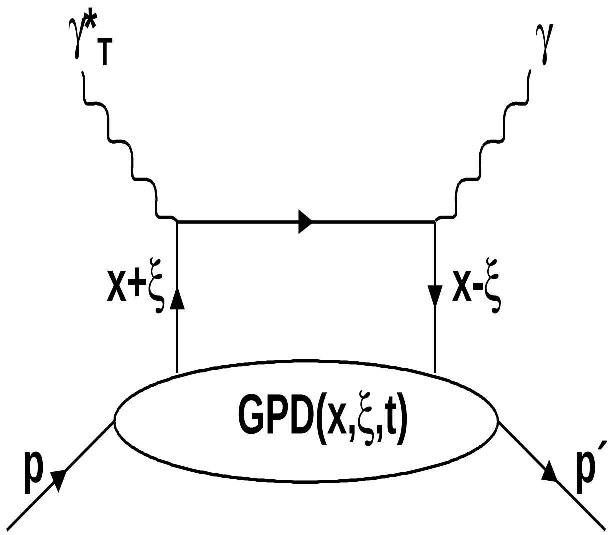
DSPIN-09 XIII Workshop on High Energy Spin Physics

September $1 \div 5$, 2009, Dubna, Russia

Latest Results on Deeply Virtual Compton Scattering

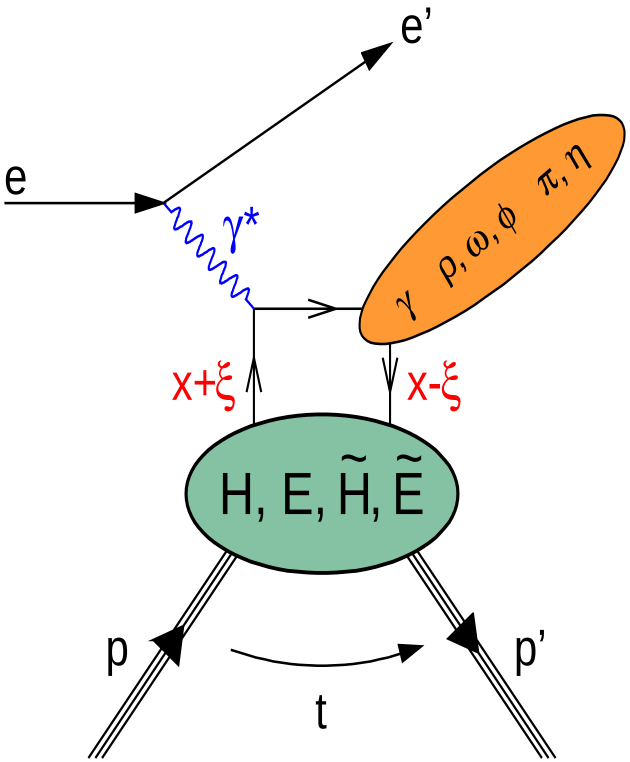
at hermes

- Motivation: Generalized Parton Distributions from DVCS
- DVCS production
- Azimuthal asymmetries:
  - beam charge
  - beam spin
  - transverse target spin
  - nuclear-mass dependence of beam charge and beam spin
- Summary and outlook



Alexander Borissov, DESY, on behalf of the HERMES Collaboration

Motivation: Generalized Parton Distributions from the exclusive reactions



- GPDs: interference of two wave functions:
  parton with $x + \xi$ emitted from nucleon
  and parton with $x - \xi$ falls back.

  x: mean value of the longitudinal momentum fraction, unaccessible
  ξ: exchanged long. momentum fraction. At Bjorken limit $\xi = \frac{x_B}{2-x_B}$
  $t = (p_{fin} - p_{ini})$ invariant momentum transfer on the target

- Natural-parity plus Unnatural-parity exchanges:
  $F_{im;jn} \equiv F_{\lambda_X \lambda_{P'};\lambda_{\gamma^*}\lambda_P} = T + U$

  – NPE: $T_{im;jn} = \frac{1}{2}\left[F_{im;jn} + (-1)^{i-j} \cdot F_{-im;-jn}\right]$

    $\Longrightarrow$ GPDs: no target spin-flip H, spin-flip E

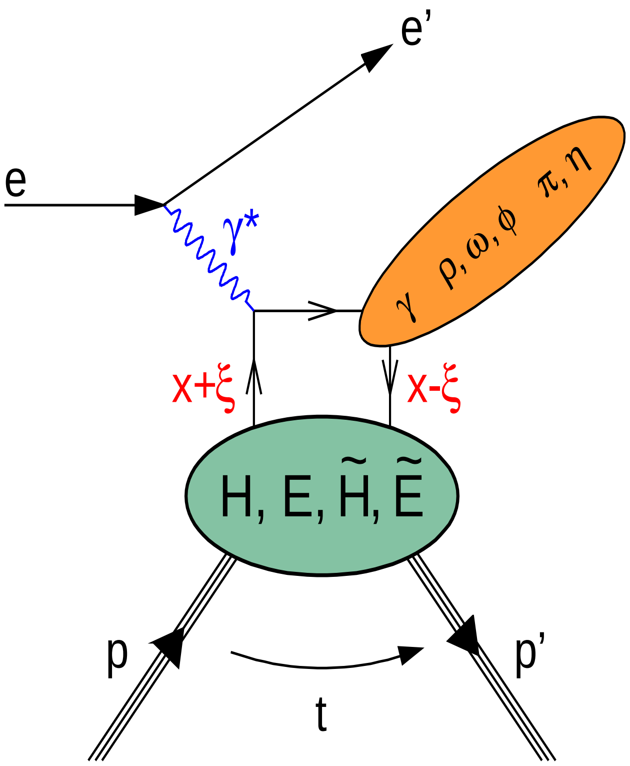
  – UPE: $U_{im;jn} = \frac{1}{2}\left[F_{im;jn} - (-1)^{i-j} \cdot F_{-im;-jn}\right]$

    $\Longrightarrow$ GPDs: no target spin-flip $\widetilde{H}$, spin-flip $\widetilde{E}$

- Total quark angular momentum (Ji relation):

  $J_q = \lim_{t\to 0} \int_0^1 dx x \left[H_q(x,\xi,t) + E_q(x,\xi,t)\right]$

Access to GPDs at HERMES: $ep \to e'Xp'$



- $F_{im;jn} \equiv F_{\lambda_X \lambda_{p'};\lambda_{\gamma^*}\lambda_P}$
  Initial: 3 spin states of γ^* : $(\lambda_\gamma \equiv j = 1, 0, -1)$
  Initial 2 nucleon helicities $(\lambda_P \equiv n = \frac{1}{2}, -\frac{1}{2})$
  Final 2 nucleon helicities $(\lambda'_p \equiv m = \frac{1}{2}, -\frac{1}{2})$
  Final photon or meson : $(\lambda_X \equiv i)$
  - DVCS (i = 1,-1) $\Longrightarrow$ access to H, E, $\widetilde{H}$,$\widetilde{E}$
  - Vector Mesons: ρ^0, ϕ, ω, ρ^+ (i = 1, 0, -1) $\Longrightarrow$ H, E, $\widetilde{H}$
  - Pseudoscalar mesons: π^+, π^0, η (i = 0) $\Longrightarrow$ $\widetilde{H}$, $\widetilde{E}$

- Similar kinematics for DVCS and all exclusive reactions:
  - $1 < Q^2 < 10$ GeV^2, $\langle Q^2 \rangle \approx 2.5$ GeV^2
  - $3 < W < 6.5$ GeV, $\langle W \rangle \approx 5$ GeV
  - $0.03 < x_B < 0.35$, $\langle x_B \rangle \approx 0.07$
  - $0.01 < -t < 0.7$ GeV^2, $\langle -t \rangle \approx 0.2$ GeV^2

- Comparable GPDs for DVCS and ρ^0, i.e.:
  $H^p_{DVCS}(x, \xi, t) \propto \frac{4}{9} H^u + \frac{1}{9} H^d + \ldots$

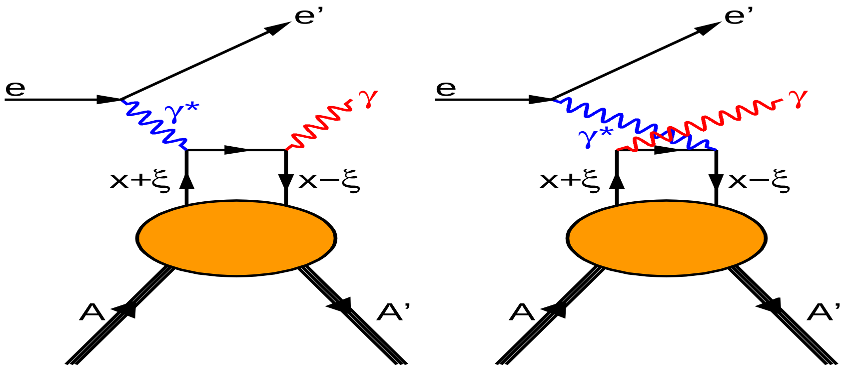
  $H^p_{\rho^0}(x, \xi, t) \propto \frac{2}{3} H^u + \frac{1}{3} H^d + \ldots$
  (M.Vanderhaeghen,P.A.M.Guichon,M.Guidal (VGG model), Phys.Rev.Lett. **80** (1998) 5064)

$\Longrightarrow$ **Sensitivity to all GPD functions at moderate x_B, where valence quarks are involved.**

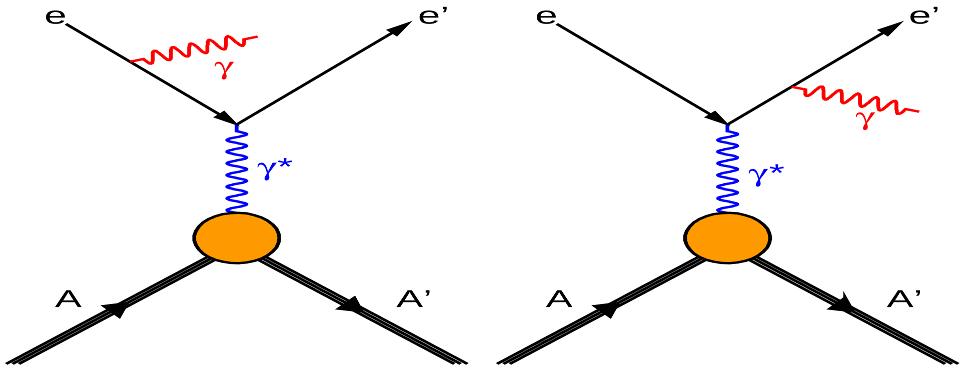
$\Longrightarrow$ **Comparison to the results on exclusive electroproduction of different particles.**

DVCS, Bethe-Heitler and their Interference

Leading order DVCS processes (left) and BH (right) are indistinguishable at event-by-event selection



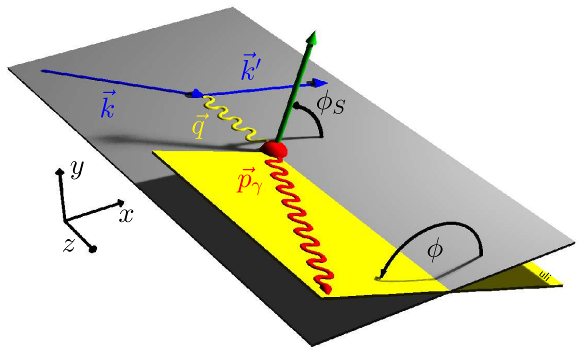
DVCS



Bethe-Heitler

$$\frac{d\sigma}{dQ^2 dx_B d|t| d\phi} = \frac{x_B e^6}{32(2\pi)^4 Q^4 \sqrt{1+\epsilon^2}} \left[|\tau_{DVCS}|^2 + |\tau_{BH}|^2 + I\{= \tau^*_{DVCS}\tau_{BH} + \tau^*_{BH}\tau_{DVCS}\} \right],$$

where $\epsilon = 2x_B M/Q$, M - proton mass



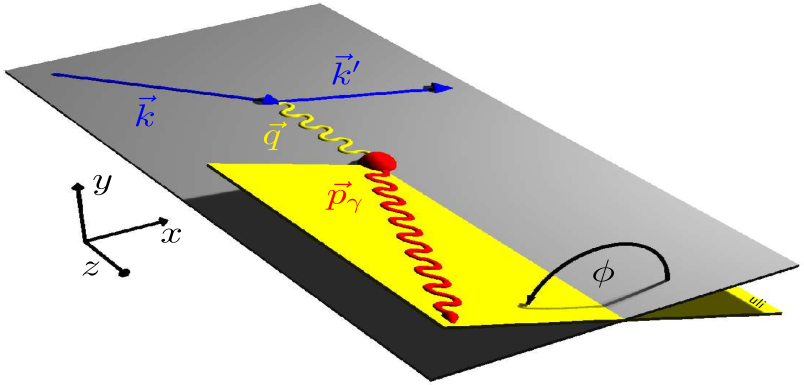
τ_{BH} is calculable in QED, τ_{DVCS} contains convolutions of GPDs

At HERMES $|\tau_{BH}|^2 >> |\tau_{DVCS}|^2$

$\Longrightarrow$ No cross section analysis for DVCS

$\Longrightarrow$ **Study Fourier harmonics of ϕ angular distributions for Beam Spin ($\mathcal{A}_{LU;I,DVCS}$), Beam Charge ($\mathcal{A}_C$) asymmetries on p, d and heavy gases, and single spin asymmetry on transversely polarized hydrogen target ($\mathcal{A}_{UT}^{\sin(n\phi - m\phi_s)}$).**

Azimuthal Dependences for DVCS and BH Processes on Unpolarized Target



- beam charge C_B
- beam polarization P_B
- kinematic factors K_{BH}, K_{DVCS}, K_I, lepton propagators $P_1(\phi), P_2(\phi)$ in BH process, c_n and s_n are the Fourier coefficients.

$$|\tau_{BH}|^2 = \frac{K_{BH}}{P_1(\phi)P_2(\phi)} \times \sum_{n=0}^{2} c_n^{BH} \cos(n\phi)$$

$$|\tau_{DVCS}|^2 = K_{DVCS} \times \left\{ c_0^{DVCS} + \sum_{n=1}^{2} c_n^{DVCS} \cos(n\phi) + P_B s_1^{DVCS} \sin(\phi) \right\}$$

$$I = \tau^*_{DVCS}\tau_{BH} + \tau^*_{BH}\tau_{DVCS}$$
$$= \frac{C_B K_I}{P_1(\phi)P_2(\phi)} \times \left\{ c_0^I + \sum_{n=1}^{3} c_n^I \cos(n\phi) + P_B \sum_{n=1}^{2} s_n^I \sin(n\phi) \right\}$$

$\Longrightarrow$ c_0^{DVCS}, c_0^I, c_1^I and s_1^I are related to the combinations of quark GPDs at leading twist (twist-2).

From Azimuthal Asymmetries to GPDs

For the leading contributions, the Fourier coefficients (i.e. asymmetry moments) are connected with the following GPDs:

- Beam Charge $\mathcal{A}_C$: $c_1^I \propto \frac{\sqrt{-t}}{Q} \mathrm{Re}\Big\{ \mathrm{F}_1 \mathcal{H} + \xi(\mathrm{F}_1 + \mathrm{F}_2)\widetilde{\mathcal{H}} - \frac{\mathrm{t}}{4\mathrm{M}^2}\mathrm{F}_2 \mathcal{E} \Big\} \sim \mathrm{Re}\Big\{ \mathrm{F}_1 \mathcal{H} \Big\}$

- Beam Charge $\mathcal{A}_C$ constant term: $c_0^I \propto -\frac{\sqrt{-t}}{Q} c_1^I$

- Beam Spin $\mathcal{A}_{LU,I}$: $s_1^I \propto \frac{\sqrt{-t}}{Q} \mathrm{Im}\Big\{ \mathrm{F}_1 \mathcal{H} + \xi(\mathrm{F}_1 + \mathrm{F}_2)\widetilde{\mathcal{H}} - \frac{\mathrm{t}}{4\mathrm{M}^2}\mathrm{F}_2 \mathcal{E} \Big\} \sim \mathrm{Im}\Big\{ \mathrm{F}_1 \mathcal{H} \Big\}$

- Beam Spin $\mathcal{A}_{LU,DVCS}$: $s_1^{DVCS} \propto \Big[\mathcal{H}\mathcal{H}^* + \widetilde{\mathcal{H}}\widetilde{\mathcal{H}}^* \Big]$ (small at HERMES energy)

where $\mathcal{H}, \widetilde{\mathcal{H}}, \mathcal{E}$ are Compton form factors, i.e. convolutions of hard scattering amplitudes and twist-2 GPDs $H, \widetilde{H}, E$, and F_1 and F_2 are Dirac and Pauli form factors of the nucleon.

$\Longrightarrow$ Data with different beam charges and helicities are combined and fit simultaneously.

Extraction of Azimuthal Asymmetries for $ep \to e'\gamma p'$

- Parameterization of the experimental yield:

$$\mathcal{N}(\phi, P_B, C_B) =$$
$$\mathcal{L}(P_B, C_B)\eta(P_B, C_B)\sigma_{UU}(\phi) \times \left[1 + P_B \mathcal{A}_{LU}^{DVCS}(\phi) + C_B P_B \mathcal{A}_{LU}^{I}(\phi) + C_B \mathcal{A}_C(\phi)\right],$$

where $\mathcal{L}$ is the integrated luminosity, η the detector efficiency, σ_{UU} the cross section for an unpolarized target averaged over beam charge and helicity.

$\Longrightarrow$ **Extraction of all amplitudes in simultaneous Maximum Likelihood fit**

- Beam Charge Asymmetry:

$$\mathcal{A}_C(\phi) = -\frac{1}{D(\phi)} \cdot \frac{x_B}{y}\left[c_0^I + c_1^I \cos(\phi) + c_2^I \cos(2\phi) + c_3^I \cos(3\phi)\right]$$

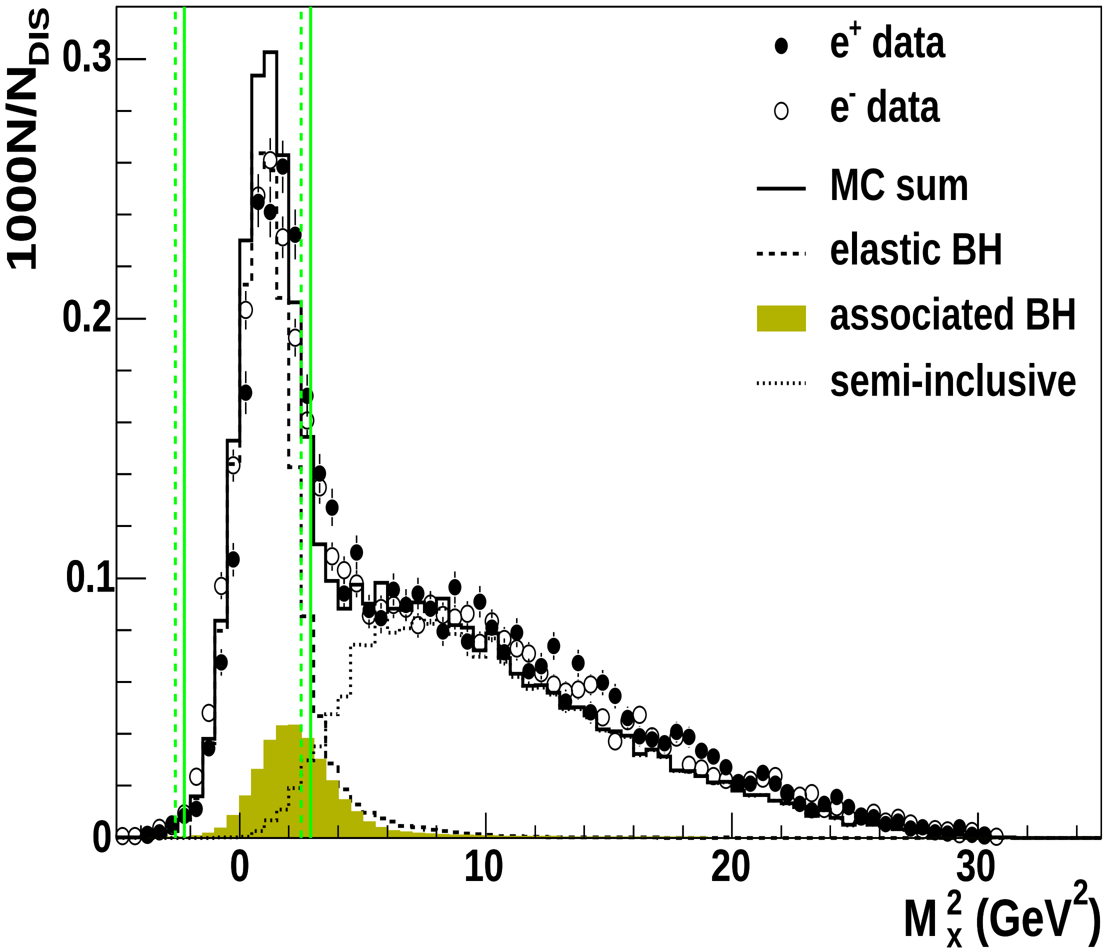
- Beam Spin Asymmetries:

$$\mathcal{A}_{LU}^{DVCS}(\phi) = \frac{1}{D(\phi)} \cdot \frac{x_B^2 t P_1(\phi) P_2(\phi)}{Q^2}\; s_1^{DVCS} \sin(\phi)$$
$$\mathcal{A}_{LU}^{I}(\phi) = \frac{1}{D(\phi)} \cdot \frac{x_B}{Q^2}\left[s_1^I \sin(\phi) + s_2^I \sin(2\phi)\right],$$

where dilution factors through lepton propagators $P_1(\phi), P_2(\phi)$:

$$D(\phi) = \frac{\sum_{n=0}^{2} c_n^{BH} \cos(n\phi)}{(1+\epsilon^2)^2} + \frac{x_B^2 t P_1(\phi) P_2(\phi)}{Q^2} \sum_{n=0}^{2} c_n^{DVCS} \cos(n\phi)$$

Exclusive $e + p \rightarrow e' + \gamma + p'$ event sample at HERMES



"Associated" (resonance) production $ep \rightarrow e\Delta^+\gamma$ is part of the signal, ~ 12 %. Its asymmetry is unknown.

- $1 < Q^2 < 10$ GeV^2
  $\nu < 22$ GeV
  $0.03 < x_B < 0.35$
  $W > 3$ GeV

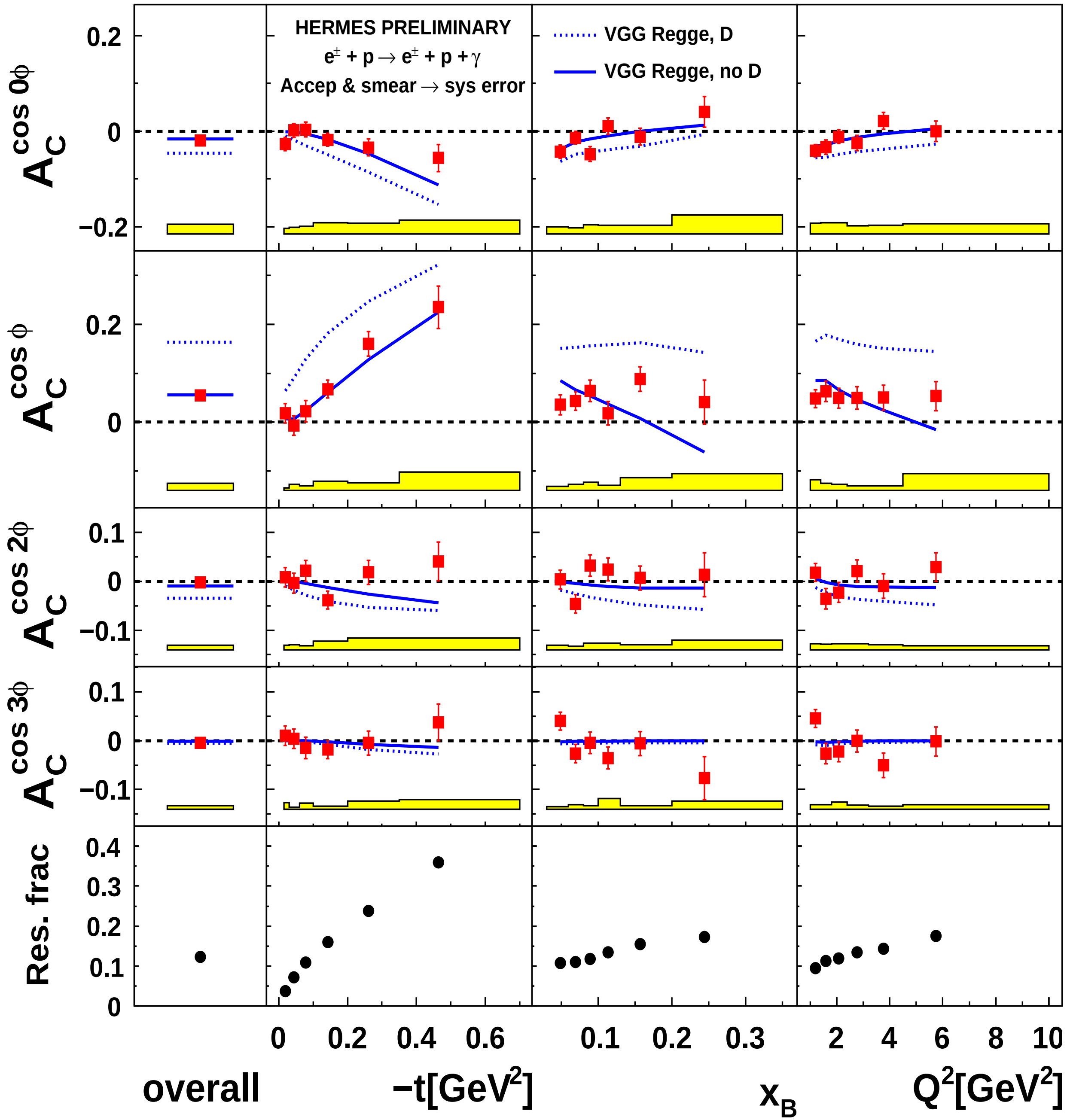
- No recoil proton detection $(1996 \div 2005) \rightarrow$ constraint on missing mass
  $M_X^2 = (P_e + P_p - P_{e'} - P_\gamma)^2$:
  DVCS&BH: $-1.5 < M_X^2 < 1.7$ GeV^2

- t is calculated without the measured energy of real photon: $t = \frac{-Q^2 - 2\nu(\nu - \sqrt{\nu^2+Q^2}\cos\Theta_{\gamma\gamma*})}{1+\frac{1}{M}(\nu - \sqrt{\nu^2+Q^2}\cos\Theta_{\gamma\gamma*})}$

  $5 < \Theta_{\gamma\gamma*} < 45$ mrad
  $-t < 0.7$ GeV^2

- SIDIS (mainly π^0) background contribution,
  $f_{bg} \sim 3$ % was estimated from MC,
  A_{bg} measured at large M_X^2 and corrected for:
  $A_{corr} = \frac{A_{raw} - f_{bg} * A_{bg}}{1 - f_{bg}}$

BCA ($\mathcal{A}_C$) of DVCS on a Hydrogen Target

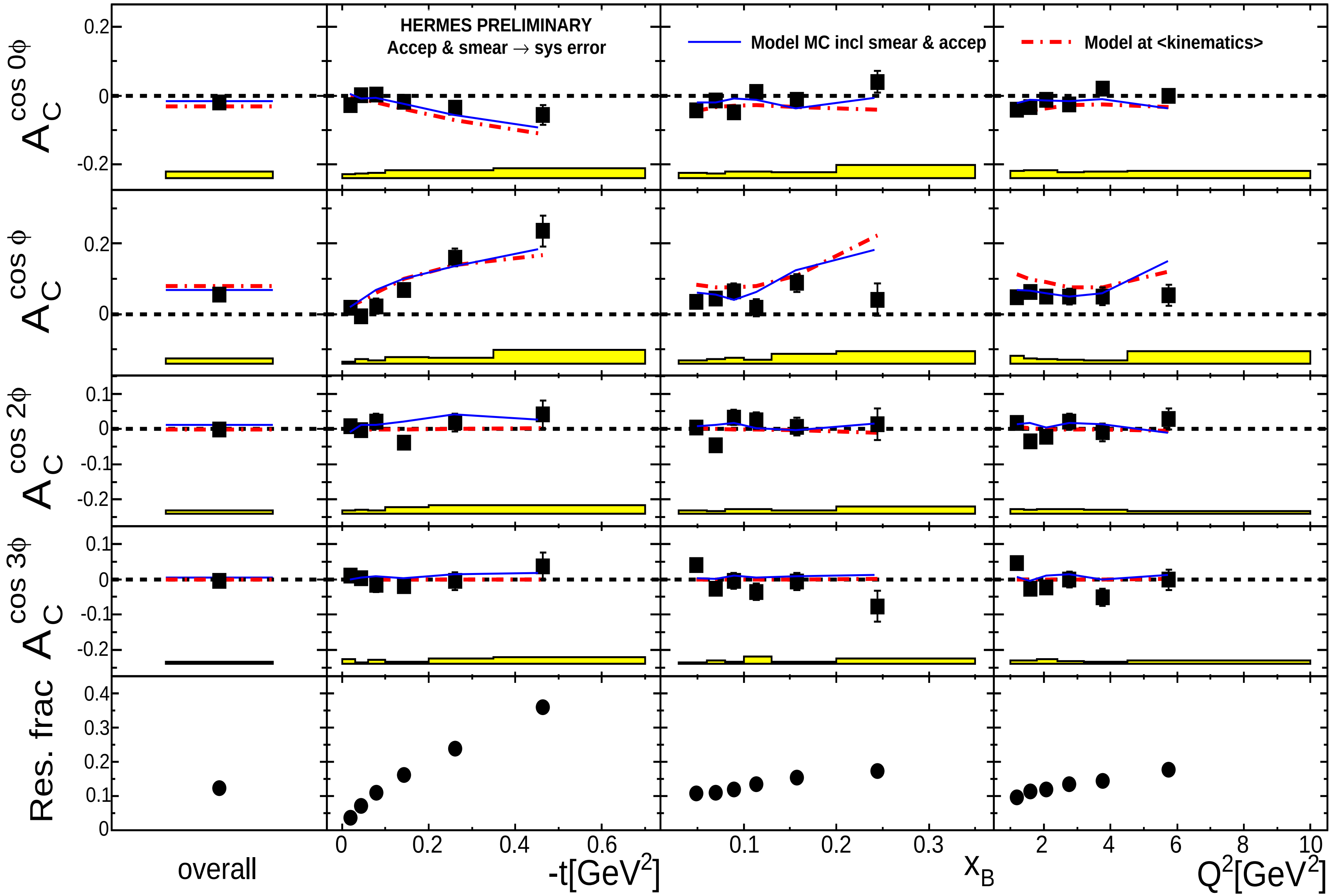


- constant term $\propto -A_C^{\cos(\phi)}$
- $\propto F_1 \mathrm{Re}\{\mathcal{H}\}$
- higher twist
- gluon leading twist
- Resonant fraction: $ep \to e\Delta^+\gamma$

VGG model calculations without D-term are more preferable for the data

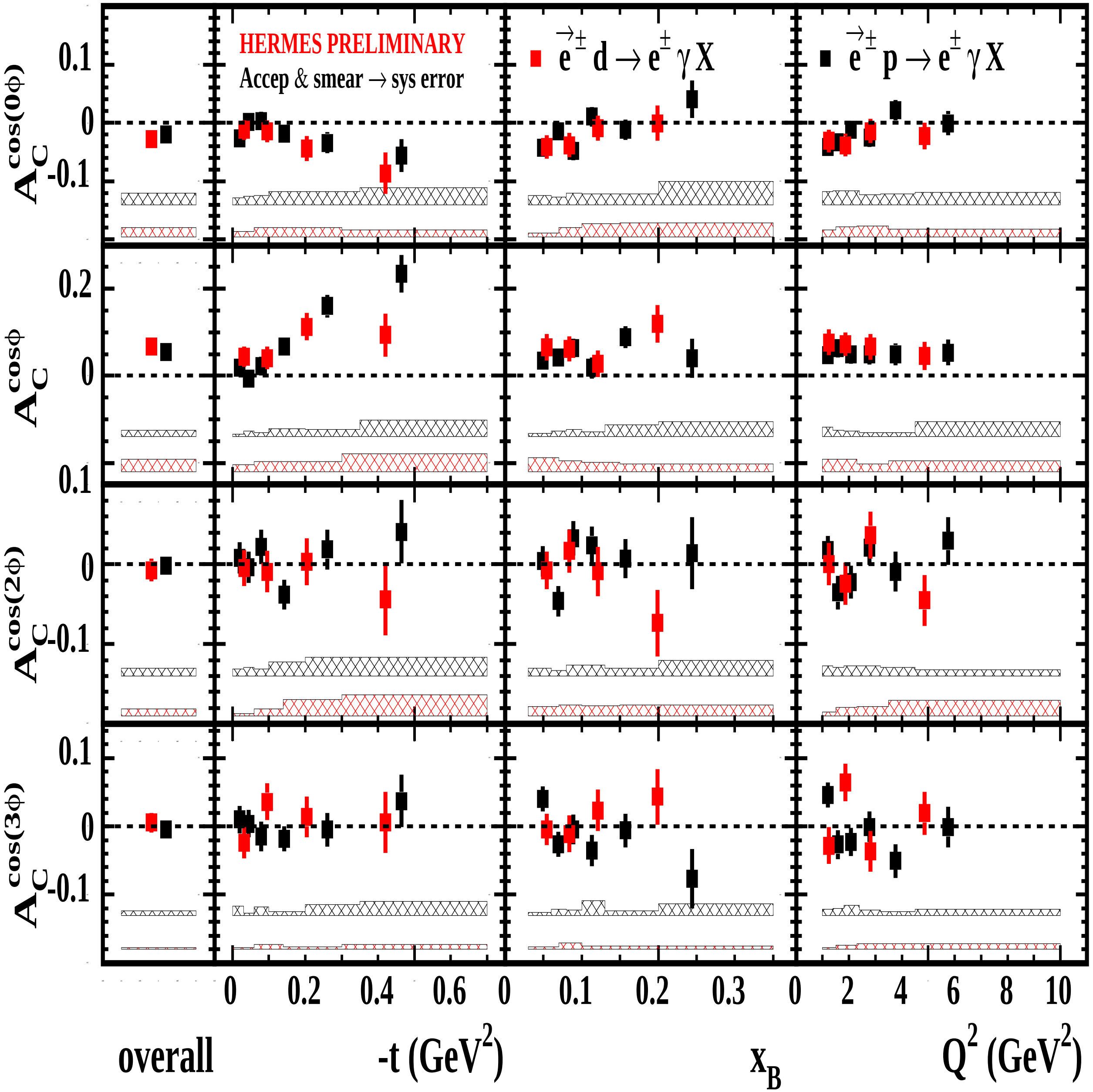
(Phys.Rev. **D60** (1999) 094017; Prog.Nucl.Phys.**47** (2001) 401)

Simulation of the Acceptance, Bin-width, Smearing and Misalignment



The difference between simulated asymmetries in 4π and reconstructed in the HERMES acceptance, with the simulation of smearing and misalignment and accounting bin-width, is taken as a systematic uncertainty.

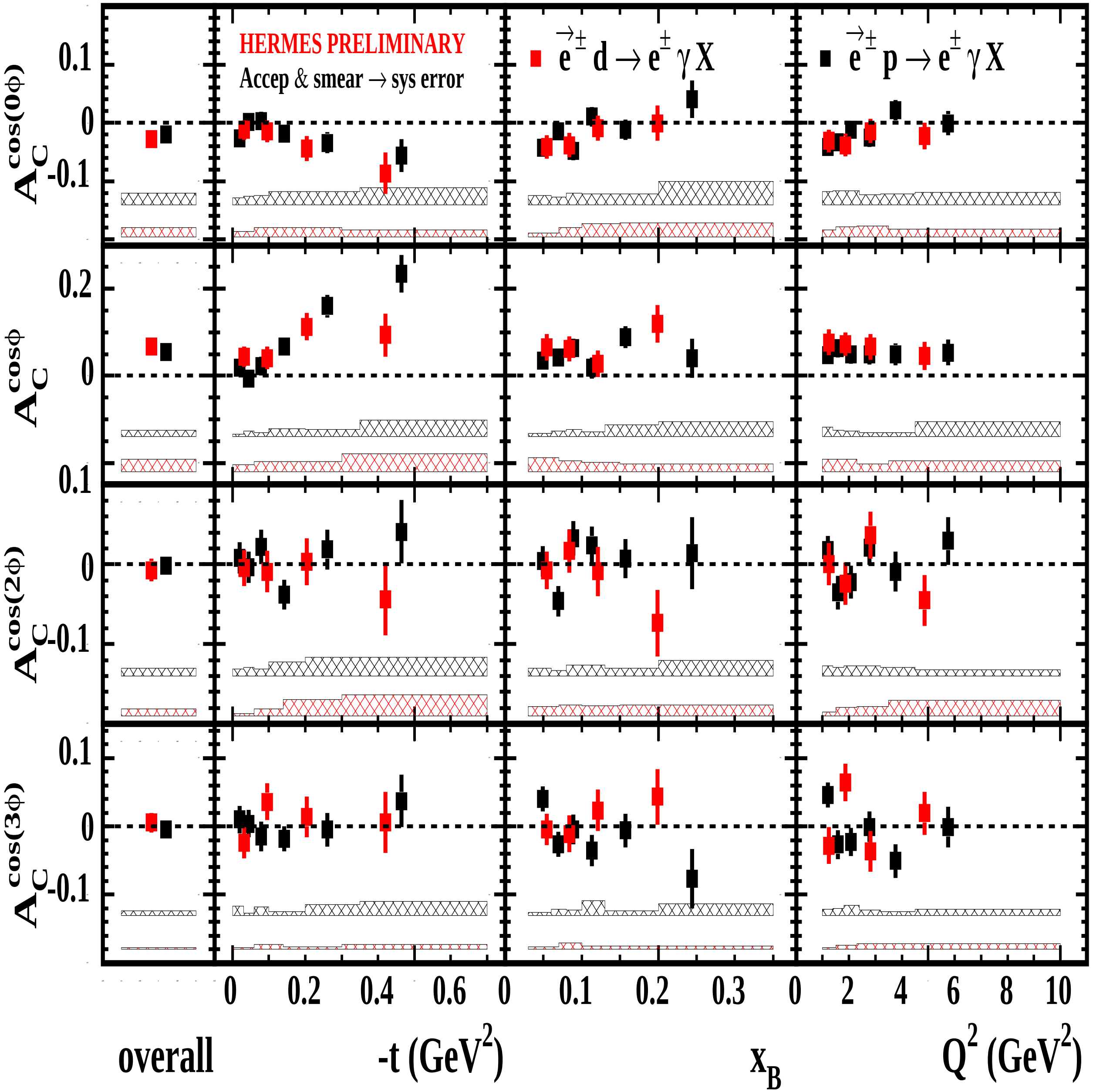
HERMES DVCS $\mathcal{A}_C$ on a Hydrogen and Deuterium Targets



- constant term $\propto -A_C^{\cos(\phi)}$
- $\propto F_1 \mathrm{Re}\{\mathcal{H}\}$
- higher twist
- gluon leading twist

$\Longrightarrow$ No difference between p and d.

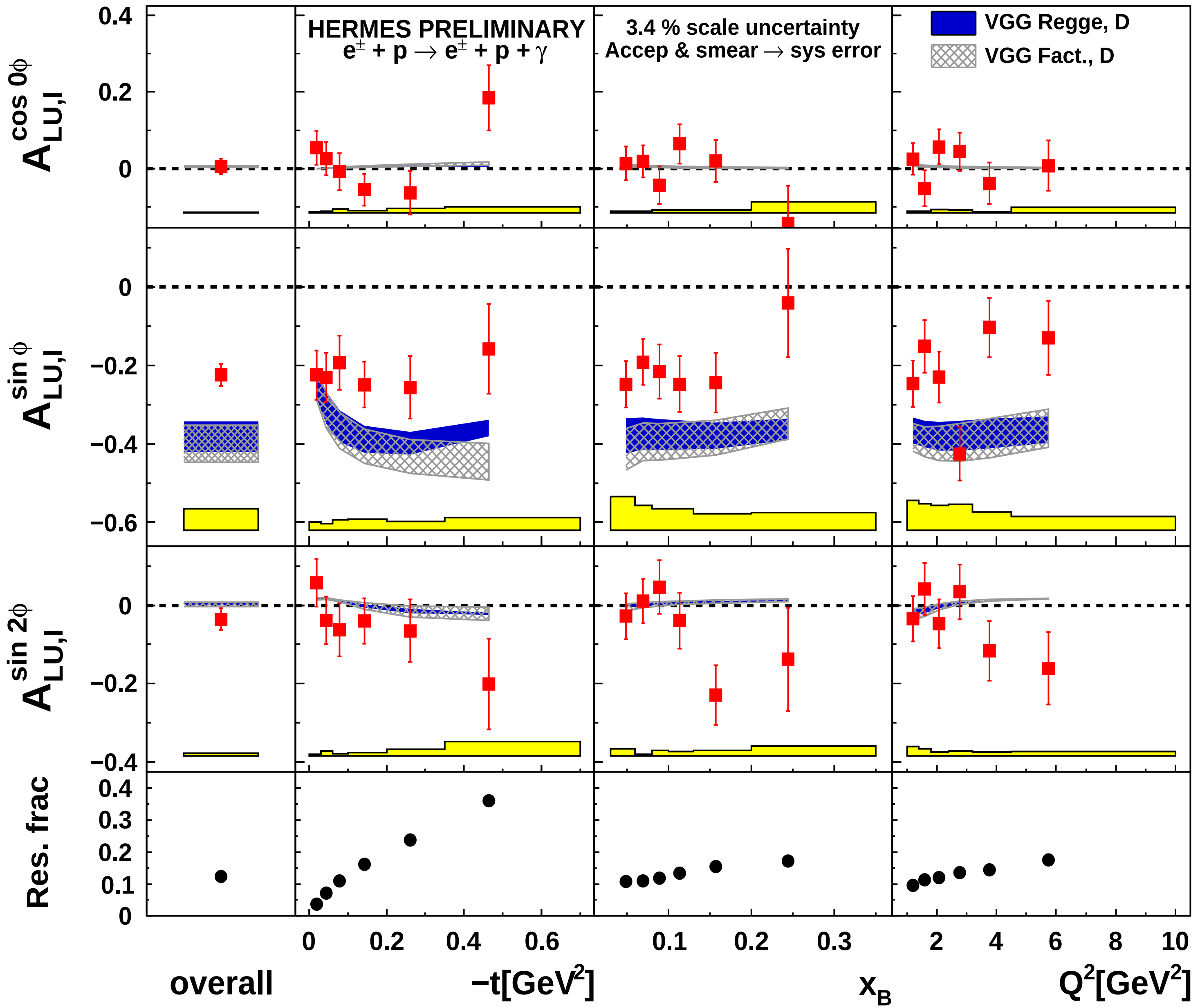
HERMES DVCS $\mathcal{A}_C$ on a Hydrogen and Deuterium Targets



- constant term $\propto -A_C^{\cos(\phi)}$
- $\propto F_1 \mathrm{Re}\{\mathcal{H}\}$
- higher twist
- gluon leading twist

$\Longrightarrow$ No difference between p and d, as well as for exclusive ρ^0 SDMEs (HERMES collab., EPJ C **62**, 4 (2009) 659) and helicity amplitudes, see talk of S.Manayenkov.

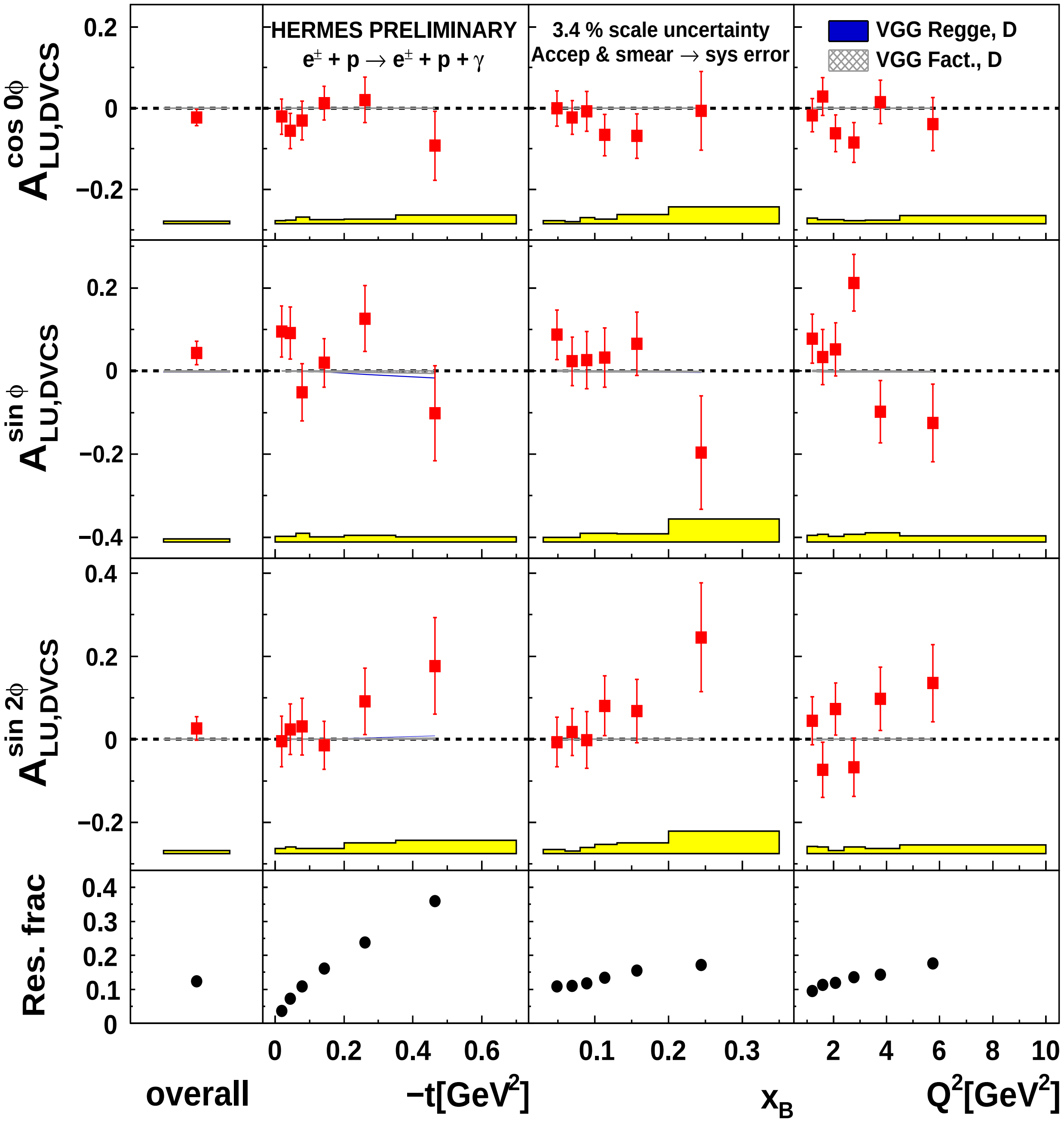
HERMES DVCS $\mathcal{A}_{LU}^{I}$ on a Hydrogen Target



- constant term $= 0$
- $\propto F_1 \mathrm{Im}\{\mathcal{H}\}$
- higher twist
- Resonant fraction of $ep \to e\Delta^{+}\gamma$

$\Longrightarrow$ Disagreement with VGG calculations for $F_1 \mathrm{Im}\{\mathcal{H}\}$. Note similar observation for ρ^0 electroproduction, see talk of S.Manayenkov.

HERMES DVCS $\mathcal{A}_{LU}^{DVCS}$ on a Hydrogen Target



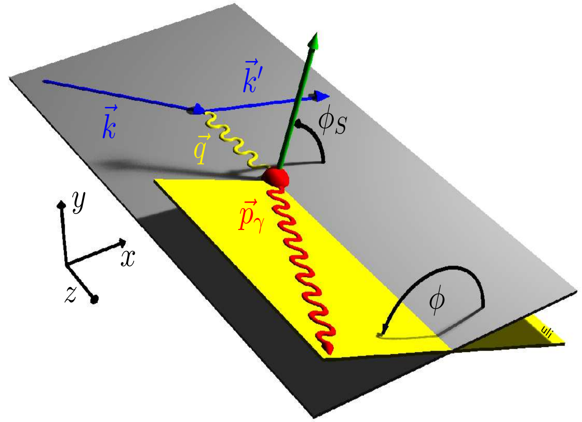
- $\propto \left(\mathcal{H}\mathcal{H}^* + \widetilde{\mathcal{H}}\widetilde{\mathcal{H}}^*\right)$, small
- higher twist
- higher twist
- Resonant fraction of $ep \to e\Delta^+\gamma$

Transverse Target Spin Asymmetry $\mathcal{A}_{UT}$ (HERMES collab. JHEP06 (2008) 066)

$$|\tau_{DVCS,UT}|^2 = \ldots + K_{DVCS} S_\perp \Big[c_{0,UT}^{DVCS} \sin(\phi - \phi_s) + \ldots \Big]$$

$$I_{UT} = \ldots + \frac{C_B K_I}{P_1(\phi) P_2(\phi)} \times S_\perp \Big[c_{1,UT}^{I} \sin(\phi - \phi_s) \cos\phi + s_{1,UT}^{I} \cos(\phi - \phi_s) \sin\phi + \ldots \Big]$$

Greatest interest due to GPD function $\mathcal{E}$ contributing in terms with ϕ_s angle



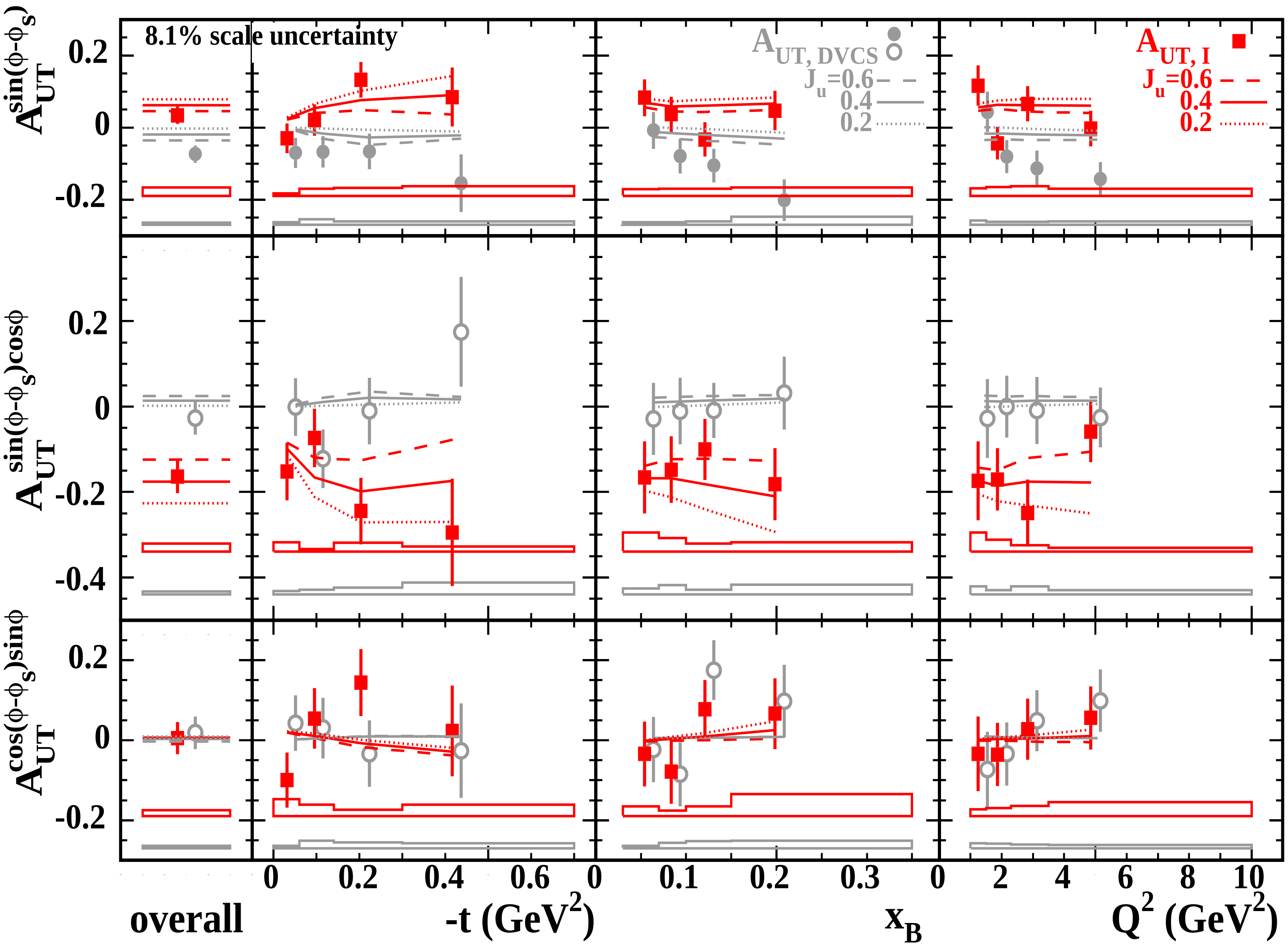
$$c_{0,UT}^{DVCS} \propto -\frac{\sqrt{-t}}{M} \mathrm{Im} \Big\{ \mathcal{H}\mathcal{E}^* - \mathcal{E}\mathcal{H}^* + \xi \widetilde{\mathcal{E}} \widetilde{\mathcal{H}}^* - \widetilde{\mathcal{H}} \xi \widetilde{\mathcal{E}}^* \Big\}$$

$$c_{1,UT}^{I} \propto -\frac{M}{Q} \mathrm{Im} \Big\{ \frac{\mathrm{t}}{4\mathrm{M}^2} \Big[(2 - \mathrm{x_B}) \mathrm{F}_1 \mathcal{E} - 4 \frac{1 - \mathrm{x_B}}{2 - \mathrm{x_B}} \mathrm{F}_2 \mathcal{H} \Big] + \mathrm{x_B} \xi \Big[\mathrm{F}_1 (\mathcal{H} + \mathcal{E}) - (\mathrm{F}_1 + \mathrm{F}_2)(\widetilde{\mathcal{H}} + \frac{\mathrm{t}}{4\mathrm{M}^2} \widetilde{\mathcal{E}} \Big] \Big\}$$

$$s_{1,UT}^{I} \propto$$
$$-\frac{M}{Q} \mathrm{Im} \Big\{ \frac{\mathrm{t}}{4\mathrm{M}^2} \Big[4 \frac{1 - \mathrm{x_B}}{2 - \mathrm{x_B}} \mathrm{F}_2 \widetilde{\mathcal{H}} - (\mathrm{F}_1 + \xi \mathrm{F}_2) \mathrm{x_B} \widetilde{\mathcal{E}} \Big] + \mathrm{x_B} \Big[(\mathrm{F}_1 + \mathrm{F}_2)(\xi \mathcal{H} + \frac{\mathrm{t}}{4\mathrm{M}^2} \mathcal{E}) - \xi \mathrm{F}_1 (\widetilde{\mathcal{H}} + \frac{\mathrm{x_B}}{2} \widetilde{\mathcal{E}}) \Big] \Big\},$$

where $S_\perp$ is the magnitude of transverse target polarization and $\xi \approx x_B/(2 - x_B)$.

HERMES $\mathcal{A}_{UT}$ Amplitudes (HERMES collab., JHEP 06 (2008) 066)



- $\propto \mathrm{Im}\left\{\mathcal{H}\mathcal{E}^* - \mathcal{E}\mathcal{H}^*\right\}$
- $\mathcal{A}_{UT,DVCS}^{\sin(\phi-\phi_s)} \neq 0$
- $\propto \mathrm{Im}\left\{\mathrm{F}_2\mathcal{H} - \mathrm{F}_1\mathcal{E}\right\}$
- $\propto \mathrm{Im}\left\{\mathrm{F}_2\widetilde{\mathcal{H}} - \mathrm{F}_1\widetilde{\mathcal{E}}\right\}$

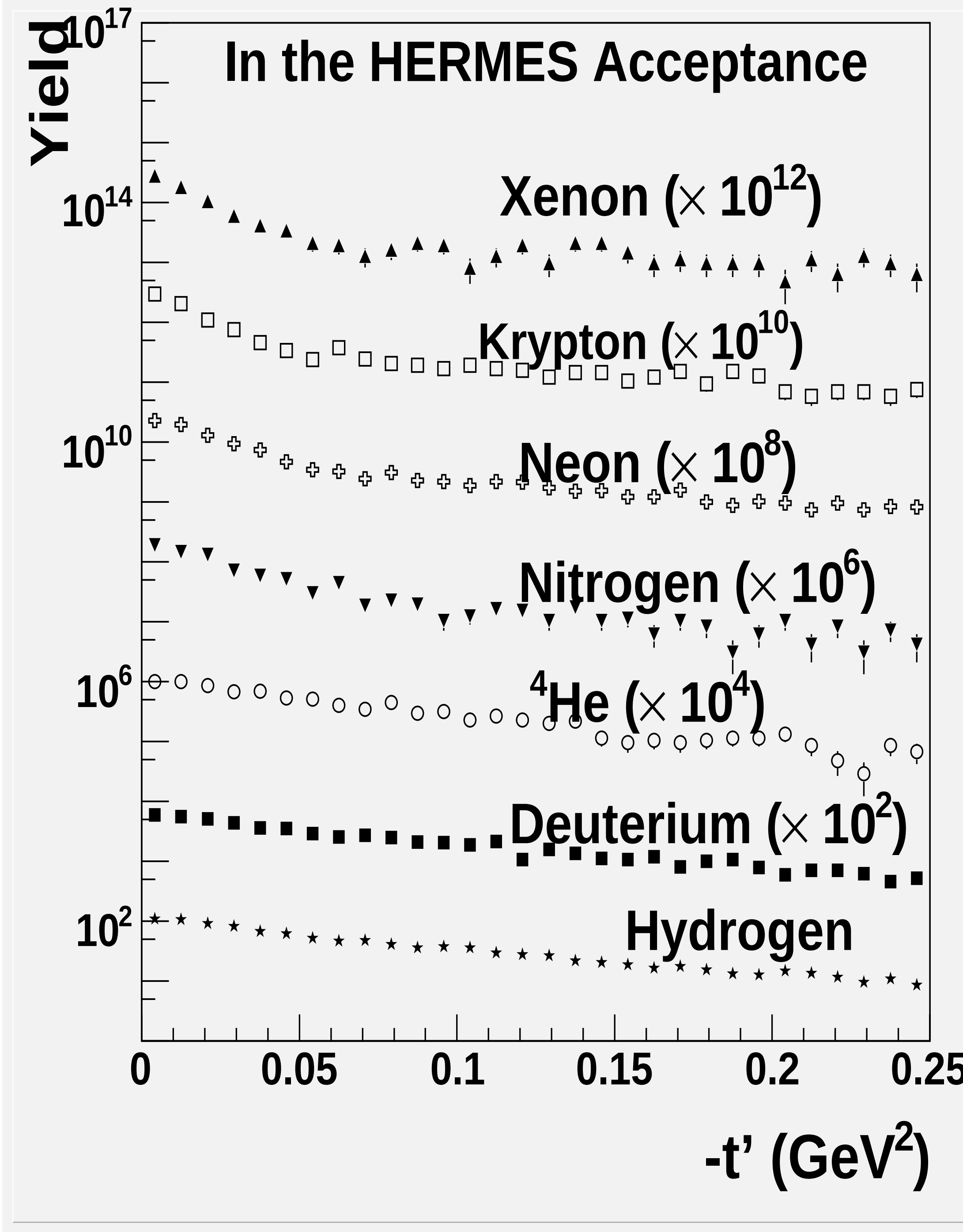
$\mathcal{A}_{UT}^{\sin(\phi-\phi_s)\cos\phi}$ is the most sensitive to parameter J_u at $J_d = 0$.

$\Longrightarrow$ With better accuracy a statistically significant constraint on J_u can be obtained

Why Nuclear DVCS?

- Any modifications of GPDs in nuclear environment?
- Any difference between *coherent* scattering off the whole nucleus and *incoherent* on the nucleon?
- Any new insights into the origin of EMC effect, e.g. connected with the transverse motion of quarks in nuclear targets?

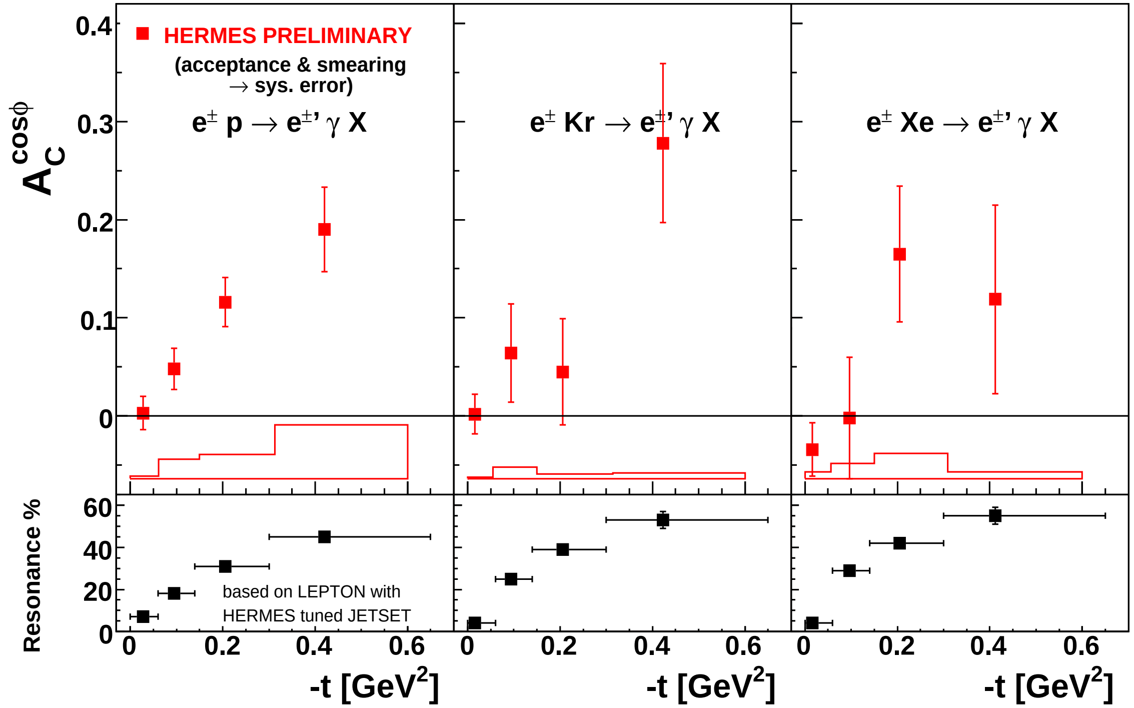
DVCS data are available $\Longrightarrow$



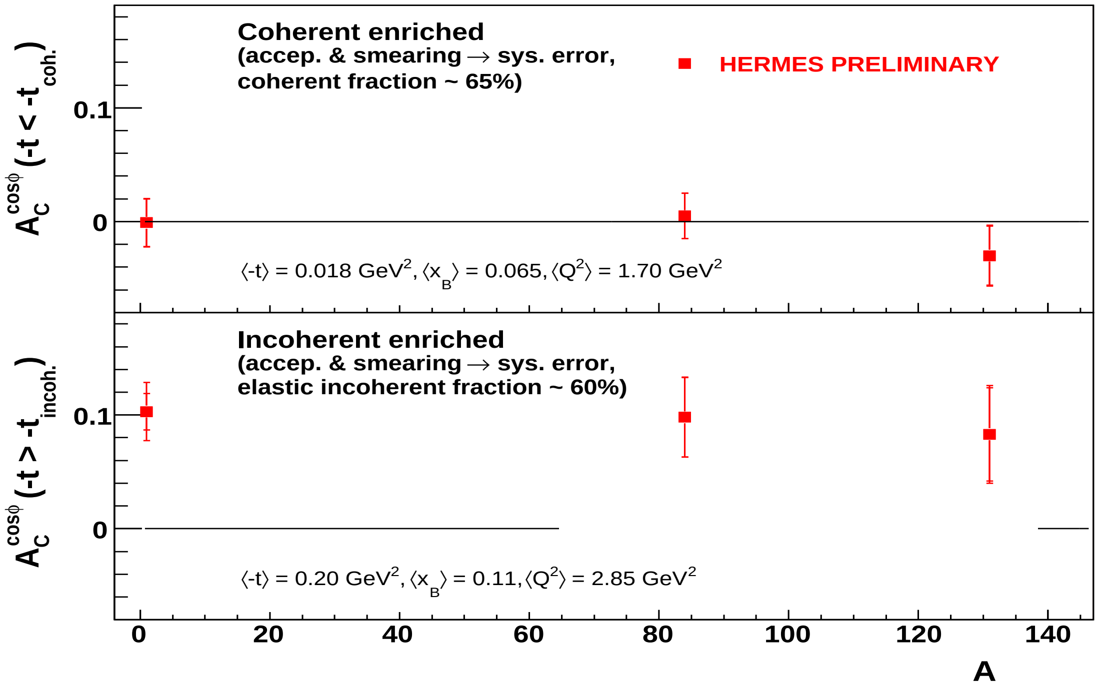
Coherent-enriched sample with purity $\sim 68\%$, assoc. DVCS $\sim 4\%$:
$\langle -t \rangle \approx 0.018$ GeV^2, $\langle x_B \rangle \approx 0.07$, $\langle Q^2 \rangle \approx 1.7$ GeV^2

Incoherent-enriched sample with purity $\sim 62\%$ and assoc. DVCS $\sim 29\%$:
$\langle -t \rangle \approx 0.2$ GeV^2, $\langle x_B \rangle \approx 0.11$, $\langle Q^2 \rangle \approx 2.8$ GeV^2

Nuclear DVCS: Beam-charge Asymmetry

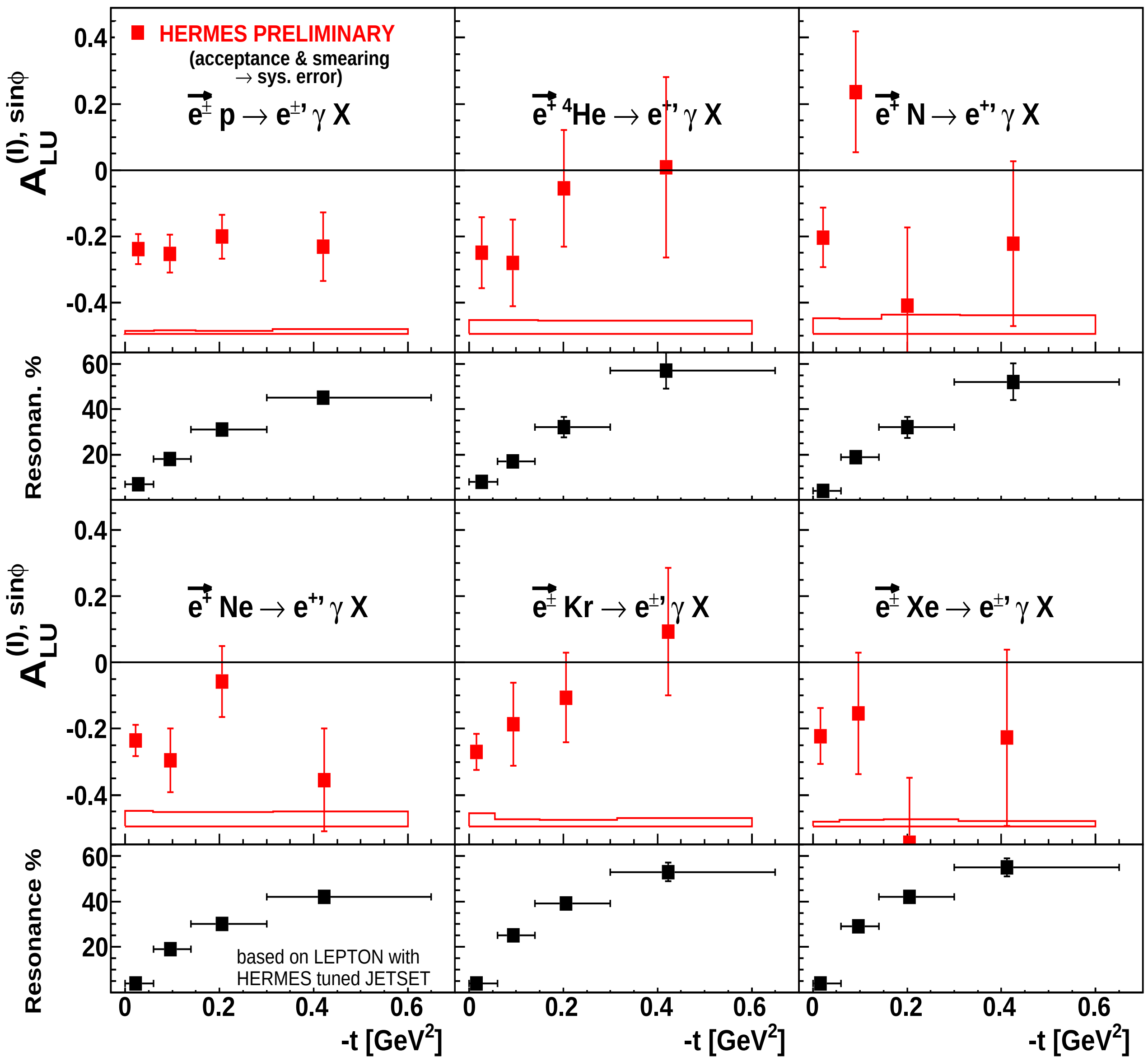


- t dependence:
  Kr and Xe are consistent with H.



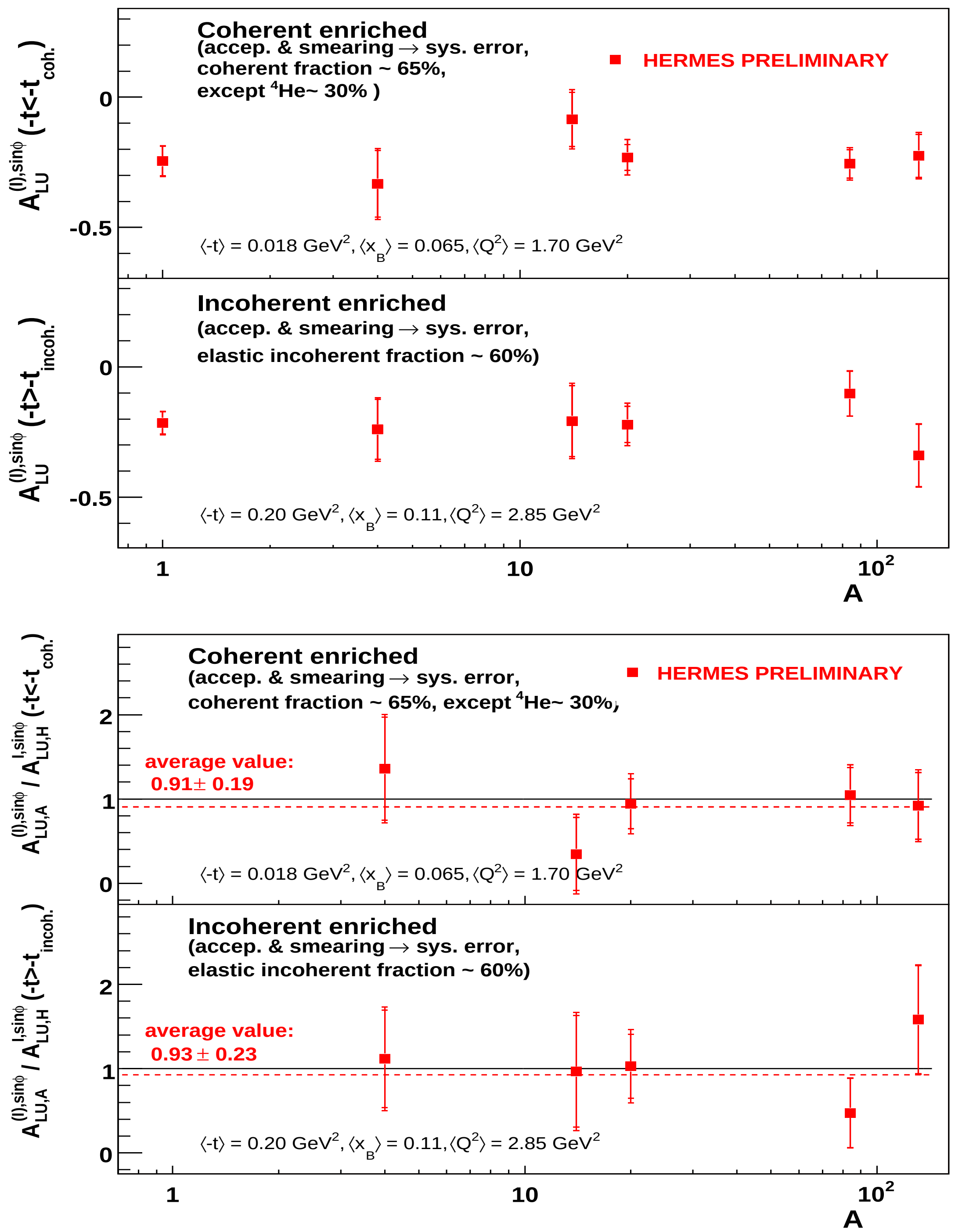
- Separated coherent and incoherent production:
  Kr and Xe are consistent with H.

Nuclear DVCS: Beam-spin Asymmetry vs. t



No statistically significant nuclear-mass dependence is observed

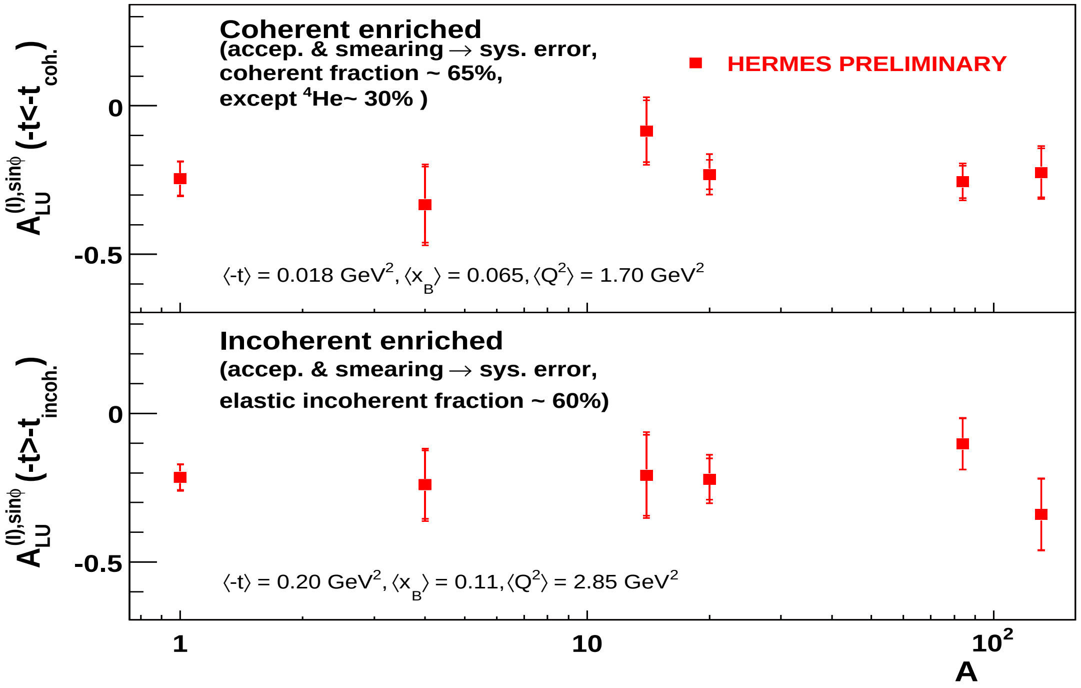
Nuclear DVCS: Beam-spin Asymmetry for Coherent and Incoherent DVCS

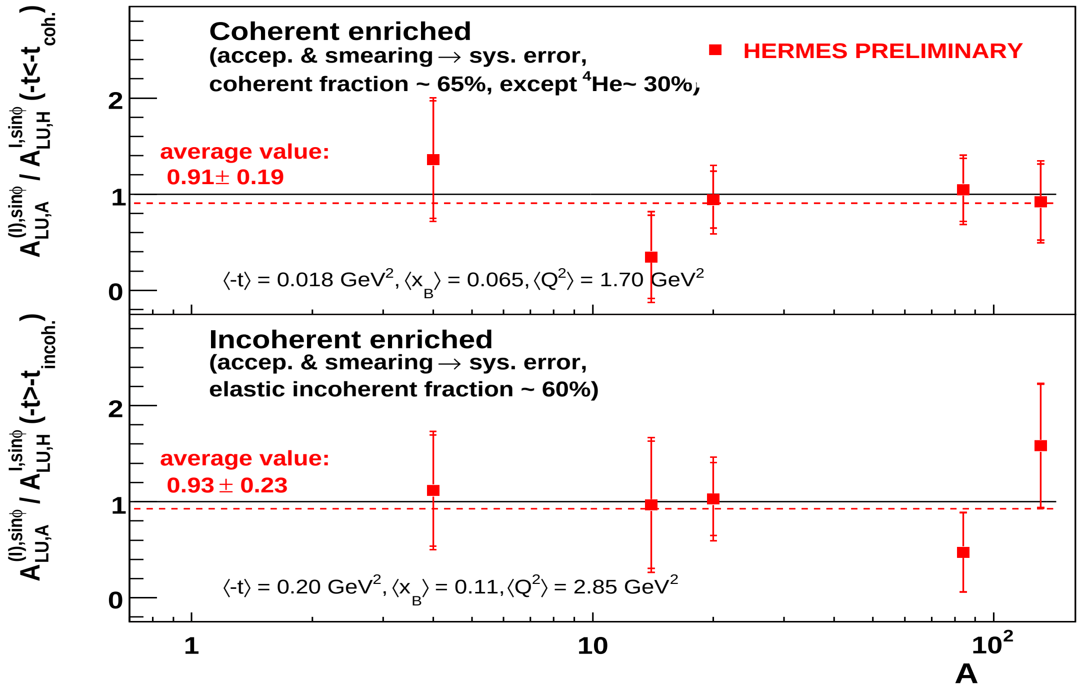


No statistically significant nuclear-mass dependence is observed for coherent and incoherent DVCS.

$\Longrightarrow$ **No nuclear-mass dependence is found for DVCS production amplitudes on D, He, N, Ne, Kr and Xe targets.**

Nuclear DVCS: Beam-spin Asymmetry for Coherent and Incoherent DVCS





No statistically significant nuclear-mass dependence is observed for coherent and incoherent DVCS.

$\Longrightarrow$ **No nuclear-mass dependence is found for DVCS production amplitudes on D, He, N, Ne, Kr and Xe targets.**

An indication that for exclusive meson production nuclear effects are caused by the propagation of meson through nuclear matter, but not by the modifications of GPDs in the nuclear environment.

Summary

- DVCS azimuthal asymmetries on proton
  - allow to constrain GPD models:
    - $\mathcal{A}_C$ and $\mathcal{A}_{LU}$ provide access to GPD $\mathcal{H}$
    - $\mathcal{A}_{UT}$ to GPD $\mathcal{E}$
  - allow to provide a constraint on total angular momentum of valence quarks.

- From the comparison with GPD based calculations of VGG model:
  - $\mathcal{A}_{UT}^{\sin(\phi-\phi_s)\cos\phi}$ is the most sensitive to parameter J_u
  - calculations without D-term are more favourable for the data
  - disagreement of $\mathcal{A}_{LU}$ data with the calculations for $\mathrm{Im}\{\mathcal{H}\}$

- The results on hydrogen and deuterium targets agree very well for all leading twist amplitudes.

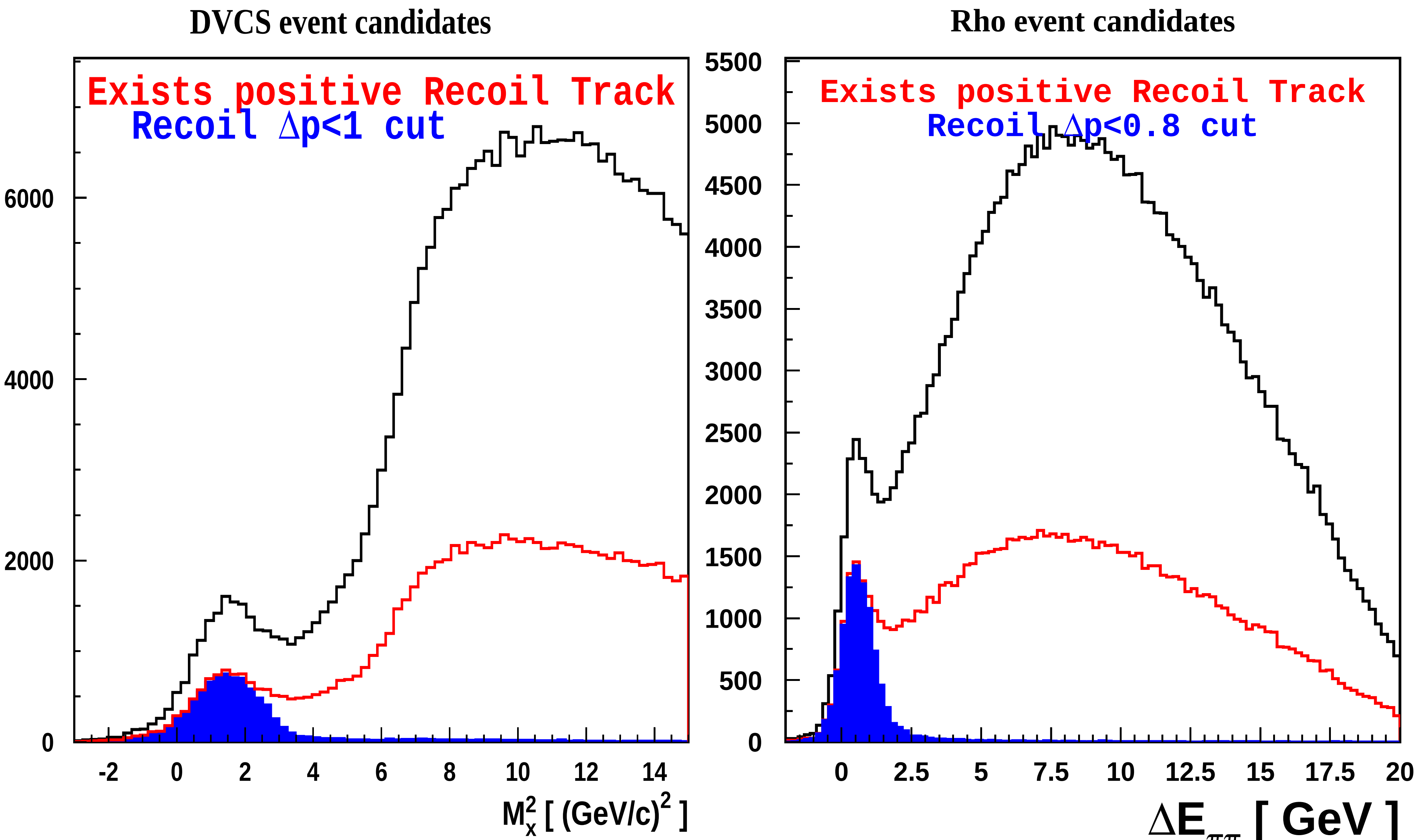
- The results on He, N, Ne, Kr and Xe targets show no nuclear-mass dependence.

$\Longrightarrow$ **Several HERMES DVCS papers will be published soon.**

Outlook: New Data with HERMES Recoil Detector

In 2006÷2007 about two times more proton data than in 1996-2005.

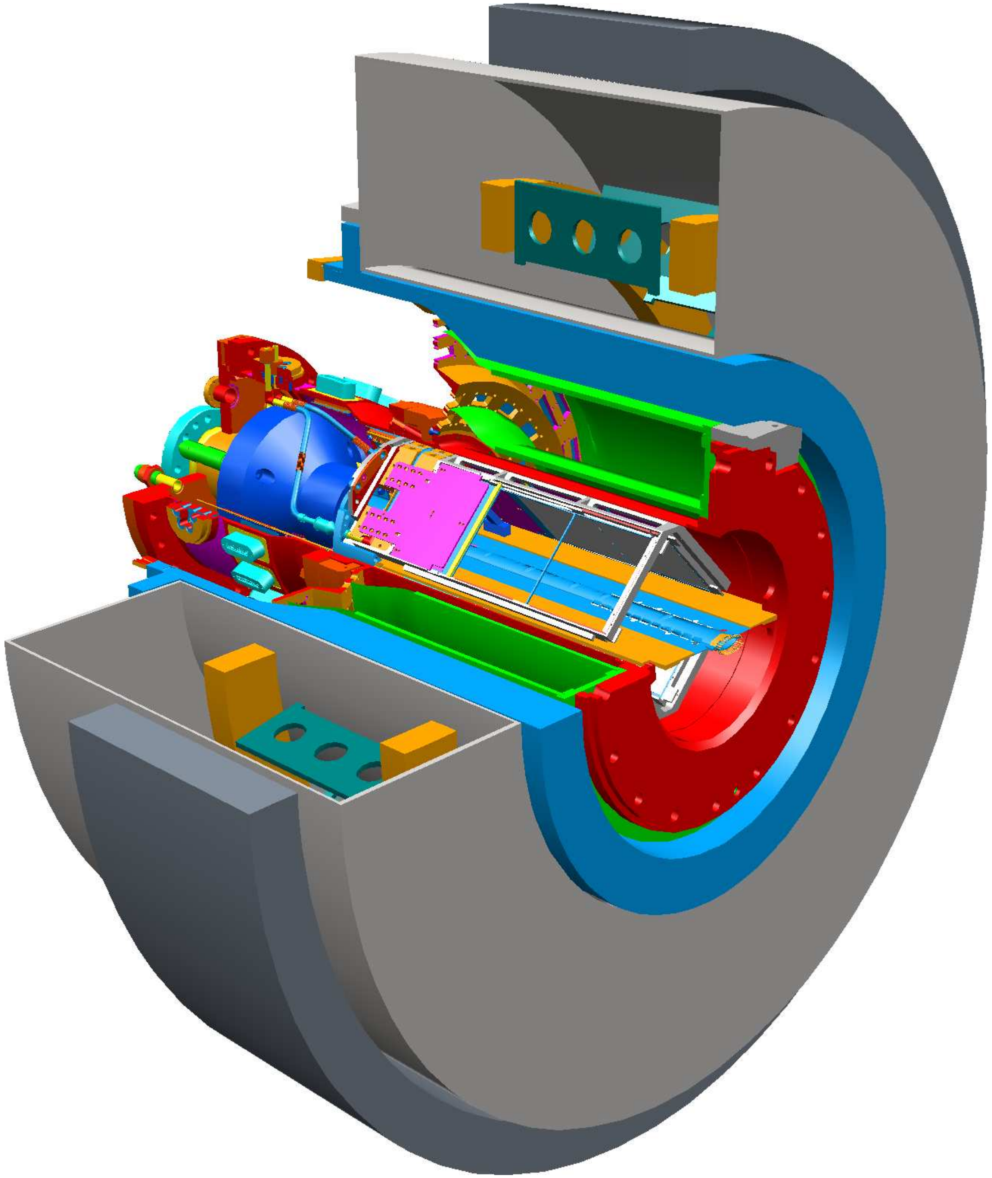
SIDIS background can be neglected for exclusive reactions with recoil proton detected:



Black histogram - event candidates without Recoil Detector

$\Delta P = P_{meas}(p') - P_{calc} \Longrightarrow$ small ΔP corresponds to the exclusive reactions

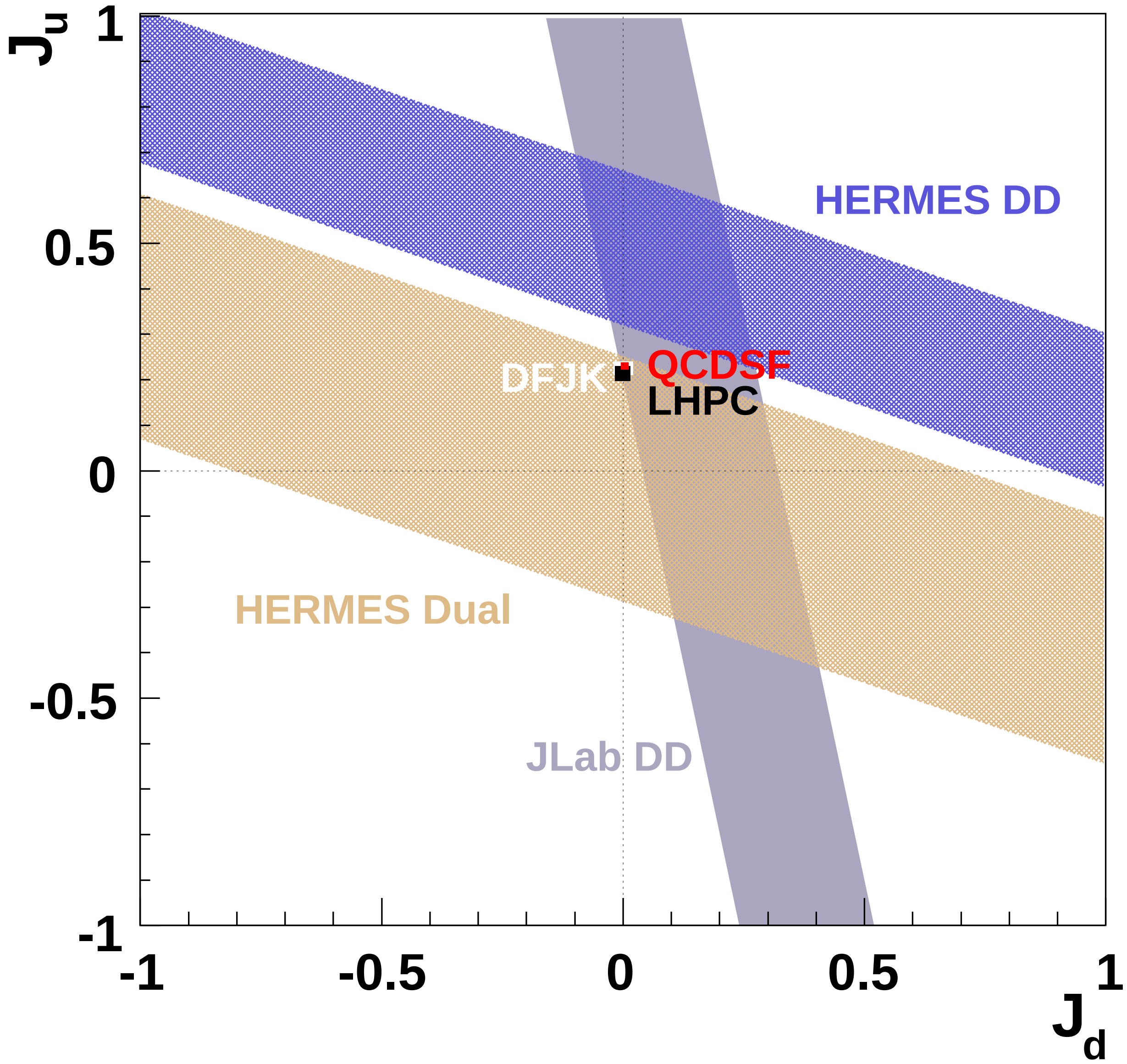
Outlook. The HERMES Recoil Detector



- SC Solenoid with 1 Tesla field
- Photon Detector with 3 layers of Tungsten/Scintillator
- Scintillating Fiber Tracker: 2 barrels with 2 parallel & 2 stereo-layers each
- Silicon Strip Detector: 2 layers of of double-sided sensors (10 cm $\times$ 10 cm) inside the beam pipe
- For Silicon & Fiber Tracker
  $135 < P_{p'} < 1200$ MeV
  p'/π PID for $P < 650 MeV/c$
- For Photon Detector
  p'/π PID for $P > 650 MeV/c$
  π^0 background supression
- Target cell with unpol. ^2H or ^2D

$\Longrightarrow$ In 2006-2007 about two times more proton data than in 1996-2005

Backup. Estimate of J_d and J_u from DVCS data and GPDs



(HERMES collab., A. Airapetian et al, JHEP 06 (2008) 066, arXiv:0802.2499, DESY-07-2 25)

Bands: 1-σ model-dependent constraint on J_u and J_d taken as free parameters in DD - double-distribution and Dual - dual parameterization GPD models. QCDSF and LHPC - lattice calculations; DFJK - fit of nucleon form factor data.