Exclusive Backward–Angle Meson Electroproduction – Unique access to $u$–channel physics

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CAP Congress
Dalhousie University, Halifax, NS
June 12, 2018
Scientific Motivation

The Key Science Problem:

- How does Quantum Chromodynamics (QCD) work in the confinement regime?
- Proton structure is dependent on the properties of the probe.
- Studying the transition of QCD

Objective:

- Establish a new experimental approach
  - Backward–angle (u–channel) observables
  - L/T separation

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Jefferson Lab Hall C Experimental Setup

- **HMS (QQQD)**
  - Angle Acceptance: 6 msr
  - Momentum: 0.5–7.5 GeV/c
  - Momentum Acceptance: ±9%
  - Angular, Position Resolution: 1mr and 1mm

- **SOS (QDDbar)**
  - Angle Acceptance: 9 msr
  - Momentum: 0.1–1.8 GeV/c
  - Momentum Acceptance: ±20%

- One of last analyses from 6 GeV era.

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Short Orbit Spectrometer (SOS)  High Momentum Spectrometer (HMS)
$t$–Channel $\pi^+$ vs $u$–Channel $\omega$ Production

\[ s = (p_1 + p_2)^2 = (p_3 + p_4)^2 \\
\[ t = (p_1 - p_3)^2 = (p_2 - p_4)^2 \\
\[ u = (p_1 - p_4)^2 = (p_2 - p_3)^2 \\

Mark Strikman: Knocking the proton out of the proton process.
Physics Background Subtraction

\[ M_x = \sqrt{(E_e + m_p - m_{e'} - E_p)^2 - (\vec{p}_e - \vec{p}_{e'} - \vec{p}_p)^2} \]

ω (782 MeV)

ρ (770 MeV)

HERMES Empirical parameterization with Soding skewness factor

2π production phase-space
Rosenbluth (L/T/LT/TT) Separation

\[ -Q^2 = (p_e - p'_e)^2 \]

\[ W^2 = (p_\omega + p_p)^2 \]

\[ u = (p_\gamma - p_p)^2 \]

\[ t = (p_\gamma - p_\omega)^2 \]

Virtual-photon polarization:

\[ \varepsilon = \left( 1 + 2 \frac{(E_e - E_e')^2 + Q^2}{Q^2} \tan^2 \theta_e' \right)^{-1} \]

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

Rosenbluth Separation requires:

- Separate measurements at different \( \varepsilon \) (virtual photon polarization)
- All Lorentz invariant physics quantities: \( Q^2, W, t, u \), remain constant
- Beam energy, scattered e’ angle and virtual photon angle will change as a result, event rates are dramatically different at high, low \( \varepsilon \)
Iterative Procedure for L/T Separation

Improve $\phi$ coverage by taking data at multiple HMS angles, $-3^\circ < \theta_{pt} < +3^\circ$.

$\theta_{pt} = 0$
$\theta_{pt} = -3$
$\theta_{pt} = +3$

3 u bins
8 phi bins

Unseparated X-section

Unseparated Cross Section (ab Strength)

Separated X-section

$R = \frac{Y_{Exp} - Y_{\omega \ sim} - Y_{Xspace \ sim}}{Y_{\omega \ sim}}$
Combine ratios for settings together, propagating errors accordingly.

$\frac{d^2\sigma}{dtd\phi}_{EXP} = R \frac{d^2\sigma}{dtd\phi}_{SIMC}$

Extract L,T,LT,TT via simultaneous fit

$2\pi \frac{d^2\sigma}{dtd\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon (\varepsilon + 1)} \frac{d\sigma_{LT}}{dt} \cos \phi + \varepsilon \frac{d\sigma_{TT}}{dt} \cos 2\phi$
Separated Cross Sections $\frac{d\sigma}{dt}$ VS $-u$

Observations:
- $\sigma_T$ falls slowly with $-u$; $\sigma_L$ falls faster.
- $\sigma_{LT}$ is small; $\sigma_{TT}$ has sign flip for different $Q^2$ values.

Error bars = statistical and uncorrelated syst. unc; Error bands = correlated syst. unc.
Hadronic Model: Evolution of Proton Structure

- Physics observables
  - $t$, $W(s)$, $Q^2$, $x$

- $x$ Evolution:
  - 0.2-0.3 valence quark distribution is pronounced

- $W$ Evolution:
  - Above the resonance region

- $Q^2$ Evolution
  - Wavelength of the probe

- $t$ Evolution
  - Impact parameter

- What about $u$?
  - Physical interpretation unclear
Hadronic Model: Regge Model by JM Laget

M. Guidal, J.-M. Laget, M. Vanderhaeghen, PLB 400(1997)6

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\( p(\gamma^*,\omega)p \)

\( Q^2 = 0 \text{ GeV}^2 \)
\( W = 2.48 \text{ GeV} \)
SLAC

\( Q^2 = 0.84 \text{ GeV}^2 \)
\( W = 2.30 \text{ GeV} \)
DESY

\( Q^2 = 1.75 \text{ GeV}^2 \)
\( W = 2.476 \text{ GeV} \)
JLab

\( Q^2 = 2.35 \text{ GeV}^2 \)
\( W = 2.472 \text{ GeV} \)
JLab

Soft structure \( \rightarrow \) Hard \( \rightarrow \) Soft transition!
Partonic Model: TDA and Factorization

- **Nucleon to Meson Transition Distribution Amplitude (TDA)**
  - Backward angle analog of GPD
  - Translate from $t$–space to $u$. Translate $V$–DA to $N$–DA
  - No consensus on applicability of TDA factorization regime.

- **Interactions of Interest:**
  - $u$–channel pseudoscalar meson and vector meson production

- **Two Predictions of TDA:** [B. Pire, K. Semenov, L. Szymanowski, PRD 91(2015)094006]
  - Dominance of the transverse polarization of the virtual photon resulting in the suppression of the longitudinal cross section by at least $1/Q^2$: $\sigma_T > \sigma_L$.
  - Characteristic $1/Q^8$–scaling behavior of $\sigma_T$ for fixed Bjorken $x$. 
Partonic Model: TDA Prediction


- TDA prediction undershoots data by a factor of 7 at $Q^2=1.60$ GeV$^2$, but has impressive agreement with data at $Q^2=2.45$ GeV$^2$
  - A true prediction, calculation made 2 years before data analysis was completed.
- TDA model also has good agreement with new CLAS $\pi^+$ backward angle data for $Q^2>2.50$ GeV$^2$ [K. Park, et al., PLB 780(2018)340].
- TDA expected to dominate for $Q^2>:10$ GeV$^2$, but some indications that TDA factorization scheme may begin to apply as soon as $Q^2=2$ GeV$^2$. 
Future Backward Meson Production Opportunities

Upcoming Jefferson Lab 12 GeV experiments

- $K^+$ L/T–experiment (E12–09–011):
  - Backward angle $\eta$, $\omega$, $\rho$, $\eta'$, $\phi$ will be obtained parasitically
  - Scheduled for Aug 22–Dec 19, 2018

- Large $\phi$ Emission Angle Experiment at CLAS: E12–12–007

- LOI (2018): Backward $\pi^0$ production at Hall C

- Backward–angle program with PANDA @ FAIR–GSI

Simulation at $Q^2=3.00$ \(W=3.14\) \(x=0.25\) \(\varepsilon=0.69\)

Missing Masses: Counts vs. Mass (GeV/c²)

Plot by: M. Hladun, URegina BSc Hons (2018)
Unseparated Cross Sections (Money Plot)

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

\[ Q^2 = 1.60 \text{ GeV}^2 \]

\[ Q^2 = 2.45 \text{ GeV}^2 \]

0 < u < 0.10 (t ~ 4.1)

High \( \varepsilon = 0.59 \)

Low \( \varepsilon = 0.33 \)

\[ 0.10 < u < 0.17 \text{ (t ~ 4)} \]

\[ 0.17 < u < 0.32 \text{ (t ~ 3.8)} \]

\[ Q^2 = 1.60 \]

\[ Q^2 = 2.45 \]

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Mandelstam variables \((s,t,u\text{-channels})\)

\(s\): invariant mass of the system

\(t\): Four-momentum-transfer squared between target before and after interaction.

\(u\): Four-momentum-transfer squared between virtual photon before interaction and target after interaction

\(t\text{-channel}: -t \sim 0\), after interaction
  - Target: stationary,
  - Meson: forward
  - Measure of how forward could the meson go.

\(u\text{-channel}: -u\sim 0\), after interaction
  - Target: forward
  - Meson: stationary
  - Measure of how backward could the meson go
### Sytematic Uncertainties

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Contribution</th>
<th>Value (%)</th>
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<td>Scale Error</td>
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<td>Common</td>
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### Table

<table>
<thead>
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<th>Source</th>
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<tbody>
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<td>Zee5.1, 6.10.2</td>
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<tr>
<td>Zee5.3, 6.10.2</td>
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</tbody>
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### Figures

- Figure 1: Diagram illustrating the systematic uncertainties.
- Figure 2: Table showing the contributions of various uncertainties.

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