Vector Mesons and DVCS at Jefferson Lab

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XIX International Workshop on Deep-Inelastic Scattering and Related Subjects
Outlook

• Introduction
• DVCS with unpolarized target
• DVCS with polarized targets
• Vector meson electroproduction
• JLAB 12 upgrade
• Conclusion
Description of hadron structure in terms of GPDs

- **Nucleon form factors**: transverse charge & current densities
- **Structure functions**: quark longitudinal momentum (polarized and unpolarized) distributions
- **GPDs**: correlated quark momentum distributions (polarized and unpolarized) in transverse space
DVCS and DVMP

- Factorization theorem
- Access to fundamental degrees of freedom

DVCS:
- the clearest way to access the GPDs
- Only $\gamma_T$ photons participate in DVCS
- Interference with BH process

DVMP:
- Factorization proven only for $\sigma_L$
  $\sigma_T/\sigma_L \sim 1/Q^2$
- Meson distribution amplitude
- Gluon exchange required
- Vector and pseudoscalar meson production allows to separate flavor and separate the helicity-dependent GPDs form helicity independent.

<table>
<thead>
<tr>
<th>Meson</th>
<th>GPD flavor composition</th>
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</thead>
<tbody>
<tr>
<td>$\pi^+$</td>
<td>$\Delta u - \Delta d$</td>
</tr>
<tr>
<td>$\pi^0$</td>
<td>$2\Delta u + \Delta d$</td>
</tr>
<tr>
<td>$\eta$</td>
<td>$2\Delta u - \Delta d$</td>
</tr>
<tr>
<td>$\rho^0$</td>
<td>$2u + d$</td>
</tr>
<tr>
<td>$\rho^+$</td>
<td>$u - d$</td>
</tr>
<tr>
<td>$\omega$</td>
<td>$2u - d$</td>
</tr>
</tbody>
</table>
Accessing GPDs through polarization

\[ A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta \sigma}{2 \sigma} \]

Polarized beam, unpolarized proton target:

\[ \Delta \sigma_{LU} \sim \sin \phi \{ F_1 \mathcal{H} + \xi(F_1+F_2) \tilde{\mathcal{H}} + kF_2 \mathcal{E} \} d\phi \]

\text{Kinematically suppressed}

Unpolarized beam, longitudinal proton target:

\[ \Delta \sigma_{UL} \sim \sin \phi \{ F_1 \tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + \xi/(1+\xi) \mathcal{E}) \} d\phi \]

\text{Kinematically suppressed}

Unpolarized beam, transverse proton target:

\[ \Delta \sigma_{UT} \sim \cos \phi \{ kF_2 \mathcal{H} - F_1 \mathcal{E} \} d\phi \]

\[ \mathcal{H}(\xi,t), \tilde{\mathcal{H}}(\xi,t), \mathcal{E}(\xi,t) \ldots \text{are CFF} \]

\[ \xi \approx x_B/(2-x_B) \]

\[ k = t/4M^2 \]
JLab Site: The 6 GeV Electron Accelerator

- 3 independent beams with energies up to 6 GeV
- Dynamic range in beam current: $10^6$
- Electron polarization: 85%
CEBAF Large Acceptance Spectrometer CLAS

CLAS Lead Tungstate Electromagnetic Calorimeter

424 crystals, 18 RL, Pointing geometry, APD readout
DVCS Beam Spin Asymmetry $A_{LU}$

\[ A_{LU} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta\sigma}{2\sigma} \]

- **VGG parameterization** reproduces $-t > 0.5\text{GeV}^2$ behavior, and overshoots asymmetry at small $t$.

- The latter could indicate that VGG misses some important contributions to the DVCS cross section.

- Regge model (J-M Laget) is in fair agreement in some kinematic bins with our results.

- The Regge mode seems to be working at low $Q^2$ while the GDP approach gets better at larger $Q^2$. This is expected by F.-X. Girod et al., PRL 100 (2008) 162002.
Extraction of Compton Form Factors from CLAS DVCS data

- $A_{LU}$ and $A_{UL}$ CLAS results only
- $\text{Im } H(t)$ $\text{Im } \tilde{H}(t)$ are extracted
- $\text{Im } \tilde{H}(t)$ flatter than $\text{Im } H(t)$


The fact that $\tilde{H}$ is "flatter" in $t$ than $H$, hints that the axial charge of the nucleon is more concentrated than the electromagnetic charge. This is related to the fact that the axial form factor is also flatter than the EM form factors. We see that via different formalism (GDPS vs FFs) and reaction (DVCS vs elastic), one reaches the same conclusions.
Radiative corrections and \( \pi^0 \) contamination accounted
DVCS target spin asymmetry

\[ \sigma(\vec{e}p \rightarrow e\vec{p}\gamma) \]

E. Seder

Longitudinal target SSA will be extracted in bins in Q2, x and t

Polarizations:
- Beam: \( \sim 80\% \)
- NH3 proton \( \sim 70\% \)
- Beam energy \( \sim 5.7 \text{ GeV} \)

\[ A_{UL} = \frac{N^\uparrow(\phi) - N^\downarrow(\phi)}{f[P^\downarrow_t N^\uparrow(\phi) + P^\uparrow_t N^\downarrow(\phi)]]} \]
DVCS double spin asymmetry

eg1-dvcs - completed data taking at 2009

\[ A_{LL} = \frac{(N^{++} + N^{--}) - (N^{+-} + N^{-+})}{fP_{\text{beam}}P_{\text{target}} (N^{++} + N^{--}) - (N^{+-} + N^{-+})} \]

Fitting function:

\[ A_{LL} = \alpha + \beta \cos \varphi + \gamma \cos^2 \varphi + \delta \sin^2 \varphi \]

- N^{+/-}: number of DVCS events with a positive (negative) target/beam polarization
- P_{\text{beam/T}}: beam/target polarization
- f: dilution factor

Very Preliminary
Hall A

• Proton DVCS, helicity dependent and independent cross sections were measured at
  \( Q^2 = (1.5, 1.9, 2.3) \text{ GeV}^2 \)
  \(-t = (0.17, 0.23, 0.28, 0.33) \text{ GeV}^2 \)
  \( x_B = 0.36 \)

• Neutron DVCS, helicity dependent cross section on deuterium. Sensitive to \( E(\xi, t) \)
  \( Q^2 = 1.9 \text{ GeV}^2 \)
  \( x_B = 0.36 \)

• Completed data taking at 2010, which included measurements of DVCS on proton and deuterium at two different energies with the aim to separate \( \text{Re} [\text{DVCS}^* \text{BH}] \) and \( |\text{DVCS}|^2 \) terms.
Imaginary Part of the Interference Term

- VGG model agrees in slope with the data but lies 30% above
- $Q^2$ independent in all $t$ bins
- Provide support for the factorization at $Q^2 > 2$ GeV$^2$
Constraint on $J_d$ and $J_u$

Helicity-dependent JLab Hall-A neutron and HERMES transversity polarized proton data constrain in a model dependent way on the total up and down quark contributions to the proton spin.

\[
J_q = \frac{1}{2} \Delta \Sigma_q + L_q = \frac{1}{2} \int_{-1}^{1} x[H_q(x, \xi, t = 0) + E_q(x, \xi, t = 0)] dx
\]
Exclusive Meson Production
**Pseudoscalar mesons**

\[ ep \rightarrow en\pi^+ \]
\[ ep \rightarrow ep\pi^0, \quad \pi^0 \rightarrow \gamma\gamma \]
\[ ep \rightarrow ep\eta, \quad \eta \rightarrow \gamma\gamma \]

**Vector mesons**

\[ ep \rightarrow en\rho^+, \quad \rho^+ \rightarrow \pi^+\pi^0 \]
\[ ep \rightarrow ep\rho^0, \quad \rho^0 \rightarrow \pi^+\pi^- \]
\[ ep \rightarrow ep\omega, \quad \omega \rightarrow \pi^+\pi^-\pi^0 \]
\[ ep \rightarrow ep\phi, \quad \phi \rightarrow K^+K^- \]

CLAS6: lots of data.
CLAS12: Exp. # E12-06-108

New proposal being prepared for PAC 38

C. Hadjidakis et al., Phys.Lett.B605:256-264,2005 ($\rho^0$, 4.2 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)
Vector Mesons
Quark and Gluon GPDs

\[ \gamma^* p \rightarrow np^+ \]

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

\[ \gamma^* p \rightarrow p\phi \]

<table>
<thead>
<tr>
<th></th>
<th>(H_u^+ - H_d^+)</th>
<th>(E_u^+ - E_d^+)</th>
</tr>
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<tbody>
<tr>
<td>(\rho^0)</td>
<td>(e_uH_u^+ - e_dH_d^+)</td>
<td>(e_uE_u^+ - e_dE_d^+)</td>
</tr>
<tr>
<td>(\omega)</td>
<td>(e_uH_u^+ + e_dH_d^+)</td>
<td>(e_uE_u^+ + e_dE_d^+)</td>
</tr>
</tbody>
</table>

\[ \rho^+ \]
\[
\frac{d\sigma}{dt} (\gamma^* p \rightarrow enp^+) \propto \sqrt{-t} e^{bt}
\]

CLAS data. The first measurement of the $\rho^+$ exclusive electroproduction
$\rho^+ \ \text{t-slope parameter}$

Slope parameter is decreasing with $x_B$. This indicates that the size of the interaction region decreases as $x_B \to 1$.

$$\frac{d\sigma}{dt}(\gamma^* p \to e n \rho^+) \propto \sqrt{-te^{bt}}$$
Vector mesons t-slope parameter

\[ W^2 = Q^2 \left( \frac{1}{x_B} - 1 \right) + m_N^2 \]

- \( b \) increases with \( W \) : the size of the nucleon increases as one probes the high \( W \) values (i.e. the sea quarks). Sea quarks tend to extend to the periphery of the nucleon.
\( \sigma_L, \sigma_T \) separation

S-channel helicity conservation

\( \gamma_L p \rightarrow n \rho^+ \)

GPD fails to describe data by more than order of magnitude
Popular GK and VGG models cannot provide the right $W$-dependence of the cross-section. This does not mean that we can’t access GPD in vector meson electroproduction. For example, model with the addition of $q$-$q\bar{q}$ exchange (M.Guidal) together with standard VGG model successfully describes data.
Goloskokov, Kroll

\( \gamma_L p \rightarrow p\phi \)

\( \gamma_L p \rightarrow p\rho^0 \)

*\( \phi \) mesons - gluon GPD are dominant

*\( \rho^0 \) and \( \omega \) - sea quarks and/or gluons dominant.

GPD approach describes well data for \( W>5 \) GeV
The JLab 12 GeV project offers an unprecedented frontier of intensity and precision for the study of deep exclusive scattering.
**Left:** CLAS12 kinematics for DVCS and DVMP on unpolarized H2 and longitudinally Polarized targets. The colors and density are proportional to the relative count rates.

**Right:** Hall A kinematics for DVCS and π0 electroproduction. Beam time is adjusted for roughly equal counts in all bins.
Jlab Upgrade Program

Deeply Virtual Exclusive **Meson** Electroproduction

\[
\begin{align*}
ep \rightarrow ep\pi^0 & \quad ep \rightarrow ep\eta \\
ep \rightarrow ep\phi & \quad ep \rightarrow ep\rho^0 \\
ep \rightarrow ep\omega & \quad ep \rightarrow ep\rho^+ \\
\end{align*}
\]

Deep Virtual Compton Scattering

\[
\begin{align*}
ep \rightarrow ep\gamma & \quad en \rightarrow en\gamma
\end{align*}
\]

- Kinematics:
  - \(Q^2\) from 3 – 10 GeV^2
  - \(-t\) from .5 to 10 Gev^2
  - \(W\) from 2-4 GeV
Summary

- Jlab DVCS experiments provide important data, crucial for the extraction of GPDs in a wide kinematical region
- DVCS with polarized and unpolarized targets provides precise information on H and $\bar{H}$
- The most extensive set of $\pi^0$, $\eta$, $\rho^+$, $\omega$, and $\phi$ electroproduction to date has been obtained with the CLAS spectrometer.
- Jlab 12 GeV program of DVCS, pseudoscalar and vector meson electroproduction will provide unique information about the:
  - transition between soft long-range phenomena and hard short range
  - quark momentum and spin distributions of the nucleons.
  - quark and gluon GPDs
DVCS

\[ T^2 = |T_{BH}|^2 + \mathcal{I} + |T_{DVCS}|^2 \]

DVMP
DVCS

\[ T^2 = |T_{BH}|^2 + I + |T_{DVCS}|^2 \]

DVMP
DVCS kinematics

\[ \sigma(ep \rightarrow ep\gamma) \]

Kinematical coverage \((x_B, Q^2)\) and \((x_B, -t)\)

Exclusive cuts
And \(\pi^0\) subtraction

Missing Energy

\(N_{events} / 0.007^\circ\)
Helicity dependent (top) and independent DVCS Cross sections

The helicity independent cross sections show the significant contribution from the sum of the interference and DVCS terms as compared to the pure BH cross section.