Transverse Target-Spin Asymmetry Associated with Deeply Virtual Compton Scattering on the Proton and A Resulting Model-Dependent Constraint on the Total Angular Momentum of Quarks in the Nucleon

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DESY

Outline

- Quark-Gluon Structure of the Nucleon
- Deeply Virtual Compton Scattering
- The HERMES Experiment
- Transverse Target-Spin Asymmetry in DVCS
- A Model-Dependent Constraint on J_u and J_d
- Summary and Outlook

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- Quark-Gluon Structure of the Nucleon
  - History, Now and Future (FFs, PDFs, GPDs)
- Deeply Virtual Compton Scattering
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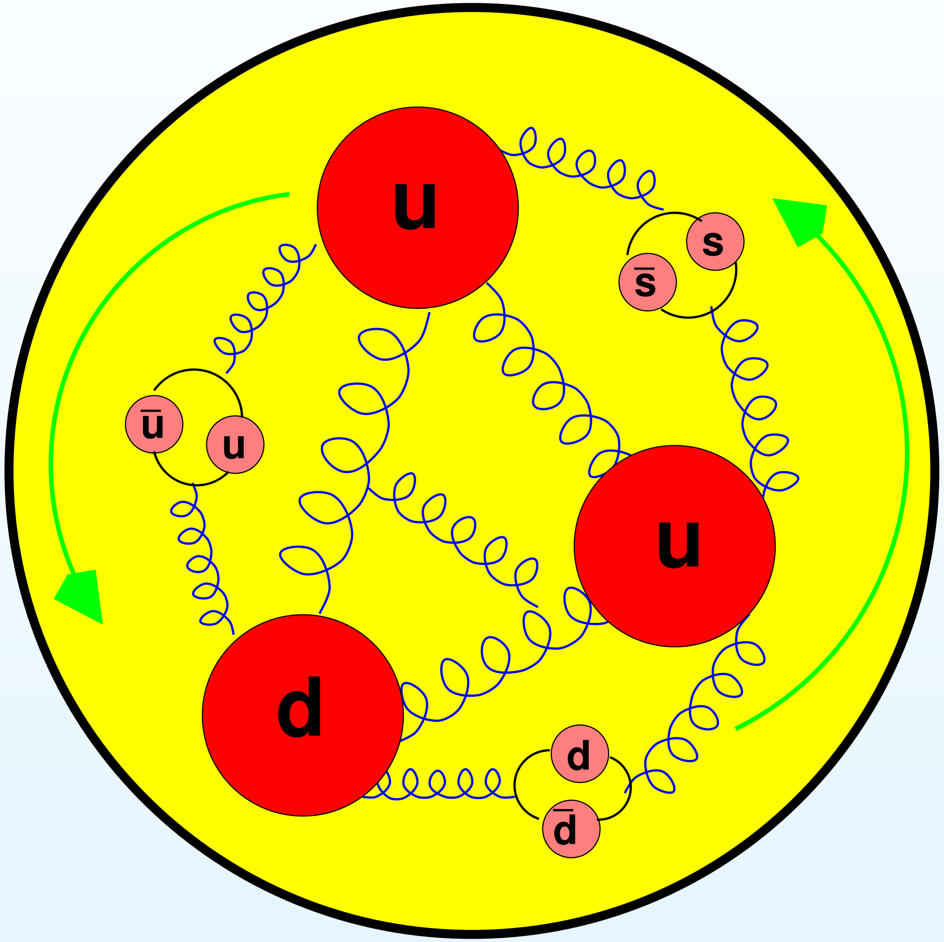
Motivation



How are the hadrons composed of quarks and gluons?

History

- The first indication that the nucleons (protons and neutrons) are not point-like, came from measurements of the proton magnetic moment in the 1940's.
  - *Stern, Nobel Prize in Physics 1943*

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- Measurements in the 1970's of nucleon structure functions in inclusive DIS discovered the existence of point-like constituents in the nucleon and asymptotic freedom of the strong force.
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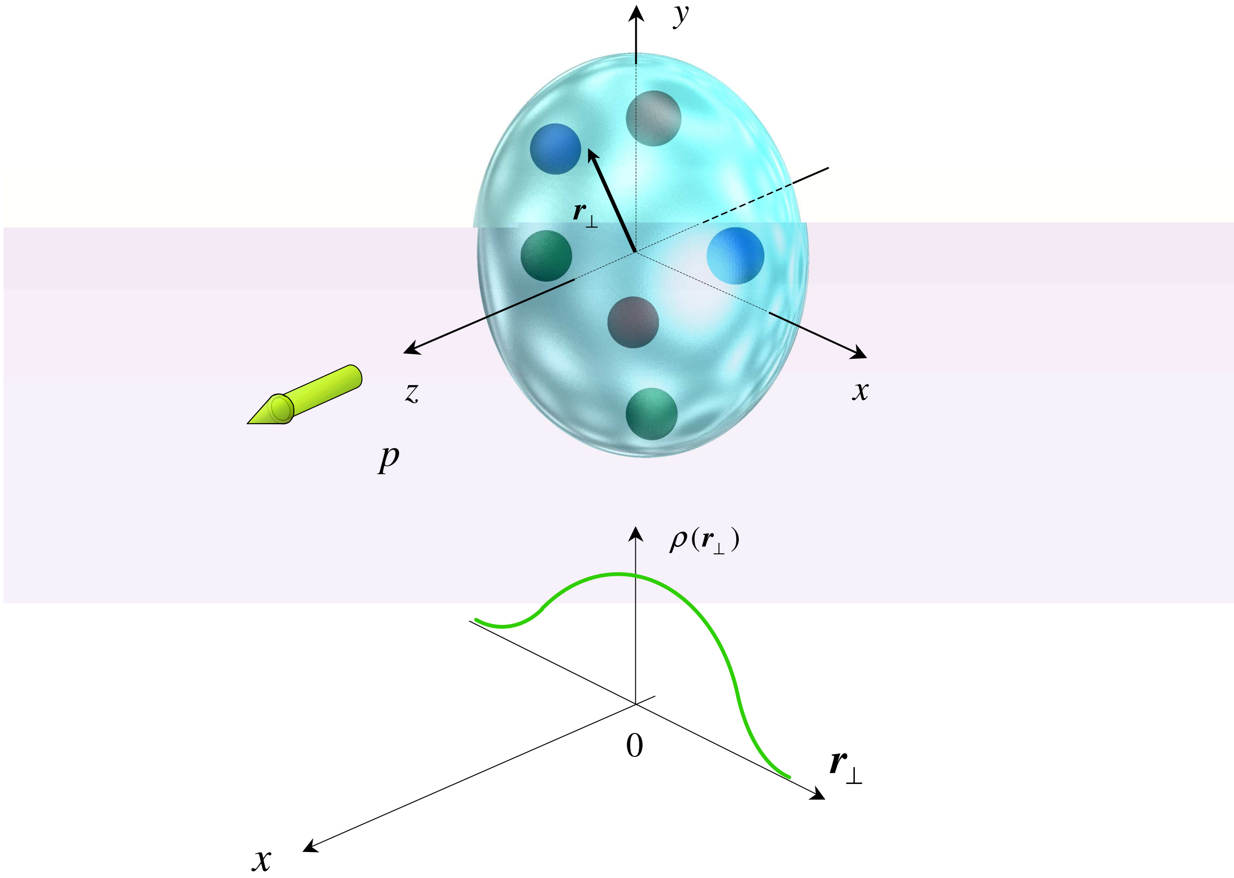
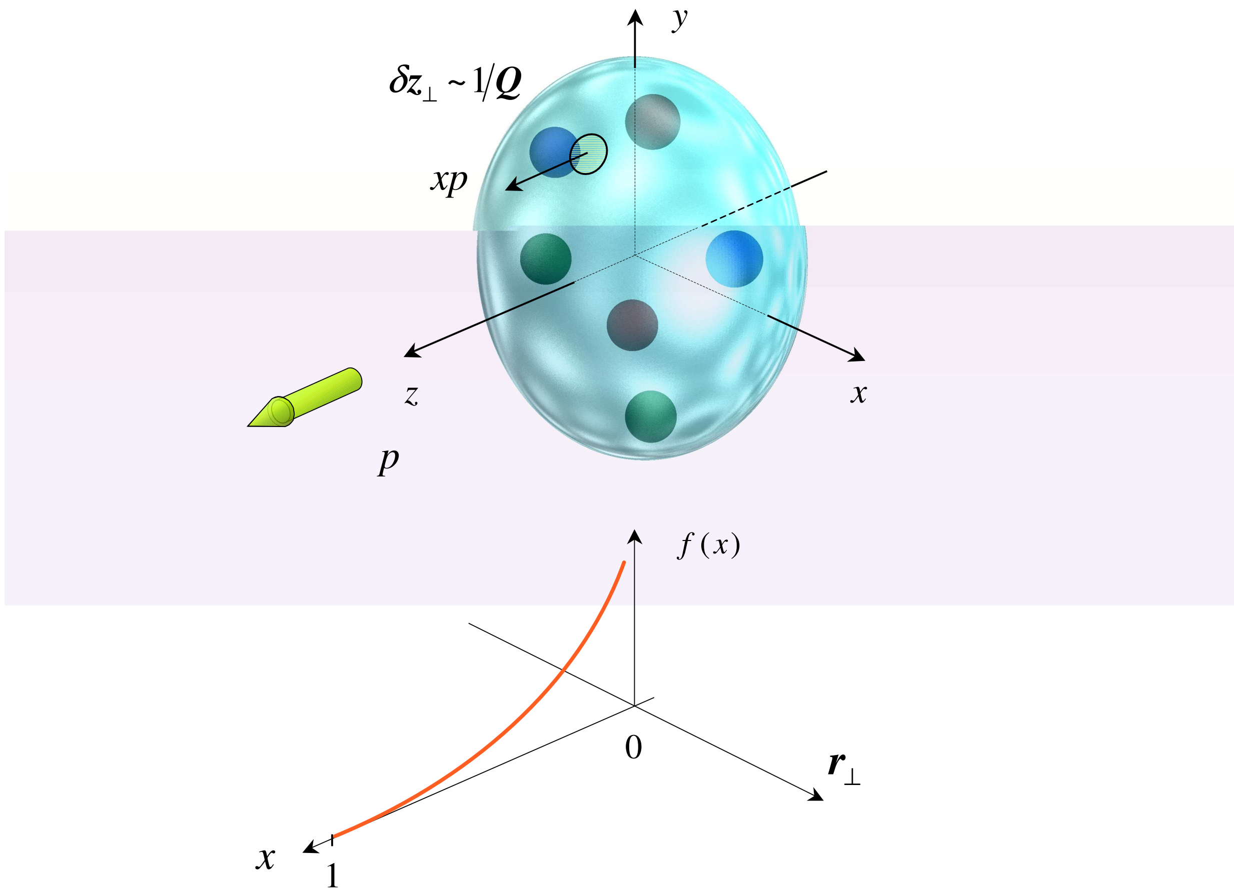
  - *Gross, Politzer, Wilczek, Nobel Prize in Physics 2004*
- Measurements in the past 40 years in e.g. DIS, Drell-Yan, incl. jet production in $p\bar{p}$ collisions, have helped us to understand the quark-gluon structure of the nucleon and the strong force.

FFs characterize charge and magnetization distributions in the impact parameter space (transverse plane in the IMF).



$$F(-\vec{\Delta}_\perp^2) = \int d^2\vec{r}_\perp \cdot e^{-i\vec{\Delta}_\perp \cdot \vec{r}_\perp} \cdot \rho(\vec{r}_\perp)$$

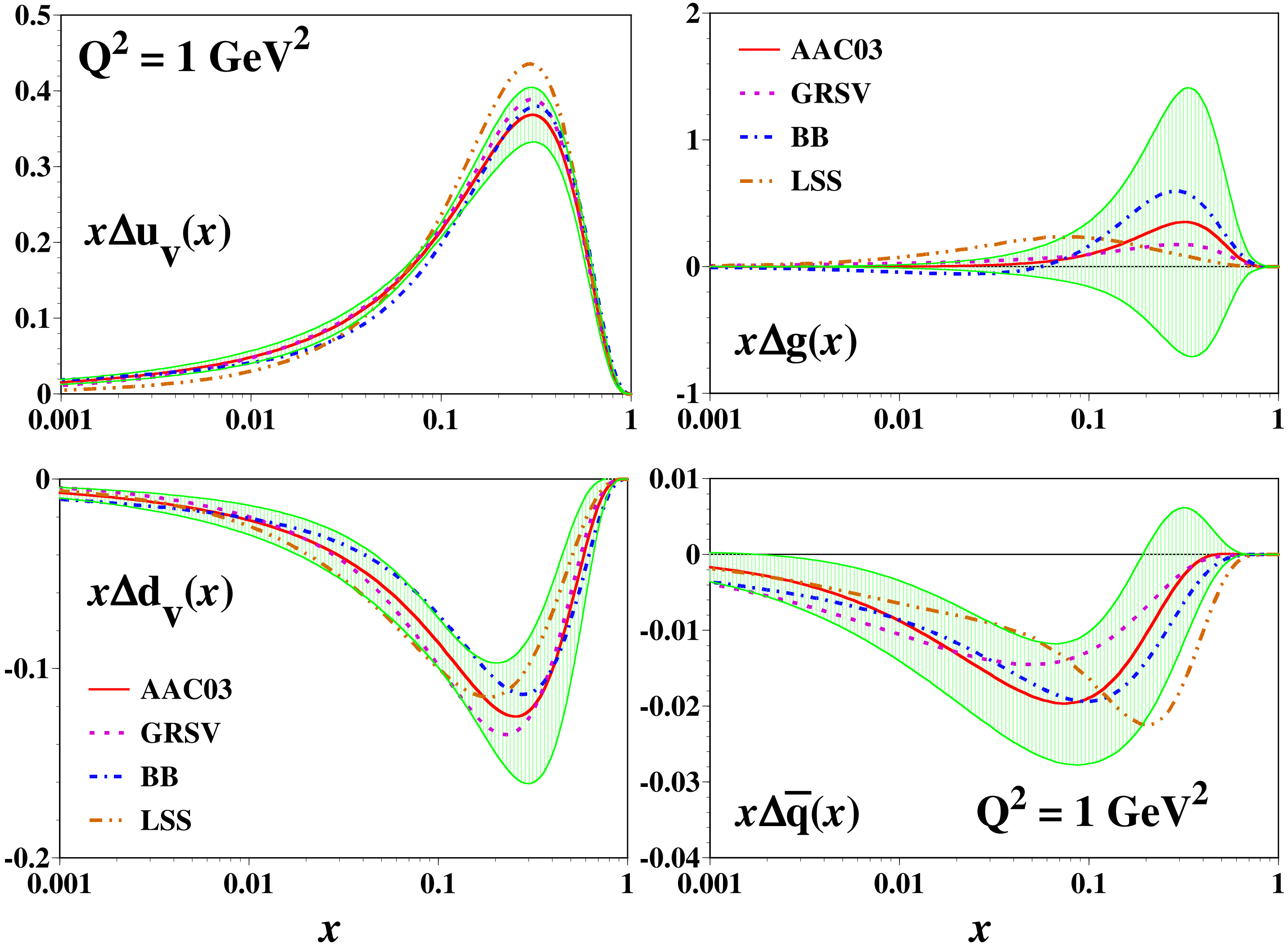
PDFs characterize longitudinal momentum distributions (IMF)



x – longitudinal momentum fraction

Hirai et al., 2003

$$\Delta q(x) = \overrightarrow{q}(x) - \overleftarrow{q}(x) \qquad \Delta g(x) = \overrightarrow{g}(x) - \overleftarrow{g}(x)$$



Spin Structure of the Nucleon

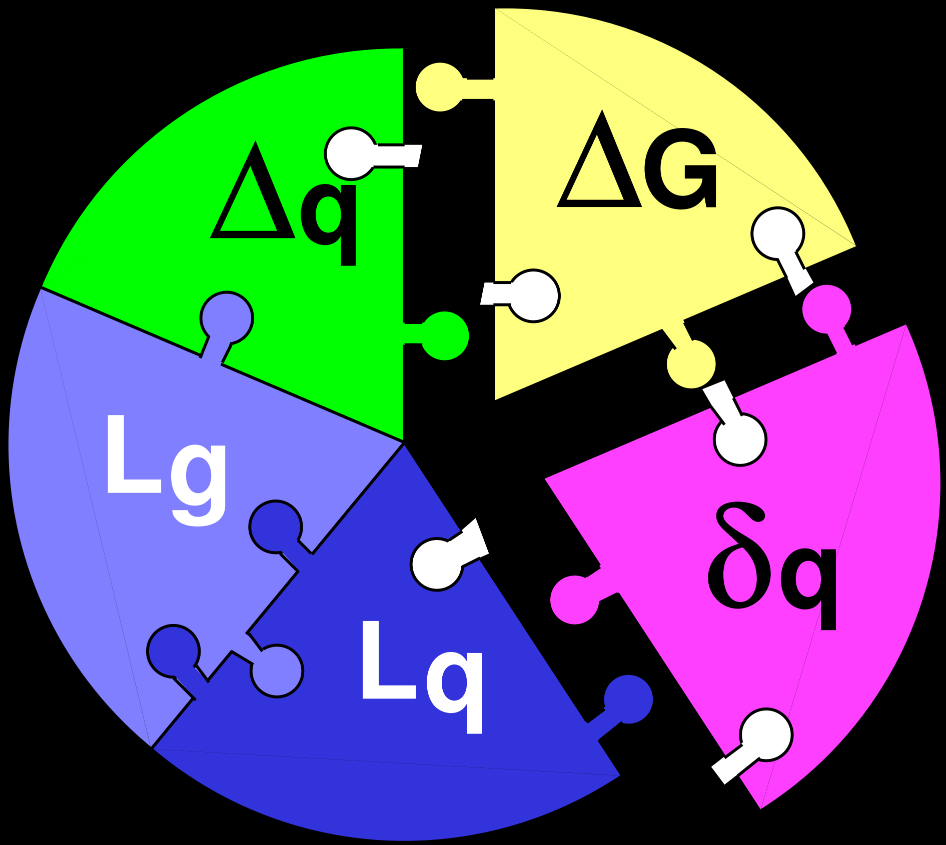
$$\Delta\Sigma = \sum_q \int_{-1}^{1} dx\, \Delta_q(x) \sim 20 - 35\%$$

hermes

Spin Structure of the Nucleon

$$\Delta\Sigma = \sum_q \int_{-1}^{1} dx\, \Delta_q(x) \sim 20 - 35\%$$

$\Longrightarrow$ Where is the rest of the nucleon spin?



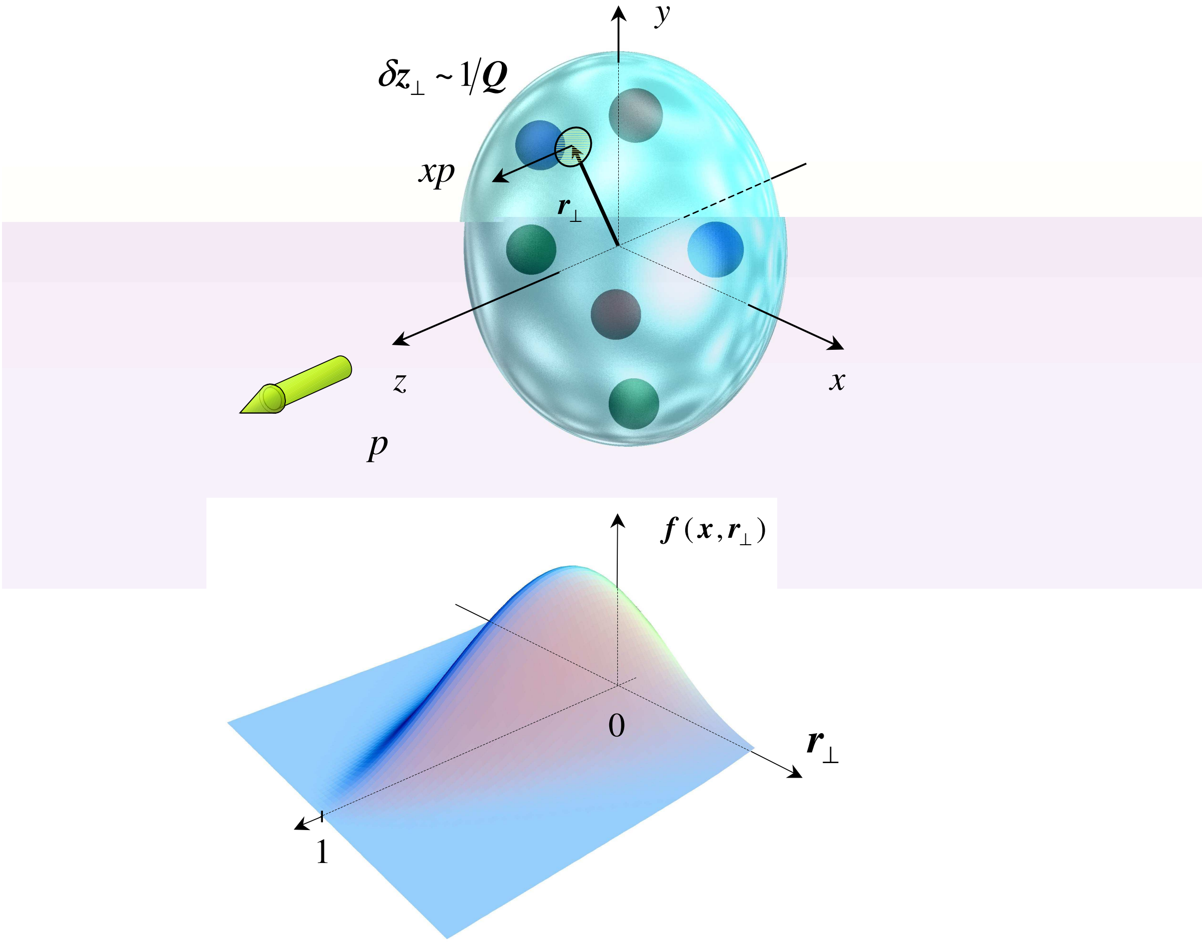
$$\frac{1}{2} = \underbrace{\frac{1}{2}\Delta\Sigma + L_q}_{J_q} + \underbrace{\Delta G + L_g}_{J_g}$$

Generalized Parton Distributions

- GPDs $\Rightarrow J_{q,g}$ (*Ji* 1997)

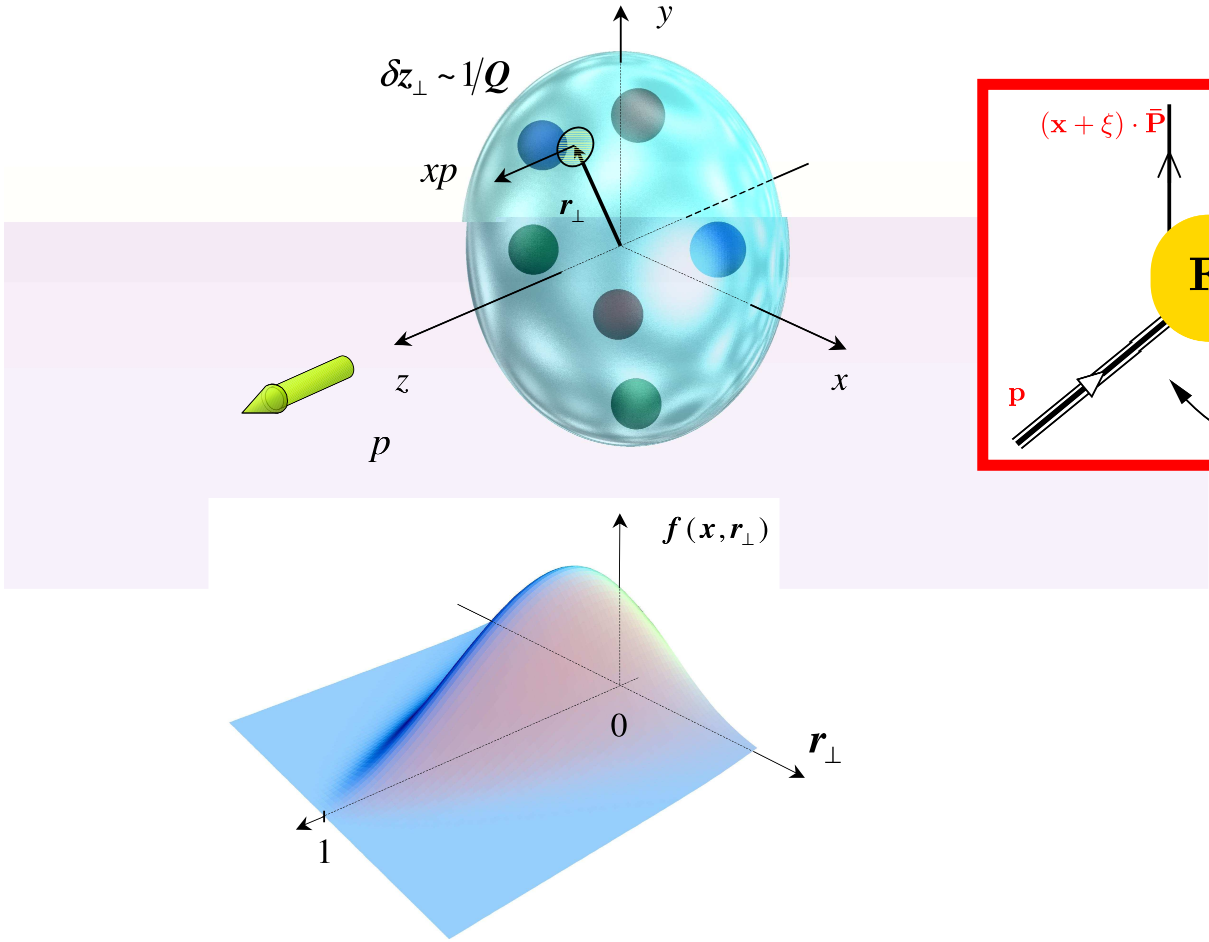
$$J_{q,g} = \frac{1}{2} \lim_{t \to 0} \int dx \cdot x \left[H_{q,g}(x, \xi, t, \mu^2) + E_{q,g}(x, \xi, t, \mu^2) \right]$$

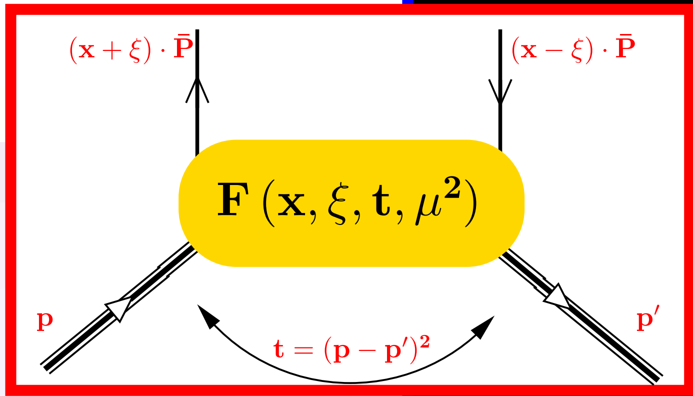
GPDs characterize long. momentum distributions in the trans. plane (IMF)



$x \pm \xi$	– longitudinal momentum fractions
t	– invariant momentum transfer

$\color{red}{\text{GPDs}}$ characterize long. momentum distributions in the trans. plane (IMF) and can be defined through $\langle P', S' | \mathcal{O}_{q/g} | P, S \rangle$.





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

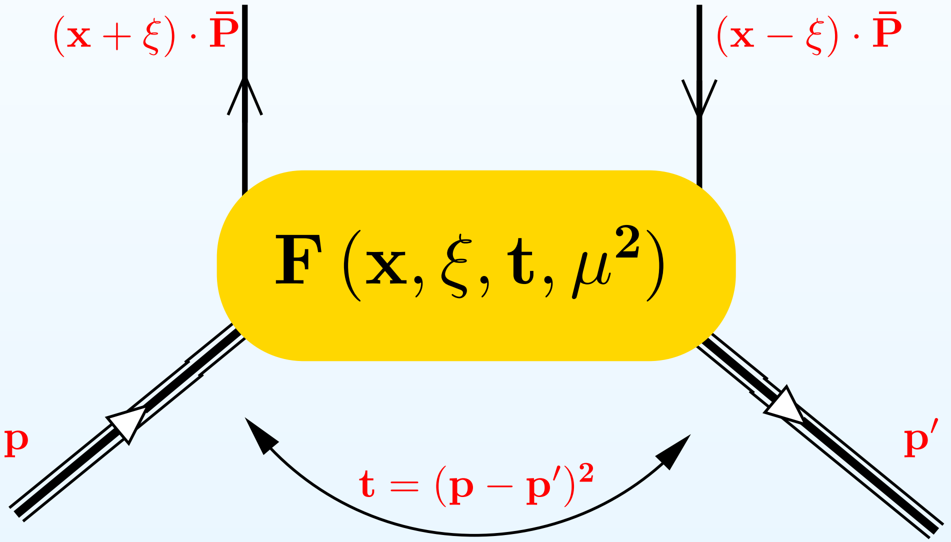
How to Study GPDs

- GPDs are related to known quantities (FFs, PDFs).

FFs	$\int_{-1}^{1} dx\, H_q\left(x,\xi,t,\mu^2\right) = F_1^q(t)$ $\int_{-1}^{1} dx\, \widetilde{H}_q\left(x,\xi,t,\mu^2\right) = g_V^q(t)$	$\int_{-1}^{1} dx\, E_q\left(x,\xi,t,\mu^2\right) = F_2^q(t)$ $\int_{-1}^{1} dx\, \widetilde{E}_q\left(x,\xi,t,\mu^2\right) = g_A^q(t)$
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

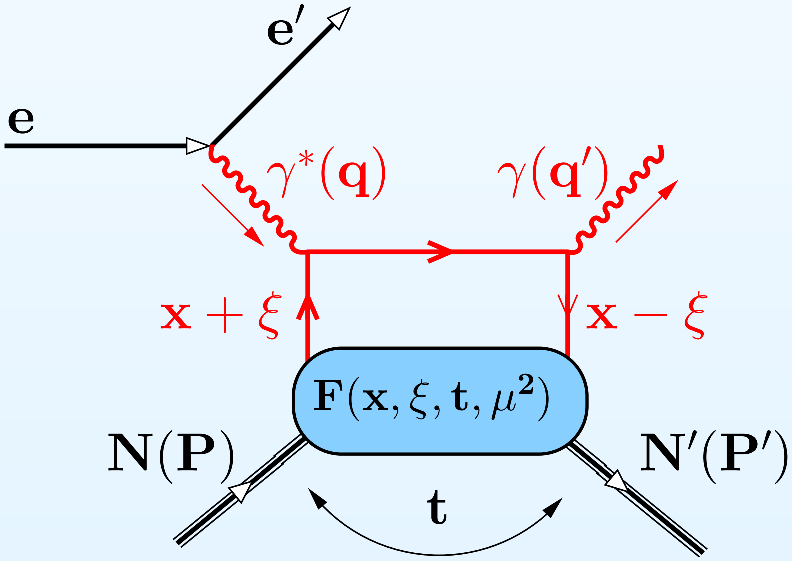
How to Study GPDs

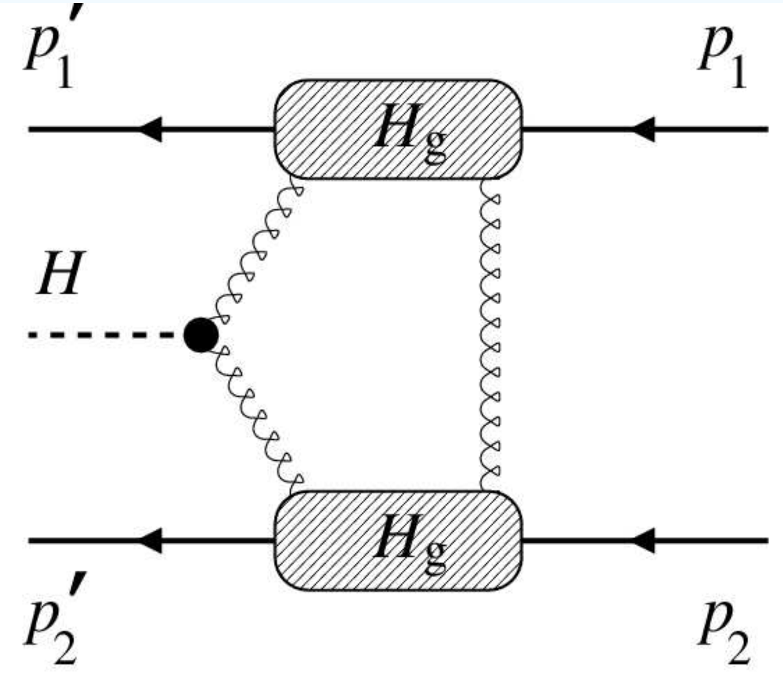
- GPDs are related to known quantities (FFs, PDFs).
- Symmetries: time-revesal $\Rightarrow F(x, \xi) = F(x, -\xi)$, ...



How to Study GPDs

- GPDs are related to known quantities (FFs, PDFs).
- Symmetries: time-revesal $\Rightarrow F(x,\xi) = F(x,-\xi)$, ...
- GPDs enter in hard exclusive reactions, e.g., DVCS $\gamma^* p \to \gamma p$, diffractive Higgs production $p\bar{p} \to p + H + \bar{p}$.





How to Study GPDs

- GPDs are related to known quantities (FFs, PDFs).
- Symmetries: time-revesal $\Rightarrow F(x,\xi) = F(x,-\xi)$, ...
- GPDs can be accessed in hard exclusive reactions.
- The Mellin x-moments of GPDs can be calculated in Lattice QCD.

$$\int_{-1}^{1} dx\, x^{n-1} H^q(x,\xi,t) \quad = \quad A^q_{n0}(t) + A^q_{n2}(t)(-2\xi)^2 + \cdots + C^q_{n+1,n}(t)(-2\xi)^n,$$

$$\int_{-1}^{1} dx\, x^{n-1} E^q(x,\xi,t) \quad = \quad B^q_{n0}(t) + B^q_{n2}(t)(-2\xi)^2 + \cdots - C^q_{n+1,n}(t)(-2\xi)^n,$$

How to Study GPDs

- GPDs are related to known quantities (FFs, PDFs).
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- μ^2 evolution of GPDs is governed by DGLAP/ERBL equations.

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- Quark-Gluon Structure of the Nucleon
- Deeply Virtual Compton Scattering
  - Kinematics, Amplitudes, and Asymmetries
- The HERMES Experiment
- Transverse Target-Spin Asymmetry in DVCS
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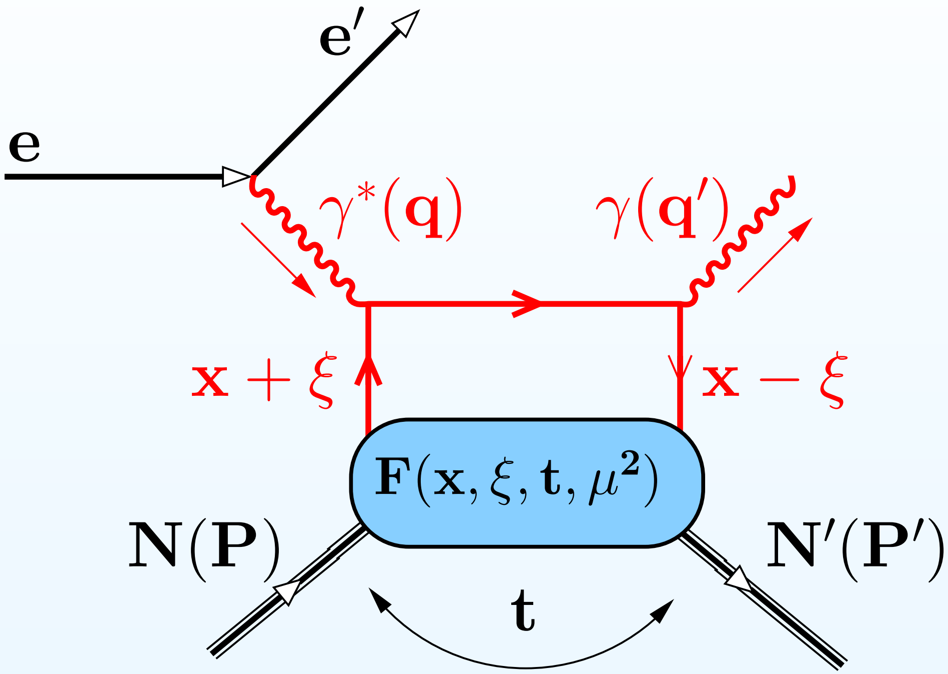
Kinematics and Amplitudes



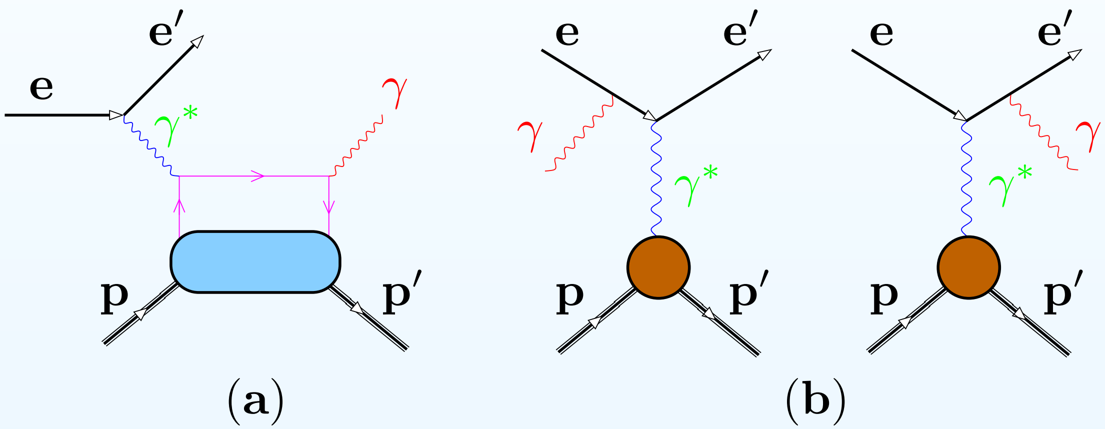
$$
\begin{aligned}
e(k) + N(p) &\longrightarrow e(k') + N(p') + \gamma(q') \\
Q^2 &\equiv -q^2 = -(k-k')^2 \\
x_B &\equiv \frac{Q^2}{2p \cdot q} \\
t &\equiv (p'-p)^2 = \Delta^2
\end{aligned}
$$

- 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



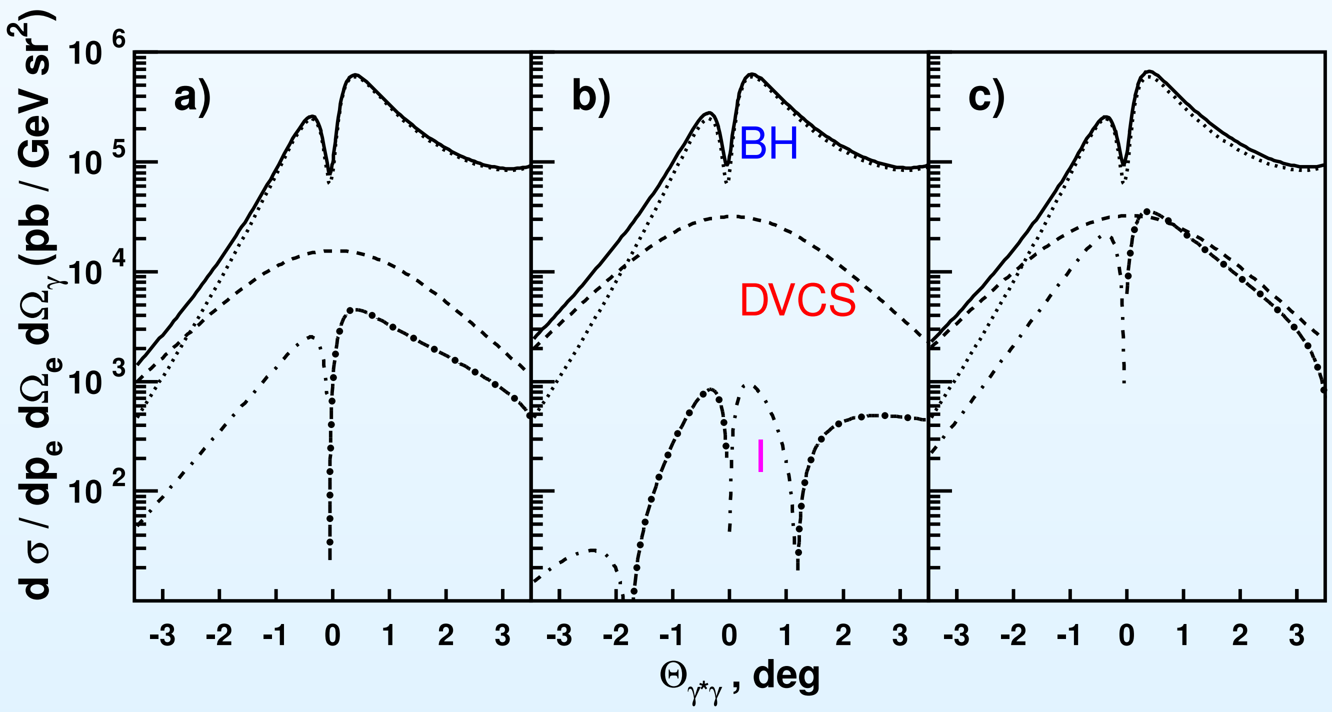
$$\sigma \propto \quad |\mathcal{T}_{\mathrm{BH}}|^2 + |\mathcal{T}_{\mathrm{DVCS}}|^2 + \underbrace{(\mathcal{T}_{\mathrm{BH}}\mathcal{T}^*_{\mathrm{DVCS}} + \mathcal{T}^*_{\mathrm{BH}}\mathcal{T}_{\mathrm{DVCS}})}_{I}$$

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

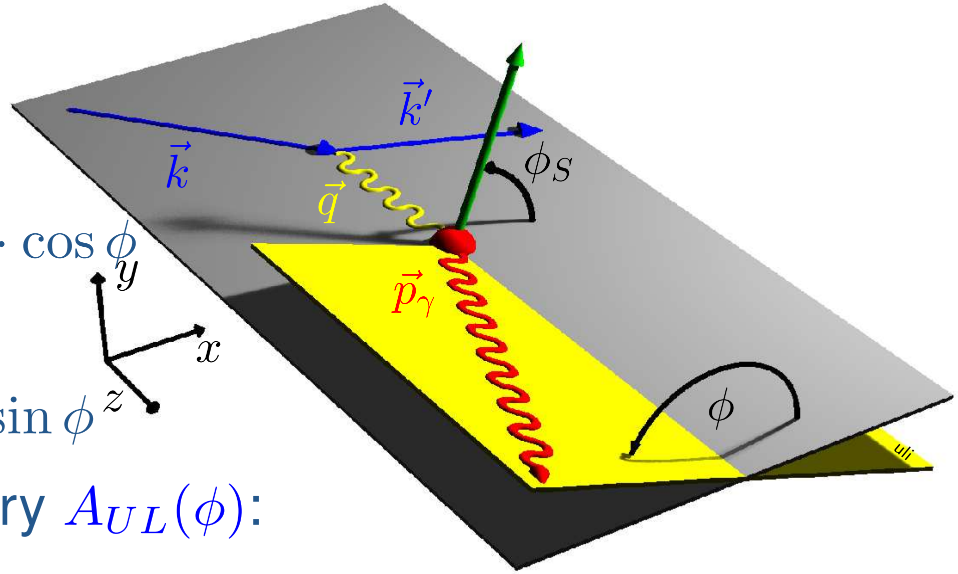
- $\mathcal{T}_{\mathrm{DVCS}}$ is calculable in terms of Compton FFs $\mathcal{H}$, $\mathcal{E}$, $\widetilde{\mathcal{H}}$, and $\widetilde{\mathcal{E}}$, which are convolutions of the respective GPDs with the hard-scattering kernels.

Kinematics and Amplitudes

- σ_{DVCS} can be measured (H1/ZEUS) after subtracting the known σ_{BH}. This gives the magnitude of $\mathcal{F}$ but not its phase.
- At HERMES kinematics, $\mathcal{T}_{BH} \gg \mathcal{T}_{DVCS}$, the DVCS amplitude can be measured through azimuthal asymmetries, which give info about both the amplitude and the phase of $\mathcal{F}$.



Azimuthal Asymmetries

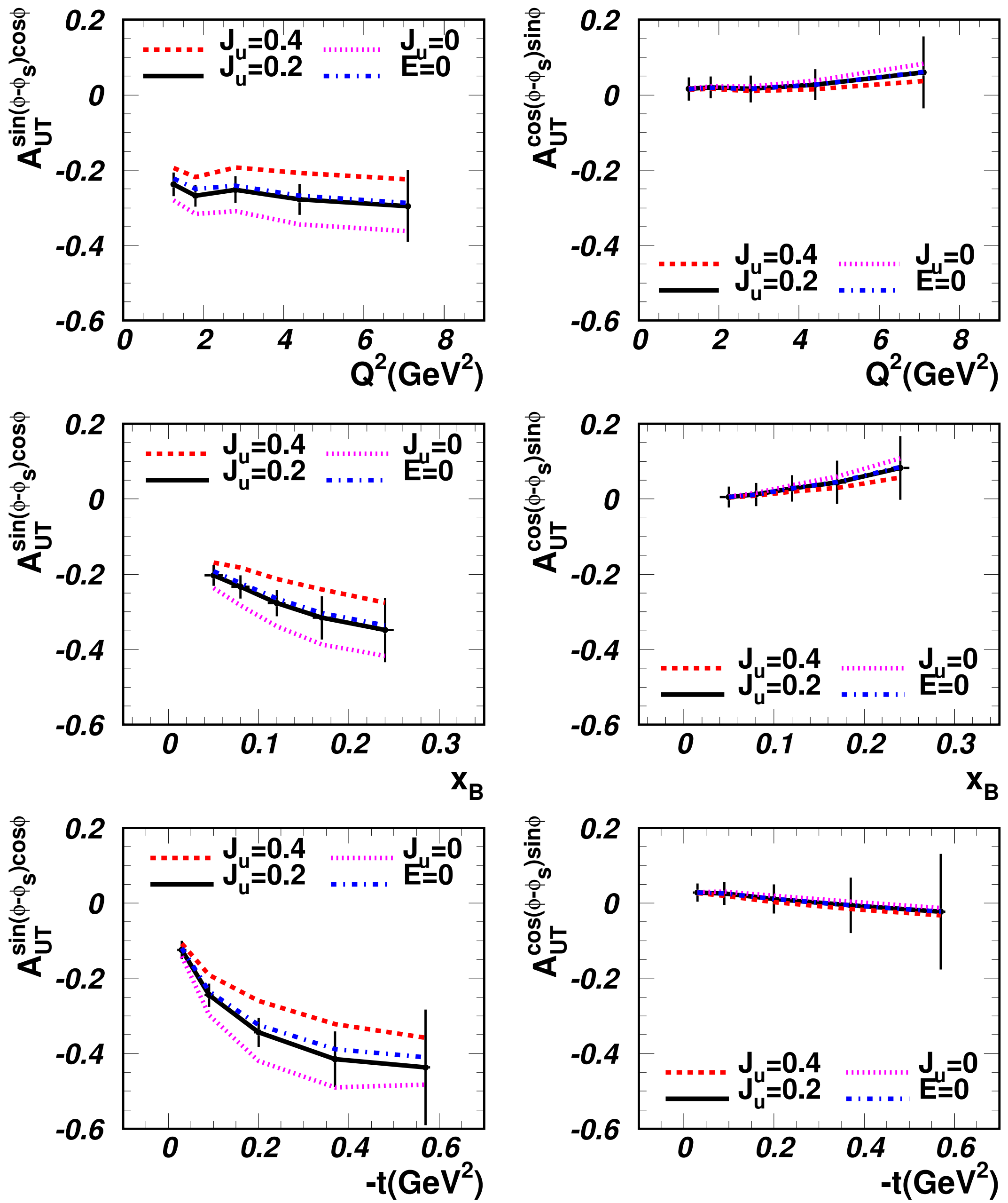


- Beam-charge asymmetry $A_C(\phi)$:
  $d\sigma(e^+,\phi) - d\sigma(e^-,\phi) \propto \mathrm{Re}[F_1\mathcal{H}]\cdot\cos\phi$
- Beam-spin asymmetry $A_{LU}(\phi)$:
  $d\sigma(\overrightarrow{e},\phi) - d\sigma(\overleftarrow{e},\phi) \propto \mathrm{Im}[F_1\mathcal{H}]\cdot\sin\phi$
- Longitudinal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

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

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

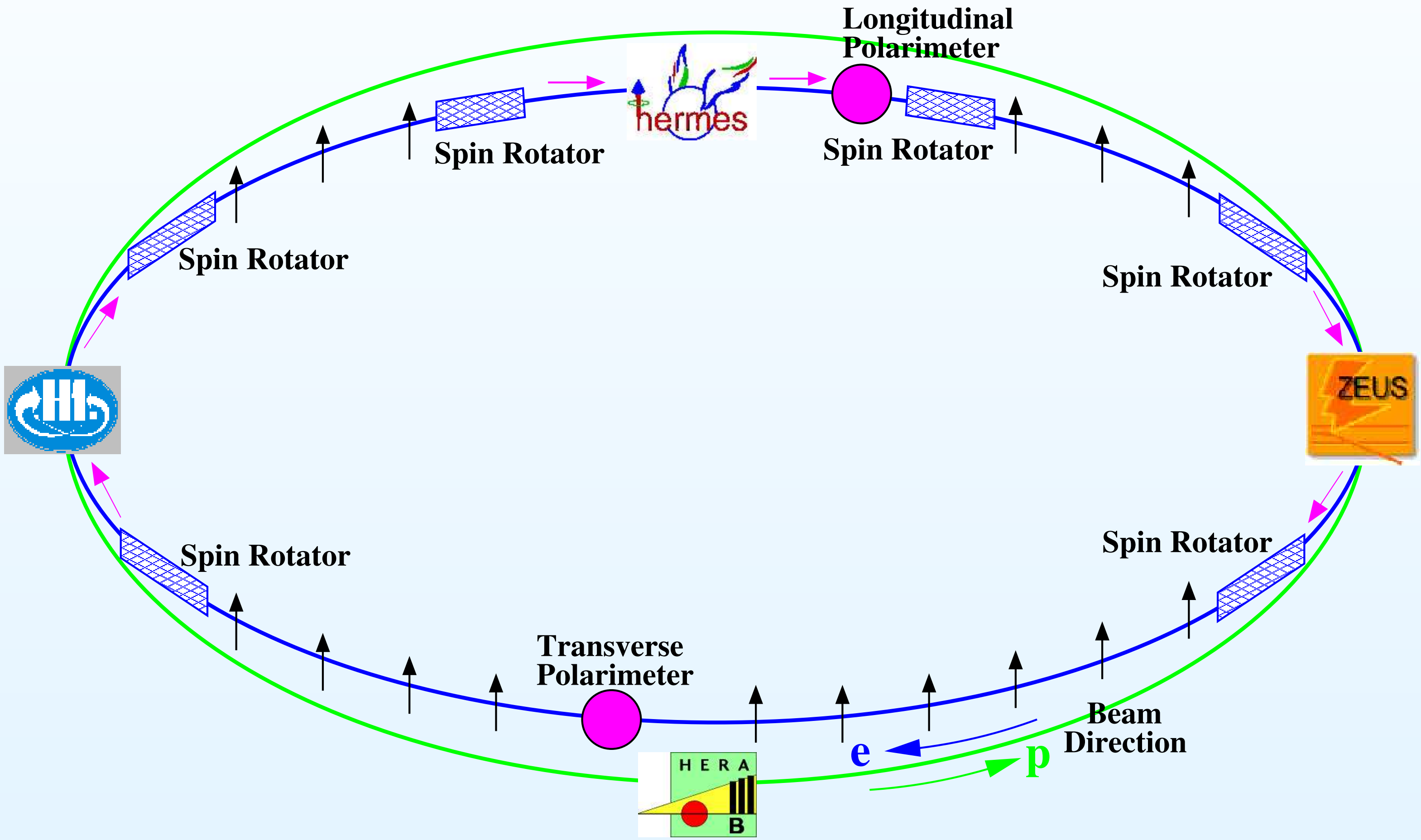
F.E., W.N., A.V., Z.Ye, EPJC 2006, hep-ph/0506264



The HERMES Experiment

HERMES Experiment

- HERMES is a fixed target experiment at HERA with 27.6 GeV $e^{\pm}$.



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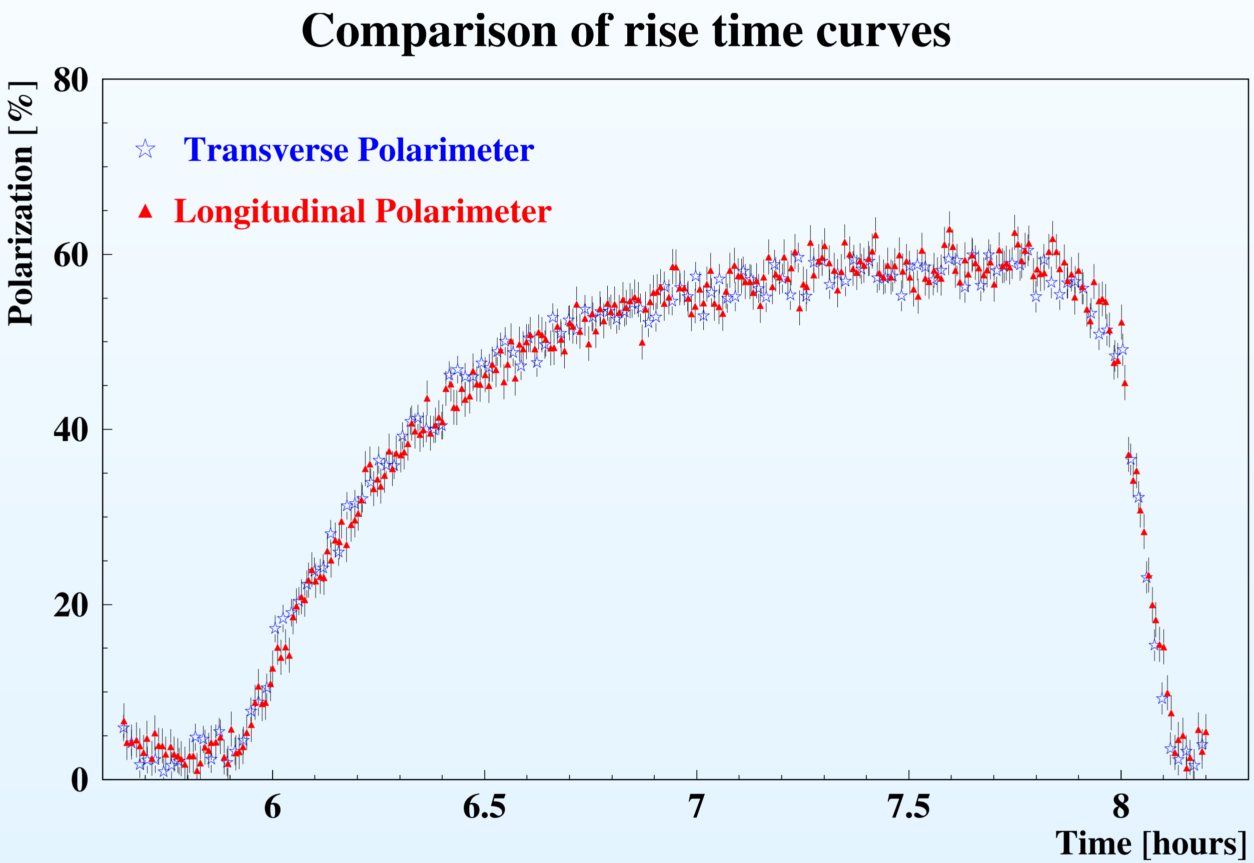
  - longitudinally polarized $e^{\pm}$



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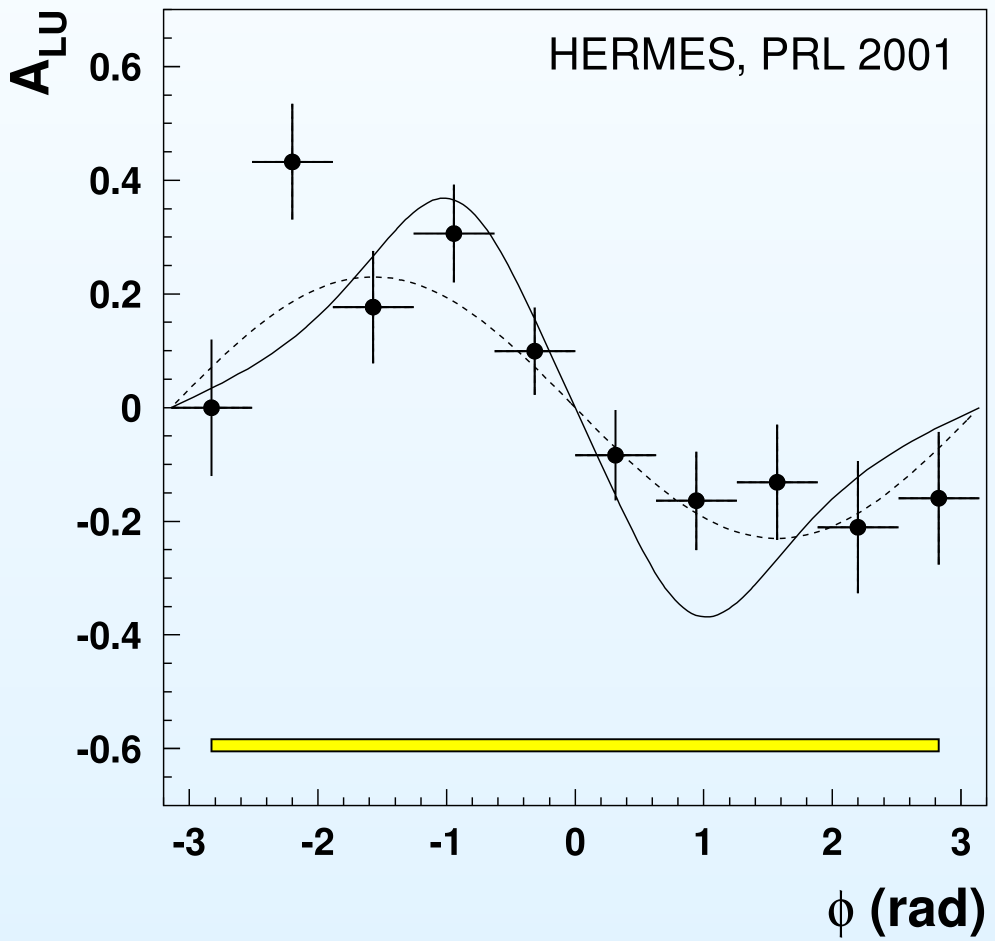
  - longitudinally polarized $e^{\pm}$ $\Rightarrow$ BCA and BSA



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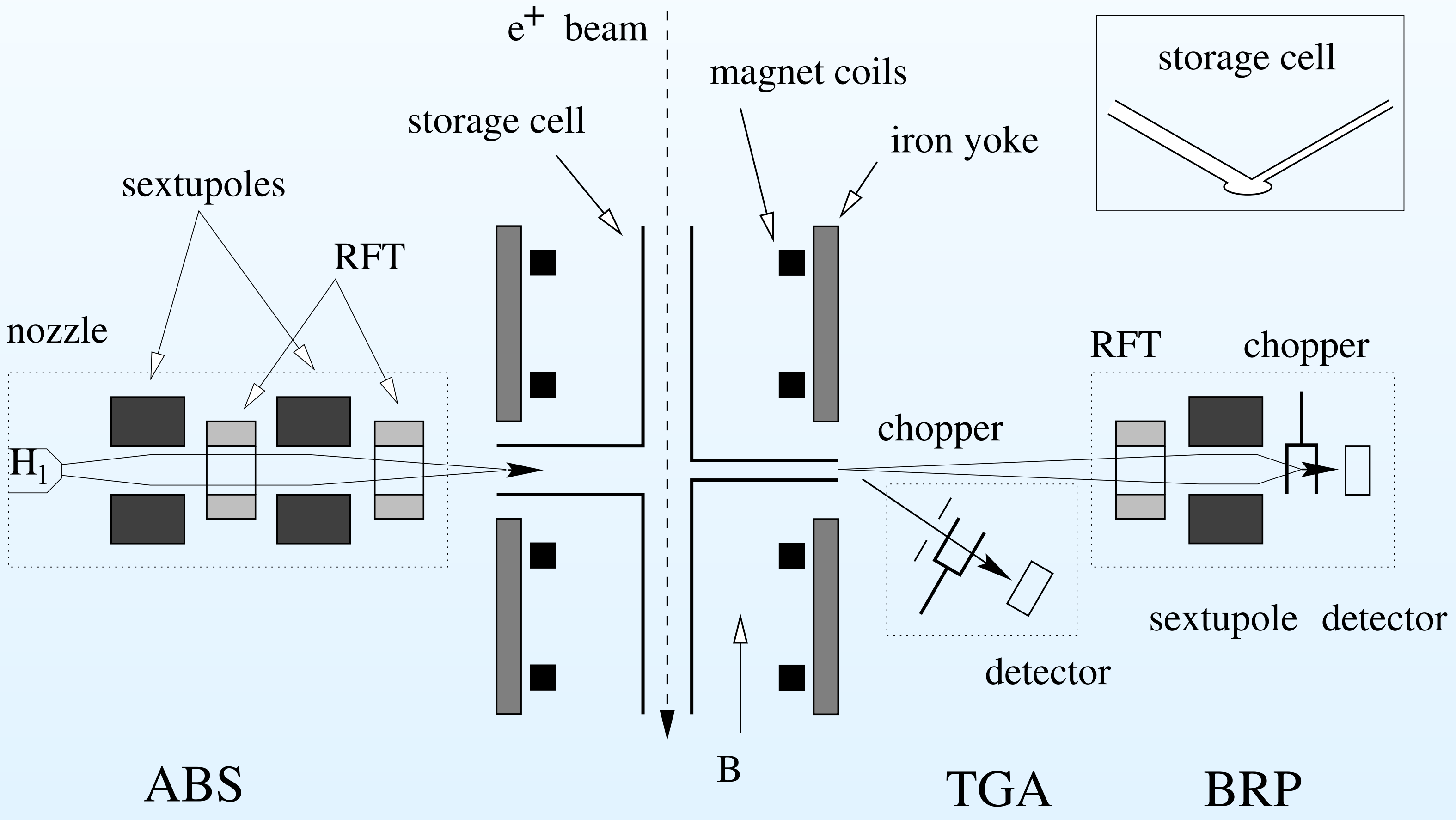
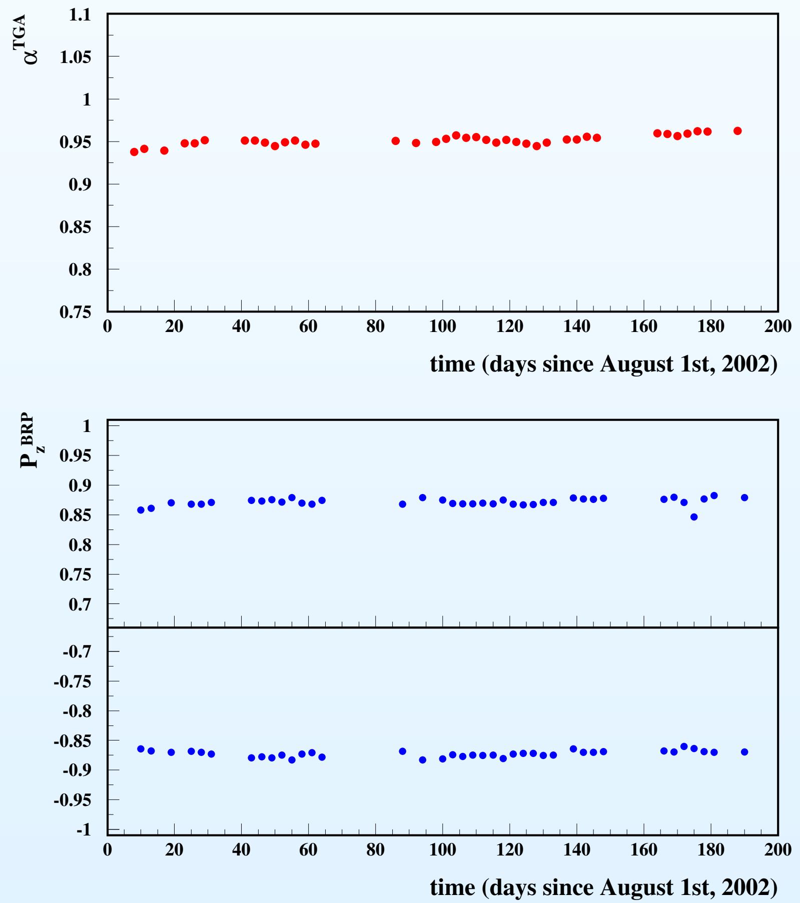
  - longitudinally polarized $e^{\pm}$ $\Rightarrow$ BCA and BSA
  - polarized gaseous targets



HERMES Experiment

- HERMES is a fixed target experiment at HERA with 27.6 GeV $e^{\pm}$.
  - longitudinally polarized $e^{\pm}$ $\Rightarrow$ BCA and BSA
  - polarized gaseous targets $\Rightarrow$ high polarization $\sim \pm 80\%$

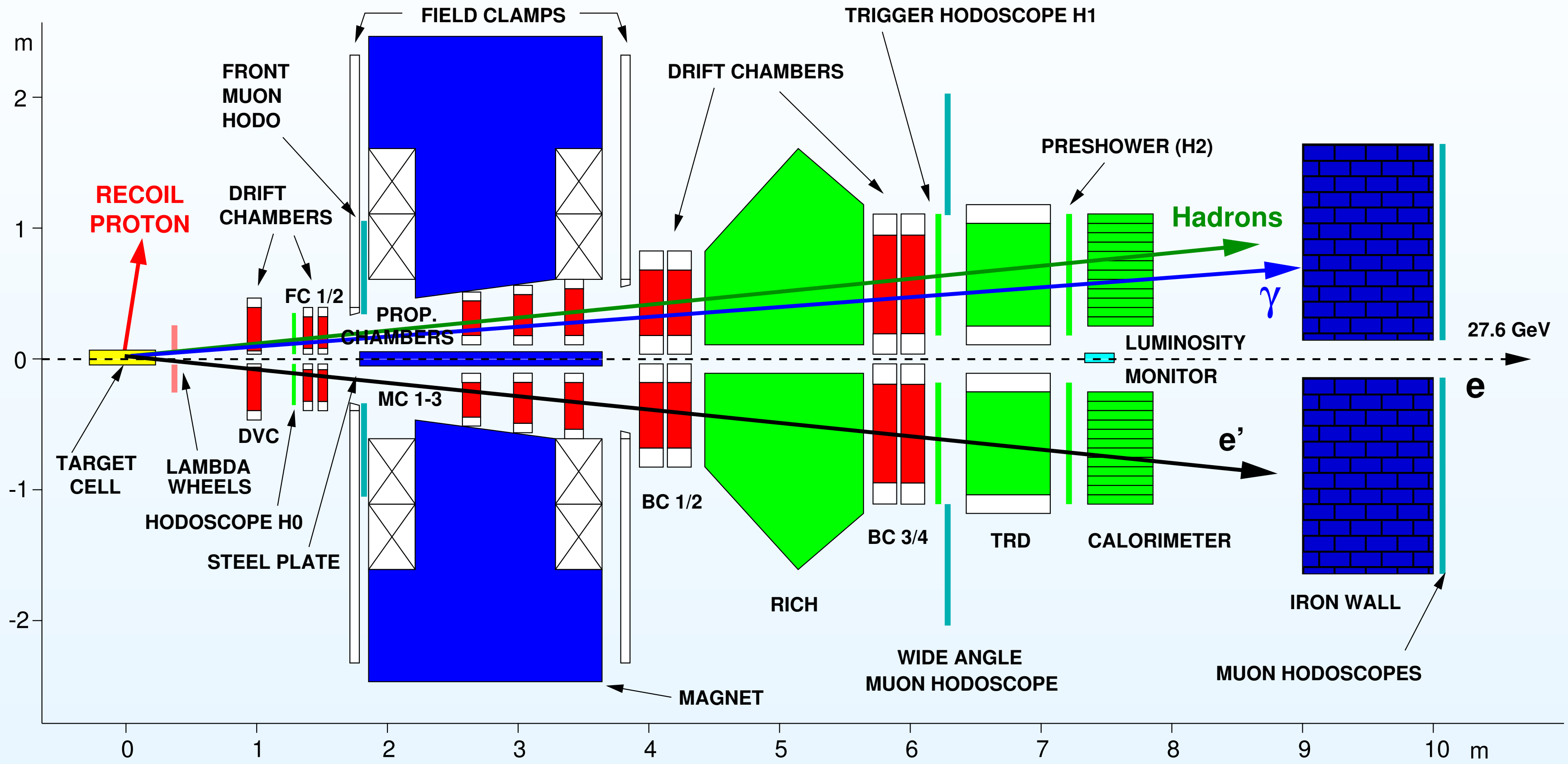


HERMES Experiment

- HERMES is a fixed target experiment at HERA with 27.6 GeV $e^{\pm}$.
  - longitudinally polarized $e^{\pm}$ $\Rightarrow$ BCA and BSA
  - polarized gaseous targets $\Rightarrow$ TSAs

  $\Rightarrow$ an ideal place to study DVCS by asymmetries!

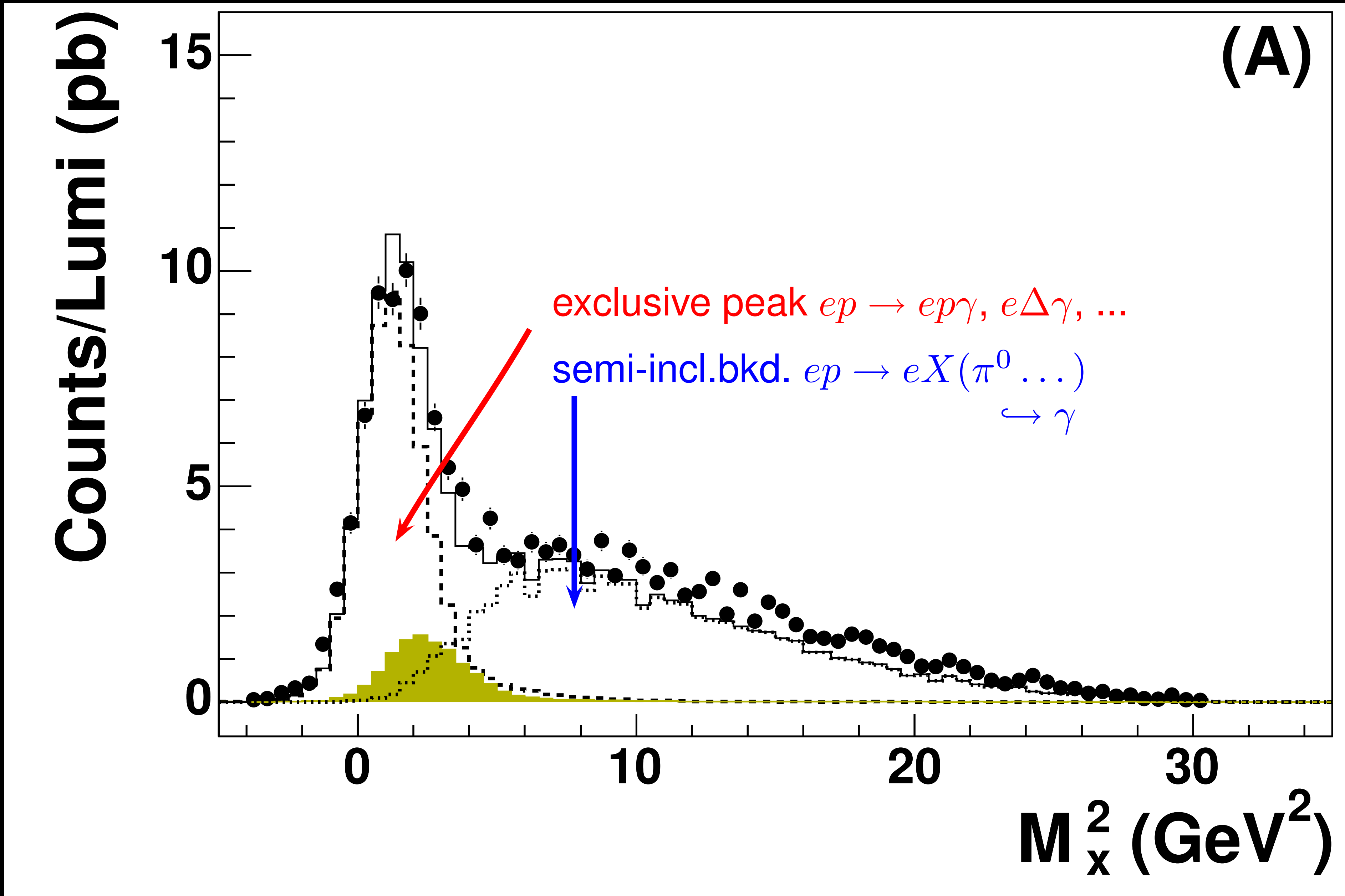
DVCS@HERMES



- Tracking: $\delta P_e/P_e < 2\%$, $\delta\theta_e < 1$ mrad
- Particle Identification: $\epsilon_e > 99\%$, hadron contamination $< 1\%$
- Photons: calorimeter $\delta E_\gamma/E_\gamma \sim 5\%$, $\delta x(y) \sim 0.5$ cm

DVCS@HERMES

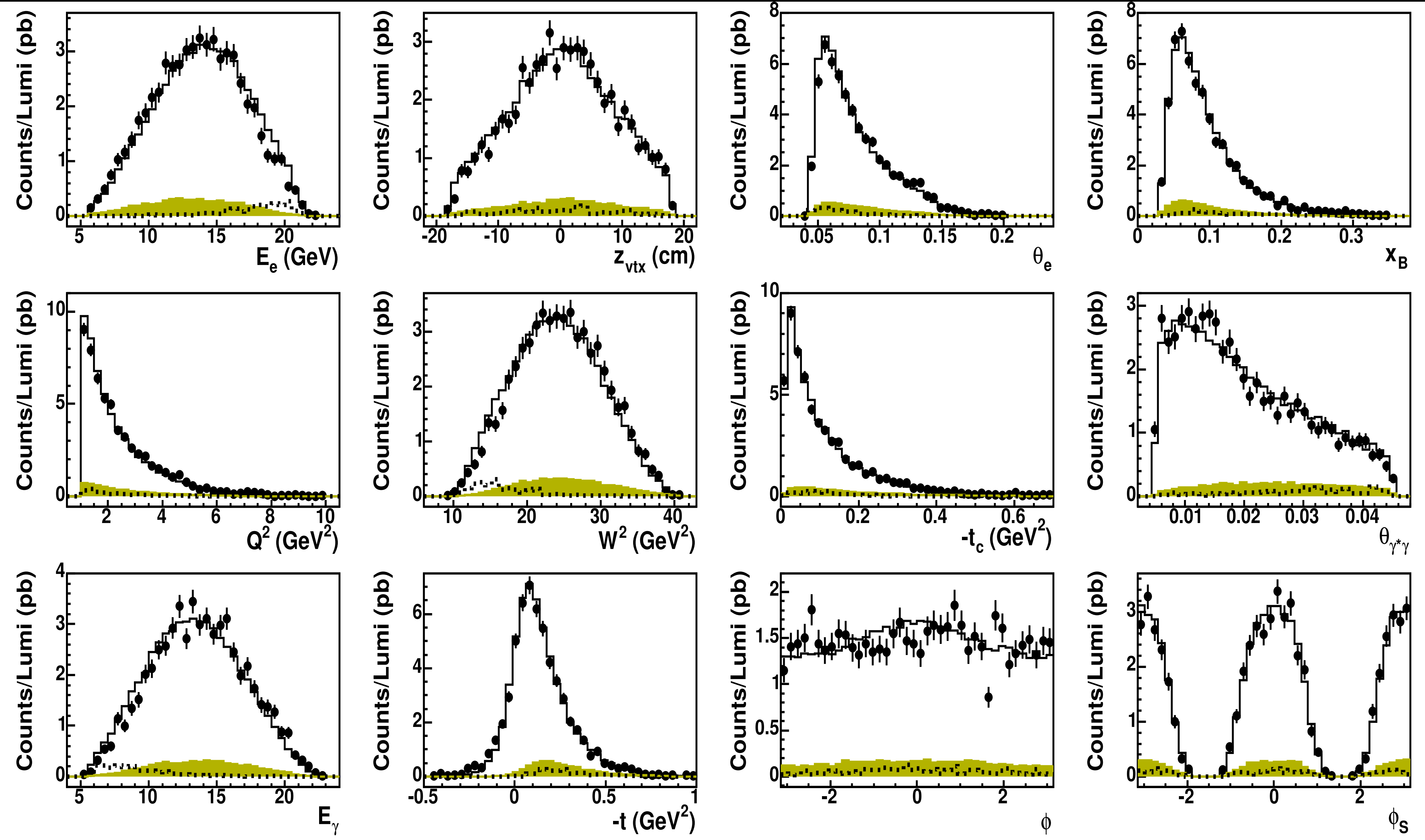
- Recoiling protons were not detected $\Rightarrow$ maitain exclusivity through missing mass $\mathrm{M}_{\mathrm{x}}^{2} = (P_e + P_p - P_{e'} - P_\gamma)^2$.


(A)
Counts/Lumi (pb)
15
10
5
0
0
10
20
30
M_x^2 (GeV^2)
exclusive peak $ep \to ep\gamma$, $e\Delta\gamma$, ...
semi-incl.bkd. $ep \to eX(\pi^0 \ldots)$
$\hookrightarrow \gamma$

DVCS@HERMES

- Recoiling protons were not detected $\Rightarrow$ maitain exclusivity through missing mass cut $-(1.5)^2 < \mathrm{M}_\mathrm{x}^2 < (1.7)^2$ GeV^2 .
- 3,813 candidates of exclusive BH+DVCS events were selected from the HERMES 02-04 data ($\sim$ 65 pb^{-1}).

$-(1.5)^2 < M_x^2 < (1.7)^2$ GeV^2



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Maximum Likelihood Method

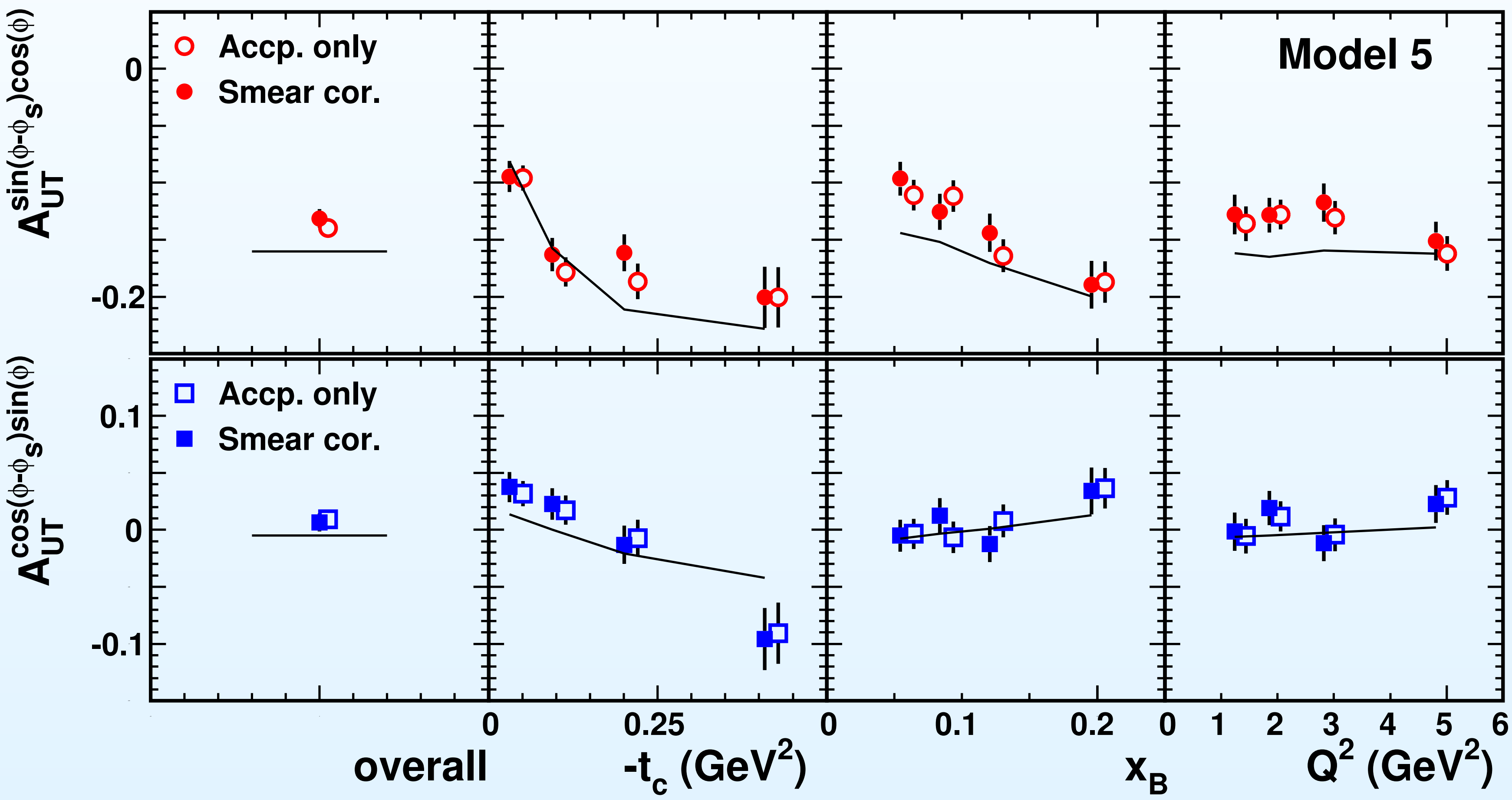
- $\sigma_P = \sigma_U(\phi)\,[1 + P_T A_{UT}(\phi, \phi_S; \boldsymbol{\theta})]$ polarized cross section
- P_T target polarization
- A_{UT} asymmetry
- ϵ detection efficiency
- L integrated luminosity
- $f = \epsilon \cdot \sigma_P \cdot L / Norm$ normalized p.d.f.

$$
\begin{aligned}
-\ln L(\boldsymbol{\theta}) &= -\sum_{i=1}^{n} \ln f^i(\phi, \phi_S, P_T; \boldsymbol{\theta}) = -\sum_{i=1}^{n} \ln \frac{1 + P_T^i A_{UT}^i(\phi, \phi_S; \boldsymbol{\theta})}{Norm(\boldsymbol{\theta})} + \ldots \\
Norm(\boldsymbol{\theta}) &= \iint \epsilon(\phi, \phi_S) \cdot \sigma_U(\phi) \cdot L \cdot \left[1 + P_T \cdot A_{UT}(\phi, \phi_S; \boldsymbol{\theta})\right] \\
&\approx \sum_{i=1}^{N_U} \left[1 + P_T \cdot A_{UT}(\phi, \phi; \boldsymbol{\theta})\right] \Bigg|_{\langle P_T \rangle = 0}
\end{aligned}
$$

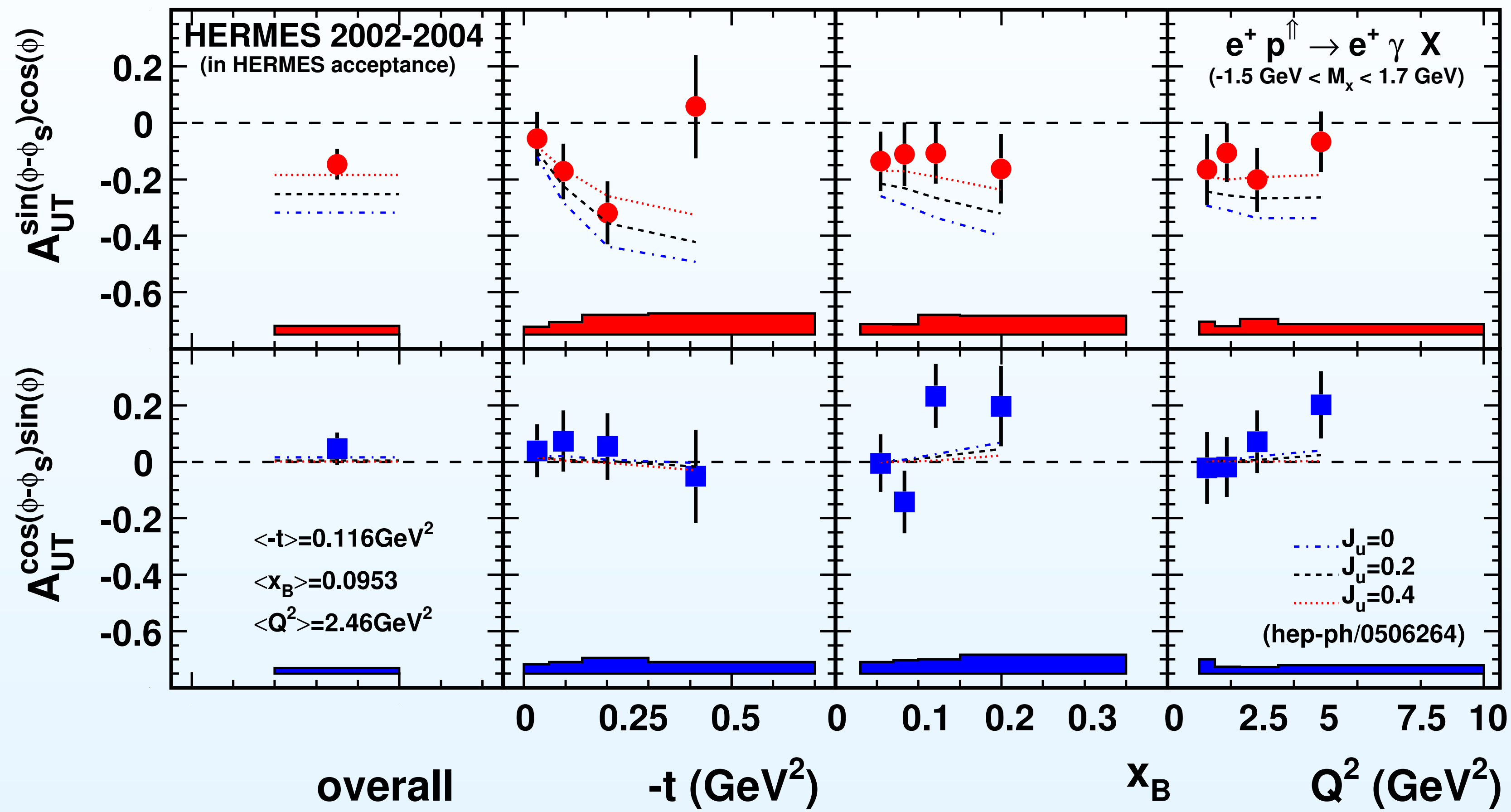
$\Rightarrow$ All the info used in the extraction is based on the real data.

Maximum Likelihood Method

- MC studies demonstrated good performance of the method: extracted (points) vs input (lines).

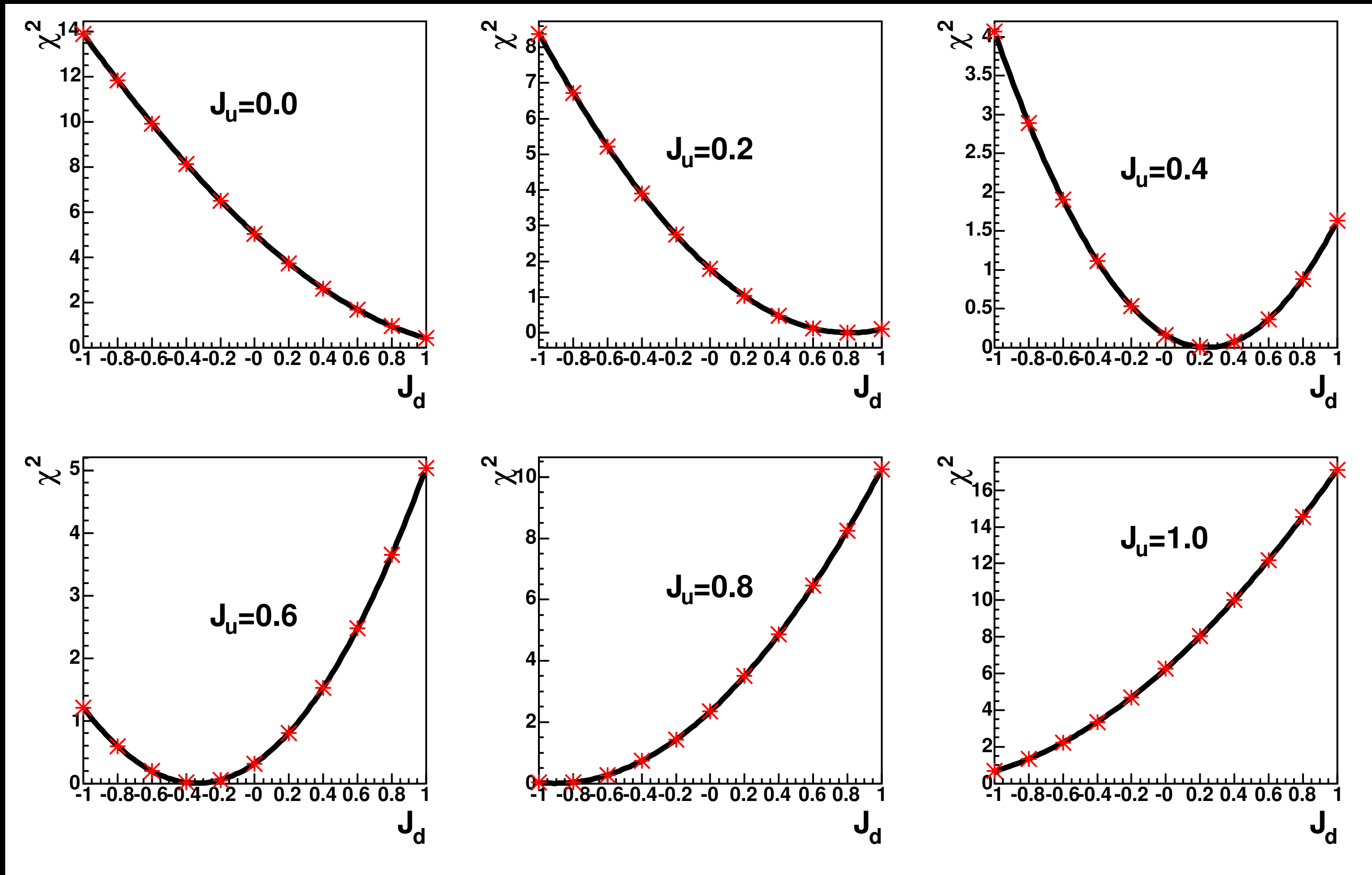


HERMES Results

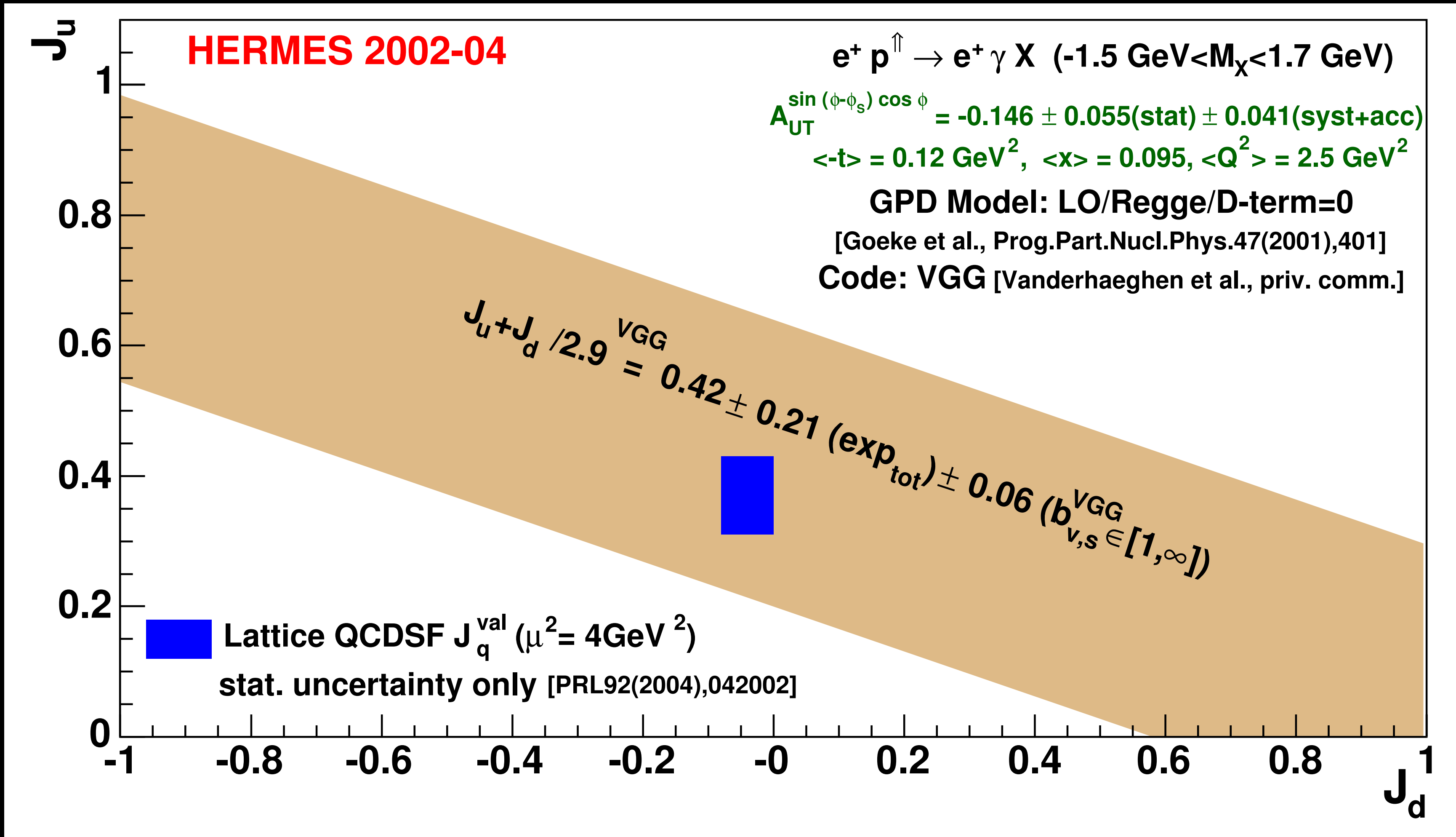


Systematic uncertainties:

- target pol≈ 0.01; fit function ≈ 0.01; background ≈ 0.02;
- smear≈ 0.02; (accp.) ≈ 0.03.



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



$$\chi^2(J_u, J_d) \leq \chi^2_{min} + 1$$

Summary and Outlook

- DVCS provides access to GPDs which contain a wealth of information about the nucleon strcture.
- A_{UT}^{DVCS} was firstly measured at HERMES, from which a model-dependent constraint on J_u vs J_d is obtained.

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- A_{UT}^{DVCS} was firstly measured at HERMES, from which a model-dependent constraint on J_u vs J_d is obtained.

- A more complete picture of the nucleon structure in terms of GPDs soon! (HERMES, COMPASS@CERN, JLab@12GeV)