HERMES Results on Hard Exclusive Reactions

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(Not covered: Determination of $\rho$ and $\phi$ 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
- Parton density
- Generalized parton distribution at \(\eta=0\)

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

\(\Rightarrow\) Parton’s transverse localization \(b_\perp\)

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 Distrib.** (GPDs) probe simultaneously transverse localization \(b_\perp\) for a given longitudinal momentum fraction \(x\).

2nd moment by Ji relation:

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

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Proton Spin Budget in a Nutshell

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

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

- 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 ($\Delta g$ 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:
\[
\frac{1}{2} = \mathcal{J}_q + \mathcal{J}_g = \frac{1}{2} \Delta \Sigma + \mathcal{L}_q + \mathcal{G} + \mathcal{L}_g
\]

- All 4 terms have a probabilistic interpretation
- $\Delta g$ is gauge invariant (being measured)

⇒ Results from both decompositions must not be mixed, as
\[
\mathcal{L}_q \neq L_q, \Delta g \neq \tilde{\Delta} g, \mathcal{L}_g \neq L_g, \text{ even } \mathcal{J}_g \neq J_g ! \text{ (courtesy M. Burkardt)}
\]
Deeply Virtual Compton Scattering

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

\[
d\sigma(eN \rightarrow eN\gamma) \propto |T_{BH}|^2 + |T_{DVCS}|^2 + T_{BH} T_{DVCS}^* + T_{BH}^* T_{DVCS} + I
\]

- \(T_{BH}\) is parameterized in terms of Dirac and Pauli Form Factors \(F_1, F_2\), calculable in QED.
- \(T_{DVCS}\) is parameterized in terms of Compton form factors \(H, E, \tilde{H}, \tilde{E}\) (which are convolutions of resp. GPDs \(H, E, \tilde{H}, \tilde{E}\))
- (Certain Parts of) interference term \(I\) can be filtered out by forming certain cross section differences (or asymmetries)

⇒ GPDs \(H, E, \tilde{H}, \tilde{E}\) indirectly accessible via interference term \(I\)
Kinematic Coverage of DVCS Experiments

Fixed-target experiments:
\[ x > 0.03, \ Q^2 < 10 \ \text{GeV}^2 \]

- 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:
\[ x_B < 0.01, \ Q^2 : 5...100 \ \text{GeV}^2: \]
- small skewness
\[ \Rightarrow \] almost forward GPDs!

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

\[ \Rightarrow \] only COMPASS can explore low-\( x_B \)!
Pure gas target: polarized H, D; unpolarized H, D, N, Ne, Kr, Xe

Forward spectrometer: 40 mrad ≤ Θ ≤ 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

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

- \( 5 < \theta_{\gamma*\gamma} < 45 \) mrad
- \(-t < 0.7 \) GeV
- \( 0.03 < x_B < 0.35 \)
- \( 1 < Q^2 < 10 \) GeV²
- \( W > 3 \) GeV
- \( \nu < 22 \) GeV
- \(- (1.5)^2 < M_X^2 < (1.7)^2 \) 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 $A$ in the measured cross-section:

- **Beam-charge asymmetry $A_C(\phi)$ [BCA]:**
  \[
  d\sigma(e^+, \phi) - d\sigma(e^-, \phi) \propto \text{Re}[F_1 \mathcal{H}] \cdot \cos \phi
  \]

- **Beam-spin asymmetry $A_{LU}(\phi)$ [BSA]:**
  \[
  d\sigma(\vec{e}, \phi) - d\sigma(\vec{e}, \phi) \propto \text{Im}[F_1 \mathcal{H}] \cdot \sin \phi
  \]

- **Long. target-spin asymmetry $A_{UL}(\phi)$:**
  \[
  d\sigma(\vec{P}, \phi) - d\sigma(\vec{P}, \phi) \propto \text{Im}[F_1 \tilde{\mathcal{H}}] \cdot \sin \phi \text{ [LTSA]}
  \]

- **Transverse target-spin asymmetry $A_{UT}(\phi, \phi_s)$ [TTSA]:**
  \[
  d\sigma(\phi, \phi_s) - d\sigma(\phi, \phi_s + \pi) \propto \text{Im}[F_2 \mathcal{H} - F_1 \mathcal{E}] \cdot \sin (\phi - \phi_s) \cos \phi \\
  + \text{Im}[F_2 \tilde{\mathcal{H}} - F_1 \tilde{\mathcal{E}}] \cdot \cos (\phi - \phi_s) \sin \phi
  \]
  ($F_1, F_2$ are the Dirac and Pauli elastic nucleon form factors)
HERMES Combined BSA & BCA Analysis

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

$$\sigma_{LU}(\phi; P_l, e_l) = \sigma_{UU}(\phi)[1 + e_1 A_C(\phi) + e_1 P_l A^I_{LU}(\phi) + P_l A^{DVCS}_{LU}(\phi)]$$

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

**BCA:**

$$A_C(\phi) = \frac{1}{\sigma_{UU}} c^I_1 \cos \phi + \cdots \quad c^I_1 \propto \frac{\sqrt{-t}}{Q} F_1 \Re \mathcal{H} + [\cdots]$$

**BSA (interference term):**

$$A^I_{LU}(\phi) = \frac{1}{\sigma_{UU}} s^I_1 \sin \phi + \cdots \quad s^I_1 \propto \frac{\sqrt{-t}}{Q} F_1 \Im \mathcal{H} + [\cdots]$$

**BSA (DVCS term):**

$$A^{DVCS}_{LU}(\phi) = \frac{1}{\sigma_{UU}} s^{DVCS}_1 \sin \phi \quad \text{(small at HERMES energy)}$$

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 $\mathcal{H}$

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

Fit to data:

$$A_C(\phi) = \sum_{n=0}^{3} A^\cos n\phi \cos n\phi$$

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

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

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

$\Rightarrow$ well defined in theory, can be compared to GPD models!
HERMES Combined BSA & BCA Results

BSA

\[ \propto F_1 \text{Im} \mathcal{H} \]

\[ \propto \sin \phi \]

\[ \propto \cos \phi \]

BCA

\[ \propto -A_C \]

\[ \propto F_1 \text{Re} \mathcal{H} \]

\[ \propto \cos 2\phi \]

\[ \propto \cos 3\phi \]

\[ 0 < -t < 0.7 \]

\[ 0.03 < x_B < 0.35 \]

\[ 1 < Q^2 < 10 \]
Discussion of Combined BSA & BCA Analysis

- HERMES BSA agrees with Dual model Guzey, (Polyakov), Teckentrup 2006
- HERMES BCA disfavours factorized $t$ dep., in both models and D-term in VGG
- Pure $|DVCS|^2$ asymmetries found compatible with zero (as models assume)
  $\Rightarrow$ HERMES data precise enough to discriminate between models or their variants
  $\Rightarrow$ 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%

$\Rightarrow$ In data associated production has to be treated as part of the signal, while in models it is not included (still unknown) $\Rightarrow$ What to do?
HERMES Long. Target-spin Asymmetry vs. $\phi$

\[ A_{UL}(\phi) = \frac{1}{\langle |P_L| \rangle} \cdot \frac{d\sigma^{\rightarrow}(\phi) - d\sigma^{\leftarrow}(\phi)}{d\sigma^{\rightarrow}(\phi) + d\sigma^{\leftarrow}(\phi)} \propto F_1 \text{Im} \tilde{H} \sin \phi \]

⇒ extract ‘effective’ asymmetry amplitudes by fitting per $\phi$-bin:
\[ A_{UL}(\phi) = c + A_{UL}^{\sin \phi} \sin \phi + A_{UL}^{\sin 2\phi} \sin 2\phi \]

\[ \leftarrow \text{proton} \quad \text{deuteron} \Rightarrow \]

- FULL existing data set analyzed (1996-2000 data)
- $s_1$ : expected $\sin \phi$ behaviour : $2\sigma$ ($1.5\sigma$) on p (d)
- $s_2$ : unexpected, sizeable ($>3\sigma$) $A_{UL}^{\sin 2\phi}$ on p ($1.7\sigma$ on d) ⇒ 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: $F_3^3 = F_{WW}^3 + F_{qGq}^3$

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

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!

Why TTSA Data Expected to be Sensitive to $J_q$ ?

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

**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: $E_q(x, \xi) = E^{DD}_q(x, \xi) - \theta(|\xi - |x||) D_q \left( \frac{x}{\xi} \right)$

- using double distr. $K_q$: $E^{DD}_q(x, \xi) = \int_{-1}^{1} d\beta \int_{-1}^{1-|\beta|} d\alpha \delta(x - \beta - \alpha \xi) K_q(\beta, \alpha)$

- with $K_q(\beta, \alpha) = h(\beta, \alpha) e_q(\beta)$ and $e_q(x) = A_q \text{qval}(x) + B_q \delta(x)$ based on chiral QSM

- where coeff.s $A_q, B_q$ 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]
Model-dependent constraints on $J_u$ vs $J_d$

**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-$\sigma$ constraints on $J_u$ vs. $J_d$:

- **Double-distribution model:** $J_u + J_d/2.8 = 0.49 \pm 0.17$ (exp$_{\text{tot}}$)

- **Dual model** [Guzey, Teckentrup]: $J_u + J_d/2.8 = -0.02 \pm 0.27$ (exp$_{\text{tot}}$)

- **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 \( t \)
  \( \rightarrow \) 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 \( t \)
- Obtain enriched samples: coherent: \( -t < -t_{coh.} \), incoherent: \( -t > -t_{incoh.} \)

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: \( \frac{A_{nucleus}}{A_{proton}} \) (generalized EMC effect)
Nuclear DVCS: Beam-charge Asymmetry

- All nuclear data (1997-2005) incl.

‘Combined’ analysis for H, Kr, Xe targets using $e^\pm$ beam

- $\pi^0$ 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 $A_{LU,A}^{(I),\sin \phi} / A_{LU,H}^{(I),\sin \phi} \approx 1$ for both samples

Good agreement with Dual Model for all targets

Not shown for both coherent and incoherent-enriched samples:
* $A_{LU,A}^{(I),\sin \phi} \approx 0.2$, $A_{LU,A}^{(DVCS),\sin \phi} \approx 0$ and $A_{C}^{\cos \phi} \approx 0$
* 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)

**HERMES PRELIMINARY**

(uncorrected for smearing & acceptance effects)

$e^+ p \rightarrow e^+ \gamma X$

$e^+ Kr \rightarrow e^+ \gamma X$

$e^+ Xe \rightarrow e^+ \gamma X$

-- Dual Model at (kinematics)

Dual Model MC including smearing & acceptance

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:

  $\gamma^*_L$ leading-twist
  
  (QCD factorisation theorem holds)

  $\gamma^*_L - \gamma^*_T$ suppressed

  $\gamma^*_T$ suppressed

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

- Exclusive production of

  $\gamma \rightarrow H, E, \tilde{H}, \tilde{E}$

  $\rho, \omega, \phi \rightarrow H, E$

  $\pi, \eta \rightarrow \tilde{H}, \tilde{E}$

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

  $\sigma_L \propto (1 - \xi^2) |\tilde{H}|^2 - \xi^2 t |\tilde{E}|^2 - \xi^2 \text{Re}(\tilde{E}^* \tilde{H})$

  $\xi$: skewness
**HERMES: Exclusive $\pi^+$ Diff. Cross Section**

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

[VGG PRD60(1999)094017]

- - - LO with power corr's

- $\tilde{E}$ dominated by pion pole $F_\pi$
- $\tilde{H}$ neglected
- Regge-inspired $t$ dependence for $\tilde{E}$
- 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


- - - - $\frac{d\sigma}{dt}$  . . . . . . . . $\frac{d\sigma_L}{dt'}$

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

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

[PLB659, 486(2008)]
HERMES: Excl. $\pi^+$ Total Cross Section vs. $Q^2$, $t$

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

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

[VGG PRD60(1999)094017]

- - - LO  with power corr's

⇒ Without power corrections: far below data
⇒ With power corrections: Still undershoot all data. Good agreement in shape, but only for $Q^2 < 6$ GeV$^2$ ⇒ ???

Regge model


- - - - - $\sigma$

⇒ For each $x_B$ bin: good agreement at higher $Q^2$, but clear overshoot at lower $Q^2$ ⇒ ??
Exclusive $\pi^+$ Transv. Target-spin Asymmetry

\[ A_{UT}^{\sin(\phi - \phi_S)} \propto \frac{\text{Im}(\tilde{E}^* \tilde{H})}{|\tilde{H}|^2 - \xi^2 t |\tilde{E}|^2 - \xi^2 \text{Re}(\tilde{E}^* \tilde{H})} \]

\[ t = -0.1 \text{ GeV}^2 \]

\[ t = -0.3 \text{ GeV}^2 \]

\[ t = 0 \text{ GeV}^2 \]

\[ Q^2 \sim 2-4 \text{ GeV}^2 \]

\[ x_{bj} \]

\[ \tilde{H}, \tilde{E} \]: Chiral-quark soliton model

\[ \text{Asymptotic & Chernyak-Zhitnitsky DA} \]

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

\[ \Rightarrow \text{Large asymmetry predicted by both models!} \]

\[ \tilde{H} \]: double-distribution ansatz

\[ \tilde{E} \]: pion-pole dominated ansatz

\[ \text{Small NLO corrections!} \]

[Belitsky,Mueller,PLB513(2001)349]
HERMES: Kinematic dependence of $A_{UT}^{\pi^+}$

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

Preliminary result:

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

- Small overall value for leading effective asymmetry amplitude $A_{UT}^{\sin(\phi-\phi_S)}$
- Unexpected large overall value for effective asymmetry amplitude $A_{UT}^{\sin(\phi_S)}$
Of main theoretical interest is the $t$ dependence of the leading asymmetry amplitude $A_{UT}^{\sin(\phi - \phi_S)} \propto \text{Im}(\tilde{E}^*\tilde{H})$:

Measurement indicates sign change-over or consistency with zero

Cross section result indicates that power corrections to $\tilde{E}$ are important
  
  therefore $\tilde{E}$ is supposedly large
  
  but $\tilde{H}$ remains small

$\Rightarrow A_{UT}^{\sin(\phi - \phi_S)}$ measurement consistent with cross section result
Transv. Target-spin Asymmetry in $\rho^0$ Prod.

Motivation to study $\rho^0$ TTSA (see EPJC46(2005)729)

Strongly simplified:

$$A_{UT}^\rho \propto \frac{E_q+E_g}{H_q+H_g}$$

- Only in $\rho$ 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

$\sigma_L, \sigma_T$ separated by preceding determination of $\rho^0$ 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 $\rho^0$ 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!