Baryon Spectroscopy at GlueX

Volker Credé

Florida State University, Tallahassee, Florida

International Conference on the Structure of Baryons

Baryons 2022

Sevilla, Spain

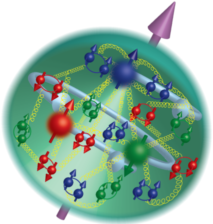
11/08/2022

Outline

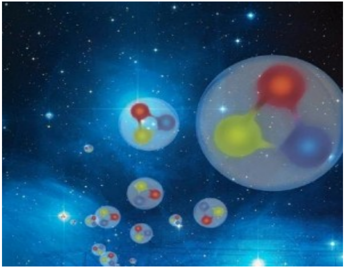
1. Introduction and Motivation
   - Strong-Coupling QCD
   - The GlueX Experiment
2. Spectroscopy of Baryon Resonances
   - First GlueX Results (Beam Asymmetries)
   - The Nucleon Spectrum
   - The Study of Strangeness -1 Hyperons
   - Spectroscopy of Ξ Resonances
3. Summary and Conclusions

Outline

1. Introduction and Motivation
   - Strong-Coupling QCD
   - The GlueX Experiment
2. Spectroscopy of Baryon Resonances
   - First GlueX Results (Beam Asymmetries)
   - The Nucleon Spectrum
   - The Study of Strangeness -1 Hyperons
   - Spectroscopy of Ξ Resonances
3. Summary and Conclusions



Non-Perturbative QCD



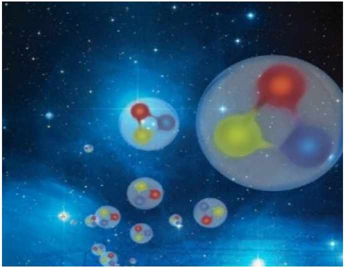
How does QCD give rise to excited hadrons?

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?

Answers to these questions will not be the direct result of some experiments.

- Models need to link observables to these fundamental questions.
- Significant observables:
  - Excitation spectra and electromagnetic couplings
  - Response of hadronic properties to a dense nuclear environment

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?

Answers to these questions will not be the direct result of some experiments.

- Models need to link observables to these fundamental questions.
- Significant observables:
  - Excitation spectra and electromagnetic couplings
  - Response of hadronic properties to a dense nuclear environment

GlueX Core Mission: Search for Hybrid Mesons

Quantum Numbers $J^{PC} \equiv {}^{2S+1}L_J$

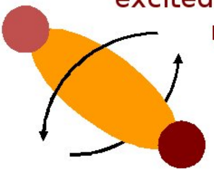
- Parity: $P = (-1)^{L+1}$
- Charge Conjugation: $C = (-1)^{L+S}$ (defined for neutral mesons)
- G parity: $G = C\,(-1)^I$

$L = 0,\ S = 0$:

e.g. $\pi,\ \eta\ (J^{PC} = 0^{-+})$

$L = 0,\ S = 1$:

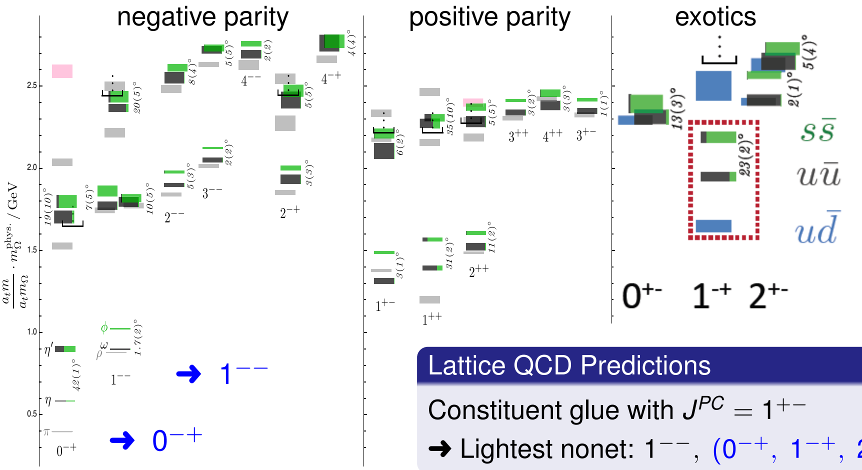
e.g. $\rho,\ \omega,\ \phi\ (J^{PC} = 1^{--})$



12 GeV CEBAF upgrade has high priority (DOE Office of Science, Long Range Plan) "[key area] is experimental verification of the powerful force fields *(flux tubes)* believed to be responsible for quark confinement."

Forbidden States (Exotics): $J^{PC} = 0^{+-},\ 0^{--},\ 1^{-+},\ 2^{+-},\ \cdots$
(hybrid kaons do not have exotic QNs)

Meson Spectroscopy on the Lattice



Lattice QCD Predictions

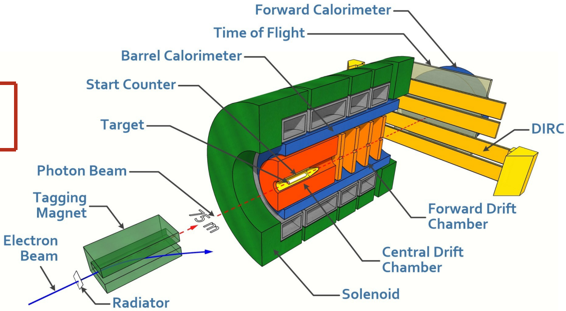
Constituent glue with $J^{PC} = 1^{+-}$

➜ Lightest nonet: 1^{--}, $(0^{-+}, 1^{-+}, 2^{-+})$

J. J. Dudek *et al.*, PRD **84**, 074023 (2011)

Hadron Spectroscopy

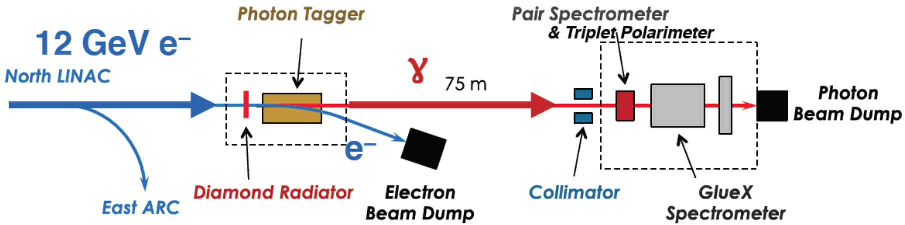
- π + Nucleus
- $\gamma\, p$ *Photoproduction*
- $e^+ e^-$
- $\bar{p}\, p$



The GlueX Collaboration

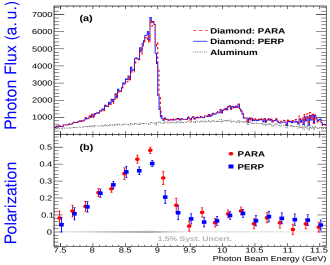
- $\sim$135 members, 29 institutions
  (Armenia, Canada, Chile, China, Germany, Greece, Russia, UK, USA)
- GlueX phase-I complete (120 PAC days)
- First physics published in 2017

The GlueX Experiment: Photon Beamline



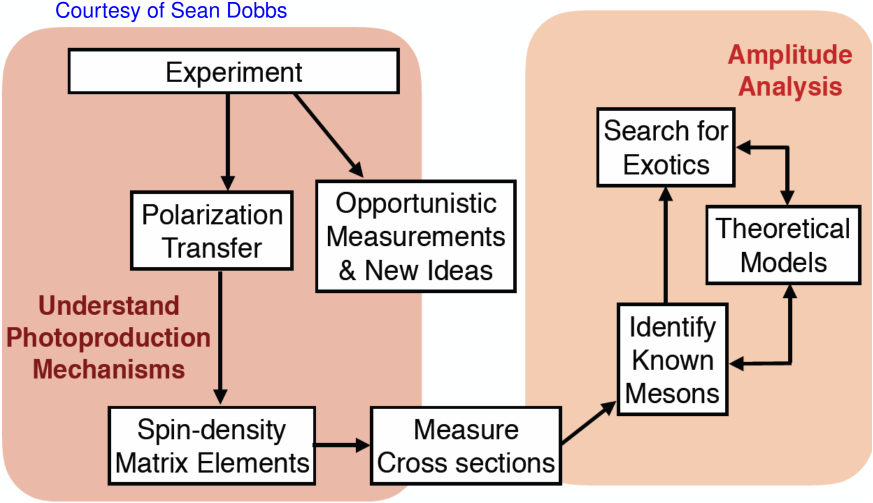
Polarized photon beam produced via coherent bremsstrahlung off thin diamond radiator:

- Tagging system with $\Delta E < 25$ MeV.
- Linear photon polarization of $P_\gamma \approx 40\,\%$ in the coherent peak.
- Phase-I intensity of 5×10^7 γ/s in peak.



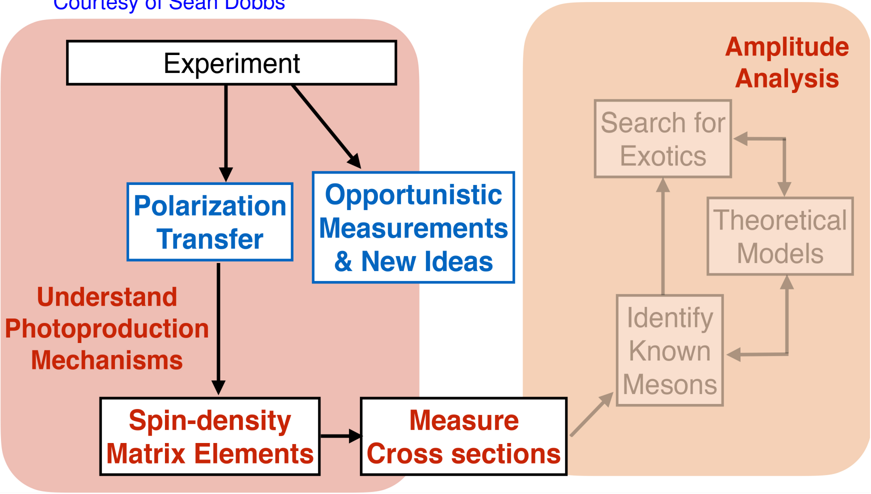
Spectroscopy and Amplitude Analysis

Courtesy of Sean Dobbs

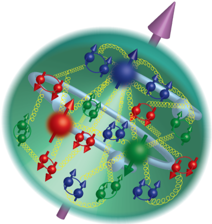


Spectroscopy and Amplitude Analysis

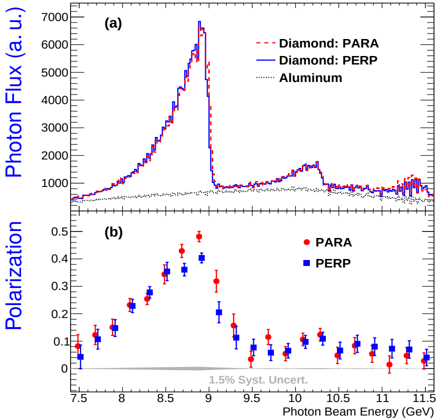
Courtesy of Sean Dobbs



Outline



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

$\gamma p \to p\,\eta'$
$\gamma p \to K^+\,\Sigma^0$
$\gamma p \to \pi^-\,\Delta^{++}$

$\gamma p \to p\,\rho$
$\gamma p \to p\,\omega$
$\gamma p \to p\,\phi$

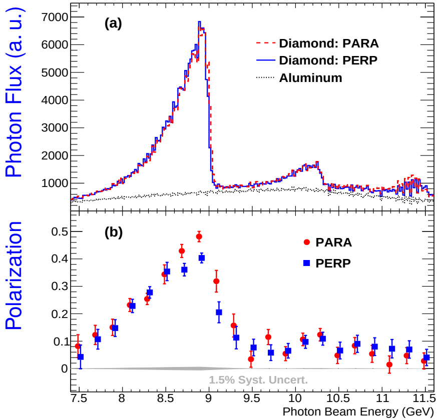
↓

cross sections
SDMEs

Initial Exotic Hybrid Searches

$\gamma p \to \eta\pi\,(p, \Delta^{++})$
$\gamma p \to \eta'\pi\,(p, \Delta^{++})$
$\gamma p \to \rho\pi\,(p, \Delta^{++})$
$\gamma p \to \omega\pi\,(p, \Delta^{++})$
$\gamma p \to \omega\pi\pi\,(p, \Delta^{++})$
$\gamma p \to \eta\pi\pi\,(p, \Delta^{++})$

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

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

$\gamma p \to K^+\,\Sigma^0$

$\gamma p \to \pi^-\,\Delta^{++}$

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

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

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

$\gamma p \to p\,J/\psi$

$\gamma p \to p\,B\overline{B}$

Initial Exotic Hybrid Searches

$\gamma p \to \eta\pi\,(p, \Delta^{++})$

$\gamma p \to \eta'\pi\,(p, \Delta^{++})$

$\gamma p \to \rho\pi\,(p, \Delta^{++})$

$\gamma p \to \omega\pi\,(p, \Delta^{++})$

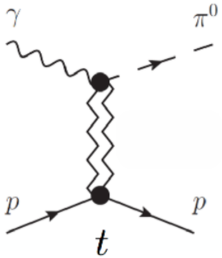
$\gamma p \to \omega\pi\pi\,(p, \Delta^{++})$

$\gamma p \to \eta\pi\pi\,(p, \Delta^{++})$

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

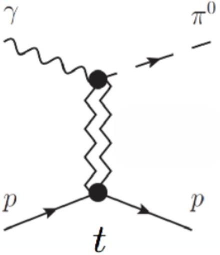
1^{+-} : $b,\ h$

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

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}

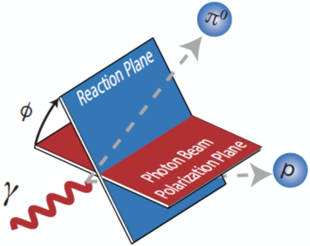
1^{--} : $\omega,\ \rho$

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

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

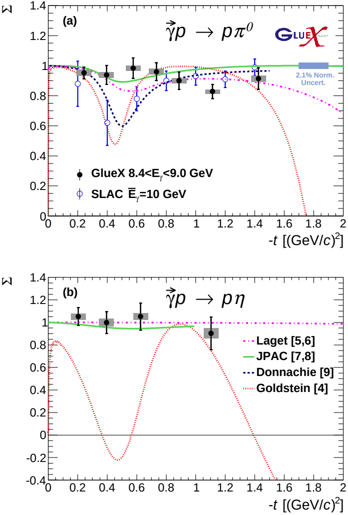
Experimentally:

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



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

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

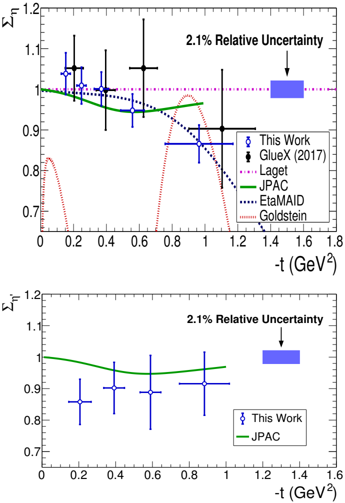


H. Al Ghoul *et al.*, Phys. Rev. C **95**, no. 4, 042201 (2017)

Significantly improved data quality

- First measurement of the η beam asymmetry for $8.4 < E_\gamma < 9.0$ GeV.
- Beam asymmetries close to unity: $\Sigma \approx 1$
  ➜ Dominance of vector-meson exchange
  No dip around $-t = 0.5$ GeV^2 for π^0
- Comparison with Regge calculations contributes to understanding of production mechanisms in photoproduction.
  ➜ Step toward search for exotic mesons.

Measurement of Beam Asymmetries: $\gamma p \to p\,\eta/\eta'$



S. Adhikari *et al.*, Phys. Rev. C **100**, no.5, 052201 (2019)

Significantly improved data quality

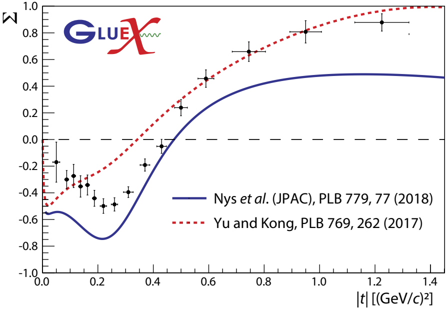
- First measurement of the $(\eta)/\eta'$ beam asymmetries for $8.2 < E_\gamma < 8.8$ GeV.
- Beam asymmetry close to unity: $\Sigma_\eta \approx 1$
  ➜ Dominance of vector-meson exchange
  No indication for 2^{--} exchange
- Comparison with Regge calculations contributes to understanding of production mechanisms in photoproduction.
  ➜ Step toward search for exotic mesons.

Measurement of Beam Asymmetries

S. Adhikari *et al.*, Phys. Rev. C **103**, no. 2, L022201 (2021)

- Charge exchange process
- Dominated by π exchange at low $|t|$

$\gamma p \to \pi^- \Delta^{++}$



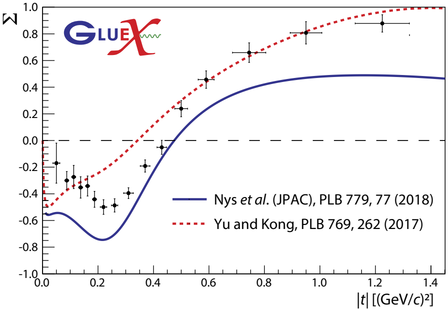
1. $|t| < 0.45$ (GeV/c)^2
   Σ negative
   ➜ neg. naturality π exchanged favored
2. $|t| < 0.25$ (GeV/c)^2
   Σ negative, downward sloped
   ➜ mixed naturality modifications to one-π exchange
3. $|t| > 0.45$ (GeV/c)^2
   Σ positive
   ➜ positive naturality vector ρ and tensor a_2 exchange

Measurement of Beam Asymmetries

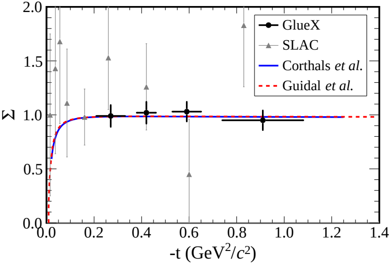
[GlueX] Phys. Rev. C **103**, no. 2, L022201 (2021)

- Charge exchange process
- Dominated by π exchange at low $|t|$

$\gamma p \to \pi^- \Delta^{++}$



$\gamma p \to K^+ \Sigma^0$



Phys. Rev. C **101**, no. 6, 065206 (2020)

- Consistent with unity
  ➜ Dominant natural parity exchange

Spectrum of N^* Resonances

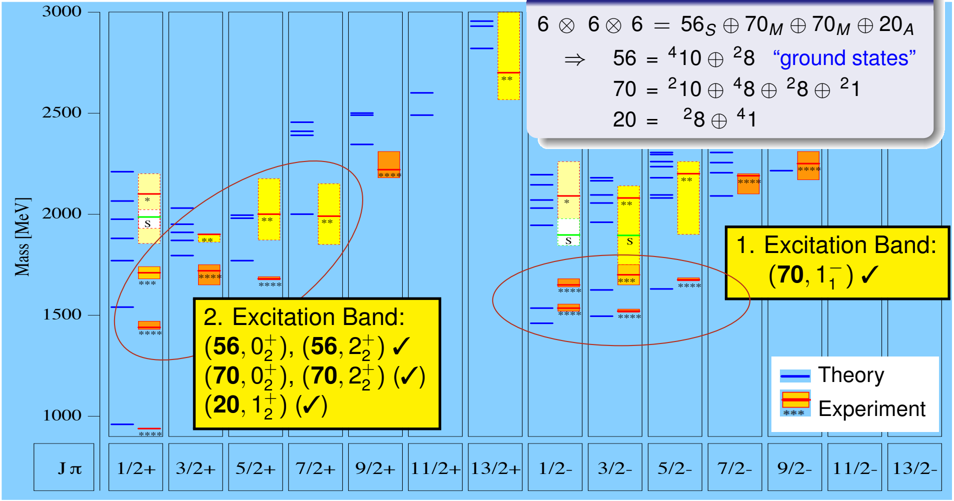
SU(6) ($^{2S+1}$multiplets; u, d, s, spin)

$$6 \otimes 6 \otimes 6 = 56_S \oplus 70_M \oplus 70_M \oplus 20_A$$

$$\Rightarrow \quad 56 = {}^4 10 \oplus {}^2 8 \quad \text{“ground states”}$$

$$70 = {}^2 10 \oplus {}^4 8 \oplus {}^2 8 \oplus {}^2 1$$

$$20 = {}^2 8 \oplus {}^4 1$$

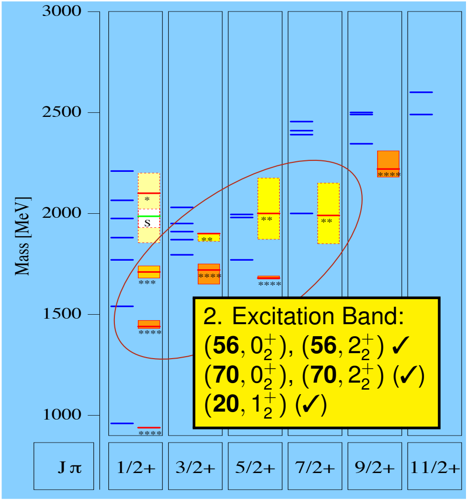


1. Excitation Band: $(\mathbf{70}, 1_1^-)$ ✓

2. Excitation Band: $(\mathbf{56}, 0_2^+)$, $(\mathbf{56}, 2_2^+)$ ✓ $(\mathbf{70}, 0_2^+)$, $(\mathbf{70}, 2_2^+)$ (✓) $(\mathbf{20}, 1_2^+)$ (✓)

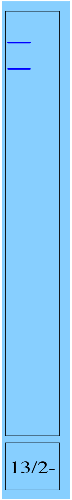
S. Capstick & N. Isgur, Phys. Rev. **D34** (1986) 2809

Spectrum of N^* Resonances



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

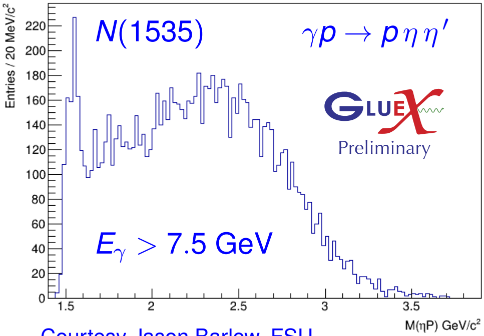
N^*	J^P $(L_{2I,2J})$	2010	2020
N(1440)	$1/2^+$ (P_{11})	* * * *	* * * *
N(1520)	$3/2^-$ (D_{13})	* * * *	* * * *
N(1535)	$1/2^-$ (S_{11})	* * * *	* * * *
N(1650)	$1/2^-$ (S_{11})	* * * *	* * * *
N(1675)	$5/2^-$ (D_{15})	* * * *	* * * *
N(1680)	$5/2^+$ (F_{15})	* * * *	* * * *
N(1685)			*
N(1700)	$3/2^-$ (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}	* *	



N^* Spectroscopy at GlueX

GlueX is not the ideal experiment for N^* spectroscopy without a polarized target. However,

- N^* resonances are abundantly produced at $E_\gamma > 7$ GeV.
- Interesting program on N^* physics is possible.



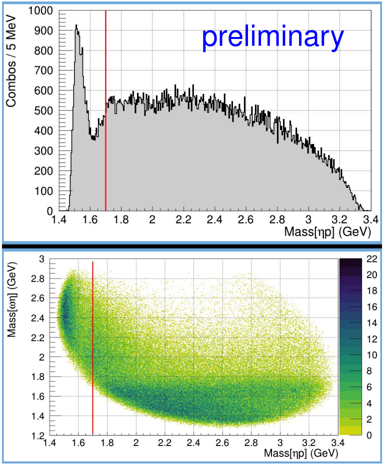
Courtesy Jason Barlow, FSU

Data selection:

- General cuts to improve overall event kinematics (CL, missing mass, etc.).
- No cuts (yet) to enhance $\gamma p \to \eta' N(1535)$ production.

Possibly, direct access to $N(1535)\,\frac{1}{2}^-$ due to t-channel production.

N^* Spectroscopy at GlueX



Courtesy Edmundo Barriga, FSU

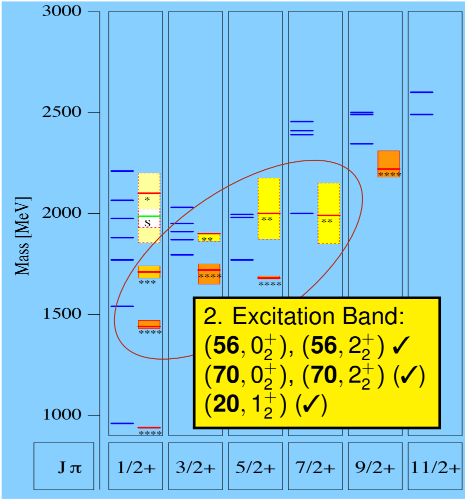
Reaction: $\gamma p \to p\,\eta\,\omega$

Data selection:

- General cuts to improve overall event kinematics (CL, missing mass, etc.).
- $8.2\ \mathrm{GeV} < E_\gamma < 8.8\ \mathrm{GeV}$
- $-t < 0.6\ \mathrm{GeV}^2$
- No cuts (yet) to enhance $\gamma p \to \omega\, N(1535)$ production.

Possibly, direct access to $N(1535)\,\frac{1}{2}$ due to t-channel production.

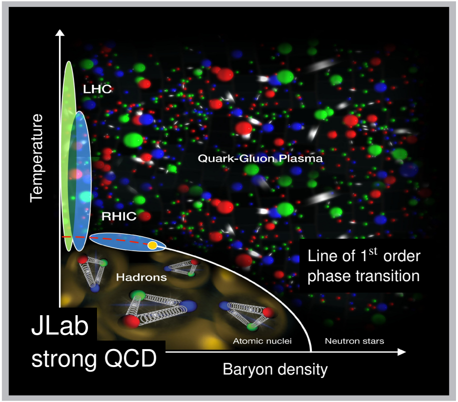
Spectrum of N^* Resonances



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

N	$(D,\, L_N^P)$	S	J^P	Octet Members				Singlets
0	$(56,\, 0_0^+)$	$\frac{1}{2}$	$\frac{1}{2}^+$	$N(939)$	$\Lambda(1116)$	$\Sigma(1193)$	$\Xi(1318)$	–
1	$(70,\, 1_1^-)$	$\frac{1}{2}$	$\frac{1}{2}^-$	$N(1535)$	$\Lambda(1670)$	$\Sigma(1620)$	$\Xi(1690)$	$\Lambda(1405)$
			$\frac{3}{2}^-$	$N(1520)$	$\Lambda(1690)$	$\Sigma(1670)$	$\Xi(1820)$	$\Lambda(1520)$
		$\frac{3}{2}$	$\frac{1}{2}^-$	$N(1650)$	$\Lambda(1800)$	$\Sigma(1750)$		–
			$\frac{3}{2}^-$	$N(1700)$				–
			$\frac{5}{2}^-$	$N(1675)$	$\Lambda(1830)$	$\Sigma(1775)$		–
2	$(56,\, 0_2^+)$	$\frac{1}{2}$	$\frac{1}{2}^+$	$N(1440)$	$\Lambda(1600)$	$\Sigma(1660)$		–
	$(70,\, 0_2^+)$	$\frac{1}{2}$	$\frac{1}{2}^+$	$N(1710)$	$\Lambda(1810)^\dagger$	$\Sigma(1770)^\dagger$		
		$\frac{3}{2}$	$\frac{3}{2}^+$					–
	$(56,\, 2_2^+)$	$\frac{1}{2}$	$\frac{3}{2}^+$	$N(1720)^\dagger$	$\Lambda(1890)^\dagger$	$\Sigma(1840)^\dagger$		–
			$\frac{5}{2}^+$	$N(1680)$	$\Lambda(1820)^\dagger$	$\Sigma(1915)^\dagger$		–
	$(70,\, 2_2^+)$	$\frac{1}{2}$	$\frac{3}{2}^+$					
			$\frac{5}{2}^+$	$N(1860)$				
		$\frac{3}{2}$	$\frac{1}{2}^+$	$N(1880)$				–
			$\frac{3}{2}^+$	$N(1900)^\dagger$		$\Sigma(2080)^\dagger$		–
			$\frac{5}{2}^+$	$N(2000)$	$\Lambda(2110)^\dagger$	$\Sigma(2070)^\dagger$		–
			$\frac{7}{2}^+$	$N(1990)$	$\Lambda(2020)$	$\Sigma(2030)^\dagger$		–
	$(20,\, 1_2^+)$	$\frac{1}{2}$	$\frac{1}{2}^+$	$N(2100)^\dagger$				
			$\frac{3}{2}^+$	$N(2040)^\dagger$				
			$\frac{5}{2}^+$	–	–	–	–	

QCD Phases and the Study of Baryon Resonances

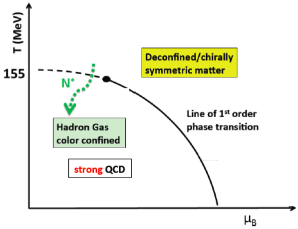


QGP

↓

hadron phase

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

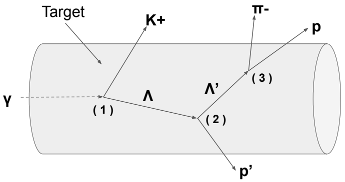


RPP (u, d, s, c) baryons not sufficient to describe freeze-out behavior.
(e. g. A. Bazavov *et al.*, PRL **113** (2014) 7, 072001)

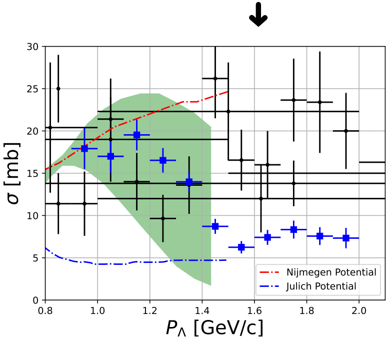
Connections to the Neutron Star Equation of State

Measurement of the $\Lambda p \to \Lambda p$ Elastic Scattering Cross Sections

(J. Rowley *et al.* [CLAS Collaboration], Phys. Rev. Lett. **127**, 272303 (2021))



likely: $\Lambda p \to \Lambda(1520)p$



Major challenges

- Preparation of a secondary beam of Λ baryons
- Estimate of Λ beam luminosity

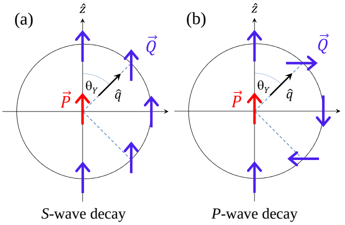
➜ Measurements possible at GlueX for Λp and Ξp.

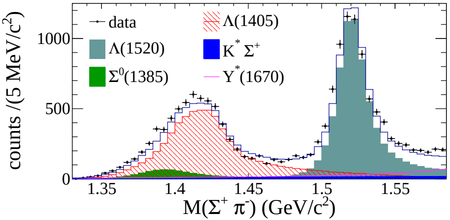
Spin and Parity Measurement of the Λ(1405) Baryon

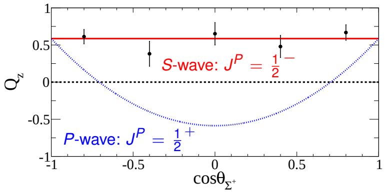
K. Moriya *et al.* [CLAS Collaboration], Phys. Rev. Lett. **112**, 082004 (2014)

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



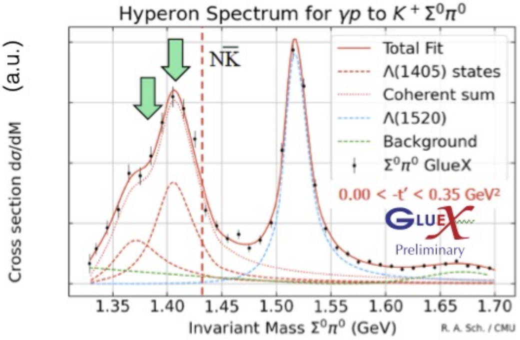




The Λ(1405)/Λ(1520) Baryons at GlueX

1. Measurement of the $\Sigma\pi$ photoproduction line shapes near the Λ(1405)
K. Moriya *et al.* [CLAS Collaboration], Phys. Rev. C **87**, no. 3, 035206 (2013)

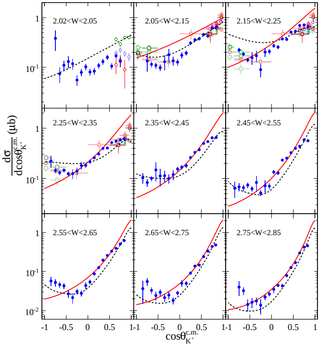
More coming from GlueX on $\Lambda(1405) \to \Sigma^0\pi^0$

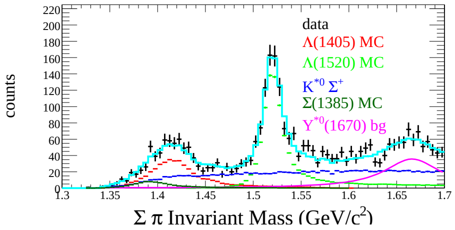


- Fit of (1) two coherent Flatté amplitudes plus (2) incoherent Λ(1520), and (3) backgrounds.
- Preliminary fit results support the two-pole structure.

The Λ(1405)/Λ(1520) Baryons at GlueX

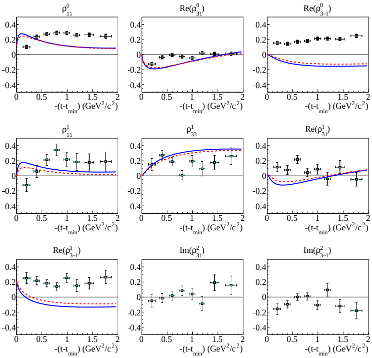
1. Measurement of the $\Sigma\pi$ photoproduction line shapes near the Λ(1405)
   K. Moriya *et al.* [CLAS Collaboration], Phys. Rev. C **87**, no. 3, 035206 (2013)
2. Differential Cross Sections for $\gamma p \to \Sigma^0(1385)$, Λ(1405), and Λ(1520)
   K. Moriya *et al.* [CLAS Collaboration], Phys. Rev. C **88**, 045201 (2013)

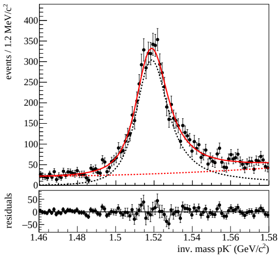




The Λ(1405)/Λ(1520) Baryons at GlueX

- Measurement of the $\Sigma\pi$ photoproduction line shapes near the Λ(1405)
  K. Moriya *et al.* [CLAS Collaboration], Phys. Rev. C **87**, no. 3, 035206 (2013)
- Measurement of SDMEs in Λ(1520) photoproduction at 8.2–8.8 GeV
  S. Adhikari *et al.* [GlueX Collaboration], Phys. Rev. C **105**, no. 3, 035201 (2022)



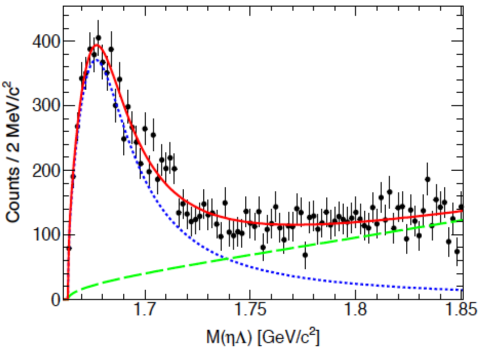


$-(t - t_0) \in [\,0.3, 0.5\,]$ GeV^2

Spectroscopy of Excited Λ^* Baryons

First direct mass and width determination for the $\Lambda(1670)$

[Belle Collaboration], Phys. Rev. D **103**, no. 5, 052005 (2021)



$\Lambda(1670)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
25 to 35 (≈ 30) OUR ESTIMATE				
36.1 ± 2.4 ± 4.8	LEE	21A	BELL	$\Lambda_c^+ \to \Lambda(1670)\pi^+$
33 ± 4	SARANTSEV	19	DPWA	$\overline{K}N$ multichannel
29 ± 5	ZHANG	13A	DPWA	$\overline{K}N$ multichannel
34.1 ± 3.7	KOISO	85	DPWA	$K^- p \to \Sigma\pi$
29 ± 5	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
29 ± 5	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
46 ± 5	HEPP	76B	DPWA	$K^- N \to \Sigma\pi$
40 ± 3	KANE	74	DPWA	$K^- p \to \Sigma\pi$
19 ± 5	PREVOST	74	DPWA	$K^- N \to \Sigma(1385)\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
23 ± 6	MANLEY	02	DPWA	$\overline{K}N$ multichannel
21.1 ± 3.6	ABAEV	96	DPWA	$K^- p \to \Lambda\eta$
45 ± 10	GOPAL	77	DPWA	$\overline{K}N$ multichannel
12	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

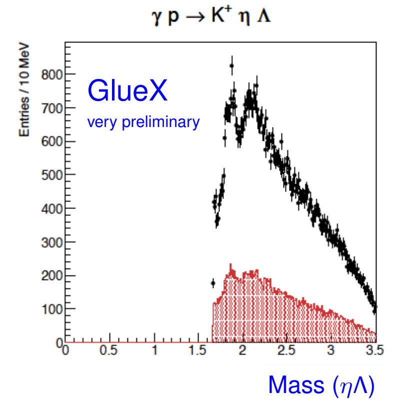
[1] MARTIN 77 obtains identical resonance parameters from a T-matrix pole and from a Breit-Wigner fit.

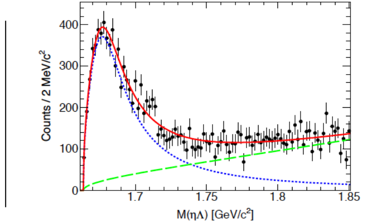
all PDG listings based on PWA

Spectroscopy of Excited Λ^* Baryons

First direct mass and width determination for the $\Lambda(1670)$

[Belle Collaboration], Phys. Rev. D **103**, no. 5, 052005 (2021)



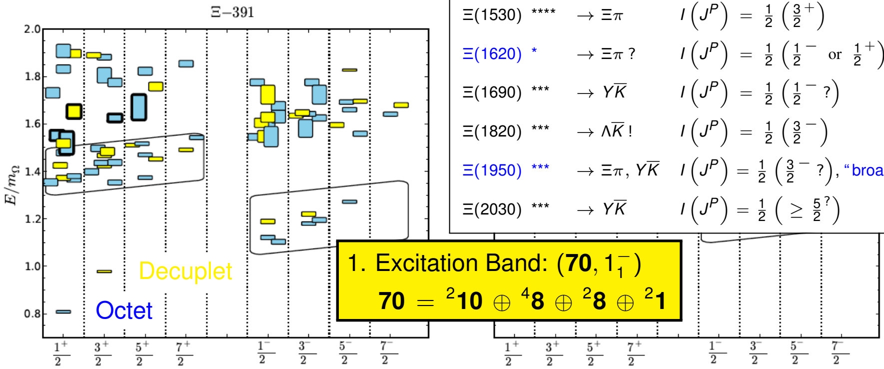


Resonances	Mass [MeV/c^2]	Width [MeV]
$\Lambda(1670)$	$1674.3 \pm 0.8 \pm 4.9$	$36.1 \pm 2.4 \pm 4.8$
$\Sigma(1385)^+$	$1384.8 \pm 0.3 \pm 1.4$	$38.1 \pm 1.5 \pm 2.1$

all PDG listings based on PWA

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

R. Edwards *et al.*, PRD **87**, 054506 (2013)



$\Xi(1320)$	****	$\to \Lambda\pi$	$I\left(J^P\right) = \frac{1}{2}\left(\frac{1}{2}^+\right)$
$\Xi(1530)$	****	$\to \Xi\pi$	$I\left(J^P\right) = \frac{1}{2}\left(\frac{3}{2}^+\right)$
$\Xi(1620)$	*	$\to \Xi\pi$?	$I\left(J^P\right) = \frac{1}{2}\left(\frac{1}{2}^- \text{ or } \frac{1}{2}^+\right)$
$\Xi(1690)$	***	$\to Y\bar{K}$	$I\left(J^P\right) = \frac{1}{2}\left(\frac{1}{2}^- ?\right)$
$\Xi(1820)$	***	$\to \Lambda\bar{K}$!	$I\left(J^P\right) = \frac{1}{2}\left(\frac{3}{2}^-\right)$
$\Xi(1950)$	***	$\to \Xi\pi,\ Y\bar{K}$	$I\left(J^P\right) = \frac{1}{2}\left(\frac{3}{2}^- ?\right)$, "broad"
$\Xi(2030)$	***	$\to Y\bar{K}$	$I\left(J^P\right) = \frac{1}{2}\left(\geq \frac{5}{2}^?\right)$

1. Excitation Band: $(\mathbf{70}, 1_1^-)$

$$\mathbf{70} = {}^2\mathbf{10} \oplus {}^4\mathbf{8} \oplus {}^2\mathbf{8} \oplus {}^2\mathbf{1}$$

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

➜ Counting of states of each flavor and spin consistent with QM for the lowest negative- and positive-parity bands.

CLAS g11a: Excited States in $\gamma p \to K^+ K^+ \pi^- (X)$

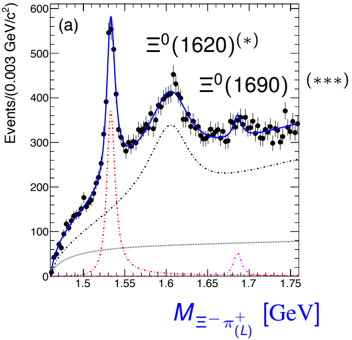
From the paper: *Although a small enhancement is observed in the $\Xi^0\pi^-$ invariant mass spectrum near the controversial 1-star $\Xi^-(1620)$ resonance, it is not possible to determine its exact nature without a full partial wave analysis.*
Phys. Rev. C **76**, 025208 (2007)

Need high-statistics, high-energy data from an experiment designed to see Ξ states:

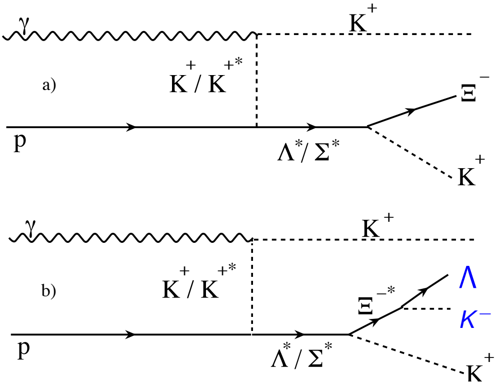
- 3- or 4-track trigger
- Reconstruction of full decay chain
- Higher photon energy
- Improved detectors

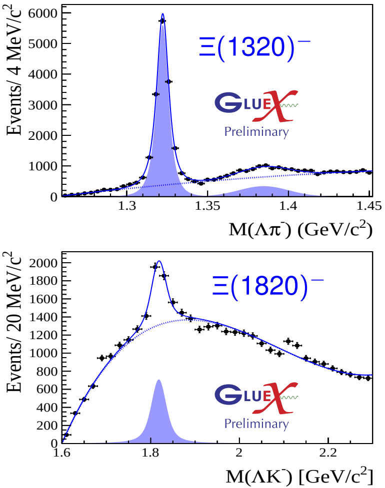
→ CLAS 12 and GlueX at Jefferson Lab

Belle: PRL **122**, 072501 (2019)



Possible Production Mechanisms



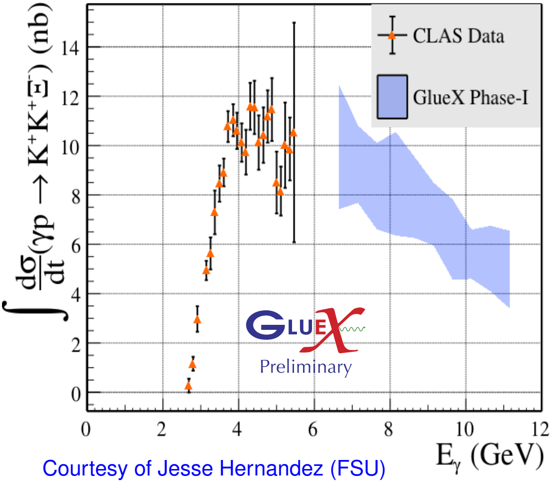


$$\gamma p \rightarrow K^+ (K^+ \Xi^{-*}) \rightarrow K^+ (p \pi^- K^-) K^+$$

Courtesy of Jesse Hernandez, Chandra Akondi (FSU)

GlueX: Cross Sections in $\gamma p \to K^+ K^+ \Xi(1320)^-$

[CLAS Collaboration], Phys. Rev. C **98** (2018) 6, 062201



Courtesy of Jesse Hernandez (FSU)

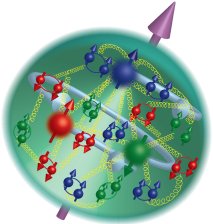
Measurements of

- Differential cross sections
- Polarization observables
- Mass, width, spin

➜ Band denotes current systematic uncertainties, not final.

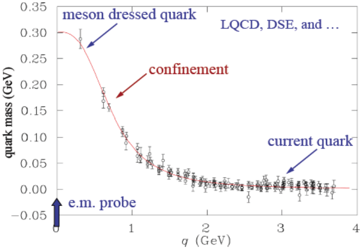
➜ Flash talk by Jesse H.

Outline



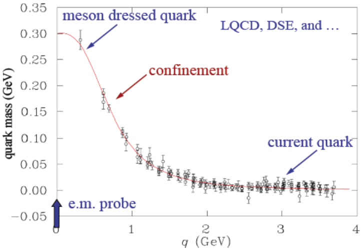
Open Issues in (Light) Baryon Spectroscopy

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. a $\Lambda(1405)$ or $N(1440)$? What is the situation with the $(\mathbf{20}, 1_2^+)$?
3. What is the nature of non-quark contributions, e. g. meson-baryon cloud or dynamically-generated states?
   ➜ Probe the running quark mass and determine the relevant degrees of freedom at different distance scales.
4. How do nearly massless quarks acquire mass? (as predicted in DSE and LQCD)



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. a $\Lambda(1405)$ or $N(1440)$? What is the situation with the $(\mathbf{20}, 1^+_2)$?
3. What is the nature of non-quark contributions, e. g. meson-baryon cloud or dynamically-generated states?
   ➜ Probe the running quark mass and determine the relevant degrees of freedom at different distance scales.
4. How do nearly massless quarks acquire mass? (as predicted in DSE and LQCD)



Summary and Conclusions

Quantum Chromodynamics (QCD) is (most likely) the correct theory of strong interactions. However, the theory remains still fairly untested and not very well understood at low energies (spectra and properties of hadrons).

Hadron spectroscopy is a powerful tool to scrutinize ideas on the effective degrees of freedom that govern hadron dynamics.

- QCD-inspired models have been very successful at describing the overall features of the spectrum of mesons and baryons, and also their decays, form factors, transition form factors, magnetic moments, etc.
- However, these models have also exhibited important failures:
  - Link between partonic degrees of freedom seen in deep inelastic scattering and constituent quarks remains poorly understood.
  - Experiments have yet to provide compelling evidence for gluonic excitations (glueballs, hybrids, etc.)