Hard exclusive vector meson leptoproduction at HERMES

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Outline

- HERMES experiment
- Physics motivation
- Data samples
- $\rho^0$ and $\phi$ spin density matrix elements
- $\rho^0$, $\phi$, $\omega$ transverse target spin asymmetry
- Summary
Deeply virtual Compton scattering

Exclusive meson electroproduction

GPD

Ji relation:

Quarks:

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

Gluons:

\[ J_g = \frac{1}{2} \lim_{t \to 0} \int_{0}^{1} dx \, x [H_g(x, \xi, t) + E_g(x, \xi, t)] \]

- \( H \) and \( \widetilde{H} \) require the nucleon helicity
- \( E \) and \( \widetilde{E} \) require the nucleon helicity flip
- Factorization theorem proved for longitudinal production only
  
  \( \gamma_L^* \Rightarrow \varphi_L, \omega_L, \rho_L \Rightarrow H, E \)
  
  - \( \gamma_T^* \Rightarrow \rho_T^0 \) transition can be calculated
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, \(^4\text{He}, \text{N, Ne, Kr, Xe} \)
• Polarized: longitudinally H, D, transversely H
- Acceptance $40 < \Theta < 220$ mrad, $|\Theta_x| < 170$ mrad, $40 < |\Theta_y| < 140$ mrad
- Momentum resolution $\leq 1\%$, $\delta \Theta \leq 0.6$ mrad
Vector meson production

Natural parity exchange

• ρ, φ meson production
• Exchange of a particle of natural parity: $P = (-1)^J$
• Suppressed by factor $M/W$
• Related to GPDs $H$ and $E$

Unnatural parity exchange

• ρ meson production
• Exchange of a particle of unnatural parity: $P = -(−1)^J$
• Suppressed by factor $M/W^2$
• Is expected only at low $W$-values
• Related to GPDs $\tilde{H}$ and $\tilde{E}$

VMD model

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

$ep \rightarrow e'p\rho^0$, $\rho^0 \rightarrow \pi^+\pi^-$
ρ^0, ϕ meson event selection
ρ^0 meson production


Kinematic cuts:
• 1 < Q^2 < 7 GeV^2
• 3 < W^2 < 6.3 GeV^2
• -t` < 0.4 GeV^2
• ΔE < 0.6 GeV
For ρ^0 additionally
• M_{2K} > 1.04 GeV
Decay angular distribution of vector meson

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

Decay angular distribution

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

parameterized by:

- helicity amplitudes \(T_{\lambda \lambda'}\)
- spin density matrix elements \(r_{\lambda V \lambda V'}\)

Schilling, Wolf 1973
SDMEs extraction procedure

**Binned maximum likelihood method:**

- Two 8x8x8-binned angular distributions in \((\cos \theta, \Phi, \phi)\) for data and for Monte Carlo.
- Start from uniform (‘fully reconstructed’) MC angular distribution (blue lines).
- To fit data to MC with 23 SDMEs (15 unpolarized and 8 longitudinally polarized) as free parameters.
- Good agreement of fitted MC distributions (red lines) and data (points)

Angular distribution in terms of SDMEs

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

\[
W^L(\Phi, \phi, \cos \Theta) = \frac{3}{8\pi^2} P_{\text{Beam}} \sqrt{1-\varepsilon^2} \left( \sqrt{2} \Im\{r_{10}^3\} \sin 2\Theta \sin \phi + \Im\{r_{1-1}^3\} \sin^2 \Theta \sin 2\phi \right) \\
+ \sqrt{2\varepsilon (1-\varepsilon)} \cos \Phi \left( \sqrt{2} \Im\{r_{10}^7\} \sin 2\Theta \sin \phi + \Im\{r_{1-1}^7\} \sin^2 \Theta \sin 2\phi \right) \\
+ \sqrt{2\varepsilon (1-\varepsilon)} \sin \Phi \left( r_{11}^8 \sin^2 \Theta + r_{00}^8 \cos^2 \Theta - \sqrt{2} \Re\{r_{10}^8\} \sin 2\Theta \cos \phi - r_{1-1}^8 \sin^2 \Theta \cos 2\phi \right) \]

\[
W^U(\Phi, \phi, \cos \Theta) = \frac{3}{8\pi^2} \left[ \frac{1}{2} \left( 1 - r_{00}^{04} \right) + \frac{1}{2} \left( 3r_{00}^{04} - 1 \right) \cos^2 \Theta - \sqrt{2} \Re\{r_{10}^{04}\} \sin 2\Theta \cos \phi - r_{1-1}^{04} \sin^2 \Theta \cos 2\phi \right] \\
- \varepsilon \cos 2\Phi \left( r_{11}^1 \sin^2 \Theta + r_{00}^1 \cos^2 \Theta - \sqrt{2} \Re\{r_{10}^1\} \sin 2\Theta \cos \phi - r_{1-1}^1 \sin^2 \Theta \cos 2\phi \right) \\
- \varepsilon \sin 2\Phi \left( \sqrt{2} \Im\{r_{10}^2\} \sin 2\Theta \sin \phi + \Im\{r_{1-1}^2\} \sin^2 \Theta \sin 2\phi \right) \\
+ \sqrt{2\varepsilon (1+\varepsilon)} \cos \Phi \left( r_{11}^5 \sin^2 \Theta + r_{00}^5 \cos^2 \Theta - \sqrt{2} \Re\{r_{10}^5\} \sin 2\Theta \cos \phi - r_{1-1}^5 \sin^2 \Theta \cos 2\phi \right) \\
+ \sqrt{2\varepsilon (1+\varepsilon)} \sin \Phi \left( \sqrt{2} \Im\{r_{10}^6\} \sin 2\Theta \sin \phi + \Im\{r_{1-1}^6\} \sin^2 \Theta \sin 2\phi \right) \]
SDMEs for $\rho^0$ meson production

- Unpolarized (white areas) and beam-polarized (green areas) SDMEs
- Squares are proton, circles are deuteron data
- $s$-channel helicity conservation (conservation the helicity of $\gamma^* \gamma_L^* \rightarrow \rho^0_L$ and $\gamma_T^* \rightarrow \rho^0_T$)
- $s$-channel helicity violation
- Unnatural parity exchange – non-zero combinations

Hierarchy of amplitudes at HERMES kinematics:

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

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

\[ u_2 = r_{11}^{5} + r_{1-1}^{5} \]

\[ u_3 = r_{11}^{8} + r_{1-1}^{8} \]
Comparison of $\phi$ and $\rho^0$ SDMEs

• Unpolarized (white areas) and beam-polarized (yellow areas) SDMEs
• Squares are proton data for $\rho^0$, circles are deuteron data for $\phi$
• No statistically significant difference between proton and deuterium
• No s-channel helicity violation for $\phi$ meson
• Amplitudes hierarchy for $\phi$ meson: $|T_{00}| \sim |T_{11}|$, $|T_{01}| \approx |T_{10}| \approx |T_{-11}| \approx |U_{11}| \approx 0.$
The target-spin asymmetry for $\rho^0$ production

Theoretically:

$$A_{UT}^{\sin(\phi-\phi_S)} \sim \frac{E}{H} \sim \frac{E_q \oplus E_g}{H_q \oplus H_g}$$

Experimentally:

Ellinghaus, Nowak, Vinnikov, Ye (2004)

Other GPD model calculations
- Goeke, Polyakov, Vanderhaeghen (1999)-
- Goloskokov, Kroll (2007)-
- Diehl, Kugler (2008)-

Compatible with zero overall value: $A_{UT}^{\rho^0_{L,S}\sin(\phi-\phi_S)} = -0.033 \pm 0.058$
The target-spin asymmetry for $\phi$ production

- Low statistic
- Small overall value, what is in agreement with theory predictions
\( \omega \) meson production

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

Kinematic cuts:

• \( 1 < Q^2 < 7 \text{ GeV}^2 \)
• \( 3 < W^2 < 6.3 \text{ GeV}^2 \)
• \( t^\prime < 0.4 \text{ GeV}^2 \)
• \( \Delta E < 0.6 \text{ GeV} \)
• \( 0.1 < M_{2\gamma} < 0.17 \text{ GeV} \)
The target-spin asymmetry for omega production

Large negative asymmetry amplitude

\[ A_{UT}^{\sin(\phi - \phi_S)} = -0.22 \pm 0.16_{\text{stat}} \pm 0.11_{\text{syst}} \]
Summary

- Extraction of unpolarized and polarized SDMEs on unpolarized proton and deuteron
  - For $\rho^0$ and $\phi$ compatible results on proton and deuteron
  - Helicity amplitudes hierarchy for $\rho^0$ and $\phi$ mesons presented
  - $s$-channel helicity conservation for $\phi$
  - $s$-channel helicity violation for $\rho^0$
  - NPE for $\phi$
  - Contribution from UPE for $\rho^0$

- $A_{UT}$ for $\rho^0$, $\phi$, $\omega$
  - Small values for $\rho^0$ and $\phi$ - confirmation theory expectation
  - Significantly negative value for $\omega$, which is in agreement with theoretical predictions