Deeply Virtual Pseudoscalar Meson Electroproduction

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Outlook

- Physics Motivation
- e1-dvcs experiment (CLAS/Jlab)
- $\pi/\eta$ electroproduction at 5.7 GeV
  - Cross section
  - Beam spin asymmetry
- Current status and future opportunities
- Conclusion
Introduction

- Deeply virtual exclusive reactions

\[ \gamma^*(Q^2) + N \rightarrow N + M \quad (M = \gamma, \text{meson}) \]

offer a unique opportunity to study the structure of the nucleon at the parton level as one varies both the size of the probe – the photon virtuality, \( Q^2 \) – and the momentum transfer to the nucleon, \( t \).

- Such processes can reveal much more information about the structure of the nucleon than either inclusive electroproduction (\( Q^2 \) only) or elastic form factors (\( t = -Q^2 \)).

- The basic for these considerations is the existence of the **QCD factorization theorems**

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Kinematic regions ($Q^2$-t)

High $Q^2$ - Low t

- Complement DVCS experiment.
- Unique access to spin dependent GPDs.

Low $Q^2$ - High t

- New form factors related to $1/x$ moments of GPDs.
- Region never accessed.

Kinematical Coverage
Factorization Theorem

Collins, Frankfurt, Strikman - 1997

High $Q^2$ Low $t$ Region

- Factorization theorem states that in the limit $Q^2 \rightarrow \infty$ exclusive electroproduction of mesons is described by hard rescattering amplitude, generalized parton distributions (GPDs), and the distribution amplitude $\Phi(z)$ of the outgoing meson.
- The prove applies only to the case when the virtual photon has longitudinal polarization.
- $Q^2 \rightarrow \infty$ $\sigma_L \sim 1/Q^6$, $\sigma_T/\sigma_L \sim 1/Q^2$.
- The full realization of this program is one of the major objectives of the 12 GeV upgrade.
Factorization in the High $t$ Low $Q^2$ Region

- It has been argued that exclusive production of photons and mesons at large $t$, effectively proceeds via a partonic mechanism, and can be again be described in terms the GPD in the nucleon.

- Theory predicts $\sigma_L$ and $\sigma_T$ in this kinematics.

Radyushkin 1998
Diehl et al, 1998
Huang, Kroll, 2000
In the case of pseudoscalar meson production the amplitude involves the axial vector-type GPDs. These GPDs are closely related to the distributions of quark spin in the proton. The function \( \tilde{H}, \tilde{E} \) reduces to the polarized quark/antiquark densities in the limit of zero momentum transfer. The Fourier transform with respect to \( t \), the so-called impact parameter distributions, describes the transverse spatial distribution of quark spin in the proton.
Flavor Separation and Helicity-Dependent GPDs

- DVCS is the cleanest way of accessing GPDs. However, it is difficult to perform a flavor separation.
- Vector and pseudoscalar meson production allows one to separate flavor and isolate the helicity-dependent GPDs.

<table>
<thead>
<tr>
<th>Meson</th>
<th>GPD flavor composition</th>
</tr>
</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>
“Precocious Factorization”

- Precocious factorization could be valid already at relatively low $Q^2$ especially for ratios of cross sections as a function of $x_B$.
- For example $\pi^0$ and $\eta$ ratio on proton.

\[
\pi^0 : \eta = \frac{1}{2} \left( \frac{2}{3} \Delta u + \frac{1}{3} \Delta d \right)^2 : \frac{1}{6} \left( \frac{2}{3} \Delta u - \frac{1}{3} \Delta d + \frac{2}{3} \Delta u \right)^2
\]
Cross Section Ratios as a function of $x_B$

Collins, Frankfurt, Strikman -1997

All data are available. $\eta/\pi^0$ ratio from proton data will be released very soon.
CLAS/Jlab e1-dvcs

- Beam line and target
- Drift chambers
- TOF counters
- Cherenkov counters
- Electromagnetic calorimeters
- Superconducting coils
CLAS Lead Tungstate 
Electromagnetic Calorimeter
Kinematic Coverage

4 dimensional grid in $Q^2$, $x_B$, $t$, and $\phi$
Remarks on the following slides

- CLAS data
- All data are preliminary
- No radiative correction were applied
- Cross sections are in arbitrary units
- No $\sigma_L/\sigma_T$ separation
- 12 GeV: Rosenbluth $L/T$ separation
\[ \frac{d\sigma}{dtd\phi}(Q^2, x, t, \phi) = \frac{1}{2\pi} \left( \frac{d\sigma_T}{dt} + \varepsilon \frac{d\sigma_L}{dt} + \varepsilon \frac{d\sigma_{TT}}{dt} \cos 2\phi + \sqrt{2\varepsilon(\varepsilon+1)} \frac{d\sigma_{LT}}{dt} \cos \phi \right) \]

Fit of the \(\phi\)-distribution gives us three structure functions:

- \( \frac{d\sigma_T}{dt} + \varepsilon \frac{d\sigma_L}{dt} \)
- \( \frac{d\sigma_{TT}}{dt} \)
- \( \frac{d\sigma_{LT}}{dt} \)
$\frac{d\sigma}{d\phi}$

$\gamma^* p \rightarrow ep\pi^0$
$\sigma_T + \varepsilon \sigma_L$ as a function of $t$
$\sigma_{LT}$ as a function of $t$
$\sigma_{TT}$ as a function $t$
\[(\sigma_T + \varepsilon\sigma_L) \sigma_{TT} \sigma_{LT}\]
as a function of \(t\)

\[
\frac{d\sigma}{dt\,d\phi} (Q^2, x, t, \phi) = (\sigma_T + \varepsilon\sigma_L) + \varepsilon\sigma_{TT} \cos 2\phi + \sqrt{2\varepsilon(\varepsilon + 1)} \sigma_{LT} \cos \phi
\]

Non-zero \(\sigma_{TT}\) and \(\sigma_{LT}\) imply that both transverse and longitudinal amplitudes participate in the process

\(Q^2 = 2.3\)
\(x_B = 0.4\)

\(t\ \text{GeV}^2\)
\[(\sigma_T + \varepsilon\sigma_L) \sigma_{TT} \sigma_{LT}\]

in Regge Model (J ML)

- The dashed lines correspond to the \(\omega/p/b1\) Regge poles and elastic rescattering
- The full lines include also charge pion nucleon and Delta intermediate states.
- Regge model qualitatively describes the experimental data

\[
p(\gamma^*, \pi^0)p
\]

\[
\frac{d\sigma}{dt} (\text{ub/GeV}^2)
\]

\[
Q^2 = 2.30 \text{ GeV}^2
\]

\[
W = 2.269 \text{ GeV}
\]

\[
X = 0.36
\]

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\frac{d\sigma}{dt} 
\gamma^* p \rightarrow ep\pi^0
t-Slope Parameter as a Function of $x_B$ and $Q^2$

- $B(x_B, Q^2)$ is almost independent of $Q^2$
- $B(x_B)$ is decreasing with increasing $x_B$
t-dependence in GDP

\[ f^q(x, t) \propto x^{\alpha_q(t)} \propto x^{\alpha t} \]

\[ \frac{d\sigma}{dt} \propto \left[ x^{\alpha t} \right]^2 = e^{2\alpha \ln(1/x)t} \]

\[ B(x) = 2\alpha \ln(1/x) \]

\[ \alpha \approx 1 \]
Impact Parameter Dependent PDFs

- Fourier transformation of GPD

\[ IPD(x, b_x, b_y) = \frac{1}{(2\pi)^2} \int d^2\Delta \ e^{i\Delta \cdot \Delta} \tilde{H}(x, 0, \Delta^2) \]

- For impact parameter dependent parton distributions the perp width should go to zero for \( x \to 1 \)

- In momentum space, this implies that t-slope should decrease with increasing \( x \), what we observe experimentally
Impact Parameter Dependant Axial Parton Distribution

\[ IPD(x, b_x, b_y = 0) = \frac{\Delta q(x, |\Delta_\perp| = 0)}{(2\pi)^2} \int d^2\Delta_\perp e^{i\Delta_\perp b} x^{0.91|\Delta_\perp|} \]

From data fit
Impact Parameter Profile
of axial current distribution

\[ IPD(x, b_x, b_y = 0) = \frac{1}{(2\pi)^2} \int d^2 \tilde{\Delta}_\perp e^{i\tilde{\Delta}_\perp \tilde{b}_\perp} x^{0.9|\tilde{\Delta}_\perp|} \]

The curve is what we obtained from experimental data.

The size of the proton decreases with increasing \( x \).
\[ \pi^0 \text{ and } \eta \text{ Beam Spin Asymmetry} \]

\[ \frac{d\sigma}{dtd\phi}(Q^2, x, t, \phi) = \frac{1}{2\pi} \left( \frac{d\sigma_T}{dt} + \varepsilon \frac{d\sigma_L}{dt} + \varepsilon \frac{d\sigma_{TT}}{dt} \cos 2\phi + \sqrt{2\varepsilon(\varepsilon + 1)} \frac{d\sigma_{LT}}{dt} \cos \phi \right) + h\sqrt{2\varepsilon(\varepsilon - 1)} \sin \phi \frac{d\sigma_{LT}}{dt} \]

\( h \) is the beam helicity

\[ A = \frac{d^4 \tilde{\sigma} - d^4 \tilde{\sigma}}{d^4 \tilde{\sigma} + d^4 \tilde{\sigma}} \approx \alpha \sin \varphi \]

Any observation of a non-zero BSA would be indicative of an L'\( T \) interference. If \( \sigma_L \) dominates, \( \sigma_{LT}, \sigma_{TT}, \) and \( \sigma_{LT} \) go to zero.

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$\pi^0$ : Kinematical Coverage
(Q$^2$-$x_B$ space)

$A(\phi)$
$X_B=0.25$
$Q^2=1.95$ GeV$^2$
$t=-0.29$ GeV$^2$

Balck curve – $A=\alpha \sin \phi$
Red curve – Regge model

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$A = \alpha \sin \phi$, $\alpha$ as a function of $t$

- The red curves correspond to the Regge model (JML)
- BSA are systematically of the order of 0.03-0.09 over wide kinematical range in $x_B$ and $Q^2$
η Beam Spin Asymmetry

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Conclusion

- Cross sections and asymmetries for the $\pi^0$ and $\eta$ exclusive electroproduction in a very wide kinematic range will be released soon.
- These data will help us to understand better the transition from soft to hard mechanisms.
- Data show that both transverse and longitudinal amplitudes participate in the exclusive processes at accessible kinematics.
- The $\pi^0/\eta$ cross section ratio will check the hypothesis of precocious scaling.
Questions to theory

What will our data tell us?

- What does t-slope $B(Q^2,x_B)$ tell us?
- What can we learn from the $Q^2$ evolution of cross section?
- Can $\sigma_{LT}$ and $\sigma_{TT}$ help us to constrain $R=\sigma_L/\sigma_T$?
- Can we constrain the GPDs within some approximations and corrections which have to be made due to non-asymptotic kinematics?
- How big are the corrections? How close are we to asymptotia?
Q: What will come out from our marriage?
THE END
\[ \frac{d\sigma}{dt} \quad ep \rightarrow ep \, \eta \]
In the past decades of electron-nucleon scattering, experiments dedicated to study the substructure of the nucleon have mainly focused either on the measurements of form factors or on measurements of deep inelastic structure functions.

- Form factors and structure functions measure the proton structure in two orthogonal sub-spaces.
- The Generalized Parton Distribution functions unite both the transverse spatial and the longitudinal momentum dependence.
Factorization Theorem

(Collins, Frankfurt, Strikman)

\[ Q^2 \gg 1 \]
\[ -t \ll 1 \]

\[ \sigma_L \text{ only} \]

\[ M(\rho_L) \approx \alpha_s \frac{1}{Q} \left[ \int du \frac{\Phi(u)}{u} \right] \int dx \frac{1}{x - \xi + i\varepsilon} \left\{ aH(x, \xi, t) + bE(x, \xi, t) \right\} \]

\[ \frac{d\sigma}{dt} = \frac{1}{16\pi(s - M^2)} |M|^2 \rightarrow \frac{1}{Q^6} \]
$Q^2$ slope as a function of $x_B$

\[
\frac{d\sigma}{dQ^2} \approx \frac{1}{Q^{n(x_B)}}
\]
$Q^2$ slope as a function of $x_B$

\[
\frac{d\sigma}{dQ^2} \approx \frac{1}{Q^{n(x_B)}}
\]
t-slope parameter as a function of $Q^2$

\[ \frac{d\sigma}{dt} \approx e^{b(Q^2)t} \]
Reduced cross sections as a function of $t$

$\sigma_T + \varepsilon \sigma_L$

$\sigma_{LT}$

$\sigma_{TT}$
Reduced cross sections

\[
\frac{d^4\sigma}{dQ^2dxdt\phi} = \Gamma(Q^2,x)\frac{d\sigma}{dt\phi}(Q^2,x,t,\phi)
\]

\[
\frac{d\sigma}{dt\phi}(Q^2,x,t,\phi) = (\sigma_T + \varepsilon\sigma_L) + \varepsilon\sigma_{TT} \cos 2\phi + \sqrt{2\varepsilon(\varepsilon + 1)}\sigma_{LT} \cos \phi
\]
Goeke, Polyakov, Vanderhaeghen (ph-0106012)
Cross Section Predictions

Q⁻⁶ Scaling

Guichon, Guidal, Vanderhaeghen
High Q2 Low t Region

- The high Q2-low t measurements are closely related to, and complement, to the DVCS experiments.
- The electroproduction of $\pi^0$ and $\eta$ mesons possess a number of unique features. In the partonic regime at high Q2, pseudoscalar production probes the ‘polarized’ GPDs, which contains information about spatial distributions of the quark spin.