Strangeness Physics at GlueX

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15th Intl. Conf. on Hypernuclear and Strange Particle Physics

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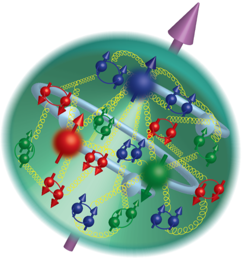
Tokyo, Japan

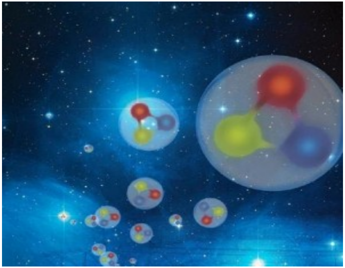
09/30/2025

Outline

Outline



Non-Perturbative QCD



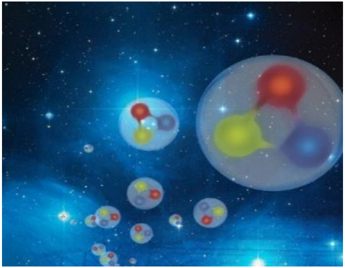
How does QCD give rise to excited hadrons?

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 hadrons, 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



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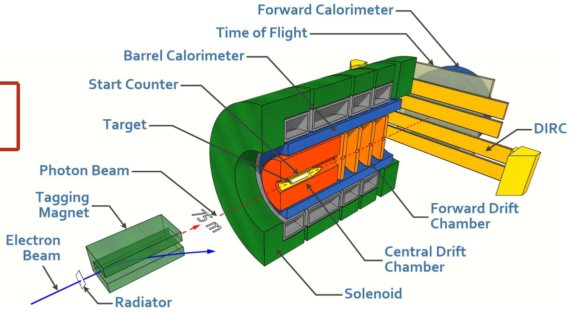
Hadron Spectroscopy

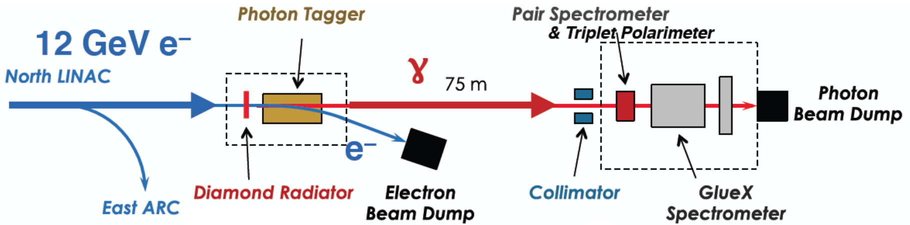
- π + Nucleus
- $\gamma\, p$ *Photoproduction*
- $e^+ e^-$
- $\bar{p}\, p$



The GlueX Collaboration

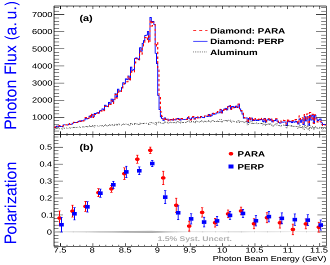
- $\sim$135 members, 29 institutions (Armenia, Canada, Chile, China, Germany, Greece, Russia, UK, USA)
- GlueX phase-I complete (120 PAC days)
- First physics published in 2017

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.



GlueX Core Mission: Search for Hybrid Mesons

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

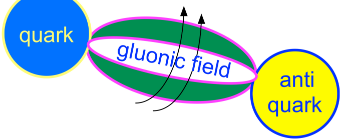
- Parity: $P = (-1)^{L+1}$
- Charge Conjugation: $C = (-1)^{L+S}$ (defined for neutral mesons)
- G parity: $G = C\,(-1)^I$

$L = 0,\ S = 0:$

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

$L = 0,\ S = 1:$

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

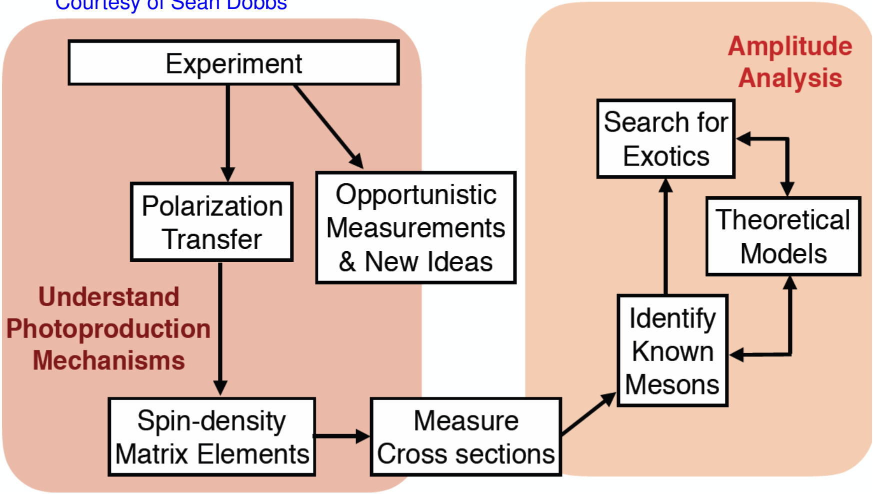


12 GeV CEBAF upgrade has high priority
(DOE Office of Science, Long Range Plan)
"[key area] is experimental verification of the powerful force fields *(flux tubes)* believed to be responsible for quark confinement."

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

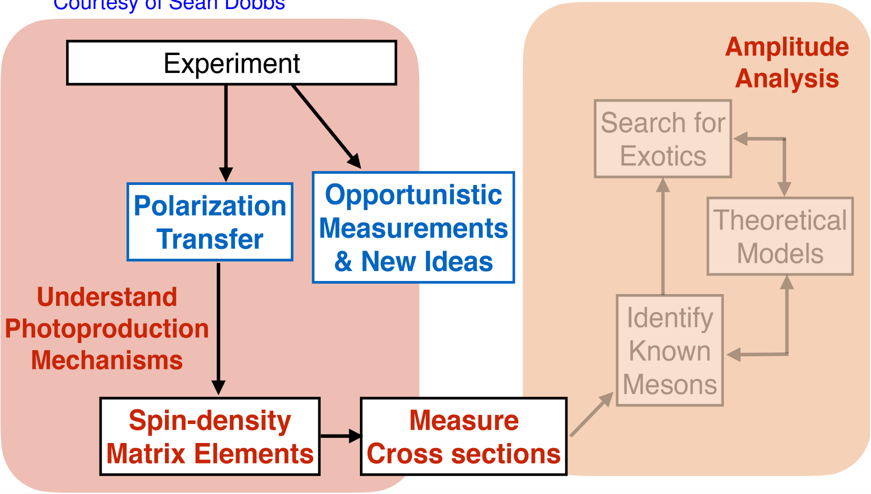
Spectroscopy and Amplitude Analysis

Courtesy of Sean Dobbs

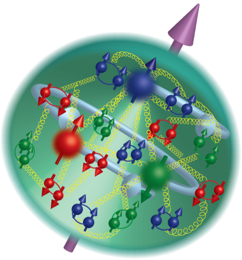


Spectroscopy and Amplitude Analysis

Courtesy of Sean Dobbs

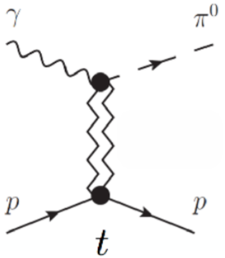


Outline



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

Beam Asymmetry, Σ, yields information on production mechanism:



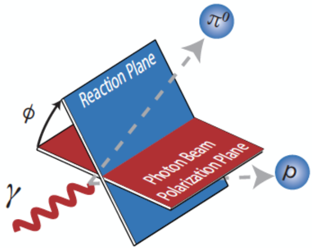
Exchange of J^{PC}

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

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

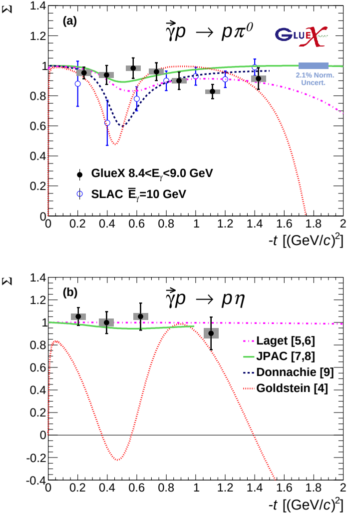
Experimentally:

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



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

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

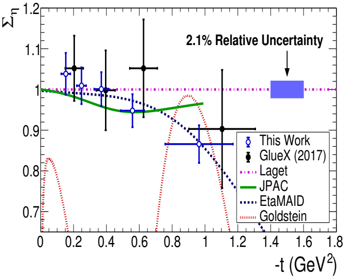


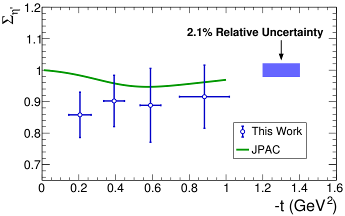
H. Al Ghoul *et al.*, Phys. Rev. C **95**, no. 4, 042201 (2017)

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.

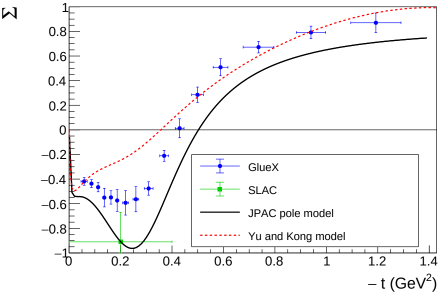
Measurement of Beam Asymmetries: $\gamma p \to \Delta^{++}\pi^-$

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

F. Afzal *et al.*, Physics Letters B **863**, 139368 (2025)

- 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)

[GlueX] Physics Letters B **863**, 139368 (2025)

- Charge exchange process
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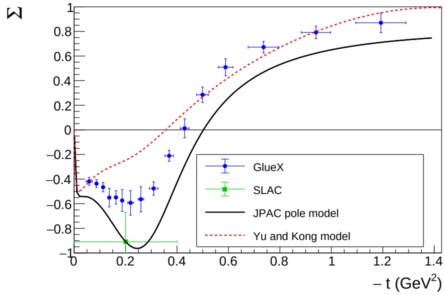
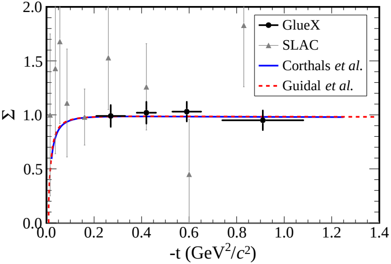


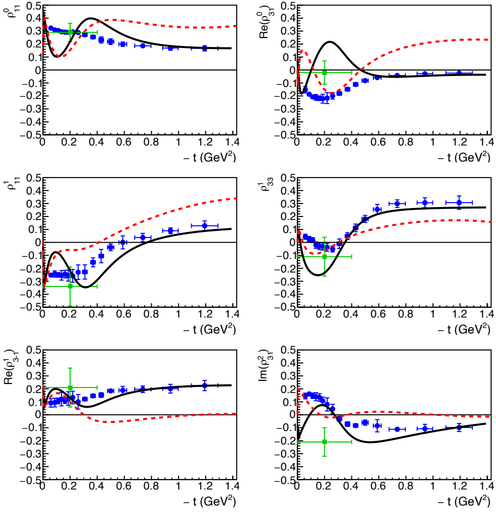
$\gamma p \to K^+ \Sigma^0$



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

- Consistent with unity
  - ➜ Dominant natural parity exchange

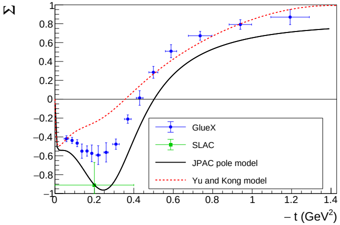
Spin-Density Matrix Elements: $\gamma p \to \Delta^{++}\pi^-$



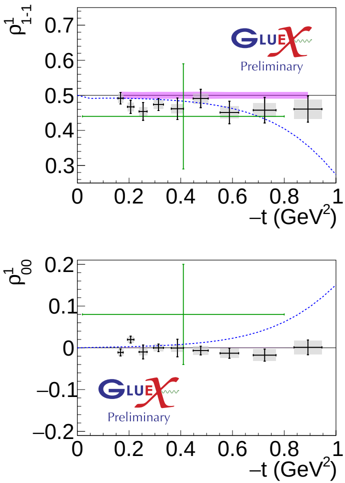
[GlueX] PL B **863**, 139368 (2025)

$$\rho^{N/U}_{ij} = \rho^0_{ij} \pm \rho^1_{ij}$$

$$\Sigma = \left(\rho^N_{11} + \rho^N_{33}\right) - \left(\rho^U_{11} + \rho^U_{33}\right)$$
$$= 2\left(\rho^1_{11} + \rho^1_{33}\right)$$

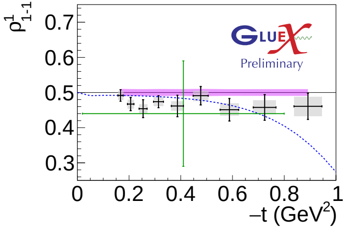


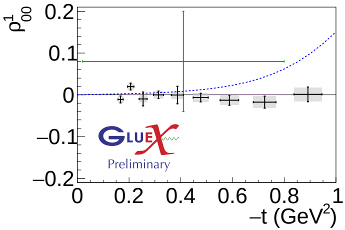
Spin-Density Matrix Elements: $\gamma p \to p\phi(1020)$



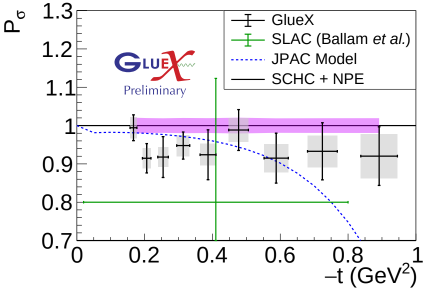
[GlueX] Phys. Rev. C **112**, 025203 (2025)

Spin-Density Matrix Elements: $\gamma p \to p\phi(1020)$





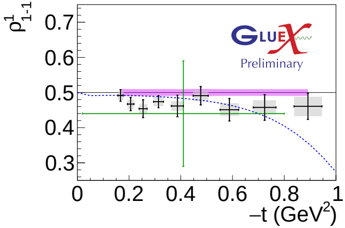
[GlueX] Phys. Rev. C **112**, 025203 (2025)

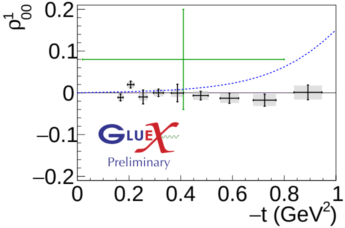


$$P_\sigma = \frac{\sigma^N - \sigma^U}{\sigma^N + \sigma^U}$$

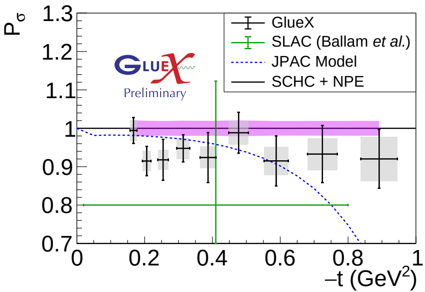
$$= 2\,\rho^1_{1-1} - \rho^1_{00}$$

Spin-Density Matrix Elements: $\gamma p \to p\phi(1020)$





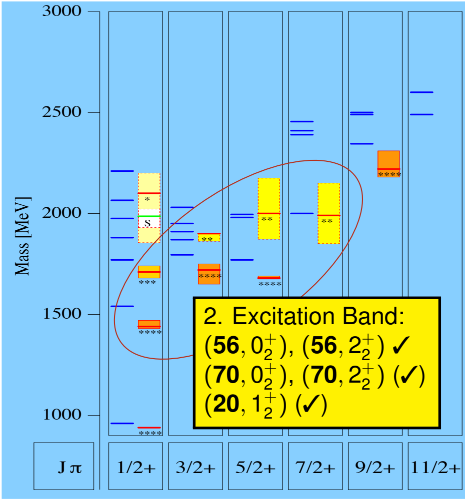
[GlueX] Phys. Rev. C **112**, 025203 (2025)



Small systematic deviation of P_σ from pure natural-parity exchange due to

- Small background, or
- Small contribution from π or η, for instance.

Spectrum of N^* Resonances

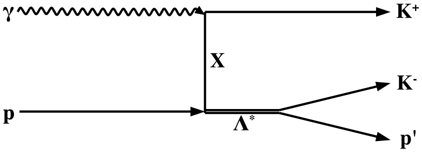


V. C. & W. Roberts, Rep. Prog. Phys. **76** (2013)

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	$(56, 0_2^+)$	$\frac{1}{2}$	$\frac{1}{2}^+$	$N(1440)$	$\Lambda(1600)$	$\Sigma(1660)$		–
	$(70, 0_2^+)$	$\frac{1}{2}$	$\frac{1}{2}^+$	$N(1710)$	$\Lambda(1810)^\dagger$	$\Sigma(1770)^\dagger$		
		$\frac{3}{2}$	$\frac{3}{2}^+$					–
	$(56, 2_2^+)$	$\frac{1}{2}$	$\frac{3}{2}^+$	$N(1720)^\dagger$	$\Lambda(1890)^\dagger$	$\Sigma(1840)^\dagger$		–
			$\frac{5}{2}^+$	$N(1680)$	$\Lambda(1820)^\dagger$	$\Sigma(1915)^\dagger$		–
	$(70, 2_2^+)$	$\frac{1}{2}$	$\frac{3}{2}^+$					
			$\frac{5}{2}^+$	$N(1860)$				
		$\frac{3}{2}$	$\frac{1}{2}^+$	$N(1880)$				–
			$\frac{3}{2}^+$	$N(1900)^\dagger$		$\Sigma(2080)^\dagger$		–
			$\frac{5}{2}^+$	$N(2000)$	$\Lambda(2110)^\dagger$	$\Sigma(2070)^\dagger$		–
			$\frac{7}{2}^+$	$N(1990)$	$\Lambda(2020)$	$\Sigma(2030)^\dagger$		–
	$(20, 1_2^+)$	$\frac{1}{2}$	$\frac{1}{2}^+$	$N(2100)^\dagger$				
			$\frac{3}{2}^+$	$N(2040)^\dagger$				
			$\frac{5}{2}^+$	–	–	–	–	

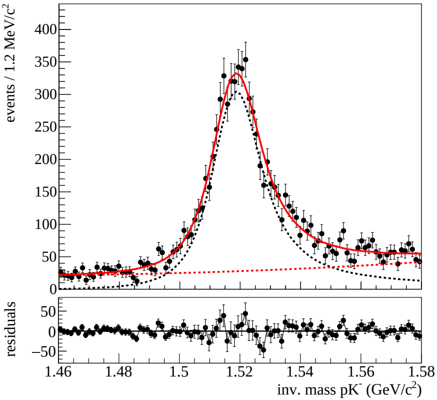
Photoproduction of Λ(1520) at GlueX

$\gamma p \to K^+ \Lambda(1520) \to K^+ \, (K^- p)$



Production mechanism in terms of naturality of exchange particle X:

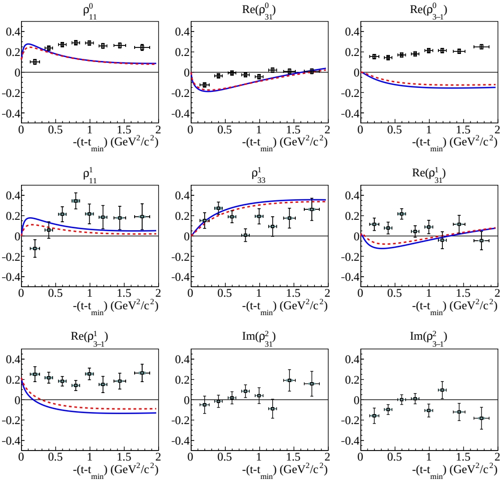
$$\eta = P(-1)^J \quad \to \quad N, U$$



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

[GlueX Collaboration], Phys. Rev. C **105**, 035201 (2022)

Photoproduction of Λ(1520) at GlueX



$\Lambda(1520)$: $J^P = \frac{3}{2}^-$

➜ 4×4 spin density matrix

Linear Polarization

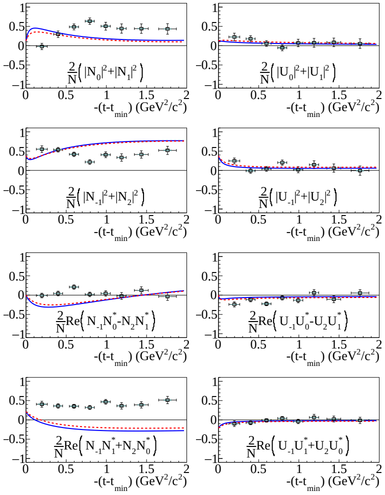
$$\rho = \rho^0 - P_\gamma \cos 2\phi \, \rho^1 - P_\gamma \sin 2\phi \, \rho^2$$

Accessible at GlueX:

four unpolarized,
six polarized SDMEs ➜ $\rho_{2\lambda_\Lambda \, 2\lambda'_\Lambda}$

[GlueX Collaboration], Phys. Rev. C **105**, 035201 (2022)

Photoproduction of Λ(1520) at GlueX



[GlueX Collaboration], Phys. Rev. C **105**, 035201 (2022)

Certain combinations of SDMEs are then linear combinations of purely natural or purely unnatural exchange amplitudes.

Example:

$$\rho^0_{11} + \rho^1_{11} = \frac{2}{\mathcal{N}} \left(|N_0|^2 + |N_1|^2 \right)$$

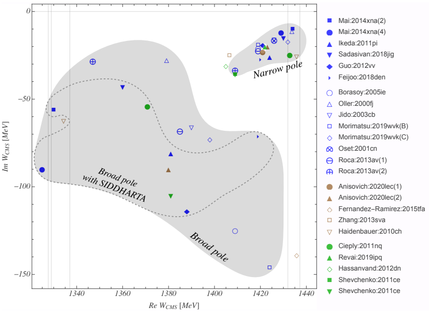
$$\rho^0_{11} - \rho^1_{11} = \frac{2}{\mathcal{N}} \left(|U_0|^2 + |U_1|^2 \right)$$

The photoproduction of Λ(1520) at GlueX energies dominated by natural exchange amplitudes over most of $-(t - t_0)$ range.

Study of Λ(1405) Hyperon at GlueX

$\gamma p \to K^+ \Lambda(1405) \to K^+ \, (\Sigma\pi)$

[M. Mai, Eur. Phys. J ST **230**, 1593 (2021)]



From the literature:

- Higher-mass pole at $\sim$ 1430 MeV coupling more strongly to $N\bar{K}$.

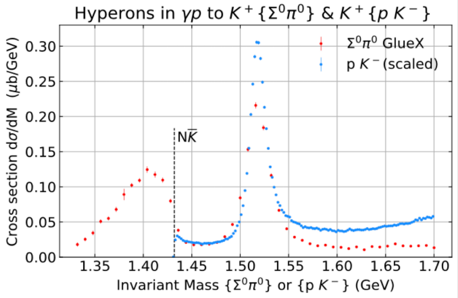
  Lower-mass pole at $\sim$ 1390 MeV coupling more strongly to $\Sigma\pi$.
- Many theorists believe:
  $N\bar{K}$ quasi-bound state submerged in $\Sigma\pi$ continuum: coupled-channel dynamics.
- Most data from low-energy NK scattering or kaonic atoms are not very sensitive to $\Sigma\pi$ pole position.

  ➜ GlueX approach is different.

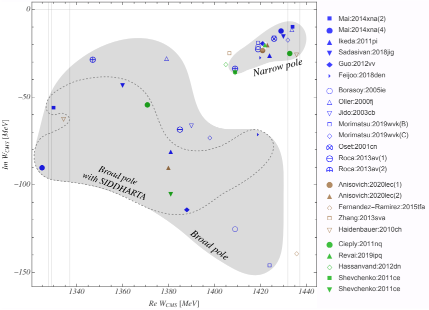
The $\Lambda(1405)/\Lambda(1520)$ Hyperons at GlueX

Motivation

- $\Lambda(1405)$ light compared to $\Lambda(1520)$.
- $\Lambda(1405)$ close to $N\bar{K}$ threshold.
- $\Lambda(1405)$ decays to $\Sigma\pi$ but MUST also decay to $N\bar{K}$.



[M. Mai, Eur. Phys. J ST **230**, 1593 (2021)]



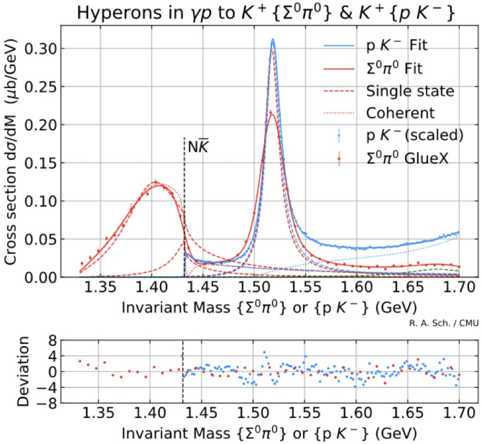
GlueX produces resonances cleanly:

$$\gamma p \to K^+\Lambda(1405) \to K^+\,(\Sigma^0\pi^0)_{\text{pure } I=0}$$

$$\to K^+\,(pK^-)$$

The Λ(1405)/Λ(1520) Hyperons at GlueX

Full range: $0.0 < -t' < 1.5$ GeV^2



Two-pole K-matrix Fit to $\Lambda(1405)_{A,B}$

$\Sigma^0\pi^0$ channel

- Solid – fit to data
- Dashed – each A, B separately
- Dotted – fit to data, full K-matrix fit
  Prior to convolving 7.8 MeV mass resolution

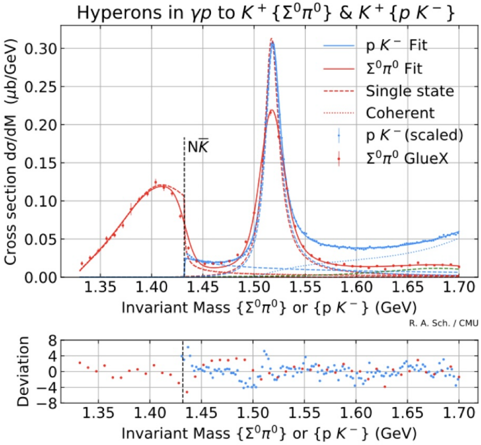
pK^- channel

- Solid – fit to data
  ($\sim$ 2 MeV resolution)
- Dashed – coherent tails of A, B
- Dotted – incoherent background

The $\Lambda(1405)/\Lambda(1520)$ Hyperons at GlueX

Full range: $0.0 < -t' < 1.5$ GeV^2

One-pole K-matrix Fit to $\Lambda(1405)_B$



$\Sigma^0\pi^0$ channel

- Solid – fit to data
- Dashed – single $\Lambda(1405)$ state

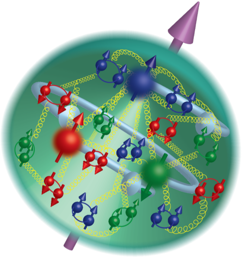
$p\,K^-$ channel

- Solid – fit to data
- Dashed – coherent tail of $\Lambda(1405)$
- Dotted – incoherent background

Worse fit compared to two-pole ansatz
(especially in critical threshold region)

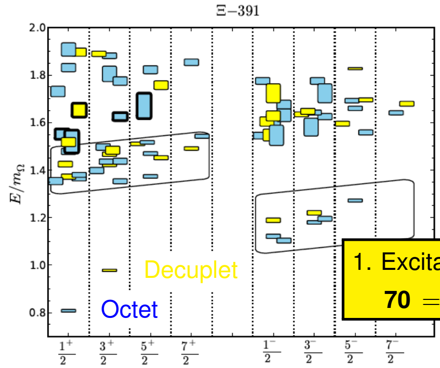
Outline

1. Introduction and Motivation
   - Strong-Coupling QCD
   - The GlueX Experiment
2. Hadron Spectroscopy at GlueX
   - Beam Asymmetries
   - Spin-Density Matrix Elements
   - Spectroscopy of Hyperons
3. Spectroscopy of Ξ Resonances
4. Summary and Conclusions

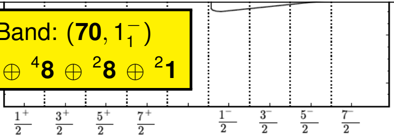


The Ξ^* and Ω^* Spectrum from Lattice QCD

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.

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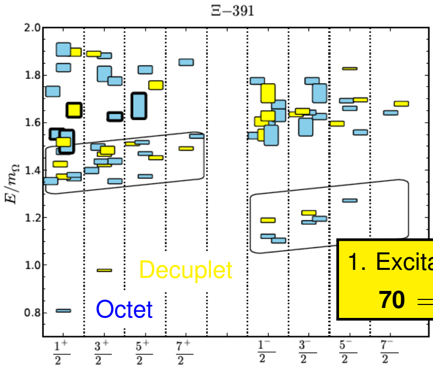

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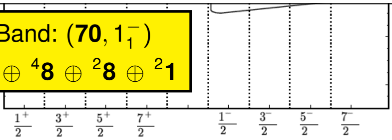

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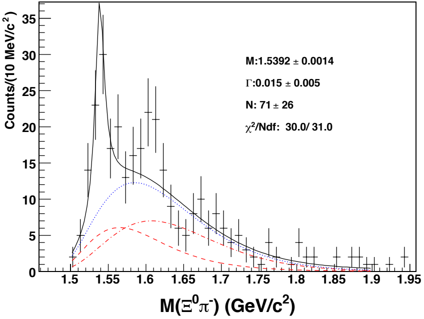
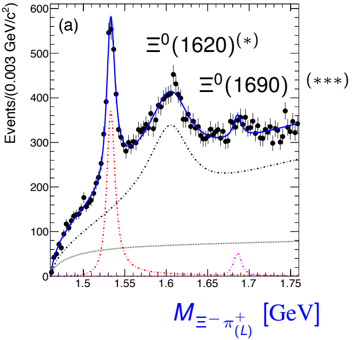
CLAS g11a: Excited States in $\gamma p \to K^+ K^+ \pi^- \, (X)$

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)



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



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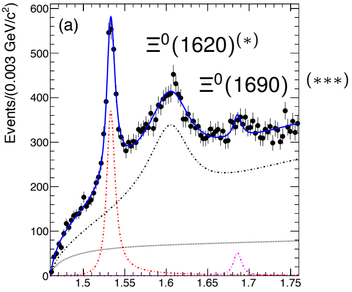
Need high-statistics, high-energy data from an experiment designed to see Ξ states:

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

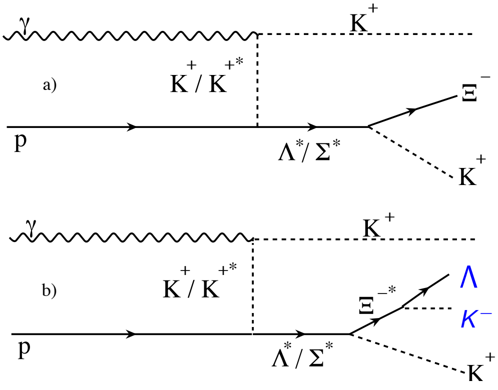
→ GlueX at Jefferson Lab

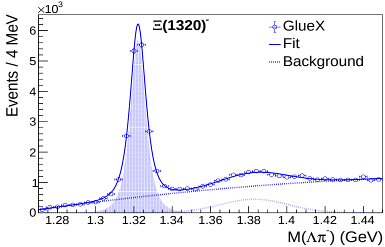
Belle: PRL **122**, 072501 (2019)

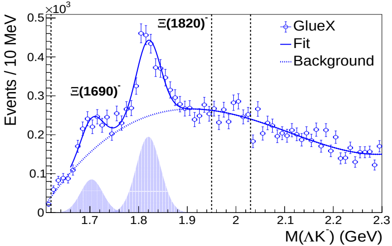


$M_{\Xi^-\pi^+_{(L)}}$ [GeV]

Possible Production Mechanisms





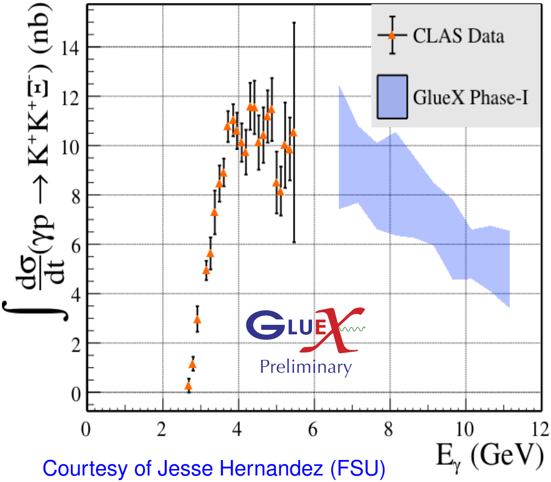


$$\gamma p \rightarrow K^+ (K^+ \Xi^{-*}) \rightarrow K^+ (p \pi^- K^-) K^+$$

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

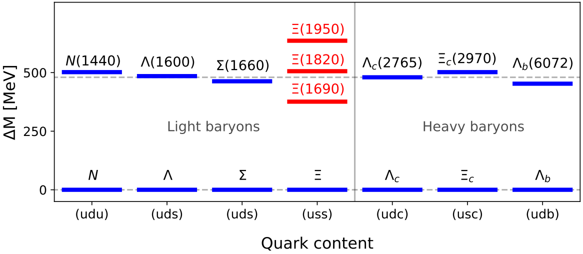
- Differential cross sections
- Polarization observables
- Mass, width, spin

➜ Band denotes current systematic uncertainties, not final.

Summary and Open Questions

Spectroscopy of (low-mass) Ξ resonances very important to understand the systematics of the baryon spectrum:

- What about the properties of the Ξ(1620) / Ξ(1690) states?
- Is the Ξ(1620) more than one state? Is the Ξ(1620) the doubly strange partner of the Λ(1405)?
- Where is the radial excitation of the Ξ(1320)?

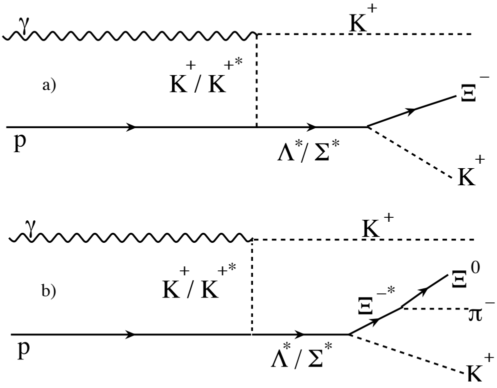


Radial Excitations (Roper-like states)

for the octet members with $J^P = \frac{1}{2}^+$

Arifi *et al.*, PRD **105**, 094006

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^*)

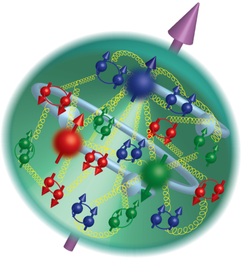
At other facilities (for comparison):

$K^- p \to K^+ \Xi^{*-}$	J-PARC (2029?)
$K_L p \to K^+ \Xi^{*0}$	Hall D (2026/30?)
$p p \to \Xi^* X$	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)

Outline

1. Introduction and Motivation
   - Strong-Coupling QCD
   - The GlueX Experiment
2. Hadron Spectroscopy at GlueX
   - Beam Asymmetries
   - Spin-Density Matrix Elements
   - Spectroscopy of Hyperons
3. Spectroscopy of Ξ Resonances
4. Summary and Conclusions



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.).

https://gluex.org/thanks.html

Opportunities with Secondary K_L^0 Beams in Hall D

Possible reactions to be studied (elastic and charge-exchange reactions):

- 2- & 3-body reactions producing $S = -1$ hyperons
- 2-body reactions producing $S = -2$ hyperons
  ➜ $K_L^0\, p \to K^+\,\Xi^0;\ \pi^+ K^+\,\Xi^-;\ K^+\,\Xi^{0*};\ \pi^+ K^+\,\Xi^{-*}$
- 3-body reactions producing $S = -3$ hyperons
  ➜ $K_L^0\, p \to K^+ K^+\,\Omega^-;\ K^+ K^+\,\Omega^{-*}$