Understanding the Spectrum of Baryons: Current Status and Future Experiments

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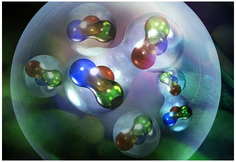
Hadronic Physics with Lepton and Hadron Beams

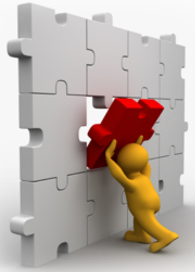


Jefferson Lab

09/05/2017

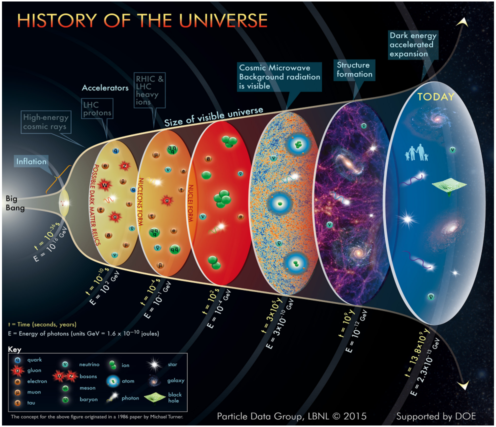
Outline

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



Outline

The Evolution of the Universe



$t \sim 10^{-9}$ s Quark-Gluon Plasma

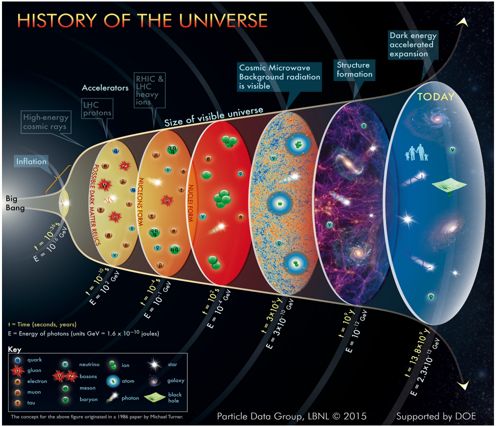
$t \sim 10^{-4}$ s Nucleons

$t \sim 10^{2}$ s Nuclei

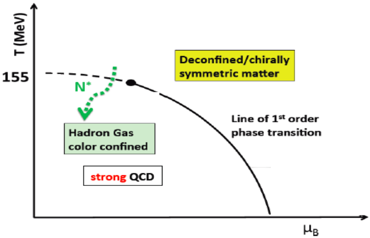
$t \sim 3 \times 10^{5}$ s Atoms

At $t \sim 10^{-6}$ s: Transition from QGP to Nucleons

The Evolution of the Universe



- Chiral symmetry is broken
- Quarks acquire mass
- Baryon resonances occur
- Color confinement emerges



At $t \sim 10^{-6}$ s: Transition from QGP to Nucleons

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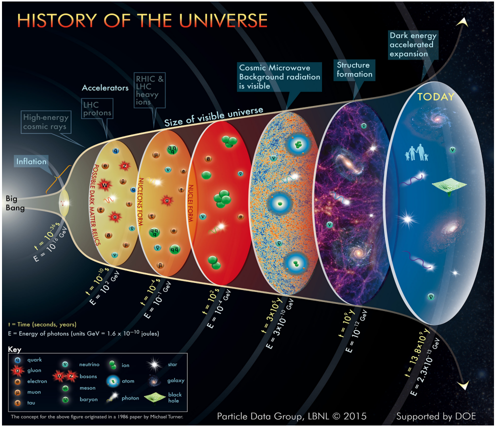

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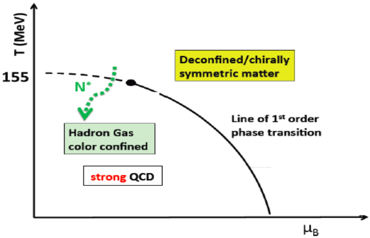
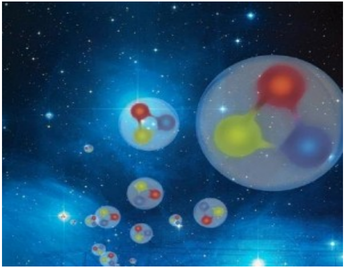


The (u, d, s, c) baryons listed in the RPP are not sufficient to describe the freeze-out behavior ➜ Spectroscopy!!

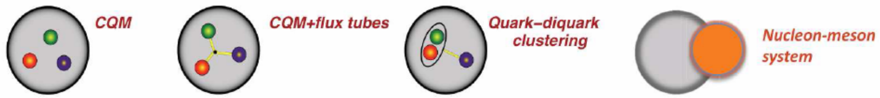
Non-Perturbative QCD



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?

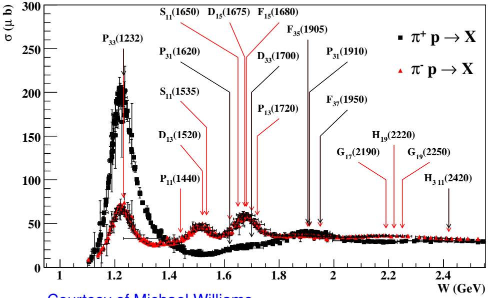


Hadrons: Baryons & Mesons

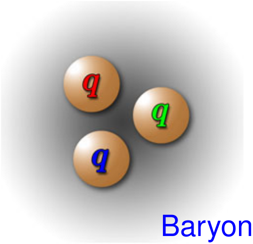
The strong coupling confines quarks and breaks chiral symmetry, and so defines the world of light hadrons.

Baryons are special because

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



Courtesy of Michael Williams



Baryons

➜ PDG 2010, J. Phys. G **37**, 075021

Great progress in recent years:

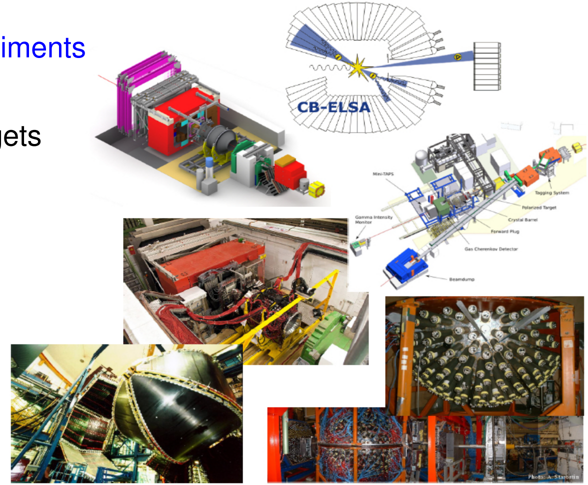
➜ γN & πN data

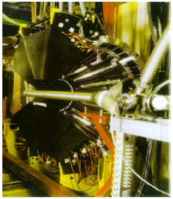
Baryon Spectroscopy in the 21st Century

Photoproduction

➜ Toward Complete Experiments

- (Double-) Polarization
- Proton & Neutron Targets





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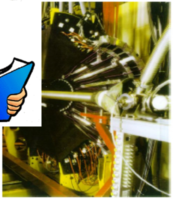
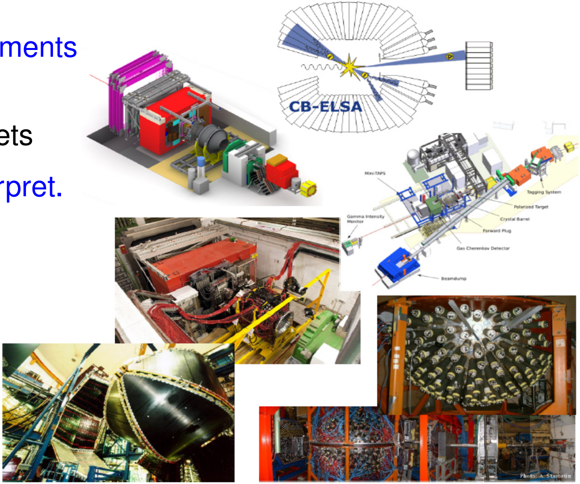
Data are still difficult to interpret.





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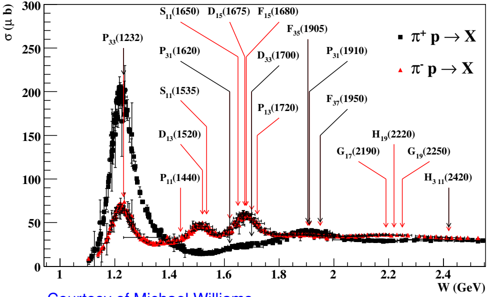

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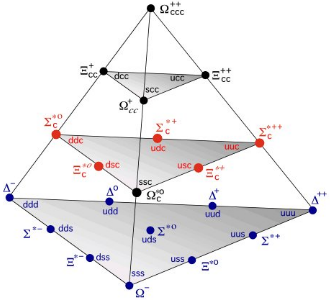


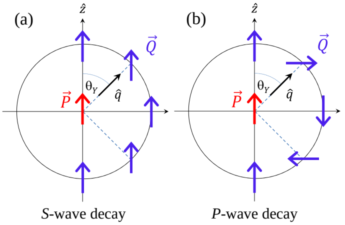
Many Y^* QN not measured:
(Quark model assignments)
➜ many Ξ^* and Ω^*, etc.

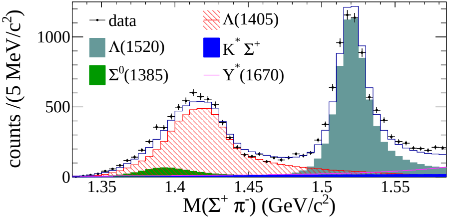
Spin and Parity Measurement of the $\Lambda(1405)$ Baryon

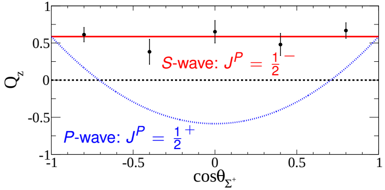
K. Moriya *et al.* [CLAS Collaboration], Phys. Rev. Lett. **112**, 082004 (2014)

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

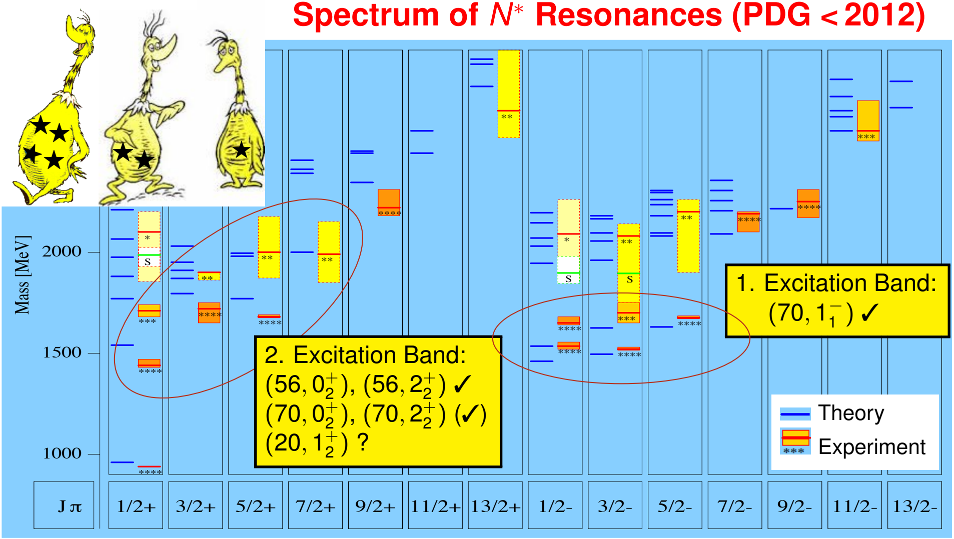
- Decay distribution of $\Lambda(1405) \to \Sigma^+\pi^-$ consistent with $J = 1/2$.
- Polarization transfer, $\vec{Q}$, in $Y^* \to Y\pi$:
  - S-wave decay: $\vec{Q}$ independent of θ_Y





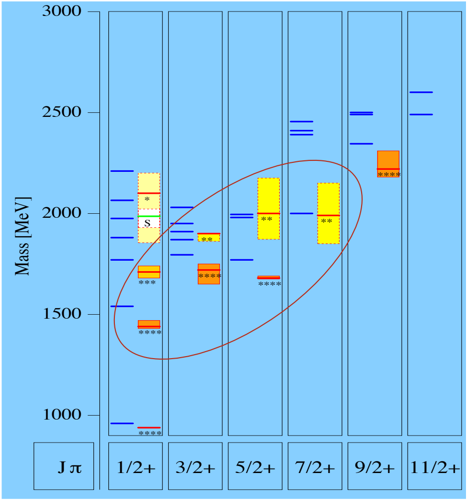


Spectrum of N^* Resonances (PDG < 2012)



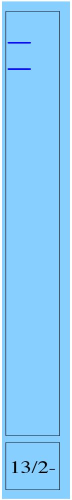
— S. Capstick and N. Isgur, Phys. Rev. **D34** (1986) 2809

Spectrum of N^* Resonances

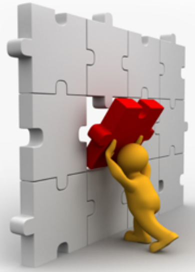


V. C. & W. Roberts, Rep. Prog. Phys. **76** (2013)

N^*	J^P ($L_{2I,2J}$)	2010	2016
$N(1440)$	$1/2^+$ (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}	**	



Outline



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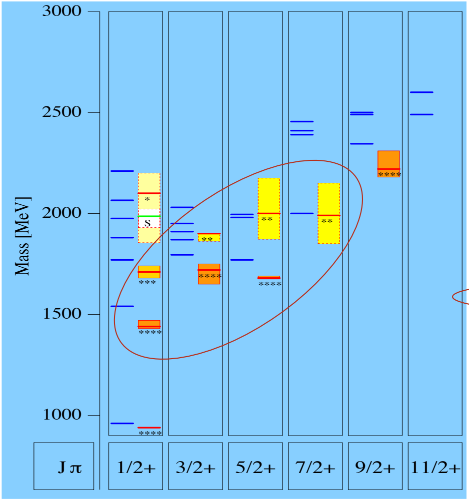

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$N(1535)$	$1/2^-$ (S_{11})	* * **	* * **
$N(1650)$	$1/2^-$ (S_{11})	* * **	* * **
$N(1675)$	$5/2^-$ (D_{15})	* * **	* * **
$N(1680)$	$5/2^+$ (F_{15})	* * **	* * **
$N(1685)$			*
$N(1700)$	$3/2^-$ (D_{13})	* * *	* * *
$N(1710)$	$1/2^+$ (P_{11})	* * *	* * **
$N(1720)$	$3/2^+$ (P_{13})	* * **	* * **
$N(1860)$	$5/2^+$		**
$N(1875)$	$3/2^-$		* * *
$N(1880)$	$1/2^+$		**
$N(1895)$	$1/2^-$		**
$N(1900)$	$3/2^+$ (P_{13})	**	* * *
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$N(2100)$	$1/2^+$ (P_{11})	*	*
$N(2120)$	$3/2^-$		**
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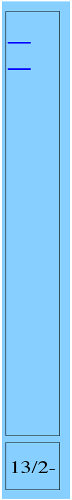
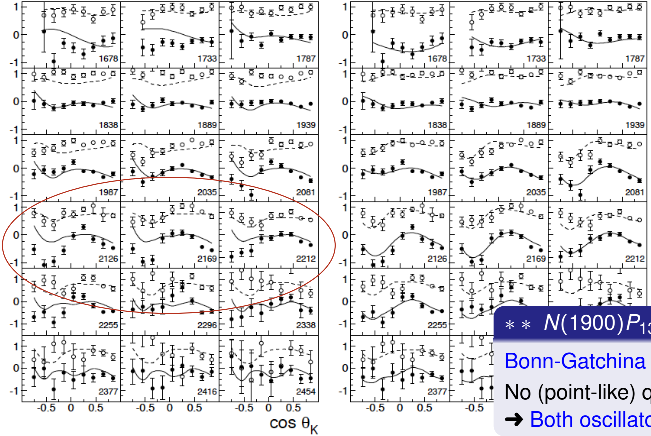
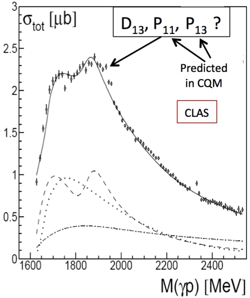


V. C. & W. Roberts, Rep. Prog. Phys. **76** (2013)

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

without $N(1900)P_{13}$ with $N(1900)P_{13}$





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

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

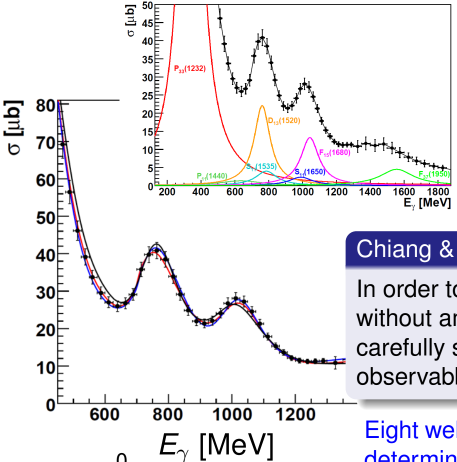
No (point-like) quark-diquark oscillations!

➜ 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?



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

Single-(pseudoscalar) meson production:

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

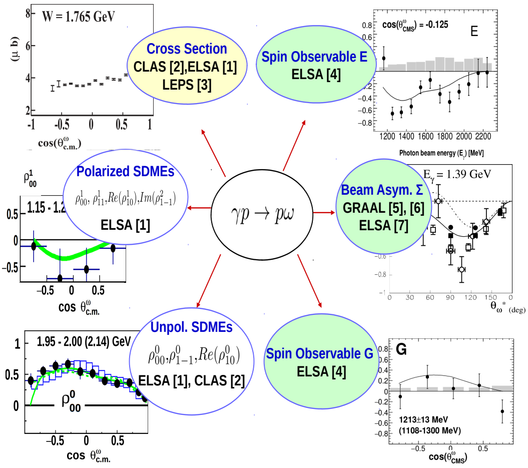
Chiang & Tabakin, Phys. Rev. C55, 2054 (1997)

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 $\gamma\, p \to p\, \omega$

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



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

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

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$N(1880)\,1/2^+$	**	*	*		**		*			
$N(1895)\,1/2^-$	**	*	**	**			**	*		
$N(1900)\,3/2^+$	***	**	***	**		**	***	**	*	**
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$N(2700)\,13/2^+$	**	**								

Reported by BnGa group

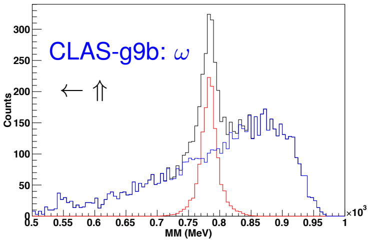
I. Denisenko *et al.*, Phys. Lett. B 755, 97-101 (2016)

Complete Experiments in $\gamma\, p \to p\,\omega$

- In analogy to pseudoscalar mesons:

$$\frac{d\sigma}{d\Omega} = \sigma_0 \{1 - \delta_l \Sigma \cos 2\phi$$
$$+ \Lambda_x(-\delta_l H \sin 2\phi + \delta_\odot F)$$
published (+ SDME's) $\quad - \Lambda_y(-T + \delta_l P \cos 2\phi)$
in progress (CLAS) $\quad - \Lambda_z(-\delta_l G \sin 2\phi + \delta_\odot E)\}$

$E_\gamma \in [1.4, 1.5]$ GeV



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

  ➜ $\gamma p \to p\pi^+\pi^-$ ✓ $\quad \gamma p \to p\pi^+\pi^-(\pi^0)$ ✓

Preparation of final state

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

Complete Experiments in $\gamma\, p \to p\,\omega$

- In analogy to pseudoscalar mesons:

$$\frac{d\sigma}{d\Omega} = \sigma_0 \{ 1 - \delta_l \Sigma \cos 2\phi$$
$$+ \Lambda_x (-\delta_l H \sin 2\phi + \delta_\odot F)$$

published (+ SDME's) $- \Lambda_y (-T + \delta_l P \cos 2\phi)$

in progress (CLAS) $- \Lambda_z (-\delta_l G \sin 2\phi + \delta_\odot E)\}$

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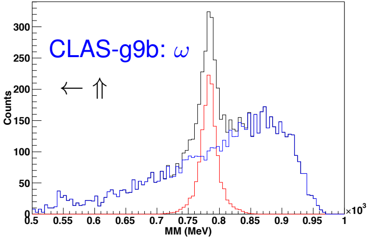

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- Kinematic fitting (π^0 reconstruction)
- Event-based background subtraction (Q factors)

Complete Experiments in $\gamma\, p \to p\,\omega$

In analogy to pseudoscalar mesons:

$$\frac{d\sigma}{d\Omega} = \sigma_0 \{ 1 - \delta_l \Sigma \cos 2\phi$$
$$+ \Lambda_x (-\delta_l H \sin 2\phi + \delta_\odot F)$$
published (+ SDME's) $$- \Lambda_y (-T + \delta_l P \cos 2\phi)$$
in progress $$- \Lambda_z (-\delta_l G \sin 2\phi + \delta_\odot E) \}$$

$\phi = \Psi \equiv$ 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.

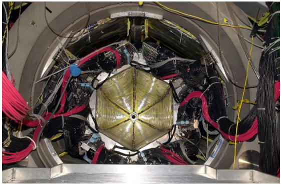
The ω is a vector meson (A. I. Titov and B. Kampfer, Phys. Rev. C 78, 038201 (2008))

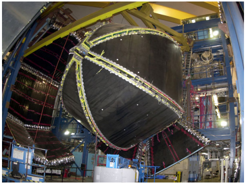
$$2\pi\, W^f(\Phi, \Psi) = 1 - \Sigma^f_\Phi \cos 2\Phi - P_\gamma \Sigma^f_b \cos 2\Psi + P_\gamma \Sigma^f_d \cos 2(\Phi - \Psi)$$

$$\Sigma^h_b = \Sigma^r_b = 2\rho^1_{11} + \rho^1_{00} \qquad -\tfrac{1}{2}\Sigma^h_d = \Sigma^r_d = \rho^1_{1\,-1} \qquad -\tfrac{1}{2}\Sigma^h_\Phi = \Sigma^r_\Phi = -\rho^0_{1\,-1}$$

Pol. SDMEs, in preparation

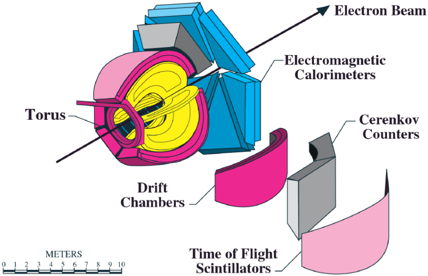
The CLAS Spectrometer at Jefferson Laboratory



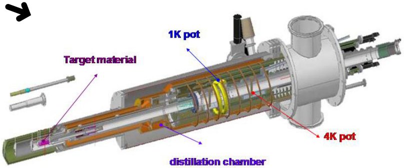


Frozen beads of butanol (C_4H_9OH)

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

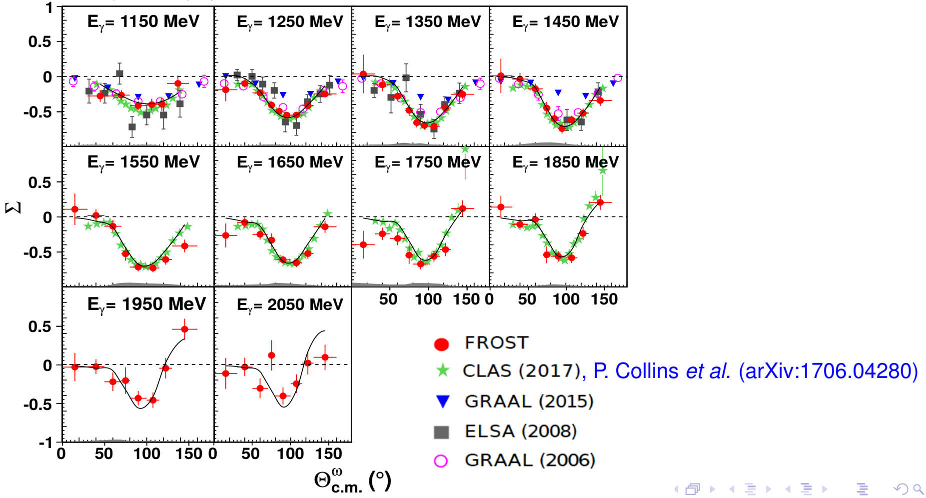


FROST Target



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

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



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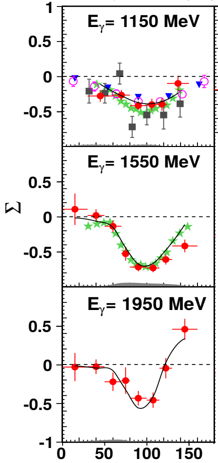
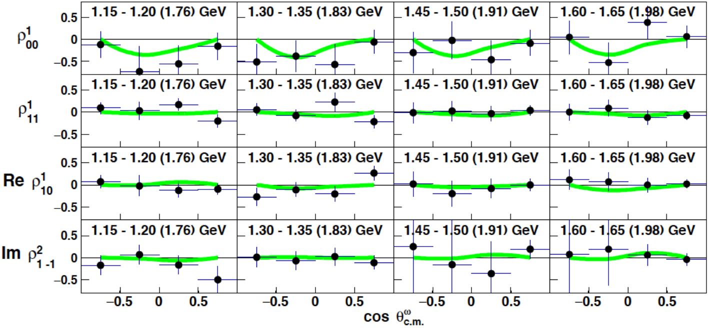
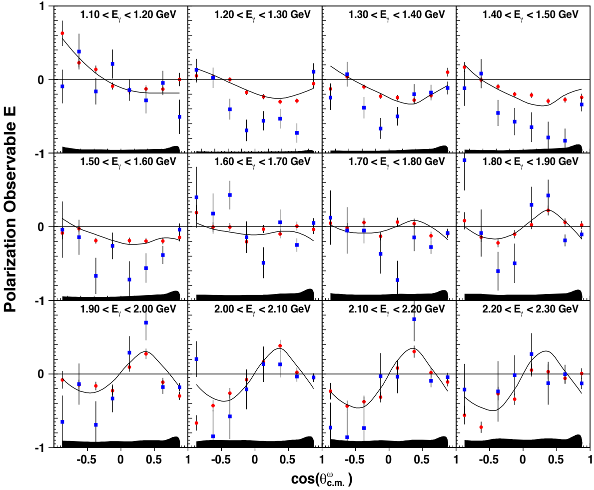


A. Wilson *et al.* [CBELSA/TAPS]
Phys. Lett. B **749**, 407 (2015)



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

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



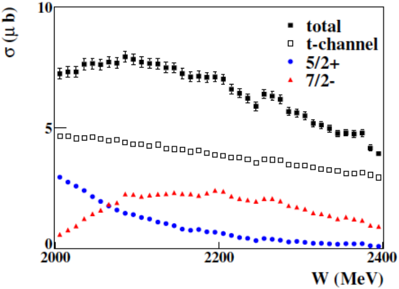
BnGa (coupled-channels) PWA

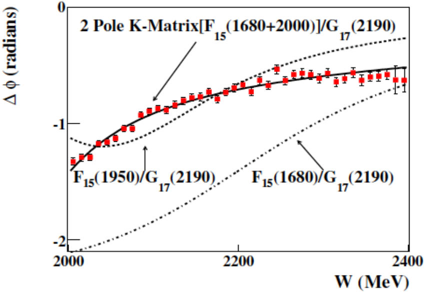
- Dominant $\mathbb{P}$ exchange
- Complex $3/2^+$ wave
  1. $N(1720)$
  2. $W \approx 1.9$ GeV
- $N(1895)\,1/2^-$ (new)
- $N(1680)$, $N(2000)\,5/2^+$
- 7/2 wave > 2.1 GeV

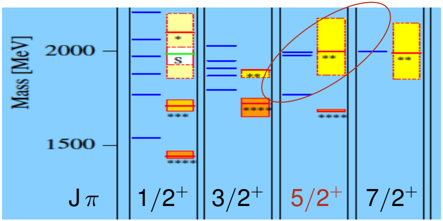
● CLAS-g9a

■ CBELSA/TAPS
Phys. Lett. B **750**, 453 (2015)

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





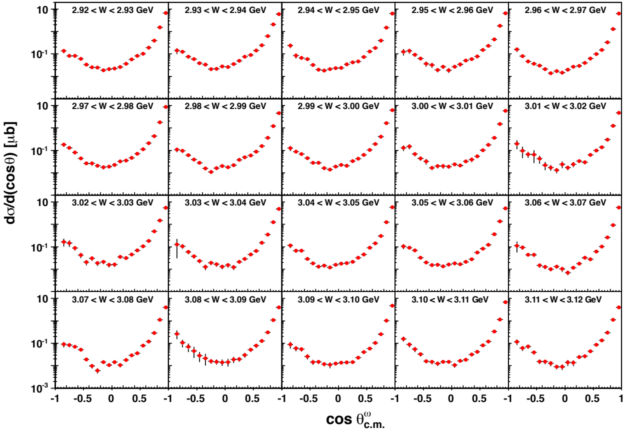


PWA fit: resonances + t-channel amplitudes

Strong evidence for:

- $(3/2)^-$ N(1700) $***$
- $(5/2)^+$ N(1680) $****$
- $(5/2)^+$ N(1950) $**$
- $(7/2)^-$ N(2190) $****$

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



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

$1.15 < E_\gamma < 5.40$ GeV, or

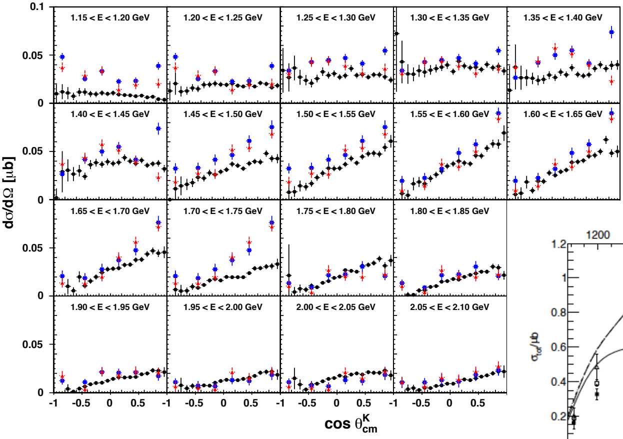
$1.75 < W < 3.32$ GeV

➜ Need theory support to understand physics at these high energies!!

(SDMEs in preparation)

➜ Data of unprecedented quality

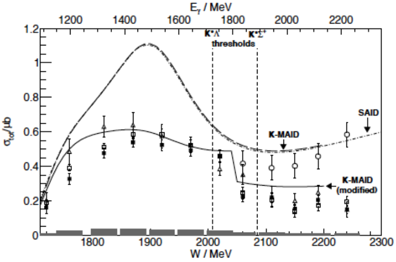
Cross Sections for $\gamma p \to K^0\,\Sigma^+ \to p\,\pi^+\pi^-\pi^0$



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 $\gamma p \to p\,\omega$
3. Open Issues in Light Baryon Spectrosocpy
4. Summary and Outlook
   - Spectroscopy of Ξ Baryons 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.

Outline

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Summary and Outlook

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

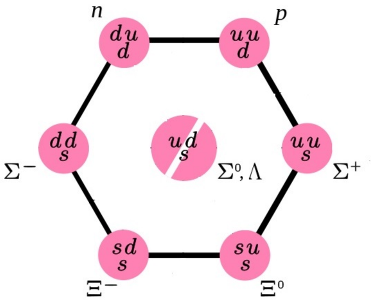
New era in the spectroscopy of strange baryons (GlueX, LHCb, PANDA, ...)

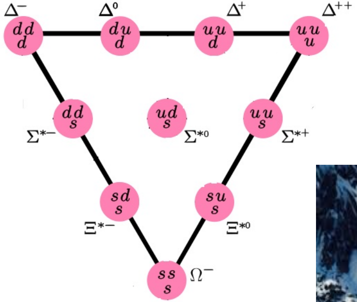
- Mapping out the spectrum of Ξ baryons is the primary motivation (including parity measurements); some hope for peak hunting.
- Ground-state Ξ in $\gamma p \to KK\,\Xi$ will allow the spectroscopy of Σ^* / Λ^* states.

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

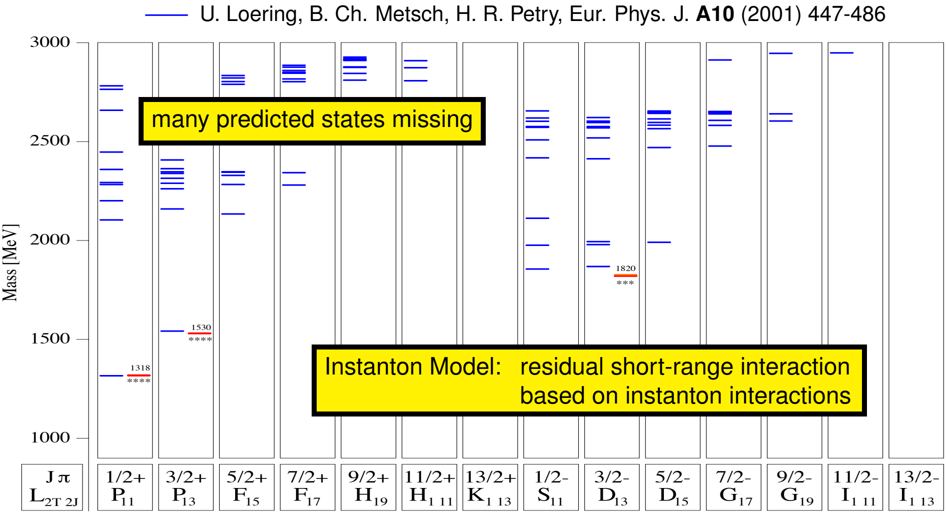




The decuplets consist of Δ^*, Σ^*, Ξ^*, and Ω^* resonances, but also the octets consist of an Ξ^* state.

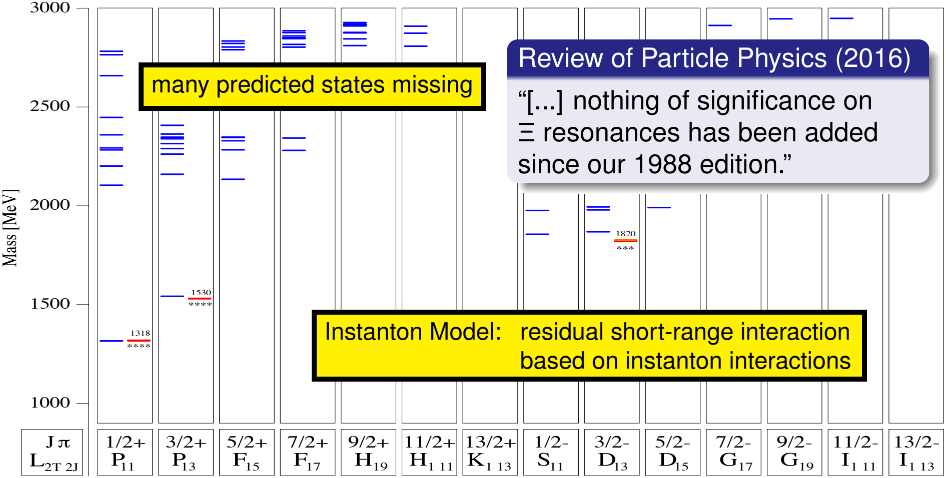
➜ We expect as many Ξ's as N^* & Δ^* states together. Moreover, their properties should be related.

Cascade Resonances: Status as of 2016



Cascade Resonances: Status as of 2016

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



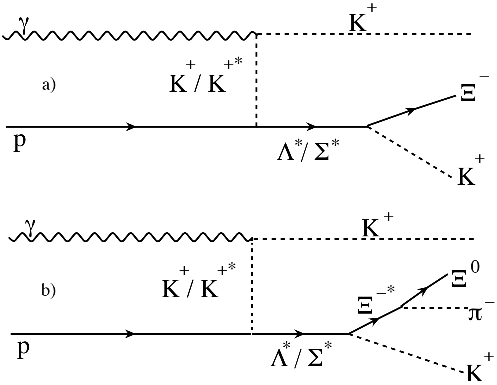
many predicted states missing

Review of Particle Physics (2016)

"[...] nothing of significance on Ξ resonances has been added since our 1988 edition."

Instanton Model: residual short-range interaction based on instanton interactions

Possible Production Mechanisms



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

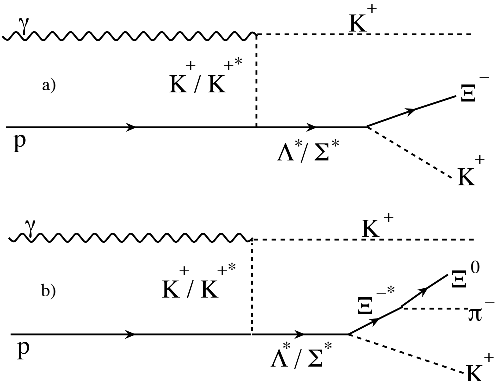
➜ Cross sections, beam asymmetries (similar to $p\pi\pi$ & pKK^*)

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



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

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

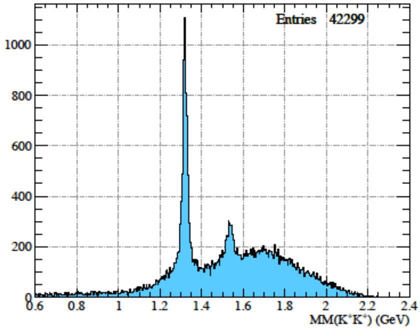
At other facilities (for comparison):

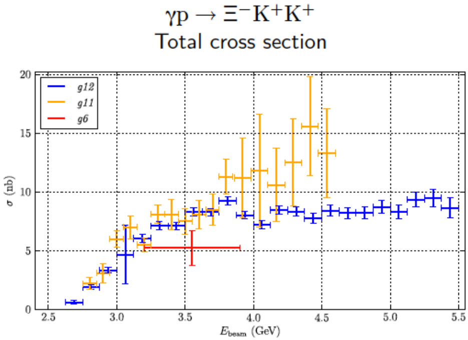
$K^- p \to K^+ \Xi^{*-}$	J-PARC
$K_L p \to K^+ \Xi^{*0}$	Hall D ?
$p p \to \Xi^* X$	LHCb
$\bar{p} p \to \Xi^* \bar{\Xi}$	$\overline{\text{P}}$ANDA
$e^+ e^- \to \Xi^* X$	Belle II, BES III

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

CLAS g12: Total Cross Section of Ξ^- (preliminary)

Johann Goetz (CLAS Collaboration), UCLA, Ph.D. Thesis

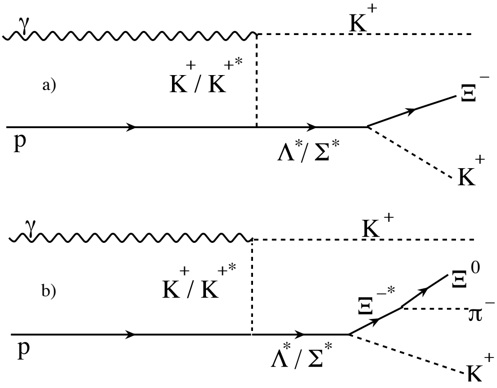


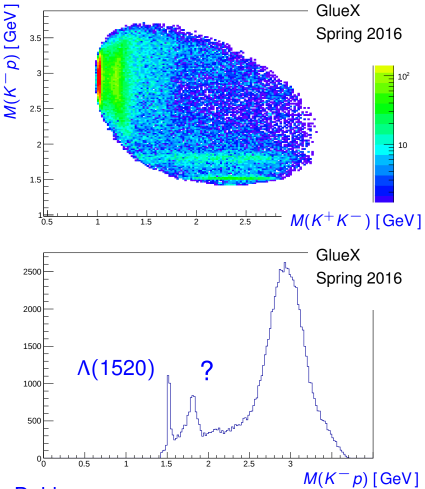


Upper Limits (integrated over 3.5-5.4 GeV):

(1) Ξ(1620): 0.78 nb (2) Ξ(1690): 0.97 nb (3) Ξ(1820): 1.09 nb

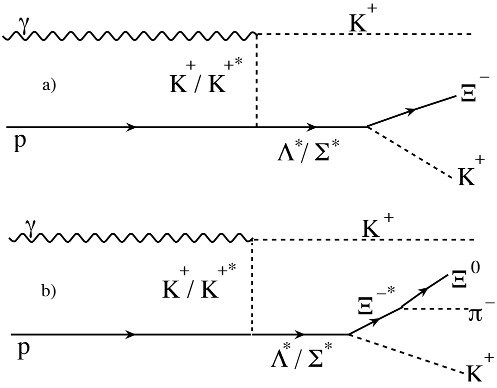
Possible Production Mechanisms

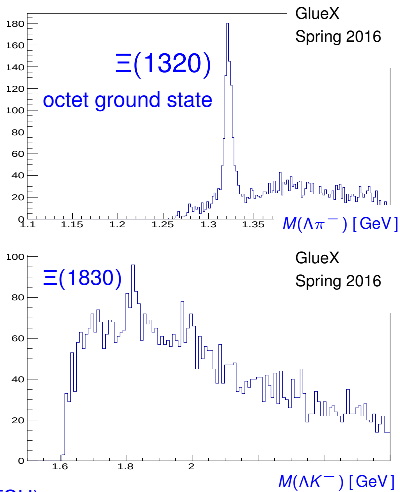




Courtesy of Sean Dobbs

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.