Exclusive Reactions at HERMES

or

The Spin Budget of the Proton

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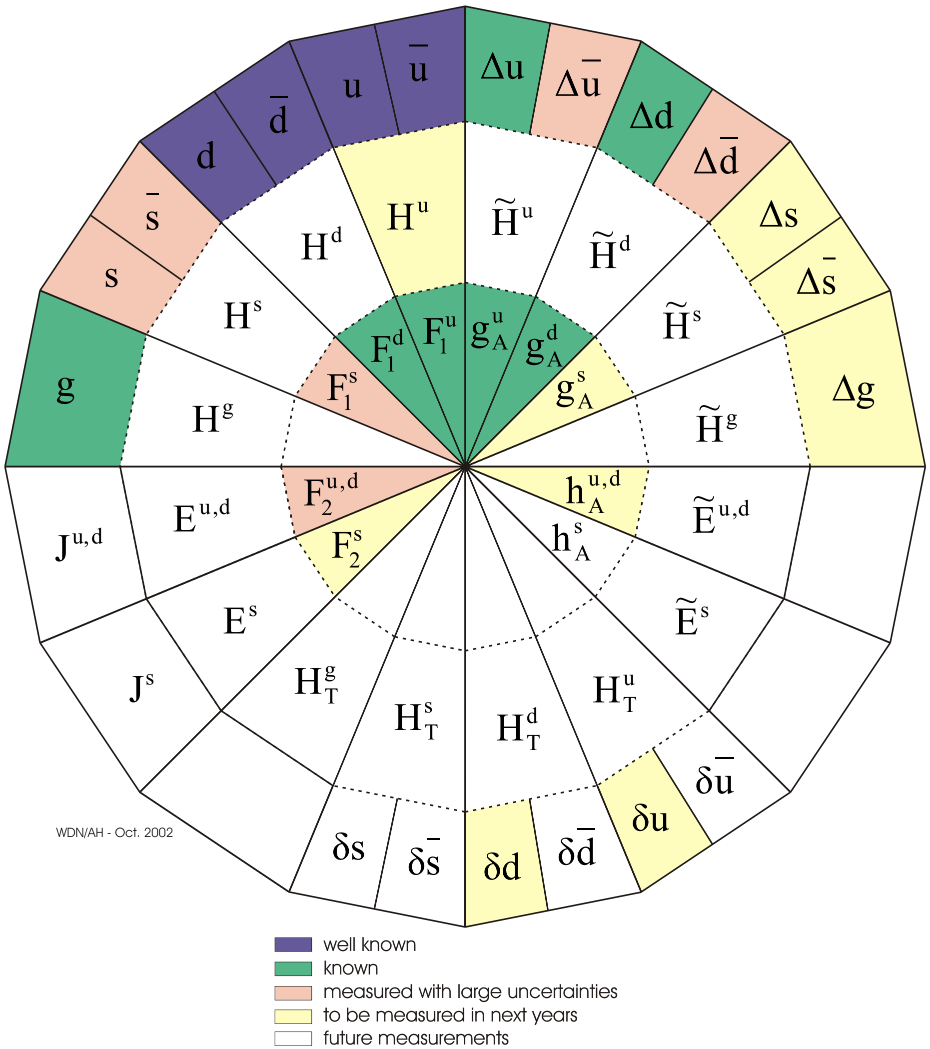
Table of Contents

Exp. Status on Parton Distribution Functions



Improvement over last 6 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
- Generalized Parton Distributions:

  CLAS, HERMES, (H1/ZEUS):

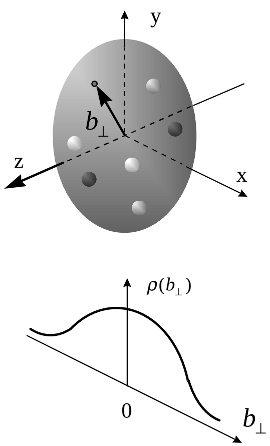
  first look on $H, \tilde{H}, E$

$\Rightarrow$ much more to come ...

3-dimensional Picture of the Proton

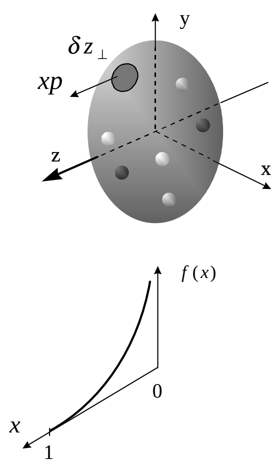
Nucleon momentum in Infinite Momentum Frame: $(p_{\gamma^*} + p_{nucl})_z \rightarrow \infty$

- Form factor



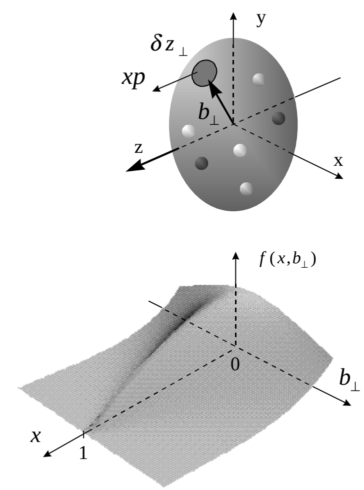
Nucleon's transv. charge distribution given by 2-dim. Fourier transform of **Form Factor**:
$\Rightarrow$ Parton's transverse localization $\mathbf{b}_\perp$

- Parton density



Probability density to find partons of given long. mom. fraction x at resol. scale $1/Q^2$ (no transv. inform.)
$\Rightarrow$ Parton's longitudinal momentum distribution function (**PDF**) f(x)

- Generalized parton distribution at η=0



GPDs probe simultaneously transverse localization $\mathbf{b}_\perp$ for a given longitudinal momentum fraction x

2nd moment by Ji relation:

$$J_{q,g} = \frac{1}{2} \lim_{t\rightarrow 0} \int x \, dx \, [H_{q,g}(x,\xi,t) + E_{q,g}(x,\xi,t)]$$

Proton Spin Budget in a Nutshell

NO unique and gauge-invariant decomposition of the nucleon spin:

(A) ‘GPD-based’: $\frac{1}{2} = J_q + J_g = \frac{1}{2}\Delta\Sigma + L_q + \widehat{\Delta g} + L_g$

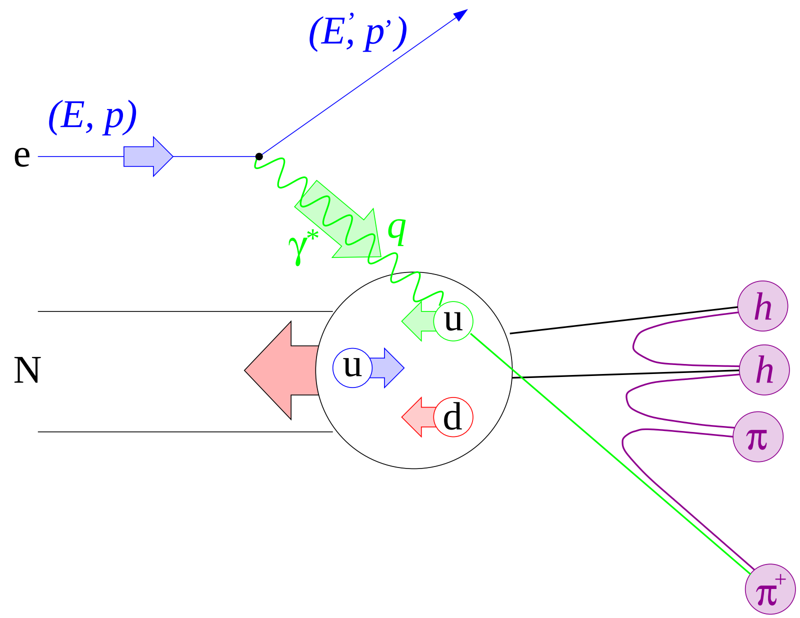
- **Total angular momenta** of quarks (J_q) and gluons (J_g) are gauge-invariant and calculable in lattice gauge theory
- **Intrinsic spin contribution** and **orbital angular momentum** are gauge inv. for quarks ($\frac{1}{2}\Delta\Sigma$ and L_q), but not for gluons ($\widehat{\Delta g}$ and L_g)
- Probabilistic interpretation only for $\frac{1}{2}\Delta\Sigma$ (well measured)
- J_q accessible through exclusive lepton nucleon scattering
- J_g very difficult to access experimentally

(B) Light-cone gauge: $\frac{1}{2} = \mathcal{J}_q + \mathcal{J}_g = \frac{1}{2}\Delta\Sigma + \mathcal{L}_q + \Delta g + \mathcal{L}_g$

- All 4 terms have a probabilistic interpretation
- Δg is gauge invariant (being measured)

$\Rightarrow$ Results from both decompositions must not be mixed, as $\mathcal{L}_q \neq L_q, \Delta g \neq \widehat{\Delta g}, \mathcal{L}_g \neq L_g$, even $\mathcal{J}_g \neq J_g$!

DIS: Kinematics, Cross Sections, Asymmetry



Virtual-photon kinematics:

$$Q^2 = -q^2 \qquad \nu = E - E'$$

Fraction of nucleon momentum carried by struck quark: $x = \frac{Q^2}{2M\nu}$

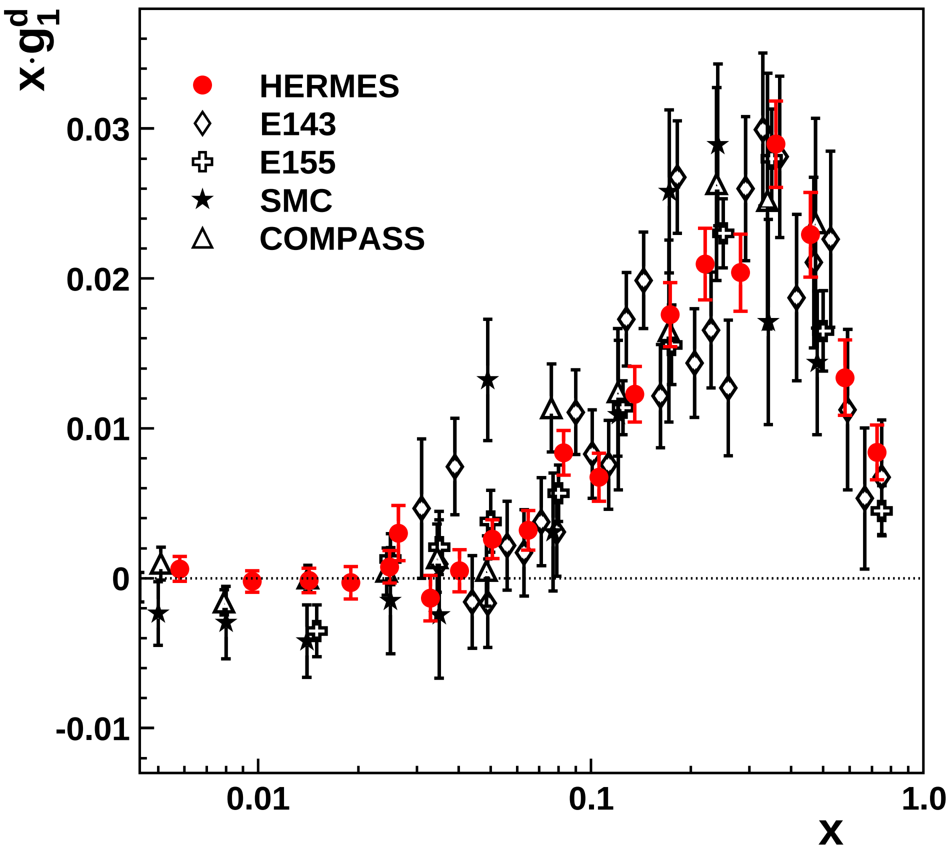
fraction of virtual-photon energy carried by produced hadron h: $z = \frac{E_h}{\nu}$

Hadron transverse momentum: $P_{h\perp}$

- Unpolarized cross section: $\sigma_{UU} \equiv \frac{1}{2}(\sigma^{\stackrel{\rightarrow}{\Leftarrow}} + \sigma^{\stackrel{\rightarrow}{\Rightarrow}})$
- Cross section (helicity) difference: $\sigma_{LL} \equiv \frac{1}{2}(\sigma^{\stackrel{\rightarrow}{\Leftarrow}} - \sigma^{\stackrel{\rightarrow}{\Rightarrow}})$
- Double-spin asymmetry: $A_{||} \equiv \frac{\sigma_{LL}}{\sigma_{UU}} \simeq \frac{g_1}{F_1}$ (neglecting small g_2 contribution)
- Measured asymmetry: $A_{||} = \frac{1}{\langle P_T \rangle \langle P_B \rangle} \frac{(\frac{N}{L})^{\stackrel{\rightarrow}{\Leftarrow}} - (\frac{N}{L})^{\stackrel{\rightarrow}{\Rightarrow}}}{(\frac{N}{L})^{\stackrel{\rightarrow}{\Leftarrow}} + (\frac{N}{L})^{\stackrel{\rightarrow}{\Rightarrow}}}$

Direct determination of quark spin contribution $\Delta\Sigma$

Most precise g_1^d result: Hermes inclusive data [PRD75(2007)012007,hep-ex/0609039]:



Method:

- NNLO leading twist analysis in $\bar{\mathrm{MS}}$ scheme
- assume SU_3 flavor symmetry in hyperon decay
- observe saturation of $\Gamma_1 = \int dx\, g_1^d(x)$ for $x < 0.04$
- assume no significant contribution of small-x region

Data for $Q^2 > 1$ GeV^2: evaluate $\Gamma_1^d(Q^2 = 5\ \mathrm{GeV}^2) = {}_{0.021}\int^{0.9} dx\, g_1^d(x)$

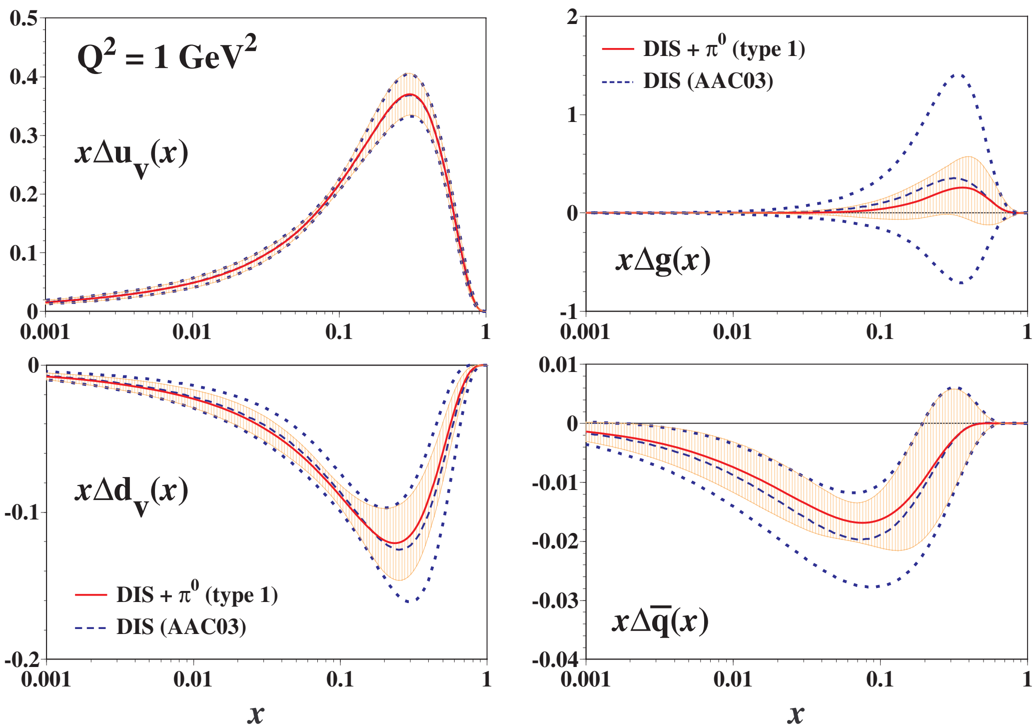
Result at $Q^2 = 5$ GeV^2 (all data points evolved):

$\Delta\Sigma = 0.330 \pm 0.011_{theor.} \pm 0.025_{exp.} \pm 0.028_{evol.}$

where 'exp.' includes stat., syst. and parameterization uncertainties

Next-to-leading Order QCD Fits

Results by AAC [PRD74(2006)014015,hep-ph/0603213]: NLO in α_s, $\overline{MS}$ scheme



Assumptions:

- Flavor-symmetric Δq_{sea}
- Integrals of Δq_u^{val} and Δq_d^{val} fixed by weak decay constants F and D

Input experimental data:

- $A_1^{p,d}$ from COMPASS,JLAB,HERMES
- $A_{LL}^{\pi^0}$ from PHENIX

Results at $Q^2 = 1$ GeV^2:

$\Delta\Sigma = 0.25 \pm 0.10$

$\Delta G = 0.47 \pm 1.08$ (DIS alone)

$\Delta G = 0.31 \pm 0.32$ (DIS+PHENIX)

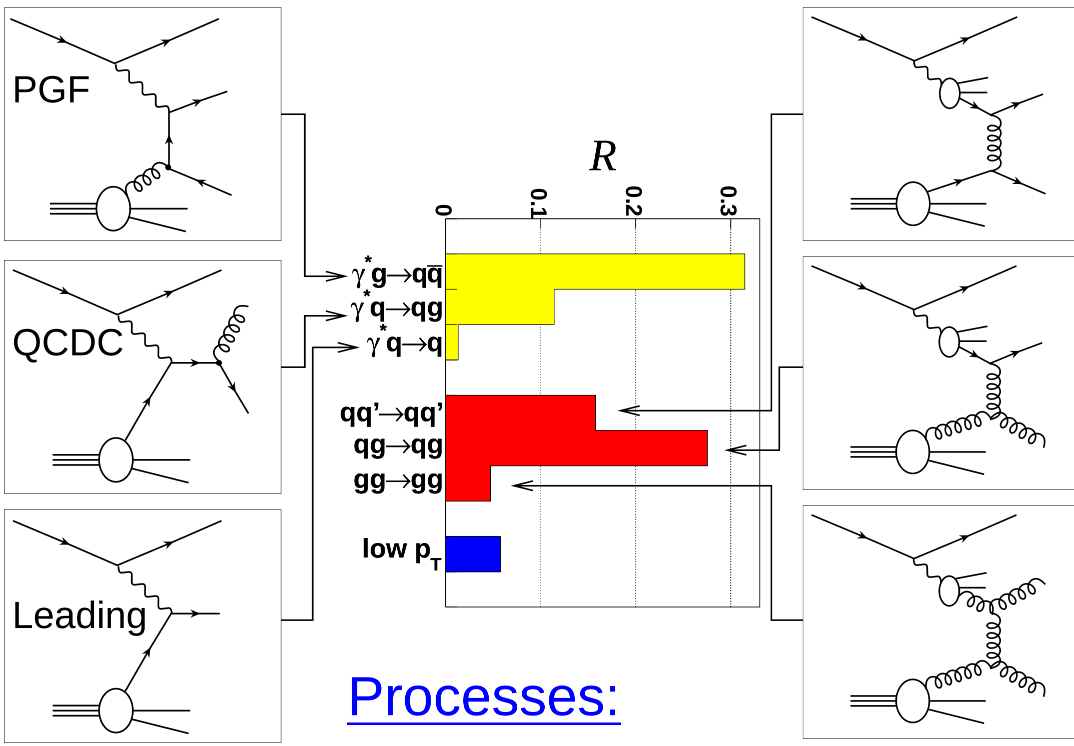
mpact of recent CLAS and COMPASS data [PRD75(2007)074027,hep-ph/0612360]:

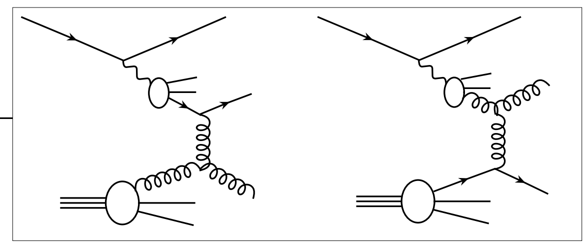
	$\Delta g > 0$	$\Delta g < 0$
$\Delta\Sigma$	0.207 ± 0.040	0.243 ± 0.065
Δs	-0.063 ± 0.005	-0.057 ± 0.010
Δg	0.129 ± 0.166	-0.200 ± 0.414

Determination of Gluon Contribution to Nucleon Spin

- Quasi-real photoprod. of high-p_t hadron pairs or single hadrons: $\langle Q^2 \rangle \approx 0.1$ Ge
- Sensitivity through $\gamma^* g$ 'direct' hard scattering or 'resolved-photon' process

left graphs: direct processes; right graphs: resolved-photon processes [COMPASS analysis]





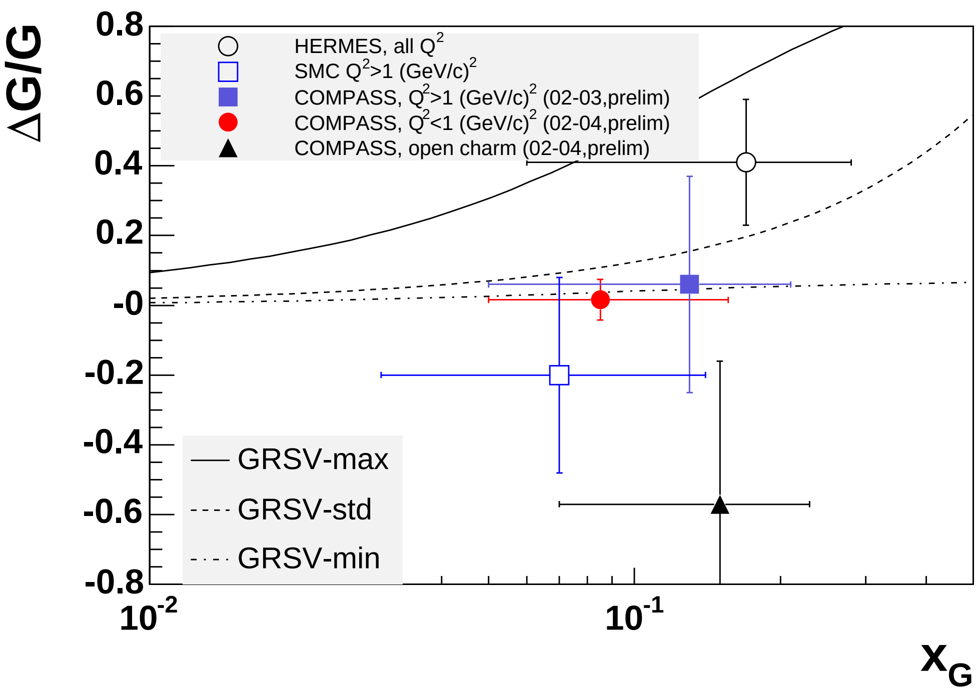
- Extraction heavily relies on PYTHIA simulation (LO only !)
- Hard scale $\mu^2 \simeq 3$ GeV^2 only 'loosely' correlated with x_g ($\langle x_g \rangle \simeq 0.1$)

- COMPASS: Open-charm production ($\gamma^* g \rightarrow c\bar{c}$) and hadron pairs
- HERMES: Single high-p_t hadrons. Pairs in old analysis (all Q^2, $\langle x_g \rangle \simeq 0.17$

  [PRL84 (2000) 2584] $\frac{\Delta g}{g} = 0.41 \pm 0.18_{stat} \pm 0.03_{sys-exp}$ ($\pm$unknown$_{sys-Model}$)
- RHIC: A_{LL} in inclusive direct γ & π^0 production, inclusive jet production

Results on Gluon Helicity Distribution $\frac{\Delta g}{g}(x)$

Most precise results on $\frac{\Delta g}{g}(x)$:



[K.Kurek, DIS06, hep-ex/0607061]

COMPASS high-p_t hadron pairs:

$Q^2 < 1$ GeV^2 ($\langle x \rangle \simeq 0.085$):

$\frac{\Delta g}{g} = 0.016 \pm 0.058_{stat} \pm 0.055_{syst}$

[PLB 612,154 (2005)]

$Q^2 > 1$ GeV^2 ($\langle x_g \rangle \simeq 0.13$) [prel.]:

$\frac{\Delta g}{g} = 0.06 \pm 0.31_{stat} \pm 0.06_{syst}$

Open charm ($\langle x_g \rangle \simeq 0.15$) [prel.]:

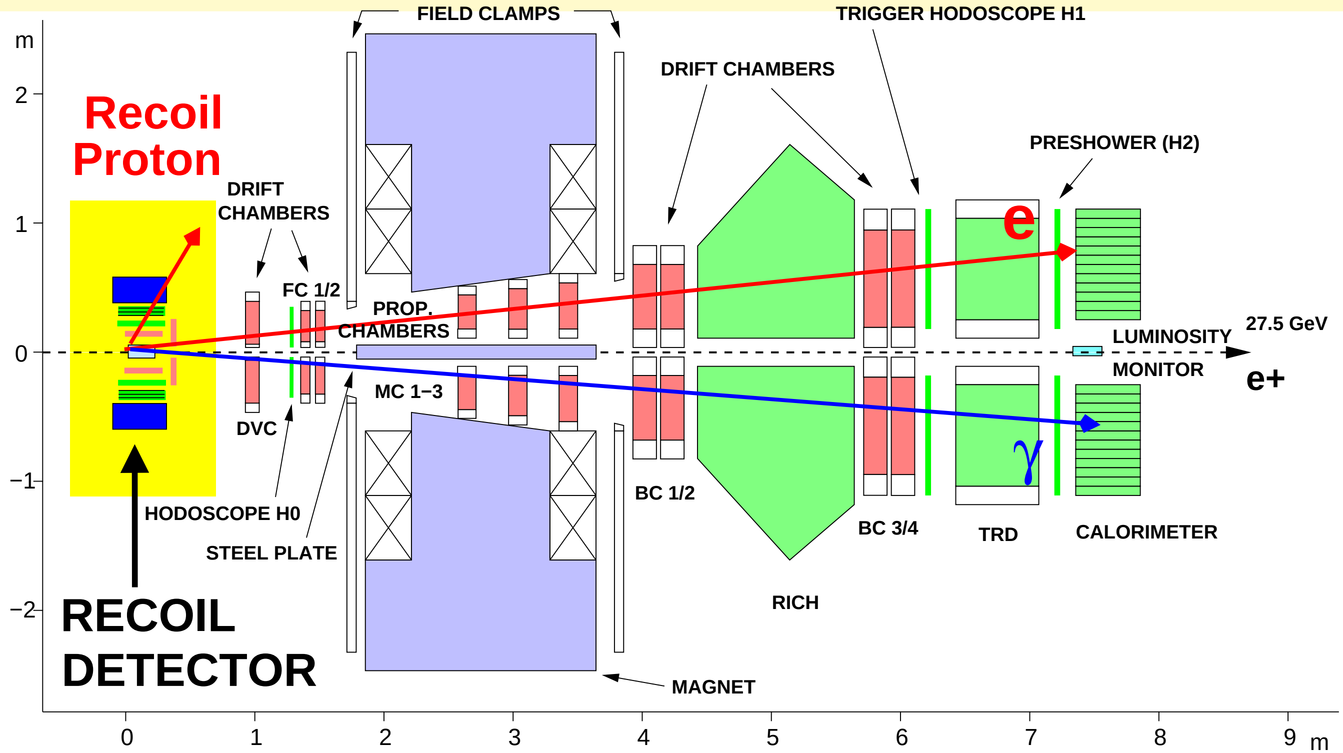
$\frac{\Delta g}{g} = -0.57 \pm 0.31_{stat}$

HERMES high-p_t single hadrons [prel.]:

$Q^2 \simeq 0; (\langle x_g \rangle \simeq 0.22)$: $\frac{\Delta g}{g} = 0.071 \pm 0.034_{stat} \pm 0.010_{sys-exp} \pm^{0.127}_{0.105}\ {}_{sys-Models}$

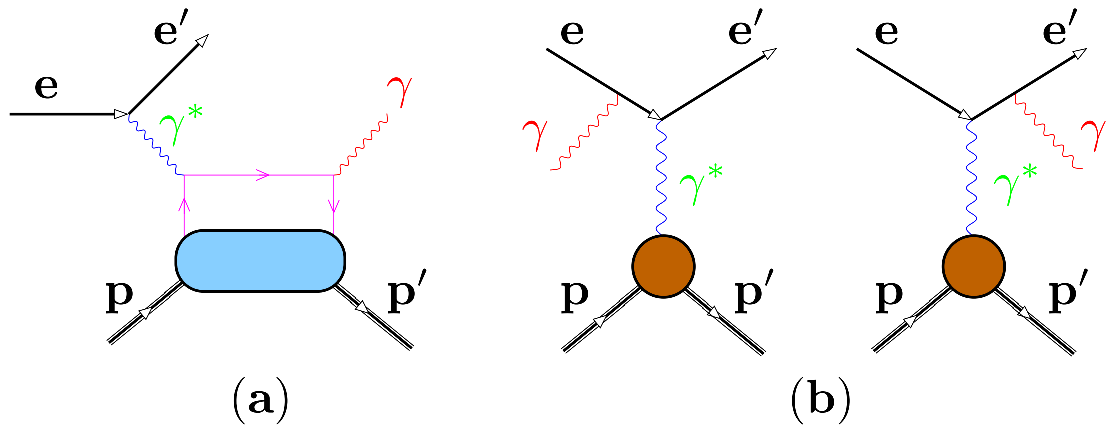
PHENIX: Confidence limits for fits with different $\frac{\Delta g}{g}$ assumptions

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 planes: $\mathcal{O}$(50) per spectrometer half: $\delta p/p \sim 2\%, \delta\Theta \leq 1$ mrad
- PID for $e^{\pm}$: TRD, Preshower, Calorimeter
- PID for $\pi^{\pm}, K^{\pm}, p$: Dual-rad. Ring-imaging Cherenkov ($2 < p < 15$ GeV)
- Recoil particle detection for data $\geq$ 2006

Deeply Virtual Compton Scattering



- Same final state in DVCS and Bethe-Heitler $\Rightarrow$ 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)

$\Rightarrow$ 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]

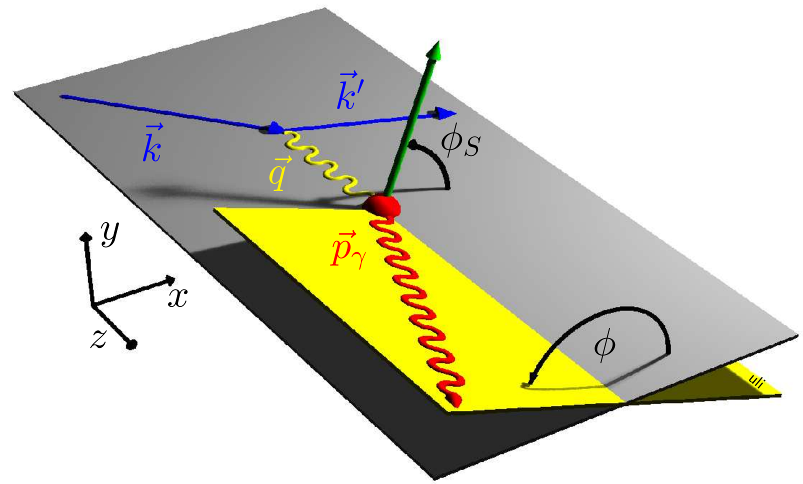
  $d\sigma(e^+,\phi) - d\sigma(e^-,\phi) \propto \mathrm{Re}[F_1\mathcal{H}] \cdot \cos\phi$

- 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 $A_{UL}(\phi)$:

  $d\sigma(\overset{\Leftarrow}{P},\phi) - d\sigma(\overset{\Rightarrow}{P},\phi) \propto \mathrm{Im}[F_1\widetilde{\mathcal{H}}] \cdot \sin\phi$ [L



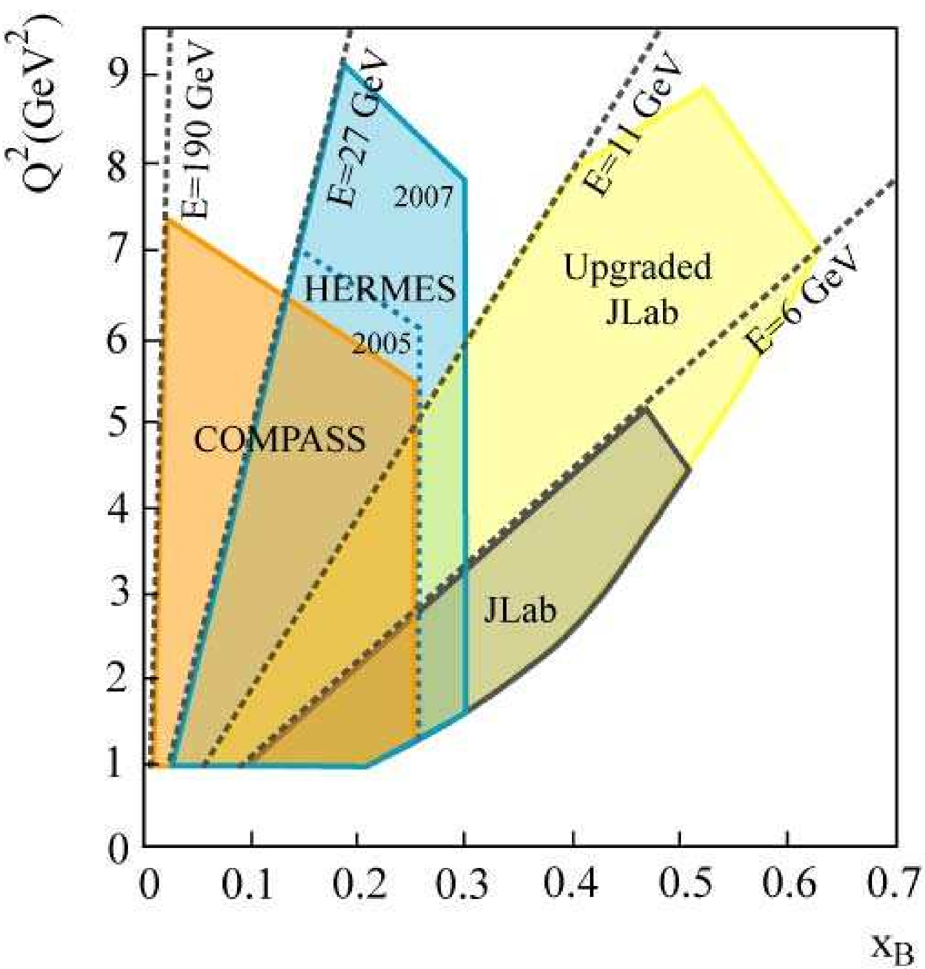
- Transverse target-spin asymmetry $A_{UT}(\phi,\phi_s)$ [TTSA]:

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

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

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:

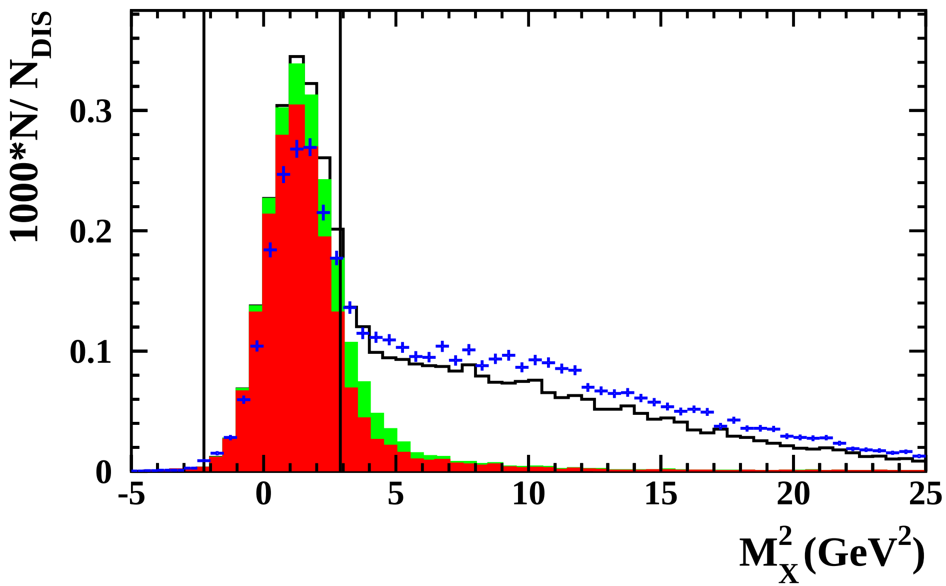
  - small skewness

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

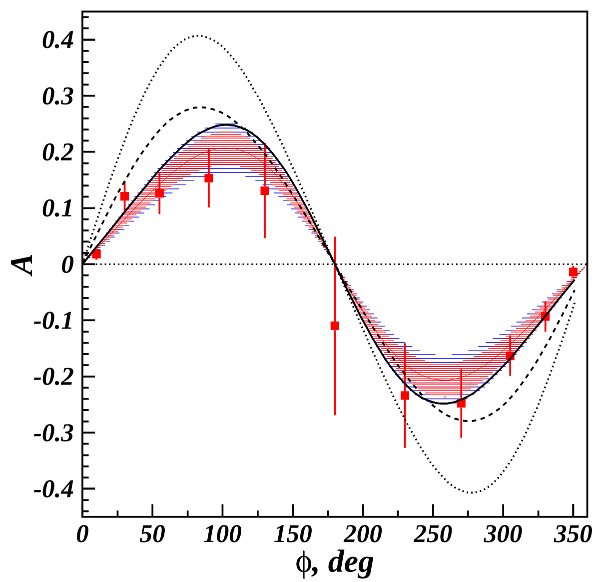
$$5 < \theta_{\gamma^*\gamma} < 45 \text{ mrad}$$
$$-t < 0.7 \text{ GeV}$$
$$0.03 < x_B < 0.35$$
$$1 < Q^2 < 10 \text{ GeV}^2$$
$$W > 3 \text{ GeV}$$
$$\nu < 22 \text{ GeV}$$
$$-(1.5)^2 < M_X^2 < (1.7)^2 \text{ GeV}$$

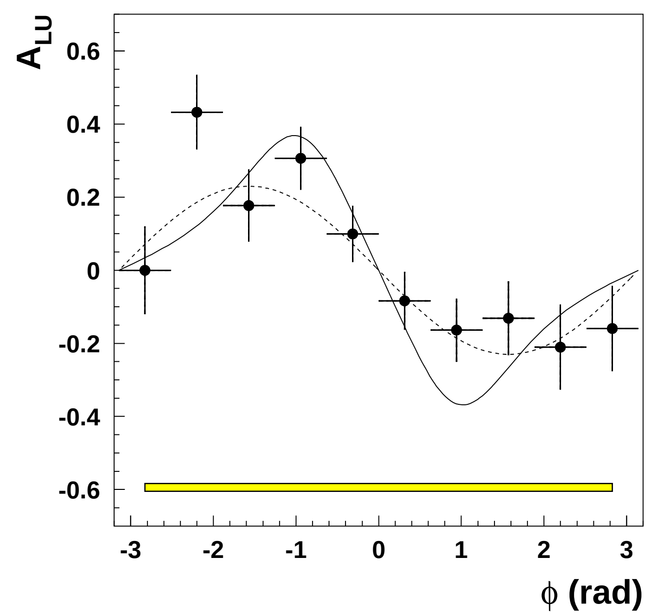
- *absolute* normalization of data and Monte Carlo [solid line]
- elastic Bethe-Heitler process is main contribution in signal region
- associated Bethe-Heitler process is a small contribution
- *semi-inclusive production* is main background at higher M_X^2
- as recoiling proton not (yet) detected, missing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

CLAS+HERMES: 1^{st} Beam-spin Asymmetries

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

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





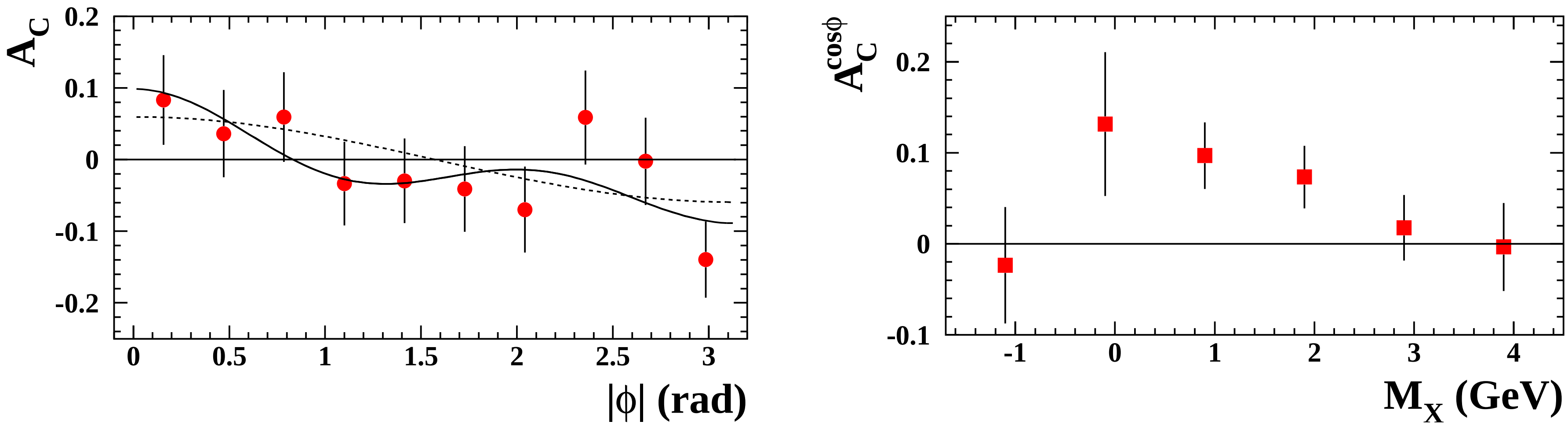
- HERMES: 27.5 GeV p, $P_B \approx 55\%$. No recoil prot. detect. [PRL87(2001,182001]
- CLAS: 4.25 GeV p, $P_B \approx 70\%$. No prod. gamma detect. [PRL87(2001,182002]
- expected $\sin\phi$ behaviour: significant $\sin\phi$ amplitudes on both targets
- other harmonics don't contribute significantly

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

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

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

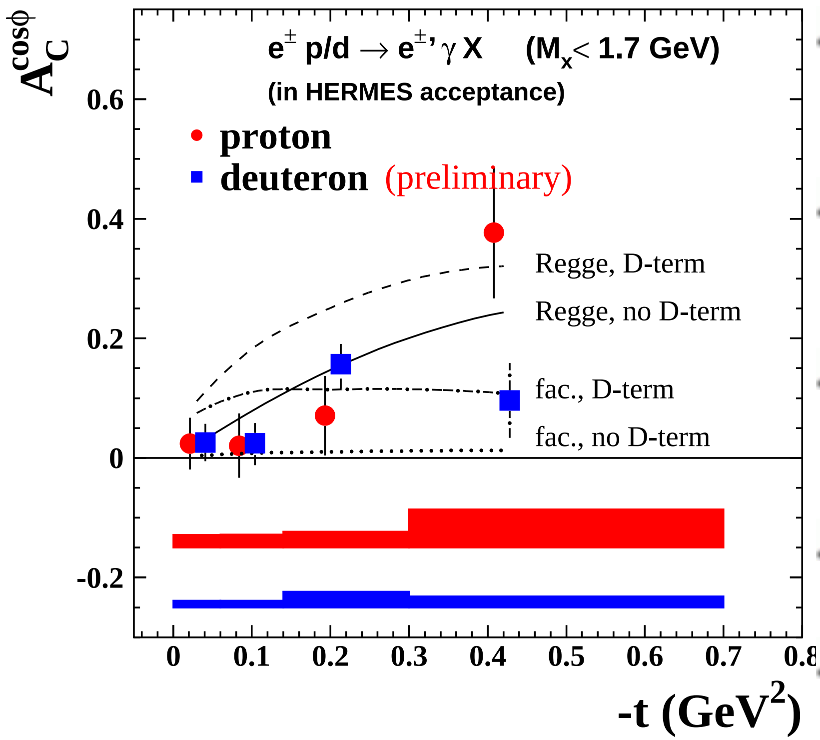
$$A_C(\phi) = const. + A_C^{\cos\phi} \cos\phi + A_C^{\cos 2\phi} \cos 2\phi + A_C^{\cos 3\phi} \cos 3\phi$$



- publ. results for *un*polarized proton target **[hep-ex/0605108, PRD75(2007)011103(R)]**
- use *symmetrization* ($\phi \to |\phi|$) 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 ($\to$ 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
  ⇒ highest t-bin mostly affected
- GPD H dominates, $\tilde{H}$ and E suppr.
  [Goeke,Polyakov,Vanderh.,PPNP 47(2001)401]
- Curves (code [Vanderh.,Guichon,Guidal]) calculated for 4 different param. sets
- BCA insensitive to profile fct. param.'s
- Only HERMES can measure BCA!

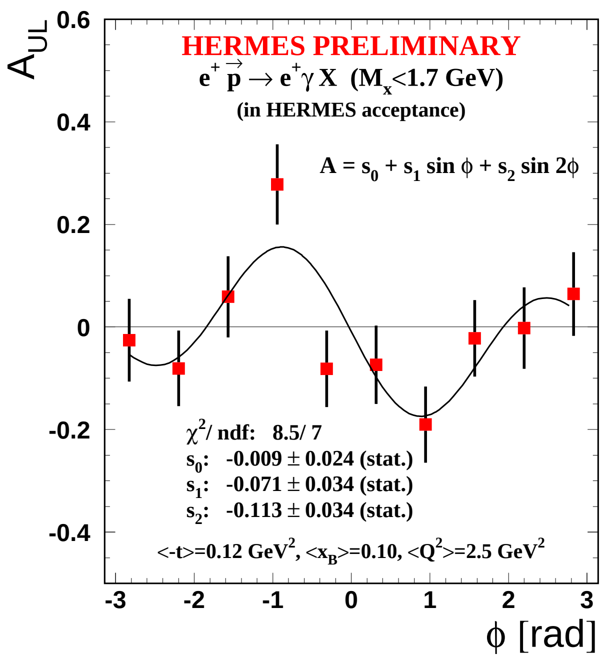
- shown here: HERA-I (1996-1998) data disfavor Regge-inspired t-dependence with D-term [PRD75(2007)011103(R)]
- more precise HERA-II BCA results from 'combined analysis' with TTSA
- For all DVCS data: reduction of background & associated contribution in recoil detector data (2006+07)

HERMES Long. Target-spin Asymmetry vs. ϕ

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

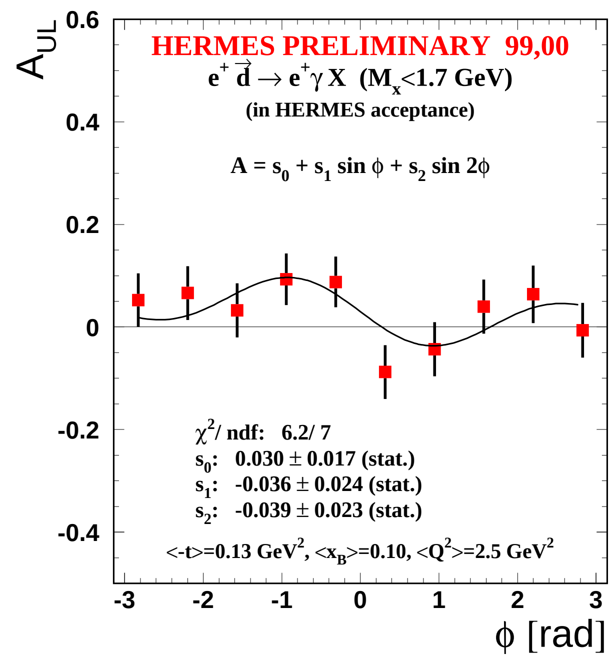
$\Rightarrow$ extract ‘azimuthal asymmetry amplitudes’ by fitting per ϕ-bin:

$$A_{UL}(\phi) = c + A_{UL}^{\sin\phi} \sin\phi + A_{UL}^{\sin 2\phi} \sin 2\phi$$



$\Leftarrow$ proton

deuteron $\Rightarrow$



- FULL existing data set analyzed (1996-2000 data)
- s_1 : expected $\sin\phi$ behaviour : 2σ (1.5σ) on p (d)
- s_2 : unexpected, sizeable ($> 3\sigma$) $A_{UL}^{\sin 2\phi}$ on p (1.7σ on d) $\Rightarrow$ twist-3 ?
- final analysis tuning and paper in progress

Why TTSA Data Expected to be Sensitive to J_q ?

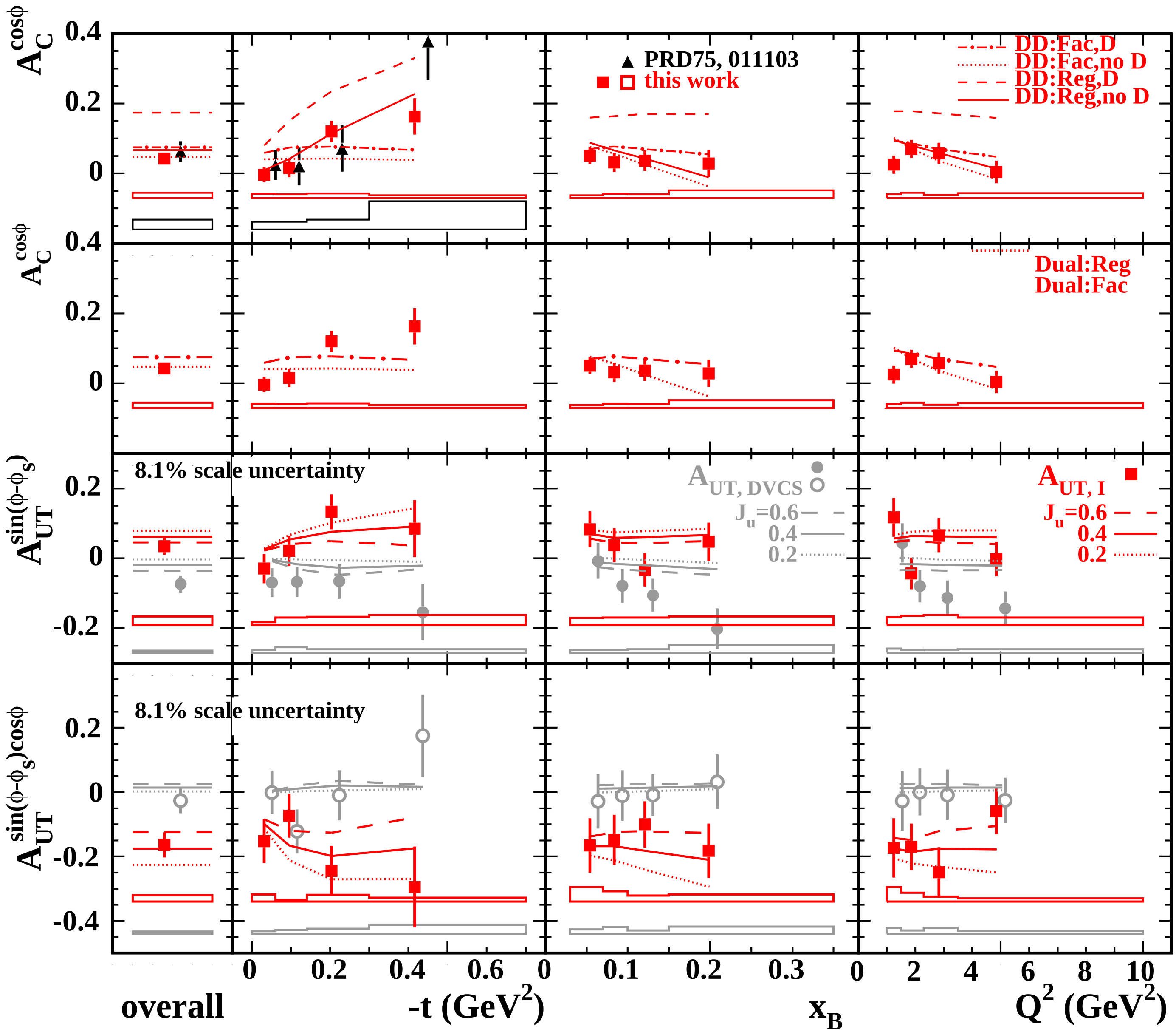
$$A_{UT}(\phi,\phi_S) \propto \mathrm{Im}[F_2\mathcal{H} - F_1\mathcal{E}]\sin(\phi-\phi_S)\cos\phi + \mathrm{Im}[F_2\widetilde{\mathcal{H}} - F_1\xi\widetilde{\mathcal{E}}]\cos(\phi-\phi_S)\sin\phi$$

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

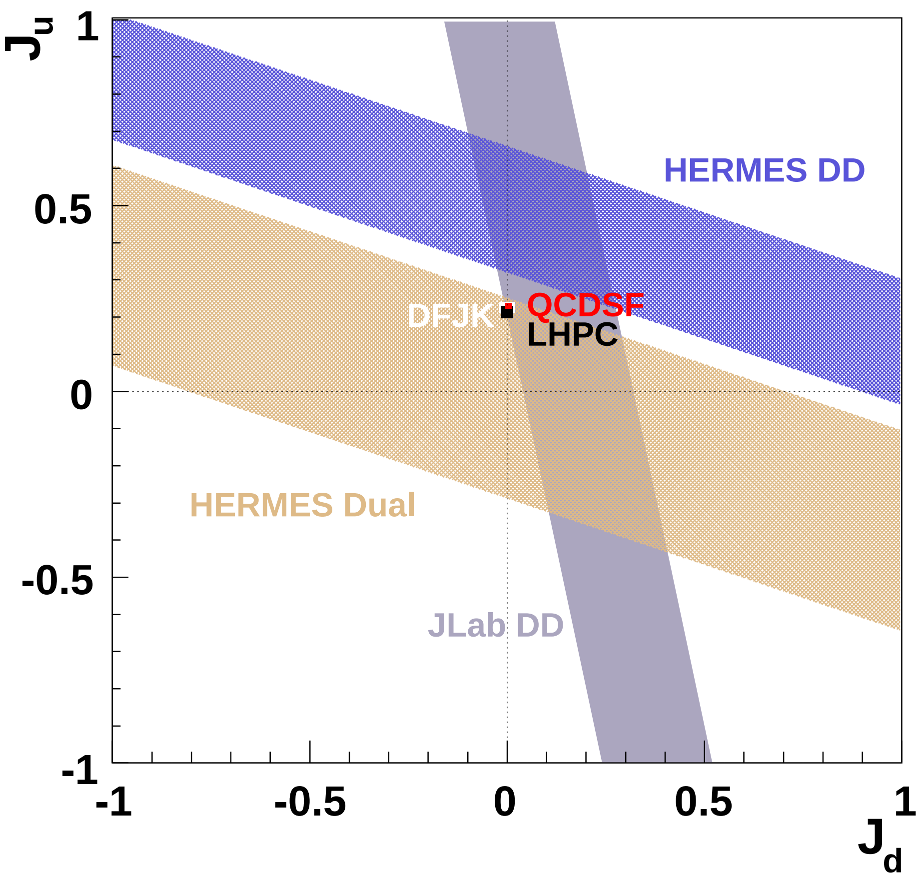
- Factorized ansatz for spin-flip quark GPDs: $E_q(x,\xi,t) = \frac{E_q(x,\xi)}{(1-t/0.71)^2}$
- t-indep. part via double distr. ansatz: $E_q(x,\xi) = E_q^{DD}(x,\xi) - \theta(\xi - |x|)D_q\left(\frac{x}{\xi}\right)$
- using double distr. K_q: $E_q^{DD}(x,\xi) = \int_{-1}^{1} d\beta \int_{-1+|\beta|}^{1-|\beta|} d\alpha\ \delta(x-\beta-\alpha\xi)\ K_q(\beta,\alpha)$
- 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**
- Sensitivity to J_u (with $J_d = 0$) studied [EPJ C46, 729 (2006), hep-ph/0506264]

HERMES: First Measurement of TTSA

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



Model-dependent constraints on J_u vs J_d



HERMES analysis method:

Unbinned maximum likelihood fit to all possible azimuthal asymmetry amplitudes at average kinematics:
⇒ 'combined fit' of HERMES BCA and TTSA data against various model calculations, leaving J_u and J_d as free parameters ⇒ model-dep. 1-σ constraints on J_u vs. J_d:

- Double-distribution model: $J_u + J_d/2.8 = 0.49 \pm 0.17(\mathrm{exp_{tot}})$
  [Vanderhaghen,Guichon,Guidal]
- Dual model [Guzey, Teckentrup]: $J_u + J_d/2.8 = -0.02 \pm 0.27(\mathrm{exp_{tot}})$
- Lattice gauge theory: QCDSF [Göckeler et al.], LHPC [Hägler et al.]
- DFJK model: zero-skewness GPDs extracted from nuclear form factor data using valence-quark contributions only [Diehl et al.])

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. Constraints on GPD models were obtained, in particular (model-dependent) constraints on the u and d-quark total angular momenta. Presently the quality of the data is higher than that of the available models !

- ▷ 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. At CERN, COMPASS prepares a proposal to measure DVCS with both beam charges after2012. 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.