HERMES Results and Projections on Exclusive Photon and Meson Production

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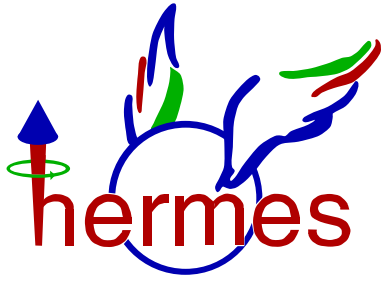
For the  Collaboration

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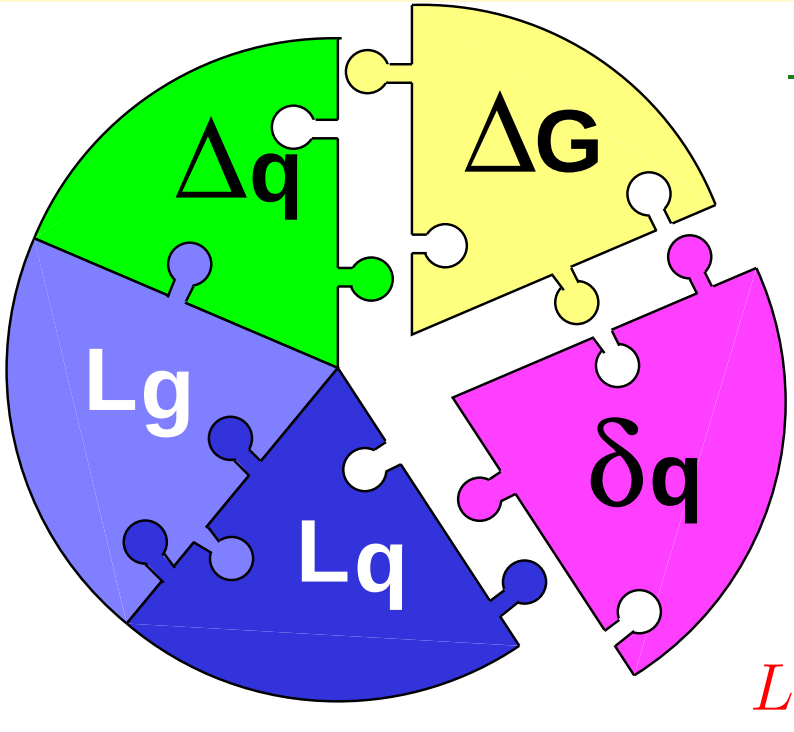
Angular Momentum Structure of the Nucleon



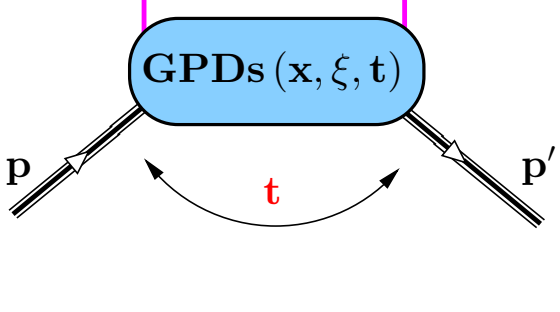
Proton Spin

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

Δq: known from DIS & SIDIS

ΔG: first indications from DIS and pp

L_q, L_g: unknown!



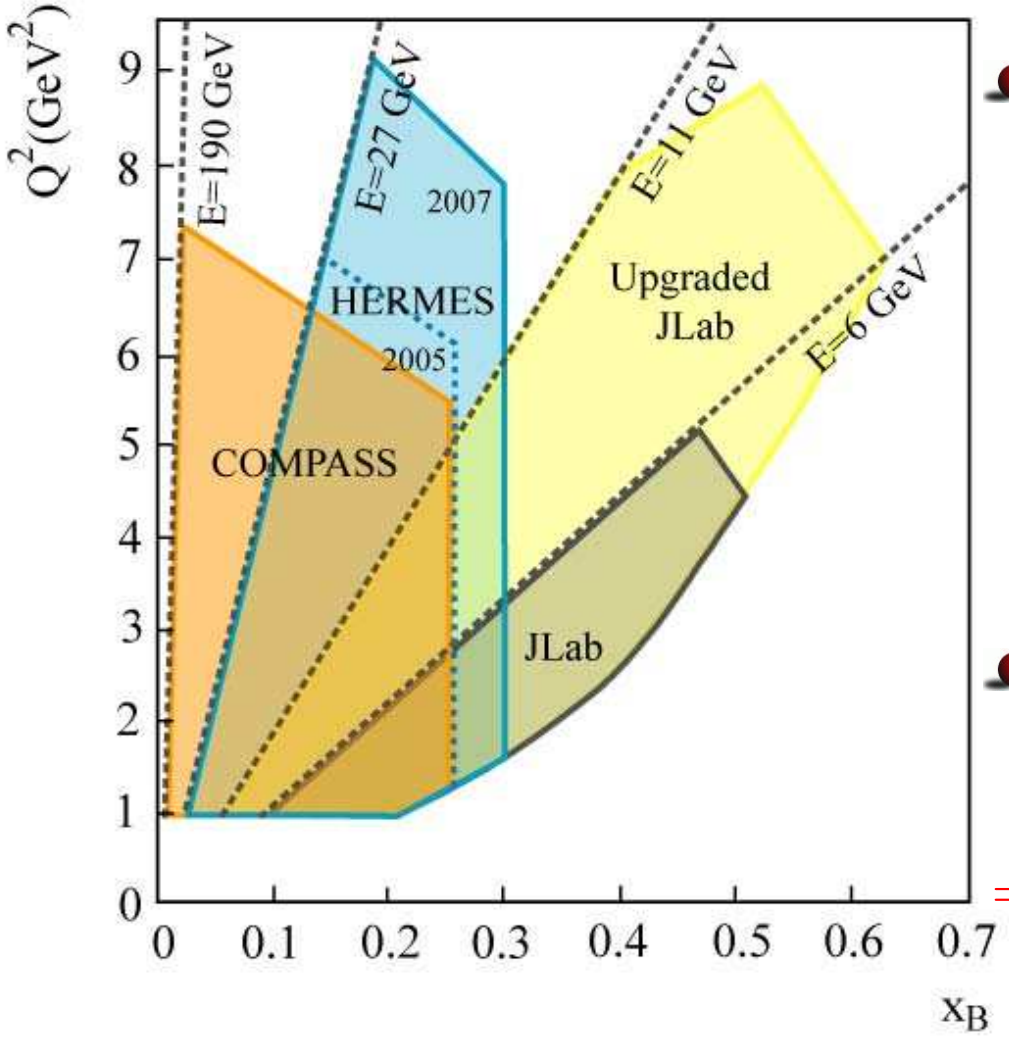
Generalized Parton Distributions $\Rightarrow$ J_q, J_g

Ji's relation — Ji, PRL 78 (1997) 610

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

Kinematic Coverage of DVCS Experiments

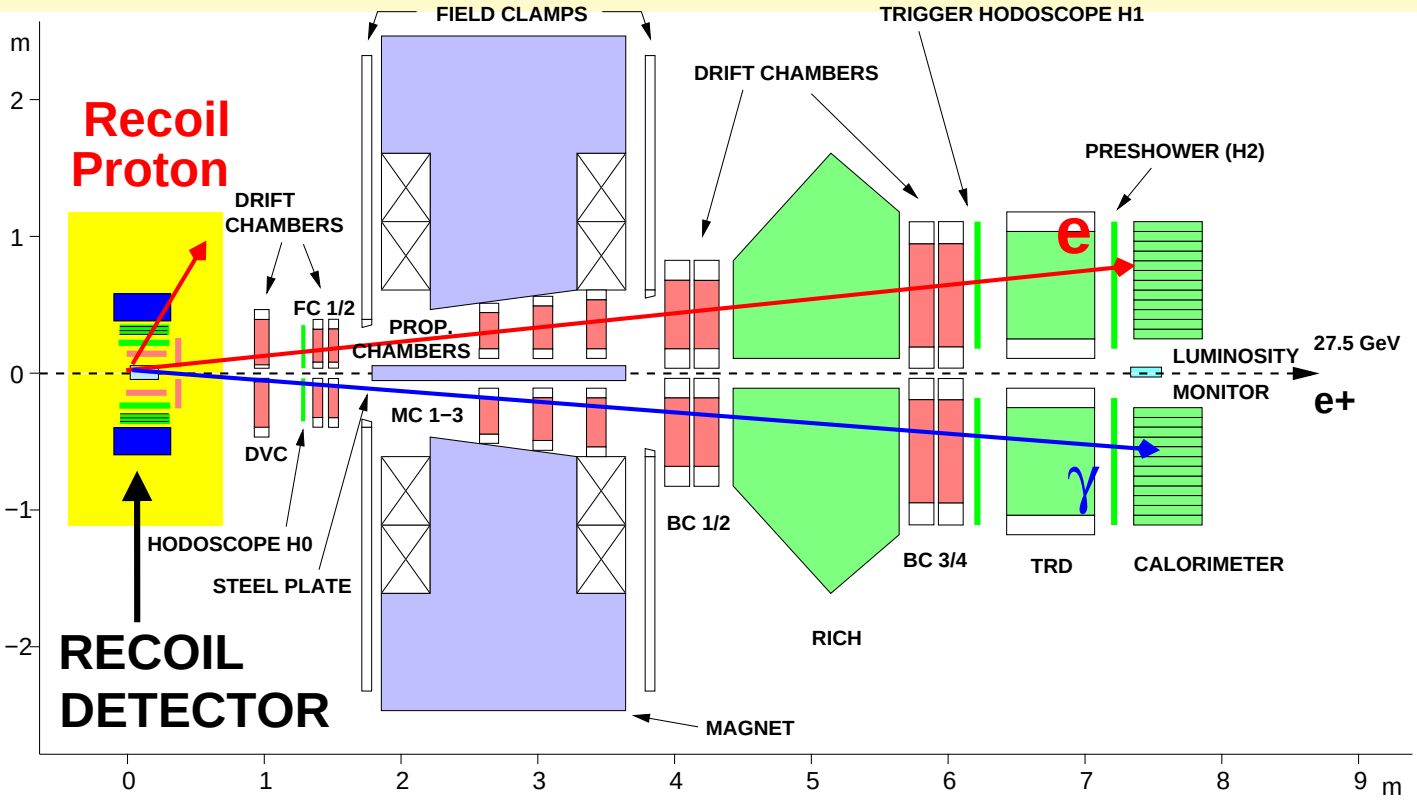
Fixed-target experiments



- Fixed-target experiments:
  $x > 0.03$, $Q^2 < 10$ GeV^2
  - COMPASS: low+medium x
  - HERMES: medium x, higher Q^2
  - JLab: medium+large x, lower Q^2
  - JLab 11 GeV: larger x, higher Q^2
- Collider experiments H1+ZEUS:
  $x < 0.01$, Q^2 : 5...100 GeV^2

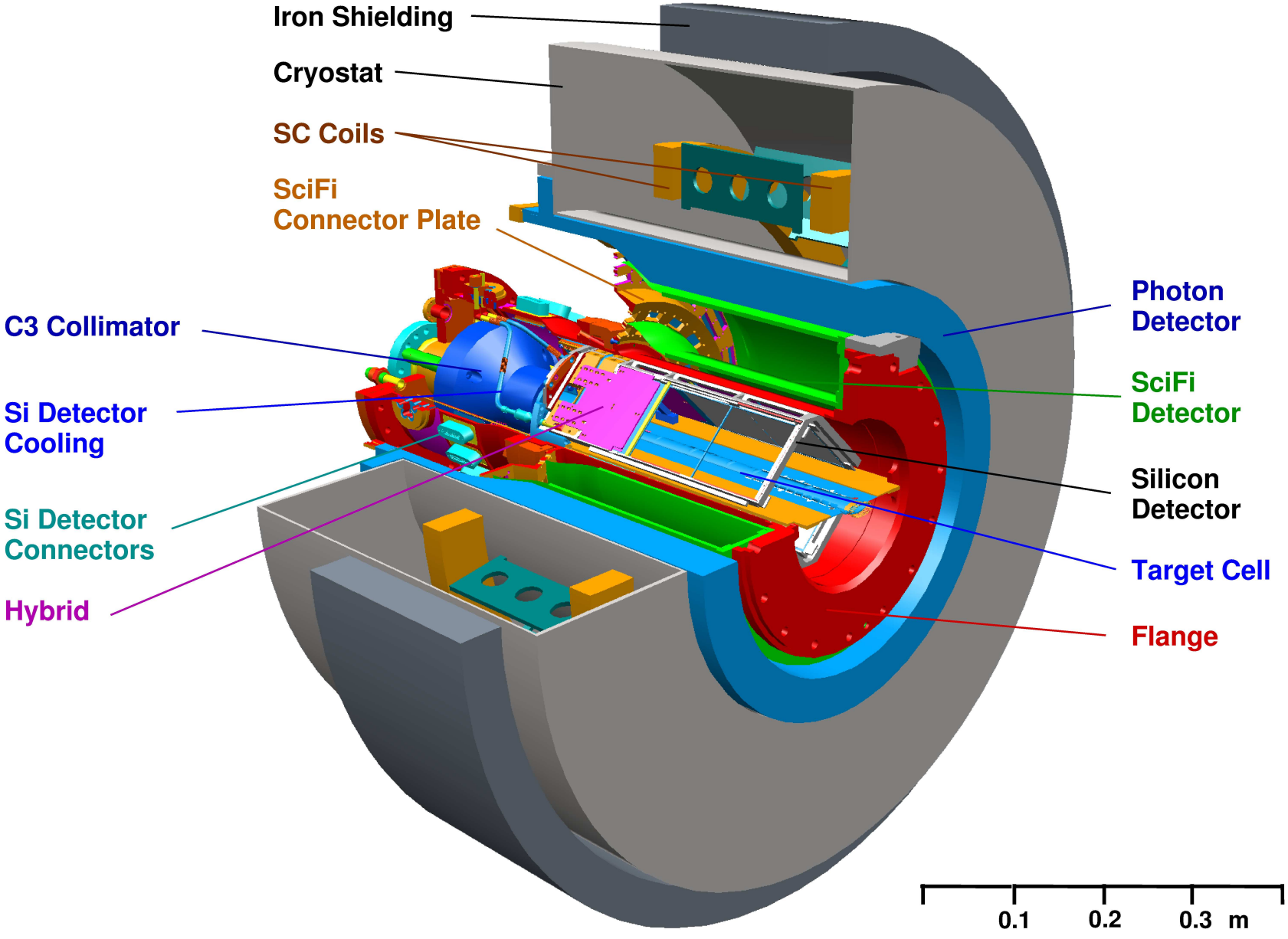
$\Rightarrow$ almost no overlap

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: $\delta p/p \sim 2\%, \delta\Theta \leq 1$ mr
- PID for $e^{\pm}$: TRD, Preshower, Calorimeter
- PID for $\pi^{\pm}, K^{\pm}, p$: Dual-radiator Ring-imaging Cherenkov ($2 < p < 15$ GeV)

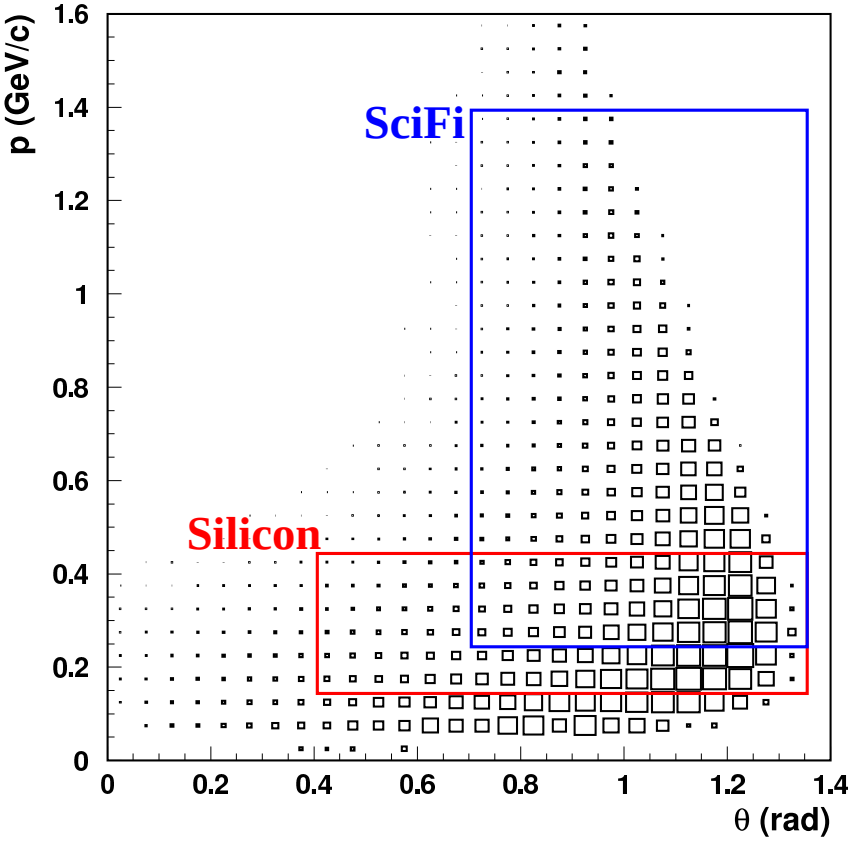
New Recoil Detector at HERMES



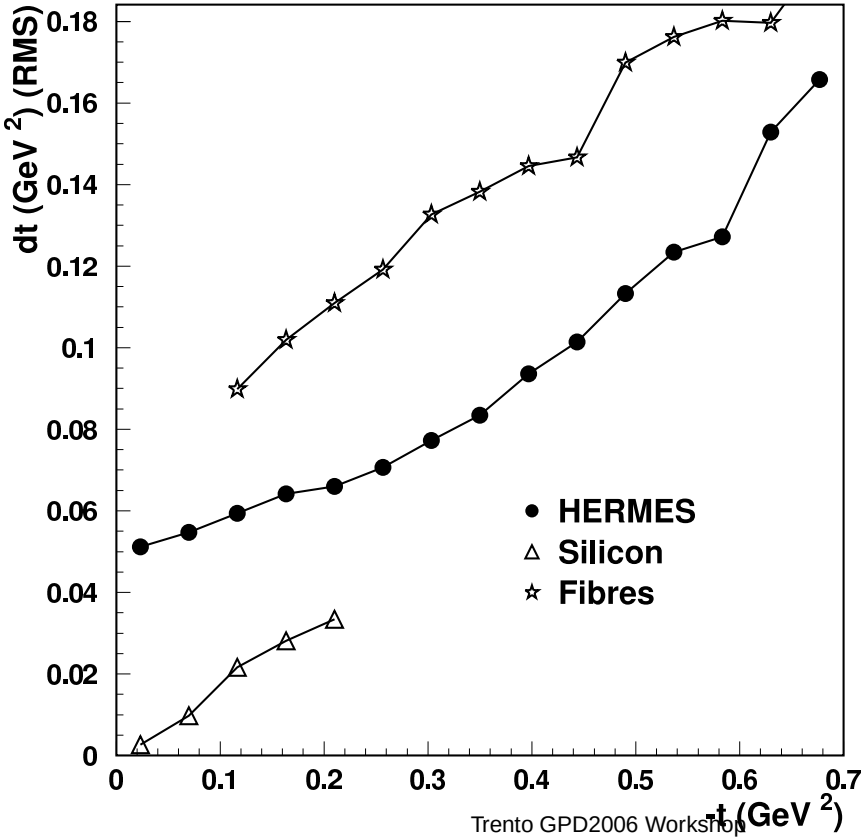
HERMES Recoil Detector Goals I

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

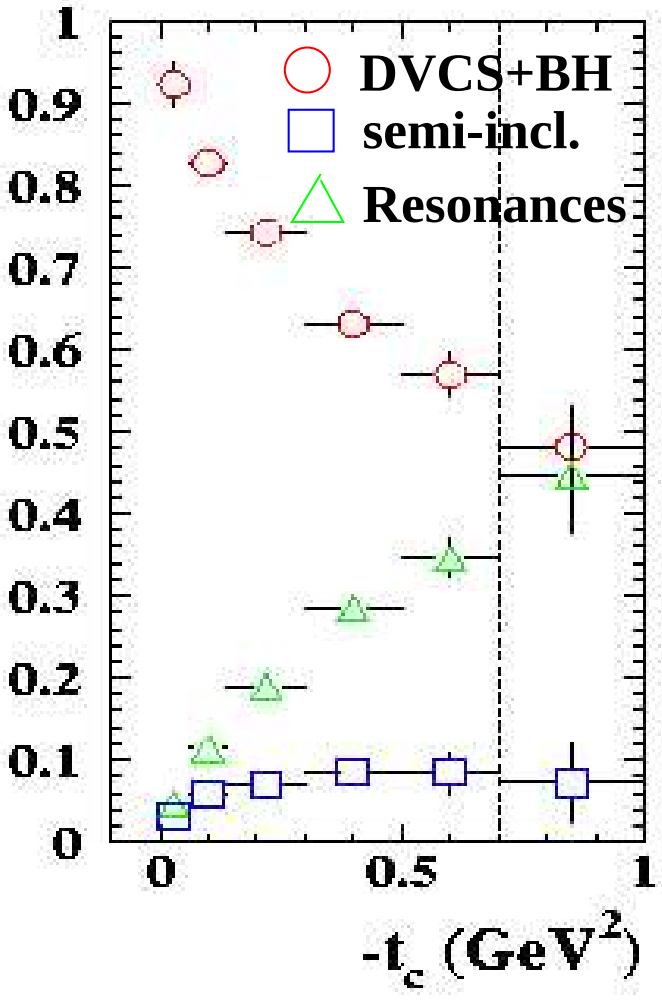
- Recoil protons (76% azim. acceptance, $135 < p < 1200$ MeV/c)
- Pions and protons from background processes (p/π PID via $\frac{dE}{dx}$)
- Photons from $\pi^0 \rightarrow \gamma\gamma$



Resolution from Monte Carlo studies:

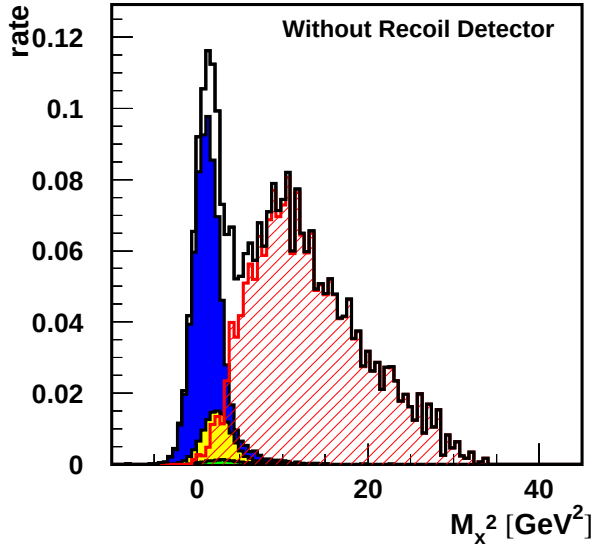


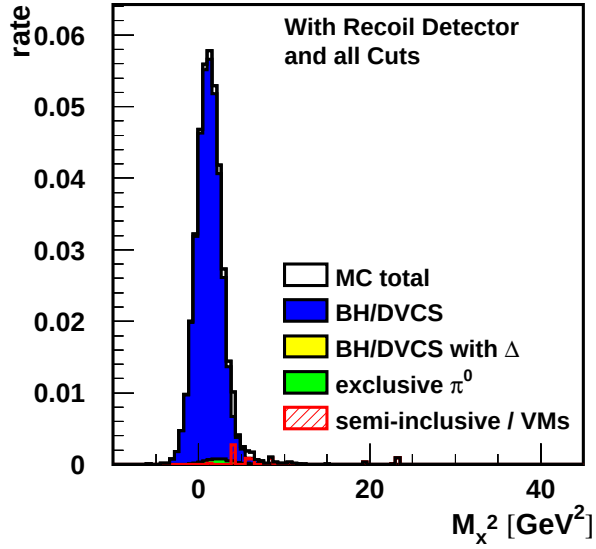
HERMES Recoil Detector Goals II & Status



(Performance improvements shown for DVCS)

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





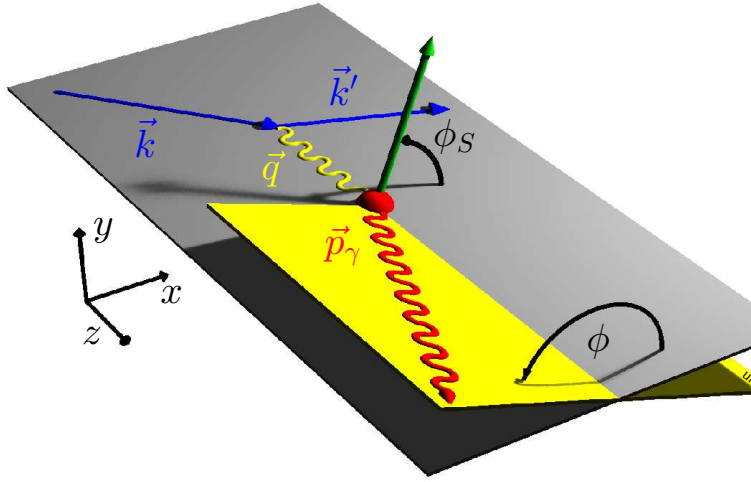
Status:

- Commissioning delayed (target cell damaged by beam)
- Silicon detector electronics damaged ($\Rightarrow$ repair under way)

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]
  $d\sigma(\overrightarrow{e},\phi) - d\sigma(\overleftarrow{e},\phi) \propto \mathrm{Im}[F_1\mathcal{H}] \cdot \sin\phi$

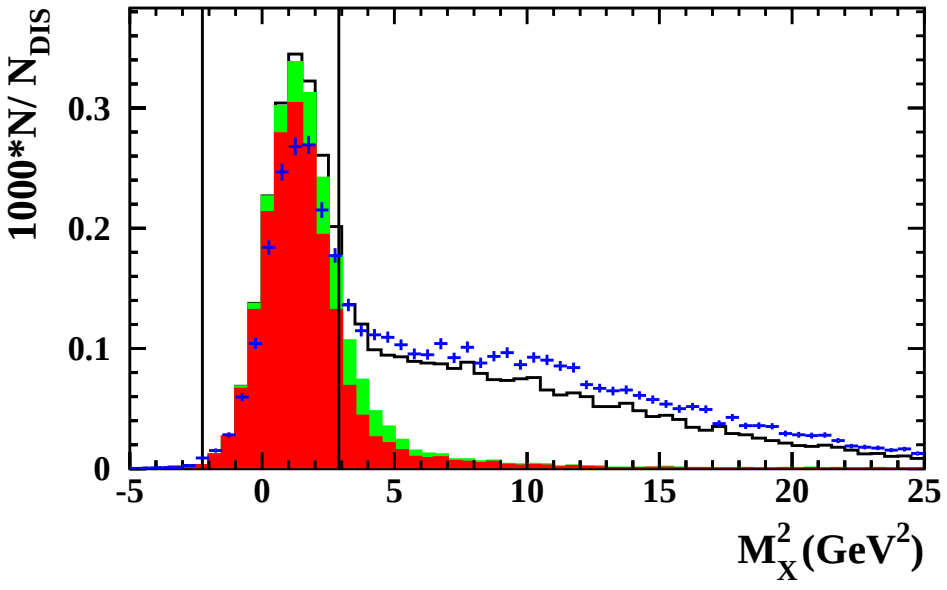
- Long. target-spin asymmetry $A_{UL}(\phi)$
  $d\sigma(\overleftrightarrow{P},\phi) - d\sigma(\overrightarrow{P},\phi) \propto \mathrm{Im}[F_1\widetilde{\mathcal{H}}] \cdot \sin\phi$ [LTSA]

- 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)

Exclusive DVCS Events at HERMES



$$\begin{array}{rcl} \text{REACTION}: & e+p(d) & \rightarrow e+\gamma\,(+X) \\ 5< & \theta_{\gamma^*\gamma} & <45\ \text{mrad} \\ & -t & <0.7\ \text{GeV} \\ 0.03< & x_B & <0.35 \\ 1< & Q^2 & <10\ \text{GeV}^2 \\ & W & >3\ \text{GeV} \\ & \nu & <22\ \text{GeV} \\ -(1.5)^2< & M_X^2 & <(1.7)^2\ \text{GeV} \end{array}$$

- *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 kinematic

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^{re}
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

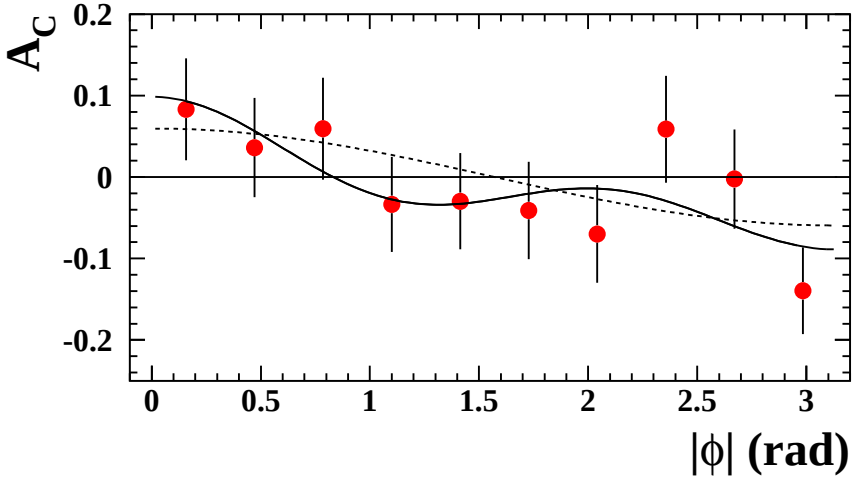
  (23M $\rightarrow$ 56M DIS events for BSA, huge improvement for BCA)
- target cell accident has most impact on BCA measurement (e^- data set)
- Recoil Detector expected to be in projected shape for e^+ running middle 2006

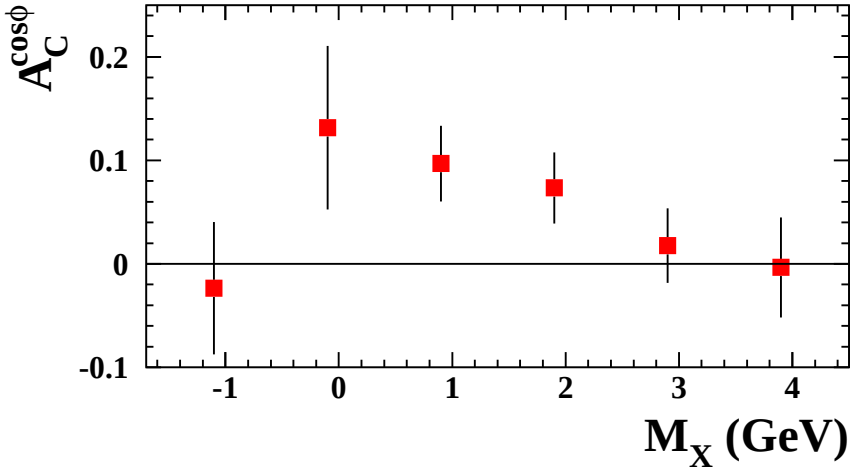
Beam-charge Asymmetry vs. ϕ and M_X^2

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

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

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

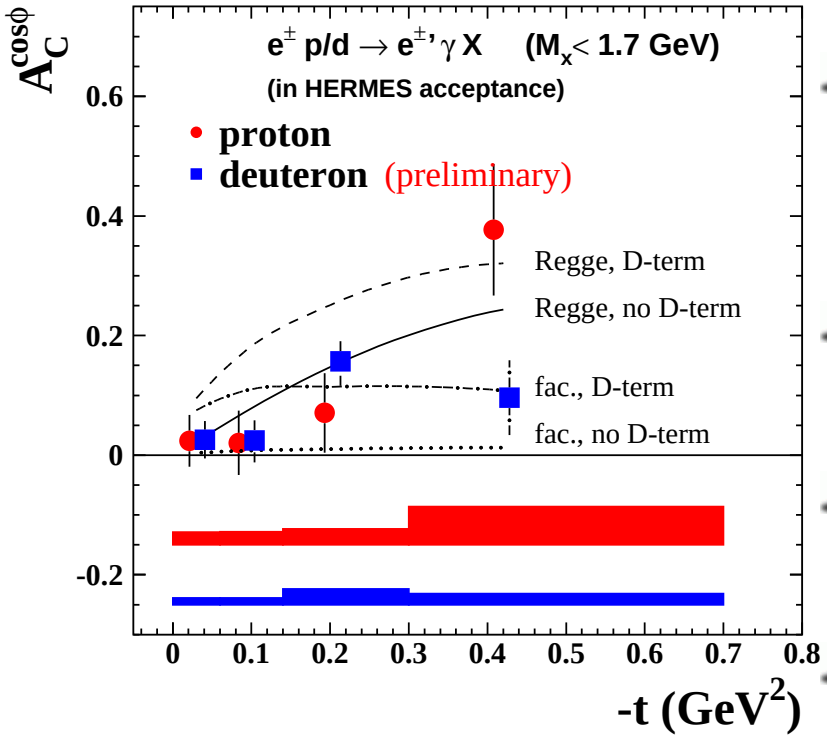




- published results shown for *un*polarized proton target **[hep-ex/0605108, subm. to PRL]**
- use *symmetrization* ($\phi \to |\phi|$) to get rid of sinusoidal terms
- $A_C^{\cos\phi} = 0.060 \pm 0.027$, other contributions insignificant (dashed = pure $\cos\phi$)
- asymmetry only in exclusive and 'associate'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

Beam-charge Asymmetry vs. t

BCA t-dependence can distinguish different GPD model versions:



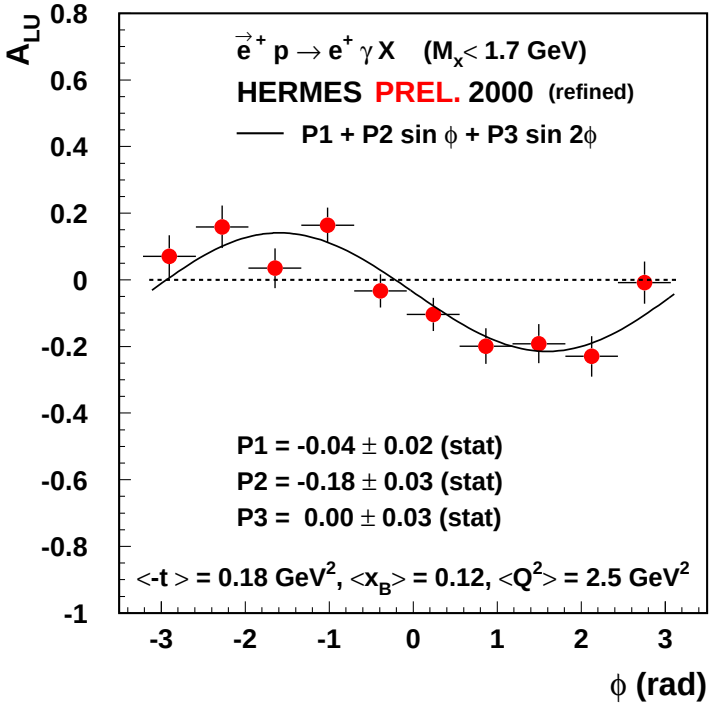
- $A_C^{\cos\phi}$: elastic + associated production
- d-data: contributions per t-bin of associated production: 5,11,18,29%
  $\Rightarrow$ highest t-bin mostly affected
- GPD H dominates, $\tilde{H}$ and E suppressed
  [Goeke,Polyakov,Vanderhaeghen,PPNP 47(2001)401]
- Curves (code [Vanderhaeghen,Guichon,Guidal])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

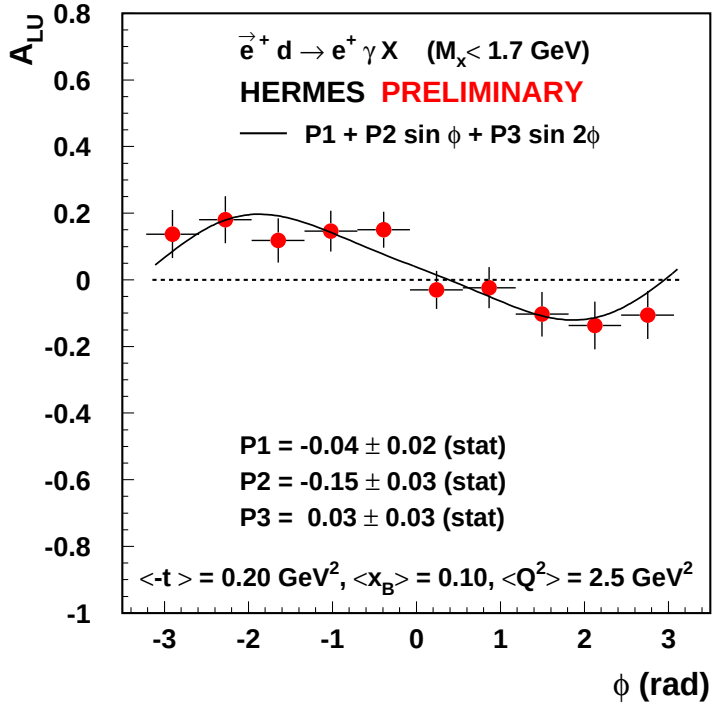
- already HERA-I data disfavor Regge-inspired t-dependence with D-term
- much more precise BCA data from HERA-II (to be analyzed)
- reduction of background & associated contribution by recoil detector expected for e^+ sample, but still t.b.d. for e^- sample

Beam-spin Asymmetry vs. ϕ

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

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

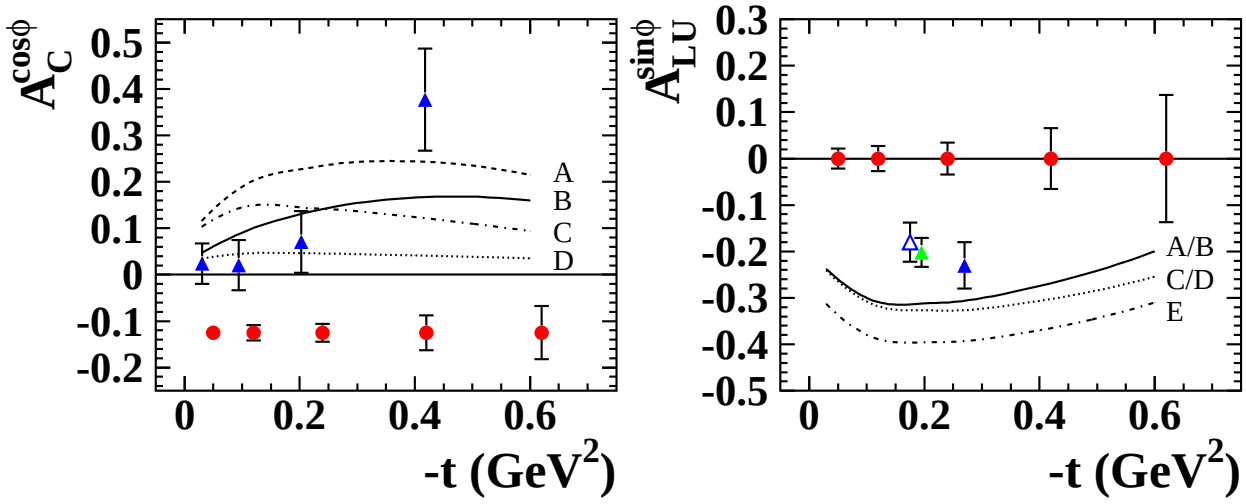




- 1996-2000 proton and deuteron data analyzed ($P_B \approx 55\%$)
- expected $\sin\phi$ behaviour: significant $\sin\phi$ amplitudes on both targets
- other harmonics don't contribute significantly

BSA and BCA 1996-2007 Projections

HERMES hep-ex/0605108 ▲ HERMES hep-ex/0212019



PROTON TARGET:

△ HERMES PRL 2001

▲ CLAS PRL 2001

● HERMES 1996-2007

- 1996-2000: $P_B \approx 55\%$, 2002-2007: $P_B \approx 35\%$
- existing GPD model versions well distinguishable via t-dependence
- statistics marginal for 2-dimensional dependences
- reduced fraction of associated production by including Recoil Detector, but:
  - statistics lower by about factor 1.4 (efficiency)
  - ok for BSA, but t.b.d. for BCA (see above)

  $\Rightarrow$ model comparison possible over *full* measured t-range (at least for BSA)

DVCS on Nuclear Targets

INCOHERENT PRODUCTION:

- nucleus breaks up & scattering occurs on single nucleon
- neutron e.m. form factor is small for small & medium t

  $\rightarrow$ BH neutron cross section small, hence also the interference term I

  $\rightarrow$ asymmetry in incoherent nuclear DVCS similar to that on the proton

COHERENT PRODUCTION:

- scattering occurs on the whole nucleus

  $\rightarrow$ coherent nuclear DVCS proceeds preferentially at very low t

  $\rightarrow$ obtain enriched samples by 'separation cut' at $t = 0.03...0.05$ GeV^2

GPD-based MODELS:

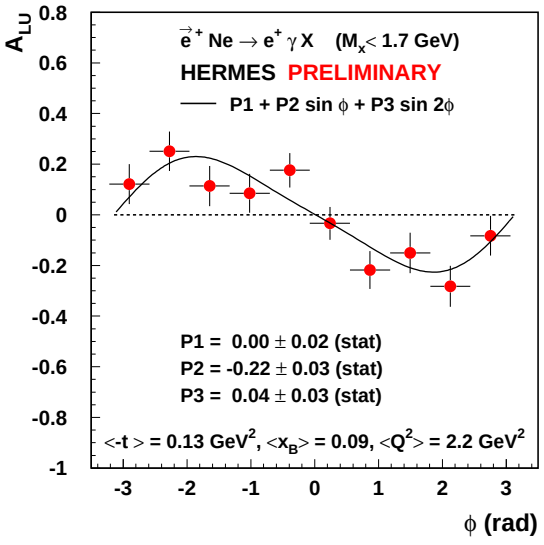
- describe modifications of parton-parton correlations in nuclear environment

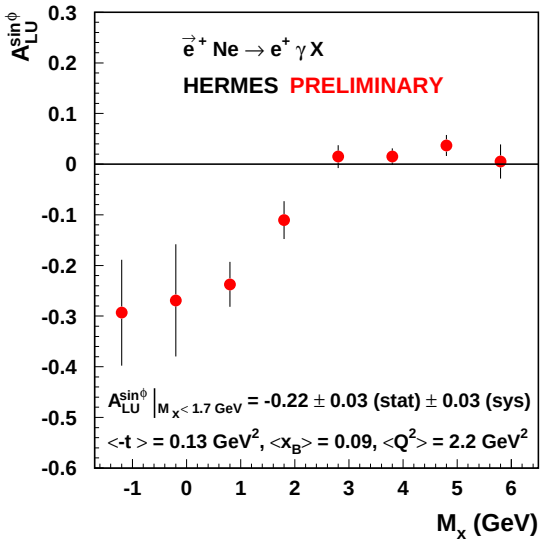
  $\rightarrow$ dynamical interplay within highly complex bound hadronic systems ?

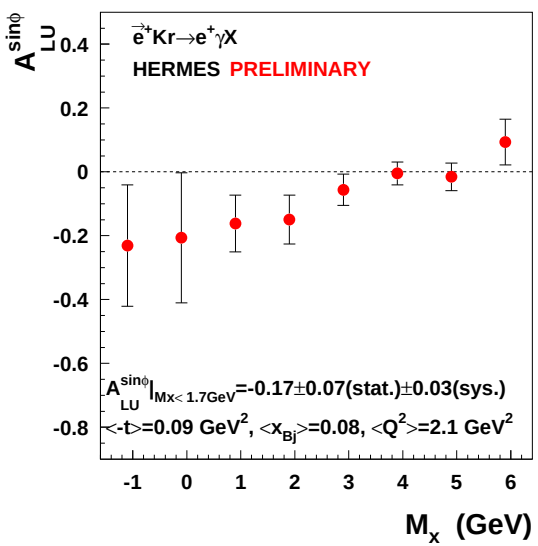
- tool to compare to theory predictions: $\frac{A_{LU}^{nucleus}}{A_{LU}^{proton}}$ (generalized EMC effect)

Beam-spin Asymmetry in Nuclear DVCS

- Preliminary results: clear $\sin\phi$ amplitude in exclusive region for Ne and Kr







- first model predictions available by Guzey&Strikhman and Liuti&Taneja
- uncertainties of released data still too large
- variety of nuclear DVCS data: ^{2}H, ^{4}He,^{14}N, ^{20}Ne, $^{82-86}$Kr, $^{129-134}$Xe

  $\longrightarrow$ presently being analyzed in order to facilitate study of:

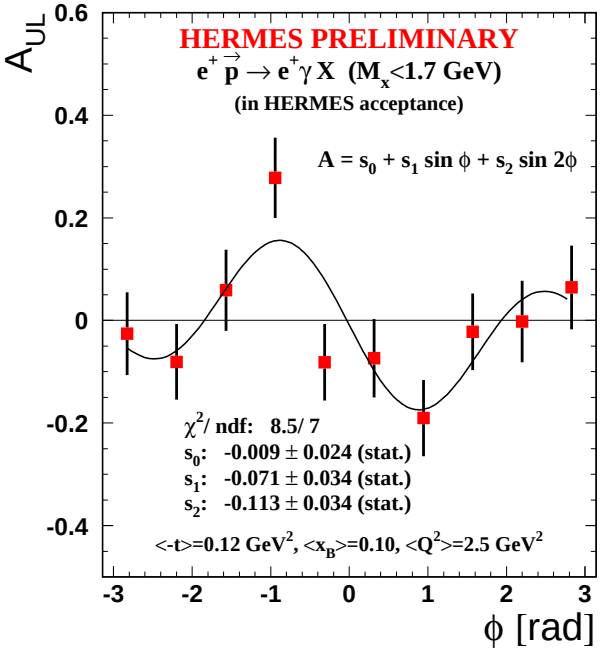
  - t-dependence of BSA for different nuclei
  - A-dependence of generalized EMC effect in coherent production

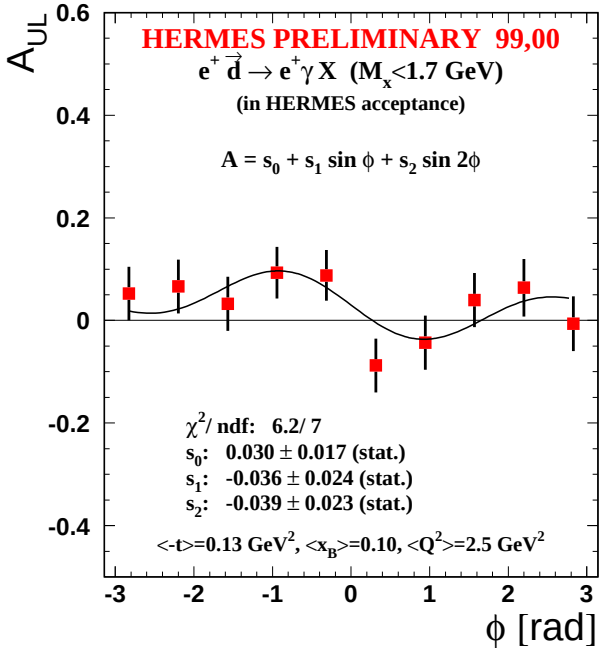
  $\longrightarrow$ more model predictions are highly appreciated

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



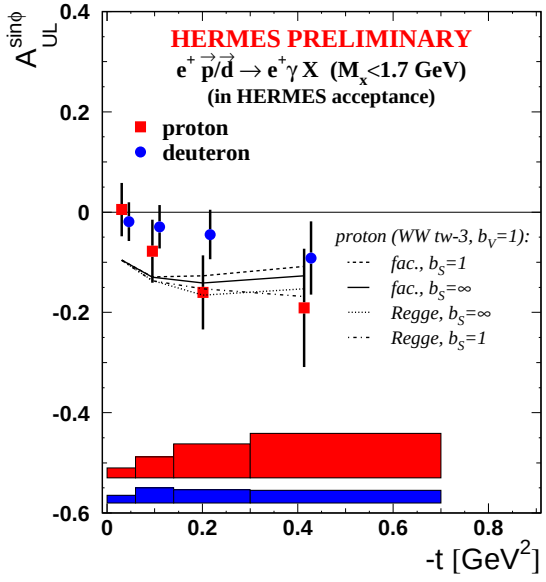


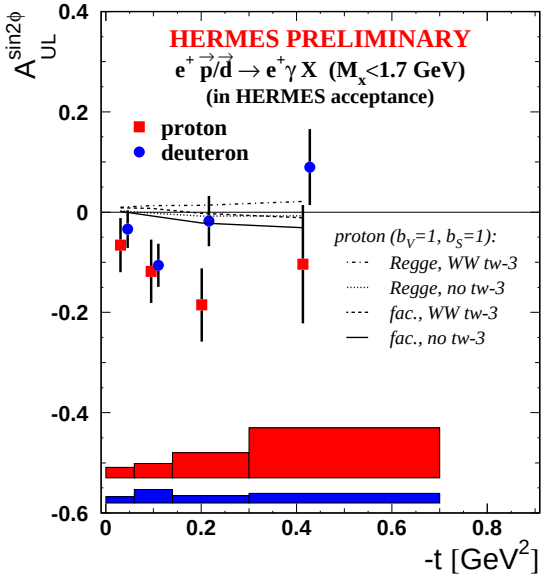
- FULL existing data set analyzed (1996-2000 data)
- expected $\sin\phi$ behaviour : 2σ (1.5σ) on proton (deuteron)
- unexpected, sizeable ($> 3\sigma$) $A_{UL}^{\sin 2\phi}$ on proton (1.7σ on deuteron) $\Rightarrow$ twist-3 ?

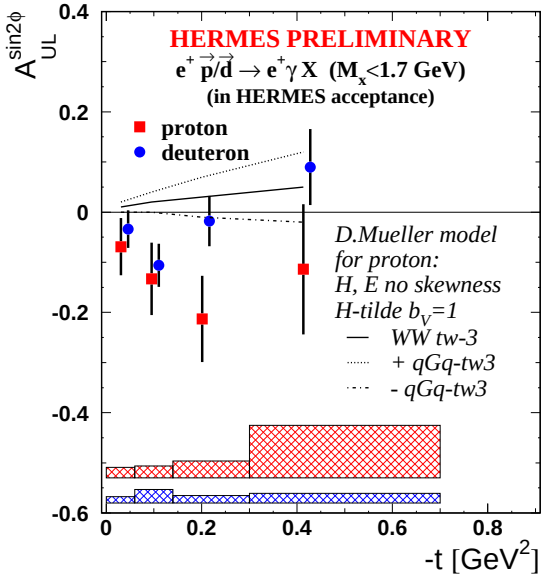
  (π^0 background found to be responsible for *at most* a small fraction of it)

Longitudinal 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





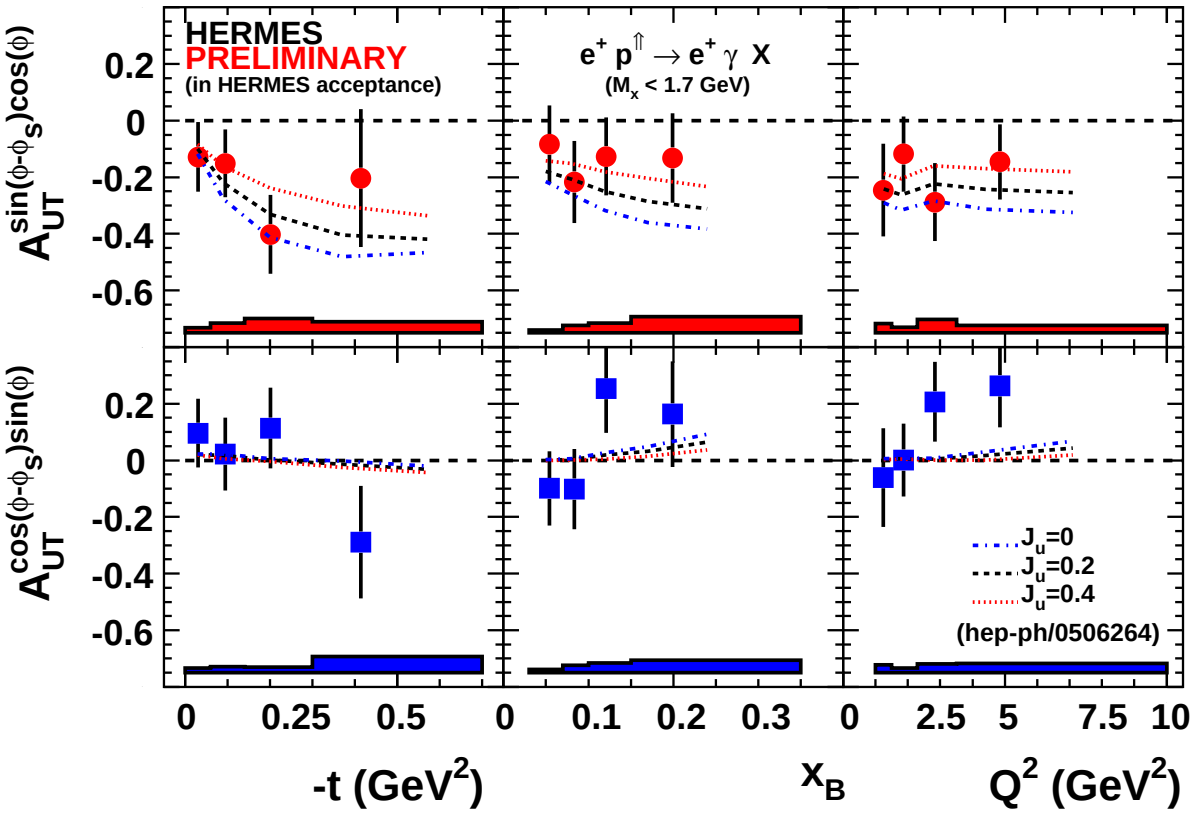


- Lowest t-bin: No effect from coherent prod. on deuteron (40% of statistics)
- higher t: $A_{UL}(ep) \neq A_{UL}(ed) \Rightarrow A_{UL}(ep) \neq A_{UL}(en)$
- Only Proton models exist: $\rightarrow$ for $A_{UL}^{\sin\phi}$; VGG model does ok.

  $\rightarrow$ 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

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: $e^-p^\Uparrow$]

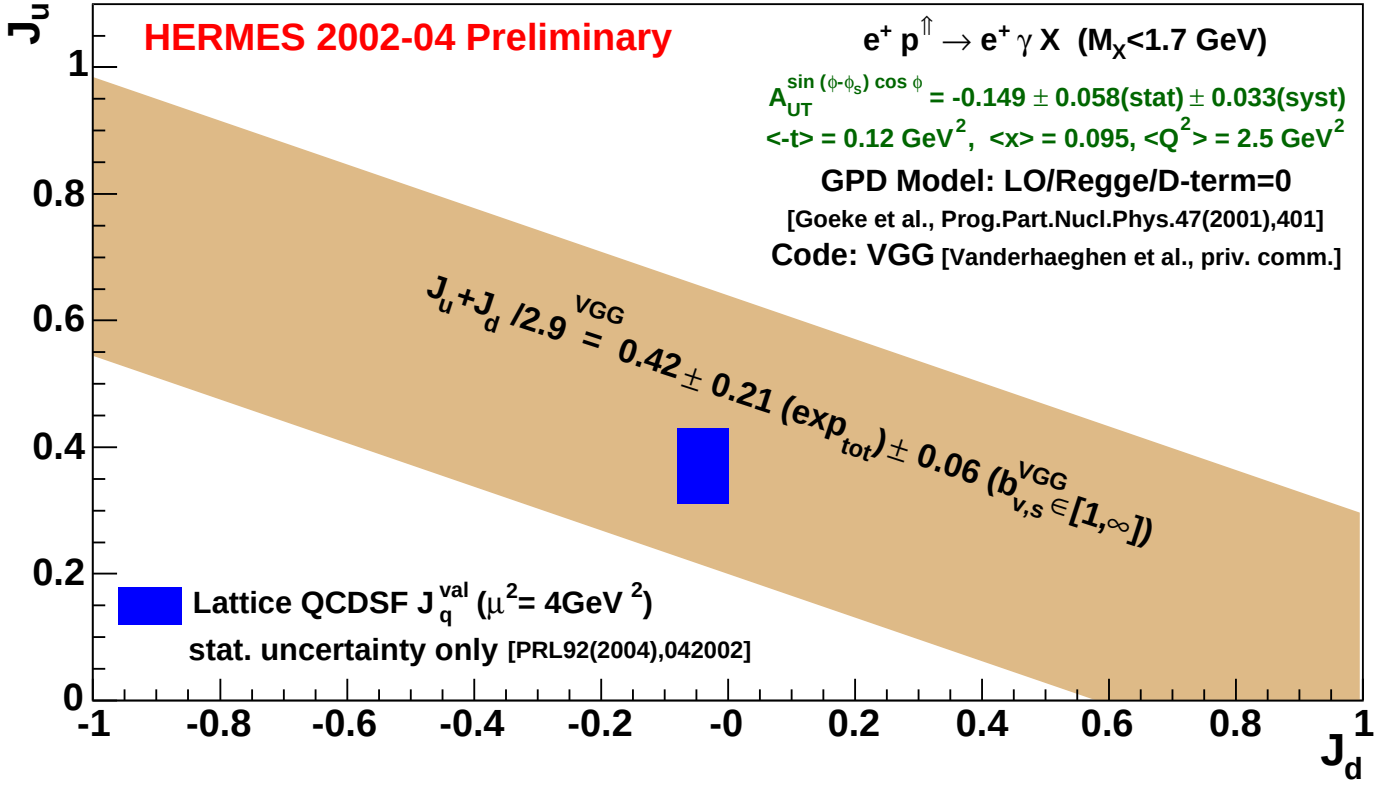
STUDY sensitivity to J_u (with $J_d = 0$) [hep-ph/0506264, based on Prog.Part.Nucl.Phys.47]:

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

Model-dependent Constraint on J_u vs J_d

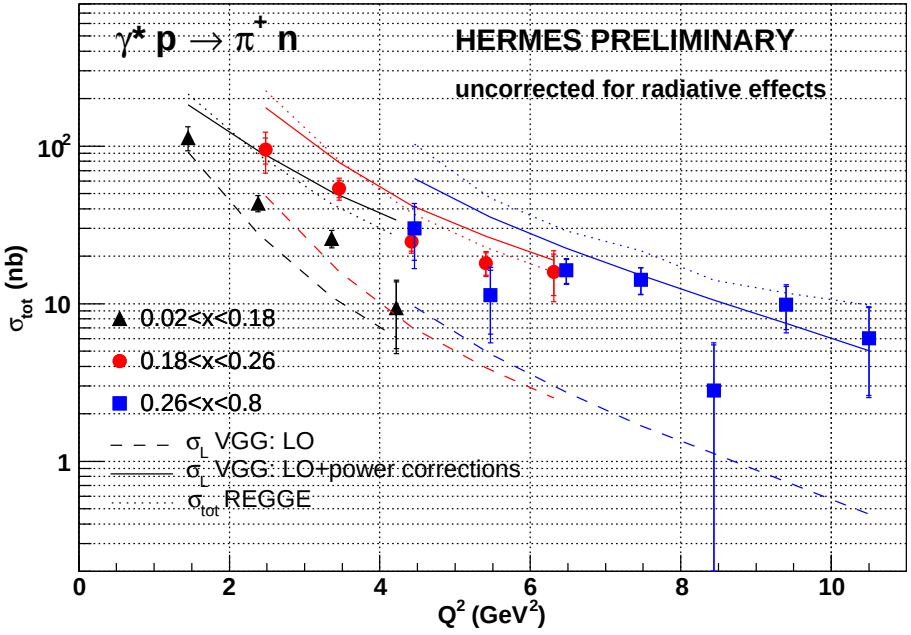
Unbinned maximum likelihood fit to $A_{UT}^{\sin(\phi-\phi_S)\cos\phi}$ at average kinematics (fitting prel. HERMES data against VGG-model based calculations), leaving J_u and J_d as free parameters $\Rightarrow$ model-dependent 1-σ constraint on J_u vs. J_d:

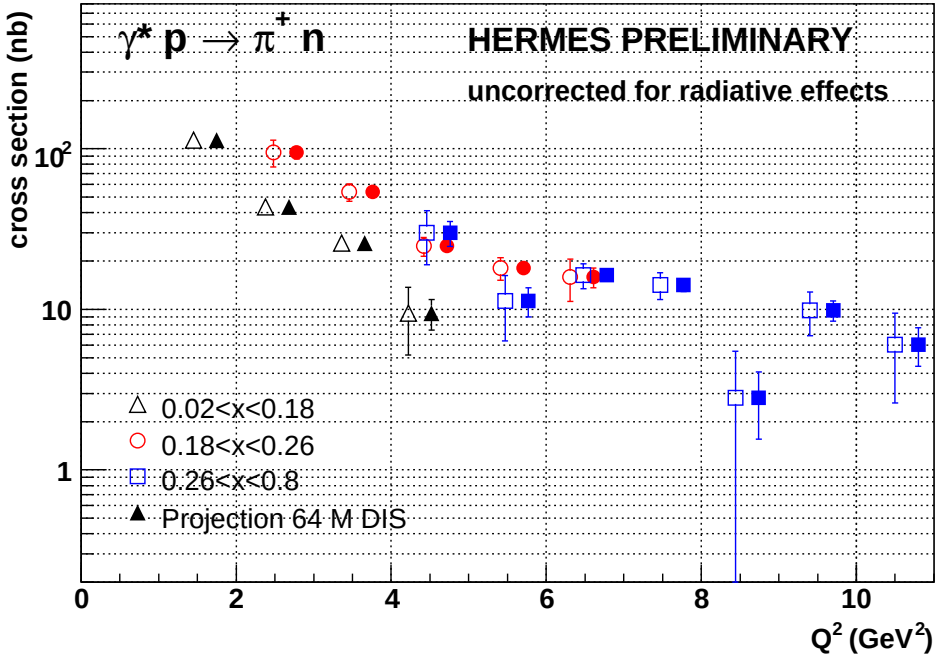


- Quenched lattice calculation done with pion masses 1070, 870, and 640 MeV, and then extrapolated linearly in m_π^2 to the physical value
- Uncertainties on VGG model parameters shown as separate uncertainty (± 0.06)

Exclusive π^+ Cross Section

- REACTION: $e\ p \longrightarrow e\ \pi^+ n$ Access to polarized GPDs $\tilde{H}$ and $\tilde{E}$
- $\sigma_{tot} = \sigma_T + \epsilon\sigma_L$; L/T separation at HERMES not possible $(0.80 < \epsilon < 0.96)$
- σ_T suppressed by $1/Q^2 \Rightarrow \sigma_L$ dominates at higher Q^2



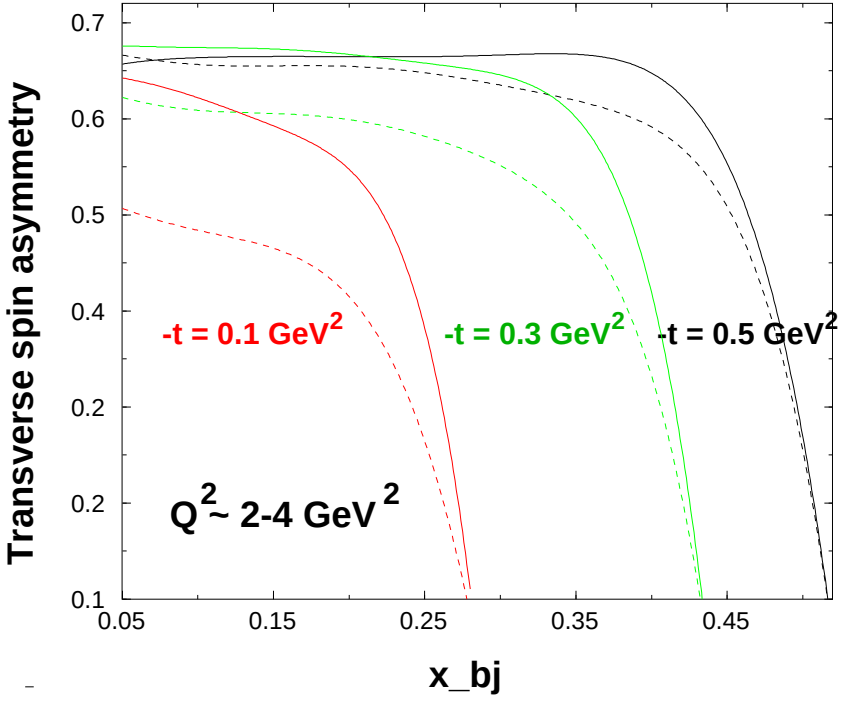


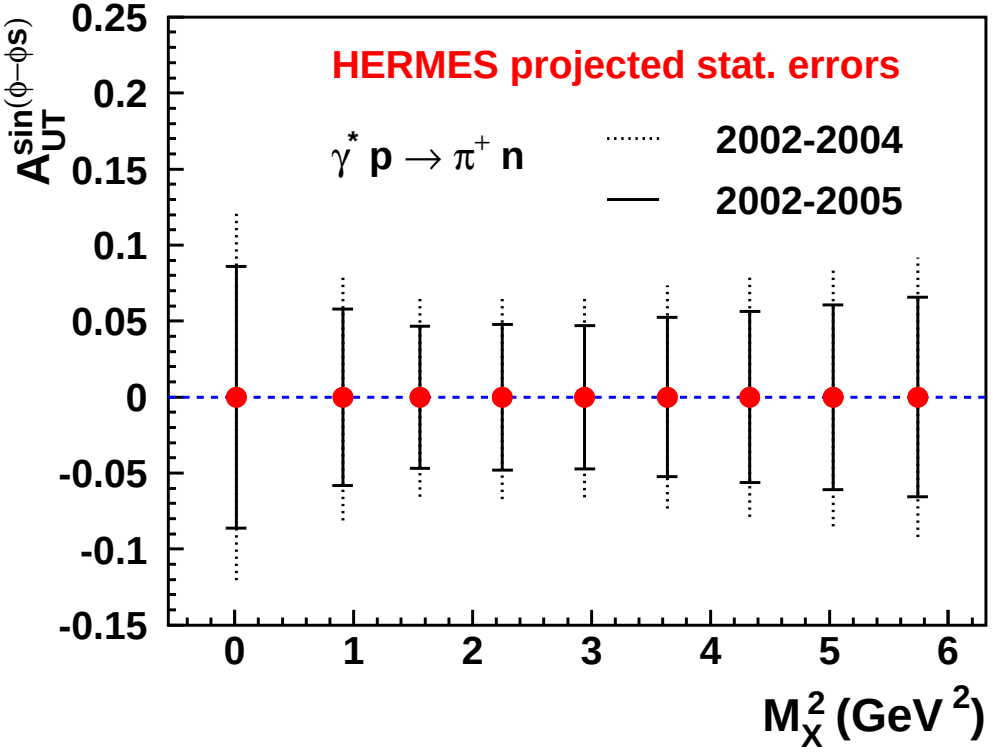
- VGG (LO+power corr.s) ≈ Regge-based, BUT: data undershoot both models
- Factorization theorem $\rightarrow \sigma_L \propto 1/Q^6$: Kinematic $1/Q^4$ * Dynamic $1/Q^p$
- p fitted in the 3 x-bins: $1.9 \pm 0.5; 1.7 \pm 0.6; 1.5 \pm 1.0$ $\Rightarrow$ as expected

Transv. Target-spin Asymmetry in π^+ Production

- Large $A_{UT}^{\sin\phi-\phi_S}$ predicted [Franfurt et al., PRL 84(2000)2589]

  from interference of pseudo-scalar ($\tilde{H}$) and pseudo-vector ($\tilde{E}$) amplitudes



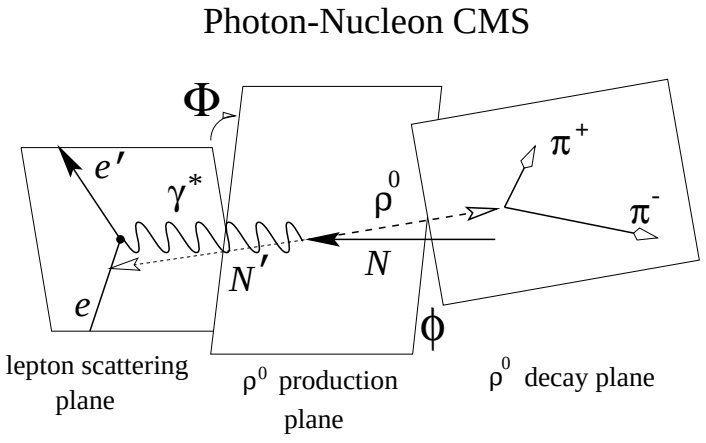


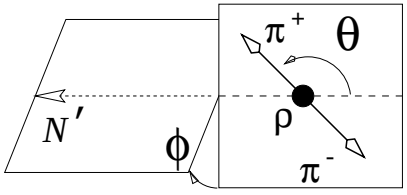
- background correction experimentally very difficult
- no released data available yet (PhD work going on)
- FULL data set (2002-2005): stat. errors may allow comparison with predictio

Transv. Target-spin Asymmetry in ρ^0 Production

See talk of A. Rostomyan

Vector Meson Production on Unpolarized Target

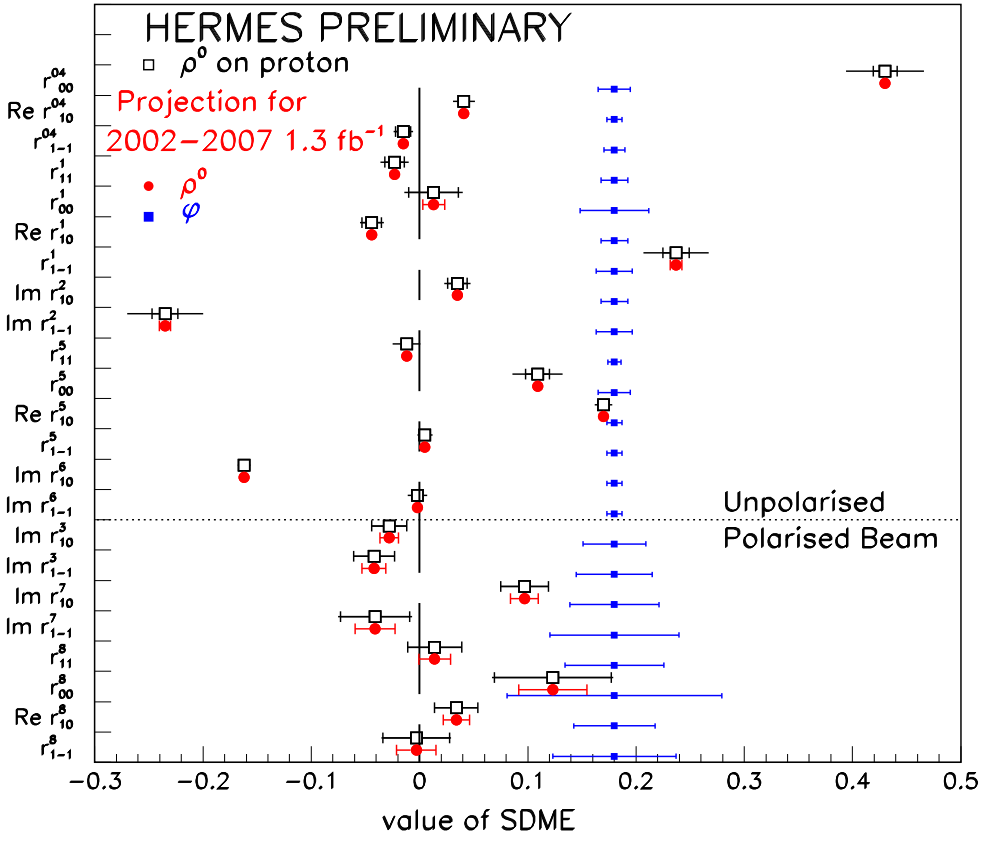


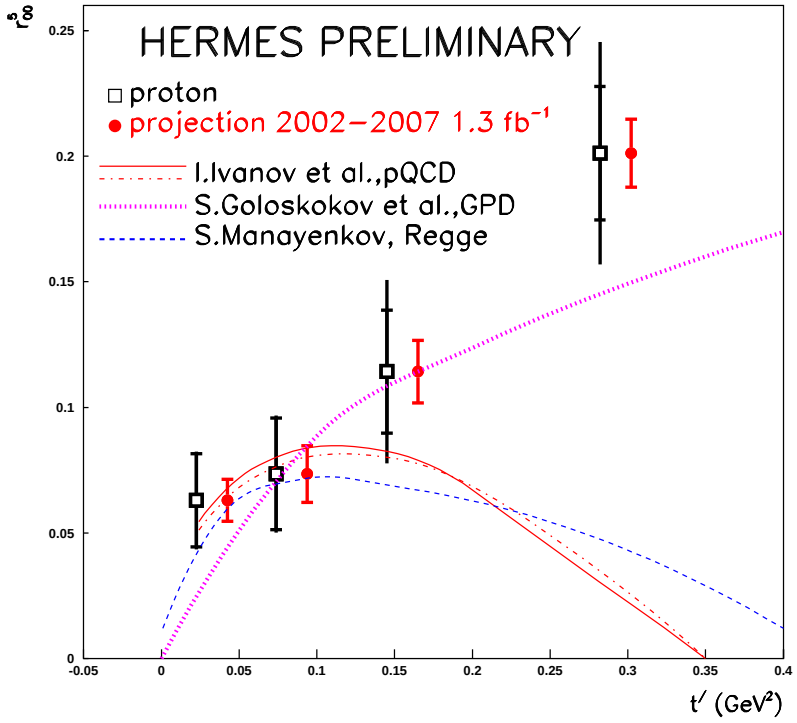


$$
\begin{array}{rcll}
\text{REACTION}: & e + p(d) & \to e + \rho^0\ (+X) & \\
0.6 < & M_{\pi^+\pi^-} & < 1.0\ \text{GeV} & \\
 & M_{K^+K^-} & \geq 1.06\ \text{GeV} & \\
-1.0 < & \delta E & < 0.6\ \text{GeV} & \mid\ \textbf{diffr.} \\
 & -t' & < 0.4\ \text{GeV} & \mid\ \textbf{excl.} \\
1 < & Q^2 & < 5\ \text{GeV}^2 & \\
3 < & W & < 6.3\ \text{GeV}^2 & \\
 & y & > 0.85 &
\end{array}
$$

- SDMEs from maximum likelihood fit minimizing difference between:
  - 3-dimensional ($\cos\Theta, \phi, \Phi$) decay angle matrix of data
  - fully reconstructed high statistics Monte Carlo set
- 1996-2000 data analyzed; polarized beam ($P_B \approx 0.53$), UNpolarized target
- 15 'unpolarized' ρ^0 SDMEs measured, precision comparable to H1/ZEUS
- 8 polarized ρ^0 SDMEs measured for the first time

ρ^0 SDMEs & Projections for ρ^0 and ϕ SDMEs



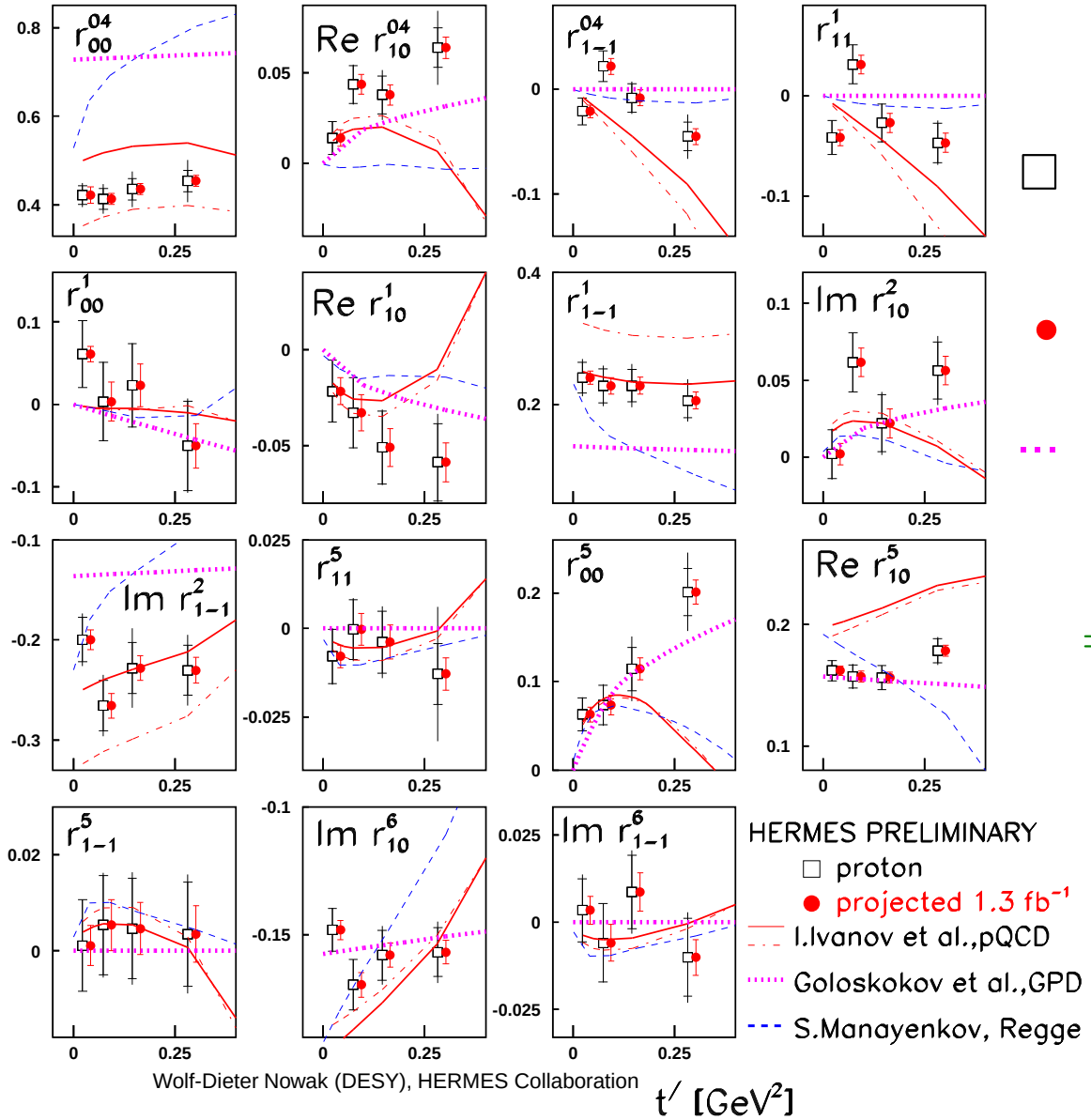


$$R = \frac{\sigma_L}{\sigma_T} \quad R^{SCHC} = \frac{1}{\epsilon}\frac{r^{00}_{04}}{1-r^{00}_{04}} \quad R^{NPE} = \frac{1}{\epsilon}\left\{\frac{1}{2r^1_{1-1}-r^1_{00}} - 1\right\} \quad \epsilon = \frac{1-y}{1-y+y^2/2}$$

- statistically significant violation of SCHC found
- indication seen for existence of unnatural-parity-exchange amplitudes

BOTH: $\Rightarrow$ existence of 2-quark exchange at intermediate energies

ρ^0 Spin-density-matrix Elements vs. t



- 15 'unpolarized' SDMEs from HERMES 1996-2000 proton data
- Projection 1996-2007 data

... GPD-based model ($Q^2 > 3$ GeV^2)

2-gluon exchange only

$\Rightarrow$ waiting for inclusion of quark-exchange into GPD-based model

(hoping for lower Q^2-limit then)

Summary and Outlook

- HERMES has been playing a pioneering role exploring the potential of exclusive photon/ meson production towards an interpretation of the data in the context of Generalized Parton Distributions. Measurements of azimuthal asymmetries with respect to beam spin and charge, and to (longitudinal and transverse) target polarization were performed. First constraints on GPD models were obtained, including a model-dependent constraint on the u and d-quark total angular momentum.
- 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 Deeply Virtual Compton Scattering, and of the cross section in exclusive π^+ production.