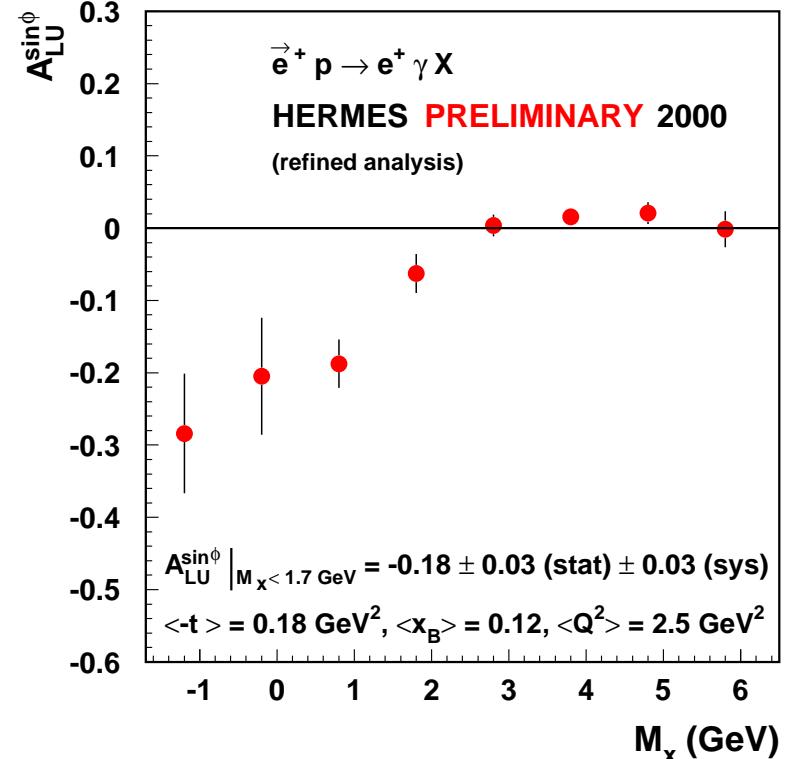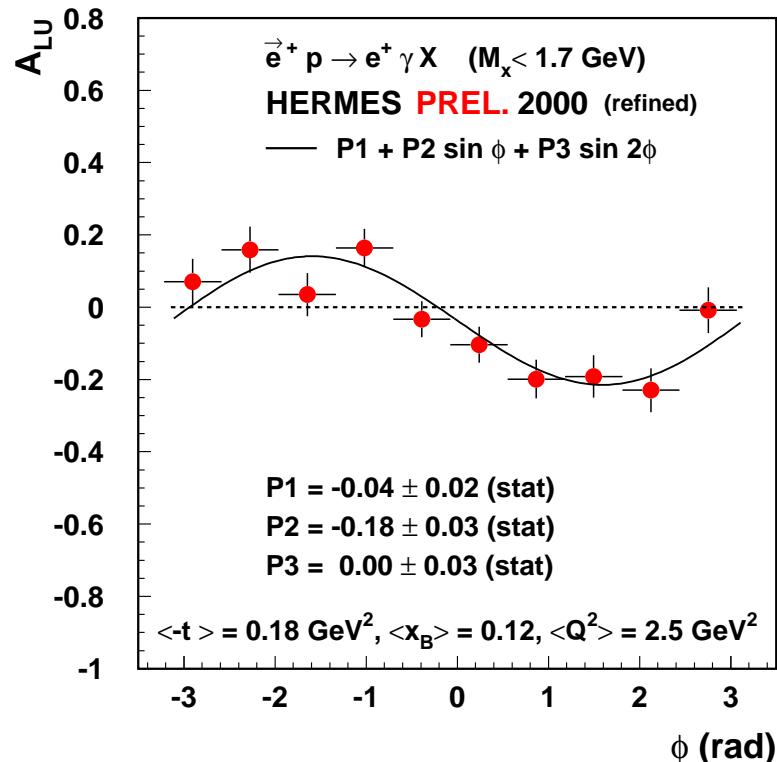
A_{LU} IN EXCLUSIVE BIN: EXPECTED
$\sin(\phi)$ DEPENDENCE $\Rightarrow$ Im $M_{unp}^{1,1}$

$\sin(\phi)$–MOMENT IN NON–EXCLUSIVE
REGION: SMALL AND SLIGHTLY
POSITIVE $\left(\to \pi^0 \right)$

(RESULTS FROM 1996/97 $\to$ PRL **87**, 182001 (2001))

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

$\Rightarrow$ Calculate "symmetrized" BCA ($\phi \to |\phi|$) to get rid of all $\sin(\phi)$–dependences due to polarized beam.
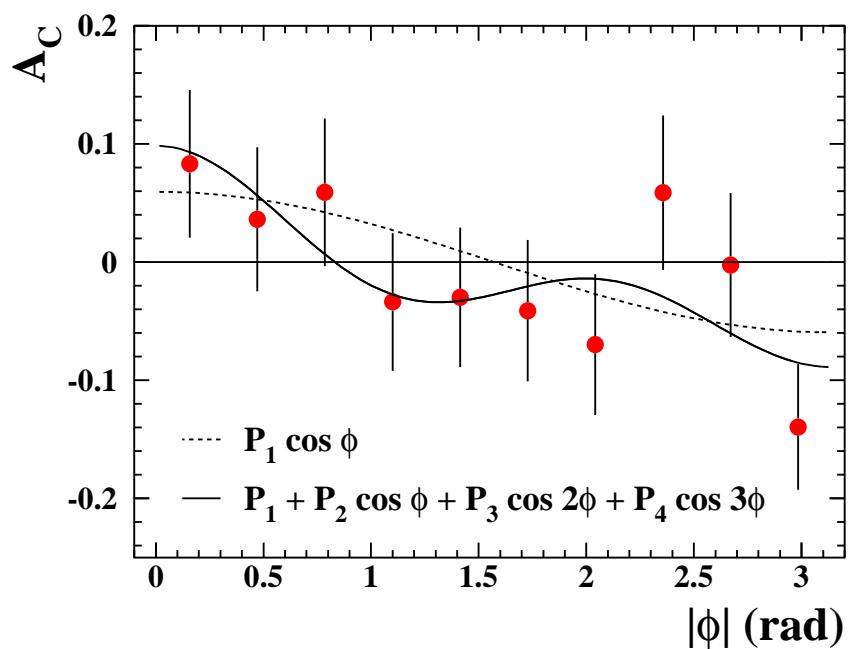
A_{C} in exclusive bin: Expected $\cos(\phi)$ dependence $\Rightarrow$ Re $M_{unp}^{1,1}$
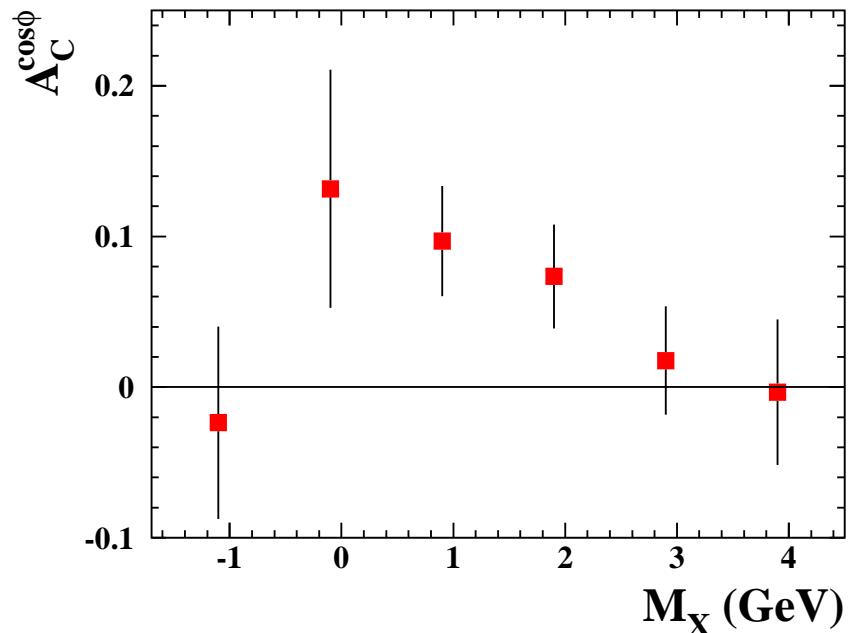
$\cos(\phi)$–Moments zero at higher missing mass
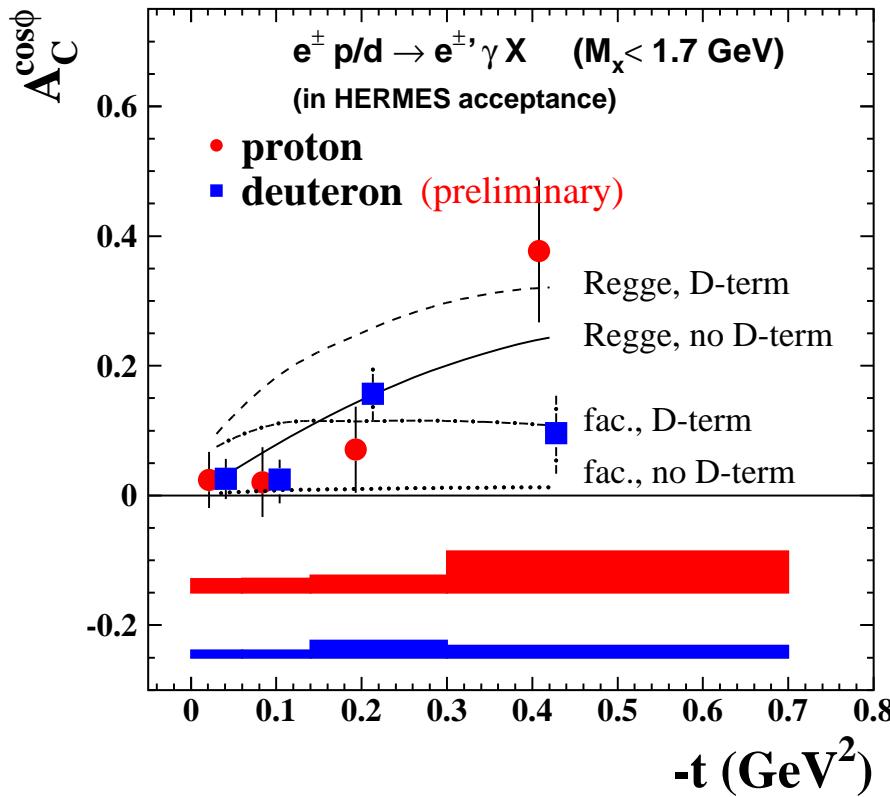
Also: DVCS on deuterium:
Coherent production on D only in first t-bin ($\approx 40\%$)
$\Rightarrow$ No effect seen
$\rightarrow$ $\approx$ P-target

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!

RECOIL DETECTOR AND UNPOL. TARGETS (2006/2007)

- ENSURES EXCLUSIVITY OF EVENTS

  – SEMI–INCLUSIVE BACKGROUND $5\% \Rightarrow \ll 1\%$

  – ASSOCIATED BACKGROUND $10\% \Rightarrow \approx 1\%$

Iron Shielding
Cryostat
SC Coils
SciFi Connector Plate
C3 Collimator
Si Detector Cooling
Si Detector Connectors
Hybrid
Photon Detector
SciFi Detector
Silicon Detector
Target Cell
Flange

0.1 0.2 0.3 m
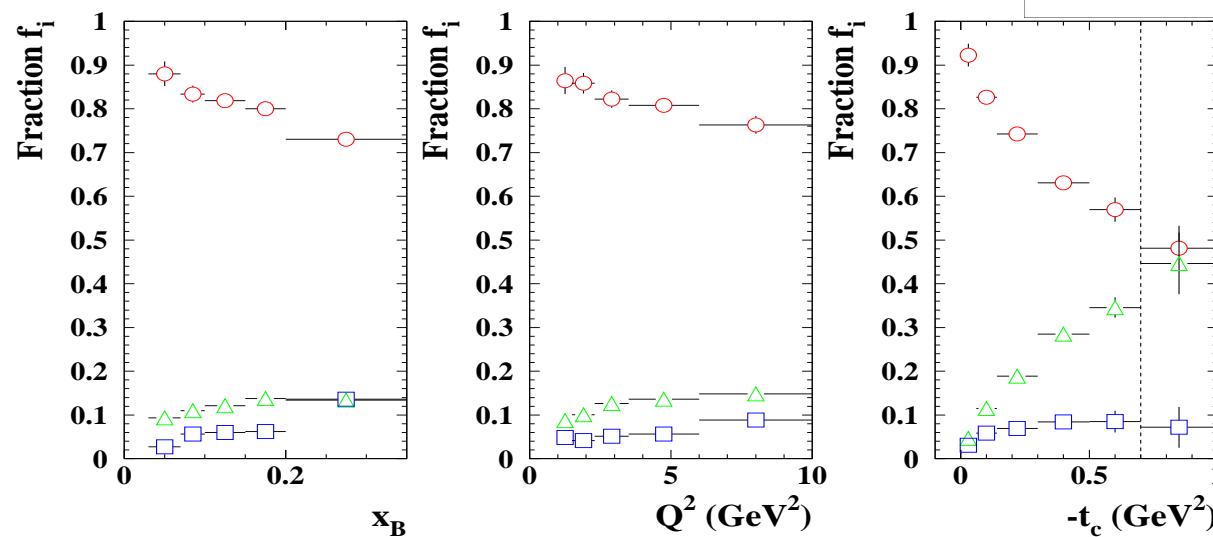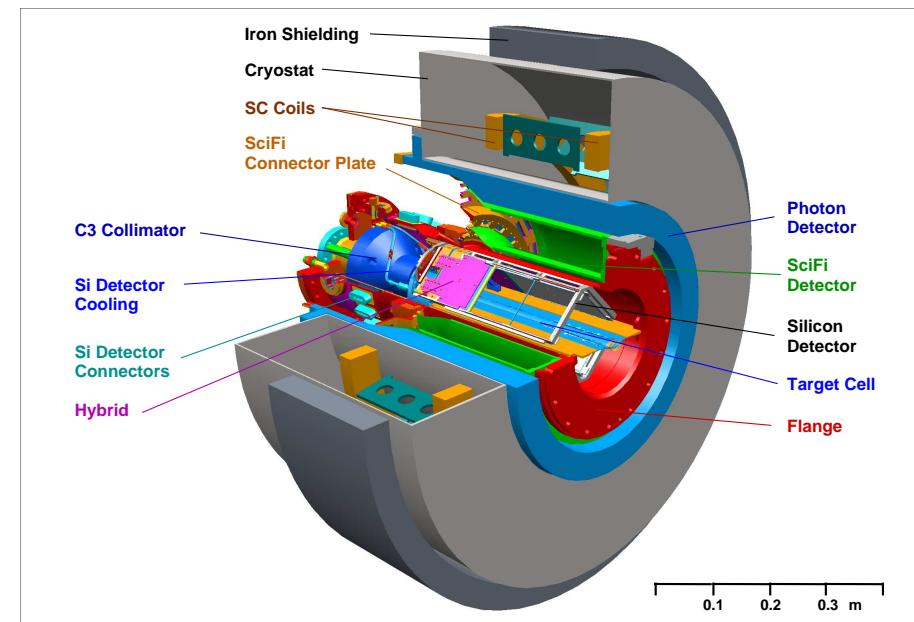
$\Rightarrow$ ESSENTIAL AT LARGER $-t$ VALUES

BCA
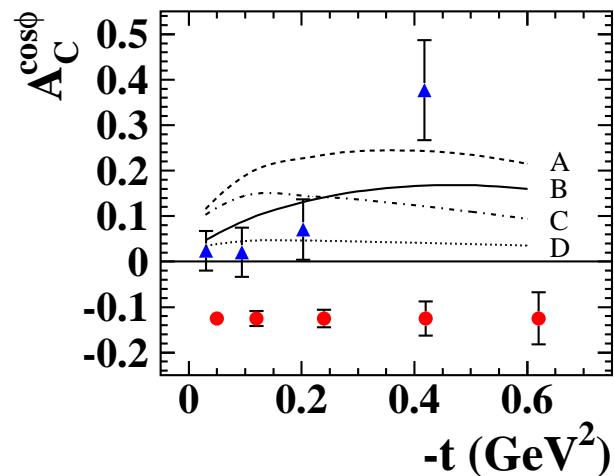
BSA
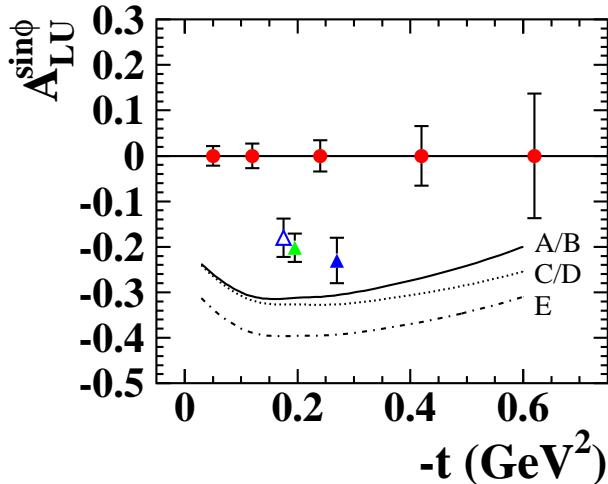
$\triangle$: HERMES PRELIM./PUBLISHED

$\triangle$: CLAS, PRL, 2001 $(\times -1)$

$\bullet$: $1fb^{-1}\,e^{+}$ AND $0.25fb^{-1}\,e^{-}$, 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.

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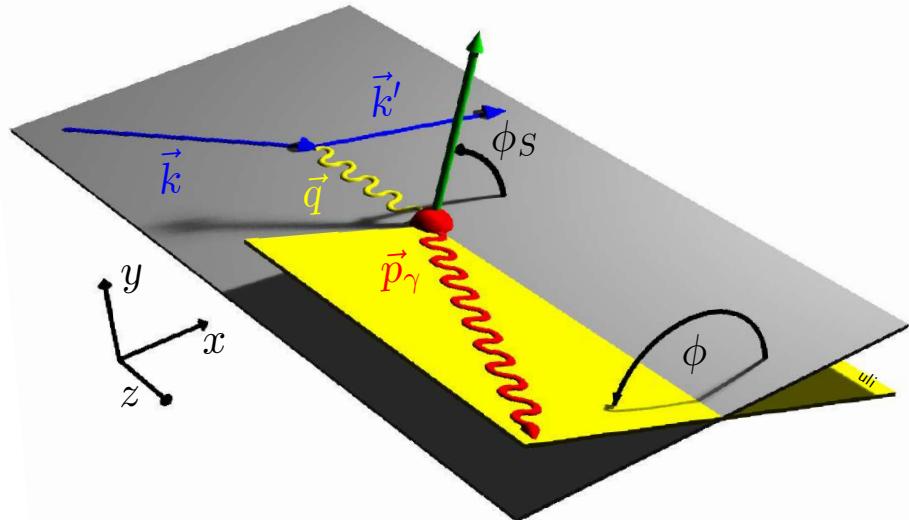
$$A_{UT}(\phi, \phi_s) = \frac{1}{|P_T|} \cdot \frac{d\sigma^{\Uparrow}(\phi, \phi_s) - d\sigma^{\Downarrow}(\phi, \phi_s')}{d\sigma^{\Uparrow}(\phi, \phi_s) + d\sigma^{\Downarrow}(\phi, \phi_s')}$$

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

DATA TAKING WITH TRANSVERSE HYDROGEN TARGET FINISHED
≈ 10 MILLION ON TAPE, HALF THE DATA (2002-2004) ANALYZED
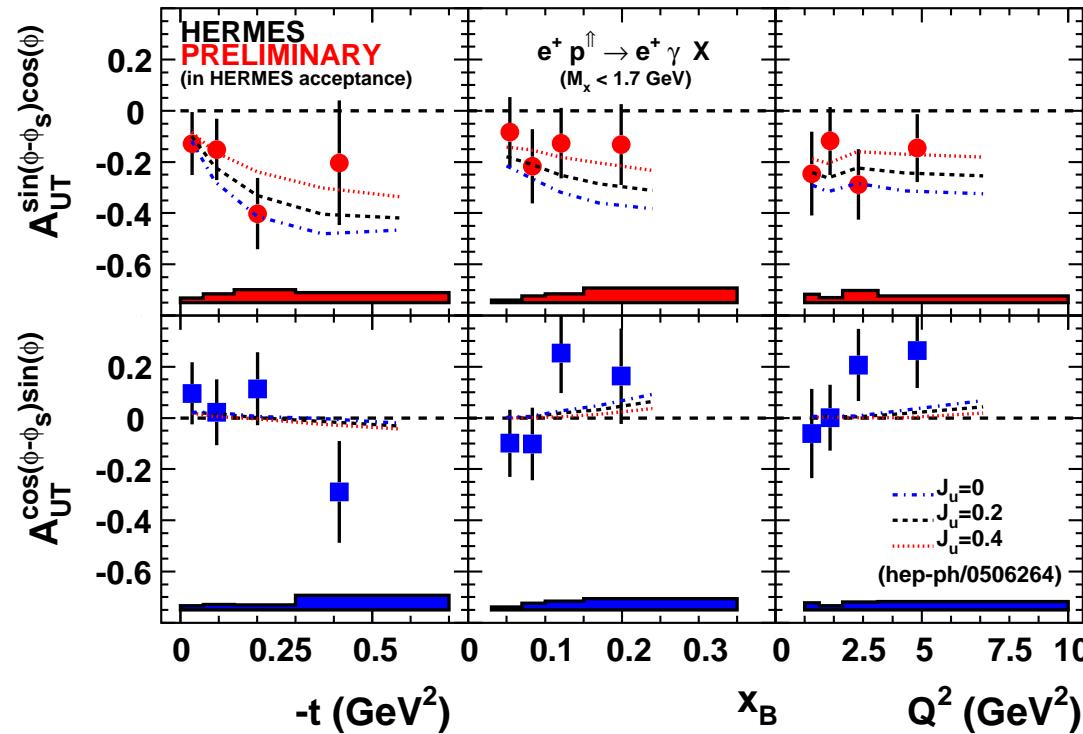

$A_{UT}^{\sin(\phi-\phi_s)\cos\phi}$ LARGELY INDEPENDENT ON ALL MODEL PARAMETERS BUT J_u

(F.E., NOWAK, VINNIKOV, YE, HEP-PH/0506264)

$\Rightarrow$ FIRST MODEL DEPENDENT EXTRACTION OF J_u POSSIBLE!

FIRST CONSTRAINT ON ANGULAR MOMENTUM !
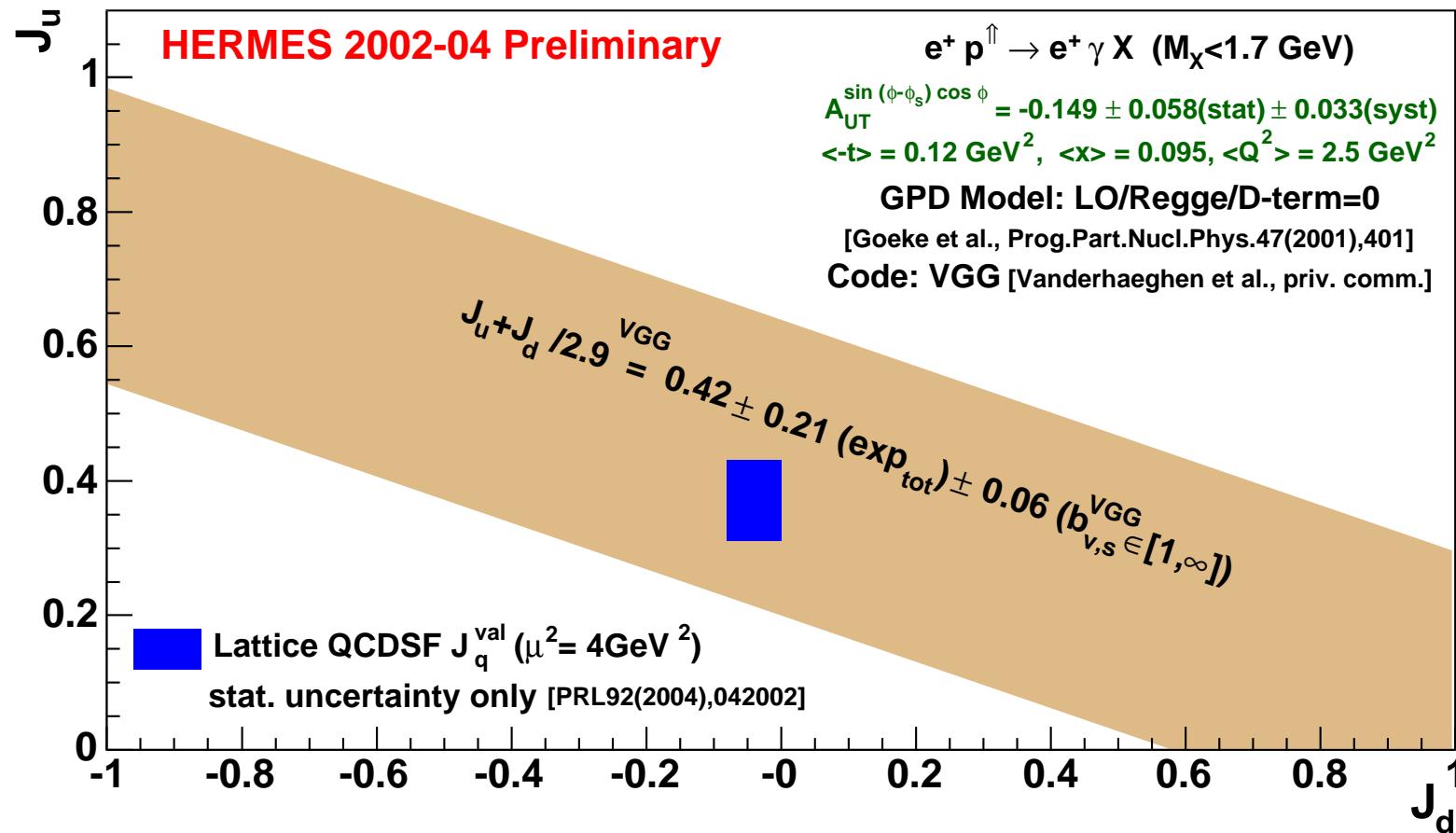
$\Rightarrow$ FIRST MODEL DEPENDENT CONSTRAINT ON TOTAL QUARK ANGULAR MOMENTUM J_u, J_d.

EXCLUSIVE VECTOR MESON PRODUCTION

THE (ONLY) OTHER (PROMISING)
ACCESS TO E (J) (ON A P TARGET):
A_{UT} IN EXCLUSIVE ρ^0 PRODUCTION:

$$e\,p \to e\,p\,\rho^0$$
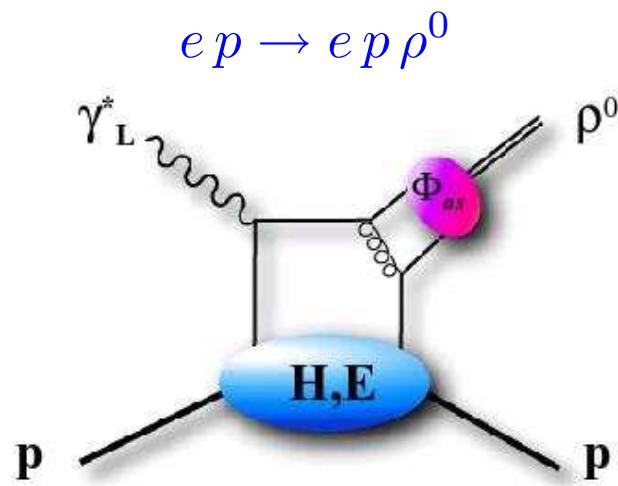
EVENT SELECTION:

- $\rho^0 \to \pi^+\pi^-$,

- NO RECOIL DETECTION
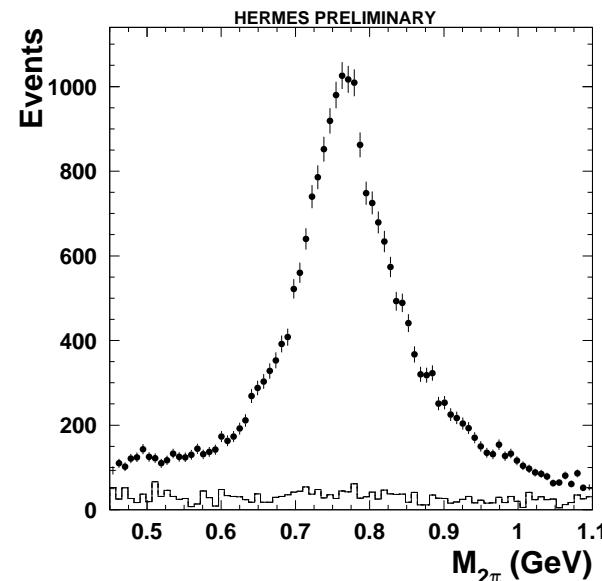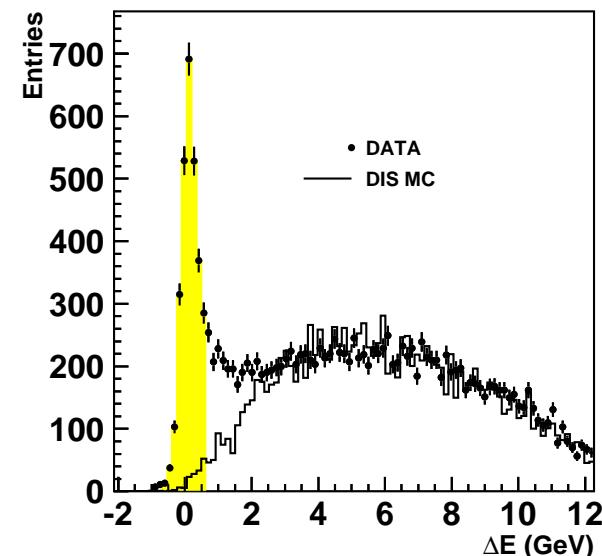
- $\to$ MISSING ENERGY

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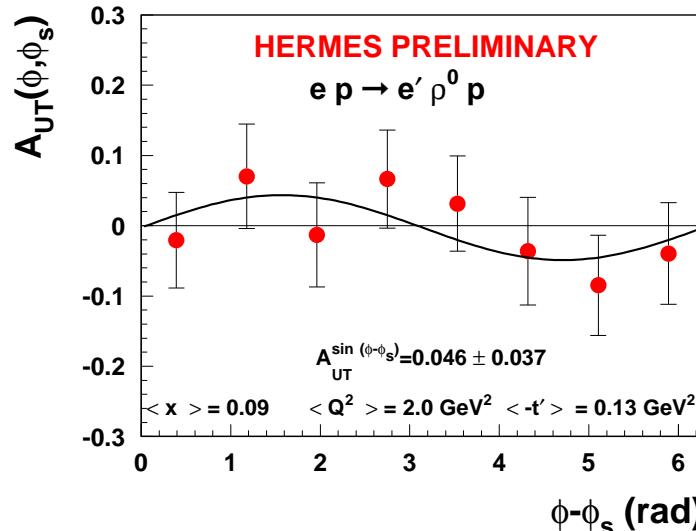
EXPECTED $\sin\phi$ BEHAVIOR

(NO L/T SEPARATION YET)
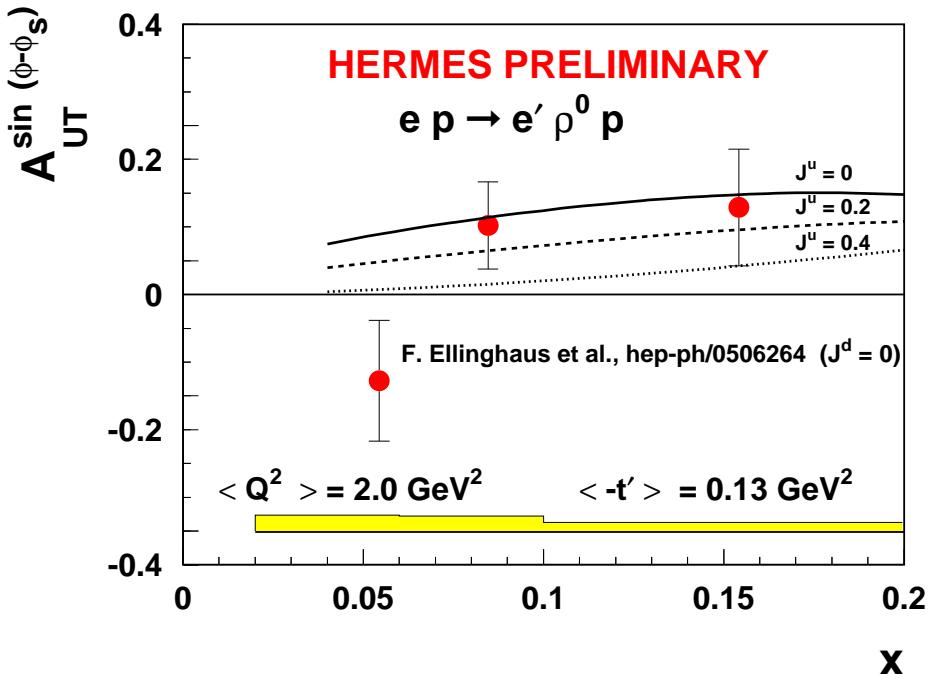
AGREEMENT WITH THEORETICAL CALCULATION.

(CALCULATION/FACTORIZATION PROOF FOR LONGITUDINAL PHOTONS ONLY)

AGAIN: SAME SIZE DATA SET TO COME, A^{ρ}_{UT} LESS SENSITIVE TO J_u WHEN COMPARED TO A^{DVCS}_{UT} → PROVIDE ADDITIONAL CONSTRAINTS

SUMMARY

- HARD EXCLUSIVE PROCESSES PROBE GPDs

- RESULTS SO FAR IN GENERAL AGREEMENT WITH BASIC MODELS AND AS-SUMPTIONS.

- 2006/2007 DATA TAKING (+RECOIL DETECTOR) DEVOTED TO EXCLUSIVE REACTIONS:
  $\rightarrow$ "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 MOMEN-TUM OF U-QUARKS (J_u) AND D-QUARKS (J_d) IN THE NUCLEON.