Exclusive vector meson with JLab 6 and 12 GeV
Regge theory: Exchange of families of mesons in the t-channel
\[ \alpha(t) \]

\[ M^2 \text{ (GeV}^2) \]

- \( f_0(2.050) \)
- \( a_0(2.040) \)
- \( \omega_3(1.670) \)
- \( \rho_3(1.690) \)
- \( f_2(1.270) \)
- \( a_2(1.320) \)
- \( \omega(1.782) \)
- \( \rho(1.770) \)
- \( b_3(1.235) \)
- \( \pi_3(1.670) \)
- \( \pi(0.139) \)

\[ \pi, \rho \text{ and } \omega \text{ trajectories} \]
**Regge theory:** Exchange of families of mesons in the $t$-channel

$$M(s,t) \sim s^{\alpha(t)}$$

where $\alpha(t)$ (trajectory) is the relation between the spin and the (squared) mass of a family of particles.

\[ \sigma_{\text{tot}} \sim \frac{1}{s} \times \text{Im}(M(s,t=0)) \rightarrow s^{\alpha(0)-1} \]  

[optical theorem]

\[ \frac{d\sigma}{dt} \sim \frac{1}{s^2} \times |M(s,t)|^2 \rightarrow s^{2\alpha(t)-2} \rightarrow e^{\alpha(t)\ln s} \]
The diagram illustrates the cross section ($\mu b$) as a function of $W$ (GeV) with $W^{0.22}$ on the upper right. The graph shows data points for the reaction $\gamma p \rightarrow \rho p$ with two Feynman diagrams depicting the process. The cross section is plotted on a logarithmic scale from $10^{-4}$ to $10^2$. The $W$ axis ranges from 1 to $10^2$ GeV.
Some signatures of the (asymptotic) « hard » processes:

**\( Q^2 \) dependence:** \( \sigma_L \sim 1/Q^6 \quad \sigma_T \sim 1/Q^8 \quad \sigma_L/\sigma_T \sim Q^2 \)

**\( W \) (or \( x_B \)) dependence:** \( \sigma \sim |xG(x)|^2 \) (for gluon handbag)

**Ratio of yields:** \( \rho/\omega/\phi/(J/\Psi) \sim 9/1/2/8 \) (for gluon handbag)

**Saturation with hard scale of** \( \alpha_p(0), b, \ldots \)

**SCHC :** checks with SDMEs
CLAS, HERMES, COMPASS, H1, ZEUS

Cross section (µb)

$W^{0.22}$

$\sigma(\gamma p \rightarrow \rho p)$

$Q^2 \gg$

+ « older » data from: E665, NMC, Cornell, …
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Steepening $W$ slope as a function of $Q^2$ indicates «hard» regime (reflects gluon distribution in the proton)
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Two ways to set a «hard» scale:
- large $Q^2$
- mass of produced VM

Universality: $\rho$, $\phi$ at large $Q^2 + M_V^2$ similar to $J/\psi$
\( \alpha_{p}(0) \) increases from “soft” (~1.1) to “hard” (~1.3) as a function of scale \( \mu^2 = (Q^2 + M_{\gamma}^2) / 4 \).

Hardening of W distributions with \( \mu^2 \)
Approaching handbag prediction of $n=6$

($Q^2$ not asymptotic, fixed $W$ vs fixed $x_B$, $\sigma_{tot}$ vs $\sigma_L$, $Q^2$ evolution of $G(x)$...)

$\sigma_L \sim 1/Q^6 \Rightarrow \text{Fit with } \sigma \sim 1/(Q^2 + M_V^2)^n$

$Q^2 > 0 \text{ GeV}^2 \Rightarrow n = 2 \pm 0.01$

$Q^2 > 10 \text{ GeV}^2 \Rightarrow n = 2.5 \pm 0.02$

$\rho$: $Q^2 > 0 \text{ GeV}^2 \Rightarrow n = 2.5 \pm 0.02$

$J/\psi$: $Q^2 > 0 \text{ GeV}^2 \Rightarrow n = 2.486 \pm 0.08$

$Q^2$ dependence is damped at low $Q^2$ and steepens at large $Q^2$
dependence decreases from "soft" (~10 GeV$^2$) to "hard" (~4-5 GeV$^2$) as a function of scale $\mu^2=(Q^2+M_V^2)/4$
Ratios

\[ \frac{\sigma_V}{\sigma_\rho} = \left( \frac{9}{2} \right) \frac{\langle uu \rangle - \langle dd \rangle}{\langle uu \rangle + \langle dd \rangle} \]

\[ \rho/\omega/\phi/(J/\Psi) \sim 9/1/2/8 \]

\[ |\rho^0| = \frac{1}{\sqrt{2}}(|uu\rangle - |dd\rangle) \]

\[ |\omega| = \frac{1}{\sqrt{2}}(|uu\rangle + |dd\rangle) \]

\[ \sim \left\{ \frac{2}{3} - \left( -\frac{1}{3} \right) \right\} \]

\[ \sim \left\{ \frac{2}{3} + \left( -\frac{1}{3} \right) \right\} \]

Ratio \( \rho/\omega = 9 \)
$\sigma_L / \sigma_T$

(almost) compatible with handbag prediction
(damping at large $Q^2$)
(almost) no SCHC violation
At high energy \((W>5 \text{ GeV})\), the general features of the kinematics dependences and of the SDMEs are relatively/qualitatively well understood.

Good indications that the “hard”/pQCD regime is dominant for \(\mu^2=(Q^2+M_V^2)/4 \sim 3-5 \text{ GeV}^2\).

Data are relatively well described by GPD/handbag approaches.
Exclusive $\rho^0$, $\omega$, $\phi$ & $\rho^+$ electroproduction on the proton @ CLAS6

K. Lukashin et al., Phys.Rev.C63:065205,2001 ($\phi$@4.2 GeV)
C. Hadjidakis et al., Phys.Lett.B605:256-264,2005 ($\rho^0$@4.2 GeV)
L. Morand et al., Eur.Phys.J.A24:445-458,2005 ($\omega$@5.75GeV)
J. Santoro et al., Phys.Rev.C78:025210,2008 ($\phi$@5.75GeV)
S. Morrow et al., Eur.Phys.J.A39:5-31,2009 ($\rho^0$@5.75GeV)
A. Fradi, Orsay Univ. PhD thesis ($\rho^+$@5.75 GeV)
e1-6 experiment ($E_e = 5.75$ GeV)

(October 2001 - January 2002)
C. Hadjidakis et al., Phys.Lett.B605:256-264,2005 ($\rho^0@4.2$ GeV)

L. Morand et al., Eur.Phys.J.A24:445-458,2005 ($\omega@5.75$ GeV)

K. Lukashin, Phys.Rev.C63:065205,2001 ($\phi@4.2$ GeV)

S. Morrow et al., Eur.Phys.J.A39:5-31,2009 ($\rho^0@5.75$ GeV)

J. Santoro et al., Phys.Rev.C78:025210,2008 ($\phi@5.75$ GeV)

A. Fradi, Orsay Univ. PhD thesis, 2009 ($\rho^+@5.75$ GeV)
\[ \text{ep} \rightarrow \text{ep} \pi^+ (\pi^-) \]

\[ \text{Mm(ep}\pi^+ \text{X)} \]

\[ \text{Mm(epX)} \]
Background Subtraction

1) Ross-Stodolsky B-W for $\rho^0(770)$, $f_0(980)$ and $f_2(1270)$ with variable skewedness parameter,

2) $\Delta^{++}(1232)$ $\pi^+\pi^-$ inv.mass spectrum and $\pi^+\pi^-$ phase space.
$IM(p\pi^+)$

$Q^2 (GeV^2)$

$X_B$

[Graph showing data distributions with $Q^2$ and $X_B$ axes.]
Background Subtraction

1) Ross-Stodolsky B-W for $\rho^0(770)$, $f_0(980)$ and $f_2(1270)$ with variable skewedness parameter,
2) $\Delta^{++}(1232)$ $\pi^+\pi^-$ inv.mass spectrum and $\pi^+\pi^-$ phase space.

![Graphs showing different mass spectra with various parameters and distributions.](image-url)
V. Mokeev

2π e-prod model

Working

up to $W=1.6$ GeV

up to $Q^2 \sim 1$ GeV$^2$
FIG. 4: (color online) Resonant (blue bars) and non-resonant (green bars) contributions to differential cross sections obtained from the CLAS data [7] fit within the framework of JM model at $W = 1.51$ GeV, $Q^2 = 0.38$ GeV$^2$. Dashed lines show the fit results.
Longitudinal cross section $\sigma_L (\gamma^*_{L} p \rightarrow p\rho_L^0)$
VGG GPD model
GK GPD model
Handbag diagram calculation needs $k_{\text{perp}}$ effects to account for preasymptotic effects.

Same thing for 2-gluon exchange process.
Comparison of cross sections is model-dependent: $k_{\text{perp}}$ dependence ansatz, model for GPDs,…

Some signatures available for gluon handbag are not relevant for quark handbag:

$W$ (or $x_B$) dependence: $\sigma \sim |x G(x)|^2$

Ratio of yields: $\rho/\omega/\phi/(J/\Psi) \sim 9/1/2/8$

Model-independent features:

$Q^2$ dependence: $\sigma_L \sim 1/Q^6$, $\sigma_T \sim 1/Q^8$, $\sigma_L/\sigma_T \sim Q^2$

Saturation with hard scale of $b$ SCHC: checks with SDMEs
CLAS@6 GeV  S. Morrow et al., Eur.Phys.J.A39:5-31,2009 ($\rho^0@5.75\text{GeV}$)

\begin{align*}
\sigma_L &\propto (Q^2)^{-1.82 \pm 0.87} \\
\sigma_L &\propto (Q^2)^{-2.77 \pm 1.24} \\
\end{align*}
Exclusive $\rho^0$ electroproduction at CLAS12

CLAS12 proposal PR12-11-103
Exclusive $\rho^0$ electroproduction at CLAS12

CLAS12 proposal PR12-11-103

$Q^2$ range at 6 GeV

$Q^2$ range at 12 GeV
Comparison of t-slope for $\rho^0$, $\omega$, $\phi$ channels at 6 GeV
Comparison of $b$ for $\rho^0$, $\omega$, $\phi$ channels at 6 GeV
$\rho^0$ decay angular distribution (polar angle $\theta_{cm}$)

CLAS12 proposal PR12-11-103

purely statistical error bars

statistical error bars +10% systematic
$e^p + e^p \phi \rightarrow K^+ [K^-]$
Exclusive $\phi$ electroproduction: gluon imaging of the proton

$x<0.01$: measured at H1/ZEUS

$x>0.1$: practically unknown: $\phi$ with CLAS12
Exclusive $\phi$ electroproduction: gluon imaging of the proton

(A. Kubarovsky’s simulations)

**CLAS12 proposal PR12-11-103:**

**Extract $t$–slope of $d\sigma_L/dt$ up to $Q^2 \sim 7$ GeV$^2$**

As a function of $Q^2$: check when $Q^2$-independence settles
As a function of $x_B$ (or $W$): first 3D-gluon imaging at large $x$
VMs ($\rho^0, \omega, \phi$) the only exclusive process [with DVCS] measured over a $W$ range of 2 orders of magnitude ($\sigma_{L,P}, d\sigma/dt, SDMEs,\ldots$)

At high energy ($W>5$ GeV), transition from “soft” to “hard” ($\mu^2$ scale) physics relatively well understood (further work needed for precision understanding/extractions)

At low energy ($W<5$ GeV), success of “hard” approach for the $\phi$ channel (nucleon gluon imaging) but large failure for the $\rho^0, \omega, \rho^+$ channels. This is not understood. Why the GPD/handbag approach should set at much larger $Q^2$ for valence quarks? Are the widely used GPD parametrisations in the valence region completely wrong?

A lot of new data expected soon from JLab@11GeV, COMPASS (transv. target), HERA new analysis,\ldots

CLAS12 PR12-11-103 proposal: broader phase space, check when $Q^2$ independence settles for a variety of observables