Latest results of exclusive meson production at HERMES

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Exclusive $\rho^0$ and $\omega$ production

-probe various types of GPDs with different sensitivity and different flavour combinations
-complementary to DVCS
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Target polarization state
- unpolarized target:
  nucleon-helicity-non-flip GPDs $H$ and $\tilde{H}$
- transversely polarized target:
  nucleon-helicity-flip GPDs $E$ and $\tilde{E}$
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Exclusive $\rho^0$ and $\omega$ production: angular distribution

\[
e + N \rightarrow e + N + \rho^0 \\
\rho^0 \rightarrow \pi^+ + \pi^- \\
\]

\[
e + N \rightarrow e + N + \omega \\
\omega \rightarrow \pi^+ + \pi^- + \rho^0(2\gamma)
\]
Exclusive $\rho^0$ and $\omega$ production: angular distribution

\[ e + N \rightarrow e + \pi^+ + \pi^- \quad \rho^0 \rightarrow \pi^+ + \pi^- \]

\[ e + N \rightarrow e + \pi^+ + \omega \quad \omega \rightarrow \pi^+ + \pi^- + \pi^0(2\gamma) \]

- $3.0 \text{ GeV} \leq W \leq 6.3 \text{ GeV}$
- $1.0 \text{ GeV}^2 \leq Q^2 \leq 7.0 \text{ GeV}^2$
- $0.0 \text{ GeV}^2 \leq -t' \leq 0.4 \text{ GeV}^2$
Exclusive $\rho^0$ and $\omega$ production: angular distribution

\[ e + N \rightarrow e + X + \rho^0 \]
\[ \rho^0 \rightarrow \pi^+ + \pi^- \]

\[ e + N \rightarrow e + X + \omega \]
\[ \omega \rightarrow \pi^+ + \pi^- + \pi^0(2\gamma) \]
Fit angular distribution of decay pions $\mathcal{W}(\Phi, \phi, \Theta, \Psi)$ and extract either
- Spin Density Matrix Elements (SDMEs)
- or
- helicity amplitude ratios

$e + N \rightarrow e + X + \rho^0$
$\rho^0 \rightarrow \pi^+ + \pi^-$

$e + N \rightarrow e + X + \omega$
$\omega \rightarrow \pi^+ + \pi^- + \pi^0(2\gamma)$
Helicity amplitude ratios and SDMEs

\[ \gamma^*(\lambda_{\gamma}) + N(\lambda_N) \rightarrow V(\lambda_V) + N(\lambda'_N) \]

- Helicity amplitude \( F^{\lambda_V \lambda'_N \lambda_{\gamma} \lambda_N} \)
Helicity amplitude ratios and SDMEs

\[ \gamma^*(\lambda_\gamma) + N(\lambda_N) \rightarrow V(\lambda_V) + N(\lambda'_N) \]

- Helicity amplitude \( F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} \)

\[ F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} = T_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} + U_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} \]
Helicity amplitude ratios and SDMEs

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- Helicity amplitude \( F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} \)

\[ F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} = T_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} \text{ natural parity amplitude} + U_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} \text{ unnatural parity amplitude} \]
Helicity amplitude ratios and SDMEs

\[ \gamma^*(\lambda_\gamma) + N(\lambda_N) \rightarrow V(\lambda_V) + N(\lambda'_N) \]

- **Helicity amplitude** 
  \[ F_{\lambda_V, \lambda'_N, \lambda_\gamma, \lambda_N} \]

  \[ F_{\lambda_V, \lambda'_N, \lambda_\gamma, \lambda_N} = T_{\lambda_V, \lambda'_N, \lambda_\gamma, \lambda_N} + U_{\lambda_V, \lambda'_N, \lambda_\gamma, \lambda_N} \]

  - **natural parity amplitude**
  - **unnatural parity amplitude**

- **Helicity amplitude ratios**
  \[ t_{\lambda_V, \lambda_\gamma}^{(n)} = T_{\lambda_V, \lambda_\gamma}^{(n)} / T_{0, 0}^{1/2} \]
  \[ u_{\lambda_V, \lambda_\gamma}^{(n)} = U_{\lambda_V, \lambda_\gamma}^{(n)} / T_{0, 0}^{1/2} \]

  \[ n = 1 \quad \lambda_N = \lambda'_N \]
  \[ n = 2 \quad \lambda_N \neq \lambda'_N \]
Helicity amplitude ratios and SDMEs

\[ \gamma^*(\lambda_\gamma) + N(\lambda_N) \rightarrow V(\lambda_V) + N(\lambda'_N) \]

- SDMEs
Helicity amplitude ratios and SDMEs

\[ \gamma^*(\lambda_\gamma) + N(\lambda_N) \rightarrow V(\lambda_V) + N(\lambda'_N) \]

- SDMEs

\[ \propto F_{\lambda_V \lambda'_N \gamma \gamma N} \sum^\alpha_{\lambda_\gamma \lambda'_\gamma} F^*_{\lambda'_V \lambda'_N \lambda'_\gamma \lambda_N} \]
Helicity amplitude ratios and SDMEs

\[ \gamma^*(\lambda_\gamma) + N(\lambda_N) \rightarrow V(\lambda_V) + N(\lambda'_N) \]

- SDMEs

\[ \propto F^{\lambda_V\lambda'_V\lambda_N\lambda_N}_{\lambda_\gamma\lambda'_\gamma} \sum_{\lambda_\gamma\lambda'_\gamma} F^{*}_{\lambda'_V\lambda'_V\lambda_N\lambda_N} \]

- SDMEs
  - unpolarized target
    \[ u^{\lambda_V\lambda'_V}_{\lambda_\gamma\lambda'_\gamma} \]
  - longitudinally polarized target
    \[ l^{\lambda_V\lambda'_V}_{\lambda_\gamma\lambda'_\gamma} \]
  - transversely polarized target
    \[ n^{\lambda_V\lambda'_V}_{\lambda_\gamma\lambda'_\gamma} \text{ and } s^{\lambda_V\lambda'_V}_{\lambda_\gamma\lambda'_\gamma} \]
Helicity amplitude ratios for exclusive $\rho^0$

- transversely polarized H target
- 8741 exclusive-$\rho$ events
- 25-parameter fit
Results helicity $\rho^0$ amplitude ratios

- 5 classes of helicity amplitude ratios

(already obtained in EPJ C71 (2011) 1609)

extracted for first time

A: $\gamma^* \rightarrow \rho_T$

B: $\gamma_L \rightarrow \rho_L$

C: $\gamma^* \rightarrow \rho_L$

ep$^\uparrow \rightarrow$ epp

0.0 GeV$^2 < -t' < 0.4$ GeV$^2$

1.0 GeV$^2 < Q^2 < 7.0$ GeV$^2$

D: $\gamma_L \rightarrow \rho_T$

EPJ C71 (2011) 1609

Phase of $u_{11}^{(1)}$ from EPJ C29 (2003) 171

E: $\gamma^* \rightarrow \rho_T$
Results helicity $\rho^0$ amplitude ratios

- 5 classes of helicity amplitude ratios
- dominant amplitudes: natural parity nucleon-helicity non-flip $t_{11}^{(1)}$
- also unnatural parity nucleon-helicity non-flip $u_{11}^{(1)} \neq 0$ by $4\sigma$

**HERMES PRELIMINARY**

<table>
<thead>
<tr>
<th>Re $t_{11}$</th>
<th>Im $t_{11}$</th>
<th>A: $\gamma_T^* \rightarrow \rho_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Re $u_{11}$</td>
<td>Im $u_{11}$</td>
<td>B: $\gamma_L \rightarrow \rho_L$</td>
</tr>
<tr>
<td>Re $t_{11}$</td>
<td>Im $t_{11}$</td>
<td>C: $\gamma_T^* \rightarrow \rho_L$</td>
</tr>
<tr>
<td>Re $t_{11}$</td>
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<td>D: $\gamma_L^* \rightarrow \rho_T$</td>
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Results helicity $\rho^0$ amplitude ratios

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- 5 classes of helicity amplitude ratios
- dominant amplitudes: natural parity nucleon-helicity non-flip $t_{11}^{(1)}$
- also unnatural parity nucleon-helicity non-flip $u_{11}^{(1)} \neq 0$ by $4\sigma$
- nucleon-helicity-flip amplitudes: small, consistent with 0
Comparison with SDMEs: unpolarized target

- Overall good agreement between direct extraction of SDMEs and SDMEs via helicity amplitude ratios
- Parameter space in two methods are ≠ → methods do not necessarily coincide
Comparison with SDMEs: transversely polarised target

- Overall good agreement between two methods
- Newly obtained SDMEs
Spin density matrix elements from exclusive $\omega$

- unpolarized H and D targets
- 2260/1332 exclusive-$\omega$ events from H/D
- 23-parameter fit
Results $\omega$ SDMEs

- 5 classes of SDMEs
- unpolarized and polarized SDMEs
- proton & deuteron similar
Results $\omega$ SDMEs

- 5 classes of SDMEs
- Unpolarized and polarized SDMEs
- Proton & deuteron similar

- $s$-channel helicity conservation ($\lambda_{\gamma^*} = \lambda_\omega$):
  - Fulfilled for class A & B
  - Class C - slight violation:
    \[ r_{10}^{5} \neq 0 \text{ by } 3(2)\sigma \text{ for } p(d) \]

- Class D - slight violation:
  \[ r_{11}^{5} + r_{11}^{5} - r_{11}^{6} \neq 0 \text{ by } 3(2.5)\sigma \text{ for } p(d) \]
Results $\omega$ and $\rho$ SDMEs

- $\omega$: $r^{1}_{1-1} < 0$ and $\Im r^{2}_{1-1} > 0$
- $\rho$: $r^{1}_{1-1} > 0$ and $\Im r^{2}_{1-1} < 0$

- $\omega$: large unnatural parity exchange
- $\rho$: large natural parity exchange

Test of unnatural-parity exchange

\[ u_1 = 1 - r_{00}^0 + 2r_{04}^{04} - 2r_{11}^1 - 2r_{1-1}^1 \]
\[ \propto 2 \epsilon |U_{10}|^2 + |U_{11} + U_{-11}|^2 \]  
(U=unnatural-parity amplitude)

- large unnatural parity exchange seen
Test of unnatural-parity exchange

\[ u_1 = 1 - r_{00}^{04} + 2r_{1-1}^{04} - 2r_{11}^{1} - 2r_{1-1}^{1} \]

\[ \propto 2 \epsilon |U_{10}|^2 + |U_{11} + U_{-11}|^2 \quad (U=\text{unnatural-parity amplitude}) \]

- large unnatural parity exchange seen
Test of unnatural-parity exchange

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\[
F_{\lambda \nu \frac{1}{2} \gamma = \nu \frac{1}{2}} \propto \sum_{q,g} I \left[ A \times \left( H^a, \frac{\xi^2}{1 - \xi^2} E^a \right) + A' \times \left( \tilde{H}^a, \frac{\xi^2}{1 - \xi^2} \tilde{E}^a \right) \right] \\
F_{\lambda \nu - \frac{1}{2} \gamma = \nu \frac{1}{2}} \propto \sum_{q,g} I \left[ A \times E^a + A' \times \xi \tilde{E}^a \right]
\]
Test of unnatural-parity exchange

- large unnatural parity exchange seen

\[ F_{\lambda \nu} \sim \frac{1}{2} \gamma = \nu \frac{1}{2} \propto \sum_{q,g} \mathcal{I} \left[ \mathcal{A} \times \left( H^{a} \frac{\xi^{2}}{1 - \xi^{2}} E^{a} \right) + \mathcal{A}' \times \left( \tilde{H}^{a} \frac{\xi^{2}}{1 - \xi^{2}} \tilde{E}^{a} \right) \right] \]

\[ F_{\lambda \nu} \sim \frac{1}{2} \lambda \gamma = \nu \frac{1}{2} \propto \sum_{q,g} \mathcal{I} \left[ \mathcal{A} \times E^{a} + \mathcal{A}' \times \xi \tilde{E}^{a} \right] \]
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\[ F_{\lambda V \gamma = V \frac{1}{2}} \propto \sum_{q,g} \mathcal{I} \left[ A \times \left( H^a, \frac{\xi^2}{1 - \xi^2} E^a \right) + A' \times \left( \tilde{H}^a, \frac{\xi^2}{1 - \xi^2} \tilde{E}^a \right) \right] \]

\[ F_{\lambda V \gamma = V \frac{1}{2}} \propto \sum_{q,g} \mathcal{I} \left[ A \times \tilde{E}^a + A' \times \xi \tilde{E}^a \right] \]

Factorization only proven for \( \gamma_L^* \rightarrow V_L \)
Assumed for \( \gamma_T^* \rightarrow V_T, V_L \)
IR singularities regularised by modified perturbative approach
Test of unnatural-parity exchange

- large unnatural parity exchange seen

\[ F_{V_{1/2}} \gamma = V_{1/2} \propto \sum_{q,g} \mathcal{I} \left[ A \times \left( H^a, \frac{\xi^2}{1 - \xi^2} E^a \right) + A' \times \left( \tilde{H}^a, \frac{\xi^2}{1 - \xi^2} \tilde{E}^a \right) \right] \]

Factorization only proven for $\gamma^*_L \rightarrow V_L$
Assumed for $\gamma^*_T \rightarrow V_T, V_L$
IR singularities regularised by modified perturbative approach
Test of unnatural-parity exchange

- large unnatural parity exchange seen

\[ F_{\lambda V \frac{1}{2}} \gamma = \frac{1}{2} \propto \sum_{q,g} \mathcal{I} \left[ A \times \left( H^a, \frac{\xi^2}{1 - \xi^2} E^a \right) + A' \times \left( \tilde{H}^a, \frac{\xi^2}{1 - \xi^2} \tilde{E}^a \right) \right] \]

without pion-pole contribution
with pion-pole contribution
pion-pole contribution seems to account completely for unnatural-parity exchange
Kinematic dependencies

class A: $\gamma_L^* \rightarrow \omega_L$ and $\gamma_T^* \rightarrow \omega_T$

- no pronounced kinematic dependence observed
- again, need for pion-pole contribution observed
Kinematic dependencies

**class B: interference** $\gamma^*_L \rightarrow \omega_L$ and $\gamma^*_T \rightarrow \omega_T$

- no pronounced kinematic dependence observed
- need for pion-pole contribution observed for unpolarized SDMEs
Longitudinal-to-transverse cross-section ratio

\[ R = \frac{d\sigma(\gamma_L^* \to \omega)}{d\sigma(\gamma_T^* \to \omega)} \approx \frac{1}{\epsilon} \frac{r_{00}^{04}}{1 - r_{00}^{04}} \]

- \( R(\omega) \) 4 times smaller than \( R(\rho) \)
- no pronounced kinematic dependence observed
- need for pion-pole contribution
Transverse-target spin asymmetry in exclusive $\omega$ production

- transversely polarized H target
- 279 exclusive-$\omega$ events
Transverse target-spin asymmetry $A_{UT}$ in exclusive $\omega$ production

\[ W(\phi, \phi_S) = 1 + A_{UU}^{\cos(\phi)} \cos(\phi) + A_{UU}^{\cos(2\phi)} \cos(2\phi) \]
\[ + S_{\perp} \left[ A_{UT}^{\sin(\phi+\phi_S)} \sin(\phi + \phi_S) + A_{UT}^{\sin(\phi-\phi_S)} \sin(\phi - \phi_S) + A_{UT}^{\sin(\phi_S)} \sin(\phi_S) \right] \]
\[ + A_{UT}^{\sin(2\phi-\phi_S)} \sin(2\phi - \phi_S) + A_{UT}^{\sin(3\phi-\phi_S)} \sin(3\phi - \phi_S) \]
Results $\omega$ $A_{UT}$

- large unnatural parity exchange seen
- with pion-pole contribution: $\pi_\omega$ transition FF > 0
- with pion-pole contribution: $\pi_\omega$ transition FF < 0
- Positive $\pi_\omega$ transition FF favoured
Results $\omega A_{UT}$: transversely polarized $\omega$


8.2% scale uncertainty

$\sigma_{\omega}^2 = \sigma_{\omega}^2 + \sigma_{\omega 0}^2 + \sigma_{\omega s}^2 + \sigma_{\omega s 0}^2$

$\sin (2\phi - \phi_s)$

$\cos (2\phi - \phi_s)$

$\sin (3\phi - \phi_s)$

$\cos (3\phi - \phi_s)$

$A_{UT}^2$

$A_{UT 0}^2$

$A_{UT s}^2$

$A_{UT s 0}^2$

$A_{UT ff}^2$

$A_{UT ff 0}^2$

$A_{UT s ff}^2$

$A_{UT s ff 0}^2$

$A_{UT ff ff}^2$

$A_{UT ff ff 0}^2$

$A_{UT s ff ff}^2$

$A_{UT s ff ff 0}^2$
Summary

- $\rho^0$ helicity amplitude ratios:
  - New: nucleon-helicity-flip amplitudes. They are consistent with zero
  - Good agreement with direct extraction of SDMEs

- $\omega$ SDMEs:
  - Large unnatural parity contribution.
  - Importance of pion pole

- $\omega A_{UT}$:
  - positive sign for $\pi\omega$ form factor favoured