Photoproduction of ω Mesons and $\pi^0\omega$ Meson Pairs off the Free Proton

Andrew Wilson

Florida State University
Physics Department

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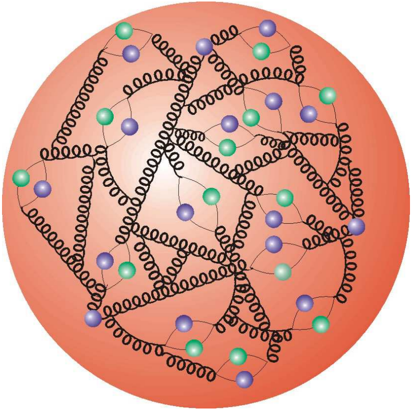
Dissertation Defense

Nucleon (Protons / Neutrons)



- composite particle
- contains quarks and gluons
- bound by the strong nuclear force, described by Quantum Chromodynamics (QCD)
- contains 3 "valence" quarks
- contains a "sea" of quark anti-quark pairs and gluons.

What is the nature of the force that binds the proton?

Strong Interaction

quarks

u
up

s
strange

b
bottom

d
down

c
charm

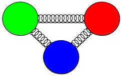
t
top

gauge boson

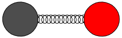
g
gluon

Hadrons

Baryons



Mesons



- Quarks are only found bound inside hadrons.
- Gluons are the force carriers.
- QCD Lagrangian describes the interaction of quarks and gluons

The QCD Lagrangian has been shown to be correct at large interaction energies.($>$ 10 GeV)

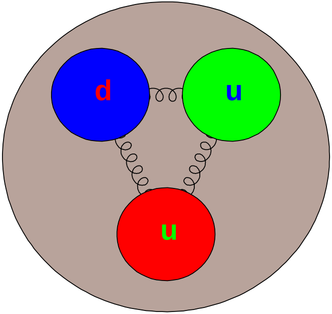
Solving the QCD Lagrangian

- Perturbative QCD: Used to show the QCD Lagrangian is correct. Can not be used! $\rightarrow$ Non-perturbative at these energies.
- Numerical Solutions: Lattice QCD (not finished yet)

$\rightarrow$ No current way to solve the QCD Lagrangian at these energies.

Can we construct effective models to understand?

Constituent Quark Model

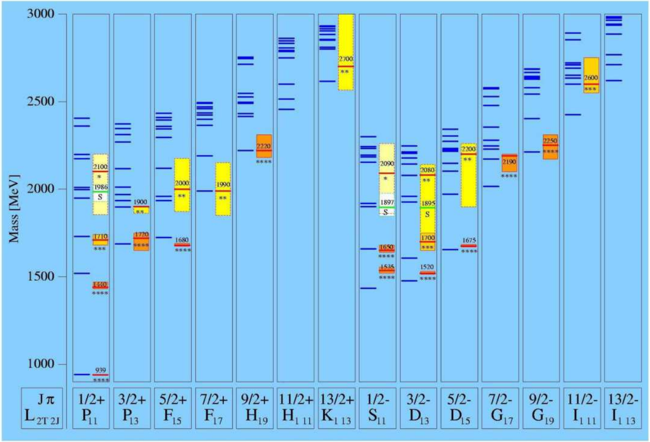


Constituent Quark Model (CQM)

- Assume only 3 quarks with a fitted mass.
- Propose an interaction which respects the known properties of the strong force.
- Fit the mass of the quarks to recreate the nucleon (proton/neutron) mass.
- Generate the excited states.

Constituent Quark Model Predictions

Isospin 1/2, Strangeness 0 Baryon Predictions
Instanton-based, relativistic solution
(U. Loring *et. al.* Eur. Phys. J. A **10**, 395 (2001))

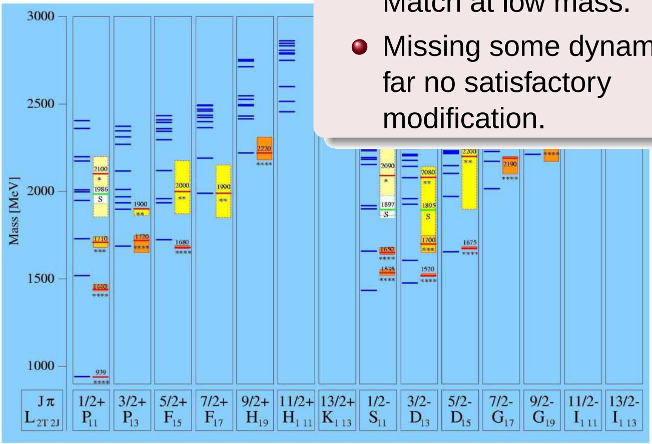


Constituent Quark Model Predictions

Isospin 1/2, Strangene

Instanton-based,

(U. Loring *et. al.* Eur. P



Are the CQMs wrong?

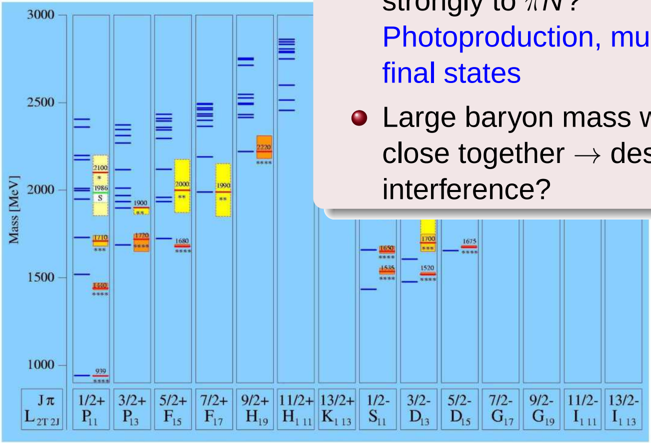
- Must be somewhat correct: Match at low mass.
- Missing some dynamics? So far no satisfactory modification.

Constituent Quark Model Predictions

Isospin 1/2, Strangene

Instanton-based,

(U. Loring *et. al.* Eur. P

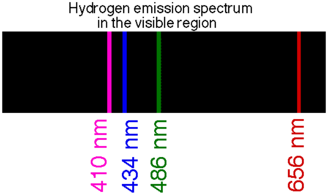


Experiment hasn't found them yet?

- Most baryon states found using πN scattering. Missing resonances do not couple strongly to πN? Photoproduction, multi-particle final states
- Large baryon mass widths close together $\rightarrow$ destructive interference?

Spectroscopy

The pattern of excited states of a bound state depends directly on the binding force.



Using a historical example:
Atomic Spectroscopy

- Map out the excited states of the atom
- Create Models to fit the spectrum
- Lead to Quantum Physics and Quantum Electrodynamics

Baryon Spectroscopy Observables

Scattering Experiment Observables used in this analysis

Differential Cross Sections $(\frac{d\sigma}{dX_i})$

Conceptually:
A measurement proportional to the probability for a reaction to happen scattering into some final state kinematics (X_i).
Total Cross Section: Integrate over final state kinematics.

Polarization Observables

Conceptually:
A relative measurement used to quantify how the differential cross section depends on the spin polarizations of the initial or final state particles.

$\rightarrow$ Spin-density Matrix Elements (ρ)

(Cross section dependence on the spin polarization of a single final state particle)

Spectroscopy

The pattern of excited states of a bound state depends directly on the binding force.

Hydrogen emission spectrum
in the visible region

Using a historical example:
Atomic Spectroscopy

- Map out the excited states of

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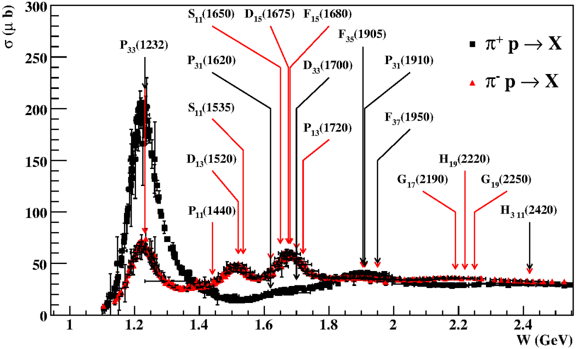
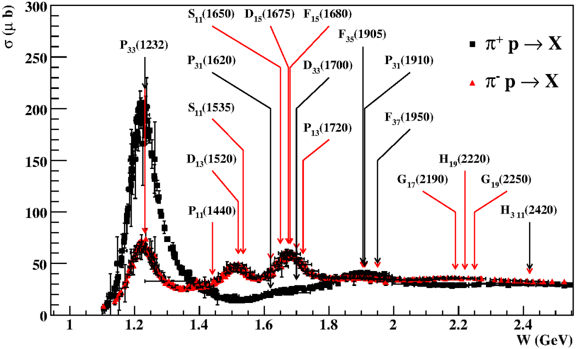
ctrodynamics



Baryon Spectroscopy

- Baryon Resonances have short lifetimes $\rightarrow$ large mass widths $\rightarrow$ destructive interference
  - Sophisticated interpretation analysis technique (Partial Wave Analysis)
  - Polarization Observables
- Baryon Resonances decay to a zoo of particles: photons, mesons, baryons, leptons. $\rightarrow$ specialized detectors



Why ω photoproduction?

- Quark model predictions suggest many of these "missing" baryon resonances couple significantly to $p\omega$ and intermediate decays in $p\pi^0\omega$.
- The first measurement of observables over the full kinematic range with characteristics useable for isolating baryon resonances.

Observables Measured

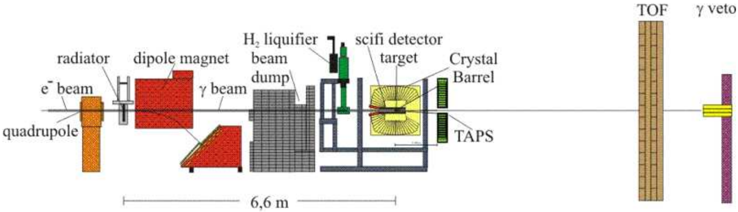
$\gamma p \to p\omega$

Differential cross sections & Spin-density matrix elements

$\gamma p \to p\pi^0\omega$

Differential cross sections

CBELSA/TAPS Experiment



Beam

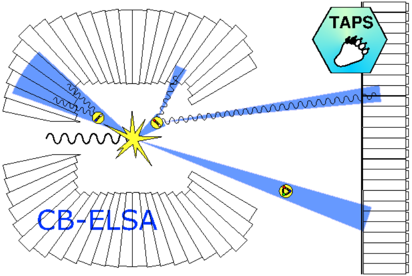
Unpolarized or linearly polarized photons tagged with energy and timing.

Target

Stationary, unpolarized free protons. Liquid hydrogen.

CBELSA/TAPS Detectors

- Crystal Barrel Detector: 1290 CsI (Tl) crystals + photodiodes
- TAPS Detector: 528 BaF_2 crystals + photomultipliers tubes
- Excellent photon energy and position reconstruction characteristics.
- Only detect the presence of charged particles by scintillating materials between the target and crystals.



Data

Data recorded : October - November 2002
Beam: Unpolarized tagged photons
Target: Unpolarized Liquid Hydrogen

Decay channel selected for:

$\gamma p \to p\omega \to p\pi^0\gamma \to p\gamma\gamma\gamma$
$\gamma p \to p\pi^0\omega \to p\pi^0\pi^0\gamma \to p\gamma\gamma\gamma\gamma\gamma$
(Branching Ratios : $\omega \to \pi^0\gamma$ = 8.9% , $\pi^0 \to \gamma\gamma$ = 98%)

Selected events with:

$\gamma p \to p\omega$ 3 uncharged reconstructed particles & 0-1 charged reconstructed particles
$\gamma p \to p\pi^0\omega$ 5 uncharged reconstructed particles & 0-1 charged reconstructed particles

Monte Carlo Simulated Data

Detector Acceptance, Cut tuning.

Data Reduction Cuts

- Multiplicity Cuts - 3(5) photons and less than 2 protons
- Timing Cut - Imposes causality between the initial photon and final state particles. Reduces the number of initial photon candidates.
- Coplanarity Cut - cut away events where extra undetected particles could have been involved
- Trigger Cut - cut away events where proton identification simulation could be wrong.

Kinematic Fitting

To evaluate the probability of an event being a desired final state.

Definition

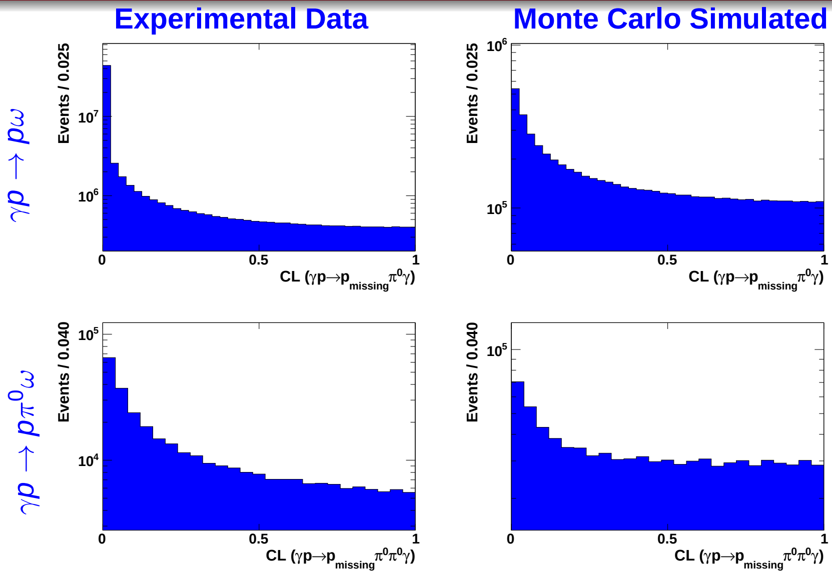
- Varies the measured values within the quoted errors of the experiment
- Matches to an "ideally" measured event using Energy-Momentum conservation and invariant masses
- Returns a confidence level value between 0 - 1 for each event.
- Used to select initial photon.

Natural Mass Width of the ω meson $\sim$ measurement error
Natural Mass Width of the π^0 meson $\sim$ 8 eV $\rightarrow$ Negligible

Fit Hypothesis

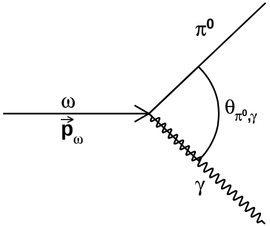
$\gamma p \rightarrow p\omega$: $\gamma p \rightarrow p_{missing}\pi^0\gamma$
$\gamma p \rightarrow p\pi^0\omega$: $\gamma p \rightarrow p_{missing}\pi^0\pi^0\gamma$

Kinematic Fitting Results

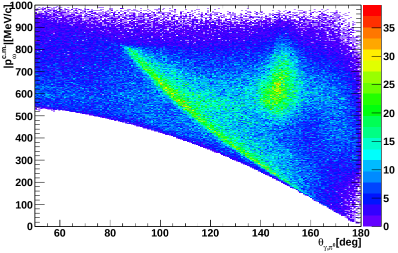


Kept all events with $CL > 0.005$

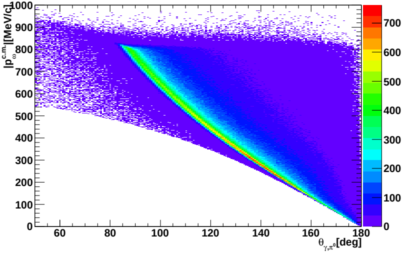
$\gamma p \to p\omega$ Opening Angle Cut



Experimental Data

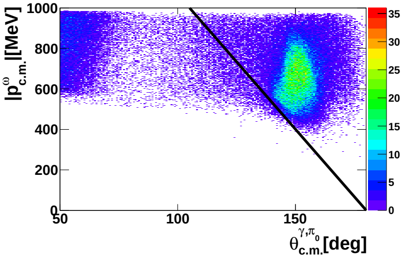


Monte Carlo Simulated

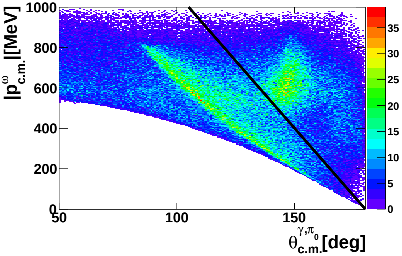


$\gamma p \rightarrow p\omega$ Opening Angle Cut

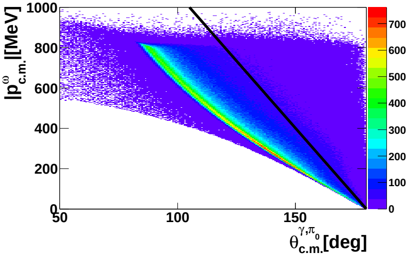
$p\pi^0$ Monte Carlo Simulated



Experimental Data



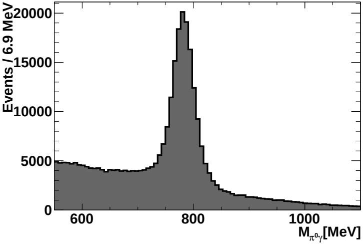
Monte Carlo Simulated

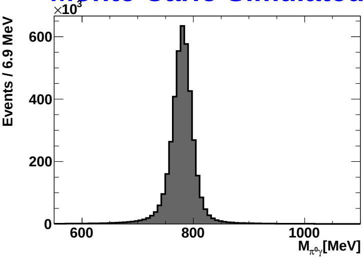


FINALLY!... Invariant Mass Distributions

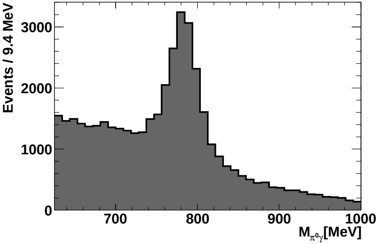
Experimental Data | **Monte Carlo Simulated**

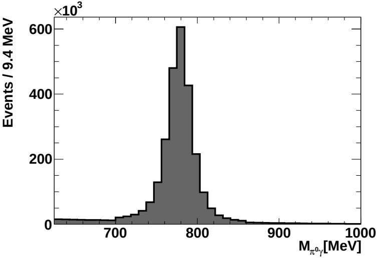
$\gamma p \to p\omega$





$\gamma p \to p\pi^0\omega$



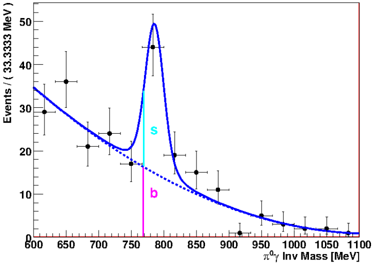


Two entries per event in $\gamma p \to p\pi^0\omega$ plots.

Q-factor Background Subtraction

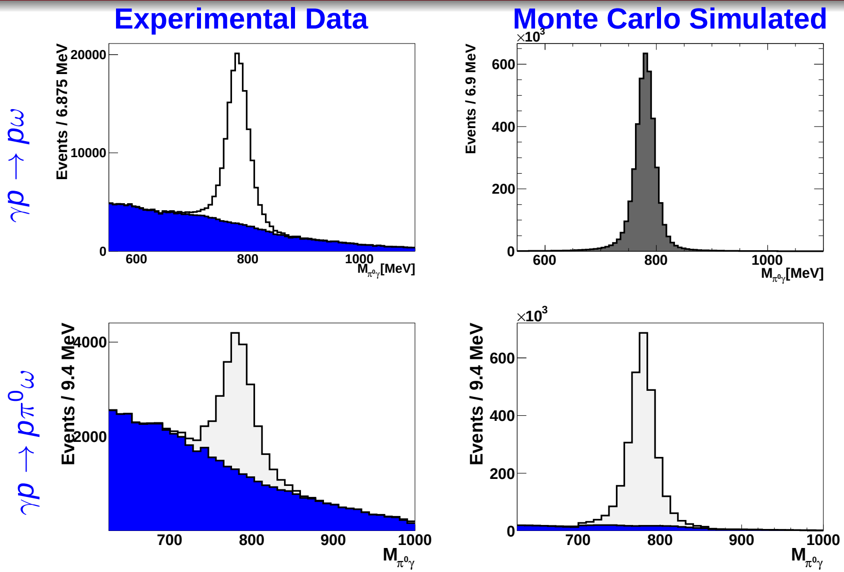
For each event left in the analysis.

- Find the nearest neighbors in the final state's kinematic phase space.
- Fit the invariant mass spectrum of a particle in the desired final state. (background & signal functions)
- Define a Q-factor from the fit. (Probability the event is the desired final state)
- Weight each event with the Q-factor.



$$Q = \frac{s}{s+b}$$

Background Subtracted



Two entries per event in $\gamma p \to p\pi^0\omega$ plots.

Differential Cross Section Methodology

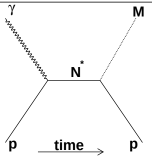
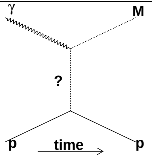
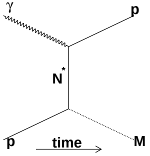
$$\frac{d\sigma}{dX_i} = \frac{N_{data}}{\mathcal{A}\ \mathcal{F}\ \rho_t^A\ B_r\ \Delta X_i}$$

N_{data}	# of observed events (timing background subtracted)
$\mathcal{A}$	detector acceptance
$\mathcal{F}$	Photon Flux
ρ_t^A	Target Area Density
B_r	Branching Ratio
X_i	Kinematic Variable
ΔX_i	Kinematic Bin Width

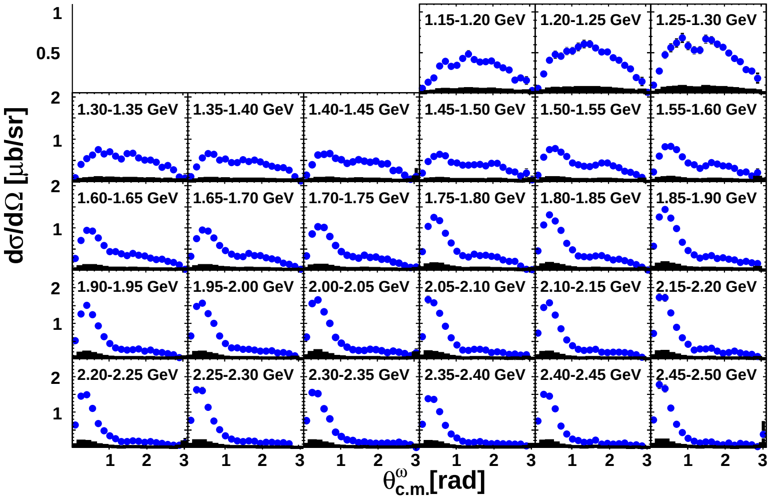
Differential Cross Section Uncertianties

- Statistical Uncertainties - Measurement Precision
- Systematic Uncertianties - Measurement Accuracy
  - Possible Target Shift
  - Acceptance Correction ($\gamma p \to p\pi^0\omega$ Only)
  - Q-factor Fit Uncertainties
  - Confidence Level Systematic Uncertianty
  - Monte Carlo Simulation Uncertianty
  - Background Contributions from other reactions

Differential Cross Section Interpretation

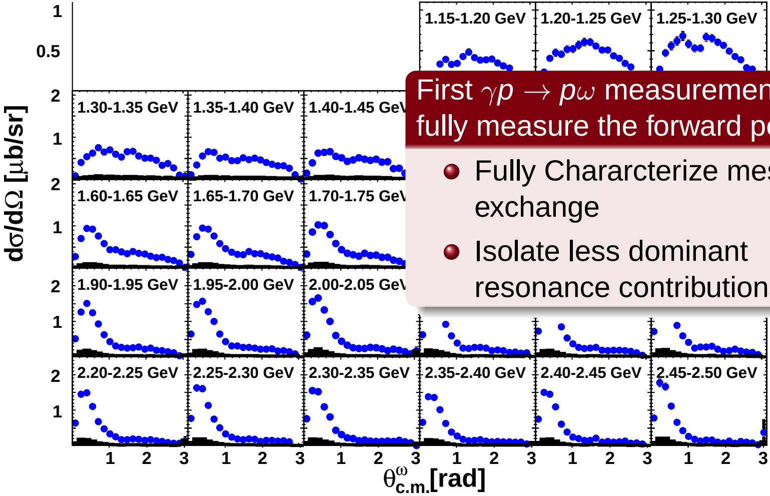
Name	Process	Meson Angular Distribution
Resonance Production		symmetric
Meson Exchange		forward angle peaked
Baryon Exchange		backward angle peaked

$\gamma p \to p\omega$ Differential Cross Sections



Labeled with incoming photon energy.

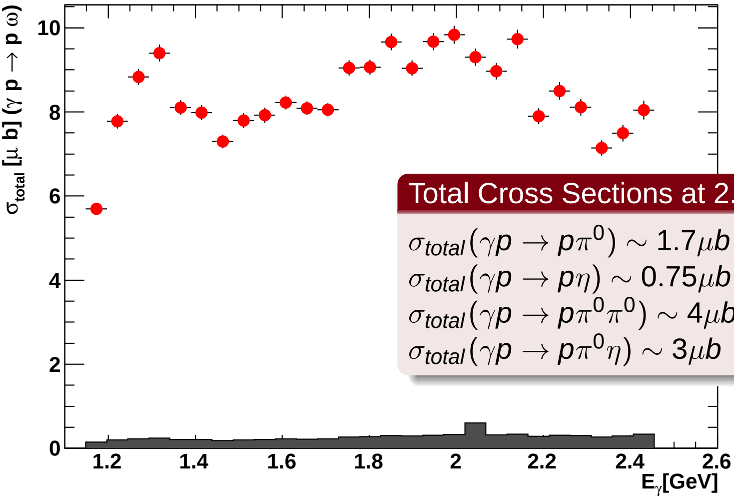
$\gamma p \to p\omega$ Differential Cross Sections



First $\gamma p \to p\omega$ measurement to fully measure the forward peak.

- Fully Chararcterize meson exchange
- Isolate less dominant resonance contributions

$\gamma p \to p\omega$ Total Cross Section



Total Cross Sections at 2.5 GeV

$\sigma_{total}(\gamma p \to p\pi^0) \sim 1.7\mu b$

$\sigma_{total}(\gamma p \to p\eta) \sim 0.75\mu b$

$\sigma_{total}(\gamma p \to p\pi^0\pi^0) \sim 4\mu b$

$\sigma_{total}(\gamma p \to p\pi^0\eta) \sim 3\mu b$

Unpolarized $\gamma p \to p\omega$ Spin Density Matrix Elements

Information in the spin of the ω meson can be extracted by analyzing the decay angular distribution.

$$\rho_{ij} \sim M_i M_j^*$$

i and j is the spin polarization of the ω $(-1,0,1)$

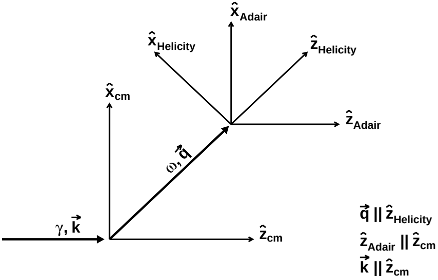
Unpolarized Spin-density Matrix Element Fitting

$$W^0(\theta_d,\phi_d,\rho^0) = \frac{3}{8\pi}\left(\sin^2\theta_d\,\rho^0_{00} + \left(1+\cos^2\theta_d\right)\rho^0_{11} + \sin^2\theta_d\cos 2\phi_d\,\rho^0_{1-1} + \sqrt{2}\sin 2\theta_d\cos\phi_d\,Re\,\rho^0_{10}\right)$$

θ_d and ϕ_d angles of the γ in $\omega \to \pi^0\gamma$ in ω rest frame.
Binning used : 6 $\cos\theta_d$ bins and 8 ϕ_d bins

Spin Density Matrix Element Reference Systems

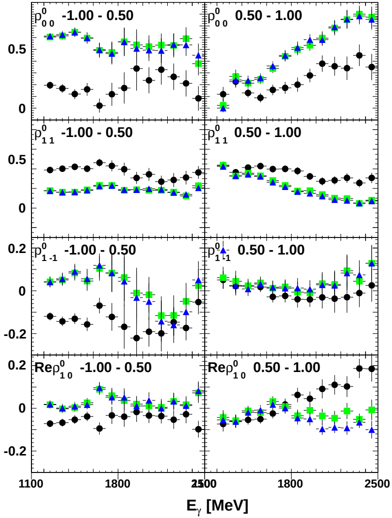
- Helicity system - z-axis $||$ $\vec{q}_{\omega}^{\,c.m.}$
- Adair system - z-axis $||$ $\vec{k}_{c.m.}$
- Gottfreid-Jackson system - z-axis $||$ $\vec{k}_{\omega\ frame}$.



y-axis is defined to be $\hat{k} \times \hat{q}$

Extracted SDMEs in all three systems.

Unpolarized $\gamma p \to p\omega$ Spin Density Matrix Elements

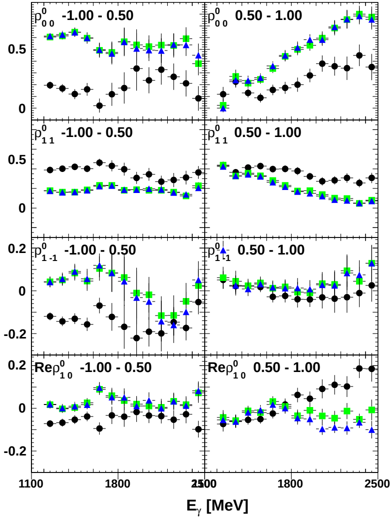


Labeled with SDME and $\cos\theta^{\omega}_{c.m.}$

- Same Data used in differential cross sections
- Q-factors used to fill angular distributions
- Angular distributions were acceptance corrected
- Monte Carlo simulation uncertianty, Q-factor fit errors, and statistical errors propagated
- Extracted using a χ^2 minimization fit

● Helicity System ■ Gottfried-Jackson system ▲ Adair system

Unpolarized $\gamma p \rightarrow p\omega$ Spin Density Matrix Elements



Labeled with SDME and $\cos\theta^{\omega}_{c.m.}$

First $\gamma p \rightarrow p\omega$ Unpolarized SDMEs measured over the full kinematic range

● Helicity System ■ Gottfried-Jackson system ▲ Adair system

Polarized $\gamma p \to p\omega$ Spin Density Matrix Elements

transversely polarized beam photons

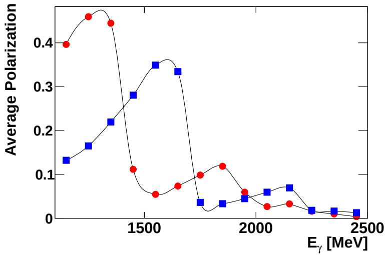
Polarized Spin-density Matrix Element Fitting

$$
\begin{aligned}
W^L(\cos\theta_d, \phi_d, \Phi_{pol}, \rho) \quad = \quad & \frac{3}{8\pi}(\sin^2\theta_d \rho^0_{00} + \left(1+\cos^2\theta_d\right)\rho^0_{11}) \\
& -\frac{3}{8\pi}P_\gamma \cos 2\Phi_{pol}(\sin^2\theta_d \rho^1_{00} \\
& + \left(1+\cos^2\theta_d\right)\rho^1_{11})
\end{aligned}
$$

θ_d and ϕ_d angles of the γ in $\omega \to \pi^0\gamma$ in ω rest frame.
Φ_{pol} is the angle between the production plane ($\omega + p_{final}$) and the polarization direction.

Polarized $\gamma p \to p\omega$ Data

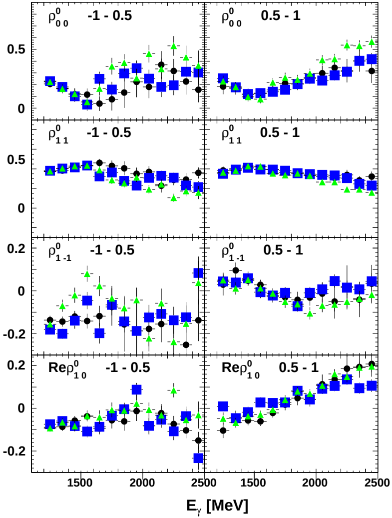
- March 2003 (1350 MeV Coherent Edge) (●)
- May 2003(1600 MeV Coherent Edge) (■)



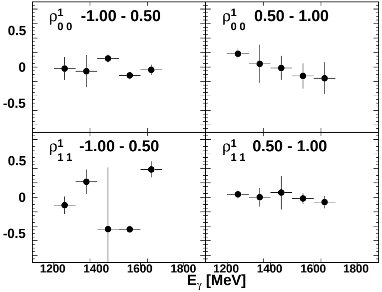
Nearly the same reconstruction and reaction selection.
No TAPS trigger cut due to a slightly different trigger.

Polarized $\gamma p \to p\omega$ Spin Density Matrix Elements

Extracted by ignoring Φ_{pol}



Integrated over ϕ_d before fitting.



First Measurement

Helicity system

Labeled with SDME and $\cos\theta^{\omega}_{c.m.}$

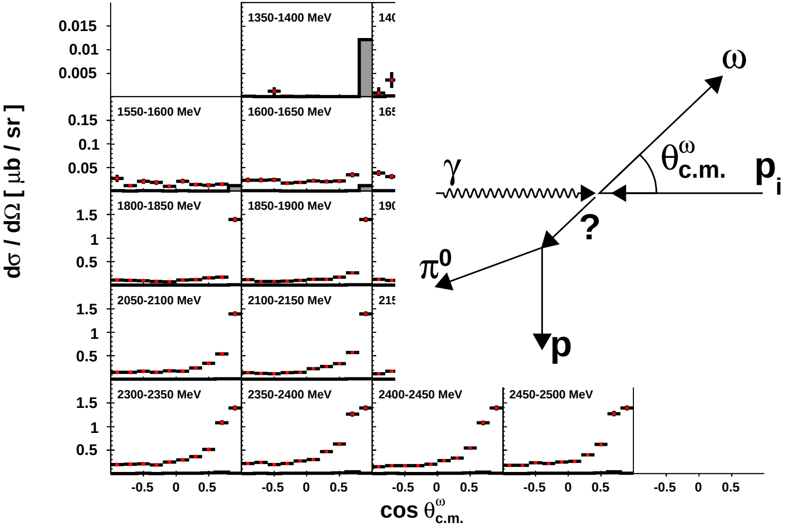
- unpolarized data ■ March 2003 data ▲ May 2003 data

$\gamma p \rightarrow p\pi^0\omega$ Differential Cross Sections Overveiw

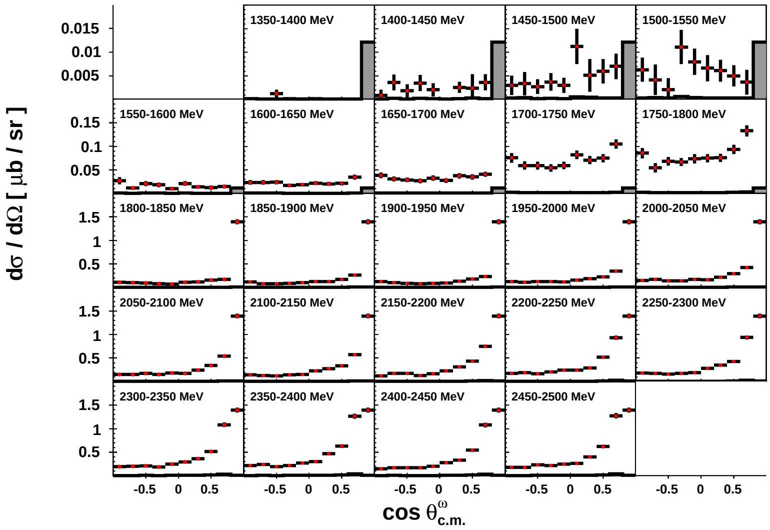
- 5 Independent Kinematic Variables
- 3 different Kinematic Variable binning
- 12,500 Differential Cross Section data points per binning

Binning Name	a	b_1	b_2
ω_{cms}	ω	π^0	p
π^0_{cms}	π^0	p	ω
p_{cms}	p	ω	π^0

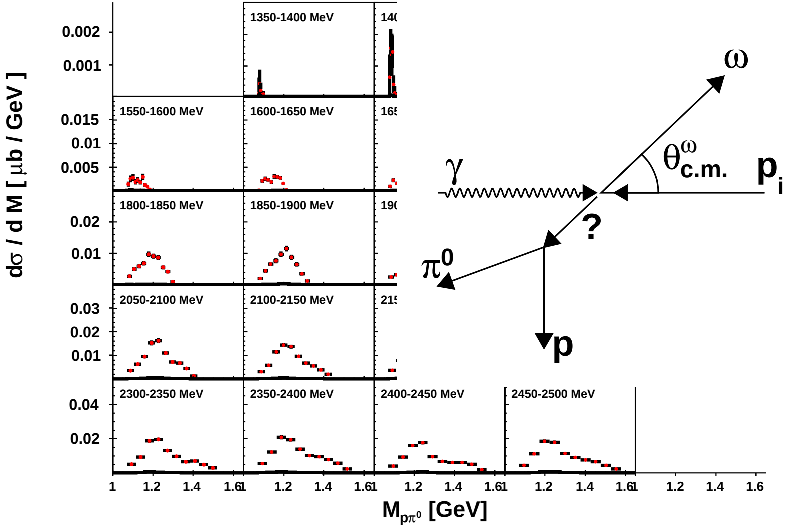
$\gamma p \to p\pi^0\omega$ ω_{cms} Differential Cross Section



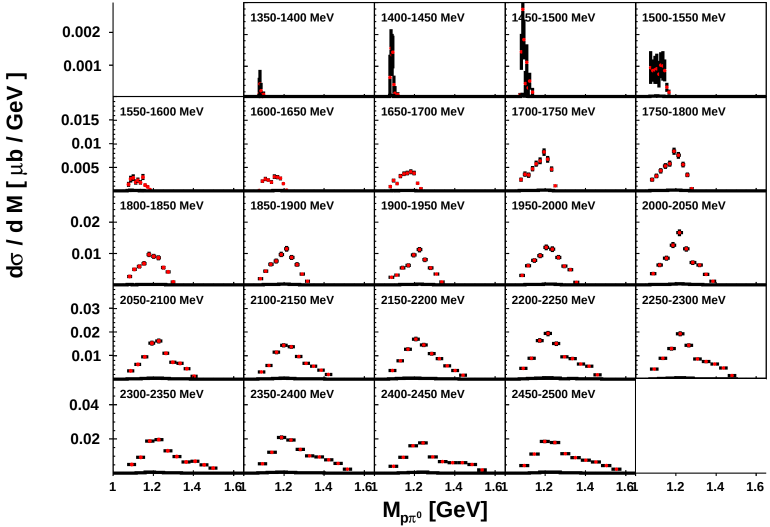
$\gamma p \rightarrow p\pi^0\omega$ ω_{cms} Differential Cross Section



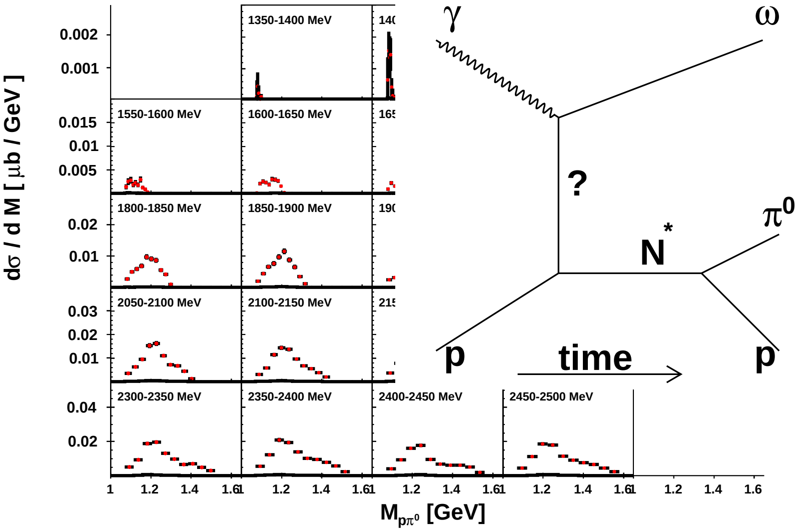
$\gamma p \rightarrow p\pi^0\omega$ ω_{cms} Differential Cross Section



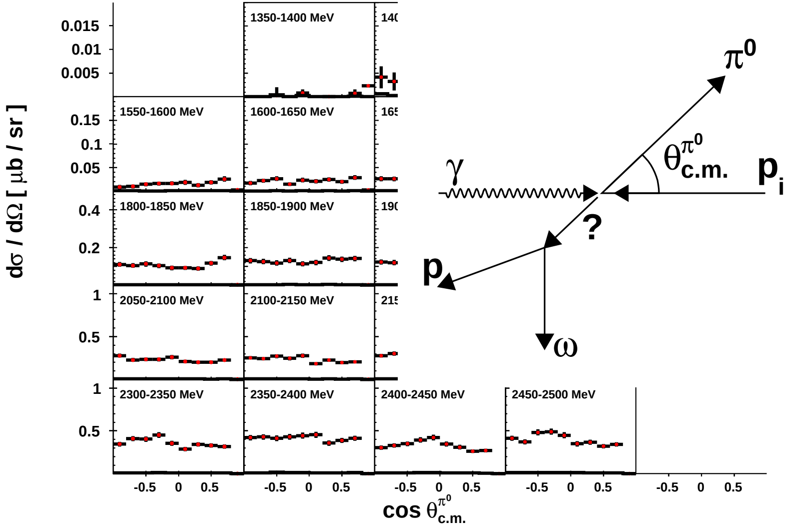
$\gamma p \to p\pi^0\omega$ ω_{cms} Differential Cross Section



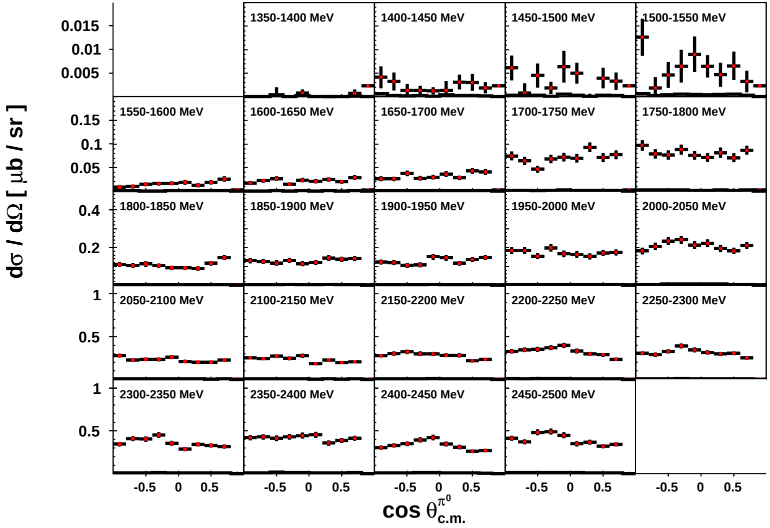
$\gamma p \rightarrow p\pi^0\omega$ ω_{cms} Differential Cross Section



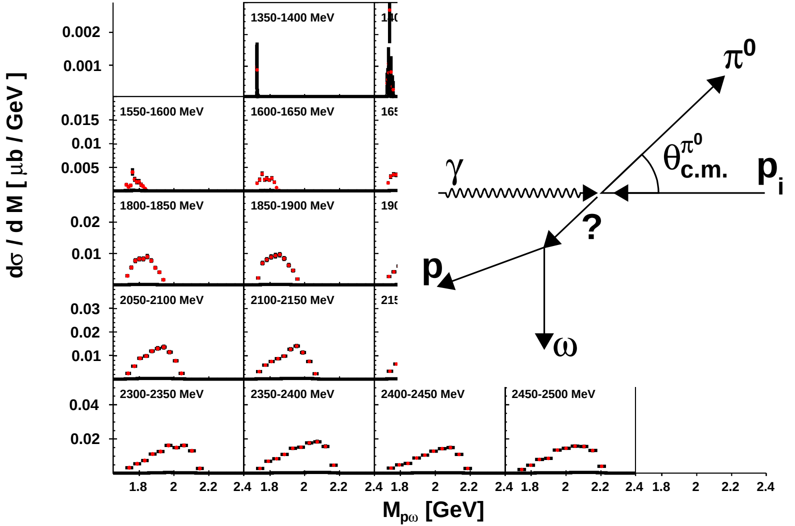
$\gamma p \rightarrow p\pi^0\omega\ \pi^0_{cms}$ Differential Cross Section



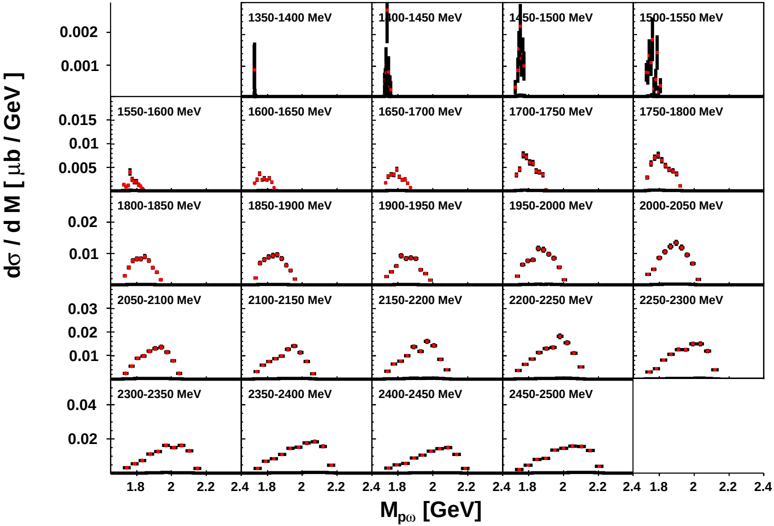
$\gamma p \rightarrow p\pi^0\omega$ π^0_{cms} Differential Cross Section



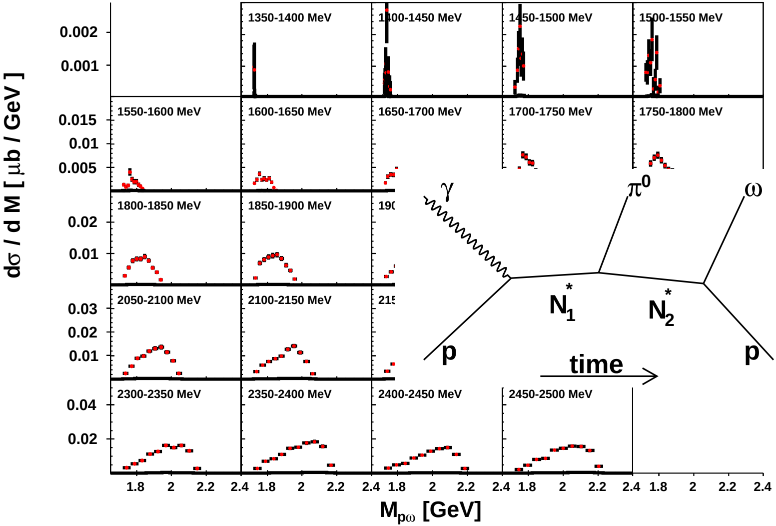
$\gamma p \to p\pi^0\omega$ π^0_{cms} Differential Cross Section



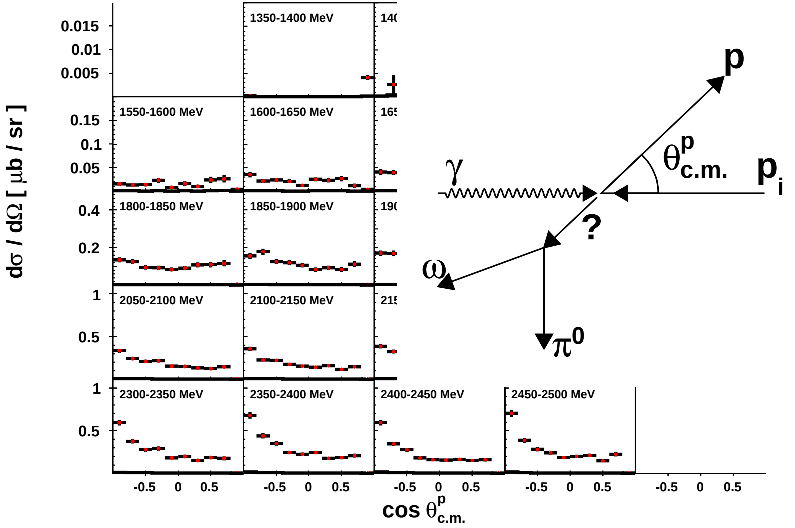
$\gamma p \to p\pi^0\omega\ \pi^0_{cms}$ Differential Cross Section



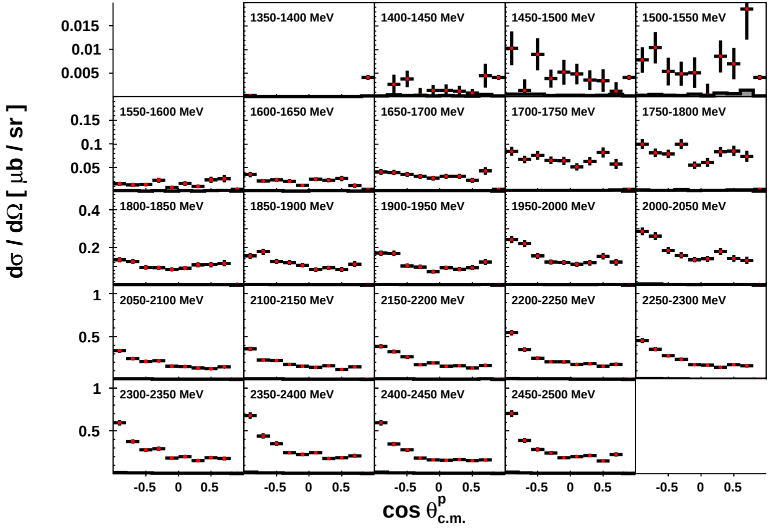
$\gamma p \to p\pi^0\omega$ π^0_{cms} Differential Cross Section



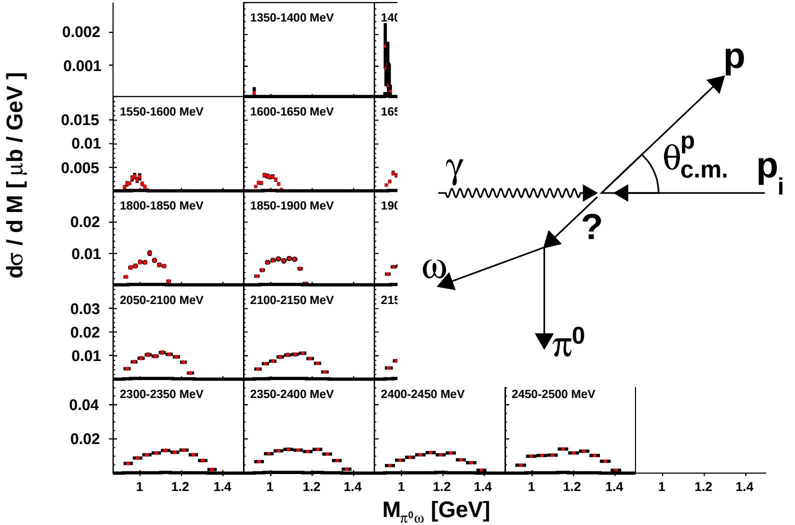
$\gamma p \to p\pi^0\omega$ p_{cms} Differential Cross Section



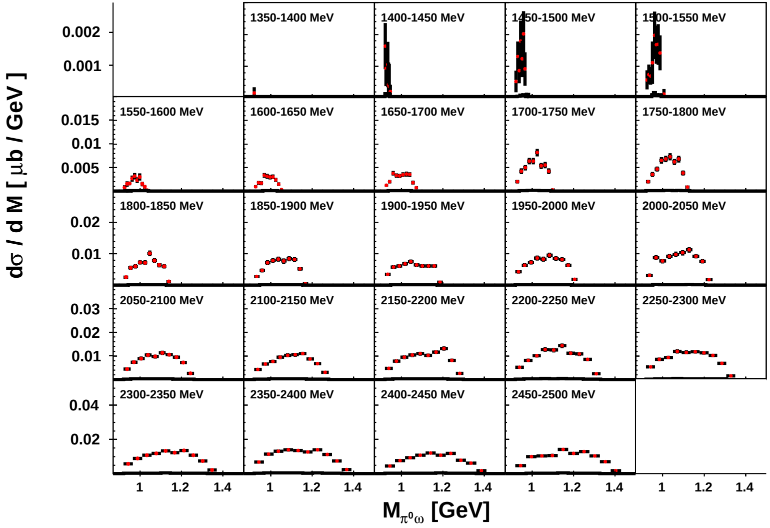
$\gamma p \to p\pi^0\omega$ p_{cms} Differential Cross Section



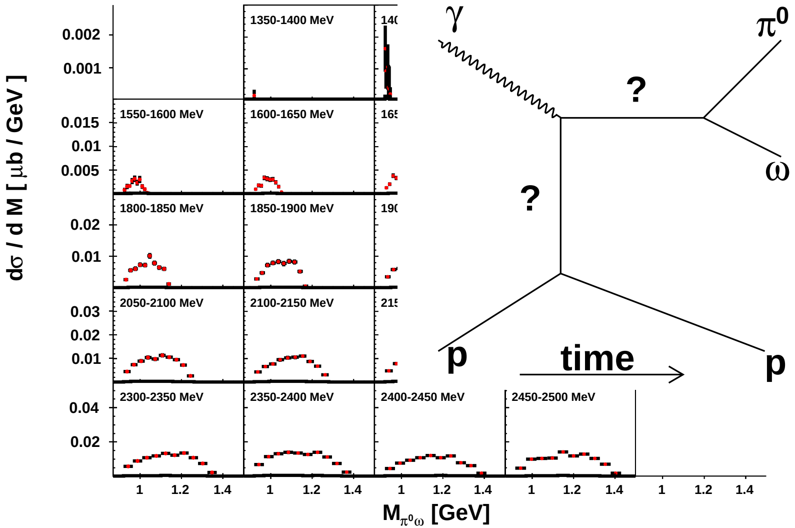
$\gamma p \to p\pi^0\omega$ p_{cms} Differential Cross Section



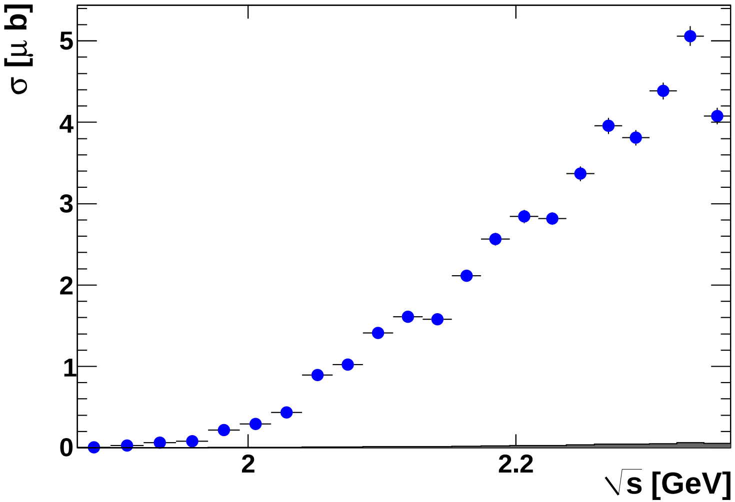
$\gamma p \rightarrow p\pi^0\omega$ p_{cms} Differential Cross Section



$\gamma p \rightarrow p\pi^0\omega$ p_{cms} Differential Cross Section



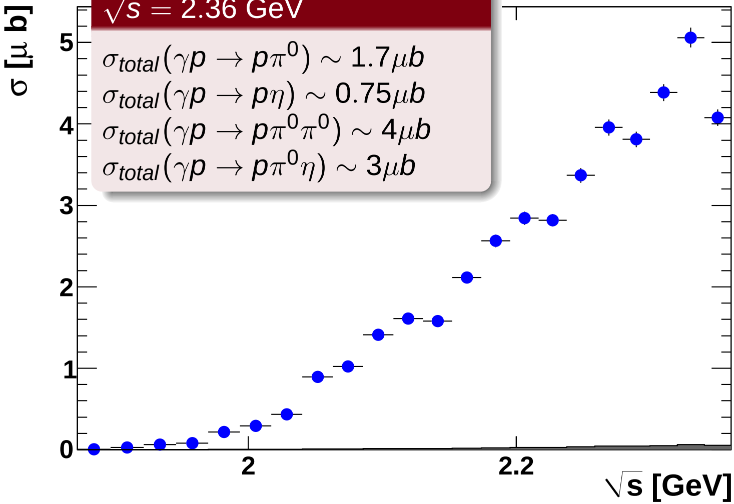
$\gamma p \to p\pi^0\omega$ Total Cross Section



$\gamma p \to p\pi^0\omega$ Total Cross Section

Total Cross Sections at $\sqrt{s} = 2.36$ GeV

$\sigma_{total}(\gamma p \to p\pi^0) \sim 1.7\mu b$
$\sigma_{total}(\gamma p \to p\eta) \sim 0.75\mu b$
$\sigma_{total}(\gamma p \to p\pi^0\pi^0) \sim 4\mu b$
$\sigma_{total}(\gamma p \to p\pi^0\eta) \sim 3\mu b$



Summary and Future Work

First Time Measurements

- $\gamma p \to p\omega$ and $\gamma p \to p\pi^0\omega$ differential cross sections, $\gamma p \to p\omega$ Spin-density Matrix Elements
  - have been measured over the full reaction kinematics
  - characteristics usable for isolating "missing" baryon resonances.
- $\gamma p \to p\omega$ polarized spin-density matrix elements
- $b_1(1235)$ meson photoproduction measurements at these energies

Future Work

- $\gamma p \to p\omega$ and $\gamma p \to p\pi^0\omega$ interpretation analysis
- $\gamma p \to p\pi^0\omega$ spin-density matrix elements

Acknowledgements

Thank You!

- Committee Members
- Volker Crede
- My Wife
- My Parents