Exclusive mesons at HERMES

PACSPIN 2009, Yamagata, Japan

Ami Rostomyan

(on behalf of the HERMES collaboration)
exclusive meson production

factorization in collinear approximation -Collins, Frankfurt, Strikman (1997)-

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

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 \((\gamma^*_L \rightarrow \rho_L, \omega_L, \phi_L)\): \(H, E\)
- 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 \(1/Q^2\)
exclusive meson production

modified perturbative approach

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

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- \(\sigma_L - \sigma_T\) 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: \( H, E, \tilde{H}, \tilde{E} \)

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- vector mesons (\( \gamma^*_L \rightarrow \rho_L, \omega_L, \phi_L \)): \( H, E \)
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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

- \( \gamma^*_T \rightarrow \rho_T^0 \) transitions can be calculated (model dependent)
  - \( \rho^0 \): contributions from \( \tilde{H} \) and \( \tilde{E} \)
  - \( \pi^+ \): contributions from \( H_T \) and \( \tilde{H}_T \)
vector meson cross section

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

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

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

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

\[
\frac{d\sigma}{d x_B \, d Q^2 \, dt \, d\phi_s \, d\phi \, d\cos\vartheta \, d\varphi} \sim \frac{d\sigma}{d x_B \, d Q^2 \, dt} W(x_B, Q^2, t, \phi_s, \phi, \cos\vartheta, \varphi)
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parametrized by helicity amplitudes \( T_{\lambda\lambda'} \) or \( T^{\nu\sigma}_{\mu\lambda} \):

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

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

Production and decay angular distributions $W$ decomposed:

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

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

- Schilling, Wolf (1973)

\[ T_{\lambda\lambda'} \]

- Diehl notation (2007)

\[ T_{\mu\lambda}^{\nu\sigma} \]

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

- Ami Rostomyan

\[ V \]

- Ami Rostomyan

- p.4
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
(un)natural-parity exchange

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

\[ e \rightarrow e^* \]

\[ e \rightarrow e^* \]

\[ W^* \rightarrow W \]

\[ V \rightarrow e \]

\[ p \rightarrow p' \]

\[ Q^2 \]

\[ t \]

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 \( W \)
### (un)natural-parity exchange

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

<table>
<thead>
<tr>
<th>Natural Parity</th>
<th>Unnatural Parity</th>
</tr>
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<tbody>
<tr>
<td>[ P = (-1)^J ]: exchange of $\rho, \omega, f_2, a_2$ or pomeron</td>
<td>[ P = -(M/W)^2 ]: exchange of $\pi, a_1, b_1$</td>
</tr>
<tr>
<td>$\propto M/W$</td>
<td>$\propto (M/W)^2$</td>
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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 $\rho^0$

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<td>Related to GPDs $H$ and $E$</td>
<td>Related to GPDs $\tilde{H}$ and $\tilde{E}$</td>
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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 \( \gamma_L^* \to \rho_L^0 \) and \( \gamma_T^* \to \rho_T^0 \)

a substantial interference

\( s \)-channel helicity violation

(vertical line corresponds to SCHC)

significant \( \gamma_T^* \to \rho_L^0 \)

smaller \( \gamma_L^* \to \rho_T^0 \) and \( \gamma_{-T}^* \to \rho_T^0 \)

2 \(- 10\sigma \) level violation
\[ \rho^0 - \phi : \text{comparison} \]

SDMEs shown according to hierarchy of NPE helicity amplitudes:

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

HERMES PRELIMINARY

- \( \rho^0 \) proton, \( <Q^2> = 1.9 \text{ GeV}^2 \), \( <W> = 5 \text{ GeV} \)
- \( \phi \) proton and deuteron

A: \( \gamma^* L \to \gamma^0 L, \gamma^* T \to \gamma^0 T \)

B: Interference \( \gamma^* L \to \gamma^0 L, \gamma^* T \to \gamma^0 T \)

C: \( \gamma^* T \to \gamma^0 T \)

D: \( \gamma^* L \to \gamma^0 L \)

E: \( \gamma^* T \to \gamma^0 T \)

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:

\[ T_{00} \sim T_{11} \]
\[ T_{01} \approx T_{10} \approx T_{-11} \approx 0 \]
\( \rho^0 \): phase difference \( \delta \) between \( T_{00} \) and \( T_{11} \)

neglecting spin-flip amplitudes

<table>
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<th>[ \delta ] obtained from unpolarizes SDMEs:</th>
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<tr>
<td>[ \cos \delta = \frac{2\sqrt{\epsilon(\Re r_{10}^5 - \Im r_{10}^6)}}{\sqrt{r_{00}^{04}(1 - r_{00}^{04} + r_{1-1}^1 - \Im r_{1-1}^2)}} ]</td>
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<th>[ \delta ] obtained from polarizes SDMEs: (for the first time)</th>
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<td>[ \sin \delta = \frac{2\sqrt{\epsilon(\Re r_{10}^8 - \Im r_{10}^7)}}{\sqrt{r_{00}^{04}(1 - r_{00}^{04} + r_{1-1}^1 - \Im r_{1-1}^2)}} ]</td>
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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

$\frac{1-r_{00}^{04}}{2}$, $r_{1-1}^{1}$, $-Im r_{1-1}^{2}$, $Re r_{10}^{5}$, $Im r_{10}^{6}$

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

$W = 5 \text{ GeV (HERMES)}$

$W = 10 \text{ GeV (COMPASS)}$

$W = 90 \text{ GeV (H1, ZEUS)}$

$\gamma_L^* \rightarrow \rho_L^0$ and $\gamma_T^* \rightarrow \rho_T^0$

$1 - r_{00}^{04} \propto r_{1-1}^{1} \propto -Im r_{1-1}^{2} \propto T_{11}$

describe data for various $W$-ranges

interference of $\gamma_L^* \rightarrow \rho_L^0$ and $\gamma_T^* \rightarrow \rho_T^0$

$r_{10}^{5} \propto -Im r_{10}^{6} \propto T_{00}$ 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
$\rho^0$: 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

UPE contribution is $W$-dependent
φ: observation of unnatural-parity exchange

Expected since dominant contribution to the production is from two gluon exchange.

\[ u_1 = 0.02 \pm 0.07_{\text{stat}} \pm 0.16_{\text{sys}} \]
\[ u_2 = -0.03 \pm 0.01_{\text{stat}} \pm 0.03_{\text{sys}} \]
\[ u_3 = -0.05 \pm 0.12_{\text{stat}} \pm 0.07_{\text{sys}} \]
transverse SDMEs: $n_{\mu\mu'}^{\nu\nu'}$ 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: $n_{\mu\mu'}^\nu\nu'$ and $s_{\mu\mu'}^\nu\nu'$

Im $s_{++}^{-0}$ and Im $(s_{0+}^{0+} - s_{0+}^{0+})$: deviate from 0 by $2.5\sigma$

expected $s_{\mu\mu'}^\nu\nu' < n_{\mu\mu'}^\nu\nu'$ (if identical indices)

$s_{--}^{-}$ and Im $s_{0+}^{0+}$ involve

-Manaenkov (2008)-

the biggest NPE amplitudes $N_{--}^{-}$ or $N_{00}^{0+}$

the biggest UPE amplitude $U_{++}^{++}$

signal for unnatural-parity exchange

related to GPDs $\vec{H}$ and $\vec{F}$


$\gamma^* L \to \rho^0_L$ and $\gamma^* T \to \rho^0_T$

-AMI Rostomyan- – p.14
'transverse' SDMEs: $n_{\mu\mu'}^{\nu\nu'}$ and $s_{\mu\mu'}^{\nu\nu'}$


$\gamma_L^* \rightarrow \rho_L^0$ and $\gamma_T^* \rightarrow \rho_T^0$

- Im $s_{--}^{0+}$ and Im $(s_{0+}^{0+} - s_{0+}^{-0})$ deviate from 0 by $2.5\sigma$
- expected $s_{\mu\mu'}^{\nu\nu'} \leq n_{\mu\mu'}^{\nu\nu'}$ (if identical indices)
- $s_{--}^{-0}$ and Im $s_{0+}^{0+}$ involve

- Manaenkov (2008)

- the biggest NPE amplitudes $N_{--}^{0+}$ or $N_{00}^{0+}$
- the biggest UPE amplitude $U_{++}^{-+}$

- signal for unnatural-parity exchange related to GPDs $\vec{H}$ and $\vec{E}$

$\gamma_T^* \rightarrow \rho_L^0$

- Im $n_{0+}^{00}$: $2.5\sigma$ deviation from 0

SDME values

- Ami Rostomyan - p.14
\( \rho^0 \): transverse target-spin asymmetry

- theoretically at leading order in \( 1/Q \)

\( (\gamma^*_L \rightarrow \rho^0_L) \):

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

- asymmetry in terms of GPDs

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

- depends linearly on the helicity-flip GPDs \( E^{q,g} \)

- no kinematic suppression \( E^{q,g} \) with respect to \( H^{q,g} \)
\( \rho^0 : \) transverse target-spin asymmetry

theoretically at leading order in \( 1/Q \)

\((\gamma_L^* \rightarrow \rho_L^0)\):

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

\[
A_{UT}^{\gamma^*_T(\phi, \phi_s)} = \frac{\text{Im}(n_{++}^{00} + \epsilon n_{00}^{00})}{u_{++}^{00} + \epsilon u_{00}^{00}}
\]

\(u_{++}^{00}\) and \(n_{++}^{00}\) are expected to be negligible

similarly, \(\gamma_T^* \rightarrow \rho_T^0\):

\[
A_{UT}^{\gamma_T^*(\phi, \phi_s)} = \frac{\text{Im} \ (n_{++}^{++} + n_{++}^{--} + 2\epsilon n_{00}^{++})}{u_{++}^{++} + \epsilon u_{++}^{++} + 2\epsilon u_{00}^{++}}
\]
\( \rho^0 \): transverse target-spin asymmetry

Theoretically at leading order in \( 1/Q \)

\( \gamma_L^* \rightarrow \rho^0_L \):

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

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:

\[
A_{UT}^{\gamma^*}(\phi, \phi_s) = \frac{\text{Im}(n_{00}^0 + \epsilon n_{00})}{u_{00}^0 + \epsilon u_{00}^0}
\]

\( u_{00}^0 \) and \( n_{00}^0 \) are expected to be negligible

Similarly, \( \gamma_T^* \rightarrow \rho^0_T \):

\[
A_{UT}^{\gamma_T^*}(\phi, \phi_s) = \frac{\text{Im}(n_{++}^0 + n_{++}^0 + 2\epsilon n_{00}^{++})}{u_{++}^0 + u_{++}^0 + 2\epsilon u_{00}^{++}}
\]

Compatible with 0 overall value:

\[
A_{UT}^{\rho^0_L}, \sin(\phi - \phi_s) = -0.033 \pm 0.058
\]

\[ \rho^0: \text{comparison with GPD models} \]

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 \( H^q, H^q, H^g \)

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

Predictions for \( J^d = 0 \)

\( E^q \) 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 \( E^q \) ?

Other GPD model calculations

- Goeke, Polyakov, Vanderhaeghen (1999)
- Goloskokov, Kroll (2007)
- Diehl, Kugler (2008)

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ω: transverse target-spin asymmetry

- 6 azimuthal moments extracted using integrated angular distributions
- due to low statistics no ω_L/ω_T separation
- predictions for large asymmetry
  \[ A_{UT}^{\sin(\phi - \phi_s)} \approx -0.10 \]
- indication of negative \( \sin(\phi - \phi_s) \) amplitude
  \[ A_{UT}^{\sin(\phi - \phi_s)} = -0.22 \pm 0.16_{\text{stat}} \pm 0.11_{\text{sys}} \]
- no contradiction with \( \rho^0 \) predictions
  \[ A_{UT}^{\rho^0, \sin(\phi - \phi_s)} \propto \Im \left\{ \frac{2E^u + E^d}{2H^u + H^d + H^g} \right\} \]
  \[ A_{UT}^{\omega, \sin(\phi - \phi_s)} \propto \Im \left\{ \frac{2E^u - E^d}{2H^u - H^d} \right\} \]
**exclusive π⁺ production:**  \( ep \rightarrow e'\pi^+(n) \)

- no recoil nucleon detection
- select exclusive π⁺ reaction through the missing mass technique:
  \[ M_x^2 = (P_e + P_p - P_{e'} - P_{\pi^+})^2 \]

**No recoil nucleon detection**

**Select exclusive π⁺ reaction through the missing mass technique:**

\[ M_x^2 = (P_e + P_p - P_{e'} - P_{\pi^+})^2 \]

\[ N_{excl} = (\pi^+ - \pi^-)^{data} - (\pi^+ - \pi^-)^{MC} \]


<table>
<thead>
<tr>
<th>π⁺</th>
<th>exclusive π⁺</th>
<th>VM_{π⁺}</th>
<th>SIDIS</th>
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<td>π⁻</td>
<td>VM_{π⁻}</td>
<td>SIDIS</td>
<td></td>
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- **π⁺ − π⁻ yield difference was used to subtract the non exclusive background**
- **exclusive peak centered at the nucleon mass**
- exclusive MC based on GPD model

-Ami Rostomyan-
kinematic dependences of $A_{UT}^{\pi^+}$


- 6 azimuthal moments extracted according to -Diehl, Sapeta (2005)-

- average kinematics:
  $\langle -t' \rangle = 0.18 \text{ GeV}^2$
  $\langle x_B \rangle = 0.13$
  $\langle Q^2 \rangle = 2.38 \text{ GeV}^2$

- no $\gamma^*_L/\gamma^*_T$ separation

- small overall value for leading asymmetry amplitude $A_{UT}^{\sin(\phi-\phi_s)}$

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

- other moments: consistent with 0

- evidence of contributions from transversely polarized photons
**theoretical interpretation of \( A_{UT}^{\pi^+} \)**

leading azimuthal amplitude \( A_{UT}^{\sin(\phi - \phi_s)} \)
- theoretical expectation: large negative asymmetry
- \( A_{UT}^{\sin(\phi - \phi_s)} \propto \sqrt{-t'} \) - Frankfurt et al. (2001) - Belitsky, Muller (2001)
- not large asymmetry with possible sign change
- calculations for \( \gamma_L^* \) and for \( \gamma_L^*/\gamma_T^* \) Contributions

azimuthal amplitude \( A_{UT}^{\sin \phi_s} \)
- no tun rover towards 0 for \( t' \to 0 \)
- milde \( t \)-dependence
- can be explained only by \( \gamma_L^*/\gamma_T^* \) interference
- predictions \( A_{UT}^{\sin \phi_s} \approx const \)
- non-vanishing model predictions: contributions \( H_T \) and \( \tilde{H}_T \)

-Go...
HERMES and GPDs

\[ \rho^0 \rightarrow SDME \rightarrow A_{UT} \]

\[ \omega \rightarrow SDME \rightarrow A_{UT} \]

\[ A_{UT} \rightarrow \phi \rightarrow SDME \]

\[ \pi^0 \rightarrow cross \text{ section} \]

\[ \pi^+ \rightarrow A_{UL} \rightarrow A_{UT} \]
\( \rho^0 \): observation of unnatural-parity exchange

UPE contributions measured from SDMEs:

\[
\begin{align*}
\rho_1 &= 1 - r_{00}^{04} + 2r_{11-1}^{04} - 2r_{11}^{11} - 2r_{1-1}^{11}, \\
\rho_2 &= r_{11}^{55} + r_{1-1}^{55}, \\
\rho_3 &= r_{11}^{88} + r_{1-1}^{88}
\end{align*}
\]

UPE contributions expressed through amplitudes:

\[
\begin{align*}
\rho_1 &\propto \epsilon |U_{10}|^2 + 2|U_{11} + U_{1-1}|^2, \\
\rho_2 + i\rho_3 &\propto (U_{11} + U_{1-1})^* U_{10}
\end{align*}
\]

the combinations of SDMEs expected to be the zero in case of NPE dominance:
\[ \rho_{\mu\mu',\lambda\lambda'} \propto \sum_{\sigma} T_{\mu\lambda}^{\nu\sigma} (T^\dagger_{\mu'\lambda'}\sigma)^* \]