New results on exclusive $\rho^0$ and $\phi$ meson production at HERMES

Objectives:
- Generalized Parton Distributions
- Total and Longitudinal Cross Sections of $\rho^0$ and $\phi$
- $\rho^0$ and $\phi$ Meson Spin Density Matrix Elements
  - Longitudinal-to-Transverse Cross-Section Ratios
  - Kinematic dependences
  - Hierarchy of Helicity Amplitudes
  - Unnatural Parity Exchange
- Beam and target polarization asymmetries
- Summary and Outlook

Alexander Borissov, DESY, on behalf of HERMES Collaboration
Properties of $\rho^0$ and $\phi$ meson data:

- different pQCD production mechanisms:
  - only two-gluon exchange for $\phi$,
  - both two-gluon and quark exchanges for $\rho^0$
  $\rightarrow$ GPDs as a flavor filter

- quark exchange mediated by
  - vector or scalar meson: $\rho^0$, $\omega$, $a_2$
    (natural parity: $J^P = 0^+, 1^-$)
    $\rightarrow$ unpolarized GPDs: $H, E$
  - pseudoscalar or axial meson: $\pi$, $a_1$, $b_1$
    (unnatural parity $J^P = 0^-, 1^+$)
    $\rightarrow$ polarized GPDs: $\tilde{H}, \tilde{E}$

Experimental observables:

- total and longitudinal cross sections $\sigma_{\text{tot}}, \sigma_L$

- Spin Density Matrix Elements (SDMEs):
  \[ r_{\lambda_\rho \lambda'_\rho} \sim \rho(V) = \frac{1}{2} T \rho(\gamma) T^+ \]
  vector meson spin-density matrix $\rho(V)$ via photon matrix $\rho(\gamma)$ and helicity amplitude $T_{\lambda_V \lambda_\gamma}$
  
  - $s$-channel helicity conservation (SCHC)?
    i.e. helicity of $\gamma^* = \text{helicity of } \rho^0$
  - Extracted from SDMEs natural and unnatural parity helicity amplitudes and its ratios

Comparison with GK model of GPDs: talk of S.V. Goloskokov, arXiv:0708.3569 hep-ph 27.08.07
**Exclusive \( \rho^0 \) and \( \phi \) Meson Production**

\[
e + p \rightarrow e' + p' + \rho^0 \rightarrow \pi^+ \pi^- \quad \text{and} \quad e + p \rightarrow e' + p' + \phi \rightarrow K^+ K^-
\]

Clean \( \rho^0 \) exclusivity peaks of missing energy \( \Delta E = \frac{M_X^2 - M_P^2}{2M_P} \) for \( \phi \)

Background is subtracted using MC (PYTHIA)

**Kinematics:**
- \( \nu = 5 \div 24 \) GeV, \( \langle \nu \rangle = 13.3 \) GeV, \( Q^2 = 0.5 \div 7.0 \)GeV\(^2\), \( \langle Q^2 \rangle = 2.3 \) GeV\(^2\)
- \( W = 3.0 \div 6.5 \) GeV, \( \langle W \rangle = 4.9 \) GeV, \( x_{ Bj} = 0.01 \div 0.35 \), \( \langle x_{ Bj} \rangle = 0.07 \)
- \( t' = 0 \div 0.4 \) GeV\(^2\), \( \langle t' \rangle = 0.13 \) GeV\(^2\)
\( \rho^0 \) Total and Longitudinal Cross Sections, application of GPDs


- The QCD factorization theorem is proven for the longitudinal part of the cross section assuming SCHC:
  \[
  \sigma_L = \frac{R}{1 + \epsilon R} \sigma_{tot},
  \]
  where \( R = \sigma_L / \sigma_T = \frac{r_{00}^{04}}{\epsilon (1 - r_{00}^{04})} \)

  - SDME \( r_{00}^{04} \) is measured from the fit of angular distributions (explained below)
  - longitudinal-to-transverse ratio of virtual photon fluxes

  \[
  \epsilon = \frac{1 - y - \frac{Q^2}{E^2}}{1 - y + \frac{y^2}{2} + \frac{Q^2}{E^2}} \approx 0.8
  \]

  \( \implies \sigma_L \) for the tests of GPDs

\( \rightarrow \) HERMES data in the transition region

\( \rightarrow \) which production mechanisms are involved?
$\rho^0$ Total and Longitudinal Cross Sections, and GK Model


$Q^2 = 0.83$ GeV$^2$

$Q^2 = 1.3$ GeV$^2$

$Q^2 = 2.3$ GeV$^2$

$Q^2 = 4.0$ GeV$^2$

→ HERMES data in the transition region

→ which production mechanisms are involved?

- two-gluon exchange
- two-gluon + sea interference
- quark exchange
- sum

Band represents uncertainties in $\sigma_L$ from Parton Distributions

⇒ Quark exchange is important for HERMES, i.e. at $W \leq 5$ GeV

$W^\delta_\phi(Q^2)$ dependence over all $W$

$\delta_\phi = 0.22$ at $Q^2 = 0$, $\delta_\phi = 0.53$ at $Q^2 = 2.5$ GeV$^2$

$\rightarrow$ Two-gluon exchange is sufficient for $\sigma_\text{tot}^\phi$

$\Rightarrow$ Two-gluon exchange is sufficient to describe $\sigma_L$ in $\phi$-meson production

Band represents uncertainties in $\sigma_L$ from Parton Distributions

$\rightarrow$ Good agreement of GK model calculations of $\sigma_L(W)$ at $Q^2 = 2.3, 3.8$ GeV$^2$. 

Asymptotic SU(4) pQCD predicts: $\rho^0 : \omega : \phi : J/\Psi = 9 : 1 : 2 : 8$


Remarkable agreement of calculations with $W$-dependence of $\sigma_L(\phi)/\sigma_L(\rho^0)$ ratio
$\rho^0$ & $\phi$-meson Spin Density Matrix Elements (SDMEs)

- $\gamma^* + N \rightarrow \rho^0(\phi) + N'$ is perfect to study the spin structure of production mechanism:
  - spin state of $\gamma^*$ is known
  - $\rho^0 \rightarrow \pi^+\pi^-$ decay is self-analysing

- SDMEs: $r^\alpha_{\lambda\rho\lambda'} \sim \rho(V) = \frac{1}{2} T_{\lambda V,\lambda \gamma} \rho(\gamma) T^+_{\lambda V,\lambda \gamma}$
  spin-density matrix of the vector meson $\rho(V)$ in terms of the photon matrix $\rho(\gamma)$
  and helicity amplitude $T_{\lambda V,\lambda \gamma}$
  - $\alpha = 04, 1 - 3, 5 - 8$ long. or trans. photon, $\lambda_\rho = -1, 0, 1$ - polarization of $\rho^0(\phi)$
  - measured experimentally at $5 < W < 75$ GeV (HERMES,COMPASS,H1,ZEUS)
  - compared with ones calculated in GK GPD model at $W = 5$ GeV, $Q^2 = 3$ GeV$^2$
  - provide access to helicity amplitudes $T_{\lambda V,\lambda \gamma}$, which are:
    * extracted experimentally from SDMEs
    * calculated from GPDs

$\Rightarrow$ Constraints and detailed tests of GPDs
Simulated Events: matrix of fully reconstructed MC events at initial uniform angular distribution

Binned Maximum Likelihood Method: $8 \times 8 \times 8$ bins of $\cos(\Theta)$, $\phi$, $\Phi$. Simultaneous fit of 23 SDMEs $r_{ij} = W(\Phi, \phi, \cos \Theta)$ for data with negative and positive beam helicity ($|P_b| \geq 53.5\%$, $\Psi = \Phi - \phi$)

⇒ Full agreement of fitted angular distributions with data
Function for the Fit of 23 SDME $r_{ij}^\alpha$

$W(\cos \Theta, \phi, \Phi) = W^{unpol} + W^{long.pol}$,

$W^{unpol}(\cos \Theta, \phi, \Phi) = \frac{3}{8\pi^2} \left[ \frac{1}{2}(1 - r_{00}^{04}) + \frac{1}{2}(3r_{00}^{04} - 1) \cos^2 \Theta - \sqrt{2} \text{Re}\{r_{10}^{104}\} \sin 2\Theta \cos \phi - r_{11-1}^{04} \sin^2 \Theta \cos 2\phi \right.$

$- \epsilon \cos 2\Phi \left( r_{11}^{11} \sin^2 \Theta + r_{00}^{04} \cos^2 \Theta - \sqrt{2} \text{Re}\{r_{10}^{101}\} \sin 2\Theta \cos \phi - r_{11-1}^{04} \sin^2 \Theta \cos 2\phi \right)$

$- \epsilon \sin 2\Phi \left( \sqrt{2} \text{Im}\{r_{10}^{2}\} \sin 2\Theta \sin \phi + \text{Im}\{r_{11-1}^{2}\} \sin^2 \Theta \sin 2\phi \right)$

$+ \sqrt{2}\epsilon(1 + \epsilon) \cos \Phi \left( r_{11}^{5} \sin^2 \Theta + r_{00}^{5} \cos^2 \Theta - \sqrt{2} \text{Re}\{r_{10}^{105}\} \sin 2\Theta \cos \phi - r_{11-1}^{5} \sin^2 \Theta \cos 2\phi \right)$

$+ \sqrt{2}\epsilon(1 + \epsilon) \sin \Phi \left( \sqrt{2} \text{Im}\{r_{10}^{6}\} \sin 2\Theta \sin \phi + \text{Im}\{r_{11-1}^{6}\} \sin^2 \Theta \sin 2\phi \right) \right]$,

$W^{long.pol}(\cos \Theta, \phi, \Phi) = \frac{3}{8\pi^2} P_{beam} \left[ \sqrt{1 - \epsilon^2} \left( \sqrt{2} \text{Im}\{r_{10}^{3}\} \sin 2\Theta \sin \phi + \text{Im}\{r_{11-1}^{3}\} \sin^2 \Theta \sin 2\phi \right) \right.$

$+ \sqrt{2}\epsilon(1 - \epsilon) \cos \Phi \left( \sqrt{2} \text{Im}\{r_{10}^{7}\} \sin 2\Theta \sin \phi + \text{Im}\{r_{11-1}^{7}\} \sin^2 \Theta \sin 2\phi \right)$

$+ \sqrt{2}\epsilon(1 - \epsilon) \sin \Phi \left( r_{11}^{8} \sin^2 \Theta + r_{00}^{8} \cos^2 \Theta - \sqrt{2} \text{Re}\{r_{10}^{108}\} \sin 2\Theta \cos \phi - r_{11-1}^{8} \sin^2 \Theta \cos 2\phi \right) \right]$
\( \rho^0 \) 23 Spin Density Matrix Elements

at \( 0 < t' < 0.4 \text{ GeV}^2 \) and \( 1 < Q^2 < 5 \text{ GeV}^2 \)

- **SDMEs:** \( r^\alpha_{\lambda \rho \lambda'} \sim \rho(V) = \frac{1}{2} T \rho(\gamma) T^+ \)
  \[ \implies \] Beam-polarization dependent SDMEs measured for the first time

- **q\bar{q}-exchange with isospin 1** can be observed in case of difference between proton and deuteron data,
  \[ \implies \] No significant difference between proton and deuteron, as well as for \( \phi \) meson SDMEs

- **SCHC?**
  \[ \implies \] Enlarged SDMEs are violating SCHC \((2 \div 5 \sigma)\). Indication on hierarchy of non-zero spin-flip amplitudes: \( T_{01}, T_{10}, T_{1-1} \)
SDMEs According to Hierarchy of Amplitudes with(out) Helicity Flip: \( \rho^0 \phi \)

- A, \( \gamma^*_L \to \rho^0_L \) and \( \gamma^*_T \to \rho^0_T \)
  \[ |T_{11}|^2 \propto 1 - r_{10}^0 \propto r_{1-1}^1 \propto -\text{Im}\{r_{1-1}^2\} \]

- B, Interference: \( \gamma^*_L, \rho^0_T \)
  \[ \text{Re}\{T_{00}T_{11}^*\} \propto \text{Re}\{r_{10}^5\} \propto -\text{Im}\{r_{10}^6\} \]
  \[ \text{Im}\{T_{11}T_{00}^*\} \propto \text{Im}\{r_{10}^7\} \propto \text{Re}\{r_{10}^8\} \]

- C, Spin Flip: \( \gamma^*_T \to \rho^0_L \)
  \[ \text{Re}\{T_{11}T_{01}^*\} \propto \text{Re}\{r_{10}^{04}\} \propto \text{Re}\{r_{10}^{10}\} \propto \text{Im}\{r_{10}^{2}\} \]
  \[ \text{Re}\{T_{01}T_{00}^*\} \propto r_{00}^5 \]
  \[ |T_{01}|^2 \propto r_{00}^1 \]
  \[ \text{Im}\{T_{01}T_{11}^*\} \propto \text{Im}\{r_{10}^3\} \]
  \[ \text{Im}\{T_{01}T_{00}^*\} \propto r_{00}^8 \]

- D, Spin Flip: \( \gamma^*_L \to \rho^0_T \)
  \[ \text{Re}\{T_{10}T_{11}^*\} \propto r_{11}^5 \propto r_{1-1}^5 \propto \text{Im}\{r_{1-1}^6\} \]
  \[ \text{Im}\{T_{10}T_{11}^*\} \propto \text{Im}\{r_{1-1}^7\} \propto r_{11}^8 \propto r_{1-1}^8 \]

- E, Spin Flip: \( \gamma^*_T \to \rho^0_{-T} \)
  \[ \text{Re}\{T_{1-1}T_{11}^*\} \propto r_{11}^{04} \propto r_{1-1}^1 \]
  \[ \text{Im}\{T_{1-1}T_{11}^*\} \propto \text{Im}\{r_{1-1}^3\} \]

\[ \Rightarrow \text{ Hierarchy of } \rho^0 \text{ amplitudes: } |T_{00}| \sim |T_{11}| \gg |T_{01}| > |T_{10}| \gtrsim |T_{1-1}|, \quad (0 \to L, 1 \to T) \]

\[ \Rightarrow \phi \text{ meson SDMEs are consistent with SCHC, } |T_{00}| \sim |T_{11}| \]
Equations for SDMEs Ordered According Helicity Transfer Amplitudes

**A:** $\gamma_L^* \to \rho_L^0$ and $\gamma_T^* \to \rho_T^0$

$$r_{00}^4 = \sum \{ \epsilon |T_{00}|^2 + |T_{01}|^2 + |U_{01}|^2 \}/N_{\text{full}},$$

$$r_{1-1}^1 = \frac{1}{2} \sum \{|T_{11}|^2 + |T_{1-1}|^2 - |U_{11}|^2 - |U_{1-1}|^2\}/N_{\text{full}},$$

$$\text{Im}\{r_{1-1}^2\} = \frac{1}{2} \sum \{-|T_{11}|^2 + |T_{1-1}|^2 + |U_{11}|^2 - |U_{1-1}|^2\}/N_{\text{full}},$$

**B:** interference of $\gamma_L^* \to \rho_L^0$ and $\gamma_T^* \to \rho_T^0$

$$\text{Re}\{r_{10}^5\} = \frac{1}{\sqrt{8}} \sum \text{Re}\{2T_{10} T_{01}^* + (T_{11} - T_{1-1}) T_{00}^*\}/N_{\text{full}},$$

$$\text{Im}\{r_{10}^6\} = \frac{1}{\sqrt{8}} \sum \text{Re}\{2U_{10} U_{01}^* - (T_{11} + T_{1-1}) T_{00}^*\}/N_{\text{full}},$$

$$\text{Im}\{r_{10}^7\} = \frac{1}{\sqrt{8}} \sum \text{Im}\{2U_{10} U_{01}^* + (T_{11} + T_{1-1}) T_{00}^*\}/N_{\text{full}},$$

$$\text{Re}\{r_{10}^8\} = \frac{1}{\sqrt{8}} \sum \text{Im}\{-2T_{10} T_{01}^* + (T_{11} - T_{1-1}) T_{00}^*\}/N_{\text{full}},$$

**C:** $\gamma_T^* \to \rho_L^0$

$$\text{Re}\{r_{10}^3\} = \frac{1}{\sqrt{2}} \sum \text{Re}\{\epsilon T_{10} T_{01}^* + \frac{1}{2} T_{01} (T_{11} - T_{1-1})^* + \frac{1}{2} U_{01} (U_{11} + U_{1-1})^*\}/N_{\text{full}},$$

$$\text{Re}\{r_{10}^4\} = \frac{1}{\sqrt{2}} \sum \text{Re}\{-T_{01} (T_{11} - T_{1-1})^* + U_{01} (U_{11} + U_{1-1})^*\}/N_{\text{full}},$$

$$\text{Im}\{r_{10}^5\} = \frac{1}{\sqrt{2}} \sum \text{Re}\{T_{01} (T_{11} + T_{1-1})^* - U_{01} (U_{11} - U_{1-1})^*\}/N_{\text{full}},$$

$$r_{00}^3 = \sqrt{2} \sum \text{Re}\{T_{01} T_{00}^*\}/N_{\text{full}},$$

$$r_{10}^1 = \frac{1}{2} \sum \{|T_{01}|^2 + |U_{01}|^2\}/N_{\text{full}},$$

$$\text{Im}\{r_{10}^2\} = -\frac{1}{2} \sum \text{Im}\{T_{01} (T_{11} + T_{1-1})^* + U_{01} (U_{11} - U_{1-1})^*\}/N_{\text{full}},$$

$$r_{00}^4 = \sqrt{2} \sum \text{Im}\{T_{01} T_{00}^*\}/N_{\text{full}},$$

**D:** $\gamma_L^* \to \rho_T^0$

$$r_{11}^5 = \frac{1}{\sqrt{2}} \sum \text{Re}\{T_{10} (T_{11} - T_{1-1})^* + U_{10} (U_{11} - U_{1-1})^*\}/N_{\text{full}},$$

$$r_{1-1}^6 = \frac{1}{\sqrt{2}} \sum \text{Re}\{-T_{10} (T_{11} - T_{1-1})^* + U_{10} (U_{11} - U_{1-1})^*\}/N_{\text{full}},$$

$$\text{Im}\{r_{1-1}^7\} = \frac{1}{\sqrt{2}} \sum \text{Re}\{T_{10} (T_{11} + T_{1-1})^* - U_{10} (U_{11} + U_{1-1})^*\}/N_{\text{full}},$$

$$\text{Im}\{r_{1-1}^8\} = \frac{1}{\sqrt{2}} \sum \text{Re}\{-T_{10} (T_{11} - T_{1-1})^* - U_{10} (U_{11} - U_{1-1})^*\}/N_{\text{full}},$$

$$r_{11}^7 = \frac{1}{\sqrt{2}} \sum \text{Im}\{T_{10} (T_{11} + T_{1-1})^* + U_{10} (U_{11} - U_{1-1})^*\}/N_{\text{full}},$$

$$r_{1-1}^8 = \frac{1}{\sqrt{2}} \sum \text{Im}\{-T_{10} (T_{11} - T_{1-1})^* - U_{10} (U_{11} - U_{1-1})^*\}/N_{\text{full}},$$

**E:** $\gamma_T^* \to \rho_T^0$

$$r_{1-1}^3 = \sum \text{Re}\{-\epsilon |T_{10}|^2 + \epsilon |U_{10}|^2 + T_{1-1} T_{11}^* - U_{1-1} U_{11}^*\}/N_{\text{full}},$$

$$r_{11}^2 = \sum \text{Re}\{T_{1-1} T_{11}^* + U_{1-1} U_{11}^*\}/N_{\text{full}},$$

$$\text{Im}\{r_{1-1}^4\} = -\sum \text{Im}\{T_{1-1} T_{11}^* - U_{1-1} U_{11}^*\}/N_{\text{full}},$$

where $N_{\text{full}}$ is normalized total $\rho^0$ production cross section
$\rho^0$ Longitudinal-to-Transverse Cross-Section Ratio

Presented commonly measured \( R^{04} = \frac{1}{\epsilon_1} r^{04}_0 \),

\[ r^{04}_0 = \sum \{ \epsilon |T_{00}|^2 + |T_{01}|^2 + |U_{01}|^2 \} / \sigma_{tot} \]

\[ \sigma_{tot} = \epsilon \sigma_L + \sigma_T \]

\[ \sigma_T = \sum \{ |T_{11}|^2 + |T_{01}|^2 + |T_{1-1}|^2 + |U_{11}|^2 \} \]

\[ \sigma_L = \sum \{ |T_{00}|^2 + 2|T_{10}|^2 \} \]

Due to the helicity-flip and unnatural parity amplitudes \( R^{04} \) depends on kinematic conditions, and is not identical to \( R \equiv |T_{00}|^2 / |T_{11}|^2 \) at SCHC and NPE dominance.

\[ \rightarrow \text{Second order contribution of spin-flip amplitudes to } R^{04} \]

\[ \rightarrow \text{HERMES } \rho^0 \text{ data on } R^{04} \text{ are suggestive to } R(W)-\text{dependence} \]
Presented commonly measured $R^{04} = \frac{r^{04}_{00}}{\epsilon (1 - r^{04}_{00})}$, where:

$$r^{04}_{00} = \sum \{ |T_{00}|^2 \} / \sigma_{tot}$$

$$\sigma_{tot} = \epsilon \sigma_L + \sigma_T$$

$$\sigma_T = \sum \{|T_{11}|^2 \}$$

$$\sigma_L = \sum \{|T_{00}|^2 \}$$

$\Rightarrow$ $R^{04}$ for $\phi$ meson at HERMES is in fair agreement with world data.
$R^{04}$ of $\rho^0$ and $\phi$-meson Compared with GK Model Calculations

blue line $W=90$ GeV, squares: H1, ZEUS, red line $W=10$ GeV, diamond: COMPASS, black line $W=5$ GeV, circle: HERMES, corrected to subtract UPE contribution for $\rho^0$

$\implies R^{04}(W)$-dependence confirmed by calculations
$Q^2$-dependence of HERMES $\rho^0$ SDMEs at $W=5$ GeV on proton and deuteron compared with H1 and ZEUS Data at $W=75$ GeV

Several SDMEs ($r_{00}^{04}, r_{1-1}^{1}, \text{Im}(r_{1-1}^{2})...$) indicate possible $W$-dependence, in addition to $Q^2$-dependence.
$\rho^0$ SDMEs Compared with GK Model Calculations

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

i.e. amplitudes for $\gamma^*_L \rightarrow \rho^0_L$, $\gamma^*_T \rightarrow \rho^0_T$

- $W=90$ GeV
- $W=10$ GeV, diamond: COMPASS
- $W=5$ GeV, circle: HERMES

Fair agreement with data, as well as for the same SDMEs of $\phi$ meson production

$Re\ r_{10}^5$ and $Im\ r_{10}^6$ correspond to interference of $\gamma^*_L, \rho^0_T$ amplitudes

data provide phase difference for

p: $\delta_{LT} = 28.1 \pm 2.8_{stat} \pm 3.7_{syst}$ degrees

d: $\delta_{LT} = 30.2 \pm 2.0_{stat} \pm 3.7_{syst}$ degrees,
while from the handbag approach $\delta_{LT} = 3.1$ degrees at $W=5$ GeV
Observation of Unnatural Parity Exchange (UPE) in $\rho^0$ Leptoproduction

- Natural-parity exchange: interaction is mediated by a particle of ‘natural’ parity: vector or scalar meson: $J^P = 0^+, 1^-$ e.g. $\rho^0, \omega, a_2$
- Unnatural parity exchange is mediated by pseudoscalar or axial meson: $J^P = 0^-, 1^+$, e.g. $\pi, a_1, b_1 \rightarrow$ only quark-exchange contribution
- UPE amplitudes correspond to the contributions of polarized GPDs: $\tilde{E}, \tilde{H}$
- No interference between NPE and UPE contributions on unpolarized target
- Extracted from SDMEs:

\[
U_2 + iU_3 \propto (U_{11} + U_{1-1}) \ast U_{10}
\]
\[
U_2 = r_{11}^5 + r_{1-1}^5
\]
\[
p: U_2 = -0.012 \pm 0.006_{stat} \pm 0.012_{syst}
\]
\[
d: U_2 = -0.008 \pm 0.0046_{stat} \pm 0.010_{syst}
\]
\[
U_3 = r_{11}^5 + r_{1-1}^5
\]
\[
p: U_3 = -0.020 \pm 0.050_{stat} \pm 0.007_{syst}
\]
\[
d: U_3 = -0.021 \pm 0.038_{stat} \pm 0.011_{syst}
\]

\[\Rightarrow\] Indication on hierarchy of $\rho^0$ UPE amplitudes: $|U_{11}| \gg |U_{10}| \sim |U_{01}|$
Only Natural Parity Exchange in $\phi$ Meson Leptoproduction

\[ U_1 = 1 - r^{04}_{00} + 2r^{04}_{11} - 2r^1_{1-1} - 2r^1_{11} \]

\[ U_2 = r^5_{1-1} + r^5_{11} \]

\[ U_3 = r^8_{1-1} + r^8_{11} \]

$Q^2$ (GeV$^2$)

$-t$ (GeV$^2$)

\[ U_1 = 0.02 \pm 0.07_{stat} \pm 0.16_{syst} \]

\[ U_2 = -0.03 \pm 0.01_{stat} \pm 0.03_{syst} \]

\[ U_3 = -0.05 \pm 0.11_{stat} \pm 0.07_{syst} \]

\[ \Rightarrow \text{no UPE for } \phi \text{ meson production, as expected} \]
Unnatural Parity Exchange contribution in GK model

- Measured at $Q^2 = 3 \text{ GeV}^2$ $U1$ corresponds to calculated
  \[ \frac{\sigma_U}{\sigma(\rho^0)} = 0.5 \cdot (1 - r_{00}^{04} - 2r_{1-1}^1) = 2|U_{11}|^2/\sigma(\rho^0) \]
- UPE requires $\tilde{H}$ GPD
- $\sigma_U \propto e_u \tilde{H}^u_{val} - e_d \tilde{H}^d_{val}$ for $\rho^0$ production

Lines:
- Extreme assumption for valence quarks:
  $\tilde{H}^u_{val} = H^u_{val}$ and $\tilde{H}^d_{val} = H^d_{val}$
- Extreme assumption for valence quarks:
  $\tilde{H}^u_{val} = H^u_{val}$ and $\tilde{H}^d_{val} = -H^d_{val}$
- $\sigma_U \approx 0.013$ for gluons and sea contribution

- $\sigma_U$ small for H1 and ZEUS $\rho^0$ data as gluon and sea contribution dominate
- $\sigma_U$ small for $\phi$ at HERMES as gluon contribution dominate

...Better precision of $|U_{11}|^2$ measurement at $Q^2 \approx 3 \text{ GeV}^2$ is planned
\[ A_1^\rho = \frac{\sigma_{1/2}^{+} - \sigma_{3/2}^{+}}{\sigma_{1/2}^{+} + \sigma_{3/2}^{-}} = \frac{A_{LL}}{D} - \eta \sqrt{R_\rho} \]

\[ D \approx 0.40 \text{ photon depolarization factor} \]

\[ \eta \approx 0.06 \text{ kinematical factor, } R_\rho = \sigma_L / \sigma_T \]

\[ A_{LL} = \frac{1}{\rho_{BPT}} \frac{N_{\uparrow \downarrow} L_{\uparrow \downarrow} - N_{\downarrow \uparrow} L_{\downarrow \uparrow}}{N_{\uparrow \downarrow} L_{\uparrow \downarrow} + N_{\downarrow \uparrow} L_{\downarrow \uparrow}} \approx \frac{A_1^\rho}{2.5} \]

\[ N_{\uparrow \downarrow} \] for \( \rho^0 \) measured with antiparallel target helicity relative lepton helicity, \( L \) luminosity

- \( A_1^\rho \) due to the linear contribution of unnatural parity amplitudes process mediated by di-quark objects:

  H.Fraas, Nucl. Phys. B113, 532, (1976);


- i.e. interference effect for \( A_{LL} \)

\[ (A_1^\phi \text{ consistent with zero}) \]
Double Spin Asymmetry in GK model

Interference between leading NPE and UPE amplitudes on longitudinally polarized target results to $A_{LL}$

$$A_{LL} = 4\sqrt{1 - \epsilon^2} \frac{\text{Re}(T_{11}U_{11}^*)}{\sigma(\rho^0)}$$

Lines:
- $W=10$ GeV, diamonds: COMPASS
- $W=5$ GeV, circle: HERMES

$A_{LL}$ small for $\phi$ at HERMES

calculated at $W=5$ GeV
In GK model (arXiv:0708.3569)

- $A_{UT}$ requires the proton helicity flip amplitudes
  
  $M^{N}_{\rho^{0}p',\gamma^*p} \propto e_u E^u_{\text{val}} - e_d E^d_{\text{val}}$

- GK model handbag calculations for HERMES provide

  $$A_{UT} = \frac{4 \text{Im}\{M_{++}^{N} + M_{--}^{N^*}\} + \epsilon \text{Im}\{M_{0-}^{N} + M_{0+}^{N^*}\}}{\sigma(\rho)}$$

  $$A_{UT} = 0.02 \pm 0.01$$

- $A_{UT}$ small for $\phi$ at HERMES

$A_{UT}^{\rho^0} = -0.033 \pm 0.058$

cf. talk of V. Korotkov
• HERMES data are unique due to the sensitivity to both quark and two-gluon exchange processes at sufficiently large $W$ and $Q^2$ for the comparison with GPD handbag diagram based calculations:

• First comprehensive comparison of data on vector meson production with GK model calculations is in fair agreement for:
  – longitudinal and total cross sections of $\rho^0$ and $\phi$ mesons
  – values of SDMEs and hierarchy of corresponding amplitudes
  – violation of SCHC in $\rho^0$ production
  – $W$-dependence of $\rho^0$ and $\phi$ SDMEs and $\sigma_L/\sigma_T$ ratios

• Constraints of HERMES data in GPDs are for:
  – phase difference in the interference of $\gamma^*_L \rightarrow \rho^0_L$ & $\gamma^*_T \rightarrow \rho^0_T$ transitions
  – $\tilde{H}_{u,d}^{val}$ contribution in Unnatural Parity Exchange amplitude and $A_{LL}^\rho$
  – $E_{u,d}^{val}$ contribution in $A_{UT}^\rho$ asymmetry
Outlook

- Target-polarization dependent SDMEs are under analysis in M. Diehl representation

- More data from 2006-2007 at Luminosity $\sim 1.3 \text{ fb}^{-1}$ will be available soon:
BACKUP SLIDES !!!
HERMES proton data at $Q^2 = 2.9$ GeV$^2$:

- $r_{00}^{04} = 0.41 \pm 0.026$
- $r_{1-1}^{1} = 0.23 \pm 0.045$
- Re $r_{10}^{5} = 0.175 \pm 0.013$

Calculations for $W = 5$ GeV are fairly compatible with data.
**HERMES PRELIMINARY**

**ep(d)→e′φp(d)**
- proton and neutron, \( <Q^2> = 1.9 \text{ GeV}^2 \), \( <W> = 5 \text{ GeV} \)

**SDMEs:**
\[
\rho(V) = \frac{1}{2} T \rho(\gamma) T^+ \]

\( \Rightarrow \) Beam-polarization dependent SDMEs measured for the first time

**SCHC?**
\( \Rightarrow \) SDMEs are consistent with SCHC: non-zero elements only in yellow bands

- proton and deuteron data combined, checked that no significant difference between proton and deuteron SDMEs
Difference between $\text{Im } r_{10}^{7}$ and $\text{Re } r_{10}^{8}$ of about 3 $\sigma$ is seen only in preliminary proton data and treated as a possible statistical fluctuation of $\text{Im } r_{10}^{7}$. These elements are completely compatible in deuteron data with $\text{Re } r_{10}^{8}$ on proton.
$Q^2$ and $t'$-Dependences of $\rho^0$ SDMEs
$Q^2$ and $t'$-Dependences of $\phi$-meson SDMEs

A: $\gamma^* \rightarrow \phi_L$ \& $\gamma^* \rightarrow \phi_T$

- Dependences of $\phi$-meson SDMEs

- HERMES PRELIMINARY

- beam-pol. independent dependent SDME

- $r_{00}$ $r_{1,1}$ $-2 \text{ Im } r_{1,1}$

- $Q^2$ (GeV$^2$)

B: Interference $\gamma^* \rightarrow \phi_L$ \& $\gamma^* \rightarrow \phi_T$

- $2\sqrt{2} \text{ Re } r_{10}$ $-2\sqrt{2} \text{ Im } r_{10}$

- $Q^2$ (GeV$^2$)

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

- $2 \text{ Re } r_{10}^0$ $-2 \text{ Re } r_{10}^0$ $2 \text{ Im } r_{10}$ $1/\sqrt{2} r_{00}$

- $Q^2$ (GeV$^2$)

D: $\gamma^* \rightarrow \phi_T$

- $\sqrt{2} r_{11}^S$ $-\sqrt{2} r_{11}^S$ $\sqrt{2} \text{ Im } r_{1,1}$

- $Q^2$ (GeV$^2$)

E: $\gamma^* \rightarrow \phi_T$

- $r_{1,1}^0$ $r_{1,1}^1$ Im $r_{1,1}$

- $Q^2$ (GeV$^2$)

- HERMES PRELIMINARY

- beam-pol. independent dependent SDME

- $r_{00}$ $r_{1,1}$ $-2 \text{ Im } r_{1,1}$

- $Q^2$ (GeV$^2$)

- $t'$ (GeV$^2$)

\[ \sigma_L(γ^* p) [\mu b] \]

\[ <Q^2> = 2.3 \text{ GeV}^2 \]

\[ <Q^2> = 4.0 \text{ GeV}^2 \]

\[ W \text{ [GeV]} \]

2-gluon exchange, quark exchange, sum of both, two-gluon exchange for \( \phi \)

\[ \rightarrow \text{ Domination of quark exchange for } \rho^0 \text{ and two-gluon for } \phi \text{ from VGG model} \]
$Q^2$-Dependence of SDMEs Compared with Calculations

Reasonable agreement for a majority of SDMEs of 12 elements.

To be compared with calculations, for example:


\[
T_{01} \sim T \rightarrow L : \quad \mathcal{H}^V \propto \frac{\sqrt{t}}{Q}
\]

\[
T_{11} \sim T \rightarrow T : \quad \mathcal{H}^V \propto \frac{\langle k_1^2 \rangle^{1/2}}{Q}
\]

\[
T_{10} \sim L \rightarrow T : \quad \mathcal{H}^V \propto \frac{\sqrt{t \langle k_1^2 \rangle^{1/2}}}{Q}
\]

\[
T_{1-1} \sim T \rightarrow -T : \quad \mathcal{H}^V \propto \frac{t \langle k_1^2 \rangle^{1/2}}{Q^2}
\]
**HERMES Detector is Two Identical Halves of Forward Spectrometer**

- **Beam**: $P = 27.56$ GeV/c, 50...100 mA, longitudinal polarization $\sim 55\%$, accuracy of 2%

- **Target**: $^1$H, $^2$H gases, integrated over polarization states

- **Acceptance**: $40 < \Theta < 220$ mrad, $|\Theta_x| < 170$ mrad, $40 < |\Theta_y| < 140$ mrad
Longitudinally Polarized $e^+(-)$ Beam at HERA

$P = 27.56 \text{ GeV/c},$ current 50...100 mA, polarization of about 55%, measured with accuracy of 2%
Internal Storage Cell Gas Target

polarized: $\sim 10^{14}$ nucl/cm$^2$, longitudinal polarization $\sim 98(92)\%$: $^1$H, ($^2$H); transverse $\sim 76\%$: $^1$H
unpolarized: $\sim 5 \cdot 10^{15}$ nucl/cm$^2$: $^1$H, $^2$H, $^4$He, $^{14}$N, $^{20}$Ne, $^{84}$Kr, $^{131}$Xe
Deep Inelastic Scattering: Important Variables and Kinematic Distributions

- \( Q^2_{\text{lab}} = 4EE' \sin^2(\Theta/2) \)
- \( \nu_{\text{lab}} = E - E' \)
- \( x_{\text{Bj}} = \frac{Q^2}{2M\nu} \)
- \( W^2_{\text{lab}} = M^2 + 2M\nu - Q^2 \)
At $-t \lesssim 0.045$ GeV$^2$ coherent $\rho^0$ dominates at $-t \gtrsim 0.1$ GeV$^2$ incoherent.

$b_{(coh)} \approx r_A^2/3$ is in agreement with world data of nuclear size measurements
(H.Alvensleben et al,Phys.Rev.Lett. 24,792 (1970)).
Kinematics of exclusive $\rho^0$ matches dimension of Nuclei

- radius of the nucleus: $r_{14N} \simeq 2.5$ fm
- coherence length: distance traversed by $qq$

\[
l_c = \frac{2 \cdot \nu}{Q^2 + m^2_V} = 0.6 \div 8 \text{ fm},
\]
\[
< l_c > = 2.7 \text{ fm}
\]
- transverse size of the $qq$ wave packet
  \[
  r_{q\bar{q}} \sim 1/ < Q^2 > \simeq 0.4 \text{ fm} < r_p = 1 \text{ fm}
  \]
- formation length: distance needed for $qq$ to develop into hadron:
  \[
l_{\text{form}} = \frac{2 \cdot \nu}{m^2_{V'} - m^2_V} = 1.3 \div 6.3 \text{ fm}
  \]
\[
< l_{\text{form}} > = 3.47 \text{ fm}
\]

$\rightarrow \rho^0$ absorbion at $l_c \geq r_{14N}$

$\rightarrow$ 2-dimensional analysis of $Q^2$, $l_c$ dependences
Coherent Length Effect

\[ T_{c/\text{inc}}(l_c) = \frac{\sigma_{\text{Ac/inc}}}{A\sigma_H} = \frac{N_{\text{Ac/inc}}L_H}{A\cdot N_H\cdot L_A}, \quad A = ^{14}\text{N} \]

Combined effect of initial and final state interactions for incoherent $\rho^0$ and additional effect of nuclear formfactor for coherent $\rho^0$. Agreement with calculations (blue curves, left panel) based on CT approach (B.Z. Kopeliovich et al, Phys.Rev. C, 65, 035201, 2002).

$b(Q^2)$ ‘Photon Shrinkage’ a Prerequisite for Color Transparency

$\rightarrow$ Size of virtual photon controlled via $Q^2$
$\rightarrow$ No strong $W-$dependence
The QCD factorization theorem rigorously not possible without the onset of the color transparency: 

\[ r(qq) \] decreases with the increase of \( Q^2 \) \[ \rightarrow T^{A}(Q^2, l_{coh}) = \sigma^{A}_{(in)coh}/\sigma^{H} \] grows with \( Q^2 \)

At fixed \( l_{coh} \):

<table>
<thead>
<tr>
<th>data</th>
<th>Slope of ( Q^2 )-dependence, GeV(^{-2} )</th>
<th>Prediction, GeV(^{-2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>N incoh.</td>
<td>0.089 ± 0.046( \pm 0.020 )( _{st} \pm 0.020 )( _{syst} )</td>
<td>0.060</td>
</tr>
<tr>
<td>N coh.</td>
<td>0.070 ± 0.027( \pm 0.017 )( _{st} \pm 0.017 )( _{syst} )</td>
<td>0.048</td>
</tr>
<tr>
<td>N combined</td>
<td>( 0.074 \pm 0.023 )</td>
<td>0.058</td>
</tr>
</tbody>
</table>

Agreement with theoretical calculations where positive slope of \( Q^2 \)-dependence was derived from the onset of the color transparency effect (B.Z. Kopeliovich et al, Phys.Rev. C, 65, 035201, 2002)