Hard exclusive $\phi$ meson leptoproduction at HERMES

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Outline

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- HERMES experiment
- Data sample
- $\phi$ meson SDMEs
- Comparison of $\phi$ and $\rho^0$ SDMEs
- Summary
Cross section and decay angular distribution

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

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

\[ \sin \phi = \frac{[(q \times v) \cdot (v \times P_{K+})]}{|(q \times v)| |v \times P_{K+}|} \]

\[ \cos \phi = \frac{(q \times v) \cdot (v \times P_{K+})}{|q \times v| |v \times P_{K+}|} \]

\[ \sin \Phi = \frac{[(q \times v) \times (k \times k')] \cdot |q|}{|q \times v| |k \times k'| |q|} \]

\[ \cos \Phi = \frac{(q \times v) \cdot (k \times k')}{|q \times v| |k \times k'|} \]

\[ \cos \theta = \frac{-P' \cdot P_{K+}}{|P'| |P_{K+}|} \]

\( \phi \) - azimuthal angle of the \( K^+ \) decay in the \( \phi \) meson rest frame

\( \theta \) - polar angle of the \( K^+ \) decay in the \( \phi \) meson rest frame

\( \Phi \) - angle between \( \phi \) meson-production plane and the lepton scattering plane
Spin density matrix elements & helicity amplitudes

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

\[ W(x_B, Q^2, t, \phi_S, \phi, \cos \theta, \Phi) \] can be parameterized by:

- **helicity amplitudes** \( T_{\lambda_V \lambda_{\gamma}} \)
  connected with SDMEs; calculated from GPDs

- **spin density matrix** \( r^\alpha_{\lambda_V \lambda_V'} \rightarrow \rho(V) = \frac{1}{2} T_{\lambda_V \lambda_{\gamma}} \rho(\gamma) T^*_{\lambda_V \lambda_{\gamma}} \)
  \( \rho(V) \) – spin density matrix of the vector meson
  \( \rho(\gamma) \) - spin density matrix of the virtual photon

\[
r^\alpha_{\lambda_V \lambda_{V'}}(V) = \frac{1}{2N_{\alpha}} \sum_{\lambda_N, \lambda_N' \lambda_{\gamma} \lambda_{\gamma}'} T_{\lambda_V \lambda_{N}, \lambda_{\gamma} \lambda_{N}'} \Sigma^\alpha_{\lambda_{\gamma} \lambda_{\gamma}} T^*_{\lambda_V' \lambda_{N}, \lambda_{\gamma}' \lambda_{N}'}
\]

\( N_{\alpha} \) are normalization factors

\( T_{\lambda_V \lambda_{N}, \lambda_{\gamma} \lambda_{N}} \) - helicity amplitudes, \( T_{\lambda_V \lambda_{N}, \lambda_{\gamma} \lambda_{N}'} \rightarrow T_{\lambda_V \lambda_{\gamma}} \)

\( \Sigma^\alpha_{\lambda_{\gamma} \lambda_{\gamma}'} \) - hermitian matrices with \( \alpha \ 0 \leq 8 \) - virtual photon polarization

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Schilling, Wolf
The angular distribution

\[ W^{U+L}(\Phi, \phi, \cos \theta) = W^{UU}(\Phi, \phi, \cos \theta) + W^{LU}(\Phi, \phi, \cos \theta) \]

For unpolarized target and beam:

\[ W^{UU}(\Phi, \phi, \cos \theta) = \frac{3}{8\pi^2} \left[ \frac{1}{2} \left( 1 - r_{00}^{04} \right) + \frac{1}{2} \left( 3r_{00}^{04} - 1 \right) \cos^2 \theta - \sqrt{2} \Re \{ r_{10}^{04} \} \sin 2\theta \cos \phi - r_{1-1}^{04} \sin^2 \theta \cos 2\phi \right. \]

\[ - \varepsilon \cos 2\Phi \left( r_{11}^{1} \sin^2 \theta + r_{00}^{1} \cos^2 \theta - \sqrt{2} \Re \{ r_{10}^{1} \} \sin 2\theta \cos \phi - r_{1-1}^{1} \sin^2 \theta \cos 2\phi \right) \]

\[ - \varepsilon \sin 2\Phi \left( \sqrt{2} \Im \{ r_{10}^{2} \} \sin 2\theta \sin \phi + \Im \{ r_{1-1}^{2} \} \sin^2 \theta \sin 2\phi \right) \]

\[ + \sqrt{2} \varepsilon \left( 1 + \varepsilon \right) \cos \Phi \left( r_{11}^{5} \sin^2 \theta + r_{00}^{5} \cos^2 \theta - \sqrt{2} \Re \{ r_{10}^{5} \} \sin 2\theta \cos \phi - r_{1-1}^{5} \sin^2 \theta \cos 2\phi \right) \]

\[ + \sqrt{2} \varepsilon \left( 1 + \varepsilon \right) \sin \Phi \left( \sqrt{2} \Im \{ r_{10}^{6} \} \sin 2\theta \sin \phi + \Im \{ r_{1-1}^{6} \} \sin^2 \theta \sin 2\phi \right) \]

For unpolarized target and longitudinally polarized beam:

\[ W^{LU}(\Phi, \phi, \cos \theta) = \frac{3}{8\pi^2} P_{\text{beam}} \left[ \sqrt{1 - \varepsilon^2} \left( \sqrt{2} \Im \{ r_{10}^{3} \} \sin 2\theta \sin \phi + \Im \{ r_{1-1}^{3} \} \sin^2 \theta \sin 2\phi \right) \right. \]

\[ + \sqrt{2} \varepsilon \left( 1 - \varepsilon \right) \cos \Phi \left( \sqrt{2} \Im \{ r_{10}^{7} \} \sin 2\theta \sin \phi + \Im \{ r_{1-1}^{7} \} \sin^2 \theta \sin 2\phi \right) \]

\[ + \sqrt{2} \varepsilon \left( 1 - \varepsilon \right) \sin \Phi \left( r_{11}^{8} \sin^2 \theta + r_{00}^{8} \cos^2 \theta - \sqrt{2} \Re \{ r_{10}^{8} \} \sin 2\theta \cos \phi - r_{1-1}^{8} \sin^2 \theta \cos 2\phi \right) \]

\[ \varepsilon = \frac{1 - y - y^2 \frac{Q^2}{4v^2}}{1 - y + \frac{1}{4} y^2 (\frac{Q^2}{v^2} + 2)} \]

the ratio of virtual photon fluxes for longitudinal and transverse polarization
Vector meson production

VMD model

\[ ep \rightarrow e'p'\varphi, \varphi \rightarrow K^+K^- \]

\[ ep \rightarrow e'p'\rho^0, \rho^0 \rightarrow \pi^+\pi^- \]

GPD model

- Four leading-twist GPDs for spin-$\frac{1}{2}$ targets
- \( H \) and \( \tilde{H} \) correspond to the nucleon helicity conservation
- \( E \) and \( \tilde{E} \) correspond to the nucleon helicity flip
- Factorization theorem proved only for \( \sigma_L \)
  \[ \gamma^*_L \Rightarrow \varphi_L, \omega_L, \rho_L \Rightarrow H, E \]
- \( \gamma^*_T \Rightarrow \rho_T^0 \) transition can be calculated \( \tilde{H} \)

Ji relation:

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

Gluons:
\[ J_g = \frac{1}{2} \lim_{t \to 0} \int_{0}^{1} dx \left[ H_g(x, \xi, t) + E_g(x, \xi, t) \right] \]
Properties of vector meson production

S-channel helicity conservation (SCHC)

Helicity conserving amplitudes:

\[ T_{\lambda\lambda'}, \, \lambda_V = \lambda_\gamma \]

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S-channel helicity non-conservation

Helicity flip amplitudes:

\[ T_{\lambda\lambda'}, \, \lambda_V \neq \lambda_\gamma \]

Theoretically predicted amplitudes hierarchy for HEMES kinematics for \( \phi \)

\[ |T_{00}| \sim |T_{11}| >> |T_{01}|, |T_{10}| \approx |T_{-11}| \approx 0. \]

Theoretically predicted amplitudes hierarchy for HEMES kinematics for \( \rho^0 \)

\[ |T_{00}|^2 \sim |T_{11}|^2 >> |T_{01}|^2 > |T_{10}|^2 \approx |T_{-11}|^2 \]
HERMES at HERA

Beam

Longitudinally polarized lepton beam with energy 27.6 GeV, $P_{\text{beam}} \sim 40 - 60\%$

Target

Internal gas target:
• Unpolarized H, D, $^4$He, N, Ne, Kr, Xe
• Polarized: longitudinally H, D, transversely H
The HERMES spectrometer

- Acceptance $40 < \theta < 220 \text{ mrad}$, $|\theta_x| < 170 \text{ mrad}$, $40 < |\theta_y| < 140 \text{ mrad}$
- Momentum resolution $\frac{\Delta P}{P} \leq 1\%$, angular resolution $\frac{\Delta \theta}{\theta} \leq 0.6 \text{ mrad}$
**φ meson event selection**

\[ ep \to e' p' \phi, \phi \to K^+ K^- \]

Exclusive region: \[ \Delta E = \frac{(M_{\bar{X}} - M^2)}{2M} = 0 \]

Kinematics:

- \[1 < Q^2 < 7 \text{ GeV}^2, \langle Q^2 \rangle = 1.95 \text{ GeV}^2\]
- \[ W^2 > 9 \text{ GeV}^2, \langle W^2 \rangle = 21.89 \text{ GeV}^2\]
- \[ 1.012 \text{ GeV} < M_{KK} < 1.028 \text{ GeV}\]
- \[-t' < 0.4 \text{ GeV}^2\]
- \[\Delta E < 0.6 \text{ GeV}\]
- \[\langle x_B \rangle = 0.088\]
SDMEs for $\phi$ meson production

Unpolarized (white areas) and beam-polarized (green areas) SDMEs are shown for the first time for the whole RICH data set.

- **A.** $\gamma_L^* \rightarrow \rho^0_L$ and $\gamma_T^* \rightarrow \rho^0_T$
  $$|T_{11}|^2 \propto 1 - r_{00}^2 + r_{11}^1 \propto -\text{Im}\{r_{00}^0\}$$

- **B.** Interference: $\gamma_L^* \rightarrow \rho^0_L$
  $$\text{Re}\{T_{00}T_{11}^*\} \propto \text{Re}\{r_{10}^2\} \propto -\text{Im}\{r_{10}^2\}$$
  $$\text{Im}\{T_{11}T_{00}\} \propto \text{Im}\{r_{10}^2\} \propto \text{Re}\{r_{10}^2\}$$

- **C.** Spin Flip: $\gamma_T^* \rightarrow \rho^0_L$
  $$\text{Re}\{T_{11}T_{00}^*\} \propto \text{Re}\{r_{10}^2\} \propto \text{Re}\{r_{10}^2\} \propto \text{Im}\{r_{10}^2\}$$
  $$\text{Re}\{T_{01}T_{00}^*\} \propto r_{00}^2$$
  $$|T_{11}|^2 \propto r_{00}^2$$
  $$\text{Im}\{T_{01}T_{11}^*\} \propto \text{Im}\{r_{10}^2\}$$
  $$\text{Im}\{T_{01}T_{00}\} \propto r_{00}^2$$

- **D.** Spin Flip: $\gamma_L^* \rightarrow \rho^0_T$
  $$\text{Re}\{T_{10}T_{11}^*\} \propto r_{11}^5 \propto r_{11}^5 \propto \text{Im}\{r_{10}^2\}$$
  $$\text{Im}\{T_{10}T_{11}^*\} \propto \text{Im}\{r_{10}^2\} \propto r_{11}^8 \propto r_{11}^8$$

- **E.** Spin Flip: $\gamma_T^* \rightarrow \rho^0_{-T}$
  $$\text{Re}\{T_{11}T_{11}^*\} \propto r_{11}^7 \propto r_{11}^7 \propto \text{Im}\{r_{11}^7\}$$
  $$\text{Im}\{T_{11}T_{11}^*\} \propto \text{Im}\{r_{11}^7\} \propto r_{11}^8 \propto r_{11}^8$$
SDMEs for $\phi$ meson production

Unpolarized (white areas) and beam-polarized (green areas) SDMEs are shown for the first time for the whole RICH data set:

- no statistically significant difference between proton and deuteron
- $s$-channel helicity conservation
  
  \[
  r_{1-1}^1 = -\text{Im}\{r_{1-1}^2\}, \text{ -fulfilled}
  \]
  
  \[
  \text{Re}\{r_{10}^5\} = -\text{Im}\{r_{10}^6\}, \text{ -fulfilled}
  \]
  
  \[
  \text{Re}\{r_{10}^8\} = \text{Im}\{r_{10}^7\}, \text{ -large uncertainties}
  \]
- $s$-channel helicity violation
  
  $\phi$ SDMEs classes C, D, E are compatible with 0 supporting SCHC, except from $r_{00}^5$

Amplitudes hierarchy for $\phi$ meson:

\[
|T_{00}| \sim |T_{11}| >> |T_{01}|, |T_{10}| \approx |T_{-11}| \approx 0.
\]
SDMEs for $\rho^0$ meson production

Unpolarized (white areas) and beam-polarized (green areas) SDMEs

- no statistically significant difference between proton and deuteron
- s-channel helicity conservation (conservation the helicity of $\gamma^*$ in $\gamma_L^* \rightarrow \rho_L^0$ and $\gamma_T^* \rightarrow \rho_T^0$) - non-zero SDMEs of classes A,B
  \[ r_{1-1}^1 = -\text{Im}\{r_{1-1}^2\}, \]
  \[ \text{Re}\{r_{10}^5\} = -\text{Im}\{r_{10}^6\}, \]
  \[ \text{Re}\{r_{10}^8\} = \text{Im}\{r_{10}^7\} \] - fulfilled
- s-channel helicity violation
  - significant $\gamma_T^* \rightarrow \rho_L^0$ - non-zero elements of class C, not so
  - significant $\gamma_{-T}^* \rightarrow \rho_T^0$ and $\gamma_L^* \rightarrow \rho_T^0$
  - non-zero elements of classes D,E

Hierarchy of amplitudes at HERMES kinematics for $\rho^0$:

\[ |T_{00}|^2 \sim |T_{11}|^2 \gg |T_{01}|^2 > |T_{10}|^2 \sim |T_{-11}|^2 \]
Comparison of $\phi$ and $\rho^0$ SDMEs

Unpolarized (white areas) and beam-polarized (green areas) SDMEs

- $r_{00}^{04}$ is 10-20% larger for $\phi$ than for $\rho^0$
- SDMEs of class B are compatible for $\phi$ and
- SDMEs of class C shows pronounced differences between $\phi$ and $\rho^0$
- For classes D and E no significant differences are seen.
Summary

• Unpolarized and beam-polarized SDMEs are extracted on proton and deuteron targets for $\varphi$ (preliminary result) and $\rho^0$ (published result)
• Compatible results on proton and deuteron targets for $\varphi$ and $\rho^0$
• Helicity amplitudes hierarchy for $\varphi$ and $\rho^0$ mesons tested
• Pronounced s-channel helicity violation for $\rho^0$
• Less pronounced s-channel helicity violation for $\varphi$