Baryon Spectroscopy at ELSA / Jefferson Lab
What have we learned about excited baryons?

Volker Credé
Florida State University, Tallahassee, FL

Frühjahrstagung der Deutschen Physikalischen Gesellschaft
Mainz, Germany, 03/20/2012
How does QCD give rise to hadrons?

Interaction between quarks fairly unknown throughout > 98% of a hadron’s volume.

Explaining the excitation spectrum of hadrons is central to our understanding of QCD in the low-energy regime (Hadron Models, Lattice QCD, etc.).

Complementary to Deep Inelastic Scattering (DIS) where information on collective degrees of freedom is lost.
Non-Perturbative QCD

How does QCD give rise to hadrons?

1. What is the origin of confinement?
2. How are confinement and chiral symmetry breaking connected?
3. Would the answers to these questions explain the origin of $\sim 99\%$ of observed matter in the universe?

Baryons: What are the fundamental degrees of freedom inside a proton or a neutron? How do they change with varying quark masses?
Components of the Experimental $N^*$ Program

The excited baryon program has two main components:

- **Probe resonance transitions at different distance scales**
  Electron beams are ideal to measure resonance form factors and their corresponding $Q^2$ dependence.
  ➜ Provides information on the structure of excited nucleons and on the confining (effective) forces of the 3-quark system.

- **Establish the systematics of the spectrum**
  Current medium-energy experiments use photon beams to map out the baryon spectrum (JLab, ELSA, MAMI, SPring-8, etc.).
  ➜ Provides information on the nature of the effective degrees of freedom in strong QCD and also addresses the issue of previously unobserved or so-called *missing resonances*. 
Helicity Amplitudes for the “Roper” Resonance

Data from CLAS

- $A_{1/2}$ and $S_{1/2}$ amplitudes:
e.g. I. Aznauryan et al.,
PRC 78, 045209 (2008);
PRC 80, 055203 (2009).

- Quark-model calculations:
  - $q^3 G$ hybrid state
  - $q^3$ radial excitation

Consistency between both channels ($N\pi\pi$, $N\pi$): sign change, magnitude, ...

- At short distances (high $Q^2$), Roper behaves like radial excitation.
- Low $Q^2$ behavior not well described by LF quark models:
e.g. meson-baryon interactions missing

$\rightarrow$ Gluonic excitation likely ruled out!
There is clear evidence for helicity switch from $\lambda = 3/2$ (at photon point) to $\lambda = 1/2$ at high $Q^2$:

- Rapid change in helicity structure when going from photo- to electroproduction of a nucleon resonance

$\Rightarrow$ Stringent prediction of the CQM!

$A_{\text{hel}} = \frac{|A_{1/2}|^2 - |A_{3/2}|^2}{|A_{1/2}|^2 + |A_{3/2}|^2}$
The excited baryon program has two main components:

- **Probe resonance transitions at different distance scales**
  Electron beams are ideal to measure resonance form factors and their corresponding $Q^2$ dependence.
  - Provides information on the structure of excited nucleons and on the confining (effective) forces of the 3-quark system.

- **Establish the systematics of the spectrum**
  Current medium-energy experiments use photon beams to map out the baryon spectrum (JLab, ELSA, MAMI, SPring-8, etc.).
  - Provides information on the nature of the effective degrees of freedom in strong QCD and also addresses the issue of previously unobserved or so-called *missing resonances.*
Spectrum of Nucleon Resonances


1. Excitation Band: $(70, 1_{1}^{-})$

2. Excitation Band: $(56, 0_{2}^{+}), (56, 2_{2}^{+})$ ✓
   $(70, 0_{2}^{+}), (70, 2_{2}^{+})$ ✓
   $(20, 1_{2}^{+})$ ?

Perhaps only the tip of the iceberg has been discovered?
Spectrum of Nucleon Resonances


Perhaps only the tip of the iceberg has been discovered?

1. Excitation Band:
   (70, 1^-) ✓

2. Excitation Band:
   (56, 0^+_2), (56, 2^+_2) ✓
   (70, 0^+_2), (70, 2^+_2) ✓
   (20, 1^-_2) ?
Excited-State Baryon Spectroscopy from Lattice QCD


Missing states?

Exhibits broad features expected of $SU(6) \otimes O(3)$ symmetry

$\Rightarrow$ Counting of levels consistent with non-rel. quark model, no parity doubling

$m_\pi = 400$ MeV
Outline

1. Introduction
   - Quarks, QCD, and Confinement
   - Structure of Baryon Resonances

2. The Search for Undiscovered States
   - Electromagnetic Probes
   - Mission Goal: Complete Experiments

3. Results from Photoproduction Experiments
   - Photoproduction of $\pi$, $\eta$, and $\omega$ Mesons
   - Observables in the Photoproduction of Two Pions

4. Summary and Outlook
Introduction
The Search for Undiscovered States
Results from Photoproduction Experiments
Summary and Outlook

Electromagnetic Probes
Mission Goal: Complete Experiments

**Reaction Thresholds**

- $\gamma p \rightarrow p \eta \eta$
- $\gamma p \rightarrow p \pi^0 \omega$
- $\gamma p \rightarrow p \pi^0 \eta$
- $\gamma p \rightarrow p \eta$
- $\gamma p \rightarrow p \pi \pi \pi$
- $\gamma p \rightarrow p \pi \pi$
- $\gamma p \rightarrow p \pi$

**W [GeV]**

- 3.0
- 2.6
- 2.6
- 1.9
- 1.7

**E\gamma [GeV]**

- 1.66
- 0.06
- 0.00

Common efforts at ELSA, JLab, and MAMI
(Double-)polarization measurements, $\gamma p$ & $\gamma n$ reactions, etc.

In addition:
- LEGS
- SPring-8

V. Credé
Light Baryon Spectroscopy
Extraction of Resonance Parameters

- Double-polarization measurements

- Measurements off neutron and proton to resolve isospin contributions:
  1. $A(\gamma N \rightarrow \pi, \eta, K)^I=3/2 \iff \Delta^*$
  2. $A(\gamma N \rightarrow \pi, \eta, K)^I=1/2 \iff N^*$

- Re-scattering effects: Large number of measurements (and reaction channels) needed to extract full scattering amplitude.

Coupled Channels
Double-Polarization: Toward Complete Experiments

Calorimeter system at ELSA is optimized for neutral particles
(Details on performance and future upgrades: HK 11.2, HK 41.6, HK 58.5, HK 58.7).

Frozen-Spin Target: Butanol (C₄H₉OH).

Crystal Barrel Setup at ELSA
- Crystal Barrel (1230 CsI crystals)
- Inner Detector (513 scintillating fibers)
- Forward Plug (90 CsI crystals with PM’s)
- MiniTAPS (216 BaF₂, 1° - 12°)
**The CLAS Spectrometer at Jefferson Laboratory**

**Mission Goal:** Complete Experiments

- **Electromagnetic Probes**
- **g8b** linear beam polarization
- **FROST** double polarization

**Electron Beam**

- **Electromagnetic Calorimeters**
- **Cerenkov Counters**
- **Time of Flight Scintillators**
- **Torus**
- **Drift Chambers**

**Data for PERP 1.3 GeV Calculation**

- Polarization corresponding to calc (Peaking at > 90%)
Double-Polarization: Frozen Spin Targets

Horizontal cryostat with integrated solenoid to freeze the proton spin.

- DNP at high B-field (2.5 T), holding mode at 0.4 T
- Relaxation time at ELSA $\sim 500$ h

Longitudinally-Polarized Target ($P_z \approx 80\%$)

Transverse Target Polarization (race-track coil - Dipole Magnet)
Why are Polarization Observables Important?

1. From π threshold up to Δ(1232) region
   - s- & p-wave approximation
   - Fermi-Watson Theorem
   ➜ Two observables sufficient, e.g. dσ/dΩ, Σ.

2. Above the ππ threshold
   ➜ More observables needed.

\[
\frac{d\sigma}{d\Omega} = \sigma_0 \left\{ 1 - \delta_1 \Sigma \cos 2\phi + \Lambda_x ( -\delta_1 H \sin 2\phi + \delta_\odot F ) + \Lambda_y ( -T + \delta_1 P \cos 2\phi ) - \Lambda_z ( -\delta_1 G \sin 2\phi + \delta_\odot E ) \right\}
\]


In order to determine the full scattering amplitude without ambiguities, one has to carry out eight carefully selected measurements: four double-spin observables along with four single-spin observables.

Eight well-chosen measurements are needed to fully determine production amplitudes \( F_1, F_2, F_3, \) and \( F_4. \)
Why are Polarization Observables Important?

1. From $\pi$ threshold up to $\Delta(1232)$ region
   - $s$- & $p$-wave approximation
   - Fermi-Watson Theorem
   - Two observables sufficient, e.g. $d\sigma/d\Omega$, $\Sigma$.

2. Above the $\pi\pi$ threshold
   - More observables needed.

\[
\frac{d\sigma}{d\Omega} = \sigma_0 \left\{ 1 - \delta_1 \Sigma \cos 2\phi 
+ \Lambda_x (-\delta_1 H \sin 2\phi + \delta_\odot F)
- \Lambda_y (-T + \delta_1 P \cos 2\phi)
- \Lambda_z (-\delta_1 G \sin 2\phi + \delta_\odot E) \right\}
\]


In order to determine the full scattering amplitude without ambiguities, one has to carry out eight carefully selected measurements: four double-spin observables along with four single-spin observables.

Eight well-chosen measurements are needed to fully determine production amplitudes $F_1$, $F_2$, $F_3$, and $F_4$. 
Example: Beam Asymmetry $\Sigma$ in $\bar{\gamma} \rho \rightarrow \rho \eta$

\[ \frac{d\sigma}{d\Omega} = \sigma_0 \left\{ 1 - \delta_{1}\Sigma \cos 2\phi \right\} \]

BoGa-PWA

$E_\gamma = 1250$ MeV

$\eta$-MAID

$D_{13}(1520)$

$P_{13}(1720)$

$O. Bartholomy, V. C. et al.,$

PRL 94 (2005) 012004,


$E_{\gamma} = 1250$ MeV

$\eta$-MAID

$D_{13}(1520)$

$P_{13}(1720)$

$\sigma_{\text{tot}} \text{[}\mu\text{b]}$

$E_{\gamma} \text{[GeV]}$

$\rightarrow N(1710)P_{11}$?

$\rightarrow N(1710)P_{11}$?

$(1720)P_{13}$

$(2070)D_{15}$

$(1535)S_{11}$

$D. Elsner et al. [CBELSA/TAPS], EPJ A 33, 147 (2007)$

V. Credé

Light Baryon Spectroscopy
Helicity-Dependent Cross Section for $\vec{\gamma} \vec{p} \to p \eta$

\[ E = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \]

M. Gottschall et al. [CBELSA/TAPS]
Helicity-Dependent Cross Section for $\vec{\gamma} \vec{p} \rightarrow p \eta$

Very preliminary: Data are positive

$N_{\frac{1}{2}} - N_{\frac{3}{2}}$

$S_{11}(1535)$

$P_{11}(1710)\ ?$

$P_{13}(1720)\ ?$

B. Morrison et al. [CLAS Collaboration]
Outline

1 Introduction
   - Quarks, QCD, and Confinement
   - Structure of Baryon Resonances

2 The Search for Undiscovered States
   - Electromagnetic Probes
   - Mission Goal: Complete Experiments

3 Results from Photoproduction Experiments
   - Photoproduction of $\pi$, $\eta$, and $\omega$ Mesons
   - Observables in the Photoproduction of Two Pions

4 Summary and Outlook
Results from CBELSA/TAPS at this Meeting

Doppelpolarisationsobservablen mit dem CBELSA/TAPS-Experiment
J. Hartmann ➔ HK 15.1, T 16:30h

Messung von Polarisationsobservablen in der \( \omega \)-Photoproduktion
H. Eberhardt ➔ HK 15.2, T 17:00h

Die Polarisationsobservablen \( T \) in der \( \pi^0 \pi^0 \)-Photoproduktion am Proton
T. Seifen ➔ HK 15.5, T 17:45h

Measurement of the Double Polarization Observable \( E \) in Photoproduction of \( \eta \) and \( 2\pi^0 \) Mesons off Quasi-Free Protons and Neutrons
L. Witthauer ➔ HK 15.6, T 18:00h

Search for \( \omega \)-mesic states, S. Friedrich ➔ HK 30.4, W 17:30h

\( \omega \) Photoproduction off Protons and Neutrons with CBELSA/TAPS
F. Dietz ➔ HK 38.3, R 17:30h

In-Medium Properties of the \( \eta' \) Meson, M. Nanova ➔ HK 38.4, R 17:45h
Fascinating Discovery in Reactions off the Neutron

Neutron measurements important:
- Different resonance contributions
- Study of isospin composition of el.-magn. couplings

Narrow structure in $\gamma d \rightarrow n \eta + p$
with $M \approx 1670$ MeV and $\sigma = 25$ MeV:
- Interference effect of the $S_{11}(1535)$ and $S_{11}(1535)$ resonances
- Coupled channel effect of $S_{11}(1535)$ and $P_{11}(1710)$
- New narrow state?

Isospin Filter: $\gamma N \rightarrow N^*(I = 1/2) \rightarrow N\omega$

\[ \begin{array}{c|c|c|c|c|c|c|c|c|c} \hline \text{Incident Beam Energy } E_\gamma & 1.2 & 1.4 & 1.6 & 1.8 & 2 & \hline \text{Cross-section } \sigma [\text{b}] & 15 & 10 & 5 & 0 & 0 & \text{b} \end{array} \]

Calculation by V. Shklyar: $\gamma n \rightarrow \omega n$

CB-ELSA: $\gamma d \rightarrow \omega n(p)$

Calculation by V. Shklyar: $\gamma p \rightarrow \omega p$

CB-ELSA: $\gamma d \rightarrow \omega p(n)$

F. Hjelm et al.
Isospin Filter: $\gamma p \rightarrow N^* (I = 1/2) \rightarrow p\omega$

A. Wilson et al. [CBELSA/TAPS], Ph.D. thesis

Good agreement between experiments
Excellent statistics
Great progress in our understanding of the differences between experiments.

Preliminary
Isospin Filter: $\gamma p \rightarrow N^* (I = 1/2) \rightarrow p \omega$

Good agreement between experiments
Excellent statistics
New CBELSA/TAPS data extend the world database in the most forward direction.

More on $p\omega (n\omega)$: F. Dietz, HK 38.3
Baryon Resonances in the Reaction $\gamma p \rightarrow p \omega$


Strong evidence for ($W < 2$ GeV):

(3/2) – $N(1700)$  ***
(5/2) + $N(1680)$  ***

Only nucleon resonances can contribute (isospin filter)

- First-time PWA of $\omega$ photoproduction channel
- High statistics data sets are key to pull out signals.
  $\Rightarrow$ CLAS at JLab can provide statistics, but there are also limitations in the acceptance.
Baryon Resonances in the Reaction $\gamma p \rightarrow p \omega$


Strong evidence for ($W > 2$ GeV):

$(5/2)^+ N(1680) \quad **$

$(5/2)^+ N(1950) \quad *$

$(7/2)^- N(2190) \quad ***$

PWA fit includes resonances + $t$-channel amplitudes.
Strong evidence for \((W > 2 \text{ GeV})\):

(5/2)+ N(1680)  ***
(5/2)+ N(1950)  **
(7/2)− N(2190)  ***

→ H. Eberhardt, HK 15.2
Photoproduction of $\pi^0$ Mesons from the Proton

Reaction $\gamma p \rightarrow p \pi^0$ remains important for our understanding of baryons.

- At ELSA, excellent data with good statistics in the forward direction.
- Forward region is very sensitive to higher-spin resonances: Observation of $N(2190)G_{17}$ within the Bonn-Gatchina PWA framework (Important to confirm high-mass states first observed in $\pi N$ scattering)

Photoproduction of $\pi$, $\eta$, and $\omega$ Mesons

Observables in the Photoproduction of Two Pions

**Beam Asymmetry $\Sigma$ in $\vec{\gamma} p \rightarrow p \pi^0$**

\[
\frac{d\sigma}{d\Omega} = \sigma_0 \left\{ 1 - \delta_I \Sigma \cos 2\phi + \Lambda_x (-\delta_I H \sin 2\phi + \delta_\odot F) - \Lambda_y (-T + \delta_I P \cos 2\phi) - \Lambda_z (-\delta_I G \sin 2\phi + \delta_\odot E) \right\}
\]

- **SAID**
- **MAID**
- **CLAS**

$(E_\gamma < 2 \text{ GeV}, \ -0.85 < \cos \theta_\pi < -0.35)$

→ Serious discrepancies between models and data above 1.4 GeV.

Photoproduction of $\pi$ mesons still not very well understood.

M. Dugger (ASU), CLAS g8b run group, to be published

V. Credé  
Light Baryon Spectroscopy
Beam Asymmetry $\Sigma$ in $\vec{\gamma} p \rightarrow p \pi^0$

Combination of $p \pi^0$ and $n \pi^+$ final states can help distinguish between $\Delta$ and $N^*$ resonances:

$\pi^0 + p : \sqrt{2/3} \left| I = \frac{3}{2}, I_3 = \frac{1}{2} \right> - \sqrt{1/3} \left| I = \frac{1}{2}, I_3 = \frac{1}{2} \right>$

$\pi^+ + n : \sqrt{1/3} \left| I = \frac{3}{2}, I_3 = \frac{1}{2} \right> + \sqrt{2/3} \left| I = \frac{1}{2}, I_3 = \frac{1}{2} \right>$
Beam Asymmetry $\Sigma$ in $\gamma p \rightarrow p \pi^0$ and $\gamma p \rightarrow n \pi^+$

M. Dugger (ASU), CLAS g8b run group, to be published
Asymmetry $G$ in $\vec{\gamma} \vec{p} \rightarrow p \pi^0$ (Results from ELSA)

$\frac{d\sigma}{d\Omega} = \sigma_0 \left\{ 1 - \delta_l \sum \cos 2\phi \right.$

$+ \Lambda_x \left( -\delta_l H \sin 2\phi + \delta \odot F \right) $

$- \Lambda_y \left( -T + \delta_l P \cos 2\phi \right) $

$- \Lambda_z \left( -\delta_l G \sin 2\phi + \delta \odot E \right) \left\} \right.$

Surprisingly, $\pi^0$ production also not well understood at lower energies:

- BoGa
- SAID
- MAID

J. Hartmann, HK 15.1

A. Thiel et al. [CBELSA/TAPS], to be published
Asymmetry $G$ in $\gamma \vec{p} \rightarrow p \pi^0$ (Results from ELSA)

$$\frac{d\sigma}{d\Omega} = \sigma_0 \left\{ 1 - \delta I \Sigma \cos 2\phi \right.$$ 

$$+ \Lambda_x \left( -\delta I H \sin 2\phi + \delta \odot F \right)$$ 

$$- \Lambda_y \left( -T + \delta I P \cos 2\phi \right)$$ 

$$- \Lambda_z \left( -\delta I G \sin 2\phi + \delta \odot E \right) \}$$

$\theta_\pi = 90 \pm 5^\circ$

$\theta_\pi = 130 \pm 5^\circ$

Surprisingly, $\pi$ production also not well understood at lower energies.

Below 1 GeV, discrepancies can be traced to the $E_{0^+}$ and $E_{2^-}$ multipoles, which are related to certain resonances.

A. Thiel et al. [CBELSA/TAPS], to be published
Transverse Target Polarization: Target Asymmetry \( T \)

\[
\Delta N(\phi) = \frac{1}{f P_{\text{target}}} \cdot \frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}}
\]

\( = T \cdot \sin(\phi - \beta) \)

\( \rightarrow \) Unprecedented statistical quality.

\( 700 < E_\gamma < 800 \text{ MeV} \)

\[
\chi^2 / \text{ndf} = 23.25 / 17 \quad T = -0.2444 \pm 0.0029
\]

\( \gamma \bar{p} \rightarrow p\pi^0 \)

\( \phi_{\pi^0} \)

\( 800 < E_\gamma < 900 \text{ MeV} \)

\[
\chi^2 / \text{ndf} = 19.97 / 17 \quad T = 0.1668 \pm 0.0091
\]

\( \gamma \bar{p} \rightarrow p\eta \)

\( \phi_{\pi^0} \)

\( \beta = 99^\circ \)

Direction of target pol.:
Target Asymmetry $T$ in $\gamma \vec{p} \rightarrow p \pi^0$ (Data from ELSA)

600 < $E_\gamma$ < 1000 MeV in bins of $\Delta E = 25$ MeV

- CBELSA/TAPS
- Maid
- Said
- Bonn Gatchina

→ Good agreement of experimental data. (improved statistics)

J. Hartmann et al. [CBELSA/TAPS] ➔ HK 15.1

V. Credé
Light Baryon Spectroscopy
Target Asymmetry $T$ in $\gamma \vec{p} \rightarrow p \pi^0$ (Data from ELSA)

1000 $< E_\gamma < 1500$ MeV

- CBELSA/TAPS
- Maid
- Said
- Bonn Gatchina

$\rightarrow$ Good agreement of experimental data.

Model disagreement toward 3$^{rd}$ resonance region: $W > 1.6$ GeV ($E_{0^+}, E_{2^-}$ multipoles?)
Target Asymmetry $T$ in $\gamma \vec{p} \to p \eta$ (Data from ELSA)

$708 < E_\gamma < 933$ MeV in bins of $\Delta E = 25$ MeV

- CBELSA/TAPS
- PHOENICS (1998)
- Maid
- Said
- Bonn Gatchina

J. Hartmann et al. [CBELSA/TAPS] $\Rightarrow$ HK 15.1
Introduction
The Search for Undiscovered States
Results from Photoproduction Experiments
Summary and Outlook

Photoproduction of $\pi$, $\eta$, and $\omega$ Mesons
Observables in the Photoproduction of Two Pions

Observables $P, H$ (Results from CBELSA/TAPS)

**Photoproduction of $\pi^0$, $\eta$, and $\omega$ Mesons**

**Observables**

$P, H$ (Results from CBELSA/TAPS)

800 $< E_{\gamma} < 900$ MeV

**Preliminary**

\[ \Delta N(\phi) = C \cdot \frac{(N_\perp \uparrow - N_\perp \downarrow) - (N_\parallel \uparrow - N_\parallel \downarrow)}{(N_\perp \uparrow + N_\perp \downarrow) + (N_\parallel \uparrow + N_\parallel \downarrow)} \]

\[ = P \left( \sin(\phi - \beta) \cos(2(\phi - \alpha)) \right) + H \left( \cos(\phi - \beta) \sin(2(\phi - \alpha)) \right) \]

angle of lin. pol. plane: \( \alpha = 45^\circ \)

direction of target pol.: \( \beta = 99^\circ \)

angle of lin. pol. plane: \( \alpha = 45^\circ \)

direction of target pol.: \( \beta = 99^\circ \)

**Target Pol. Axis**

<table>
<thead>
<tr>
<th>Photon Pol.</th>
<th>Target Pol. Axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unpolarized</td>
<td>$\sigma$</td>
</tr>
<tr>
<td>Linear</td>
<td>$-\Sigma$</td>
</tr>
<tr>
<td>Circular</td>
<td>$H$</td>
</tr>
<tr>
<td></td>
<td>$-P$</td>
</tr>
<tr>
<td></td>
<td>$-G$</td>
</tr>
<tr>
<td></td>
<td>$F$</td>
</tr>
<tr>
<td></td>
<td>$-E$</td>
</tr>
</tbody>
</table>
Introduction

The Search for Undiscovered States

Results from Photoproduction Experiments

Summary and Outlook

Photoproduction of $\pi$, $\eta$, and $\omega$ Mesons

Observables in the Photoproduction of Two Pions

Beam-Target Polarization Observables in $\gamma p \rightarrow p \pi\pi$

\[ I = I_0 \left\{ (1 + \vec{\Lambda}_i \cdot \vec{P}) \right. \\
+ \delta \odot (I^\odot + \vec{\Lambda}_i \cdot \vec{P}^\odot) \right. \\
+ \delta \odot \left[ \sin 2\beta \left( I^S + \vec{\Lambda}_i \cdot \vec{P}^S \right) + \right. \\
\left. \cos 2\beta \left( I^C + \vec{\Lambda}_i \cdot \vec{P}^C \right) \right] \right\} \]


Double-Meson Final States
(15 Observables)

At higher excitation energies:

Multi-meson final states important.

Search for states in decay cascades!
Two mesons in the final state require 5 independent variables!

For example: $E_\gamma$, $\Theta_{c.m.}$, $\phi^*$, $\theta^*$, $M_{p + \text{meson}_1}$

Single-meson reactions:
- $p$-meson system in the reaction plane

Two-meson reactions:
- Reaction and decay plane form angle $\phi$
Beam Asymmetries $I^s, I^c$ in $\gamma p \rightarrow p \pi^0 \pi^0$

First measurements of beam asymmetries $I^s$ and $I^c$ using linearly-polarized photons in the reaction $\gamma p \rightarrow p \pi^0 \pi^0$.

Among other things, study of decays into $\Delta \pi$:

$\Delta(1700)D_{33} \rightarrow \Delta \pi$ $D$-wave

BoGa-PWA solution with a dominant $\Delta(1700)D_{33} \rightarrow \Delta \pi$ $S$-wave

- Direct measurements
- From mirror operation $I^s(\Phi^*) \rightarrow I^s(2\pi - \Phi^*)$

V. Sokhoyan et al. [CBELSA/TAPS], to be published
Data of unprecedented stat. quality

Here: 3-dim. phasespace \((E_\gamma, \theta_{\pi^+}^*, \phi_{\pi^+}^*)\)

C. Hanretty \textit{et al.}, CLAS-g8b run group, under review
Beam Asymmetry $I^\circ$ in $\gamma p \rightarrow p \pi^+\pi^-$ from JLab

Analysis of butanol target challenging:

- Determination of dilution factor ➔ (event-based dilution factors possible)

The interpretation of these $\pi\pi$ data has only just begun.

S. Park et al., CLAS (FROST), to be published
Introduction

Quarks, QCD, and Confinement
Structure of Baryon Resonances

The Search for Undiscovered States
Electromagnetic Probes
Mission Goal: Complete Experiments

Results from Photoproduction Experiments
Photoproduction of $\pi$, $\eta$, and $\omega$ Mesons
Observables in the Photoproduction of Two Pions

Summary and Outlook
Our understanding of baryon resonances has made great leaps forward. There is good evidence that most of the known states (listed in the PDG) will be confirmed in photoproduction and that new states will be revealed:

- The current $N^*$ (6 GeV) program at Jefferson Laboratory is complete, but the data need to be analyzed in the coming years.

- The excited-baryon program at ELSA continues and has great potential to contribute significantly, in particular in reactions off the neutron and the all-neutral (multi-photon) final states:
  
  \[ \gamma N \rightarrow N \pi^0 \pi^0, \quad \gamma N \rightarrow N \pi^0 \eta, \quad \gamma N \rightarrow N \pi^0 \omega \]

Conclusions

Advances in both theory and experiment will allow us to finally understand QCD and confinement.