DVCS at HERMES

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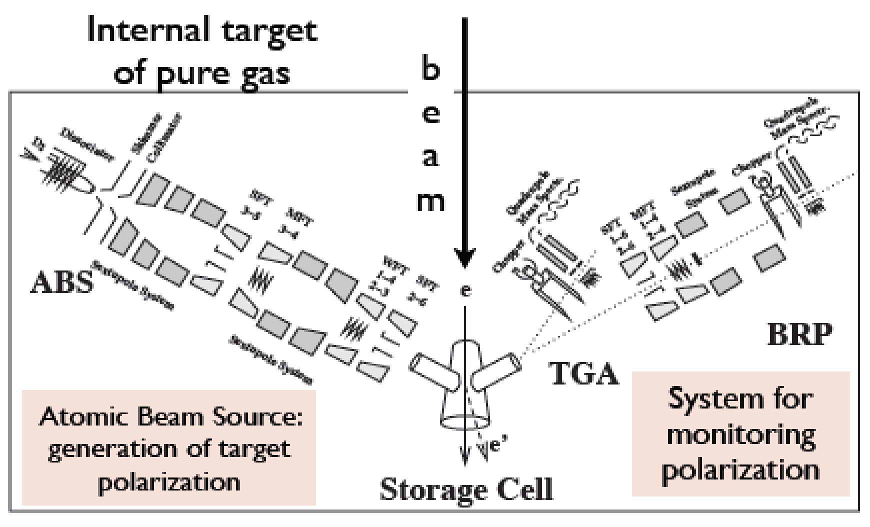
21st International Symposium on Spin Physics (SPIN14)
Beijing, China, Oct. 20-24, 2014

- HERMES experiment at HERA
- DVCS measurements and GPDs
- HERMES experiment at HERA
- DVCS: measurement of azimuthal asymmetries at HERMES
- Measurements of BSAs: use of Recoil Detector information

  Summary

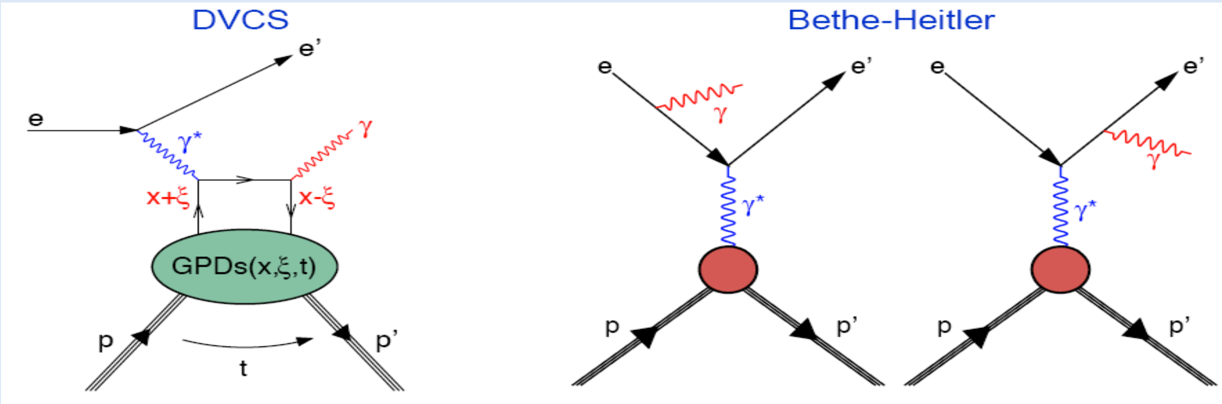
HERMES at DESY

Self-polarized e^+ and e^- beams
27.6 GeV
Helicity switched every few months



Polarized hydrogen (Long.,Trans.), deuterium (Long.)
Polarization flipped at 60-180 s time interval
Unpolarized *He,N,Ne,Kr,Xe*

Deeply virtual Compton scattering & GPDs



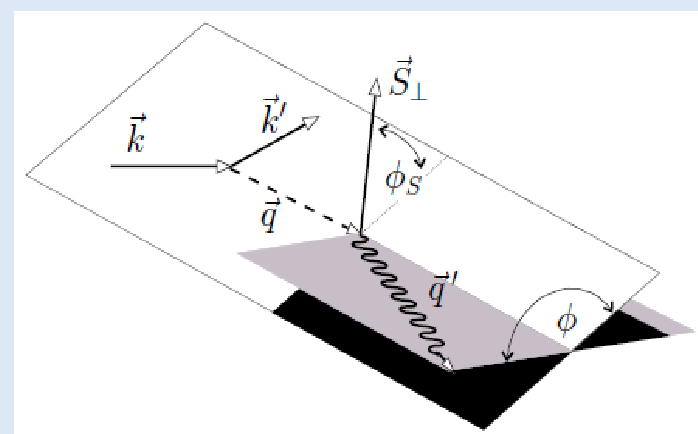
- Theoretically cleanest way to access GPDs
- Interference between DVCS and Bethe-Heitler amplitude
- $|\tau_{DVCS}| \ll |\tau_{BH}|$ at HERMES

Access to GPD combinations through azimuthal asymmetries

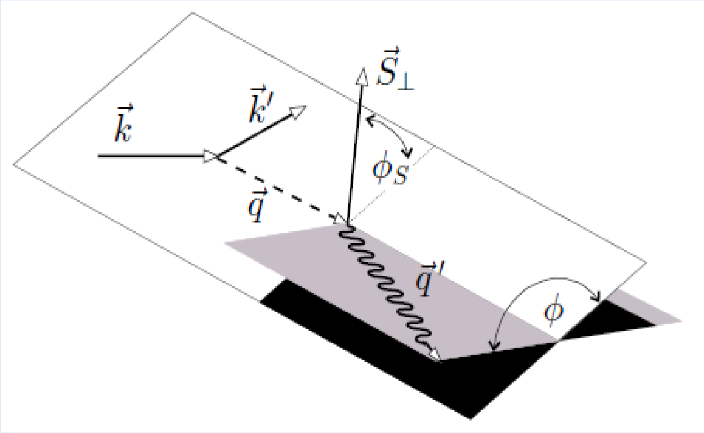
A_{XY} (X: beam, Y: target)

HERMES: Complete set of asymmetries

- Both beam charges
- Both beam helicities
- Unpolarized ^1H, ^2H, and also nuclear targets
- Longitudinally polarized ^1H and ^2H targets
- Transversely polarized ^1H target
- Recoil detector: unpolarized ^1H and ^2H



Accessing GPDs in DVCS



- Beam-Charge Asymmetry
  $$\sigma(e^{+},\phi)-\sigma(e^{-},\phi)\propto \Re e[F_1\mathcal{H}]$$
- Beam-Spin Asymmetry
  $$\sigma(\vec{e},\phi)-\sigma(\overleftarrow{e},\phi)\propto \Im m[F_1\mathcal{H}]$$
- Longitudinal Target-Spin Asymmetry
  $$\sigma(\overset{\Rightarrow}{P},\phi)-\sigma(\overset{\Leftarrow}{P},\phi)\propto \Im m[F_1\widetilde{\mathcal{H}}]$$
- Longitudinal Double-Spin Asymmetry
  $$\sigma(\overset{\Rightarrow}{P},\vec{e},\phi)-\sigma(\overset{\Leftarrow}{P},\overleftarrow{e},\phi)\propto \Re e[F_1\widetilde{\mathcal{H}}]$$
- Transverse Target-Spin Asymmetry
  $$\sigma(\phi,\phi_S)-\sigma(\phi,\phi_S+\pi)\propto \Im m[F_2\mathcal{H} - F_1\mathcal{E}]$$
- Transverse Double-Spin Asymmetry
  $$\sigma(\vec{e},\phi,\phi_S)-\sigma(\overleftarrow{e},\phi,\phi_S+\pi)\propto \Re e[F_2\mathcal{H} - F_1\mathcal{E}]$$

Compton Form Factors: convolutions of GPDs with hard scattering kernels

$$\mathcal{F}(\xi,t)=\sum_q\int_{-1}^{1}\mathrm{d}x\,C_q^{\mp}(\xi,x)\,F^q(x,\xi,t) \Longrightarrow \text{GPD}$$

DVCS without recoil detector

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

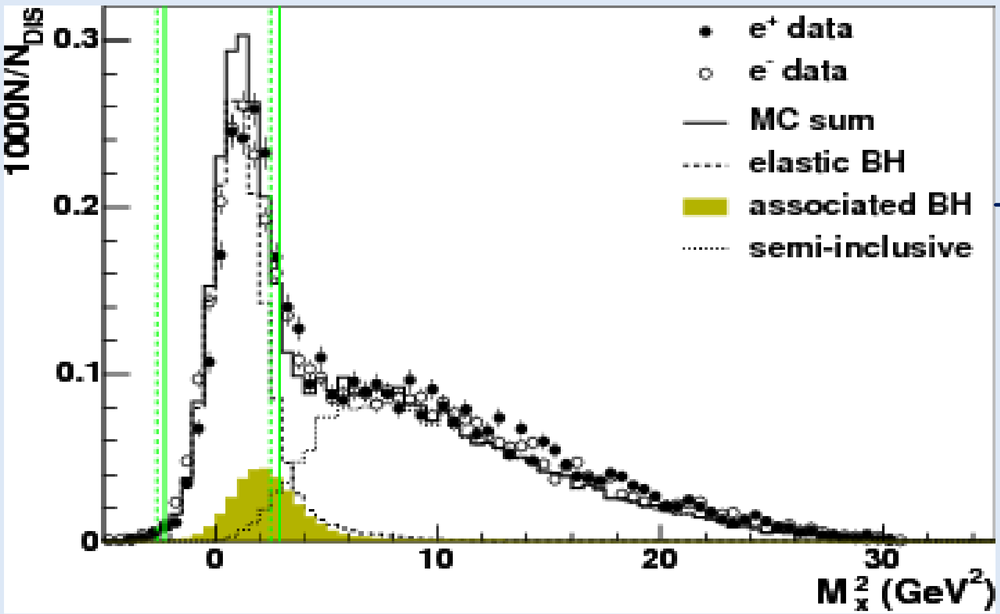
$5 < \Theta_{\gamma^*\gamma} < 45$ mrad

$-t < 0.7\ \mathrm{GeV}^2,\ E_\gamma > 5$ GeV

$0.03 < x_B < 0.35,\ 1 < Q^2 < 10\ \mathrm{GeV}^2$

$W > 3$ GeV, $\nu < 22$ GeV

MC for background and cuts, systematic uncertainty



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

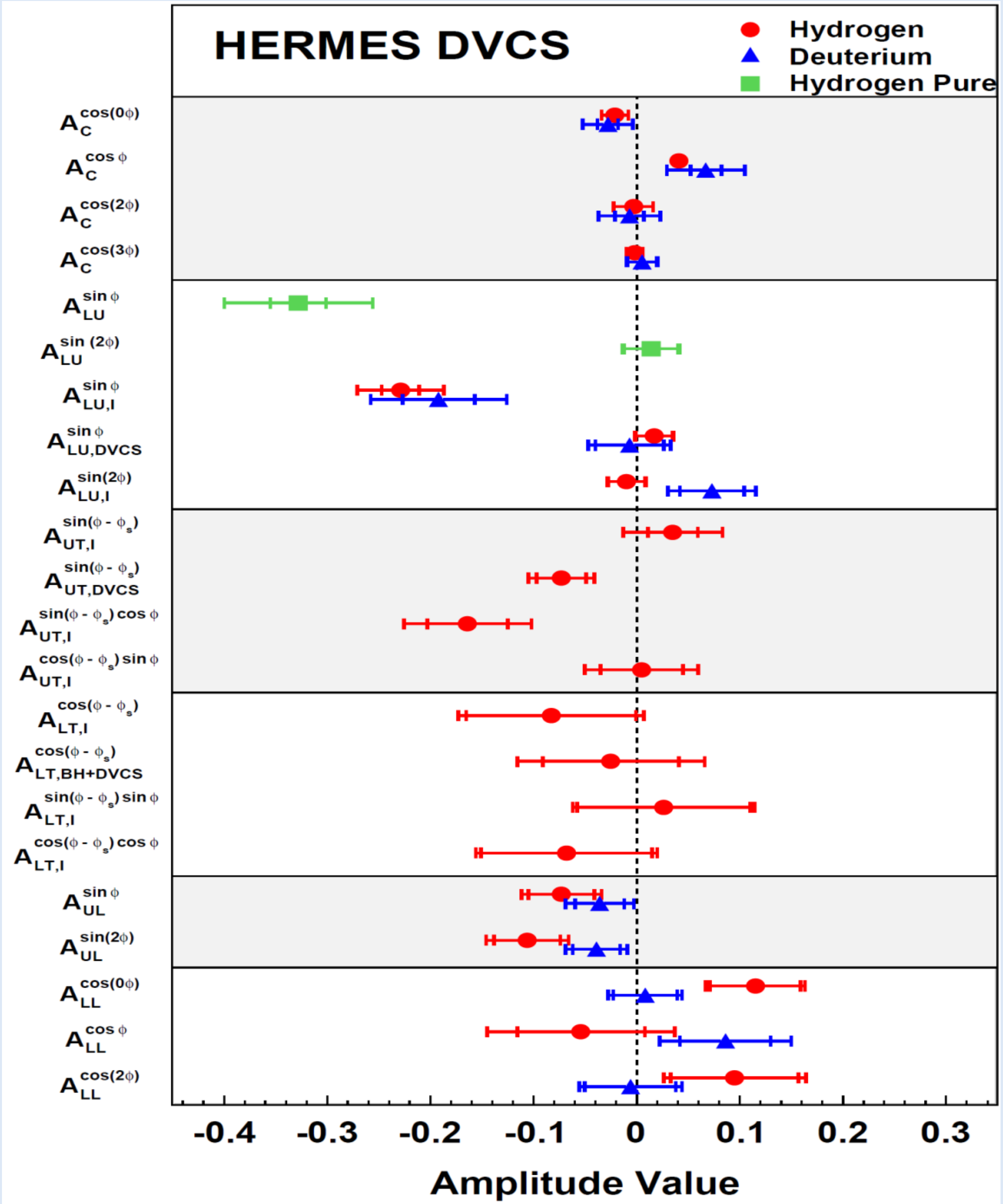
- $e\ p \rightarrow e'\ p\ \gamma$; elastic BH
- $e\ p \rightarrow e'\ \Delta^+\ \gamma$; associated BH
- $e\ p \rightarrow e'\ \pi^0\ X$; semi-inclusive

Correction; π^0 background ($\approx 3\%$)

Associated ($\approx 12\%$) ; part of signal

➡ Exclusive bin ($-(1.5)^2 < M_X^2 < (1.7)^2\ \mathrm{GeV}^2$)

DVCS asymmetries at HERMES



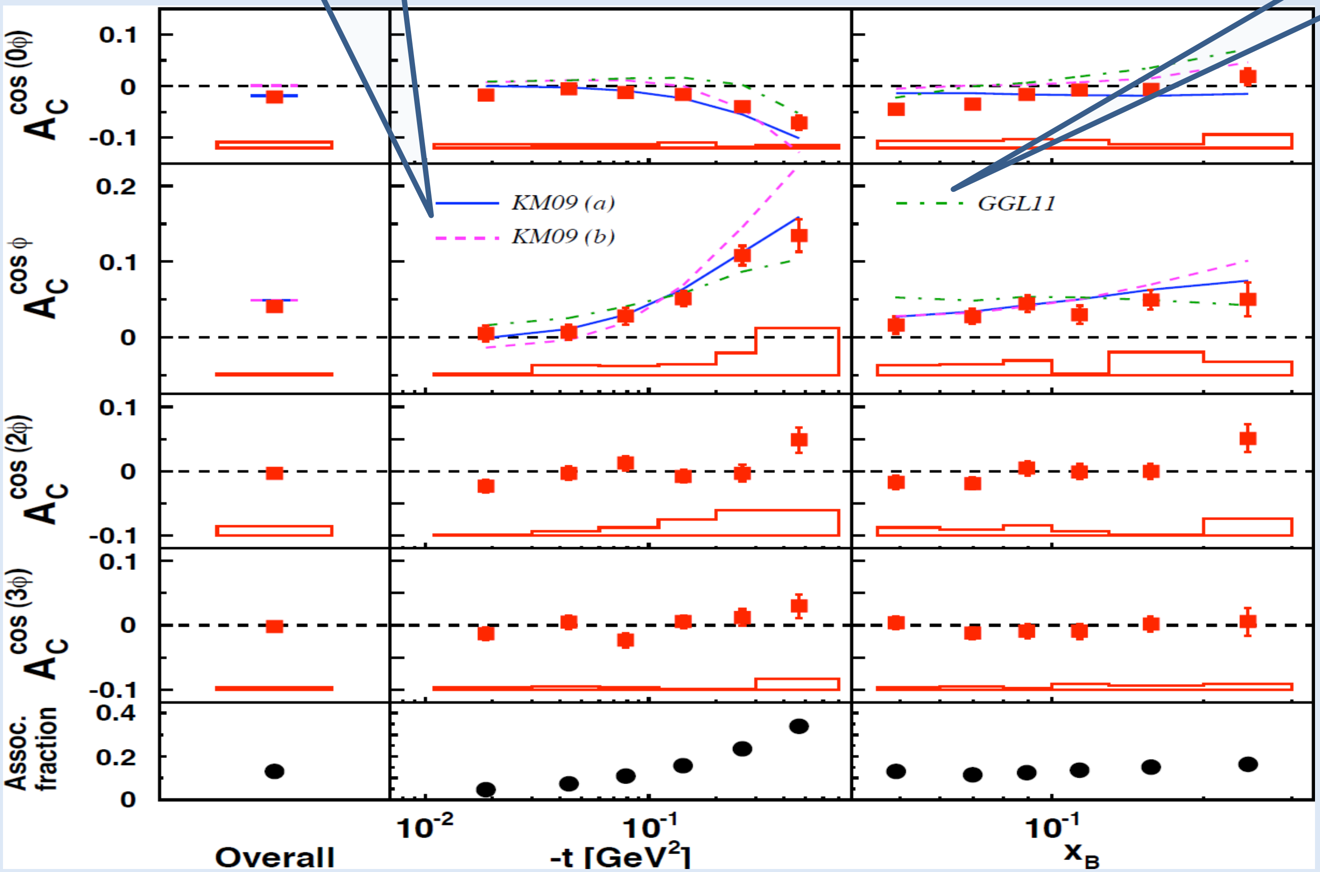
- Beam-charge asymmetry
  GPD H H: PRL 87 (2001) 182001
  PRD 75 (2007) 011103
  JHEP 11 (2009) 083
  JHEP 07 (2012) 032 JHEP 10 (2012) 042
  D: Nucl. Phys. B 829 (2010)1
- Beam-spin asymmetry
  GPD H
- Transverse target-spin asymmetry
  GPD E H: JHEP 06 (2008) 066
- Transverse double-spin asymmetry
  GPD E H: Phys. Lett. B 704 (2011) 15
- Longitudinal target spin asymmetry
  GPD $\tilde{\mathrm{H}}$ H: JHEP 06 (2010) 019
  D: Nucl. Phys. B 842 (2011) 265
- Longitudinal double spin asymmetry
  GPD $\tilde{\mathrm{H}}$

Beam-charge asymmetry A_C

KM09:global fit
Including data from HERA
HERMES and Jlab
K. Kumerički, D. Müller
Nucl. Phys. **B 84** (2010) 1

JHEP 07 (2012) 032, arXiv:1203.6287

GGL11:model calculation
G. Goldstein, S. Liuti,
J. Hernandez
Phys. Rev. **D 84** 034007 (2010)



$$\propto -A_C^{\cos(\phi)}$$

$$\propto \Re e\,[F_1\mathcal{H}]$$

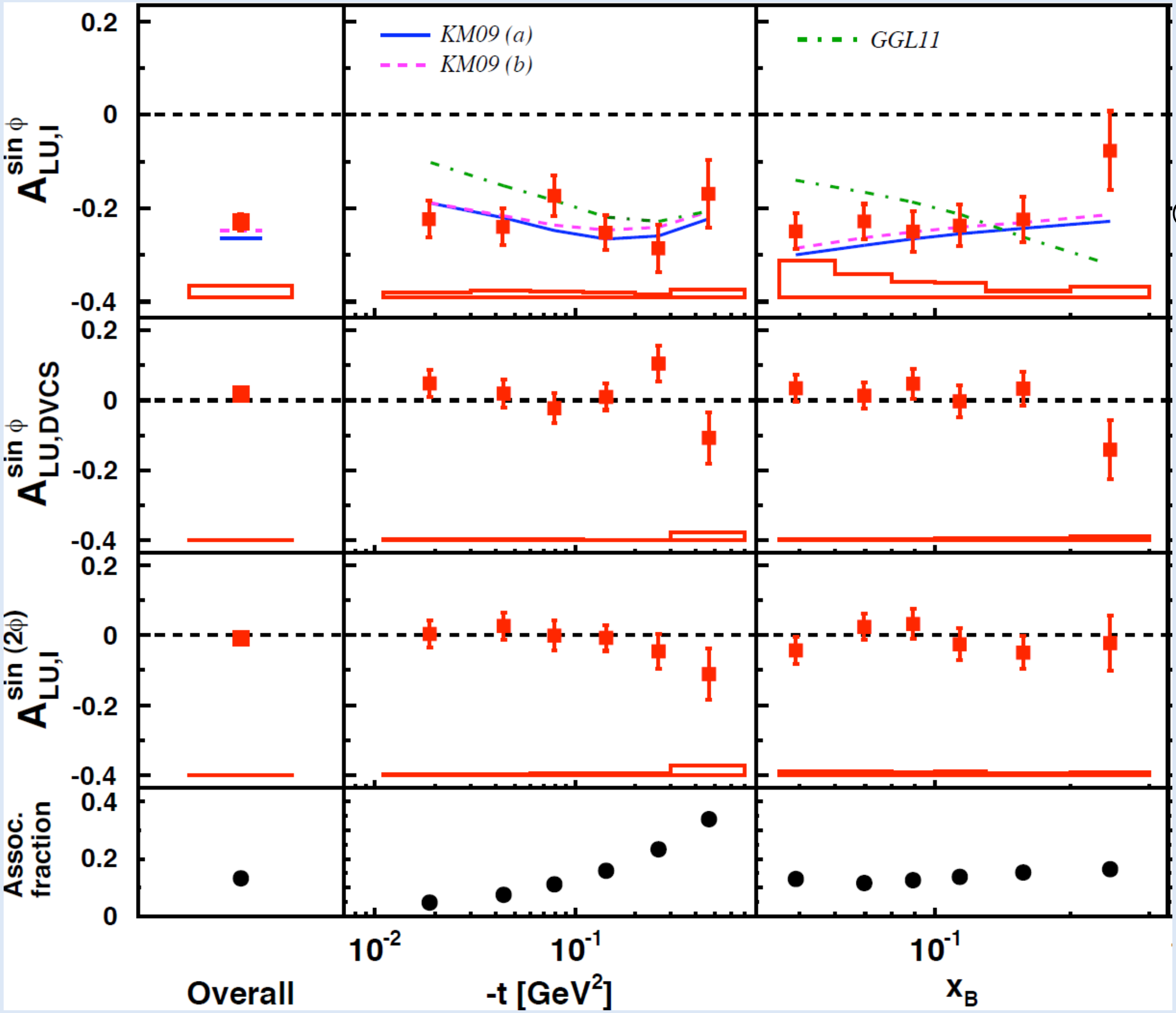
Higher twist

Gluon leading twist

Fractions of associated process from MC

Beam-charge-separated asymmetries $A_{LU,I}$ & $A_{LU,DVCS}$

JHEP 07 (2012) 032, arXiv:1203.6287



$\propto \Im m\,[F_1\mathcal{H}]$

$\propto \Im m\,[\mathcal{H}\mathcal{H}^* + \tilde{\mathcal{H}}\tilde{\mathcal{H}}^*]$

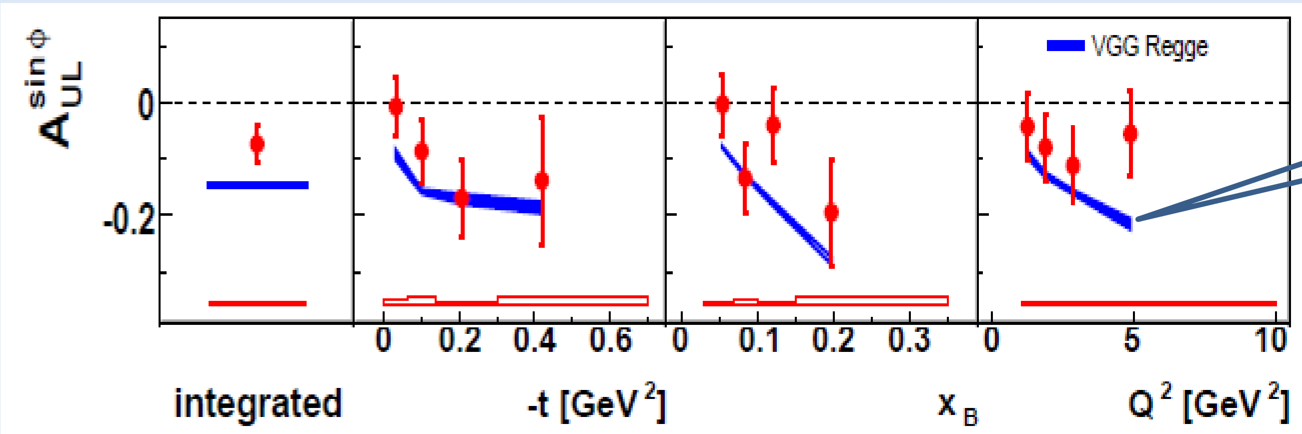
Higher twist

Fractions of associated process from MC

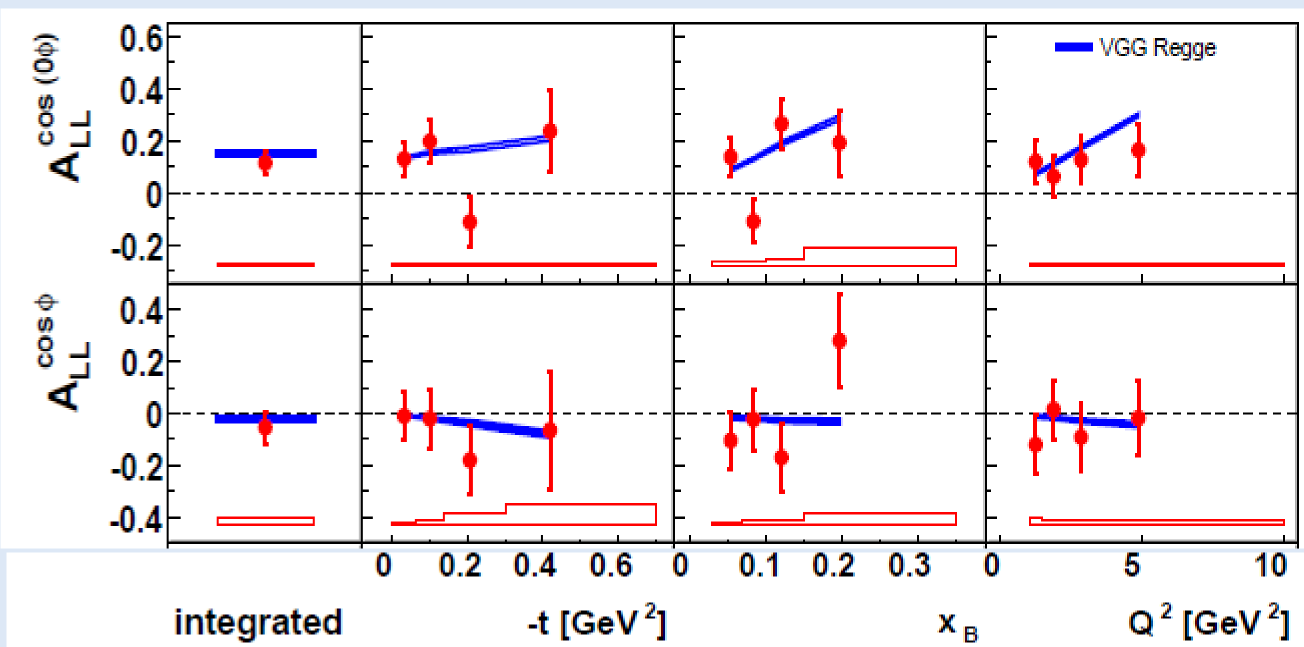
Longitudinal single- and double-spin asymmetries $A_{U(L)L}$

JHEP 06 (2010) 019, arXiv:1004.0177

VGG: model calculation
M. Vanderhaeghen, P. Guichon, M. Guidal
Phys. Rev. **D60** (1999) 0940177
Prog. Nucl. Phys. **47** (2001) 401



$\propto \Im m\,[F_1 \tilde{\mathcal{H}}]$

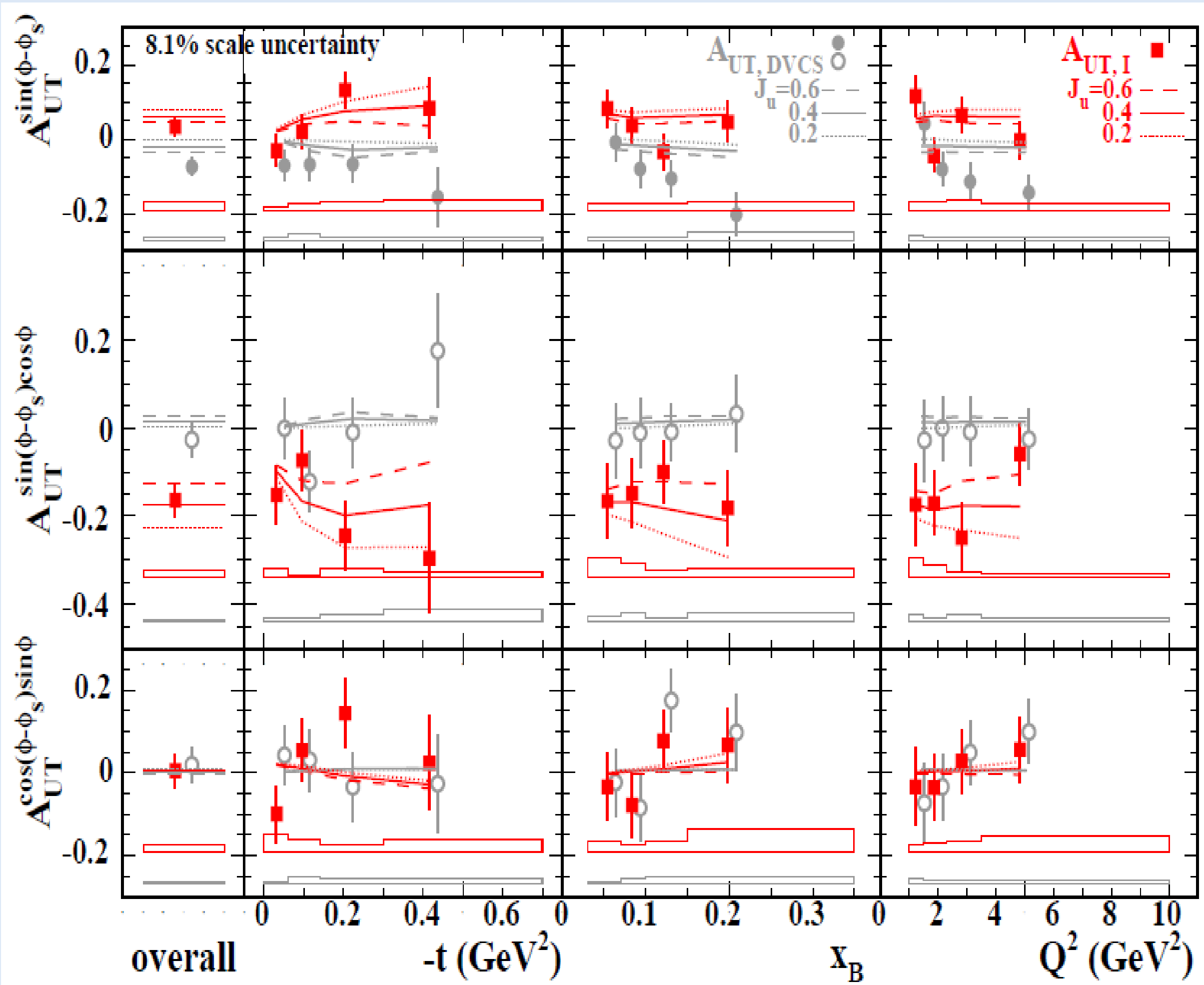


Relatively large BH contribution to these asymmetries

$\propto \Re e\,[F_1 \tilde{\mathcal{H}}]$

DVCS: Transverse target-spin asymmetry A_{UT}

Sensitive to GPD E   JHEP 06 (2008) 066, arXiv:0802.2499



Sensitive to J_u

$$\propto \Im m\,[F_2\mathcal{H} - F_1\mathcal{E}]$$

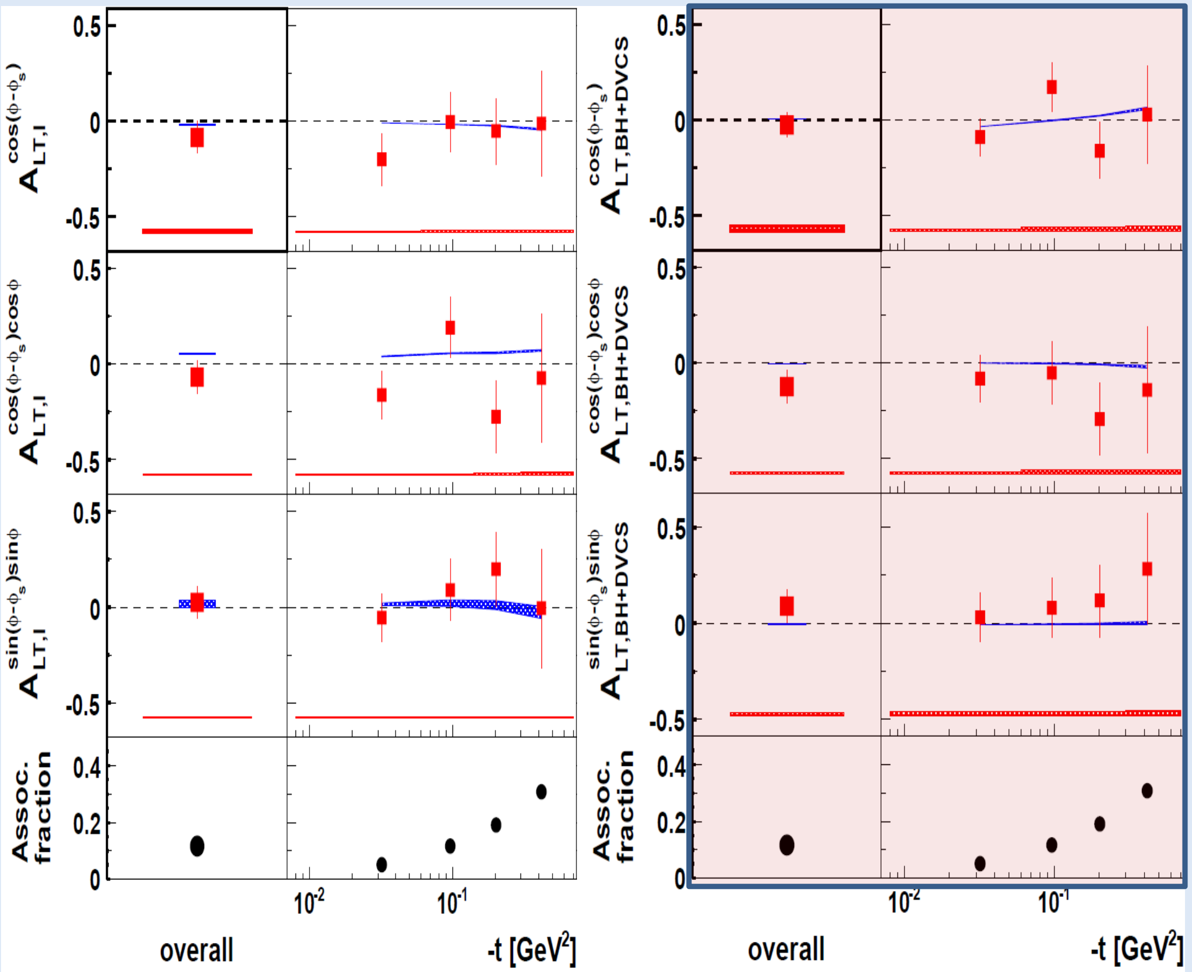
Not sensitive to J_u

$$\propto \Im m\,[F_2\tilde{\mathcal{H}} - (F_1 + \xi F_2)\tilde{\mathcal{E}}]$$

Model: VGG with variation of J_u, while J_d=0

DVCS: Transverse double-spin asymmetry A_{LT}

Phys Lett. B704 (2011) 15, arXiv:1106.2990



Full set of data: e+/e- beams; both helicities; target polarization - positive/negative.

$\propto A_{LT}^{\cos(\phi-\phi_S)\cos(\phi)}$

$$\Re e\left[F_2\tilde{\mathcal{H}} - (F_1+\xi F_2)\tilde{\mathcal{E}}\right]$$

$$\propto \Re e\left[\mathcal{H}\mathcal{E}^* - \mathcal{E}\mathcal{H}^* - \xi\left(\tilde{\mathcal{H}}\tilde{\mathcal{E}}^* - \tilde{\mathcal{E}}\tilde{\mathcal{H}}^*\right)\right]$$

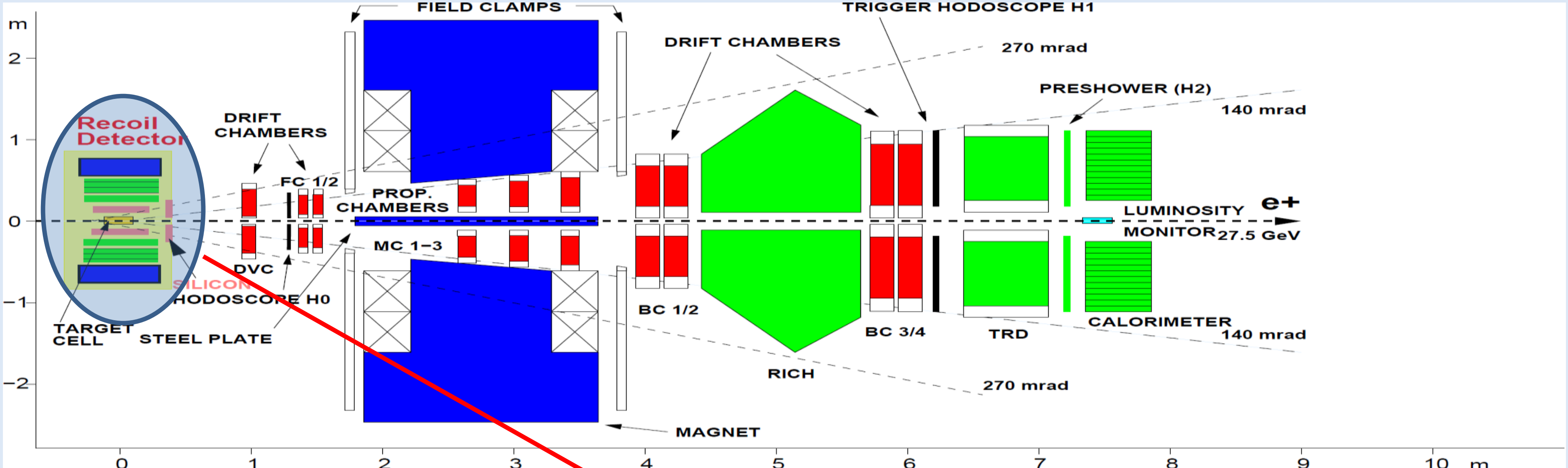
$$\Re e\left[F_2\mathcal{H} - F_1\mathcal{E}\right]$$

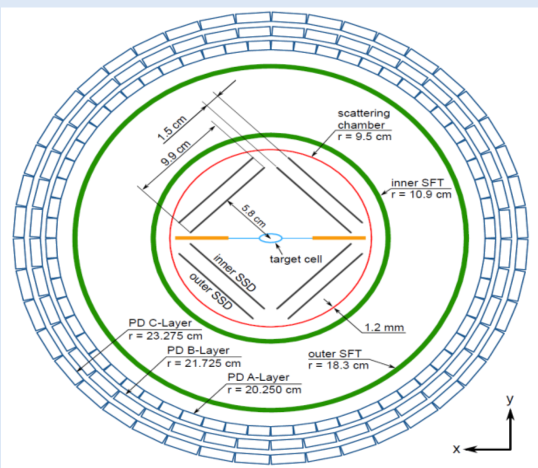
$$\propto \Re e\left[-\tilde{\mathcal{H}}\mathcal{E}^* - \tilde{\mathcal{H}}^*\mathcal{E} + \xi\left(\mathcal{H}\tilde{\mathcal{E}}^* + \tilde{\mathcal{E}}\mathcal{H}^*\right)\right]$$

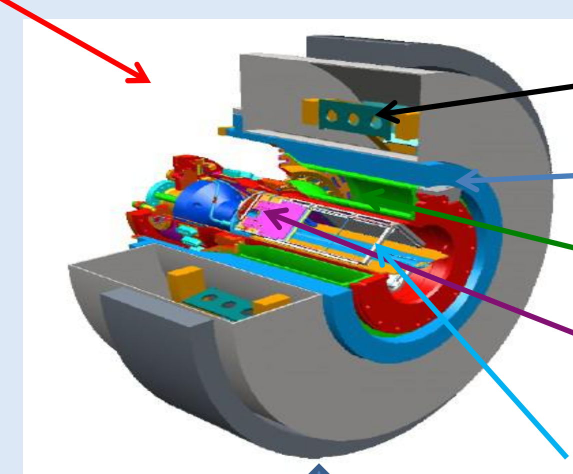
Sensitive to both GPDs entering the Ji sum rule

Consistent with zero, cancellations between E and H
Sensitivity to J_u is suppressed by kinematic factors

DVCS with recoil detector







1 T SC Solenoid

Photon Detector

Scintillating-Fiber Tracker

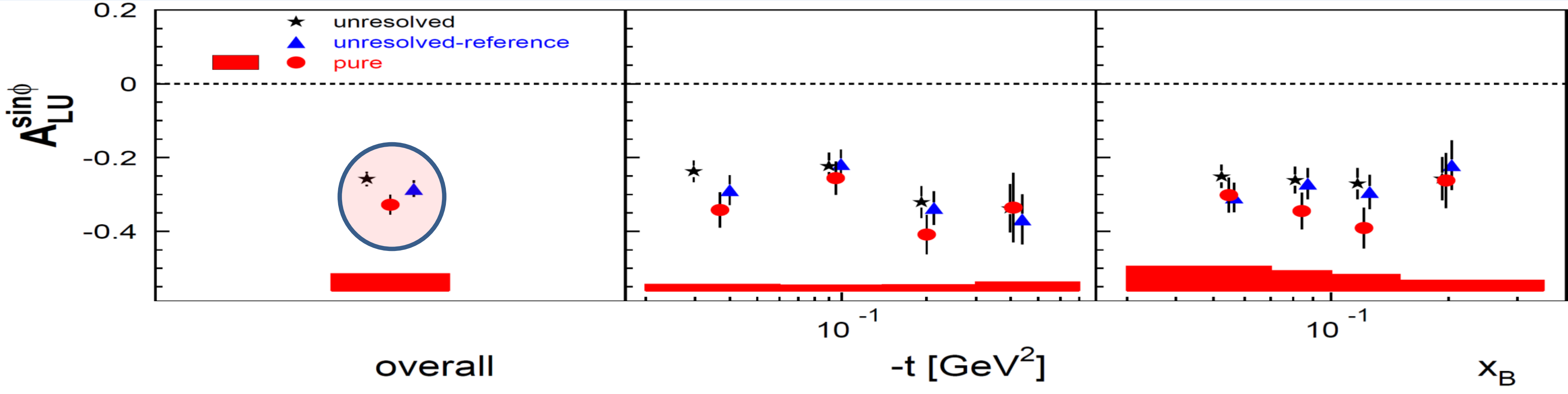
Silicon-Strip Detector

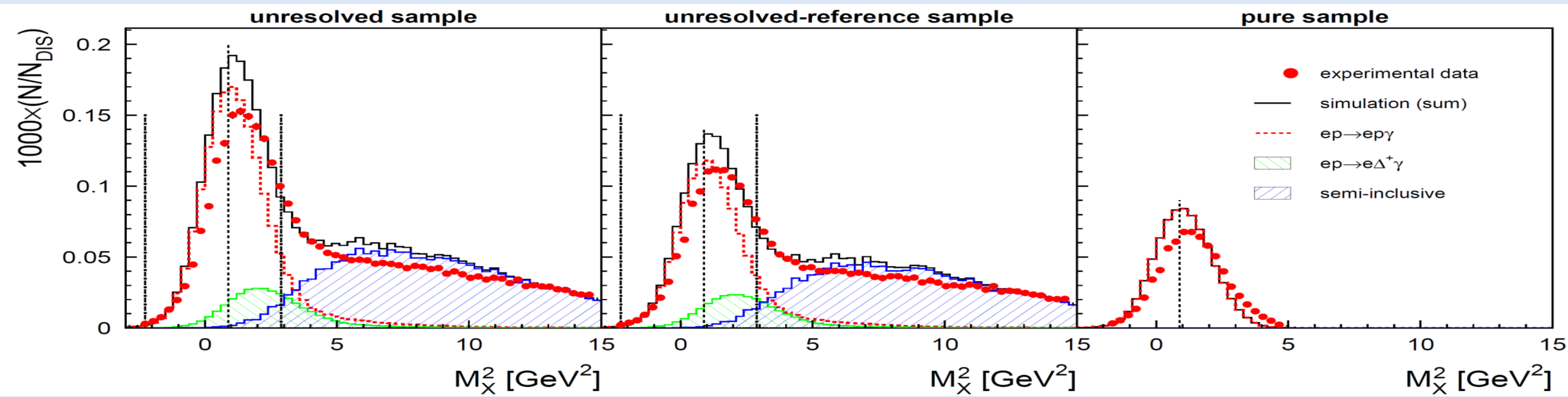
Unpolarized H and D targets

Recoil Detector to tag exclusivity

A. Airapetian et al., JINST B (2013) P05012

Pure elastic DVCS

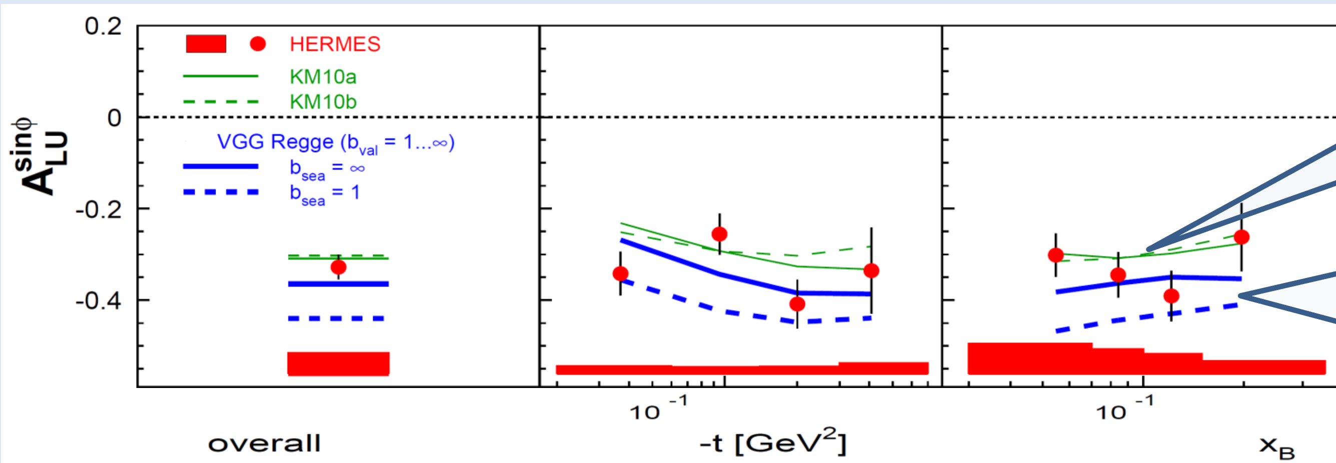




- Practically no contamination of associated process.
- Indication that leading amplitude for pure elastic process is larger (0.054 ± 0.016) than for unresolved signal (elastic+associated).

Pure elastic DVCS

JHEP 10 (2012) 042, arXiv:1206.5683



KM10:global fit
Including data from HERA
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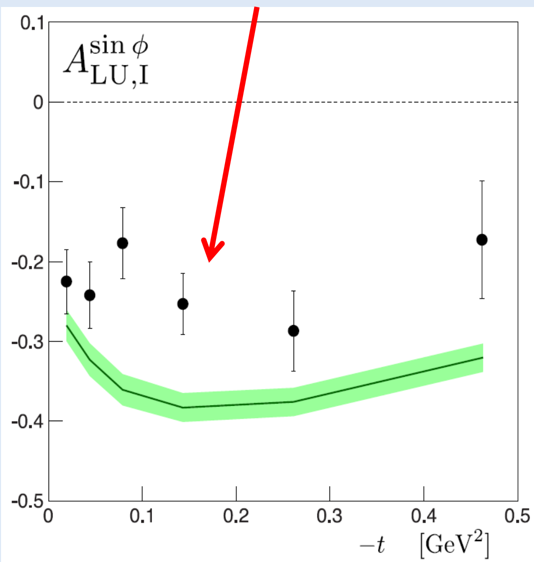
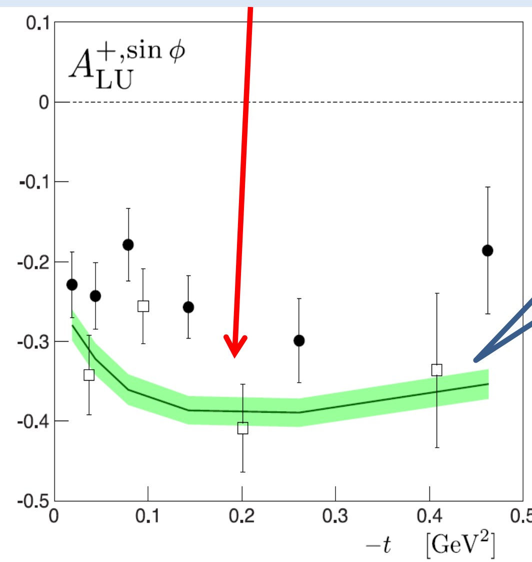
JHEP 07 (2012) 032



JHEP 10 (2012) 042

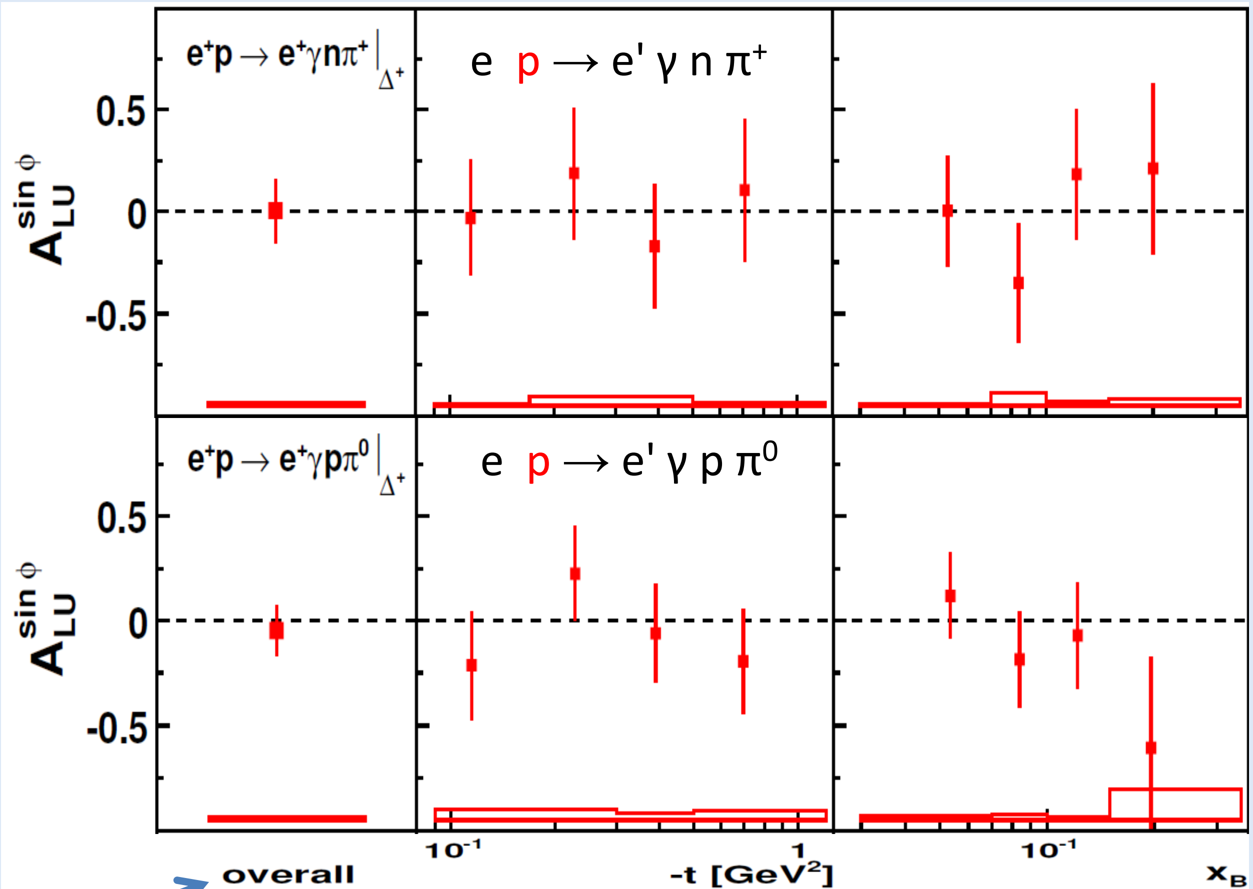


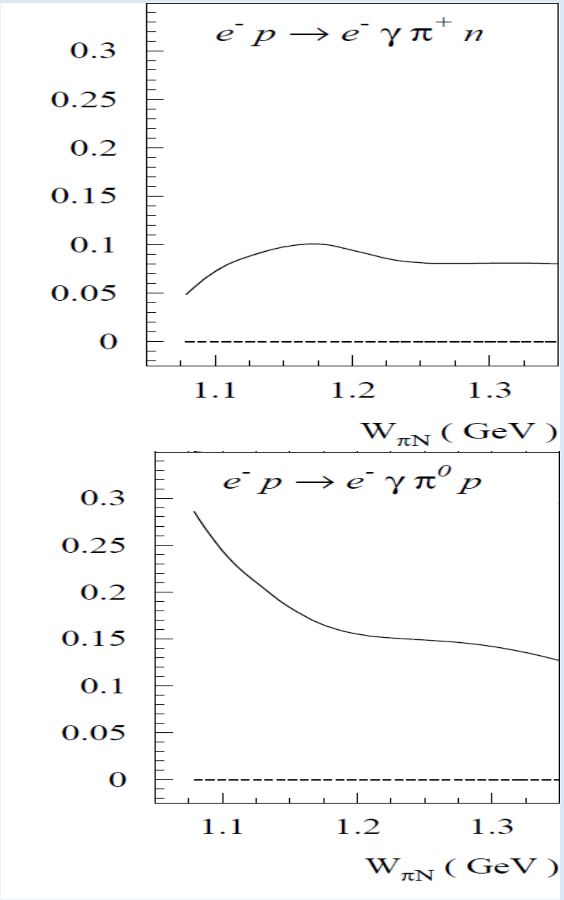
KMS: model calculation
GPDs are extracted from HEMP.
P. Kroll, H Moutarde, F. Sabatie,
Eur. Phys. J. C **73** (2001) 2278

The leading amplitude for pure elastic process is well described by recent fits to previously published data and by KMS model fit to exclusive meson data.

Beam-spin asymmetry in „associated“ DVCS : $ep \rightarrow e\gamma\Delta^+$

JHEP 01 (2014) 077, arXiv:1206.5683

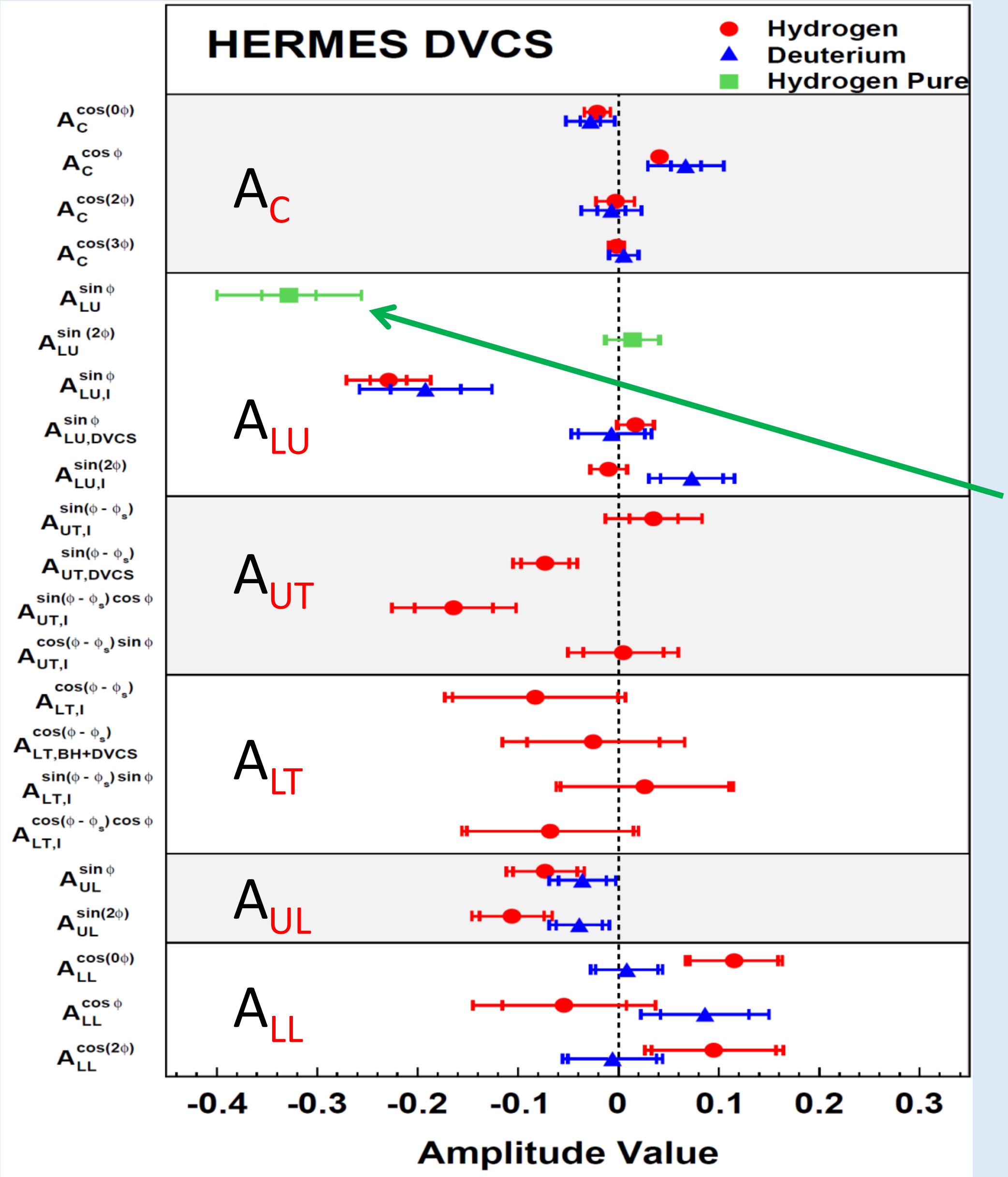




- Associated DVCS/BH: (77 ± 2% for $n\pi^+$ & 85 ± 1% for $p\pi^0$)
- Correction: π^0 SIDIS background: (23 ± 3% for $p\pi^0$ & 11 ± 1% for $n\pi^+$ channel);
- Elastic: (0.2 ± 0.1% for $n\pi^+$ & 4.6 ± 0.1% for $p\pi^0$)

P. Guichon et al., PRD 68 (2003) 034018

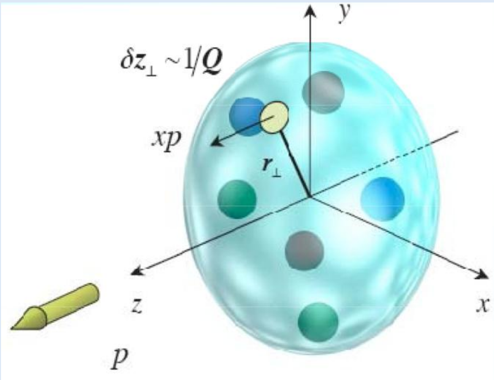
Summary

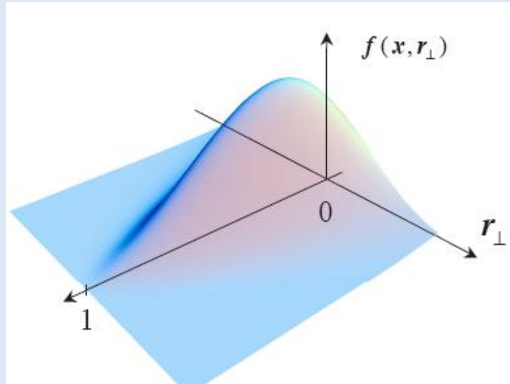


- HERMES measured “full set” of DVCS-related asymmetries on proton and nuclear targets.
- Data with recoil-proton detection allows clean separation of DVCS/BH contribution in a signal.
- Indication of larger amplitude for pure sample.
- Associated DVCS results consistent with zero and also with model prediction.

Backup Slides

Deeply virtual Compton scattering & GPDs





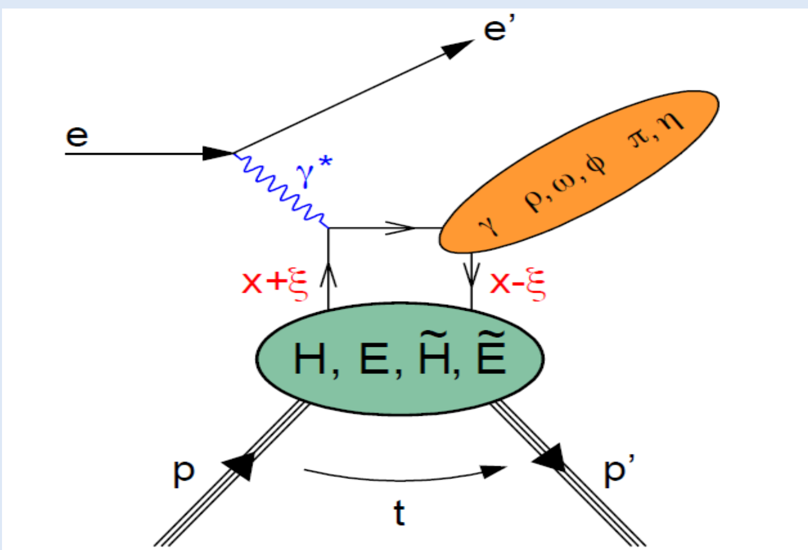
Ji sum rule ⟹ access OAM

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

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_q$$

Correlated information about longitudinal momentum xp and transverse spatial position $r_\perp$

H^q and *E^q* *:* quark Generalized Parton Distributions (GPDs)



Spin-½ target: 4 chiral-even leading-twist quark GPDs $H, E, \widetilde{H}, \widetilde{E}$

Final state sensitive to different GPDs

DVCS (γ) $H, E, \widetilde{H}, \widetilde{E}$

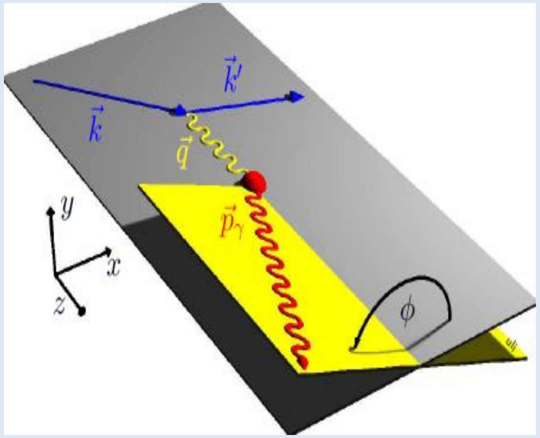
Vector mesons (ρ, ω, ϕ) $H, E,$

Pseudoscalar mesons (π,η) $\widetilde{H}, \widetilde{E}$

Azimuthal dependences in DVCS

Unpolarized proton target

$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} \propto \left(|\tau_{BH}|^2 + |\tau_{DVCS}|^2 + I \right)$$



$$|\tau_{BH}|^2 = \frac{K_{BH}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \sum_{n=0}^{2} C_n^{BH} \cos(n\phi)$$

$$|\tau_{DVCS}|^2 = K_{DVCS} \left\{ \sum_{n=0}^{2} C_n^{DVCS} \cos(n\phi) + \sum_{n=1}^{2} S_n^{DVCS} \sin(n\phi) \right\}$$

$$I = -\frac{e_l K_I}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left\{ \sum_{n=0}^{3} C_n^{I} \cos(n\phi) + \sum_{n=1}^{3} S_n^{I} \sin(n\phi) \right\}$$

Fourier coefficients are related to certain linear or bi-linear combinations of Compton Form Factors (CFFs):

$$\mathcal{F}(\xi,t) = \sum_q \int_{-1}^{1} dx C_q^{\mp}(\xi,x) F^q(x,\xi,t) \Rightarrow \text{GPD}$$

Azimuthal asymmetries in DVCS off unpolarized targets

$$\sigma_{LU}(\phi, P_l, e_l) = \sigma_{UU}[1 + e_l A_C(\phi) + e_l P_l A_{LU}^{I}(\phi) + P_l A_{LU}^{DVCS}(\phi)]$$

A_{LU}: L → beam, U → target

Charge-difference beam-helicity asymmetry:

$$A_{LU}^{I}(\phi) = \frac{(\sigma^{+\rightarrow} - \sigma^{+\leftarrow}) - (\sigma^{-\rightarrow} - \sigma^{-\leftarrow})}{(\sigma^{+\rightarrow} + \sigma^{+\leftarrow}) + (\sigma^{-\rightarrow} + \sigma^{-\leftarrow})} = -\frac{1}{D(\phi)}\frac{x_B}{y}\sum_{n=1}^{2} s_n^I \sin(n\phi)$$

Charge-averaged beam-helicity asymmetry:

$$A_{LU}^{DVCS}(\phi) = \frac{(\sigma^{+\rightarrow} - \sigma^{+\leftarrow}) + (\sigma^{-\rightarrow} - \sigma^{-\leftarrow})}{(\sigma^{+\rightarrow} + \sigma^{+\leftarrow}) + (\sigma^{-\rightarrow} + \sigma^{-\leftarrow})} = \frac{1}{D(\phi)} \cdot \frac{x_B^2 t \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}{Q^2} s_1^{DVCS} \sin(\phi)$$

Beam-Charge asymmetry:

$$A_C(\phi) = \frac{(\sigma^{+\rightarrow} + \sigma^{+\leftarrow}) - (\sigma^{-\rightarrow} + \sigma^{-\leftarrow})}{(\sigma^{+\rightarrow} + \sigma^{+\leftarrow}) + (\sigma^{-\rightarrow} + \sigma^{-\leftarrow})} = -\frac{1}{D(\phi)}\frac{x_B}{y}\sum_{n=0}^{3} c_n^I \cos(n\phi)$$

- Measurement with both beam helicity and both beam charges
  ⇒ separate contributions from DVCS and Interference term
- This separation is impossible in measurements of single-charge beam-helicity asymmetry $A_{LU}(\phi) = (\sigma^{\rightarrow} - \sigma^{\leftarrow})/(\sigma^{\rightarrow} + \sigma^{\leftarrow})$

Asymmetries on longitudinally polarized targets

Single-charge target-spin asymmetry (Hydrogen/Deuterium):

$$A_{UL}(\phi, e_l) = \frac{[\sigma^{\rightarrow\Rightarrow}(\phi, e_l) + \sigma^{\leftarrow\Rightarrow}(\phi, e_l)] - [\sigma^{\rightarrow\Leftarrow}(\phi, e_l) + \sigma^{\leftarrow\Leftarrow}(\phi, e_l)]}{[\sigma^{\rightarrow\Rightarrow}(\phi, e_l) + \sigma^{\leftarrow\Rightarrow}(\phi, e_l)] + [\sigma^{\rightarrow\Leftarrow}(\phi, e_l) + \sigma^{\leftarrow\Leftarrow}(\phi, e_l)]}$$

Single-charge double-spin asymmetry (Hydrogen/Deuterium):

$$A_{LL}(\phi, e_l) = \frac{[\sigma^{\rightarrow\Rightarrow}(\phi, e_l) + \sigma^{\leftarrow\Leftarrow}(\phi, e_l)] - [\sigma^{\leftarrow\Rightarrow}(\phi, e_l) + \sigma^{\rightarrow\Leftarrow}(\phi, e_l)]}{[\sigma^{\rightarrow\Rightarrow}(\phi, e_l) + \sigma^{\leftarrow\Leftarrow}(\phi, e_l)] + [\sigma^{\leftarrow\Rightarrow}(\phi, e_l) + \sigma^{\rightarrow\Leftarrow}(\phi, e_l)]}$$

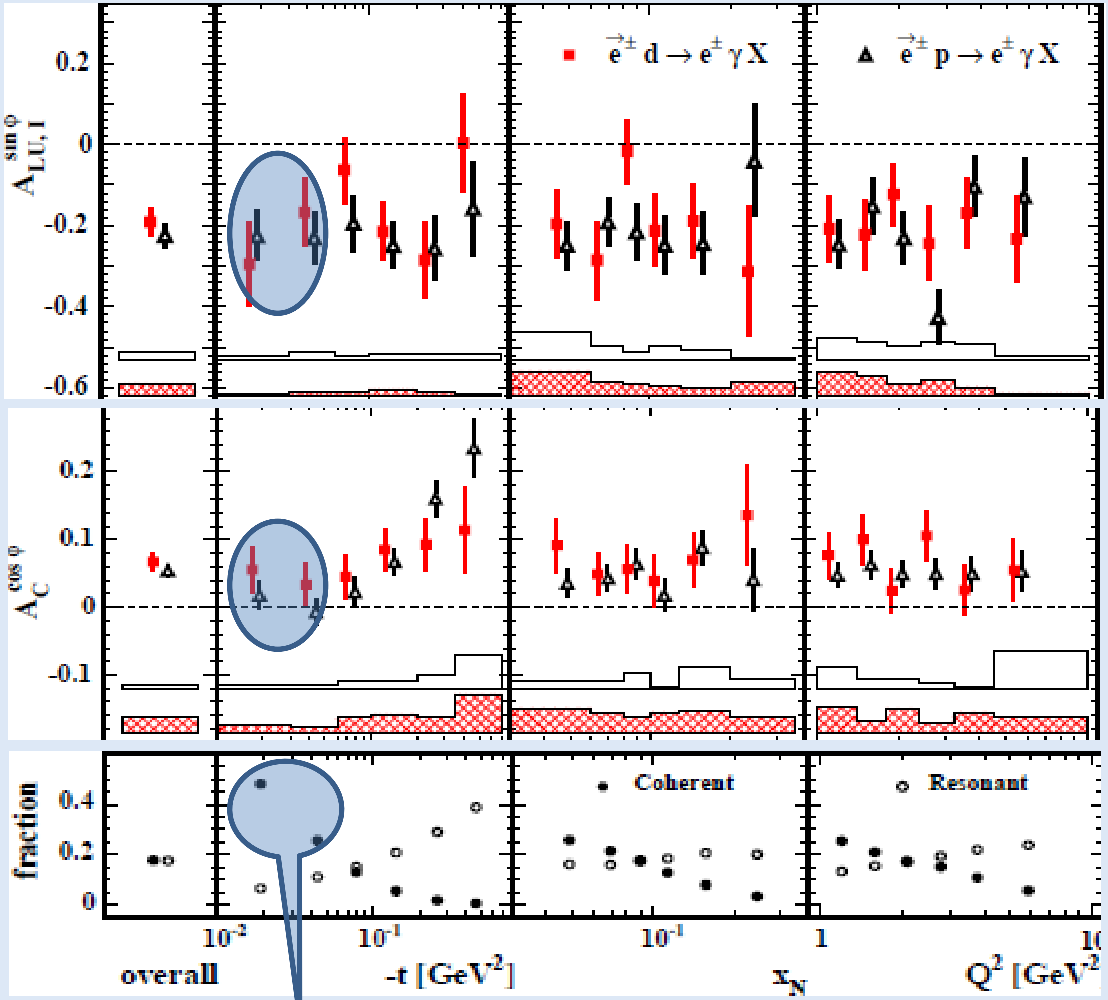
Single-charge beam-helicity asymmetry (Deuterium):

$$A_{L\overset{\Rightarrow}{\Leftarrow}}(\phi, e_l) = \frac{[\sigma^{\rightarrow\Rightarrow}(\phi, e_l) + \sigma^{\rightarrow\Leftarrow}(\phi, e_l)] - [\sigma^{\leftarrow\Rightarrow}(\phi, e_l) + \sigma^{\leftarrow\Leftarrow}(\phi, e_l)]}{[\sigma^{\rightarrow\Rightarrow}(\phi, e_l) + \sigma^{\rightarrow\Leftarrow}(\phi, e_l)] + [\sigma^{\leftarrow\Rightarrow}(\phi, e_l) + \sigma^{\leftarrow\Leftarrow}(\phi, e_l)]}$$

Single-helicity (⟵) beam-charge asymmetry (Deuterium):

$$A_{C\overset{\Rightarrow}{\Leftarrow}}(\phi) = \frac{[\sigma^{+\Rightarrow}(\phi) + \sigma^{+\Leftarrow}(\phi)] - [\sigma^{-\Rightarrow}(\phi) + \sigma^{-\Leftarrow}(\phi)]}{[\sigma^{+\Rightarrow}(\phi) + \sigma^{+\Leftarrow}(\phi)] + [\sigma^{-\Rightarrow}(\phi) + \sigma^{-\Leftarrow}(\phi)]}$$

Deuterium (Hydrogen): unpolarized target



JHEP 11 (2009) 083

Nucl. Phys. B 829 (2010) 1

$\Im m(\mathcal{H})$

$\Im m(\mathcal{H}_1)$

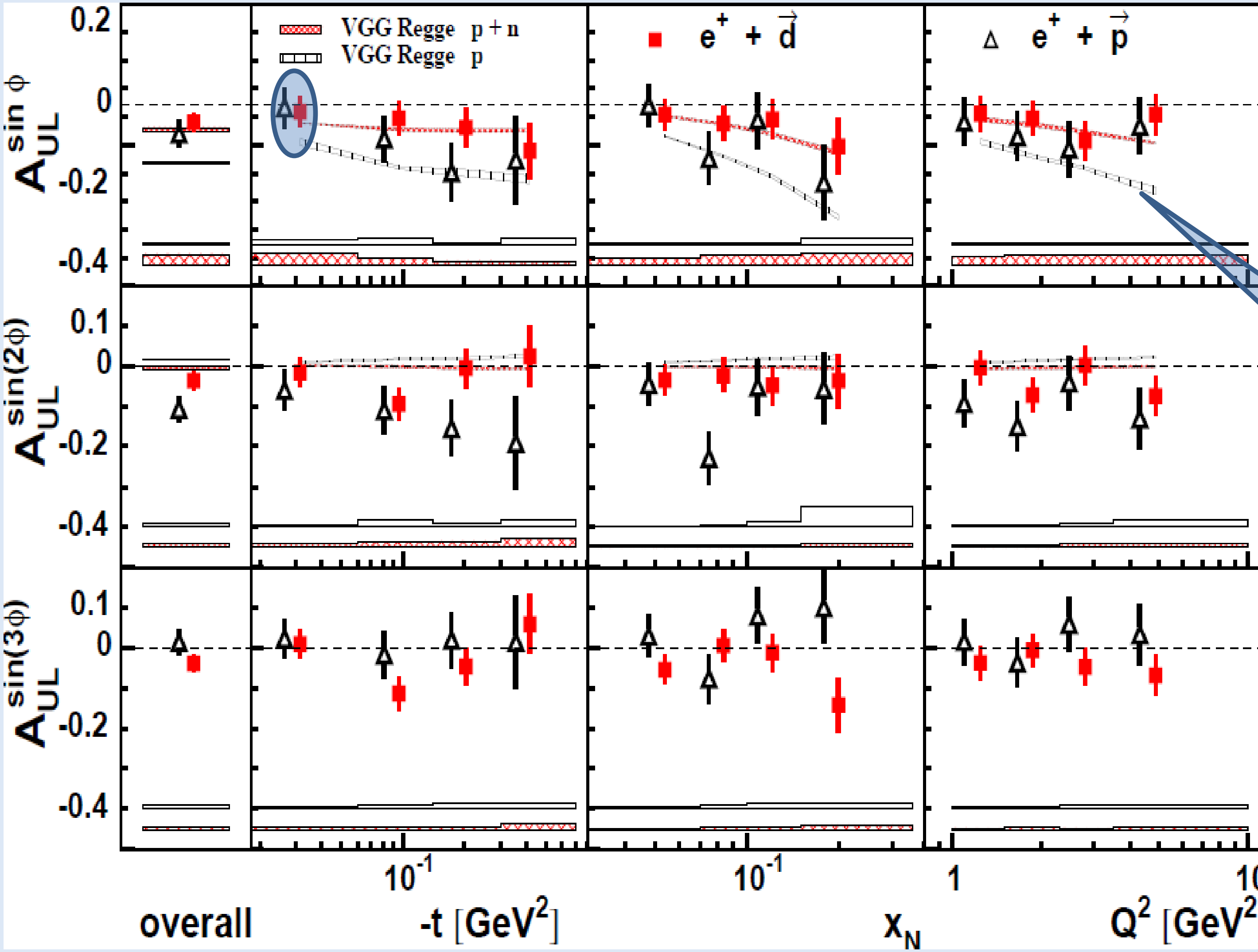
$\Re e(\mathcal{H})$

$\Re e(\mathcal{H}_1)$

- $A_{LU,I,Coh}^{\sin\phi}$ -0.29 ± 0.18 (stat) ± 0.03 (syst)
- $A_{C,Coh}^{\cos\phi}$ 0.11 ± 0.07 (stat) ± 0.03 (syst)

Deuterium (Hydrogen): target-spin asymmetry

JHEP 11 (2009) 083 **Nucl. Phys. B 842 (2011) 265**



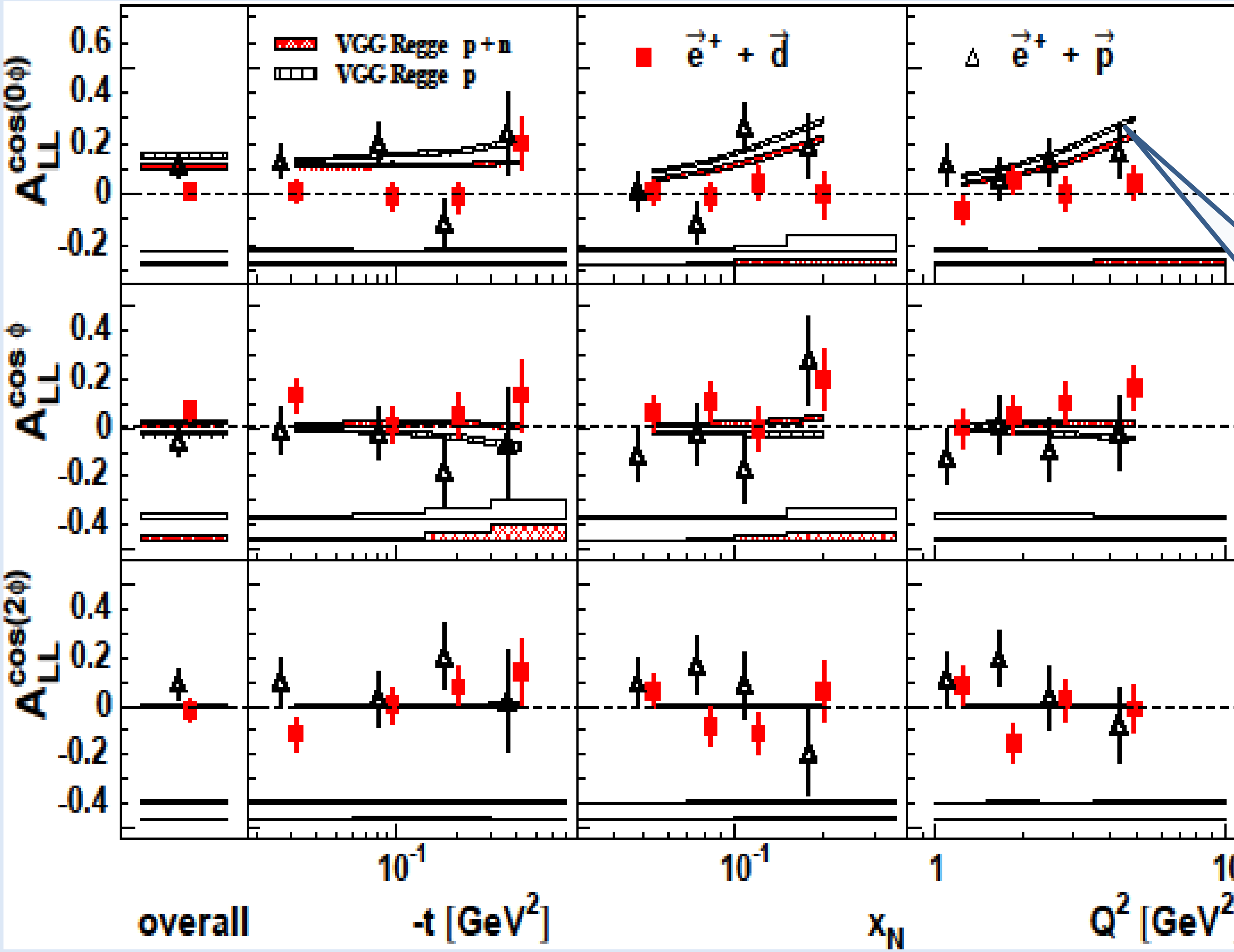
$\Im m(\tilde{H})$

$\Im m(\tilde{H}_1)$

VGG:
Phys. Rev. **D60** (1999) 0940177
&
Prog. Nucl. Phys. **47** (2001) 401

Deuterium (Hydrogen): double-spin asymmetry

JHEP 11 (2009) 083 **Nucl. Phys. B 842 (2011) 265**

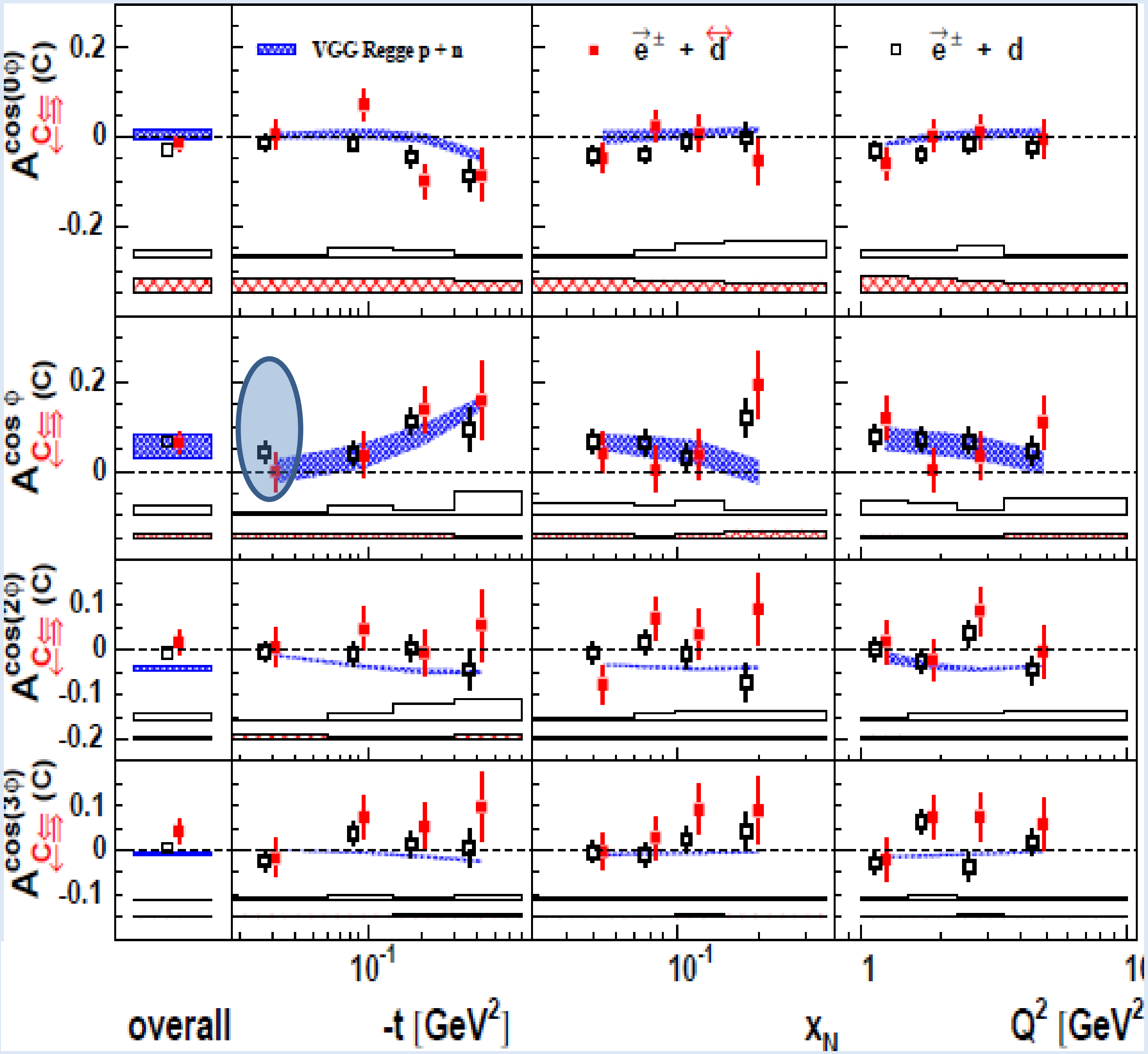


$\propto$ (BH)

VGG:
Phys. Rev. **D60** (1999) 0940177
&
Prog. Nucl. Phys. **47** (2001) 401

A_C ($A_{C\leftrightarrow}$) on (un)polarized Deuterium

Nucl. Phys. B 842 (2011) 265



For coherent scattering

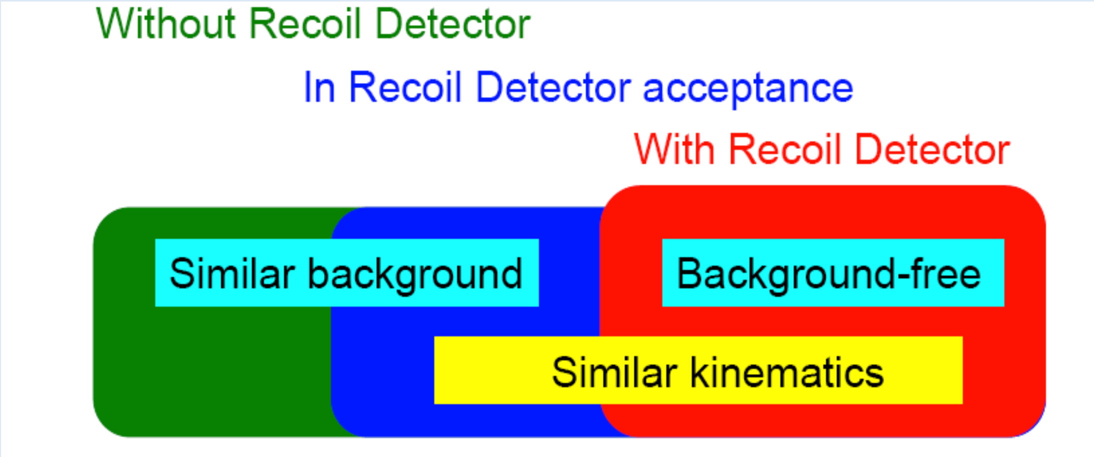
$$\Re e(\mathcal{H}_1)$$

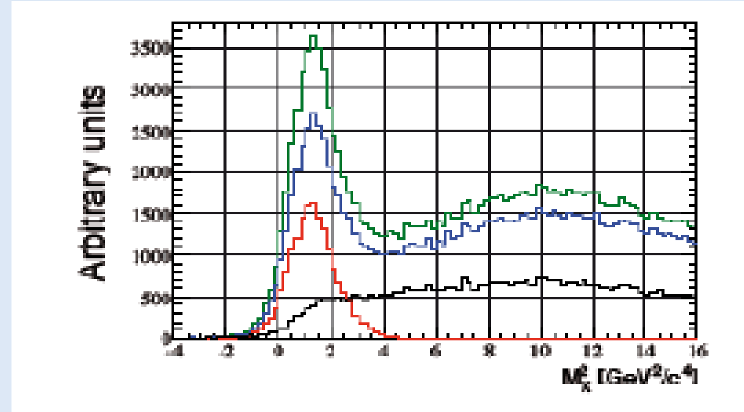
$$\Re e(\mathcal{H}_1 - {}^1\!/\!_3\,\mathcal{H}_5)$$

$$\Im m(H_5)$$

A_{LZZ} sin φ amplitude:
0.074 ± 0.196 ± 0.022
(-*t* < 0.06 GeV2, 40% coherent)

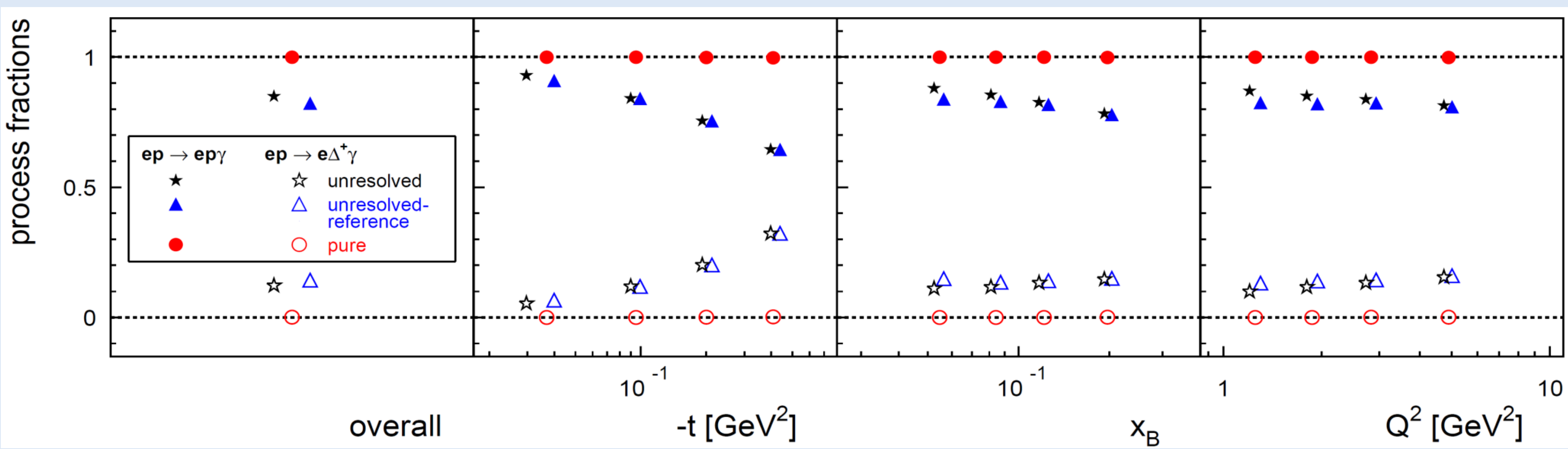
DVCS with recoil detector





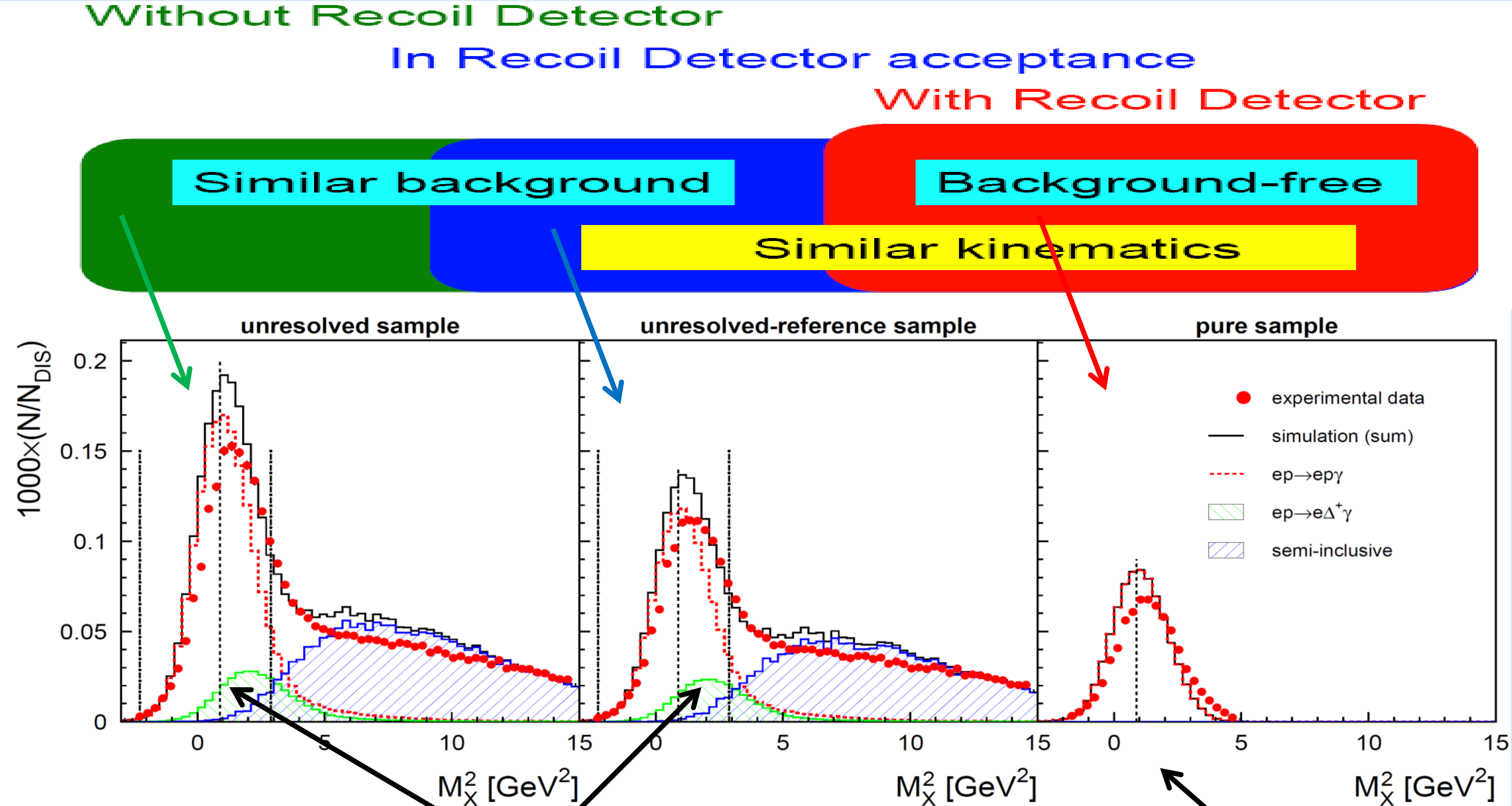
- No requirement for Recoil
- Charged recoil track in acceptance
- Kinematic fit probability > 1 %
- Kinematic fit probability < 1 %

Kinematic event fitting technique: all 3 particles
In the final state detected should satisfy
4-constraints on energy-momentum conservation



Hrachya Marukyan, 24.10.2014, SPIN14, Beijing, China

Missing mass distribution: exclusivity with RD



Associated processes (e p → e' γ Δ⁺)

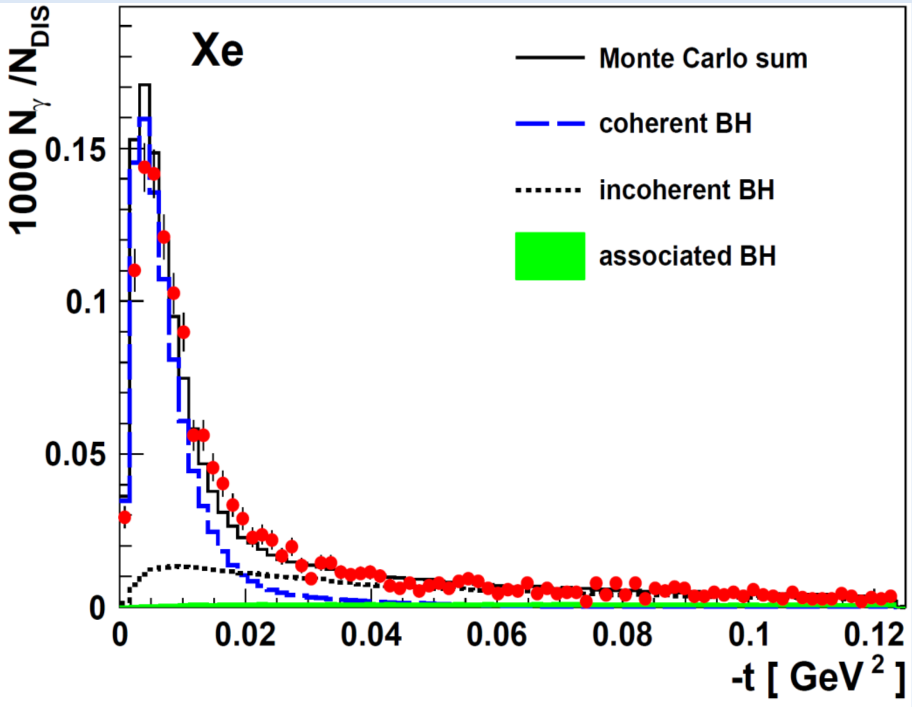
Pure e p → e' γ p

$$\text{Missing mass: } M_X^2 = (q + P - q')^2 = M^2 + 2M(\nu - E_\gamma + t)$$

Beam-charge /spin asymmetries on heavier nuclei

Phys. Rev. C 81 (2010) 035202

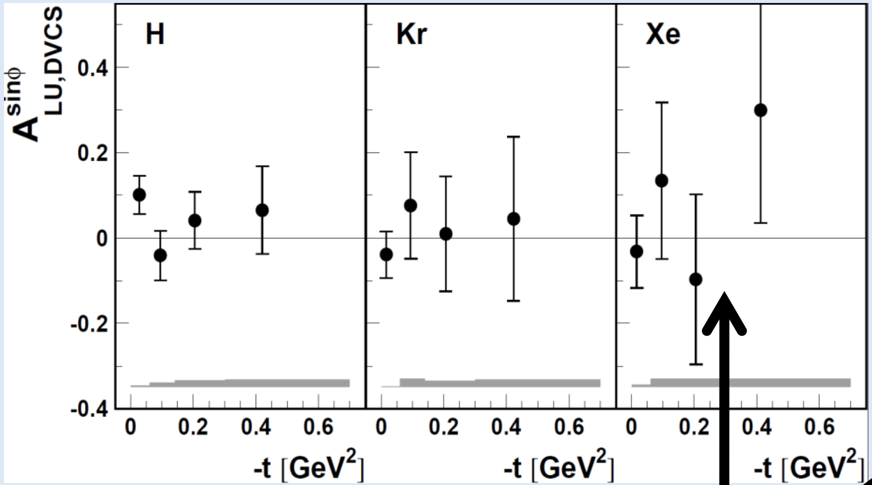
Target	Spin	L (pb^{-1})
^{1}H	1/2	227
He	0	32
N	1	51
Ne	0	86
Kr	0	77
Xe	0, 1/2, 3/2	47



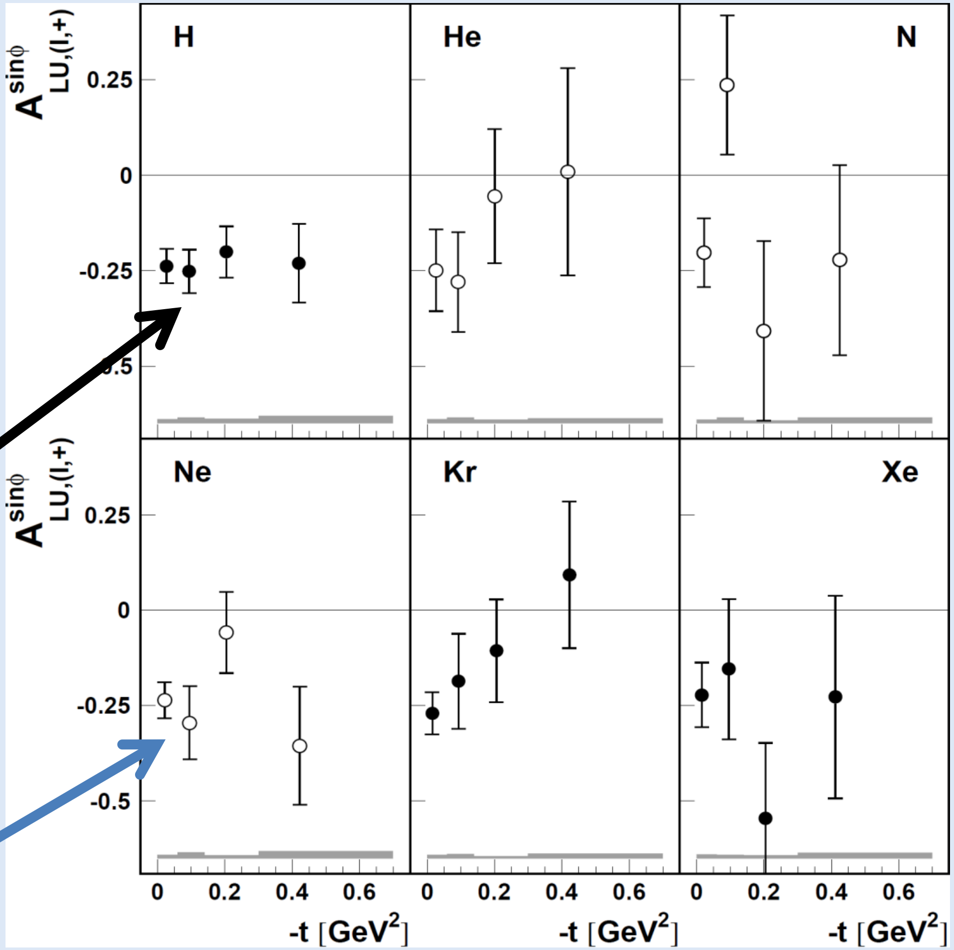
- Separation of coherent-enriched and incoherent-enriched data samples by t- cutoffs : similar average kinematics
- Coherent-enriched samples: ≈ 65 %
- Incoherent enriched samples: ≈ 60 %

Leading amplitudes of asymmetries on nuclei

Leading amplitude of
Beam-charge asymmetry



Leading amplitudes of
Beam-helicity asymmetry

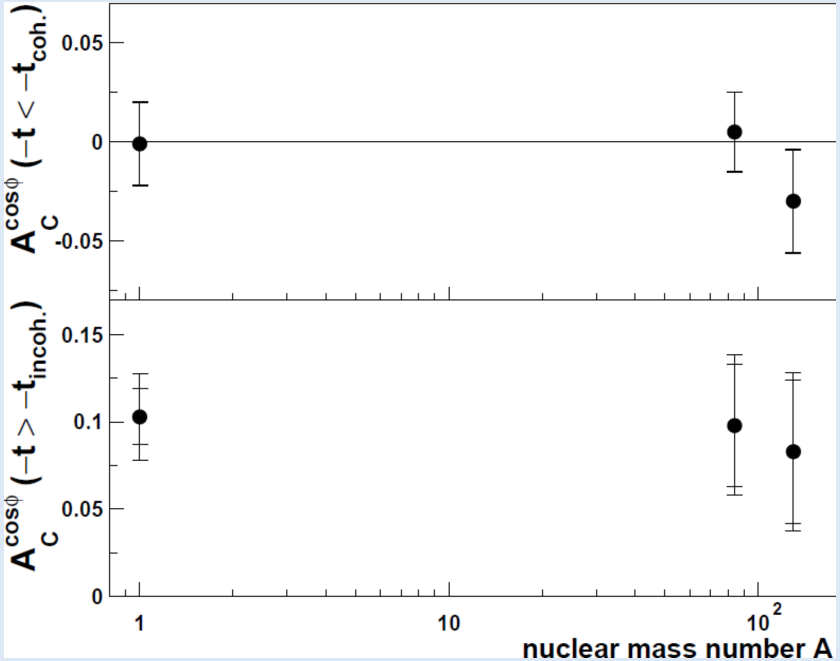


- ● Two beam charges available

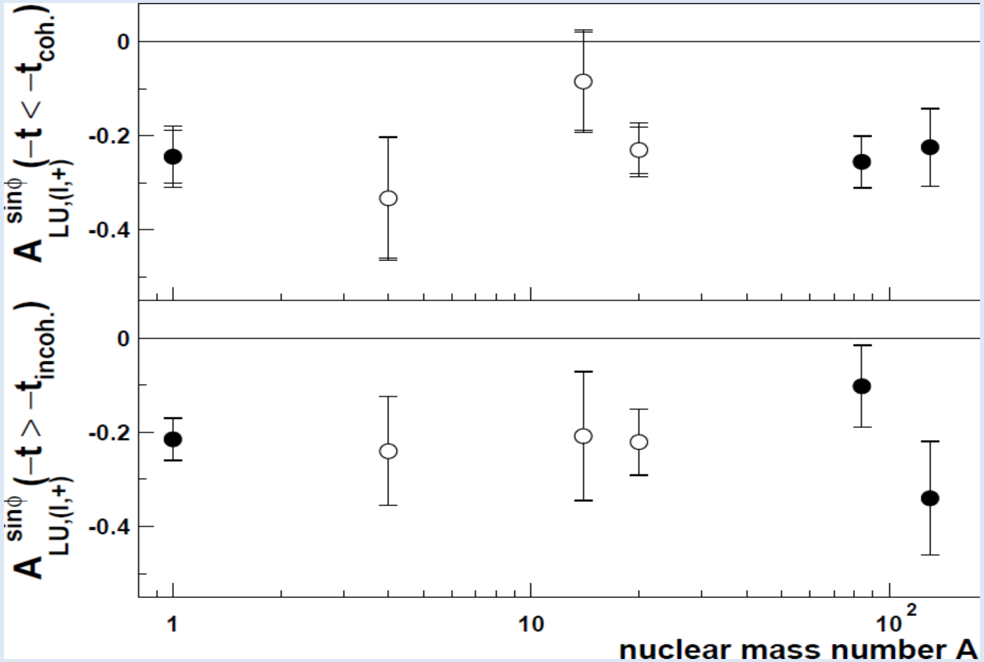
- ○ Only one beam charge available: single-charge asymmetry without entanglement of squared DVCS and Interference terms

Nuclear-mass dependence of asymmetries

$A_C^{\cos\phi}$ vs. A



$A_{LU}^{\sin\phi}$ vs. A

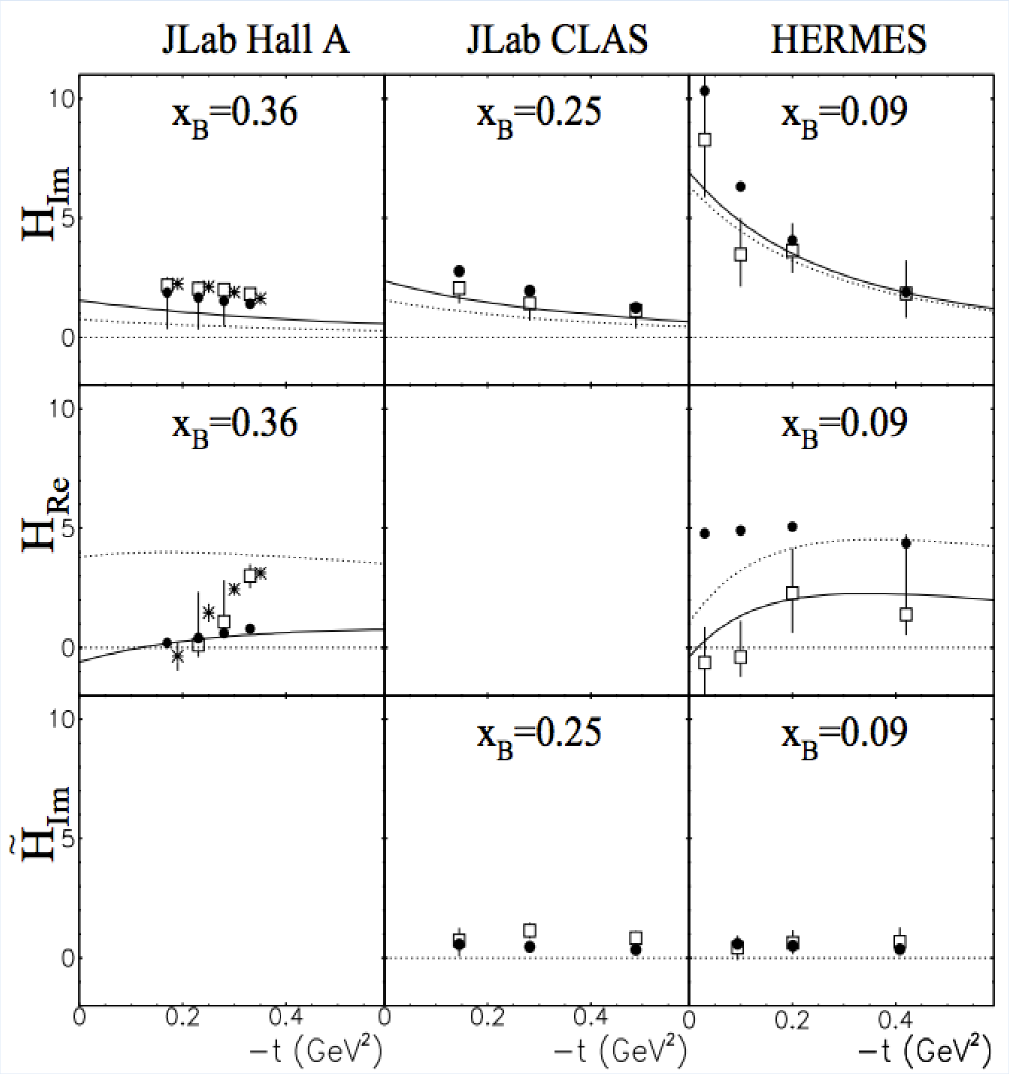


A_{LU}^{A} / A_{LU}^{H} ⟹

Coherent-enriched:	0.91 ± 0.19
Incoherent-enriched:	0.93 ± 0.23

GPD extraction

M. Guidal ICHEP Proc. (2010) 148



CFFs are extracted from experimental measurements

- VGG model:
  GPD H in this model is not consistent with experimental results.

❑ M. Guidal, ICHEP Proc. (2010) 148

⋆ H. Moutarde, Phys. Rev. **D** 79 (2009)

<u>Curves:</u>

K. Kumericki, D. Muller
Nucl. Phys. **B** 841 (2010)

Results of different fits

D. Müller: e-Print, arXiv:1405.2817 [hep-ph]