European Perspectives for Lepton-Nucleon Scattering at the luminosity frontier

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— High Intensity Frontier Workshop —
La Biodola, Isola d'Elba, June 5-8, 2004

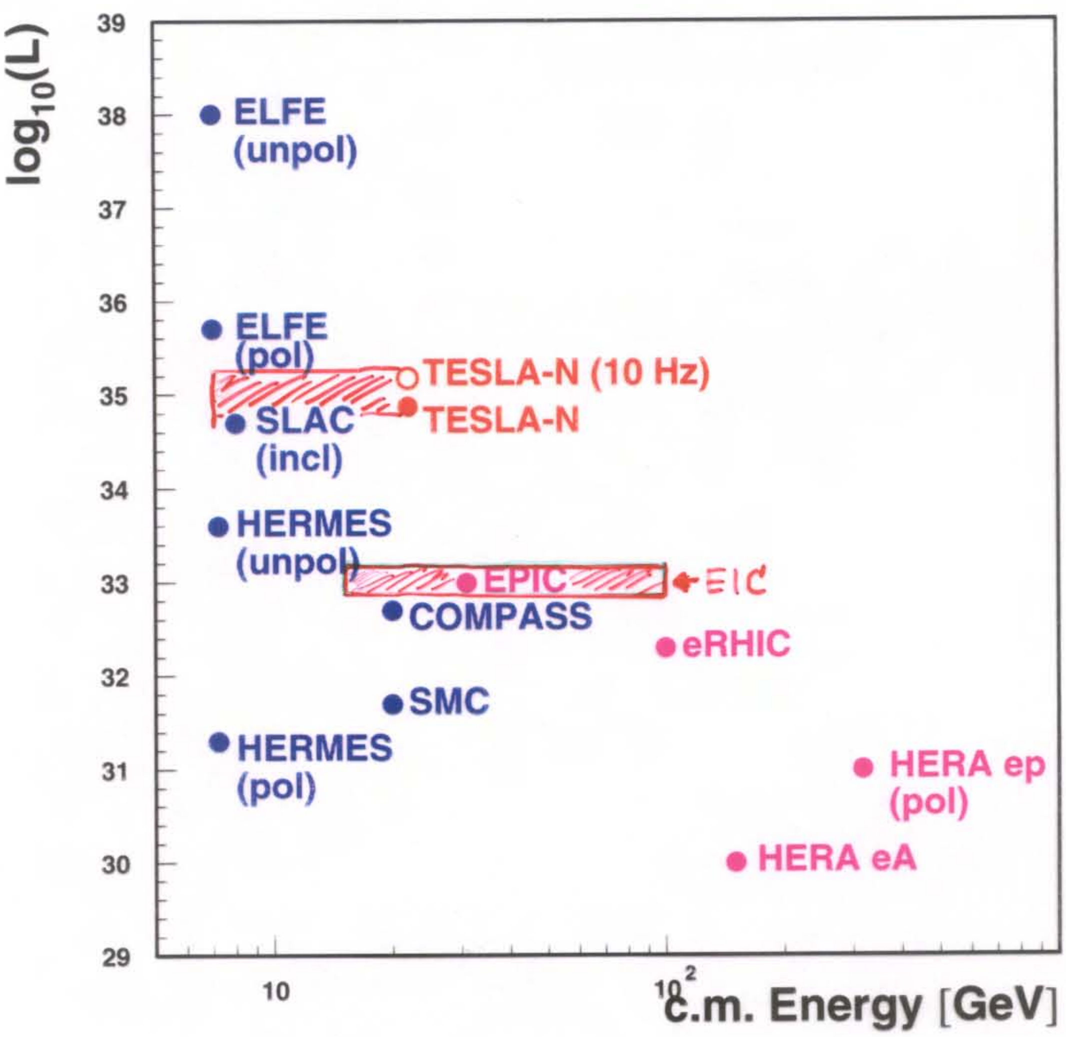
——— EXPERIMENTS ———

Short-term: (2004+)	HERMES Run II COMPASS-1
Medium-term: (2007+)	HERA running ends middle 2007 COMPASS-2 ?
long-term: (2012+)	New high-rate, high-resolution spectrometer to realize ELFE/TESLA-N physics ? → Lepton-Nucleon high luminosity experiment at a high intensity proton machine ??

——— PHYSICS ———

Sea quark helicity distributions	Δq_s	$\rightarrow$	$\Delta\bar{u} - \Delta\bar{d}$
Quark transversity distributions	$\delta q, \delta q_s$	$\rightarrow$	$\delta\Sigma$
Polarized Gluon Distribution			ΔG
Generalized Quark Distributions	$H_{u,d}, E_{u,d}$	$\rightarrow$	$J_{u,d}$
$\longrightarrow$ Long-term goal		$\rightarrow$	$L_{u,d}$

Luminosity (II)



THE EFFECTIVE POLARIZED LUMINOSITY FOR A SOLID-STATE FIXED-TARGET EXPERIMENT IS A FACTOR OF ABOUT 25 LOWER THAN FOR POLARIZED ep-COLLIDERS.

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)

ELFE

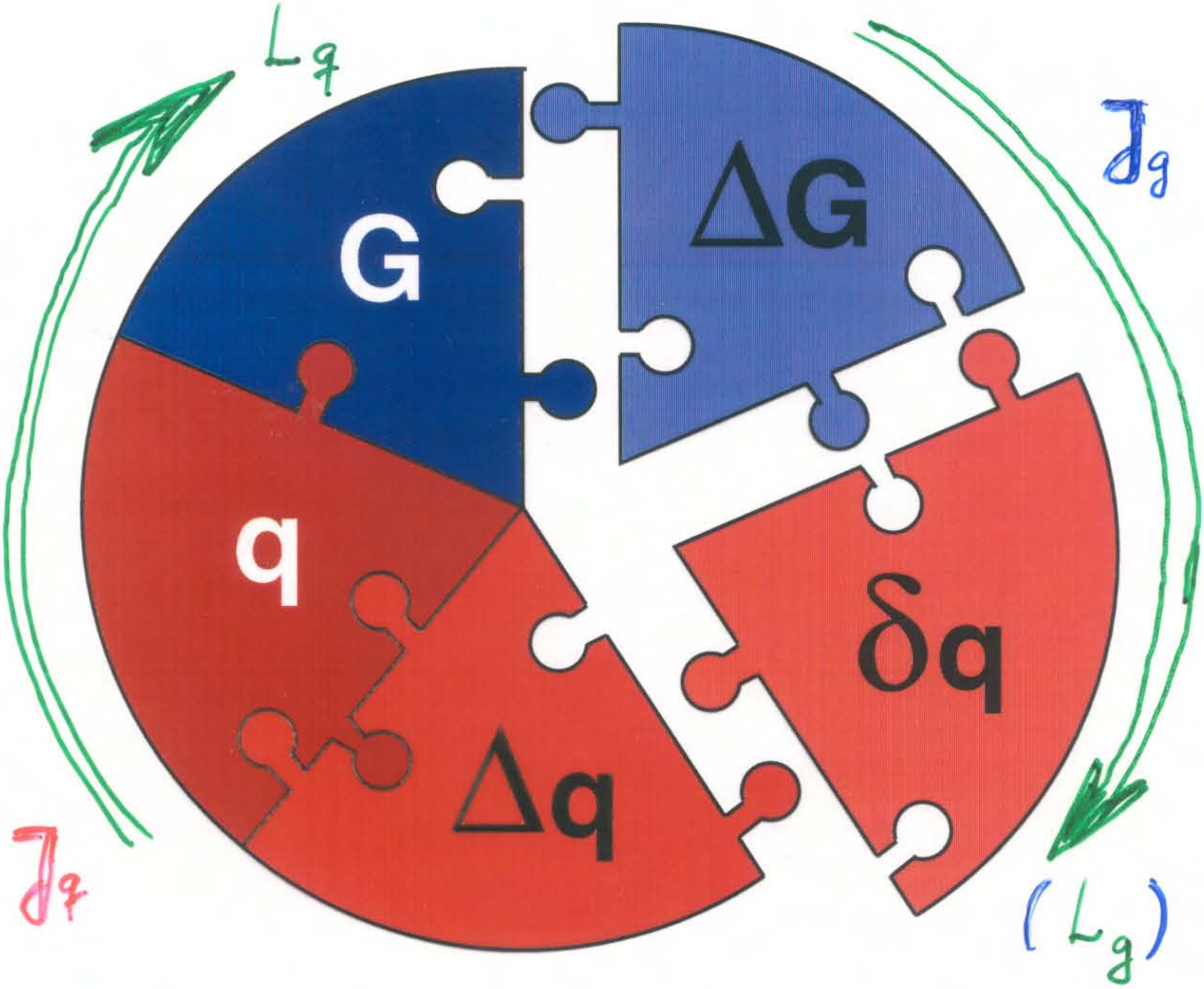
- Inject electron beam @ 30 GeV in modified HERA-e
- Use HERA as stretcher ring ⇒ extract high dutyfactor beam
- Fully exploit high resolution for exclusive reactions

- Skewed Parton Distributions
- High precision exclusive reactions

HERMES kinematics

⇒ HERA will definitely stop ≤ middle 2007

MOTIVATION (I)



PARTON DISTRIBUTIONS OF THE NUCLEON

AT LEADING TWIST IN PQCD

$q(x, Q^2)$	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)
$G(x, Q^2)$	GLUON NUMBER DENSITY DISTRIBUTION
$\Delta G(x, Q^2)$	POLARIZED GLUON DISTRIBUTION

$\delta q(x, Q^2)$ AND $\Delta G(x, Q^2)$ PRESENTLY NOT KNOWN !

Physics Motivation I

$q^{\rightarrow}(x), q^{\leftarrow}(x)$: longitudinally polarized quarks
$q^{\uparrow}(x), q^{\downarrow}(x)$: transversely polarized quarks

Distribution of unpolarized quark species q:

$$f_1^q(x) \equiv q(x) = q^{\rightarrow}(x) + q^{\leftarrow}(x) = q^{\uparrow}(x) + q^{\downarrow}(x)$$

Helicity distr.: $g_1^q(x) \equiv \Delta q(x) = q^{\rightarrow}(x) - q^{\leftarrow}(x)$

Axial charge: $\Delta\Sigma = \sum_q \int_0^1 dx (g_1^q(x) + \bar{g}_1^q(x))$

Transversity: $h_1^q(x) \equiv \delta q(x) = q^{\uparrow}(x) - q^{\downarrow}(x)$

Tensor charge: $\delta\Sigma = \sum_q \int_0^1 dx (h_1^q(x) - \bar{h}_1^q(x))$

Quark distributions & nucleon charges depend on virtuality Q^2.

Transverse Spin Structure of the Nucleon

Last missing piece in the leading spin structure of the nucleon

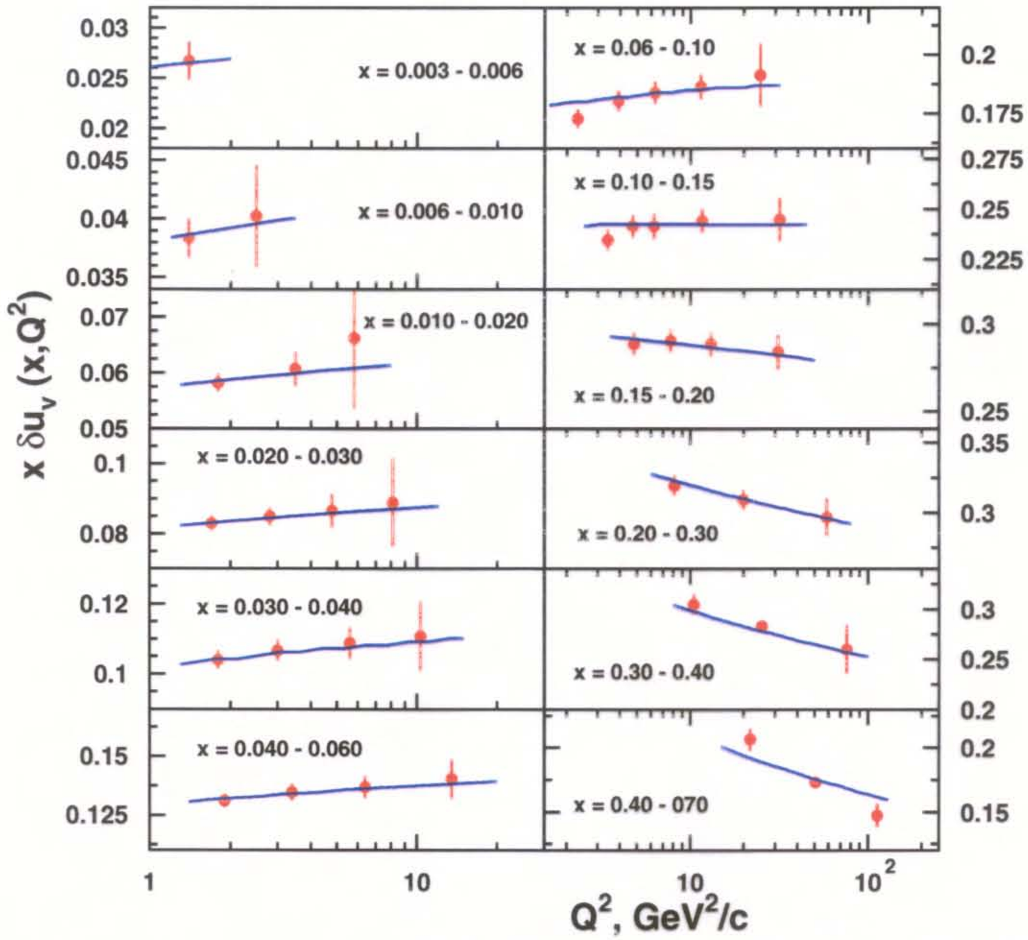
- New information on the dynamics of quarks inside hadrons

- Study validity of untested QCD predictions:

1) Tensor charge >> axial charge
2) Transversity has weaker Q^2 evolution than helicity distribution

TESLA-N

Quark Transversity from semi-inclusive Pions (IV)



PROJECTION FOR THE VALENCE u-QUARK TRANSVERSITY DISTRIBUTION BASED ON $100\ \text{fb}^{-1}$ AND A MINIMUM DETECTOR ACCEPTANCE OF 5 mrad.

TENSOR CHARGE / TRANSVERSE SPIN OF THE NUCLEON: ('ALL-VALENCE OBJECT')

$$\delta\Sigma(Q^2) = \sum_q \int_0^1 dx(\delta q(x,Q^2) - \delta\bar{q}(x,Q^2))$$

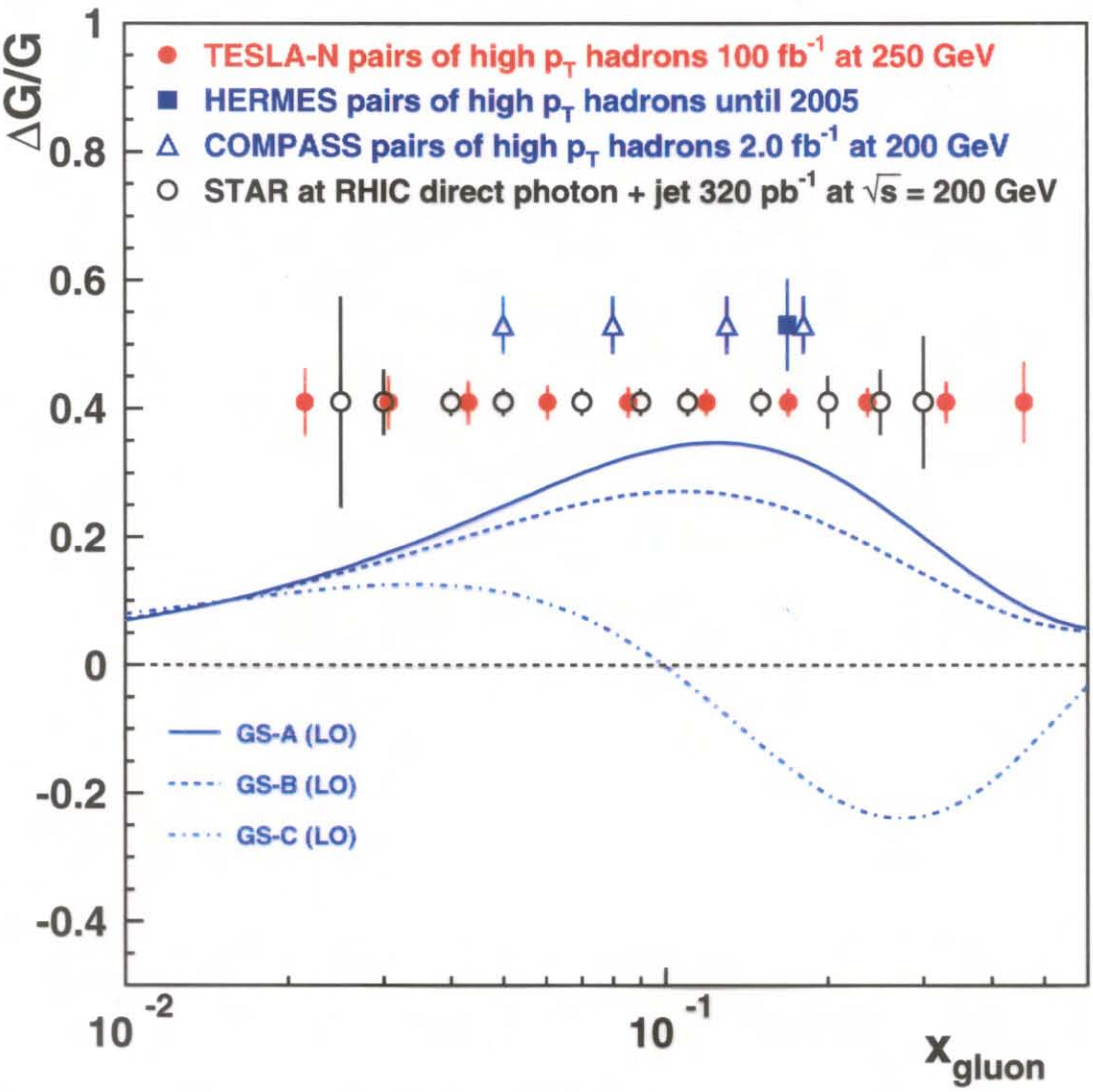
⇒ chiral symmetry !

PROJECTED ACCURACIES AT $Q^2 = 1\ \text{GeV}^2$:

$$\delta u = 0.88 \pm 0.01,\ \delta d = -0.32 \pm 0.02$$

!

Future (Direct) Measurements of the Gluon Polarization



Phenomenological predictions for $Q^2 = 10\ \mathrm{GeV}^2$

HERMES points in the figure:

Data with longitudinal target polarization, originally planned until 2005, are to about 80% already on tape thanks to excellent HERA conditions in 2000 and due to an improvement of the target density by about a factor of 2.

Quark Helicity Distributions

HERMES 1996/97 (p) & 1998–2000 (d) long. pol.

$\int \mathcal{L}dt \sim 0.3\ fb^{-1}$

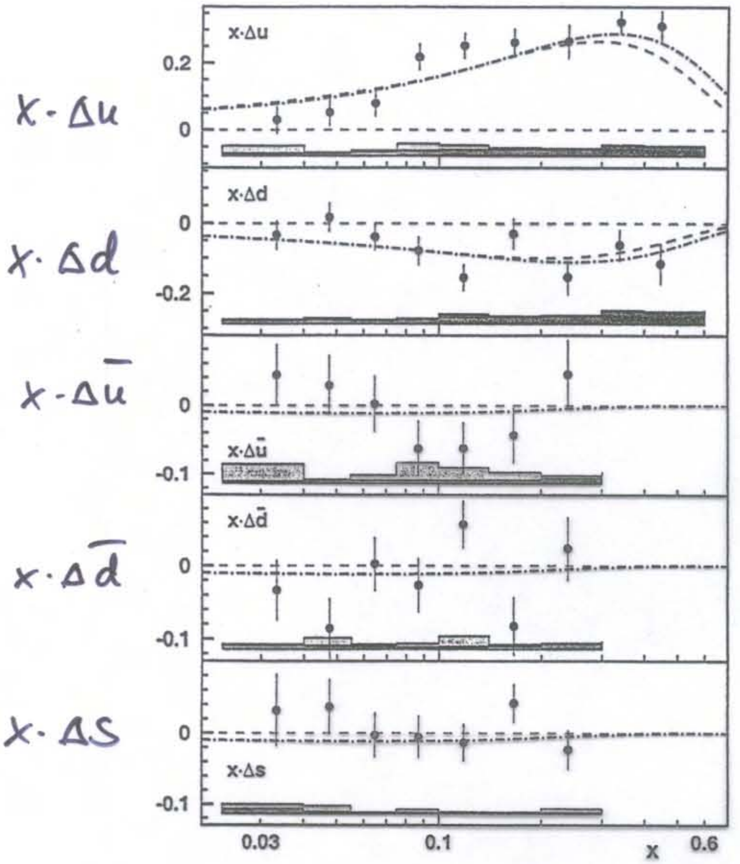


FIG. 2: Quark helicity distributions at $\langle Q^2 \rangle = 2.5\,\mathrm{GeV}^2$, as a function of Bjorken x, compared to two LO QCD fits to previously published inclusive data shown as dashed [28] ("standard scenario") and dot-dashed [29] ("scenario 1") curves. The error bars are statistical and the bands at the bottom represent the systematic uncertainties, where the light area is the contribution due to the uncertainties of the fragmentation model, and the dark area is the contribution due to those of the asymmetries.

Sea quark flavor asymmetry

$\int dx(\Delta\bar{u} - \Delta\bar{d})$:

0.21 ± 0.05 ← chiral quark soliton model [Dressler et al. Eur. Phys. J. C14, 147 (2000)]

data: 0.05 ± 0.06 ± 0.03

↓

stat. errors for 100 fb^{-1}: $\mathcal{O}$(symbol size)!

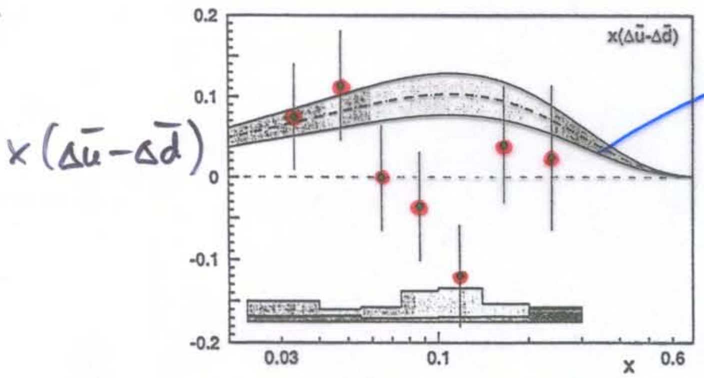


FIG. 3: The light quark sea flavor asymmetry $x \cdot (\Delta\bar{u} - \Delta\bar{d})$ in the helicity distributions, at $\langle Q^2 \rangle = 2.5\,\mathrm{GeV}^2$, compared to a theoretical prediction [30] (dashed curve with theoretical uncertainty band). The experimental error bars and bands have the same meaning as in Fig. 2.

Physics Motivation II

Generalized Parton Distributions:

Unified theoretical description of inclusive and (hard) exclusive processes

H^q, $\tilde{H}^q$: reduce to ordinary PDFs for $t \rightarrow 0$
E^q, $\tilde{E}^q$: do not exist in DIS

t: momentum transfer at nucleon vertex

Access to Generalized Parton Distributions

Exclusive processes bear qualitatively new information on structure of the nucleon

- Dependence of GPDs on momentum transfer t allows conclusions on parton distribution(s) transverse to nucleon's direction of motion $\Rightarrow$ 3-dimensional picture of the nucleon

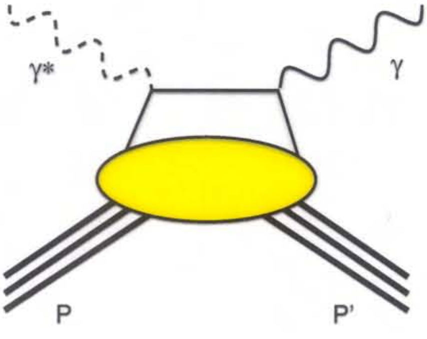
- 2nd moment of 'unpolarized' GPDs H^q and E^q allows, in limit of vanishing t, determination of total angular momentum, carried by quarks q

GPDs and DVCS

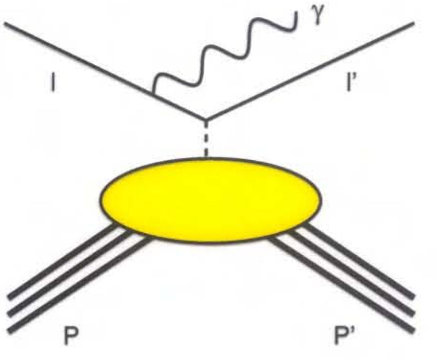
Simplest hard exclusive process: $ep \rightarrow ep\gamma$
$(\gamma^* p \rightarrow \gamma p)$

Consider $\gamma^* p$ in Bjorken limit $\Longrightarrow$
Deeply Virtual Compton Scattering

- Highly virtual quark in γ^* scattering
  $\longrightarrow$ propagates perturbatively
- Simplest (and dominating) QCD mechanism to form Compton final state: quark radiates real γ and falls back to nucleon ground state
  ('hand-bag' subprocess in pQCD)
  $\Downarrow$



DVCS



Bethe-Heitler

$$d\sigma \sim |\tau_{BH} + \tau_{DVCS}|^2 = |\tau_{BH}|^2 + |\tau_{DVCS}|^2 + \mathcal{I}$$

$$\mathcal{I} = \tau^*_{BH}\tau_{DVCS} + \tau_{BH}\tau^*_{DVCS}$$

- DVCS dominated by BH in most of kin. region
- Interference term: access to DVCS amplitudes

$\Rightarrow$ Use BH as an 'amplifier' to study DVCS

GPDs and DVCS (II)

- Generalized Parton Distributions: generalization of usual Parton Distributions and nucleon form factors
- Usual parton distributions (PDs): probability to find a parton in the nucleon with momentum fraction x
- GPDs: interference of 2 wave functions: parton with $x+\xi$ emitted from nucleon, parton with $x-\xi$ falls back (GPDs sensitive to momentum correlations)

Variables:

- Parton long. momentum fractions x and ξ
- $\gamma^* \to \gamma$ mom. transfer $\Delta^2 = (p_{\gamma^*} - p_\gamma)$ (or t)

In DVCS: 4 (chirally-even) quark GPDs

$H^q(x, \xi, \Delta^2)$, $\widetilde{H}^q(x, \xi, \Delta^2)$ Nucleon-hel. conserving

$E^q(x, \xi, \Delta^2)$, $\widetilde{E}^q(x, \xi, \Delta^2)$ Nucleon-hel. non-cons.

$\Downarrow$ $\Downarrow$

'unpolarized' 'polarized' GPDs

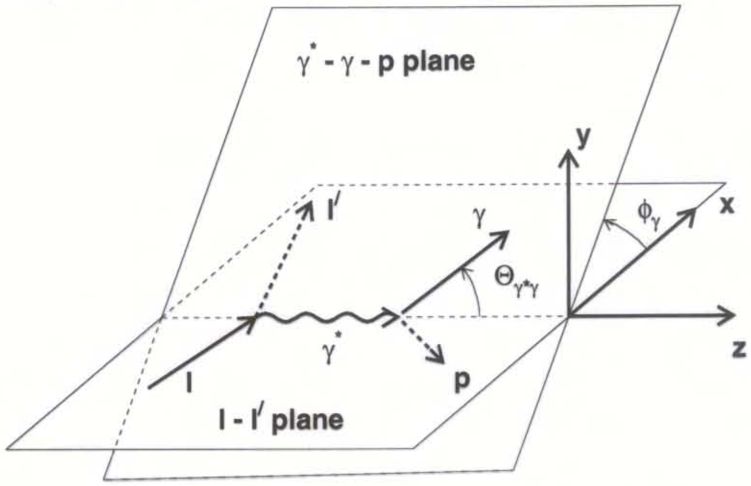
In the limit $\Delta^2 = 0$ (i.e. $\xi = 0$):

$$H^q(x, 0, 0) = q(x), \quad \widetilde{H}^q(x, 0, 0) = \Delta q(x)$$

$q(x)$ and $\Delta q(x)$: quark distr. and quark helicity distr.
(no 'usual' PD equivalents for E^q and $\widetilde{E}^q$)

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

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

$\Rightarrow$ access to real part of (certain combination of) GPD amplitudes

B) Measure lepton helicity asymmetry:

long. polarized beam, unpolarized target

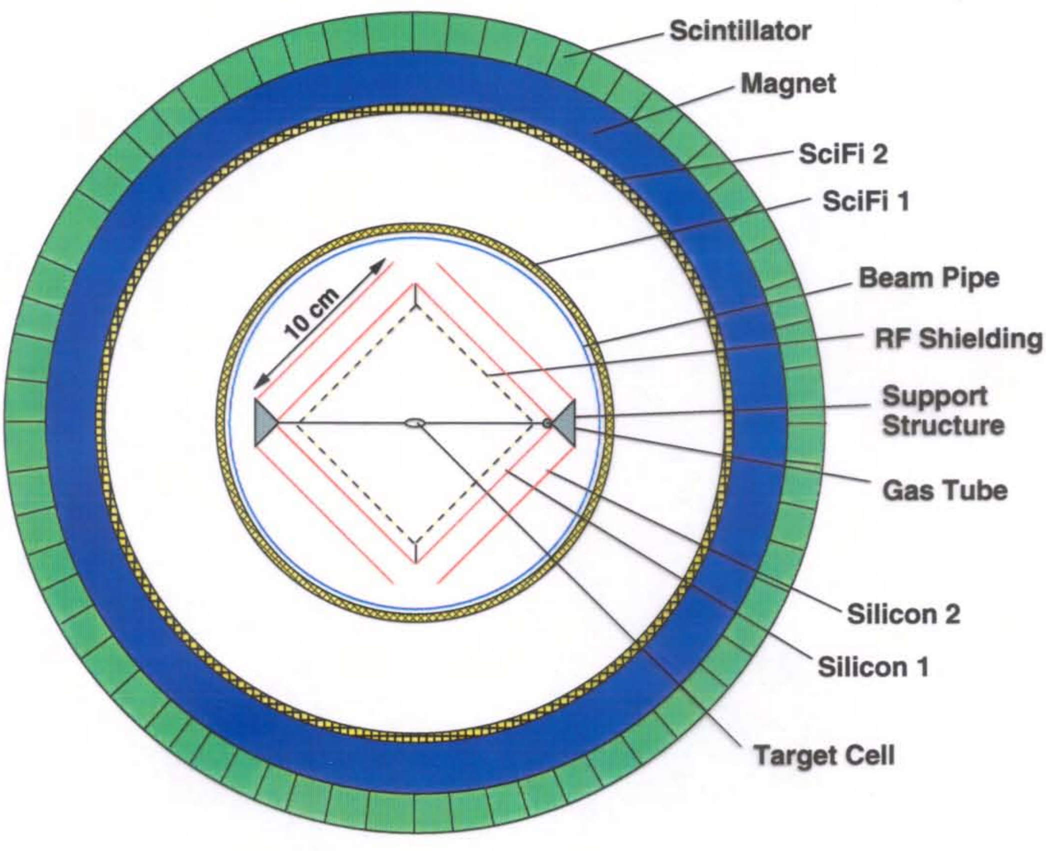
$$A_{LU} \sim d\sigma(\overrightarrow{e^+}p) - d\sigma(\overleftarrow{e^+}p) \sim \sin(\phi_\gamma) \times \mathrm{Im}\mathcal{I}$$

$\Rightarrow$ access to imaginary part of (certain combination of) GPD amplitudes

HERMES: 2004+

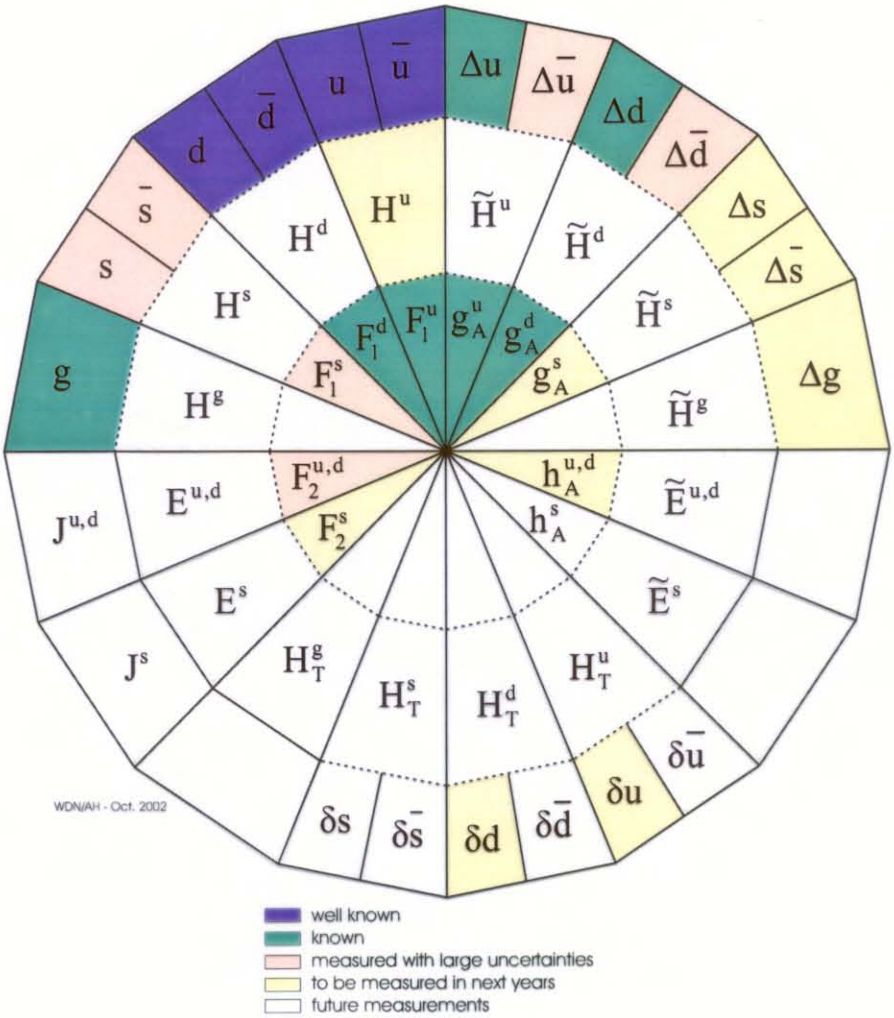
A new Recoil Detector for Hard Exclusive Reactions

DVCS	$\gamma^* p$	$\longrightarrow$	$\gamma\ p$	$\mathbf{H}\ \tilde{\mathbf{H}}\ \mathbf{E}\ \tilde{\mathbf{E}}$
exclusive pseudoscalar meson production	$\gamma^* p$ $\gamma^* p$	$\longrightarrow$ $\longrightarrow$	$\pi^0\ p$ $\pi^+\ n$	$\tilde{\mathbf{H}}\ \ \tilde{\mathbf{E}}$
exclusive vector meson production	$\gamma^* p$ $\gamma^* p$ $\gamma^* p$	$\longrightarrow$ $\longrightarrow$ $\longrightarrow$	$\rho^0\ p$ $\omega\ p$ $\phi\ p$	$\mathbf{H}\ \ \mathbf{E}$



Schematic cross section

Exp. Status on Parton Distr.'s



(cf. W.-D. N., hep-ex/0210409)

Generalized Parton Distributions:

$H^q, \tilde{H}^q, E^q, \tilde{E}^q$ chirally-even quark GPDs

$H_T^q, \tilde{H}_T^q, E_T^q, \tilde{E}_T^q$ chirally-odd quark GPDs

Forward Parton Distributions:

$q(x, Q^2)$ quark number density distribution (f_1^q)

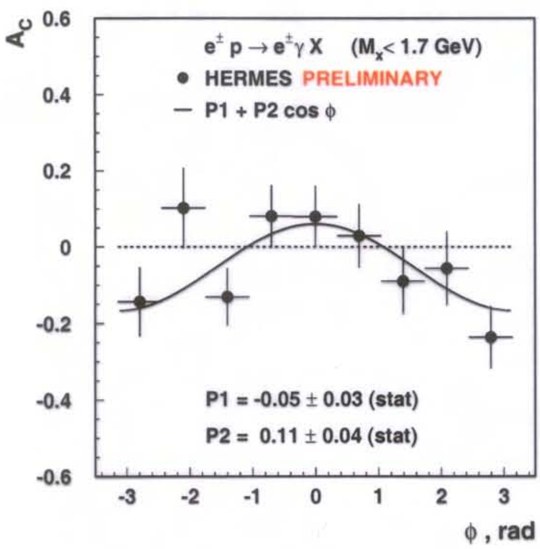
$\Delta q(x, Q^2)$ quark helicity distribution (g_1^q)

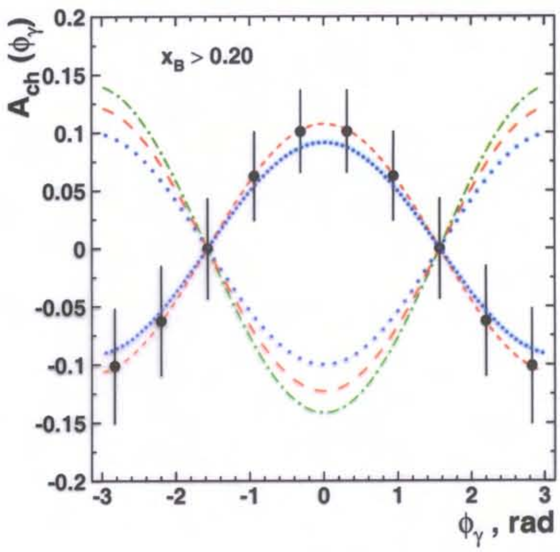
$\delta q(x, Q^2)$ quark transversity distribution (h_1^q)

HERMES DVCS Results and 2006 Asymmetry Projections

A) Lepton charge asym. (unpol. beam, unpol. target):

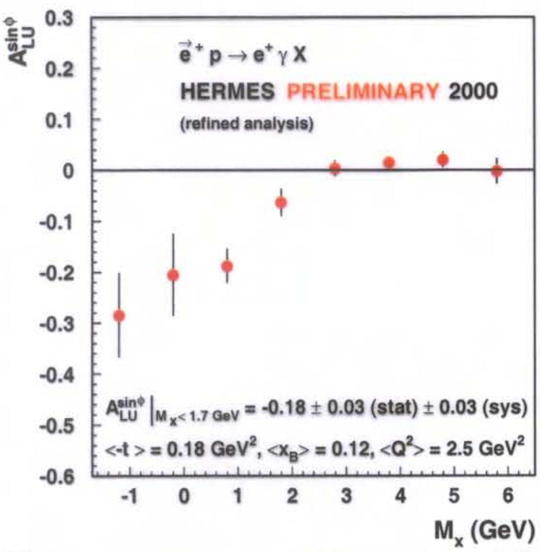
Prel. result 2002 — Projection* ($x_B > 0.2$)

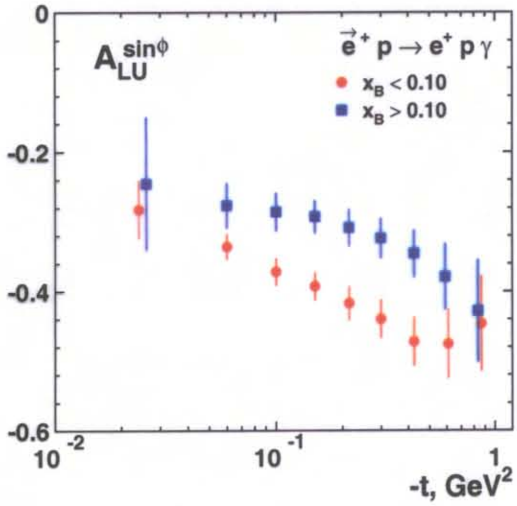




B) Lepton helicity asym. (pol. beam, unpol. target):

Refined prel. result 2002 — Projection*





*) Projections: V. Korotkov, W.-D. N., EPJC 23 (2002), 455

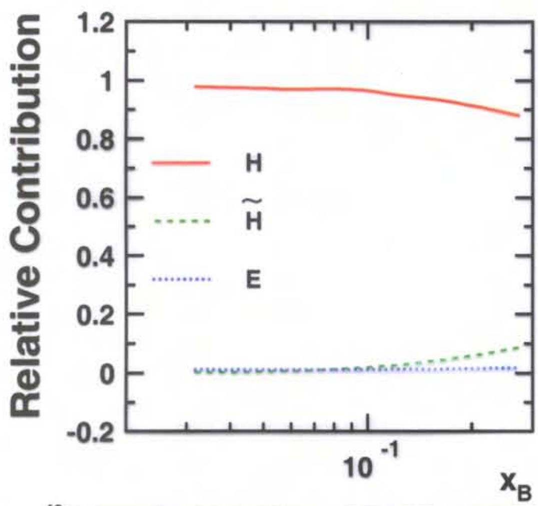
Im$\mathcal{H}$ MEASUREMENT IN 2006 ? *

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

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

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

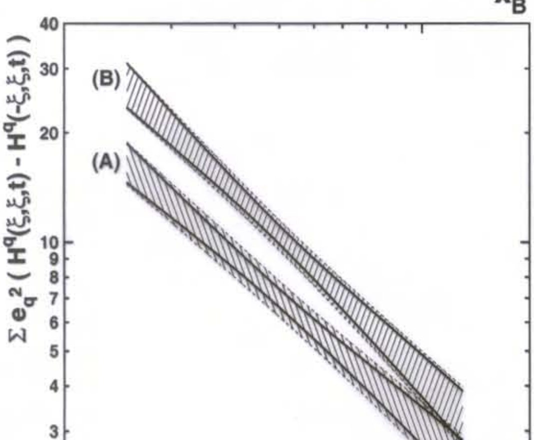
$$\mathcal{C}^{\mathcal{I}}_{\rm unp} = F_1\mathcal{H} + \frac{x_{\rm B}}{2-x_{\rm B}}(F_1+F_2)\widetilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}$$



At $-t < 0.15$ GeV^2:

Relative contribution of GPD H dominates

$\Rightarrow$ Asymmetry $A_{LU}^{sin\phi}$ mainly depending on Im$\mathcal{H}$



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

$\Leftarrow$ Two different bands for different GPD param.'s

$\Leftarrow$ Solid line: 1σ stat. errors

$\Leftarrow$ Dashed line: syst. extraction uncertainty added

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

Transverse Target Spin Asymmetries in DVCS

$A_{UT,1}^{DVCS}$ is sensitive to GPD E, and thus to J_u

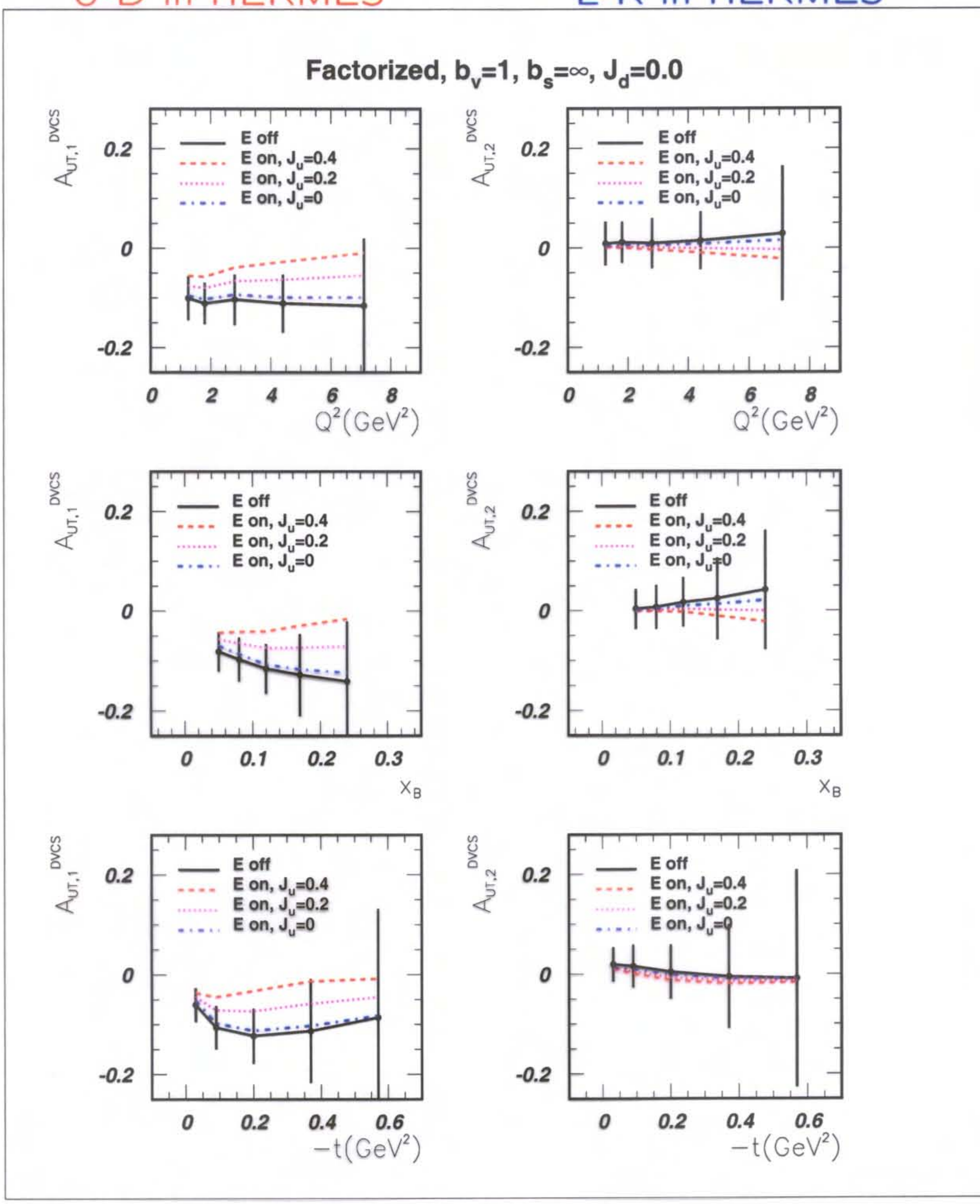
$A_{UT,1}^{DVCS}$ can be measured at HERMES. With 4M DIS = 0.1 fb^{-1}, a 2σ sensitivity can be reached providing first access to GPD E;

$A_{UT,2}^{DVCS}$ also interesting to measure providing first access to GPD $\tilde{E}$.

Results with Factorized Ansatz

L-R in Rest Frame
U-D in HERMES

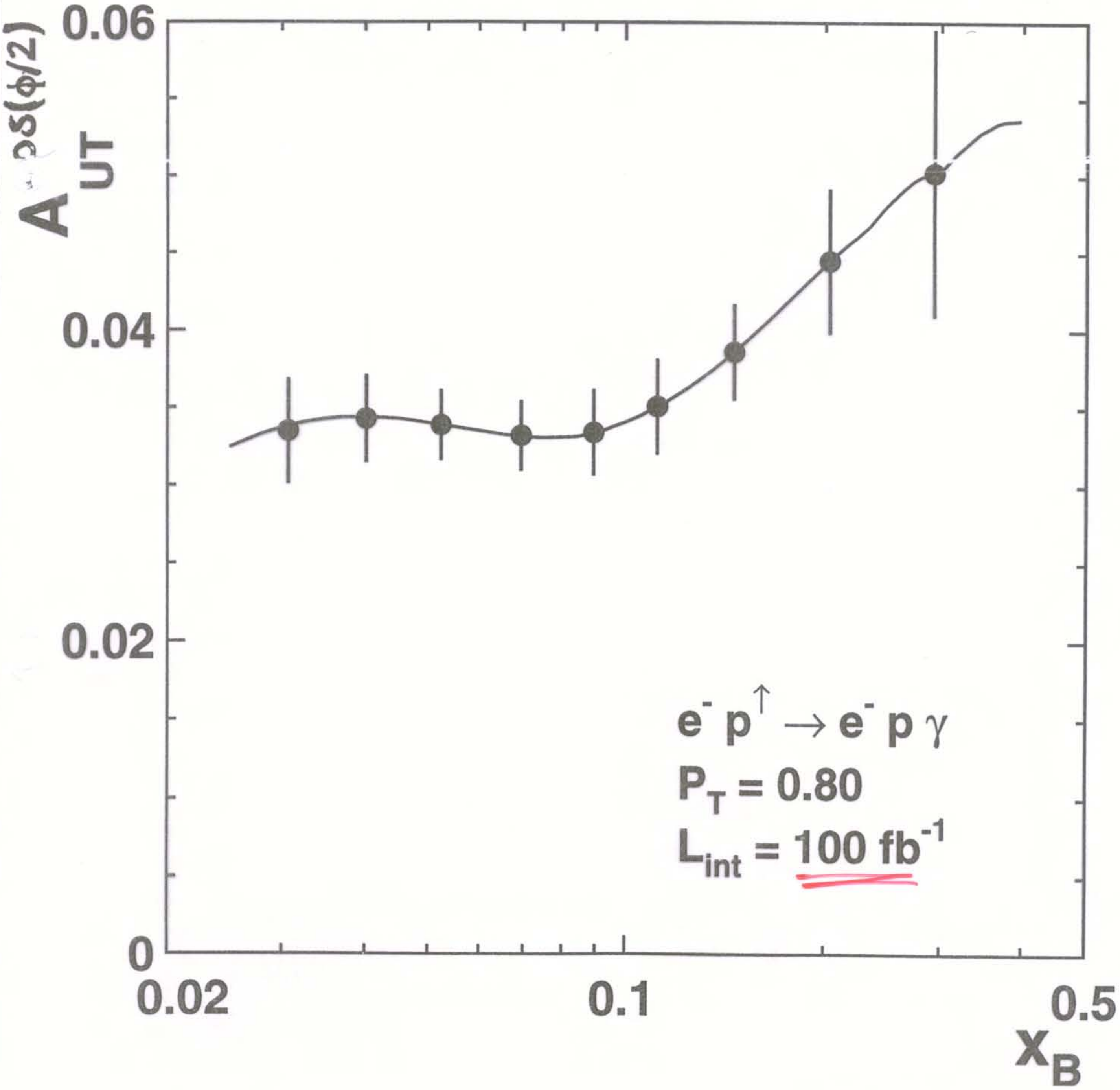
U-D in Rest Frame
L-R in HERMES



HERMES: 4M DIS = 0.1 fb^{-1}

⇒ error ↓ by factor 30 for 100 fb^{-1}

High luminosity
TESLA-N / ELFE - type exp.
w/ transv. pol. target



[Korotkov]

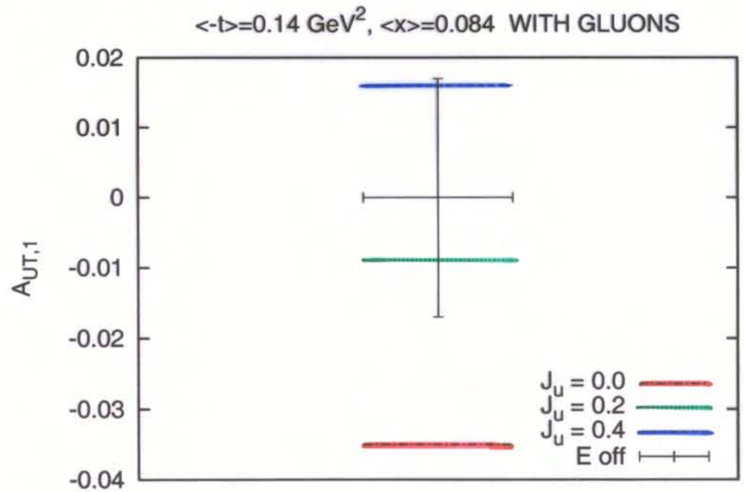
SENSITIVITY OF ELASTIC ρ^0 ELECTROPRODUCTION TO THE GPD E

A_{UT} looks like a unique tool to access the GPD E

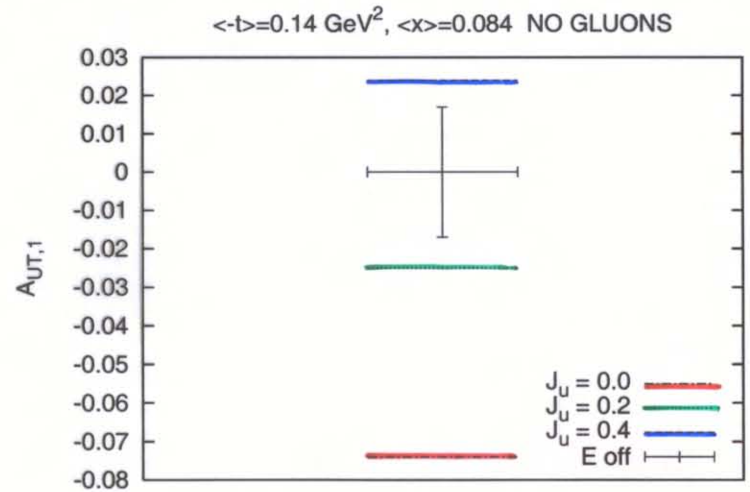
Present parameterizations of E depend on J_u

$\Rightarrow$ A possible way to access J_u ?

PASSIVE GLUONS



NO GLUONS



HERMES-2: transverse target polarization

Projected statistics: 4M DIS $= 0.1$ fb^{-1} ⇗ error ↓ by factor 30 for 100 fb^{-1}

Long-term Objectives

Once the quark total momentum contributions J_u, J_d will have been determined from (a variety of) GPD measurements with acceptable accuracy, remaining major unknowns in the nucleon spin puzzle get into reach:

L_f: quark orbital angular momenta, through

$$\sum_{f=u,d} J_f = \frac{1}{2}\Delta\Sigma + \sum_{f=u,d} L_f$$

[X.Ji, PRL 78, 610 (1997)]

J_g: gluon total angular momentum, through

$$\frac{1}{2} = \sum_f J_f + J_g$$

NOTES: [R.L.Jaffe, AIP Conf. Proc. 588 (2001),54]

1) Only $J_g = L_g + \Delta g$ physically meaningful (separately not gauge invariant)

2) This Δg is NOT the integral over the experimentally accessible polarized gluon distribution $\Delta G(x, Q^2)$

$\Rightarrow$ Experimental results on $\Delta G(x, Q^2)$ (at present) NOT useful to access L_g

Major Physics Topics to Study the Hadron Structure at a High-luminosity Fixed-target eN-facility

Physics	Measured Functions	Processes	Experimental Requests				
			target	σ	t	Q^2	E_{beam}
EXCLUSIVE REACTIONS: • Total quark angular momentum J^{q} *) $J^q = \sum_f J^f$ ($\rightarrow$ Orbital quark ang. mom. L^q) $1^{\underline{st}}$ step: J^u (2006 +)	GPDs: Ji's relation: $J^f = \lim_{t \to 0} \int x dx \left\{ H^f(x,\xi,t) + E^f(x,\xi,t) \right\}$ $1^{\underline{st}}$ extraction: $Im\ H$ (< 2006 ?)	DVCS: $H, E, \tilde{H}, \tilde{E}$ DVEM: pseudo-scalar: $\tilde{H}, \tilde{E}$ vector: H, E	U,T	low $\sigma \rightarrow$ high $\int \mathcal{L}$dt	low t $\rightarrow$ recoil det.	$1 \cdots 20$ GeV^2	$30 \cdots 100$ GeV
SEMI-INCLUSIVE DIS: • PRECISE Measurement of $\Longrightarrow$ tensor charge: ($\rightarrow$ chiral symmetry breaking) *) $\Longrightarrow$ axial charge:	transversity distributions $\delta q_f(x,Q^2) \equiv h_1^f(x,Q^2) \equiv \Delta_T^f(x,Q^2)$ $\delta \sum(Q^2) = \sum_f \int dx \{\delta q_f(x,Q^2) - \delta \bar{q}_f(x,Q^2)\}$ $\Delta \sum(Q^2) = \sum_f \int dx \{\Delta q_f(x,Q^2) + \Delta \bar{q}_f(x,Q^2)\}$	SIDIS + DIS • eN $\rightarrow$ e' KX for access to $\delta s(x,Q^2)$	T L	high precision $\rightarrow$high $\int \mathcal{L}$dt	don't care	$1 \cdots 20$ GeV^2	$50 \cdots 200$ GeV

*) fundamental issues !

Summary of requests:

- polarized solid-state targets (T,L);
- sufficient duty cycle ($\geq$ 10 %)
- Variable beam energy (30 ... 200 GeV)

} $\int \mathcal{L}$dt $\geq 100\ fb^{-1}/year$ (braced against the first two items)

WDN/KP-Oct.2002

OUTLOOK (as of 05.06.2004)

Possible road map towards a future high-luminosity fixed-target muon-nucleon experiment in Europe

- SHORT-TERM ($\rightarrow$ 2007):
  COMPASS-1 and HERMES Run II,
  in conjunction with RHIC-Spin & Jlab,
  will give accurate (first) answers on $\Delta u, \Delta d$, $\Delta \bar{u}, \Delta \bar{d}, \Delta G$, (Δs), δu, (δd), and may allow for an approximate determination of H^u

- MEDIUM-TERM (2007+):
  'Window' for a measurement of H^u, $\tilde{H}^u, E^u$ at COMPASS-2 $\rightarrow$ Possible 'flagship' physics:

  $\Rightarrow$ Determination of the u-quark TOTAL ANGULAR MOMENTUM

- LONG-TERM (2012+):
  Presently no realistic machine option for a European high-luminosity fixed-target experiment using polarized beams and targets at energies 25$\div$100 GeV (JLab : 24 GeV ?)
  $\Rightarrow$ High intensity proton facility offers very exciting option for muon physics at $\mathcal{L} \gtrsim 10^{34}$ cm^{-2}s^{-1}

  $\Rightarrow$ realize best combination of ELFE/TESLA-N physics under the (then) given conditions.