Deeply Virtual Compton Scattering at HERMES

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For the hermes Collaboration

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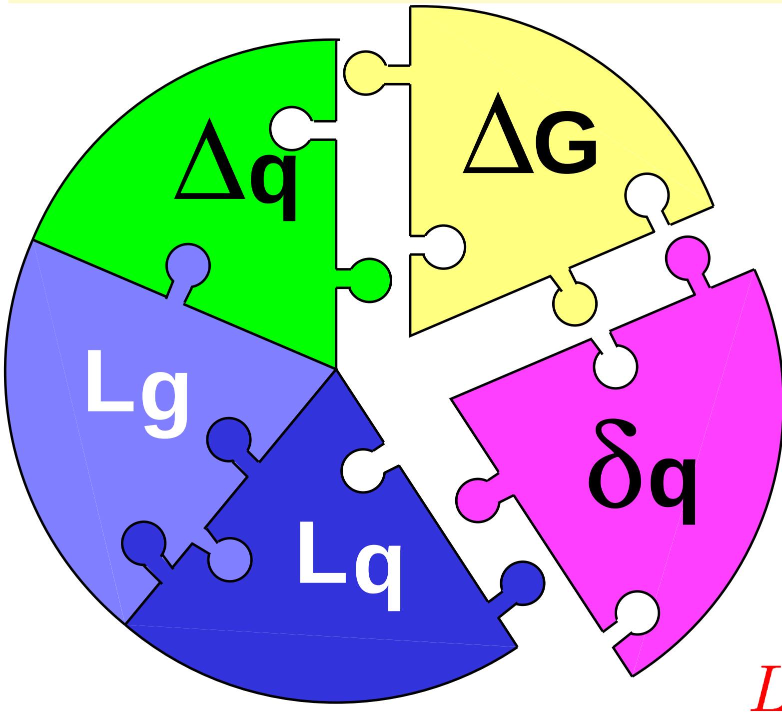
Angular Momentum Structure of the Nucleon



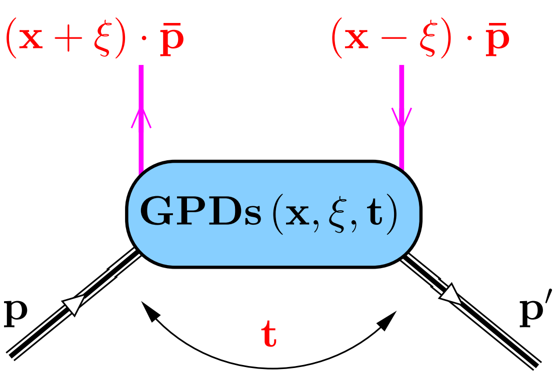
Proton Spin

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

Δq: known from DIS & SIDIS

ΔG: first indications from DIS and pp

L_q, L_g: unknown!

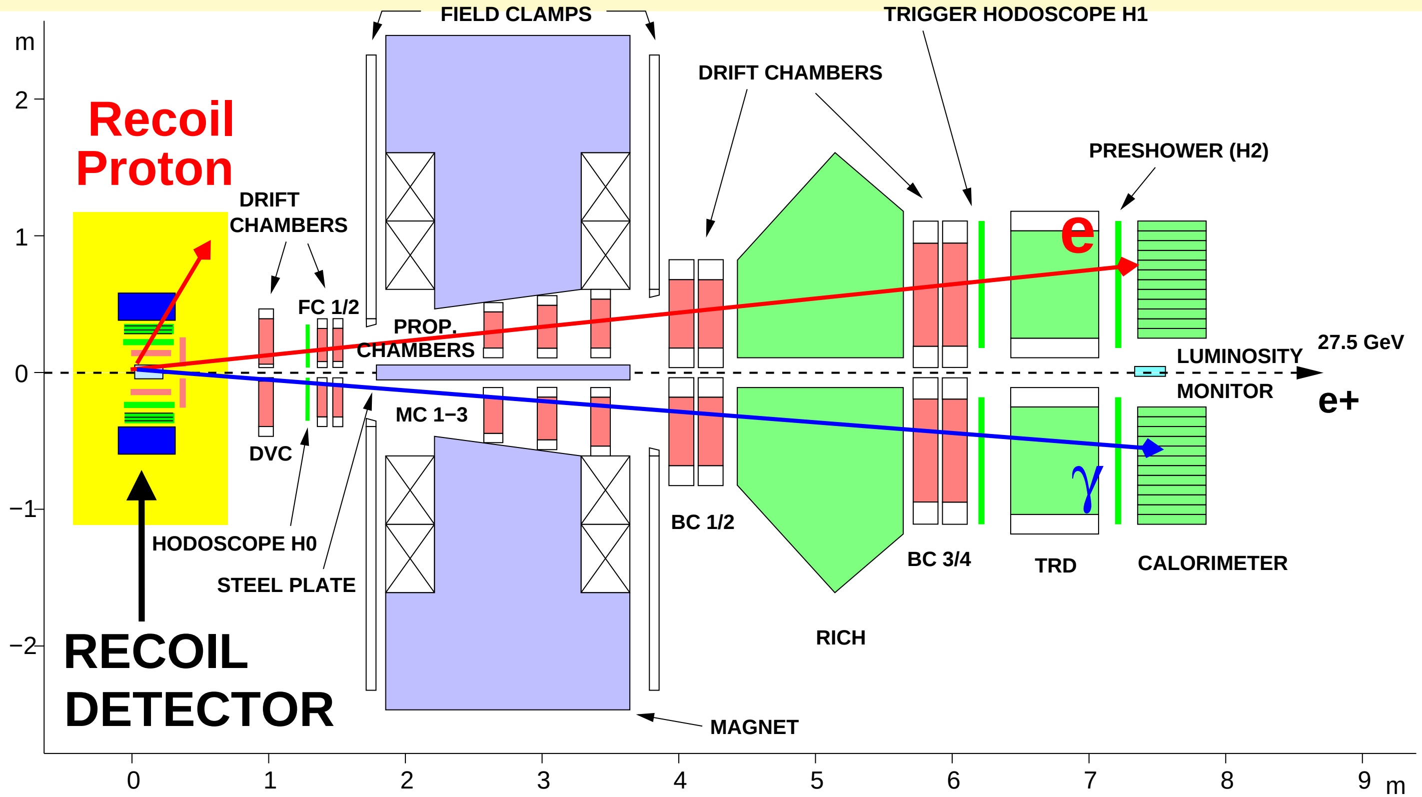


Generalized Parton Distributions $\Rightarrow J_q,\ J_g$

Ji's relation — Ji, PRL 78 (1997) 610

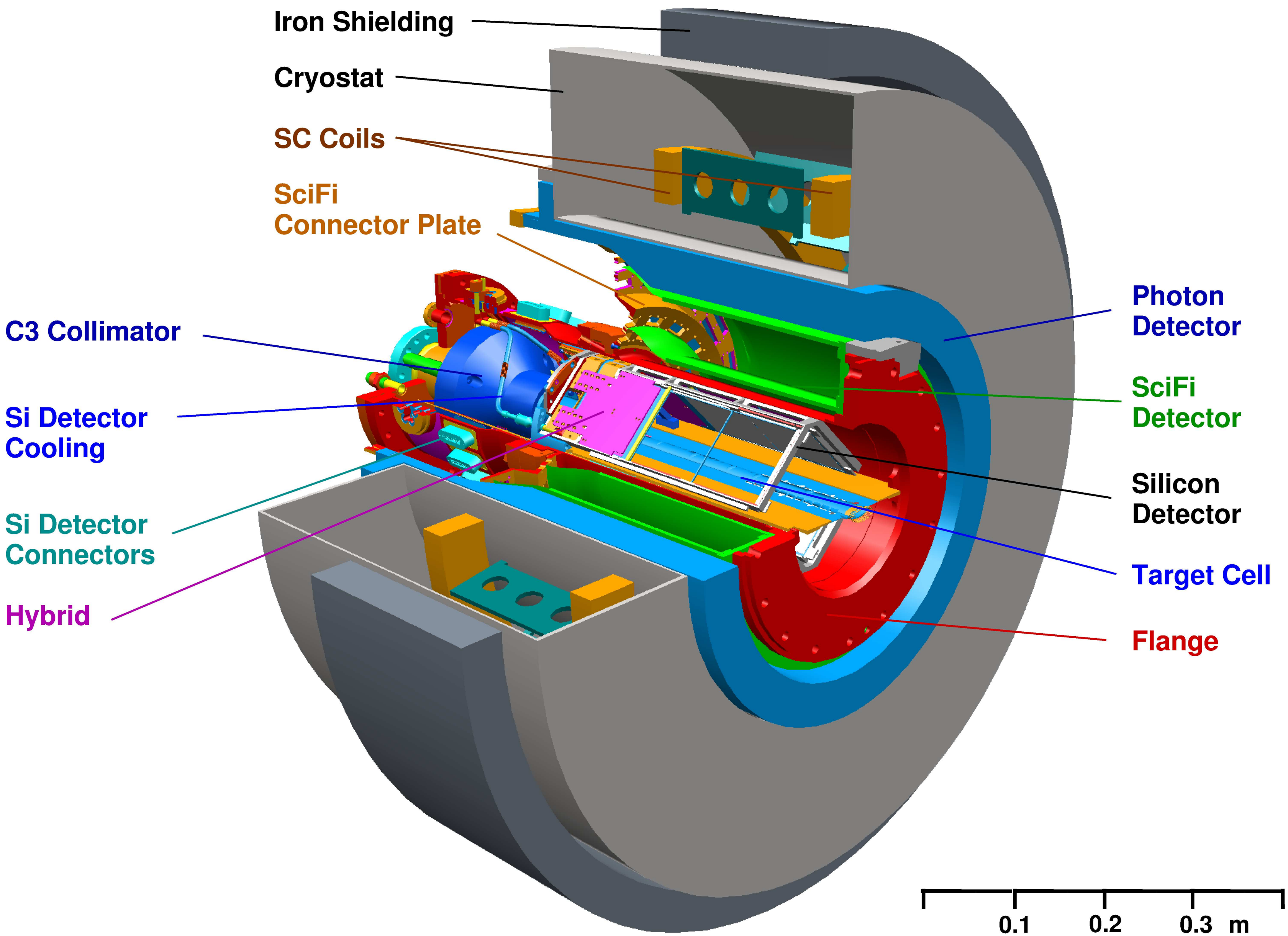
$$J_{q,g} = \frac{1}{2} \lim_{t\to 0} \int_{-1}^{1} dx \cdot x \cdot [H_{q,g}(x,\xi,t) + E_{q,g}(x,\xi,t)]$$

The HERMES Spectrometer



- Pure gas target: polarized H, D; unpolarized H, D, N, Ne, Kr, Xe
- Forward spectrometer: 40 mrad $\leq \Theta \leq$ 220 mrad
- Tracking: $\mathcal{O}$(50) tracking planes per half spectrometer: $\delta p/p \sim 2\%, \delta\Theta \leq 1$ mrad
- PID for $e^{\pm}$: TRD, Preshower, Calorimeter
- PID for $\pi^{\pm}, K^{\pm}, p$: Dual-radiator Ring-imaging Cherenkov ($2 < p < 15$ GeV)

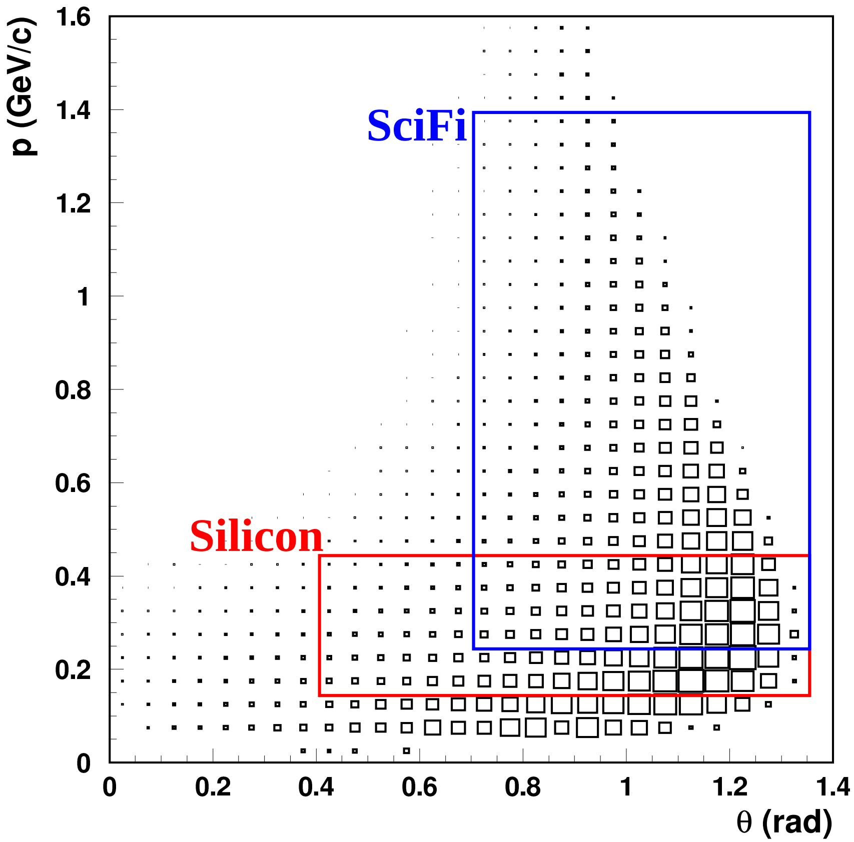
New Recoil Detector at HERMES



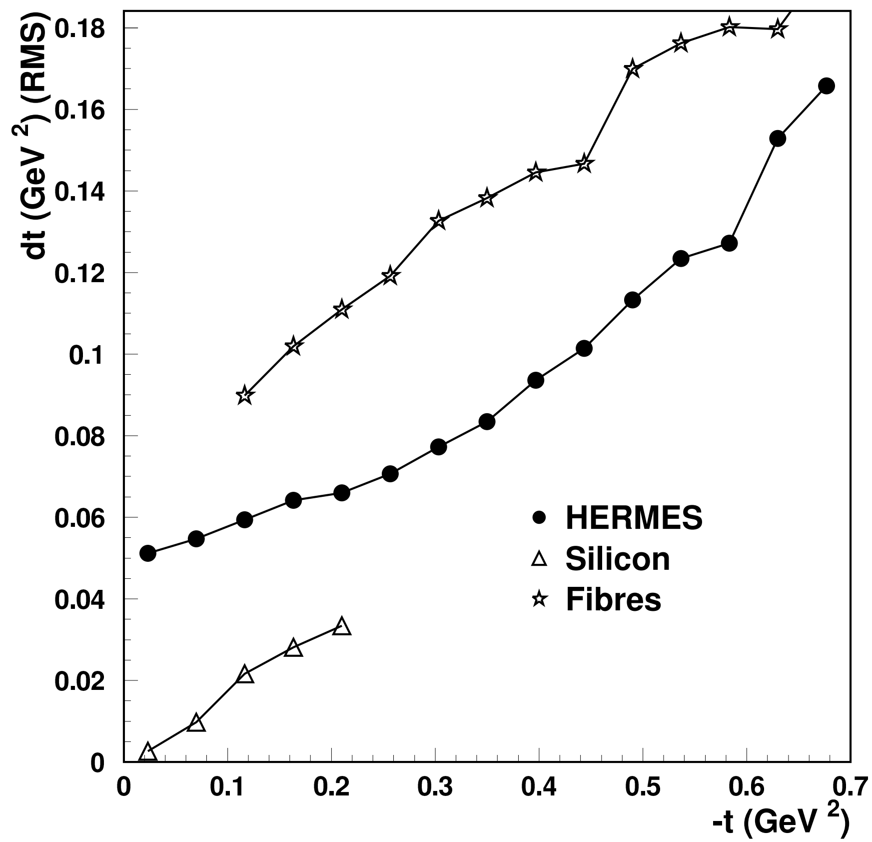
HERMES Recoil Detector Goals I

For the study of DVCS and exclusive meson production, detect over largest possible momentum range and at best possible t-resolution:

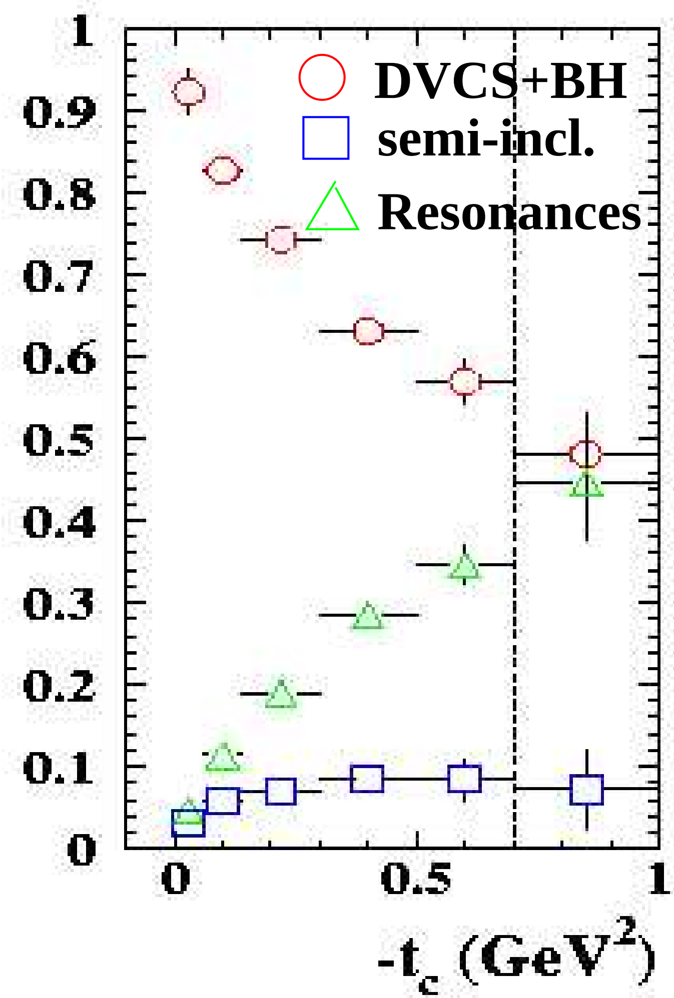
- Recoil protons (76% azim. acceptance, $135 < p < 1200$ MeV/c)
- Pions and protons from background processes (p/π PID via $\frac{dE}{dx}$)
- Photons from $\pi^0 \to \gamma\gamma$



Resolution from Monte Carlo studies:

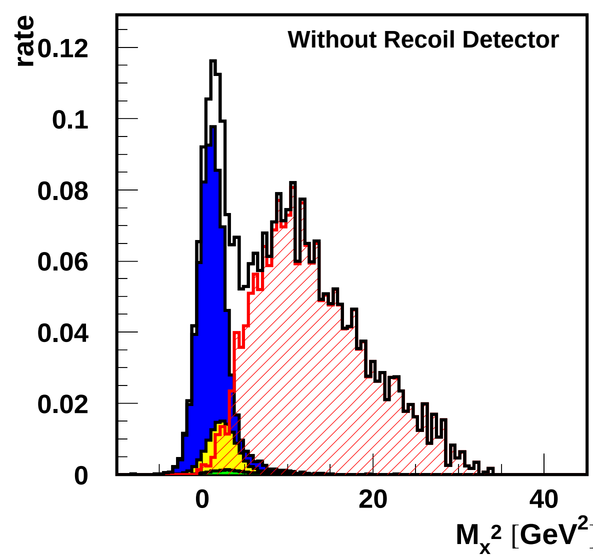


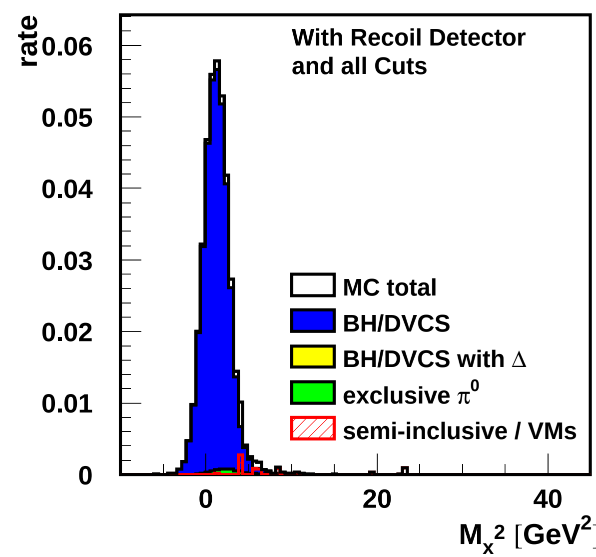
HERMES Recoil Detector Goals II & Status



(Performance improvements shown for DVCS)

- Enhance signal fraction
- Reduce background contributions
  - semi-incl.: 5% $\rightarrow <<$ 1%,
  - associated prod.: 11% $\rightarrow \sim$ 1%

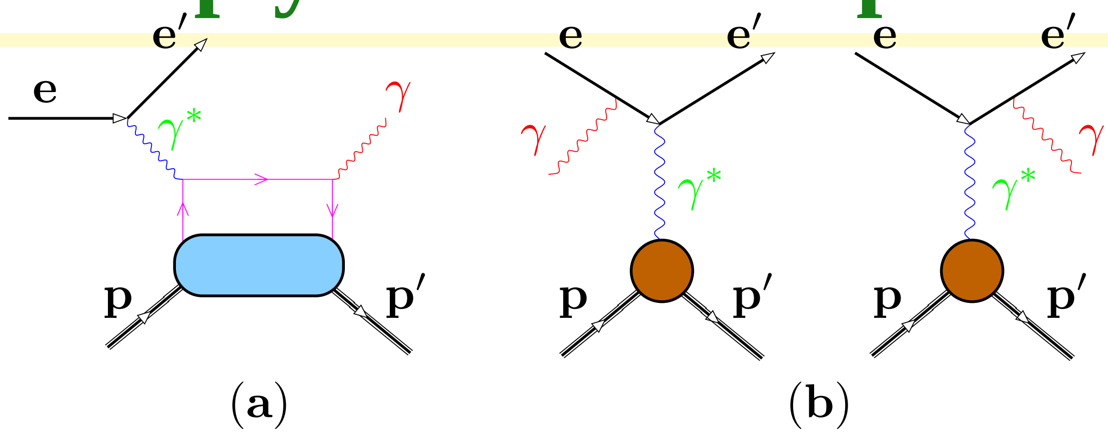




Status:

- Detector components ok, final calibration & alignment ongoing
- Tracking & connection to forward spectrometer being set up

Deeply Virtual Compton Scattering



- Same final state in DVCS and Bethe-Heitler ⇒ Interference!

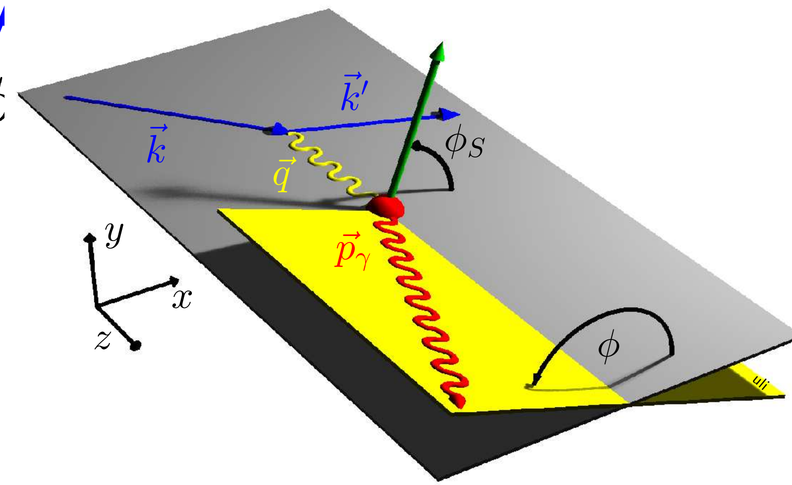
$$d\sigma(\mathrm{eN} \to \mathrm{eN}\gamma) \propto |\mathcal{T}_{BH}|^2 + |\mathcal{T}_{DVCS}|^2 + \underbrace{\mathcal{T}_{BH}\mathcal{T}^*_{DVCS} + \mathcal{T}^*_{BH}\mathcal{T}_{DVCS}}_{\mathcal{I}}$$

- $\mathcal{T}_{BH}$ 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 $\mathcal{H}, \mathcal{E}, \widetilde{\mathcal{H}}, \widetilde{\mathcal{E}}$ (which are convolutions of resp. GPDs $H, E, \widetilde{H}, \widetilde{E}$)
- (Certain Parts of) interference term can be filtered out by forming certain cross section differences (or asymmetries)

⇒ GPDs $H, E, \widetilde{H}, \widetilde{E}$ **indirectly** accessible via interference term $\mathcal{I}$

Azimuthal Asymmetries in DVCS

DVCS–Bethe-Heitler Interference term $\mathcal{I}$
induces azimuthal asymmetries in cross-section:



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

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

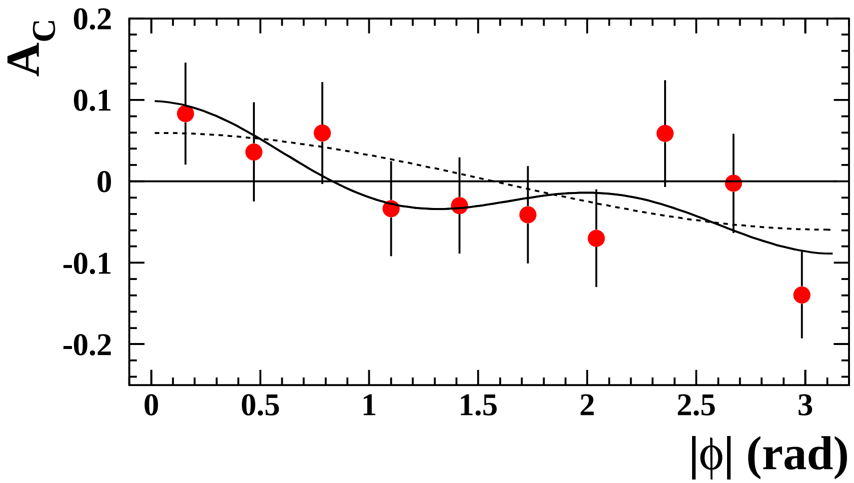
(F_1, F_2 are the Dirac and Pauli elastic nucleon form factors)

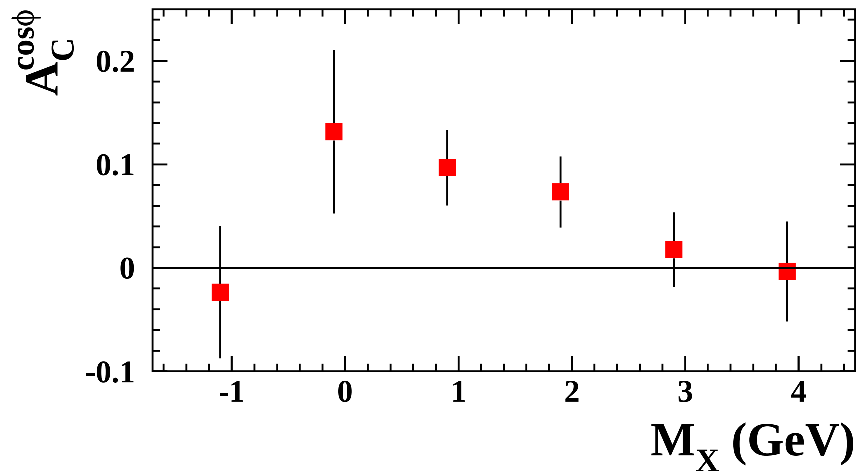
HERMES Beam-charge Asymmetry vs. ϕ and M_X^2

$$A_C(\phi) = \frac{d\sigma^+(\phi) - d\sigma^-(\phi)}{d\sigma^+(\phi) + d\sigma^-(\phi)} \propto \mathrm{Im} F_1 \mathcal{H} \cdot \cos\phi$$

$\Rightarrow$ extract 'amplitudes' by fitting in every ϕ-bin

$$A_C(\phi) = const. + A_C^{\cos\phi} \cos\phi + A_C^{\cos 2\phi} \cos 2\phi + A_C^{\cos 3\phi} \cos 3\phi$$

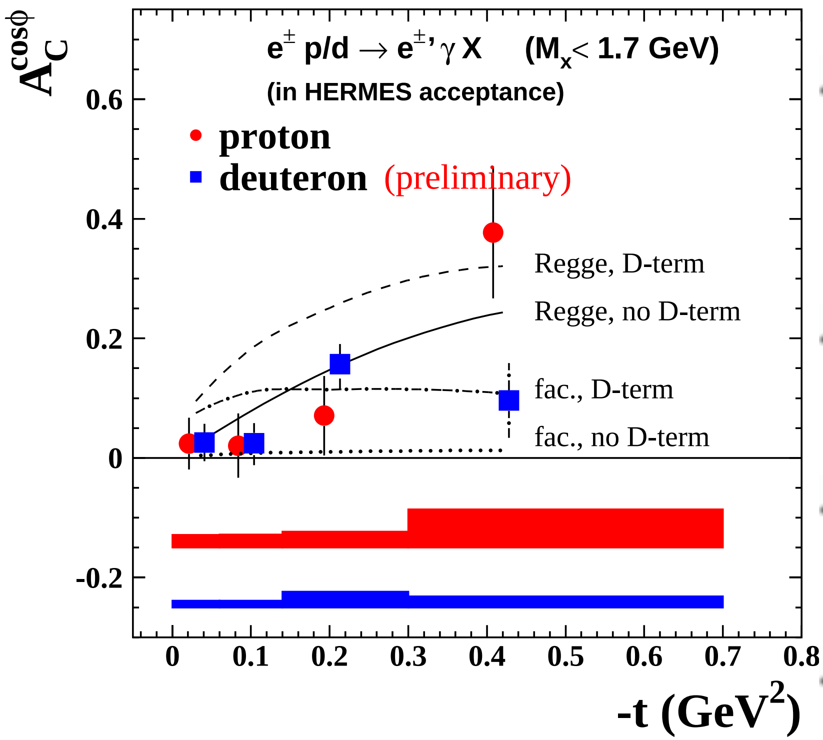




- published results shown for *un*polarized proton target **[hep-ex/0605108, PRD75(2007)01110**
- use *symmetrization* ($\phi \rightarrow |\phi|$) to get rid of sinusoidal terms
- $A_C^{\cos\phi} = 0.060 \pm 0.027$, other contributions insignificant (dashed = pure $\cos\phi$)
- asymmetry only in exclusive and 'associate' M_X^2 region ($\rightarrow$ resol. smearing)
- preliminary deuteron data (not shown) completely consistent

HERMES Beam-charge Asymmetry vs. t

BCA t-dependence can distinguish different GPD model versions:



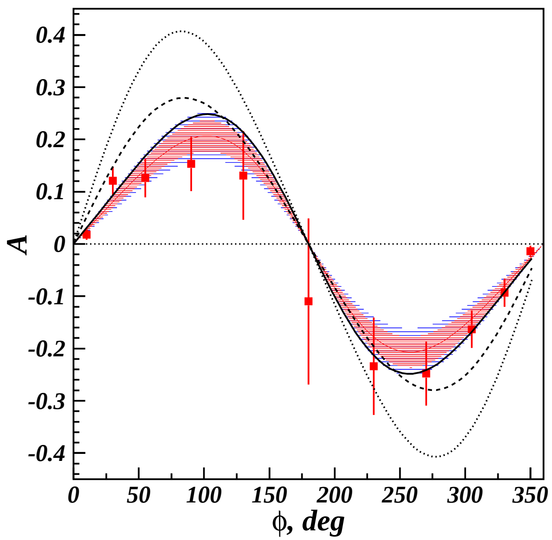
- $A_C^{\cos\phi}$: elastic + associated production
- d-data: contributions per t-bin of associated production: 5,11,18,29%
  $\Rightarrow$ highest t-bin mostly affected
- GPD H dominates, $\tilde{H}$ and E suppressed
  [Goeke,Polyakov,Vanderhaeghen,PPNP 47(2001)401]
- Curves (code [Vanderhaeghen,Guichon,Guidal]) calculated for 4 different parameter sets
- BCA insensitive to profile fct. parameters

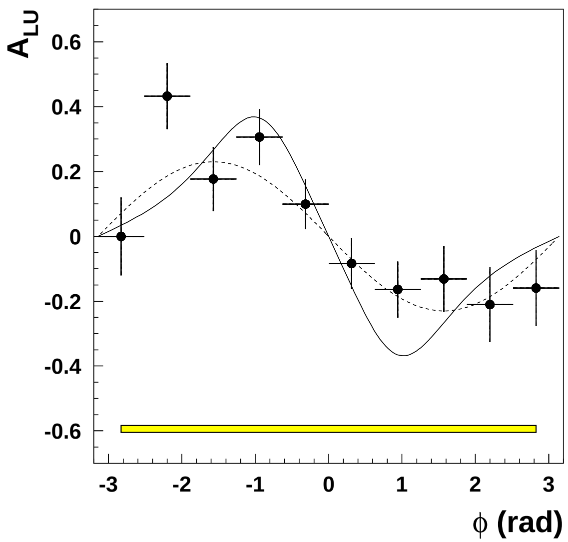
- already HERA-I data disfavor Regge-inspired t-dependence with D-term
- more precise BCA data from HERA-II (to be analyzed)
- reduction of background & associated contribution by recoil detector:
  expected for e^+ sample, but no e^- sample with recoil
  (can one rely on 'similarity' cuts ??)

CLAS & HERMES: early Beam-spin Asymmetries

$$A_{LU}(\phi) = \frac{1}{\langle|P_B|\rangle} \cdot \frac{d\sigma^{\rightarrow}(\phi) - d\sigma^{\leftarrow}(\phi)}{d\sigma^{\rightarrow}(\phi) + d\sigma^{\leftarrow}(\phi)} \propto \mathrm{Im} F_1 \mathcal{H} \cdot \sin\phi$$

$\Rightarrow$ extract 'amplitudes' fitting per ϕ-bin $A_{LU}(\phi) = c + A_{LU}^{\sin\phi} \sin\phi + A_{LU}^{\sin 2\phi} \sin 2\phi$



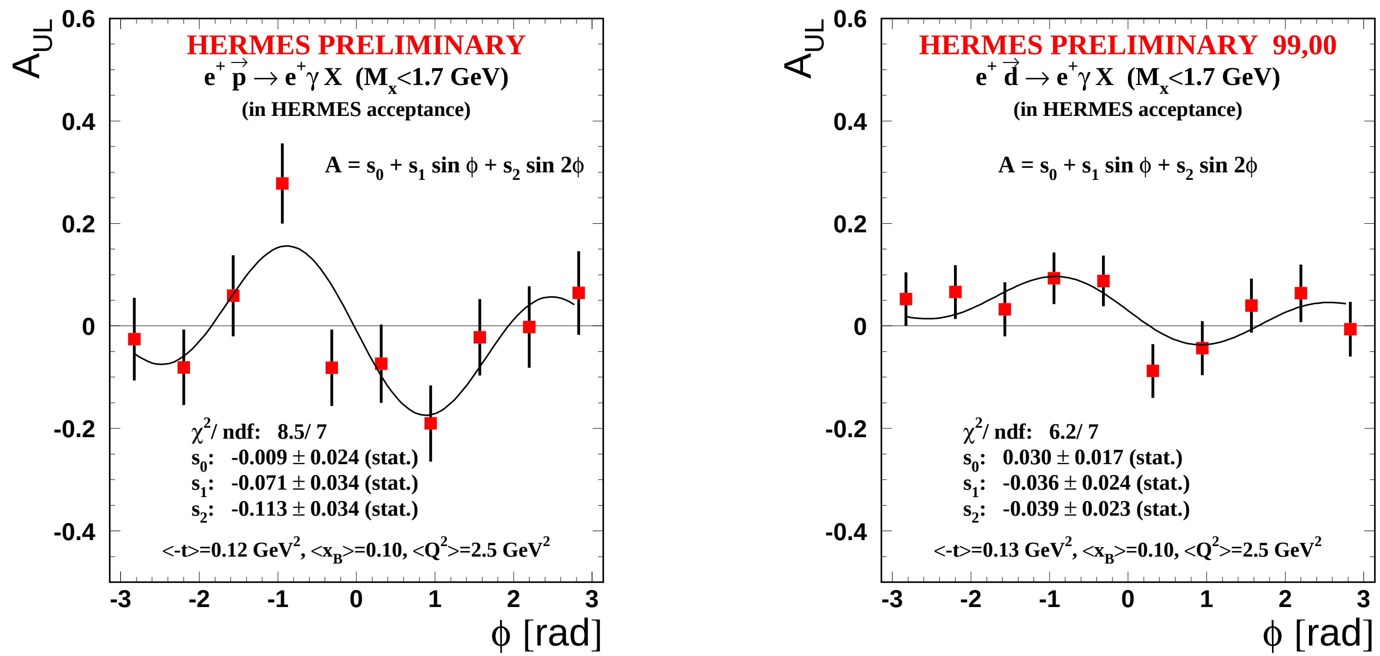


- HERMES: 27.5 GeV p, $P_B \approx 55\%$. Recoil proton not detected [PRL87(2001,1820…
- CLAS: 4.25 GeV p, $P_B \approx 70\%$. Produced gamma not detected [PRL87(2001,182…
- expected $\sin\phi$ behaviour: significant $\sin\phi$ amplitudes on both targets
- other harmonics don't contribute significantly

HERMES Long. Target-spin Asymmetry vs. ϕ

$$A_{UL}(\phi) = \frac{1}{\langle|P_L|\rangle} \cdot \frac{d\sigma^{\Rightarrow}(\phi) - d\sigma^{\Leftarrow}(\phi)}{d\sigma^{\Rightarrow}(\phi) + d\sigma^{\Leftarrow}(\phi)} \propto \mathrm{Im} F_1 \widetilde{\mathcal{H}} \sin\phi$$

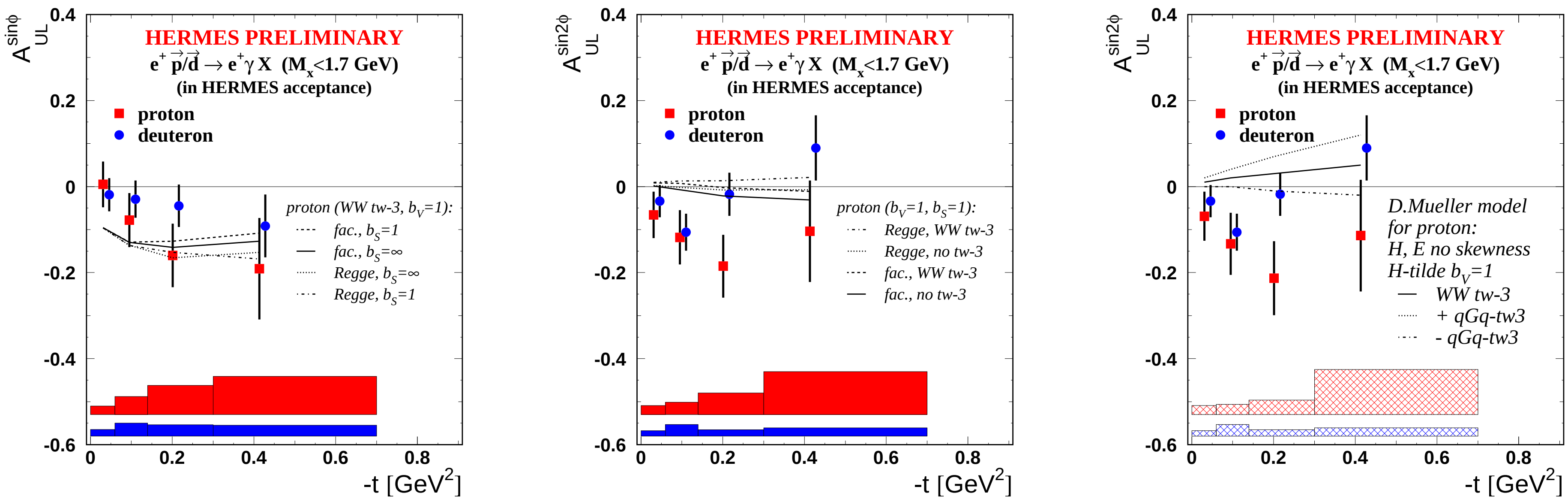
$\Rightarrow$ extract 'amplitudes' fitting per ϕ-bin $A_{UL}(\phi) = c + A_{UL}^{\sin\phi} \sin\phi + A_{UL}^{\sin 2\phi} \sin 2\phi$



- FULL existing data set analyzed (1996-2000 data)
- expected $\sin\phi$ behaviour : 2σ (1.5σ) on proton (deuteron)
- unexpected, sizeable ($> 3\sigma$) $A_{UL}^{\sin 2\phi}$ on proton (1.7σ on deuteron) $\Rightarrow$ twist-3 ?
  (π^0 background found to be responsible for *at most* a small fraction of it)

HERMES Long. Target-Spin Asymmetry vs. t

- Twist-3 GPDs: WW-term + interaction-dep. (qGq) term: $F^3 = F^3_{WW} + F^3_{qGq}$
- Existing models include only WW-terms of twist-3 GPDs



- Lowest t-bin: No effect from coherent prod. on deuteron (40% of statistics)
- higher t: $A_{UL}(ep) \neq A_{UL}(ed) \Rightarrow A_{UL}(ep) \neq A_{UL}(en)$
- Only Proton models exist: $\rightarrow$ for $A_{UL}^{\sin\phi}$; VGG model does ok.

  $\rightarrow$ for $A_{UL}^{\sin 2\phi}$: • VGG (twist-3 only WW) fails completely

  • D.Müller [priv.comm.]: Upper limits for qGq (dynamic) twist-3 corrections

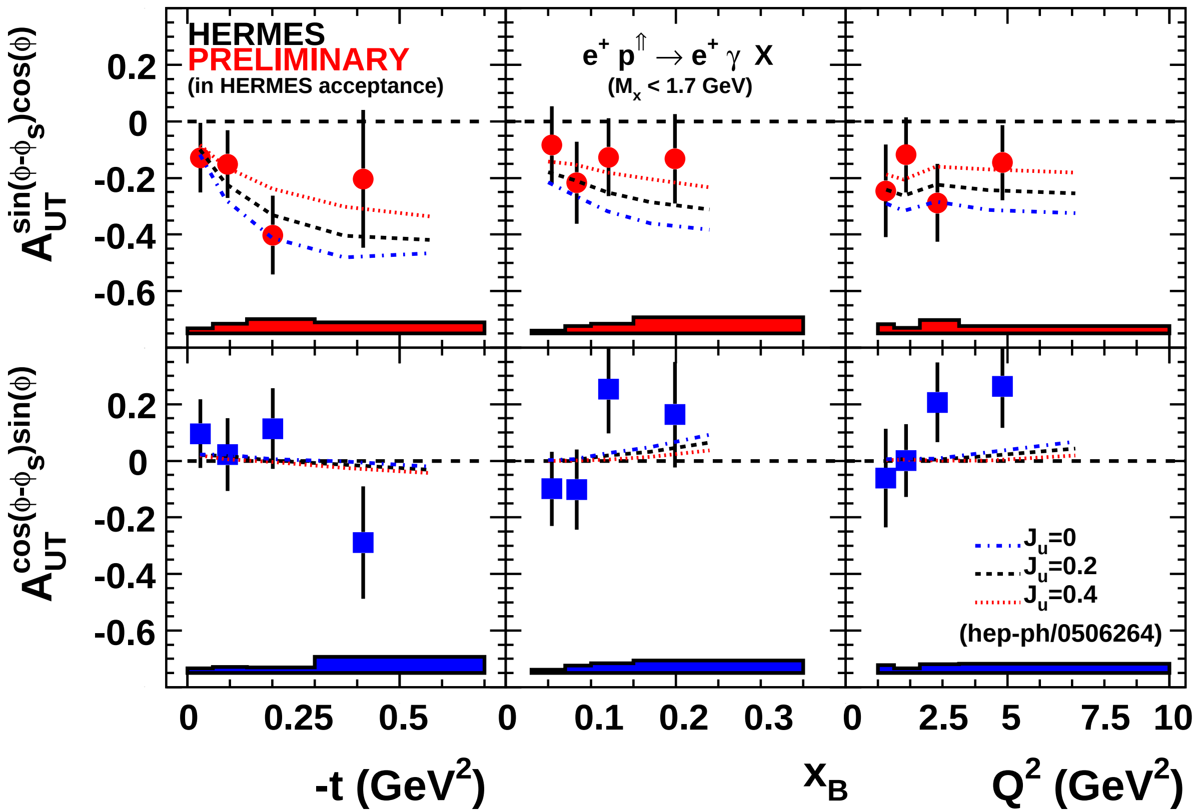
Why TTSA Data Expected to be Sensitive to J_q ?

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

ANSATZ: spin-flip Generalized Parton Distribution E can be parameterized as follows:

- Factorized ansatz for spin-flip quark GPDs: $E_q(x,\xi,t) = \frac{E_q(x,\xi)}{(1-t/0.71)^2}$
- t-indep. part via double distr. ansatz: $E_q(x,\xi) = E_q^{DD}(x,\xi) - \theta(\xi - |x|)D_q\left(\frac{x}{\xi}\right)$
- using double distr. K_q: $E_q^{DD}(x,\xi) = \int_{-1}^{1} d\beta \int_{-1+|\beta|}^{1-|\beta|} d\alpha\ \delta(x-\beta-\alpha\xi)\ K_q(\beta,\alpha)$
- with $K_q(\beta,\alpha) = h(\beta,\alpha)\ e_q(\beta)$ and $e_q(x) = A_q q_{val}(x) + B_q\delta(x)$
  based on chiral QSM
- where coeff.s A, B constrained by Ji relation, and $\int_{-1}^{+1} dx\ e_q(x) = \kappa_q$
- A_u, A_d, B_u, B_d are functions of J_u, J_d
  $\Rightarrow J_u, J_d$ **are free parameters when calculating TTSA**

DVCS TTSA: HERMES Data vs. Predictions



$$A_{UT}(\phi, \phi_S) = \frac{1}{\langle|P_T|\rangle} \cdot \frac{d\sigma(\phi,\phi_S) - d\sigma(\phi,\phi_S+\pi)}{d\sigma(\phi,\phi_S)+d\sigma(\phi,\phi_S+\pi)}$$

$$= A_{UT}^{\sin(\phi-\phi_S)\cos\phi} \cdot \sin(\phi-\phi_S)\cos\phi + A_{UT}^{\cos(\phi-\phi_S)\sin\phi} \cdot \cos(\phi-\phi_S)\sin\phi$$

HERMES $e^+p^\Uparrow$ 2002-04:

- U: unpolarized beam
- T: transv. pol. target
- ca. 50% of total stat.
- [2004-05 data: $e^-p^\Uparrow$]

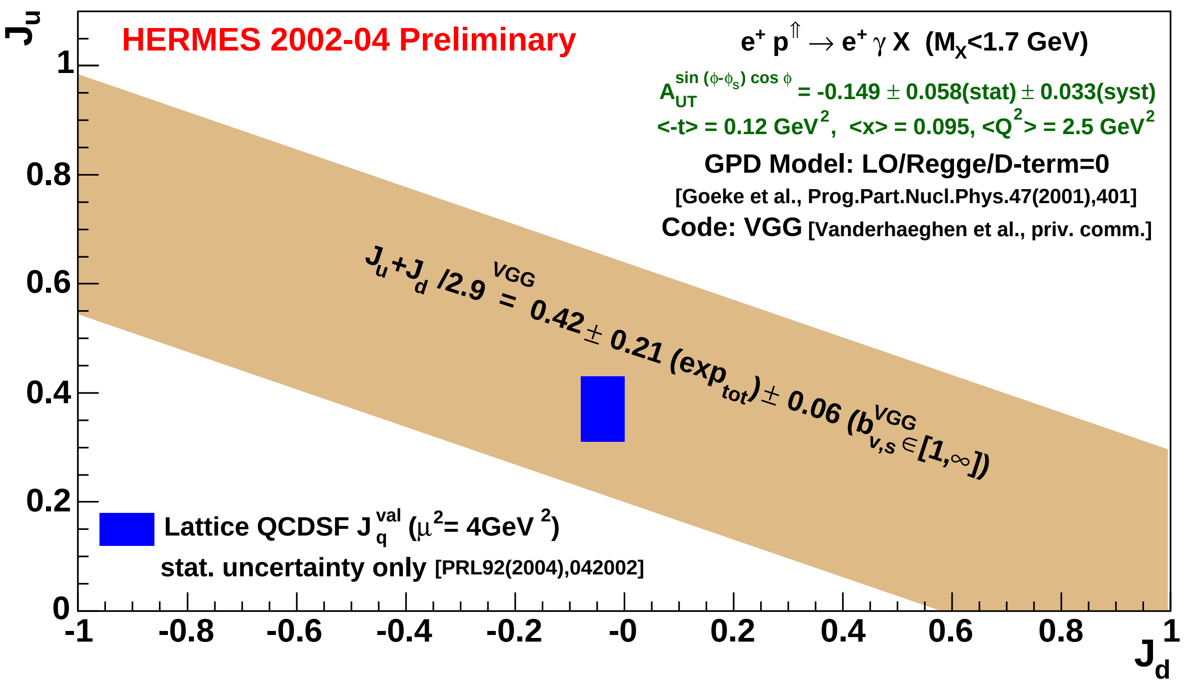
STUDY sensitivity to J_u (with $J_d = 0$) [hep-ph/0506264, based on Prog.Part.Nucl.Phys.47]:

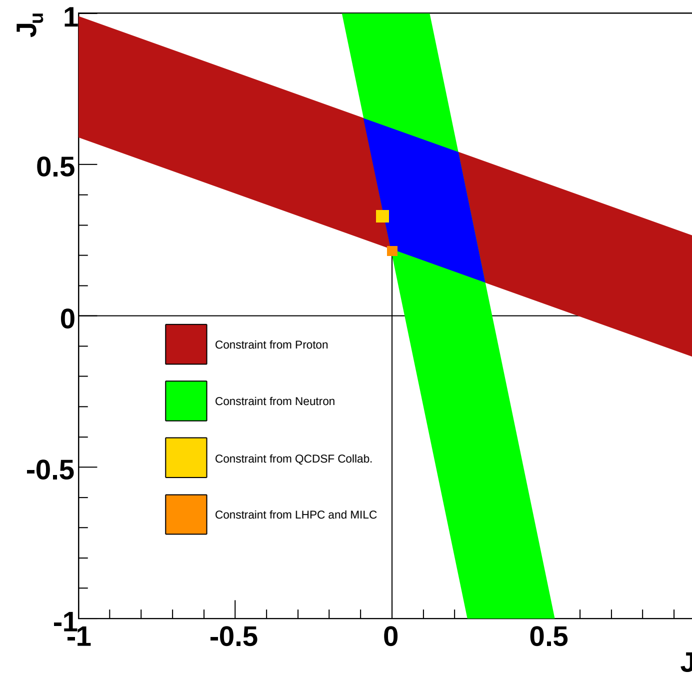
- $A_{UT}^{\sin(\phi-\phi_S)\cos\phi}$ found sensitive to J_u, while $A_{UT}^{\cos(\phi-\phi_S)\sin\phi}$ is not
- only weak sensitivity found to other GPD model parameters

  (profile parameters, Regge/factorized ansatz for t-dependence)

HERMES: Model-dependent Constraint: J_u vs J_d

Unbinned maximum likelihood fit to $A_{UT}^{\sin(\phi-\phi_S)\cos\phi}$ at average kinematics (fitting prel. HERMES data against VGG-model based calculations), leaving J_u and J_d as free parameters $\Rightarrow$ model-dependent 1-σ constraint on J_u vs. J_d:





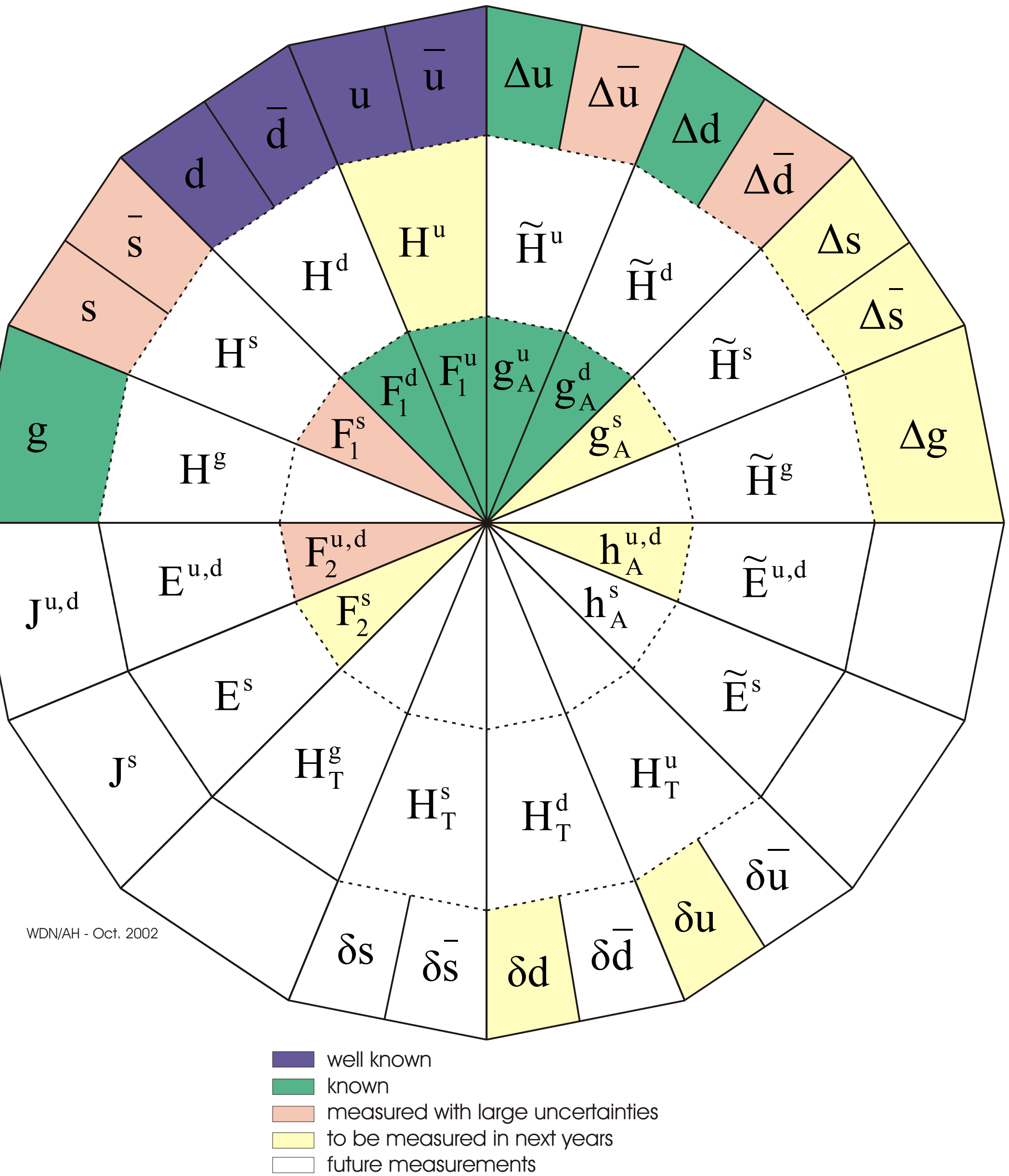
- Hermes: prel. constraint from proton DVCS (TTSA) using VGG [F. Ye, DIS2006]
- JLab Hall-A: prel. constraint from neutron DVCS (BSA) using VGG [M. Mazouz, DIS2007]
- Lattice calculations (valence quarks only): blue (left) $=$ yellow (right) rectangle: QCDSF, orange (right) rectangle: LHPC and MILC

Summary and Outlook

- ▷ The HERMES experiment played a pioneering role exploring the potential of exclusive photon (also meson) production towards an interpretation of the data in terms of GPDs. Azimuthal asymmetries were measured with respect to beam spin and charge, and to longitudinal and transverse target polarization. First constraints on GPD models were obtained, in particular a model-dependent constraint on the u and d-quark total angular momenta. The HERMES RECOIL DETECTOR is in full operation since summer 2006; the goal of $\approx$ 1 fb^{-1} data was reached by mid 2007, the end of HERA running.
- ▷ At JLab, many dedicated high-statistics DVCS measurements on various targets were/are/will be performed, which will have strong impact on constraining GPDs. Plans are being substantiated for measurements at 12 GeV that are hoped to become reality beyond 2012. Exclusive reactions will hence presumably be mapped in the next decade, allowing the construction of precise GPD models which are expected to describe the 3-dimensional structure of the nucleon.

Back-up Slides

Exp. Status on Parton Distribution Functions



Improvement over last 5 years:

- spin-independent & helicity PDFs:
  - COMPASS: $\frac{\Delta g}{g}$
  - HERMES: $\Delta u, \Delta d, \Delta s, \frac{\Delta g}{g}$
  - JLab: $\Delta u, \Delta d$ at large x
- transversity & friends:

  HERMES: Sivers function

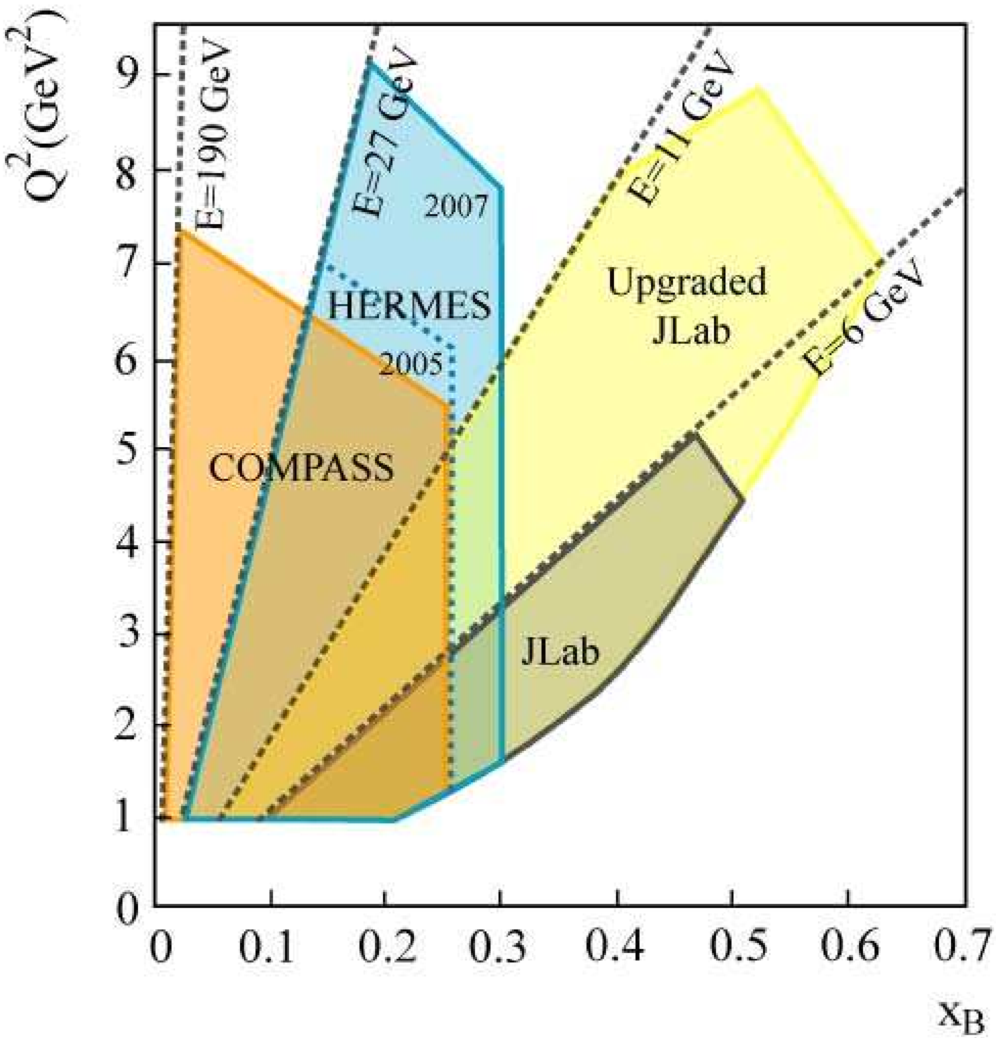
  BELLE: Collins (fragm.) function
- GPDs:

  CLAS, HERMES, (H1/ZEUS):
  first look on $H, \tilde{H}, E$

$\Rightarrow$ much more to come ...

Kinematic Coverage of DVCS Experiments

Fixed-target kinematics



- Fixed-target experiments:

  $x > 0.03$, $Q^2 < 10$ GeV^2

  - COMPASS: low + medium x_B
  - HERMES: medium x_B, higher Q^2
  - JLab: medium+large x_B, lower Q^2
  - JLab 11 GeV: larger x_B, higher Q^2

- Collider experiments H1+ZEUS:

  $x_B < 0.01$, Q^2 : 5...100 GeV^2:

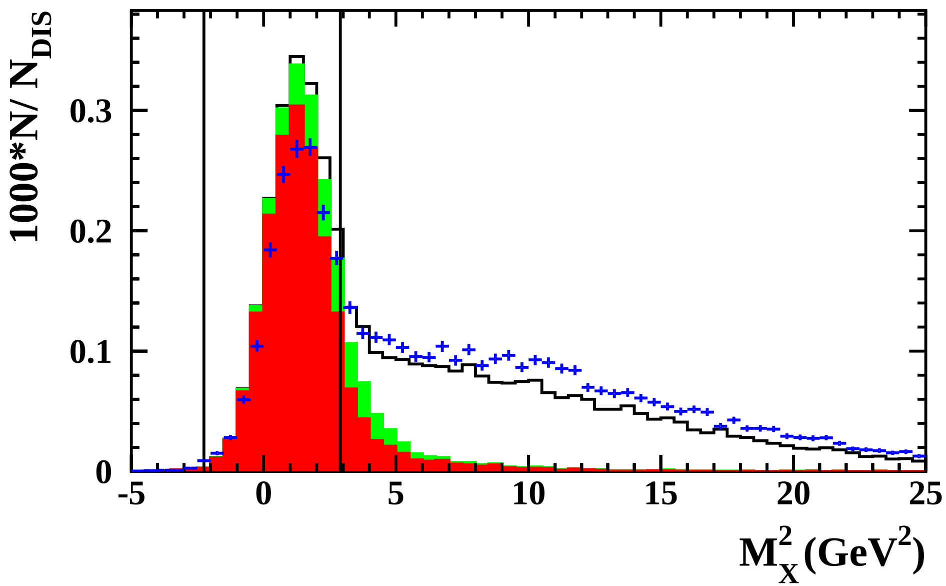
  - small skewness

  $\Rightarrow$ almost forward GPDs !

$\Rightarrow$ fixed-target experiments essential to study non-forward region of GPDs !

$\Rightarrow$ only COMPASS can explore low-x !

Exclusive DVCS Events at HERMES



REACTION : $e + p(d) \rightarrow e + \gamma\ (+X)$

$$5 < \theta_{\gamma^*\gamma} < 45 \text{ mrad}$$
$$-t < 0.7 \text{ GeV}$$
$$0.03 < x_B < 0.35$$
$$1 < Q^2 < 10 \text{ GeV}^2$$
$$W > 3 \text{ GeV}$$
$$\nu < 22 \text{ GeV}$$
$$-(1.5)^2 < M_X^2 < (1.7)^2 \text{ GeV}$$

- *absolute* normalization of data and Monte Carlo [solid line]
- elastic Bethe-Heitler process is main contribution in signal region
- associated Bethe-Heitler process is a small contribution
- *semi-inclusive production* is main background at higher M_X^2
- as recoiling proton not (yet) detected, missing mass cut used instead
- t calculated under assumption of exclusivity, via scattered lepton kinematics

HERMES Data Taking DVCS Statistics (in pb^{-1})

HERA-I (1996-2000)	H	D	^{4}He	N_2	Ne	Kr
BSA/BCA e^-	11	50	-	-	-	-
BSA/BCA e^+	240	320	30	50	86	30
contains LTSA (e^+)	50	170				

HERA-II (2002-2007)	H	TTSA (H)	D	Kr	Xe	$H^{rec.}$	$D^{rec.}$
BSA/BCA e^-	250 ($^{BCA}_{pub}$:10)	85	150	50	50	t.b.d.	t.b.d.
BSA/BCA e^+	820	60	200	55	30	750	200

- Beam polarization $\langle P_{beam}\rangle$: only $\geq$30% for HERA-II (while $\geq$50% for HERA-I !)
- 2006-2007 running will more than double statistics on UNpolarized H target

  (23M $\rightarrow$ 56M DIS events for BSA, huge improvement for BCA)
- No e^- data set, i.e. no BCA *with Recoil detector* due to target cell accident
- Recoil Detector in projected shape since start of e^+ running middle 2006