Deeply Virtual Compton Scattering at HERMES

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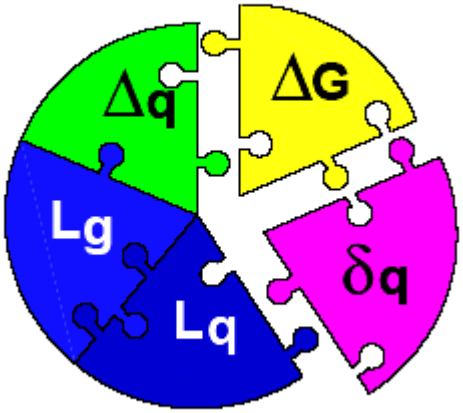
for the HERMES Collaboration

CGSWHP06, Tbilisi, Georgia, September 4-8, 2006

- Motivation: Spin Composition of the Nucleon
- Generalized Parton Distributions and DVCS process
- DVCS Measurement at HERMES
- HERMES Results on Azimuthal Asymmetries
- Summary and Outlook

Nucleon Spin Composition



NUCLEON SPIN:

$$\frac{1}{2} = \underbrace{\frac{1}{2}\overbrace{(\Delta u + \Delta d + \Delta s)}^{\Delta\Sigma} + L_q}_{J_q} + \underbrace{\Delta G + L_g}_{J_g}$$

$\Delta\Sigma \sim 20 - 35\%$: MEASURED IN DIS,
HERMES ~ 0.3

ΔG: FIRST MEASUREMENTS

L_q, L_g: UNKNOWN!

JI'S RELATION: TOTAL ANGULAR MOMENTUM — **Ji, PRL 78 (1997) 610**

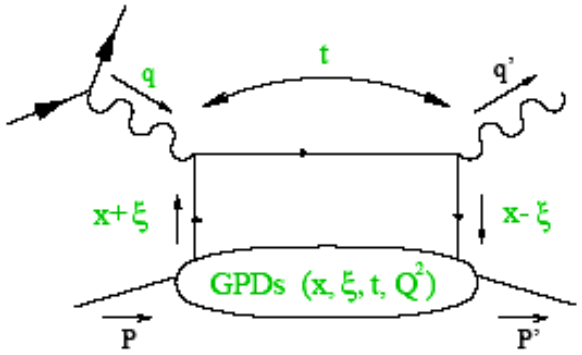
$$J_{q,g} = \lim_{t\to 0} \frac{1}{2} \int_{-1}^{1} dx\, x\, \underbrace{[H_{q,g} + E_{q,g}]}_{GPDs}$$

$\Longrightarrow$THE HUNT FOR L_q

GPDs and DVCS Process

GPDs ACCESSIBLE IN HARD EXCLUSIVE PROCESSES:
DVCS: HARD PHOTOPRODUCTION OF A REAL PHOTON ($\gamma^* N \to N' \gamma$),
VIRTUAL PHOTON GENERATED BY LEPTON SCATTERING $\Rightarrow e N \to e' N' \gamma$

FACTORIZATION THEOREM:



$x \pm \xi$: PARTON LONGITUDINAL MOMENTUM FRACTIONS,

ξ: FRACTION OF THE MOMENTUM TRANSFER, $\xi \simeq \frac{x_B}{2-x_B}$,

t: INVARIANT MOMENTUM TRANSFER, $t \equiv (p-p')^2$

NUCLEON STRUCTURE:

$GPDs: \quad H_q, \widetilde{H}_q, E_q, \widetilde{E}_q$

$GPDs \to PDFs$

$H_q(x,0,0) = q(x)$

$\widetilde{H}_q(x,0,0) = \Delta q(x)$

$H_q, \widetilde{H}_q$ — CONSERVE NUCLEON HELICITY

$E_q, \widetilde{E}_q$ — FLIP NUCLEON HELICITY, NOT ACCESSIBLE IN DIS

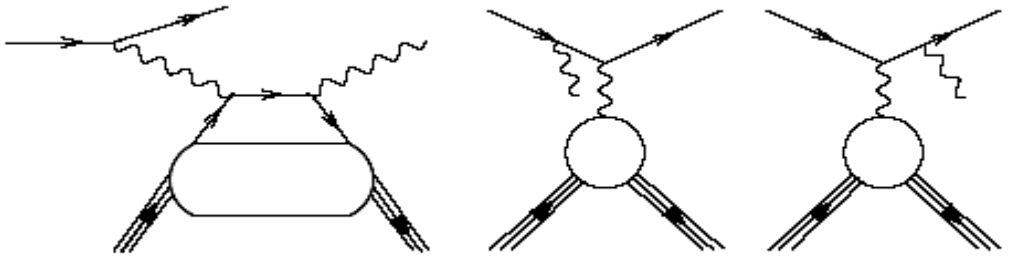
$GPDs \to FFs$

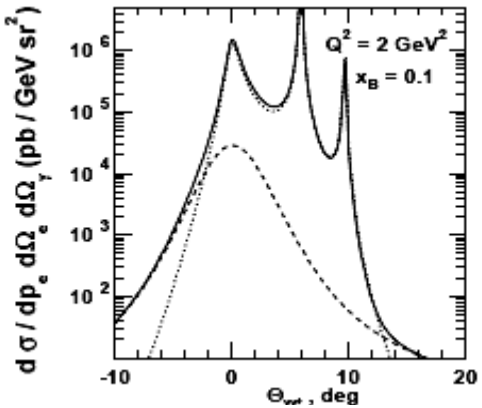
$\int_{-1}^{1} dx\, H_q(x,\xi,t) = F_1^q(t)$,

$\int_{-1}^{1} dx\, E_q(x,\xi,t) = F_2^q(t)$

DVCS and BH Interference

DVCS (a) AND BETHE-HEITLER (BH) (b) PROCESSES EXPERIMENTALLY INDISTINGUISHABLE





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

HERMES KINEMATICS:

$$|\tau_{\mathrm{DVCS}}|^2 << |\tau_{\mathrm{BH}}|^2$$

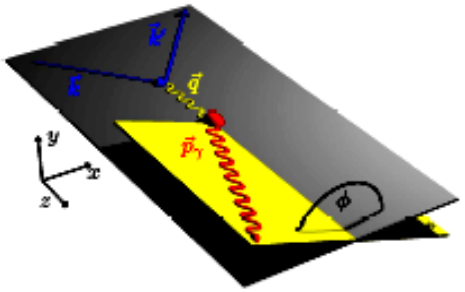
DVCS AMPLITUDES: ACCESSIBLE THROUGH AZIMUTHAL ASYMMETRIES VIA I
(GPDs ENTER IN LINEAR COMBINATIONS IN AMPLITUDES)

- BEAM–SPIN ASYMMETRY (BSA):

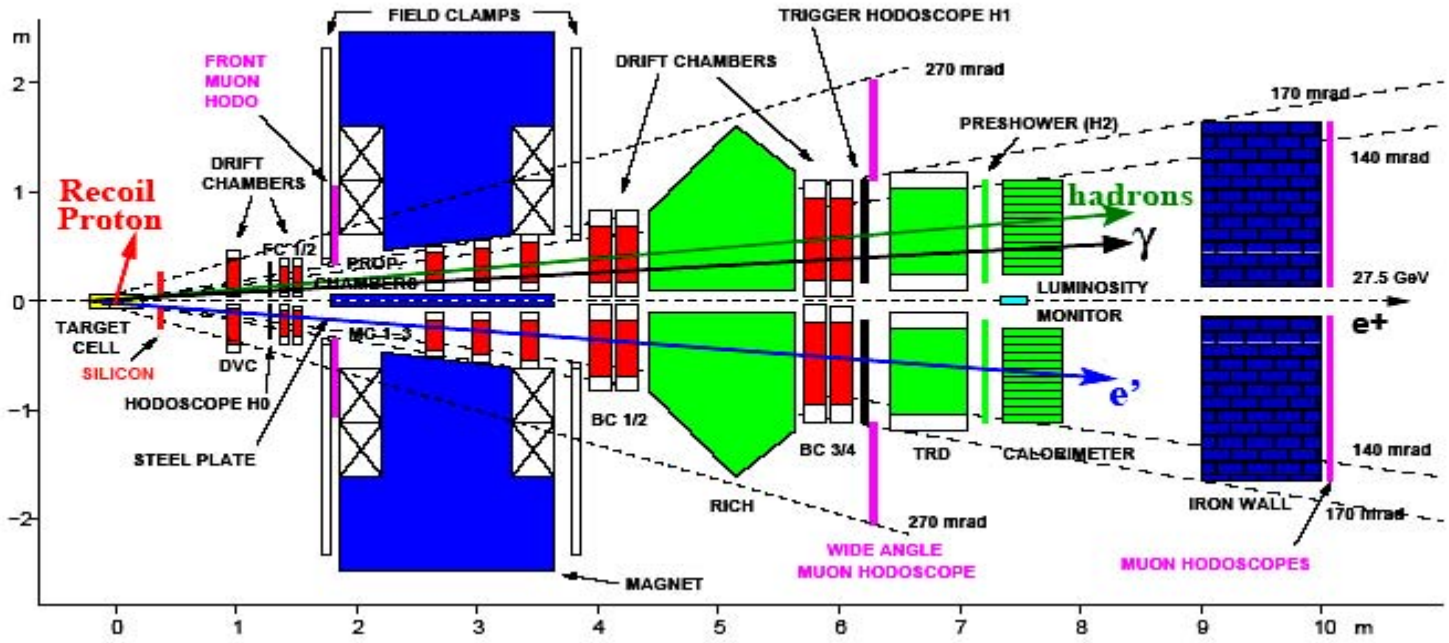
$$d\sigma(\overrightarrow{e^+}p) - d\sigma(\overleftarrow{e^+}p) \propto \mathrm{Im}\,[F_1\mathcal{H}] \times \sin(\phi)$$

- BEAM–CHARGE ASYMMETRY (BCA):

$$d\sigma(e^+p) - d\sigma(e^-p) \propto \mathrm{Re}\,[F_1\mathcal{H}] \times \cos(\phi)$$



The HERMES Experiment



Gas Target:

- Long. polarized H, D
- Unpolarized H, D, Ne, Kr, Xe
- Transversely polarized H

$\langle |P_T| \rangle \approx 85\%$

Beam:

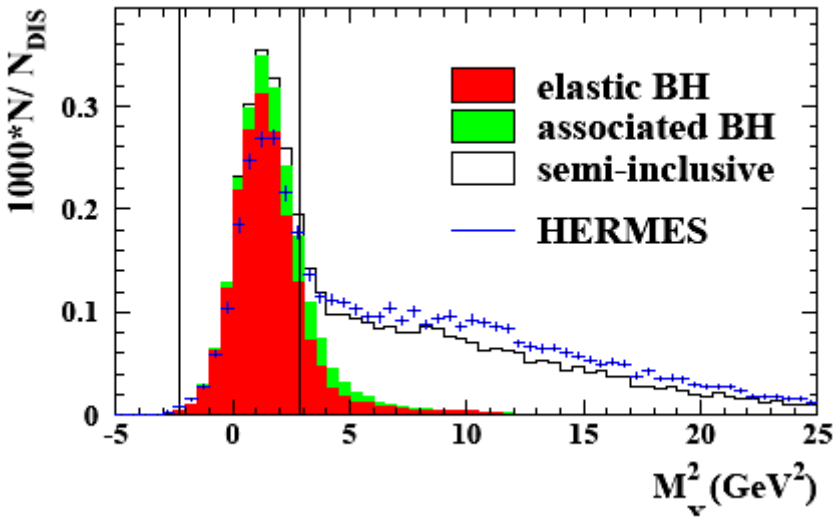
- Long. polarized e^+ and e^-
- Energy 27.6 GeV
- Both helicities

$\langle |P_B| \rangle \approx 55\%$ (HERA I)

PID: $\epsilon_e > 99\%$, $\delta P/P < 2\%, \delta\theta < 1mrad$, $\delta E_\gamma / E_\gamma \approx 5\%$.

DVCS Event Selection

- Events with exactly one DIS - lepton and exactly one trackless cluster in the calorimeter.
- No recoil detection $\Rightarrow$ Exclusivity via missing mass: $M_X^2 = (q + P - q')^2$



MC for background and cuts

$e\,p \rightarrow e'\,\gamma\,X$

Contributed Processes:

$e\,p \rightarrow e'\,p\,\gamma$; Elastic BH

$e\,p \rightarrow e'\,\Delta^+\,\gamma$; Associated BH

$e\,p \rightarrow e'\,\pi^0\,X$; Semi-inclusive

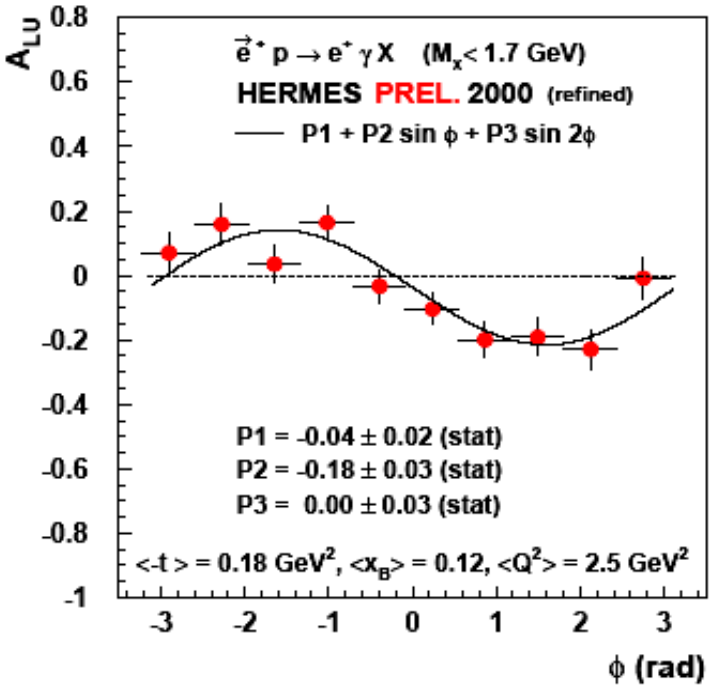
Correction on Background $\Rightarrow$ Mostly Decay Photons From Semi-inclusive π^0 ($\approx 6\%$)

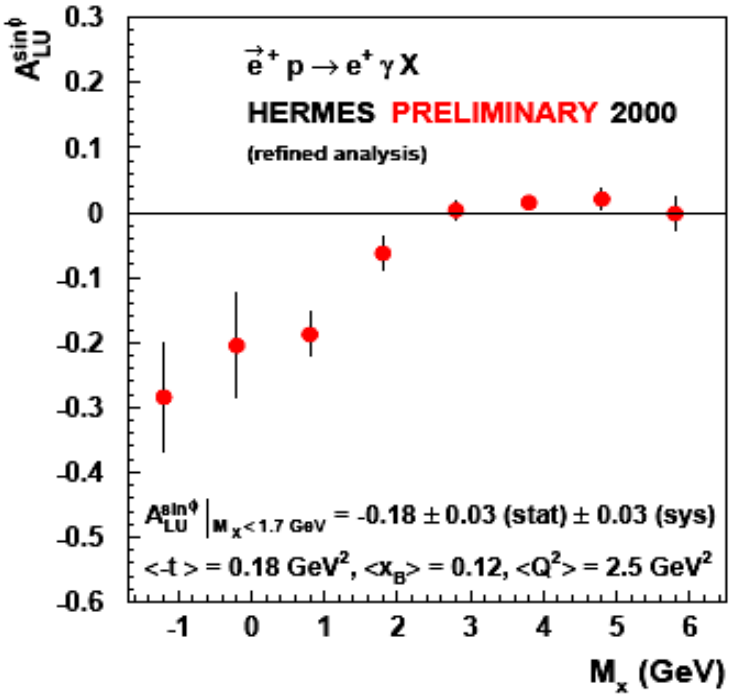
Background Contribution Overall $\approx 15\ \%$

$\Rightarrow$ Exclusive bin $(-(1.5)^2 < M_X^2 < (1.7)^2\ GeV^2)$

Beam-Spin Asymmetry on Proton

$$A_{\mathrm{LU}}(\phi) = \frac{1}{\langle |P_b| \rangle} \frac{\overrightarrow{N}(\phi) - \overleftarrow{N}(\phi)}{\overrightarrow{N}(\phi) + \overleftarrow{N}(\phi)} \propto \frac{\mathrm{Im}\,\mathcal{H}}{F_1} \sin\phi$$





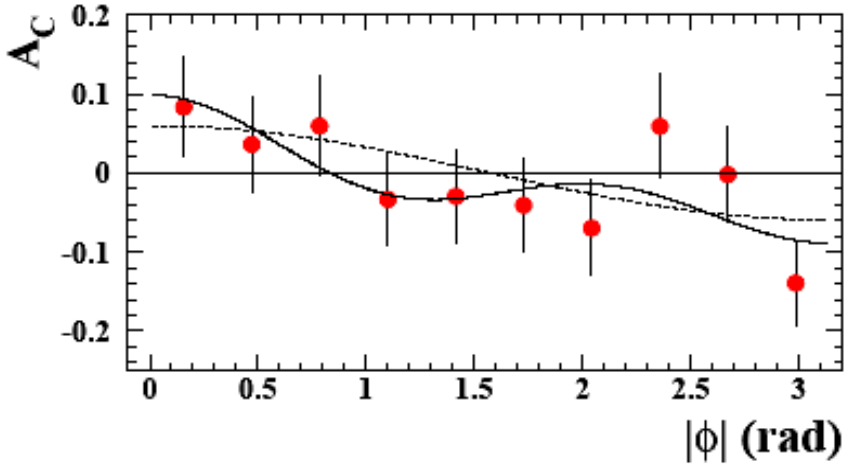
A_{LU} IN EXCLUSIVE BIN: EXPECTED $\sin(\phi)$ DEPENDENCE $\Longrightarrow \mathrm{Im}\,\mathcal{H}$

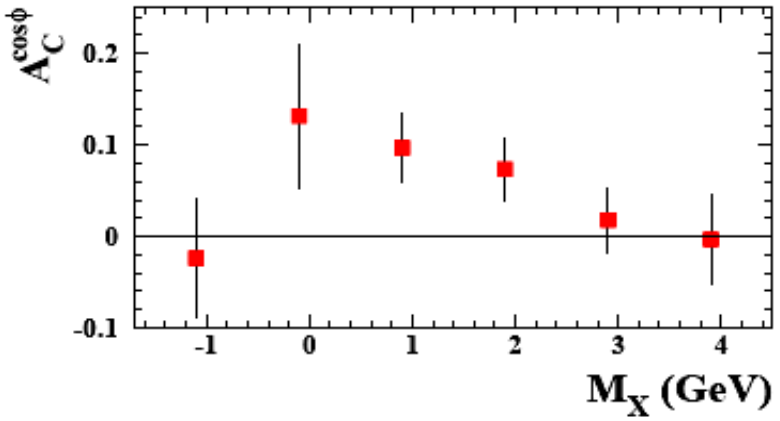
$\sin(\phi)$-MOMENTS IN NON-EXCLUSIVE REGION IS SMALL AND POSITIVE

BSA RESULTS: HERMES-PRL **87**, 182001 (2001)

Beam-Charge Asymmetry on Proton

$$A_C(\phi) = \frac{N^+(\phi) - N^-(\phi)}{N^+(\phi) + N^-(\phi)} \propto \frac{\mathrm{Re}\,\mathcal{H}}{F_1} \cos\phi$$





'SYMMETRIZED' BCA IN EXCLUSIVE BIN

$(\phi \to |\phi|) \Longrightarrow$ CANCEL SINUSOIDAL TERMS

(DUE TO POLARIZED BEAM)

THE SOLID CURVE $\to$ 4-PARAMETER FIT:

$P_0 + P_1 \cos\phi + P_2 \cos 2\phi + P_3 \cos 3\phi$

THE DASHED CURVE $\to$ PURE $\cos\phi$

EXPECTED $\cos\phi$ DEPENDENCE

$\cos(\phi)$-MOMENTS ZERO

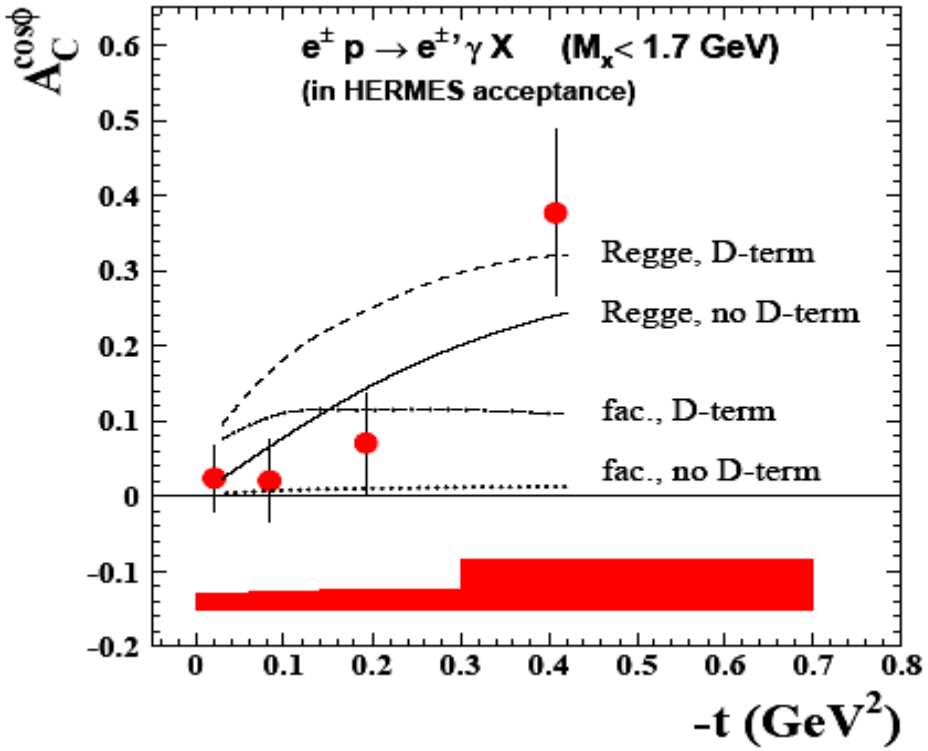
AT HIGHER MISSING MASS

$$A_{C,Proton}^{\cos(\phi)} =$$

$$0.063 \pm 0.029(\text{STAT.}) \pm 0.026(\text{SYS.})$$

A. AIRAPETIAN *et al.*, HEP-EX/0605108 , SUBMITTED TO PRL

Comparison to model calculations

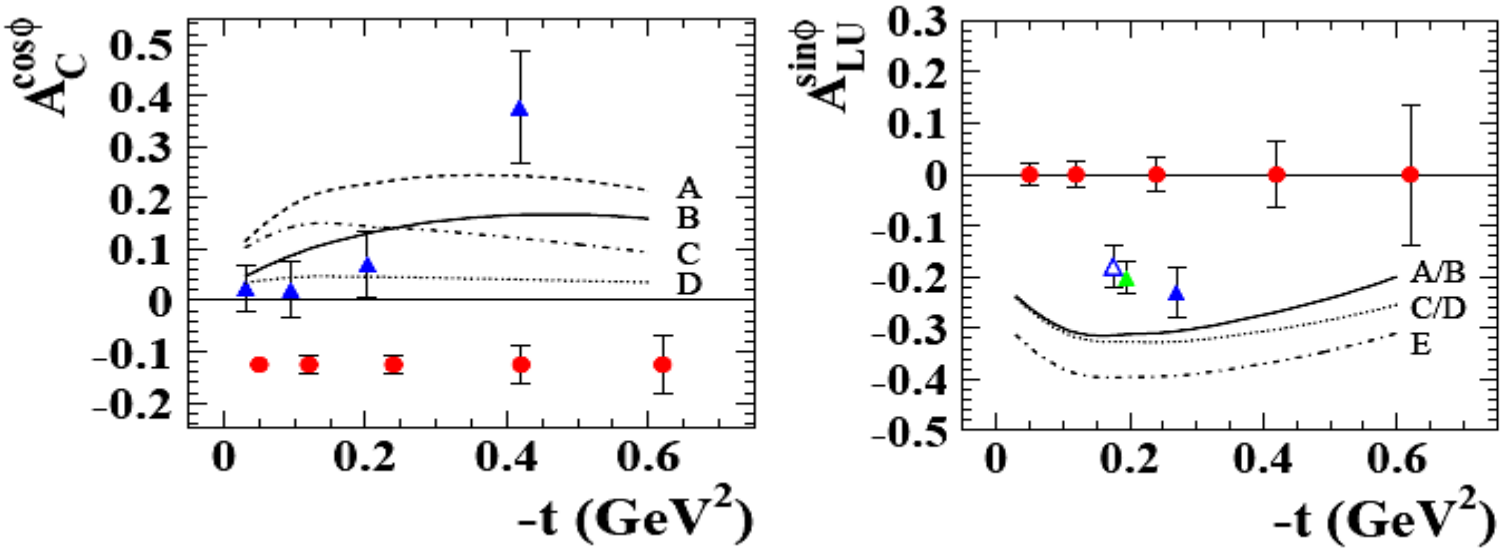


GPD MODELS: M. VANDERHAEGHEN *et al.*, PHYS. REV. D60 (1999) 094017; K. GOEKE *et al.*, PROG. PART. NUCL. PHYS. 47 (2001) 401.

- GPD H DOMINATES, E SUPPRESSED
- CURVES: 4 DIFFERENT PARAMETER SETS
- MODEL CALCULATIONS AT AVERAGE KINEMATIC VALUES PER BIN

IN LAST t-BIN: LARGE CONTRIBUTION FROM THE ASSOCIATED PRODUCTION (NOT INCLUDED IN MODEL CALCULATION) $\Rightarrow$
DATA DISFAVOR REGGE-INSPIRED t-DEPENDENCE WITH D-TERM
SMALL $e^- p$ SAMPLE ($L \approx 10$ PB^{-1})
$\Rightarrow$ t–DEPENDENCE OF BCA $\rightarrow$ POSSIBLE TOOL TO CONSTRAIN GPD H

Projection for GPD H (HERA **II**)



LEFT PANEL: ▲ (HEP-EX/0605108) RIGHT PANEL: ▲ HERMES (PRL 2001) △ HERMES (PRELIMIMNARY HEP-EX/0212019) ▲CLAS (PRL 2001)

- BCA: 1 fb^{-1} e^+ AND 0.25 fb^{-1} e^-
- BSA: 1 fb^{-1} e^+, BEAM POL. $\approx 35\%$

MODELS: FACT. - (C/D)/REGGE - (A/B) WITH AND WITHOUT D-TERM; b_{val}=1,b_{sea}=∞

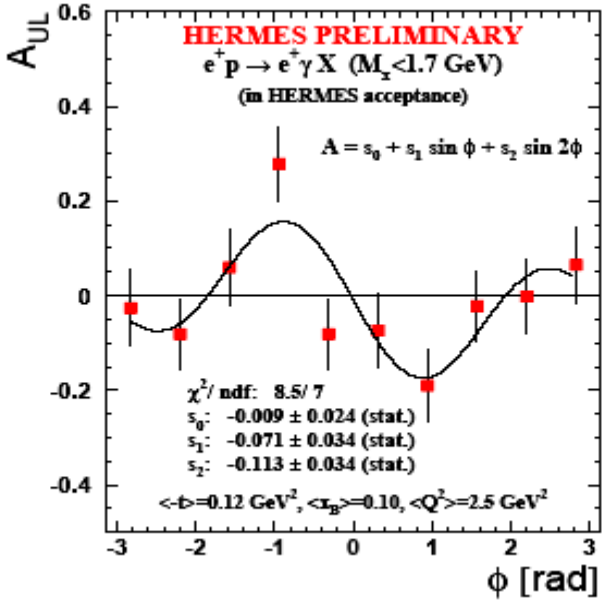
BCA: HIGH SENSITIVITY TO t-DEPENDENCE

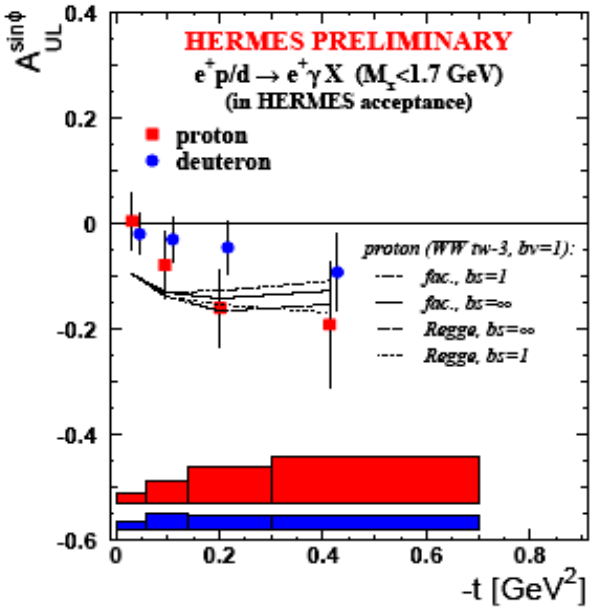
BSA: HIGHEST SENSITIVITY TO b_{sea} PARAMETER IN PROFILE FUNCTION(E; b_{val}=b_{sea}=1)

POSSIBILITY TO CONSTRAIN GPD H_u

Longitudinal Target-Spin Asymmetry

$$A_{\mathrm{UL}}(\phi) = \frac{1}{\langle |P_T| \rangle} \frac{N^{\rightleftarrows}(\phi) + N^{\leftleftarrows}(\phi) - N^{\rightrightarrows}(\phi) - N^{\leftrightarrows}(\phi)}{N^{\rightleftarrows}(\phi) + N^{\leftleftarrows}(\phi) + N^{\rightrightarrows}(\phi) + N^{\leftrightarrows}(\phi)} \propto \frac{\mathrm{Im}\,\tilde{\mathcal{H}}}{F_1} \sin\phi$$





A_{UL} IN EXCLUSIVE BIN: EXPECTED $\sin(\phi)$ DEPENDENCE $\Longrightarrow \mathrm{Im}\,\tilde{\mathcal{H}}$

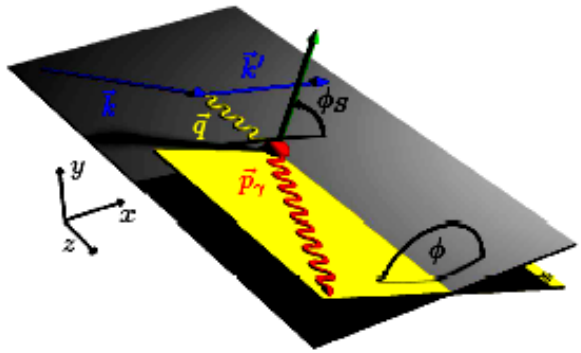
- GPD MODEL: TWIST-3 IS A SIMPLE W.W. TWIST-3
- $A_{UL}^{\sin 2\phi} \Longrightarrow (qGq)$ TWIST-3 IS MISSING ?

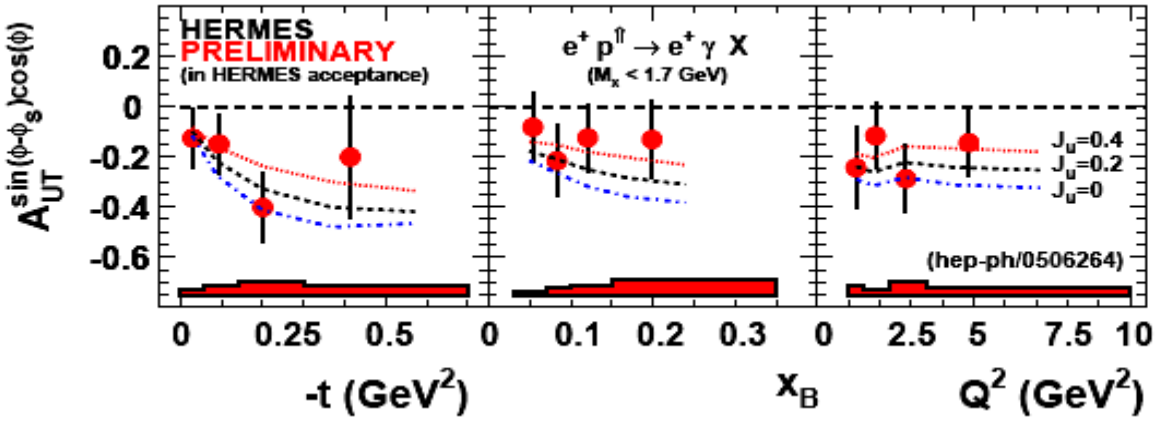
Transverse Target-Spin Asymmetry from HERMES

$$d\sigma(e^+p^{\uparrow}) - d\sigma(e^+p^{\downarrow}) \propto \mathrm{Im}\,[F_2\mathcal{H} - F_1\mathcal{E}] \times \sin(\phi - \phi_S)\cos(\phi) + \cdots$$

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

$$A_{\mathrm{UT}}(\phi,(\phi-\phi_S)) = \frac{1}{\langle |P_T| \rangle} \frac{N^{\uparrow}(\phi,(\phi-\phi_S)) - N^{\downarrow}(\phi,(\phi-\phi_S))}{N^{\uparrow}(\phi,(\phi-\phi_S)) + N^{\downarrow}(\phi,(\phi-\phi_S))}$$





- RESULTS FROM HERMES 2002-2004 DATA ONLY; $\simeq 60 pb^{-1}$
- MODEL FROM GOEKE *et al.*: THE GPD E IS UNKNOWN IN THE FORWARD LIMIT; PARAMETRIZED ACCORDING TO χQSM MODEL
- $A_{\mathrm{UT}}^{\sin(\phi-\phi_S)cos(\phi)}$ SENSITIVE TO J_u $(J_d{=}0)$

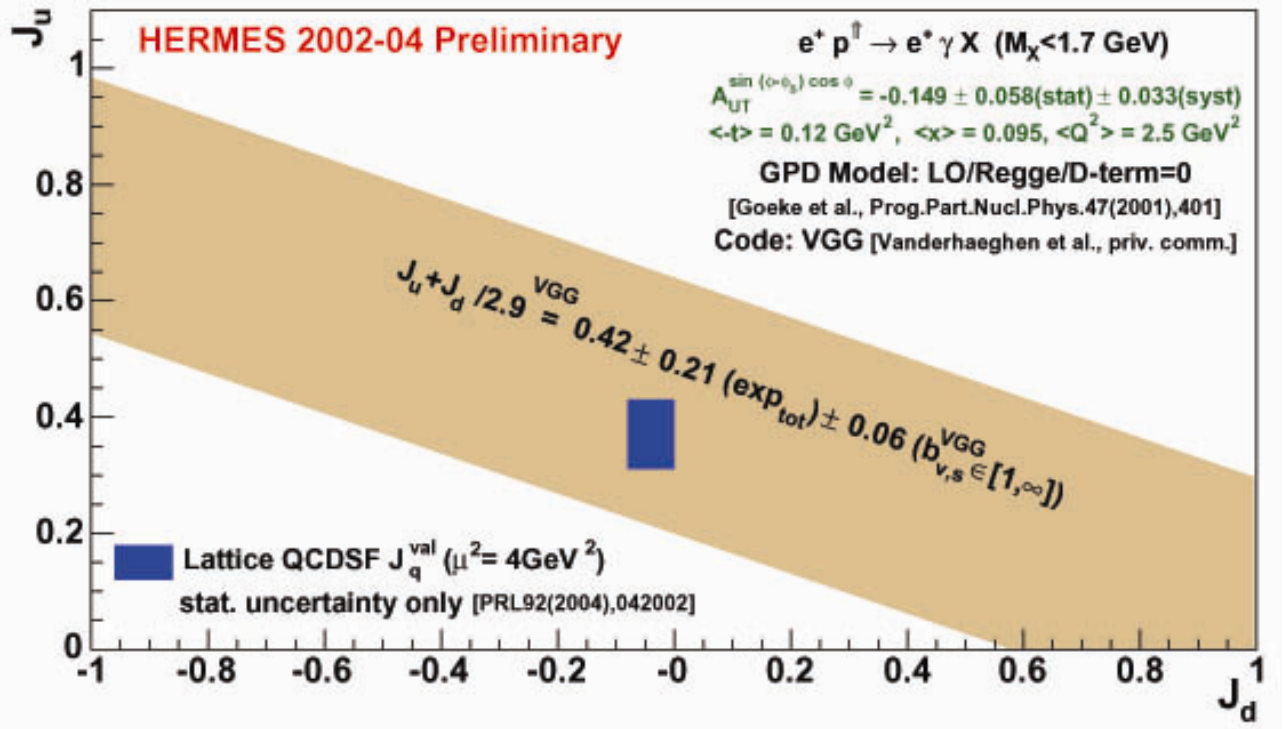
Model-Dependent Constraint on J_u vs J_d

- COMPARISON OF THE THEORETICAL PREDICTIONS WITH THE EXPERIMENTAL RESULTS:

$$\chi^2(J_u, J_d) = \frac{\left[A_{\mathrm{UT}}^{\sin(\phi-\phi_S)\cos(\phi)}|_{exp} - A_{\mathrm{UT}}^{\sin(\phi-\phi_S)\cos(\phi)}|_{VGG}(J_u, J_d)\right]^2}{\delta A^2_{stat} + \delta A^2_{sys}}$$

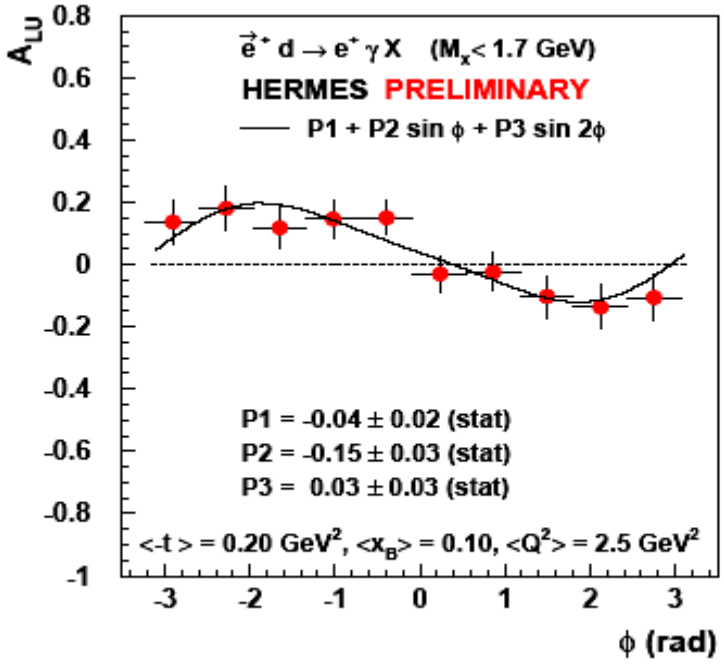
CALCULATED IN STEP OF 0.2 IN J_u AND J_d, INTERPOLATED BY A 5TH ORDER POLINOMIAL.

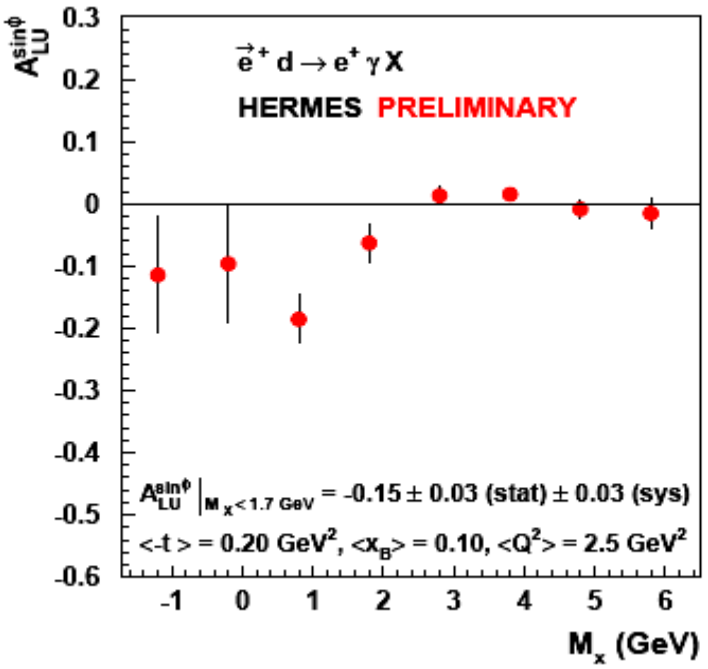
- THE 1-σ CONSTRAINT ON J_u VS J_d DETERMINED BY $\chi^2(J_u, J_d) \leq \chi^2_{min} + 1$.



Beam-Spin Asymmetry on Deuteron

$$A_{L\pm}(\phi) = \frac{1}{\langle |P_b| \rangle} \frac{N^{\vec{\Rightarrow}}(\phi) + N^{\vec{\Leftarrow}}(\phi) - N^{\overleftarrow{\Rightarrow}}(\phi) - N^{\overleftarrow{\Leftarrow}}(\phi)}{N^{\vec{\Rightarrow}}(\phi) + N^{\vec{\Leftarrow}}(\phi) + N^{\overleftarrow{\Rightarrow}}(\phi) + N^{\overleftarrow{\Leftarrow}}(\phi)} \propto \frac{\mathrm{Im}\,(\mathcal{H}_1 - \frac{1}{3}\mathcal{H}_5)}{G_1} \sin\phi$$



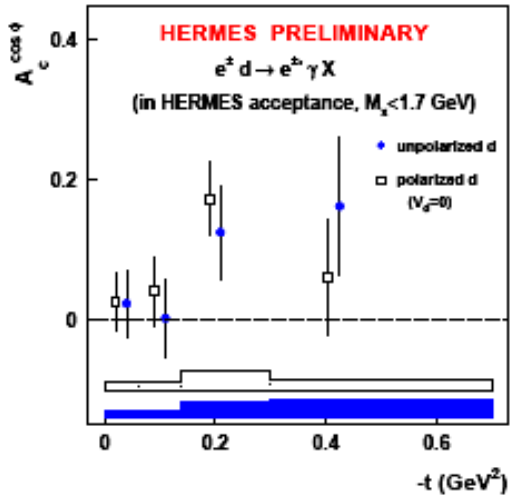


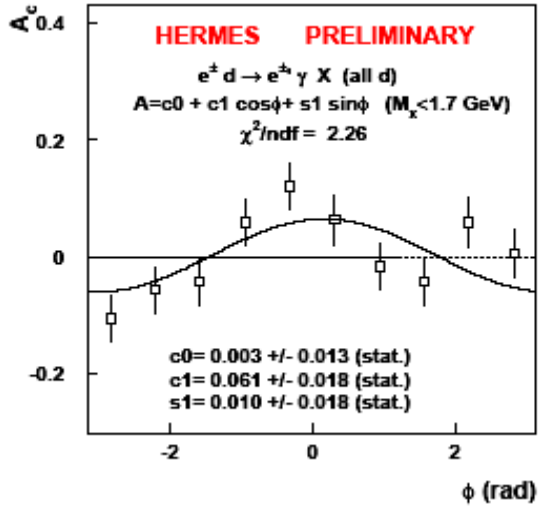
$$A_{L\pm,\,Deuteron}^{\sin\phi} = -0.15 \pm 0.03$$

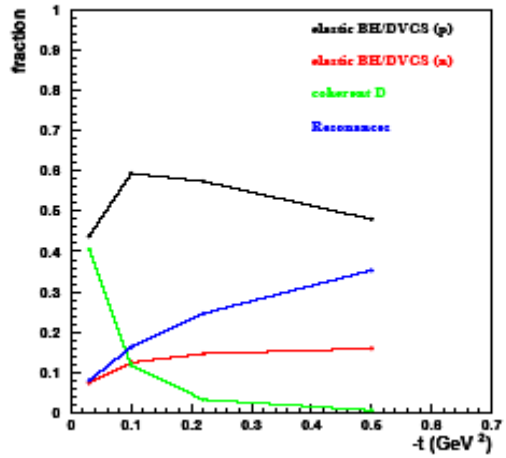
$$A_{LU,\,Proton}^{\sin\phi} = -0.18 \pm 0.03$$

$\sin(\phi)$-MOMENTS ZERO AT HIGHER MISSING MASS

Beam-Charge Asymmetry on Deuteron







40 % COHERENT IN FIRST t-BIN

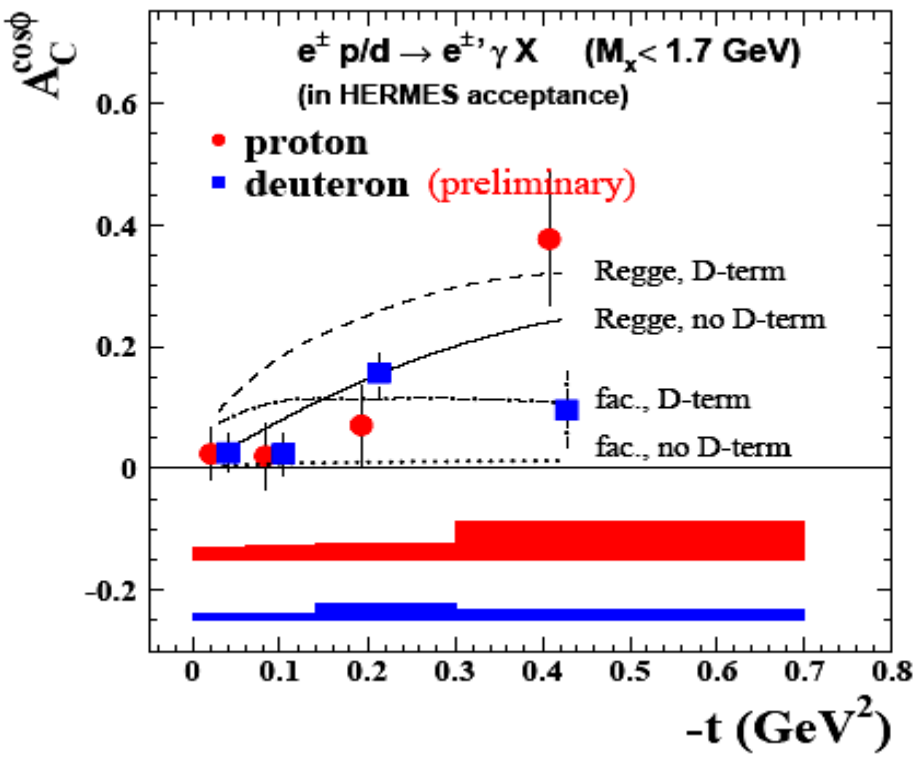
$\Rightarrow$ NO TENSOR EFFECT SEEN

$\Rightarrow$ DATA CAN BE COMBINED

$$A_{\mathrm{CU},Deuteron}^{\cos\phi} \propto \frac{\mathrm{Re}\,\mathcal{H}_1}{G_1}\cos\phi$$

$$A_{\mathrm{C},Deuteron}^{\cos\phi} \approx A_{\mathrm{C},Proton}^{\cos(\phi)}$$

Comparison to model calculations



$e\,d \rightarrow e\,\gamma\,X$

CONTRIBUTED PROCESSES:

$e\,d \rightarrow e\,d\,\gamma$, COHERENT PROCESS

$e\,d \rightarrow e\,pn\,\gamma$, INCOHERENT PROCESS

$e\,N \rightarrow e\,N^*\,\gamma$, RESONANT STATES

$-t < 0.7\ GeV^2 \Rightarrow$ COHERENT $\approx 20\%$

$\Rightarrow M_X$ CALCULATED VIA PROTON MASS

SMALLER $-t \Rightarrow$ COHERENT ENHANCED

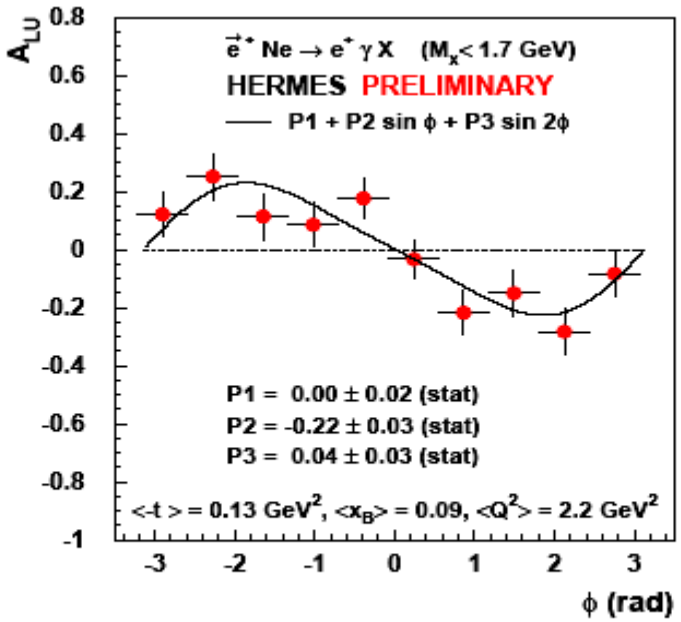
GPD MODELS: M. VANDERHAEGHEN *et al.*, PHYS. REV. D60 (1999) 094017; K. GOEKE *et al.*, PROG. PART. NUCL. PHYS. 47 (2001) 401.

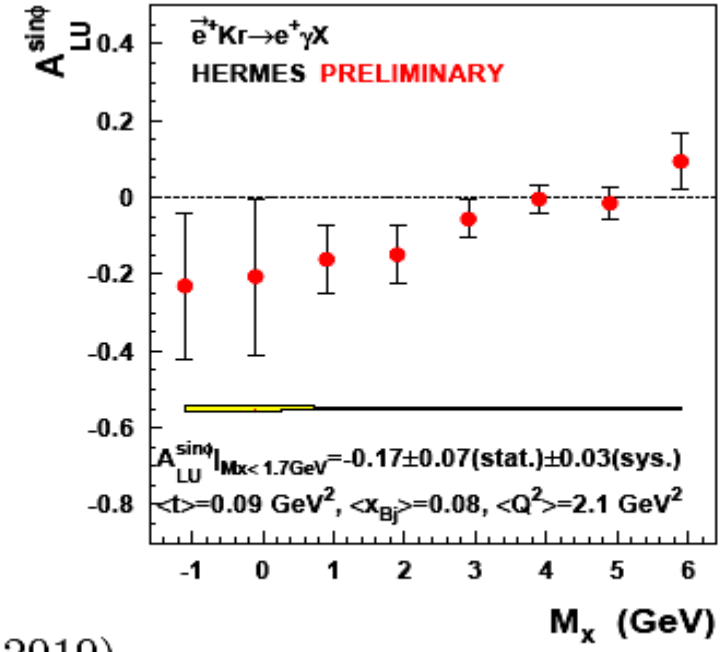
- ed COHERENT (FIRST t-BIN $\approx 40\%$) $\Rightarrow$ NO DIFFERENCE ep AND ed
- DIFFERENCE IN LAST BIN $\Rightarrow$ NEUTRON RESONANCES, NEUTRON

SMALL e^-p SAMPLE ($L \approx 10$ PB^{-1})

$\Rightarrow$ t–DEPENDENCE OF BCA $\rightarrow$ POSSIBLE TOOL TO CONSTRAIN GPDs

Beam-Spin Asymmetries on Neon and Krypton





(HEP-EX/02012019)

Calculations for DVCS on (heavier) Nuclei (Kirchner, Müller, hep-ph/0302007, Guzey, Strikman, hep-ph/0301216, ...)

- Sizeable BSA; Comparison to theory $\Longrightarrow$ separate coherent and incoherent parts $\Longrightarrow$ through t-dependence of BSA (in progress) $\Longrightarrow$ A-dependence of BSA (H, D, Ne, Kr, Xe) and BCA (H, D, Kr, Xe) $\Longrightarrow$ Generalized EMC-Effect in nuclear DVCS

Summary and Outlook

Azimuthal Asymmetries $\Rightarrow$ DVCS-Amplitudes $\Rightarrow$ GPDs
$\Rightarrow$ Structure of Nucleons (L_q)

Existing HERA I data on H:

- Beam–Spin Asymmetry $\Rightarrow$ ImH
- Beam–Charge Asymmetry $\Rightarrow$ ReH
- First constraints on GPD models

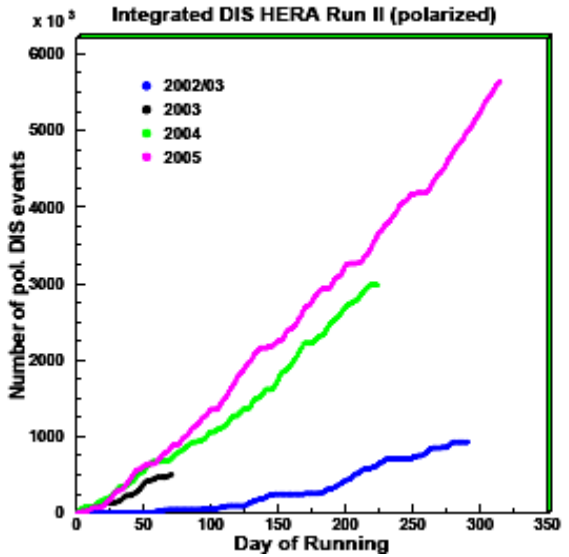
Longitudinally polarized H $\Rightarrow$ LTSA $\Rightarrow$ Im$\tilde{H}$

Transverse polarized H $\Rightarrow$ TTSA $\Rightarrow$ E

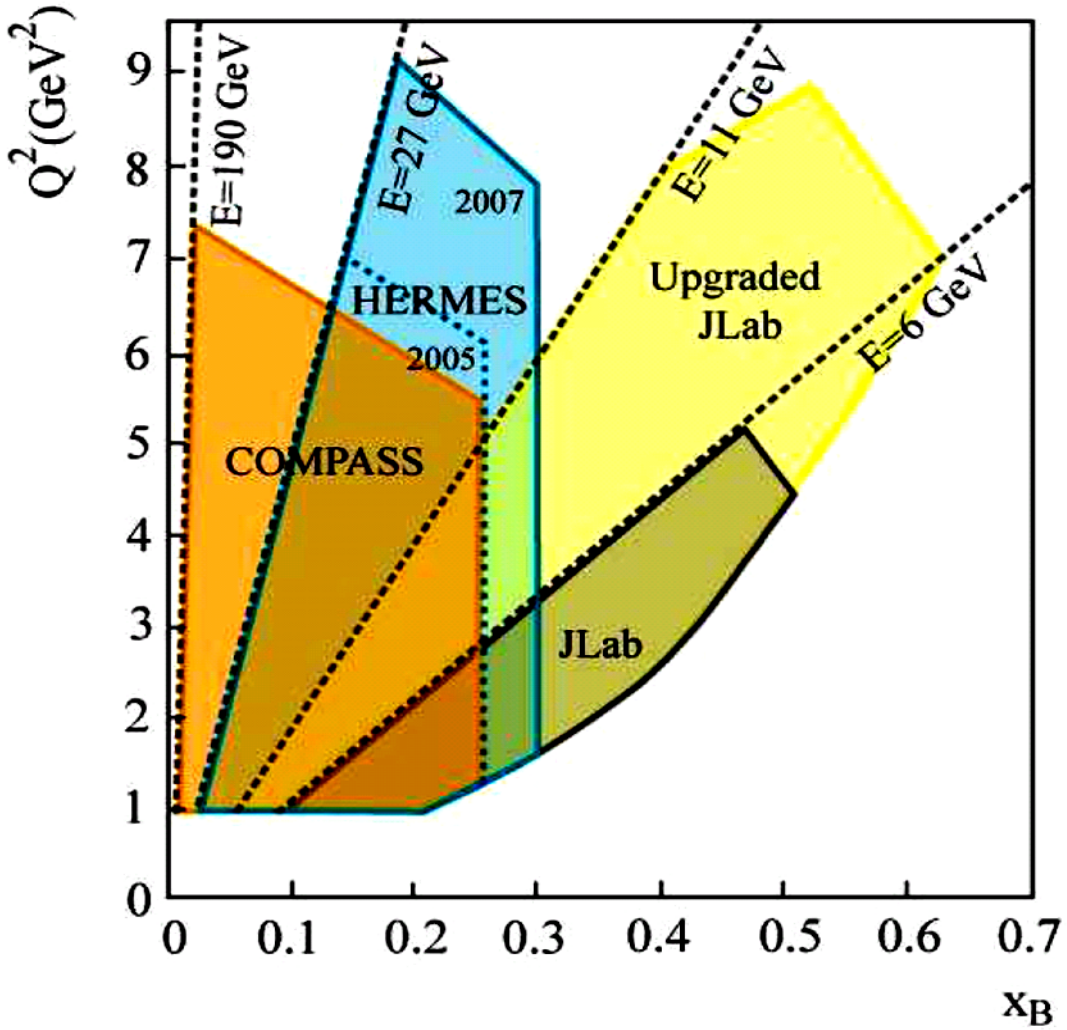
- First model-dependent constraint on J_u vs J_d

Outlook

- Including the 2005 data will double the statistics for TTSA
- HERA II(2002-2007) data on H probably map out the GPD H_u
- improvement of t-resolution with Recoil Detector

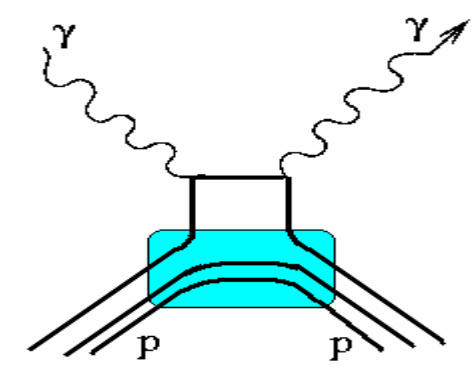


Fixed Target Experiments



GPDs in Future $P\bar{P}$ Experiments

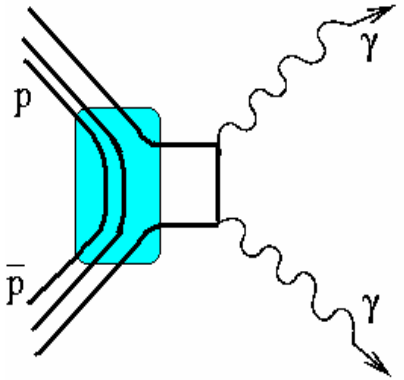
- Instead of having an initial electromagnetic process, a final state electromagnetic process is selected => Generalizing the GPDs for $P\bar{P}$ interaction



Compton scattering

- At intermediate energies (S ~ 10 Gev) Handbag diagram

- PANDA-PAX programs at GSI-FAIR. Handbag approach can be probed over larger range of energy and perhaps with higher precision.
  Polarization of P and $\bar{P}$ is helpful.
- Detectors should be ready to measure different kind of exclusive reaction at FAIR.



Annihilation