DVCS at HERMES

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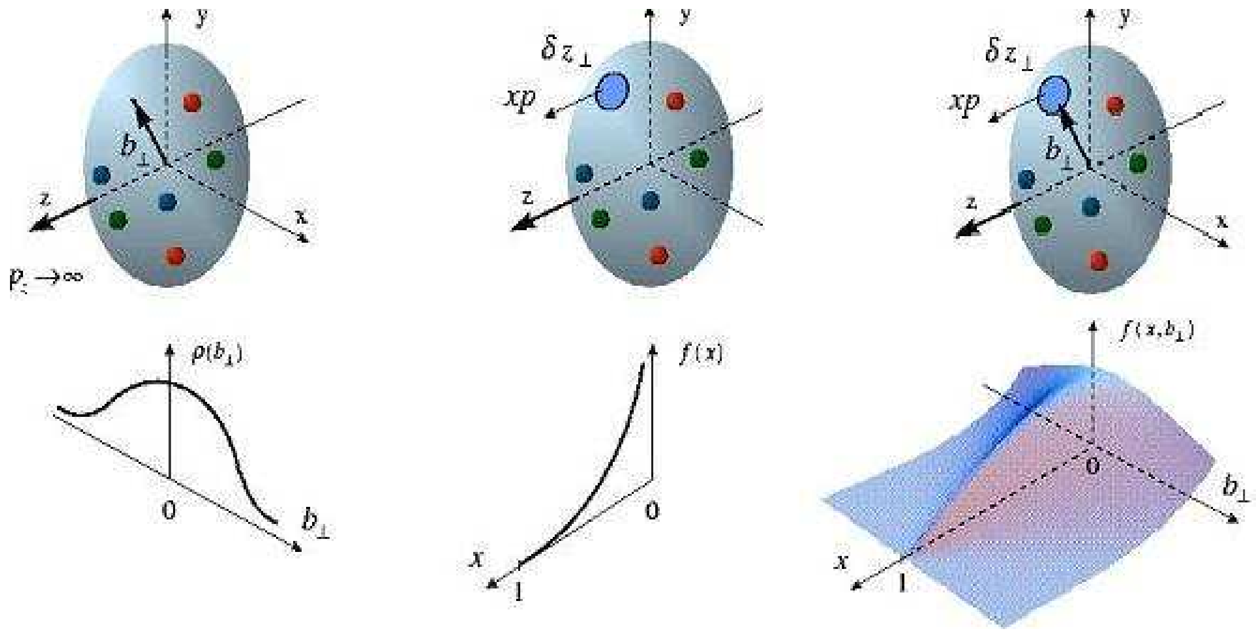
Exclusive Reactions, JLab, USA, May 2007

- The GPD H via:
  - Beam-Spin Asymmetry (BSA)
  - Beam-Charge Asymmetry (BCA)
- The GPD E via transverse Target-Spin Asymmetry (TTSA)
- DVCS on Nuclei

Parameterization of the Nucleon Structure

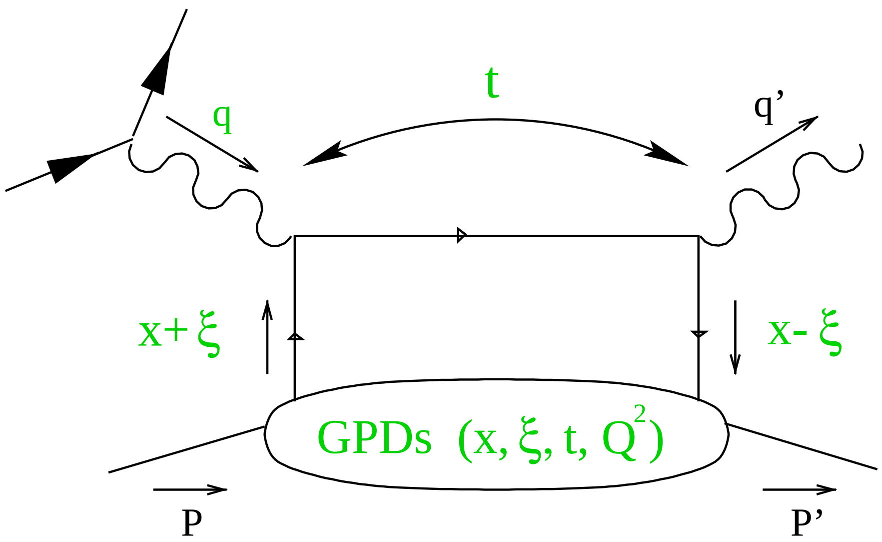


FF **PDF** **GPD**

- 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: $e\,p \rightarrow e'\,p'\,\gamma$
Deeply-virtual Compton Scattering (DVCS):

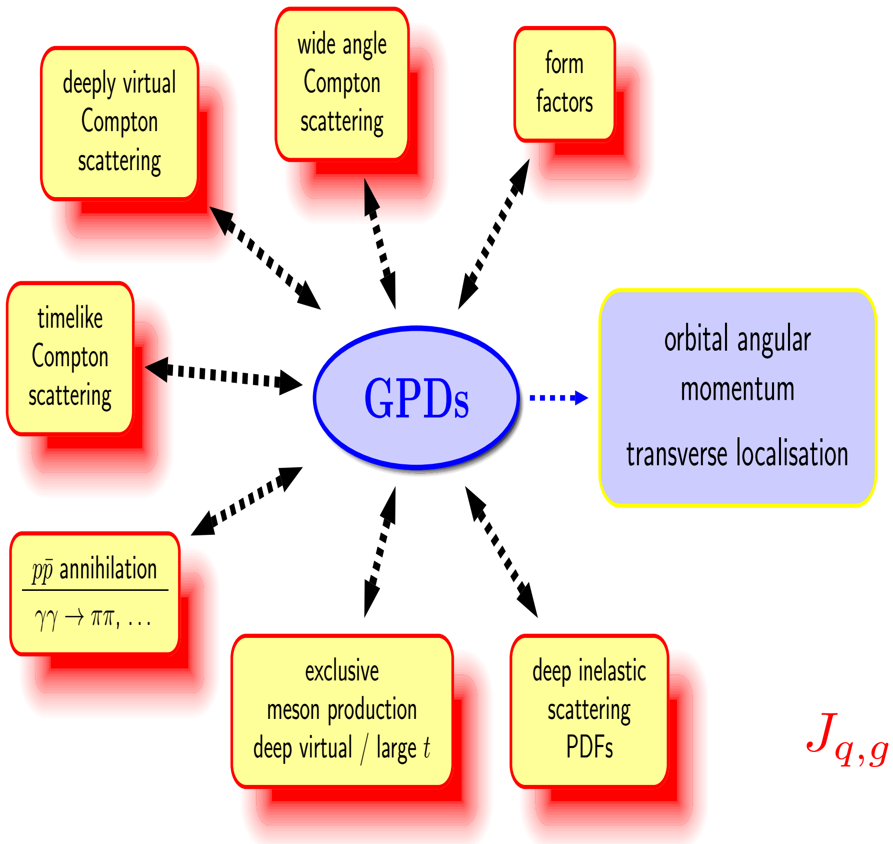


- Longitudinal momentum fractions:
  $x \in [-1, 1]$ (not accessible)
  $\xi \approx x_B/(2 - x_B)$
- $t = (q - q')^2$
  ($\gamma^* \rightarrow \gamma$ Momentum transfer)
- $Q^2 = -q^2$

$\Rightarrow$ 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 $t \to 0$

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

FFs: First moments of GPDs

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

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

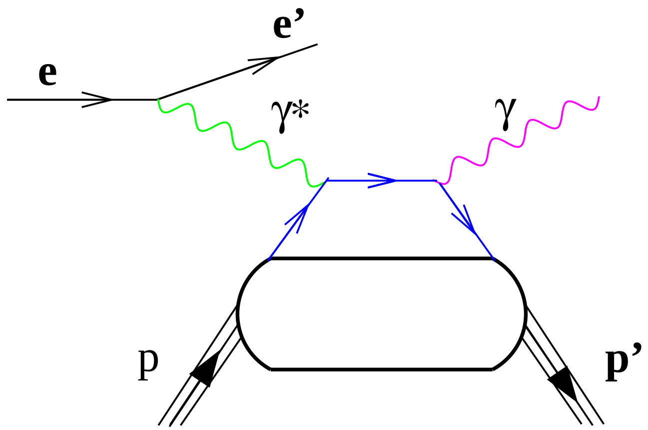
$$J_{q,g} = \lim_{t \to 0} \frac{1}{2} \int_{-1}^{1} dx\, x\, [H^{q,g}(x,\xi,t) + E^{q,g}(x,\xi,t)]$$

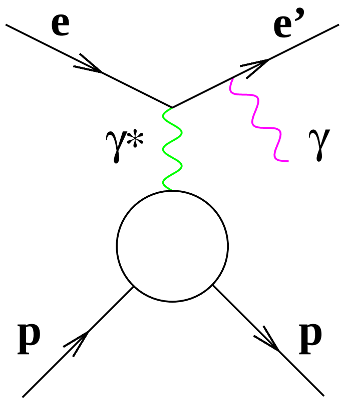
(X. Ji, 97)

Original (HERMES) Motivation:

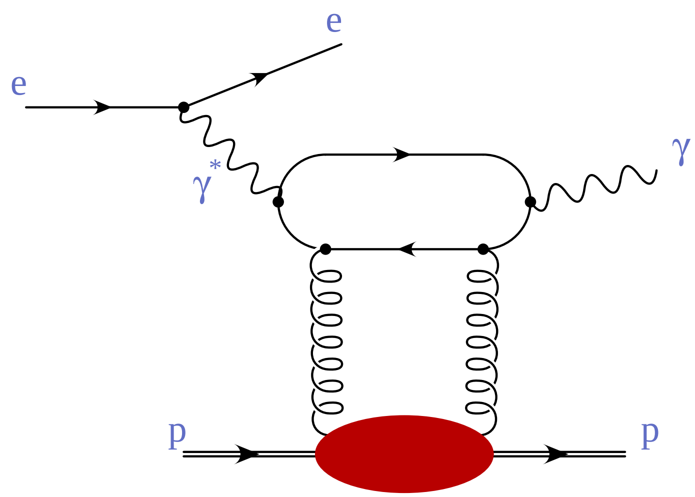
Nucleon (Long.) Spin Structure: $1/2 = \underbrace{1/2(\overbrace{\Delta u + \Delta d + \Delta s}^{\sim 30\%}) + \overbrace{L_q}^{?}}_{J_q = ?} + \overbrace{J_g}^{?}$

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:

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

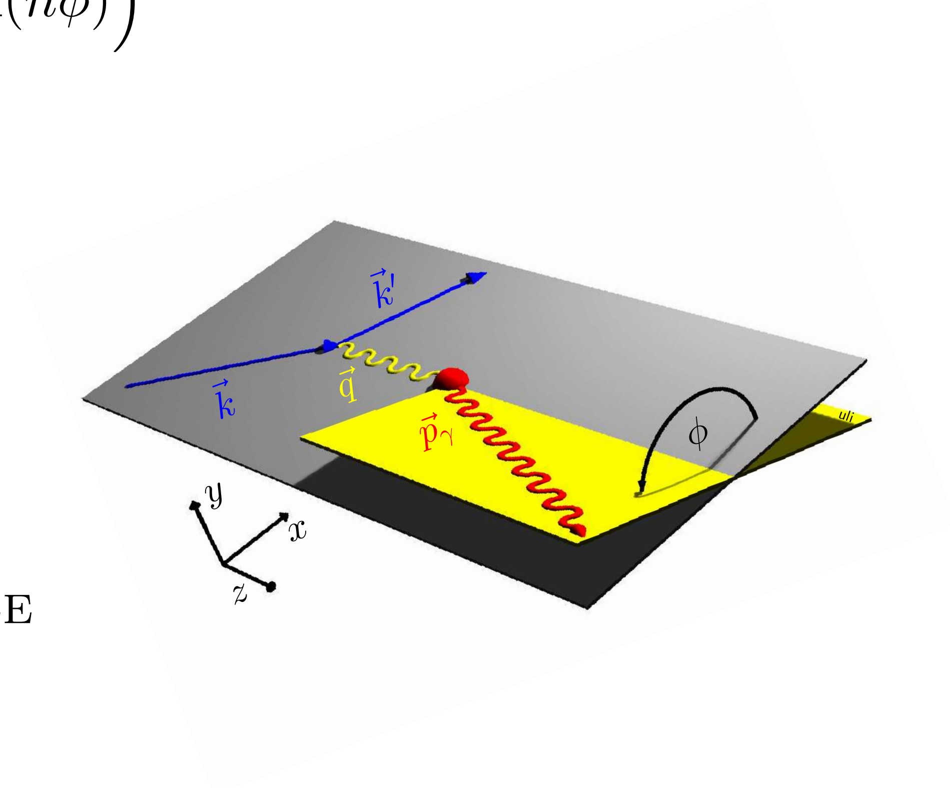
$$d\sigma \propto |\tau_{BH}|^2 + \underbrace{(\tau^*_{DVCS}\tau_{BH} + \tau^*_{BH}\tau_{DVCS})}_{I} + |\tau_{DVCS}|^2$$

$|\tau_{BH}|^2$ 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 $|\tau_{BH}|^2$
(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 $\longrightarrow$ $\cos 2\phi$, $\cos 3\phi$, $\sin 2\phi$)

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 $\longrightarrow$ $\sin 2\phi$, $\sin 3\phi$)

FROM AMPLITUDES TO GPDs

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

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

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

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

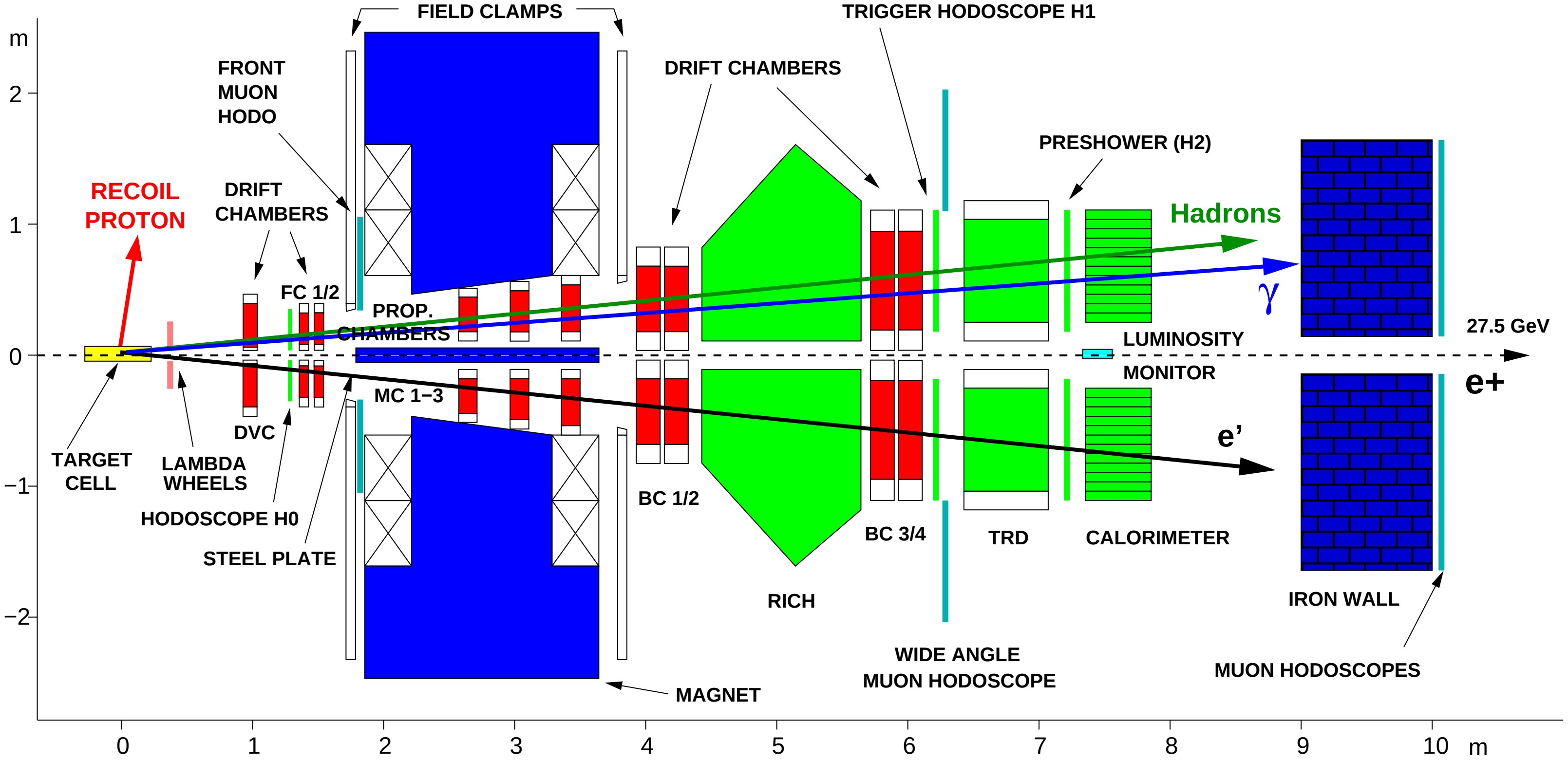
BSA: $\mathrm{Im}\, M_{unp}^{1,1}$ MAINLY ACCESSES THE GPD $H^q(x,\xi,t)$ AT $x=\xi \Rightarrow$ MEASURES $H^q(\xi,\xi,t)$

BCA: $\mathrm{Re}\, M_{unp}^{1,1}$ CONTAINS FULL x–DEPENDENCE OF THE GPD $H^q(x,\xi,t)$,
x IS NOT ACCESSIBLE $\Rightarrow$
GPD MODEL $\longrightarrow$ OBSERVABLES $\longleftarrow$ MEASUREMENT

HERMES Event Selection

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

pol. + unpol. Gas Targets: H/D/Ne/Kr/..

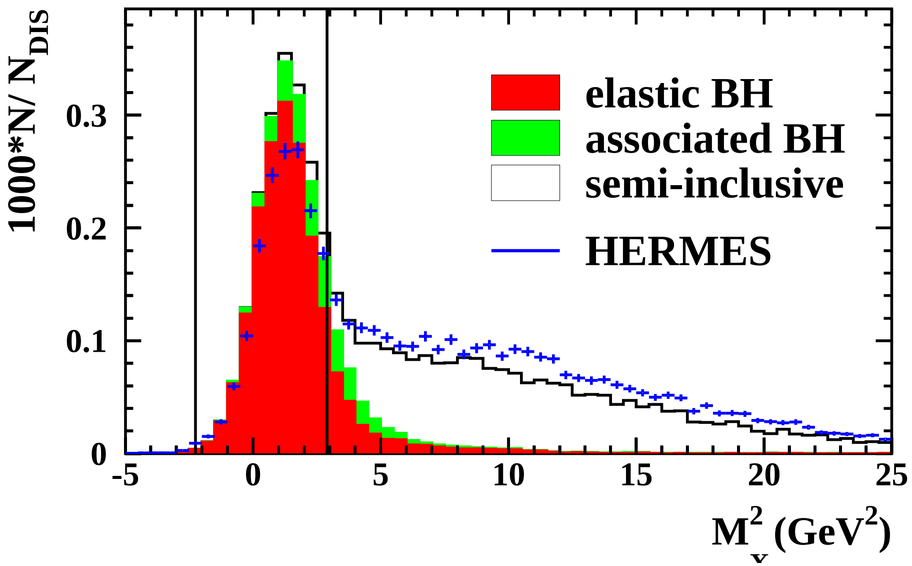


Events with exactly one DIS-positron/DIS-electron and exactly one photon in the calorimeter

Data shown taken before installation of recoil detctor ⇒

Exclusivity for DVCS via Missing Mass

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



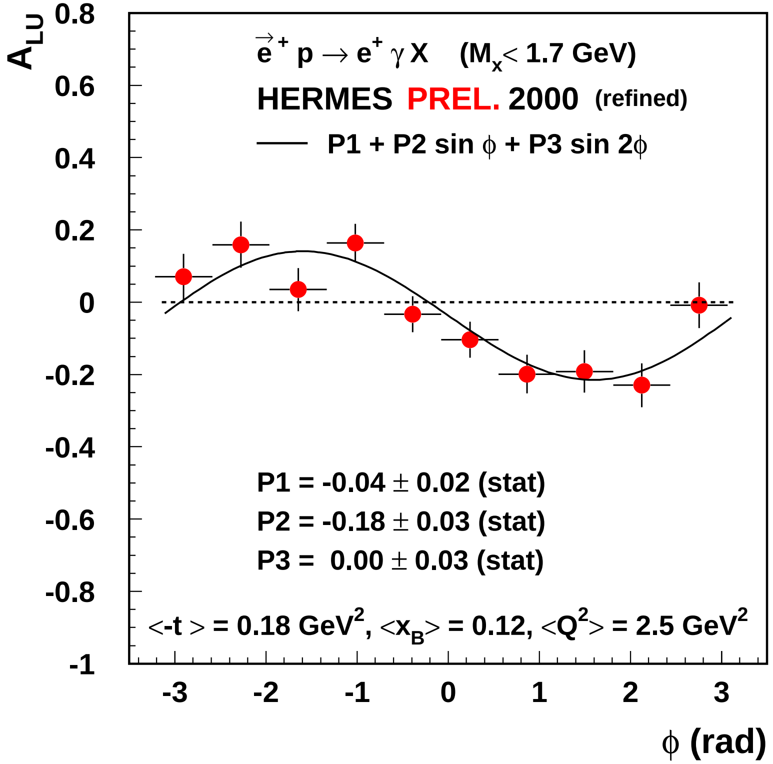
- elastic BH ($e\,p \rightarrow e'\,p'\,\gamma$)
- associated BH (mainly $e\,p \rightarrow e'\,\Delta^+\,\gamma$)
- semi–inclusive (mainly $e\,p \rightarrow e'\,\pi^0\,X$)
- exclusive π^0 ($e\,p \rightarrow e'\,\pi^0$) not shown (small)

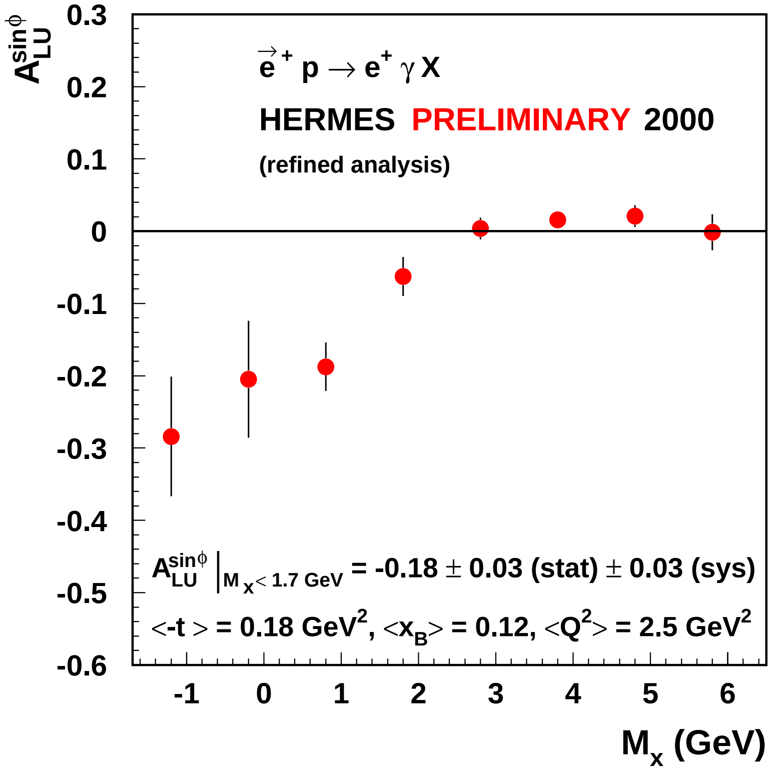
Not simulated: DVCS process (DVCS c.s. "unknown", DVCS << BH) +Radiative corrections to BH ($\rightarrow$ excl. peak overestimated, BG underestimated)

$\Rightarrow$ "Exclusive" bin (-1.5 $< M_x <$ 1.7 GeV)
$\Rightarrow$ Overall background contribution $\approx$ 15%

Beam–Spin Asymmetry (BSA)

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





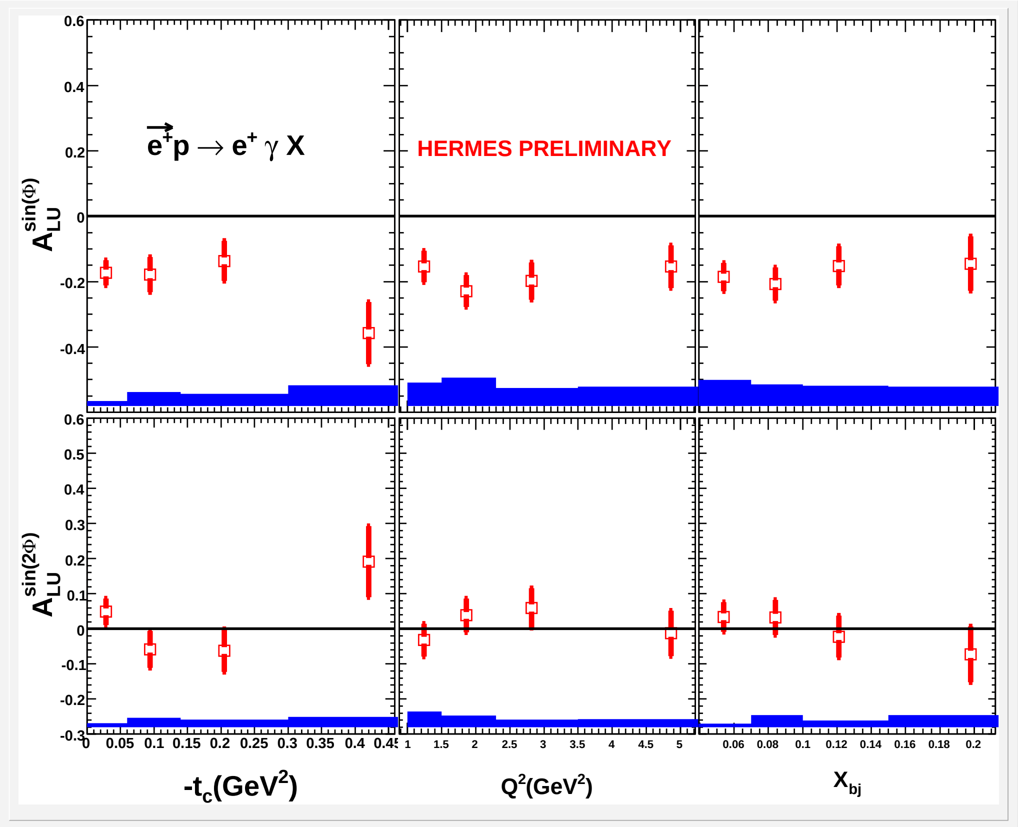
$A_{\rm LU}$ in exclusive bin: Expected $\sin(\phi)$ dependence $\Rightarrow \mathrm{Im}\, M^{1,1}_{unp}$

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

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

Kinematic dependences of Beam–Spin Asymmetry (BSA)

Kinematic dependence of combined 96/97 (published, PRL) and 2000 (preliminary, hep-ex/0212019) data, reanalyzed with common cuts



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

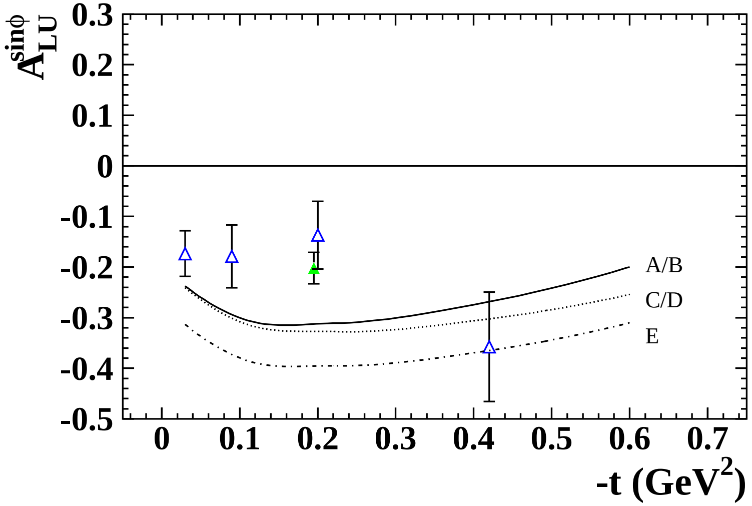
$A_{LU}^{sin\phi} \leq 0.2$

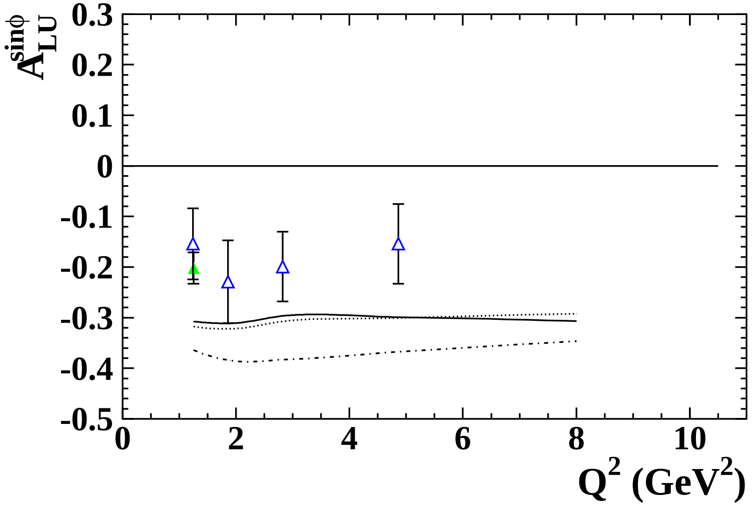
$A_{LU}^{sin2\phi}$ consistent with zero

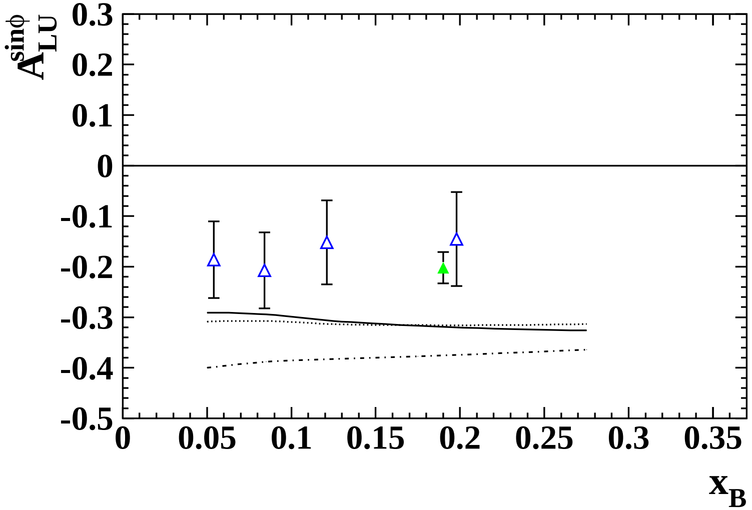
$\Rightarrow$ Weak kinematic dependence (kinematics correlated!)

Compare to calculations at average x, Q^2, t per bin $\rightarrow$

Kinematic dependences of Beam–Spin Asymmetry (BSA)



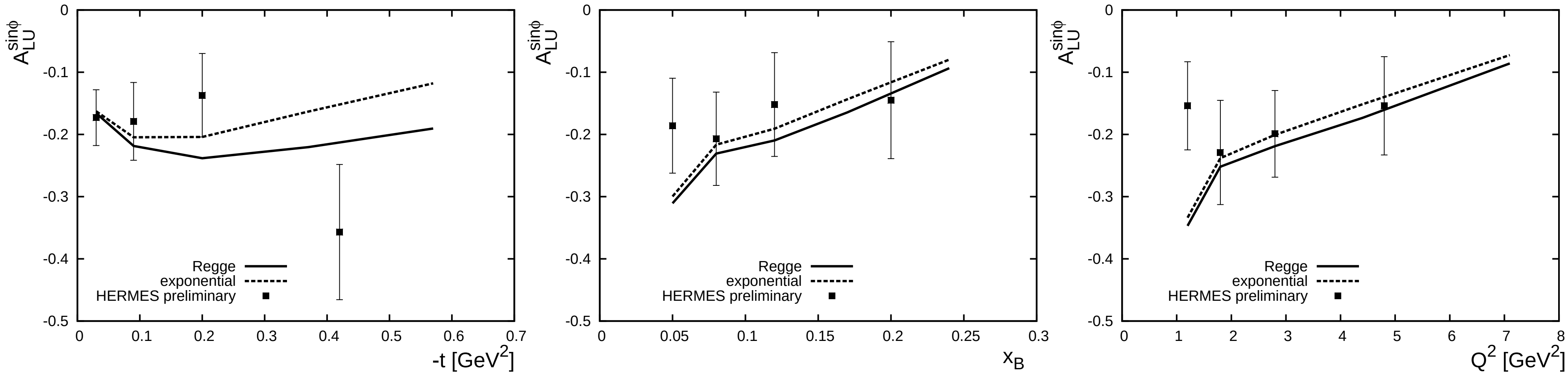




- Model calculations using VGG code give too large asymmetries compared to perliminary HERMES (blue) and published CLAS (green , PRL) data
- similar magnitude seen in other model calculations
- Flat kinematic dependence well described by models

Kinematic dependences of Beam–Spin Asymmetry (BSA)

The models (Guzey/Teckentrup, PRD 74, 2006) are in agreement with "all" other DVCS data so far:
→ Cross section at H1/ZEUS
→ BCA at HERMES (→ later...)
→ published average BSA values from HERMES+CLAS (PRL, 2001)



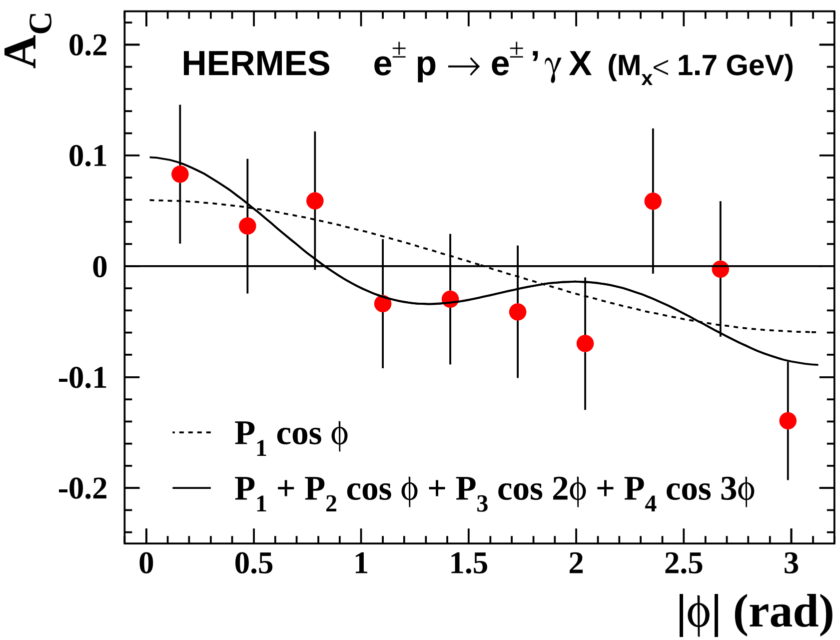
The size and kinematic dependence of the asymmetry is reproduced (except maybe at small Q2).

More data with improved systematics to come, but BSA less sensitive to models when compared to BCA.

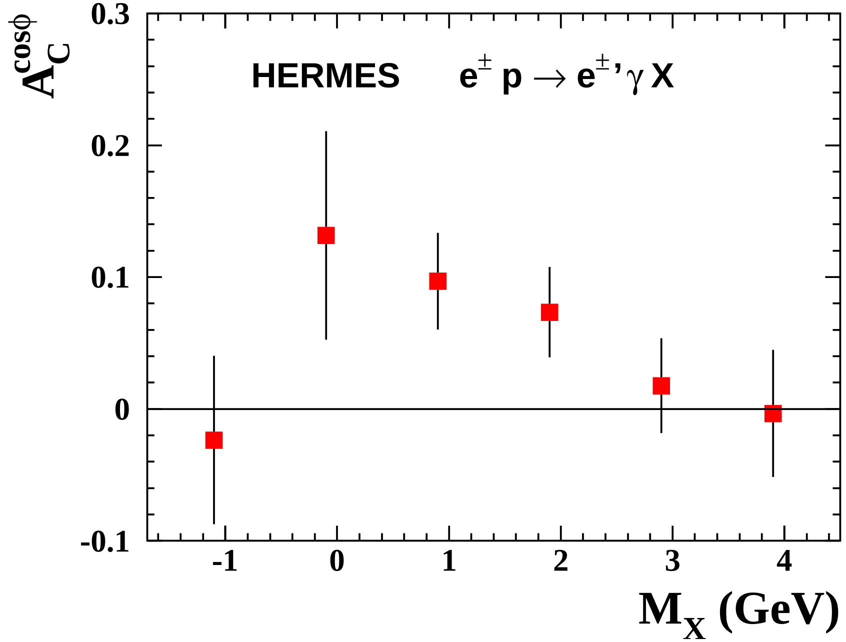
BCA: Beam–Charge Asymmetry *(hep-ex/0605108, PRD 2007)*

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

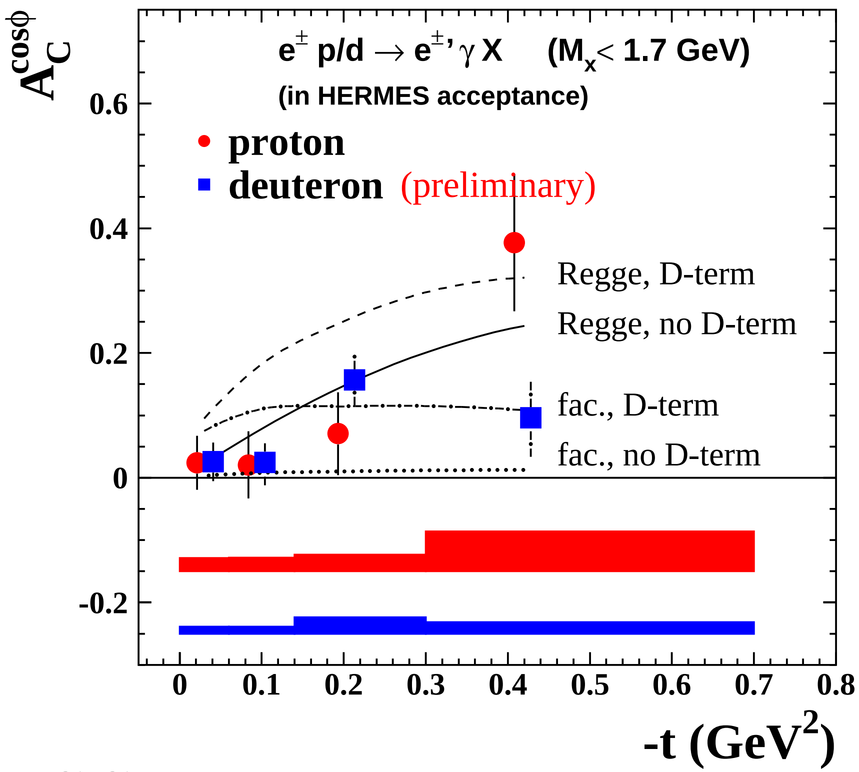
⇒ Calculate "symmetrized" BCA ($\phi \to |\phi|$) to get rid of all $\sin(\phi)$–dependences due to polarized beam.



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

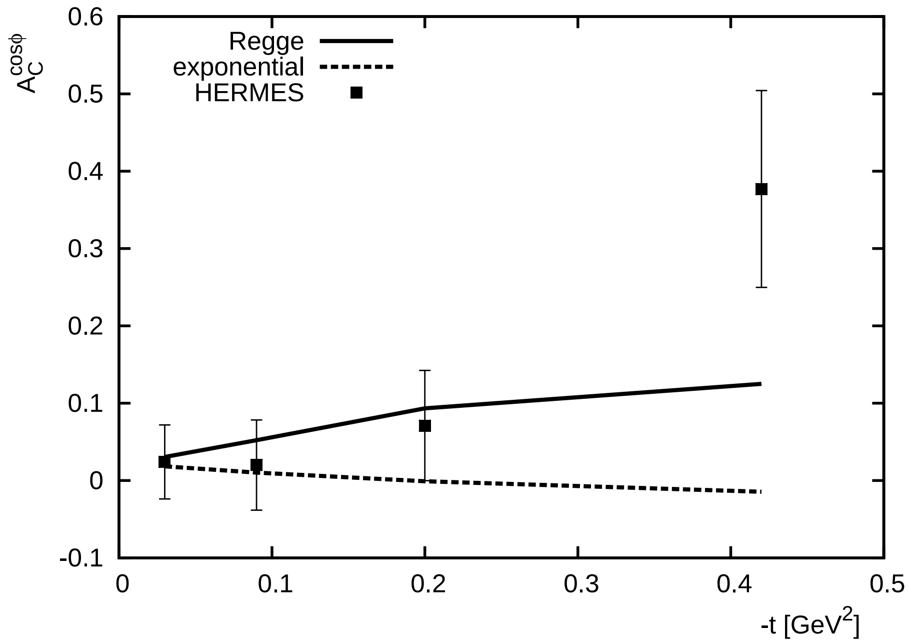


$\cos(\phi)$–Moments zero at higher missing mass



VGG

⇒ Regge+D-Term disfavored



Guzey/Teckentrup, PRD 74, 2006

⇒ Both in agreement

tiny e^-p sample (only ≈ 700 events) ⇒ Now ≈ 20 times more on disk!

⇒ t–dependence of BCA has high sensitivity to GPD models!

Utilize both charges for BSA: A closer look ...

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

Fourier expansion (unpolarized p target):

$$|\tau_{BH}|^2 \propto c_0^{BH} + \sum_{n=1}^{2} c_n^{BH} \cos(n\phi)$$

$$|\tau_{DVCS}|^2 \propto c_0^{DVCS} + \sum_{n=1}^{2} c_n^{DVCS} \cos(n\phi) + \lambda\, s_1^{DVCS} \sin(\phi)$$

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

The approximation: $A_{\mathrm{LU}}^{e-/e+}(\phi) = \frac{1}{<|P_b|>} \frac{\overrightarrow{N}(\phi) - \overleftarrow{N}(\phi)}{\overrightarrow{N}(\phi) + \overleftarrow{N}(\phi)} \simeq \frac{\pm s_1^I \sin\phi}{|\tau_{BH}|^2}$

is too simple ...

$$A_{\mathrm{LU}}^{e-/e+}(\phi) = \frac{1}{<|P_b|>} \frac{\overrightarrow{N}(\phi) - \overleftarrow{N}(\phi)}{\overrightarrow{N}(\phi) + \overleftarrow{N}(\phi)} \simeq \frac{\pm s_1^I \sin\phi + s_1^{DVCS} \sin\phi}{|\tau_{BH}|^2 + c_0^{DVCS} + c_1^{DVCS}\cos\phi \pm c_0^I \pm c_1^I \cos\phi}$$

Using both beam charges for the BSA:

$$A_{\rm LU}^{e-/e+}(\phi) = \frac{1}{<|P_b|>}\frac{\overrightarrow{N}(\phi)-\overleftarrow{N}(\phi)}{\overrightarrow{N}(\phi)+\overleftarrow{N}(\phi)} \simeq \frac{\pm s_1^I \sin\phi + s_1^{DVCS}\sin\phi}{|\tau_{BH}|^2 + c_0^{DVCS} + c_1^{DVCS}\cos\phi \pm c_0^I \pm c_1^I\cos\phi}$$

$\sin\phi$ amplitude of the "usual" BSA is not only sensitive to the interference term, but gets contributions from the DVCS term

The "usual" BSA is complicated, it depends on the beam-charge and on the size of the BCA

⇒ Disentangle contributions from the interference term and the DVCS term by measuring two new asymmetries:

The "Interference" BSA:

$$A_{\rm LU}^{I}(\phi) = \frac{1}{<|P_b|>}\frac{\overrightarrow{N^+}(\phi)+\overleftarrow{N^-}(\phi)-\overleftarrow{N^+}(\phi)-\overrightarrow{N^-}(\phi)}{\overrightarrow{N^+}(\phi)+\overleftarrow{N^-}(\phi)+\overleftarrow{N^+}(\phi)+\overrightarrow{N^-}(\phi)} \simeq \frac{-s_1^I \sin\phi}{|\tau_{BH}|^2 + c_0^{DVCS} + c_1^{DVCS}\cos\phi}$$

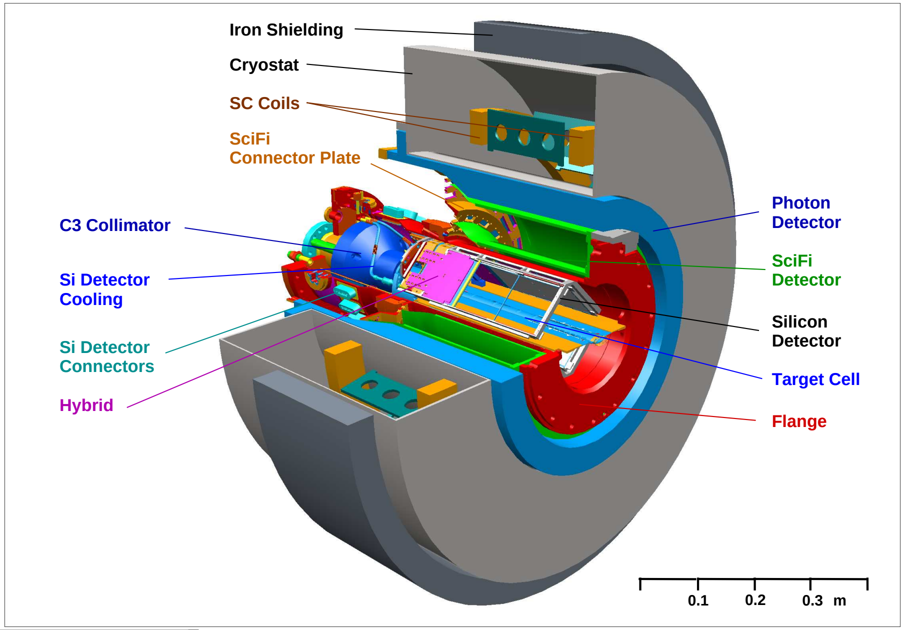
The "DVCS" BSA:

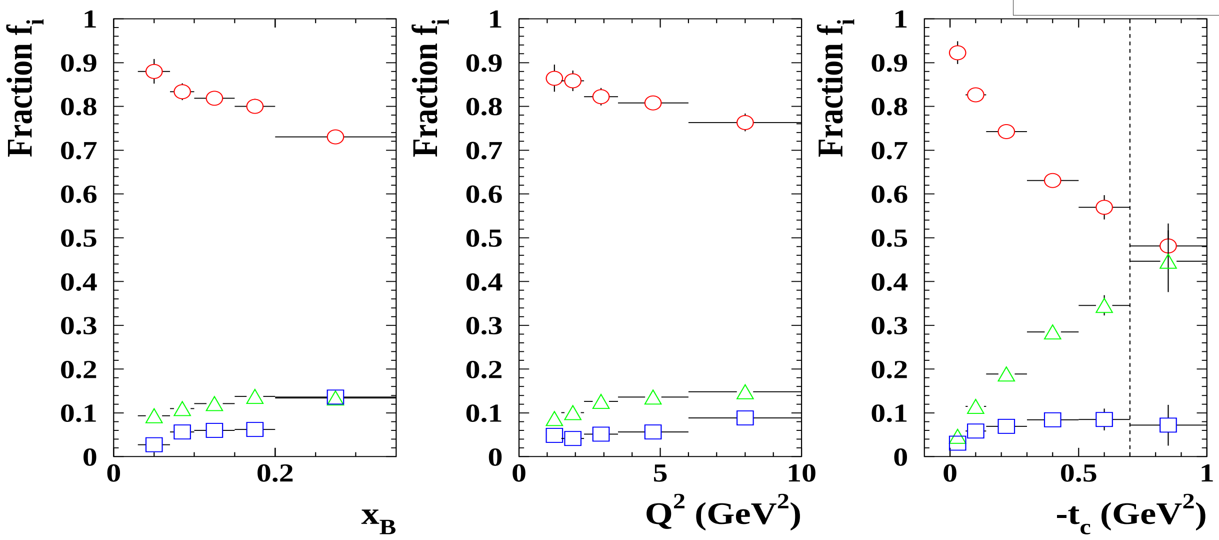
$$A_{\rm LU}^{DVCS}(\phi) = \frac{1}{<|P_b|>}\frac{\overrightarrow{N^+}(\phi)-\overleftarrow{N^-}(\phi)-\overleftarrow{N^+}(\phi)+\overrightarrow{N^-}(\phi)}{\overrightarrow{N^+}(\phi)+\overleftarrow{N^-}(\phi)+\overleftarrow{N^+}(\phi)+\overrightarrow{N^-}(\phi)} \simeq \frac{s_1^{DVCS} \sin\phi}{|\tau_{BH}|^2 + c_0^{DVCS} + c_1^{DVCS}\cos\phi}$$

⇒ New asymmetries can disentangle (both charges needed) the contributions from interference and DVCS^2 term

Recoil Detector and unpol. Targets (2006/2007)

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





⇒ Essential at larger $-t$ values

⇒ Talk by R. Perez-Benito

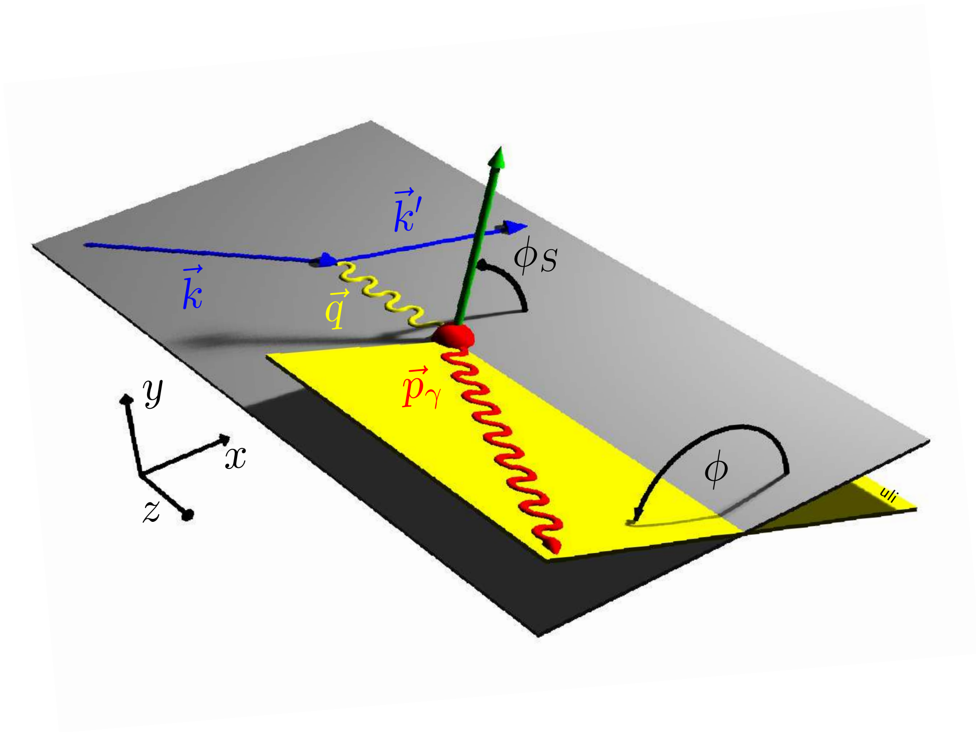
WHAT ABOUT THE GDP E ?

REMEMBER:

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

GPD E (ON P TARGET) IS ALWAYS KINEMATICALLY SUPPRESSED, EXCEPT IN:

A_{UT}: UNPOLARIZED BEAM, TRANSVERSELY POL. TARGET



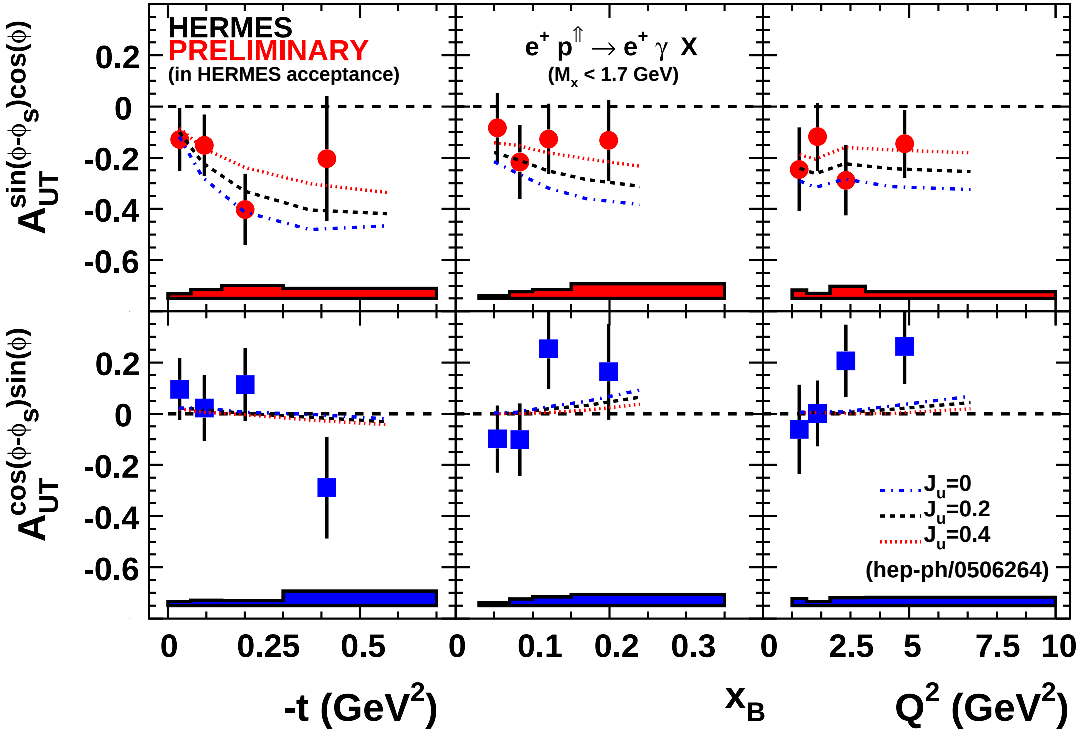
$$A_{UT}(\phi,\phi_s) = \frac{1}{|P_T|} \cdot \frac{d\sigma^{\Uparrow}(\phi,\phi_s) - d\sigma^{\Downarrow}(\phi,\phi'_s)}{d\sigma^{\Uparrow}(\phi,\phi_s) + d\sigma^{\Downarrow}(\phi,\phi'_s)}$$

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

DVCS TTSA compared to the Model Calculations!

Data taking with transverse Hydrogen target finished

$\approx$ 10 million on tape, half the data (2002-2004) analyzed

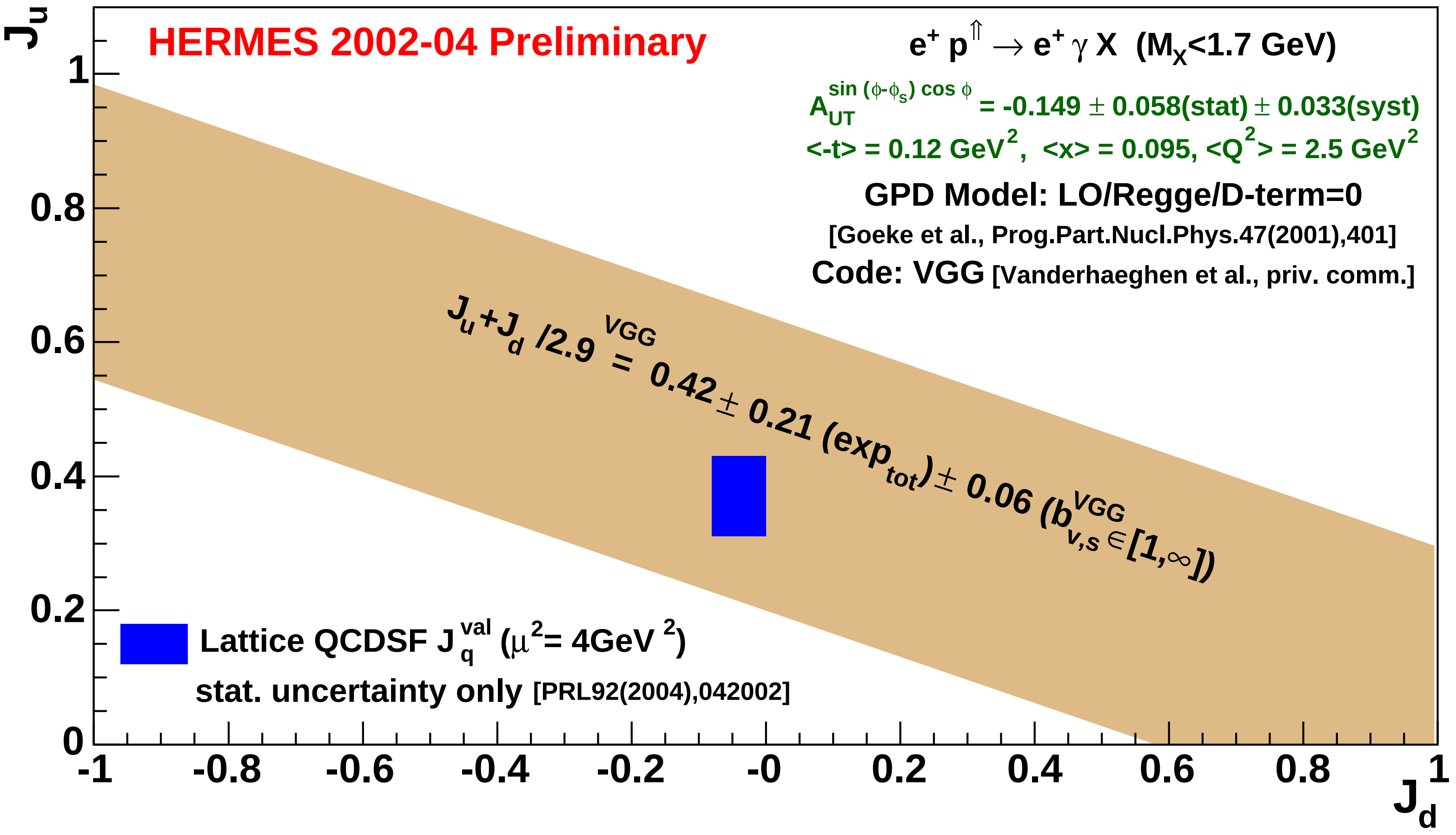


$A_{UT}^{\sin(\phi-\phi_s)\cos\phi}$ largely independent on all model parameters but J_u

(F.E., Nowak, Vinnikov, Ye, EPJ C46 (2006), hep-ph/0506264)

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

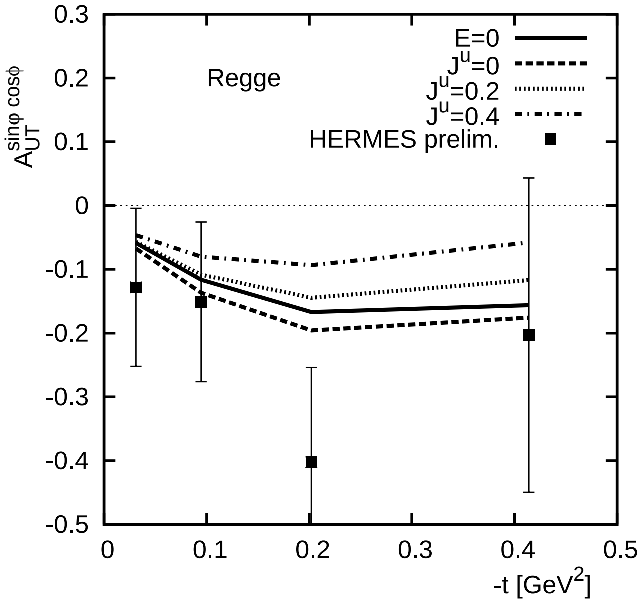
First Constraint on Angular Momentum !

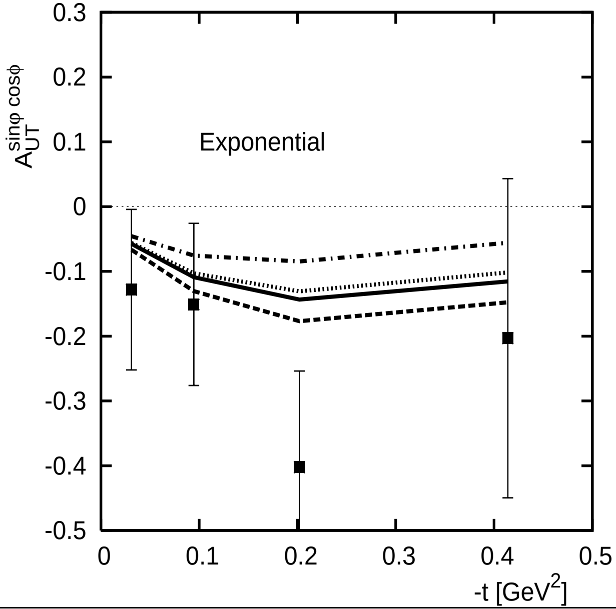


⇒ First model dependent constraint on total quark angular momentum J_u, J_d.

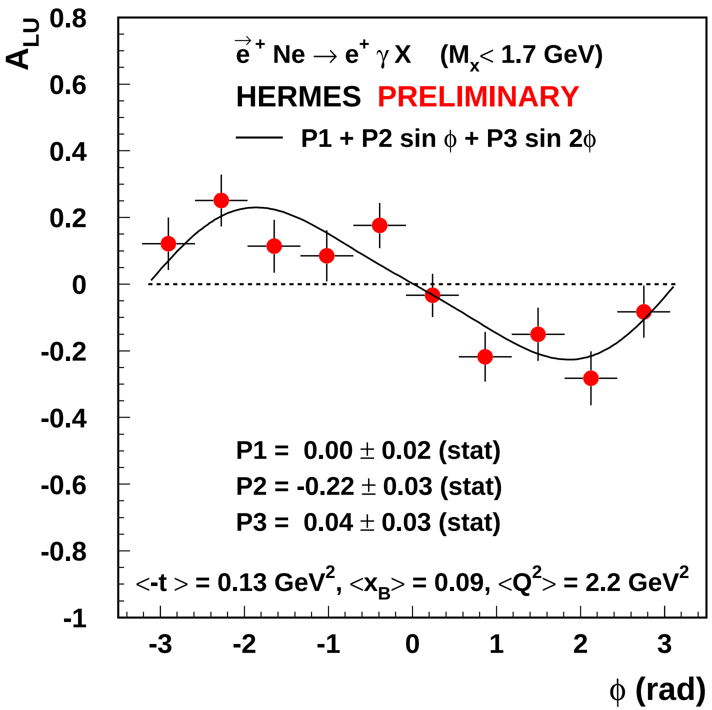
- ON THE OTHER HAND, THE MODELS (GUZEY/TECKENTRUP, PRD 74, 2006) SUGGEST A SMALL VALUE FOR J_u UNDER THE ASSUMPTION THAT $J_d = 0$.

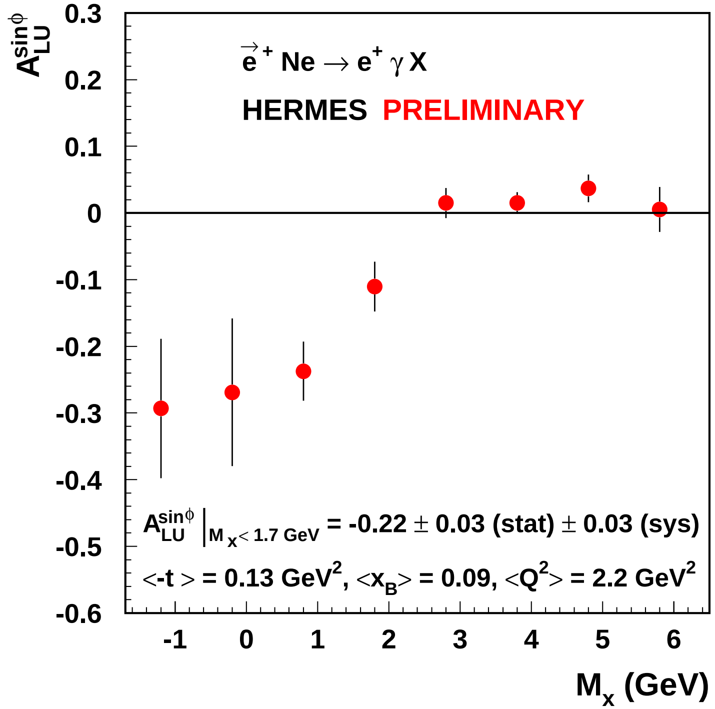
- THE WAY TO GO: CONSTRAIN MODELS FOR GPD H BY BSA/BCA (FIRST). SOME MODEL PARAMETERS MIGHT BE THE SAME FOR THE GPD E ...
  $\Rightarrow$ COMPARE THE REMAINING MODELS TO THE TTSA AND LEARN ABOUT THE GPD E $(J_u,\ J_d)$





Investigate the internal structure of Nuclei

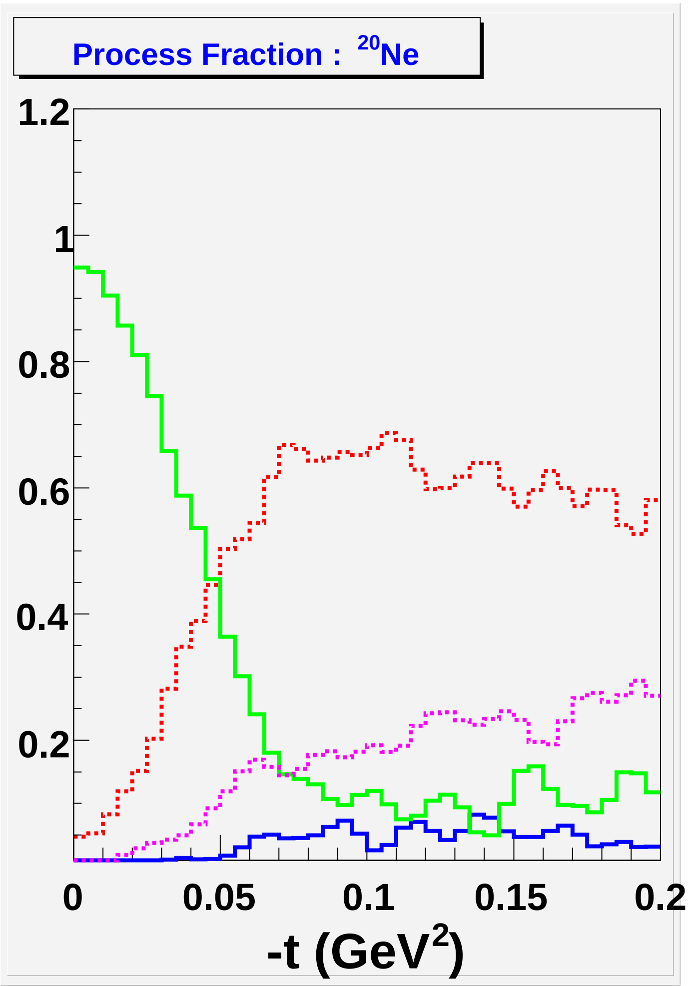




DVCS on Neon (hep-ex/0212019) triggered first calculations for DVCS on Nuclei

⇒ Possibility (?) to explore nuclear structure in terms of quarks and gluons, EMC effect, (anti-)shadowing, color transparency, ...

Contributions from different processes from MC



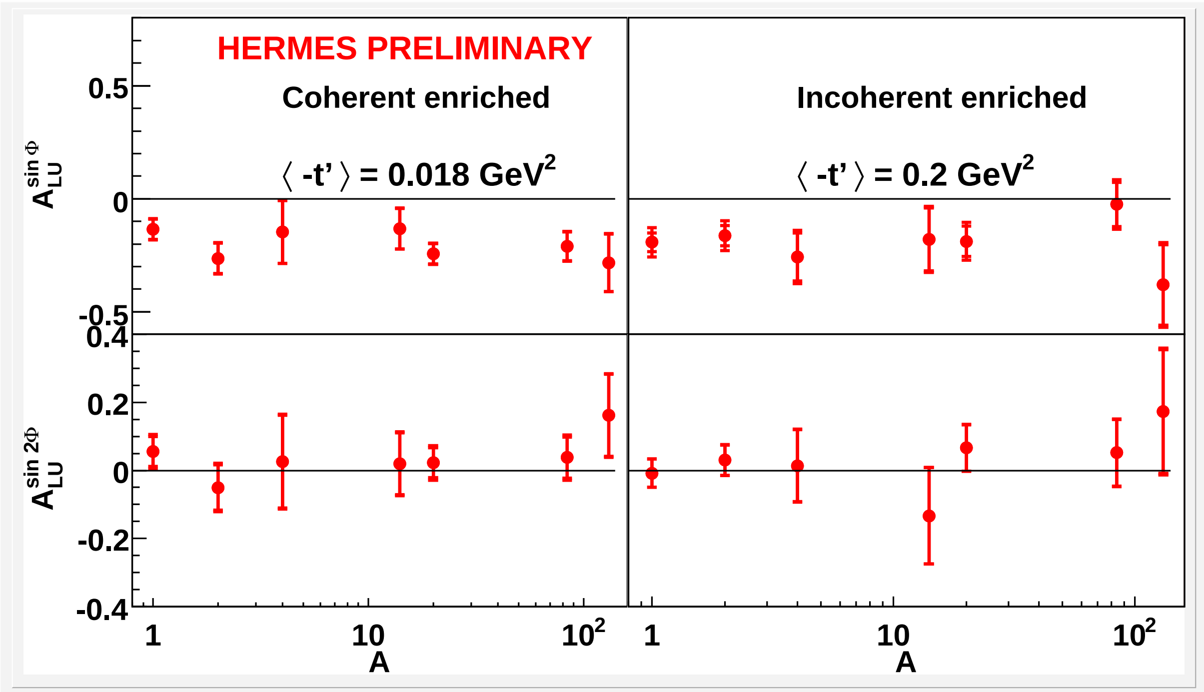
- Coherent Bethe-Heitler contribution
  Incoherent Bethe-Heitler contribution
  semi-inclusive π^0
  resonances
- DVCS not simulated
- Task: Find upper (lower) $-t'$ cut for each target in order to compare the BSA for the coherent (incoherent) production at similar average values of $-t'$, x_B, and Q^2
  - coherent: $\langle -t' \rangle = 0.018$ GeV^2
  - incoherent: $\langle -t' \rangle = 0.2$ GeV^2

Average kinematic values for coherent production

Target	$\langle -t' \rangle = 0.018$	%coherent	$\langle Q^2 \rangle$	$\langle x_B \rangle$
Proton	$-t' < 0.030$	0	1.68	0.068
Deuterium	$-t' < 0.030$	56%	1.70	0.066
Helium-4	$-t' < 0.030$	68%	1.74	0.066
Nitrogen	$-t' < 0.043$	82%	1.77	0.064
Neon	$-t' < 0.050$	82%	1.73	0.064
Krypton	$-t' < 0.081$	82%	1.63	0.060
Xenon	$-t' < 0.085$	82%	1.60	0.059

- $\langle Q^2 \rangle$ and $\langle x_B \rangle$ very similar.
- Fraction of coherent production is $\simeq 82\%$ for all but light targets

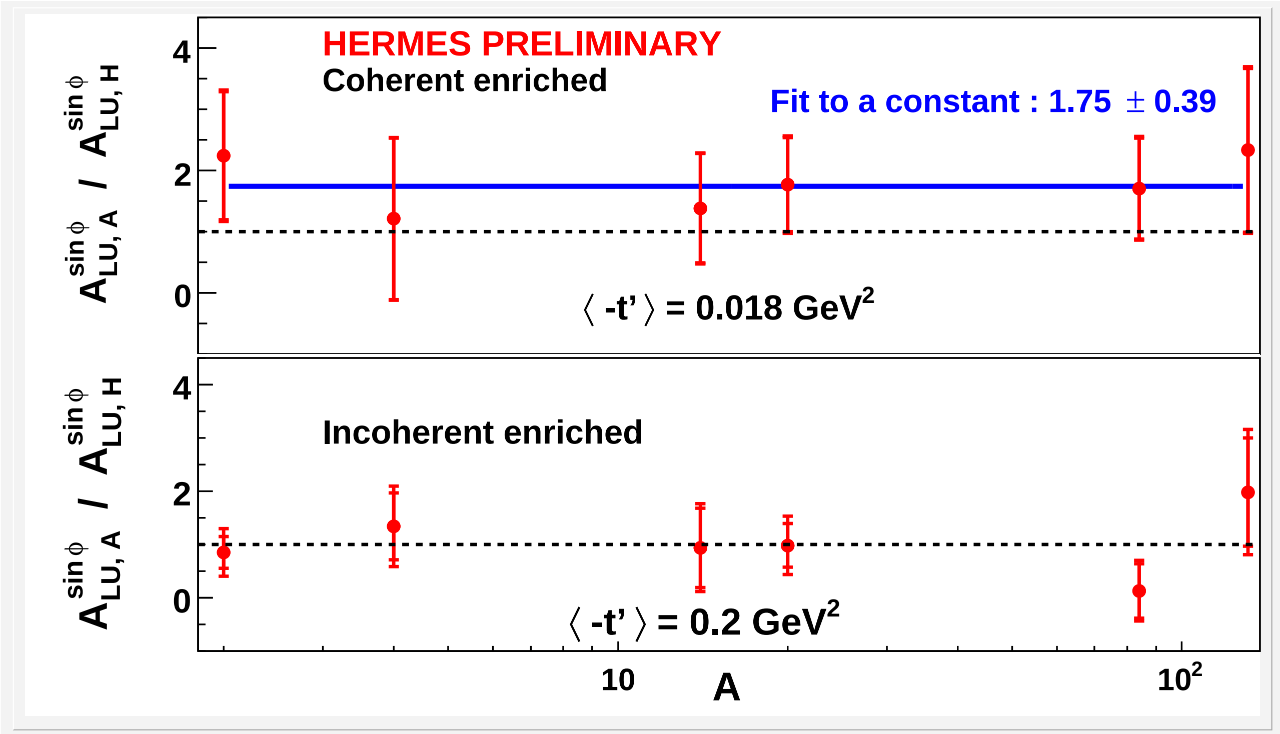
A-dependence of the BSA



- No obvious A-dependence seen.
  Consistent with Guzey/Siddikov (J.Phys.G:Nucl.Part.Phys.32(2006))

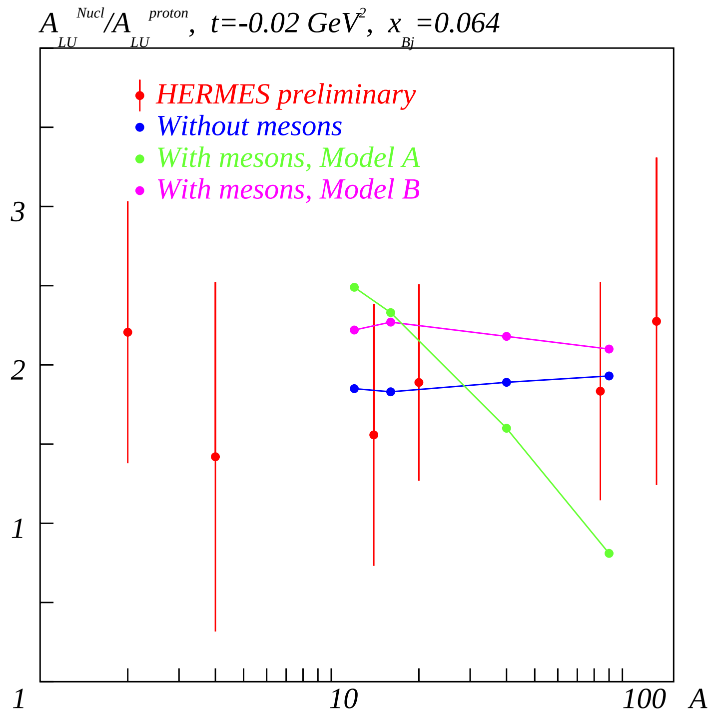
- $A_{LU}^{\sin 2\phi}$ is consistent with zero for all targets

Ratio A^A_{LU}/A^p_{LU}

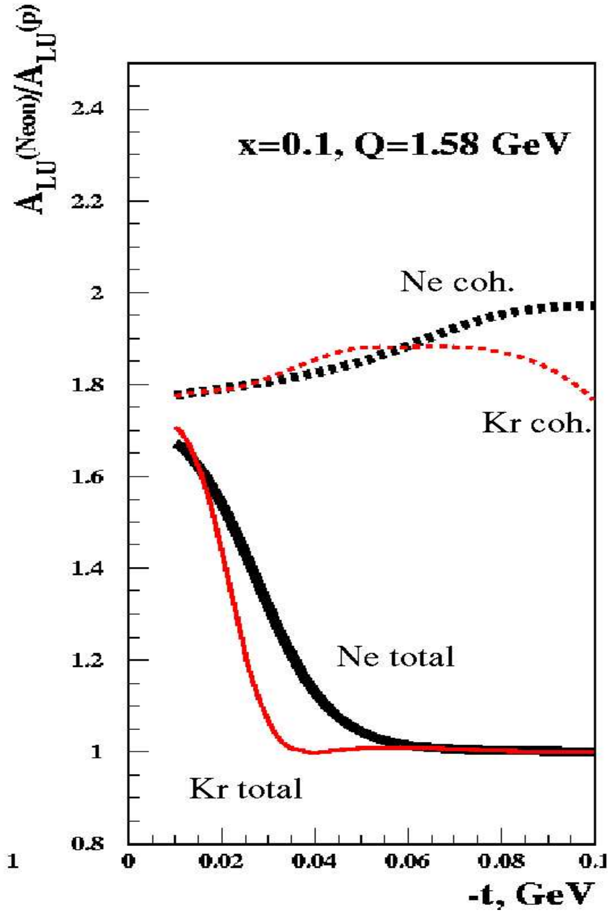


- Coherent enriched: mean ratio deviates from unity by 2σ.
  - Consistent with prediction of R $= 5/3$ for Spin-0 and Spin-1/2 targets (Kirchner/Mueller, Eur.Phys.J. 2003)
  - Calculation of R=1-1.1 for ^4He (Liuti, Taneja, Phys.Rev.C 2005) consistent with measurement (large stat. error, calculations for heavier targets underway)
- Incoherent enriched: Consistent with unity as naively expected

Ratio A_{LU}^{A}/A_{LU}^{p}



Consistent with two predictions by Guzey/Siddikov, one disfavored (J.Phys.G, 2006)



Consistent with predictions by Guzey/Strikman (Phys.Rev.C, 2003)

⇒ Promising, more data needed ...

Summary and Outlook

- HERA/HERMES: End of data taking 7/2/2007:
  Goal: "map out" GPD H^u via DVCS Beam-Spin and Beam-Charge Asymmetries

- Contributions form the Interference term and the DVCS^2 term can be disentangeled by new asymmetries involving both beam charges

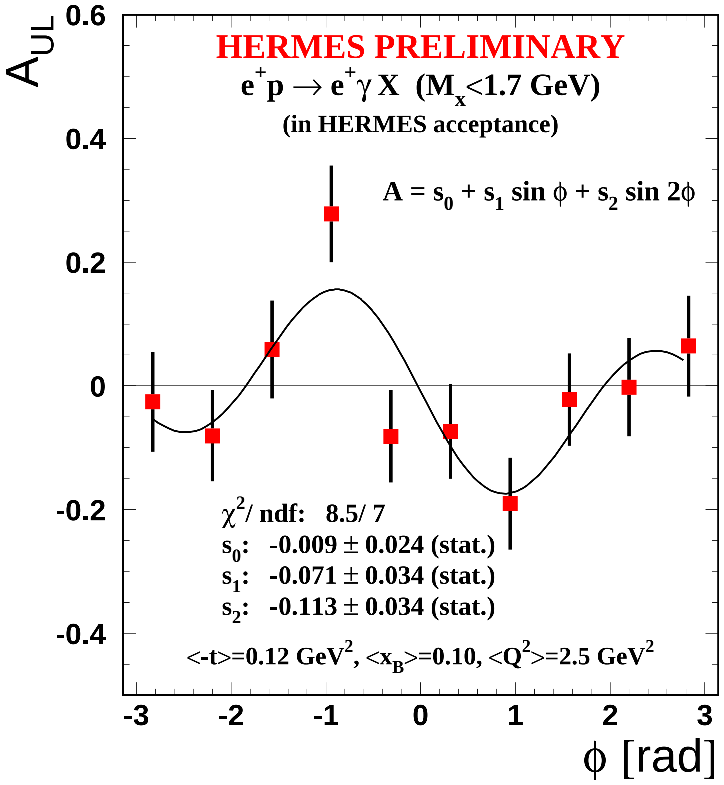
- First model dependent constraint on the total angular momentum of u-quarks (J_u) and d-quarks (J_d) in the nucleon.

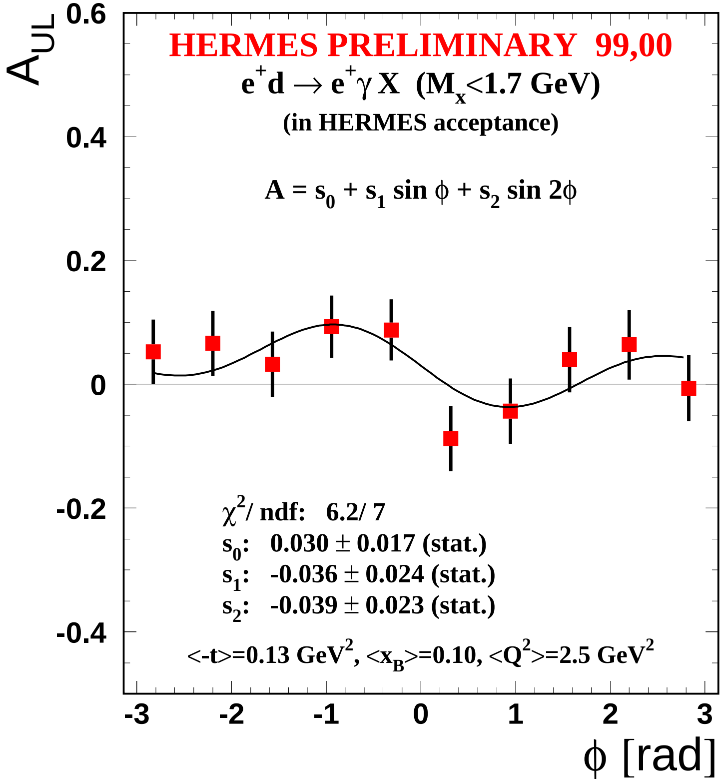
- DVCS on Nuclei looks promising

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

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

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

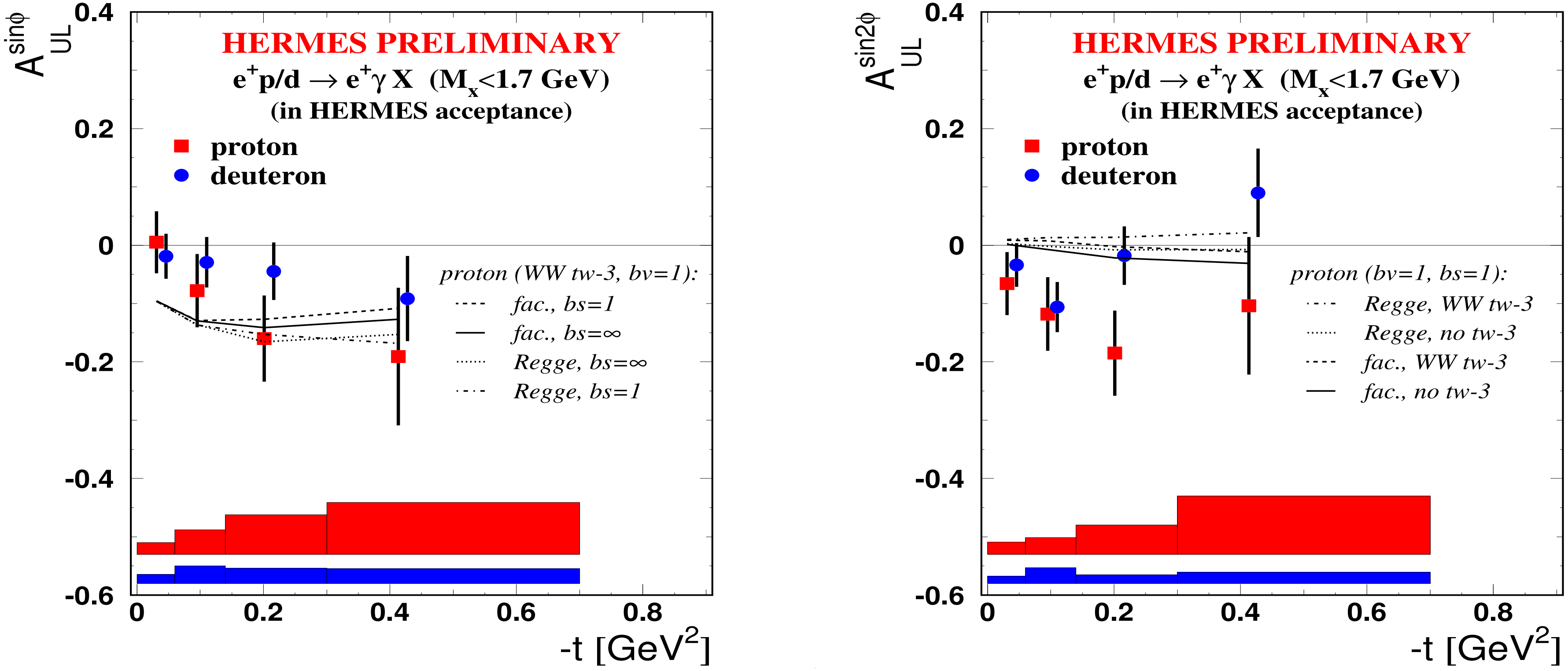




$A_{UL}(\overrightarrow{p})$ in exclusive bin:
Expected $\sin(\phi)$ dep. ⇒ GPD $\widetilde{H}$,
Unexpected $\sin(2\phi)$ dependence

$A_{UL}(\overrightarrow{d})$ in exclusive bin:
⇒ 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?
  $A_{UL}^{\sin 2\phi} \Rightarrow$ Difference due to large $\sin 2\phi$ (while $\sin\phi$ is small) in π^0 background (CLAS, hep–ex/0605012)?