Extraction of Generalized Parton Distributions – Experimental Aspects

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DESY, 15738 Zeuthen, Germany

Semi-Inclusive Reactions (SIR) Workshop 2005
JLab, May 18-20 2005

Talks to follow:

* DVCS program at Hermes — F. Ellinghaus — 9:00
* GPD studies at Jlab — M. Garcon — 9:20
* GPD studies at Compass — E. Burtin — 9:40
* Excl. meson production at Hermes — R. Fabbri — 17:30

THIS TALK:

* Experimentalist's introduction to GPDs
  - DVCS
  - Exclusive meson production at Hermes
  - Cross section measurements for DVCS at H1 / ZEUS
* Prospects for accessing quark GDDs
* Towards a global analysis of quark GPDs

Motivation.
Nucleon Spin Composition

Proton's Spin = $\underbrace{\overbrace{\tfrac{1}{2}(\Delta u + \Delta d + \Delta s)}^{30\%} + \boxed{L_q}}_{J_q} + J_g$

unknown ! (L_q, J_g)

↑ gluons

Ji's relation:

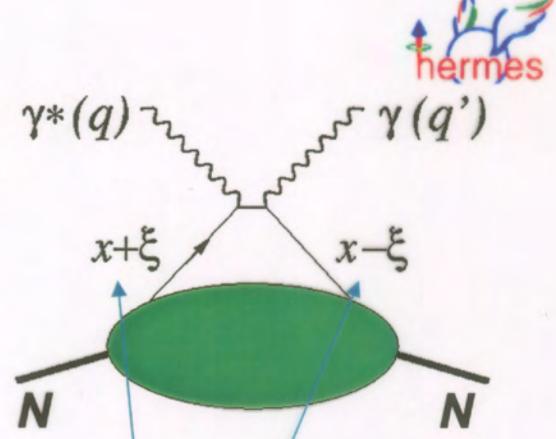
$$J_q^3(Q^2) = \lim_{t\to 0}\int_{-1}^{1} dx\, x \boxed{\left[\mathrm{H}_q(x,\xi,t) + \mathrm{E}_q(x,\xi,t)\right]}$$

GPDs

same for gluons

We study {DVCS / DVEM} to constrain quark GPDs

GPDs for DVCS on a spin-½ target



twist 2 GPDs:

UNPOL. POLAR.

$H(x,\xi,t), \widetilde{H}(x,\xi,t)$ target helicity conserving

$E(x,\xi,t), \widetilde{E}(x,\xi,t)$ target helicity non conserving

where:

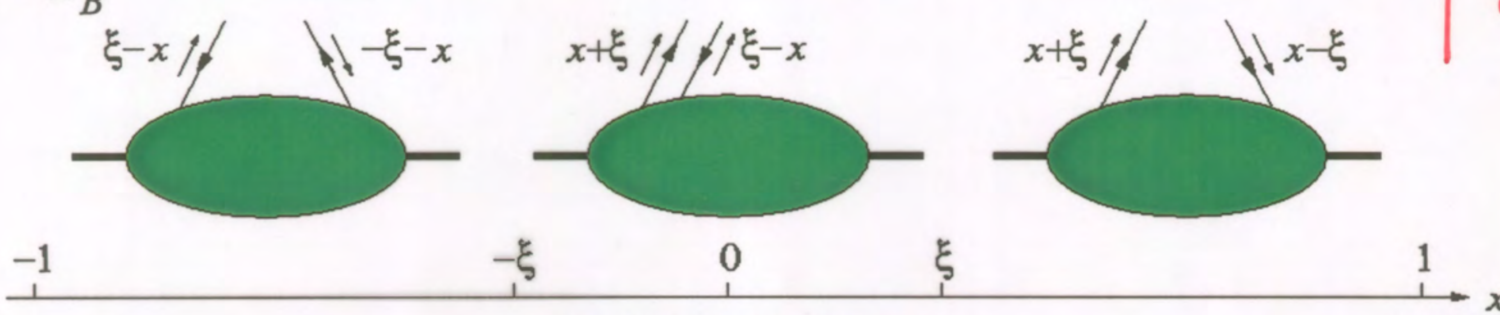
t momentum transfer (Mandelstam ***t***)

$x \pm \xi$ parton's longitudinal momentum fractions

x unobservable internal variable in DVCS

$\xi \cong \frac{x_B}{2-x_B}$ longitudinal momentum transfer between two partons

→ t contains transverse momentum transfer component



Properties of GPDs

Forward limit: $H^q(x,0,0) = q(x) \quad \tilde{H}^q(x,0,0) = \Delta q(x)$

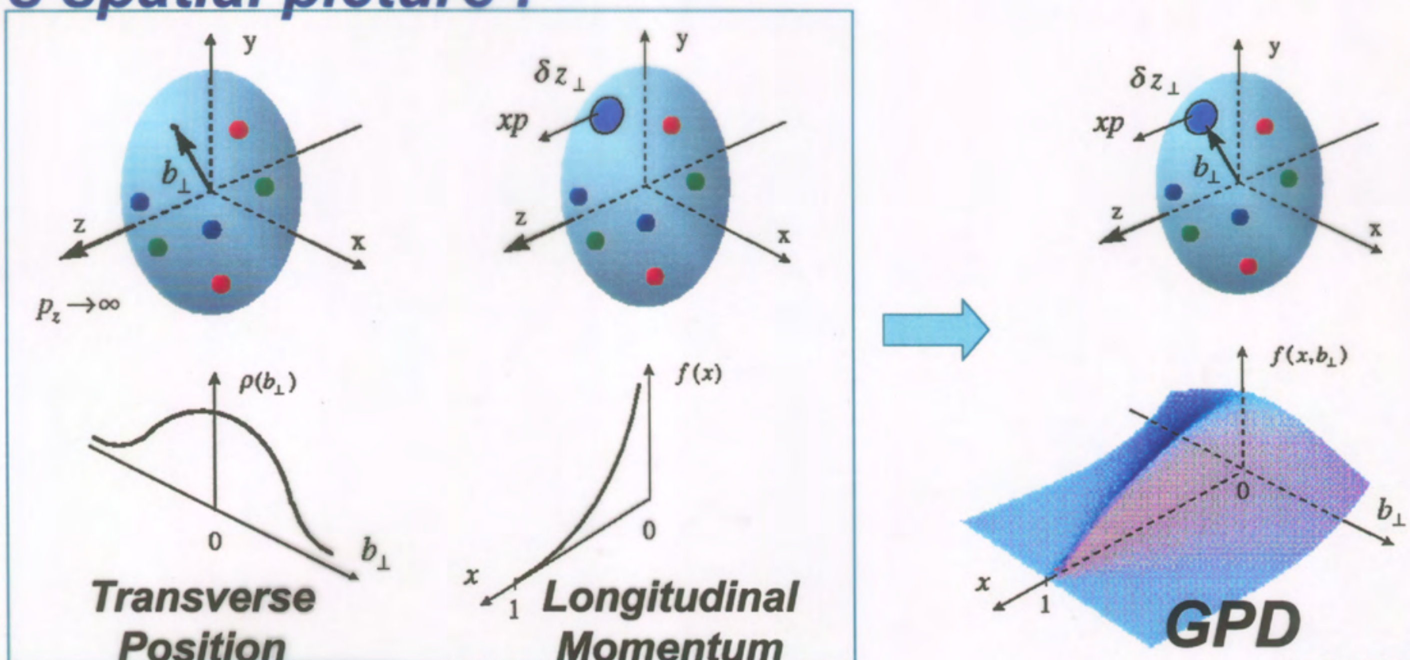
$t = 0, \xi = 0$

Sum Rules: $\int_{-1}^{1} dx H^q(x,\xi,t) = F_1(t) \quad \int_{-1}^{1} dx E^q(x,\xi,t) = F_2(t)$

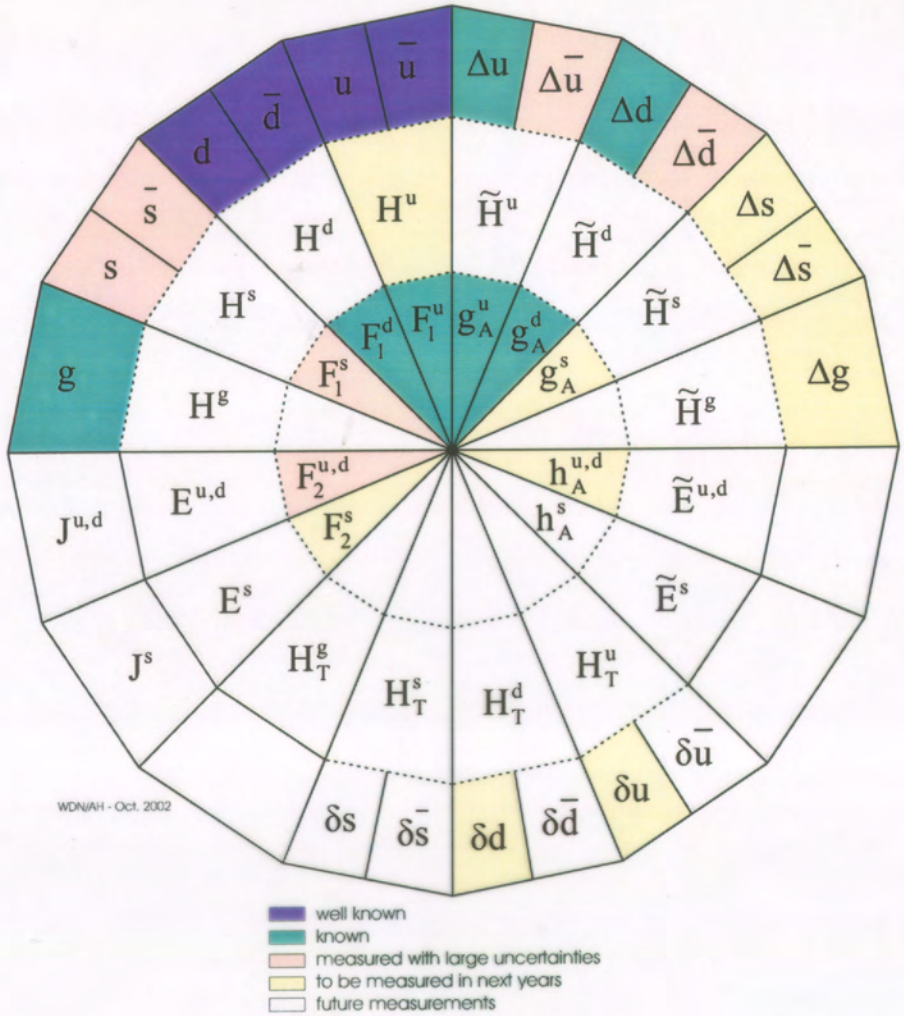
F_1, F_2 – Dirac and Pauli form factors

Nucleon's spatial picture :

See M. Burkardt's talk



Exp. Status on Parton Distr.'s



(cf. W.-D. N., hep-ex/0210409)
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Generalized Parton Distributions:

$H^q, \tilde{H}^q, E^q, \tilde{E}^q$ CHIRALLY-EVEN QUARK GPDs

$H^q_T, \tilde{H}^q_T, E^q_T, \tilde{E}^q_T$ CHIRALLY-ODD QUARK GPDs

Forward Parton Distributions:

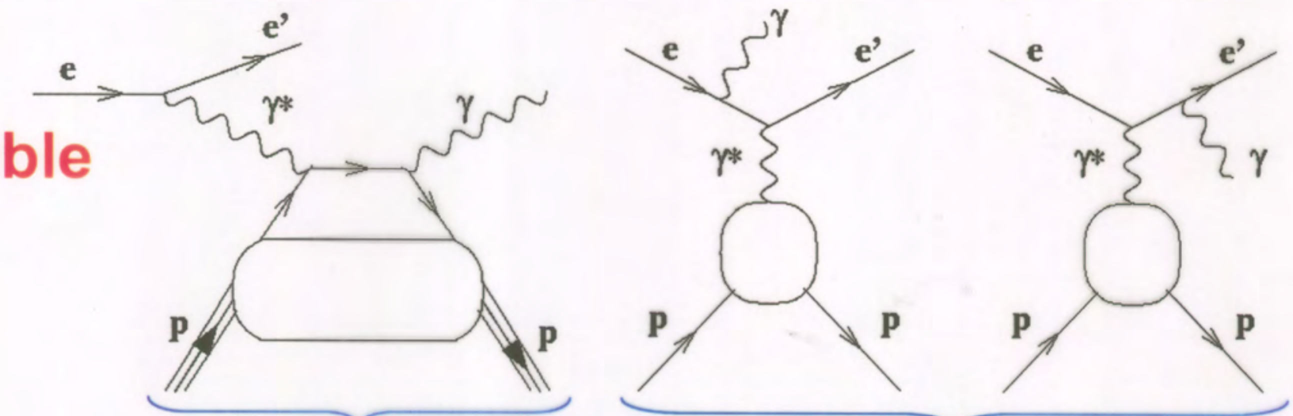
$q(x, Q^2)$ QUARK NUMBER DENSITY DISTRIBUTION (f_1^q)

$\Delta q(x, Q^2)$ QUARK HELICITY DISTRIBUTION (g_1^q)

$\delta q(x, Q^2)$ QUARK TRANSVERSITY DISTRIBUTION (h_1^q)

DVCS & **B**ethe-**H**eitler (BH)

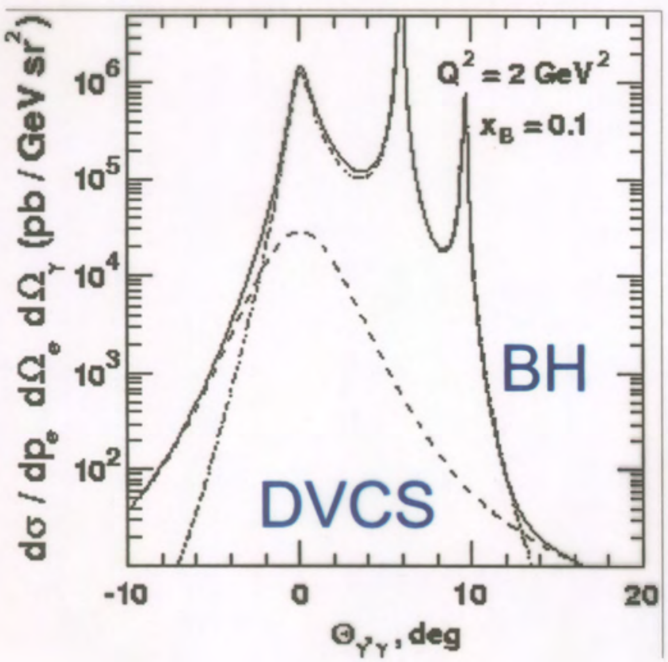
indistinguishable
final state



DVCS & Bethe-Heitler

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

@ HERMES

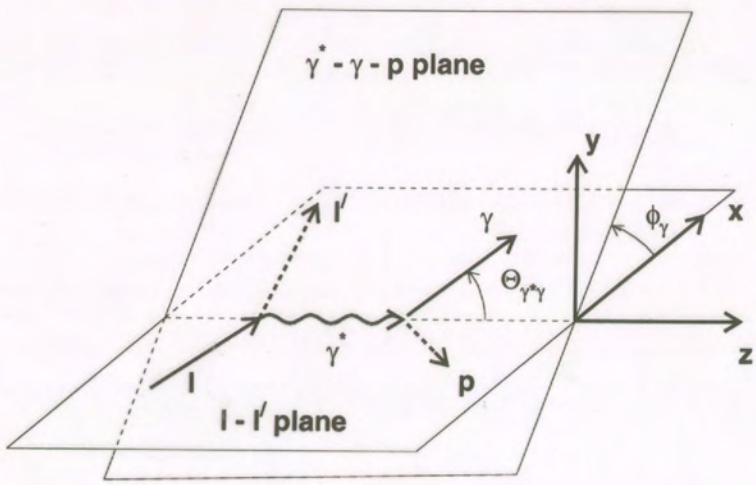


one measures interference of two processes
but BH is calculable in QED

DVCS is suppressed in respect to BH
@ HERMES

ϕ-DEPENDENCE OF ASYMMETRIES

DVCS KINEMATICAL CONFIGURATION:



ϕ_γ: azimuthal angle between scattering and reaction plane.

ϕ_γ: ASYMMETRIES SHOW DIFFERENT CHARACTERISTICS

A) MEASURE LEPTON CHARGE ASYMMETRY:

unpolarized beam, unpolarized target

$$A_{ch} \sim d\sigma(e^+p) - d\sigma(e^-p) \sim \cos(\phi_\gamma) \times \mathrm{Re}\mathcal{I}$$

⇒ access to real part of (certain combination of) ~~GPD~~ Compton ~~amplitudes~~ form factors, essentially ~ Re $\mathcal{H}$ (convolution of H_q's)

B) Measure lepton helicity asymmetry:

long. polarized beam, unpolarized target

$$A_{LU} \sim d\sigma(\overrightarrow{e^+}p) - d\sigma(\overleftarrow{e^+}p) \sim \sin(\phi_\gamma) \times \mathrm{Im}\mathcal{I} \sim \mathrm{Im}\,\mathcal{H}$$

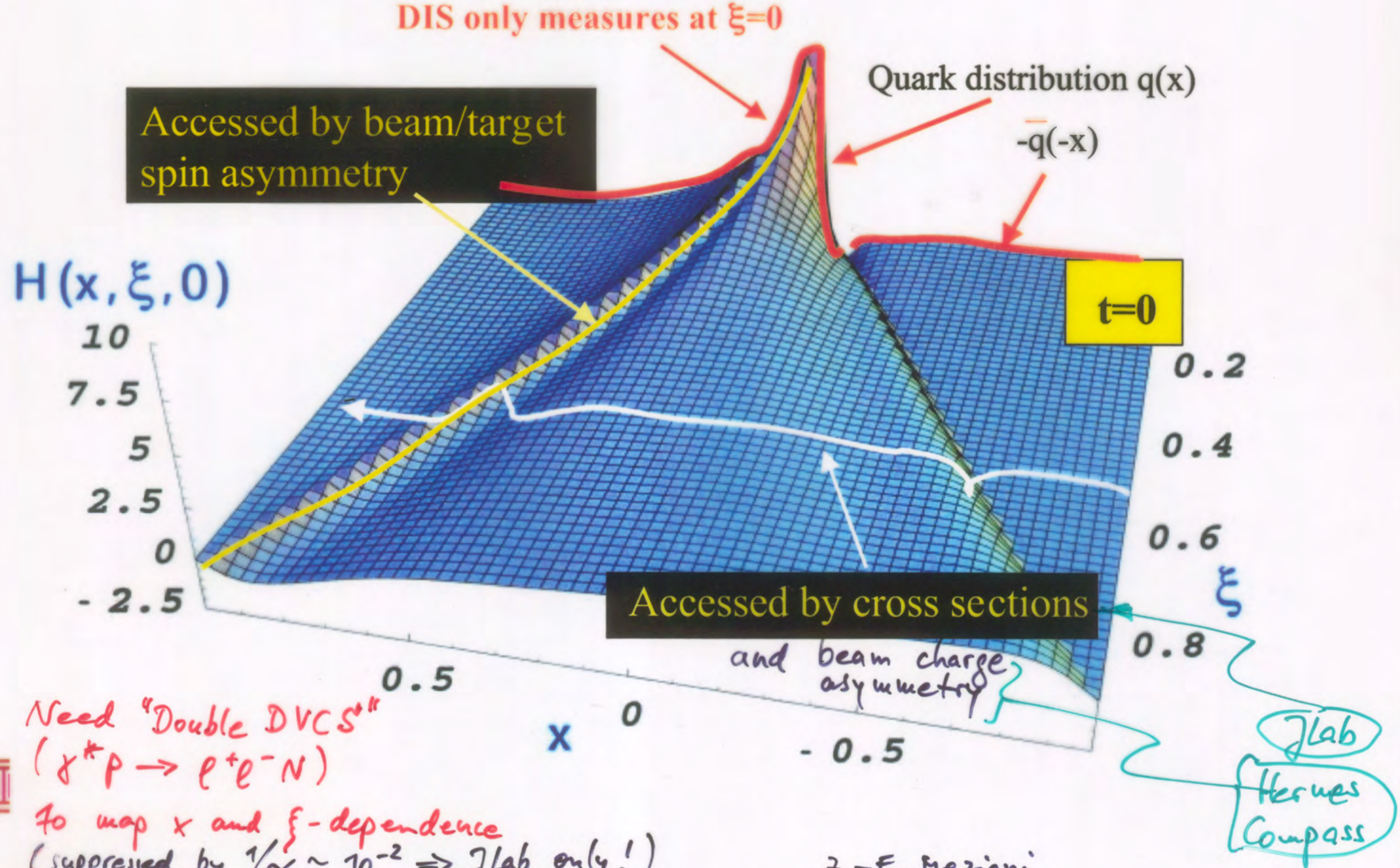
($H_q(\xi, \xi, t)$)

⇒ access to imaginary part of (certain combination of) ~~GPD amplitudes~~ Compton form factors

c) Measure target-spin asymmetry: unpol. beam, polarized target

$A_{UL} \sim \sin(\phi_\gamma) \times \mathrm{Im}\,\widetilde{\mathcal{H}}$ (for long. pol. target)

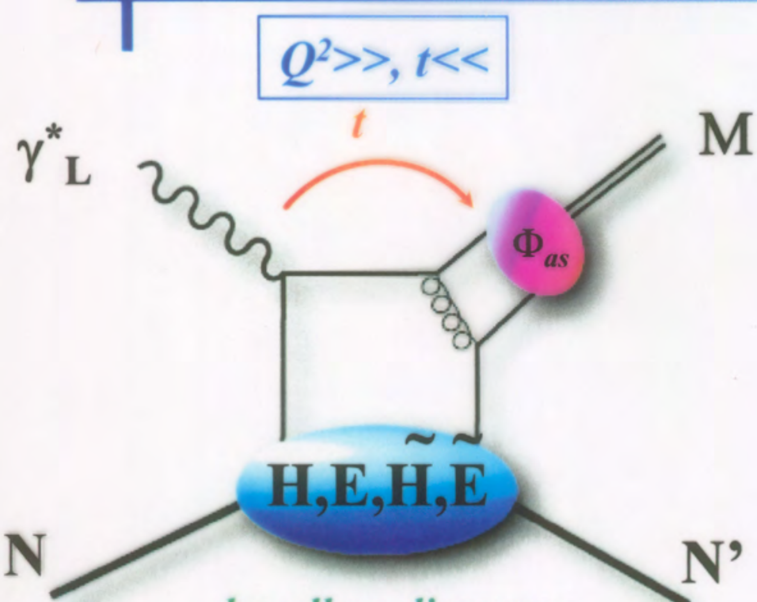
Modeling Generalized Parton Distributions



Need "Double DVCS"
($\gamma^* p \rightarrow \ell^+ \ell^- N$)
to map x and ξ-dependence
(suppressed by $1/\alpha \sim 10^{-2} \Rightarrow$ JLab only!)

Z.-E. Meziani

Factorization theorem for meson production



handbag diagram

- *Müller (1994)* -
- *Ji & Radyushkin (1996)* -
- *Collins, Frankfurt & Strikman (1997)* -

→ 4 **G**eneralized **P**arton **D**istributions (**GPD**s) per flavor

H_q	$\tilde{H}_q$	conserve nucleon helicity
E_q	$\tilde{E}_q$	flip nucleon helicity
↓ unpolarized	↓ polarized	

→ Quantum number of final state selects different GPDs

Vector mesons (ρ, ω, φ): unpolarized GPDs H_q, E_q

Pseudoscalar mesons (π, η): polarized GPDs $\tilde{H}_q$, $\tilde{E}_q$ (pion pole)

→ Factorization for longitudinal photons only

→ $$\frac{d\sigma_L}{dt} \xrightarrow[\textit{for fixed } x_B \textit{ and } t]{\textit{asymptotically}} \frac{1}{Q^6}$$

Pseudoscalar Mesons

Cross section: $\sim (\tilde{H} + \tilde{E})^2$

Factorization theorem: $\sigma_L \sim 1/Q^6$ at fixed x, t:

$$d\sigma = \underbrace{\frac{1}{16\pi}\frac{x^2}{1-x}\frac{1}{Q^4}K_{TMC}}_{QED} \cdot \underbrace{\sum_{spin} |A(\gamma^* p \to p M)|^2}_{QCD:\ \sigma_{reduced} \sim \frac{1}{Q^2}}$$

Asymmetries

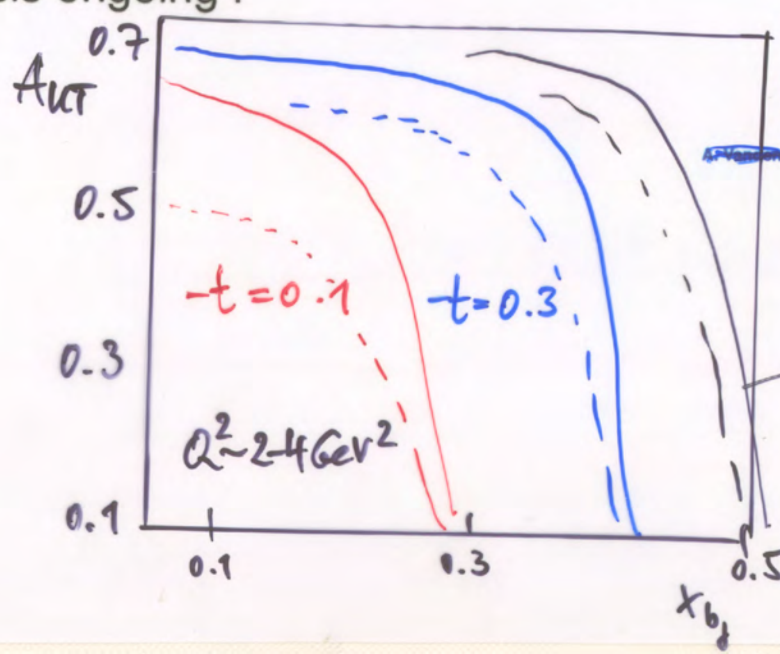
prel. results ⇒ next page

- Target Related Single Spin Asymmetry $\sim \tilde{E} \cdot \tilde{H}$
- Theoretical expectation for asymmetries: Scaling region reached at lower Q^2

Transverse Spin Asymetry:

$$\sigma^{U\uparrow} - \sigma^{U\downarrow} \sim |S_\perp| \sin\phi \cdot A_{UT} \sim |S_\perp| \sin\phi \cdot \underbrace{\tilde{E} \cdot \tilde{H}}_{\text{Interference}}$$

- 2002-2005: HERMES run with transversely polarized target
- Analysis ongoing !



Frankfurt et al. PRD 60 (1999)

(2 models with diff. π form factor)

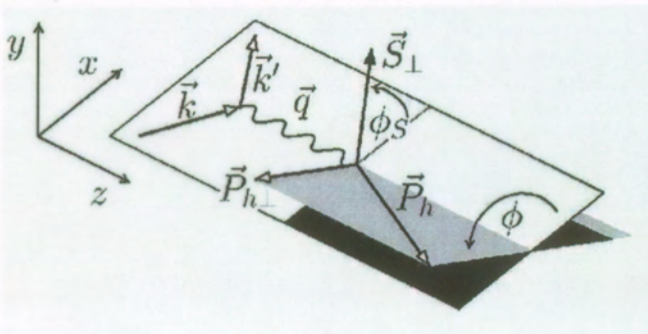
$-t = 0.5\ GeV^2$

Vector Meson Production

Target Spin Asymmetry A_{UT}

- Experimentally:

$$A_{UT}(\phi-\phi_S) = \frac{1}{|P|}\frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$



- $A_{UT} \sim$ GPD E
- Model for E has J_q as 'free' parameter

  ⇒ can we constrain it ?

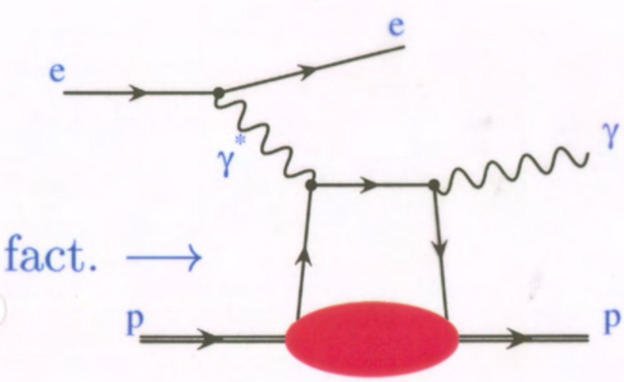
$\sin(\phi - \phi_S)$ amplitude of asymmetry: $A_{UT}^{\sin(\phi-\phi_S)}$

prel. Hermes results
will be shown in
R. Fabbri's talk (17:30)

HERA collider: DVCS Introduction

QCD

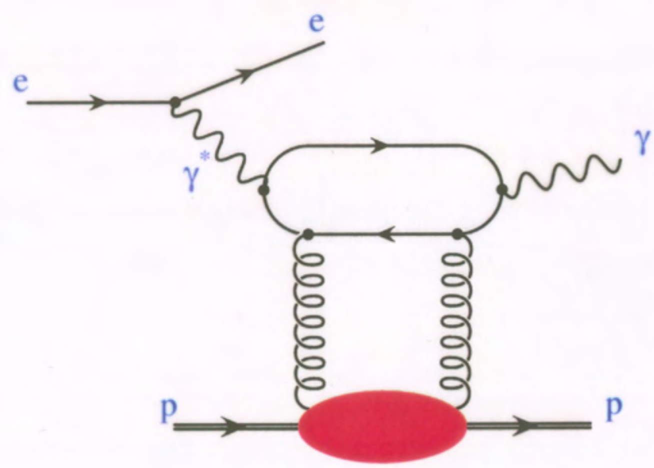
LO



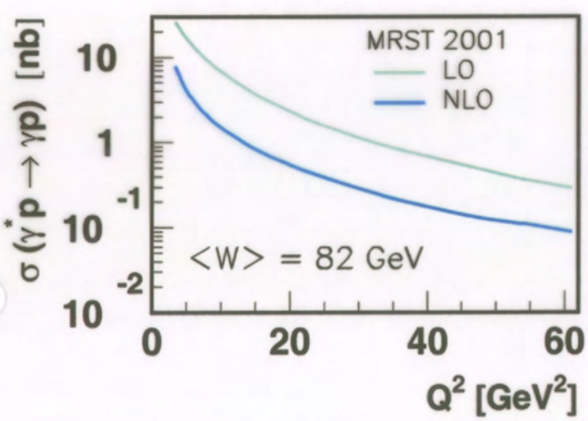
H1, ZEUS

HERMES, CLAS

NLO



H1, ZEUS



NLO leading twist calc. by A. Freund and M. McDermott

Eur.Phys.J. **C23** (2002) 651

Input: GPD

GPD modeling Freund [hep-ph/0306012]

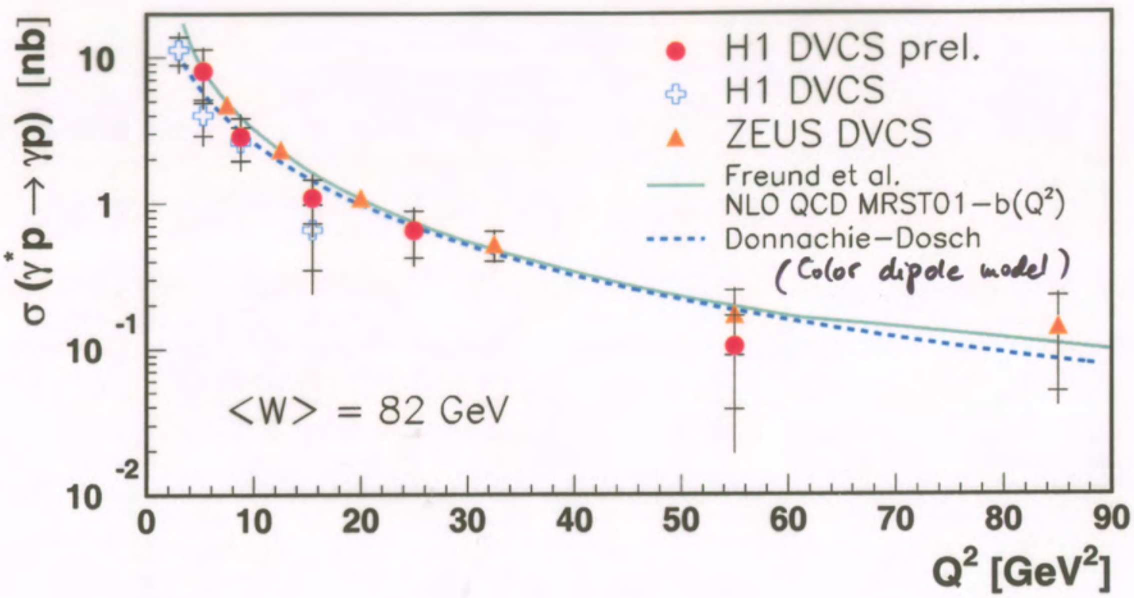
$$GPD(x,\xi,Q^2,t) \sim \frac{PDF(\frac{x-\xi/2}{1-\xi/2},Q^2)}{1-\xi/2} \times e^{-b|t|}$$

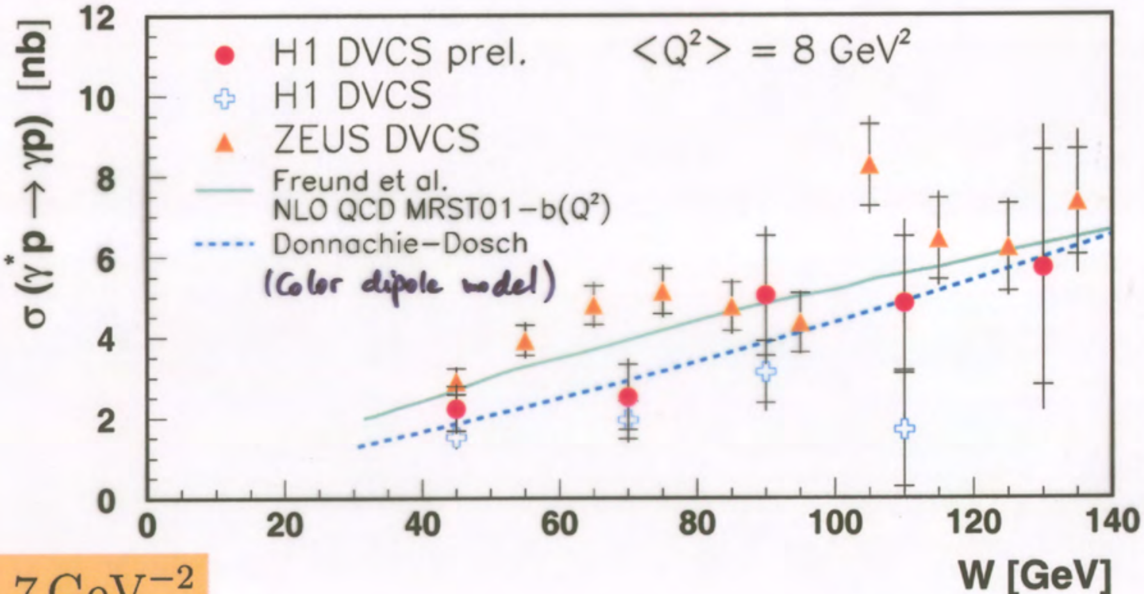
PDF: MRST2001 and CTEQ6

$b = b_0(1 - 0.15\log(Q^2/2))\,\mathrm{GeV}^{-2}$

All H1 and ZEUS Results

(presently only cross sections, no asymmetries, yet)





$b = 7\,\mathrm{GeV}^{-2}$

$\Longrightarrow$ Good agreement between H1 results

$\Longrightarrow$ Fair agreement between H1-prel and ZEUS results except for $W \sim 70$ GeV: H1 lower by 2σ

BUT: * Q^2 dep: equally well described by NLO-QCD and Color dipole model

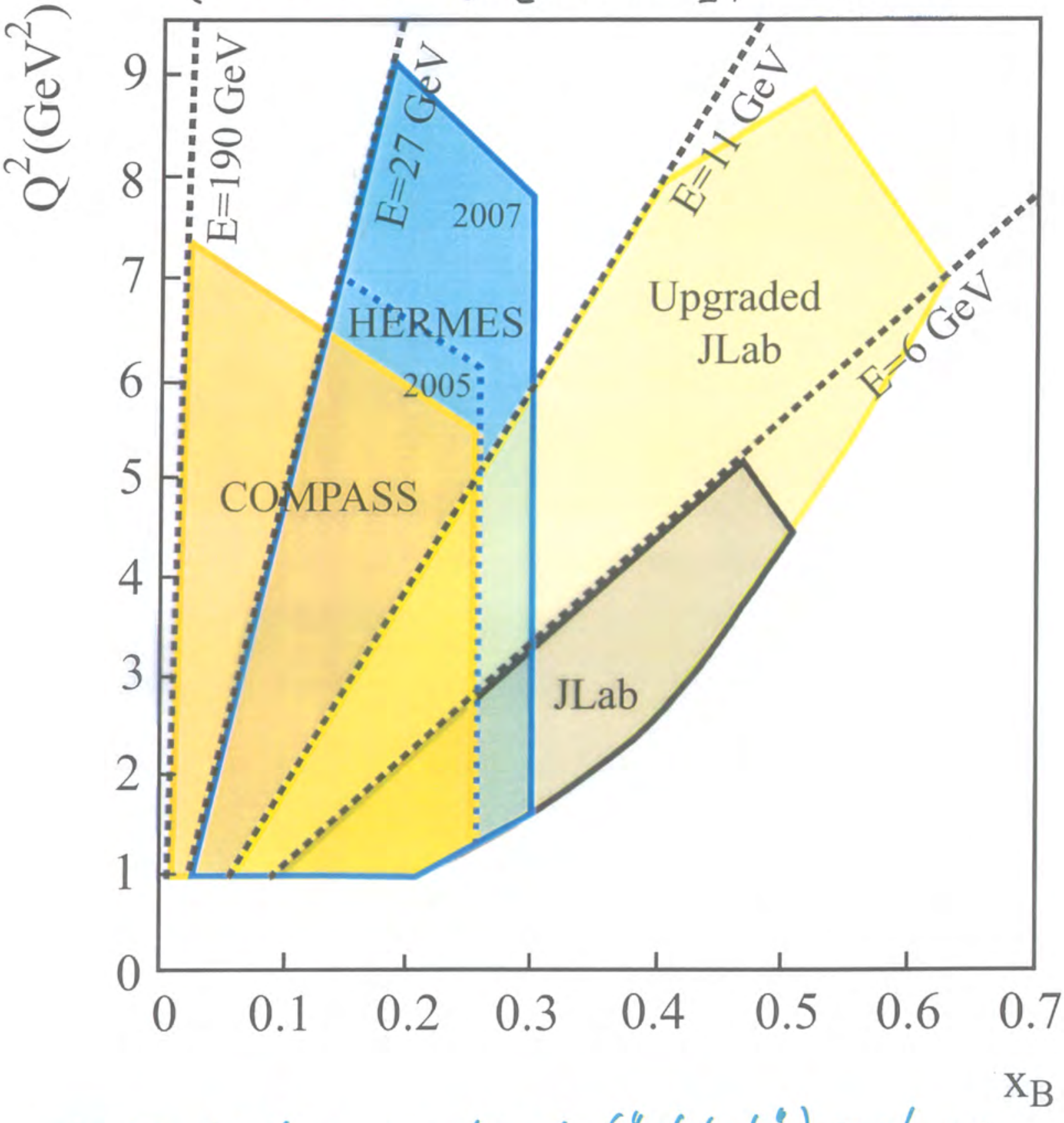
* W-dep: If H1 is right, NLO QCD slightly favored

$\Rightarrow$ Need to study asymmetries ($e^\pm$, beam spin rotators)

GPD extraction in medium-term future

* Complementary experiments
(beam charge, polarization; target pol.; luminosity)

Kinematics:
(H1 + ZEUS at $x_B \lesssim [10^{-2} \dots 10^{-4}]$, $Q^2 > [4 \dots 100]$ GeV^2



⇒ we need a combined ("global") analysis of GPD-related data measured in only partly overlapping regions of phase space!

⇒ obvious need for close cooperation exp. ⟷ theory
(effort analogous to global PDF analyses over decades!)

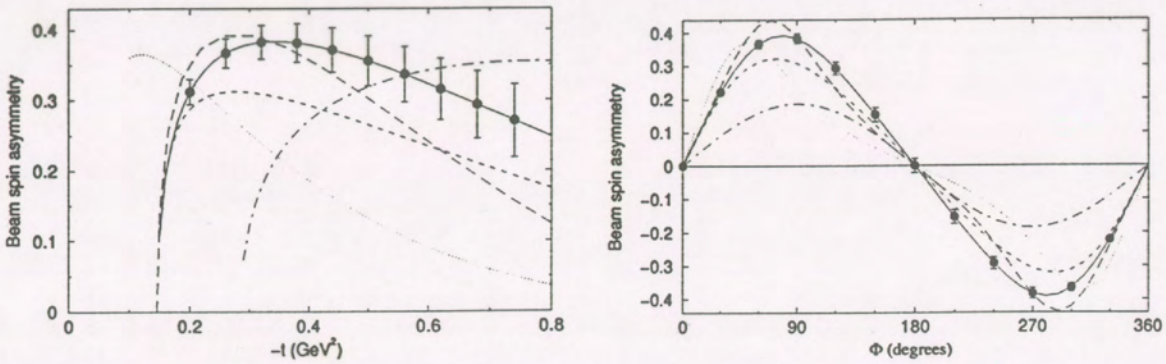


Figure 12. CLAS: *Projections for beam-spin asymmetries at 6 GeV: t-dependence at $\phi = 90^o$ (left) and ϕ-dependence at $-t = 0.325\ GeV^2$ (right). Projected statistical errors are given at $Q^2 = 2\pm0.5\ GeV^2$ and $x_B = 0.35\pm0.05$, for which the solid (dashed) curve shows a calculation (Vanderhaeghen et al. 2001) with ξ-(in)dependent GPDs (Vanderhaeghen et al. 1999). The long-dashed curve shows a calculation including twist-3 effects. Other curves are for other kinematics. The Figure is taken from (Elouadrhiri 2002).*

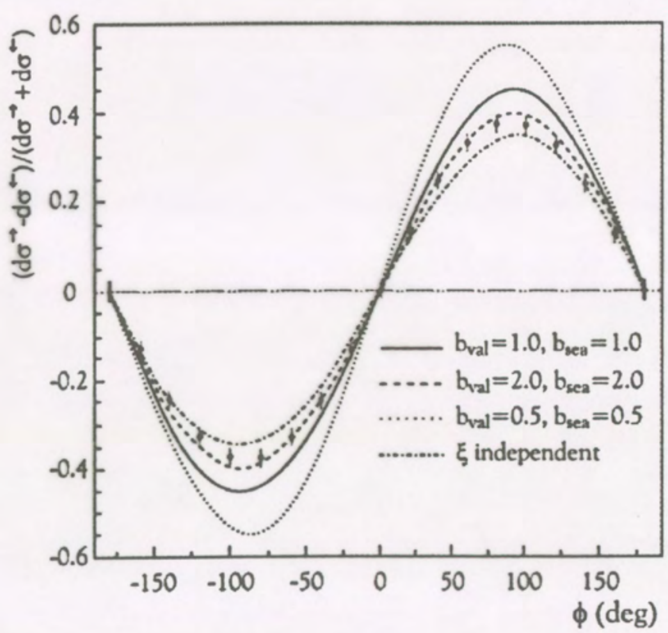
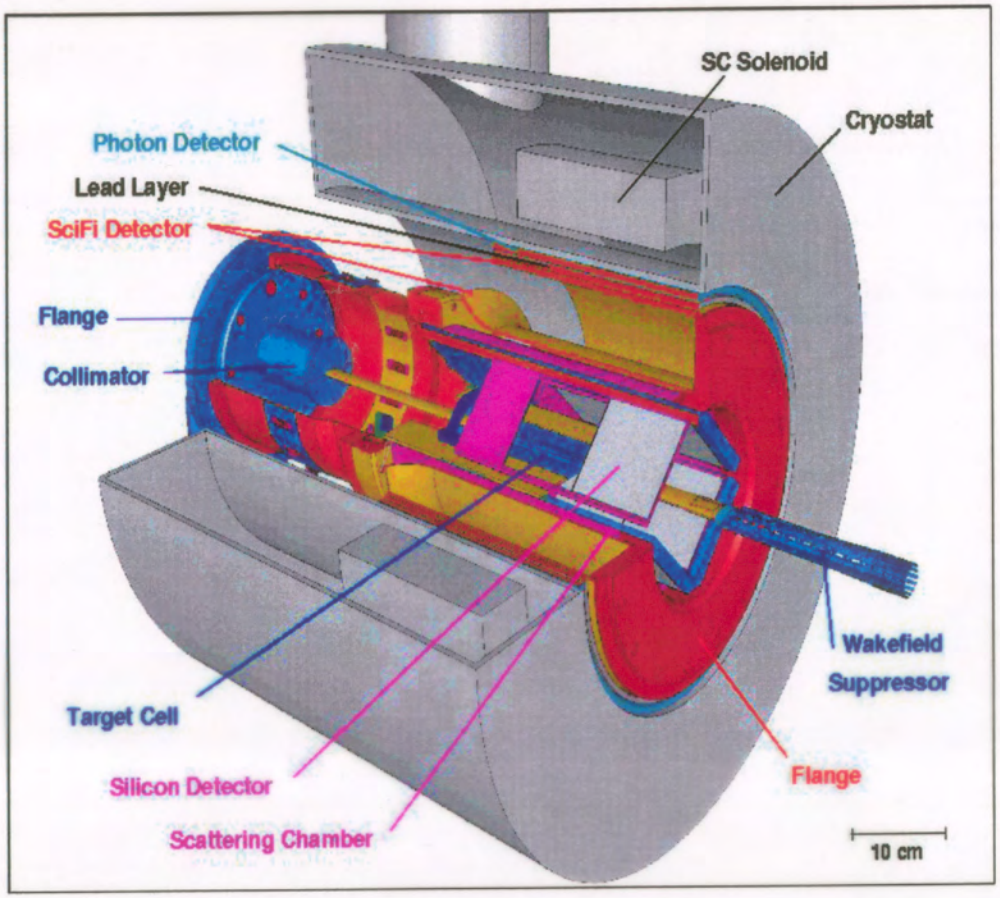


Figure 13. CLAS: *Projected statistical accuracy for a high-statistics BSA measurement at 11 GeV with an upgraded detector. Bins of $Q^2 = (3\pm0.1)\ GeV^2$, $W = (2.8\pm0.15)$ GeV, and $-t = 0.3\pm0.1\ GeV^2$ are used. GPD calculations (Vanderhaeghen et al. 2001) are shown for different combinations of profile parameters (Vanderhaeghen et al. 1999). The Figure is taken from (Mecking 2002).*

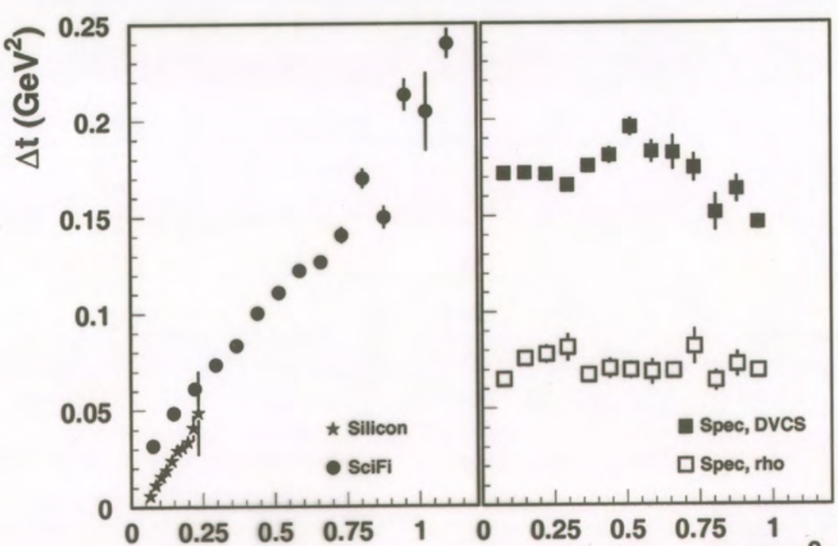
measured with good statistical precision in most of the cells.

No plans are published to also install a positron beam at JLAB, so that no high-precision measurements of beam-charge asymmetries can be expected.

A new Recoil Detector for Hard Exclusive Reactions



Considerable improvement in t resolution:



Unpolarized target ⇒ High density possible!

HERMES' (2 fb^{-1}):

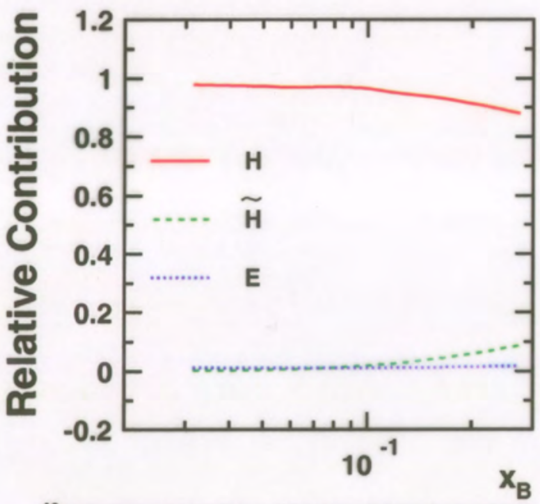
Im$\mathcal{H}$ Measurement in 2006 ? *

Lepton helicity asymmetry: $A_{LU}^{sin\phi} \approx \mathcal{C}_{unp}^{\mathcal{I}}/\mathcal{C}_{unp}^{DVCS}$ with

$$\mathcal{C}_{\rm unp}^{\rm DVCS} = \frac{1}{(2-x_{\rm B})^2}\Big\{4(1-x_{\rm B})\left(\mathcal{H}\mathcal{H}^* + \widetilde{\mathcal{H}}\widetilde{\mathcal{H}}^*\right) - x_{\rm B}^2\Big(\mathcal{H}\mathcal{E}^* + \mathcal{E}\mathcal{H}^* + \widetilde{\mathcal{H}}\widetilde{\mathcal{E}}^* + \widetilde{\mathcal{E}}\widetilde{\mathcal{H}}$$

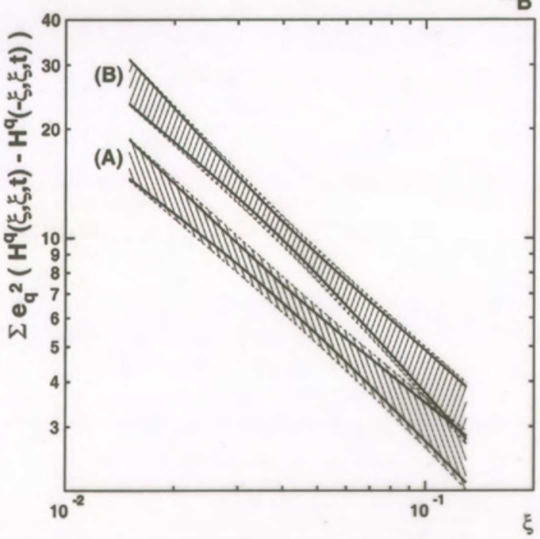
$$-\left(x_{\rm B}^2 + (2-x_{\rm B})^2\frac{t}{4M^2}\right)\mathcal{E}\mathcal{E}^* - x_{\rm B}^2\frac{t}{4M^2}\widetilde{\mathcal{E}}\widetilde{\mathcal{E}}^*\Big\}.$$

$$\mathcal{C}_{\rm unp}^{\mathcal{I}} = F_1\mathcal{H} + \frac{x_{\rm B}}{2-x_{\rm B}}(F_1+F_2)\widetilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}$$



At $-t < 0.15$ GeV^2:

Relative contribution of GPD H dominates
⇒ Asymmetry $A_{LU}^{sin\phi}$ mainly depending on Im$\mathcal{H}$



Extraction of Im$\mathcal{H}$ possible:

⇐ Two different bands for different GPD param.'s
⇐ Solid line: 1σ stat. errors
⇐ Dashed line: syst. extraction uncertainty added

*) Projections: V. Korotkov, W.-D. N., NPA 711, 175c, (2002)

DVCS with Unpol. Beam on Transv. polarized Target

- Contributions not related to target spin:

$$\left|\mathcal{T}^{BH}_{unp}\right|^2 \propto \frac{c^{BH}_{0,unp} + c^{BH}_{1,unp}\cos\phi + c^{BH}_{2,unp}\cos 2\phi}{P_1(\phi)P_2(\phi)} \qquad (4)$$

$$\mathcal{T}^{I}_{unp} \propto \frac{c^{I}_{0,unp} + c^{I}_{1,unp}\cos\phi + c^{I}_{2,unp}\cos 2\phi + c^{I}_{3,unp}\cos 3\phi}{P_1(\phi)P_2(\phi)}$$

$\beta \equiv \phi - \phi_s$

- Contributions related to target spin:

$$\mathcal{T}^{I}_{TP} = \frac{e^6}{x_B y^3 t} \cdot \frac{\cos\phi\sin\beta\cdot Im\widehat{M}_1 - \sin\phi\cos\beta\cdot Im\widehat{M}_2}{P_1(\phi)P_2(\phi)}$$

$$\widehat{M}_1 \simeq f(x_B, y, Q^2, t)\cdot\left(F_2\mathcal{H} - F_1\mathcal{E}\right)$$

⇒ Once $\mathcal{H}$ known, can conclude on $\mathcal{E}$, in princ.

$$\widehat{M}_2 \simeq f(x_B, y, Q^2, t)\cdot\left(F_2\widetilde{\mathcal{H}} - F_1\xi\widetilde{\mathcal{E}}\right) \qquad (5)$$

Hermes: DVCS on transversely polarized target

projections to appear soon on hep-ph → EPJC

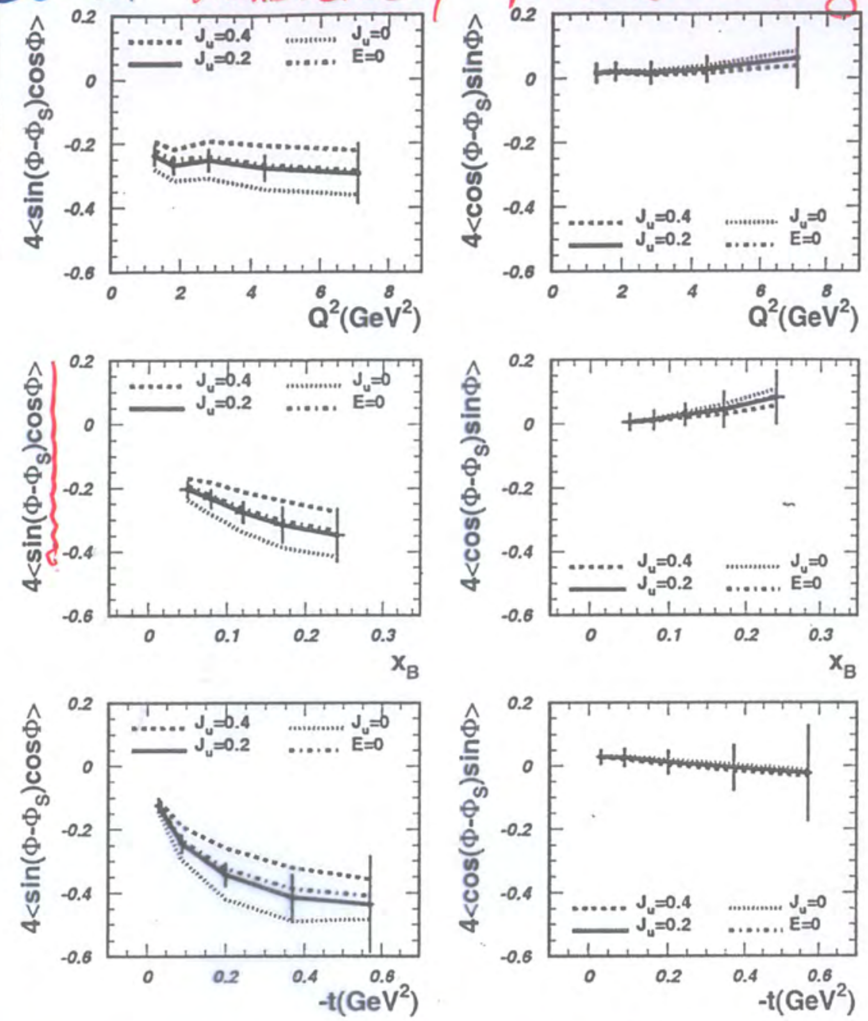


Fig. 5. Expected DVCS asymmetries $A_{UT}^{\sin(\phi-\phi_S)\cos\phi}$ and $A_{UT}^{\cos(\phi-\phi_S)\sin\phi}$ in the Regge ansatz for $b_{val} = 1$, $b_{sea} = 1$, $J_u = 0.4\ (0.2, 0.0)$, $J_d = 0.0$. $E = 0$ denotes zero effective contribution from the quark GPDs E_q. The calculations are done at the average kinematic values as listed in Tab. 1. Projected statistical errors are shown.

projections for HERMES (2003 - 2005) 8 M DIS = 0.2 fb⁻¹

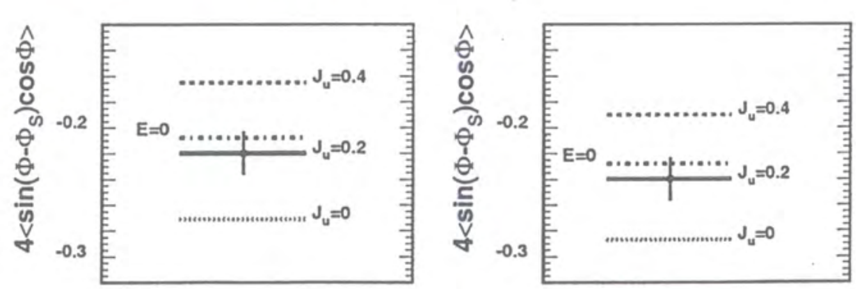


Fig. 6. Expected DVCS asymmetry $A_{UT}^{\sin(\phi-\phi_S)\cos\phi}$ with $b_{val} = 1$ and $b_{sea} = \infty$ (left panel) or $b_{sea} = 1$ (right panel), $J_u = 0.4\ (0.2, 0.0)$, $J_d = 0.0$ in the Regge ansatz at the average kinematics of the full measurement. $E = 0$ denotes zero effective contribution from the GPDs E_q. The projected statistical error for 8 million DIS events is shown. The systematic error is expected to not exceed the statistical one.

⇒ promising sensitivity !

Sensitivity of excl. ρ^0 prod. to J_u (through E)

Hermes: PROJECTIONS for transv. pol. target

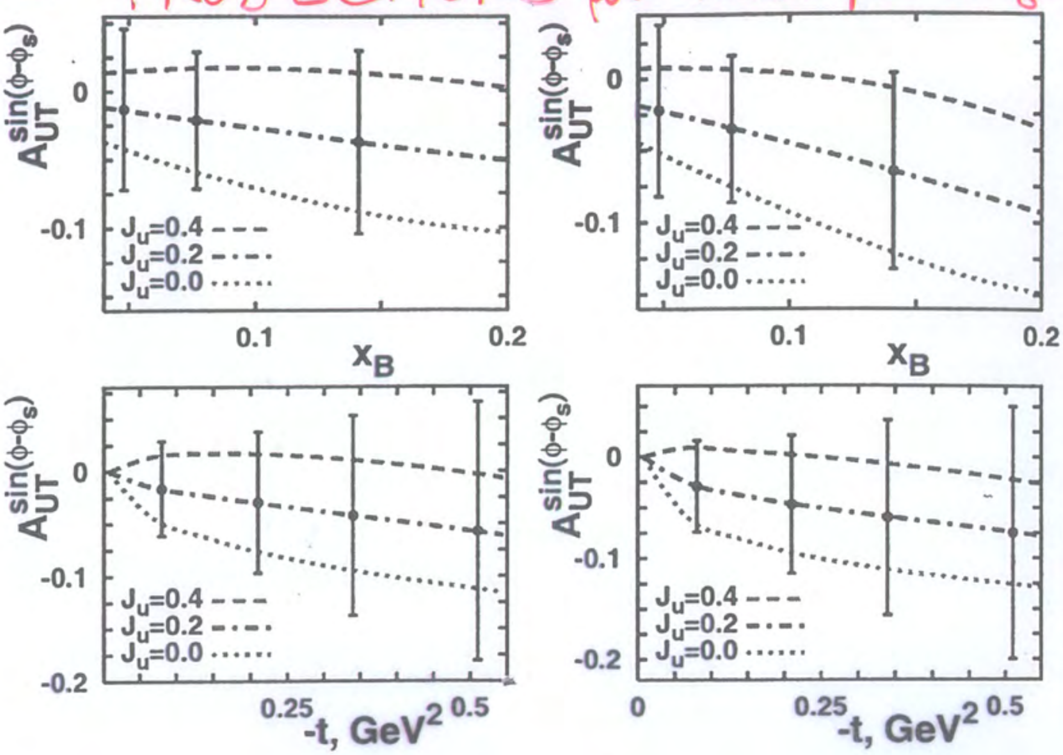


Fig. 8. Comparison of expected ρ^0asymmetries in the kinematic range of HERMES calculated in the Regge ansatz with $b_{val} = 1$ and $b_{sea} = 1$ (left) or $b_{sea} = \infty$ (right). Average kinematic values $\langle -t \rangle = 0.14$ GeV^2 and $\langle x_B \rangle = 0.085$ for x_B and t-dependences, respectively, correspond to an analysis of existing HERMES data [46]. Projected statistical errors are shown. The systematic uncertainty is expected to be smaller than the statistical one. HERMES 8 M DIS = 0.2 fb^{-1}

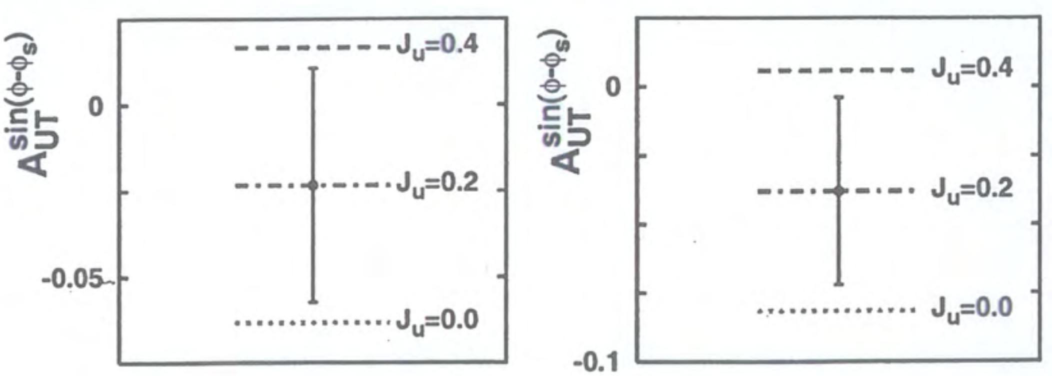


Fig. 9. Comparison of expected ρ^0 asymmetries calculated in the Regge ansatz with $b_{val} = 1$ and $b_{sea} = 1$ (left) or $b_{sea} = \infty$ (right). Projected statistical errors are shown. The systematic uncertainty is expected to be smaller than the statistical one.

⇒ Hard to conclude on J_u!

the *total* experimental uncertainty. Thus it can be ex-

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Nuclear Physics A721 (2003) 368c–371c

NUCLEAR PHYSICS A

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Deeply Virtual Compton Scattering using COMPASS at CERN

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[a]CEA-Saclay, DSM/DAPNIA/SPHN, F-91191 Gif-sur-Yvette Cedex, France.

In this paper, we present the recent studies our group has conducted in order to show the feasibility of a Deeply Virtual Compton Scattering experiment using COMPASS and its high energy muon beam at CERN. The measurement of the cross section and the beam charge asymmetry in the kinematical domain : $0.03 < x_{bj} < 0.25$ and $1.5 < Q^2 < 7.5$ GeV^2 will provide a check of the factorization and will put strong constraints on the models. Experimental studies show that detection of the DVCS exclusive reaction is feasible with some upgrade of the COMPASS apparatus.

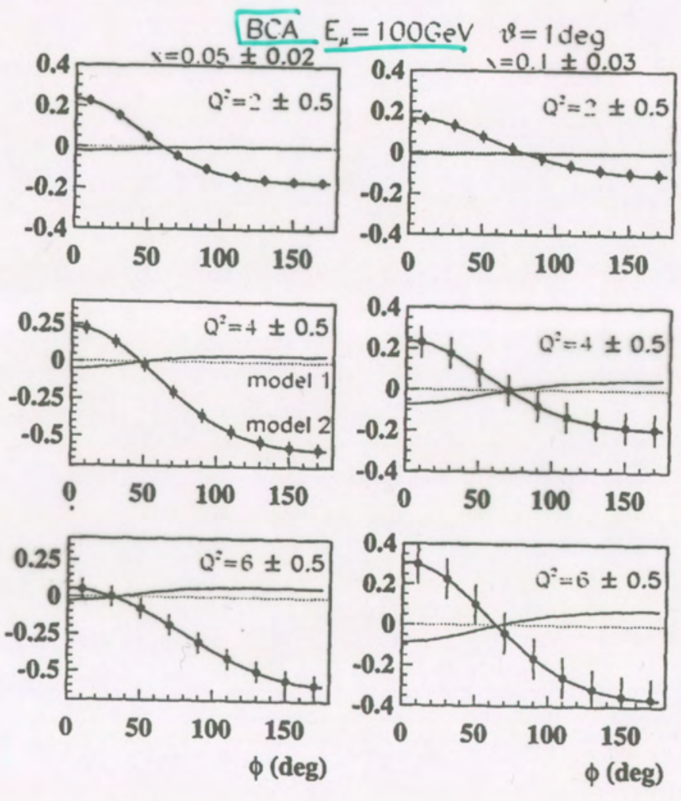

Figure 1. Experimental precision achievable for a 6 month running with 25 % global efficiency. The Beam Charge Asymmetry is plotted as a function of the angle between the leptonic and proton/photon plane. On each plot 2 models of GPD are represented. The first model just fulfills the sum rules while the second model[3] (corresponding to the expected data points) uses Regge theory to relate x and t dependences. This shows that an experiment using COMPASS has good sensitivity to discriminate between models.

The JLab GPD Program @ 12 GeV

DVCS:

- DVCS/BH interference with polarized beam
  - ⇨ twist-2/3, Q^2 evolution
  - ⇨ linear combination of GPDs
- Differential cross section
  - ⇨ moments of GPDs
- DVCS/BH interference with polarized targets
  - ⇨ access different combinations of GPDs

DVMP:

- Establish kinematics range where theory is tractable (if not known)
- Separation of flavor- and spin-dependent GPDs (ρ^o, ω, π^0,η, $K^{+,0}$)
- Access J^q contributions at $x_B > 0.15$

➡ **Quark distributions in transverse coordinates**

DDVCS: Allows access to $x \neq \xi$ kinematics $ep \rightarrow ep\gamma^* \rightarrow e^+e^-$

ΔDVCS: Hard baryon spectroscopy $ep \rightarrow e\gamma\Delta$, ($e\gamma N^*$)

2001:

TESLA-TDR/Appendices:

2 Proposals

TESLA-N

- Use one (positron) arm of TESLA for polarized fixed target experiment
- Beam energy varied between 30 - 250 GeV
- Use large kinematic domain for Q^2 evolution studies

- Transversity distribution
- Gluon polarization

HERMES ⇒ COMPASS kinematics

⇒ still a viable proposal for any LC with high repetition rate (cold LC)!

$\mathcal{L}_{int} = \mathcal{O}(100\ fb^{-1})$

ELFE

- Inject electron beam @ 30 GeV in modified HERA-e
- Use HERA as stretcher ring ⇒ extract high dutyfactor beam
- Fully exploit high resolution for exclusive reactions

- Skewed Parton Distributions
- High precision exclusive reactions

HERMES kinematics

⇒ HERA will definitely stop ≤ middle 2007

SUMMARY

- GENERALIZED PARTON DISTRIBUTIONS BEAR A FASCINATING POTENTIAL TO FULLY DESCRIBE THE MOMENTUM AND ANGULAR MOMENTUM STRUCTURE OF THE NUCLEON

- HERA:
  THE NEW HERMES RECOIL DETECTOR, COMBINED WITH AN UNPOLARIZED PROTON TARGET, WILL LEAD TO SIGNIFICANT IMPROVEMENTS IN RESOLUTION AND STATISTICS FOR MEASUREMENTS OF AZIMUTHAL ASYMMETRIES IN HARD EXCLUSIVE REACTIONS (DVCS, PSEUDOSCALAR AND VECTOR MESON PRODUCTION).
  H1, ZEUS AND ALSO HERMES WILL CONTRIBUTE BY IMPORTANT CROSS SECTION MEASUREMENTS.

- JLAB:
  KINEMATICALLY COMPLEMENTARY MEASUREMENTS BEING CARRIED OUT NOW. HIGH STATISTICS MEASUREMENTS AFTER 11 GEV UPGRADE WILL MAKE DETAILED STUDIES OF KINEMATIC DEPENDENCES POSSIBLE. UNIQUE PLACE TO STUDY FULL (x, ξ) PLANE (DDVCS)

- THE WORLD-WIDE EFFORT TO MEASURE EXCLUSIVE REACTIONS WILL HAVE TO BE FOLLOWED BY A GLOBAL ANALYSIS TO SORT OUT THE BEST MODELS FOR GENERALIZED PARTON DISTRIBUTIONS.