Partial Wave Analysis for $\gamma p \rightarrow p\omega$ using the CLAS at JLab

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Gluex Collaboration Meeting

Outline

1. PWA Overview
2. $\gamma p \to p\omega$: Data/Observables
3. $\gamma p \to p\omega$: PWA
4. Summary

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What is PWA?

Some basic principles of scattering (or decay) processes:

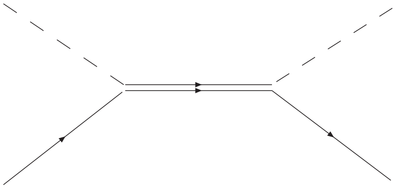
- The Lorentz-invariant scattering amplitude is related to elements of the S-matrix via: $\langle f|S|i\rangle \propto -i\mathcal{M}(\vec{x})$, where $\vec{x}$ is the complete set of *relevant* kinematic variables in $i \longrightarrow f$ scattering.
  e.g. $\vec{x} = (W, \cos\theta^f_{CM})$ in $\pi N \longrightarrow \pi N$.

- The scattering amplitude is comprised of a number of interfering waves corresponding to different $i \longrightarrow f$ scattering processes: $\mathcal{M}(\vec{x}) \equiv \sum_a \mathcal{A}_a(\vec{x})$.

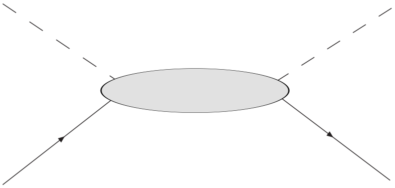
Partial wave analysis seeks to determine the nature of these amplitudes by examining the $\vec{x}$-dependence of $i \longrightarrow f$ scattering.
e.g. $\cos\theta^f_{CM}$-dependence at fixed W in $\pi N \longrightarrow \pi N$.

Types of Processes

We divide all 2 $\rightarrow$ 2 scattering processes into two main categories:



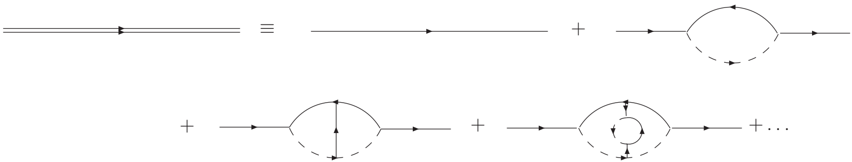
Resonant Terms



Non-Resonant Terms

Resonance Propagators

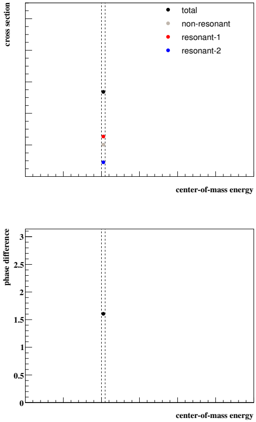
The *propagator* of a resonance is determined by the sum of an infinite number of Feynman diagrams:



Thus, the *mass-dependence* (or W-dependence in $2 \rightarrow 2$ scattering) of the resonance is a complex function of its invariant mass, often modeled as a Breit-Wigner; however, there are times when the Breit-Wigner approximation is not accurate and/or valid.

Mass-Independent PWA (Toy Example)

A quick overview of the *mass-independent* partial wave analysis technique



- Bin the data finely in W
- The *mass-dependence* (propagator) of the resonance can be approximated in each bin as a constant complex number
- Select a bin and allow the fit to find the optimal physics for this small energy range
- Extract the yields and phase differences of the waves in this bin

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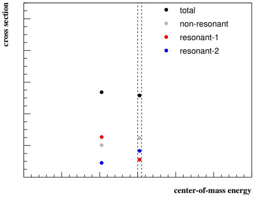
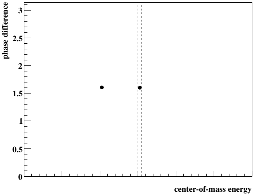
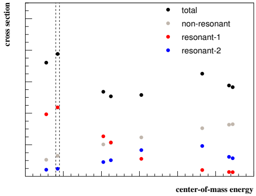


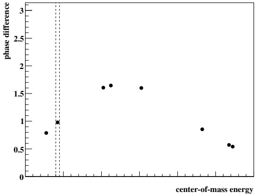


- Bin the data finely in W
- The *mass-dependence* (propagator) of the resonance can be approximated in each bin as a constant complex number
- Select another bin and run another *independent* fit
- Extract the yields and phase differences of the waves in this bin

Mass-Independent PWA (Toy Example)

A quick overview of the *mass-independent* partial wave analysis technique





- Repeat this process over the entire energy range – all fits are *independent*

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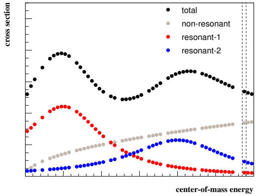

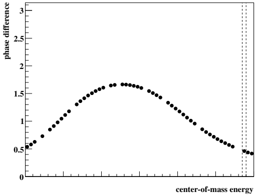

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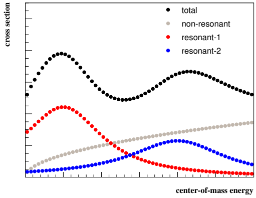

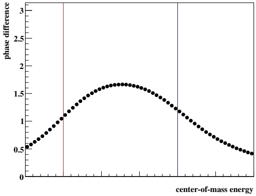

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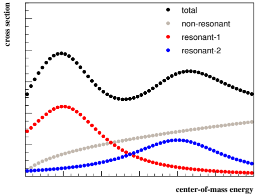
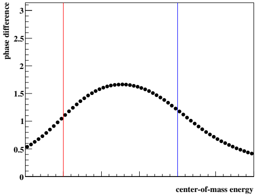
Mass-Independent PWA (Toy Example)

A quick overview of the *mass-independent* partial wave analysis technique





- Repeat this process over the entire energy range – all fits are *independent*
- If the data contains resonances, we should be able to extract them without enforcing resonance shapes and biasing the result

PWA Procedure

The mass-independent PWA procedure can be summarized as:

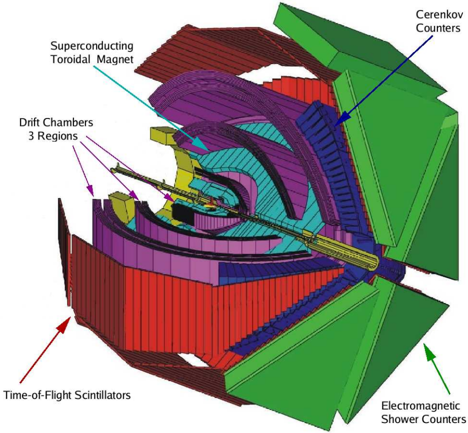
- Bin the data finely in W (premits treatment of mass-dependence of resonant terms as constant complex numbers in each bin).
- Find the optimal physics in each bin (independently).
- Extract yields and phase motion — compare these to what would be expected from resonance contributions.

Outline

The CLAS detector is housed in Hall-B at JLab.

- Cryotarget (LH_2)
  cylinder: $\ell = 40$ cm, $\rho = 2$ cm
- Start Counter
- Superconducting Toroidal Magnet
  $I_{max} = 3861$ A, $B_{max} = 3.5$ T
- Drift Chambers (3 regions)
  $35,148$ hexagonal drift cells
  $\sigma_p/p \sim 0.1\%$,$\sigma_\theta \sim 0.5$ mrad,
  $\sigma_\phi \sim 3$ mrad
- TOF Scintillators
  342 bars, $\sigma \sim 100$ ps
- Cerenkov Counters
- Electromagnetic Calorimeters

CLAS: CEBAF Large Acceptance Spectrometer



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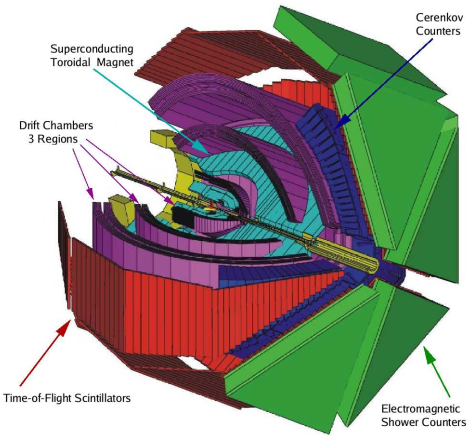


Analysis Overview

$\gamma p \to p\omega$ event selection utilizes the $\omega \to \pi^+\pi^-\pi^0$ decay:

- require detection of all charged particles ($p\pi^+\pi^-$)
- reconstruct π^0 from missing 4-momentum (via kinematic fitting)
- select ω's using *event-based* signal-background separation method which preserves ALL multi-dimensional correlations
- an absolute normalization measurement was performed using "out-of-time" photon tagger hits.

After all cuts, etc..., we have over 10 M ω events!

What Do We Want to Know?

We want to know the physics, *i.e.* we want to know the scattering amplitude for $\gamma p \longrightarrow p\omega$: $\mathcal{M}_{m_i,m_\gamma,m_f,m_\omega}(\sqrt{s},\theta^{\omega}_{CM})$

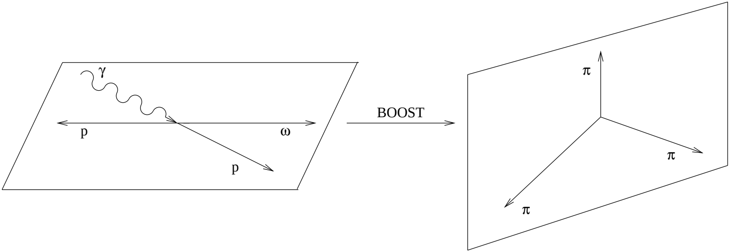
A total of $2 \times 2 \times 2 \times 3 = 24$ complex numbers $\xrightarrow[parity]{}$ 12 independent complex numbers (23 independent real numbers, overall phase irrelevant) at each $(\sqrt{s},\theta^{\omega}_{CM})$.

A *complete* measurement requires (at least) 23 very carefully chosen measurements (including triple and quadruple polarization measurements), not (currently) possible . . . What can we measure?

What Can We Measure?

At each $(\sqrt{s}, \theta^{\omega}_{CM})$ point, we can measure the following quantities:

- Differential Cross Section, $\frac{d\sigma}{d\cos\theta^{\omega}_{CM}}(\sqrt{s}, \theta^{\omega}_{CM})$
- Spin Density Matrix Elements, $\rho^0_{00}, \rho^0_{1-1}, Re\rho^0_{10}$



$\rho^0_{MM'}$ extracted from relative orientation of the decay plane to the production plane.

What Can We Measure?

How do we measure $\frac{d\sigma}{d\cos\theta^{\omega}_{CM}}$, ρ^0_{00}, ρ^0_{1-1} and $Re(\rho^0_{10})$ at each $(\sqrt{s}, \theta^{\omega}_{CM})$?

The Mother of All Fits

To make all of our measurements, we expand the scattering amplitude in a (nearly) complete basis of s-channel waves:

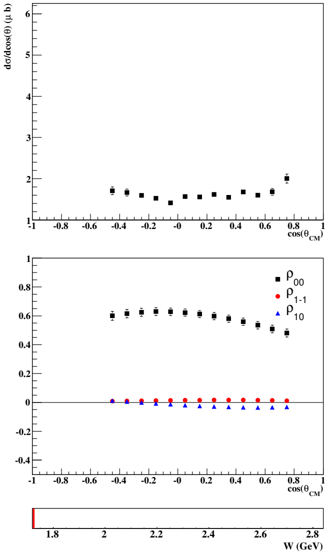
$$\mathcal{M}_{m_i,m_\gamma,m_f,m_\omega}(\sqrt{s},\theta^{\omega}_{CM}) \approx \sum_{J=\frac{1}{2}}^{\frac{21}{2}} \sum_{P=\pm} \alpha^{J^P}_{MP,LS} \mathcal{A}^{\gamma p \to J^P \to p\omega, MP, LS}_{m_i,m_\gamma,m_f,m_\omega}(\sqrt{s},\theta^{\omega}_{CM}),$$

where $\alpha^{J^P}_{MP,LS}$ are complex numbers (108 total fit parameters).

The results of this fit are NOT interpreted as physics, they simply provide the best possible description of our data (including ALL kinematic correlations) from which we can extract $d\sigma/d\cos\theta^{\omega}_{CM}$ and $\rho^0_{MM'}$ in a model-independent way.

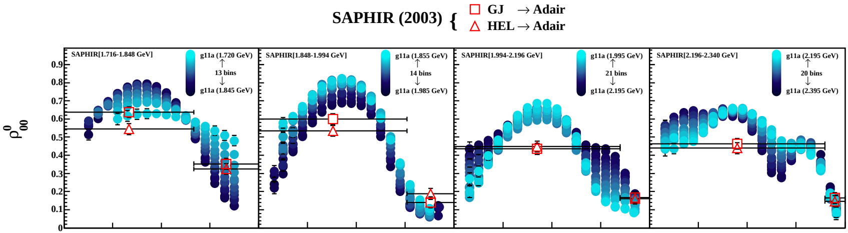
Final Results

Lights, Camera . . . Physics.



Comparison of ρ^0_{00} to Previous Measurement

ρ^0_{00} vs $\cos\theta_{CM}$: comparison to SAPHIR (2003) — 1.72 GeV $< W <$ 2.4 GeV



Outline

PWA Procedure

A quick review of the mass-independent PWA procedure:

- Bin the data finely in W (premits treatment of mass-dependence of resonant terms as constant complex numbers in each bin).
- Find the optimal physics in each bin (independently).
- Extract yields and phase motion — compare these to what would be expected from resonance contributions.

Let's apply this procedure to the $\gamma p \longrightarrow p\omega$ reaction.

How Do We Find the Optimal Physics?

We use the unbinned extended maximum likelihood method which defines the likelihood for detecting n events as $\mathcal{L} = \left(\frac{\bar{n}^n}{n!} e^{-\bar{n}}\right) \prod_i^n \frac{|\mathcal{M}_i|^2 \eta_i \phi_i}{\mathcal{N}}$

- $\mathcal{M}_i$ scattering amplitude for event i
- η_i detector acceptance for event i
- ϕ_i available phase space for event i
- $\mathcal{N}$ normalization factor for p.d.f.

The optimal physics is found my maximizing $\mathcal{L}$.

How Do We Find the Optimal Physics?

To maximize $\mathcal{L}$, we minimize

$$-\ln\mathcal{L} = -\sum_{i}^{n} Q_i \ln|\mathcal{M}_i|^2 + \frac{\mathcal{S}(s)}{n_{raw}}\sum_{j}^{n_{acc}}|\mathcal{M}_j|^2 + const,$$

where Q_i handles background subtraction and $\mathcal{S}(s)$ is a normalization factor given by

$$\mathcal{S}(s) = \frac{\mathcal{F}(\sqrt{s})\rho_{targ}\ell_{targ}N_A}{A_{targ}}\frac{\left[(s-(m_p+m_\omega)^2)(s-(m_p-m_\omega)^2)\right]^{1/2}}{64\pi s(s-m_p^2)},$$

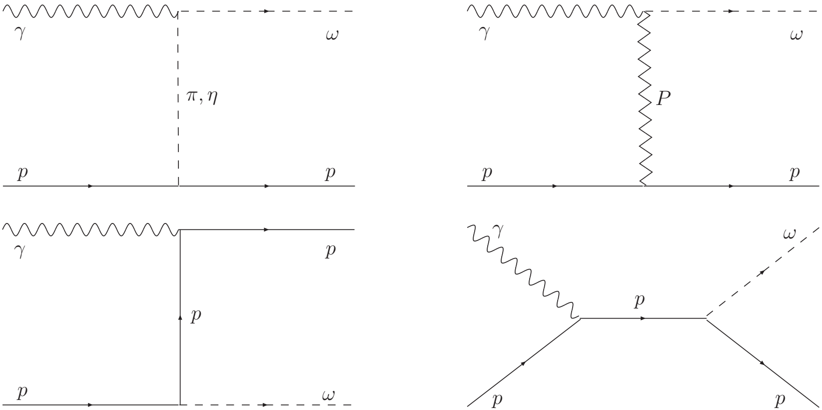
which allows us to input coupling constants directly from theory.

How Do We Find the Optimal Physics?

OK, great, but . . . what physics (amplitudes) should we include in the fits?

Non-Resonant Terms

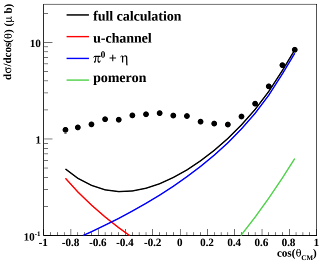
Non-resonant terms taken from the Oh, Titov and Lee model.

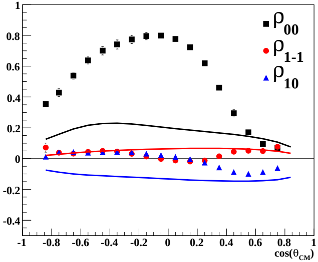


All parameters locked by fitting to previous ω cross sections.

Non-resonant Terms

What do these diagrams look like in the resonance region ($W = 2\ GeV$)?
Oh, Titov, Lee Model

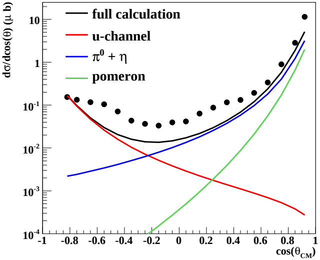


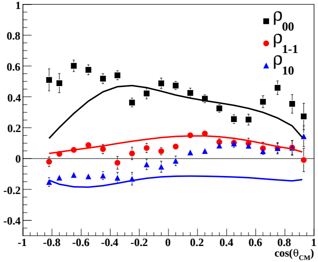


Good agreement in forward direction.

Non-resonant Terms

What do these diagrams look like at higher energies ($W = 2.8$ GeV)?
Oh, Titov, Lee Model ($\kappa_\omega = 0$)





Clearly, there's room for improvement.

Non-resonant Terms

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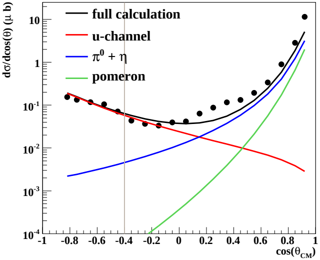
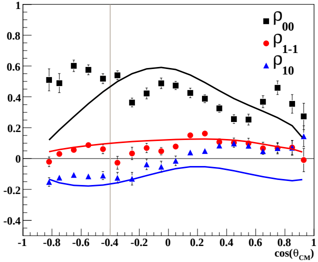
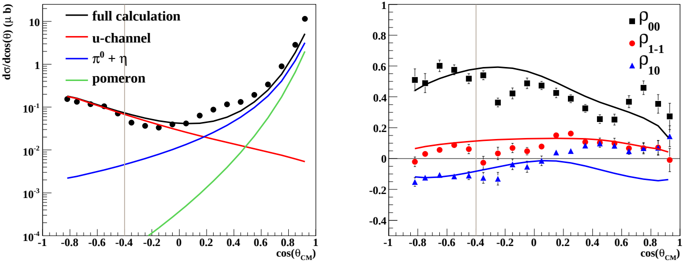




Clearly, there's room for improvement.

Non-resonant Terms

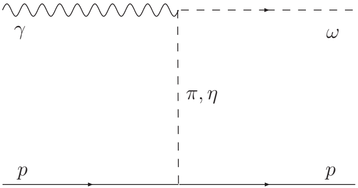
What do these diagrams look like at higher energies ($W = 2.8\ GeV$)?
Oh, Titov, Lee Model ($\kappa_\omega = -1.05$, QM $\rightarrow -1.5$)

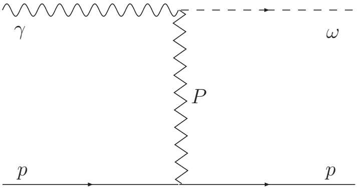


Clearly, there's room for improvement.

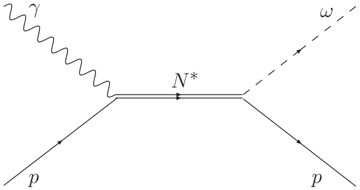
Amplitudes Used in Our Fits

Non-resonant terms taken from the Oh, Titov and Lee model (no free parameters).





Resonant terms built using the Rarita-Schwinger Covariant Formalism.



Fit Results

Before we look at some results, I'd like to point out that:

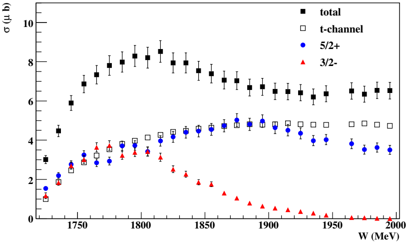
- We ARE NOT trying to build a *complete* model of ω photoproduction:
  - We do not claim that our fits contain all of the physics; thus, we do not expect to provide *perfect* descriptions of our data.
  - We do not claim to have extracted every resonance contribution.
- We ARE trying to extract strong resonance contributions in a model-independent way:
  - We do extract phase motion and compare it to what would be expected from resonances.
  - Our technique is not well suited for extracting small (*eg* $< 10\%$) resonance contributions.

OK, let's look at some results!

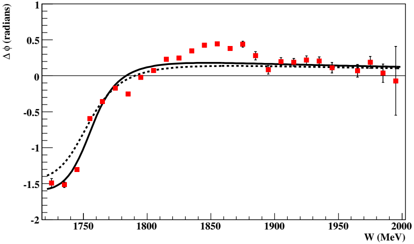
Fit: 1.72 GeV $< \sqrt{s} <$ 2 GeV

Free $3/2^-$,$5/2^+$ with Locked Oh, Titov, Lee *t*-channel

Yields vs $\sqrt{s}$



Phase Difference vs $\sqrt{s}$



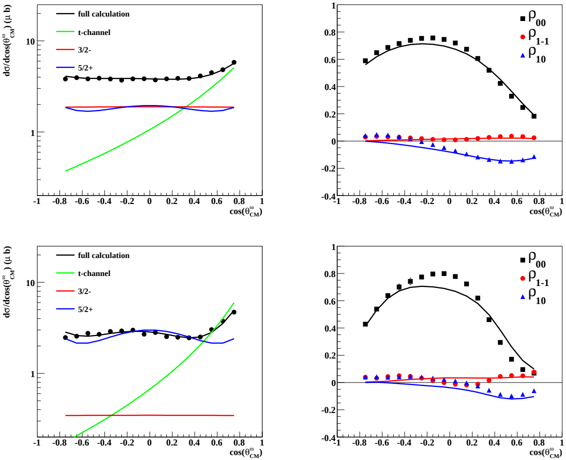
$$J^P = 3/2^-: \ \frac{A_{3/2}}{A_{1/2}} \epsilon [-0.06, 0.13], \text{ PDG: } 0.11 \pm 1.34$$

$$J^P = 5/2^+: \ \frac{A_{1/2}}{A_{3/2}} \sim -0, \text{ PDG: } -0.11 \pm 0.05$$

Are these the **** $F_{15}(1680)$ and *** $D_{13}(1700)$? Yes

Fit: 1.72 GeV $< \sqrt{s} <$ 2 GeV

Comparison to $d\sigma/d\cos\theta$ and $\rho^0_{MM'}$ ($W = 1.8$ and 1.9 GeV)

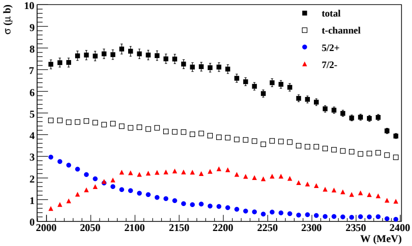


Excellent agreement for only 2 free waves!

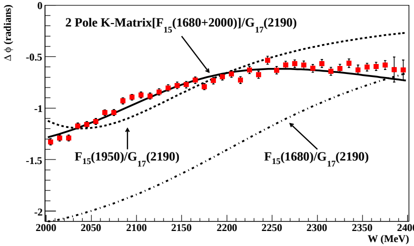
Fit: 2 GeV $< \sqrt{s} <$ 2.4 GeV

Free $5/2^{+}$,$7/2^{-}$ with Locked Oh, Titov, Lee t-channel

Yields vs $\sqrt{s}$



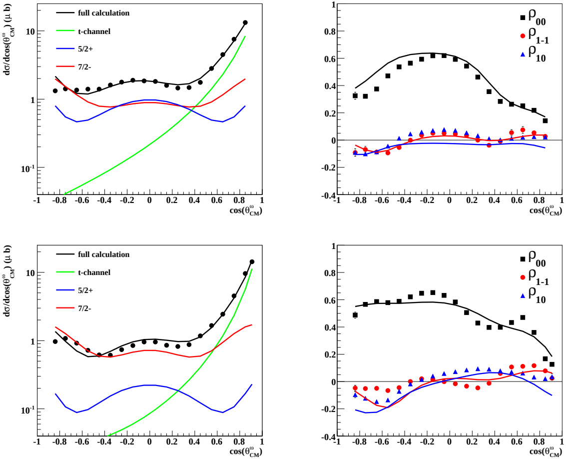
Phase Difference vs $\sqrt{s}$



Is this the **** $G_{17}(2190)$? Yes (most likely).
Suggestive (but not conclusive) evidence for a *missing* $F_{15}(2000)$ state.

Fit: 2 GeV $< \sqrt{s} <$ 2.4 GeV

Comparison to $d\sigma/d\cos\theta$ and $\rho^0_{MM'}$ (W $=$ 2.1 and 2.3 GeV)

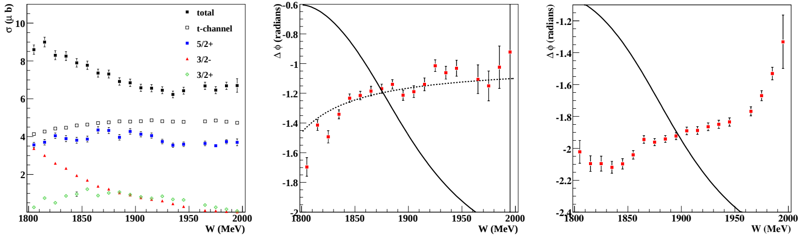


Agreement is OK — Recall non-resonant model could be improved.

Missing States?

Free $3/2^-$,$5/2^+$,$3/2^+$ with Locked Oh, Titov, Lee t-channel

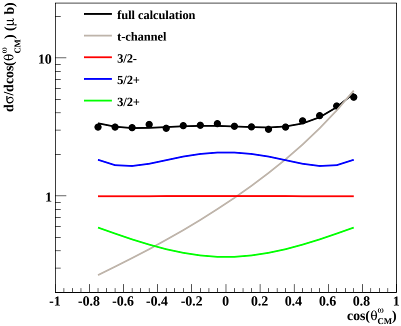
Yields vs $\sqrt{s}$ | $\Delta\phi_{3/2^-,3/2^+}$ vs $\sqrt{s}$ | $\Delta\phi_{5/2^+,3/2^+}$ vs $\sqrt{s}$

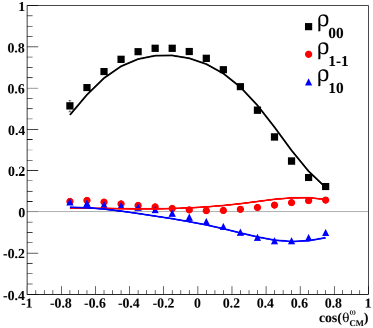


Is this a *missing* resonance(s)? ?????

Missing States?

Comparison to $d\sigma/d\cos\theta$ and $\rho^0_{MM'}$ ($W = 1.85$ GeV)





Excellent Agreement!

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3 $\gamma p \to p\omega$: PWA

4 Summary

Summary

- Measurements of $\frac{d\sigma}{d\cos\theta^{\omega}_{CM}}$ and $\rho^{0}_{MM'}$ have been made for $\sim 20 \cos\theta^{\omega}_{CM}$ points in each of 112 W bins using the CLAS $g11a$ dataset.
- Our measurements show discrepancies with current non-resonant models at high energies — this should keep theorists busy for a while.
- A *mass independent* PWA has been performed and the dominant waves are found to be the *** $D_{13}(1700)$ and **** $F_{15}(1680)$ states near threshold, along with (most likely) the **** $G_{17}(2190)$ at higher energy.
- Evidence exists for other states — harder to interpret
- Future work:
  - Incorporate CLAS $g8$ $\rho^{1,2}_{MM'}$ (CUA) measurements — when available
  - Measure $\rho^{3}_{MM'}$ from CLAS $g1c$ (CMU), include this when done
  - Measure everything we can from FROST (CUA and CMU), include this when done