Deeply Virtual Compton Scattering

– continued –

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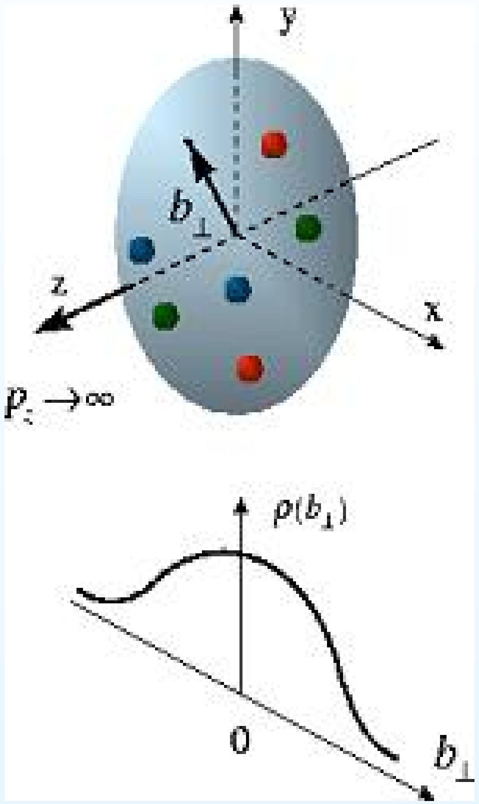
- Physics Background
    - Quark-Gluon Structure of the Nucleon
    - Generalized Parton Distributions
    - Deeply Virtual Compton Scattering
- How to perform a DVCS analysis
    - Knowledge about HERMES
    - An example – TTSA extraction
    - My analysis code ...

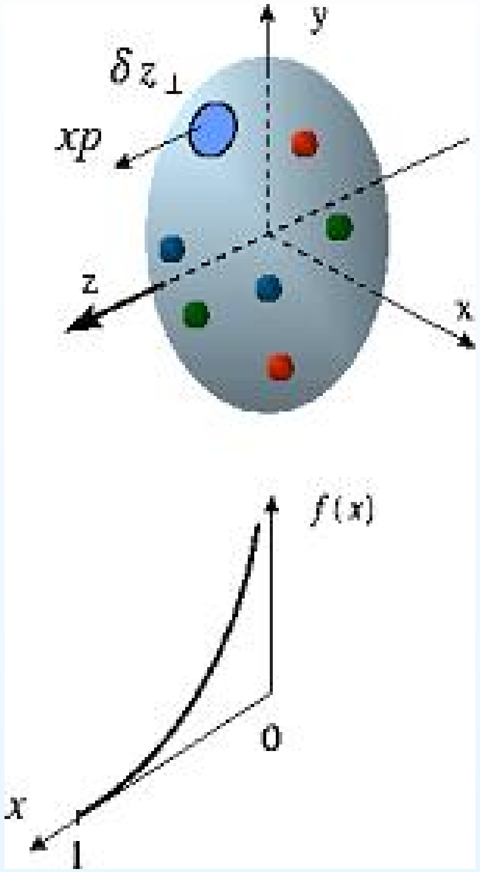
Motivation

- Measurements of nucleon electromagnetic form factors in elastic lepton scattering investigate parton distributions in the impact parameter space (transverse plane in the I.M.F.).

- Measurements of Parton Distribution Functions in e.g. Deep Inelastic Scattering investigate longitudinal momentum distributions of partons in the nucleon.

Generalized Parton Distributions





Form Factors

PDFs

Motivation

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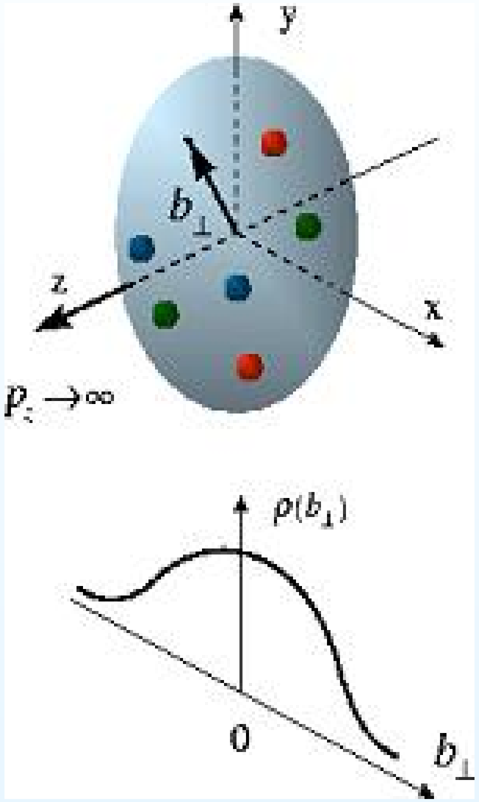
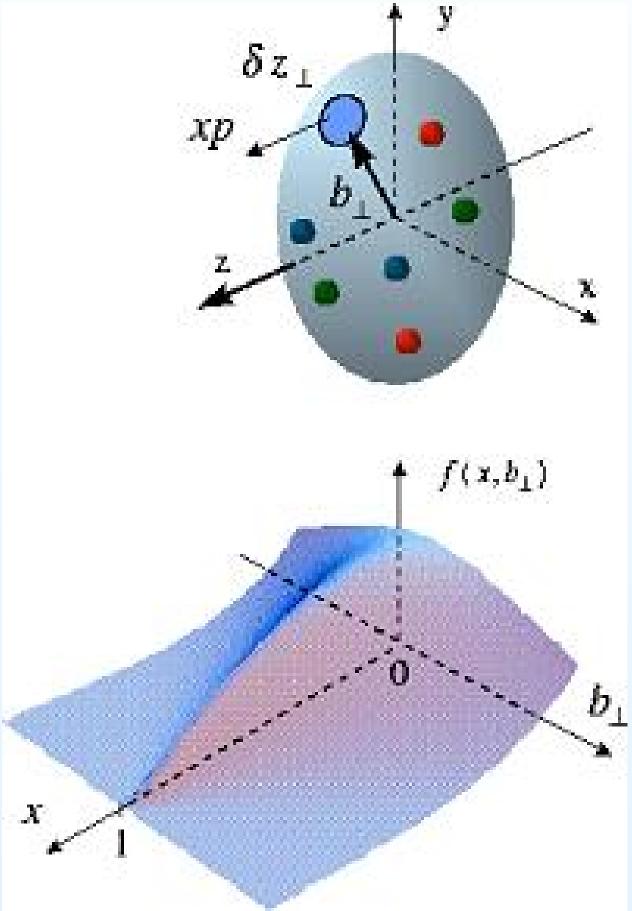
- Measurements of Parton Distribution Functions in e.g. Deep Inelastic Scattering investigate longitudinal momentum distributions of partons in the nucleon.

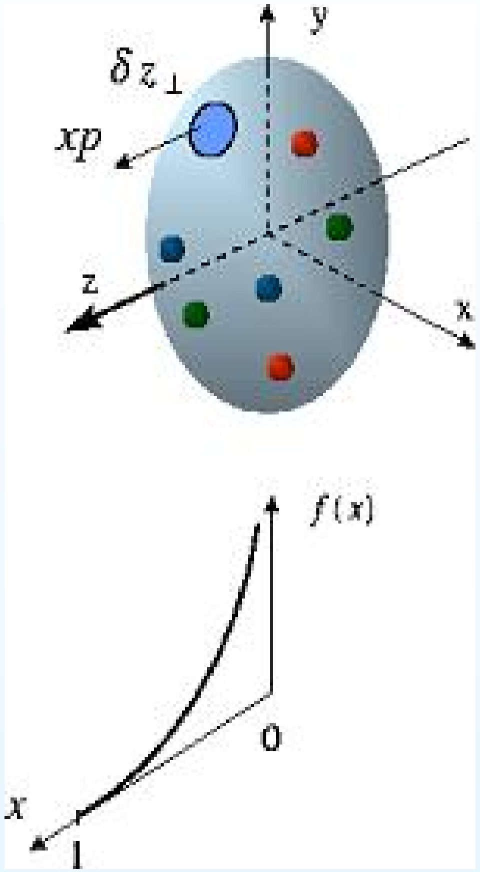
- Measuring Generalized Parton Distributions in Deeply Virtual Compton Scattering will help us to know longitudinal momentum distributions of partons in the transverse plane.

  $\Rightarrow$ 3D picture of the nucleon structure

Generalized Parton Distributions





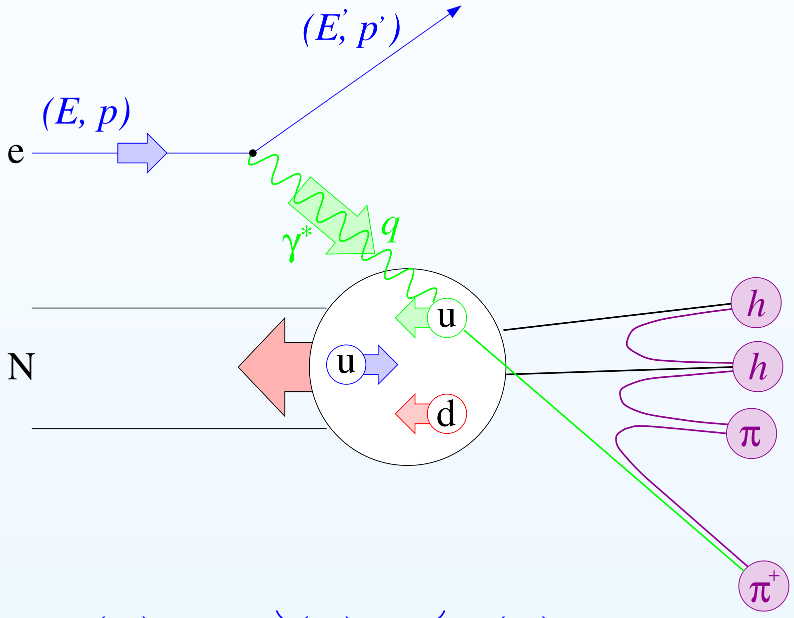


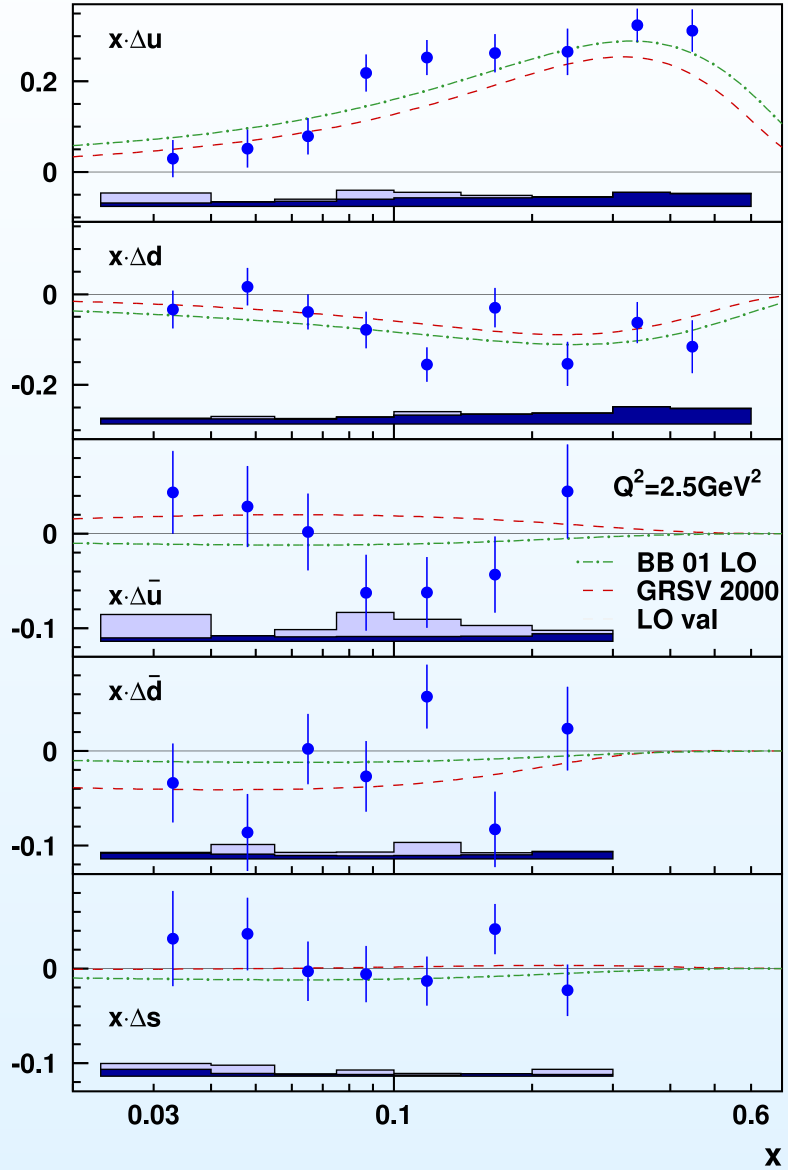
Form Factors

GPDs

PDFs

Spin Structure of the Nucleon





- $\Delta q(x) = \overrightarrow{q}(x) - \overleftarrow{q}(x)$
  describe the helicity distributions of quarks in the nucleon as a function of x (momentum fraction)
- HERMES, PRD 71(2005)012003
  $\int dx(\Delta u + \Delta d + \Delta s) \simeq \frac{1}{2} \cdot 35\%$

Where is the rest of the nucleon spin?

Motivation

- Measurements of nucleon electromagnetic form factors in elastic lepton scattering investigate parton distributions in the impact parameter space (transverse plane in the I.M.F.).
- Measurements of Parton Distribution Functions in e.g. Deep Inelastic Scattering investigate longitudinal momentum distributions of partons in the nucleon.
- Measuring Generalized Parton Distributions in Deeply Virtual Compton Scattering will help us to understand longitudinal momentum distributions of partons in the transverse plane.

  $\Rightarrow$ 3D picture of the nucleon structure

- Measuring GPDs in e.g. DVCS will also help us to understand the nucleon spin structure.

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

Generalized Parton Distributions

- GPDs $\Rightarrow J_{q(g)} = \Delta\Sigma(\Delta G) + L_{q(g)} \Rightarrow L_{q(g)}$ (Ji, 1997)

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

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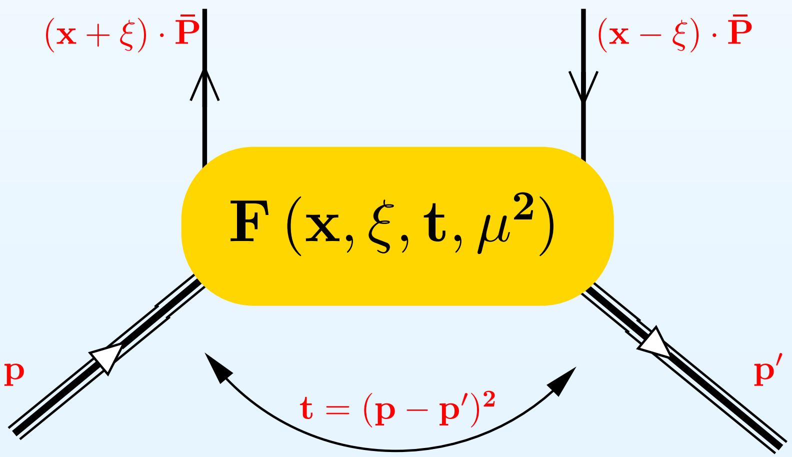
- GPDs can be defined through matrix elements $\langle p', S'|\mathcal{O}_{q/g}|p, S\rangle$.



$x \pm \xi$ – long. momentum fractions
t – invariant momentum transfer
μ^2 – renormalization scale

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- For a spin-$\frac{1}{2}$ nucleon, there are 4 twist-2 GPDs for each parton species (parton helicity conserved).

	unpolarized	polarized
$S' = S$	$H_{q,g}$	$\widetilde{H}_{q,g}$
$S' = -S$	$E_{q,g}$	$\widetilde{E}_{q,g}$

Generalized Parton Distributions

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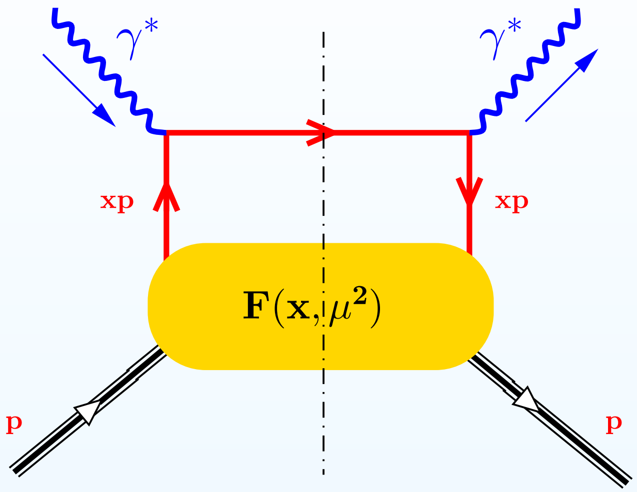
- GPDs can be defined through matrix elements $\langle p', S' | \mathcal{O}_{q/g} | p, S\rangle$.
- For a spin-$\frac{1}{2}$ nucleon, there are 4 twist-2 GPDs for each parton species (parton helicity conserved).
- GPDs are related to known quantities (FFs, PDFs).

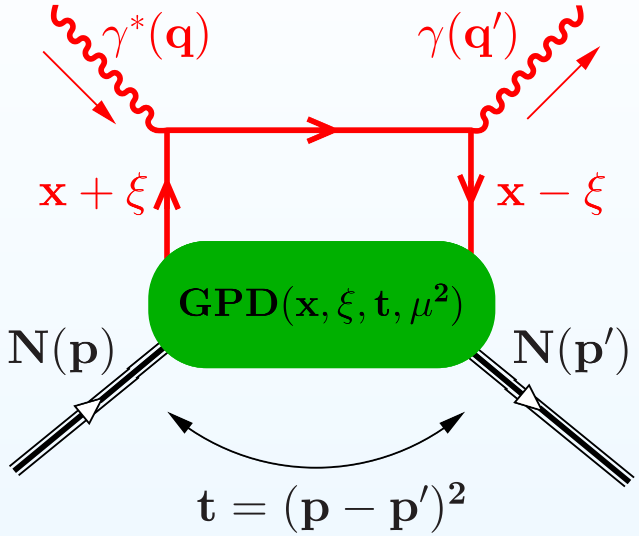
FFs	$\int_{-1}^{1} dx\, H_q\left(x,\xi,t,\mu^2\right) = F_1^q\left(t\right)$ $\int_{-1}^{1} dx\, \widetilde{H}_q\left(x,\xi,t,\mu^2\right) = g_V^q\left(t\right)$	$\int_{-1}^{1} dx\, E_q\left(x,\xi,t,\mu^2\right) = F_2^q\left(t\right)$ $\int_{-1}^{1} dx\, \widetilde{E}_q\left(x,\xi,t,\mu^2\right) = g_A^q\left(t\right)$
PDFs	$H_q\left(x,0,0,\mu^2\right) = q\left(x,\mu^2\right)$ $\widetilde{H}_q\left(x,0,0,\mu^2\right) = \Delta q\left(x,\mu^2\right)$	E_q and $\widetilde{E}_q$ decouple in the forward limit.

Connecting GPDs and PDFs



forward Compton scattering

$\gamma^*(q) + N(p) \to \gamma^*(q) + N(p)$



nonforward Compton scattering

$\gamma^*(q) + N(p) \to \gamma(q') + N(p')$

- Parton Distribution Functions have been studied over decades by inclusive DIS. The latter is described via the optical theorem by forward Compton scattering $\gamma^* + N \to \gamma^* + N$.
- PDFs are generalized by Generalized Parton Distributions. The latter enter into nonforward Compton scattering $\gamma^*(q) + N \to \gamma(q') + N$.

How to Access GPDs?

- GPDs are constrained by known quantities (FFs, PDFs, . . .), and certain symmetries. For example, time-reversal invariance asserts $H(x,\xi) = H(x,-\xi)$.
- Insufficient knowledge about GPDs at the moment, theoretical calculations rely on phenomenological parameterizations for GPDs , e.g., the factorized ansatz in the Double-distribution representation:

$$
\begin{aligned}
H(x,\xi,t,\mu^2) &= \left[H_{DD}(x,\xi,\mu^2) + D(x,\xi,\mu^2)\right] \cdot F_1(t) \\
H_{DD}(x,\xi) &= \int_{-1}^{1} d\beta \int_{-1+|\beta|}^{1-|\beta|} d\alpha \delta(x-\beta-\alpha\xi) h(\beta,\alpha) q(\alpha,\mu^2) \\
h(\beta,\alpha) &= \frac{\Gamma(2b+2)}{2^(2b+1)\Gamma^2(b+1)} \frac{\left[(1-|\beta|)^2 - \alpha^2\right]^b}{(1-|\beta|)^(2b+1)}
\end{aligned}
$$

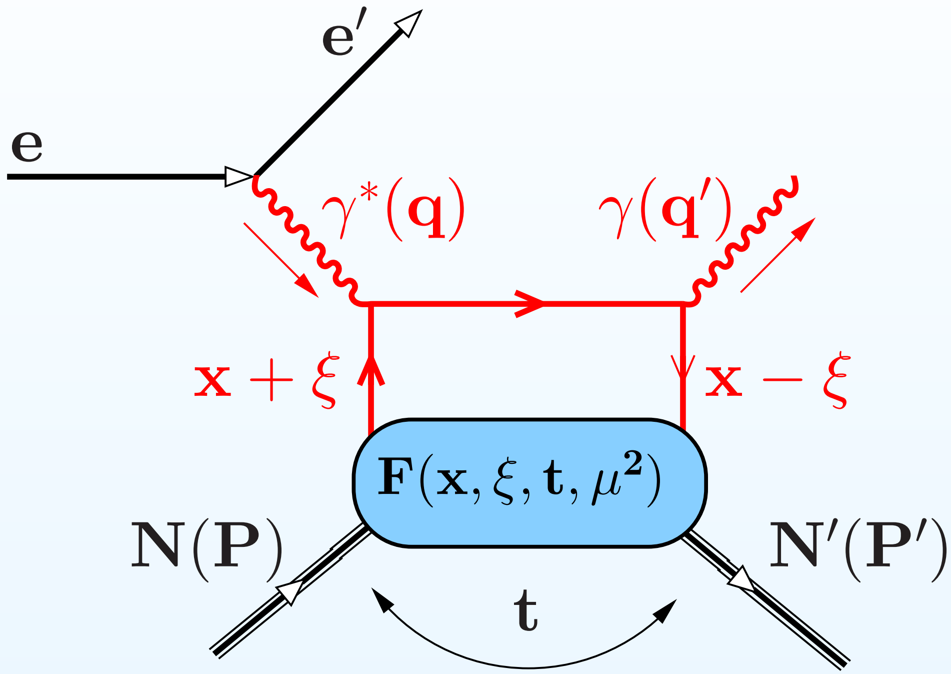
- x-moments of GPDs can be calculated in Lattice QCD, whose results certainly need to be confronted with experimental results.
- GPDs are accessible in Deeply Virtual Compton Scattering .

hermes

Deeply Virtual Compton Scattering

- Kinematics and Amplitudes
- Asymmetries

Kinematics and Amplitudes



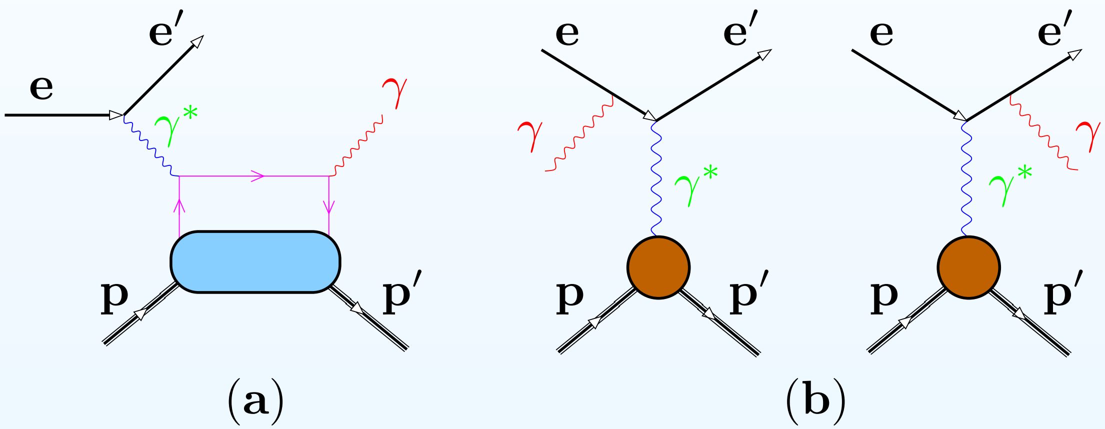
$$
\begin{aligned}
e(k) + N(p) &\rightarrow e(k') + N(p') + \gamma(q') \\
Q^2 &\equiv -q^2 = -(k-k')^2 \\
x_B &\equiv \frac{Q^2}{2p\cdot q} \\
t &\equiv (p'-p)^2 = \Delta^2
\end{aligned}
$$

- At large Q^2 and fixed x_B and t, the DVCS amplitude can be factorized into a hard (perturbative) part and a soft (non-perturbative) part:

$$\mathcal{A}(\xi \simeq \frac{x_B}{2-x_B}, t, Q^2) = \int dx \cdot f_{pert.}(x,\xi,Q^2) \cdot F(x,\xi,t,Q^2) + \cdots$$

Kinematics and Amplitudes

- The same final state in DVCS (a) and Bethe-Heithler (b) $\Rightarrow$ interference



$$\sigma \propto \quad |\mathcal{T}_{\rm BH}|^2 + |\mathcal{T}_{\rm DVCS}|^2 + \underbrace{(\mathcal{T}_{\rm BH}\mathcal{T}^*_{\rm DVCS} + \mathcal{T}^*_{\rm BH}\mathcal{T}_{\rm DVCS})}_{I}$$

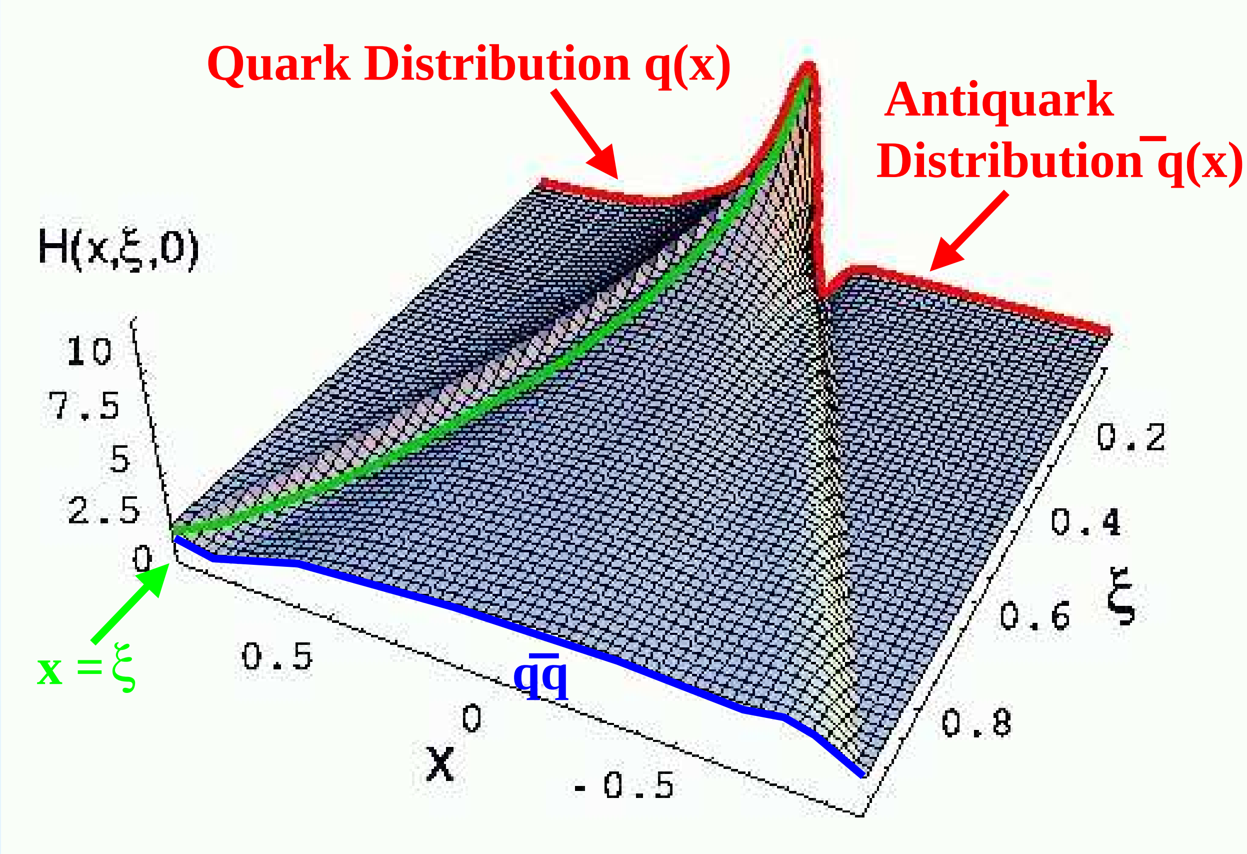
- $\mathcal{T}_{\rm BH}$ is calculable in terms of nucleon EM FFs F_1 and F_2.

- $\mathcal{T}_{\rm DVCS}$ is calculable in terms of Compton FFs $\mathcal{H}$, $\mathcal{E}$, $\widetilde{\mathcal{H}}$, and $\widetilde{\mathcal{E}}$, which are convolutions of the respective GPDs with the hard-scattering kernels.

Studying GPDs in DVCS

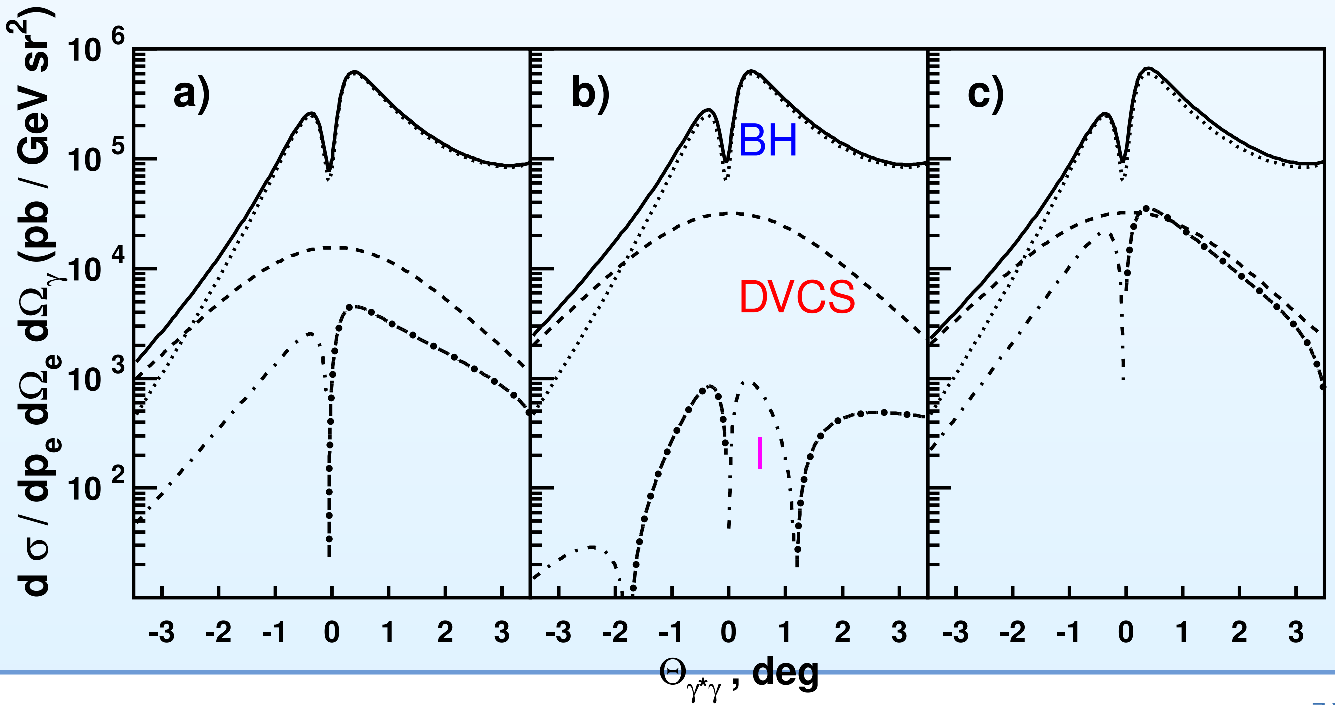
- $\mathcal{T}_{DVCS}$ is parameterized in terms of CFFs (convolution of GPDs):

$$\mathcal{F}_{LO} \simeq \int dx \cdot \frac{1}{x \pm \xi + i\epsilon} \cdot F(x,\xi) \simeq P. \int dx \frac{F(x,\xi)}{x \pm \xi} + i\pi F(\xi, \pm\xi)$$

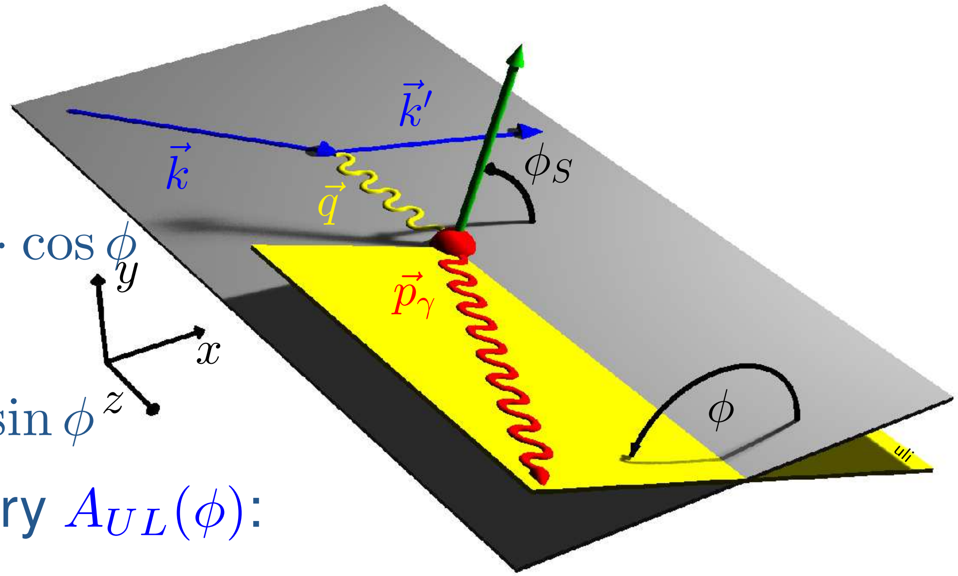


Kinematics and Amplitudes

- σ_{DVCS} can be measured (H1/ZEUS) after subtracting the known σ_{BH}. This gives the magnitudes of CFFs $\mathcal{F}$ but not their phases.
- At HERMES kinematics, $\mathcal{T}_{BH} \gg \mathcal{T}_{DVCS}$, the DVCS amplitude can be measured through azimuthal asymmetries, which are mainly induced by the charge and spin dependence of I and provide info about both the amplitudes and the phases of CFFs $\mathcal{F}$.



Azimuthal Asymmetries



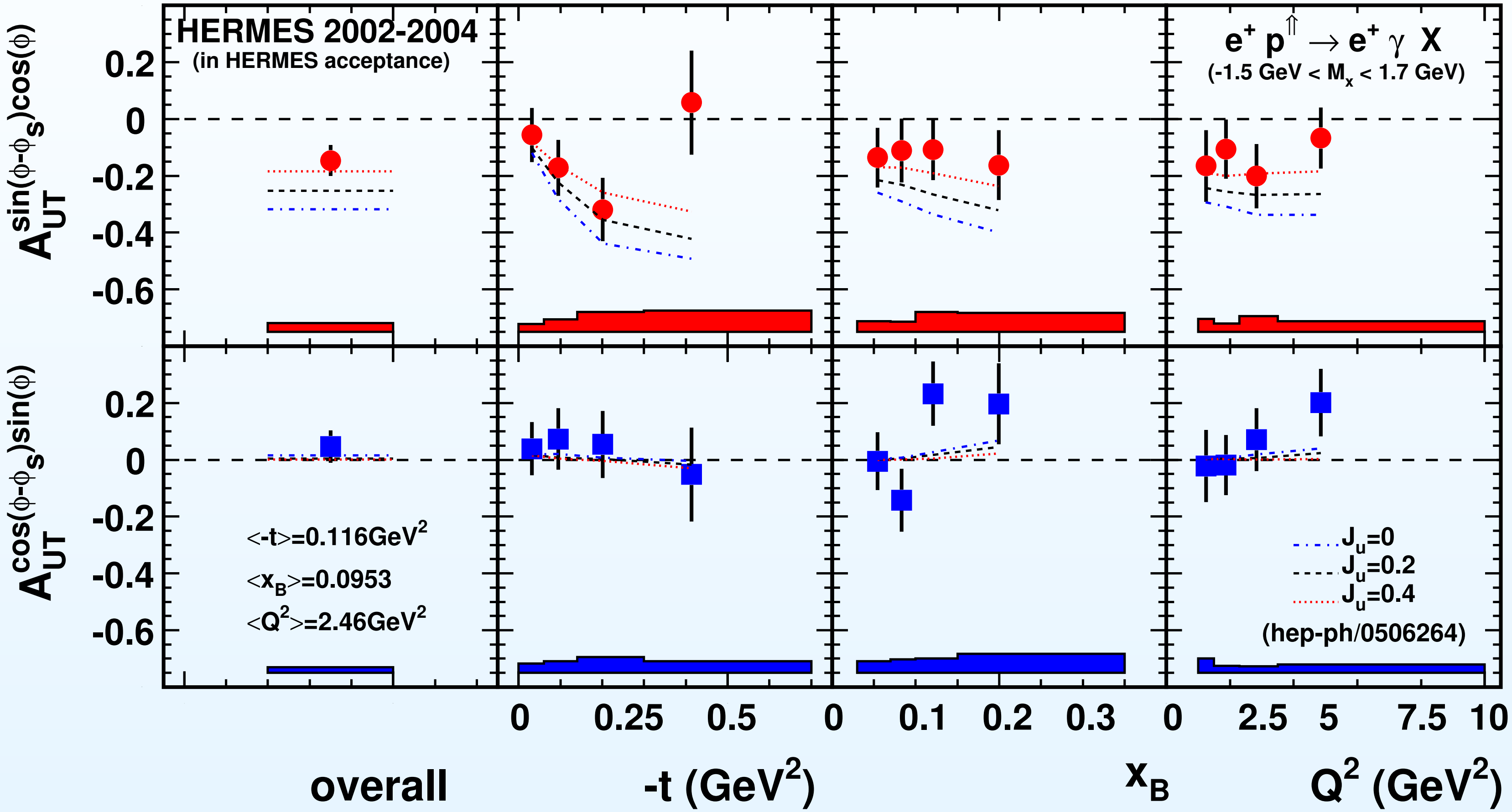
- Beam-charge asymmetry $A_C(\phi)$:
  $d\sigma(e^+,\phi) - d\sigma(e^-,\phi) \propto \mathrm{Re}[F_1\mathcal{H}] \cdot \cos\phi$
- Beam-spin asymmetry $A_{LU}(\phi)$:
  $d\sigma(\overrightarrow{e},\phi) - d\sigma(\overleftarrow{e},\phi) \propto \mathrm{Im}[F_1\mathcal{H}] \cdot \sin\phi$
- Longitudinal target-spin asymmetry $A_{UL}(\phi)$:
  $d\sigma(\overset{\Leftarrow}{P},\phi) - d\sigma(\overset{\Rightarrow}{P},\phi) \propto \mathrm{Im}[F_1\widetilde{\mathcal{H}}] \cdot \sin\phi$

- Transverse target-spin asymmetry $A_{UT}(\phi,\phi_s)$:
  $d\sigma(\phi,\phi_S) - d\sigma(\phi,\phi_S+\pi) \propto \mathrm{Im}[F_2\mathcal{H} - F_1\mathcal{E}] \cdot \sin(\phi-\phi_S)\cos\phi$
  $+\mathrm{Im}[F_2\widetilde{\mathcal{H}} - F_1\xi\widetilde{\mathcal{E}}] \cdot \cos(\phi-\phi_S)\sin\phi$

  $\Longrightarrow$ $\mathcal{E}$ not suppressed $\Longrightarrow \mathrm{A}_{\mathrm{UT}}^{\sin(\phi-\phi_S)\cos\phi}$ sensitive to J_q

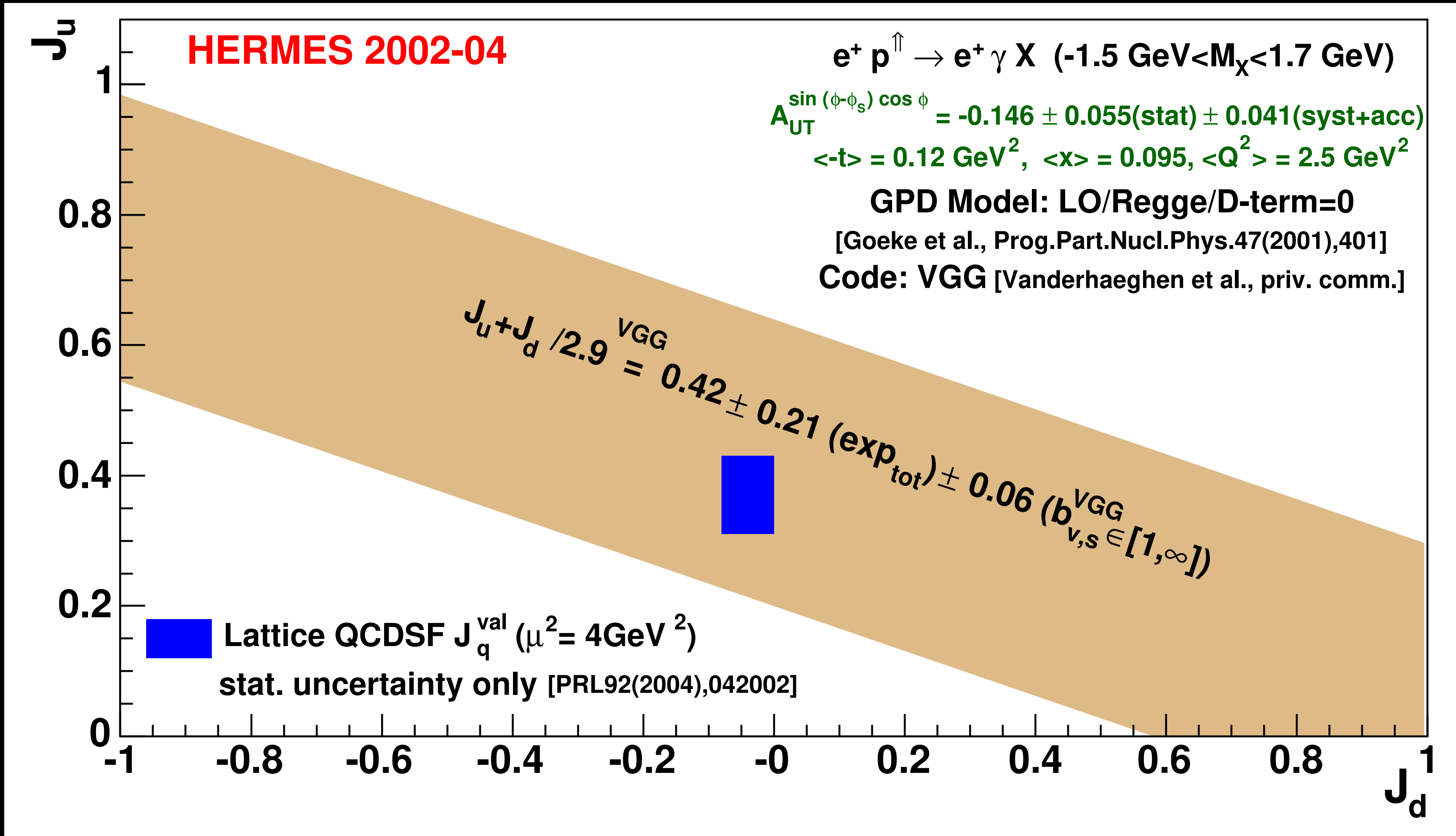
$$J_q = \frac{1}{2}\lim_{t\to 0}\int dx \cdot x(H_q + E_q)$$

Results on TTSA



Systematic uncertainties:

- target pol≈ 0.01; fit function ≈ 0.01; background ≈ 0.02;
- misalign+cali≈ -; smearing≈ 0.02; (accptance) ≈ 0.03.



$$\chi^2(J_u, J_d) = \frac{\left[A_{UT}^{\sin(\phi-\phi_S)\cos\phi}|_{exp} - A_{UT}^{\sin(\phi-\phi_S)\cos\phi}|_{VGG}(J_u, J_d)\right]^2}{\delta A_{stat}^2 + \delta A_{syst}^2 + \delta A_{accp}^2}$$

$$\leq \chi^2_{min} + 1$$