Positrons and Electrons at HERA and HERMES

Caroline Riedl

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Outline

- Motivation: what can we learn from different beam charges?
- HERA: a storage ring for electrons and positrons
- HERMES: azimuthal asymmetries in Deeply Virtual Compton Scattering (DVCS)
- HERMES: search for a two-photon exchange signal

Motivation: Physics with two beam charges

- Electromagnetic coupling $\surd$
  - Usually, cross-section $\propto |\mathcal{T}|^2$ ▶ beam charge dependence squared out
  - Need interference process involving odd number of couplings beam!
    - ★ Example 1: DVCS / Bethe-Heitler interference
    - ★ Example 2: transverse single-spin asymmetries from interference of 1-photon and 2-photon exchange amplitudes
- Electroweak coupling $\surd$
  - Gauge bosons $W^{\pm}$ carry electric charge ▶ not flavor-blind
  - Beam charge generates sensitiveness to quark flavor
- QCD, Gravitation, Higgs $\times$

HERA at DESY (Hamburg)

HERA & preaccelerators

Leptons (e^+/e^-): 40 mA

Protons: 90 mA

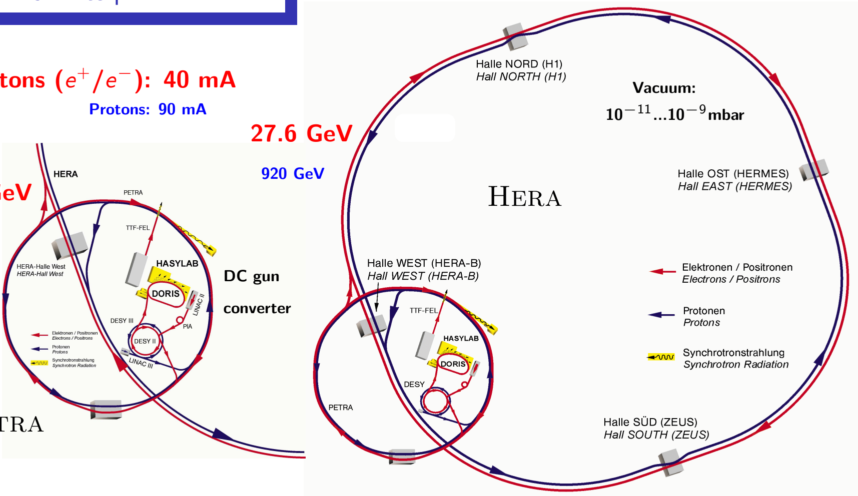
27.6 GeV

920 GeV

12 GeV

DC gun converter

Vacuum: $10^{-11} \ldots 10^{-9}$ **mbar**



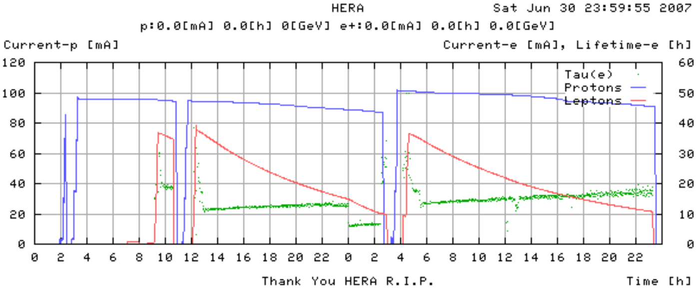
- Life time: longer for positron beam (e^+ push out residual gas cores)

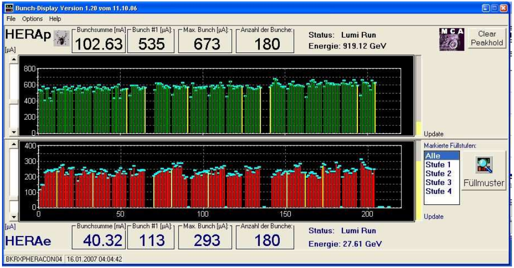
HERA fills and bunch structure

Protons [mA]

Positrons [mA]

Life time [h]

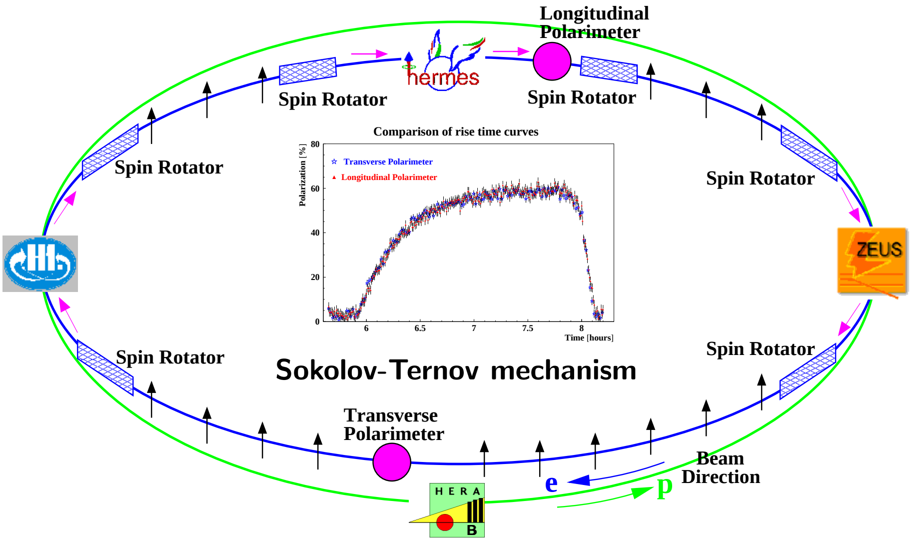




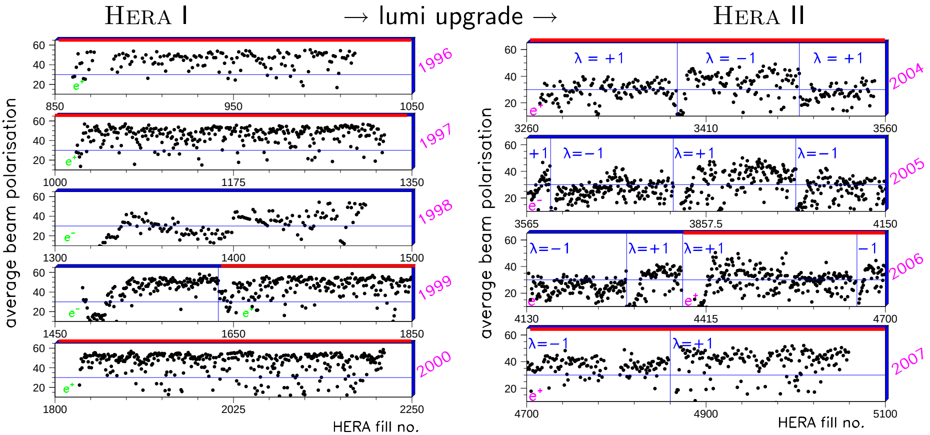
Positrons:

- 180 bunches (max.220)
- Bunch length 27 ps
- Separated by 96 ns

HERA and lepton beam polarization



HERA's beam polarization over the years (e^+, e^-)



- Beam-beam effects: (e^--p) beam focussing, (e^+-p) defocussing
- Polarization lower after HERA lumi upgrade
  - Tune was optimized for luminosity and not lepton polarization
- Accuracy of measurement: 2% (sys)

Physics with two beam charges

DVCS at HERMES

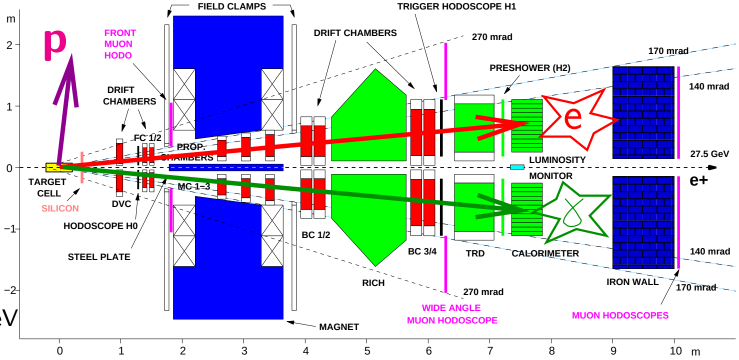
Statistics 1996-2005 on gas targets:
hydrogen: 25.000 DVCS events
unpolarized **deuterium**: 15.000 DVCS events

$e^{\pm}N \rightarrow e^{\pm}N\gamma$ $\quad N \in \{p,d\}$

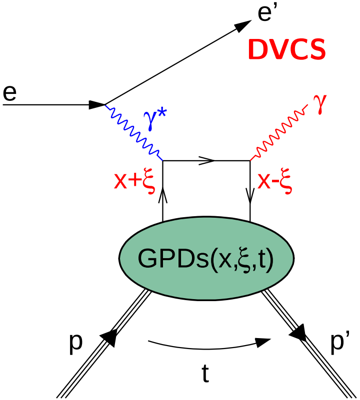
$e^{+}, \overleftrightarrow{}$

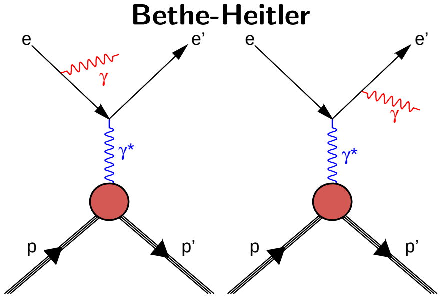
$e^{-}, \overleftrightarrow{}$

$E_{\text{beam}} = 27.6$ GeV



DVCS/Bethe-Heitler interference in $\mathrm{eN} \to \mathrm{eN}\gamma$



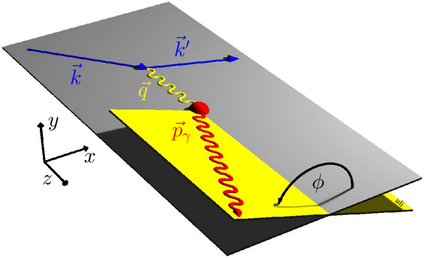


$$\frac{\mathrm{d}^4\sigma}{\mathrm{d}Q^2\mathrm{d}x_B\mathrm{d}t\mathrm{d}\phi} = \frac{y^2 x_B}{32(2\pi)^4 Q^4 \sqrt{1+\frac{4M^2x_B^2}{Q^2}}} \left(|\mathcal{T}_{\mathrm{DVCS}}|^2 + |\mathcal{T}_{\mathrm{BH}}|^2 + \mathcal{I}\right)$$

Azimuthal dependences in $\mathrm{eN} \rightarrow \mathrm{eN}\gamma$

Fourier expansion in ϕ for

- **beam polarization P_B**
- **beam charge C_B**
- **unpolarized target**:



$$|\mathcal{T}_{\mathrm{BH}}|^2 = \frac{K_{\mathrm{BH}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \sum_{n=0}^{2} c_n^{\mathrm{BH}} \cos(n\phi)$$

$$|\mathcal{T}_{\mathrm{DVCS}}|^2 = K_{\mathrm{DVCS}} \left[\sum_{n=0}^{2} c_n^{\mathrm{DVCS}} \cos(n\phi) + P_B \sum_{n=1}^{1} s_n^{\mathrm{DVCS}} \sin(n\phi) \right]$$

$$\mathcal{I} = \frac{C_B K_{\mathcal{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left[\sum_{n=0}^{3} c_n^{\mathcal{I}} \cos(n\phi) + P_B \sum_{n=1}^{2} s_n^{\mathcal{I}} \sin(n\phi) \right]$$

Measured Azimuthal Asymmetries in $\mathrm{eN} \to \mathrm{eN}\gamma$

- Born cross-section:

$$\sigma(\phi; P_B, C_B) = \sigma_{\mathrm{UU}}(\phi) \cdot \left[1 + P_B \mathcal{A}_{\mathrm{LU}}^{\mathrm{DVCS}}(\phi) + C_B P_B \mathcal{A}_{\mathrm{LU}}^{\mathcal{I}}(\phi) + C_B \mathcal{A}_{\mathrm{C}}(\phi)\right]$$

- **Beam Spin Asymmetries:**

$$\mathcal{A}_{\mathrm{LU}}^{\mathrm{DVCS}}(\phi) = \frac{1}{\mathcal{D}(\phi)} \cdot \frac{x_B^2 t \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}{Q^2} s_1^{\mathrm{DVCS}} \sin(\phi)$$

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

- **Beam Charge Asymmetry:**

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

- Dilution factor through lepton propagators $\mathcal{P}_1(\phi)$, $\mathcal{P}_2(\phi)$:

$$\mathcal{D}(\phi) = \frac{\sum_{n=0}^{2} c_n^{\mathrm{BH}} \cos(n\phi)}{(1+\epsilon^2)^2} + \frac{x_B^2 t \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}{Q^2} \sum_{n=0}^{2} c_n^{\mathrm{DVCS}} \cos(n\phi)$$

From Azimuthal Asymmetries to GPDs

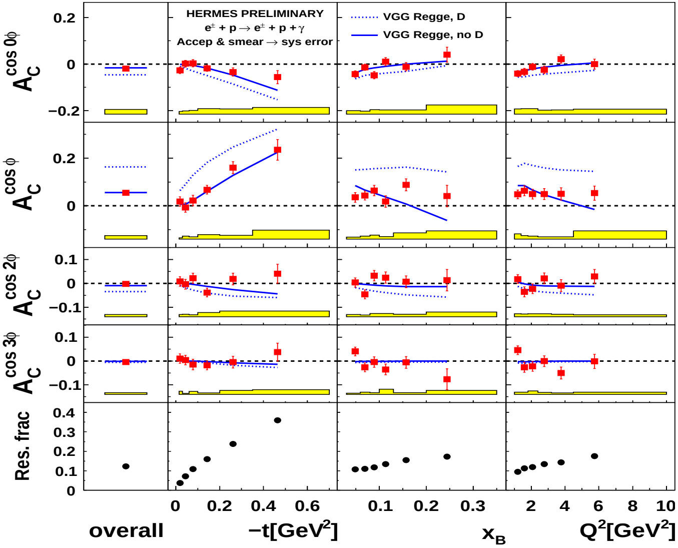
- To obtain Fourier coefficients = asymmetry amplitudes:
  ▶ Data with different beam charges and beam helicities are combined and **fit simultaneously**
- Connection to GPDs (leading contributions):

$$
\begin{aligned}
c_1^{\mathcal{I}} &\propto \frac{\sqrt{-t}}{Q}\,\mathrm{Re}\left[F_1\mathcal{H} + \xi(F_1+F_2)\widetilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}\right] \\
&\propto -\frac{Q}{\sqrt{-t}}\,c_0^{\mathcal{I}} \qquad \leftarrow \text{constant term} \\
s_1^{\mathcal{I}} &\propto \frac{\sqrt{-t}}{Q}\,\mathrm{Im}\left[F_1\mathcal{H} + \xi(F_1+F_2)\widetilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}\right]
\end{aligned}
$$

- $\mathcal{H}$, $\widetilde{\mathcal{H}}$, $\mathcal{E}$, $\widetilde{\mathcal{E}}$: Compton form factors
  = convolutions of hard scattering amplitude and twist-2 GPDs H, $\widetilde{H}$, E, $\widetilde{E}$
- F_1: Dirac, F_2: Pauli form factor of the nucleon

HERMES DVCS $\mathcal{A}_C$ on a hydrogen target

All data 1996-2005



constant term $\propto -A_C^{\cos\phi}$

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

[higher twist]

[gluon leading twist]

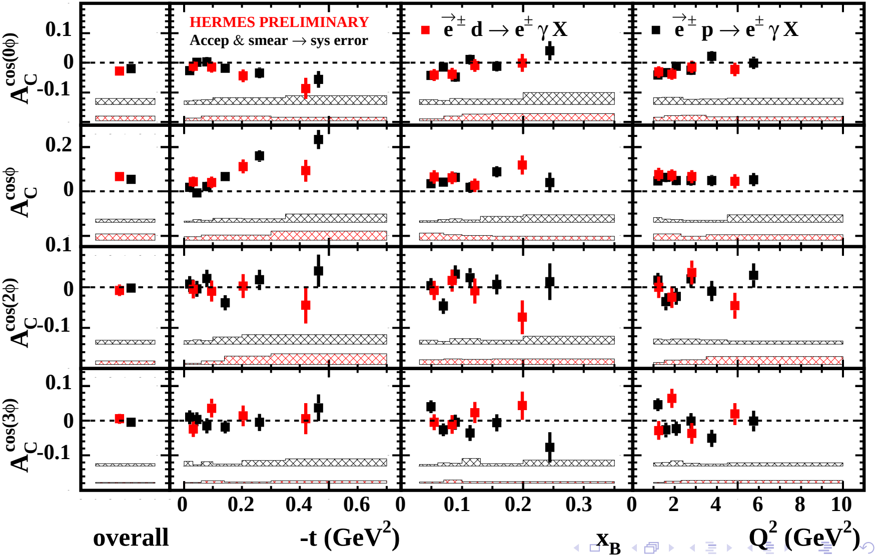
Resonant fraction

$ep \to e\Delta^+\gamma$

- GPD model: VGG – Phys. Rev. **D60** (1999) 094017 — Prog. Nucl. Phys. **47** (2001) 401 —

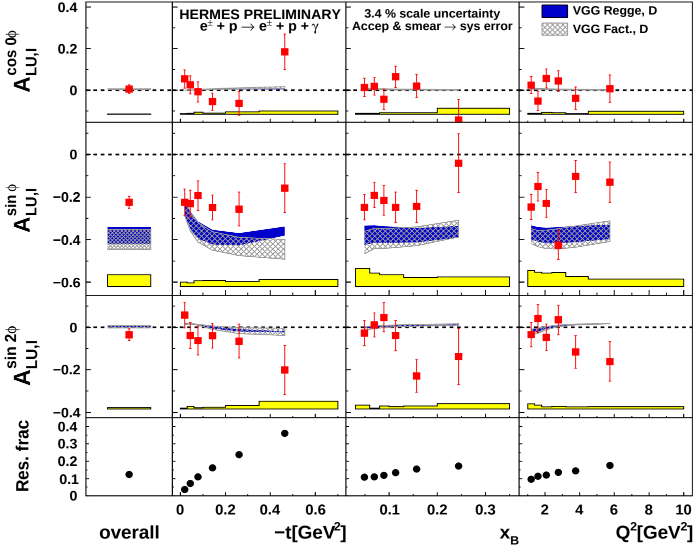
HERMES DVCS $\mathcal{A}_C$: H_2 vs. D_2 target

All data
1996-2005



HERMES DVCS $\mathcal{A}_{\mathrm{LU}}^{\mathcal{I}}$ on a hydrogen target

All data
1996-2005

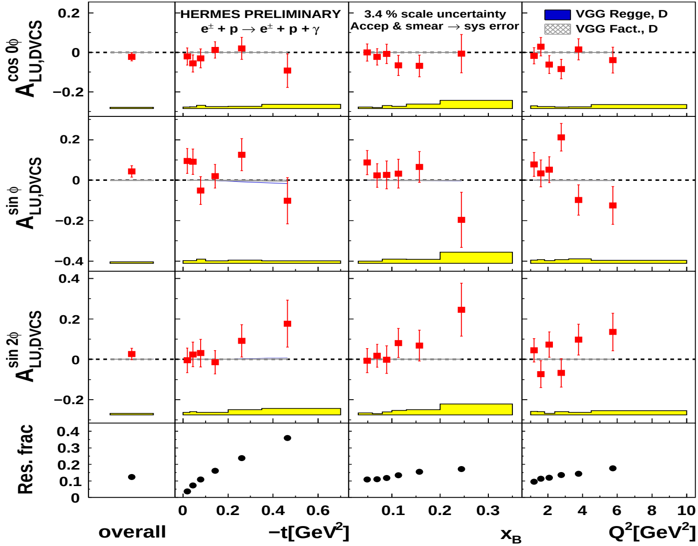


$\propto \mathrm{Im}\,[F_1\mathcal{H}]$

←[higher twist]

Resonant fraction

HERMES DVCS $\mathcal{A}_{LU}^{DVCS}$ on a hydrogen target



All data
1996-2005

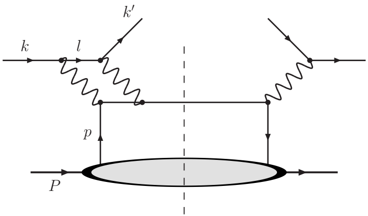
$\propto [\mathcal{H}\mathcal{H}^* + \widetilde{\mathcal{H}}\widetilde{\mathcal{H}}^*]$

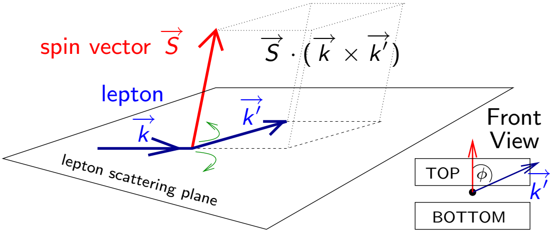
←[higher twist]

Resonant fraction

Two-Photon exchange contribution in DIS?

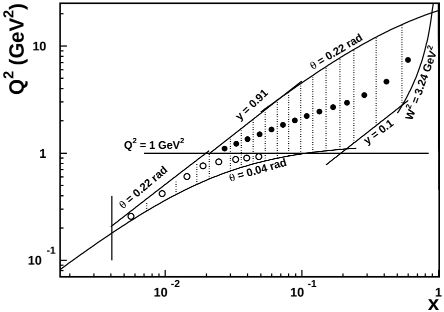
- Hint for two-photon exchange so far only in elastic ep-scattering
  - Discrepancy in FF measurements: 2γ-exchange as explanation?





- Transverse single-spin asymmetry $\mathcal{A}_{\mathrm{UT}}$ in inclusive DIS
  - Forbidden in one-photon exchange approximation
  - Caused by interference of multi-photon exchange with one-photon exchange (A. Metz *et al.*, **Phys.Lett.B 643**, 319-324, 2006)
- $\sigma^{\uparrow\downarrow} \propto \vec{S} \cdot (\vec{k} \times \vec{k'})$
  - Measure left-right asymmetry A_{N} or sine-modulation $A_{\mathrm{UT}}^{\sin\phi}$
  - $\mathcal{A}_{\mathrm{UT}}$ expected to be $\mathcal{O}(\alpha_{\mathrm{em}} M_{\mathrm{pol}}/Q) \approx 0.01$. Sign switch for $e^{\pm}$!

Measurement of left-right asymmetry at HERMES

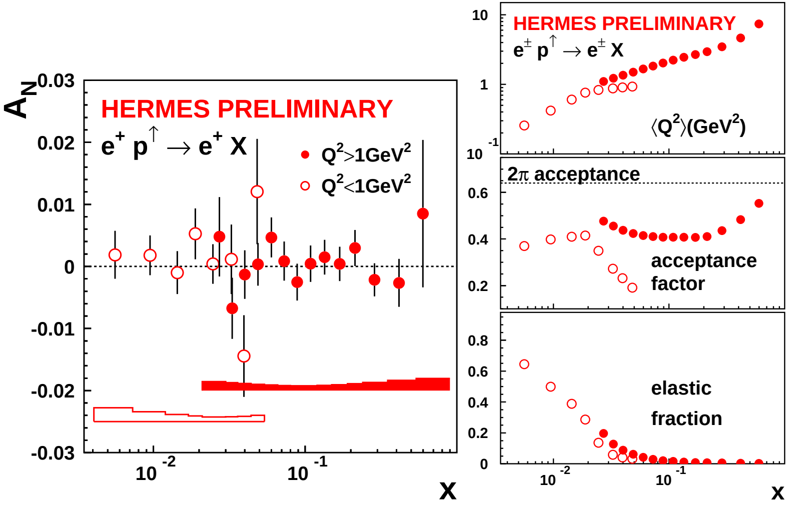


- Inclusive measurement
- Transversely polarized hydrogen target with polarization $P^{\uparrow\downarrow}$
- Positron and electron data
- Beam helicity balancing
- Expr. for A_{N}: false asymmetries due to acceptance cancel

$$A_{\mathrm{N}} = \frac{\sqrt{\frac{N_R^\uparrow}{L_P^\uparrow}\frac{N_L^\downarrow}{L_P^\downarrow}} - \sqrt{\frac{N_L^\uparrow}{L_P^\uparrow}\frac{N_R^\downarrow}{L_P^\downarrow}}}{\sqrt{\frac{N_R^\uparrow}{L^\uparrow}\frac{N_L^\downarrow}{L^\downarrow}} + \sqrt{\frac{N_L^\uparrow}{L^\uparrow}\frac{N_R^\downarrow}{L^\downarrow}}} = A_{\mathrm{true}}\left(1 + \frac{P^\uparrow - P^\downarrow}{P^\uparrow + P^\downarrow}\right) \approx A_{\mathrm{true}}$$

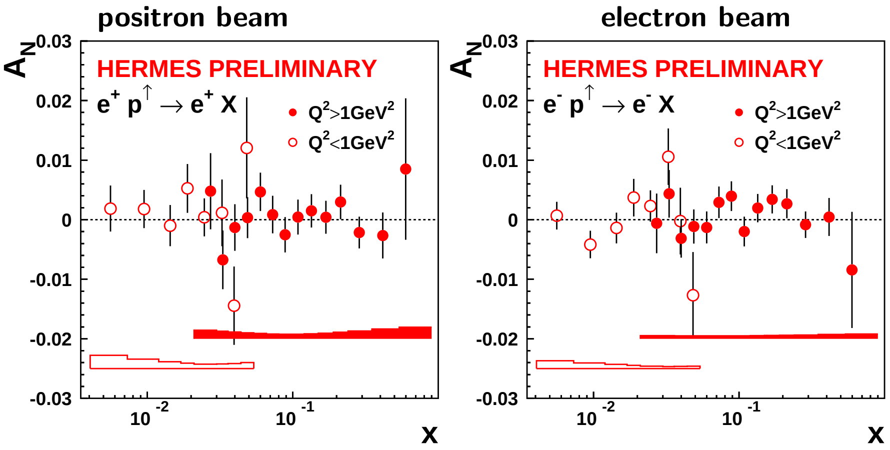
- Systematics:
  - Particle identification; trigger efficiencies; target polarization
  - Correction for e^+/e^- bending in magnetic dipole field of transv. target
  - Effects of misalignment of detector and beam

HERMES inclusive left-right asymmetry



Acceptance scaling factor due to not full 2π coverage in ϕ

HERMES inclusive left-right asymmetry



For both beam charges consistent with 0!

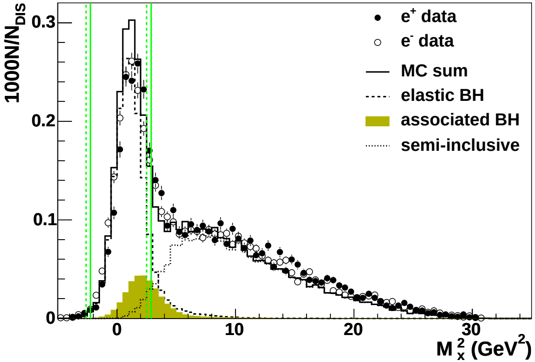
Summary and Outlook

- Data with two beam charges offer extraction of interesting physics
- Provide odd number of couplings to beam charge
  - E. g. DVCS/Bethe-Heitler interference term sensitive to beam charge
- DVCS azimuthal asymmetries at HERMES
  - Help to constrain GPD models
    - $\mathcal{A}_{\mathrm{C}}$ and $\mathcal{A}_{\mathrm{LU}}$ provide access to GPD H
    - Data set with transverse target polarization ($\mathcal{A}_{\mathrm{UT}}$): access to GPD E (supressed otherwise)
  - Provide model-dependent constrain on $J_u + k \cdot J_d$
- Two-Photon exchange signal at HERMES
  - Consistent with zero
  - Publication to come in 2009
- HERMES high lumi data set 2006/2007
  - Recoil detector to detect recoiling target proton
  - More data on tape
    - Unpolarized hydrogen: factor of ≈ 2.5 more data
    - Unpolarized deuterium: 50% more
  - Results to come!

BACKUP

Exclusivity at HERMES

- 1996-2005: **missing mass technique** for **ep→eX**γ (Monte Carlo)



X=p

X=$\Delta^+ \rightarrow \begin{cases} n\pi^+ \\ p\pi^0 \end{cases}$

X=π^0**+..**

- With the **Recoil Detector** (2006/2007): tag exclusive events
  - Identify recoiling protons
  - Identify particles from background processes

    ⇒ semi-inclusive DIS: 3% ↘≪ 1%, **resonant:** 12% ↘ 1%

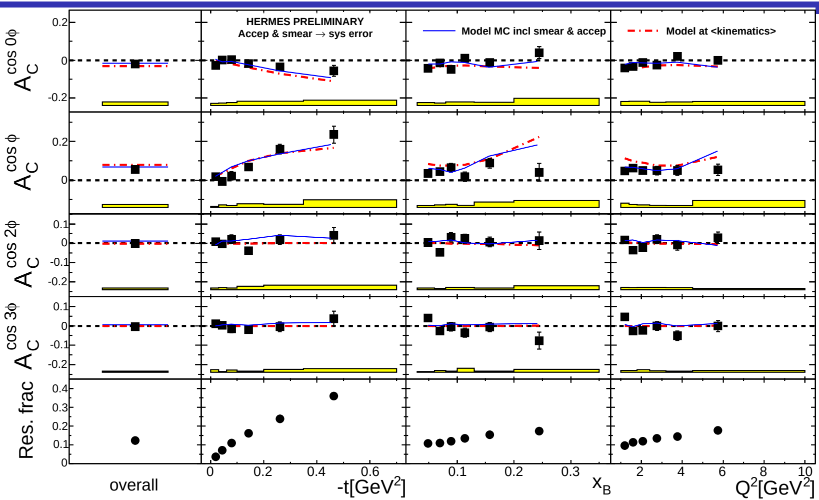
Corrections √ and systematic uncertainties ■

- (√, ■) Shift of exclusive peak between e^- and e^+ data (small)
- (√, ■) Semi-inclusive and exclusive background
  ⇒ Fractions from Monte Carlo
- (■) Acceptance, bin-width, smearing and detector misalignment (main contribution)
  ⇒ Estimated from Monte Carlo simulation employing range of available models
  ⇒ Model dependence
- The contributions from the resonance region, e.g.

$$eN \rightarrow e\Delta^+\gamma$$

  stays part of the signal, in average 12%!
  The underlying **"associated" asymmetry is unknown!**

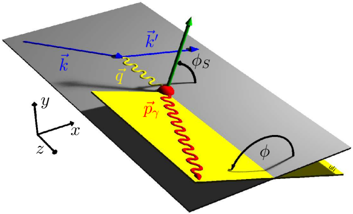
Acceptance, bin-width, smearing and misalignment effects



The difference between "model-generated" and in the HERMES acceptance reconstructed MC amplitudes is taken as sytematic uncertainty

Transverse Target Spin Asymmetry $\mathcal{A}_{\mathrm{UT}}(\phi, \phi_s)$

- Reminder: DVCS-BH interference term sensitive to beam charge
- $\mathcal{A}_{\mathrm{UT}}$: the only DVCS asymmetry (on p) for which GPD E is not supressed



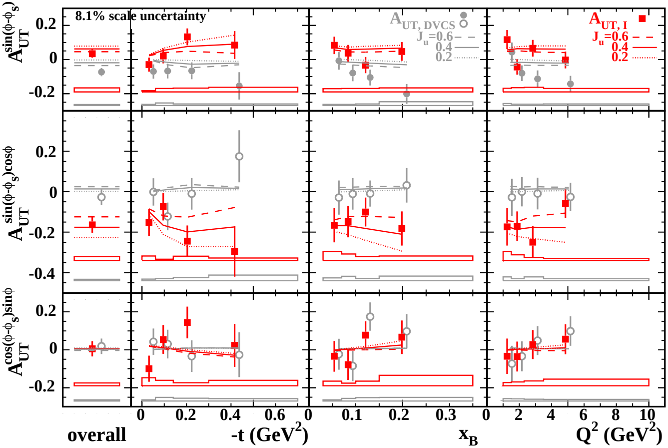
- Ji relation: access to total angular momentum of quarks
  $J_{\mathrm{q}} = \frac{1}{2} \lim_{t \to 0} \int_{-1}^{1} \mathrm{d}x\, x \left[H_{\mathrm{q}}(x, \xi, t) + E_{\mathrm{q}}(x, \xi, t) \right]$

$$A_{\mathrm{UT}}^{\mathcal{I}}(\phi, \phi_s) \propto \left[\mathrm{d}\sigma^{+}(\phi, \phi_s) - \mathrm{d}\sigma^{-}(\phi, \phi_s)\right] - \left[\mathrm{d}\sigma^{+}(\phi, \phi_s + \pi) - \mathrm{d}\sigma^{-}(\phi, \phi_s + \pi)\right]$$

$$\begin{aligned} A_{\mathrm{UT}}^{\mathcal{I}}(\phi, \phi_s) \;&\propto\; \mathrm{Im}\left(F_2 \mathcal{H} - F_1 \mathcal{E}\right) \sin(\phi - \phi_s) \cos\phi \\ &+\; \mathrm{Im}\left(F_2 \widetilde{\mathcal{H}} - (F_1 + \xi F_2) \widetilde{\mathcal{E}}\right) \cos(\phi - \phi_s) \sin\phi \end{aligned}$$

HERMES $\mathcal{A}_{\mathrm{UT}}$ amplitudes

Complete transversely polarized data set



sensitive to J_{u}:

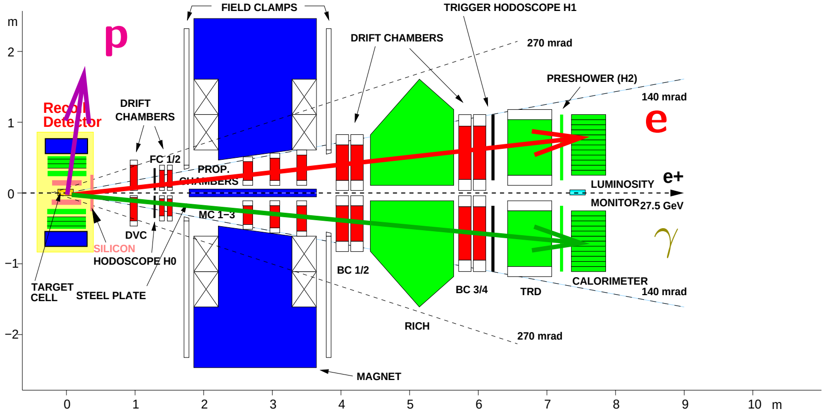
$$\mathrm{Im}(F_2\mathcal{H} - F_1\mathcal{E}) \cdot$$
$$\sin(\phi - \phi_s)\cos(n\phi)$$

←NOT sensitive to J_{u}:

$$\mathrm{Im}\left(F_2\widetilde{\mathcal{H}} - (F_1 + \xi F_2)\widetilde{\mathcal{E}}\right) \cdot$$
$$\cos(\phi - \phi_s)\sin\phi$$

Sensitivity on J_{u}: GPD-model (VGG), assuming $J_{\mathrm{d}} = 0$

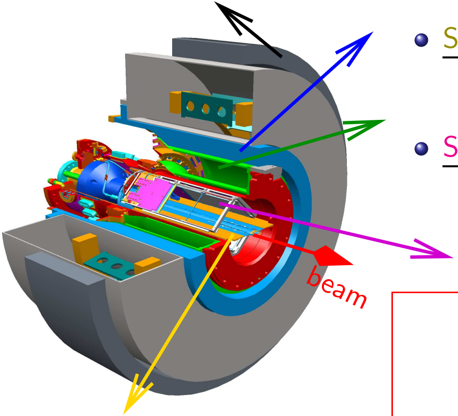
Dedicated high lumi run 2006/2007 with Recoil



- Unpolarized H_2 target: 58 Mio DIS (factor of ≈ 3 more), Recoil: 38
- Unpolarized D_2 target: 14 Mio DIS (factor of > 1 more), Recoil: 10
- **2 Beam helicities**, $\mathbf{e^+}$ **and** $\mathbf{e^-}$, Recoil: only e^+

The HERMES Recoil Detector

- SC Solenoid (1 Tesla)



- Target Cell with unpol. H_2 or D_2

- Photon Detector
  - 3 layers of Tungsten/Scintillator
- Scintillating Fiber Tracker
  - 2 Barrels
  - Each 2 parallel- & 2 stereo-layers
- Silicon Strip Detector
  - 2 Layers of 16 double-sided sensors
  - (10cm×10cm) active area
  - Inside accelerator vacuum

Silicon & Fiber Tracker:

$p_\mathrm{p} \in [135, 1200]$ MeV/c

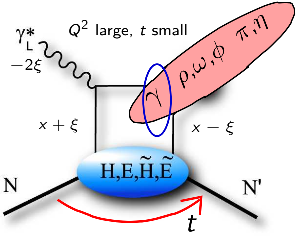
p/π **PID** for $p < 650$ MeV/c

Photon Detector:

p/π **PID** for $p > 600$ MeV/c

π^0 background supression

Exclusivity at HERMES in a nutshell



GPD access at HERMES:

unpolarized	polarized
photon: $J^{\mathcal{P}} = 1^-$ (DVCS)	
H: A_{C}, A_{LU}, A_{UT} **E:** A_{UT}	$\widetilde{\mathbf{H}}$: A_{UL} , $[A_{\mathrm{UT}}]$ $\widetilde{\mathbf{E}}$: $[A_{\mathrm{UT}}]$
$J^{\mathcal{P}} = 1^-$ mesons	$J^{\mathcal{P}} = 0^-$ mesons