

Understanding the Spectrum of Excited Nucleons using CLAS at Jefferson Lab

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NSTAR 2017

University of South Carolina

08/22/2017



Outline

- 1 Introduction
 - Non-Perturbative QCD
 - The Spectrum of Baryons
- 2 Spectroscopy of Baryon Resonances
 - Complete Experiments
 - Polarization Observables in $\gamma p \rightarrow p \omega$
- 3 Decay Cascades of Excited Baryons
- 4 Summary and Outlook
 - Open Issues in (Light) Baryon Spectroscopy
 - Ξ Spectroscopy with the GlueX Detector



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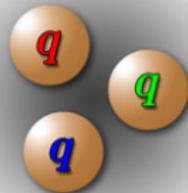


Hadrons: Baryons & Mesons

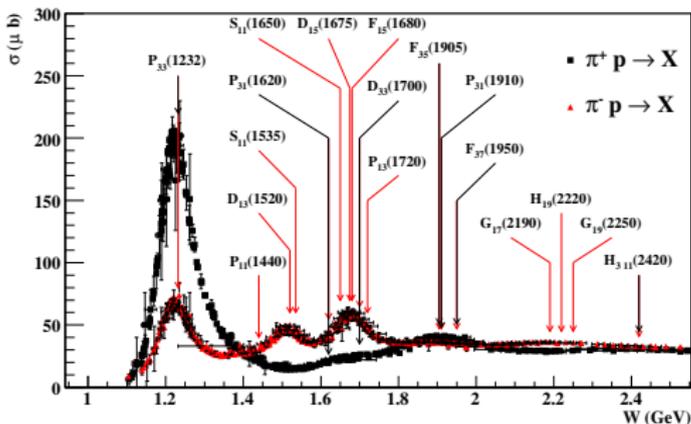
The strong coupling confines quarks and breaks chiral symmetry, and so defines the world of light hadrons.

Baryons are special because

Their structure is most obviously related to the color degree of freedom, e.g. $|\Delta^{++}\rangle = |u^\uparrow u^\uparrow u^\uparrow\rangle$.



Baryons



Courtesy of Michael Williams

→ PDG 2010, J. Phys. G **37**, 075021



Great progress
in recent years:

→ γN & πN data

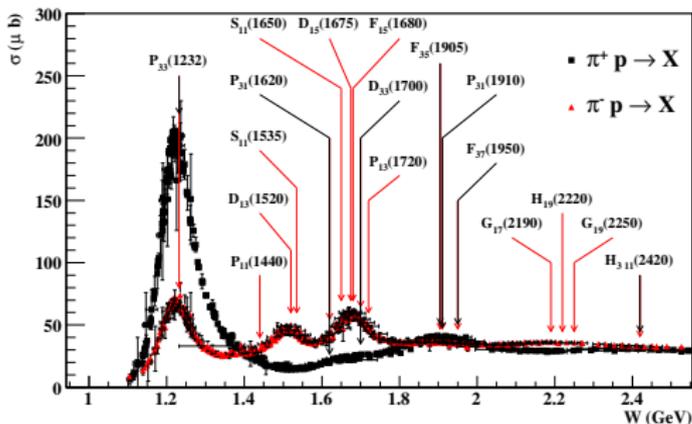


Hadrons: Baryons & Mesons

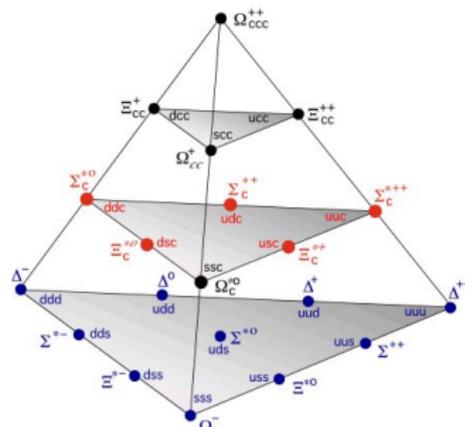
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Courtesy of Michael Williams



Many Y^* QN not measured:
(Quark model assignments)

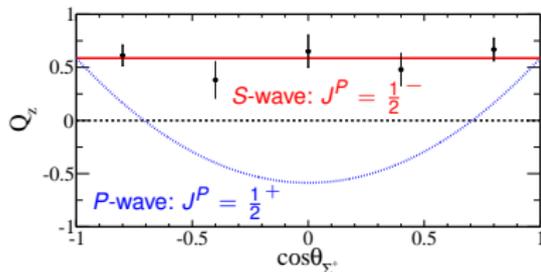
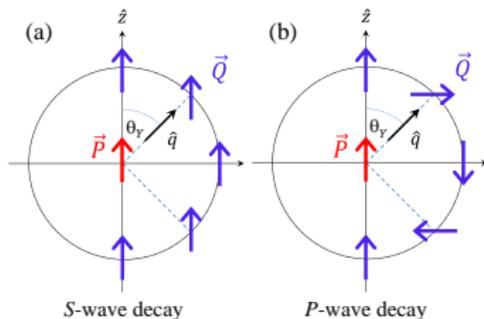
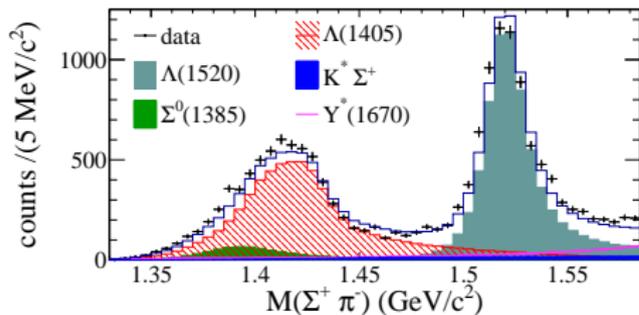
→ many Ξ^* and Ω^* , etc.

Spin and Parity Measurement of the $\Lambda(1405)$ Baryon

K. Moriya *et al.* [CLAS Collaboration], Phys. Rev. Lett. **112**, 082004 (2014)

Data for $\gamma p \rightarrow K^+ \Lambda(1405)$ support $J^P = \frac{1}{2}^-$

- Decay distribution of $\Lambda(1405) \rightarrow \Sigma^+ \pi^-$ consistent with $J = 1/2$.
- Polarization transfer, \vec{Q} , in $Y^* \rightarrow Y\pi$:
 - S-wave decay: \vec{Q} independent of θ_Y



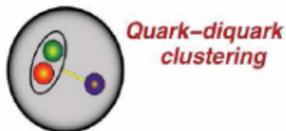
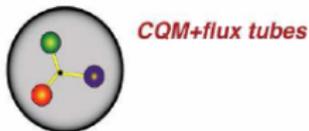
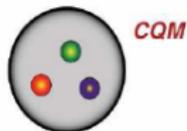
Non-Perturbative QCD

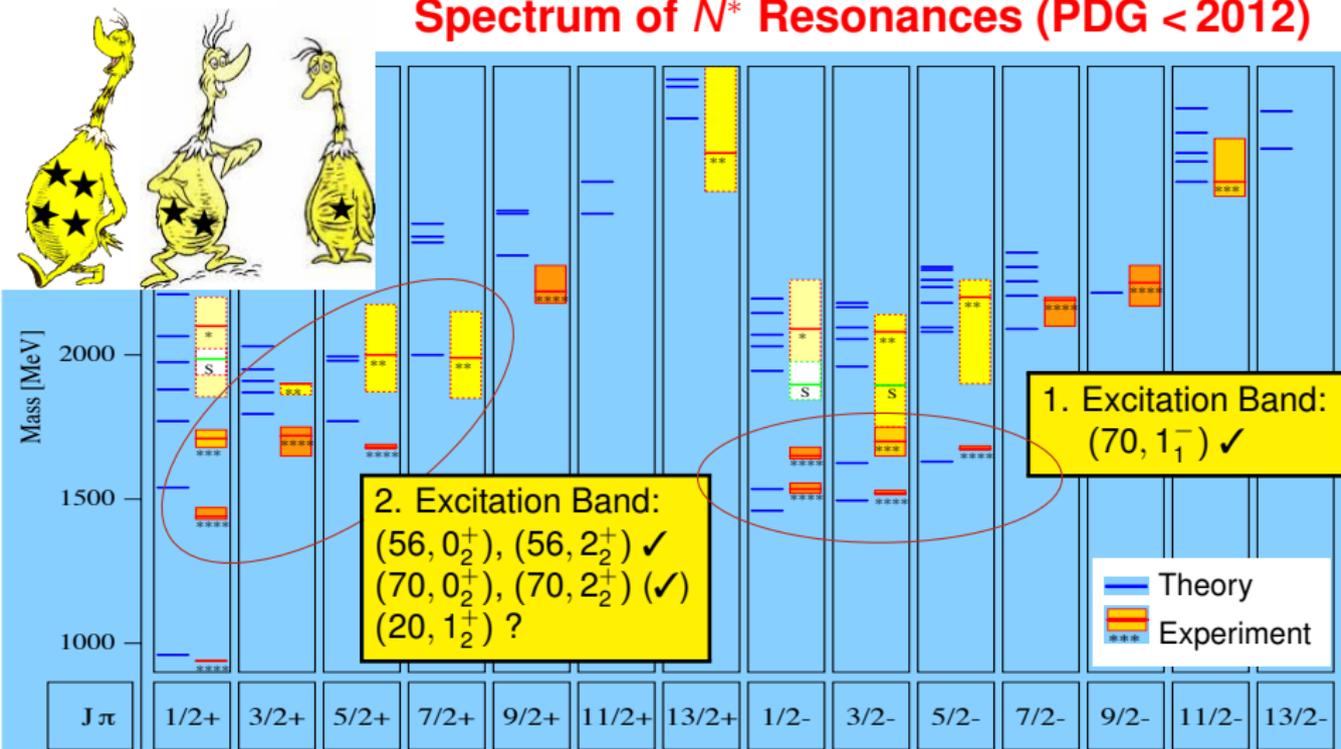


How does QCD give rise to excited hadrons?

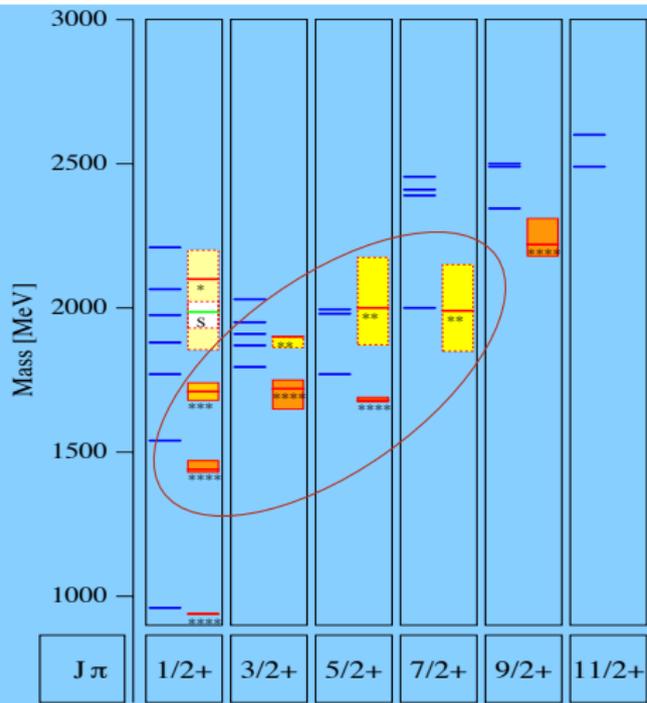
- ① What is the origin of confinement?
- ② How are confinement and chiral symmetry breaking connected?
- ③ What role do gluonic excitations play in the spectroscopy of light mesons, and can they help explain quark confinement?

Baryons: What are the fundamental degrees of freedom inside a nucleon?
Constituent quarks? How do the degrees change with varying quark masses?



Spectrum of N^* Resonances (PDG < 2012)

— S. Capstick and N. Isgur, Phys. Rev. **D34** (1986) 2809

Spectrum of N^* Resonances

V. C. & W. Roberts, Rep. Prog. Phys. 76 (2013)

N^*	$J^P (L_{2l,2J})$	2010	2014
$N(1440)$	$1/2^+ (P_{11})$	****	****
$N(1520)$	$3/2^- (D_{13})$	****	****
$N(1535)$	$1/2^- (S_{11})$	****	****
$N(1650)$	$1/2^- (S_{11})$	****	****
$N(1675)$	$5/2^- (D_{15})$	****	****
$N(1680)$	$5/2^+ (F_{15})$	****	****
$N(1685)$			*
$N(1700)$	$3/2^- (D_{13})$	***	**
$N(1710)$	$1/2^+ (P_{11})$	***	**
$N(1720)$	$3/2^+ (P_{13})$	****	****
$N(1860)$	$5/2^+$		**
$N(1875)$	$3/2^-$		**
$N(1880)$	$1/2^+$		**
$N(1895)$	$1/2^-$		**
$N(1900)$	$3/2^+ (P_{13})$	**	**
$N(1990)$	$7/2^+ (F_{17})$	**	**
$N(2000)$	$5/2^+ (F_{15})$	**	**
$N(2080)$	D_{13}	**	
$N(2090)$	S_{11}	*	
$N(2040)$	$3/2^+$		*
$N(2060)$	$5/2^-$		**
$N(2100)$	$1/2^+ (P_{11})$	*	*
$N(2120)$	$3/2^-$		**
$N(2190)$	$7/2^- (G_{17})$	****	****
$N(2200)$	D_{15}	**	

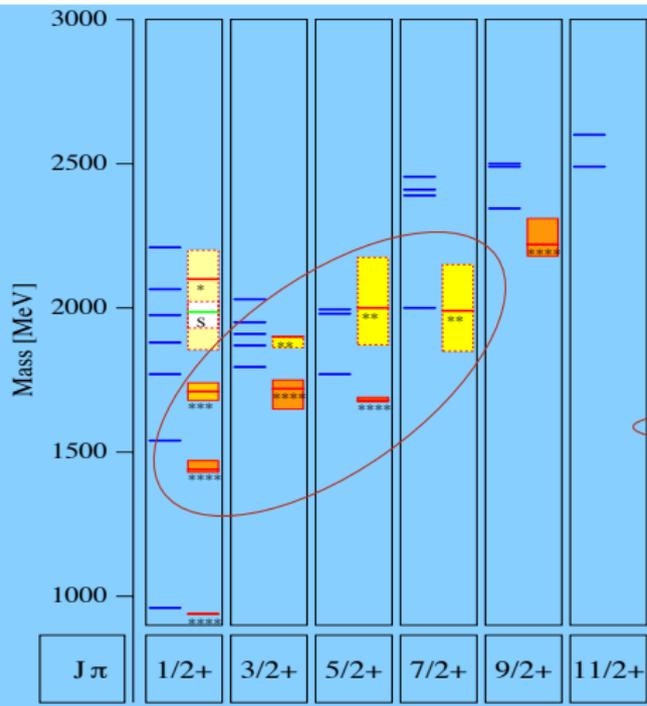
13/2-

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Spectrum of N^* Resonances

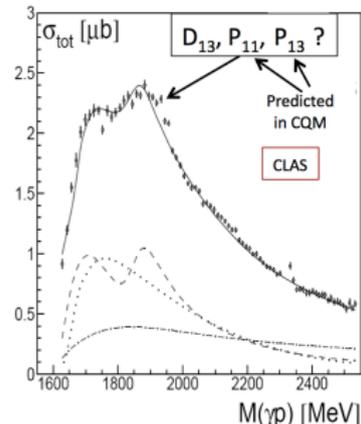
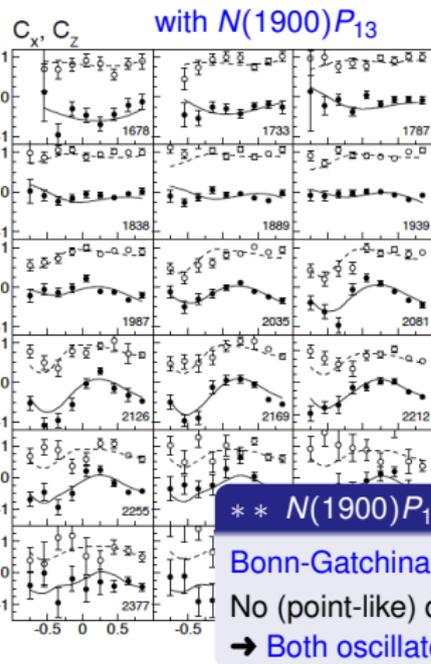
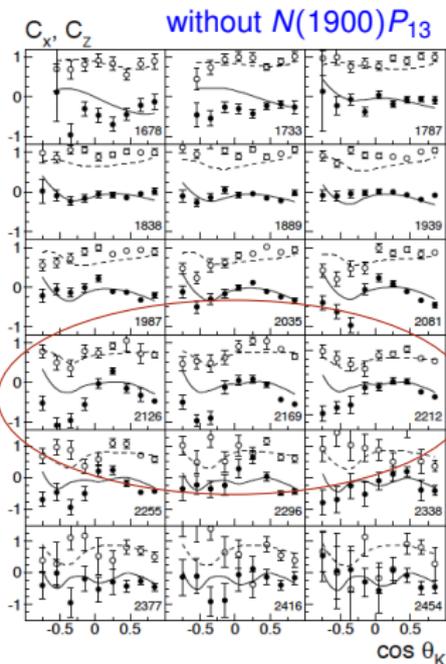


V. C. & W. Roberts, Rep. Prog. Phys. 76 (2013)

N^*	$J^P (L_{2l,2J})$	2010	2014
$N(1440)$	$1/2^+ (P_{11})$	****	****
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$N(1650)$	$1/2^- (S_{11})$	****	****
$N(1675)$	$5/2^- (D_{15})$	****	****
$N(1680)$	$5/2^+ (F_{15})$	****	****
$N(1685)$			*
$N(1700)$	$3/2^- (D_{13})$	***	**
$N(1710)$	$1/2^+ (P_{11})$	***	**
$N(1720)$	$3/2^+ (P_{13})$	****	****
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$N(1990)$	$7/2^+ (F_{17})$	**	**
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$N(2100)$	$1/2^+ (P_{11})$	*	*
$N(2120)$	$3/2^-$		**
$N(2190)$	$7/2^- (G_{17})$	****	****
$N(2200)$	D_{15}	**	

13/2-

Polarization Transfer in $\vec{\gamma} p \rightarrow K^+ \vec{\Lambda}$: C_x, C_z



**** $N(1900)P_{13}, N(2000)F_{15}, N(1990)F_{17}$**

Bonn-Gatchina PWA requires $N(1900)P_{13}$

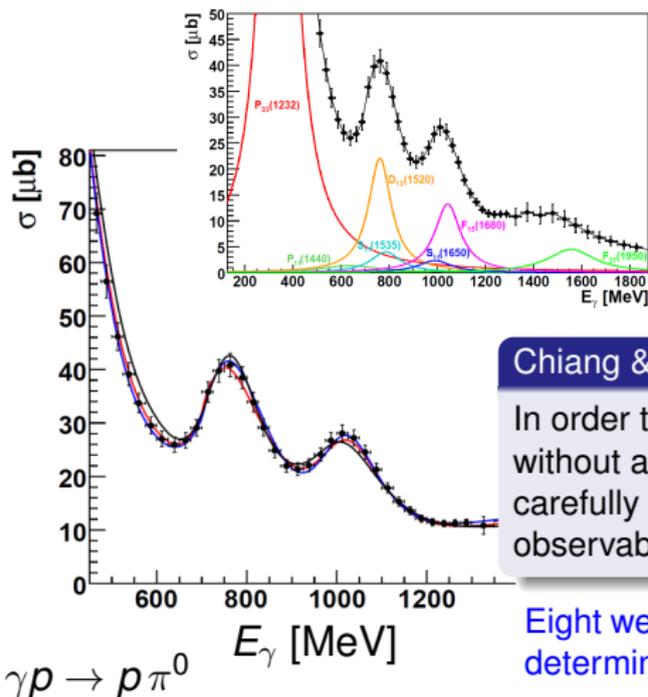
No (point-like) quark-diquark oscillations!

→ Both oscillators need to be excited.

R. Bradford *et al.* [CLAS Collaboration], *PRC* **75**, 035205 (2007)

Fits: BoGa-Model, V. A. Nikonov *et al.*, *Phys. Lett. B* **662**, 245 (2008)

Why are Polarization Observables Important?



Single-(pseudoscalar) meson production:

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

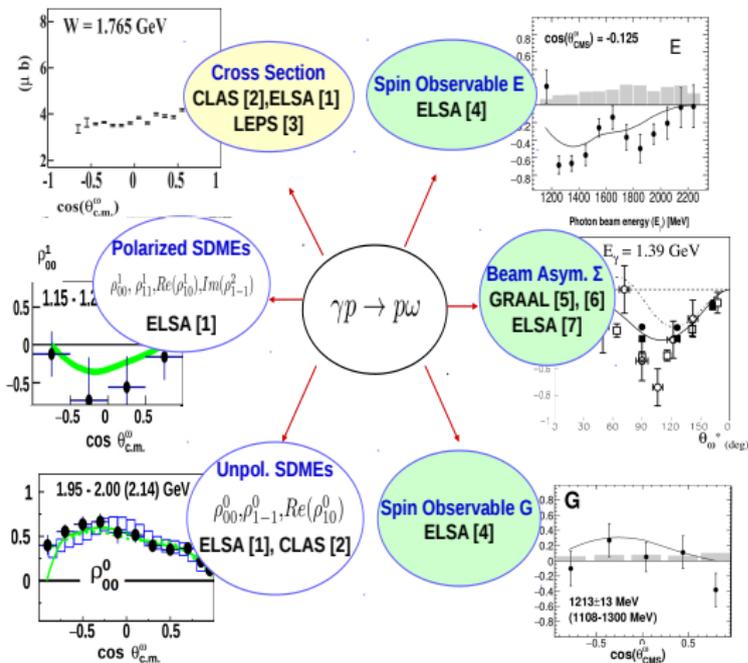
Chiang & Tabakin, Phys. Rev. C55, 2054 (1997)

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 .

Baryon Resonances in the Reaction $\gamma p \rightarrow p \omega$

Vector-meson photoproduction (ω , ρ , ϕ) is still underexplored.



Particle J^P	Status as seen in —									
	overall	πN	γN	$N\eta$	$N\sigma$	$N\omega$	ΛK	ΣK	$N\rho$	$\Delta\pi$
$N(1700) 3/2^-$	***	***	**	*			*	*	*	***
$N(1710) 1/2^+$	***	***	***	***		**	***	***	*	**
$N(1720) 3/2^+$	****	****	***	***			**	**	***	*
$N(1860) 5/2^+$	**	**							*	*
$N(1875) 3/2^-$	***	*	***			**	***	**		***
$N(1880) 1/2^+$	**	*	*		**		*	*		
$N(1895) 1/2^-$	**	*	**	**			**	*		
$N(1900) 3/2^+$	***	**	***	**		**	***	**	*	**
$N(1990) 7/2^+$	**	**	**				*			
$N(2000) 5/2^+$	**	*	**	**			**	*	**	
$N(2040) 3/2^+$	*									
$N(2060) 5/2^-$	**	**	**	*				**		
$N(2100) 1/2^+$	*									
$N(2150) 3/2^-$	**	**	**				**			**
$N(2190) 7/2^-$	****	****	***			*	**		*	
$N(2220) 9/2^+$	****	****								
$N(2250) 9/2^-$	****	****								
$N(2600) 11/2^-$	***	***								
$N(2700) 13/2^+$	**	**								

Particle J^P	overall	πN	γN	$N\eta$	$N\sigma$	$N\omega$	ΛK	ΣK	$N\rho$	$\Delta\pi$
$N(1440) 1/2^+$	****	****	****		***				*	***
$N(1520) 3/2^-$	****	****	****	***					***	***
$N(1535) 1/2^-$	****	****	****	****					**	*
$N(1650) 1/2^-$	****	****	**	**			***	**	**	***
$N(1675) 5/2^-$	****	****	**	*			*		*	***
$N(1680) 5/2^+$	****	****	****	*	**				***	***
$N(1700) 3/2^-$	***	**	**	*			*	*	*	***
$N(1710) 1/2^+$	***	**	**	**		**	***	**	*	**
$N(1720) 3/2^+$	****	****	**	**			**	**	**	*
$N(1860) 5/2^+$	**	**							*	*
$N(1875) 3/2^-$	***	*	**			**	***	**		***
$N(1880) 1/2^+$	**	*	*		**		*			
$N(1895) 1/2^-$	**	*	**	**			**	*		
$N(1900) 3/2^+$	***	**	**	**		**	***	**	*	**
$N(1990) 7/2^+$	**	**	**					*		
$N(2000) 5/2^+$	**	*	**	**			**	*	**	
...										
$N(2190) 7/2^-$	****	****	**			*	**		*	
$N(2220) 9/2^+$	****	****								
$N(2250) 9/2^-$	****	****								
$N(2600) 11/2^-$	***	**								
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$N(1520) 3/2^-$	****	****	****	***					***	***
$N(1535) 1/2^-$	****	****	****	****					**	*
$N(1650) 1/2^-$	****	****	**	**			**	**	**	**
$N(1675) 5/2^-$	****	****	**	*			*		*	**
$N(1680) 5/2^+$	****	****	****	*	**				***	**
$N(1700) 3/2^-$	***	**	**	*			*	*	*	**
$N(1710) 1/2^+$	***	**	**	**		**	**	**	*	**
$N(1720) 3/2^+$	****	****	**	**			**	**	**	*
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$N(1875) 3/2^-$	***	*	**			**	**	**		**
$N(1880) 1/2^+$	**	*	*		**		*			
$N(1895) 1/2^-$	**	*	**	**			**	*		
$N(1900) 3/2^+$	***	**	**	**		**	**	**	*	**
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$N(2000) 5/2^+$	**	*	**	**			**	*	**	
...										
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$N(2220) 9/2^+$	****	****								
$N(2250) 9/2^-$	****	****								
$N(2600) 11/2^-$	***	**								
$N(2700) 13/2^+$	**	**								

Reported by BnGa group

I. Denisenko *et al.*, Phys. Lett. B 755, 97-101 (2016)

Complete Experiments in $\gamma p \rightarrow p \omega$

- In analogy to pseudoscalar mesons:

$$\frac{d\sigma}{d\Omega} = \sigma_0 \{ 1 - \delta_I \Sigma \cos 2\phi$$

$$+ \Lambda_x (-\delta_I H \sin 2\phi + \delta_{\odot} F)$$

published (+ SDME's)

$$- \Lambda_y (-T + \delta_I P \cos 2\phi)$$

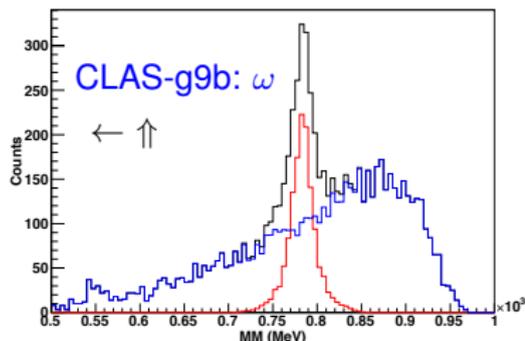
in progress (CLAS)

$$- \Lambda_z (-\delta_I G \sin 2\phi + \delta_{\odot} E) \}$$

- Event-based background subtraction
(event-based dilution factors)

$$\rightarrow \gamma p \rightarrow p \pi^+ \pi^- \checkmark \quad \gamma p \rightarrow p \pi^+ \pi^- (\pi^0) \checkmark$$

$E_\gamma \in [1.4, 1.5] \text{ GeV}$



Preparation of final state

- Standard PID, timing cuts
- Kinematic fitting (π^0 reconstruction)
- Event-based background subtraction (Q factors)

Complete Experiments in $\gamma p \rightarrow p \omega$

- In analogy to pseudoscalar mesons:

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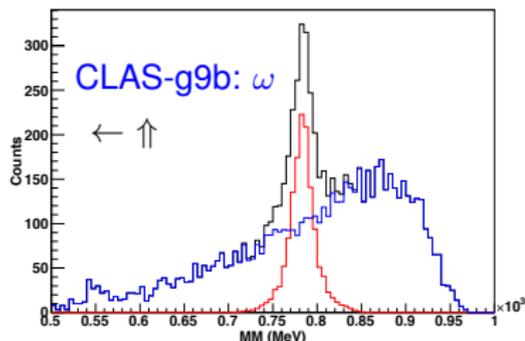
published (+ SDME's)

in progress (CLAS)

- Event-based background subtraction
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$$\rightarrow \gamma p \rightarrow p \pi^+ \pi^- \quad \checkmark \quad \gamma p \rightarrow p \pi^+ \pi^- (\pi^0) \quad \checkmark$$

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Preparation of final state

- Standard PID, timing cuts
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Complete Experiments in $\gamma p \rightarrow p \omega$

In analogy to pseudoscalar mesons:

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

published (+ SDME's)

in progress

$\phi = \Psi \equiv$ Angle between $p \omega$ production plane and the photon polarization plane in the overall CM frame.

$\Phi \equiv$ Azimuthal angle of normal to the ω decay plane in helicity frame - quantization axis in the direction opposite the recoiling proton in the ω rest frame.

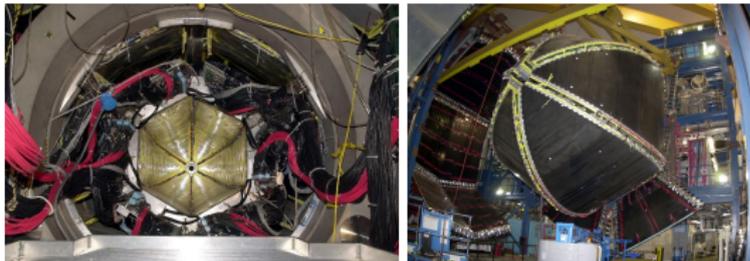
The ω is a vector meson (A. I. Titov and B. Kampfer, Phys. Rev. C 78, 038201 (2008))

$$2\pi W^f(\Phi, \Psi) = 1 - \Sigma_{\Phi}^f \cos 2\Phi - P_{\gamma} \Sigma_b^f \cos 2\Psi + P_{\gamma} \Sigma_d^f \cos 2(\Phi - \Psi)$$

$$\Sigma_b^h = \Sigma_b^r = 2\rho_{11}^1 + \rho_{00}^1 \quad -\frac{1}{2}\Sigma_d^h = \Sigma_d^r = \rho_{1-1}^1 \quad -\frac{1}{2}\Sigma_{\Phi}^h = \Sigma_{\Phi}^r = -\rho_{1-1}^0$$

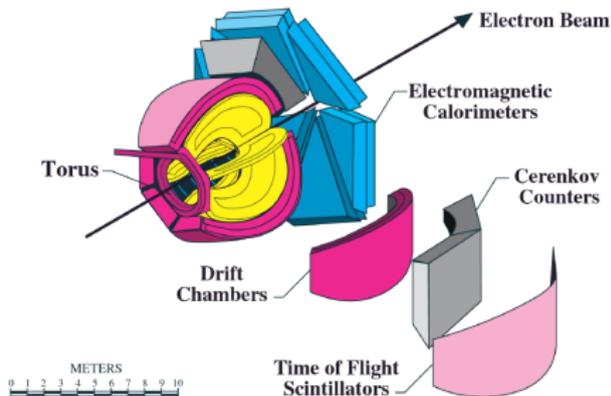
Pol. SDMEs, in preparation

The CLAS Spectrometer at Jefferson Laboratory



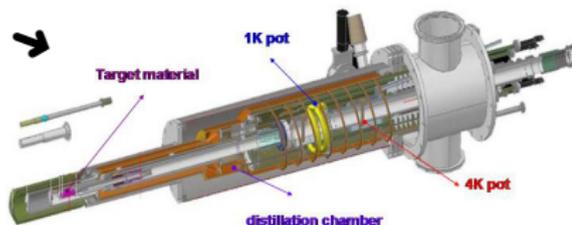
Frozen beads of butanol (C_4H_9OH)

- DNP at high B-field of 5.0 T, holding mode at 0.5 T
- Relaxation time of ~ 2800 h
- $\delta_{\max} \approx 94\%$



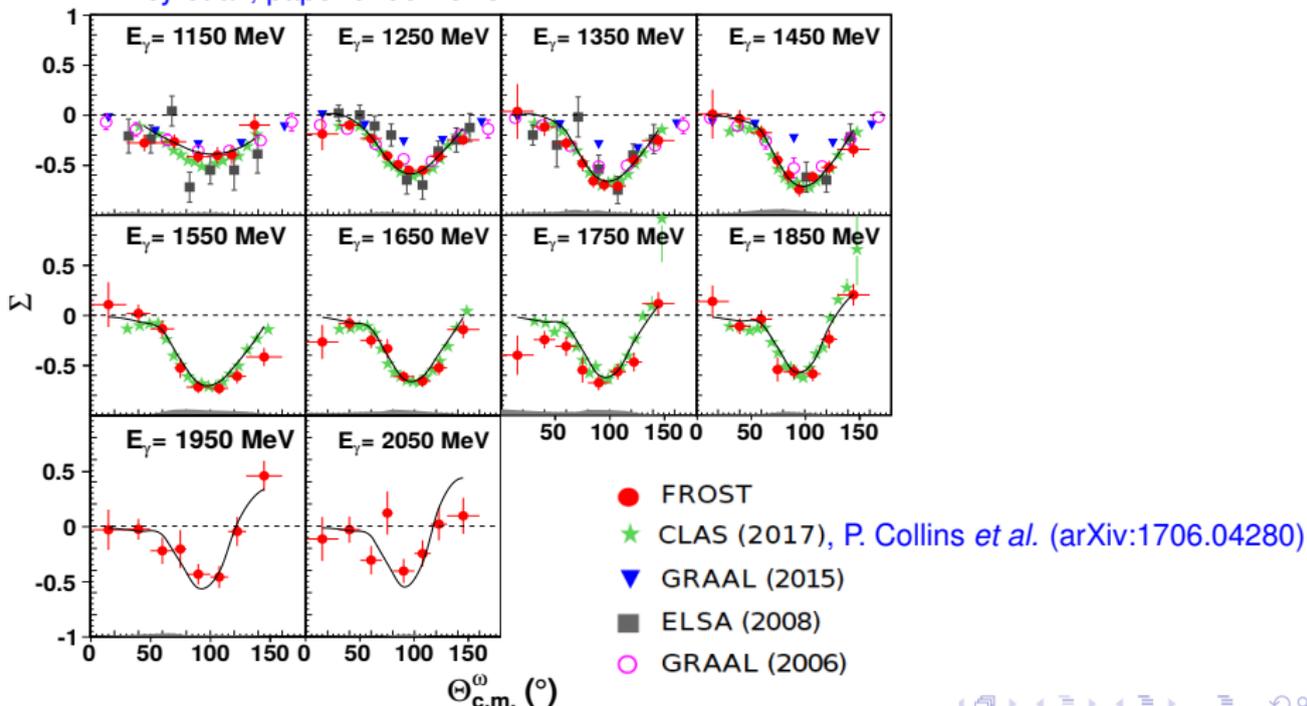
Session A3 (Pasyuk, Akbar, Walford, Net)

FROST



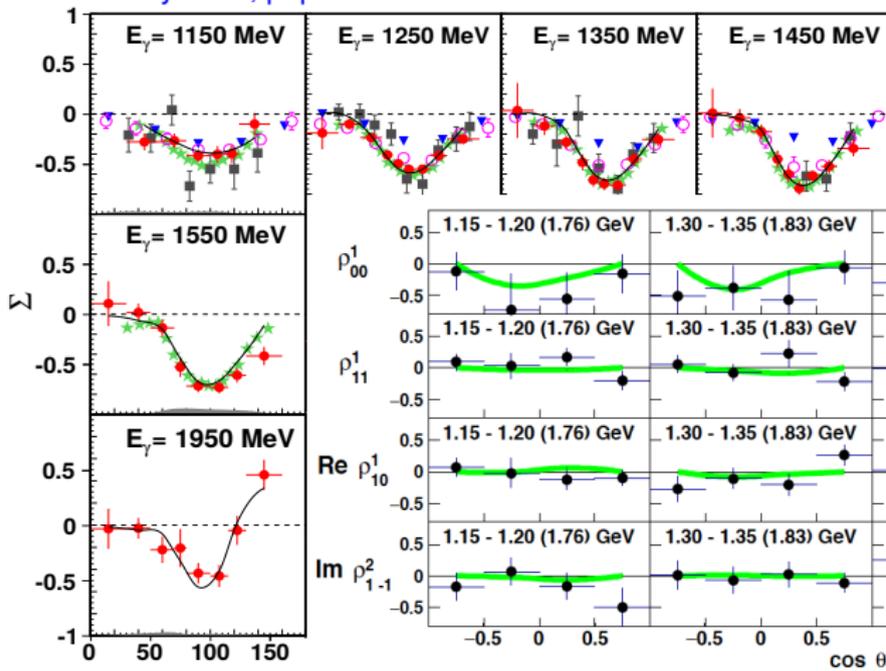
The Beam Asymmetry in $\vec{\gamma} p \rightarrow p \omega$ (CLAS-g9b)

P. Roy *et al.*, paper under review



The Beam Asymmetry in $\vec{\gamma} p \rightarrow p \omega$ (CLAS-g9b)

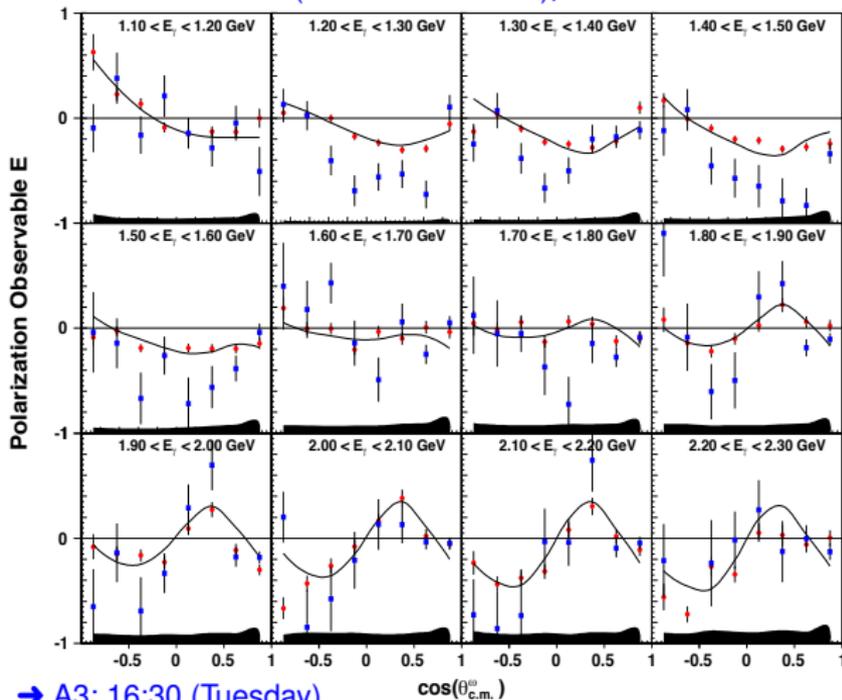
P. Roy *et al.*, paper under review



A. Wilson *et al.* [CBELSA/TAPS]
Phys. Lett. B **749**, 407 (2015)

Helicity Asymmetry in $\vec{\gamma} \vec{p} \rightarrow p \omega$ (CLAS-g9a)

Z. Akbar *et al.* (arXiv:1708.02608), submitted to PRC

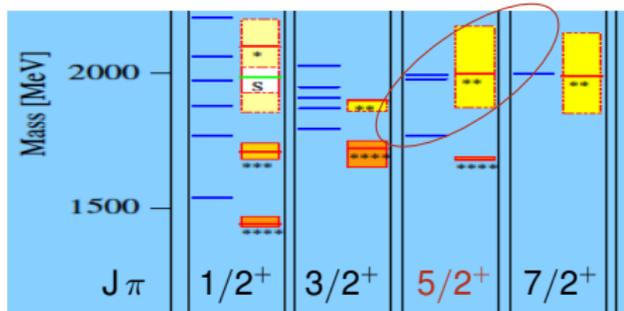
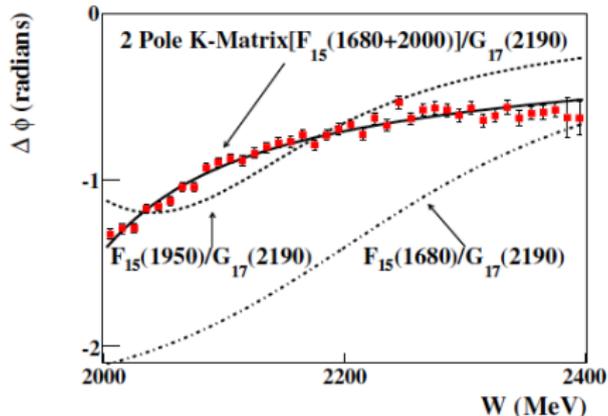
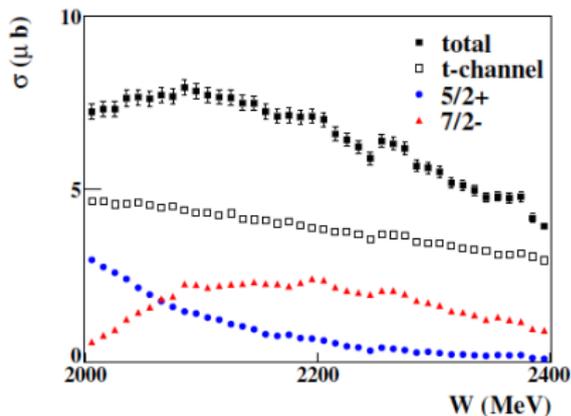


BnGa (coupled-channels) PWA

- Dominant **P** exchange
 - Complex $3/2^+$ wave
 - ① $N(1720)$
 - ② $W \approx 1.9$ GeV
 - $N(1895) 1/2^-$ (new)
 - $N(1680), N(2000) 5/2^+$
 - $7/2$ wave > 2.1 GeV
- CLAS-g9a
■ CBELSA/TAPS
Phys. Lett. B **750**, 453 (2015)

→ A3: 16:30 (Tuesday)

M. Williams *et al.* [CLAS Collaboration], Phys. Rev. C **80**, 065209 (2009)



PWA fit: resonances + t -channel amplitudes

Strong evidence for:

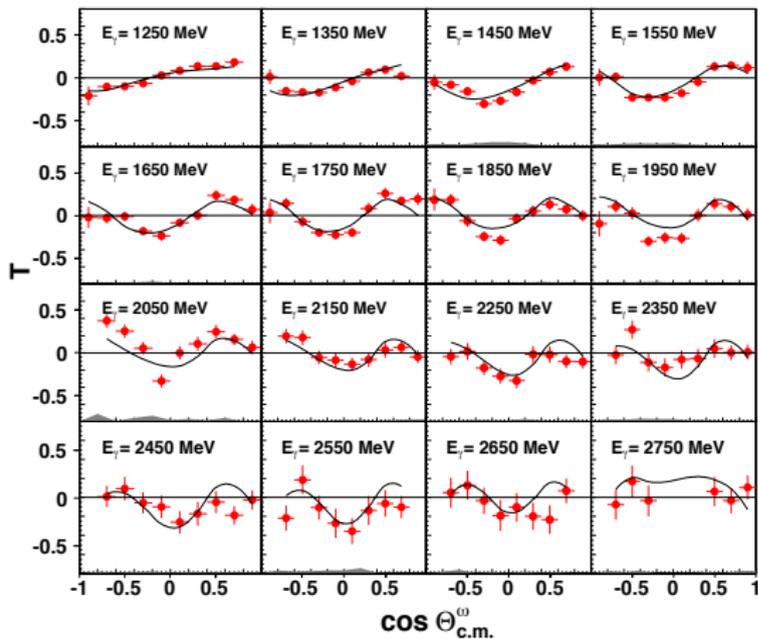
$(3/2)^- N(1700)$ * * *

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

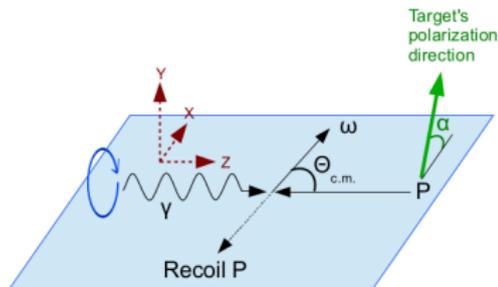
$(5/2)^+ N(1950)$ **

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

Target Asymmetry T in $\gamma \vec{p} \rightarrow p \omega$ (CLAS-g9b)

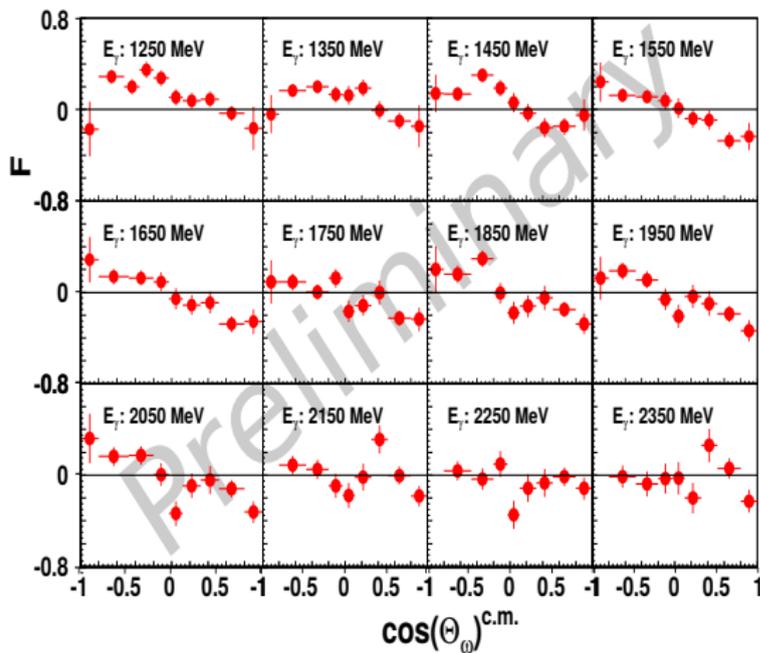


$$\frac{d\sigma}{d\Omega} = \sigma_0 \left\{ 1 - \delta_I \Sigma \cos 2\phi \right. \\ \left. + \Lambda_x (-\delta_I H \sin 2\phi + \delta_\odot F) \right. \\ \left. - \Lambda_y (-T + \delta_I P \cos 2\phi) \right. \\ \left. - \Lambda_z (-\delta_I G \sin 2\phi + \delta_\odot E) \right\}$$

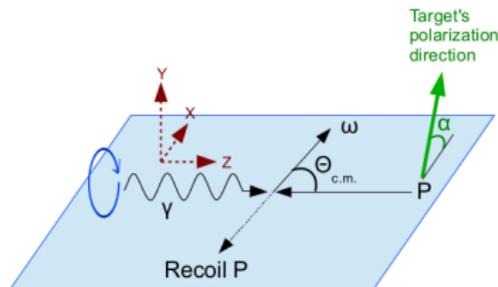


P. Roy *et al.* (Florida State), paper under review

Beam-Target Asymmetry F in $\vec{\gamma} \vec{p} \rightarrow p \omega$ (CLAS-g9b)



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



P. Roy (Florida State University), to be published

Toward a complete experiment in ω photoproduction ...

Toward a complete experiment in ω photoproduction:

- Cross sections and unpol. spin-density matrix elements for $E_\gamma \in [E_{\text{thres.}}, 3.6 \text{ GeV}]$
M. Williams *et al.* (CLAS Collaboration), Phys. Rev. C **80**, 065208 (2009)
- Polarization observables submitted / under review: E, Σ, T, F, P, H
Z. Akbar *et al.* (CLAS Collaboration), arXiv:1708.02608 [nucl-ex]; P. Roy *et al.*
P. Collins *et al.* (CLAS Collaboration), arXiv:1706.04280 [nucl-ex]
- Spin-density matrix elements (linear beam polarization) for $E_\gamma < 2.1 \text{ GeV}$
B. Vernarsky *et al.* (CLAS Collaboration), in preparation
- Spin-density matrix elements (circular beam polarization) for $E_\gamma < 5.0 \text{ GeV}$
Z. Akbar *et al.* (CLAS Collaboration), in preparation
- Measurement of ω cross sections for $E_{\text{thres.}} < E_\gamma < 5.4 \text{ GeV}$
→ Example for $4.1 < E_\gamma < 4.7 \text{ GeV}$

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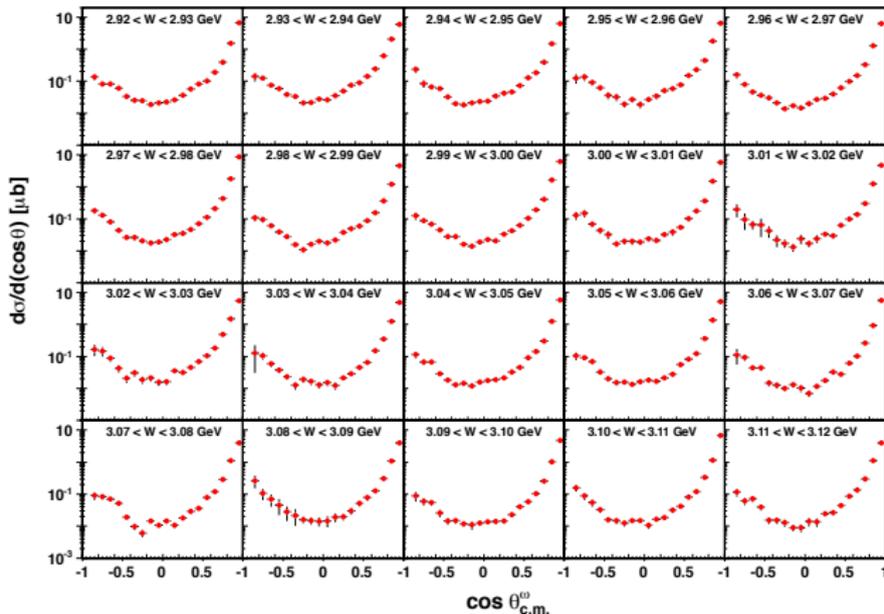
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Cross Sections for the Reaction $\gamma p \rightarrow p \omega \rightarrow p \pi^+ \pi^- \pi^0$

New cross section results
in 10-MeV-wide W bins for

$1.15 < E_\gamma < 5.40$ GeV, or
 $1.75 < W < 3.32$ GeV

→ Need theory support to
understand physics at
these high energies!!
(SDMEs in preparation)



→ Data of unprecedented quality

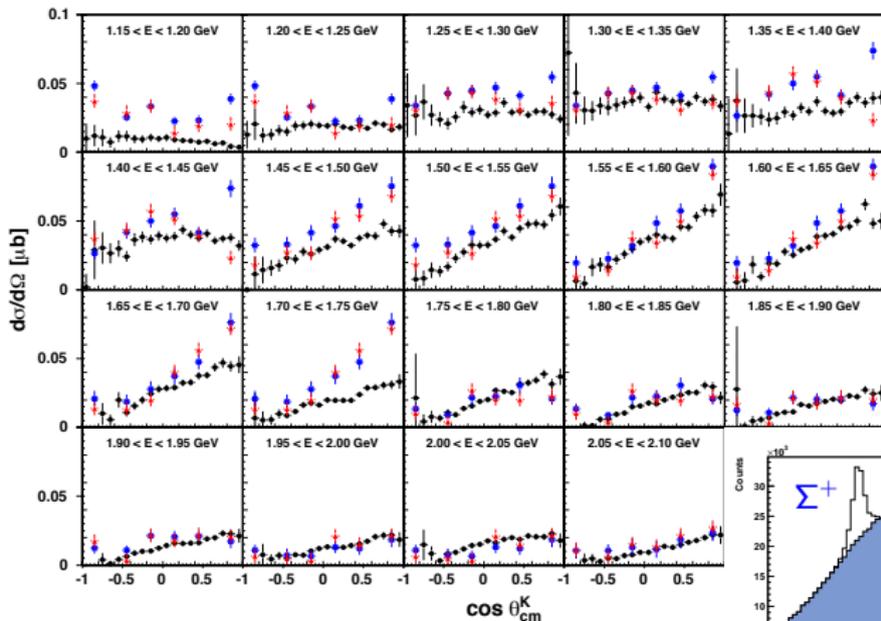
Cross Sections for $\gamma p \rightarrow K^0 \Sigma^+ \rightarrow p \pi^+ \pi^- \pi^0$

→ Session A3, Z. Akbar

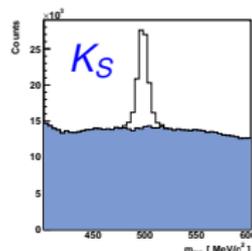
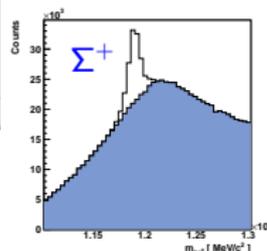
New cross section results
in 50-MeV-wide E_γ bins for

$$1.15 < E_\gamma < 3.0 \text{ GeV}$$

→ Need theory support to
understand physics!!



CLAS-g12 ● CB-ELSA ● CBELSA/TAPS ●



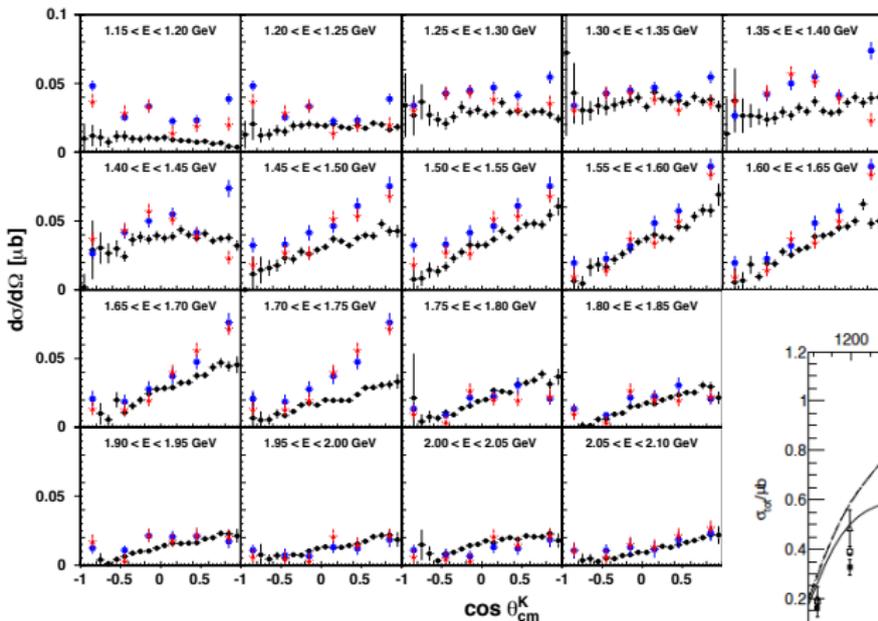
Cross Sections for $\gamma p \rightarrow K^0 \Sigma^+ \rightarrow p \pi^+ \pi^- \pi^0$

→ Session A3, Z. Akbar

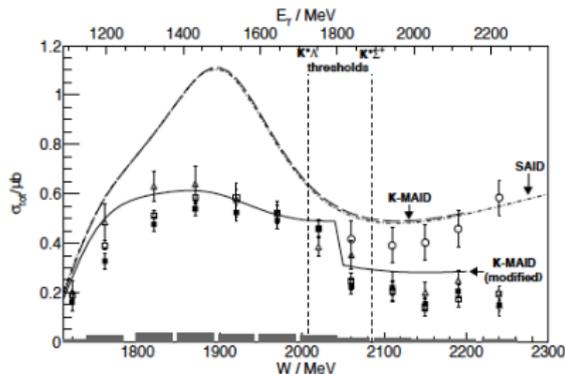
New cross section results
in 50-MeV-wide E_γ bins for

$1.15 < E_\gamma < 3.0$ GeV

Phys. Lett. B **713**, 180 (2012)



CLAS-g12 ● CB-ELSA ● CBELSA/TAPS ●

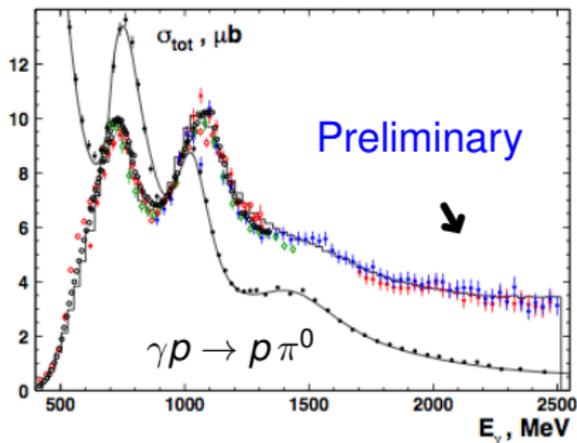


Outline

- 1 Introduction
 - Non-Perturbative QCD
 - The Spectrum of Baryons
- 2 Spectroscopy of Baryon Resonances
 - Complete Experiments
 - Polarization Observables in $\gamma p \rightarrow p \omega$
- 3 Decay Cascades of Excited Baryons
- 4 Summary and Outlook
 - Open Issues in (Light) Baryon Spectroscopy
 - Ξ Spectroscopy with the GlueX Detector



Observation of Decay Cascades in $\gamma p \rightarrow p \pi^0 \pi^0$



Observation of new decay modes in the decay of N^* resonances; weak at most in Δ^* decays.

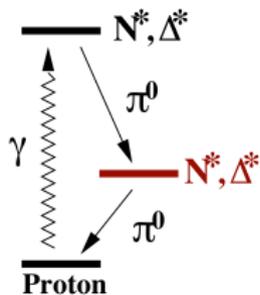
— Bonn-Gatchina PWA

Sokhoyan, Gutz, V. C. *et al.*, EPJ A **51**, no. 8, 95 (2015)

Cross Section and Polarization Observables

(W. Roberts *et al.*, PRC **71**, 055201 (2005))

$$I = I_0 \{ (1 + \vec{\Lambda}_i \cdot \vec{P}) + \delta_{\odot} (I^{\odot} + \vec{\Lambda}_i \cdot \vec{P}^{\odot}) + \delta_I [\sin 2\beta (I^s + \vec{\Lambda}_i \cdot \vec{P}^s) + \cos 2\beta (I^c + \vec{\Lambda}_i \cdot \vec{P}^c)] \}$$



→ Search for states in decay cascades!

Observation of Decay Cascades in $\gamma p \rightarrow p \pi^0 \pi^0$

Decays observed
in PWA into, e. g.

$$\left. \begin{array}{l} N(1880) 1/2^+ \\ N(1900) 3/2^+ \\ N(2000) 5/2^+ \\ N(1990) 7/2^+ \end{array} \right\} \begin{array}{l} N(1520)\pi \\ N(1535)\pi \\ N(1680)\pi \\ N\sigma \ (l=1) \end{array}$$

→ Quartet of $(70, 2_2^+)$ with $S = \frac{3}{2}$.

Observation of new decay modes in the decay of N^* resonances; weak at most in Δ^* decays.

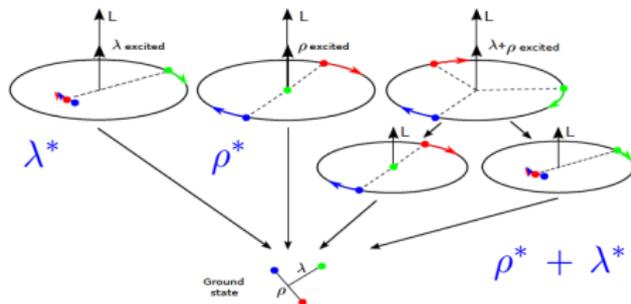
— Bonn-Gatchina PWA

Sokhoyan, Gutz, V. C. *et al.*, EPJ A **51**, no. 8, 95 (2015)

Nucleon states with $S = \frac{3}{2}$ require spatial wave functions of mixed symmetry. For $L = 2$ the wave functions do have equal admixtures of \mathcal{M}_S and

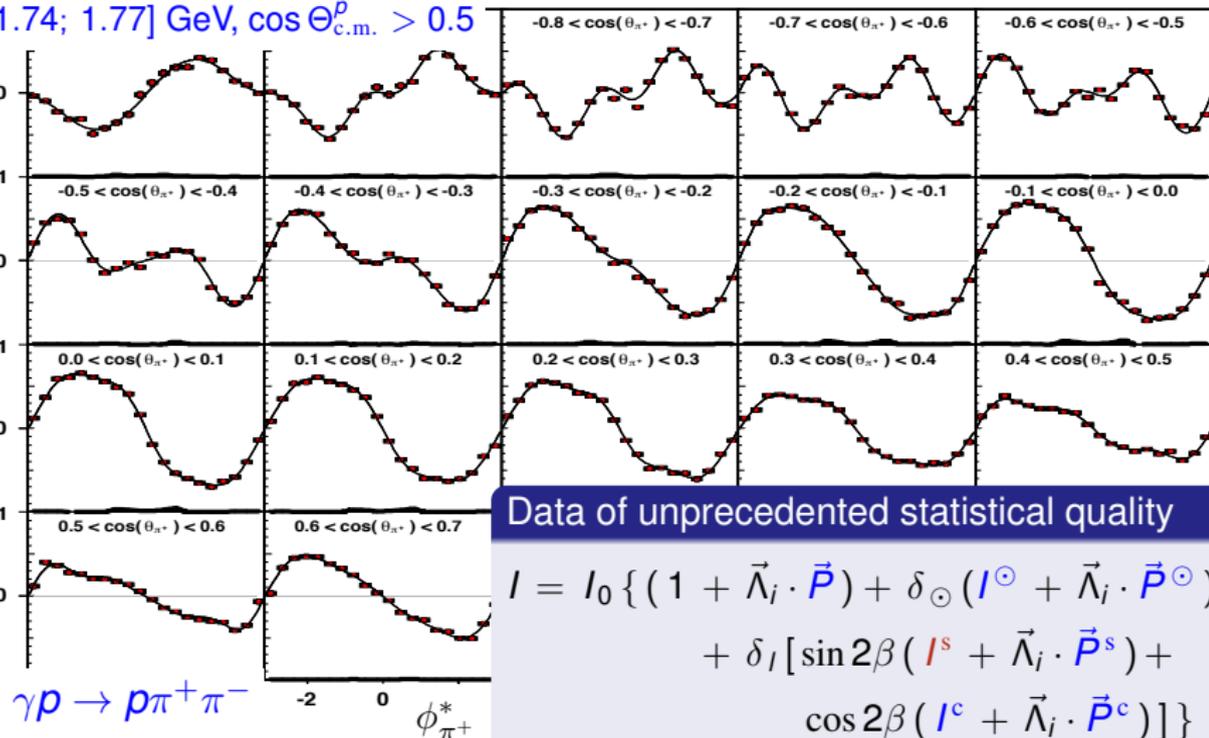
$$\mathcal{M}_A = [\phi_{0\rho}(\vec{\rho}) \times \phi_{0\rho}(\vec{\lambda})]^{(L=2)},$$

a component in which both the ρ and the λ oscillator are excited simultaneously.



$W \in [1.74; 1.77] \text{ GeV}, \cos \Theta_{c.m.}^p > 0.5$

Polarization Observable I^s



Data of unprecedented statistical quality

$$I = I_0 \{ (1 + \vec{\Lambda}_i \cdot \vec{P}) + \delta_{\odot} (I^{\odot} + \vec{\Lambda}_i \cdot \vec{P}^{\odot}) + \delta_l [\sin 2\beta (I^s + \vec{\Lambda}_i \cdot \vec{P}^s) + \cos 2\beta (I^c + \vec{\Lambda}_i \cdot \vec{P}^c)] \}$$

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 - ≡ Spectroscopy with the GlueX Detector



Open Issues in (Light) Baryon Spectroscopy

- 1 What are the relevant degrees of freedom in (excited) baryons?
→ Can the high-mass states be described by the dynamics of three flavored quarks? To what extent are diquark correlations, gluonic modes or hadronic degrees of freedom important in this physics?
- 2 Can we identify unconventional states in the strangeness sector, e.g. $\Lambda(1405)$ or the $N(1440)$?
- 3 What is the challenging situation with the $(20, 1_2^+)$ multiplet?
- 4 Can we identify the leading interactions between the constituents?
- 5 Do we understand the decay of high-mass baryon resonances?
Is a similar dynamical mechanism applicable (hadronic d.o.f.)?
- 6 What are the missing resonances and why are so many still missing?

Hyperon spectroscopy will help shed some light on the fascinating challenges in QCD Resonance Physics.

Summary and Outlook

Baryon Spectroscopy: Are we there, yet? Certainly not ...

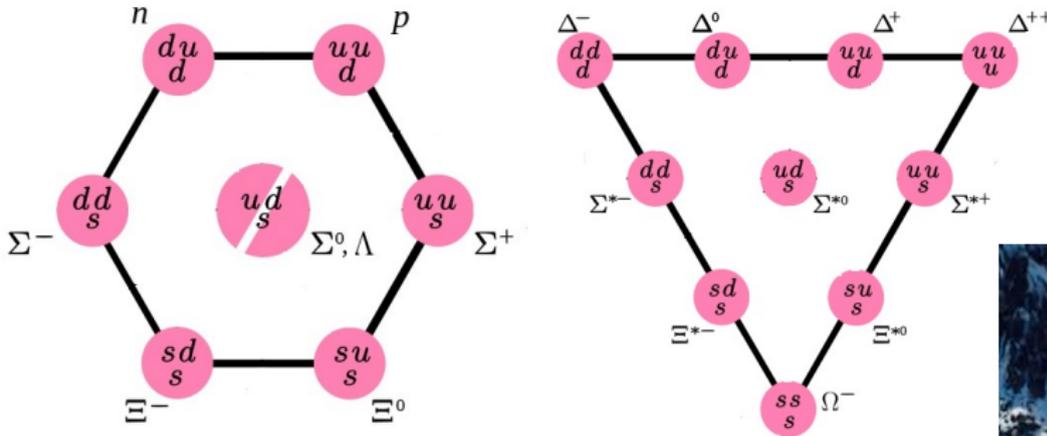
New era in the spectroscopy of strange baryons (GlueX, LHCb, PANDA, ...)

- Mapping out the spectrum of Ξ baryons is the primary motivation (including parity measurements); some hope for peak hunting.
- Ground-state Ξ in $\gamma p \rightarrow KK \Xi$ will allow the spectroscopy of Σ^* / Λ^* states.

The multi-strange baryons provide a missing link between the light-flavor and the heavy-flavor baryons. Also:

- 1 Do the lightest excited Ξ states in certain partial waves decouple from the $\Xi\pi$ channel, confirming the flavor independence of confinement?
- 2 Ξ baryons as a probe of excited hadron structure?
 - Measurements of the isospin splittings in spatially excited Ξ states appear possible for the first time (similar to $n - p$ or $\Delta^0 - \Delta^{++}$).

Cascade Spectrum and Multiplets

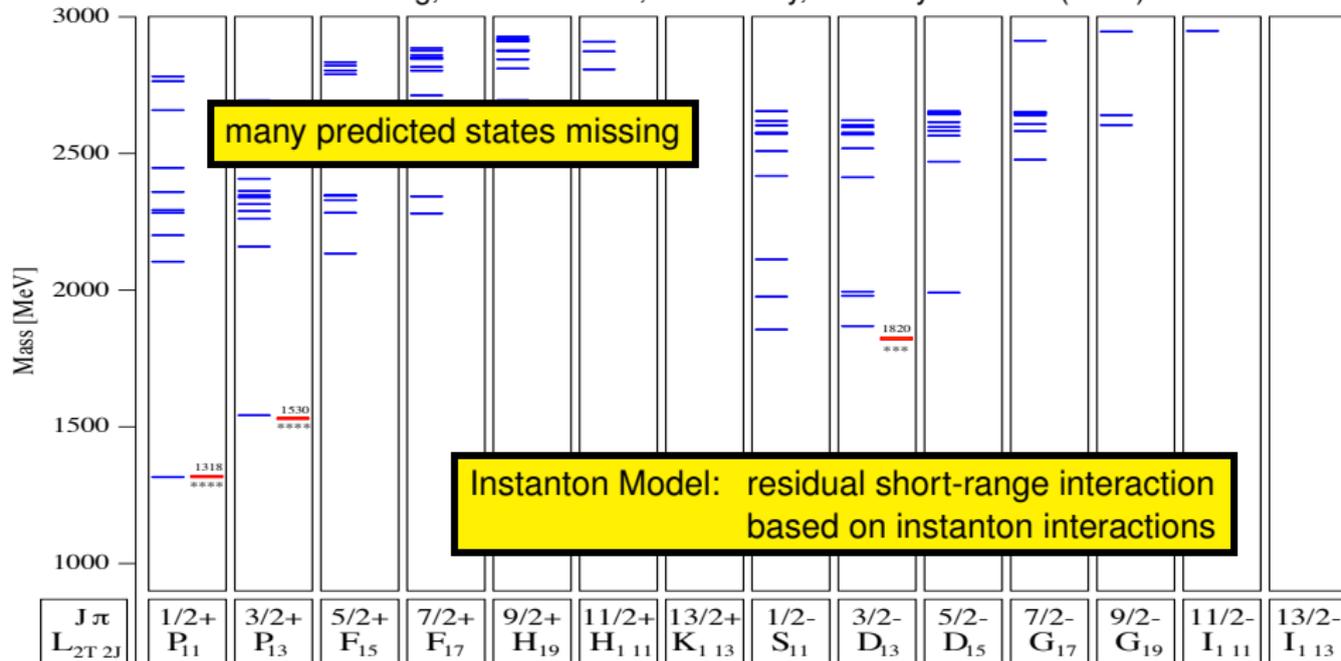


The decuplets consist of Δ^* , Σ^* , Ξ^* , and Ω^* resonances, but also the octets consist of an Ξ^* state.

→ We expect as many Ξ^* 's as N^* & Δ^* states together. Moreover, their properties should be related.

Cascade Resonances: Status of 2015

— U. Loering, B. Ch. Metsch, H. R. Petry, Eur. Phys. J. **A10** (2001) 447-486



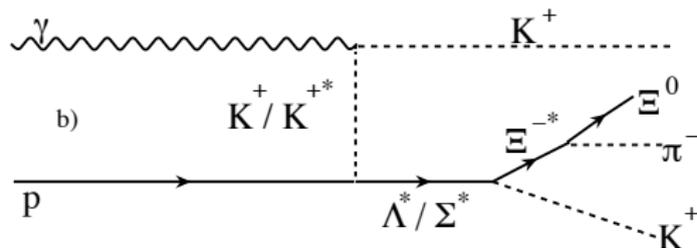
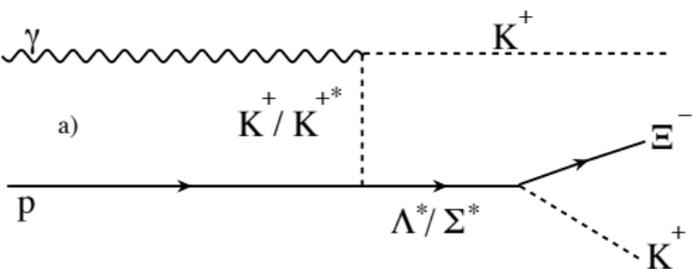
Possible Production Mechanisms

$K^+(\Xi^- K^+)$, $K^+(\Xi^0 K^0)$, $K^0(\Xi^0 K^+)$

→ Cross sections, beam asymmetries
(similar to $p\pi\pi$ & pKK^*)

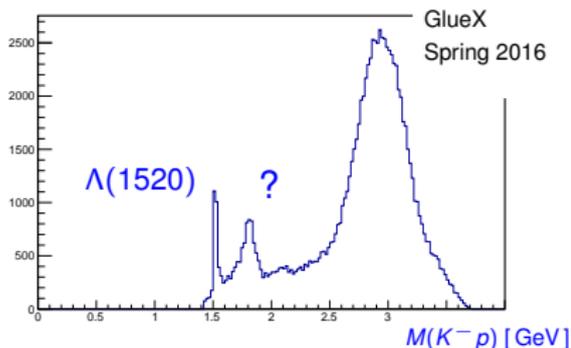
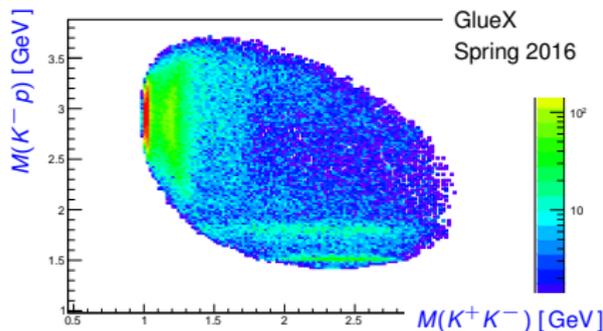
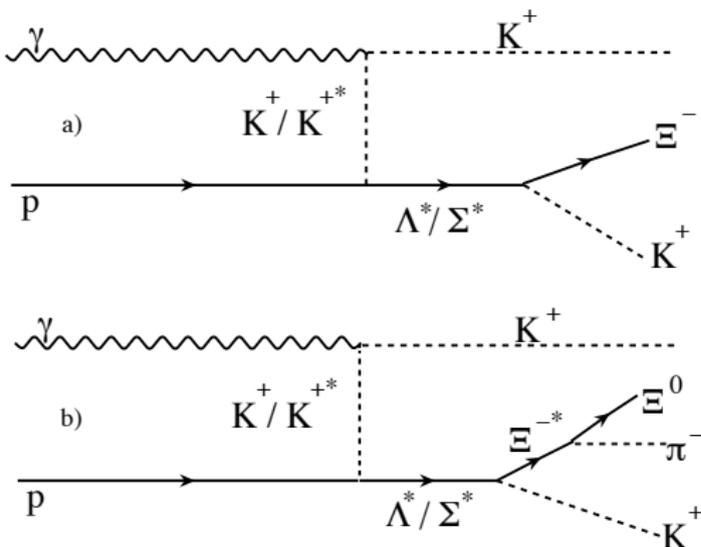
Production of excited states via a

- 1 forward-going K^0 meson
→ $K^0(\Xi^- \pi^+) K^+$, etc.
- 2 forward-going K^+ meson
→ $K^+(\Xi^- \pi^+) K^0$,
 $K^+(\Xi^0 \pi^-) K^+$, etc.



* W. Roberts *et al.*, Phys. Rev. C **71**, 055201 (2005)

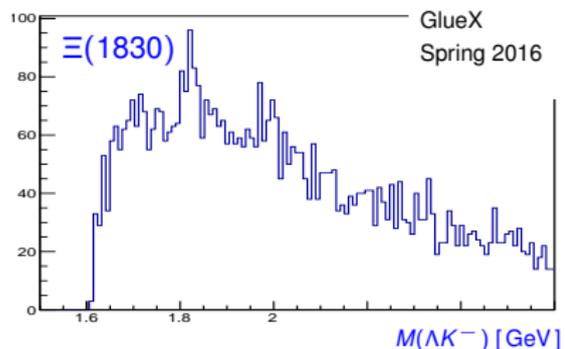
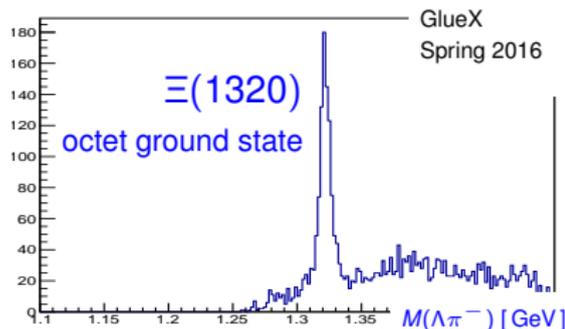
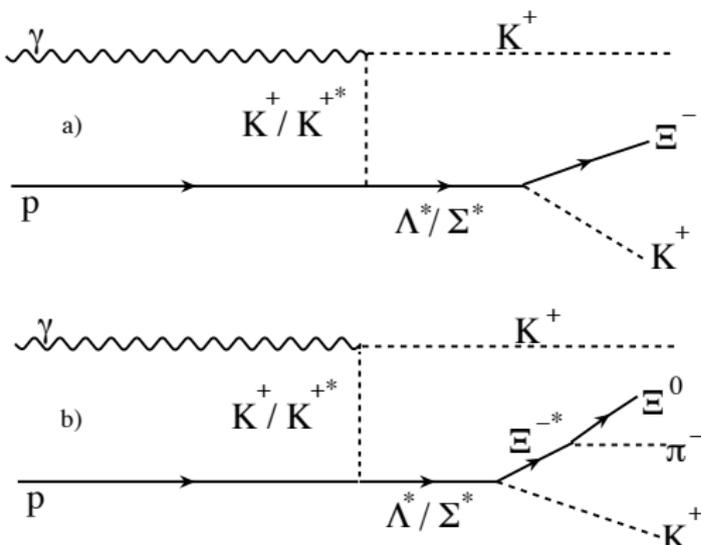
Possible Production Mechanisms



Courtesy of Sean Dobbs



Possible Production Mechanisms



Courtesy of Ashley Ernst (FSU)

Acknowledgement

This material is based upon work supported in part by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under Award Number DE-FG02-92ER40735.