Exclusive hard processes at HERMES

10th international workshop on hadron structure and spectroscopy
Venice, Italy, 2010

Ami Rostomyan
(on behalf of the HERMES collaboration)
**deeply virtual Compton scattering**

\[ \gamma^* \rightarrow \gamma : H, E, \tilde{H}, \tilde{E} \text{ (twist-2, chiral even)} \]

- \( H \) and \( \tilde{H} \) conserve the nucleon helicity
- \( E \) and \( \tilde{E} \) describe the nucleon helicity flip

**Ji relation**

\[
J_q = \frac{1}{2} \lim_{t \to 0} \int_{-1}^{1} dx \, x \left[ H_q(x, \xi, t) + E_q(x, \xi, t) \right]
\]

\[
= \frac{1}{2} \Delta \Sigma_q + L_q
\]

**why DVCS?**

- the cleanest probe of GPDs
- theoretical accuracy at NNLO
- no gluons in the LO

**Compton form factors**

convolutions of GPDs (\( F : H, E, \tilde{H}, \tilde{E} \)) and hard scattering functions

\[
\mathcal{F}(\xi, t) = \sum_q \int_{-1}^{1} dx \, C_q(\xi, x) \, F^q(x, \xi, t)
\]
exclusive meson production

factorization in collinear approximation

\[ A \propto F(x, \xi, t; \mu^2) \otimes K(x, \xi, z; \log(Q^2/\mu^2) \otimes \Phi(z; \mu^2) \]

at leading-twist: \( H, E, \tilde{H}, \tilde{E} \)
- \( H \) and \( \tilde{H} \) conserve the nucleon helicity
- \( E \) and \( \tilde{E} \) describe the nucleon helicity flip

quantum numbers of final state selects different GPDs

- **vector mesons** (\( \gamma^*_L \to \rho_L, \omega_L, \phi_L \)): \( H, E \)
- **pseudoscalar mesons** (\( \gamma^*_L \to \pi, \eta \)): \( \tilde{H}, \tilde{E} \)

factorization for \( \sigma_L \) (and \( \rho_L, \omega_L, \phi_L \) only)
- \( \sigma_L - \sigma_T \) suppressed by \( 1/Q \)
- \( \sigma_T \) suppressed by \( 1/Q^2 \)
exclusive meson production

modified perturbative approach

\[ \mathcal{A} \propto F(x, \xi, t; \mu^2) \otimes K(x, \xi, z; \log(Q^2/\mu^2)) \otimes \Phi(z, k_\perp; \mu^2) \]

at leading-twist: \( H, E, \tilde{H}, \tilde{E} \)

- \( H \) and \( \tilde{H} \) conserve the nucleon helicity
- \( E \) and \( \tilde{E} \) describe the nucleon helicity flip

quantum numbers of final state selects different GPDs

- vector mesons (\( \gamma^*_L \rightarrow L, \omega_L, \phi_L \)): \( H, E \)
- pseudoscalar mesons (\( \gamma^*_L \rightarrow \pi, \eta \)): \( \tilde{H}, \tilde{E} \)

factorization for \( \sigma_L \) (and \( \rho_L, \omega_L, \phi_L \)) only

- \( \sigma_L - \sigma_T \) suppressed by \( 1/Q \)
- \( \sigma_T \) suppressed by \( 1/Q^2 \)

power corrections: \( k_\perp \) is not neglected

- regulate the singularity in the transverse amplitude
- \( \gamma^*_T \rightarrow \rho^0_T \) transitions can be calculated (model dependent)
exclusive meson production

modified perturbative approach

\[ A \propto F(x, \xi, t; \mu^2) \otimes K(x, \xi, z; \log(Q^2/\mu^2)) \otimes \Phi(z, k_\perp; \mu^2) \]

at leading-twist: \( H, E, \tilde{H}, \tilde{E} \)
- \( H \) and \( \tilde{H} \) conserve the nucleon helicity
- \( E \) and \( \tilde{E} \) describe the nucleon helicity flip
quantum numbers of final state selects different GPDs
- vector mesons \( (\gamma^*_L \rightarrow \rho_L, \omega_L, \phi_L) \): \( H, E \)
- pseudoscalar mesons \( (\gamma^*_L \rightarrow \pi, \eta) \): \( \tilde{H}, \tilde{E} \)

factorization for \( \sigma_L \) (and \( \rho_L, \omega_L, \phi_L \)) only
- \( \sigma_L - \sigma_T \) suppressed by \( 1/Q \)
- \( \sigma_T \) suppressed by \( 1/Q^2 \)

power corrections: \( k_\perp \) is not neglected
- \( \gamma^*_T \rightarrow \rho_0^T \) transitions can be calculated (model dependent)
  - \( \rho^0 \): contributions from \( \tilde{H} \) and \( \tilde{E} \)
  - \( \pi^+ \): contributions from \( H_T \)

-Goloskokov, Kroll (2006)-
Deeply Virtual Compton Scattering (DVCS)

\( e^+ \gamma p \rightarrow e^+ \gamma p \Rightarrow \text{Interference!} \)

\[ \sigma_{ep} \propto |T_{BH}|^2 + |T_{DVCS}|^2 + T_{BH} T_{DVCS}^* + T_{BH}^* T_{DVCS} \]
Deeply Virtual Compton Scattering (DVCS)

Same initial and final states in DVCS and Bethe-Heitler $\Rightarrow$ Interference!

$$\sigma_{ep} \propto |T_{BH}|^2 + |T_{DVCS}|^2 + T_{BH}T_{DVCS}^* + T_{DVCS}^*T_{BH}$$

$\sigma_{XY}$

beam: $P_l$

target: $S_LS_T$

d$s_{ep} \sim s_{BH_{UU}} + s_{DVCS_{UU}}$

$+ e_\ell d\sigma_{LU} + P_\ell d\sigma_{DVCS_{LU}}$

$+ e_\ell S_L d\sigma_{UL} + S_L d\sigma_{DVCS_{UL}}$

$+ e_\ell S_T d\sigma_{UT} + S_T d\sigma_{DVCS_{UT}}$

$+ P_\ell S_L d\sigma_{LL} + e_\ell P_\ell S_L d\sigma_{DVCS_{LL}}$

$+ P_\ell S_T d\sigma_{LT} + e_\ell P_\ell S_T d\sigma_{DVCS_{LT}}$

Single spin terms: $LU, UL, UT$

- no pure Bethe-Heitler contribution

- project imaginary parts of Compton form factors

Unpolarized and double-spin terms:

$UU, LL, LT$

- project real parts of Compton form factors
Deeply Virtual Compton Scattering (DVCS)

same initial and final states in DVCS and Bethe-Heitler $\Rightarrow$ Interference!

$$\sigma_{ep} \propto |T_{BH}|^2 + |T_{DVCS}|^2 + T_{BH} T_{DVCS}^* + T_{BH}^* T_{DVCS}$$

Bethe-Heitler contribution: calculated at QED

DVCS contribution:

- HERMES: $|T_{DVCS}|^2 << |T_{BH}|^2$

interference term:

- depend on a linear combination of Compton form factors
- access to GPD combinations through azimuthal asymmetries

\[ d\sigma \sim d\sigma_{UU}^{BH} + e_\ell d\sigma_{UL}^I + d\sigma_{UL}^{DVCS} \]
\[ + e_\ell P_\ell d\sigma_{LU}^I + P_\ell d\sigma_{LU}^{DVCS} \]
\[ + e_\ell S_L d\sigma_{UL}^I + S_L d\sigma_{UL}^{DVCS} \]
\[ + e_\ell S_T d\sigma_{UT}^I + S_T d\sigma_{UT}^{DVCS} \]
\[ + P_\ell S_L d\sigma_{LL}^{BH} \]
\[ + e_\ell P_\ell S_L d\sigma_{LL}^I + P_\ell S_L d\sigma_{LL}^{DVCS} \]
\[ + e_\ell P_\ell S_T d\sigma_{LT}^I + P_\ell S_T d\sigma_{LT}^{DVCS} \]
express asymmetries in terms of Fourier coefficients

\[ \sigma(\phi, P_l, e_\ell) = \sigma_{UU}(\phi) \times \left[ 1 + P_l A_{LU}^{DVCS}(\phi) + e_\ell P_l A_{LU}^I(\phi) + e_\ell A_C(\phi) \right] \]

Fourier expansion in azimuthal angle \( \phi \)

\[ |\tau_{BH}|^2 \propto \sum_{n=0}^{2} c_n^{BH} \cos(n\phi) \]

\[ |\tau_{DVCS}|^2 \propto \sum_{n=0}^{2} c_n^{DVCS} \cos(n\phi) + P_l s_1^{DVCS} \sin \phi \]

\[ 1 \propto \sum_{n=0}^{3} c_n^{I} \cos(n\phi) + \sum_{n=1}^{2} P_l s_n^{I} \sin(n\phi) \]
express asymmetries in terms of Fourier coefficients

\[
\sigma(\phi, P_\ell, e_\ell) = \sigma_{UU}(\phi) \times \left[ 1 + P_\ell A_{LU}^{DVCS}(\phi) + e_\ell P_\ell A_{LU}^I(\phi) + e_\ell A_C(\phi) \right]
\]

Fourier expansion in azimuthal angle \( \phi \)

\[
|\tau_{BH}|^2 \propto \sum_{n=0}^{2} c_{n}^{BH} \cos(n\phi)
\]

\[
|\tau_{DVCS}|^2 \propto \sum_{n=0}^{2} c_{n}^{DVCS} \cos(n\phi) + P_\ell s_{1}^{DVCS} \sin \phi
\]

\[
1 \propto \sum_{n=0}^{3} c_{n}^{I} \cos(n\phi) + \sum_{n=1}^{2} P_\ell s_{n}^{I} \sin(n\phi)
\]

\[
c_{1}^{I} \propto F_1 \text{Re}\mathcal{H}
\]

\[
c_{0}^{I} \propto -\frac{t}{Q} c_{1}^{I}
\]

\[
s_{1}^{I} \propto F_1 \text{Im}\mathcal{H}
\]
express asymmetries in terms of Fourier coefficients

$$\sigma(\phi, P_\ell, e_\ell) = \sigma_{UU}(\phi) \times \left[ 1 + P_\ell A_{LU}^{DVCS}(\phi) + e_\ell P_\ell A_{LU}^I(\phi) + e_\ell A_C(\phi) \right]$$

Fourier expansion in azimuthal angle $\phi$

$$|\tau_{BH}|^2 \propto \sum_{n=0}^{2} c_n^{BH} \cos(n\phi)$$

$$|\tau_{DVCS}|^2 \propto \sum_{n=0}^{2} c_n^{DVCS} \cos(n\phi) + P_\ell s_1^{DVCS} \sin \phi$$

$$1 \propto \sum_{n=0}^{3} c_n^{I} \cos(n\phi) + \sum_{n=1}^{2} P_\ell s_n^{I} \sin(n\phi)$$

DVCS term:

<table>
<thead>
<tr>
<th>azimuthal modulation</th>
<th>$\gamma^*(\mu) \rightarrow \gamma(\mu')$</th>
<th>relative order</th>
</tr>
</thead>
<tbody>
<tr>
<td>constant</td>
<td>$+1 \rightarrow +1$</td>
<td>$1$</td>
</tr>
<tr>
<td>$\cos \phi, \sin \phi$</td>
<td>$0 \rightarrow +1$</td>
<td>$1/Q$</td>
</tr>
<tr>
<td>$\cos 2\phi, \sin 2\phi$</td>
<td>$-1 \rightarrow +1$</td>
<td>$1/Q^2$ (gluon GPDs)</td>
</tr>
</tbody>
</table>

$$c_1^{I} \propto F_1 \Re \mathcal{H}$$
$$c_0^{I} \propto -\frac{-t}{Q} c_1^{I}$$
$$s_1^{I} \propto F_1 \Im \mathcal{H}$$
Express asymmetries in terms of Fourier coefficients

\[
\sigma(\phi, P_\ell, e_\ell) = \sigma_{UU}(\phi) \times \left[ 1 + P_\ell A_{LU}^{DVCS}(\phi) + e_\ell P_\ell A_{LU}^I(\phi) + e_\ell A_C(\phi) \right]
\]

Fourier expansion in azimuthal angle \( \phi \)

\[
|\tau_{BH}|^2 \propto \sum_{n=0}^{2} c_{n}^{BH} \cos(n\phi)
\]

\[
|\tau_{DVCS}|^2 \propto \sum_{n=0}^{2} c_n^{DVCS} \cos(n\phi) + P_\ell s_1^{DVCS} \sin \phi
\]

\[
1 \propto \sum_{n=0}^{3} c_n^{I} \cos(n\phi) + \sum_{n=1}^{2} P_\ell s_n^{I} \sin(n\phi)
\]

Interference term:

| azimuthal modulation | \( \gamma^* (\mu) \rightarrow \gamma(\mu') \) | relative order |
|----------------------|------------------------------------------|
| constant             | +1 \rightarrow +1                        | 1/Q |
| \( \cos \phi, \sin \phi \) | +1 \rightarrow +1                        | 1 |
| \( \cos 2\phi, \sin 2\phi \) | 0 \rightarrow +1                        | 1/Q |
| \( \cos 3\phi, \sin 3\phi \) | -1 \rightarrow +1                        | 1/Q^2 \text{ or } \alpha_s |

\[
c_1^{I} \propto F_1 \text{Re} H
\]

\[
c_0^{I} \propto -\frac{t}{Q} c_1^{I}
\]

\[
s_1^{I} \propto F_1 \text{Im} H
\]
DVCS at HERMES (pre-recoil data)

\[ e + p \rightarrow e' + \gamma + p' \]

- Detected particles: lepton and photon
- Missing mass technique for

\[ ep \rightarrow e'\gamma X : \quad M^2_X = (p + e - e' - \gamma)^2 \]
unpolarized-target asymmetries

\[ \sigma(\phi, P_\ell, e_\ell) = \sigma_{UU}(\phi) \times \left[ 1 + P_\ell A_{LU}^{DVCS}(\phi) + e_\ell P_\ell A_{LU}^I(\phi) + e_\ell A_C(\phi) \right] \]

beam-helicity asymmetry (single charge):

\[ A_{LU}(\phi) \equiv \frac{d\sigma^{\rightarrow \rightarrow} - d\sigma^{\leftarrow \leftarrow}}{d\sigma^{\rightarrow \rightarrow} + d\sigma^{\leftarrow \leftarrow}} \]

- projects the imaginary part of \( \tau_{DVCS} \)
- no separate access to \( s_{1,DVCS} \) and \( s_{1,I} \)

beam-helicity asymmetry (new approach):

- charge-difference beam-helicity asymmetry

\[ A_{LU}^I(\phi) \equiv \frac{(d\sigma^{+ \rightarrow} - d\sigma^{+ \leftarrow}) - (d\sigma^{- \rightarrow} - d\sigma^{- \leftarrow})}{(d\sigma^{+ \rightarrow} + d\sigma^{+ \leftarrow}) + (d\sigma^{- \rightarrow} + d\sigma^{- \leftarrow})} \]

- charge-averaged beam-helicity asymmetry

\[ A_{LU}^{DVCS}(\phi) \equiv \frac{(d\sigma^{+ \rightarrow} - d\sigma^{+ \leftarrow}) + (d\sigma^{- \rightarrow} - d\sigma^{- \leftarrow})}{(d\sigma^{+ \rightarrow} + d\sigma^{+ \leftarrow}) + (d\sigma^{- \rightarrow} + d\sigma^{- \leftarrow})} \]

- \( s_{1,DVCS} \) and \( s_{1,I} \) can be disentangled

beam-charge asymmetry:

\[ A_C(\phi) \equiv \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} \]

- projects the real part of \( \tau_{DVCS} \)
**beam helicity asymmetry**

\[ A_{LU}^I(\phi) = 2 \sum_{n=1}^{2} A_{LU,I}^{\sin(n\phi)} \sin(n\phi) \propto \sum_{n=1}^{2} s_I^n \sin(n\phi) \]

\[ A_{LU,DVCS}^{\sin \phi} \propto s_{1}^{DVCS} \sin \phi \]


<table>
<thead>
<tr>
<th>( A_{LU,I}^{\sin \phi} )</th>
<th>( A_{LU,DVCS}^{\sin \phi} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>VGG Regge</td>
<td>Dual-GT Regge</td>
</tr>
</tbody>
</table>

- twist-2:
  - large overall value
  - no kin. dependencies

- twist-3
  - overall value compatible with 0
  - no kin. dependencies

- overshoot the magnitude of \( A_{LU,I}^{\sin \phi} \) by a factor of 2
- describe the shape of kin dependencies on \( x_B \) and \( Q^2 \), but not on \( t \)
- overestimation is not due to the associated production

-Ami Rostomyan- – p. 9
beam charge asymmetry

\[ A_C(\phi) = \sum_{n=0}^{3} A_C^{\cos(n\phi)} \cos(n\phi) \propto \sum_{n=0}^{3} c_i \cos(n\phi) \]


- Ami Rostomyan - p. 10

**twist-2 GPDs:** \( A_C^{\cos \phi}, A_C^{\cos 0\phi} 

- strong \( t \)-dependence
- no \( x_B, Q^2 \) dependencies

\[ A_C^{\cos \phi} \propto F_1 \text{Re}\mathcal{H} \]
\[ A_C^{\cos 0\phi} \propto -\frac{t}{Q} A_C^{\cos \phi} \]

\( A_C^{\cos(2\phi)} \approx 0 \): twist-3 GPDs
\( A_C^{\cos(3\phi)} \approx 0 \): gluon helicity-flip GPDs

**theoretical predictions:**
- does not describe the beam-helicity data, but in good agreement with this data
unpolarized deuterium targets

cohherent: $e^\pm d \rightarrow e^\pm d\gamma$

target stays intact

spin-1 targets described by 9 GPDs:
$H_1^q, H_2^q, H_3^q, H_4^q, H_5^q, \tilde{H}_1^q, \tilde{H}_2^q, \tilde{H}_3^q, \tilde{H}_4^q$

incoherent: $e^\pm d \rightarrow e^\pm pn\gamma$

target brakes up

spin-$\frac{1}{2}$ targets described by 4 GPDs:
$H, E, \tilde{H}, \tilde{E}$

- Data
- Monte Carlo sum
- incoherent BH + DVCS
- coherent BH + DVCS
- BH with resonance exc.

coherent: contribution at small $-t$

incoherent: contribution at larger $-t$

contribution from coherent $[0.06 : 0.7]$ GeV$^2$: 20%
beam-charge asymmetry

\[ A_C(\phi) = \sum_{n=0}^{3} A_C^{\cos(n\phi)} \cos(n\phi) \]


twist-2:

\[ A_{C,coh}^{\cos \phi} \propto G_1 \text{Re}H_1 \]

\[ A_{C,incoh}^{\cos \phi} \propto F_1 \text{Re}H \]

\[ A_C^{\cos 0\phi} \propto -\frac{t}{Q} A_C^{\cos \phi} \]

higher twist:

\[ A_C^{\cos(2\phi)} \approx 0 \]

\[ A_C^{\cos(3\phi)} \approx 0 \]

- d and p results consistent
- small values of \(-t\):
  differences due to coherent contribution
- larger values of \(-t\):
  differences due to neutron contribution
transversely polarized target

\[ \sigma(\phi, P_S, S_T) = \sigma_{UU}(\phi) \times \left[ 1 + S_T A^{DVCS}_{UT}(\phi, \phi_S) + S_T e_\ell A^I_{UT}(\phi, \phi_S) + e_\ell A_C(\phi) \right] \]

transverse target-spin asymmetry:

\[ A_{UT}(\phi, \phi_S) = \frac{1}{S_T} \cdot \frac{d\sigma^{\uparrow\uparrow}(\phi, \phi_S) - d\sigma^{\downarrow\downarrow}(\phi, \phi_S)}{d\sigma^{\uparrow\uparrow}(\phi, \phi_S) + d\sigma^{\downarrow\downarrow}(\phi, \phi_S)} \]

beam-charge asymmetry:

\[ A_C(\phi) \equiv \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} \]

\[ A^{DVCS}_{UT}(\phi, \phi_S) \equiv \frac{1}{S_T} \cdot \frac{d\sigma^{\uparrow\uparrow}(\phi, \phi_S) - d\sigma^{\downarrow\downarrow}(\phi, \phi_S) + d\sigma^{-\uparrow}(\phi, \phi_S) - d\sigma^{-\downarrow}(\phi, \phi_S)}{d\sigma^{\uparrow\uparrow}(\phi, \phi_S) + d\sigma^{\downarrow\downarrow}(\phi, \phi_S) + d\sigma^{-\uparrow}(\phi, \phi_S) + d\sigma^{-\downarrow}(\phi, \phi_S)} \]

\[ A^I_{UT}(\phi, \phi_S) \equiv \frac{1}{S_T} \cdot \frac{d\sigma^{\uparrow\uparrow}(\phi, \phi_S) - d\sigma^{\downarrow\downarrow}(\phi, \phi_S) - d\sigma^{-\uparrow}(\phi, \phi_S) + d\sigma^{-\downarrow}(\phi, \phi_S)}{d\sigma^{\uparrow\uparrow}(\phi, \phi_S) + d\sigma^{\downarrow\downarrow}(\phi, \phi_S) - d\sigma^{-\uparrow}(\phi, \phi_S) + d\sigma^{-\downarrow}(\phi, \phi_S)} \]

- separation of \( s^{DVCS}_i, c^{DVCS}_i \) and \( s^I_i, c^I_i \) terms with same harmonic signatures
- projects the imaginary part of \( \tau_{DVCS} \)
transverse target-spin asymmetry

\[ A_{UT}(\phi, \phi_S) \propto \text{Im}\left[F_2 \mathcal{H} - F_1 \mathcal{E}\right] \sin(\phi - \phi_S) \cos \phi + \text{Im}\left[F_2 \mathcal{H} - F_1 \mathcal{E}\right] \sin(\phi - \phi_S) + \text{Im}\left[\mathcal{H}\mathcal{E}^* - \mathcal{E}\mathcal{H}^* + \xi \tilde{\mathcal{H}}\mathcal{E}^* - \tilde{\mathcal{H}} \xi \mathcal{E}^*\right] \sin(\phi - \phi_S) + \ldots \]

- \[ A_{UT}^{\sin(\phi-S)} \cos \phi \] found much more sensitive to \( J_u \) than others
- insensitive to \( J_d \), assumed \( J_d = 0 \) (supported by lattice QCD)
- with a good model, allows a model-dependent constraint
### HERMES DVCS

<table>
<thead>
<tr>
<th>Amplitude Value</th>
<th>Hydrogen</th>
<th>Deuterium</th>
<th>Preliminary</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_C^{\cos(0\phi)}$</td>
<td><img src="image1" alt="Graph" /></td>
<td><img src="image2" alt="Graph" /></td>
<td><img src="image3" alt="Graph" /></td>
</tr>
<tr>
<td>$A_C^{\cos \phi}$</td>
<td><img src="image4" alt="Graph" /></td>
<td><img src="image5" alt="Graph" /></td>
<td><img src="image6" alt="Graph" /></td>
</tr>
<tr>
<td>$A_C^{\cos(2\phi)}$</td>
<td><img src="image7" alt="Graph" /></td>
<td><img src="image8" alt="Graph" /></td>
<td><img src="image9" alt="Graph" /></td>
</tr>
<tr>
<td>$A_C^{\cos(3\phi)}$</td>
<td><img src="image10" alt="Graph" /></td>
<td><img src="image11" alt="Graph" /></td>
<td><img src="image12" alt="Graph" /></td>
</tr>
<tr>
<td>$A_{LU,I}^{\sin \phi}$</td>
<td><img src="image13" alt="Graph" /></td>
<td><img src="image14" alt="Graph" /></td>
<td><img src="image15" alt="Graph" /></td>
</tr>
<tr>
<td>$A_{LU,DVCS}^{\sin(2\phi)}$</td>
<td><img src="image16" alt="Graph" /></td>
<td><img src="image17" alt="Graph" /></td>
<td><img src="image18" alt="Graph" /></td>
</tr>
<tr>
<td>$A_{LU,I}^{\sin(\phi - \theta)}$</td>
<td><img src="image19" alt="Graph" /></td>
<td><img src="image20" alt="Graph" /></td>
<td><img src="image21" alt="Graph" /></td>
</tr>
<tr>
<td>$A_{UT,I}^{\sin(\phi - \theta)}$</td>
<td><img src="image22" alt="Graph" /></td>
<td><img src="image23" alt="Graph" /></td>
<td><img src="image24" alt="Graph" /></td>
</tr>
<tr>
<td>$A_{UT,DVCS}^{\sin(\phi - \theta) \cos \phi}$</td>
<td><img src="image25" alt="Graph" /></td>
<td><img src="image26" alt="Graph" /></td>
<td><img src="image27" alt="Graph" /></td>
</tr>
<tr>
<td>$A_{UT,I}^{\cos(\phi - \theta) \sin \phi}$</td>
<td><img src="image28" alt="Graph" /></td>
<td><img src="image29" alt="Graph" /></td>
<td><img src="image30" alt="Graph" /></td>
</tr>
<tr>
<td>$A_{UL}^{\sin \phi}$</td>
<td><img src="image31" alt="Graph" /></td>
<td><img src="image32" alt="Graph" /></td>
<td><img src="image33" alt="Graph" /></td>
</tr>
<tr>
<td>$A_{UL}^{\sin(2\phi)}$</td>
<td><img src="image34" alt="Graph" /></td>
<td><img src="image35" alt="Graph" /></td>
<td><img src="image36" alt="Graph" /></td>
</tr>
<tr>
<td>$A_{UL}^{\cos(0\phi)}$</td>
<td><img src="image37" alt="Graph" /></td>
<td><img src="image38" alt="Graph" /></td>
<td><img src="image39" alt="Graph" /></td>
</tr>
<tr>
<td>$A_{LL}^{\cos \phi}$</td>
<td><img src="image40" alt="Graph" /></td>
<td><img src="image41" alt="Graph" /></td>
<td><img src="image42" alt="Graph" /></td>
</tr>
<tr>
<td>$A_{LL}^{\cos(2\phi)}$</td>
<td><img src="image43" alt="Graph" /></td>
<td><img src="image44" alt="Graph" /></td>
<td><img src="image45" alt="Graph" /></td>
</tr>
<tr>
<td>$A_{LL}^{\cos(\phi)}$</td>
<td><img src="image46" alt="Graph" /></td>
<td><img src="image47" alt="Graph" /></td>
<td><img src="image48" alt="Graph" /></td>
</tr>
</tbody>
</table>

- **Beam-charge asymmetry:** \( \text{Re}\mathcal{H} \)
- **Beam-helicity asymmetry:** \( \text{Im}\mathcal{H} \)
- **Transverse target-spin asymmetry:** \( \text{Im}(\mathcal{H}\mathcal{E}) \)
- **Longitudinal target-spin asymmetry:** \( \text{Im}\tilde{\mathcal{H}} \)
- **Double-spin asymmetry:** \( \text{Re}\tilde{\mathcal{H}} \)
vector meson polarization

- $\gamma^*$ and $\rho^0, \phi, \omega$ have the same quantum numbers
- helicity transfer $\gamma^* \rightarrow \rho^0, \phi, \omega$
- signature: $\rho^0, \phi, \omega$ production angular distribution

- the spin-state of the $\rho^0, \phi, \omega$ is reflected in the orbital angular momentum of decay particles
- $\rho^0, \phi, \omega$ (in the rest frame): $J = L + S = 1$
- $\pi, K : S = 0, \ L = 1$
- signature: decay angular distribution
\[
\frac{d\sigma}{dx_B dQ^2 dt d\phi_s d\phi d\cos \vartheta d\varphi} \sim \frac{d\sigma}{dx_B dQ^2 dt} W(x_B, Q^2, t, \phi_s, \phi, \cos \vartheta, \varphi)
\]
vector meson cross section

\[ \frac{d\sigma}{dx_B \, dQ^2 \, dt \, d\phi_s \, d\phi \, d\cos \, \theta \, d\phi} \sim \frac{d\sigma}{dx_B \, dQ^2 \, dt} \, W(x_B, Q^2, t, \phi_s, \phi, \cos \, \theta, \varphi) \]

production and decay angular distributions $W$ decomposed:

\[ W = W_{UU} + P_l W_{LU} + S_L W_{UL} + P_l S_L W_{LL} + S_T W_{UT} + P_l S_T W_{LT} \]
vector meson cross section

\[
\frac{d\sigma}{dx_B dQ^2 dt d\phi_s d\phi d\cos \vartheta d\varphi} \sim \frac{d\sigma}{dx_B dQ^2 dt} W(x_B, Q^2, t, \phi_s, \phi, \cos \vartheta, \varphi)
\]

production and decay angular distributions \(W\) decomposed:

\[
W = W_{UU} + P_l W_{LU} + S_L W_{UL} + P_l S_L W_{LL} + S_T W_{UT} + P_l S_T W_{LT}
\]

parametrized by helicity amplitudes \(T_{\lambda\lambda'}\) or \(T^\nu_{\mu\lambda}\):

- Schilling, Wolf (1973)
- Diehl notation (2007)
**vector meson cross section**

\[
\frac{d\sigma}{dx_B \, dQ^2 \, dt \, d\phi_s \, d\phi \, d\cos \vartheta \, d\varphi} \sim \frac{d\sigma}{dx_B \, dQ^2 \, dt} \cdot W(x_B, Q^2, t, \phi_s, \phi, \cos \vartheta, \varphi)
\]

Production and decay angular distributions \(W\) decomposed:

\[W = W_{UU} + P_l W_{LU} + S_L W_{UL} + P_l S_L W_{LL} + S_T W_{UT} + P_l S_T W_{LT}\]

Parametrized by helicity amplitudes \(T_{\lambda\lambda'}\) or \(T_{\mu\lambda}^{\nu\sigma}\):

- Schilling, Wolf (1973)

\[T_{\lambda\lambda'}, \quad T_{\mu\lambda}^{\nu\sigma}\]

Or alternatively by spin-density matrix elements (SDMEs):

\[\rho^0, \quad p^*, \quad \rho_{\mu\mu'}, \quad \gamma^*, \quad \gamma^*, \quad p\]

- Diehl notation (2007)
Regge theory: the diffractive production of vector meson via an exchange of a particle

\[ e + p \rightarrow e' + V + Q^2 \]

natural parity

\[ P = (-1)^J \text{ : exchange of } \rho, \omega, f_2, a_2 \]
\[ \propto M/W \]

unnatural parity

\[ P = -(-1)^J \text{ : exchange of } \pi, a_1, b_1 \]
\[ \propto (M/W)^2 \]

unnatural-parity exchange contribution is expected only at lower values of \( W \)
(un)natural-parity exchange

Regge theory: the diffractive production of vector meson via an exchange of a particle

natural parity

\[ P = (-1)^J \text{: exchange of } \rho, \omega, f_2, a_2 \]
or pomeron

\[ \propto \frac{M}{W} \]

unnatural parity

\[ P = -(-1)^J \text{: exchange of } \pi, a_1, b_1 \]

\[ \propto \left(\frac{M}{W}\right)^2 \]

unnatural-parity exchange contribution is expected only at lower values of \( W \)

GPD formalism: generalized to characterize the symmetry properties of amplitudes under
the helicity reversal of the \( \gamma^* \) and \( \rho^0 \)

natural parity

related to GPDs \( H \) and \( E \)

unnatural parity

related to GPDs \( \bar{H} \) and \( \bar{E} \)

pomeron exchange \( \Rightarrow \) gluon exchange

only NPE

reggeon exchange \( \Rightarrow \) quark exchange

NPE and UPE
exclusive vector meson sample

- no recoil proton detection
- elastic scattering:
  \[ \Delta E = \frac{M_x^2 - M^2}{2M} \approx 0 \]
- only little energy transferred to the target
  \[ t = (q - v)^2 \]
- transverse four-momentum transfer is used
  \[ t' = t - t_0 \]
- main contribution at small values of \( \Delta E \) and \( t' \)
- non-exclusive events:
  \[ \Delta E > 0 \]
- SIDIS background estimated by PYTHIA MC
$\rho^0$: unpolarized & beam-polarized SDMEs

SDMEs shown according to hierarchy of NPE helicity amplitudes:

$$|T_{00}|^2 \sim |T_{11}|^2 \gg |T_{01}|^2 > |T_{10}|^2 \sim |T_{-11}|^2$$


unpolarized SDMEs: $W_{UU}$
beam-polarized SDMEs: $W_{UL}$
hierarchy confirmed experimentally
proton and deuteron data consistent

$s$-channel helicity conservation:
($\rho^0$ conserves the helicity of $\gamma^*$)

- significant $\gamma^*_L \to \rho^0_L$ and $\gamma^*_T \to \rho^0_T$
- a substantial interference

$s$-channel helicity violation
(vertically line corresponds to SCHC)

- significant $\gamma^*_T \to \rho^0_L$
- smaller $\gamma^*_L \to \rho^0_T$ and $\gamma^*_T \to \rho^0_T$
- $2 - 10\sigma$ level violation
\( \rho^0 - \phi: \text{ comparison} \)

SDMEs shown according to hierarchy of NPE helicity amplitudes:

\[
|T_{00}|^2 \sim |T_{11}|^2 \gg |T_{01}|^2 > |T_{10}|^2 \sim |T_{-11}|^2
\]

unpolarized SDMEs: \( W_{UU} \)

beam-polarized SDMEs: \( W_{UL} \)

polarized SDMEs have been measured by HERMES for the first time

no statistically significant difference between proton and deuteron

no s-channel helicity violation

hierarchy of amplitudes:

\[
T_{00} \sim T_{11} \\
T_{01} \approx T_{10} \approx T_{-11} \approx 0
\]
$\rho^0$: observation of unnatural-parity exchange

UPE contributions measured from SDMEs:

$$u_1 = 1 - r_{00}^{04} + 2r_{1-1}^{04} - 2r_{11}^{1} - 2r_{1-1}^{1}, \quad u_2 = r_{11}^{5} + r_{1-1}^{5}, \quad u_3 = r_{11}^{8} + r_{1-1}^{8}$$

the combinations of SDMEs expected to be the zero in case of NPE dominance

![Graphs showing $u_1$, $u_2$, and $u_3$ as functions of $Q^2$ and $-t'$](image)

proton: $u_1 = 0.125 \pm 0.021_{\text{stat}} \pm 0.050_{\text{sys}}$

deuteron: $u_1 = 0.091 \pm 0.016_{\text{stat}} \pm 0.046_{\text{sys}}$

UPE contribution is $W$-dependent
\( \phi \): observation of unnatural-parity exchange

\[
U_1 = 1 - r_{00}^{04} + 2r_{1,-1}^{04} - 2r_{1,-1}^{1} - 2r_{11}^{1}
\]

\[
U_2 = r_{1,-1}^{5} + r_{11}^{5}
\]

\[
U_3 = r_{1,-1}^{8} + r_{11}^{8}
\]

\[
Q^2 \text{(GeV}^2\text{)}
\]

\[
-t' \text{ (GeV}^2\text{)}
\]

- Ami Rostomyan -

\[
u_1 = 0.02 \pm 0.07_{\text{stat}} \pm 0.16_{\text{sys}}
\]

\[
u_2 = -0.03 \pm 0.01_{\text{stat}} \pm 0.03_{\text{sys}}
\]

\[
u_3 = -0.05 \pm 0.12_{\text{stat}} \pm 0.07_{\text{sys}}
\]

no signal of unnatural-parity exchange

expected since dominant contribution to the production is from two gluon exchange
transverse SDMEs: $n_{\nu \nu'}^{\rho}$ and $s_{\mu \mu'}^{\nu \nu'}$


- measured for the first time

- average kinematics:
  - $\langle -t' \rangle = 0.13$ GeV$^2$
  - $\langle x_B \rangle = 0.09$
  - $\langle Q^2 \rangle = 2.0$ GeV$^2$

- related to the proton helicity-flip amplitude

- suppressed by a factor $\sqrt{-t}/2M_p$
'transverse' SDMEs: $n_{\nu\nu}'$ and $s_{\mu\mu}'$


\[
\gamma_L^* \to \rho_L^0 \quad \text{and} \quad \gamma_T^* \to \rho_T^0
\]

\[
\text{Im } s_{-+}^{-+}, \text{ and } \text{Im } (s_{0+}^{0+} - s_{0+}^{-0}) : \text{ deviate from 0 by } 2.5\sigma
\]

\[
\text{expected } s_{\mu\mu}' < n_{\nu\nu}' \quad \text{(if identical indices)}
\]

\[
s_{-+}^{-+} \text{ and } \text{Im } s_{0+}^{0+} \text{ involve }
\]

- Manaenkov (2008)

- the biggest NPE amplitudes
  \[N_{-+}^{-+} \text{ or } N_{0+}^{0+}\]

- the biggest UPE amplitude
  \[U_{-+}^{++}\]

- signal for unnatural-parity exchange

- related to GPDs $\bar{H}$ and $\bar{E}$

- dominant transitions

- single spin flip

- double spin flip
'transverse' SDMEs: $n^{\nu\nu'}_{\mu\mu'}$ and $s^{\nu\nu'}_{\mu\mu'}$


\[ \gamma^*_L \rightarrow \rho^0_L \text{ and } \gamma^*_T \rightarrow \rho^0_T \]

1. \( \text{Im} s^{-+}_{0+} \) and \( \text{Im}(s^{0+}_{0+} - s^{-+}_{00}) \) deviate from 0 by 2.5\( \sigma \).
2. Expected \( s^{\nu\nu'}_{\mu\mu'} < n^{\nu\nu'}_{\mu\mu'} \) (if identical indices).
3. \( s^{-+}_{0+} \) and \( \text{Im} s^{0+}_{0+} \) involve the biggest NPE amplitudes \( N^{-+} \) or \( N^{0+} \).
4. The biggest UPE amplitude \( U^{++}_{++} \).
5. Signal for unnatural-parity exchange related to GPDs $\vec{H}$ and $\vec{E}$.

\[ \gamma^*_T \rightarrow \rho^0_L \]

- Manaenkov (2008) -

\[ \text{Im} n^{00}_{0+}: 2.5\sigma \text{ deviation from 0} \]

- Ami Rostomyan - p. 25
$\rho^0$: transverse target-spin asymmetry


theoretically at leading order in $1/Q$

\[(\gamma^+_L \to \rho^0_L):\]

\[
A_{UT}^\sin(\phi-\phi_s) = \frac{\text{Im} n_{00}^{00}}{u_{00}^{00}}
\]

asymmetry in terms of GPDs

\[
A_{UT}^\sin(\phi-\phi_s) \propto \frac{E}{H} \propto \frac{E^q + E^g}{H^q + H^g}
\]

experimentally:

\[
A_{UT}^{\gamma^*_L}(\phi, \phi_s) = \frac{\text{Im}(n^{00}_{++} + \epsilon n^{00}_{00})}{u^{00}_{++} + \epsilon u^{00}_{00}}
\]

$u^{00}_{++}$ and $n^{00}_{++}$ are expected to be negligible

similarly, $\gamma^*_T \to \rho^0_T$:

\[
A_{UT}^{\gamma^*_T}(\phi, \phi_s) = \frac{\text{Im}(n^{++}_{++} + n^{--}_{++} + 2\epsilon n^{+++}_{00})}{u^{++}_{++} + u^{--}_{++} + 2\epsilon u^{+++}_{00}}
\]

compatible with 0 overall value:

\[
A_{UT}^{\rho^0_L, \sin(\phi-\phi_s)} = -0.033 \pm 0.058
\]
exclusive $\pi^+$ production: $ep \rightarrow e'\pi^+(n)$

- no recoil nucleon detection
- select exclusive $\pi^+$ reaction through the missing mass technique:

$$M_{x}^2 = (P_e + P_p - P_{e'} - P_{\pi^+})^2$$

$$N_{\text{excl}} = (\pi^+ - \pi^-)_{\text{data}} - (\pi^+ - \pi^-)_{\text{MC}}$$


<table>
<thead>
<tr>
<th>$\pi^+$</th>
<th>exclusive $\pi^+$</th>
<th>$VM_{\pi^+}$</th>
<th>SIDIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^-$</td>
<td>$VM_{\pi^-}$</td>
<td>SIDIS</td>
<td></td>
</tr>
</tbody>
</table>

$\pi^+ - \pi^-$ yield difference was used to subtract the non exclusive background

- exclusive peak centered at the nucleon mass
- exclusive MC based on GPD model
kinematic dependences of $A_{UT}^{π^+}$


- Diehl, Sapeta (2005)-

6 azimuthal moments extracted according to

average kinematics:

$\langle -t' \rangle = 0.18$ GeV$^2$
$\langle x_B \rangle = 0.13$
$\langle Q^2 \rangle = 2.38$ GeV$^2$

no $γ^*_L/γ^*_T$ separation

small overall value for leading asymmetry amplitude $A_{UT}^{\sin(φ−φ_s)}$

unexpected large overall value for asymmetry amplitude $A_{UT}^{\sin φ_s}$

other moments: consistent with 0

evidence of contributions from transversely polarized photons
leading azimuthal amplitude \( A^{\sin(\phi-\phi_s)}_{UT} \)

- not large asymmetry with possible sign change
- theoretical expectation: \( A^{\sin(\phi-\phi_s)}_{UT} \propto \sqrt{-t'} \)
- large negative asymmetry
  - Frankfurt et al. (2001)
  - Belitsky, Muller (2001)
- are the differences due to \( \gamma^*_T \)?
  - Goloskokov, Kroll (2009)
  - Bechler, Muller (2009)

azimuthal amplitude \( A^{\sin \phi_s}_{UT} \)

- no turnover towards 0 for \( t' \to 0 \)
- milde \( t \)-dependence
- can be explained only by \( \gamma^*_L / \gamma^*_T \) interference
- predictions \( A^{\sin \phi_s}_{UT} \approx \text{const} \)
- non-vanishing model predictions: contribution from \( H_T \)
GPDs, Meson Production and HERMES
backup slides
transverse target-spin asymmetry

\[
A_{UT}^{DVCS}(\phi, \phi_S) = \sum_{n=0}^{2} A_{UT}^{\sin(\phi-\phi_S)\cos(n\phi)} \sin(\phi - \phi_S) \cos(n\phi) \\
+ \sum_{n=1}^{2} A_{UT, DVCS}^{\cos(\phi-\phi_S)\sin(n\phi)} \cos(\phi - \phi_S) \sin(n\phi)
\]

\[
A_{UT}^{I}(\phi, \phi_S) = \sum_{n=0}^{2} A_{UT, I}^{\sin(\phi-\phi_S)\cos(n\phi)} \sin(\phi - \phi_S) \cos(n\phi) \\
+ \sum_{n=1}^{2} A_{UT, I}^{\cos(\phi-\phi_S)\sin(n\phi)} \cos(\phi - \phi_S) \sin(n\phi)
\]
longitudinal target polarization

\[
\sigma(\phi, P_L, S_L) = \sigma_{UU}(\phi) \times [1 + P_L A_{LU} + S_L A_{UL}(\phi) + S_L P_L A_{LL}(\phi)]
\]

beam helicity asymmetry:
\[
A_{LU}(\phi) \equiv \frac{d\sigma \rightarrow - d\sigma \leftarrow}{d\sigma \rightarrow + d\sigma \leftarrow}
\]

projects the imaginary part of \( \tau_{DVCS} \)

no separate access to \( s_1^{DVCS} \) and \( s_1^I \)

longitudinal target-spin asymmetry:
\[
A_{UL}(\phi) \equiv \frac{(d\sigma \rightarrow \Rightarrow + d\sigma \leftarrow \Rightarrow) - (d\sigma \rightarrow \Leftarrow + d\sigma \leftarrow \Leftarrow)}{(d\sigma \rightarrow \Rightarrow + d\sigma \leftarrow \Rightarrow) + (d\sigma \rightarrow \Leftarrow + d\sigma \leftarrow \Leftarrow)}
\]

projects the imaginary part of \( \tau_{DVCS} \)

double-spin asymmetry:
\[
A_{LL}(\phi) \equiv \frac{(d\sigma \rightarrow \Rightarrow + d\sigma \leftarrow \Leftarrow) - (d\sigma \rightarrow \Leftarrow \Rightarrow + d\sigma \Leftarrow \Leftarrow)}{(d\sigma \rightarrow \Rightarrow + d\sigma \leftarrow \Rightarrow) + (d\sigma \rightarrow \Leftarrow \Rightarrow + d\sigma \Leftarrow \Leftarrow)}
\]

projects the real part of \( \tau_{DVCS} \)
longitudinal target-spin asymmetry

\[ A_{UL}(\phi) = \sum_{n=1}^{2} A_{UL}^{n}(n\phi) \sin(n\phi) \propto \sum_{n=1}^{2} s_{n}^{I}, s_{n}^{DVCS} \]

HERMES PRELIMINARY
\( e^+ p/d \to e^+ \gamma X \) (M_\gamma < 1.7 GeV)
(in HERMES acceptance)

\( A_{UL}^{\sin \phi} \propto s_{1}^{I} \propto F_1 \text{Im} \tilde{H} \)

\( s_{1}^{I} \): twist-2

\( s_{1}^{DVCS} \): twist-3

model in good agreement with data

unexpected large value

\( s_{2}^{I} \): quark twist-3 or gluon twist-2

\( s_{2}^{DVCS} \): twist-4

model does not describe the data
**double-spin asymmetry**

\[ A_{LL}(\phi) \propto 2 \sum_{n=0}^{2} A_{LL}^{\cos(n\phi)} \cos(n\phi) \propto 2 \sum_{n=0}^{2} c_n^{DVCS} \]

- **twist-2**: \( \propto F_1 \text{Re} \bar{H} \)

- **twist-2 / twist-3**:

  \[ A_{LL}^{\cos \phi} \propto \begin{cases} c_0^{DVCS} \\ c_1^{I} \end{cases} \]

- **twist-3**:

  \[ A_{LL}^{\cos 2\phi} \propto \begin{cases} c_2^{I} \end{cases} \]

**model predictions**: The same model, as for BCA and BHA in good agreement with data.
\( \rho^0 \): observation of unnatural-parity exchange

UPE contributions measured from SDMEs:

\[
\begin{align*}
    u_1 &= 1 - r_{00}^{04} + 2r_{1-1}^{04} - 2r_{11}^{1} - 2r_{1-1}^{1}, \quad u_2 = r_{11}^{5} + r_{1-1}^{5}, \quad u_3 = r_{11}^{8} + r_{1-1}^{8} \\

    \text{UPE contributions expressed through amplitudes:}
    \end{align*}
\]

\[
\begin{align*}
    u_1 &\propto |U_{10}|^2 + 2|U_{11} + U_{1-1}|^2, \quad u_2 + iu_3 \propto (U_{11} + U_{1-1}) \ast U_{10} \\

    \text{the combinations of SDMEs expected to be the zero in case of NPE dominance:}
    \end{align*}
\]
\[ \rho_{\mu\mu',\lambda\lambda'} \propto \sum_{\sigma} T_{\mu\lambda}^{\nu\sigma} (T_{\mu'\lambda'}^{\nu'\sigma})^* \]
\( \rho^0 \): phase difference \( \delta \) between \( T_{00} \) and \( T_{11} \)


|\( \delta \)| obtained from unpolarizes SDMEs:
\[
\cos \delta = \frac{2 \sqrt{\epsilon (\Re r^{0}_{10} - \Im r^{0}_{10})}}{\sqrt{r^{04}_{00} (1 - r^{04}_{00} + r^{1}_{1-1} - \Im r^{2}_{1-1})}}
\]

sign of \( \delta \) obtained from polarizes SDMEs:
(for the first time)
\[
\sin \delta = \frac{2 \sqrt{\epsilon (\Re r^{8}_{10} - \Im r^{7}_{10})}}{\sqrt{r^{04}_{00} (1 - r^{04}_{00} + r^{1}_{1-1} - \Im r^{2}_{1-1})}}
\]

results on \( \delta \) (in degrees):
- proton: \( |\delta| = 26.4 \pm 2.3_{\text{stat}} \pm 4.9_{\text{sys}} \); \( \delta = 30.6 \pm 5.0_{\text{stat}} \pm 2.4_{\text{sys}} \)
- deuteron: \( |\delta| = 29.3 \pm 1.6_{\text{stat}} \pm 3.6_{\text{sys}} \); \( \delta = 36.3 \pm 3.9_{\text{stat}} \pm 1.7_{\text{sys}} \)

values are consistent
- with each other
- with H1 results: \( |\delta| = 21.5 \pm 4.3_{\text{stat}} \pm 5.3_{\text{sys}} \)
comparison with a GPD model

$Q^2$-dependence calculated for 3 different $W$ values:

- $W = 5$ GeV (HERMES)
- $W = 10$ GeV (COMPASS)
- $W = 90$ GeV (H1, ZEUS)

$\gamma^*_L \rightarrow \rho^0_L$ and $\gamma^*_T \rightarrow \rho^0_T$

- $1 - r_{00}^{04} \propto r_{1-1}^1 \propto -\Im r_{1-1}^2 \propto T_{11}$
- describe data for various $W$-ranges

interference of $\gamma^*_L \rightarrow \rho^0_L$ and $\gamma^*_T \rightarrow \rho^0_T$

- $r_{10}^5 \propto -\Im r_{10}^6 \propto T_{00}$ and $T_{11}$ interference
- model does not describe the data

- model uses phase difference $\delta = 3.1$ degree between $T_{00}$ and $T_{11}$

HERMES result: $\delta \approx 30$ degree
\( \rho^0: \text{comparison with GPD models} \)

Asymmetry in terms of GPDs

\[
A_{UT}^\sin(\phi - \phi_s) \propto \frac{E}{H} \propto \frac{E^q + E^g}{H^q + H^g}
\]

- Ellinghaus, Nowak, Vinnikov, Ye (2004)

Parametrization for \( H^q, H^{\bar{q}}, H^g \)

\( E^q \) is related to the total angular momenta \( J^u \) and \( J^d \)

Predictions for \( J^d = 0 \)

\( E^{\bar{q}} \) and \( E^g \) are neglected

Data favors positive \( J^u \)

Statistics too low to reliably determine the value of \( J^u \) and its uncertainty

Within the statistical uncertainty in agreement with theoretical calculations

Indication of small \( E^g \) and \( E^{\bar{q}} \)?

Other GPD model calculations

- Goeke, Polyakov, Vanderhaeghen (1999)-
- Goloskokov, Kroll (2007)-
- Diehl, Kugler (2008)-
ω: transverse target-spin asymmetry

6 azimuthal moments extracted using integrated angular distributions

- due to low statistics no $\omega_L/\omega_T$ separation
- predictions for large asymmetry
  \[ A_{\sin(\phi - \phi_s)}^{\omega} \approx -0.10 \]
- indication of negative $\sin(\phi - \phi_s)$ amplitude
  \[ A_{\sin(\phi - \phi_s)}^{\omega} = -0.22 \pm 0.16_{\text{stat}} \pm 0.11_{\text{sys}} \]
- no contradiction with $\rho^0$ predictions
  \[ A_{\sin(\phi - \phi_s)}^{\rho^0} \propto \Im \left\{ \frac{2E^u + E^d}{2H^u + H^d + H_g} \right\} \]
  \[ A_{\sin(2\phi - \phi_s)}^{\rho^0} \propto \Im \left\{ \frac{2E^u - E^d}{2H^u - H^d} \right\} \]