First Measurements of the Polarized Spin Density Matrix Elements along with a Partial Wave Analysis for $\gamma p \rightarrow p\omega$ using CLAS at Jefferson Lab

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Thesis Defense

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Outline

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Quantum Chromodynamics

- What is happening inside of a nucleon?
- Nucleons are made of quarks and gluons
- QCD is the theory of how quarks and gluons interact
- The *charge* term for QCD is called color charge and comes in three forms: red, green, and blue
- Quarks and gluons carry color charge, as well as electromagnetic charge
- How can we study what is happening inside of a nucleon?

Baryon Spectroscopy

- Photons can be used to probe nucleons
- A photon strikes a nucleon, which absorbs the photon and enters an excited state briefly before returning to the ground state
- It returns to the ground state by emitting baryons and mesons
- The spectrum of excited nucleon states, or resonances, is discrete
- Excited states are characterized by
  - Total Angular Momentum, J
  - Parity, P
  - Mass
  - Width/Lifetime

Resonances

- The PDG currently lists 15 resonances whose presence is likely
- There are an additional 11 states that have been detected, but not confirmed
- Theory predicts more than twice as many states: *missing baryon problem*
- Simplify by looking at a single decay product
- We will attempt to probe the resonances by looking at one particular decay product, the ω meson

The ω Meson

- Spin-1, or vector, meson
- Rest mass = 782.59±0.11 MeV
- Width = 8.49 MeV → Lifetime = 7.75x10^{-23}s
- Charge = 0
- Isospin = 0
  - Can only couple to N^* states, not Δ^*s
- Branching Ratios:
  - $\pi^+\pi^-\pi^0 \rightarrow$ 89.1%
  - $\pi^0\gamma \rightarrow$ 8.92%
  - $\pi^+\pi^- \rightarrow$ 1.70%
  - All others → 0.28%
- We will be looking at the $\pi^+\pi^-\pi^0$ decay channel

Methodology

- To perform a complete analysis of ω photoproduction, the elements of its spin density matrix (SDM) must be measured
- The method used to extract the SDM elements (SDMEs) is to run a unbinned expanded maximum likelihood fits of the four vectors using partial wave amplitudes
- Use the parameters from that fit to calculate the SDMEs
- The formalism has been developed over the last few years to deal with polarized photons
- Determine which resonances are important for ω production using partial wave analysis
- Knowledge of the SDM will help constrain the partial wave analysis
- Adding in photon polarization increases analyzing power for PWA

Outline

Jefferson Lab

- The data for this analysis was taken at Jefferson Lab in Newport News, VA, using the CEBAF Large Acceptance Spectrometer (CLAS)
- Jefferson Lab utilized a continuous electron beam, with energies up to 6 GeV, that is converted to a photon beam via bremsstrahlung reactions for the experiments analyzed here
- The photon beam can have linear or circular polarization or be unpolarized
- The experiments analyzed, g1c and g8b, used an unpolarized liquid hydrogen target with a circularly/linearly polarized photon beam

The g1c Dataset

- Collected in October and November of 1999
- 4.5 billion triggers
- Unpolarized target
- Three different beam energies:
  - 3.115 GeV - No polarization values recorded (not analyzed)
  - 2.897 GeV - Incomplete normalization values
  - 2.445 GeV
- Circularly polarized photons
- Degree of circular polarization determined from Maximon and Olson relation

$$\zeta_c = \frac{k(\epsilon_{beam} + \frac{1}{3}\epsilon_{recoil})\zeta_{beam}}{\epsilon_{beam}^2 + \epsilon_{recoil}^2 - \frac{2}{3}\epsilon_{beam}\epsilon_{recoil}}$$

The g8b Dataset

- Collected in July and August of 2005
- 10.5 billion triggers
- Unpolarized target
- Linearly polarized photons (coherent bremsstrahlung)
- Five different coherent edge settings from 1.3 GeV - 2.1 GeV
- Polarization in PARA and PERP directions
- Degree of linear polarization determined from tables based on photon energy and the instantaneous coherent edge

Event Selection

- Require detection of p, π^+, and π^-
- Apply ELoss, tagger and momentum corrections
- Require events meet the requirements:
  - $|\vec{p_p}| \geq 350$ MeV
  - $0 \leq$ missing mass ≤ 450 MeV
  - Missing mass off proton within 25 MeV of ω mass, 782 MeV
  - Confidence Level from 1C kinematic fit to $\gamma p \rightarrow p\pi^+\pi^-(\pi^0) \geq 10\%$
  - Pass PID, fiducial volume, and TOF paddle cuts
  - $\cos\theta^{\pi^0}_{CM} > 0.99$
- Event-based Q-values to weight signal and background events
- g1c: 650,000 ω events in $1720 \leq \sqrt{s} \leq 2470$ MeV
- g8b: 2,900,000 ω events in $1720 \leq \sqrt{s} \leq 2210$ MeV

Outline

Spin Density Matrix

- The spin density matrix of a vector meson photoproduced from an unpolarized target can be thought of as the sum of four 3x3 Hermitian matrices
  - ρ^0 - Any photon polarization
  - ρ^{1-2} - Linear photon polarization
  - ρ^3 - Circular photon polarization
- Each of these matrices contains 9 complex values, but the properties of being a Hermitian matrix and parity reduce that number to 5 real values for each matrix
- All 5 values cannot be measured for each matrix
- The next slide shows each matrix, the measurable elements are underlined

Spin Density Matrix

$$\rho^0 = \begin{pmatrix} \underline{\frac{1}{2}(1-\rho^0_{00})} & \underline{Re\{\rho^0_{10}\}} + i * Im\{\rho^0_{10}\} & \underline{Re\{\rho^0_{1-1}\}} \\ . & \underline{\rho^0_{00}} & \underline{-Re\{\rho^0_{10}\}} + i * Im\{\rho^0_{10}\} \\ . & . & \underline{\frac{1}{2}(1-\rho^0_{00})} \end{pmatrix}$$

$$\rho^1 = \begin{pmatrix} \underline{\rho^1_{11}} & \underline{Re\{\rho^1_{10}\}} + i * Im\{\rho^1_{10}\} & \underline{Re\{\rho^1_{1-1}\}} \\ . & \underline{\rho^1_{00}} & \underline{-Re\{\rho^1_{10}\}} + i * Im\{\rho^1_{10}\} \\ . & . & \underline{\rho^1_{11}} \end{pmatrix}$$

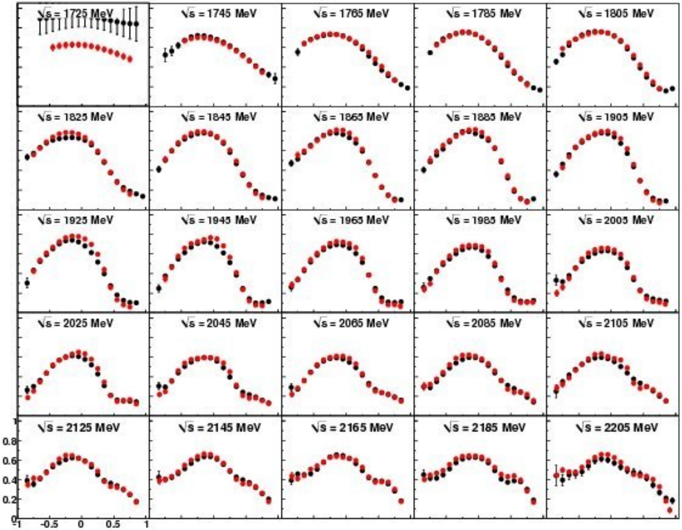
$$\rho^2 = \begin{pmatrix} \rho^2_{11} & Re\{\rho^2_{10}\} + i * \underline{Im\{\rho^2_{10}\}} & i * \underline{Im\{\rho^2_{1-1}\}} \\ . & 0 & Re\{\rho^2_{10}\} - i * \underline{Im\{\rho^2_{10}\}} \\ . & . & -\rho^2_{11} \end{pmatrix}$$

$$\rho^3 = \begin{pmatrix} \rho^3_{11} & Re\{\rho^3_{10}\} + i * \underline{Im\{\rho^3_{10}\}} & i * \underline{Im\{\rho^3_{1-1}\}} \\ . & 0 & Re\{\rho^3_{10}\} - i * \underline{Im\{\rho^3_{10}\}} \\ . & . & -\rho^3_{11} \end{pmatrix}$$

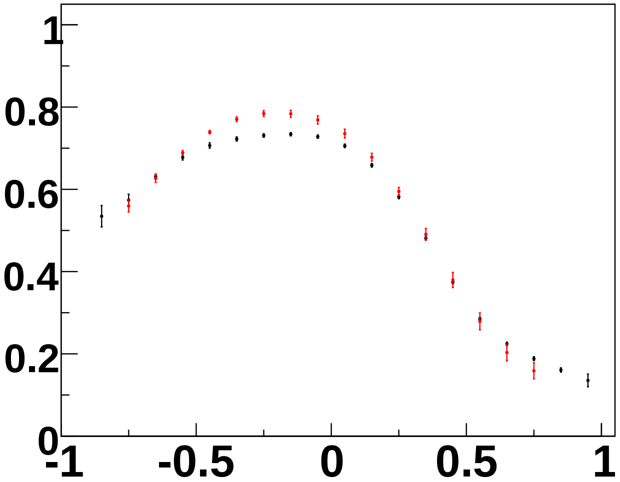
Results

- Results presented come from *mother* fit
  - Amplitudes from J=1/2 up to J=11/2, both parities
- Previous experiment, g11a
- The three ρ^0 elements from g8b are presented compared to the results from g11a
- Then the ρ^1 and ρ^2 elements from g8b and the ρ^3 elements from g1c will be presented
- Errors are calculated using the bootstrap method
- The g8b data is in black, the g11a data is in red, and the g1c data is in blue when presented together

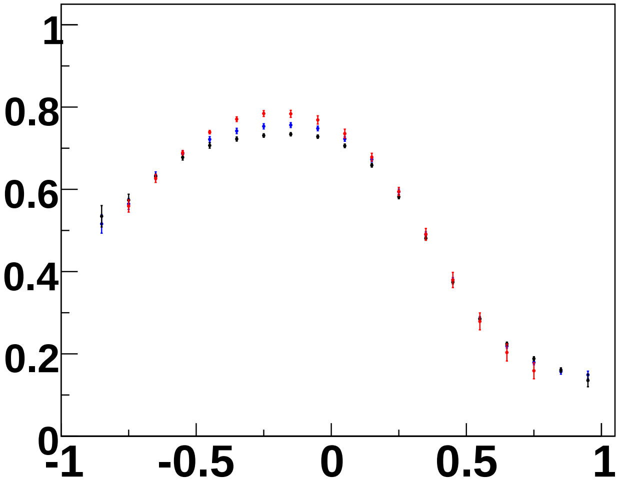
ρ^0_{00} IN G8B



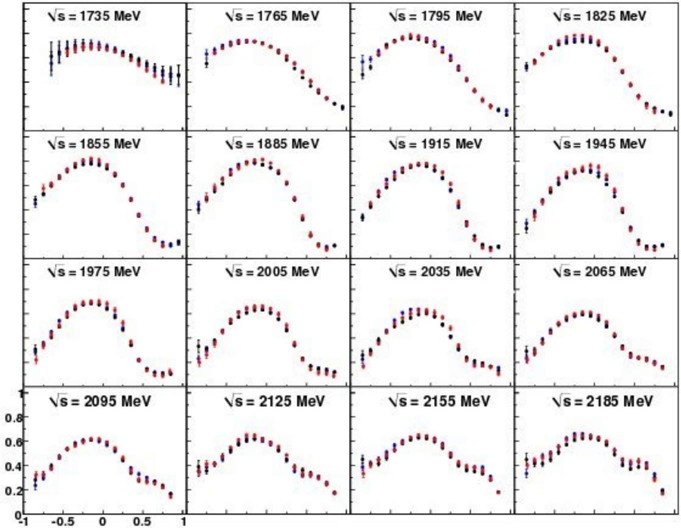
ρ^0_{00} in $\sqrt{s} = 1825$ MeV bin



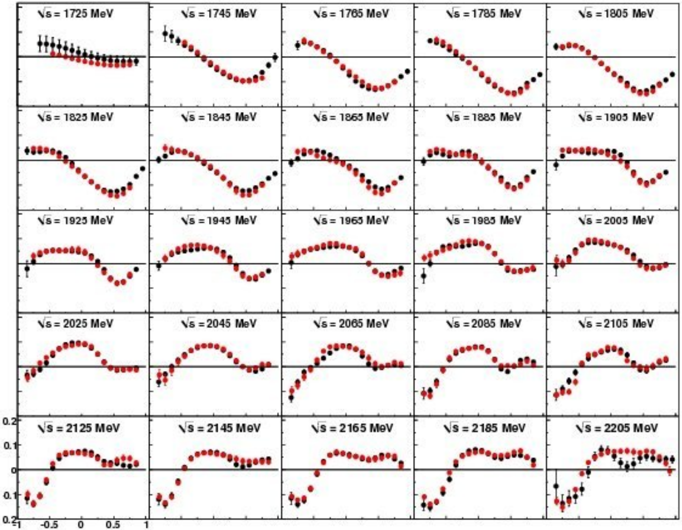
ρ^0_{00} from g8b (black), g1c (blue), g11a (red)



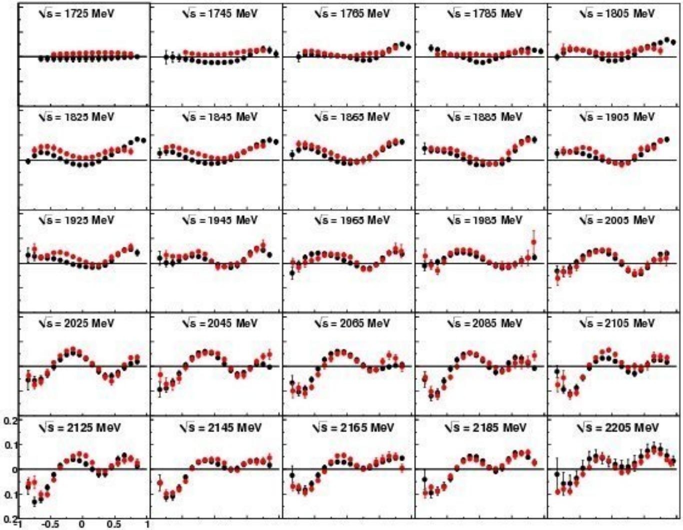
ρ^0_{00} from g8b (black), g1c (blue), g11a (red)



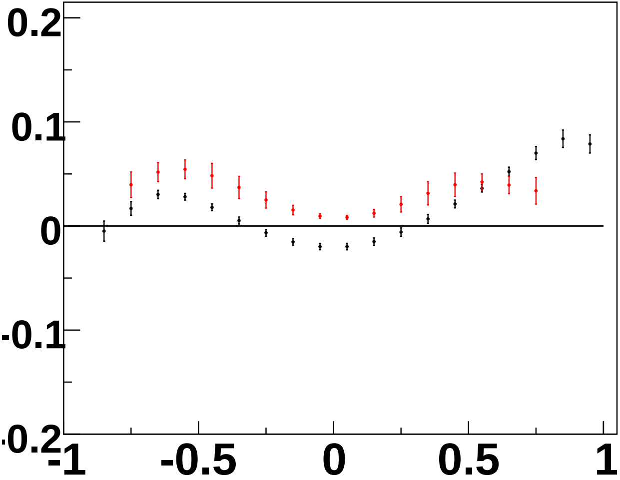
$\mathrm{Re}(\rho^0_{10})$ in g8b



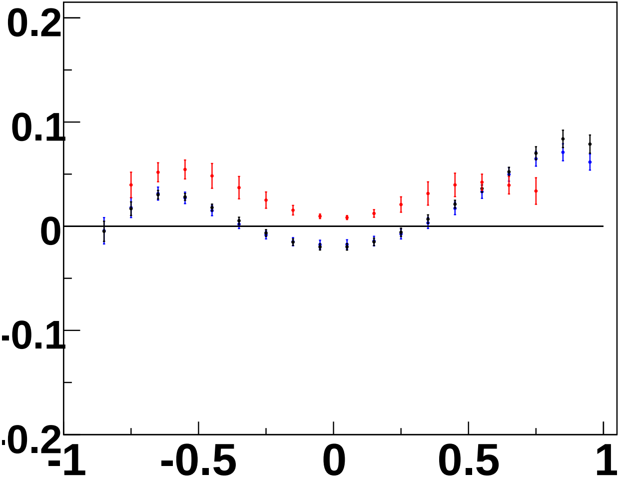
ρ^0_{1-1} IN G8B



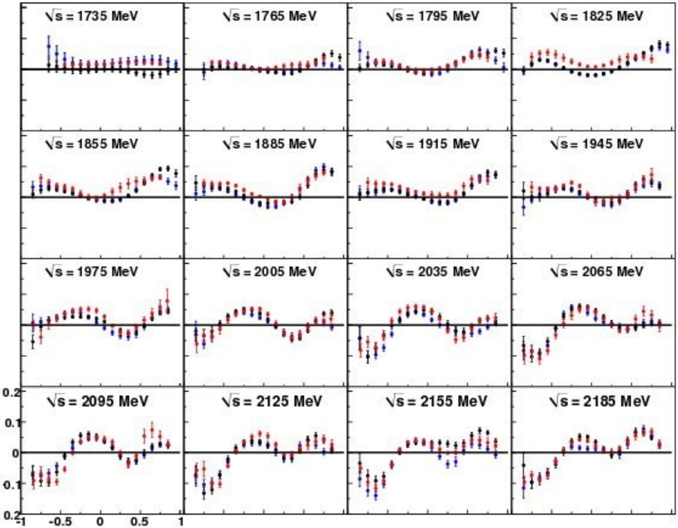
ρ^0_{1-1} in $\sqrt{s} = 1825$ MeV bin



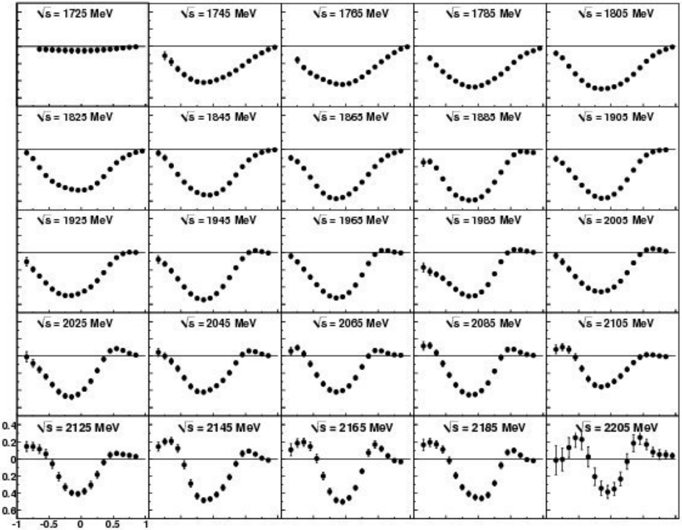
ρ^0_{1-1} FROM G8B (BLACK), G1C (BLUE), G11A (RED)



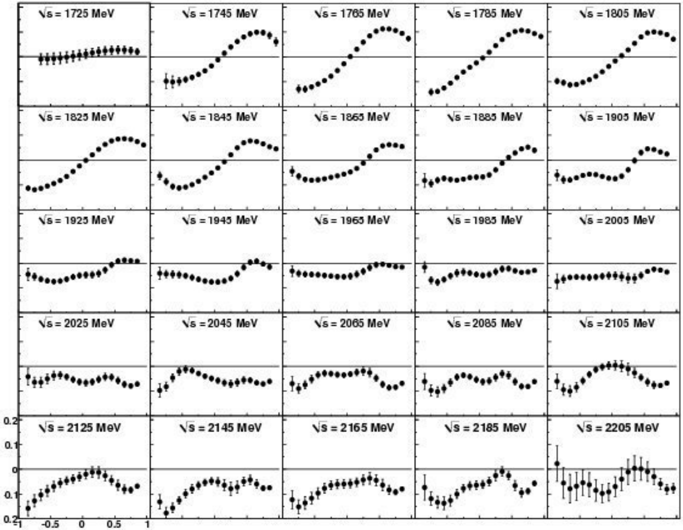
ρ^0_{1-1} from g8b (black), g1c (blue), g11a (red)



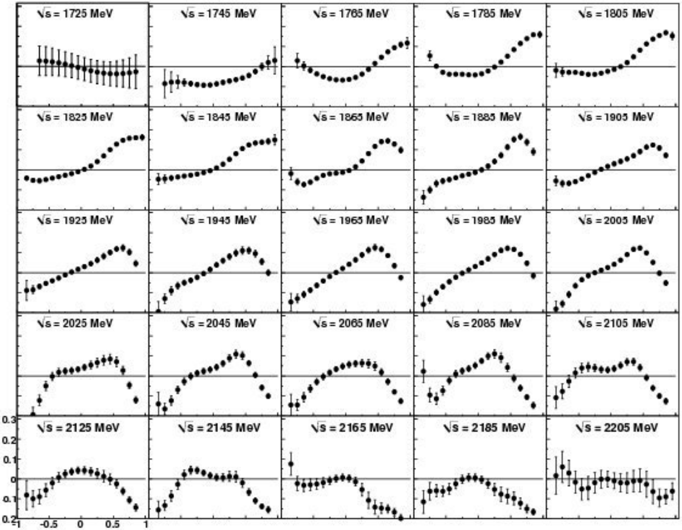
ρ^1_{00} IN G8B



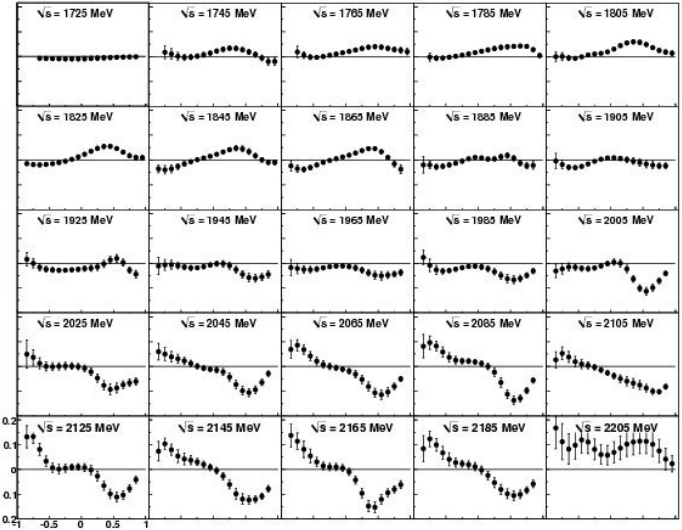
$\mathrm{Re}(\rho^1_{10})$ in g8b



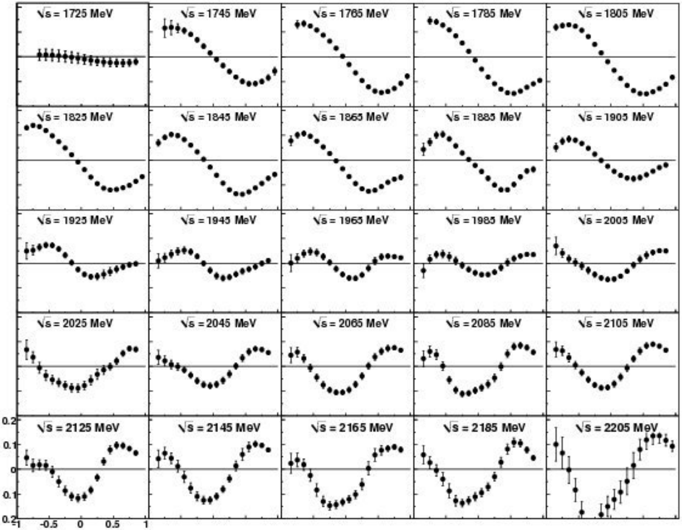
ρ^1_{1-1} IN G8B



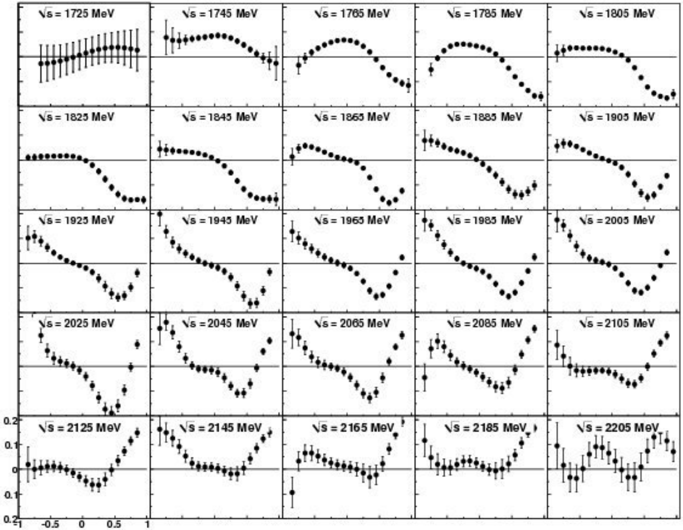
ρ^1_{11} IN G8B



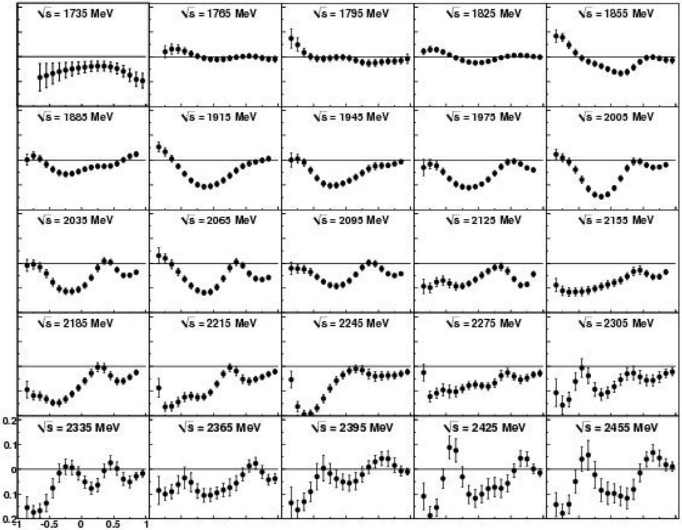
$\mathrm{Im}(\rho^2_{10})$ IN G8B



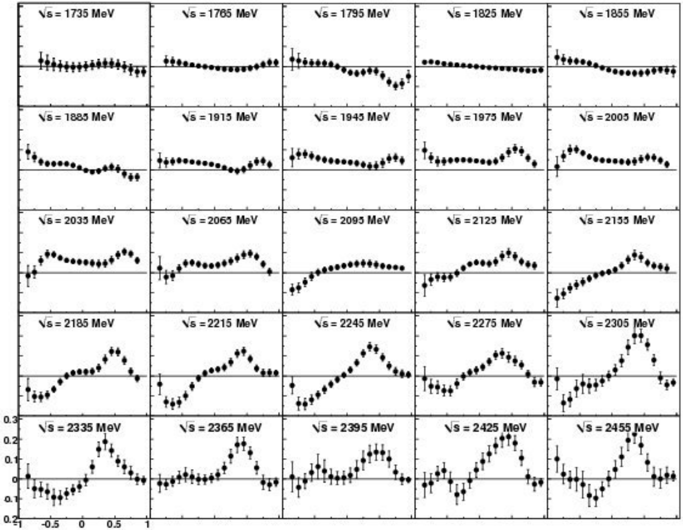
$\mathrm{Im}(\rho^2_{1-1})$ in g8b



$\mathrm{Im}(\rho^3_{10})$ in g1c



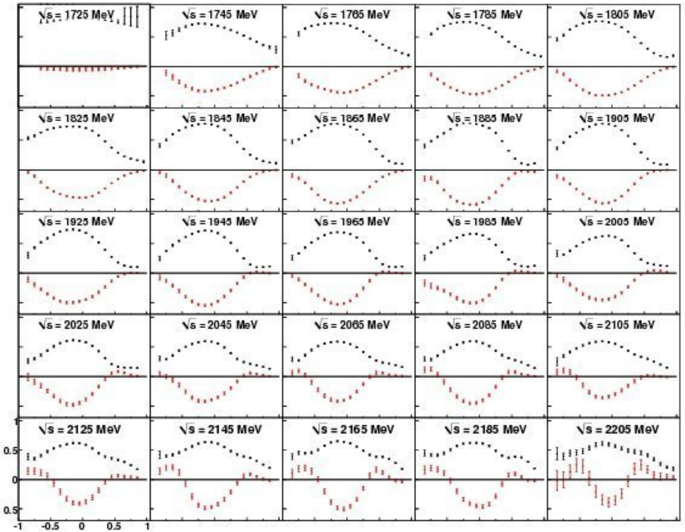
$\mathrm{Im}(\rho^3_{1-1})$ in g1c



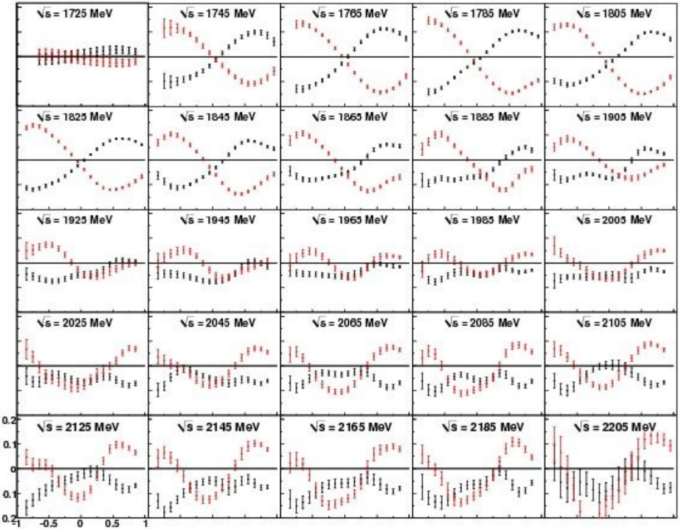
Symmetries

- There are a few symmetries that are present among the new SDMEs
- For almost the entire energy range under study the ρ^1_{00} element mirrors the ρ^0_{00} element
- Below 1825 MeV, $\mathrm{Re}(\rho^1_{10})$ and $\mathrm{Im}(\rho^2_{10})$ mirror each other's movements
- At almost all energies, ρ^1_{1-1} and $\mathrm{Im}(\rho^2_{1-1})$ elements are near exact mirrors

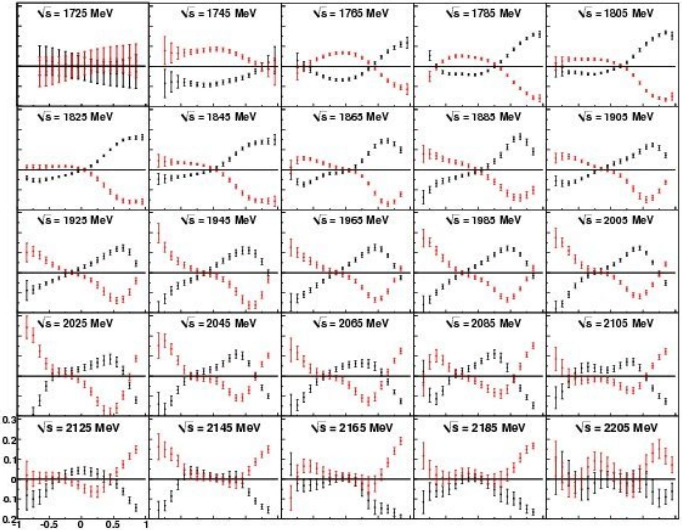
ρ^0_{00} (black) Compared to ρ^1_{00} (red)



$\mathrm{Re}(\rho^1_{10})$ (black) Compared to $\mathrm{Im}(\rho^2_{10})$ (red)



ρ^1_{1-1} (black) Compared to $\mathrm{Im}(\rho^2_{1-1})$ (red)

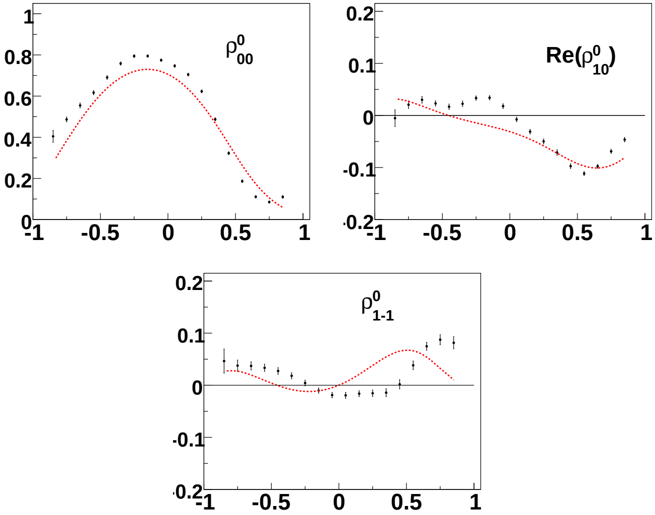


Outline

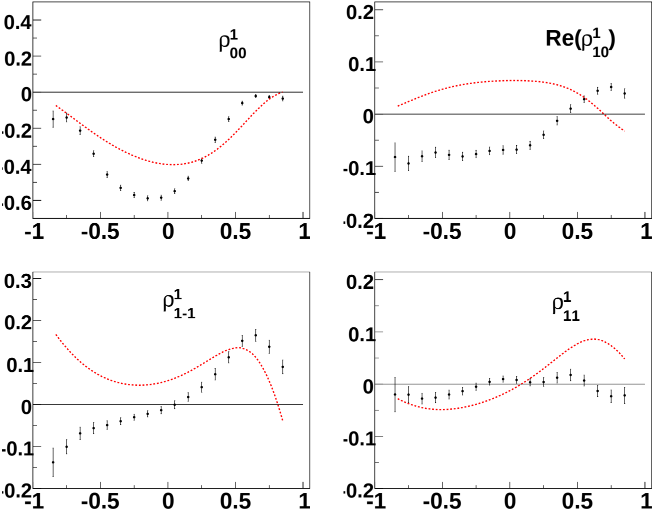
PWA in g8b

- Our PWA fits are computed with a limited number of s-wave amplitudes along with t-channel amplitudes constructed and parameters locked to the Oh, Titov and Lee model for non-resonant channels
- All combinations of two s-waves (up to J $= 11/2$) with the t-channel are run through the same fitter used for the mother fit
- Determine best fits by comparing final log likelihood values and comparing observables, SDMEs
- In g11a, the 3/2-, 5/2$+$ combination was the best fit from 1720-2000 MeV, and was able to reproduce many aspects of the ρ^0 elements
- The added SDMEs prove that more resonances are required

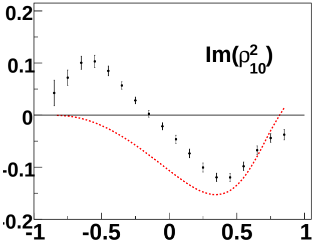
ρ^0 from g8b 3/2-, 5/2+ fit for $\sqrt{s} = 1885$ MeV



ρ^1 from g8b 3/2-, 5/2+ for $\sqrt{s}$ = 1885 MeV



ρ^2 from g8b 3/2-, 5/2+ for $\sqrt{s} = 1885$ MeV



Outline

Summary

- We have modified out fitting code to include photon polarization
- Measurements of the unpolarized SDMEs agree well with what was seen in g11a
- First measurements have been made of the ρ^{1-3} SDMEs for ω photoproduction over a wide range of angles and energies
- These additional elements have aided our search for the resonances important in ω production, making it clear that there is more going on than was seen in the unpolarized fits
- Adding in target polarization will increase the analyzing power even more

BACKUP SLIDES

- BACKUP SLIDES

Brief Density Matrix Reminder

- Density matricies represent particles that can be in multiple states
- If the density matrix for a particle is known then all QM observables can be calculated
- For a particle with n states, each having wave function $|\psi_i>$, the density matrix can be constructed as

$$\rho = \sum_{i,i'}^{n} a_{ii'} |\psi_{i'} >< \psi_i| \tag{2}$$

- Diagonal elements represent the probability that the particle is in state $|\psi_i>$
- Off-diagonal elements, $\rho_{ii'}$, represent the probability of a transition from state $|\psi_i>$ to state $|\psi_{i'}>$
- An unpolarized particle's density matrix is the identity matrix
- For this talk the density matrix will always be in the spin space

DETERMINING ρ_γ

- The density matrix for a photon can be contructed by knowing the photon has two spin states
- These are denoted as $|m_\gamma = + >$ and $|m_\gamma = - >$
- Now ρ_γ can be written as a linear combination of the identity matrix and the Pauli matrices dotted into the polarization vector

$$\rho_\gamma = \frac{1}{2}\mathcal{I} + \frac{1}{2}\vec{P}_\gamma\vec{\sigma} \tag{3}$$

$$\vec{P} = (-\eta_L \cos(2\alpha), -\eta_L \sin(2\alpha), \eta_c) \tag{4}$$

- $\eta_{c/L}$ are the polarization values for the circularly/linearly polarized photons, $-1 \leq \eta_c \leq 1$, $0 \leq \eta_L \leq 1$
- Generically the photon density matrix is written

$$\rho_\gamma = \frac{1}{2}\begin{pmatrix} (1+\eta_c) & -\eta_L e^{-2i\alpha} \\ -\eta_L e^{2i\alpha} & (1-\eta_c) \end{pmatrix} \tag{5}$$

Decomposition of ρ_V

- The density matrix for a photoproduced vector meson with an unpolarized target is related to the density matrix of the photon by:

$$\rho_V = J\rho_\gamma J^\dagger \tag{6}$$

- J can be taken to be a matrix of the production amplitudes calculated in the center of mass frame
- Since ρ_γ can be decomposed so can ρ_V

$$\rho_V = \rho_V^0 + \sum_{i=1}^{3} P_\gamma^i \rho_V^i \tag{7}$$

$$\rho_V^i = J\rho_\gamma^i J^\dagger \tag{8}$$

- No measurements of of the $\rho^{1,2,3}$ elements have previously been performed for the ω meson

Equations for ρ_V

- The equations for the SDMEs are then as follows:

$$\rho^0_{m_V m_{V'}} = \frac{1}{2N} \sum_{m_\gamma m_i m_f} A_{m_\gamma, m_i, m_f, m_V} * A^\dagger_{m_\gamma, m_i, m_f, m_{V'}} \tag{9}$$

$$\rho^1_{m_V m_{V'}} = \frac{1}{2N} \sum_{m_\gamma m_i m_f} A_{m_\gamma, m_i, m_f, m_V} * A^\dagger_{-m_\gamma, m_i, m_f, m_{V'}} \tag{10}$$

$$\rho^2_{m_V m_{V'}} = \frac{i}{2N} \sum_{m_\gamma m_i m_f} (-m_\gamma) A_{m_\gamma, m_i, m_f, m_V} * A^\dagger_{-m_\gamma, m_i, m_f, m_{V'}} \tag{11}$$

$$\rho^3_{m_V m_{V'}} = \frac{1}{2N} \sum_{m_\gamma m_i m_f} m_\gamma A_{m_\gamma, m_i, m_f, m_V} * A^\dagger_{m_\gamma, m_i, m_f, m_{V'}} \tag{12}$$

Measurable Elements

$$
\rho^0 = \begin{pmatrix} \underline{\frac{1}{2}(1-\rho^0_{00})} & \underline{Re\{\rho^0_{10}\}} + i * Im\{\rho^0_{10}\} & \underline{Re\{\rho^0_{1-1}\}} \\ & \underline{\rho^0_{00}} & \underline{-Re\{\rho^0_{10}\}} + i * Im\{\rho^0_{10}\} \\ & & \underline{\frac{1}{2}(1-\rho^0_{00})} \end{pmatrix}
$$

$$
\rho^1 = \begin{pmatrix} \underline{\rho^1_{11}} & \underline{Re\{\rho^1_{10}\}} + i * Im\{\rho^1_{10}\} & \underline{Re\{\rho^1_{1-1}\}} \\ & \underline{\rho^1_{00}} & \underline{-Re\{\rho^1_{10}\}} + i * Im\{\rho^1_{10}\} \\ & & \underline{\rho^1_{11}} \end{pmatrix}
$$

$$
\rho^2 = \begin{pmatrix} \rho^2_{11} & Re\{\rho^2_{10}\} + i * \underline{Im\{\rho^2_{10}\}} & i * \underline{Im\{\rho^2_{1-1}\}} \\ & 0 & Re\{\rho^2_{10}\} - i * \underline{Im\{\rho^2_{10}\}} \\ & & -\rho^2_{11} \end{pmatrix}
$$

$$
\rho^3 = \begin{pmatrix} \rho^3_{11} & Re\{\rho^3_{10}\} + i * \underline{Im\{\rho^3_{10}\}} & i * \underline{Im\{\rho^3_{1-1}\}} \\ & 0 & Re\{\rho^3_{10}\} - i * \underline{Im\{\rho^3_{10}\}} \\ & & -\rho^3_{11} \end{pmatrix}
$$

Partial Wave Fits

- The method used for our partial wave analysis is an event-based extended maximum liklihood fit
- No binning is done to the data other than in narrow $\sqrt{s}$ bins
- The liklihood function, $\mathcal{L}$, is dependent upon a set of parameters acting as weights for the amplitudes
- For all data the function we need to minimize is

$$-\ln\mathcal{L} = -\sum_{i}^{N_{events}} \ln|\mathcal{M}(\vec{x}, X_i)|^2 + \frac{\mathcal{S}(s)}{N_{raw}} \sum_{i}^{N_{acc}} |\mathcal{M}(\vec{x}, X_i)|^2 + const. \quad (14)$$

- $\mathcal{M}$ is the Lorentz invariant transition amplitude taking the initial state γp to the final state $p\pi^+\pi^-\pi^0$
- $\mathcal{M}$ can be interpreted as the non-normalized cross section

Determining the Transition Amplitude

- $\mathcal{M}$ is determined from the following equation

$$|\mathcal{M}|^2 = \text{Tr}[J(\rho_\gamma \otimes \rho_i)J^\dagger] \tag{15}$$

- J in the above equation is a 2x4 matrix of the production amplitudes

$$J = \begin{pmatrix} A_{+++} & A_{+-+} & A_{-++} & A_{--+} \\ A_{++-} & A_{+--} & A_{-+-} & A_{---} \end{pmatrix} \tag{16}$$

- The direct product between ρ^γ and ρ^i results in a 4x4 matrix which represents the initial space of the reaction
- In the unpolarized case both ρ_γ and ρ_i are the identity matrix and so M becomes:

$$|\mathcal{M}|^2 = \text{Tr}[JJ^\dagger] = \sum_{m_\gamma, m_i, m_f} |A_{m_\gamma, m_i, m_f}|^2 \tag{17}$$

Circular Polarization

- Recall that the photon density matrix is written

$$\rho_\gamma = \frac{1}{2}\begin{pmatrix} (1+\eta_c) & -\eta_L e^{-2i\alpha} \\ -\eta_L e^{2i\alpha} & (1-\eta_c) \end{pmatrix} \tag{18}$$

- For the case of circular polarization this leads to

$$|\mathcal{M}|^2 = \sum_{m_i,m_f} \left((1+\eta_c)|A_{+,m_i,m_f}|^2 + (1-\eta_c)|A_{-,m_i,m_f}|^2\right) \tag{19}$$

- Note that η_c ranges from -1 to 1, being negative/positive when the helicity is measured to be left/right

Linear Polarization

- In the case of linear polarization $\mathcal{M}$ is the following

$$|\mathcal{M}|^2 = \sum_{m_i,m_f} (\quad |A_{+,m_i,m_f}|^2 + |A_{-,m_i,m_f}|^2 - \eta_L(e^{-2i\alpha} A_{+,m_i,m_f} A^{\dagger}_{-,m_i,m_f} + e^{2i\alpha} A_{-,m_i,m_f} A^{\dagger}_{+,m_i,m_f}) \tag{20}$$

- Clearly there is an unpolarized part and a polarized part,
- The polarized part includes a mixing of amplitude types
- The polarized part is separated into a sum of conjugates
- Thus the polarized part is completely real

Monte Carlo

- The same $\mathcal{M}$ function must be used for the monte carlo data as for the measured data to properly normalize the data
- MC data is thrown only as 4-vectors to equally populate the allowed phase space
- This requires each MC event be assigned a polarization
- For circularly polarized experiments each MC event is assigned a polarization according to the Maximon and Olson relationship
- For linearly polarized data η_L depends on the instantaneous coherent edge, which does not exist in the MC
- The average polarization for the data in a given bin is used as η_L for all MC events in that bin
- This approximation should be valid as long as the polarization in a bin is tightly bound, which is true