HERMES Results on Hard Exclusive Reactions

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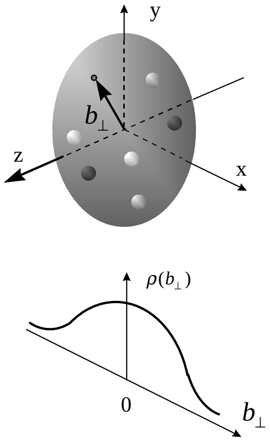
(Not covered: Determination of ρ and ϕ spin-density matrix elements)

3-dimensional Picture of the Proton

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

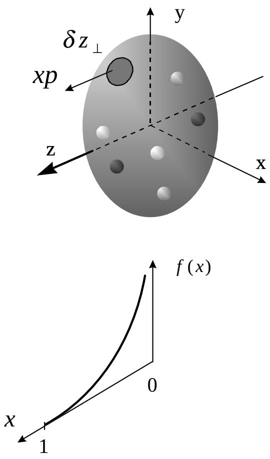
- Form factor



Nucleon's transv. charge distribution given by 2-dim. Fourier transform of **Form Factor**:

⇒ Parton's transverse localization $\mathbf{b}_\perp$

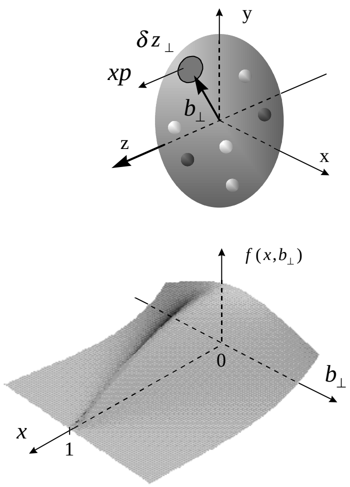
- Parton density



Probability density to find partons of given long. mom. fraction x at resol. scale $1/Q^2$ (no transv. inform.)

⇒ Parton's longitudinal momentum distribution function (**PDF**) f(x)

- Generalized parton distribution at η=0



Generalized Parton Distrib.^{s} (GPDs) probe simultaneously transverse localization $\mathbf{b}_\perp$ for a given longitudinal momentum fraction x.

2nd moment by Ji relation:

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

Proton Spin Budget in a Nutshell

NO unique & gauge-invar. decomposition of the nucleon spin [R.L.Jaffe, X.Ji]:

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

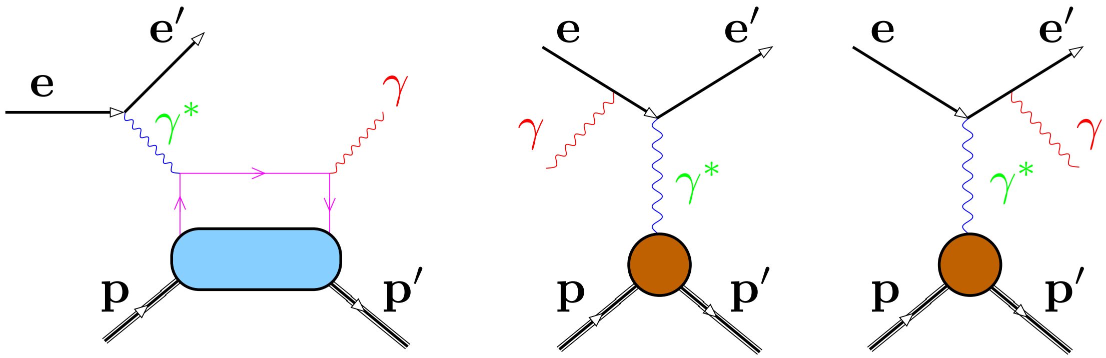
- **Total angular momenta** of quarks (J_q) and gluons (J_g) are gauge-invariant and calculable in lattice gauge theory
- **Intrinsic spin contribution** and **orbital angular momentum** are gauge inv. for quarks ($\frac{1}{2}\Delta\Sigma$ and L_q), but not for gluons ($\widehat{\Delta g}$ and L_g)
- 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 $\mathcal{J}_g \neq J_g$! (courtesy M. Burkardt)

Deeply Virtual Compton Scattering



(a) (b)

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

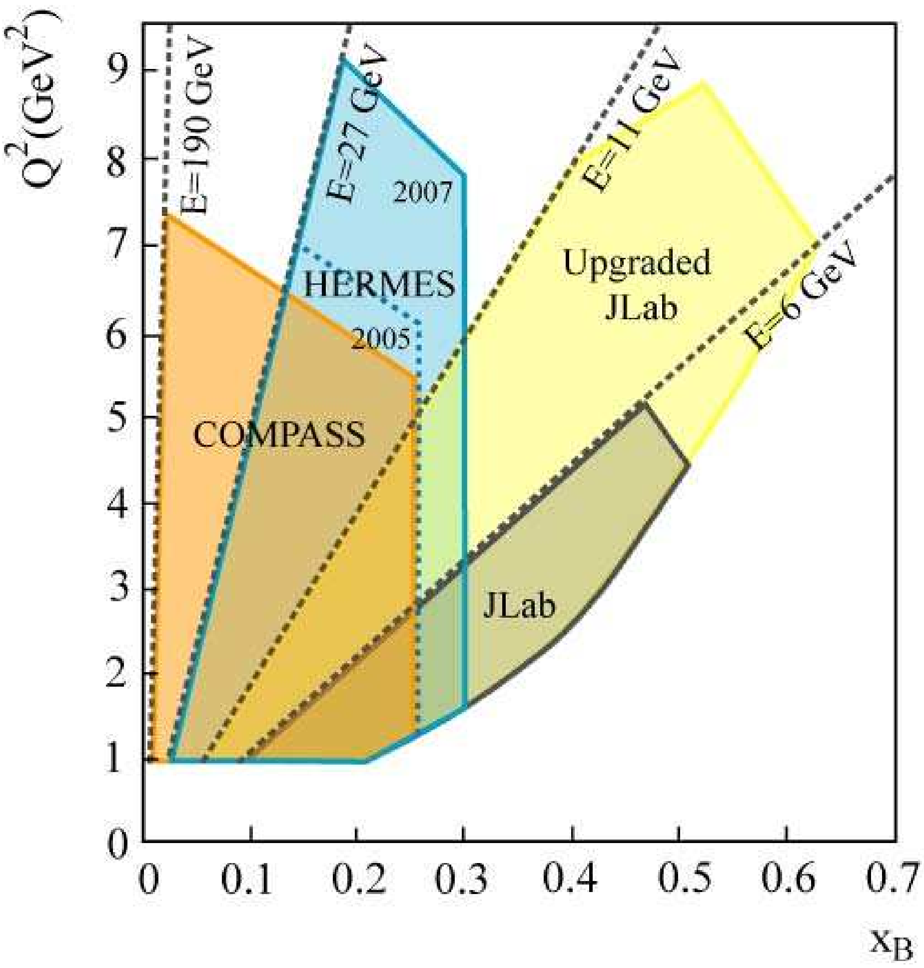
$$d\sigma(\mathrm{eN}\to\mathrm{eN}\gamma) \propto |\mathcal{T}_{BH}|^2 + |\mathcal{T}_{DVCS}|^2 + \underbrace{\mathcal{T}_{BH}\mathcal{T}^*_{DVCS} + \mathcal{T}^*_{BH}\mathcal{T}_{DVCS}}_{I}$$

- $\mathcal{T}_{BH}$ 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 I can be filtered out by forming certain cross section differences (or asymmetries)

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

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:

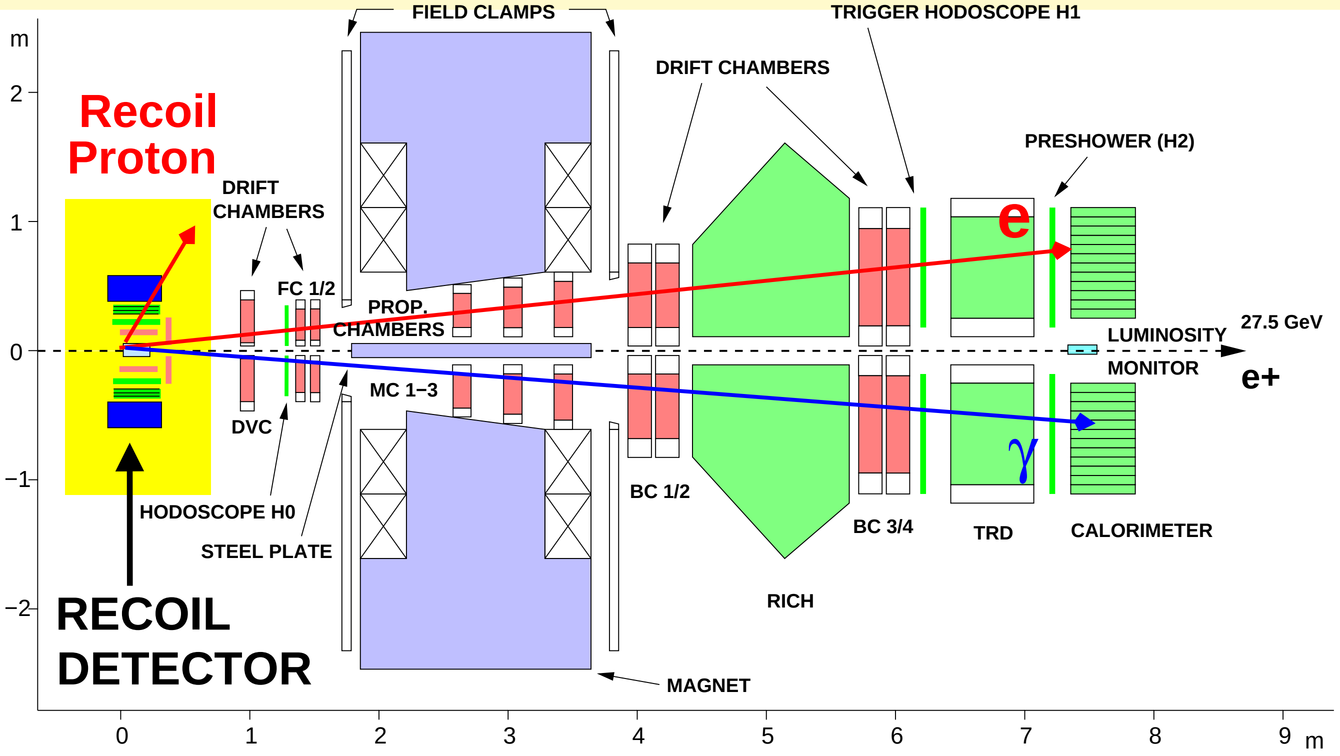
  - small skewness

  $\Rightarrow$ almost forward GPDs !

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

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

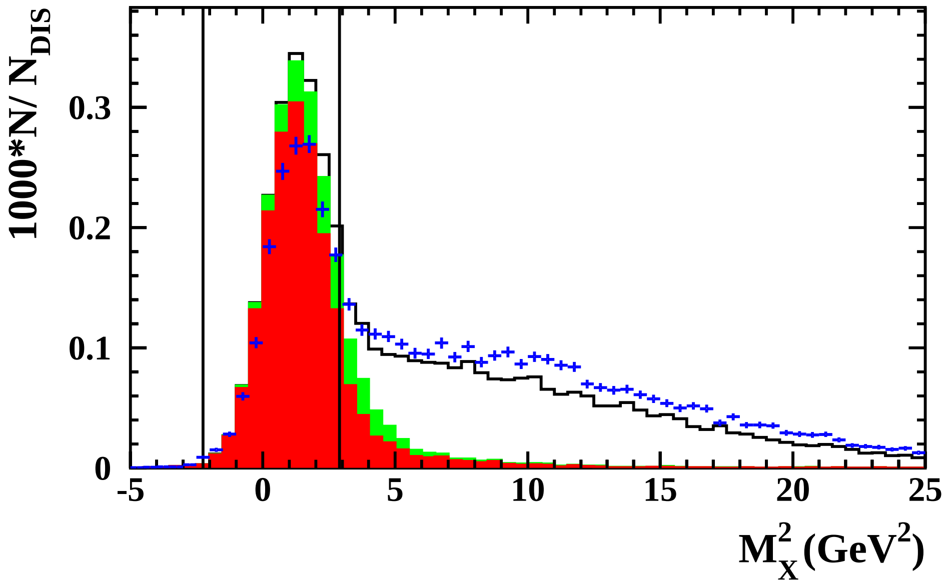
The HERMES Spectrometer



- 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 (unpolarized H target)

Exclusive DVCS Events at HERMES

$\text{REACTION}: \quad e + p(d) \quad \rightarrow e + \gamma\ (+X)$



$$5 < \quad \theta_{\gamma^*\gamma} \quad < 45\ \text{mrad}$$

$$-t \quad < 0.7\ \text{GeV}$$

$$0.03 < \quad x_B \quad < 0.35$$

$$1 < \quad Q^2 \quad < 10\ \text{GeV}^2$$

$$W \quad > 3\ \text{GeV}$$

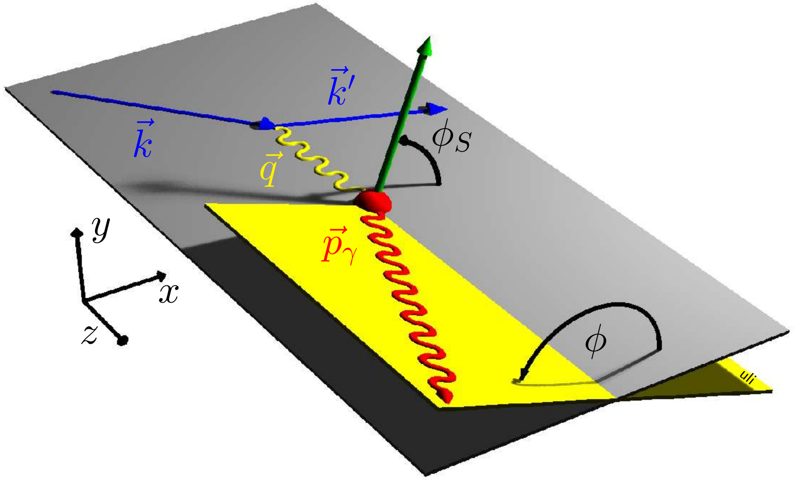
$$\nu \quad < 22\ \text{GeV}$$

$$-(1.5)^2 < \quad M_X^2 \quad < (1.7)^2\ \text{GeV}$$

- *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

Azimuthal Asymmetries in DVCS

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



- Beam-charge asymmetry $\mathcal{A}_C(\phi)$ [BCA] :

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

- Beam-spin asymmetry $\mathcal{A}_{LU}(\phi)$ [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 $\mathcal{A}_{UL}(\phi)$:

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

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

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

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

HERMES Combined BSA & BCA Analysis

Various asymmetry amplitudes $\mathcal{A}$ contribute to polarized cross section σ_{LU}:

$$\sigma_{LU}(\phi; P_l, e_l) = \sigma_{UU}(\phi)[1 + e_l \mathcal{A}_C(\phi) + e_l P_l \mathcal{A}^I_{LU}(\phi) + P_l \mathcal{A}^{DVCS}_{LU}(\phi)]$$

L: longitudinally polarized lepton beam of charge e_l & polarization P_l; U: unpolarized proton target

BCA: $\mathcal{A}_C(\phi) = \frac{1}{\sigma_{UU}} c_1^I \cos\phi + \cdots$ $\qquad c_1^I \propto \frac{\sqrt{-t}}{Q} F_1 \mathrm{Re}\mathcal{H} + [\cdots]$

BSA (interference term): $\mathcal{A}^I_{LU}(\phi) = \frac{1}{\sigma_{UU}} s_1^I \sin\phi + \cdots$ $\qquad s_1^I \propto \frac{\sqrt{-t}}{Q} F_1 \mathrm{Im}\mathcal{H} + [\cdots]$

BSA (DVCS term): $\mathcal{A}^{DVCS}_{LU}(\phi) = \frac{1}{\sigma_{UU}} s_1^{DVCS} \sin\phi$ (small at HERMES energy)

Unpolarized cross section: $\sigma_{UU} = \sigma_{BH} + \sigma_{DVCS} + \sigma_I$

F_1 : Dirac elastic nucleon form factor

$\mathcal{H}$: Compton Form Factor (CFF), embodies GPD H

$[\cdots]$: kinematically suppressed CFFs ($\widetilde{\mathcal{H}}, \mathcal{E}$) embodying GPDs $\widetilde{H}, E$

Fit to data: $\mathcal{A}_C(\phi) = \sum_{n=0}^{3} A_C^{\cos n\phi} \cos n\phi$

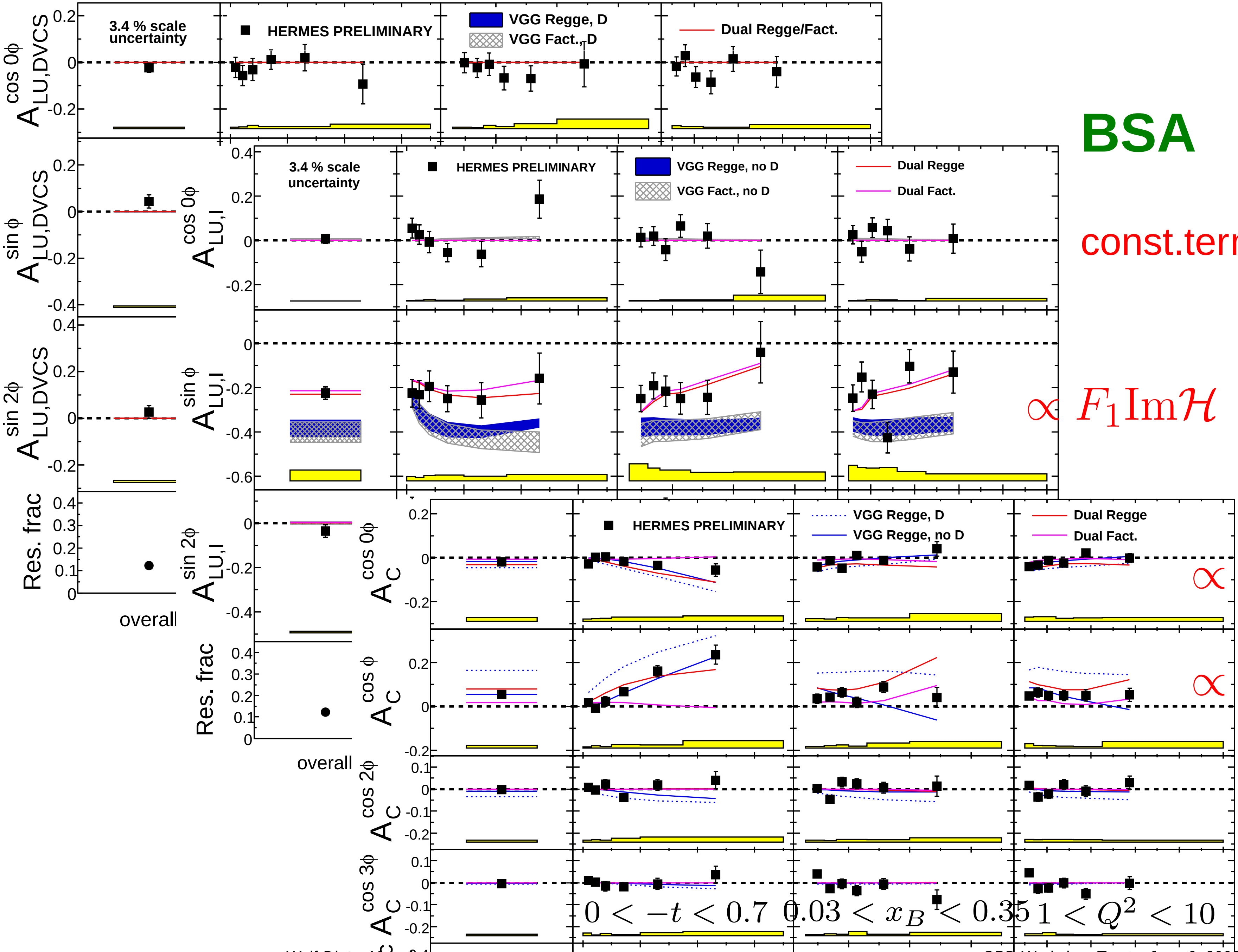
$$\mathcal{A}^I_{LU}(\phi) = \sum_{m=1}^{2} A_{LU,I}^{\sin m\phi} \sin m\phi$$

$$\mathcal{A}^{DVCS}_{LU}(\phi) = A_{LU,DVCS}^{\sin\phi} \sin\phi$$

Fit results: ‘effective’ asymmetry amplitudes: $A_C^{\cos n\phi}, A_{LU,I}^{\sin m\phi}, A_{LU,DVCS}^{\sin\phi}$

$\Rightarrow$ well defined in theory, can be compared to GPD models !

HERMES Combined BSA & BCA Results



BSA

const.term

$\propto F_1 \mathrm{Im}\mathcal{H}$

BCA

$\propto -A_C^{\cos\phi}$

$\propto F_1 \mathrm{Re}\mathcal{H}$

HT

HT

Discussion of Combined BSA & BCA Analysis

- HERMES BSA agrees with Dual model Guzey,(Polyakov),Teckentrup 2006
- VGG model Vanderhaeghen, Guichon,Guidal 1999 clearly undershoots HERMES BSA

  (Improvement recently proposed Polyakov,Vanderhaeghen arXiv:0803.1271 [hep-ph])
- HERMES BCA disfavours factorized t dep., in both models and D-term in VGG
- Pure $|\mathrm{DVCS}|^2$ asymmetries found compatible with zero (as models assume)

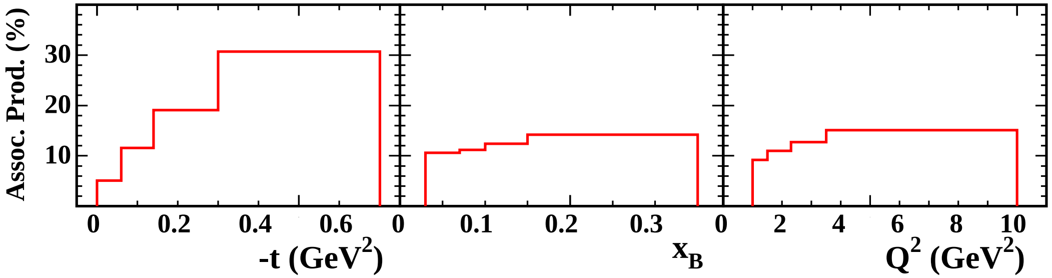
⇒ HERMES data precise enough to discriminate between models or their variants

⇒ new models eagerly awaited !!! Müller,Kumericki

- PROBLEM: Asymmetries of ‘associated (resonance) production’ unknown !!!

  Kinematic dependence of fractions of associated production known from MC:

Average is 12%



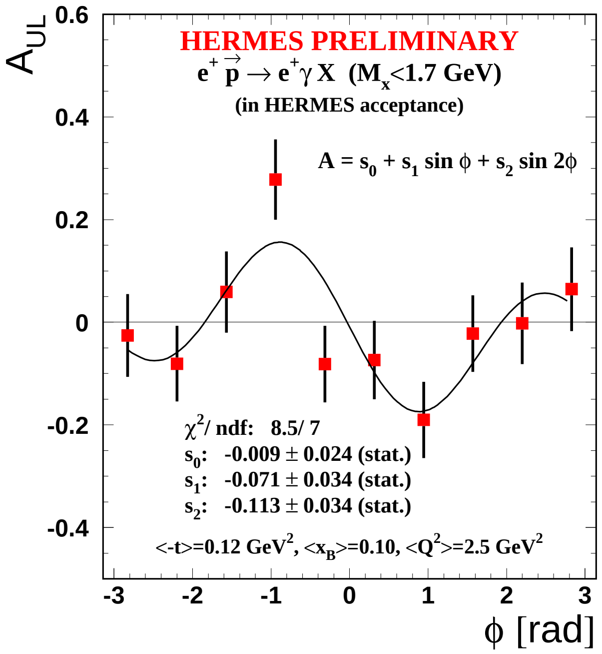
⇒ In data associated production has to be treated as part of the signal, while in models it is not included (still unknown) ⇒ **What to do ?**

HERMES Long. Target-spin Asymmetry vs. ϕ

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

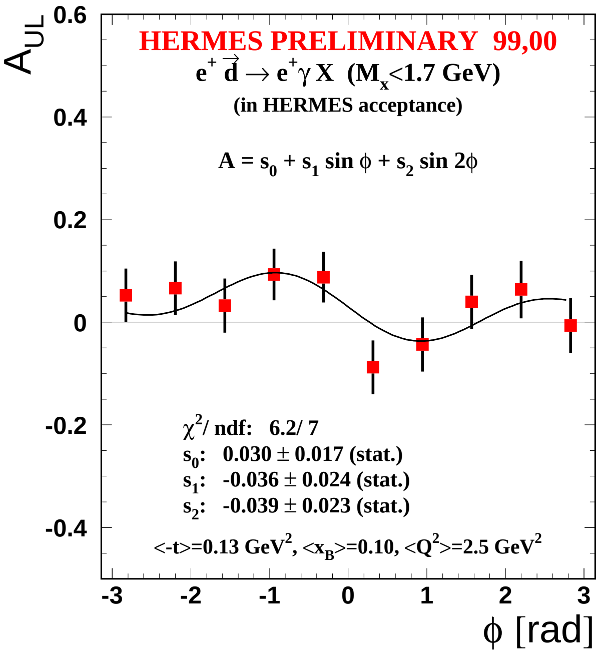
$\Rightarrow$ extract ‘effective’ asymmetry amplitudes by fitting per ϕ-bin:

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



⇐ proton

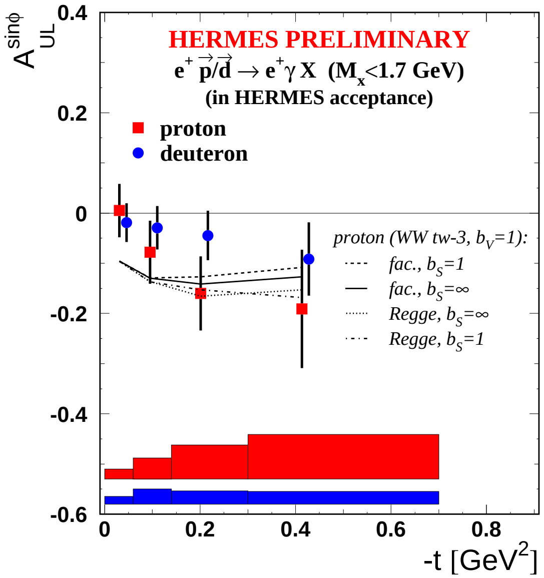
deuteron ⇒

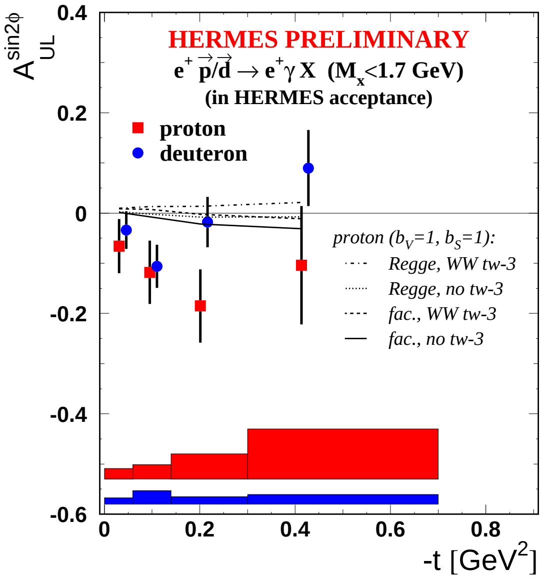


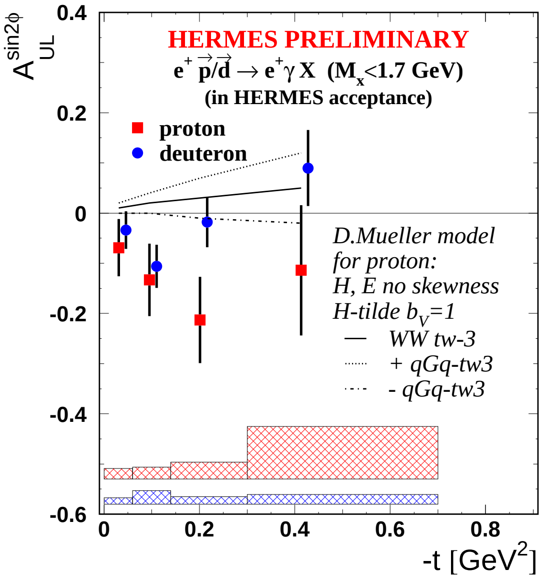
- FULL existing data set analyzed (1996-2000 data)
- s_1 : expected $\sin\phi$ behaviour : 2σ (1.5σ) on p (d)
- s_2 : unexpected, sizeable ($> 3\sigma$) $A_{UL}^{\sin 2\phi}$ on p (1.7σ on d) $\Rightarrow$ twist-3 ?
- final analysis tuning and paper in progress

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







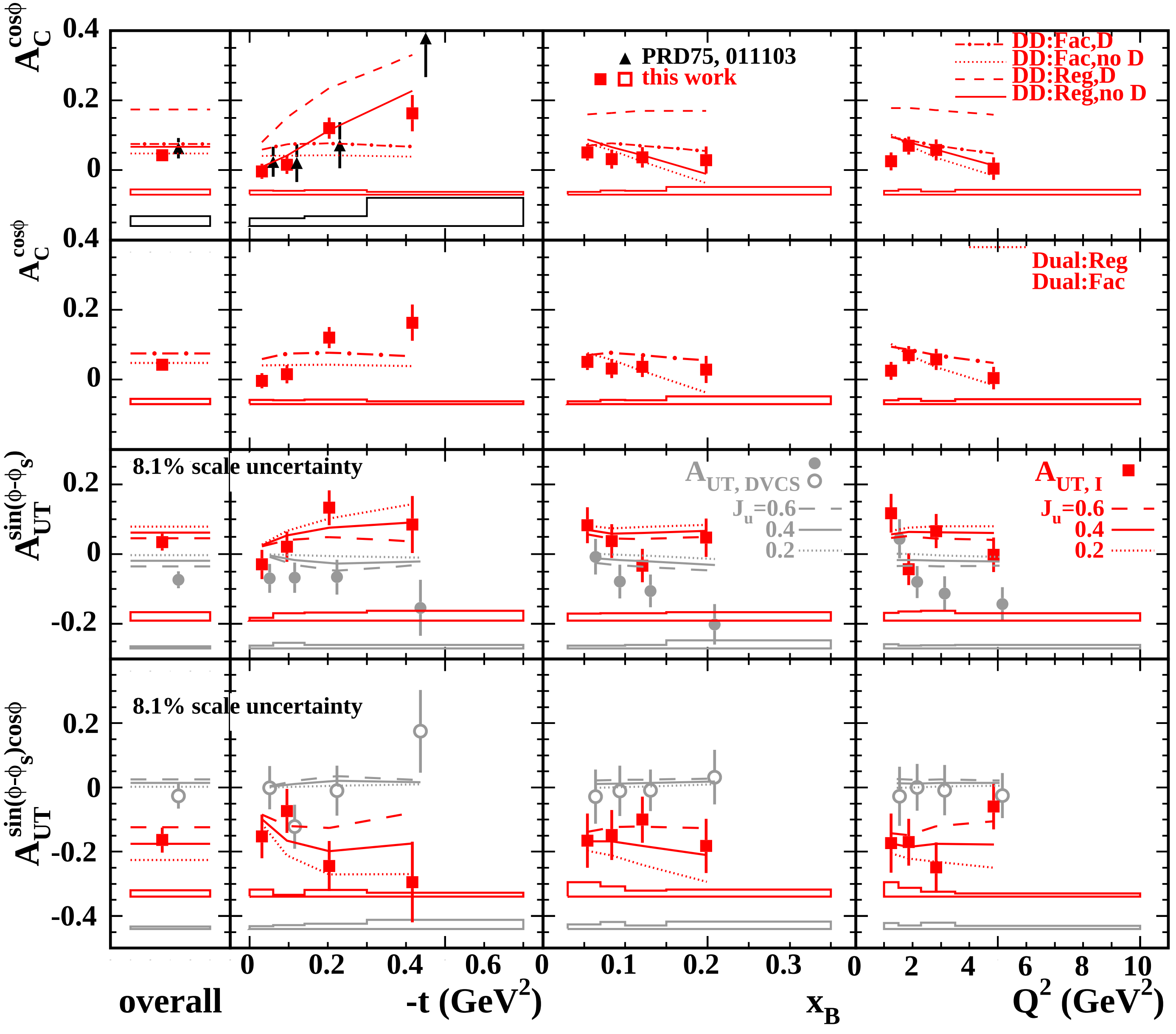
- Lowest t-bin: No effect from coherent prod. on deuteron (40% of statistics)
- higher t: $A_{UL}(ep) \neq A_{UL}(ed) \Rightarrow A_{UL}(ep) \neq A_{UL}(en)$
- Only Proton models exist: $\longrightarrow$ for $A_{UL}^{\sin\phi}$; VGG model does ok.

  $\longrightarrow$ 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

HERMES: First Measurement of TTSA

$$\mathcal{A}_{UT}(\phi,\phi_S) = A_{UT}^{\sin(\phi-\phi_S)\cos\phi} \cdot \sin(\phi-\phi_S)\cos\phi + A_{UT}^{\cos(\phi-\phi_S)\sin\phi} \cdot \cos(\phi-\phi_S)\sin\phi + \dots$$



- HERMES final data set with ‘unpolarized’ (U) $e^{\pm}$ beam and transversely (T) polarized target
- ‘Combined’ fit: simultaneous extraction of A_C and various ‘effective’ A_{UT} amplitudes for interference term **and** DVCS !
- acc. by JHEP arXiv:0822.2499 [hep-ex]

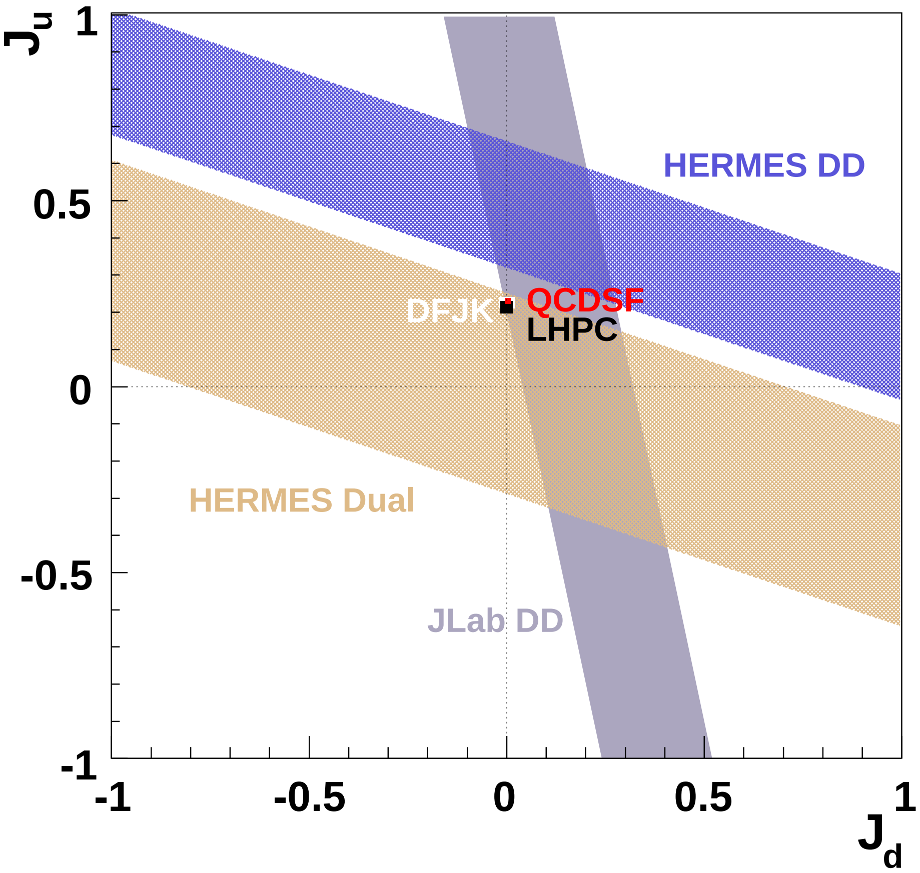
Why TTSA Data Expected to be Sensitive to $\mathrm{J_q}$?

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

ANSATZ: spin-flip Generalized Parton Distribution E is 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: $E_q^{DD}(x,\xi) = \int\limits_{-1}^{1} d\beta \int\limits_{-1+|\beta|}^{1-|\beta|} d\alpha\, \delta(x-\beta-\alpha\xi)\, K_q(\beta,\alpha)$
- 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_q, B_q constrained by Ji relation, and $\int\limits_{-1}^{+1} dx\; e_q(x) \;=\; \kappa_q$
- 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]

Model-dependent constraints on $\mathrm{J_u}$ vs $\mathrm{J_d}$



HERMES analysis method:

(acc. by JHEP; arXiv:0802.2499 [hep-ex])

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.])

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

  → BH neutron cross section small, hence also the interference term I

  → asymmetry in incoherent nuclear DVCS similar to that on the proton

COHERENT PRODUCTION:

- scattering occurs on the whole nucleus

  → coherent nuclear DVCS proceeds preferentially at very low t

- Obtain enriched samples: coherent: $-t < -t_{coh.}$, incoherent: $-t > -t_{incoh.}$

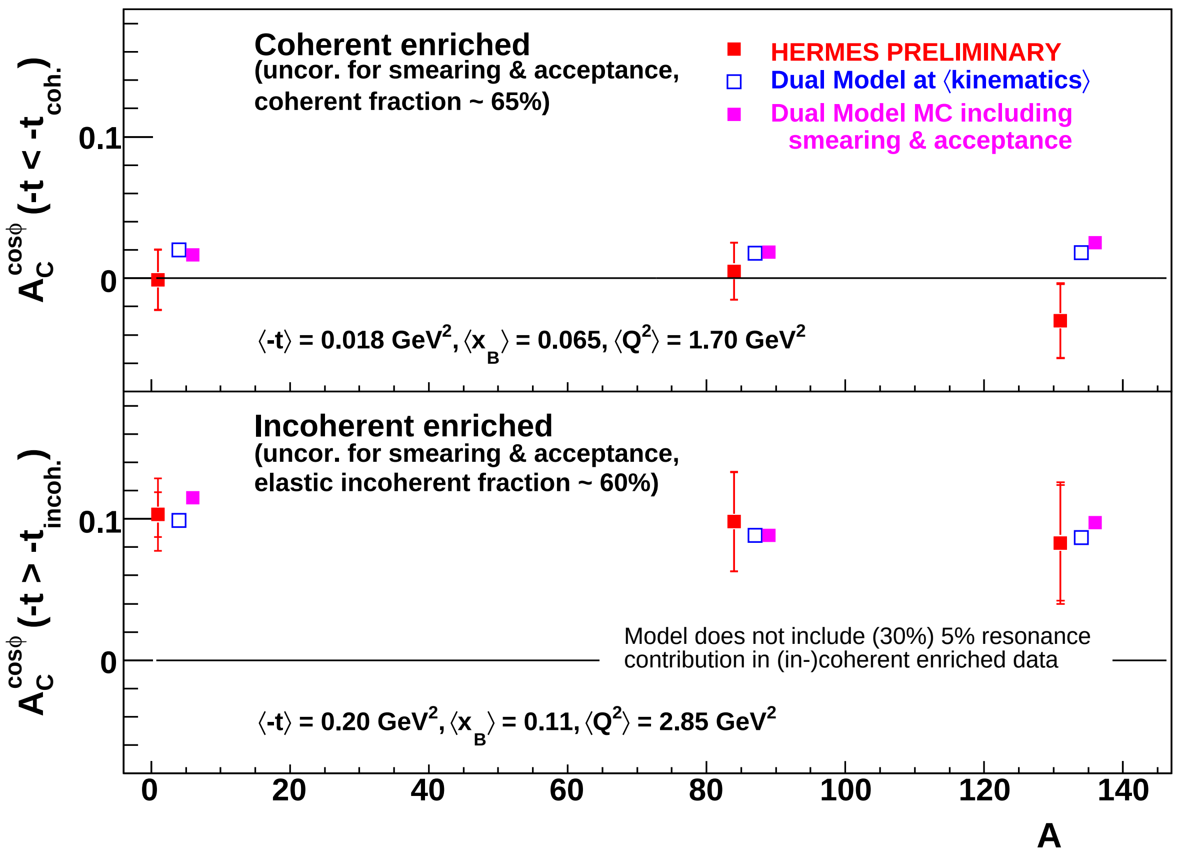
GPD-based MODELS:

- describe modifications of parton-parton correlations in nuclear environment

  → dynamical interplay within highly complex bound hadronic systems ?

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

Nuclear DVCS: Beam-charge Asymmetry



$\ast$ All nuclear data (1997-2005) incl.

$\ast$ Hydrogen data 2000+2005 incl.

'Combined' analysis for H, Kr, Xe targets using $e^{\pm}$ beam

$\ast$ π^0 background $\approx 5\%$, corrected for

- Coherent-enriched sample: no significant BCA observed

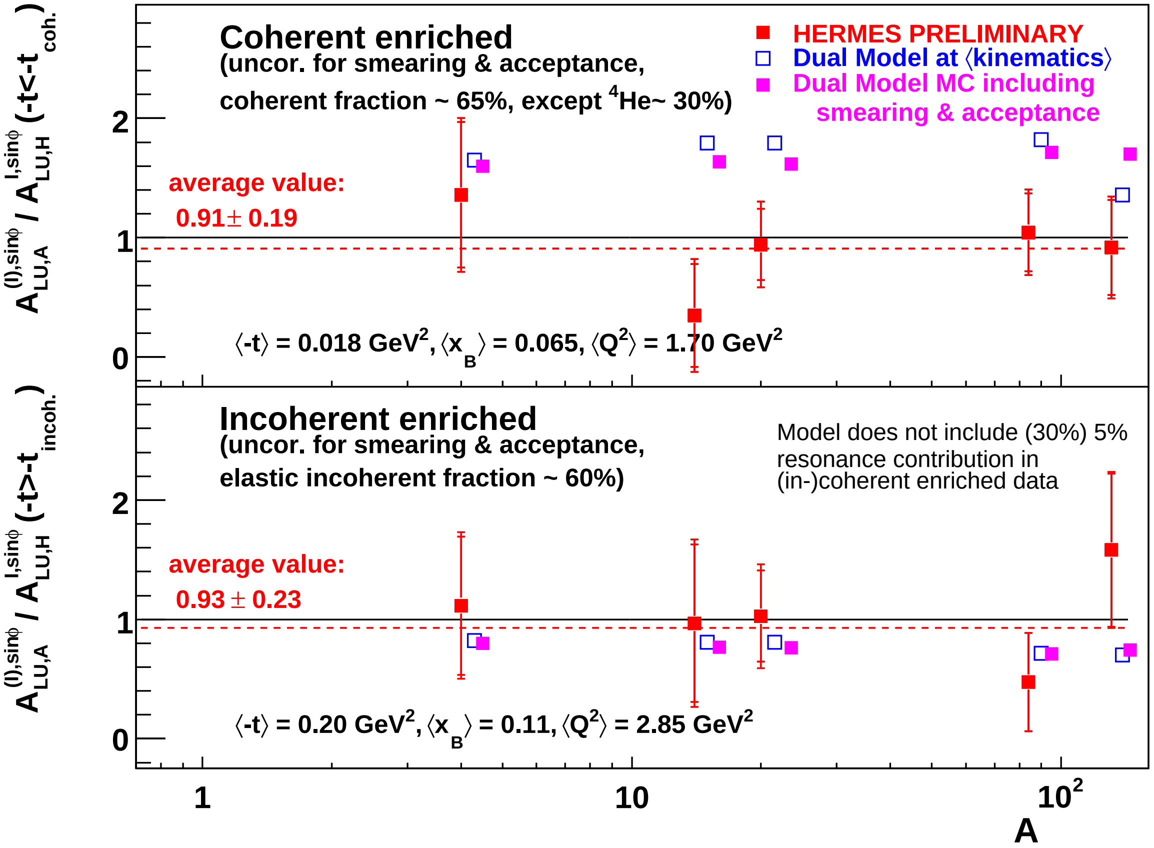
  Inner error bars are statistical and outer ones the total exp. uncertainty

- Incoherent-enriched sample: same asymmetry seen for H, Kr, Xe

  Smearing (always small) and acceptance not yet included in error bar,
  but demonstrated with Dual Model (V. Guzey, arXiv:0801.3235 [hep-ph])

- Good agreement with Dual Model for all targets

Nuclear vs. Hydrogen BSA Ratio in DVCS



'Combined' analysis

for H, Kr, Xe targets

using $e^{\pm}$ beam

Single-BSA analysis

for He, N, Ne

(e^{+} data only)

Background and other

exp. effects corrected.

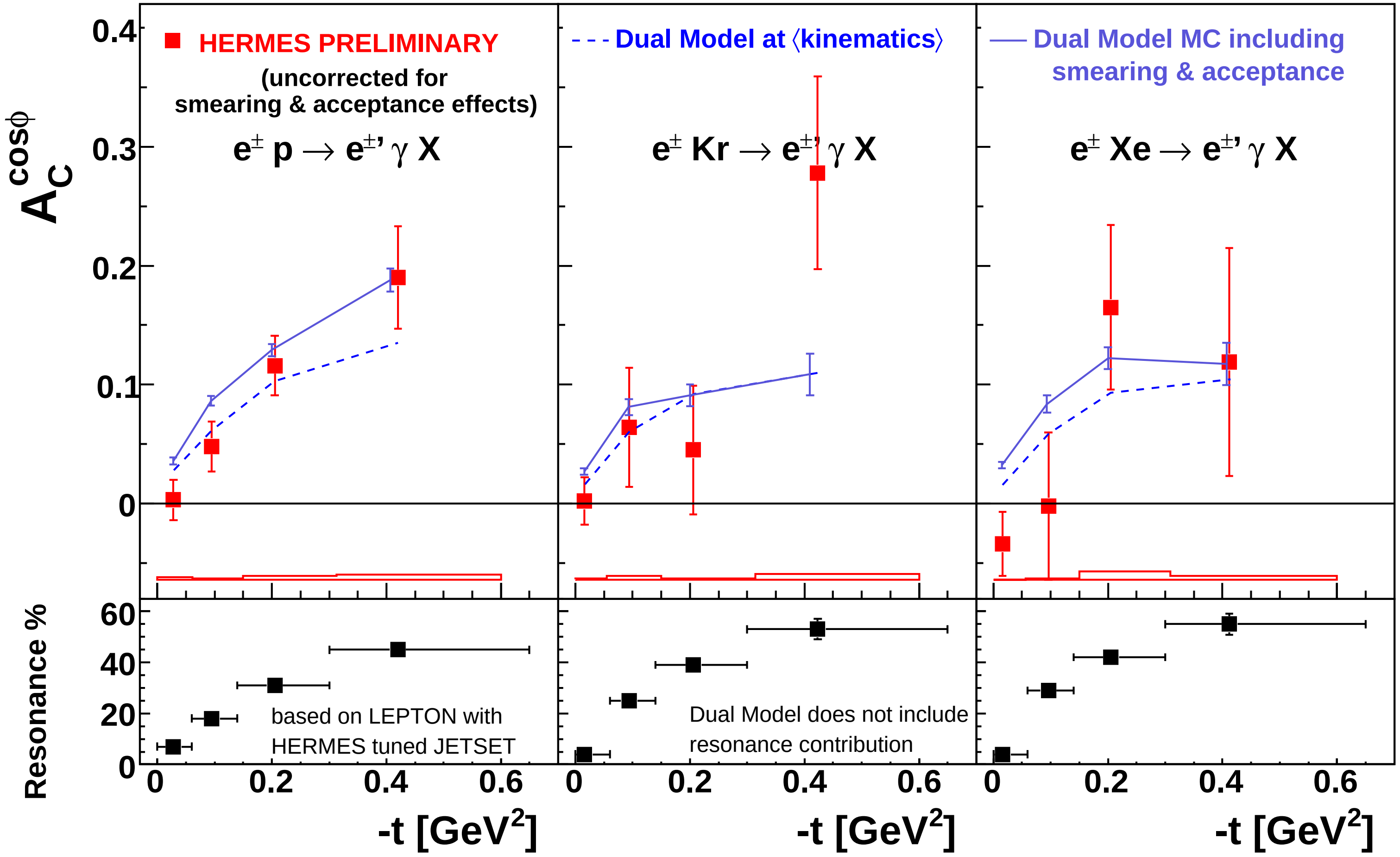
Smearing (small) and

acceptance not included.

- Measured ratio $A^{(I),\sin\phi}_{LU,A} / A^{(I),\sin\phi}_{LU,H} \approx 1$ for both samples
- Good agreement with Dual Model for all targets
- Not shown for both coherent and incoherent-enriched samples:
  - $*$ $A^{(I),\sin\phi}_{LU,A} \approx 0.2$, $A^{(DVCS),\sin\phi}_{LU,A} \approx 0$ and and $A^{\cos\phi}_{C} \approx 0$
  - $*$ No significant A-dependence from H to Xe for any of them

Nuclear DVCS: BCA vs. t

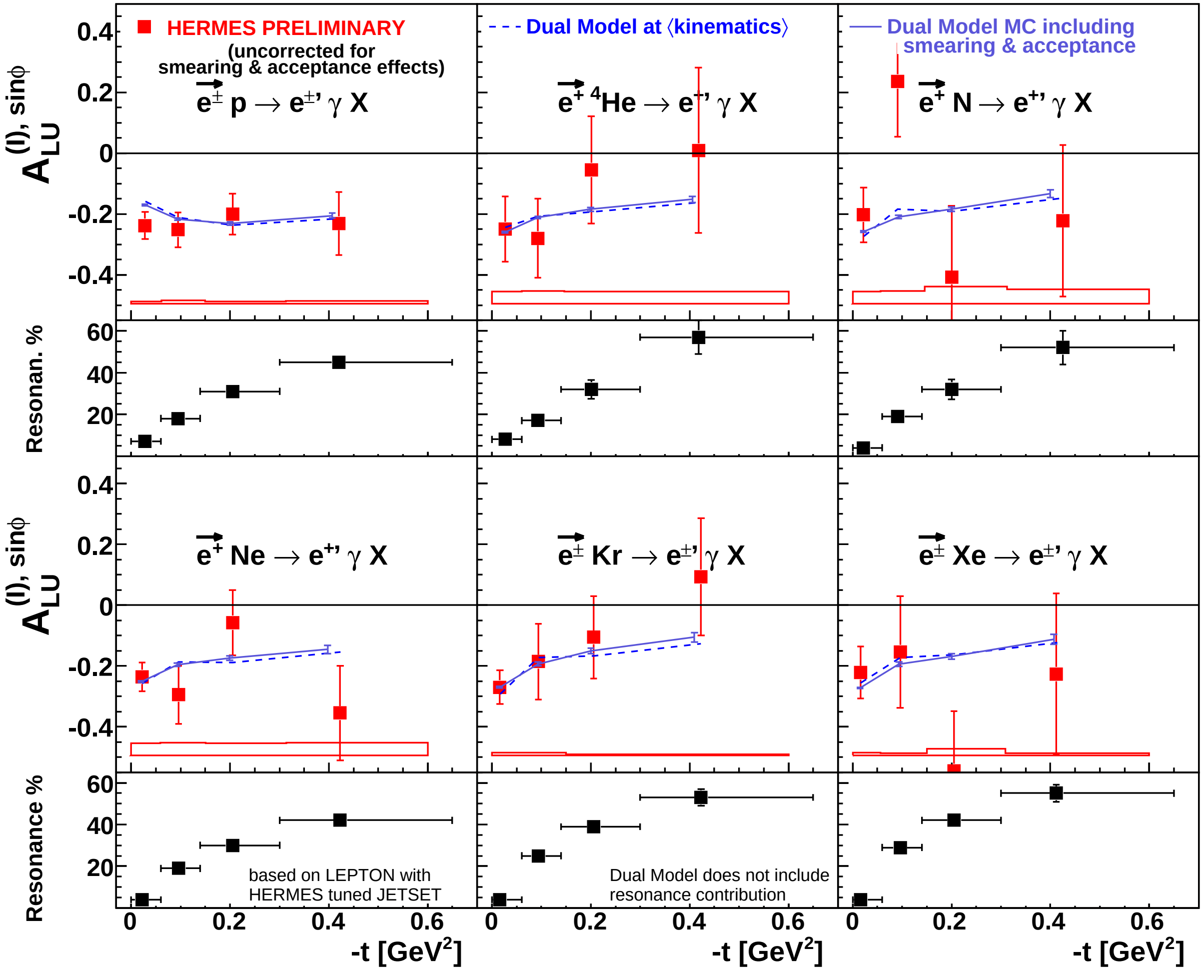
- Measured $A_C^{\cos\phi}$ vs. t (estimated resonance fraction shown for each bin)



- Kr and Xe agree with H within larger uncertainties of nuclear data
- all 3 targets agree with Dual Model calculations

Nuclear DVCS: BSA_I vs. t

- Measured $A_{LU}^{(I),\sin\phi}$ vs. t (estim. resonance fraction shown for each bin)



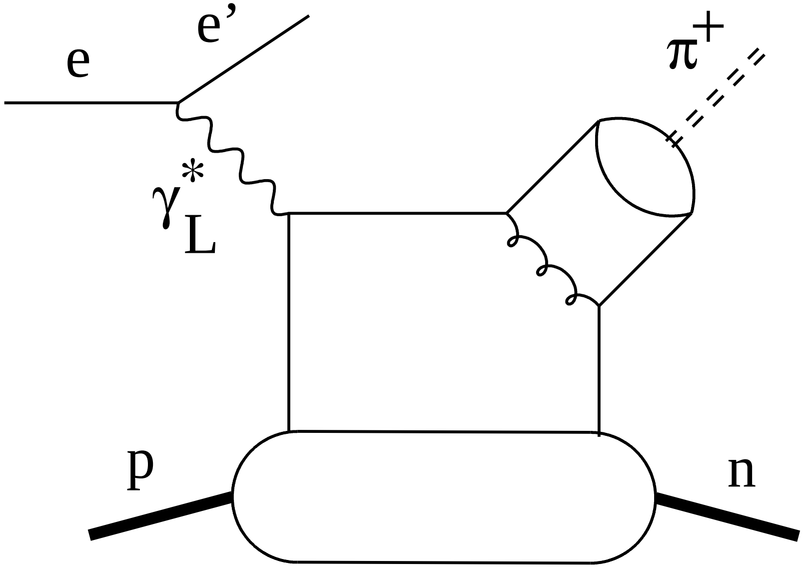
- Kr shows t dep. different from H, other 4 targets not conclusive
- all 6 targets agree with Dual Model calculations

Exclusive Meson Production

- In the limit of Q^2 large at x_B, t fixed, the $\gamma^* p$ amplitude factorises
- Contributions to the cross section:

γ_L^*	leading-twist
	(QCD factorisation theorem holds)
γ_L^*-γ_T^*	$\frac{1}{Q}$ suppressed
γ_T^*	$\frac{1}{Q^2}$ suppressed

! No precocious scaling at $Q^2 \geq 1\,\mathrm{GeV}^2$ for hard exclusive meson production !



- Exclusive production of

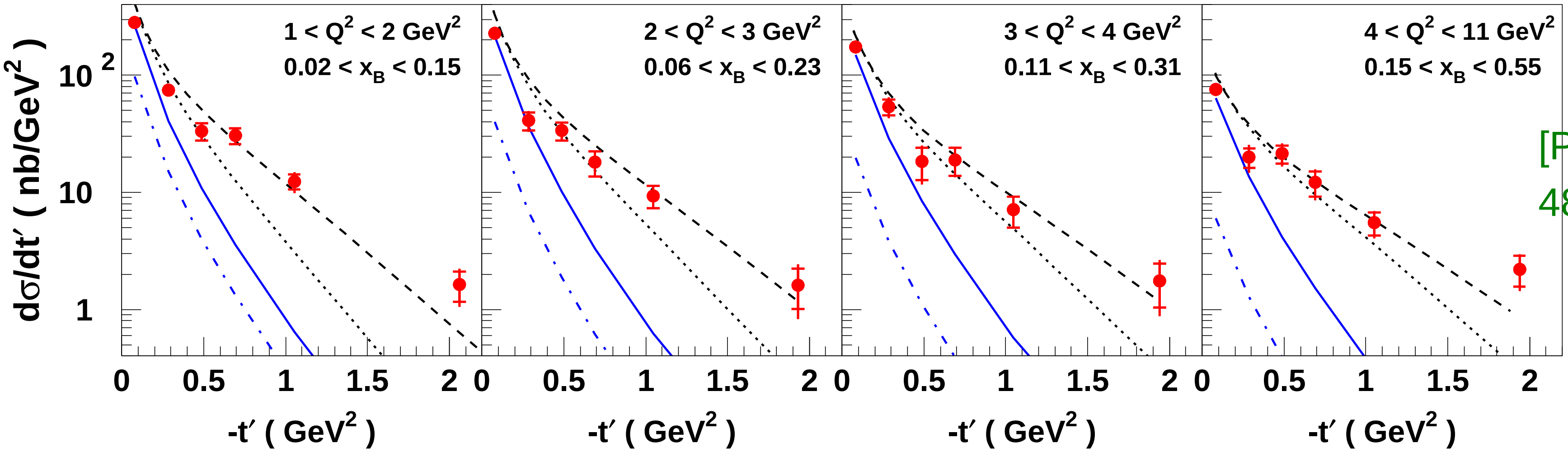
$$\gamma \rightarrow H, E, \widetilde{H}, \widetilde{E}$$
$$\rho, \omega, \phi \rightarrow H, E$$
$$\pi, \eta \rightarrow \widetilde{H}, \widetilde{E}$$

- For exclusive π^+ production $\gamma^* p \rightarrow \pi^+ n$:

$$\sigma_L \propto (1-\xi^2)|\widetilde{\mathcal{H}}|^2 - \xi^2\, t|\widetilde{\mathcal{E}}|^2 - \xi^2 \mathrm{Re}(\widetilde{\mathcal{E}}^* \widetilde{\mathcal{H}})$$

ξ: skewness

HERMES: Exclusive π^+ Diff. Cross Section



[PLB659, 486(2008)]

GPD model for $\frac{d\sigma_L}{dt'}$

[VGG PRD60(1999)094017]

$- \cdot -$ LO —— with power corr's

- $\widetilde{E}$ dominated by pion pole F_π
- $\widetilde{H}$ neglected
- Regge-inspired t dependence for $\widetilde{E}$
- power corrections due to intrinsic $k_\perp$ and soft-overlap contribution

⇒ Power corrections are needed! Fair agreement with data only at lower t'

Regge model

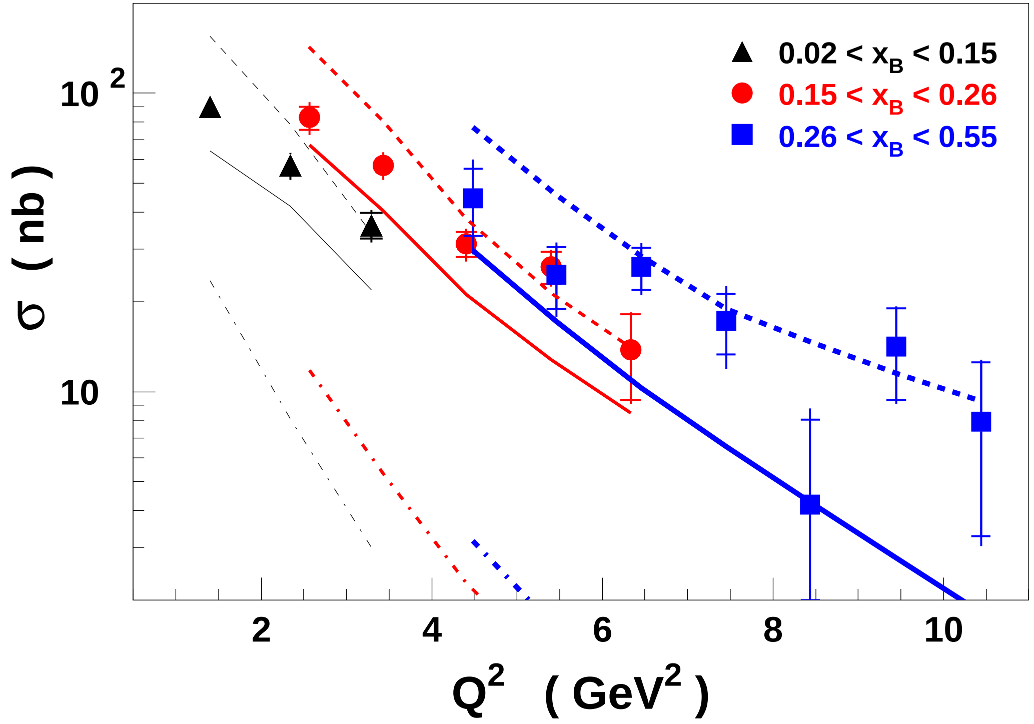
[J.M.Laget PRD70(2004)054023]

$- - - -$ $\frac{d\sigma}{dt}$ $\cdots\cdots$ $\frac{d\sigma_L}{dt}$

- π^+ production described by exchange of π and ρ Regge trajectories
- Q^2 and t' dep. FFs for $\pi\pi\gamma$ and $\pi\rho\gamma$
- σ_T predicted to be 15-25% of σ (about 6% at low t')

⇒ Good description of magnitude and $-t', Q^2$ dependences of the data

HERMES: Excl. π^+ Total Cross Section vs. Q^2, t



For analysis details see PLB659,486(2008), arXiv:0707.0222 [hep-ph]

GPD model for $\frac{d\sigma_L}{dt'}$

[VGG PRD60(1999)094017]

$- \cdot -$ LO $\quad$ —— with power corr's

$\Rightarrow$ Without power corrections: far below data

$\Rightarrow$ With power corrections: Still undershoot all data. Good agreement in shape, but only for $Q^2 < 6$ GeV^2 $\Rightarrow$???

Regge model

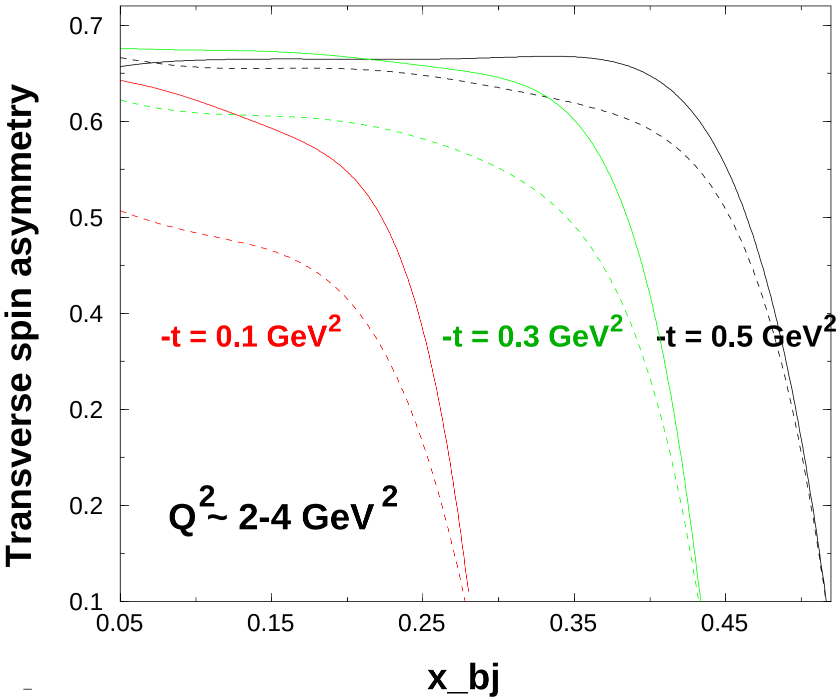
[J.M.Laget PRD70(2004)054023]

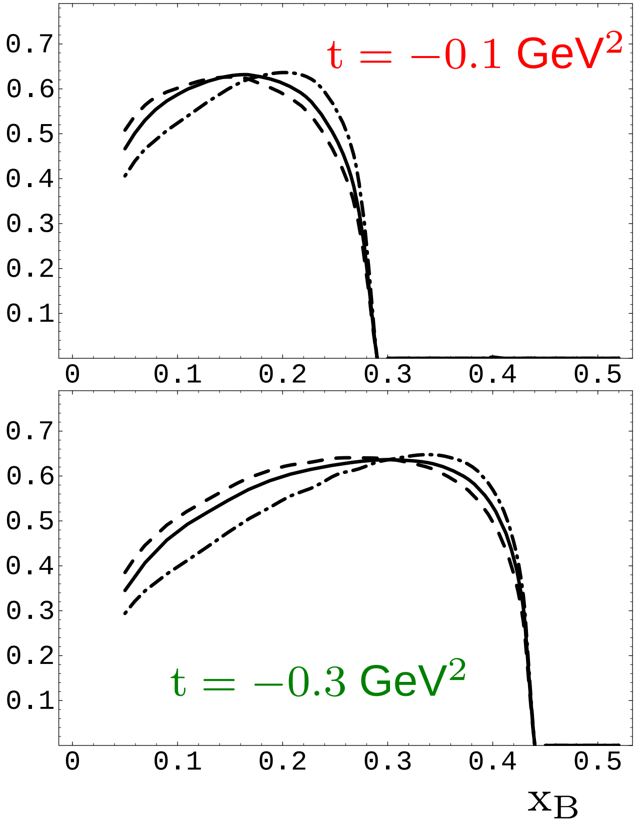
$- - -- \sigma$

$\Rightarrow$ For each x_B bin: good agreement at higher Q^2, but clear overshoot at lower Q^2 $\Rightarrow$???

Exclusive π^+ Transv. Target-spin Asymmetry

$$A_{UT}^{\sin(\phi-\phi_S)} \propto \frac{\mathrm{Im}(\widetilde{\mathcal{E}}^*\widetilde{\mathcal{H}})}{|\widetilde{\mathcal{H}}|^2-\xi^2\, t|\widetilde{\mathcal{E}}^2-\xi^2\mathrm{Re}(\widetilde{\mathcal{E}}^*\widetilde{\mathcal{H}})}$$





- $\widetilde{H}, \widetilde{E}$: Chiral-quark soliton model
- Asymptotic & Chernyak-Zhitnitsky DA

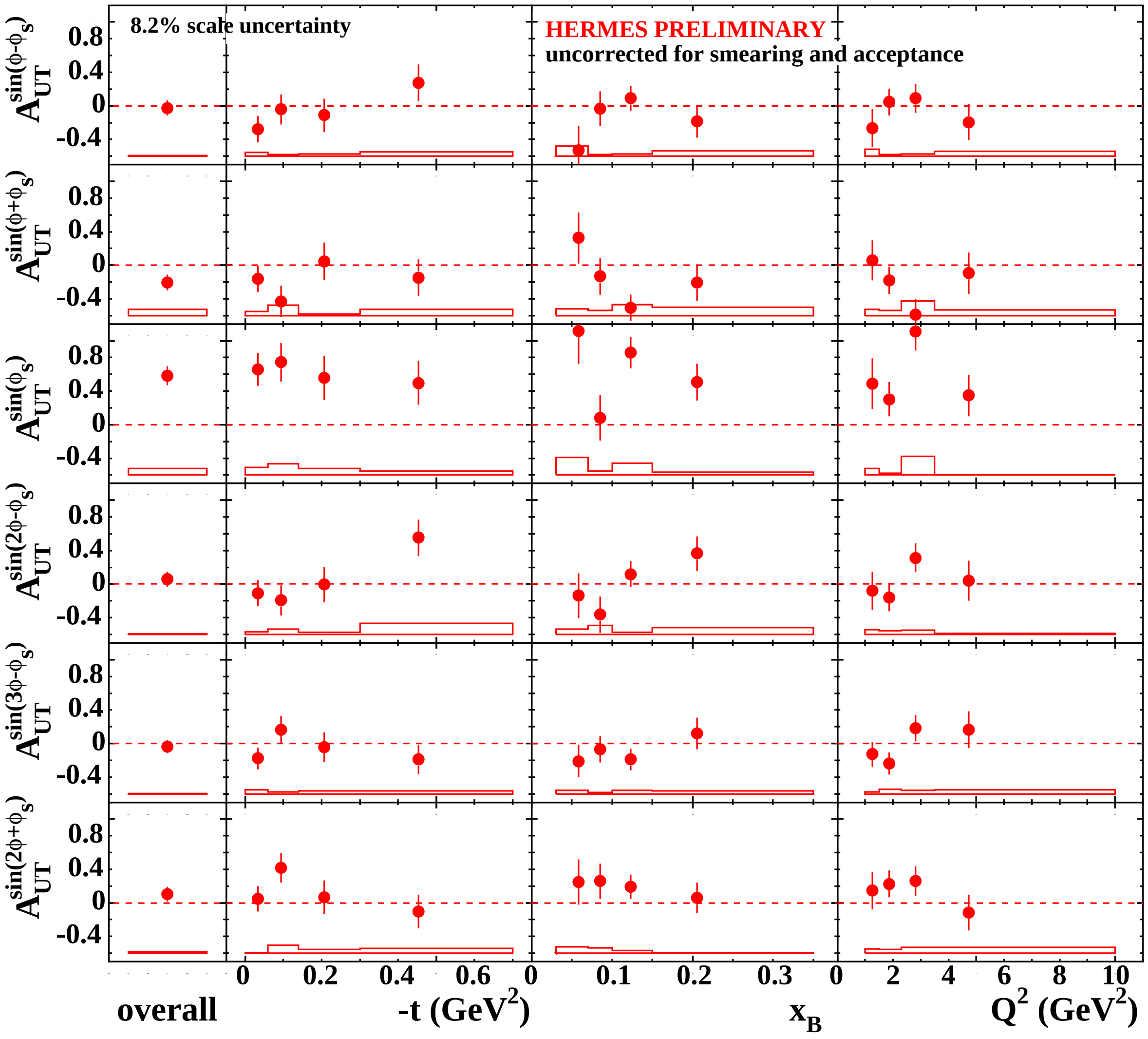
[Franfurt et al., PRL 84(2000)2589]

- $\widetilde{H}$: double-distribution ansatz
- $\widetilde{E}$: pion-pole dominated ansat
- Small NLO corrections!

[Belitsky,Mueller,PLB513(2001)349]

$\Longrightarrow$ Large asymmetry predicted by both models !

HERMES: Kinematic dependence of $A_{UT}^{\pi^+}$



$$e\;p \rightarrow e'\;\pi^+\;n$$

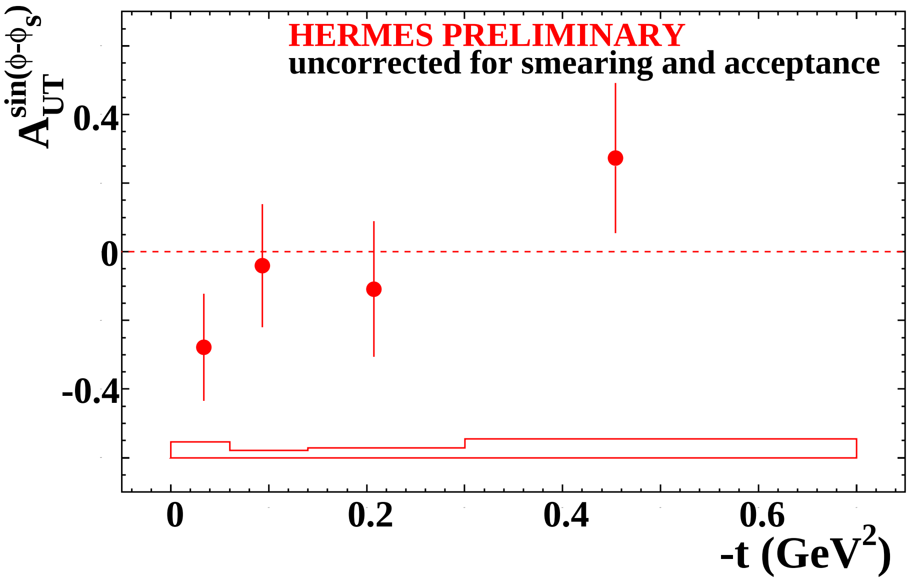
Preliminary result:

- Exclusive asymmetry in: $M_X^2 = [0.5 - 1.2]$ GeV^2
- Backgr. asymmetry from $M_X^2 = [1.9 - 3.3]$ GeV^2
- Average kinematics:
  $\langle -t \rangle = 0.182$ GeV^2
  $\langle x \rangle = 0.126$
  $\langle Q^2 \rangle = 2.38$ GeV^2

- Small overall value for leading effective asymmetry amplitude $A_{UT}^{\sin(\phi-\phi_S)}$
- Unexpected large overall value for effective asymmetry amplitude $A_{UT}^{\sin(\phi_S)}$

Exclusive π^+: Leading Asymmetry Amplitude

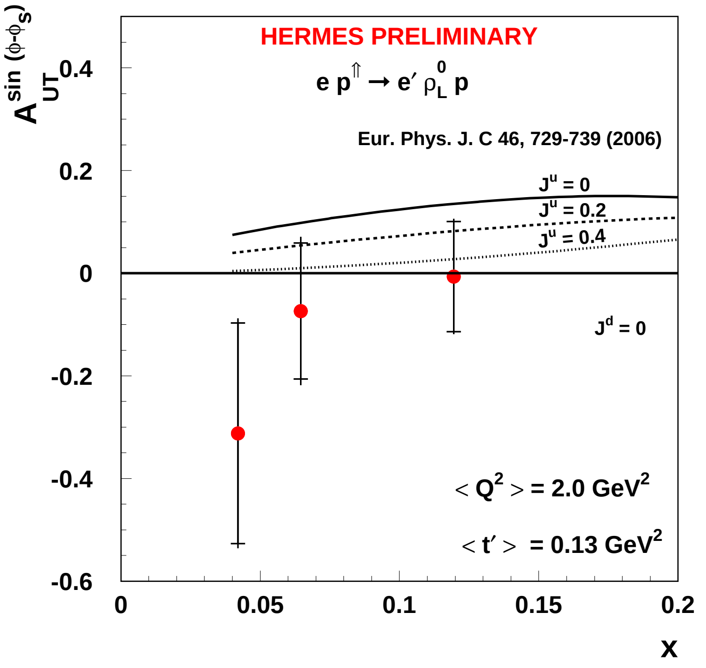
- Of main theoretical interest is the t dependence of the leading asymmetry amplitude $A_{UT}^{\sin(\phi-\phi_S)} \propto \mathrm{Im}(\widetilde{\mathcal{E}}^* \widetilde{\mathcal{H}})$:

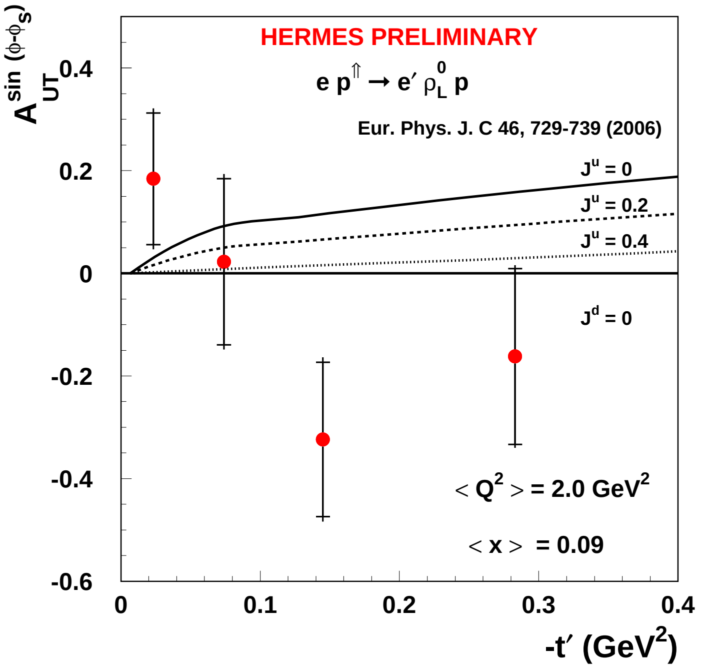


- Measurement indicates sign change-over or consistency with zero
- Cross section result indicates that power corrections to $\widetilde{E}$ are important
  - therefore $\widetilde{E}$ is supposedly large
  - but $\widetilde{H}$ remains small

$\Rightarrow$ $A_{UT}^{\sin(\phi-\phi_S)}$ measurement consistent with cross section result

Transv. Target-spin Asymmetry in ρ Prod.





Motivation to study ρ^0 TTSA (see EPJC46(2005)729)

Strongly simplified: $A^{\rho}_{UT} \propto \frac{E_q+E_g}{H_q+H_g}$

- **Only in ρ prod. gluon contribution enters in LO**
- asymmetry projections shown left are for **passive gluons**, i.e. $H_g \neq 0$ but $E_g = 0$
- for **active gluons**, i.e. $H_g \neq 0$ **and** $E_g \neq 0$, the asymmetry **may be** considerably larger

Preliminary result: full transverse target data set

- σ_L, σ_T separated by preceding determination of ρ^0 spin density matrix elements

Compare data vs. projections

- suggested value of J_u of order of 0.2 at $J_d = 0$
- consistent with J_u result from DVCS data
- statistics too low to reliably determine this value and its uncertainty
- simultaneous J_u, J_d fit from ρ^0 data impossible
- no indication for large active gluon contribution

Summary

- The HERMES experiment played a pioneering role in the study of exclusive photon and meson production. Azimuthal asymmetries were measured with respect to beam spin and charge, and to longitudinal and transverse target polarization. Also, a variety of unpolarized nuclear targets was used.
- An interpretation of the data in terms of GPDs has been started, also Regge-based models are challenged. Constraints on GPD models were obtained, in particular (model-dependent) constraints on the u and d-quark total angular momenta.
- Presently it appears that the quality of the data is higher than that of the available models !