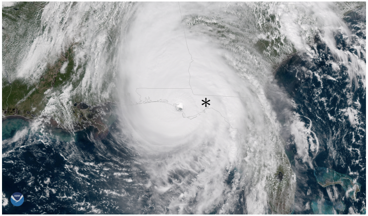
Hadron Spectroscopy from GlueX to the EIC

Volker Credé

Florida State University, Tallahassee, FL *

The Spectroscopy Program at EIC and Future Accelerators

ECT* Workshop



Trento, Italy

12/19/2018

Outline

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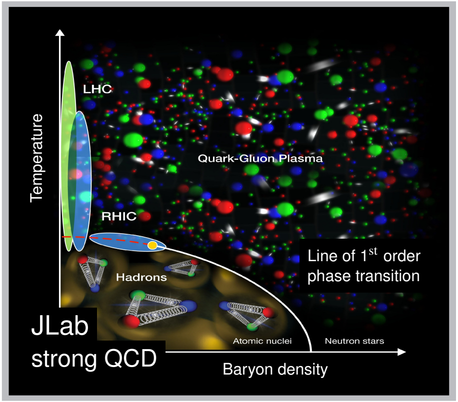
1. Introduction
   - Non-Perturbative QCD
2. Hadron Spectroscopy at Jefferson Lab
   - First Results from GlueX
3. Hyperon Spectroscopy
4. Spectroscopy from GlueX to EIC
   - Lattice Calculations: Ξ^* and Ω Spectrum
   - (Doubly-) Charmed Baryons

QCD Phases and the Study of Baryon Resonances

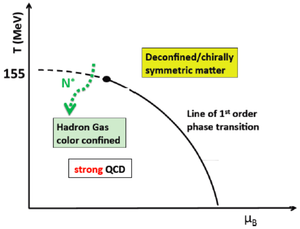


QGP

↓

hadron phase

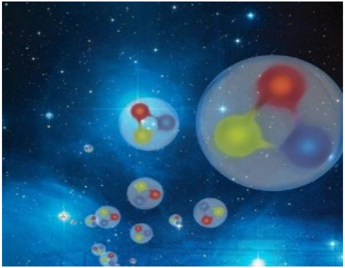
- Chiral symmetry is broken
- Quarks acquire mass
- Baryon resonances occur
- Color confinement emerges



RPP (u, d, s, c) baryons not sufficient to describe freeze-out behavior.

(e. g. A. Bazavov *et al.*, PRL **113** (2014) 7, 072001)

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?

Mesons: What are the properties of the predicted states beyond simple quark-antiquark systems (hybrid mesons, glueballs, tetraquarks, ...)?

➜ Gluonic Excitations provide a measurement of the excited QCD potential.

Hybrid baryons are also possible ...

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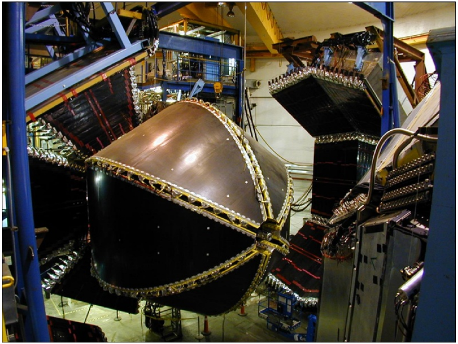
CLAS (6 GeV) at JLab 1998 - 2012



Double-Polarization Experiments

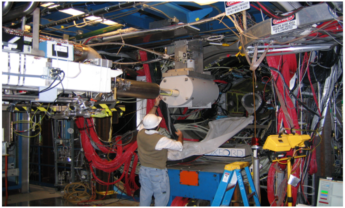
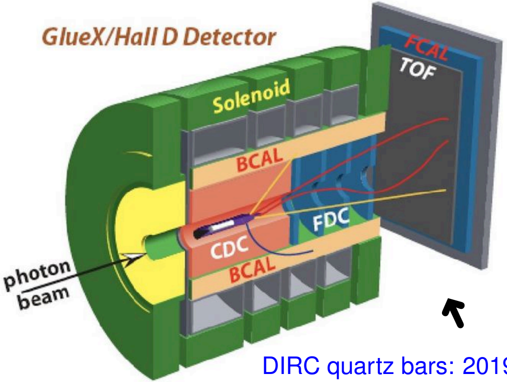


Photo-/electroproduction experiments in search for N^* states and measurement of the transition amplitudes.

← CLAS FROST

Hadron Spectroscopy

- π + Nucleus
- $\gamma\, p$ *Photoproduction*
- $e^+ e^-$
- $\bar{p}\, p$



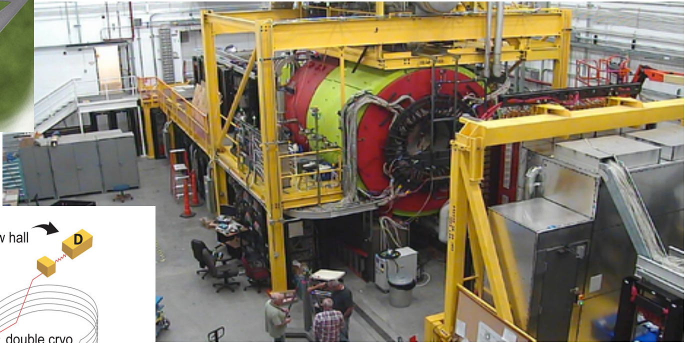
DIRC quartz bars: 2019+

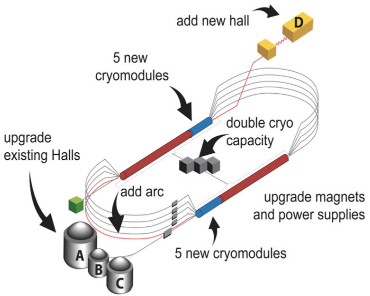
The GlueX Collaboration

- $\sim$130 members, 28 institutions (USA, Chile, China, Armenia, Greece, Russia, UK)
- Production data-taking in full swing (Phase I)
- First physics published in 2017

Jefferson Lab Upgrade to 12 GeV

Hall D

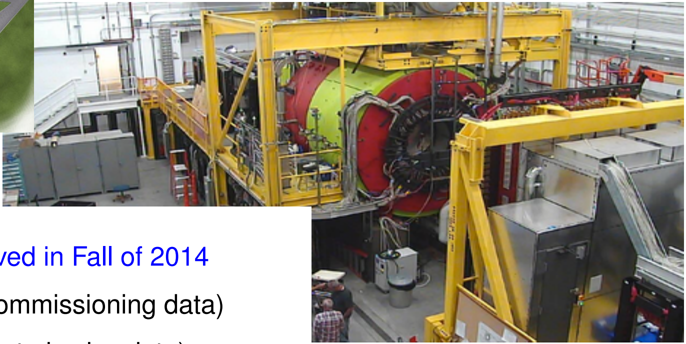




- Linearly-polarized γ's: $P_\gamma \approx 40\,\%$ in peak
- Design intensity $< 10^8$ photons/sec. in peak
- Incident-photon energy resolution $<$ 25 MeV

Jefferson Lab Upgrade to 12 GeV

Hall D



10.1 GeV achieved in Fall of 2014

2016: 10 pb^{-1} (commissioning data)

2017: 45 pb^{-1} (first physics data)

➜ Used for most physics analyses

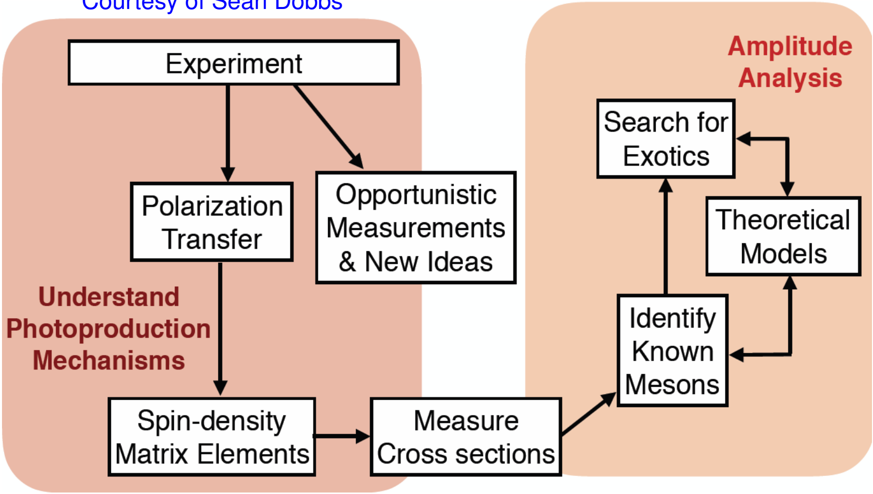
2018: 100 pb^{-1} (Spring data)

➜ GlueX Phase-I completed this Fall

GlueX

Spectroscopy and Amplitude Analysis

Courtesy of Sean Dobbs



Spectroscopy and Amplitude Analysis

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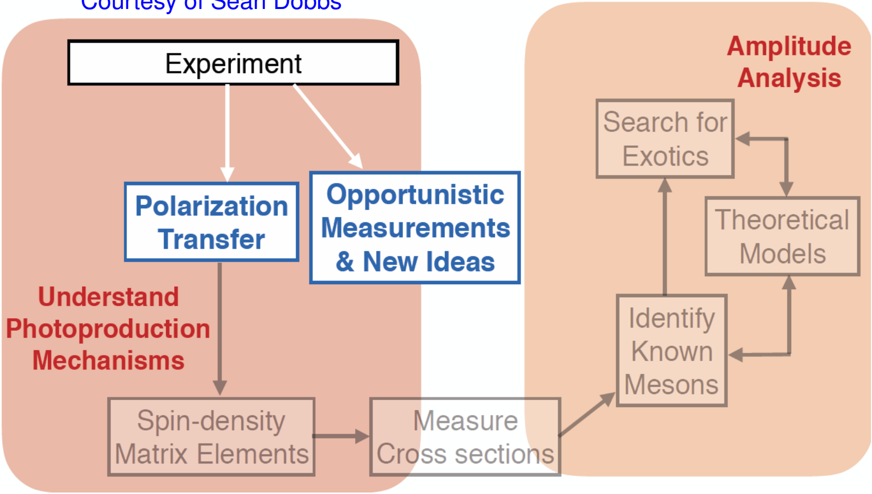
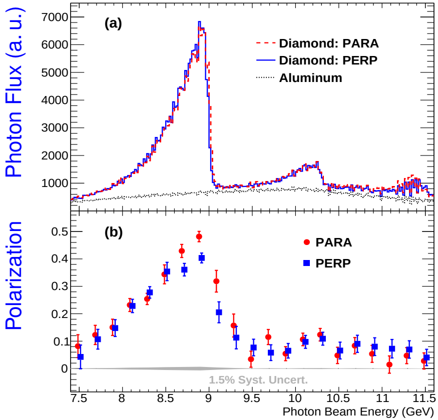


First GlueX “Physics:” Initial Analyses



← H. Al Ghoul *et al.*, PRC **95**, 042201 (2017)

Detector Understanding:

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

$\gamma p \to p\,\eta$ ➜ Beam Asymmetries

$\gamma p \to p\,\rho$

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

$\gamma p \to p\,\eta'$

$\gamma p \to p\,\phi$

Initial Exotic Hybrid Searches

$\gamma p \to \eta\pi\,(n,p)$

$\gamma p \to \eta'\pi\,(n,p)$

$\gamma p \to \rho\pi\,(n,p)$

$\gamma p \to \omega\pi\,(n,p)$

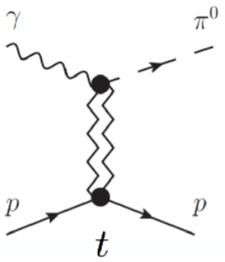
$\gamma p \to \omega\pi\pi\,(n,p)$

$\gamma p \to \eta\pi\pi\,(n,p)$

Strange Baryons: $\gamma p \to K^+\Lambda,\ K\,\Sigma,\ KK\,\Xi$

Measurement of Beam Asymmetries: $\gamma p \to p\,\pi^0$

Beam Asymmetry, Σ, yields information on production mechanism



Exchange of J^{PC}

1^{--} : ω, ρ

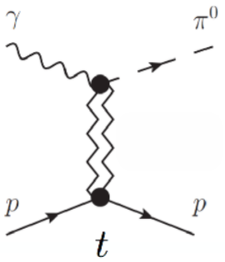
1^{+-} : b, h

$$\Sigma = \frac{|\omega + \rho| - |h + b|}{|\omega + \rho| + |h + b|}$$

V. Mathieu *et al.*, Phys. Rev. D **92**, no. 7, 074004 (2015)

Measurement of Beam Asymmetries: $\gamma p \to p \pi^0$

Beam Asymmetry, Σ, yields information on production mechanism



Exchange of J^{PC}

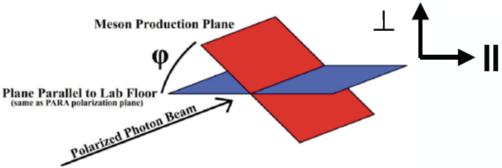
1^{--} : $\omega, \ \rho$

1^{+-} : $b, \ h$

$$\Sigma = \frac{|\omega + \rho| - |h + b|}{|\omega + \rho| + |h + b|}$$

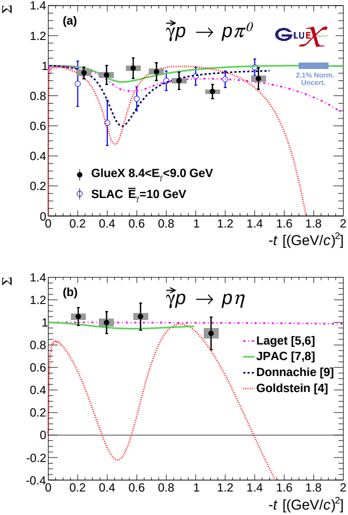
Experimentally:

$$\frac{Y_\perp - F_R Y_\parallel}{Y_\perp + F_R Y_\parallel} = P_\gamma \, \Sigma \cos 2\phi_p$$



V. Mathieu *et al.*, Phys. Rev. D **92**, no. 7, 074004 (2015)

Measurement of Beam Asymmetries: $\gamma p \to p\pi^0/\eta$

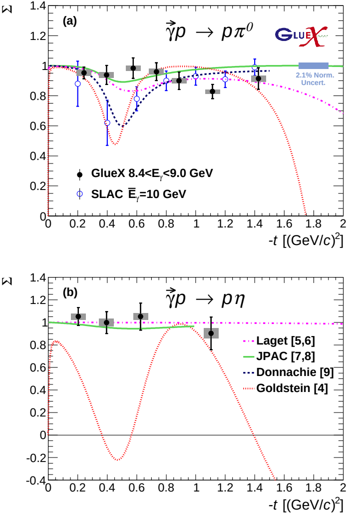


H. Al Ghoul *et al.*, Phys. Rev. C **95**, no. 4, 042201 (2017)

Significantly improved data quality

- First-time measurement of the η beam asymmetry for $8.4 < E_\gamma < 9.0$ GeV.
- Beam asymmetry close to unity: $\Sigma \approx 1$
  ➜ Dominance of vector-meson exchange.
- Comparison with Regge calculations contributes to understanding of production mechanisms at high photon energies.
  ➜ Step toward search for exotic mesons.

Measurement of Beam Asymmetries: $\gamma p \to p\,\pi^0/\eta$



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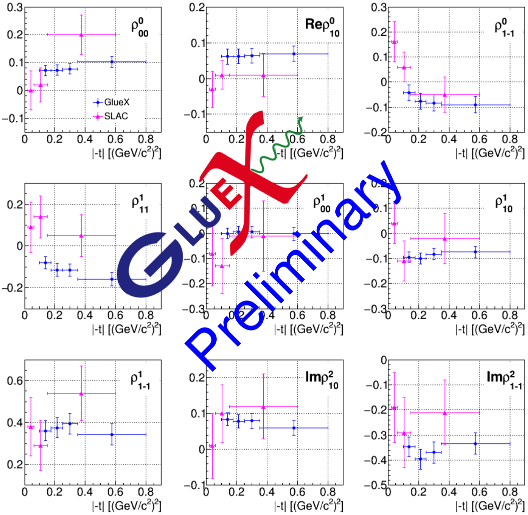
- Comparison with Regge calculations contributes to understanding of production mechanisms at high photon energies.
  ➜ Step toward search for exotic mesons.
- Next in line: $\gamma p \to p\,\eta/\eta'$, $K\Sigma$, $K\Lambda(1520)$, $\pi^-\,\Delta^{++}$, ...

Cross Sections & SDMEs for $\gamma p \to p\omega \to p\pi^+\pi^-\pi^0$



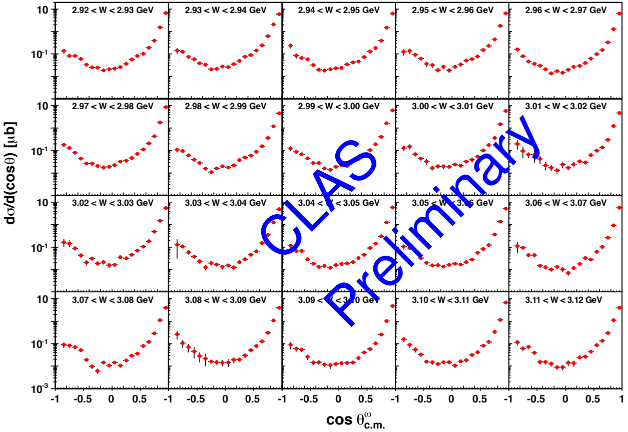
At high energies and forward scattering, ω reaction dominated by t-channel exchanges:

- Spin density matrix elements (SDME) used to describe polarization of photoproduced meson.
- The two matrix elements

  $$\rho^1_{1-1} \quad \text{and} \quad \mathrm{Im}\,\rho^2_{1-1}$$

  particularly sensitive to exchange particle.
- $\mathbb{P}$ exchange surprisingly strong at low energies.

Cross Sections & SDMEs for $\gamma p \to p\omega \to p\pi^+\pi^-\pi^0$



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!!

Working with JPAC.
(V. Mathieu *et al.*)

(SDMEs under review)

➜ Data of unprecedented quality

Z. Akbar *et al.* [CLAS Collaboration], under review.

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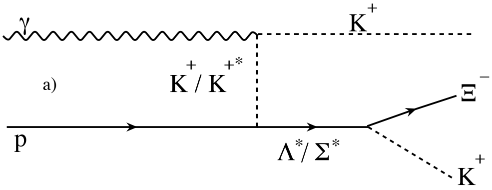
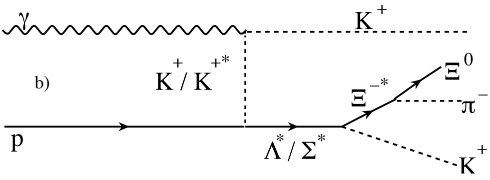
Possible Production Mechanisms





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

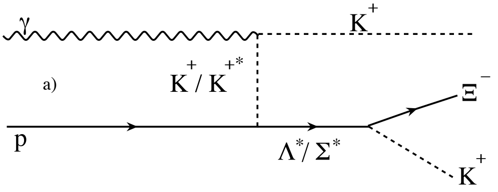
➜ Cross sections, beam asymmetries (similar to $p\pi\pi$ & pKK^*)

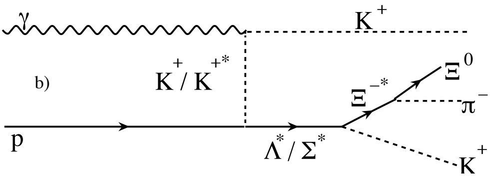
At other facilities (for comparison):

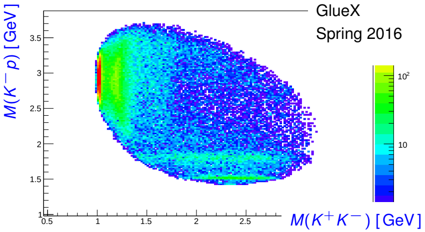
$K^- p \rightarrow K^+ \Xi^{*-}$	J-PARC
$K_L p \rightarrow K^+ \Xi^{*0}$	Hall D ?
$p p \rightarrow \Xi^* X$	LHCb
$\bar{p} p \rightarrow \Xi^* \bar{\Xi}$	$\overline{\text{P}}$ANDA
$e^+ e^- \rightarrow \Xi^* X$	Belle II, BES III

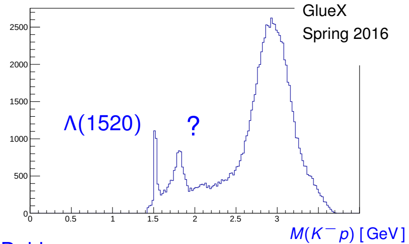
* W. Roberts *et al.*, Phys. Rev. C **71**, 055201 (2005)

Possible Production Mechanisms



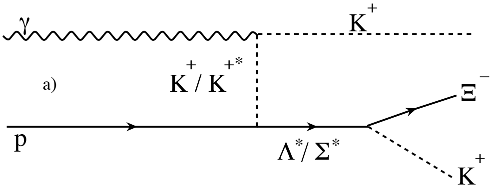


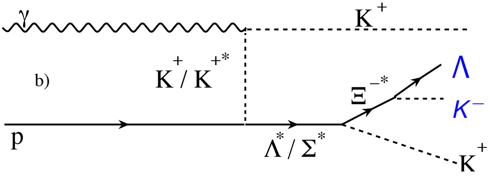




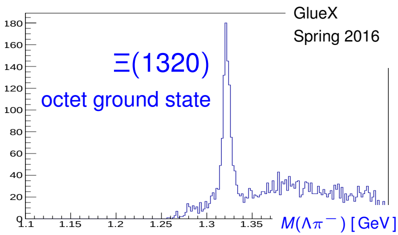
Courtesy of Sean Dobbs

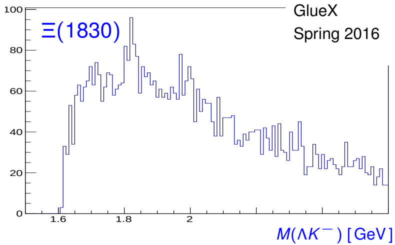
Possible Production Mechanisms





$$\gamma p \to K^+ (K^+ \Xi^{-*}) \to K^+ (p \pi^- K^-) K^+$$

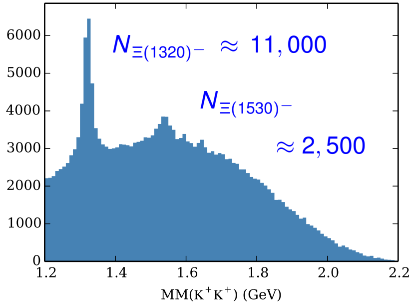


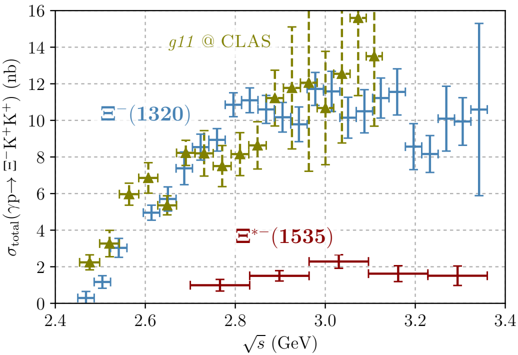


Courtesy of Ashley Ernst (FSU)

CLAS g12: Total Cross Sections of $(\Xi^-)^*$

$2.31 < \sqrt{s} < 3.4$ GeV



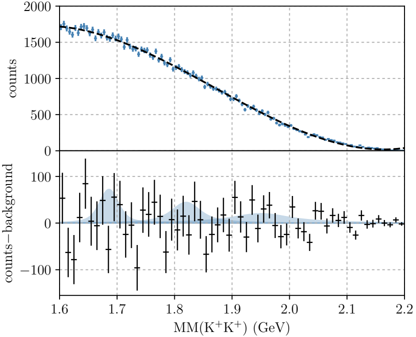


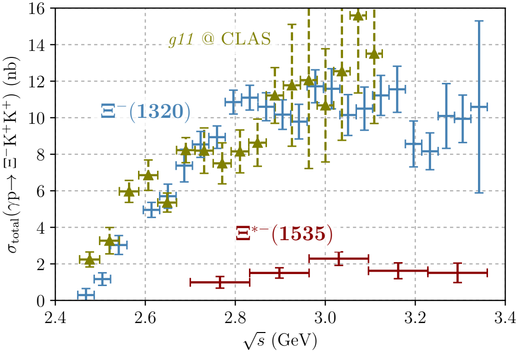
J. T. Goetz *et al.* [CLAS Collaboration], arXiv:1809.00074 [nucl-ex].

No statistically significant structures beyond the 1530 MeV peak: different reaction (production) mechanism for Ξ^* states?

CLAS g12: Total Cross Sections of $(\Xi^-)^*$

arXiv:1809.00074 [nucl-ex]

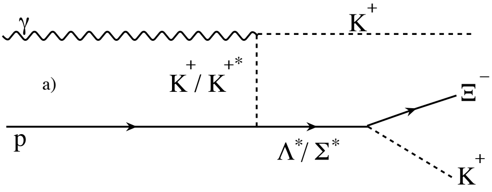


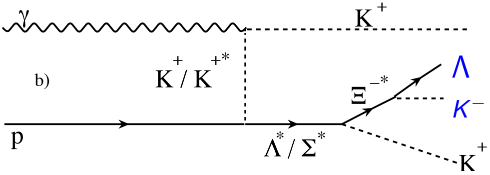


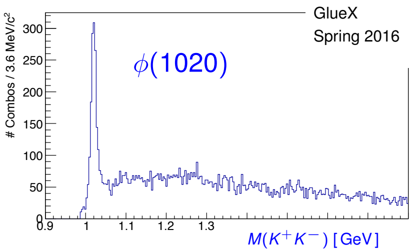
Upper Limits (integrated over all energies):

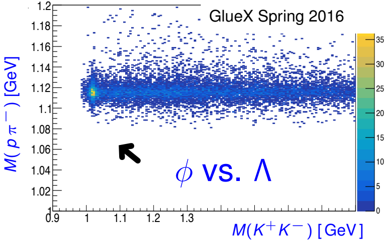
(1) Ξ(1690): 0.75 nb (2) Ξ(1820): 1.01 nb (3) Ξ(1950): 1.58 nb

Possible Production Mechanisms









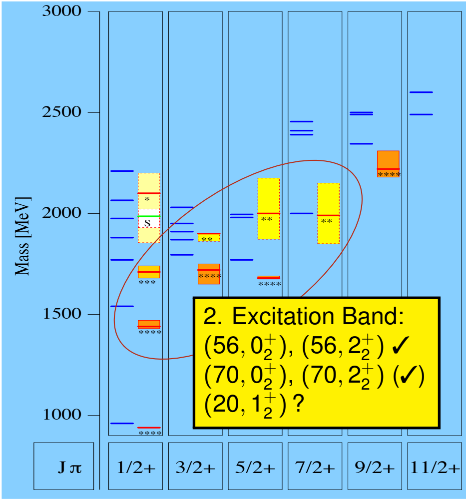
$\gamma p \to K^+ (\Lambda\, K^+ K^-)$

1) $K^+ (\Xi^{-*}\, K^+)$, 2) $K^+ (\Lambda\, \phi)$

Courtesy of Ashley Ernst (FSU)

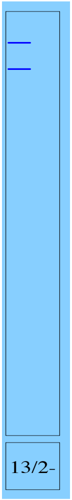
Outline

Spectrum of N^* Resonances



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

N^*	J^P $(L_{2I,2J})$	2010	2018
$N(1440)$	$1/2^+$ (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}	**	



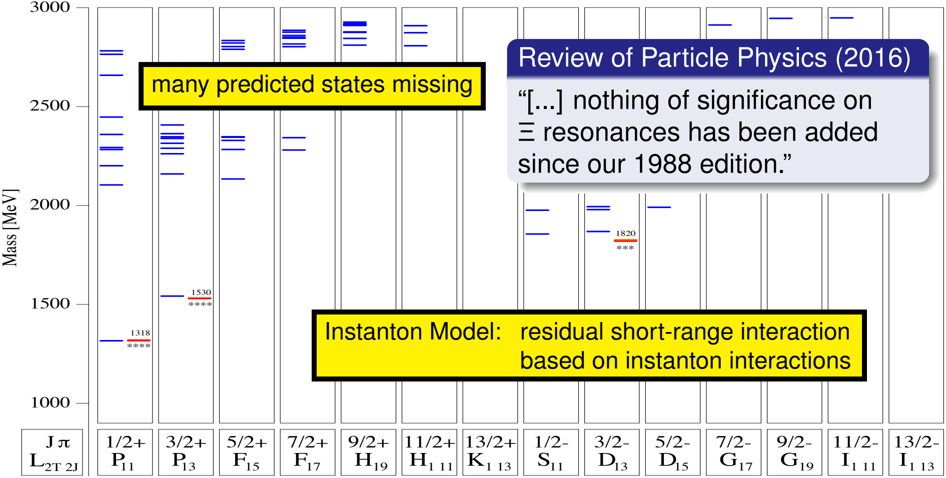
The impact of photoproduction on baryon resonances	Decay modes of nucleon resonances	
	black: PDG 2004	$****$ Existence is certain.
	red: PDG 2018	$***$ Existence is very likely.
	blue: BESIII resonances	$**$ Evidence of existence is fair.
		$*$ Evidence of existence is poor.

		overall	$N\gamma$	$N\pi$	$\Delta\pi$	$N\sigma$	$N\eta$	ΛK	ΣK	$N\rho$	$N\omega$	$N\eta\prime$	$N_{1440}\pi$	$N_{1520}\pi$	$N_{1535}\pi$	$N_{1680}\pi$
N	$1/2^+$	****														
$N(1440)$	$1/2^+$	****	****	****	****	***										
$N(1520)$	$3/2^-$	****	****	****	****	**	****									
$N(1535)$	$1/2^-$	****	****	****	***	*	****									
$N(1650)$	$1/2^-$	****	****	****	***	*	****	***					*			
$N(1675)$	$5/2^-$	****	****	****	****	***	*	*	*	**				*		
$N(1680)$	$5/2^+$	****	****	****	****	***	*			****						
$N(1700)$	$3/2^-$	***	**	***	***	*	*	**	*	*						
$N(1710)$	$1/2^+$	****	****	****	**		***	**	*	*	*				*	
$N(1720)$	$3/2^+$	****	****	****	***	*	*	****	*	**	*					
$N(1860)$	$5/2^+$	**	*	**		*	*									
$N(1875)$	$3/2^-$	***	**	**	*	**	*	*	*	*	*	*	*			
$N(1880)$	$1/2^+$	***	**	*	**	*	*	**	**		**				*	
$N(1895)$	$1/2^-$	****	****	*	*	*	****	**	**	*	*	****	*			
$N(1900)$	$3/2^+$	****	****	**	**	*	*	**	**	*	*	**				
$N(1990)$	$7/2^+$	**	**	**	*	*	*	**	**							
$N(2000)$	$5/2^+$	**	**	**	**	*	*	*	*		*					
$N(2040)$	$3/2^+$	*		*												
$N(2060)$	$5/2^-$	***	***	**	*	*	*	*	*	*	*		*	*		*
$N(2100)$	$1/2^+$	***	**	***	**	**	*	*		*	*	**			***	
$N(2120)$	$3/2^-$	***	***	***	**	**		**	*		*	*	*	*	*	
$N(2190)$	$7/2^-$	****	****	****	****	**	*	**	*	*	*					
$N(2220)$	$9/2^+$	****	**	****			*	*	*							
$N(2250)$	$9/2^-$	****	**	****			*	*	*							
$N(2300)$	$1/2^+$	*		*												
$N(2570)$	$5/2^-$	*		*												
$N(2600)$	$11/2^-$	***		***												
$N(2700)$	$13/2^+$	**		**												

Based on results at Jefferson Lab, ELSA, MAMI, ...

Cascade Resonances: Status as of 2018

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



many predicted states missing

Review of Particle Physics (2016)

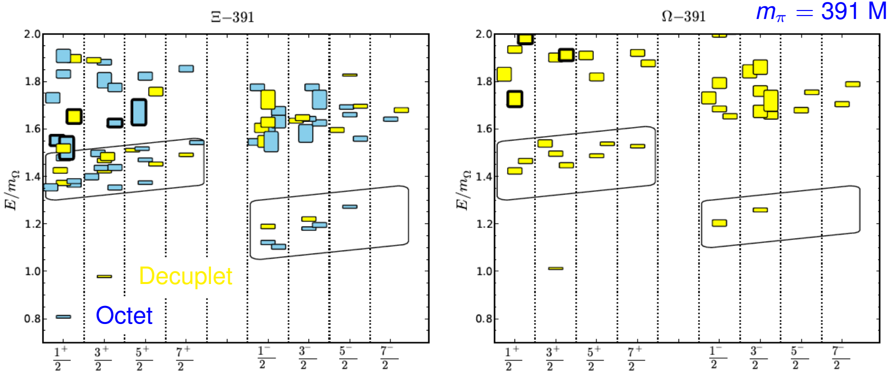
"[...] nothing of significance on Ξ resonances has been added since our 1988 edition."

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

The Ξ^* and Ω^* Spectrum from Lattice QCD

R. Edwards *et al.*, Phys. Rev. D **87**, no. 5, 054506 (2013)

$m_\pi = 391$ MeV

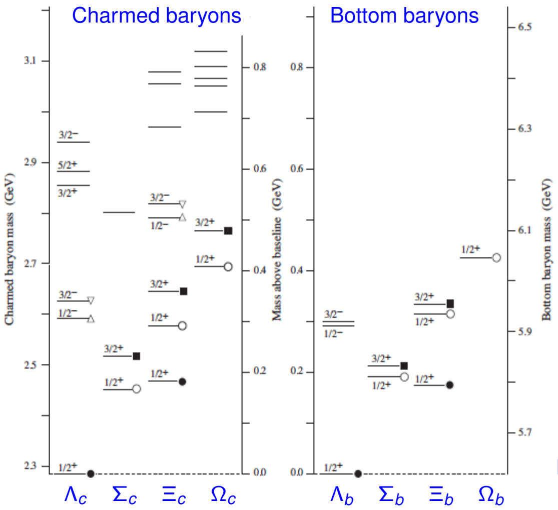


Exhibits broad features expected of $SU(6) \otimes O(3)$ symmetry

➜ Rich spectra predicted (narrow states):

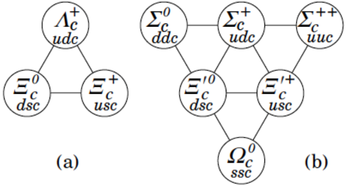
Ω^* spectrum beyond GlueX energy range.

Charmed and Bottom Baryons (as of 2018)



24 known charmed baryons

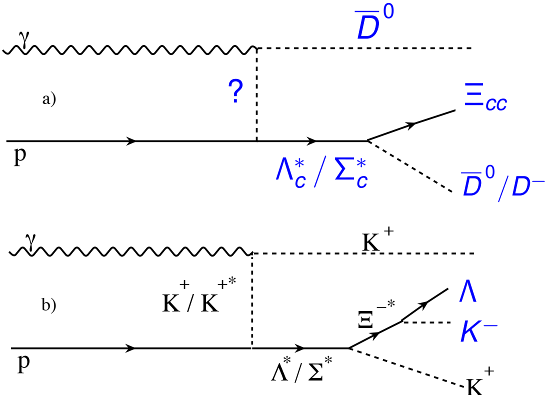
9 known bottom baryons



➜ No confimred doubly-charmed states!

PDG, Phys. Rev. D 98, 030001 (2018)

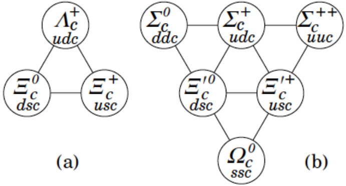
Charmed and Bottom Baryons (as of 2018)



$$\gamma p \to K^+ (K^+ \Xi^{-*}) \to K^+ (p \pi^- K^-) K^+$$

24 known charmed baryons

9 known bottom baryons



➜ No confimred doubly-charmed states!