Exclusive Meson Production

at HERMES

Quarks and Nuclear Physics 2009, Beijing, China

Eduard Avetisyan

(on behalf of the HERMES collaboration)
exclusive meson production

factorization in collinear approximation

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

- Collins, Frankfurt, Strikman (1997) -

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

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

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

- 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

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

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 \( (\gamma^*_L \rightarrow \rho_L, \omega_L, \phi_L) \): \( H, E \)
- 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 \( H_T \) and \( \tilde{H}_T \)
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
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

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

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

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

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

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

\[
W = W_{UU} + PlW_{LU} + SLW_{UL} + PlSLW_{LL} + STW_{UT} + PlSTW_{LT}
\]

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

-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)-

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

-Eduard Avetisyan- – Quarks and Nuclear Physics 2009, Beijing, China – page 5
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
\( \rho^0 \): 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: \( W_{LU} \)

hierarchy confirmed experimentally

proton and deuteron data consistent

\( s \)-channel helicity conservation:

(\( \rho^0 \) conserves the helicity of \( \gamma^* \))

- significant \( \gamma_L^* \rightarrow \rho_L^0 \) and \( \gamma_T^* \rightarrow \rho_T^0 \),

- a substantial interference

\( s \)-channel helicity violation

(vertical line corresponds to SCHC)

- significant \( \gamma_T^* \rightarrow \rho_L^0 \)

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

- 2 \( - 10 \sigma \) level violation

-Eduard Avetisyan-

– Quarks and Nuclear Physics 2009, Beijing, China – page 7
$\rho^0 - \phi$: 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: $W_{LU}$

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:

$T_{00} \sim T_{11}$

$T_{01} \approx T_{10} \approx T_{-11} \approx 0$

- Eduard Avetisyan -

Quarks and Nuclear Physics 2009, Beijing, China – page 8
$\rho^0$: phase difference $\delta$ between $T_{00}$ and $T_{11}$

Neglecting spin-flip amplitudes

|δ| obtained from unpolarized SDMEs:

$$\cos \delta = \frac{2\sqrt{\epsilon (\Re r_{00}^5 - \Im r_{10}^5)}}{\sqrt{r_{00}^{04}(1 - r_{00}^{04} + r_{1-1}^{1} - \Im r_{2-2}^{2})}}$$

Sign of $\delta$ obtained from polarized SDMEs: (for the first time)

$$\sin \delta = \frac{2\sqrt{\epsilon (\Re r_{10}^8 - \Im r_{10}^7)}}{\sqrt{r_{00}^{04}(1 - r_{00}^{04} + r_{1-1}^{1} - \Im r_{2-2}^{2})}}$$

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: $|\delta| = 29.3 \pm 1.6_{\text{stat}} \pm 3.0_{\text{sys}}; \delta = 36.3 \pm 3.9_{\text{stat}} \pm 1.7_{\text{sys}}$

Values are consistent with each other and 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:

\[
W = 5 \text{ GeV (HERMES)}
\]
\[
W = 10 \text{ GeV (COMPASS)}
\]
\[
W = 90 \text{ GeV (H1, ZEUS)}
\]

\( \gamma^*_L \rightarrow \rho_L^0 \) 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 \( \gamma^*_T \rightarrow \rho_T^0 \)

\[
\gamma^*_L \rightarrow \rho_L^0 \propto -\Im r_{10}^5 \propto T_{00} \text{ and } T_{11} \text{ interference}
\]

model does not describe the data

model uses phase difference \( \delta = 3.1 \text{ degree} \) between \( T_{00} \) and \( T_{11} \)

HERMESIS result: \( \delta \approx 30 \text{ degree} \)
Regge theory: the diffractive production of vector meson via an exchange of a particle

\[ e \rightarrow q^* \rightarrow V \rightarrow e' \]

natural parity

\[ P = (-1)^J \]: exchange of \( \rho, \omega, f_2, a_2 \)

or pomeron

\[ \propto M/W \]

unnatural parity

\[ P = -(-1)^J \]: 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

\[ \text{related to GPDs } H \text{ and } E \]

unnatural parity

\[ \text{related to GPDs } \bar{H} \text{ and } \bar{E} \]

\[ \text{pomeron exchange } \Rightarrow \text{ gluon exchange } \]
\[ \text{only NPE} \]

\[ \text{reggeon exchange } \Rightarrow \text{ quark exchange} \]
\[ \text{NPE and UPE} \]
ρ₀: 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

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
\(\phi: \text{observation of unnatural-parity exchange}\)

\[U_1 = 1 - r_0^4 + 2r_{1,1}^1 - 2r_{11}^1\]

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

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

\(u_1 = 0.02 \pm 0.07 \text{ stat} \pm 0.16 \text{ sys}\)

\(u_2 = -0.03 \pm 0.01 \text{ stat} \pm 0.03 \text{ sys}\)

\(u_3 = -0.05 \pm 0.12 \text{ stat} \pm 0.07 \text{ sys}\)

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


transverse SDMEs: $W_{UT}$ 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: $n^{\nu
\nu'}_{\mu\mu'}$ and $s^{\nu
\nu'}_{\mu\mu'}$

\[ \gamma_L^* \rightarrow \rho_L^0 \] and \[ \gamma_T^* \rightarrow \rho_T^0 \]

- Im $s^{0+}_{-+}$ and Im($s^{0+}_{00} - s^{-0}_{0+}$): deviate from 0 by $2.5\sigma$
- expected $s^{\nu\nu'}_{\mu\mu'} < n^{\nu\nu'}_{\mu\mu'}$ (if identical indices)

\[ \text{Im } s^{0+}_{-+} \text{ and Im } s^{0+}_{00} \text{ involve} \]

- the biggest NPE amplitudes $N^{0+}$ or $N'^{-+}$
- the biggest UPE amplitude $U^{++}$

signal for unnatural-parity exchange related to GPDs $\bar{R}$ and $\bar{E}$

- \[ \gamma_L^* \rightarrow \rho_L^0 \]
- \[ \gamma_T^* \rightarrow \rho_T^0 \]
- \[ \gamma_L^* \rightarrow \rho_T^0 \]
- \[ \gamma_T^* \rightarrow \rho_L^0 \]

- Manaenkov (2008)

'transverse' SDMEs: $n_{\mu\mu'}^u$ and $s_{\mu\mu'}^u$


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

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

- expected $s_{\mu\mu'}^u < n_{\mu\mu'}^u$

- **Im $s_{-+}^u$** and **Im $s_{0+}^u$** involve the biggest NPE amplitudes $N_{--}^0$ or $N_{0+}^0$

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

- Manaenkov (2008)

- dominant transitions

- single spin flip

- double spin flip

- Eduard Avetisyan - Quarks and Nuclear Physics 2009, Beijing, China – page 14
$\rho^0$: transverse target-spin asymmetry

theoretically at leading order in $1/Q$

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

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

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 \( 1/Q \)

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

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

Asymmetry in terms of GPDs

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

Experimentally:

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

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

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

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

theoretically at leading order in \( 1/Q \) 
\((\gamma_L^* \rightarrow \rho_L^0)\):

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

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:

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

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

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

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

compatible with 0 overall value:

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

$\rho^0$: 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)-

---

-Eduard Avetisyan-
**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
  \[ A_{UT}^{\sin(\phi-\phi_s)} \approx -0.10 \]
- 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 $\pi^+$ production: $ep \rightarrow e'\pi^+(n)$

- no recoil nucleon detection
- select exclusive $\pi^+$ reaction through the missing mass technique:
  $$M^2_{\pi^+} = (P_e + P_P - P_{e'} - P_{\pi^+})^2$$

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


<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></td>
<td>$VM_{\pi^-}$</td>
<td>SIDIS</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

-Eduard Avetisyan-
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 turnover against 0 for $t' \to 0$
- mild $t$-dependence
- can be explained only by $\gamma_L^*/\gamma_T^*$ interference
- predictions $A_{UT}^{\sin \phi_s} \approx \text{const}$
- non-vanishing model predictions: contributions $H_T$ and $\tilde{H}_T$

-Goloskokov, Kroll (2009)-
-Bechler, Muller (2009)-
HERMES and GPDs

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

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

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

\[ \pi^0 \rightarrow SDME \rightarrow A_{UL} \]

\[ \pi^+ \rightarrow SDME \rightarrow A_{UT} \]

\[ \text{cross section} \]

-Eduard Avetisyan-
$\rho^0$: observation of unnatural-parity exchange

UPE contributions measured from SDMEs:

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

UPE contributions expressed through amplitudes:

$$u_1 \propto \epsilon|U_{10}|^2 + 2|U_{11} + U_{1-1}|^2, \quad u_2 + iu_3 \propto (U_{11} + U_{1-1}) \ast U_{10}$$

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