Recent Studies of the Leptonic Decays of Photoproduced Vector and Pseudoscalar Mesons off of $^1$H at Jefferson Lab

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For the CLAS Collaboration

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Photoproduction of light neutral mesons

$\gamma p \rightarrow e^+ e^- (p)$  Vector Mesons
- No Final State Interactions (FSI) in medium modification studies
- Interference between the $\rho$ and the $\omega$

$\gamma p \rightarrow p e^+ e^- \gamma$  Pseudoscalar Mesons
- Access to transition charge form factors
- Limited world statistics on Dalitz decays of photoproduced $\eta$ and upper limits to the $\eta'$ cross section.
Jefferson Lab Experiment g12

- Jefferson Lab is a 6 GeV continuous electron beam accelerator, capable of delivering beam to 3 independent experimental halls.

- Hall-B houses the CLAS detector, ideal for photoproduction and lepton identification.

- g12 in CLAS
  - Up to a 5.5 GeV photon beam incident on a LH$_2$ target
  - Raw sensitivity of $\sim 68$ pb$^{-1}$
  - $26.2 \times 10^9$ production triggers (3 x $10^6$ di-lepton triggers)

- **EC** and **CC** combine to provide an $e/\pi$ rejection factor of $10^{-6}$ for di-lepton pairs.
Selecting VM or PSM

- By knowing:
  - Tagged photon energy.
  - Target mass
  - Scattered proton and dilepton four-vectors.
- Cuts can isolate VM from PSM:
  - Missing Energy
  - Dilepton Opening Angle
Selecting VM or PSM

- By knowing:
  - Tagged photon energy.
  - Target mass
  - Scattered proton and dilepton four-vectors.
- Cuts can isolate VM from PSM:
  - Missing energy greater than zero: additional particle:
    - $ME > 0.0$
  - Small dilepton opening angle: virtual photon $\rightarrow$ dilepton
    - $\theta_{ee} < 0.5$ rad

\[ \gamma p \rightarrow e^+ e^- p(X) \]
Selecting VM or PSM

- By knowing:
  - Tagged photon energy.
  - Target mass.
  - Scattered proton and dilepton four-vectors.

- Cuts can isolate VM from PSM:
  - Missing energy equal to zero: no additional photon
    - $\text{ME} = 0$
  - Large dilepton opening angle: VM $\rightarrow$ dilepton
    - $\theta_{ee} > 0.5 \text{ rad}$
Part I: Vector Mesons and $\rho$-$\omega$ Interference

- Understanding the interference with electromagnetic production and decay is useful in interpretation of recent Medium Modification studies (Chaden Djalali's earlier talk).

- Previous publications on the interference are from nuclear targets:

<table>
<thead>
<tr>
<th>Target</th>
<th>$K_{\text{max}}$ (GeV)</th>
<th>Range $m_{e^+e^-}$ (MeV/c$^2$)</th>
<th>Phase $\phi$ (in deg)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Be</td>
<td>7.0, 5.1</td>
<td>700-870</td>
<td>41 $\pm$ 20</td>
<td>PRL25 (1970) 1373</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>NPB25 (1971) 333</td>
</tr>
<tr>
<td>C</td>
<td>4.1</td>
<td>675-850</td>
<td>100$^{+38}_{-30}$</td>
<td>PRL24 (1970) 1197</td>
</tr>
<tr>
<td>C</td>
<td>4.1</td>
<td>590-830</td>
<td>118$^{+13}_{-22}$</td>
<td>PRL27 (1971) 1157</td>
</tr>
</tbody>
</table>

- Theoretical predictions from Lutz and Soyeur (NPA750 2005) predict significant constructive interference on the proton, destructive on the neutron.
Signal and Background

- Looking for $\rho \rightarrow e^+ e^-$ and $\omega \rightarrow e^+ e^-$
- Known Backgrounds:
  - $\omega \rightarrow e^+ e^- \pi^0$: Background reduced with tight missing mass cut on the proton.
  - Due to an upstream $^1H$ target, the Bethe-Heitler is significant and must be accounted for.
  - Uncorrelated lepton pairs are also eliminated by tight missing mass cuts on the proton.
The Vector Meson Dominance (VMD) model assumes the photon interacts with hadrons as a virtual vector meson.

Photoproduction of the $\rho$ and $\omega$ off of a proton, leaving a proton in the final state can be described an exchange between scalar / pseudoscalar mesons. Vector mesons are prohibited by charge conjugation invariance. The Feynman diagrams can be drawn:

\begin{align*}
\frac{1}{g_\rho} & \rho (I = 0) + \frac{1}{g_\omega} \omega (I = 1) + \frac{1}{g_\rho} \eta (I = 0) \\
\Gamma_{\rho \rightarrow \pi\gamma} & \approx 2.0 \\
\frac{\Gamma_{\rho \rightarrow \pi\gamma}}{\Gamma_{\rho \rightarrow \pi\gamma}} & \approx 2.0 \\
(1/g_\rho)^2 & = 11.4(1/g_\omega)^2
\end{align*}
VMD and t-channel VM production

- The Vector Meson Dominance (VMD) model assumes the photon interacts with hadrons as a virtual vector meson.

- Photoproduction of the $\rho$ and $\omega$ off of a proton, leaving a proton in the final state can be described an exchange between scalar / pseudoscalar mesons. Vector mesons are prohibited by charge conjugation invariance. The Feynman diagrams can be drawn:

\[ \omega\text{-production:} \]

\[ \frac{\Gamma_{\omega \rightarrow \pi \gamma}}{\Gamma_{\omega \rightarrow \eta \gamma}} \approx 100.0 \]

\[ \left(\frac{1}{g_\rho}\right)^2 = 11.4\left(\frac{1}{g_\omega}\right)^2 \]
Selecting an Outgoing Proton

- Initial cuts must be made on the missing mass to isolate a proton in the final state and reduce background contamination.
Selecting the Delta

- If a secondary cut is made on a $(n \pi^+)$ mass to be $(1232 \pm 100 \text{ MeV})$, the $\Delta^+$ baryon resonance can be selected.

- This channel prefers $\omega$ production:

  - For $I_C = 1$,
    - Allowed
    - $\pi^0$ $(I = 1)$
  - For $I_C = 0$,
    - Isospin Restricted
    - $\pi^0$ $(I = 1)$
Selecting the Delta

- If a secondary cut is made on a ($n\pi^+$) mass to be (1232 +/- 100 MeV), the $\Delta^+$ baryon resonance can be selected.

- This channel prefers $\omega$ production:

\[
\begin{align*}
\text{Allowed} & \quad I_C = 1 \\
\text{Isospin Restricted} & \quad I_C = 1
\end{align*}
\]
Interference Formalism

- The $\rho$-$\omega$ interference can be described by constructing a complex and symmetric mass matrix:

$$M = \begin{bmatrix} M_\rho & -\delta \\ -\delta & M_\omega \end{bmatrix}$$

$$M_a = (m^2 - m_a^2 + im\Gamma_a)/m\Gamma_a$$

- The propagator can then be constructed as:

$$P = |M|^{-1} = \frac{1}{M_\rho M_\omega - \delta^2} \begin{bmatrix} M_\omega +\delta \\ +\delta & M_\rho \end{bmatrix} \cong \begin{bmatrix} 1/M_\rho & \delta/M_\rho M_\omega \\ \delta/M_\rho M_\omega & 1/M_\omega \end{bmatrix}$$

- And the amplitude then takes the form:

$$F(e^+e^-) = [T(\rho \rightarrow e^+e^-) \ T(\omega \rightarrow e^+e^-)]P \begin{bmatrix} A(\gamma p \rightarrow \rho) \\ A(\gamma p \rightarrow \omega) \end{bmatrix}$$

- Combining to make:

$$F(e^+e^-) = \frac{T_\rho A_\rho}{M_\rho} + \frac{T_\omega A_\omega}{M_\omega} + \frac{\delta(T_\rho A_\omega + T_\omega A_\rho)}{M_\omega M_\rho}$$
Interference Formalism

- The $a$ phase is then introduced, accounting for the cross amplitudes and mass term:

$$1 - i e^{i \phi_{\rho}} = -\frac{\delta}{M_{\rho}} \left( \frac{T_{\rho} A_{\omega} + T_{\omega} A_{\rho}}{T_{\omega} A_{\omega}} \right)$$

- The amplitude is then rewritten as a combination of the meson amplitudes with a complex phase term:

$$F = f_{\rho} + i e^{i \phi_{\rho}} f_{\omega}$$

- When squared, the amplitude takes the form:

$$F^2 = f_{\rho}^2 + f_{\omega}^2 - \frac{2a}{b^2 + c^2} (b \sin \phi_{\rho} + c \cos \phi_{\rho})$$
Fitting Procedure

• The $e^+ e^-$ invariant mass spectrum is fit with:
  • Two Breit-Wigner functions
    – Relativistic
    – Mass dependent widths
    – Interference term
    – Gaussian convolution
  • Background function for Bethe-Heitler:
    1: Monte Carlo GiBUU form
    2: Third-order Polynomial
Fits with a Selected Proton
Fit / non-interfering / MC background

- Proton MM cut.
- No interference term
- The mass resolution is fitted
- Bethe-Heitler form is taken from Monte Carlo and allowed to scale.

\[ \chi^2 / \text{ndf} = 98.13 / 55 \]
\[ \text{Prob} = 0.0003133 \]
\[ \omega \text{ Mass} = 0.7795 \pm 0.0004 \]
\[ A_{\omega} / A_{\rho} = 7.005 \pm 0.336 \]
\[ \text{norm} = 0.02771 \pm 0.00121 \]
\[ \text{MC Scale} = 3.739 \times 10^6 \pm 2.297 \times 10^5 \]
\[ \text{res} = 0.007884 \pm 0.000586 \]
Fit / interfering / MC background

- Proton MM cut
- Allowed to interfere
- The mass resolution is fitted
- Bethe-Heitler form is taken from Monte Carlo and allowed to scale.

```
Total
\omega
\rho
Bethe-Heitler
Interference Term
```

\[ \chi^2 / \text{ndf} = 66.58 / 54 \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>\omega Mass</td>
<td>0.7823 ± 0.0007</td>
</tr>
<tr>
<td>A / A_\omega</td>
<td>8.413 ± 0.614</td>
</tr>
<tr>
<td>phase</td>
<td>5.308 ± 0.105</td>
</tr>
<tr>
<td>norm</td>
<td>0.01537 ± 0.00121</td>
</tr>
<tr>
<td>MC Scale</td>
<td>3.91e+06 ± 2.29e+05</td>
</tr>
<tr>
<td>res</td>
<td>0.008225 ± 0.000570</td>
</tr>
</tbody>
</table>
Fit / non-interfering / polynomial background

- Proton MM cut
- No interference term
- The mass resolution is fitted
- Bethe-Heitler form is a 3\textsuperscript{rd} order polynomial, all parameters allowed to float.

\begin{align*}
\text{Total} & \quad \text{\omega} & \quad \text{\rho} \\
\text{Bethe-Heitler} & \quad & \quad
\end{align*}
Fit / interfering / polynomial background

- Proton MM cut
- Allowed to interfere
- The mass resolution is fitted
- Bethe-Heitler is a 3\textsuperscript{rd} order polynomial, all parameters allowed to float.

Total

$\omega$

$\rho$

Bethe-Heitler

Interference Term

\begin{verbatim}
\begin{tabular}{|l|c|}
\hline
$\chi^2$ / ndf & 53.84 / 51 \\
Prob & 0.3661 \\
$\omega$ Mass & 0.7815 \pm 0.0008 \\
$A_\omega/A_\omega$ & 6.75 \pm 0.82 \\
phase & 5.203 \pm 0.164 \\
norm & 0.01694 \pm 0.00164 \\
pol3-0 & -3921 \pm 78.8 \\
res & 0.008165 \pm 0.000586 \\
pol3-1 & 1.716e+04 \pm 1.118e+02 \\
pol3-2 & -2.331e+04 \pm 1.021e+02 \\
pol3-3 & 1.013e+04 \pm 1.436e+02 \\
\hline
\end{tabular}
\end{verbatim}
Fits Without Proton Selection

- Must subtract “uncorrelated” lepton pairs by looking at like-charge mass spectra:
  \[ N_{+-} = 2\sqrt{N_{++} + N_{--}} \]
Fit / non-interfering / MC background

- No proton MM cut.
- No interference term
- The mass resolution is fitted
- Bethe-Heitler form is taken from Monte Carlo and allowed to scale.

\[
\begin{align*}
\text{Total} & \quad \rho & \quad \omega & \quad \text{Bethe-Heitler} \\
\text{Counts} / 5.0 \text{ MeV} & \quad & & \\
\end{align*}
\]

\[
\begin{align*}
\chi^2 / \text{ndf} & = 324 / 55 \\
\text{Prob} & = 9.083 \times 10^{-40} \\
\omega \text{ Mass} & = 0.7782 \pm 0.0003 \\
A_\omega / A_\omega & = 6.198 \pm 0.250 \\
\text{norm} & = 0.07606 \pm 0.00221 \\
\text{MC Scale} & = 9.789 \times 10^6 \pm 4.701 \times 10^5 \\
\text{res} & = 0.008716 \pm 0.000395
\end{align*}
\]
Fit / interfering / MC background

- No proton MM cut
- Allowed to interfere
- The mass resolution is fitted
- Bethe-Heitler form is taken from Monte Carlo and allowed to scale.

\[
\chi^2 / \text{ndf} \quad 111.4 / 54 \\
\text{Prob} \quad 7.118 \times 10^{-6} \\
\omega \text{ Mass} \quad 0.7836 \pm 0.0005 \\
A_\omega / A_{1\omega} \quad 6.746 \pm 0.378 \\
\text{phase} \quad 5.83 \pm 0.08 \\
\text{norm} \quad 0.05324 \pm 0.00321 \\
\text{MC Scale} \quad 1.044 \times 10^7 \pm 4.618 \times 10^4 \\
\text{res} \quad 0.009025 \pm 0.000374
\]
Fit / non-interfering / polynomial background

- No proton MM cut
- No interference term
- The mass resolution is fitted
- Bethe-Heitler form is a 3\(^{rd}\) order polynomial, all parameters allowed to float.

\[
\begin{align*}
\chi^2 / \text{ndf} & \quad 90.88 / 52 \\
\text{Prob} & \quad 0.0006859 \\
\omega \text{ Mass} & \quad 0.7794 \pm 0.0003 \\
\lambda \text{ / } \lambda_{\text{max}} & \quad 8.876 \pm 0.490 \\
\text{norm} & \quad 0.07075 \pm 0.00219 \\
pol3-0 & \quad 3.021e+04 \pm 7.242e+03 \\
\text{res} & \quad 0.007848 \pm 0.000378 \\
pol3-1 & \quad -1.045e+05 \pm 2.707e+04 \\
pol3-2 & \quad 1.194e+05 \pm 3.321e+04 \\
pol3-3 & \quad -4.511e+04 \pm 1.341e+04
\end{align*}
\]

![Graph showing fit results with various lines representing different components and data points.]
Fit / interfering / polynomial background

- No proton MM cut
- Allowed to interfere
- The mass resolution is fitted
- Bethe-Heitler is a 3\textsuperscript{rd} order polynomial, all parameters allowed to float.

```
\begin{align*}
\text{Total} & \quad \text{\textcolor{black}{--}} \\
\omega & \quad \text{\textcolor{blue}{--}} \\
\rho & \quad \text{\textcolor{red}{--}} \\
\text{Bethe-Heitler} & \quad \text{\textcolor{brown}{--}} \\
\text{Interference Term} & \quad \text{\textcolor{magenta}{--}} \\
\end{align*}
```

\begin{table}[h]
\centering
\begin{tabular}{|c|c|}
\hline
\textbf{\textsuperscript{2}} / \textit{ndf} & 65.4 / 51 \\
\hline
\textbf{Prob} & 0.08463 \\
\hline
\hline
\textbf{\textomega} Mass & 0.7821 \pm 0.0005 \\
\hline
\textbf{\textfrac{A_1}{A_0}} & 5.984 \pm 0.558 \\
\hline
\textbf{\textphase} & 5.541 \pm 0.128 \\
\hline
\textbf{\textnorm} & 0.05086 \pm 0.00384 \\
\hline
\textbf{\textpol}0 & -9357 \pm 154.0 \\
\hline
\textbf{\textres} & 0.008651 \pm 0.000373 \\
\hline
\textbf{\textpol}1 & 4.231e+04 \pm 2.136e+02 \\
\hline
\textbf{\textpol}2 & -5.884e+04 \pm 1.963e+02 \\
\hline
\textbf{\textpol}3 & 2.605e+04 \pm 2.716e+02 \\
\hline
\end{tabular}
\end{table}

\begin{figure}[h]
\begin{center}
\includegraphics[width=\textwidth]{graph.png}
\end{center}
\end{figure}
## Interference Phase Preliminary Results

<table>
<thead>
<tr>
<th>Fit Type</th>
<th>Interference Phase</th>
<th>$X^2$/ndf</th>
</tr>
</thead>
<tbody>
<tr>
<td>MM cut / MC background</td>
<td>Not fit</td>
<td>1.784</td>
</tr>
<tr>
<td>MM cut / MC background</td>
<td>5.308 +/- 0.105</td>
<td>1.270</td>
</tr>
<tr>
<td>MM cut / 3$^{rd}$ order pol.</td>
<td>Not fit</td>
<td>1.187</td>
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<tr>
<td>MM cut / 3$^{rd}$ order pol.</td>
<td>5.203 +/- 0.164</td>
<td>1.056</td>
</tr>
<tr>
<td>No MM cut / MC background</td>
<td>Not fit</td>
<td>5.891</td>
</tr>
<tr>
<td>No MM cut / MC background</td>
<td>5.830 +/- 0.080</td>
<td>2.063</td>
</tr>
<tr>
<td>No MM cut / 3$^{rd}$ order pol.</td>
<td>Not fit</td>
<td>1.748</td>
</tr>
<tr>
<td>No MM cut / 3$^{rd}$ order pol.</td>
<td>5.541 +/- 0.128</td>
<td>1.263</td>
</tr>
</tbody>
</table>
Part II: Pseudoscalar Mesons $\eta$ and $\eta'$

Dissertation work from Michael C. Kunkel

- Limited statistics on $\eta$ and $\eta'$ Dalitz decay studies.
- Currently only an upper limit on $\eta'$ Dalitz cross section.

- Soon to be published data from CB / TAPS@MAMI:

M. Berlowski, et. al., Phys. Rev. D77
WASA / CELCIUS, 2008

A. Lopez, et. al., Phys. Rev. Lett. 9
CLEO Collaboration, 2007

R. A. Briere, et. al., Phys. Rev. Lett. 84
CLEO Collaboration, 2000

$\eta$

$N_\eta = 729$

$\eta'$

$N_{\eta'}_{\text{tot}} < 300$

Counts: $1345 \pm 59$

$\sigma_\eta = (14.1 \pm 0.4) \text{ MeV}$
η Statistics from g12

η → e^+e^−γ  3,440 events

- g12 experiment has largest world statistics for η reconstructed from Dalitz decays
- Data has not yet been corrected for η → γγ, where one of the photons pair creates in the target medium.
Selecting Dalitz Decays

- Beyond Exclusivity Cuts:
  - Correcting for the detected photon momentum significantly increases statistics within exclusivity cuts.
The Charge Form Factor of $\eta$

- For $\eta \rightarrow e^+ e^- \gamma$:

$$\frac{d\Gamma}{dq^2} = \left(\frac{d\Gamma}{dq^2}\right)_{\text{point like}} \cdot |F(q^2)|^2$$

$$\frac{d\Gamma(P \rightarrow e^+ e^- \gamma)}{dm \Gamma(P \rightarrow \gamma \gamma)} = \frac{4\alpha}{3\pi m} \sqrt{1 - \frac{4m_e^2}{m^2}} \left(1 + \frac{2m_e^2}{m^2}\right) \left[1 - \frac{m^2}{m_P^2}\right]^3 |F(q^2)|^2$$

$$F(q^2) = \frac{1}{1 - \frac{q^2}{\Lambda^2}}$$

$m$ is the dilepton mass
$m_e$ is the electron mass
$m_P$ is the parent meson mass
$\Lambda$ is the monopole FF parameter
The $\eta$ dilepton mass spectrum

- The lowest mass bin has more events than are expected. This is likely from two sources:
  - Acceptance in the low mass region drops significantly.
  - The decay $\eta \rightarrow \gamma\gamma$, where one of the photons pair produce in the target or target walls. Currently, simulation is being run on this process.
$\eta'$ Dalitz

- G12 data shows a clear enhancement at the $\eta'$ mass (958 MeV): $\eta' \rightarrow e^+e^-\gamma$  

213 events

\[ \text{PRELIMINARY} \]

Conclusion

- Understanding the $\rho$-$\omega$ interference in the elementary process will help with the interpretation of in-medium studies.

- The interference phase itself from fits with different background shapes all agree within statistical error: preliminary phase: $\varphi = 5.25 \pm 0.20$.

- The transition charge FF for the $\eta$ (and $\pi^0$) are being studied.

- The first ever $\eta'$ dalitz decay is being measured in experiment g12, with cross sections and branching ratios upcoming.
Extra Slides:
Bethe-Heitler

- Problems:
  - Bethe-Heitler MC and data do not agree well.
  - Possible Bethe-Heitler / VM interference.
    - Shows up in detected asymmetries. CLAS is asymmetric in electron / positron acceptance.
Background and Cuts

- **Cut 1**: Two leptons are skimmed from the total g12 data set.
- **Cut 2**: Both leptons must be in different sectors of CLAS.
- **Cut 3**: Vertex cut on event to be inside target walls.
- **Cut 4**: Coincidence timing cut between the leptons and the tagged photon.
- **Cut 5**: Additional EC cut to remove pions.
- **Cut 6**: Opening angle cut between leptons.
Background and Cuts

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![Dilepton Invariant Mass (GeV/c²)](image)
Background and Cuts

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- Cut 5: Additional EC cut to remove pions.
- Cut 6: Opening angle cut between leptons.
CLAS Positron / Electron Acceptance
Fit Results (Non-Interfering)

- Assuming two separate non-interfering Breit-Wigner forms, the fit does not describe the data very well:
  - $\chi^2/\text{ndf} \sim 2.8$
  - $\rho$ mass is 35 MeV low
Fit Results (Interfering)

- Fit results much better with an interfering Breit-Wigner.
  - $\chi^2/\text{ndf} \sim 0.8$
  - $\rho$ mass and width consistent with pdg values.
  - Interference phase of $5.772 \pm 0.076$
    $1.837\pi \pm 0.002\pi$
Alternate Subtraction / Fit (non-interfering)

- Subtraction of uncorrelated lepton pairs and MC background.
- Tighter fit range to exclude low mass backgrounds.
  - $\chi^2$/ndf $\sim 2.8$
  - $\rho$ mass is 50 MeV low
  - $\rho$ width is 30 MeV too small

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2$/ndf</td>
<td>80.72 / 29</td>
</tr>
<tr>
<td>Prob</td>
<td>9.072e-07</td>
</tr>
<tr>
<td>M_rho</td>
<td>0.7142 ± 0.009671</td>
</tr>
<tr>
<td>M_omga</td>
<td>0.7784 ± 0.0004033</td>
</tr>
<tr>
<td>W_rho</td>
<td>0.12 ± 0.001622</td>
</tr>
<tr>
<td>W_omga</td>
<td>0.02173 ± 0.001134</td>
</tr>
<tr>
<td>A_rho</td>
<td>2.181 ± 0.08237</td>
</tr>
<tr>
<td>A_omga</td>
<td>4.318 ± 0.06207</td>
</tr>
<tr>
<td>phi</td>
<td>3.142 ± 3.822</td>
</tr>
<tr>
<td>norm</td>
<td>17.13 ± 0.2984</td>
</tr>
</tbody>
</table>
Alternate Subtraction / Fit (Interfering)

- Subtraction of uncorrelated lepton pairs and MC background.
- Tighter fit range to exclude low mass backgrounds.
- Fit is better / reasonable
  - $\chi^2$/ndf $\sim$ 1.5
  - $\rho$ mass is low, width is within errors.
- Interference phase consistent with alternate method of background subtraction.
Conclusion

• $\rho$ and $\omega$ in-medium publications have produced conflicting results.

• The $\rho$ and $\omega$ have been studied in experiment g12 at JLab; photoproduced off of Hydrogen and reconstructed via the dileptonic decay channel to eliminate FSIs.

• When allowed to interfere, a good fit is obtained to the $\rho$-$\omega$ mass spectrum, giving a preliminary interference phase ($\Phi$) of $5.772 \pm 0.076$ (stat) radians.
A number of studies have looked for medium modification effects in the $\rho$ and $\omega$, with somewhat conflicting results:

- **$\rho$ studies:**
  - NA45 / CERES-CERN -- Width broadening
  - NA60 / CERN-SPS -- Width broadening
  - KEK-PS – Mass shift
  - JLAB / g7a – No change to mass or width

- **$\omega$ studies:**
  - KEK-PS -- Mass Shift
  - CBELSA / TAPS – Inconclusive.
  - JLAB / g7a – Large width broadening through absorption

ω Absorption at Jefferson Lab (Experiment g7a)

γ A \rightarrow e^+ e^- (X)

- Mass “dip” after ω-peak and calculated transparency significantly less than predicted or previously measured.
- Can ρ-ω interference account for this?
- High statistics analysis needed on the elementary production channel.

In leptonic pair photoproduction, the 2\textsuperscript{nd} order Born contributions can be accessed through asymmetric detector acceptance between electrons and positrons.

\( N_+ (\delta) \) \{or \( N_- (\delta) \) \} is the rate of positrons \{or electrons\} with identical and opposite angle of the electron pair, but have an excess momentum of \( \delta \).

\[
\epsilon (\delta) = \frac{N_+ (\delta) - N_- (\delta)}{N_+ (\delta) + N_- (\delta)}
\]
Title

• text