Target single- and double-spin asymmetries in DVCS off a longitudinal polarised hydrogen target at HERMES

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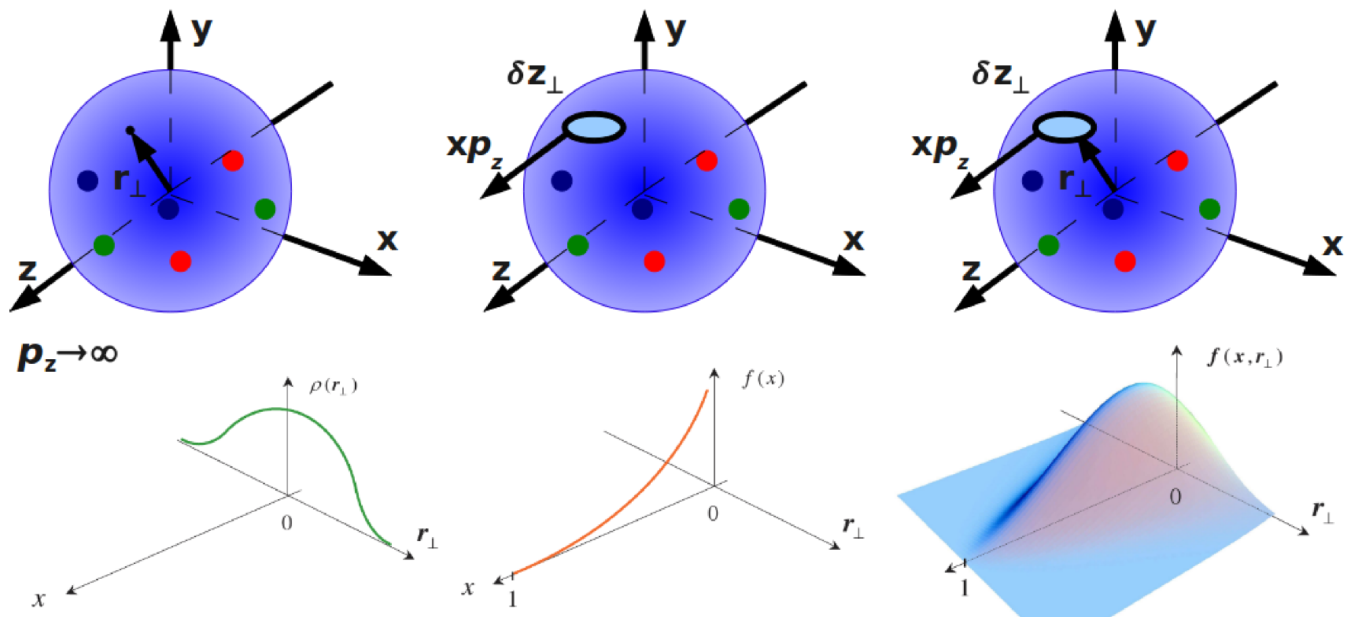
Overview

- Generalised Parton Distributions
- Deeply Virtual Compton Scattering
- Longitudinally-Polarised Target Asymmetries
- The HERMES Experiment @ DESY
- Data Selection and Extraction of Asymmetries
- Systematic Uncertainties
- Final Results and Theory Comparison

Generalised Parton Distributions

A multi-dimensional representation of the nucleon



Form Factors | **Parton Distribution Functions** | **Generalised Parton Distributions**

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

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

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

$$\int_{-1}^{1} \widetilde{E}(x,\xi,t)\,dx = G_P(t)$$

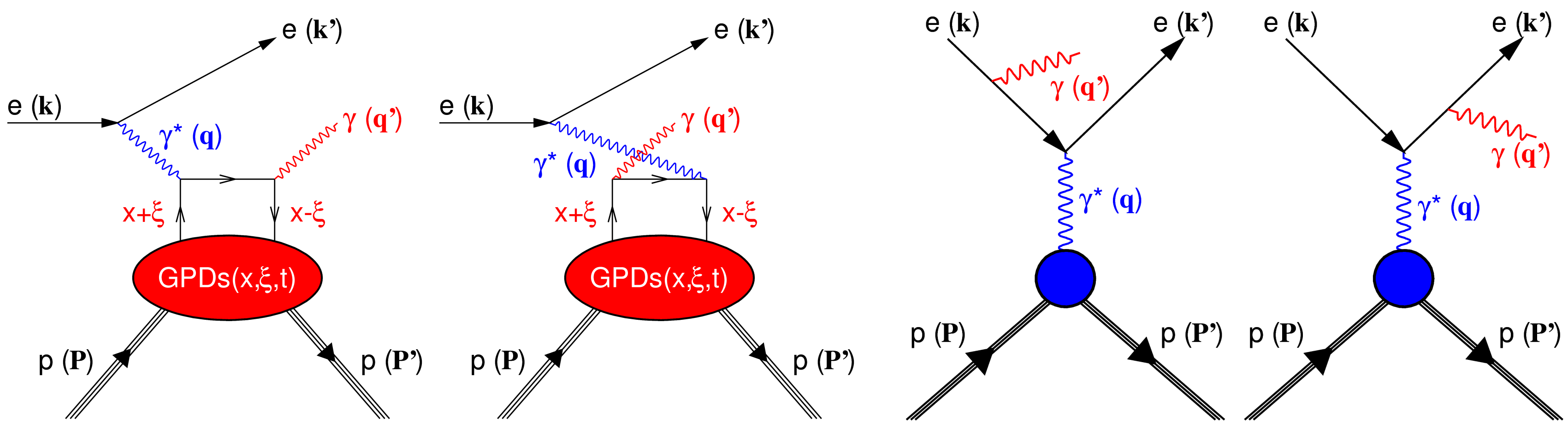
$$H^q(x,0,0) = q(x)$$

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

At leading twist and for a proton target there are 4 quark GPDs:

$$H, E, \widetilde{H}, \widetilde{E}$$

The $e\vec{p}\rightarrow ep\gamma$ Interaction



Deeply Virtual Compton Scattering (DVCS)

$$e(\mathbf{k})\,p(\mathbf{p}) \overset{\gamma^*(\mathbf{q})}{\longrightarrow} e(\mathbf{k}')\,p(\mathbf{p}')\,\gamma(\mathbf{q}')$$

Bethe-Heitler (BH)

The four-fold differential cross-section (neglecting transverse components) can be expressed as

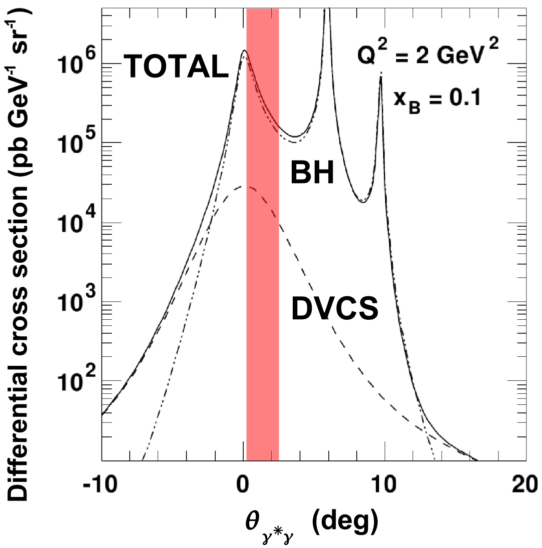
$$\frac{\mathrm{d}\sigma}{\mathrm{d}x_\mathrm{B}\,\mathrm{d}Q^2\,\mathrm{d}|t|\,\mathrm{d}\phi} = \frac{x_\mathrm{B}\,e_\ell^6\,|\tau|^2}{32(2\pi)^4\,Q^4\,\sqrt{1+\epsilon^2}}$$

where $\epsilon = 2x_\mathrm{B}\frac{M_p}{Q}$

As the DVCS and BH processes have the same initial and final states, their scattering amplitudes interfere, *i.e.*

$$|\tau|^2 = |\tau_\mathrm{BH}|^2 + |\tau_\mathrm{DVCS}|^2 + \overbrace{\tau_\mathrm{BH}\tau^*_\mathrm{DVCS} + \tau^*_\mathrm{BH}\tau_\mathrm{DVCS}}^{\mathcal{I}}$$

The $e\vec{p} \rightarrow ep\gamma$ Interaction



Eur. Phys. J. **C23** (2005) 455

The DVCS interaction is **suppressed** with respect to BH at HERMES kinematics and in the analysed $\theta_{\gamma^*\gamma}$ range.

Important GPD-related information can be accessed via the Interference and squared-DVCS terms which are Fourier expanded in ϕ to twist-3 level as

$$\mathcal{I} = \frac{-e_\ell K_\mathcal{I}}{\mathcal{P}(\phi)} \left(P_\ell \, P_\mathrm{L} \sum_{n=0}^{2} c_{n,\mathrm{LP}}^{\mathcal{I}} \cos(n\phi) + P_\mathrm{L} \sum_{n=1}^{3} s_{n,\mathrm{LP}}^{\mathcal{I}} \sin(n\phi) \right)$$

Beam Polarisation (P_ℓ)

Target Polarisation (P_L)

+ terms associated with an unpolarised target

$$|\tau_\mathrm{DVCS}|^2 = K_\mathrm{DVCS} \left(P_\ell \, P_\mathrm{L} \sum_{n=0}^{1} c_{n,\mathrm{LP}}^{\mathrm{DVCS}} \cos(n\phi) + P_\mathrm{L} \sum_{n=1}^{2} s_{n,\mathrm{LP}}^{\mathrm{DVCS}} \sin(n\phi) \right)$$

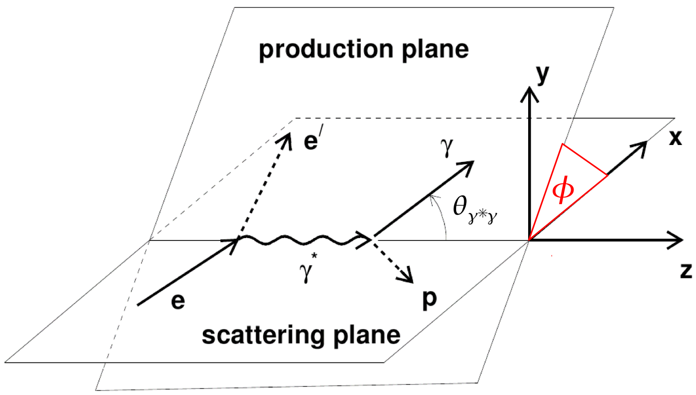
The Fourier coefficients relate to combinations of **Compton Form Factors** (CFFs) which are convolutions of the corresponding GPD with a hard-scattering kernel.

The squared-BH terms are exactly calculable in terms of the Dirac and Pauli FFs and known kinematic conditions.

Nucl. Phys. **B629** (2002) 323-392

Long. Pol. Target Asymmetries associated with DVCS

Two asymmetries in the distribution of real photons with respect to the azimuthal angle ϕ are extracted:



$$\mathcal{A}_{\rm UL}(\phi) \equiv \frac{[\sigma^{\leftarrow\Rightarrow}(\phi)+\sigma^{\rightarrow\Rightarrow}(\phi)]-[\sigma^{\leftarrow\Leftarrow}(\phi)+\sigma^{\rightarrow\Leftarrow}(\phi)]}{[\sigma^{\leftarrow\Rightarrow}(\phi)+\sigma^{\rightarrow\Rightarrow}(\phi)]+[\sigma^{\leftarrow\Leftarrow}(\phi)+\sigma^{\rightarrow\Leftarrow}(\phi)]}$$

Beam Target

$$= \frac{K_{\rm DVCS}}{\mathcal{D}_{\rm unp}(\phi)}\sum_{n=1}^{2} s_{n,\rm LP}^{\rm DVCS}\sin(n\phi) - \frac{e_\ell K_{\mathcal{I}}}{\mathcal{D}_{\rm unp}(\phi)\mathcal{P}(\phi)}\sum_{n=1}^{3} s_{n,\rm LP}^{\mathcal{I}}\sin(n\phi)$$

The single-spin target asymmetry is sensitive to the imaginary part of CFF $\widetilde{\mathcal{H}}$

$$\mathcal{A}_{\rm LL}(\phi) \equiv \frac{[\sigma^{\rightarrow\Rightarrow}(\phi)+\sigma^{\leftarrow\Leftarrow}(\phi)]-[\sigma^{\leftarrow\Rightarrow}(\phi)+\sigma^{\rightarrow\Leftarrow}(\phi)]}{[\sigma^{\rightarrow\Rightarrow}(\phi)+\sigma^{\leftarrow\Leftarrow}(\phi)]+[\sigma^{\leftarrow\Rightarrow}(\phi)+\sigma^{\rightarrow\Leftarrow}(\phi)]}$$

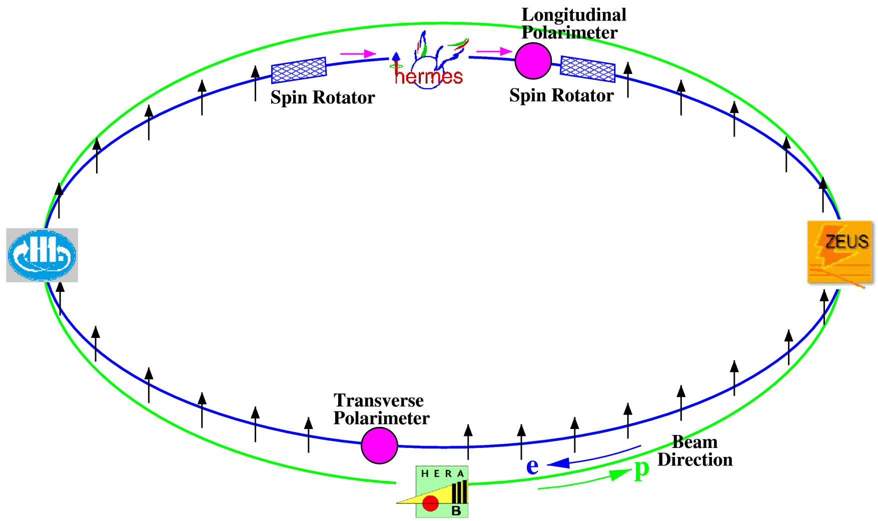
$$= \frac{K_{\rm BH}}{\mathcal{D}_{\rm unp}(\phi)}\sum_{n=0}^{1} c_{n,\rm LP}^{\rm BH}\cos(n\phi) + \frac{K_{\rm DVCS}}{\mathcal{D}_{\rm unp}(\phi)}\sum_{n=0}^{1} c_{n,\rm LP}^{\rm DVCS}\cos(n\phi) - \frac{e_\ell K_{\mathcal{I}}}{\mathcal{D}_{\rm unp}(\phi)\mathcal{P}(\phi)}\sum_{n=0}^{2} c_{n,\rm LP}^{\mathcal{I}}\cos(n\phi)$$

The double-spin asymmetry is sensitive to the real part of CFF $\widetilde{\mathcal{H}}$

The beam-helicity asymmetry has been extracted at HERMES from a larger superset of data. *JHEP* **11** (2009) 083

$$\mathcal{A}_{\rm LU}(\phi) \equiv \frac{[\sigma^{\rightarrow\Leftarrow}(\phi)+\sigma^{\rightarrow\Rightarrow}(\phi)]-[\sigma^{\leftarrow\Leftarrow}(\phi)+\sigma^{\leftarrow\Rightarrow}(\phi)]}{[\sigma^{\rightarrow\Leftarrow}(\phi)+\sigma^{\rightarrow\Rightarrow}(\phi)]+[\sigma^{\leftarrow\Leftarrow}(\phi)+\sigma^{\leftarrow\Rightarrow}(\phi)]} \quad \propto \Im m\mathcal{H}$$

The HERMES Experiment: The Long. Pol. Proton Data Set



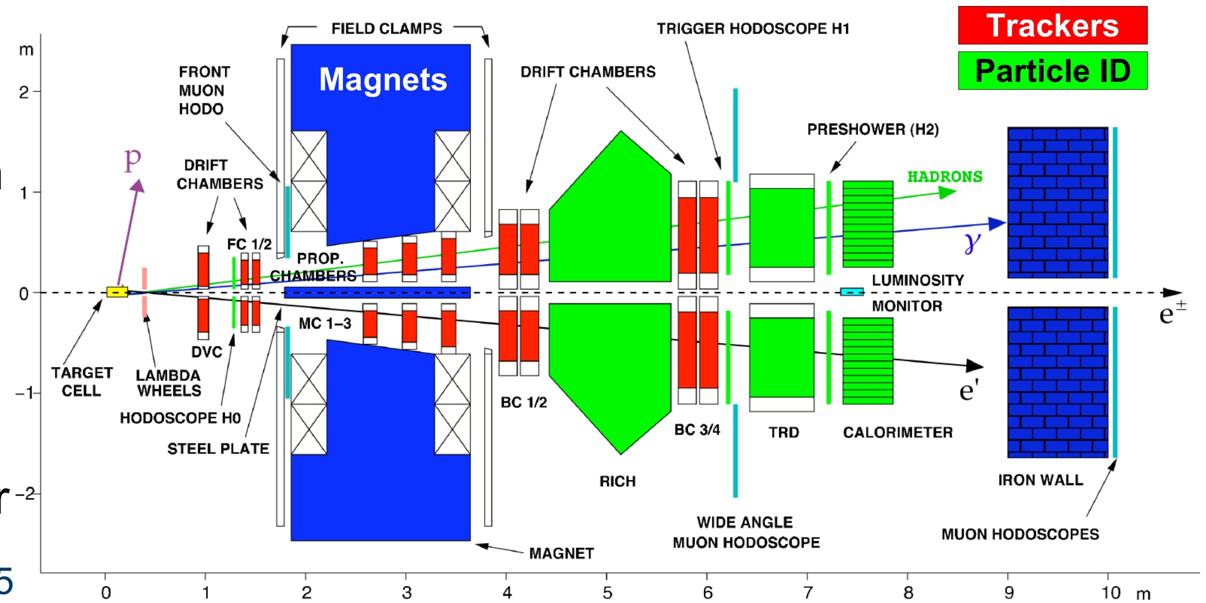
- Situated on the HERA ring at DESY
- Fixed Gas Target Experiment
- Data taken in 1996 – 1997
- Long. pol. (~80%) Hydrogen gas
- 27.57GeV long. pol. (~50%) e^+ beam
- Luminosity ~50pb^{-1}

γ detected in the calorimeter

Charged track identified as an **e^+** detected in the calorimeter and tracked through the spectrometer

p is not detected. This data was taken pre-Recoil Detector

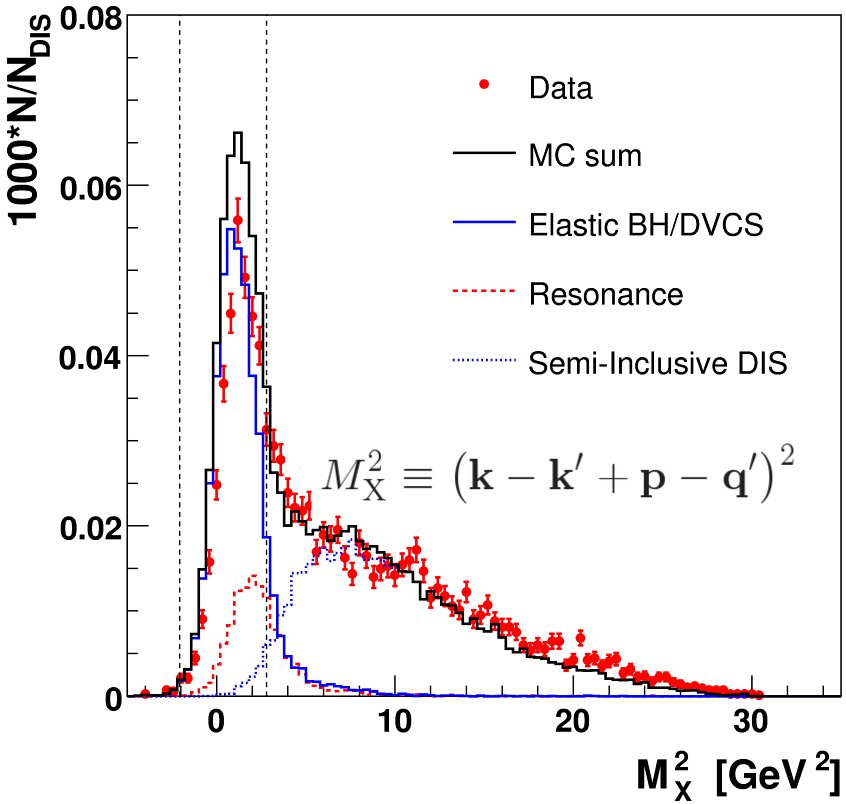
Nucl. Inst. Meth. **A417** (1998) 230-265



Data Selection Criteria

One positron, fully tracked through the spectrometer and one photon, identified as a single signal cluster with no track, must be detected with:

$$1\ \mathrm{GeV}^2 \leq Q^2 \leq 10\mathrm{GeV}^2,\ 0.03 \leq x_B \leq 0.35,$$
$$W > 3\mathrm{GeV},\ \nu < 22\mathrm{GeV},\ -t < 0.7\mathrm{GeV}^2$$



Pre-Recoil 'exclusive' data sample is selected by constraining the missing mass:

$$-2.08\ \mathrm{GeV}^2 \leq M_X^2 \leq 2.81\ \mathrm{GeV}^2$$

MC studies show that the final sample contains contributions from:

- DVCS/BH – 84%
- Resonance production – 13%
- Semi-Inclusive M^0 production – 3%
- Exclusive π^0 production < 1%

The resultant yield is written for each beam and target polarisation state as:

$$\langle \mathcal{N}(P_\ell, P_\mathrm{L}, \phi)\rangle = L(P_\ell)\eta(\phi)\sigma_\mathrm{UU}(\phi)[1 + P_\mathrm{L}\mathcal{A}_\mathrm{UL}(\phi) + P_\ell P_\mathrm{L}\mathcal{A}_\mathrm{LL}(\phi)]$$

Detection Efficiency ($\eta(\phi)$); Time-integrated Luminosity ($L(P_\ell)$); Unpolarised Cross Section ($\sigma_\mathrm{UU}(\phi)$)

The asymmetries are simultaneously extracted using the Maximum Likelihood fitting formalism as:

$$-\ln \mathcal{L}_\mathrm{EML}(\theta) = -\sum_{\mathbf{i}}^{N} \ln[1 + P_\mathrm{L}\mathcal{A}_\mathrm{UL}(\mathbf{x_i};\theta) + P_\ell P_\mathrm{L}\mathcal{A}_\mathrm{LL}(\mathbf{x_i};\theta)] + \mathcal{N}(\theta)$$

where $\mathbf{x_i} \in \{\phi, -t, x_B, Q^2\}$ are variables for an event **i** and θ are the most likely set of asymmetry amplitudes.

The extracted asymmetry amplitudes are:

$$\mathcal{A}_\mathrm{UL}(\phi) \simeq A_\mathrm{UL}^{\cos(0\phi)} + \sum_{n=1}^{3} A_\mathrm{UL}^{\sin(n\phi)}\sin(n\phi) \qquad \mathcal{A}_\mathrm{LL}(\phi) \simeq \sum_{n=0}^{2} A_\mathrm{LL}^{\cos(n\phi)}\cos(n\phi)\,.$$

These amplitudes relate to Fourier coefficients appearing in the expansion of $|\tau|^2$.

Linking Extracted Amplitudes and Fourier Coefficients

These asymmetry amplitudes relate to the Fourier coefficients which depend on $\mathcal{C}$-functions – functions of real or imaginary parts of CFFs

Asymmetry Amplitude	Contributing Fourier-Coefficient	Twist Level	CFF Dependence
$A_{\mathrm{UL}}^{\sin\phi}$	$s_{1,\mathrm{LP}}^{\mathcal{I}}$	2	$\Im\mathrm{m}\,\mathcal{C}_{\mathrm{LP}}^{\mathcal{I}}$
	$s_{1,\mathrm{LP}}^{\mathrm{DVCS}}$	3	$\Im\mathrm{m}\,\mathcal{C}_{\mathrm{LP}}^{\mathrm{DVCS}}$
$A_{\mathrm{UL}}^{\sin(2\phi)}$	$s_{2,\mathrm{LP}}^{\mathcal{I}}$	3	$\Im\mathrm{m}\,\mathcal{C}_{\mathrm{LP}}^{\mathcal{I}}$
	$s_{2,\mathrm{LP}}^{\mathrm{DVCS}}$	2	$\Im\mathrm{m}\,\mathcal{C}_{\mathrm{T,LP}}^{\mathrm{DVCS}}$
$A_{\mathrm{UL}}^{\sin(3\phi)}$	$s_{3,\mathrm{LP}}^{\mathcal{I}}$	2	$\Im\mathrm{m}\,\mathcal{C}_{\mathrm{T,LP}}^{\mathcal{I}}$
$A_{\mathrm{LL}}^{\cos(0\phi)}$	$c_{0,\mathrm{LP}}^{\mathcal{I}}$	2	$\Re\mathrm{e}\,\mathcal{C}_{\mathrm{LP}}^{\mathcal{I}}$
	$c_{0,\mathrm{LP}}^{\mathrm{DVCS}}$	2	$\Re\mathrm{e}\,\mathcal{C}_{\mathrm{LP}}^{\mathrm{DVCS}}$
	$c_{0,\mathrm{LP}}^{\mathrm{BH}}$	-	-
$A_{\mathrm{LL}}^{\cos\phi}$	$c_{1,\mathrm{LP}}^{\mathcal{I}}$	2	$\Re\mathrm{e}\,\mathcal{C}_{\mathrm{LP}}^{\mathcal{I}}$
	$c_{1,\mathrm{LP}}^{\mathrm{DVCS}}$	3	$\Re\mathrm{e}\,\mathcal{C}_{\mathrm{LP}}^{\mathrm{DVCS}}$
	$c_{1,\mathrm{LP}}^{\mathrm{BH}}$	-	-
$A_{\mathrm{LL}}^{\cos(2\phi)}$	$c_{2,\mathrm{LP}}^{\mathcal{I}}$	3	$\Re\mathrm{e}\,\mathcal{C}_{\mathrm{LP}}^{\mathcal{I}}$

Unlike other HERMES analyses using both beam charges, the contributions from the interference and squared-DVCS terms cannot be disentangled.

Functions of gluon-helicity-flip CFFs suppressed by α_s/π

The leading-twist amplitudes $A_{\mathrm{UL}}^{\sin\phi}$ and $A_{\mathrm{LL}}^{\cos\phi}$ offer the best opportunity to access information on the real and imaginary parts of CFF $\widetilde{\mathcal{H}}$ via $\mathcal{C}_{\mathrm{LP}}^{\mathcal{I}}$ which is linear in CFFs:

$$\mathcal{C}_{\mathrm{LP}}^{\mathcal{I}} = \frac{x_B}{2-x_B}(F_1+F_2)\left(\mathcal{H}+\frac{x_B}{2}\mathcal{E}\right)+F_1\tilde{\mathcal{H}}-\frac{x_B}{2-x_B}\left(\frac{x_B}{2}F_1+\frac{t}{4M^2}F_2\right)\tilde{\mathcal{E}}$$

Systematic Uncertainties

Several sources of systematic uncertainty affect the results shown:

- $\delta_{M_X^2}$ - introduced by accounting for shifts in the mean of the M_X^2 distributions between data taking years
- δ_{Bg} - accounts for the effect of corrections made to the asymmetries to remove contributions from background processes
- δ_{4in1} - correlated effects of detector smearing, misalignment and acceptance, and finite bin-width effects
- Scale uncertainties in the measurement of the beam and target polarisations of 3.4% and 4.2% respectively

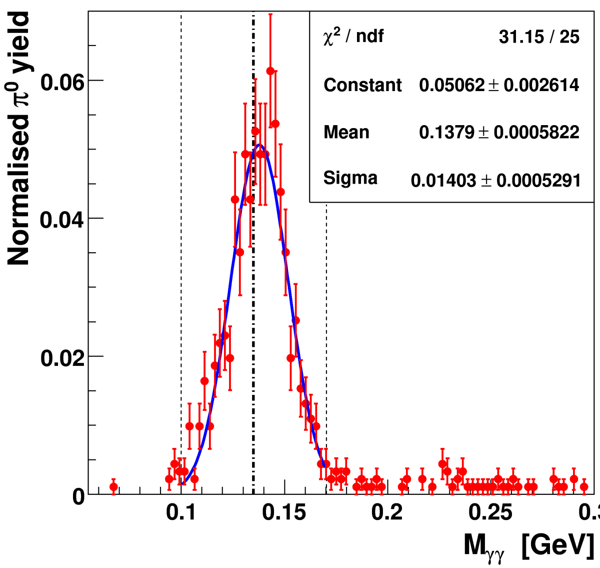
Systematic Uncertainties: Background and M_X^2 Corrections

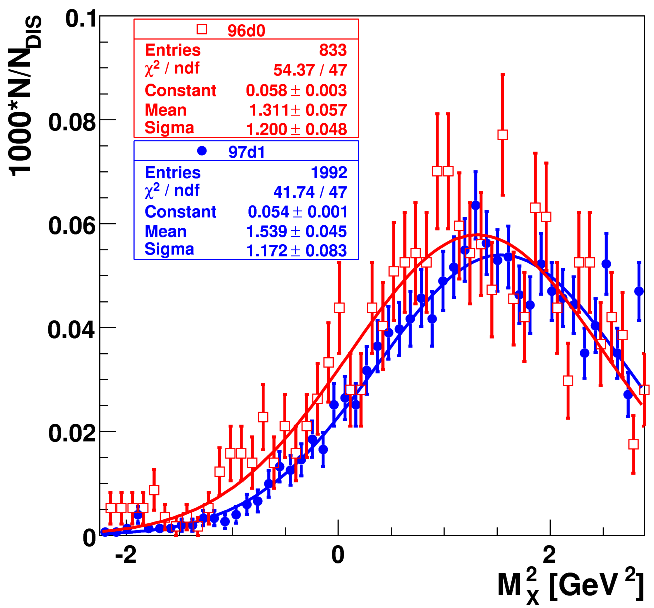
π^0 Background Correction

- Semi-inclusive DIS background dominated by π^0
- Same data selection as for exclusive sample but with two photons required in the final state
- Corrected amplitudes determined as

$$A_{\text{corrected}} = \frac{1}{1 - f_{\text{sidis}} - f_{\text{excl}}}(A_{\text{measured}} - f_{\text{sidis}}A_{\text{sidis}} - f_{\text{excl}}A_{\text{excl}})$$

- δ_{Bg} is evaluated as half the magnitude of the correction in each bin





Missing-Mass Shift Correction

Shifts were discovered between data years.

New year-dependent regions were calculated

$\delta_{M_X^2}$ = ¼ of the effect the new year-dependent regions have on the extracted amplitudes

Systematic Uncertainties: '4-in-1' Uncertainty

Correlated uncertainty from the effects of detector misalignment, smearing, acceptance and finite bin-widths in -t, x_B and Q^2.

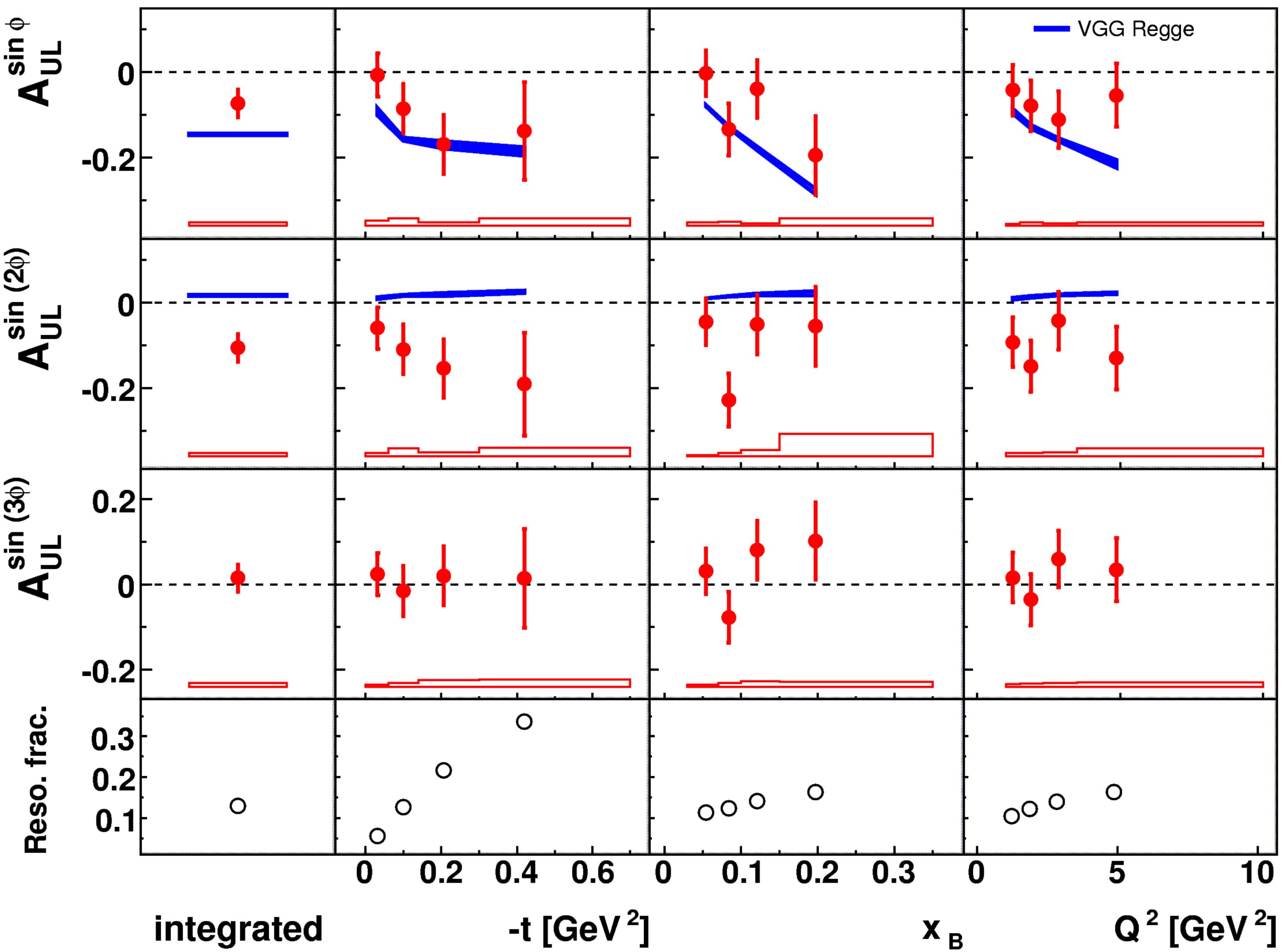
- Amplitudes 'generated' from 5 GPD parametrisations from the model in *Eur. Phys. J.* **C23** (2005) 455.
- Amplitudes 'reconstructed' from MC simulation using each model at the same average kinematics of each bin.

- Uncertainty from each model determined as

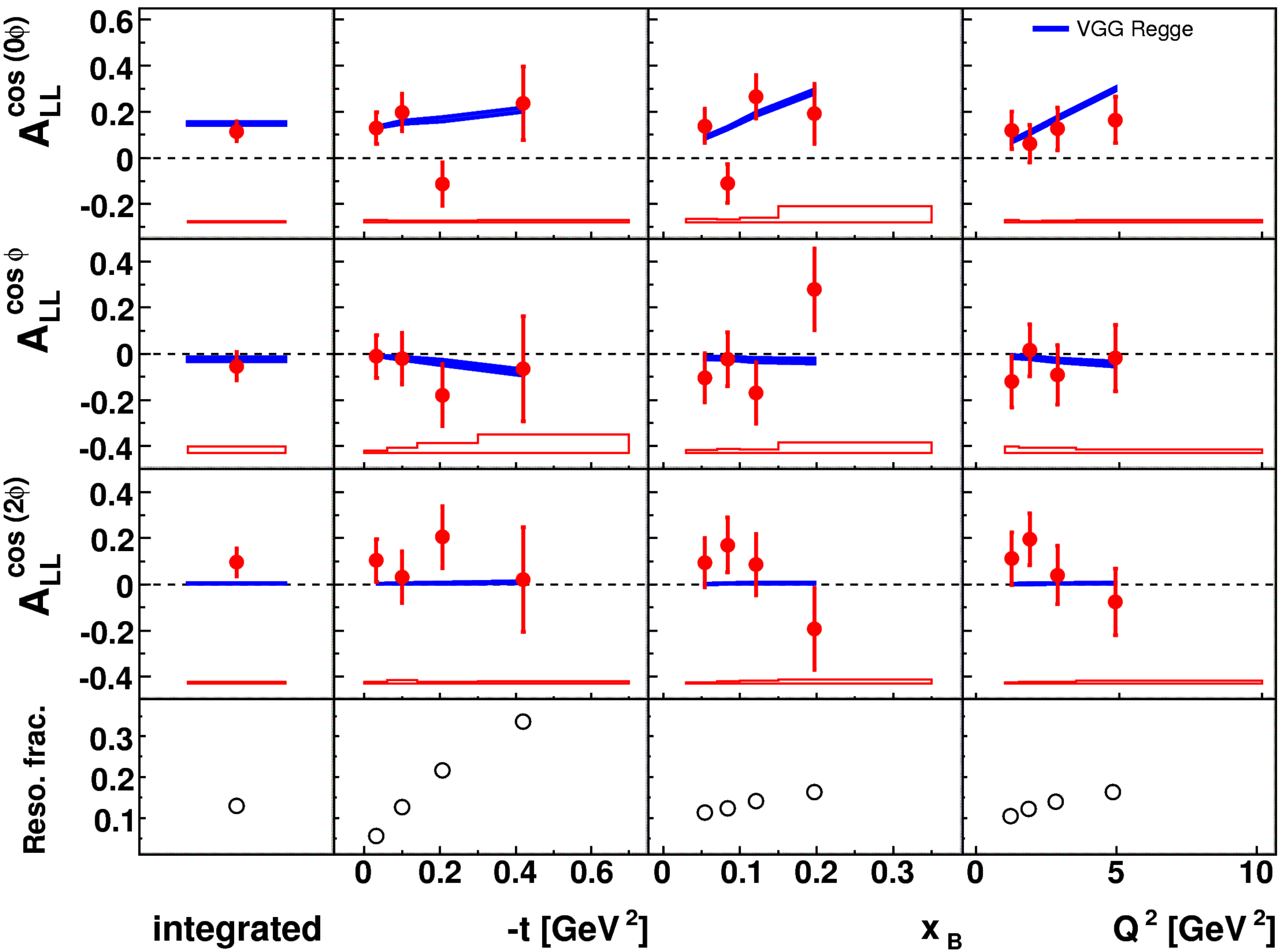
$$\delta_{\text{4-in-1}} = \left| A_{\text{generated}} - A_{\text{reconstructed}} \right|$$

- Overall 4-in-1 uncertainty is determined as the RMS of all 5 models

Results of the Single-Spin Target Asymmetry



Results of the Double-Spin Asymmetry



Summary and Conclusions

- Two azimuthal asymmetries in the distribution of real photons from the $e\vec{p}\rightarrow ep\gamma$ interaction were extracted arXiv:1004.0177
  - The single-spin asymmetry $\mathcal{A}_{\mathrm{UL}}$
  - The double-spin asymmetry $\mathcal{A}_{\mathrm{LL}}$
- These provide information of the imaginary and real parts of CFF $\widetilde{\mathcal{H}}$
- Non-zero sinϕ and and unexpectedly large sin(2ϕ) amplitude were observed for the single-spin asymmetry
- Non-zero cos(0ϕ) amplitudes observed for the double-spin

- It is foreseen these results will be used in future extractions of CFF $\widetilde{\mathcal{H}}$ leading to a better understanding of GPD $\mathcal{H}$

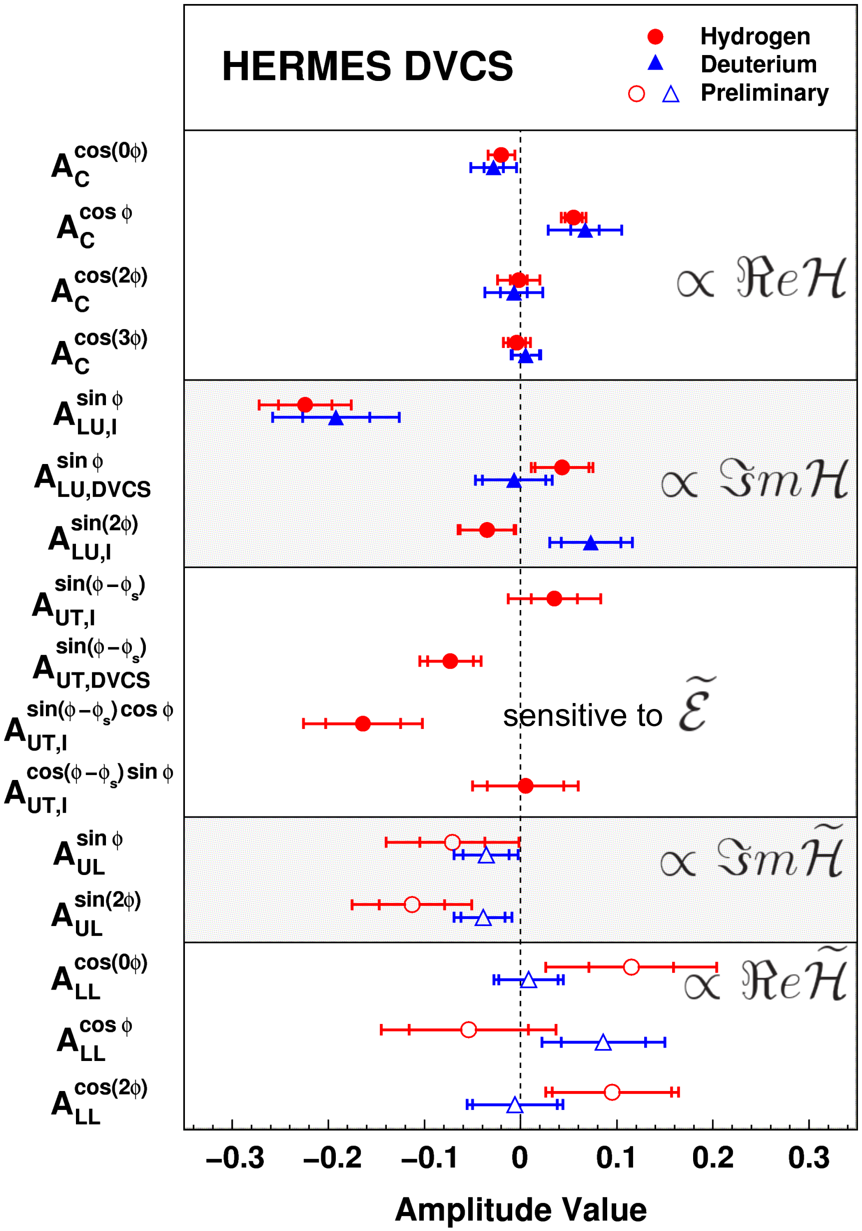
BACKUP SLIDES

Theoretical Calculations

- Results shown are compared with theoretical calculations from the GPV model implementation of Radyushkin's Double Distribution formalism from VGG (Vanderhaeghen, Guichon and Guidal) *Phys. Rev.* **D60** (1999) 094017

- Regge-inspired t-dependent ansatz used
- Predicts GPD information up to twist-3 level
- Width of theory bands arises from varying the skewness parameters between unity and infinity
- The 'D term' has not been included for these plots

Overview of HERMES DVCS Results



● *JHEP* **11** (2009) 083

▲ *Nucl. Phys.* **B829** (2010) 1-27

● *JHEP* **06** (2008) 066

○ Submitted to *JHEP* (April 2010) arXiv:1004.0177

△ Submission to *Nucl. Phys.* **B** (later in 2010)