Backward Angle Omega Meson Electroproduction
(The Final Analysis Presentation)

Wenliang (Bill) Li
UofR Ph.D Student (this work)
WM Post-doc
Ph. D supervisor: Garth Huber
Outline

- Introduction to the data (history)
- Theory
- Experiment and technique
- Results and Outlook
Fpi-2 (E01-004) 2003
- Spokesperson: Garth Huber, Henk Blok
- Standard HMS and SOS (e) configuration
- Electric form factor of charged $\pi$ through exclusive $\pi$ production

Primary reaction for Fpi-2
- $p(e, e' \pi^+)n$

In addition, we have for free
- $p(e,e' p)\omega$

Kinematics coverage
- $W= 2.21$ GeV, $Q^2=1.6$ and $2.45$ GeV$^2$
- Two $\epsilon$ settings for each $Q^2$

LT Separation!
Mandelstam variables \((s,t,u\)-Channels\)

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

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

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

- **\(u\)-channel: \(-u \sim 0\), after interaction**
  - Target: forward
  - Meson: stationary
  - Measure of how backward could the meson go.

\[
\begin{align*}
  s &= (p_1 + p_2)^2 = (p_3 + p_4)^2 \\
  t &= (p_1 - p_3)^2 = (p_2 - p_4)^2 \\
  u &= (p_1 - p_4)^2 = (p_2 - p_3)^2
\end{align*}
\]
**t-Channel \( \pi \) vs \( u \)-Channel \( \omega^0 \) Production**

- **HMS along the \( q \)-vector (\( p_{\gamma^*} \))**
  - \( p_{\pi^+} \) is parallel to \( p_{\gamma^*} \) (Forward)
  - \( p_{\omega} \) is anti-parallel to \( p_{\gamma^*} \) (Backward)

- **Exclusive channel!**
  - \( p(e, e' p) \)\( \omega \)
  - We do not detect any part of decayed \( \omega \)
  - Contain physics background

- **Full L/T separation on this \( u \)-channel process**

- **One of the last Hall C 6 GeV analysis**

Mark Strikman: A proton being knocked out of a proton process.
Exclusive $\omega$ Electro-Production Data

Closest data set to ours is the Hall B Morand data

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$Q^2$ (GeV$^2$)</th>
<th>$W$ (GeV)</th>
<th>$x$</th>
<th>$-t$ (GeV$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HERMES (Airapetian et al., 2014)</td>
<td>$&gt;1$</td>
<td>3-6.3</td>
<td>0.06-0.14</td>
<td>&lt; 0.2</td>
</tr>
<tr>
<td>DESY (Joos et al., 1977)</td>
<td>0.3-1.4</td>
<td>1.7-2.8</td>
<td>0.1-0.3</td>
<td>&lt; 0.5</td>
</tr>
<tr>
<td>Zeus (Breitweg et al., 2000)</td>
<td>3-20</td>
<td>40-120</td>
<td>~0.01</td>
<td>&lt; 0.6</td>
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<tr>
<td>Cornell (Cassel et al., 1981)</td>
<td>0.7-3</td>
<td>2.2-3.7</td>
<td>0.1-0.4</td>
<td>&lt;1</td>
</tr>
<tr>
<td>JLab Hall C (Ambrozewicz et al., 2004)</td>
<td>~0.5</td>
<td>~1.75</td>
<td>0.2</td>
<td>0.7-1.2</td>
</tr>
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<td>JLab Hall B (Morand et al., 2005)</td>
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<td>1.8-2.8</td>
<td>0.16-0.64</td>
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<td>JLab Fpi-2 (2017)</td>
<td>1.6, 2.45</td>
<td>2.21</td>
<td>0.29, 0.38</td>
<td>4.0, 4.74</td>
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</table>

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### Regge Trajectory Model by JM Laget

**Physics observables parameterized in** $t$, $W(s)$, $Q^2$, $x$

- $x$ and $W$ are fixed

**$Q^2$ Evolution**

- Wavelength of the probe

**$t$ Evolution**

- Impact parameter

**What about $u$?**

---

**Table:**

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**Figure:**

- Real $\gamma$
- Virtual $\gamma$

J. M. Laget, Phys. Rev. D 70, 2004
Regge Trajectory: Real photon vs virtual photon

\[ \gamma + p \rightarrow \pi + n \]

\[ \gamma^* + p \rightarrow \omega + n \]

\[ \text{Soft structure} \rightarrow \text{Hard} \rightarrow \text{Soft transition!} \]

J. M. Laget, Phys. Rev. D 70, 2004

Real \( \gamma \)

Virtual \( \gamma^* \)

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

\( W = 2.48 \text{ GeV} \)

SLAC

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

\( W = 2.30 \text{ GeV} \)

DESY

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

\( W = 2.47 \text{ GeV} \)

JLab preliminary

\( F_{\pi\gamma}(Q^2,t) \)

\( F_{\pi\gamma}(Q^2) \)

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Parton Based Model: TDA

- **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 the TDA factorization regime
  - If t is impact parameter, physical meaning of u is unclear.

- **Interaction of Interest:** u-channel pseudoscalar meson and vector meson productions

  - The dominance of the transverse polarization of the virtual photon resulting in the suppression of the longitudinal cross section by at least 1/Q^2: \( \sigma_T > \sigma_L \).
  - The Characteristic 1/Q^8-scaling behaviour of the \( \sigma_T \) for a fixed Bjorken x.
Experimental Setup

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

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

High Momentum Spectrometer (HMS)

High Momentum Spectrometer (SOS)

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Experimental Setup and Acceptance

HMS detector (focal plane) layout, SOS is very similar
Trigger: 3/4 planes of Hodoscopes

Data-simulation comparison for acceptance parameter

Charged Particle

Q^2 = 2.45
Low \( \varepsilon \)

Q^2 = 1.60
High \( \varepsilon \)
**PID Cuts**

- **SOS:** select electron
  - Calorimeter cut
  - Cherenkov cut  
  - 99% efficiency

- **HMS:** select proton
  - Coincidence timing cut
  - Hebeta (particle velocity)
  - Aerogel Cut
  - Cherenkov Cut: veto $e^+$
Coincidence Subtraction

- **Random subtraction:**
  
  Coincidence proton = Real Events - \( \frac{\text{Late Random Events} + \text{Early Random Events}}{7} \)

- **Missing proton due to scattering, absorption: \( \sim 7\% \)**

Blob events: good events

Zero event: hbeta=0 !
Cause: Missed the fiducial cut during the reconstruction

Tail event: losing momentum due to multiple scattering

Multiple scattering: dipole exit window to the last layer of hodoscope

Time flow
Dummy Subtraction

- Cryotarget
  - Tuna can shaped
  - With thin Al cell wall
- Dummy Target
  - 4cm apart Al sheets
  - Dummy target distribution is corrected for the real/dummy target thickness difference before subtracted from the real proton events

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Analysis: e+H Elastic Cross-Section

- ±2.0% (point to point) error from Heep will be included to the final Omega analysis systematics.

**Fitted Result:** $0.9991 \pm 0.0060$
Rosenbluth Separation

- 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 the result, thus event rates are dramatically different
Physics Background Subtraction

\[ \omega (782 \text{ MeV}) \]

\[ \eta (547) \]

\[ \rho (770) \]

\[ \eta' (947) \]

\[ 2\pi \]

HERMES Empirical parameterization with Soding factor

Width from PDG with \( Ae^{-Bu} \) dependence
Improve $\varphi$ coverage by taking data at multiple HMS angles, $-3^0 < \theta_{pq} < +3^o$.

**Iterative Procedure (Recipe) to a Full LT Separation**

*Background Subtraction*

$\chi^2$/dof: 1.20

$R = \frac{Y_{Exp} - Y_{\rho \text{ sim}} - Y_{Xspace \text{ sim}} - Y_{\eta \text{ sim}}}{Y_{\omega \text{ sim}}}$

Combine ratios for settings together, propagating errors accordingly.

Extract $T, L, LT, TT$ via simultaneous fit

$$2\pi \frac{d^2\sigma}{dt d\varphi} = \frac{d\sigma_T}{dt} + \varepsilon \frac{d\sigma_L}{dt} + \sqrt{2\varepsilon(\varepsilon + 1)} \frac{d\sigma_{LT}}{dt} \cos\varphi + \varepsilon \frac{d\sigma_{TT}}{dt} \cos 2\varphi$$

**Empirical Model**

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Fitting step (Background Subtraction)

- Fitting data within the with four simulations
  - Fitting
  - Subtracting background distributions
  - Obtain omega experimental yield: $Y_{\omega \text{Exp}}$
  - Each simulation distribution has scale factor

$$R = \frac{Y_{\text{Exp}} - Y_{\rho \text{sim}} - Y_{X\text{space sim}} - Y_{\eta \text{sim}}}{Y_{\omega \text{sim}}}$$

Data (blue point)
X-space Sim (green)
$\rho$ Sim (light blue)
$\omega$ Sim (red)
$\eta$ or $\eta'$ (black)
Simulation Sum (pink)
Fitting Quality Control

- Omega Comparison
  - $\chi^2$/dof: 1.20
- Background Comparison
  - $\chi^2$/dof: 1.50
- Zero Comparison
  - Int: 0.001778
  - Fit: 0.000928 ± 0.001220

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Integration step

- Integrating within the integration limit
  - Obtain Omega simulation yield: \( Y_{\omega \text{ sim}} \)

\[
R = \frac{Y_{\text{Exp}} - Y_{\rho \text{ sim}} - Y_{\text{Xspace sim}} - Y_{\eta \text{ sim}}}{Y_{\omega \text{ sim}}}
\]

Reconstructed Kinematics and Optical Parameters

- \( E_m \)
- \( P_m \)
- \( h_{s\delta\tau} \)
- \( h_{s\gamma\pi} \)
Yield Ratio and Simulated Cross-Section

\[ \chi^2 / \text{ndf} = 59.13 / 10 \]
\[ p_0 = 0.9289 \pm 0.02507 \]
\[ p_1 = 0.01118 \pm 0.1034 \]

\[ Q^2 = 1.6, \text{ Low } \varepsilon = 0.33 \]

0 < \( u < 0.10 \) (\( t \approx 4.1 \))
0.10 < \( u < 0.17 \) (\( t \approx 4 \))
0.17 < \( u < 0.32 \) (\( t \approx 3.8 \))

Model Cross Section

\[ 2\pi \frac{d\sigma}{dtd\phi} = R \left( \frac{d^2\sigma}{dtd\phi} \right)_{\text{EXP}} \]

\[ \frac{d^2\sigma}{dtd\phi} = \frac{d\sigma_T}{dt} + \varepsilon \frac{d\sigma_L}{dt} + \sqrt{2\varepsilon(\varepsilon+1)} \frac{d\sigma_{LT}}{dt} \cos\phi + \varepsilon \frac{d\sigma_{TT}}{dt} \cos2\phi \]

Exp/Sim Yield Ratio

\[ R = 1 \]

\[ Q^2 = 1.6, \text{ Low } \varepsilon = 0.33 \]

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Unseparated Cross Section (Money Plot)

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

- **0<u<0.10** (t~4.1)
  - Anti-parallel Kinetics u-bin
  - High \(\varepsilon=0.59\)
  - Low \(\varepsilon=0.33\)

- **0.10<u<0.17** (t~4)
  - High \(\varepsilon=0.59\)

- **0.17<u<0.32** (t~3.8)
  - \(Q^2 = 1.60\)

- **0<u<0.10** (t~4.1)
  - Anti-parallel Kinetics u-bin
  - High \(\varepsilon=0.55\)
  - Low \(\varepsilon=0.27\)

- **0.19<u<0.30** (t~4.7)
  - High \(\varepsilon=0.55\)

- **0.30<u<0.50** (t~4.5)
  - \(Q^2 = 2.45\)
Observations:
- $\text{SigT}$ fall slow, $\text{SigL}$ fall faster
- $\text{SigLT}$ is small, $\text{Sig TT}$ has sign flip for different $Q^2$ values
## Uncertainties budget

<table>
<thead>
<tr>
<th>Correction</th>
<th>Uncorrelated (Pt-to-Pt) (%)</th>
<th>$\epsilon$ uncorr. $u$ corr. (%)</th>
<th>Correlated (scale) (%)</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>HMS Cherenkov</td>
<td>0.04</td>
<td></td>
<td>0.02</td>
<td>Sec. 3.6.3</td>
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<tr>
<td>HMS Aerogel</td>
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<td></td>
<td>0.04</td>
<td>Sec. 5.3.7</td>
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<td>SOS Colorimeter</td>
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<tr>
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<td>HMS beta</td>
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<td>Sec. 5.1.2</td>
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<td>HMS Tracking</td>
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<td>1.0</td>
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<tr>
<td>SOS Tracking</td>
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<td>0.5</td>
<td>Sec. 5.3.3</td>
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<tr>
<td>HMS Trigger</td>
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<td></td>
<td>0.1</td>
<td>Sec. 3.7</td>
</tr>
<tr>
<td>SOS Trigger</td>
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<td></td>
<td>0.1</td>
<td>Sec. 3.7</td>
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<td>Target Thickness</td>
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<td>1.0</td>
<td>Secs. 3.5.2, 5.3.5</td>
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<td>Electronic LT</td>
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<td>Coincidence Blocking</td>
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<td>0.1</td>
<td>Sec. 5.3.6</td>
</tr>
</tbody>
</table>

- **Unseparated $\sigma$**
  - **Statistical**
  - **Systematic Error**
    - **Uncorrelated Error**
    - $\epsilon$ uncorrelated $u$ correlated
    - Scale error

- **Model dependent Error to the separated (Scale error)**
  - Parameterization
  - $\phi$ limits
  - $u$ limits (small contribution)
Backward Angle Omega Electroproduction Peak!

First observation for the backward $\omega$ electroproduction peak!

Calls for the resurrection of the backward angle study through Regge based model (JML, etc.)
Backward Angle Omega Electroproduction Peak!

\[ \gamma^* + p \rightarrow p + \omega, \; W = 2.48 \text{ GeV}, \; Q^2 = 1.75 \text{ GeV}^2 \]

\[ \sigma_u \text{ vs } -u \]

CLAS 6 data

Forward Angle Physics (low \( -t \))

Backward Angle Physics (low \( -u \))

JML Model

Morand Data

Fpi-2 Data (Scaled)
Scaling of $\sigma_L$, $\sigma_T$ and $\sigma_L/\sigma_T$ Ratio

$u - u_{min} = 0$

- $\sigma_L$ drops expected $\sim 1/Q^8$
  - Close to expectation
- $\sigma_T$ is almost constant!
- Dominance of $\sigma_T$ observed at higher $Q^2 = 2.45$, confirms the TDA prediction
Optimal $Q^2$ range for TDA: $>10$ GeV$^2$

TDA prediction has impressive agreement with data at $Q^2 = 2.45$ GeV$^2$

Studying the effectiveness of JML model and TDA model is equivalent to studying the evolution of the proton structure
Analysis Status and what have we learned

■ Analysis Status:
  ■ Final round of uncertainty review is under way
  ■ Expected publication data: summer 2018
  ■ Contacted theory group ……

■ Achieved Objectives
  ■ Studying the model effectiveness in both Regge Based Model and TDA is the studying the QCD transition
  ■ Established a new experimental access to the previously accessible kinematics
  ■ Abstracted the theory framework that can be used to study the previously ignored backward angle process
  ■ Final release of the result calls for more studies on backward angle physics, particularly among the junior physicist.

■ Software avaliable: https://github.com/billlee77/omega_analysis
Backward Angle Physics Strategy

- **We are ready for the \(-u\) channel physics studies.**
  - Variary of existing and proposed backward angle physics, i.e recent CLAS paper by K. Park

- **What can we learn?**
  - Regge Model
  - GPD/TDA factorization

- **Strategy moving forward with backward physics**
  - Large angle region (large \(-t\) and \(-u\)) scan by CLAS
  - L/T separation near the meson (-\(t\)) and baryon (-\(u\))
    - Hall A and C
  - Q2 evolution for L/T cross section
  - Real photon data from GlueX

- **LOI: Backward DVCS and DVMP**
  - Previous studies done by Charles, Carlos in 2007.
  - Hall A
    - 2 HRS capable of resolving DVCS peak, with limited kinematics
  - Hall C
    - Possible L/T separation with full kinematics!
    - HMS + SHMS may not have enough resolution
    - HMS + SHMS + NPS? (Currently under study)

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Thank you

$p(e, e'p)X$
Future Backward Meson Production Opportunities

- **6 GeV data mining**
  - Pion transparency experiment (E92-110)
    - 2 GeV and 4.7 GeV (poor statistics)

- **Upcoming 12 GeV experiment**
  - Fpi-12 experiment (E12-06-101):
    - $\eta, \eta', \omega, \phi(s\bar{s}), \rho$
    - $\omega, \phi(s\bar{s})$ production ratio would yield valuable information.
  - Large Emission Experiment at CLAS: E12-12-007
    - $\phi(s\bar{s})$

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

- Backward-angle program with Panda @ GSI

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Background Extraction and Check

**Worse example**

Reconstructed Missing Energy For the **worse** example

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**PID Cuts**

- **SOS**: select electron
  - Calorimeter cut
  - Cherenkov cut
  - **99% efficiency**

- **HMS**: select proton
  - Coincidence timing cut
  - Hebeta (particle velocity)
  - Aerogel Cut
  - Cherenkov Cut: veto $e^+$

---

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Missing Mass Distribution Background Extraction

- Integration limits and fitting limits
- Exclusion criteria
  - Exclude the radiative only omega bins
  - Exclude the low statistics bins

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Bin Exclusion criteria

- Low Statistics

- Radiative Tail

Excluded Due to Statistics

Excluded Due to Radiation

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Background Extraction and Check

**Worse example**

**Missmass edge example**

Reconstructed Missing Energy For the worse example

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Standard Physics at Hall C (Jefferson Lab)

- **s-Channel Physics**

  - Compton scattering
  - Incident photon
  - Target electron at rest
  - Scattered photon
  - \( \lambda_f - \lambda_i = \Delta \lambda = \frac{h}{m_0 c} (1 - \cos \theta) \)

- **t-Channel Physics**

  - Pion form factor (charged \( \pi \) electroproduction)
  - GlueX J/psi photoproduction

**All could be parameterized in four Lorentz invariant Quantities: \( x, W(\sqrt{s}), Q^2 \) and \( t \)**

What about \( u \)? Should we include \( u \)?
High $t$ Data from CLAS Hall B (2005)

- Hall B Experiment $e1-6$
  - Beam energy: 5.754 GeV

- Kinematic coverage:
  - $W$: 1.8-2.8 GeV
  - $Q^2$: 1.6-5.1 GeV$^2$
  - $-t$: < 2.7 GeV$^2$
  - $x$: 0.16-0.64

- Event selection:
  - Reconstructed $e^-pX$ missing mass consistent with the $\omega$ mass

- Data published in 2005:
Regge Trajectory Model by JM Laget

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Hard Scattering Mechanism schematics

Low $Q^2$ \( \rightarrow \) High $Q^2$

$t$-Channel Forward \( u $-Channel Backward

J. M. Laget, Phys. Rev. D 70, 2004
Nucleon Fragmentation Process

Before interaction

\[ e + H \]

Standard nucleon Fragmentation gives a weird picture

After interaction

\[ n (938 \text{ MeV}) \]

Remains at target position

\[ \text{H}(e, e' \pi^+) n \]

\[ \omega (770 \text{ MeV}) \]

Remains at target position

\[ \text{H}(e, e' p) \omega \]

Exclusive Channel: \( \omega \) is not tagged Allows for kinematic settings which was previously not available

\[ t\text{-channel} \]

\[ \text{SOS} \]

\[ \text{HMS} \]

\[ u\text{-channel} \]

\[ \text{SOS} \]

\[ \text{HMS} \]

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Omega Data Analysis

- Fpi-2 (E01-004) 2003
  - Spokesperson: Garth Huber, Henk Blok
  - Standard HMS and SOS (e) configuration
  - Electric form factor of charged through exclusive $\pi$ production

- Primary reaction for Fpi-2
  - $p(e, e' \pi^+)n$

- In addition, we have for free
  - $p(e,e' p)\omega$

- Kinematics coverage
  - $W= 2.21$ GeV, $Q^2=1.6$ and 2.45 GeV$^2$
  - Two $\epsilon$ settings for each $Q^2$
L/T Separation Iterative Procedure

Experiment Data Ntuple (Ref. [56])
SIMC Data (Sec. 6.2)
Improving Omega Physics Model in SIMC (Sec. 6.8)
Separated Cross section (Sec. 6.7)

Analysis Step shown Fig 4.2

Event Selection (Sec. 6.3)
Fitting Quality Control (Sec. 6.5.3.1)
Consistency Cross Check (Sec. 6.6.1)
Omega Simulation Cross Section (Sec. 6.2.1)

Binning and Yield Extraction (Sec. 6.4)
Bin Exclusion (Sec. 6.4.1)
Fitting Step and Background Subtraction (Sec. 6.5)
Integration Step and Yield Ratio (Sec. 6.6)

Experimental Unseparated Cross Section (Sec. 6.7)

Determine Experimental Efficiency (Chap. 5.3)
\[ \Gamma^+ p \rightarrow p + \omega, \ W = 2.48 \text{ GeV}, \ Q^2 = 1.75 \text{ GeV}^2 \]
Nucleon DA Model

\[ \phi_N(x) \]

Asymptotic

\( x_2 = 0.30 \)

COZ

KS
Missing Mass Distribution Background Extraction

- **Data (blue point)**
- **Xspace Sim (green)**
- **$\rho$ Sim (light blue)**
- **$\omega$ Sim (red)**
- **$\eta$ or $\eta'$ (black)**
- **Simulation Sum (pink)**

**Omega**

**Background Sum**

Zero = Data – Omega - Bg

- **Fitting Limits (red dashed line):**
  - Not fixed, fit 95% data distribution

- **Integration Limits (blue dashed line):**
  - Fixed for all $u$-phi bins!

- **Bin Exclusion criteria:**
  - Radiative tail exceeds 50% total $\omega$ sim
  - Less than 100 raw counts

\[
R = \frac{Y_{\text{Exp}} - Y_{\rho \text{ sim}} - Y_{\text{Xspace sim}} - Y_{\eta \text{ sim}}}{Y_{\omega \text{ sim}}}
\]
Yield Ratio and Simulated Cross-Section

\[ \chi^2 / \text{ndf} = 59.13 / 10 \]
\[ p_0 = 0.9289 \pm 0.02507 \]
\[ p_1 = 0.01118 \pm 0.1034 \]

\[ \sigma_T = \frac{t_0 + t_1 \cdot (-u)}{Q} \]
\[ \sigma_L = \frac{t_0 + t_1 \cdot (-u)}{Q^4} \]
\[ \sigma_{LT} = \left[ \frac{t_0 + t_1 \cdot (-u)}{Q^2} \right] \cdot \sin \theta^* \]
\[ \sigma_{TT} = \left[ \frac{t_0 + t_1 \cdot (-u)}{Q^2} \right] \cdot \sin^2 \theta^* \]

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

Model Cross Section

\[ \frac{d^2\sigma}{dt \, d\phi} \quad \text{EXP} = R \frac{d^2\sigma}{dt \, d\phi} \quad \text{SIMC} \]

Exp/Sim Yield Ratio

Omega Yield Ratio: \text{Yexp/Ysim}

- 0 < u < 0.10 (t ~ 4.1)
- 0.10 < u < 0.17 (t ~ 4)
- 0.17 < u < 0.32 (t ~ 3.8)

R = 1

\[ Q^2 = 1.6, \text{ Low } \varepsilon = 0.33 \]

Wenliang Li, Dept. of Physics, Univ. of Regina, Regina, SK S4S0A2, Canada.
Proton Structure: Known and Unknown

- Proton
  - Dynamic Structure
    - Parton Distribution
    - Interaction
- Static proton structural map is known
- Unknown
  - Transition (evolution) of the proton structure
  - General description of the proton structure
- Goal: Study the transition of the proton structure
Modulus Check for SigLT and SigTT

![Function Modulus Check Graph]

- Black line: \(\cos(x)\)
- Red line: \(\cos(2x)\)
- Blue line: \(f_1 + f_2\)

Wenliang Li, Dept. of Physics, Univ. of Regina, Regina, SK S4S0A2, Canada.
Proton Structure Description

- Hadronic Model

- Partonic Model
Scaling of $\sigma_L$, $\sigma_T$ and $\sigma_L/\sigma_T$ Ratio

- Dominance of $\sigma_T$ observed at higher $Q^2 = 2.45$, confirms the TDA prediction
- $\sigma_L$ drops expected $\sim 1/Q^8$
- $\sigma_T$ is almost constant
Trajectory

---

\[ M^2 \text{[GeV}^2] = t \]

\[ M^2 \text{[GeV}^2] = u \]

---

\( \pi \) Trajectory
\( \rho \) Trajectory
\( \omega \) Trajectory
\( \Lambda \) Trajectory
\( \Lambda^* \) Trajectory

---

\( \omega \) (1670)
\( \rho \) (1770)
\( \pi \) (1390)
\( f_2 \) (1500)
\( a_1 \) (1320)
\( N^* \) (1520)

---

\( \omega \) (2250)
\( \rho_8 \) (2350)
\( \omega \) (2050)
\( a_8 \) (2040)
\( \Delta^* \) (1950)

---

\( \Delta \) Trajectory
\( N \) Trajectory

---

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Proof: These are not Elastic Events!

- **Good News!**
  - We see **other Scalar and Vector Mesons**: $\rho$, $\eta$, $\eta'$, *two-$\pi$ phasespace*

- **Bad News!**
  - Channel is **not clean**!

- **Worse News!**
  - We can’t use Polynomial fit!!
Most Challenging Issue: Background Subtraction!

Omega is not always in the center

Four sets of Monte-Carlo is used fit the data
- $\omega + \rho + $ Phase-space + $\eta$ or $\eta'$
Mandelstam variables \((s,t,u\text{-Channels})\)
Exclusive $\omega$ Electro-Production Data

Closest data set to ours is the Hall B Morand data

<table>
<thead>
<tr>
<th></th>
<th>$Q^2$ GeV$^2$</th>
<th>$W$ GeV</th>
<th>$x$</th>
<th>$-t$ GeV$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HERMES</td>
<td>&gt; 1</td>
<td>3-6.3</td>
<td>0.06-0.14</td>
<td>&lt; 0.2</td>
</tr>
<tr>
<td>DESY</td>
<td>0.3-1.4</td>
<td>1.7-2.8</td>
<td>0.1-0.3</td>
<td>&lt; 0.5</td>
</tr>
<tr>
<td>Zeus</td>
<td>3-20</td>
<td>40-120</td>
<td>~0.01</td>
<td>&lt; 0.6</td>
</tr>
<tr>
<td>Cornell</td>
<td>0.7-3</td>
<td>2.2-3.7</td>
<td>0.1-0.4</td>
<td>&lt;1</td>
</tr>
<tr>
<td>JLab Hall C</td>
<td>~0.5</td>
<td>~1.75</td>
<td>0.2</td>
<td>0.7-1.2</td>
</tr>
<tr>
<td>JLab Hall B</td>
<td>1.6-5.1</td>
<td>1.8-2.8</td>
<td>0.16-0.64</td>
<td>&lt;2.7</td>
</tr>
<tr>
<td>JLab Fpi-2</td>
<td>1.6, 2.45</td>
<td>2.21</td>
<td>0.29, 0.38</td>
<td>4.0, 4.74</td>
</tr>
</tbody>
</table>
$\sigma_T$ and $\sigma_L$ Uncertainty Propagation

$$\frac{\delta \sigma_T}{\sigma_T}(\%) = \frac{1}{(\epsilon_1 - \epsilon_2)} \sqrt{\epsilon_1^2 \left( \frac{\delta \sigma_1}{\sigma_1} \right)^2 \left( 1 + \frac{\epsilon_2}{R} \right)^2 + \epsilon_2^2 \left( \frac{\delta \sigma_2}{\sigma_2} \right)^2 \left( 1 + \frac{\epsilon_1}{R} \right)^2}, \quad (6.35)$$

$$\frac{\delta \sigma_L}{\sigma_L}(\%) = \frac{1}{(\epsilon_1 - \epsilon_2)} \sqrt{\left( \frac{\delta \sigma_1}{\sigma_1} \right)^2 (R + \epsilon_1)^2 + \left( \frac{\delta \sigma_2}{\sigma_2} \right)^2 (R + \epsilon_2)^2}, \quad (6.36)$$
Rutherford Experiment Atomic Structure

- **Rutherford Experiment:**
  - Need both *forward* and *backward* scattered alpha particles to yield complete atomic structure!

- **What about nucleons?**
  - Does *t-channel* physics contain all the nucleon structure information?
  - *u-channel* physics contain *unique information* whose meaning is unclear (B. Pire et. al)

- How do we access *u-channel* physics?
Separation Method

\[ Q^2 = 1.60 \]

High \( \epsilon = 0.59 \)

Low \( \epsilon = 0.33 \)

0 < u < 0.10

(\( t \approx 4.1 \))

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

- **L/T separation**
  - Requires detailed comparison at high and low epsilon value
  - High and low epsilon runs involved

- **Simple L/T separation**
  - \( \sigma_{total} = \sigma_T + \epsilon \sigma_L \)
    - \( \sigma_T \): difference
    - \( \sigma_L \): offset
    - \( \sigma_{LT} \) and \( \sigma_{TT} \): modulation

- **Experimental Kinematics**
  - \( W \) is fixed
  - Two \( Q^2 \) settings
  - High and low epsilon runs for each \( Q^2 \) setting

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**Motivation**

- Probing dynamic property of the proton structure
  - Dependent on the properties of the probe
- Studying the transition of QCD

**Objective**

- Establishing a new approach
  - Backward-angle ($u$-channel) observables
  - LT separation
Jefferson Lab Hall C

- **Main Structure**
  - Two Super- Conducting Linear Accelerators
  - Experimental Hall: A, B, C, D

- **Hall C**
  - High precision high beam current
  - LT separation

- **April 2017: 12 GeV upgrade completed**
  - New spectrometer is on line
Message to the world and thank you

- **Studying the model effectiveness in both Regge Based Model and TDA** is the studying the QCD transition
- Established a new experimental **access to the previously accessible kinematics**
- **Abstracted the theory framework** that can be used to study the previously ignored **backward angle process**
- **Final release of the result** calls for more studies on **backward angle physics**, particularly among the junior physicist.
Updated Uncertainties since the Thesis

- Fitting Error is now used as the Statistical Error
- New method used for computation the scale error
- Sig_LT and Sig_TT now have scale error band
Theory Motivation: Regge Trajectory Model by JM Laget

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<td>&gt; 1.68</td>
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<td>2.21</td>
<td>0.29</td>
<td>1.6</td>
<td>4.014</td>
<td>0.08-0.13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.38</td>
<td>2.45</td>
<td>4.724</td>
<td>0.17-0.24</td>
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</tbody>
</table>

J. M. Laget, Phys. Rev. D 70, 2004
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$$R = \frac{Y_{Exp} - Y_{\rho \text{ sim}} - Y_{Xspace \text{ sim}} - Y_{\eta \text{ sim}}}{Y_{\omega \text{ sim}}}$$

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Conclusion

- *u*-channel omega electroproduction peak observed for the first time.

- $\sigma_T$ has $\sim 1/Q$ dependence, where $\sigma_L$ has $\sim 1/Q^8$ dependence. Dominance of $\sigma_T$ over $\sigma_L$ observed at $Q^2 = 2.45 \text{ GeV}^2$

- At $Q^2 = 2.45 \text{ GeV}^2$, TDA prediction agrees with data!