Deep exclusive meson electroproduction: review
cross section (μb) vs W (GeV)

σ(γp → ρp)
Regge theory: Exchange of families of mesons in the t-channel
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.

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

\[ d\sigma/dt \sim 1/s^2 \times |M(s,t)|^2 \rightarrow s^{2\alpha(t)-2} \rightarrow e^{\alpha(t) \ln s} \]
The cross section versus $W$ is plotted on a log-log scale. The graphs show the dependence of the cross section on $Q^2$ with $Q^2 \gg \rho_L^0$. The data points are scattered around a curve that can be approximated by $\sigma(\gamma p \rightarrow \rho p) \propto W^{0.22}$. The diagrams illustrate the contributions from $\sigma, f_2$ and $\rho$ to the cross section.
Some signatures of the (asymptotic) « hard » processes:

\[
\begin{align*}
\sigma_L & \sim 1/Q^6 \\
\sigma_T & \sim 1/Q^8 \\
\sigma_L / \sigma_T & \sim Q^2
\end{align*}
\]

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

\(W\) (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
H1, ZEUS
CLAS
HERMES
COMPASS
H1,
ZEUS
+ « older » data from:
E665, NMC, Cornell,...
+ « older »
data from:
E665, NMC, Cornell,…
Steepening $W$ slope as a function of $Q^2$ indicates «hard» regime (reflects gluon distribution in the proton)
Two ways to set a «hard» scale:

* large $Q^2$
* mass of produced VM

Steepleing $W$ slope as a function of $Q^2$ indicates «hard» regime (reflects gluon distribution in the proton)

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

Hardening of \( W \) distributions with \( \mu^2 \)
Q^2 dependence

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

ρ:
Q^2 > 0 \text{ GeV}^2 \Rightarrow n = 2 +/- 0.01
Q^2 > 10 \text{ GeV}^2 \Rightarrow n = 2.5 +/- 0.02

J/ψ:
Q^2 > 0 \text{ GeV}^2 \Rightarrow n = 2.486 +/- 0.08
(n = 2.486 +/- 0.08)

Q^2 dependence is damped at low Q^2 and steepens at large Q^2

Approaching handbag prediction of n = 6
(Q^2 not asymptotic, fixed W vs fixed x_B, σ_{tot} vs σ_L, Q^2 evolution of G(x)...)
b decreases from “soft” (~10 GeV\(-2\)) to “hard” (~4-5 GeV\(-2\)) as a function of scale $\mu^2 = (Q^2 + M_V^2) / 4$
\[ \rho / \omega / \phi / (J/\Psi) \sim 9/1/2/8 \]

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

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

\[ \sim \{2/3 - (-1/3)\} \]

\[ \sim \{2/3 + (-1/3)\} \]

Ratio \( \rho / \omega = 9 \)
(almost) compatible with handbag prediction
(damping at large $Q^2$)
(almost) no SCHC violation
At high energy ($W>5$ 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 $\mu^2=(Q^2+M_V^2)/4 \sim 3-5$ GeV$^2$.

Data are relatively well described by GPD/handbag approaches.
JLab & CLAS in Hall B

Duty cycle $\sim$100%  \hspace{1cm} E_{\text{max}} \sim$6 GeV
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 ($\omega@5.75$GeV)
J. Santoro et al., Phys.Rev.C78:025210,2008 ($\phi@5.75$GeV)
S. Morrow et al., Eur.Phys.J.A39:5-31,2009 ($\rho^0@5.75$GeV)
A. Fradi, Orsay Univ. PhD thesis ($\rho^+@5.75$ 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 ($\omega@5.75$ 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)
\( \text{ep} \rightarrow \text{ep}\phi (\xrightarrow{\text{K}^+ [\text{K}^-])} \)
Handbag diagram calculation needs \( k_{\text{perp}} \) effects to account for preasymptotic effects.

Same thing for 2-gluon exchange process.
Exclusive $\phi$ electroproduction: gluon imaging of the proton

$x < 0.01$: measured at H1/ZEUS

$x > 0.1$: practically unknown: $\phi$ with CLAS12

(from JLab PAC38 PR12-11-103, C. Weiss/P. Stoler’s slides)
Exclusive $\phi$ electroproduction: gluon imaging of the proton

CLAS12 proposal PR12-11-103:
Extract $t$–slope of $d\sigma_L/dt$

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 $x$
VGG GPD model

$\sigma_L(p \rightarrow p') (u, b)$

$W (GeV)^{10}$

$1.60 < Q^2 (GeV^2) < 1.90$

$1.90 < Q^2 (GeV^2) < 2.20$

$2.20 < Q^2 (GeV^2) < 2.50$

$2.50 < Q^2 (GeV^2) < 2.80$

$2.80 < Q^2 (GeV^2) < 3.10$

$3.10 < Q^2 (GeV^2) < 3.60$

$3.60 < Q^2 (GeV^2) < 4.10$

$4.10 < Q^2 (GeV^2) < 4.60$

$4.60 < Q^2 (GeV^2) < 5.10$

$5.10 < Q^2 (GeV^2) < 5.60$

VGG GPD model
VGG GPD model

GK GPD model

\begin{align*}
\sigma_\text{\textsc{vgg}} (p^+ \rightarrow p^0)^0 (\mu \cdot b) \quad & \quad \text{for different} \quad Q (GeV) \\
\sigma_\text{\textsc{gk}} (p^+ \rightarrow p^0)^0 (\mu \cdot b) \quad & \quad \text{for different} \quad Q (GeV)
\end{align*}

\begin{align*}
\text{CLAS (5.754 GeV)} \\
\text{CLAS (4.2 GeV)} \\
\text{CORNELL} \\
\text{HERMES} \\
\text{E665}
\end{align*}
\[ H, \tilde{H}, E, \tilde{E} (x, \xi, t) \]

\[ J, \pi, \rho, \omega \ldots \]

\[ x+\xi, x-\xi \]

**“ERBL” region**

**“DGLAP” region**

Antiquark distribution

\[ q \bar{q} \] Distribution amplitude

Quark distribution

\[ W \sim 1/\xi \]
DDs + “meson exchange”

DDs w/o “meson exchange” (VGG)

CLAS (5.754 GeV)
CLAS (4.2 GeV)
CORNELL
HERMES
E665

“meson exchange”
Exclusive $\rho^0$ electroproduction at CLAS12

CLAS12 proposal PR12-11-103
High–\(t\): Small–size \(qqq\) configurations

(from JLab PAC38 PR12-11-103, C. Weiss/P. Stoler’s slides)

- Meson production at \(|t| \gg 1 \text{ GeV}^2\):
  Nucleon in small–size configuration

  Cf. high–\(t\) elastic nucleon form factors

  Progress with GPD description of high–\(t\) processes
  Kumano, Strikman, Sudoh 10

- Backward production: \(|u| < 1 \text{ GeV}^2\)

  Knockout of small–size \(qqq\) configuration, mesonic system left behind

  Transition distribution amplitude \(\langle V|qqq|N\rangle\)
  New information on short–range nucleon structure
  Frankfurt et al. 02; Pire, Semenov–Tian–Shansky, Szymanowski 10/11
  Great interest! Cross section calculations available soon

- CLAS12: Explore high–\(|t|\), high–\(Q^2\) region for the first time

  New QCD probe of nucleon’s valence quark core!
VMs ($\rho^0, \omega, \phi$) the only exclusive process [with DVCS] measured over a $W$ range of 2 orders of magnitude ($\sigma_{L,T}$, $d\sigma/dt$, SDMEs,...)

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 ($\rightarrow$ nucleon gluon imaging) but large failure for the $\rho^0, \omega, \rho^+$ channels. This is not understood. Why the GPD/handbag approach sould 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,…

CLAS12 PR12-11-103 proposal: broader phase space, check when $Q^2$ independence settles for a variety of observables
\( \gamma N \rightarrow N \pi \)
\( \sigma_\rho (\gamma^* p \rightarrow p \rho^0) \) vs \( W \)
Angular distribution analysis, \( \cos \theta_{\text{cm}} \)

Relying on SCHC
(exp. check to the \(~25\%\) level)
Longitudinal cross section $\sigma_L \left( \gamma^*_L p \rightarrow p\rho_L^0 \right)$
Interpretation “a la Regge” : Laget model

\[ \gamma^*p \rightarrow p \rho^0 \]
\[ \gamma^*p \rightarrow p \omega \]
\[ \gamma^*p \rightarrow p \phi \]

Free parameters:

- Hadronic coupling constants: \( g_{\text{MNN}} \)
- Mass scales of EM FFs: \( (1+Q^2/\Lambda^2)^{-2} \)
\[ \sigma_L \left( \gamma^* L p \rightarrow p \rho_L L^0 \right) \]
Exclusive $\rho^+$ electroproduction
Channel selection

\[ e \ p \rightarrow e' \ [n] \ \rho^+ \rightarrow e' \ [n] \ \pi^+\pi^0 \rightarrow e' \ [n] \ \pi^+ \gamma \gamma \]

One event in CLAS
Invariant mass $\text{IM}(\pi^+ \pi^0)$

Total cross section $\sigma(Q^2, x_B) \rho^+$
Regge “hadronic” approach

\[ \pi^+ p \to \rho^+ n + \rho^+ n \]

GPD “partonic” approach

\[ H, E \]

\[
\begin{array}{|c|c|}
\hline
\rho^0 & e_u H^u - e_d H^d \\
& e_u E^u - e_d E^d \\
\hline
\omega & e_u H^u + e_d H^d \\
& e_u E^u + e_d E^d \\
\hline
\rho^+ & H^u - H^d \\
& E^u - E^d \\
\hline
\end{array}
\]
"Hadronic approach": Laget model
Partonic approach: GPDs
Exclusive $\phi$ electroproduction
$e p \rightarrow e p \phi \left( \leftrightarrow K^+[K^-] \right)$
Laget $\sigma_T + \epsilon \sigma_L$

- $W = 2.9 \text{ GeV}$
- $W = 2.45 \text{ GeV}$
- $W = 2.1 \text{ GeV}$

GK $\sigma_L$
Exclusive $\omega$ electroproduction
$e^+ p \rightarrow e^- p \omega$ (→ $\pi^+ \pi^- [\pi^0]$)
The abscissa on each graph corresponds to the following list of matrix elements: $r_{00}^{104}$, Re $r_{10}^{104}$, $r_{00}^{104}$, $r_{11}^{104}$, Re $r_{10}^{1}$, $r_{10}^{1}$, Im $r_{10}^{2}$, $r_{00}^{2}$, $r_{11}^{2}$, Re $r_{00}^{3}$, $r_{11}^{3}$, Im $r_{00}^{6}$, $r_{11}^{6}$. The red filled symbols indicate those matrix elements which are zero if SCHC applies.
Cross section $\sigma(\gamma^* p \rightarrow p\omega)$

Laget Regge model for $\gamma^* p \rightarrow p\omega$

Issue with GPD approach if $\pi^0$ exchange dominant:

$\pi^0 \rightarrow \bar{E}$

while

$E$ subleading in handbag for VM production
Cross section $\sigma(\gamma^*p \rightarrow p\omega)$

–Comparison with GPD calculation (VGG)–
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)
$\sigma_L(\gamma p \rightarrow p' p^0) (\mu b)$

$3.60 < Q^2 (GeV) < 4.10$

GPDs/handbag ???

GPDs/handbag
Motivation to go to higher $Q^2$ (but stay in valence region):

Approach asymptotic regime and test validity of power corrections

If (power corrected) handbag diagram in valence region:
same $Q^2$ dependence at low $W$ than at large $W$:
$\rho^0$ and $\phi$ should be different from $\omega$ and $\rho^+$, these latter having higher-twist $t$-channel exchanges

If higher twist contribution in valence region: cross section will drop faster as a function of $Q^2$ at low $W$ than at large $W$: 
Overview of existing data (valence region)

\[ \rho^0, \omega, \phi \text{ & } \rho^+ \text{ electroproduction on the proton @ CLAS6} \]

\[ \text{GPDs or not GPDs ?} \]

Perspectives with CLAS12 & EIC
100% acceptance & integrated over all variables but \((x_B, Q^2)\)

Counting rates for 1000 hours at \(10^{34}\) cm\(^{-2}\) s\(^{-1}\)

Limitation comes from phase space

6 GeV e
fixed p target
100% acceptance & integrated over all variables but \((x_B, Q^2)\)

Counting rates for 100 hours at \(10^{34} \text{ cm}^{-2}\text{s}^{-1}\)

Limitation comes from phase space
100% acceptance & integrated over all variables but \((x_B, Q^2)\)

11 GeV e
fixed p target

Counting rates
for 1000 hours
at \(10^{35}\) cm\(^{-2}\) s\(^{-1}\)

Limitation comes from phase space
100% acceptance & integrated over all variables but $(x_B, Q^2)$

11 GeV e
fixed p target

Counting rates for 1000 hours at $10^{35}$ cm$^{-2}$s$^{-1}$

Limitation comes from phase space
100% acceptance & integrated over all variables but $(x_B, Q^2)$

Counting rates for 1000 hours at $10^{34}$ cm$^{-2}$ s$^{-1}$

11 GeV e
60 GeV p
100% acceptance & integrated over all variables but $(x_B, Q^2)$

Counting rates for 1000 hours at $10^{34}$ cm$^{-2}$s$^{-1}$

Limitation comes from luminosity
6 GeV e
fixed p target

11 GeV e
fixed p target

11 GeV e
60 GeV p
CLAS@6 GeV  S. Morrow et al., Eur.Phys.J.A39:5-31,2009 ($\rho^0@5.75$GeV)
Back-up slides
$\mathcal{IM}(p\pi^+)$
$\text{IM}(p\pi^-)$
Handbag diagram calculation has $k_{\text{perp}}$ effects to account for preasymptotic effects.

Interpretation in terms of GPDs?
Background Subtraction (normalized spectra)

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.
\[ \frac{d\sigma}{dt} \left( \gamma^* p \rightarrow pp^0 \right) \]

Large \( t_{\text{min}} \)!
(1.6 GeV\(^2\))

Fit by \( e^{bt} \)
Longitudinal cross sections

$\sigma_L(\rho^+)[\mu b]$

$\frac{d\sigma_L}{dt}(\rho^+)[\mu b]$
Comparison with $\rho^0$, $\omega$, $\phi$
Increasing $Q^2$:

$e^{-} \quad Q^2 \sim \text{MeV}^2 \quad 2$

$\downarrow$

$Q^2 >>$

$e^{-} \quad Q^2 >> \text{GeV}^2 \quad 2$

$?$
GPDs parametrization based on DDs (VGG/GK model)

Strong power corrections… but seems to work at large $W$…
\[ d\sigma/dt \ (\gamma^* p \rightarrow pp^0) \]

Large \( t_{\text{min}} \):
\[ (1.6 \text{ GeV}^2) \]

Fit by \( e^{bt} \)
Regge theory: Exchange of families of mesons in the $t$-channel
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.

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

\[ d\sigma/dt \sim 1/s^2 \times |M(s,t)|^2 \rightarrow s^{2\alpha(t)-2} \rightarrow e^{\alpha(t)\ln(s)} \]
e1-6 experiment \((E_e = 5.75 \text{ GeV})\) 
(October 2001 – January 2002)
$e p \rightarrow e p \pi^+ (\pi^-)$

$M_{m}(e p \pi^+ \ X)$

$M_{m}(e p X)$
$\sigma_\rho \ (\gamma^* p \rightarrow p\rho^0)$ vs $W$
Comparison with $\rho^0$, $\omega$, $\phi$