# Exclusive Processes at Hermes

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for the hermes collaboration

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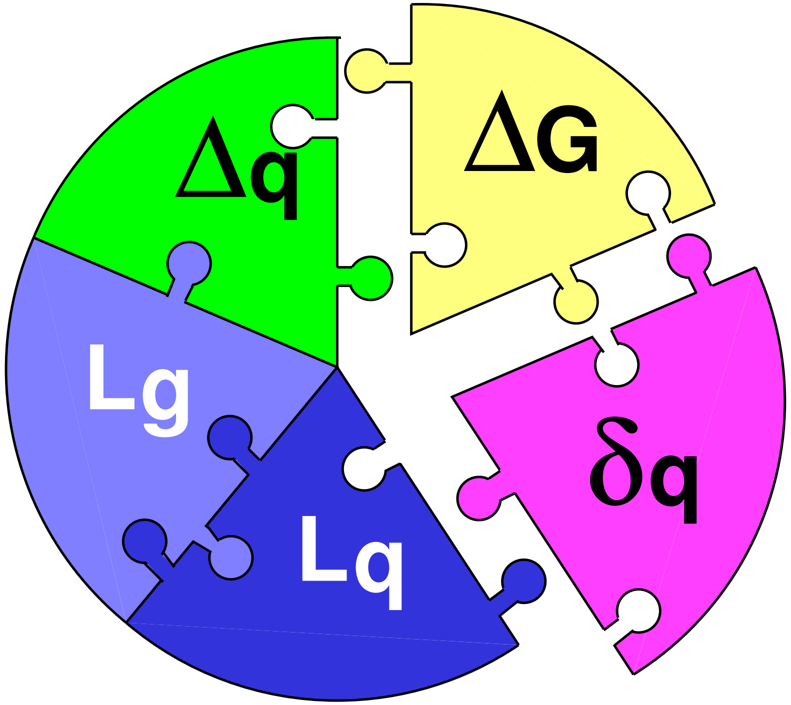
## Outline

- Motivation
- Deeply Virtual Compton Scattering
- DVCS Measurements at HERMES
- Summary and Outlook

# Motivation — Nucleon Structure




Proton Spin

$$\frac{1}{2} = \underbrace{\frac{1}{2}(\overbrace{\Delta u + \Delta d + \Delta s}^{\sim 30\%}) + L_q}_{J_q} + \underbrace{\Delta G + L_g}_{J_g}$$

$\Delta q$: known from DIS

$\Delta G$: first measurments in DIS

$L_q$, $L_g$: unknown!

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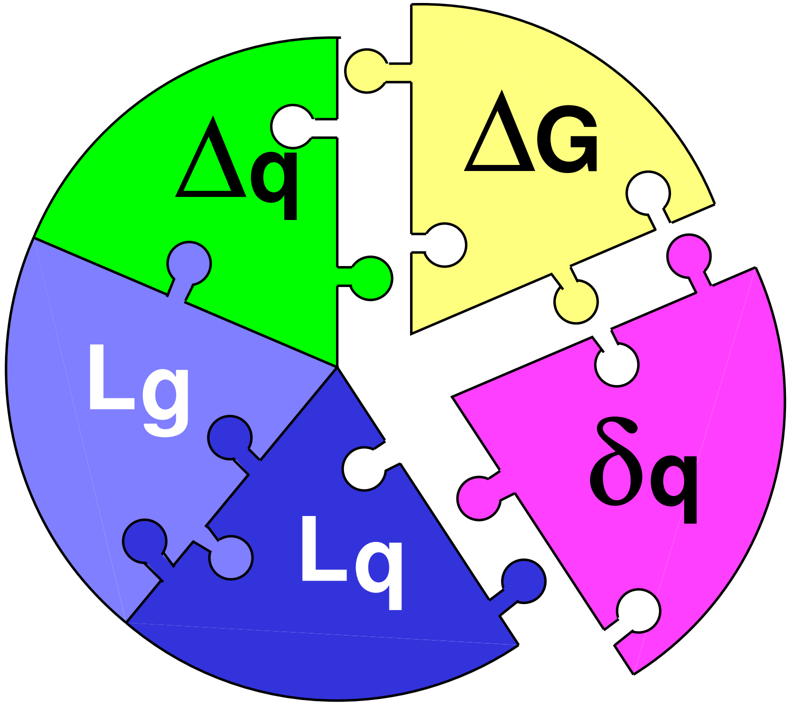


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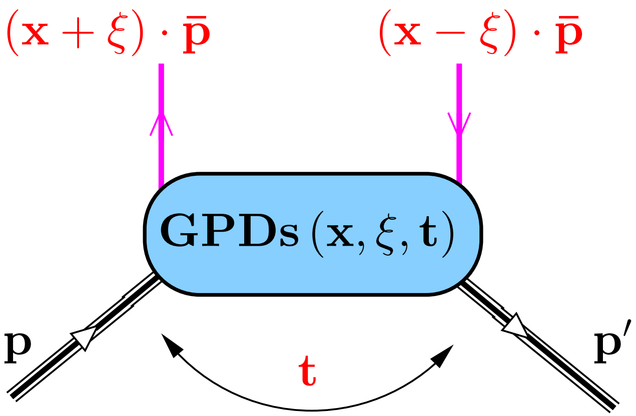



Generalized Parton Distributions $\Rightarrow J_q,\ J_g$

## Ji's Sum Rule — Ji, PRL 78 (1997) 610

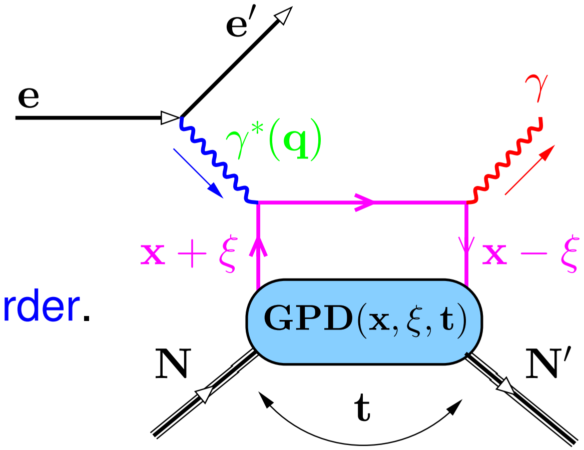
$$J_{q,g} = \frac{1}{2}\lim_{t\to 0}\int_{-1}^{1} dx \cdot x \cdot [H_{q,g}(x,\xi,t) + E_{q,g}(x,\xi,t)]$$

# How to Access GPDs?

- GPDs constrained by known quantities (FFs, PDFs, ...) and accessible in exclusive processes.
- At large $Q^2$ and small $t$, exclusive electroproduction of real photons or mesons can be factorized into a hard, perturbative part and a soft, non-perturbative part (GPDs).
- Deeply Virtual Compton Scattering

  $e + N \rightarrow e' + N' + \gamma$

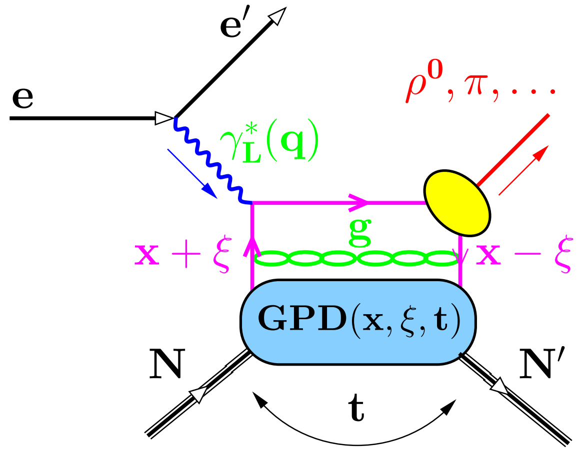
  - described by GPDs $H, E, \widetilde{H}, \widetilde{E}$,
  - simplest process, gluons absent in the leading order.




- Exclusive Meson Production

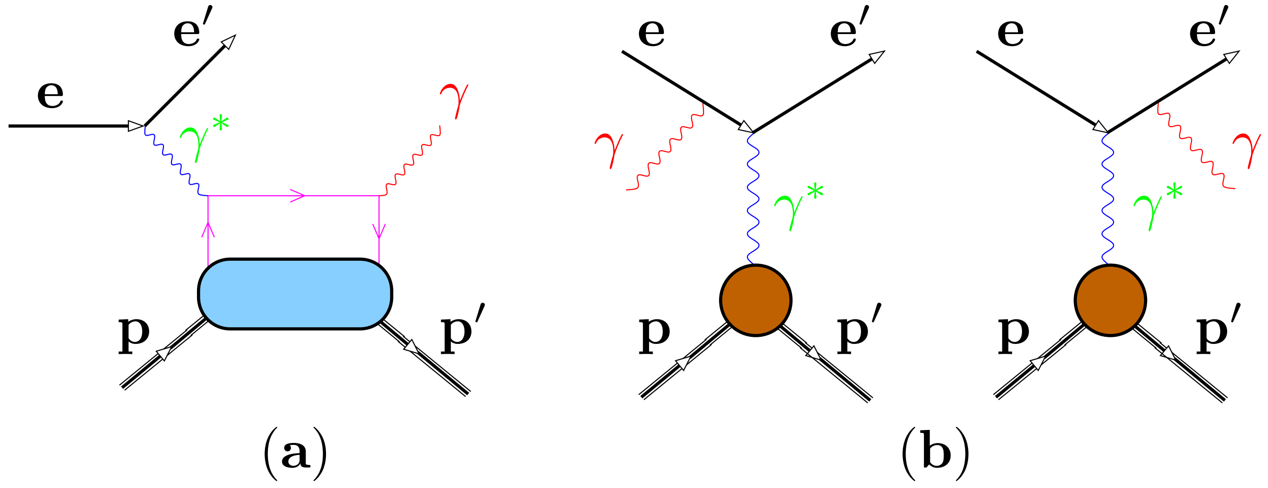
  $e + N \rightarrow e' + N' + (\rho^0, \pi, \ldots)$

  - vector mesons $(\rho^0, \omega, \phi)$: $H, E$,
  - pseudoscalar mesons $(\pi, \eta)$: $\widetilde{H}, \widetilde{E}$,
  - pion pairs $(\pi^+\pi^-)$: $H, E$,
  - meson distribution amplitude should be taken care of.



# Deeply Virtual Compton Scattering

- DVCS (a) and Bethe-Heithler (b) processes have the same initial and final states:




- Interference between DVCS and Bethe-Heitler:

$$d\sigma(\mathrm{eN} \rightarrow \mathrm{eN}\gamma) \propto |\mathcal{T}_{BH}|^2 + |\mathcal{T}_{DVCS}|^2 + \underbrace{\mathcal{T}_{BH}\mathcal{T}^*_{DVCS} + \mathcal{T}^*_{BH}\mathcal{T}_{DVCS}}_{\mathcal{I}}$$

- $\mathcal{T}_{BH}$ is parameterized in terms of Dirac and Pauli Form Factors $F_1, F_2$, calculable in QED.

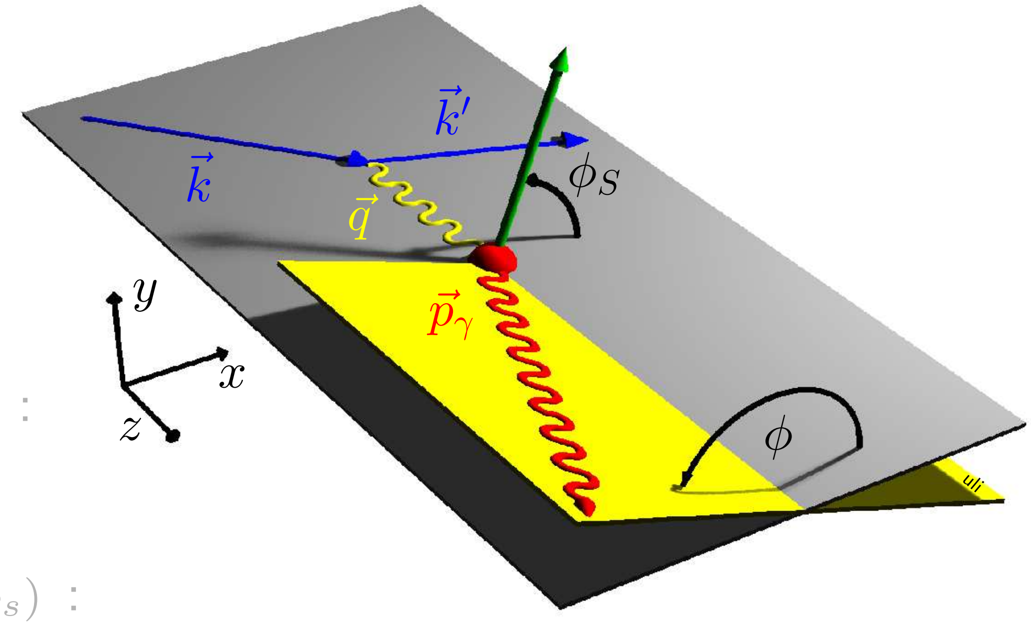
- $\mathcal{T}_{DVCS}$ is parameterized in terms of Compton form factors (convolution of GPDs) $\mathcal{H}, \mathcal{E}, \widetilde{\mathcal{H}}, \widetilde{\mathcal{E}}$.

- At HERMES kinematics, $\mathcal{T}^{BH} \gg \mathcal{T}^{DVCS}$ , $\mathcal{H}, \mathcal{E}, \widetilde{\mathcal{H}}, \widetilde{\mathcal{E}}$ are accessed through $\mathcal{I}$.

# Azimuthal Asymmetries in DVCS

$$d\sigma(\mathrm{eN} \to \mathrm{eN}\gamma) \propto |\mathcal{T}_{BH}|^2 + |\mathcal{T}_{DVCS}|^2 + \underbrace{\mathcal{T}_{BH}\mathcal{T}^*_{DVCS} + \mathcal{T}^*_{BH}\mathcal{T}_{DVCS}}_{\mathcal{I}}$$

- $\mathcal{I}$ induces azimuthal asymmetries in the cross-section:
  - Beam-charge asymmetry $A_C(\phi)$ :
    $d\sigma(e^+,\phi) - d\sigma(e^-,\phi) \propto \mathrm{Re}[F_1\mathcal{H}] \cdot \cos\phi$
  - Beam-spin asymmetry $A_{LU}(\phi)$ :
    $d\sigma(\overrightarrow{e},\phi) - d\sigma(\overleftarrow{e},\phi) \propto \mathrm{Im}[F_1\mathcal{H}] \cdot \sin\phi$
  - Longitudinal target-spin asymmetry $A_{UL}(\phi)$ :
    $d\sigma(\overleftarrow{P},\phi) - d\sigma(\overrightarrow{P},\phi) \propto \mathrm{Im}[F_1\widetilde{\mathcal{H}}] \cdot \sin\phi$
  - Transverse target-spin asymmetry $A_{UT}(\phi,\phi_s)$ :
    $d\sigma(\phi,\phi_S) - d\sigma(\phi,\phi_S+\pi)$
    $\propto \mathrm{Im}[F_2\mathcal{H} - F_1\mathcal{E}] \cdot \sin(\phi-\phi_S)\cos\phi + \mathrm{Im}[F_2\widetilde{\mathcal{H}} - F_1\xi\widetilde{\mathcal{E}}] \cdot \cos(\phi-\phi_S)\sin\phi$




$\Longrightarrow$ the only place $\mathcal{E}$ enters in the leading order $\Longrightarrow$ $\mathrm{A}_{\mathrm{UT}}^{\sin(\phi-\phi_S)\cos\phi}$ sensitive to $J_q$

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

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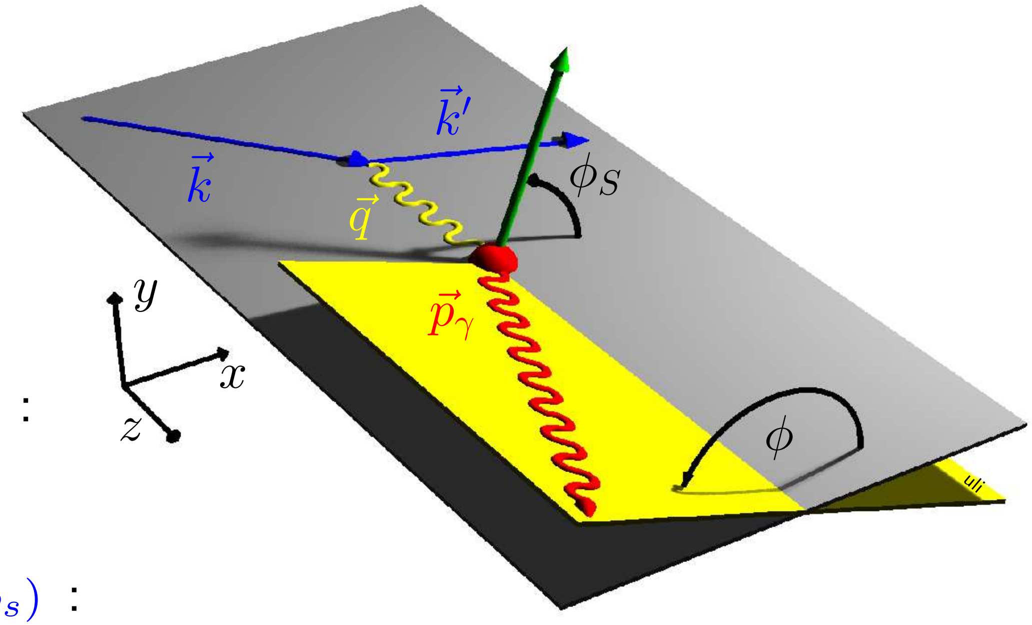


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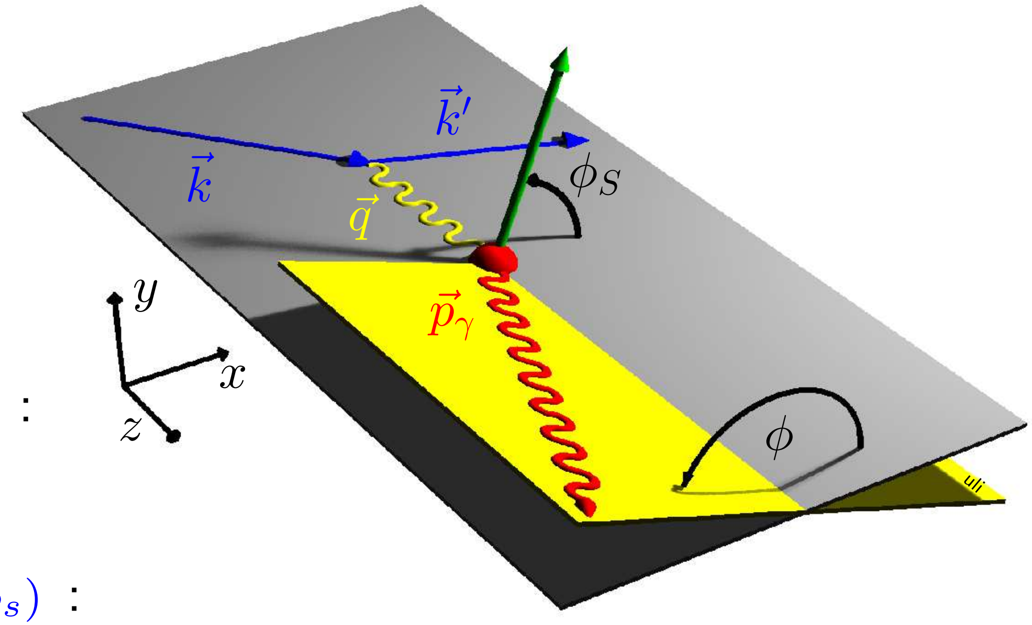


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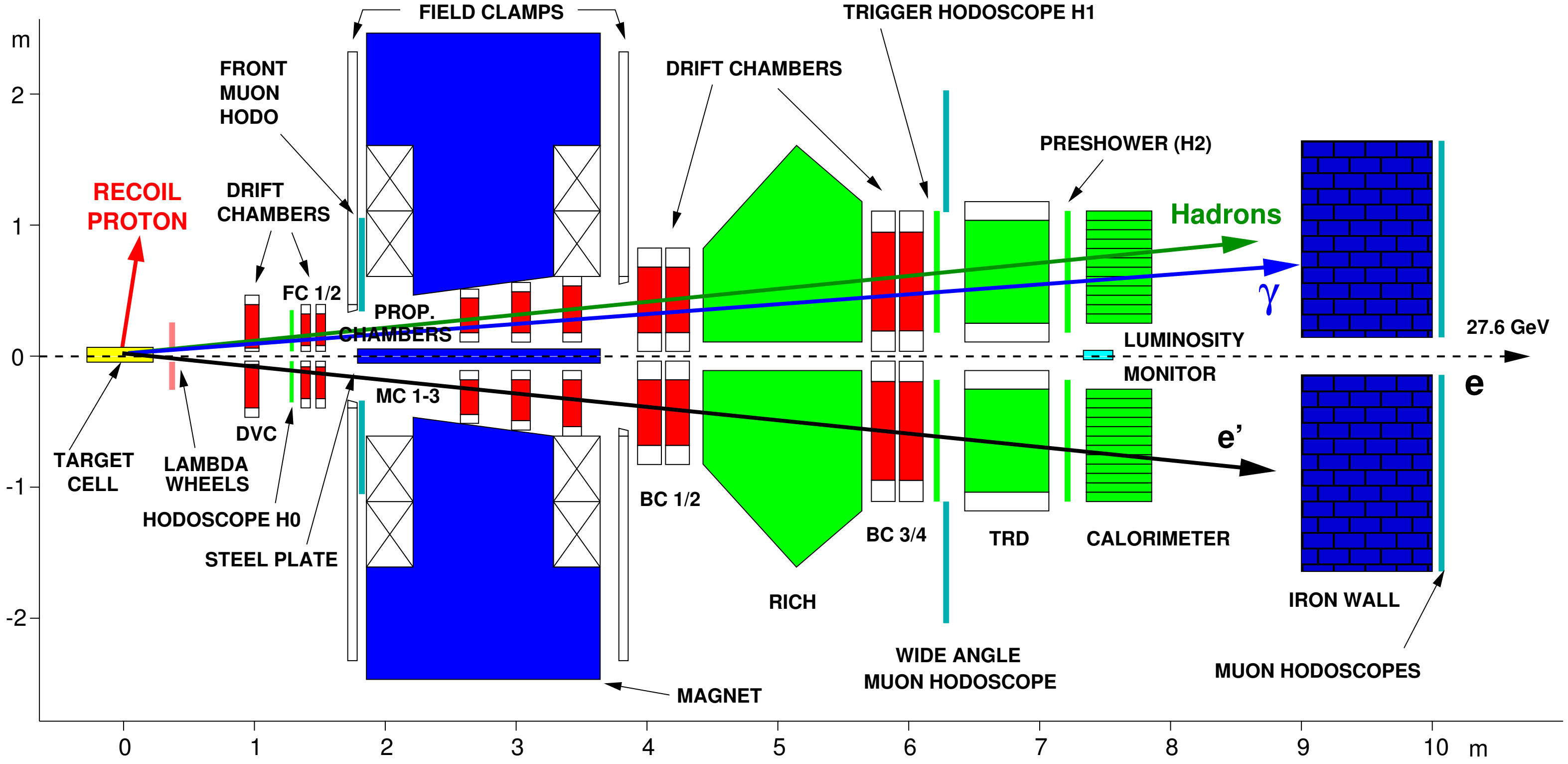
# DVCS Measurements at HERMES

- Fixed target experiment, Forward spectrometer
  - Tracking: $\delta P/P < 2\%$, $\delta\theta < 1$ mrad
  - Particle Identification: $\epsilon_e > 99\%$, hadron contamination $< 1\%$
  - Photons: calorimeter $\delta E_\gamma / E_\gamma \sim 5\%$
  - Recoiling protons not detected $\Rightarrow$ missing mass technique ($ep \rightarrow e'p\gamma$)

$$\mathrm{M_x^2 = (P_e + P_p - P_{e'} - P_\gamma)^2}$$

  - Background contribution $\sim 5\%$ is determined from MC and corrected.



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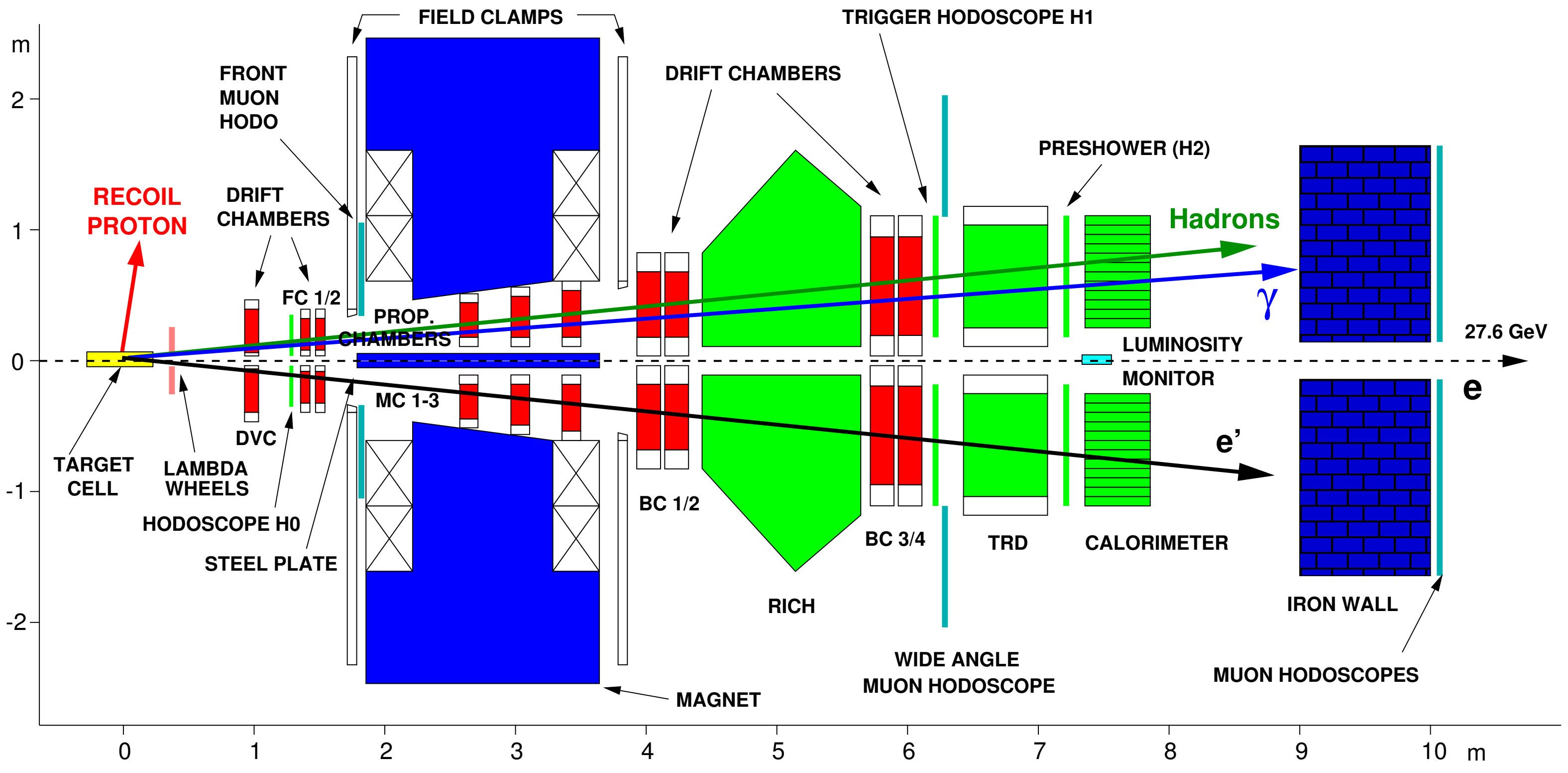

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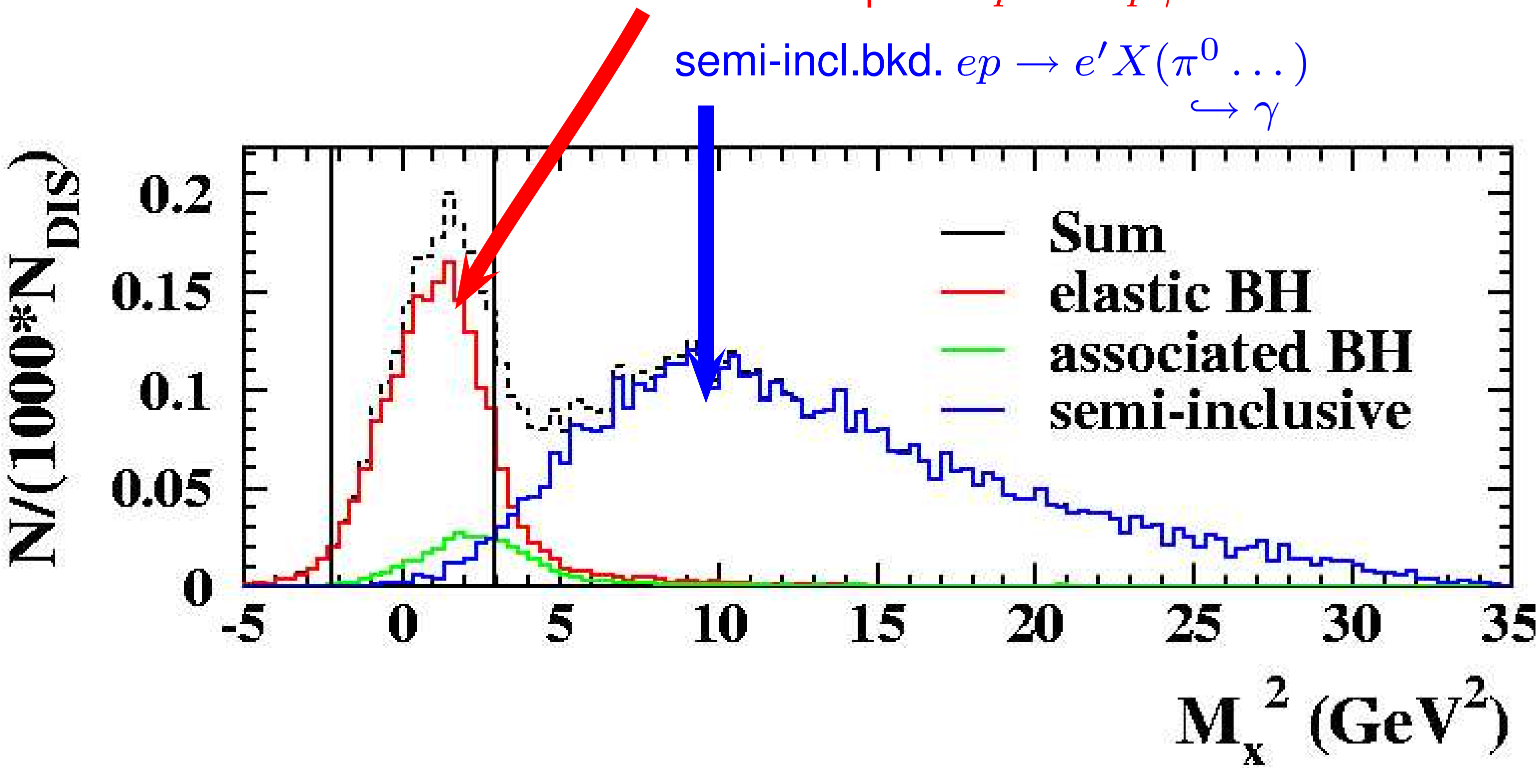

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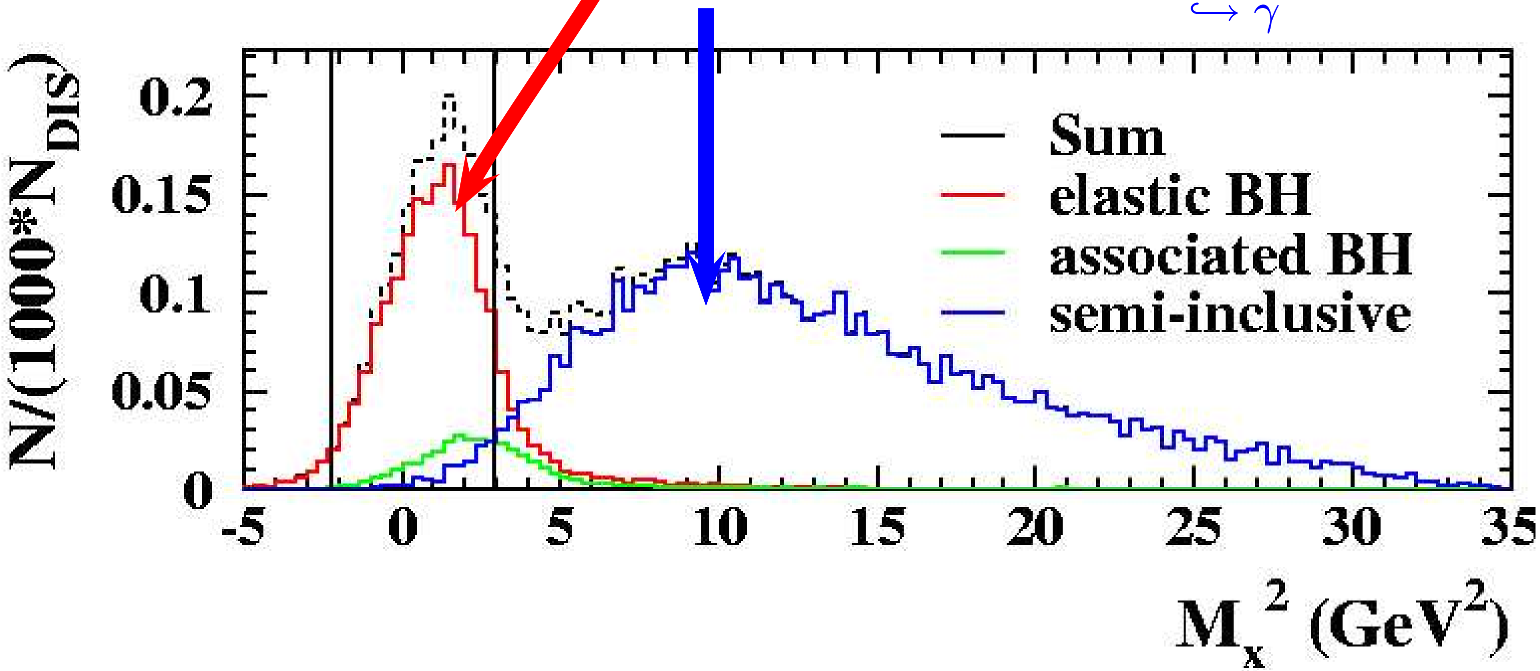
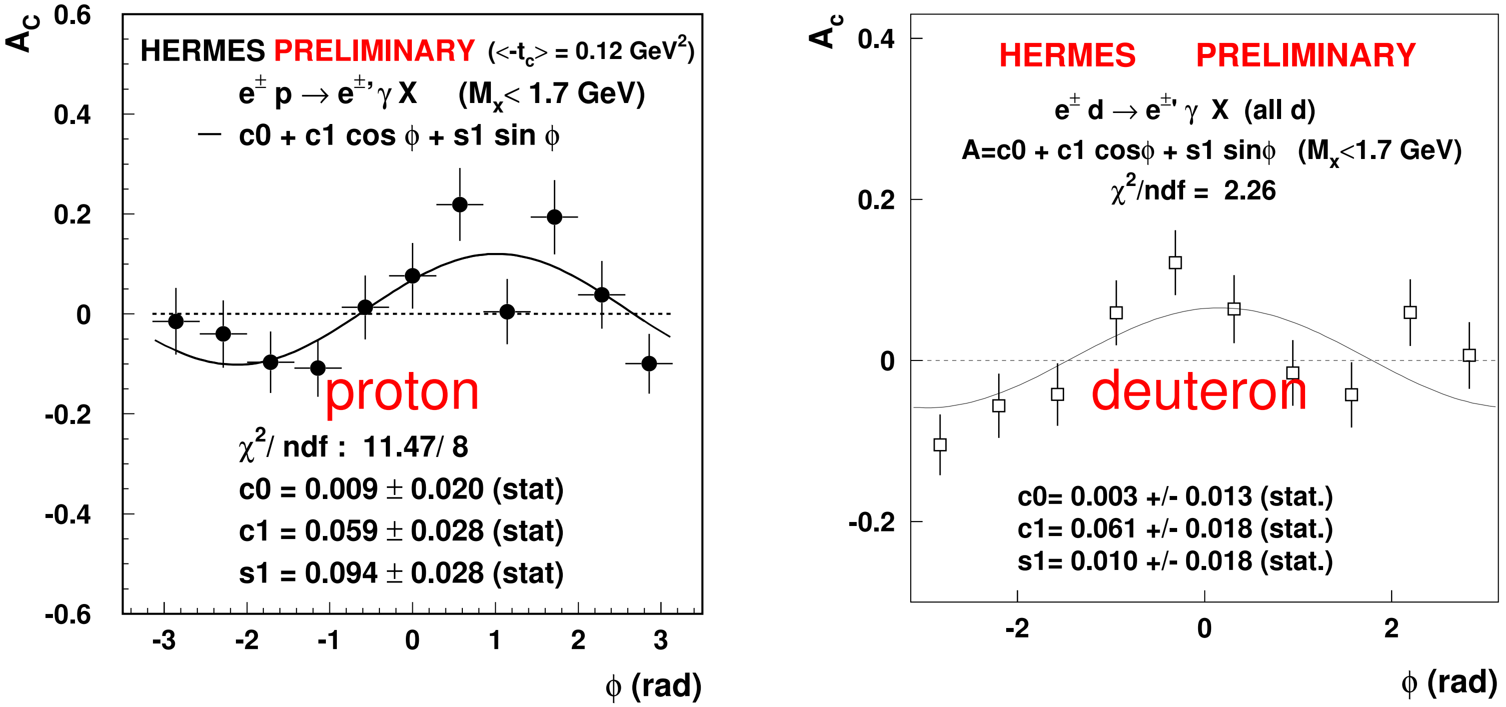


# Beam-Charge Asymmetry in DVCS



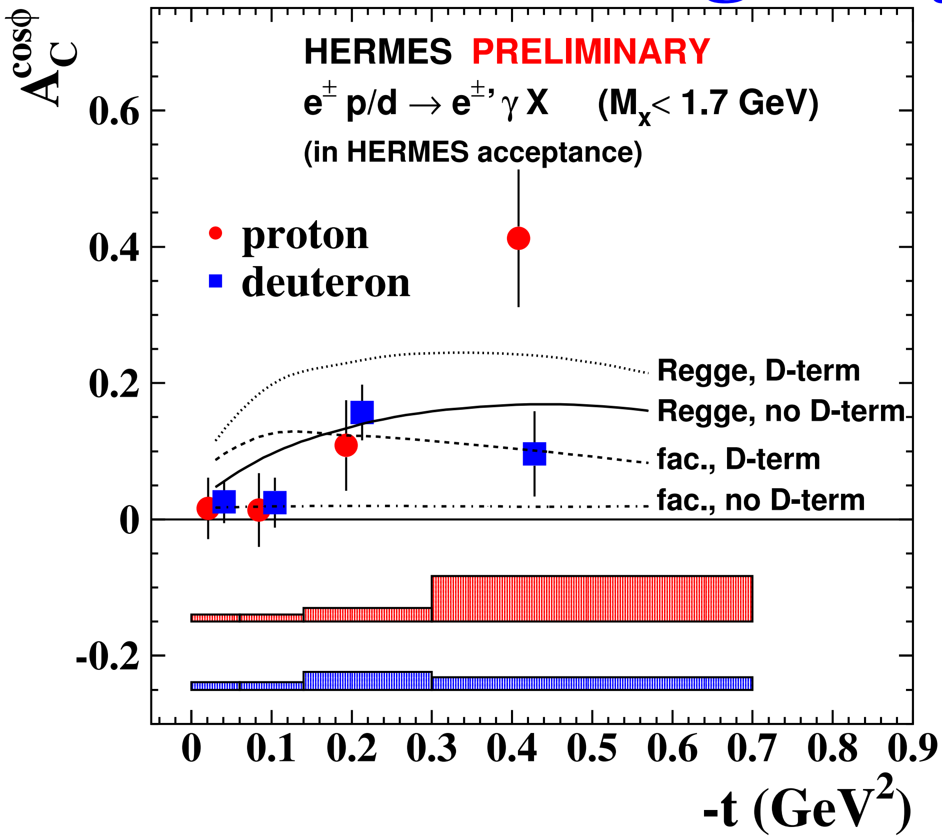

Beam-Charge Asymmetry:

$$A_C(\phi) = \frac{d\sigma(e^+,\phi) - d\sigma(e^-,\phi)}{d\sigma(e^+,\phi) + d\sigma(e^-,\phi)} \propto \mathrm{Re}\,[F_1\mathcal{H}] \cdot \cos\phi$$

proton: $A_C^{\cos\phi} = 0.059 \pm 0.028(stat)$

deuteron: $A_C^{\cos\phi} = 0.061 \pm 0.018(stat)$

# Beam-Charge Asymmetry in DVCS




- Contributions to $ed \to eX\gamma$

  $ed \to ed\gamma$ coherent production $\sim 20\%$

  $ed \to epn\gamma$ incoherent production $\sim 60\%$

  $ed \to e\Delta\gamma$ associated processes $\sim 15\%$

- coherent contribution enhanced at small $-t$

  first $-t$-bin $\sim 40\%$

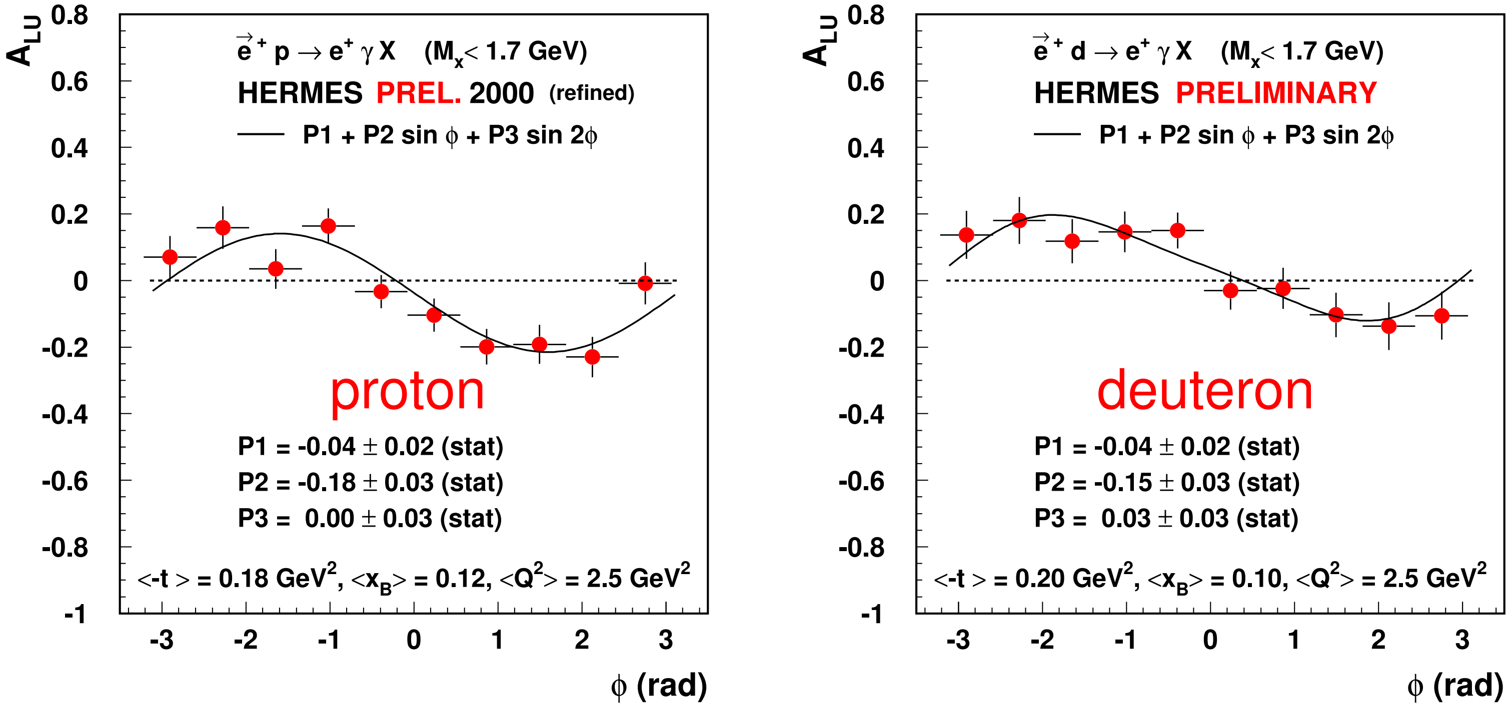
- neutron contribution ONLY at large $-t$

  last $-t$-bin $\sim 25\%$

GPD Model: M.Vanderhaeghen et al.
PRD 60 (1999) 094017

- $t$-dependence of BCA can be used to constrain GPD models
- limited by $e^-p$ sample (L$\sim 10$ pb$^{-1}$), HERMES is running with $e^-$ beam in 2005.

# Beam-Spin Asymmetry in DVCS



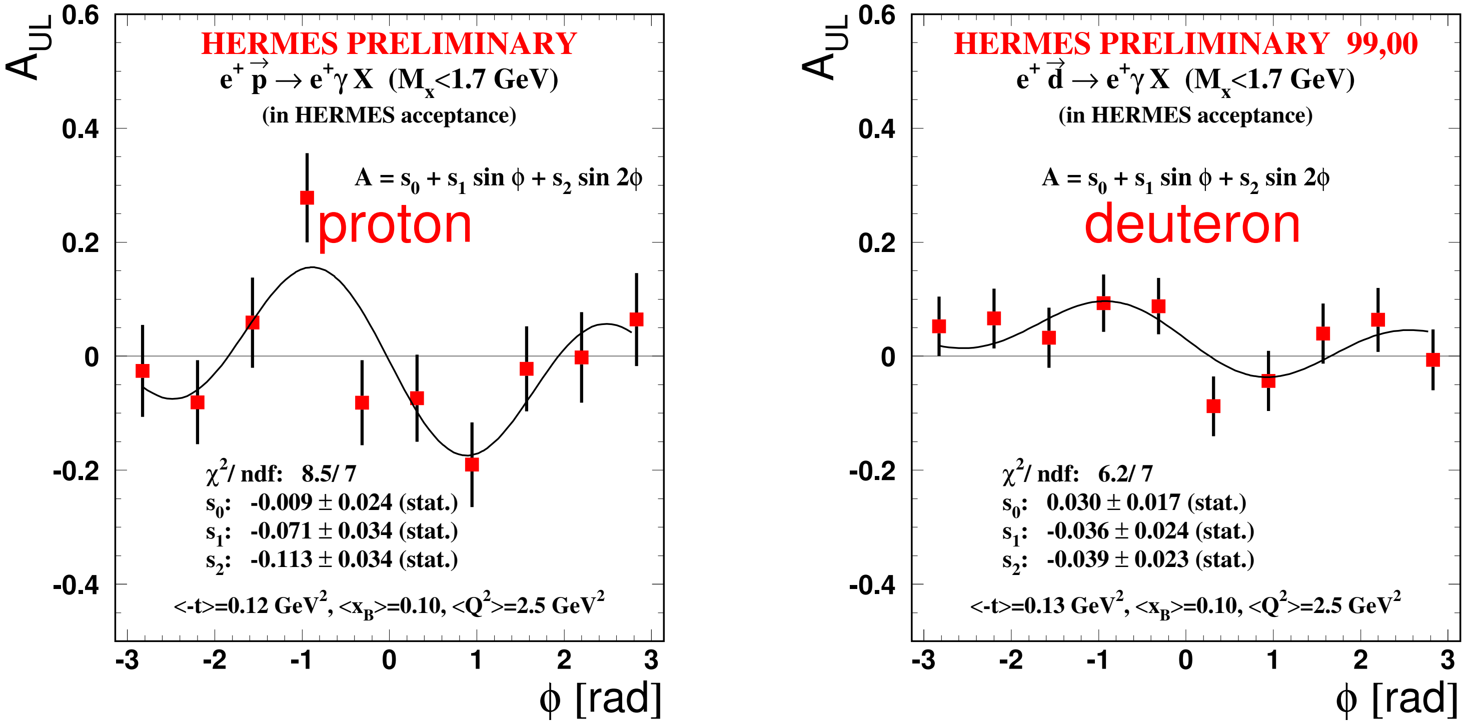

Beam-Spin Asymmetry: — [HERMES, PRL 87 (2001) 182001]

$$A_{LU}(\phi) = \frac{1}{|P_B|} \cdot \frac{d\sigma(\overrightarrow{e},\phi) - d\sigma(\overleftarrow{e},\phi)}{d\sigma(\overrightarrow{e},\phi) + d\sigma(\overleftarrow{e},\phi)} \propto \mathrm{Im}\,[F_1\mathcal{H}] \cdot \sin\phi$$

proton: $A_{LU}^{\sin\phi} = -0.18 \pm 0.03(stat)$

deuteron: $A_{LU}^{\sin\phi} = -0.15 \pm 0.03(stat)$

# Longitudinal Target-Spin Asymmetry in DVCS



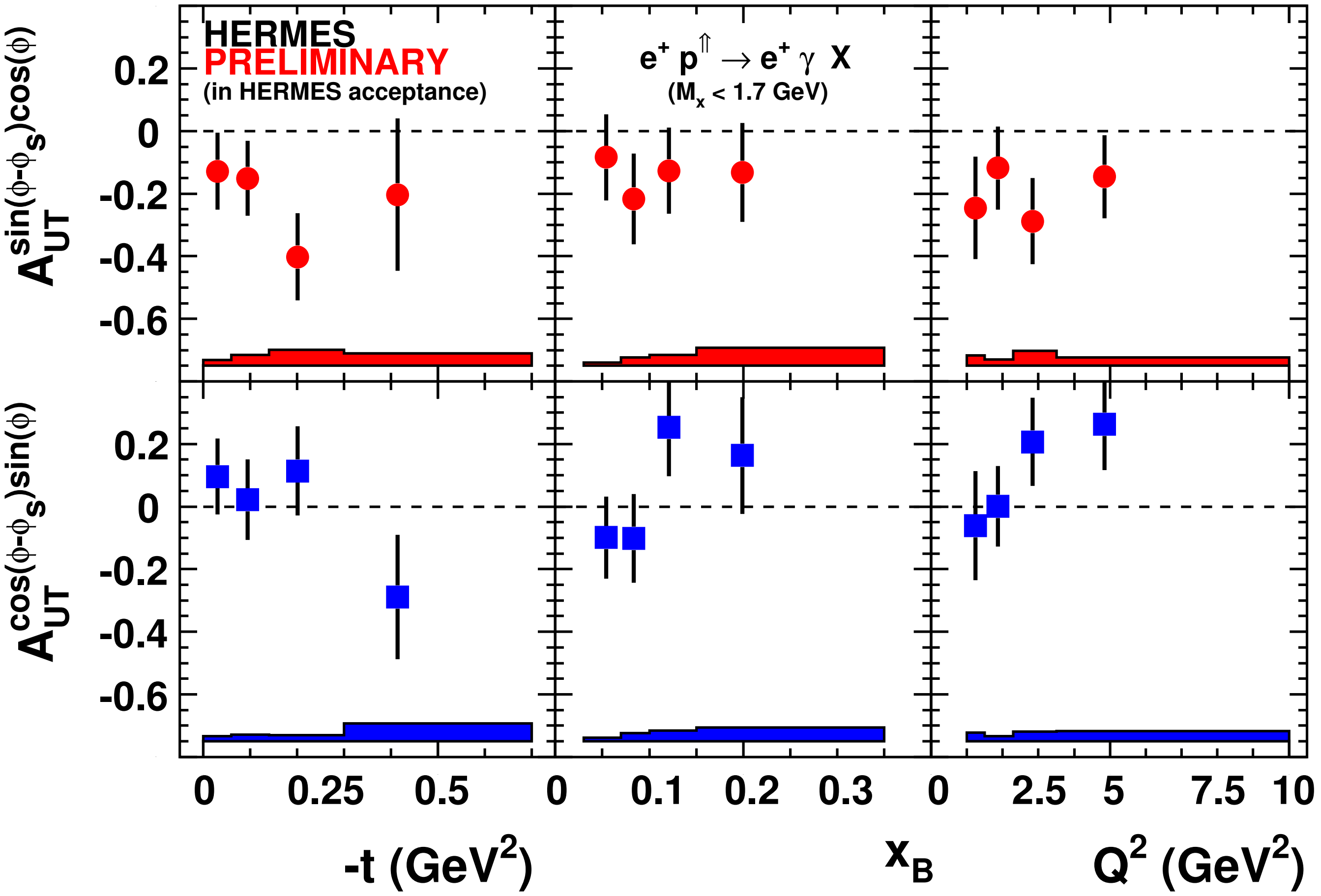

Longitudinal Target-Spin Asymmetry:

$$A_{UL}(\phi) = \frac{1}{|P_T|} \cdot \frac{d\sigma(\overleftarrow{P},\phi) - d\sigma(\overrightarrow{P},\phi)}{d\sigma(\overleftarrow{P},\phi) + d\sigma(\overrightarrow{P},\phi)} \propto \mathrm{Im}[F_1 \widetilde{\mathcal{H}}] \cdot \sin\phi$$

proton: $A_{UL}^{\sin\phi} = -0.071 \pm 0.034(stat)$

deuteron: $A_{UL}^{\sin\phi} = -0.036 \pm 0.024(stat)$

# Transverse Target-Spin Asymmetry in DVCS




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

$\propto \mathrm{Im}[F_2\widetilde{\mathcal{H}} - F_1\xi\widetilde{\mathcal{E}}]$

Transverse Target-Spin Asymmetry:

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

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

hermes

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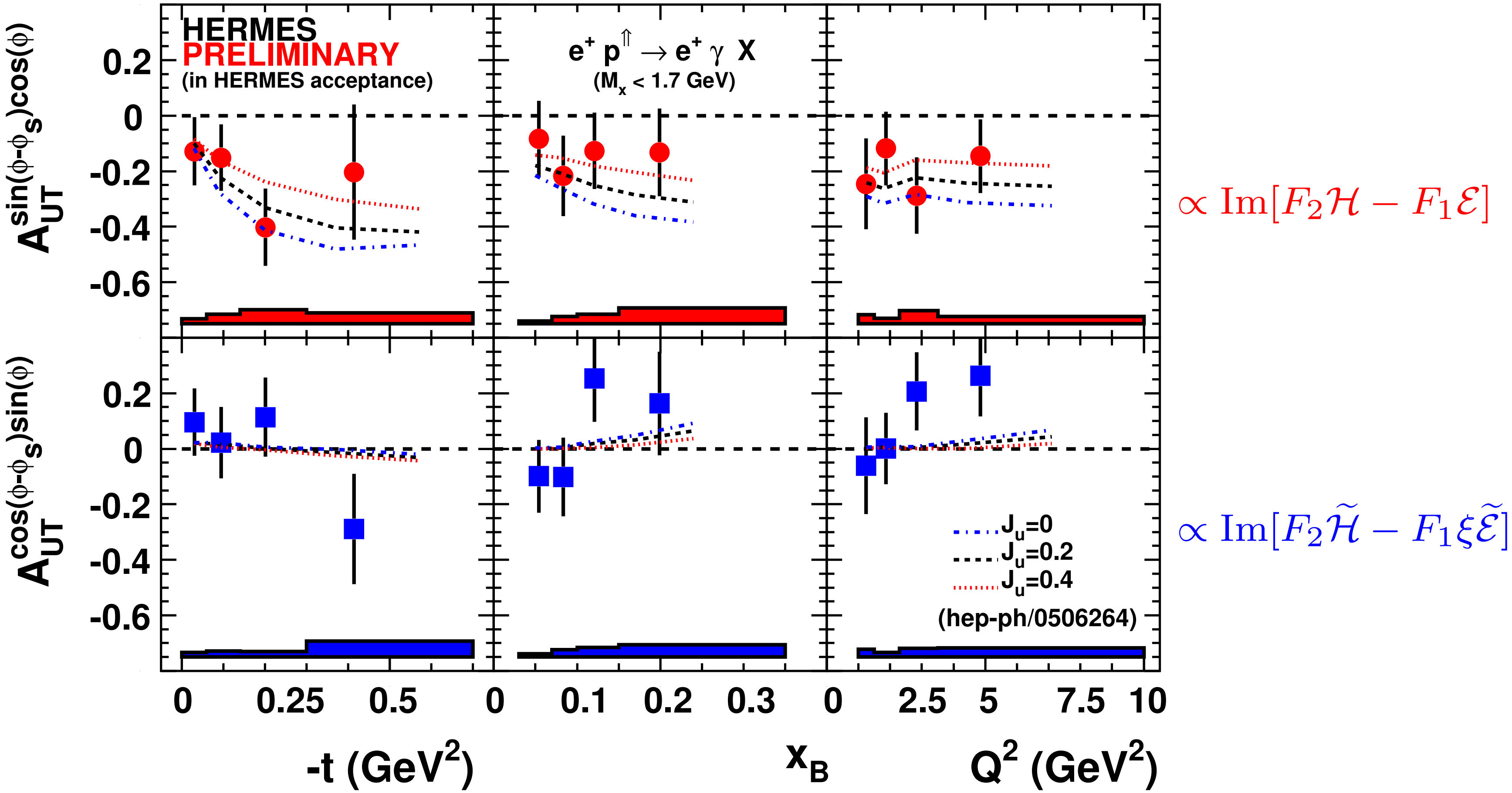


$$A_{UT}(\phi,\phi_s) \propto \mathrm{Im}[F_2\mathcal{H} - F_1\mathcal{E}] \cdot \sin(\phi-\phi_S)\cos\phi + \mathrm{Im}[F_2\widetilde{\mathcal{H}} - F_1\xi\widetilde{\mathcal{E}}] \cdot \cos(\phi-\phi_S)\sin\phi$$

- $A_{UT}^{\sin(\phi-\phi_S)\cos\phi}$ sensitive to $J_u$ and not to GPD model parameters (hep-ph/0506264)

$\Longrightarrow$ allows extraction of $J_u$ within these GPD models

- More data is coming (HERMES 2005 $e^-p^\Uparrow$, about the same statistics as here)

# Summary and Outlook

- Measurements of exclusive processes can increase our knowledge on the nucleon structure by determining the Generalized Parton Distributions.
- Measurement of the Transverse Target-Spin Asymmetry in DVCS will allow the first determination of $J_u$ through certain GPD models.
- Dedicated study on exclusive processes at HERMES with the new recoil detector starts at the end of 2005 (BSA, BCA in DVCS):
  - Allows to detect the recoiling proton
  - Background 'free' DVCS: Background $\sim 5\% \Rightarrow < 1\%$

$\Rightarrow$ Talk by Nils Pickert (404)

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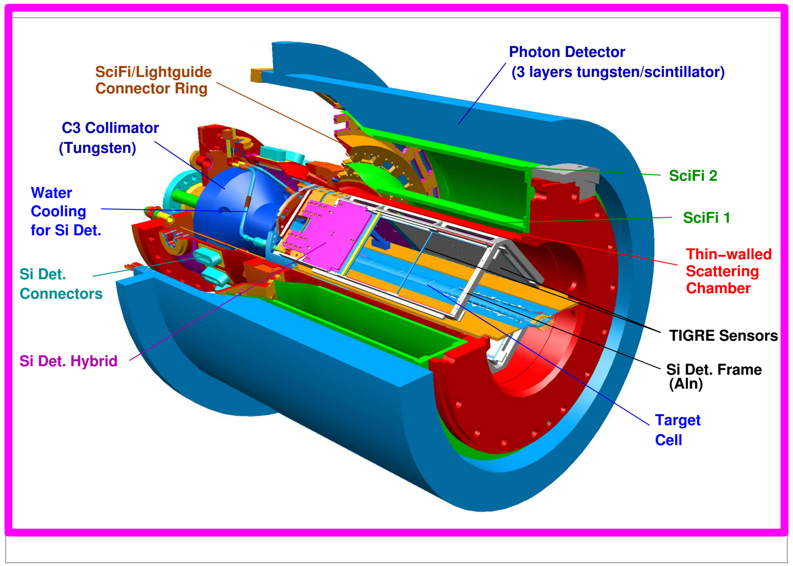


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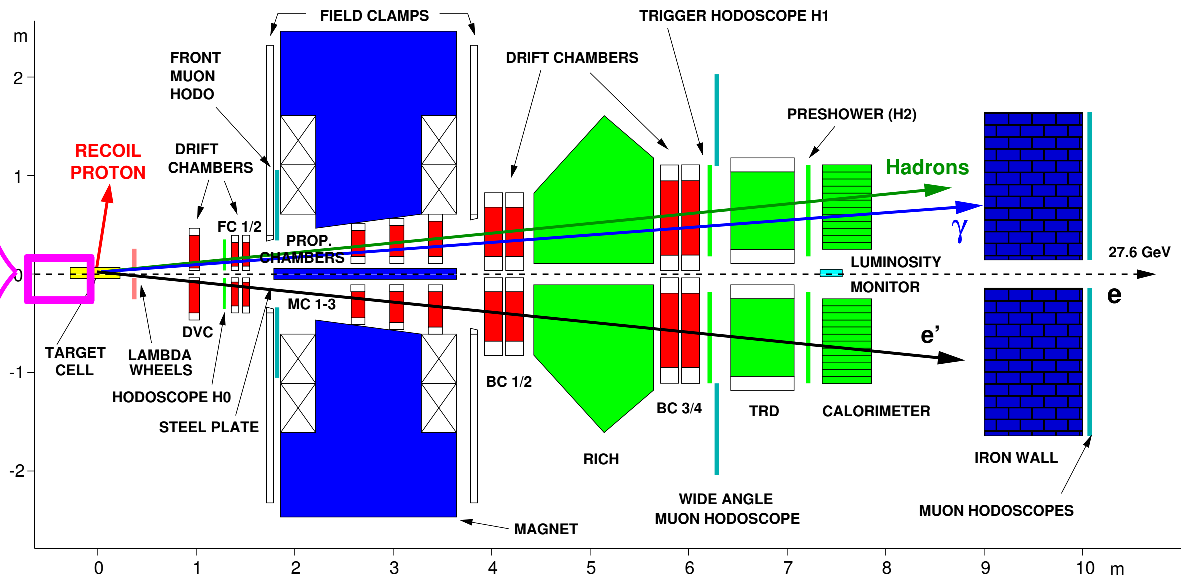

# Backup Slides!

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# Nucleon Structure

- Nucleon Form Factors
  - well known, measured by e.g. elastic scattering:

    $$e + N \rightarrow e' + N$$

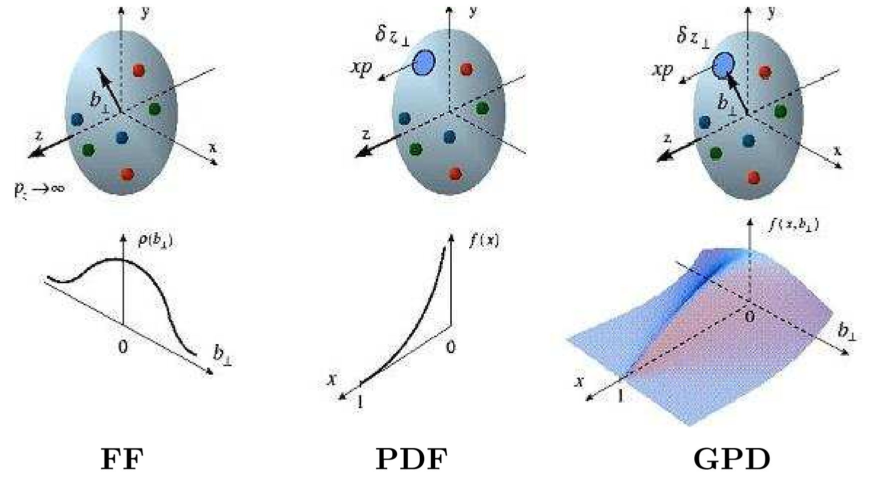
  - provide the $1^{st}$ direct knowledge about the internal structure of the nucleon [Hofstadter1955−61]
- Parton Distribution Functions
  - measured through e.g. deep inelastic scattering:

    $$e + N \rightarrow e' + h + X$$

  - unpolarized quark density $q(x)$
  - longitudinal spin density $\Delta q(x) = q^{\rightrightarrows}(x) - q^{\leftleftarrows}(x)$
  - transverse spin density $\delta q(x) = q^{\uparrow\Uparrow}(x) - q^{\uparrow\Downarrow}(x)$
  - gluon polarization $\Delta G/G$
- Generalized Parton Distributions
  - accessible in exclusive processes, e.g.:

    $$e + N \rightarrow e' + \gamma + N$$

  - provide a 3D picture of the nucleon structure
  - access the total angular momentum of quark $J_q$




Proton Spin

$$\frac{1}{2} = \underbrace{\frac{1}{2}(\overbrace{\Delta u + \Delta d + \Delta s}^{\sim 30\%}) + L_q}_{J_q} + \underbrace{\Delta G + L_g}_{J_g}$$

Ji's Sum Rule

$$J_q = \frac{1}{2}\int_{-1}^{1} dx \cdot x[H_q(x,\xi,0) + E_q(x,\xi,0)]$$

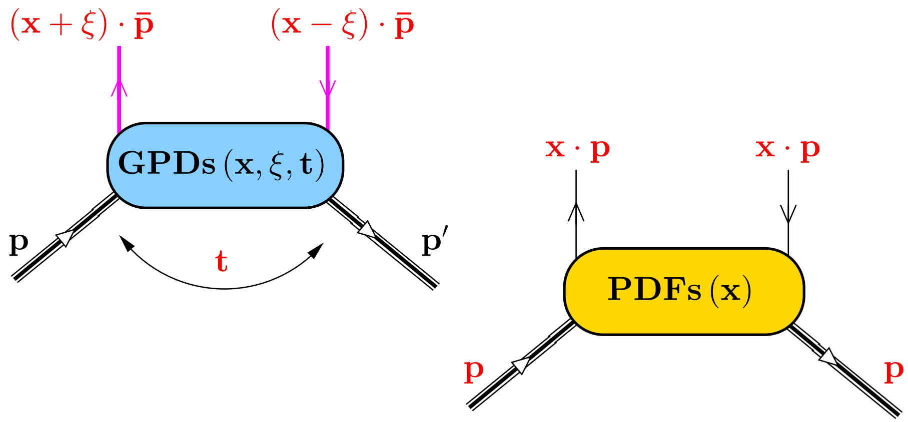
# Generalized Parton Distributions

- twist-2 GPDs $H, E, \widetilde{H}, \widetilde{E}\,(x,\xi,t)$ for spin 1/2 hadron

  $x \pm \xi$: longitudinal momentum fractions of the partons,

  $\xi$: fraction of the momentum transfer, $\xi \simeq \frac{x_B}{2-x_B}$,

  $t$: invariant momentum transfer, $t \equiv (p-p')^2$.




- GPDs $\Rightarrow$ Form Factors:

$$\int_{-1}^{1} dx \cdot H_q\,(x,\xi,t) = F_1^q\,(t),$$
$$\int_{-1}^{1} dx \cdot E_q\,(x,\xi,t) = F_2^q\,(t),$$
$$\int_{-1}^{1} dx \cdot \tilde{H}_q\,(x,\xi,t) = G_A^q\,(t),$$
$$\int_{-1}^{1} dx \cdot \tilde{E}_q\,(x,\xi,t) = G_P^q\,(t).$$

- GPDs $\Rightarrow$ PDFs :

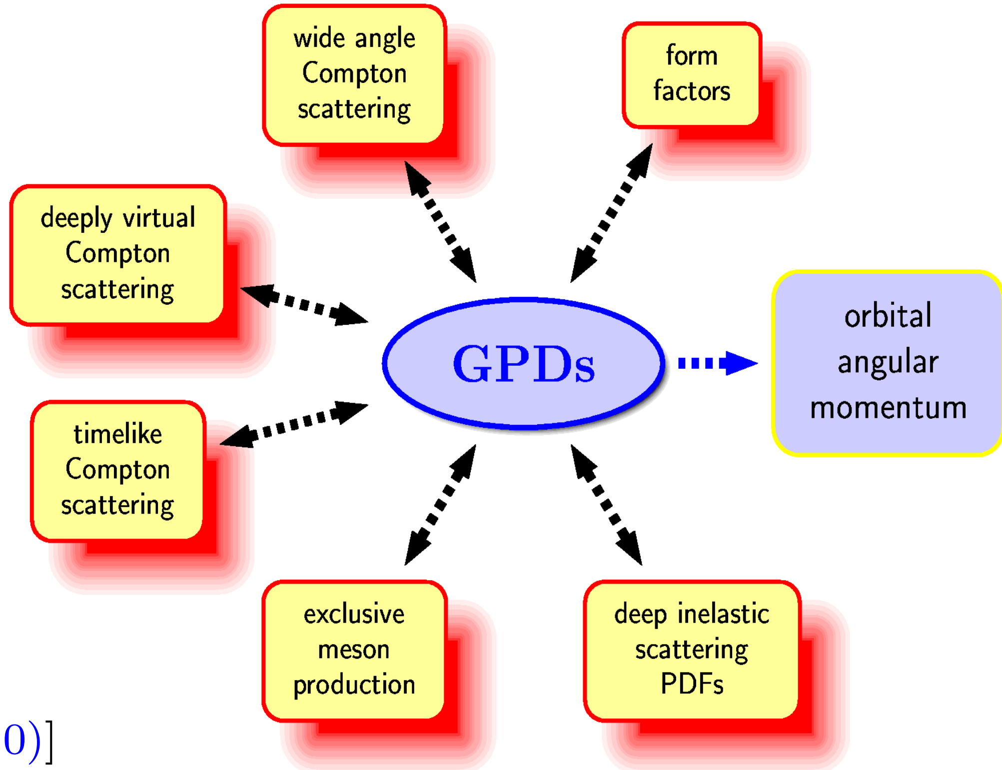
$$H_q\,(x,0,0) = q\,(x),\ \tilde{H}_q\,(x,0,0) = \Delta q\,(x).$$
$$H_g\,(x,0,0) = g\,(x),\ \tilde{H}_g\,(x,0,0) = \Delta g\,(x).$$

- GPDs $\Rightarrow$ impact parameter dependent PDFs :

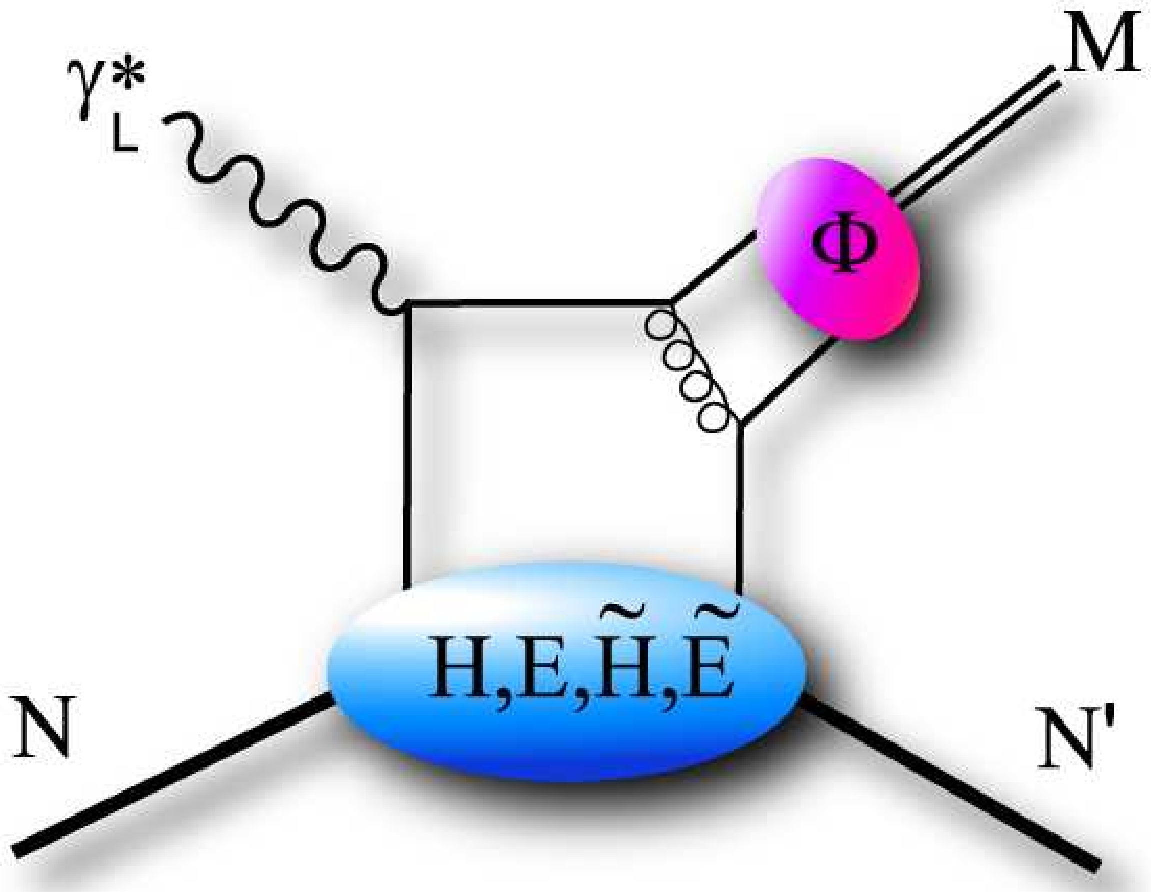
$$H_q\,(x,0,-\Delta_\perp^2) \rightarrow q\,(x,b_\perp),$$
$$\tilde{H}_q\,(x,0,-\Delta_\perp^2) \rightarrow \Delta q\,(x,b_\perp).$$

- GPDs $\Rightarrow$ Total Angular Momentum of Partons

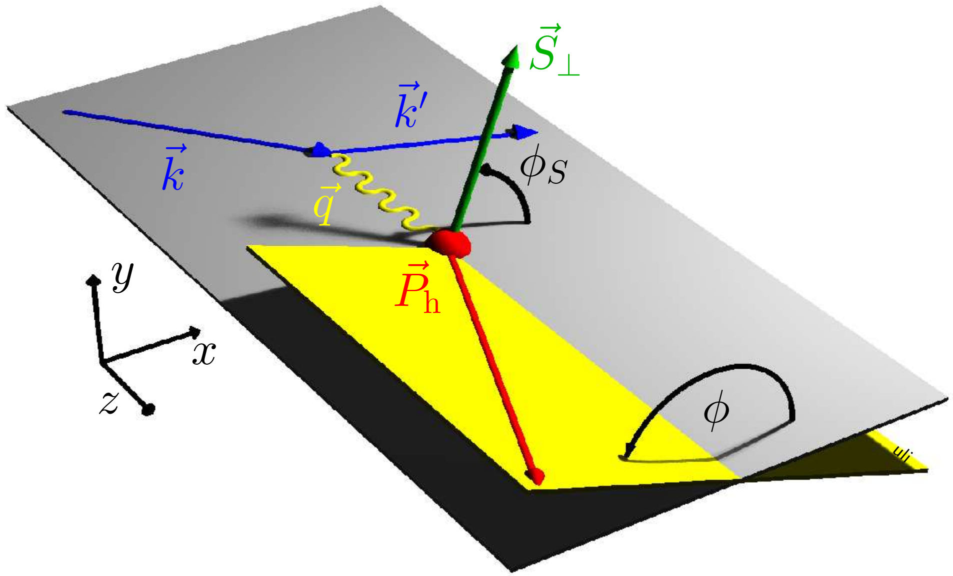
$$J_{q,g} = \frac{1}{2}\int_{-1}^{1} dx \cdot x[H_{q,g}(x,\xi,0) + E_{q,g}(x,\xi,0)]$$

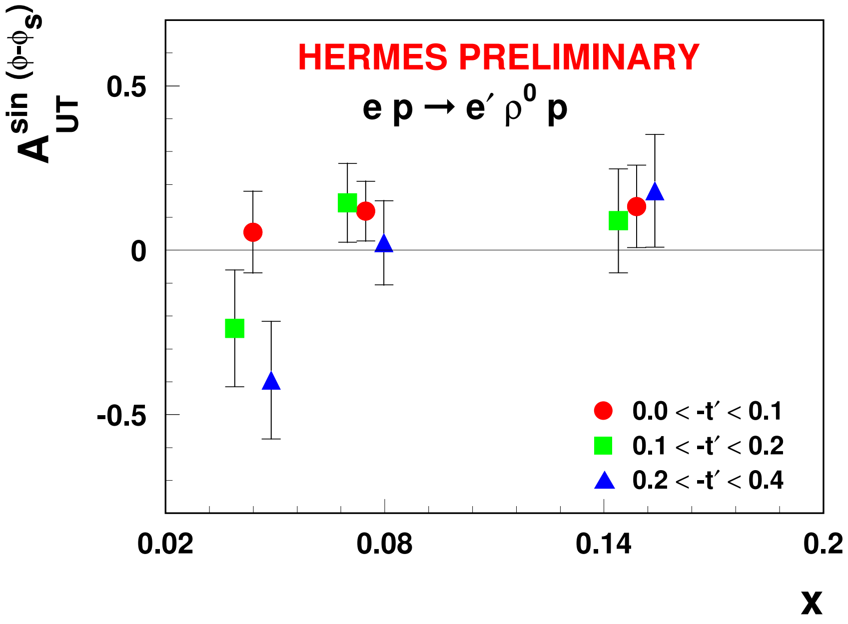


# Exclusive Meson Production



# TTSA in $\rho^0$ Production



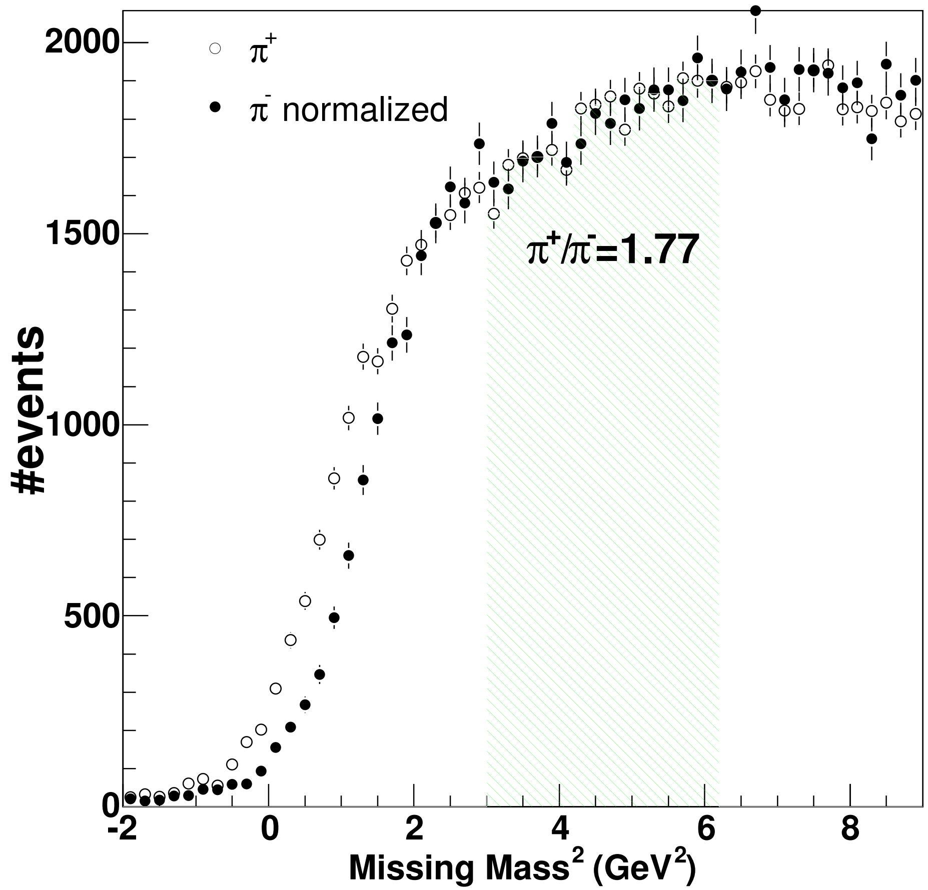



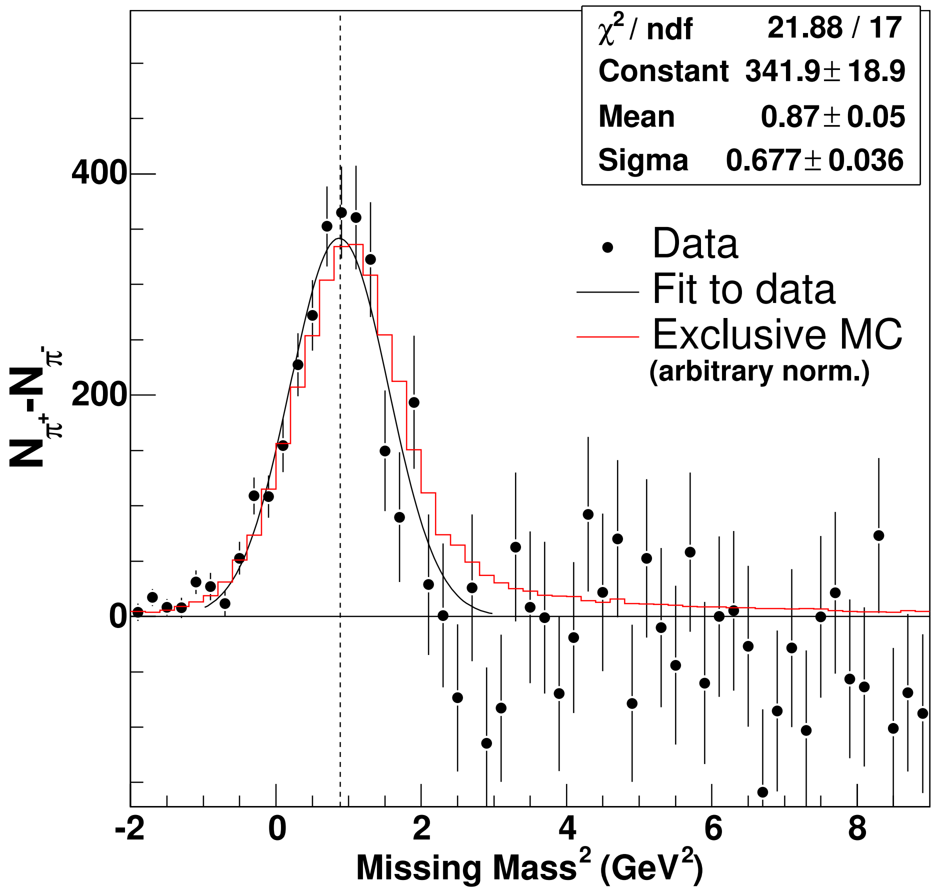

Transverse Target-Spin Asymmetry:

$$A_{UT}(\phi,\phi_s) = \frac{1}{|P_T|}\cdot\frac{d\sigma(P^{\Uparrow},\phi,\phi_s)-d\sigma(P^{\Downarrow},\phi,\phi_s)}{d\sigma(P^{\Uparrow},\phi,\phi_s)+d\sigma(P^{\Downarrow},\phi,\phi_s)}$$
$$\propto E\cdot H\sin(\phi-\phi_S)$$

- √ Large negative asymmetry at low x and large t
- √ $A_{UT}^{\sin(\phi-\phi_S)}$ sensitive to $J_u$ (hep-ph/0506264), no direct theoretical comparison yet

# $\pi^+$ Cross-Section Measurement

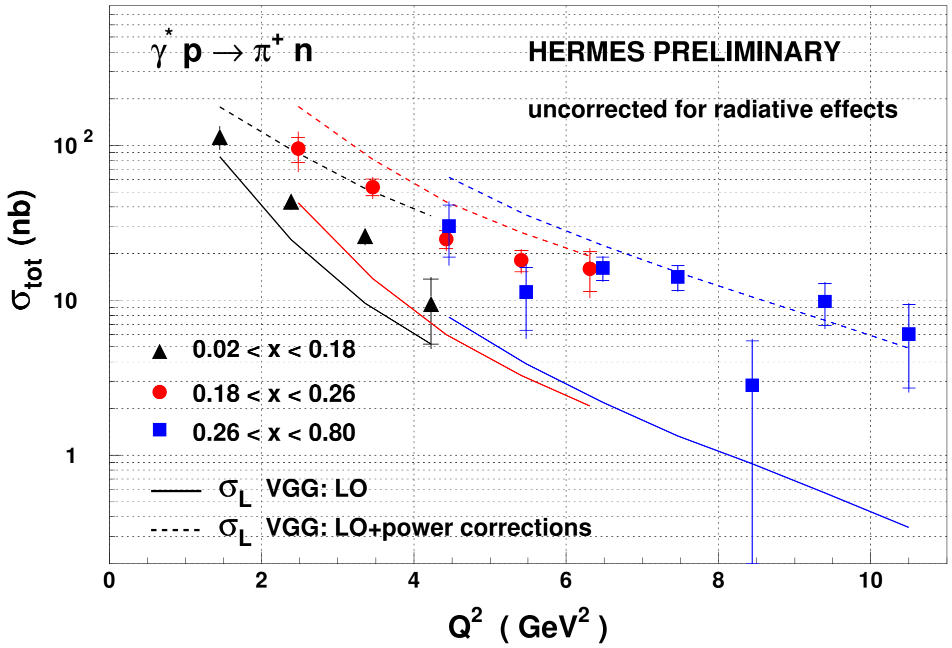



$ep \rightarrow en\pi^+$ cross-section ($\widetilde{H}, \widetilde{E}$):

Background estimated from $\pi^-$ yield.

# $\pi^+$ Cross-Section Measurement




GPD Model: M.Vanderhaeghen et al.

- $\sigma_{tot} = \sigma_T + \epsilon\sigma_L$, L/T separation not possible, but:

  $\sigma_T$ suppressed by $1/Q^2$

  At HERMES kinematics, $0.8 < \epsilon < 0.96$

- At large $Q^2$, $\sigma_L$ dominates

- $Q^2$ dependence is in general agreement with the theoretical expectation
- Power corrections ($k_\perp$ and soft overlap) calculations overestimate the data