Exclusive Diffractive Electroproduction of Vector Mesons at

- Objectives: Generalized Parton Distributions
- Kinematics of Exclusive Vector Mesons
- Selected Results:
  - Color Transparency as a Prerequisite for Factorization
  - Total and Longitudinal Cross Sections and its Ratios
  - $\rho^0$ Transversely Polarized Target Spin Asymmetry
  - Spin Density Matrix Elements
- Projections until June 2007
- Summary

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Generalized Parton Distributions (GPDs)

a bridge between fundamental QCD, phenomenology and experimental observables:

Unified description of hard exclusive processes via \( H^{q(g)}(x, \xi, t) \), \( \tilde{H} \), \( E \), \( \tilde{E} \)

\( \rho^0 \), \( \omega \) and \( \phi \) vector mesons as a helicity and flavour filter → access to unpolarised \( E, H \) via

\[ \begin{align*}
    \gamma^* &\rightarrow \rho^0, \\
    \gamma^* &\rightarrow \phi
\end{align*} \]

Cross Sections

quark exchange and/or two-gluon exchange, tested via: Transversely Pol. Target Spin Asymmetry
Spin Density Matrix Elements
Kinematics of exclusive $\rho^0$, $\omega$ and $\phi$

- $\nu = 5 \div 24 \text{ GeV}$, $<\nu> = 13.3 \text{ GeV}$, $Q^2 = 1.0 \div 5.0 \text{ GeV}^2$, $<Q^2> = 2.3 \text{ GeV}^2$
- $W = 3.0 \div 6.5 \text{ GeV}$, $<W> = 4.9 \text{ GeV}$, $x_{Bj} = 0.01 \div 0.35$, $<x_{Bj}> = 0.07$
- $t' = 0.0 \div 0.4 \text{ GeV}^2$, $<t'> = 0.13 \text{ GeV}^2$

$\rho^0$ Exclusivity and Invariant Mass

$\Delta E = \frac{M_X^2 - M_p^2}{2M_p}$ with $M_X^2 = (p + q - \nu)^2$

Background is subtracted with the aid of MC (PYTHIA)
**Kinematics of exclusive $\rho^0$ matches dimension of Nuclei**

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

\[
l_c = \frac{2\nu}{Q^2 + m_V^2} = 0.6 \div 8 \text{ fm}, \quad < l_c > \simeq 2.7 \text{ fm}, \quad l_c \gtrsim r_{14N}
\]

- transverse size of the $qq$ wave packet

\[
r_{qq} \sim 1/ < Q^2 > \simeq 0.4 \text{ fm} < r_p = 1 \text{ fm}
\]

- formation length: distance needed for $qq$ to develop into hadron:

\[
l_{\text{form}} = \frac{2\nu}{m_V^2 + m_V^2} = 1.3 \div 6.3 \text{ fm}
\]

\[
< l_{\text{form}} > \simeq 3.47 \text{ fm}
\]

Transparency $T(l_c, Q^2) = \sigma^A / \sigma^H$

- $l_c$-dependent due to Glauber attenuation: coherence length effect


- $Q^2$-dependent: color transparency effect

$\implies$ 2-dimensional analysis of $T(l_c, Q^2)$ was developed
Prerequisites for Color Transparency: 'Photon Shrinkage' and $A$-dependence of Coherent Slope

$\rightarrow$ Size of $\gamma^*$ controlled via $Q^2$
$\rightarrow$ No strong $W$—dependence

$\rightarrow$ $b_{(coh)} \approx r_A^2/3$ is in agreement with world data of nuclear size measurements

(H.Alvensleben et al,Phys.Rev.Let. 24,792 (1970)).
The QCD factorization theorem rigorously not possible without the onset of the color transparency:

\[ r(qq) \text{ decreases with the increase of } Q^2 \implies T_{c(inc)}(l_c, Q^2) = \frac{\sigma_c^{A(inc)}}{\sigma^H} \text{ grows with } Q^2 \]

At fixed \( l_{c(inc)} \) (HERMES collab., Phys.Rev.Let., 90, 5, 052501, 2003):

<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 \pm 0.046_{st} \pm 0.020_{syst} )</td>
<td>0.060</td>
</tr>
<tr>
<td>N coh.</td>
<td>( 0.070 \pm 0.027_{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).
Color Transparency Analysis was started on DIFFRACTION 2000:
$\rho^0$ and $\phi$ Total Cross Section

\[ \sigma(\gamma^* p) \sim W \left( Q^2 \right) \]

- $\rho^0$ (and $\omega$) are in the transition region, which production mechanisms are involved?
- $\phi$: $W^{\delta\phi(Q^2)}$ describes all data, $\delta\phi = 0.22$ at $Q^2 = 0$, $\delta\phi = 0.53$ at $Q^2 = 2.5$ GeV$^2$
- $\phi$: Two-gluon (or Pomeron) exchange could be sufficient

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

- $W$ dependence at $Q^2 = 2.5 \sim 4$ GeV$^2$
- Substantial two-gluon contribution for $\rho^0$: $0.38 \leq |g_\rho/q_\rho| \leq 1.5$
  

- Trend to $W$ dependence of $\sigma_\omega/\sigma_{\rho^0}$
- VGG model: $\sigma_L^\omega/\sigma_L^{\rho^0} \sim 0.2$
  

2-gluon exchange, quark exchange, sum of both \((R_ω = R_ρ)\)  
2-gluon exchange only

→ Dominance of quark exchange for \(ρ^0\) and \(ω\) from VGG model.  
→ Dominance of 2-gluon exchange for \(φ\) meson

Transversely Polarized Target Spin Asymmetry $A_{UT}^\sin(\phi-\phi_s)$

$$A_{UT}^\sin(\phi-\phi_s) \sim \frac{E(\rho_L)}{H(\rho_L)} \sim \frac{E_g+E_q}{H_q+H_g} \sim -A = \frac{1}{|S_\perp|} \int_0^\pi d\beta \sigma(\beta) - \int_0^{2\pi} d\beta \sigma(\beta)$$

$\beta = \phi - \phi_s$

Open a way to the total spin of the quarks $J_q$ and therefore to their orbital angular momentum $L_q$: $J_q = \frac{1}{2} \Delta \Sigma + L_q$


→ general agreement with GPD calculations (F. Ellinghaus et al, hep-ph/0506264), but not enough to estimate $J^u$

→ FULL data (2002-2005) are under analysis, factor of two in statistics

→ L/T separation has not been done yet, will reduce accuracy on some factor

⇒ ...hard to conclude on the sensitivity to $J^u$
Spin density matrix elements \( r^{\alpha}_{\lambda \rho \lambda'} \) from \( \gamma^* + N \rightarrow \rho^0 + N' \)

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

- \( r^{\alpha}_{\lambda \rho \lambda'} \sim \rho(V) = \frac{1}{2} T \rho(\gamma) T^+ \)
  Spin-density matrix of the vector meson \( \rho(V) \) in terms of the photon matrix \( \rho(\gamma) \) and helicity amplitude \( T_{\lambda V \lambda'} \)

- Access to the spin structure of \( \rho^0 \) production mechanism and \( \rho^0 \) wave function: spin state of \( \gamma^* \) is known, decay \( \rho^0 \rightarrow \pi^+ + \pi^- \) is self-analysing \( \Rightarrow \) tested by comparing kinematic dependences of SDMEs with calculations

- \( q\bar{q} \)-exchange with isospin 1 can be observed in case of difference between proton and deuteron data \( \Rightarrow \) No significant difference between proton and deuteron.

- Spin flip amplitudes or \( s \)-channel helicity violation \( \Rightarrow \) enlarged SDMEs violating SCHC (\( 2 \div 5 \sigma \)), indicating non-zero spin-flip amplitudes: \( T_{01}, T_{10}, T_{1-1} \)

- Estimate of hierarchy of amplitudes \( \Rightarrow \) \( T_{00} \sim T_{11} \gg T_{01} > T_{10} \sim T_{1-1} \)
- Dependence of SDMEs Compared with Calculations for HERMES kinematics

- I.Ivanov: pQCD, two-gluon exchange, oscillator and Coulomb $\rho^0$ wave functions $T_{00}, T_{11}, T_{01}, T_{10}, T_{1-1} \implies$ Disagreement for Re{$r^5_{10}$}, Im{$r^6_{10}$}

- S.Goloskokov: GPD at $Q^2 > 3.0$ GeV$^2$ parameterization of gluonic double distributions Gaussian $\rho$-meson wave function (S-wave), accounted secondary reggeon exchange amplitudes $T_{00}, T_{11}, T_{01} \implies$ Disagreement $r^{04}_{00}, r^{1}_{1-1}, \text{Im}\{r^{2}_{1-1}\}$ connected with $\sigma_L/\sigma_T$ ratio

- S.I.Manayenkov: Regge phenomenology with Pomeron,$\rho, \omega, f, A_2$ exchanges, parton-hadron duality, $T_{00}, T_{11}, T_{01}, T_{10}, T_{1-1} \implies$ Disagreement for $r^{04}_{00}, r^{1}_{1-1}, \text{Im}\{r^{2}_{1-1}\}$ connected with $\sigma_L/\sigma_T$ ratio

- Still reasonable agreement for the majority of SDMEs (12 elements) at low $t'$

- But no model describes well all unpolarized SDMEs $\implies$ Waiting for the inclusion of quark-exchange into GPD-based model, which lowest $Q^2$-limit is possible???
Same comments as for $t'$-dependences

References on models:

Longitudinal-to-Transverse Cross-section Ratio \( R = \sigma_L / \sigma_T \)

In general: \( \sigma_L = \frac{1}{2} \sum N \lambda_N^2 [ |T_{00}|^2 + |T_{10}|^2 + |T_{-10}|^2 ] \), \( \sigma_T = \frac{1}{2} \sum N \lambda_N^2 [ |T_{11}|^2 + |T_{01}|^2 + |T_{-11}|^2 ] \)

at SCHC: \( R^{SCHC} = |T_{00}|^2 / |T_{11}|^2 \approx \frac{r_{04}}{\epsilon(1-r_{04})} \)

at NPE: \( R^{NPE} = \frac{1}{\epsilon} \left\{ \frac{1}{2r_{1-1}r_{00} - 1} \right\} \)

NPE - Natural Parity Exchange with particle quantum numbers \( J^P = 0^+, 1^-, 2^+, \ldots \)

(but accuracy of \( R^{NPE} \) is lower than \( R^{SCHC} \))

\( R^{NPE} \) is the upper limit for \( R \) (\( R \leq R^{NPE} \))
Experimental data for UnPE contribution from SDMEs

\begin{align*}
U_1 &= 1 - r^{04}_{00} + 2r^{04}_{1-1} - 2r^{1}_{11} - 2r^{1}_{1-1} \\
&= \sum_{\lambda'_N, \lambda_N} \frac{2|T^{U}_{1\lambda'_N,0\lambda_N}|^2 + |T^{U}_{1\lambda'_N,1\lambda_N} + T^{U}_{-1\lambda'_N,1\lambda_N}|^2}{\sigma_T + \epsilon \sigma_L} \\
U_2 &= r^5_{11} + r^5_{1-1} \\
\text{p: } U_2 &= -0.0066 \pm 0.0063_{st} \pm 0.0098_{syst} \\
\text{d: } U_2 &= -0.0064 \pm 0.0048_{st} \pm 0.0095_{syst} \\
U_3 &= r^8_{11} + r^8_{1-1} \\
\text{p: } U_3 &= +0.0112 \pm 0.040_{st} \pm 0.0092_{syst} \\
\text{d: } U_3 &= -0.0142 \pm 0.031_{st} \pm 0.0061_{syst} \\
U_2 + iU_3 &= \frac{1}{\sqrt{2}} \sum_{\lambda'_N, \lambda'_N} \frac{T^{U}_{1\lambda'_N,0\lambda_N}[T^{U}_{1\lambda'_N,1\lambda_N} + T^{U}_{-1\lambda'_N,1\lambda_N}]}{\sigma_T + \epsilon \sigma_L} \\
\text{for coherent } \rho^0 \text{ production only NPE is expected}
\end{align*}

→ indication on hierarchy of UnP amplitudes, as \( |T^{U}_{10} \cdot T^{U}_{11}| \) is consistent with zero, \\
→ only one out of two is non-zero
More Data are expected until June 2007 at Planned Luminosity 1.3 fb⁻¹

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

...

More than factor of two in accuracy for \(\rho^0\) and \(\phi\) SDMEs

...and detailed comparison with GPD-based calculations anticipated
Summary

- Color transparency of exclusive $\rho^0$ production supports factorization
- Quark exchange is essential for $\rho^0$ and $\omega$ production
- $\phi$ production can be explained by two-gluon exchange mechanism
- Longitudinal cross sections of $\rho^0$ and $\omega$ are in agreement with VGG calculations.
- Longitudinal cross sections of $\phi$ are in agreement with VGG and GK calculations.
- First measurement of $A_{UT}$ for exclusive $\rho^0$ done, more data available
- Recent $\rho^0$ SDMEs analysis:
  - 23 SDMEs, including 8 polarized, measured in the first time
  - No significant difference between proton and deuteron data
  - Violation of SCHC from non-zero values of several elements
  - $Q^2$ and $t'$-dependences compared with calculations for Pomeron/two-gluon exchange
    $\Longrightarrow$ Quark-exchange GPD-based calculations are necessary!
  - $\sigma_L/\sigma_T$ ratio measured under SCHC and NPE assumptions
  - An indication on unnatural parity exchange amplitude on proton

$\rightarrow$ Vector meson data are available for the tests of GPD models
$\rightarrow$ Significant increase of HERMES statistics is expected