Baryon spectroscopy at GlueX

IWHSS - CPHI workshop

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University of Bonn

Motivation - baryon spectroscopy

- **Goal: Study excited states ($N^*, \Delta^*, \Lambda^*, \Sigma^*, \Xi^*, \Omega^*$) and properties**
- More states expected than have been found so far!
  - Do these states exist?
  - Is SU(6)xO(3)-symmetry realized?
  - At least 23 missing Σ^*
- What is the nature of the observed states, e.g. $\Lambda(1405)$ two-pole structure

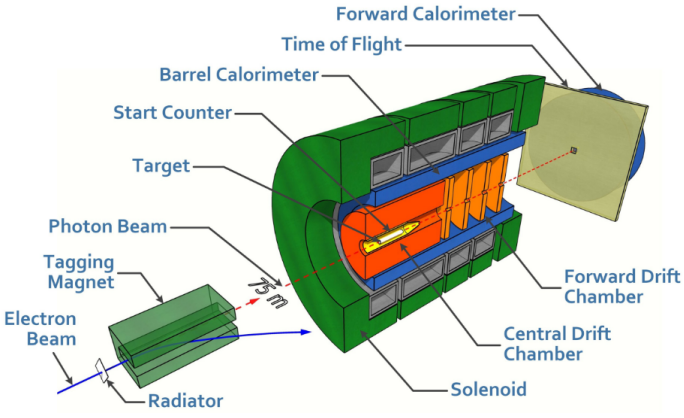
PDG2021:"...the field ($\Lambda^*, \Sigma^*, \Xi^*, \Omega^*$) is starved for data ...

GlueX experiment probes hadron spectrum using photo-induced reactions
$\rightarrow$ covers large mass range up to bound charmonium states (E_γ : 6.5 – 11.4 GeV)!

N	(D, L_N^P)	S	J^P	Octet Members					Singlets
0	$(56, 0_0^+)$	1/2	$1/2^+$	$N(939)$	****	$\Lambda(1116)$	$\Sigma(1193)$	$\Xi(1318)$	–
1	$(70, 1_1^-)$	1/2	$1/2^-$	$N(1535)$	****	$\Lambda(1670)$	$\Sigma(1620)$	$\Xi(1690)$	$\Lambda(1405)$
			$3/2^-$	$N(1520)$	****	$\Lambda(1690)$	$\Sigma(1670)$	$\Xi(1820)$	$\Lambda(1520)$
		3/2	$1/2^-$	$N(1650)$	****	$\Lambda(1800)$	$\Sigma(1750)$		–
			$3/2^-$	$N(1700)$	***				–
			$5/2^-$	$N(1675)$	****	$\Lambda(1830)$	$\Sigma(1775)$		–
2	$(56, 0_2^+)$	1/2	$1/2^+$	$N(1440)$	****	$\Lambda(1600)$	$\Sigma(1660)$		–
	$(70, 0_2^+)$	1/2	$1/2^+$	$N(1710)$	****	$\Lambda(1810)^\dagger$	$\Sigma(1770)^\dagger$		
		3/2	$3/2^+$						–
	$(56, 2_2^+)$	1/2	$3/2^+$	$N(1720)^\dagger$	****	$\Lambda(1890)^\dagger$	$\Sigma(1840)^\dagger$		–
			$5/2^+$	$N(1680)$	****	$\Lambda(1820)^\dagger$	$\Sigma(1915)^\dagger$		–
	$(70, 2_2^+)$	1/2	$3/2^+$						
			$5/2^+$	$N(1860)$	**				
		3/2	$1/2^+$	$N(1880)$	***			–	
			$3/2^+$	$N(1900)^\dagger$	****		$\Sigma(2080)^\dagger$		–
			$5/2^+$	$N(2000)$	**	$\Lambda(2110)^\dagger$	$\Sigma(2070)^\dagger$		–
			$7/2^+$	$N(1990)$	**	$\Lambda(2020)$	$\Sigma(2030)^\dagger$		–
	$(20, 1_2^+)$	1/2	$1/2^+$	$N(2100)^\dagger$	***				
			$3/2^+$	$N(2040)^\dagger$	*				
			$5/2^+$	–		–	–	–	
3	$(56, 1_3^-)$	1/2	$1/2^-$	$N(1895)^\dagger$	****				–
			$3/2^-$	$N(1875)^\dagger$	***		$\Sigma(1940)^\dagger$		–
	$(70, 1_3^-)$			5 x					
	$(70, 1_3^-)$			5 x					
	$(20, 1_3^-)$	1/2		2 x					
	$(70, 2_3^-)$			6 x					
	$(56, 3_3^-)$	1/2		2 x					–
	$(70, 3_3^-)$	1/2	$7/2^-$	$N(2190)^\dagger$	****	$\Lambda(2100)^\dagger$			
		3/2	$9/2^-$	$N(2250)$	****				
	$(20, 3_3^-)$	1/2		2 x					
4			$9/2^+$	$N(2220)$	****	$\Lambda(2350)$			
5			$11/2^-$	$N(2600)$	***				

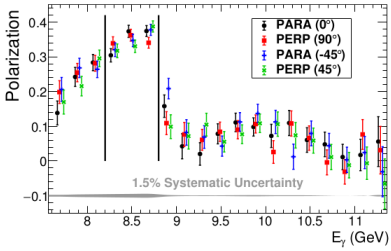
V. Crede

The GlueX experiment at CEBAF (JLab)



(GlueX) NIMA 987 (2021) 164807

Linearly polarized photon beam

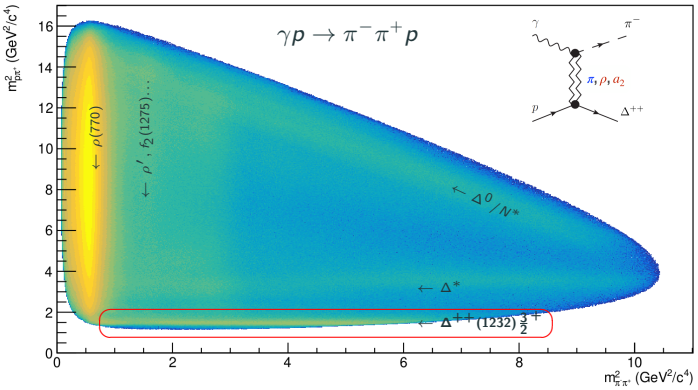


→ Gives insight to production processes

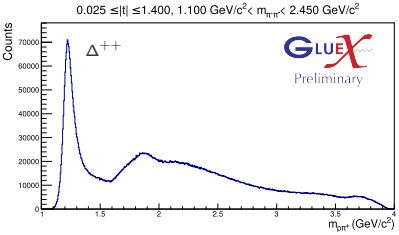
Experiment is optimized for light meson spectroscopy → see talk by J. Stevens

- Coherent Bremsstrahlung on diamond radiator
- Beam intensity: 1-5×$10^7\gamma/s$ in peak
- GlueX Phase-I completed ($\int L = 125$ pb^{-1} in coherent peak), Phase-II: ongoing, 3-4 × Phase-I data

Study of charge exchange mechanism $\gamma p \to \pi^- \Delta^{++} \to \pi^- \pi^+ p$



- High statistics available
- Clear Δ^{++} signal with small background contributions from $\pi^+\pi^-$ system



Analyzing decay angles of $\Delta^{++} \to p\pi^+$ gives access to Spin-density matrix elements!

Study of exchange mechanism with SDMEs in $\gamma p \to \pi^- \Delta^{++} \to \pi^- \pi^+ p$

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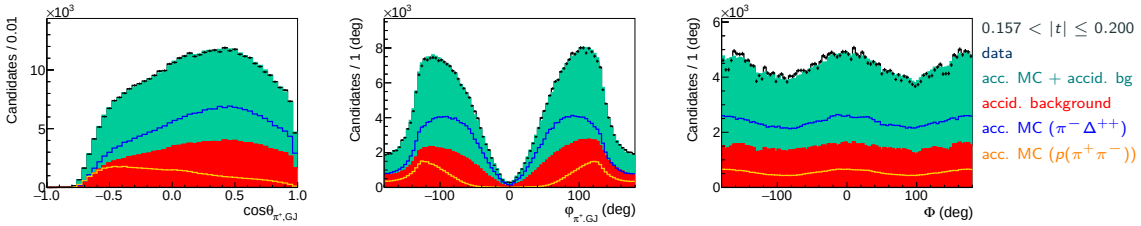
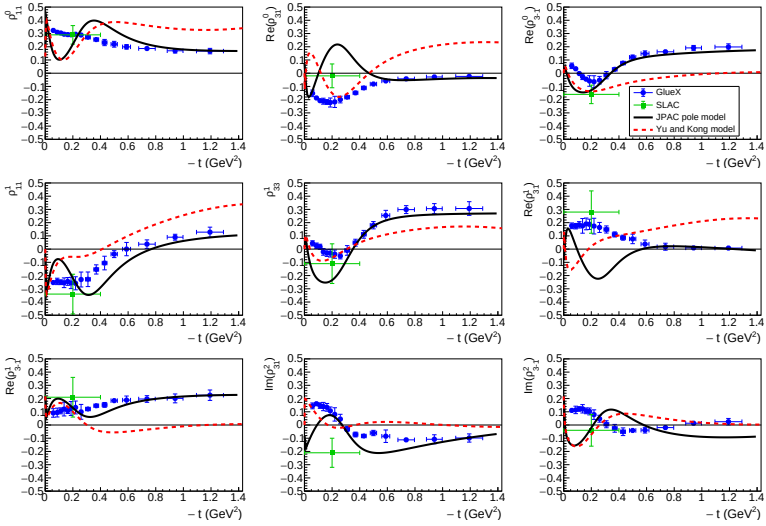
- Spin-density matrix elements (SDMEs) ρ^k_{ij} describe full angular distribution of Δ^{++} production and decay
- Linearly polarized beam provides access to nine linearly independent SDMEs

$$W(\theta,\varphi,\Phi) = \frac{3}{4\pi}(\rho^0_{33}\sin^2\theta + \rho^0_{11}\left(\frac{1}{3}+\cos^2\theta\right) - \frac{2}{\sqrt{3}}Re[\rho^0_{31}\cos\varphi\sin 2\theta + \rho^0_{3-1}\cos 2\varphi\sin^2\theta]$$
$$- P_\gamma\cos 2\Phi\left[\rho^1_{33}\sin^2\theta + \rho^1_{11}\left(\frac{1}{3}+\cos^2\theta\right) - \frac{2}{\sqrt{3}}Re[\rho^1_{31}\cos\varphi\sin 2\theta + \rho^1_{3-1}\cos 2\varphi\sin^2\theta]\right]$$
$$- P_\gamma\sin 2\Phi\frac{2}{\sqrt{3}}Im[\rho^2_{31}\sin\varphi\sin 2\theta + \rho^2_{3-1}\sin 2\varphi\sin^2\theta)])$$



F. Afzal et. al. (GlueX), arXiv:2406.12829

Spin-Density Matrix Elements in Δ^{++} production



- First precise determination of the t-dependence of the $\Delta^{++}(1232)$ SDMEs
- Data provide important constraints on the Regge-theory models
- Relative sign ambiguity of two helicity amplitude couplings in the JPAC model can be resolved with GlueX data

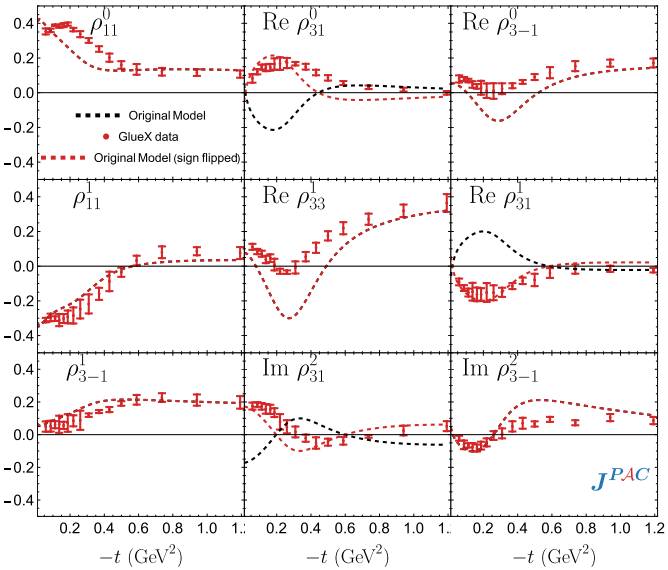
- GlueX: arXiv:2406.12829
- SLAC: Phys. Rev. D 7 (1973), 3150

— JPAC: PLB 779, 77 (2018)

- - - Yu and Kong: PLB 769, 262-266 (2017)

Spin-Density Matrix Elements in Δ^{++} production

Courtesy of Vanamali Shastry (JPAC)



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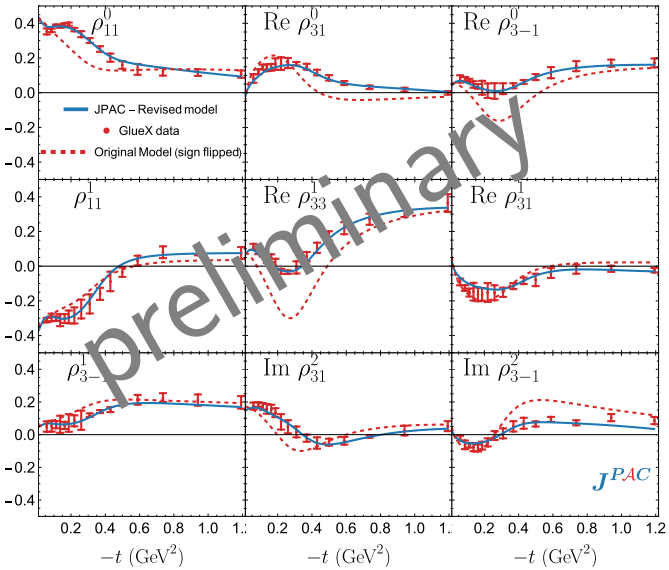

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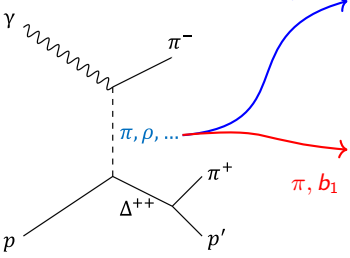
Charge exchange mechanism - $\pi^- \Delta^{++}$

- Separation of unnatural-parity (U) and natural-parity (N) exchanges

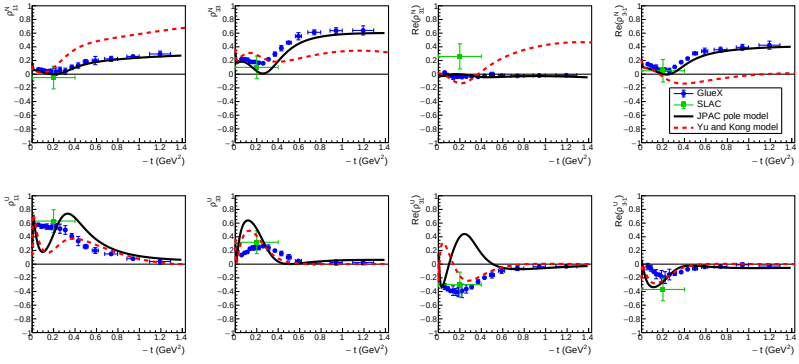
$$\rho_{ij}^{N/U} = \rho_{ij}^{0} \pm \rho_{ij}^{1}$$



naturality of exchanged particle: $\eta = P(-1)^J$

$\eta = +1$ → natural-parity exchange

$\eta = -1$ → unnatural-parity exchange



F. Afzal et al. (GlueX), arXiv:2406.12829

— JPAC: Phys. Lett. B 779, 77-81 (2018)

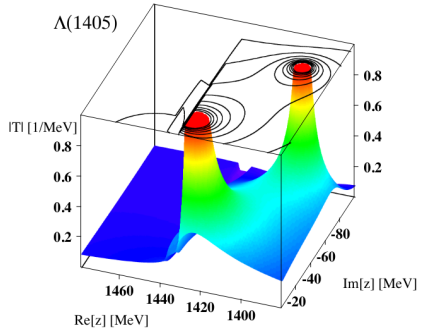
- - - Yu and Kong: PLB 769, 262-266 (2017)

- JPAC model: π (a_2) is the dominant unnatural (natural) exchange
- Important for charge-exchange reactions e.g. $\gamma p \to \eta' \pi \Delta^{++}$

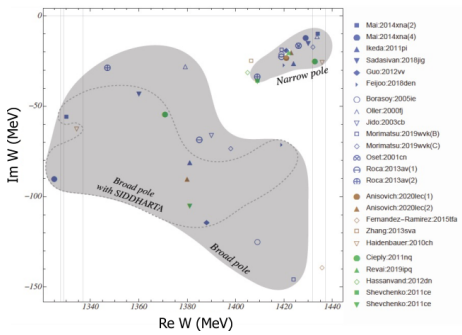
Strangeness Photoproduction at GlueX

What is the nature of the Λ(1405)?

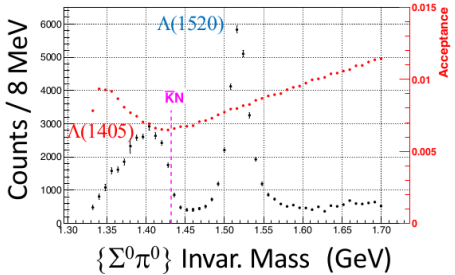
- It is too low in mass for the quark model
- Close to $N\bar{K}$ mass threshold - molecular/pentaquark nature?
- Chiral unitary models, CPT, LQCD (& others) predict two $I = 0$ states in Λ(1405) mass range, one close to the $N\bar{K}$ and the other close to the $\pi\Sigma$ thresholds

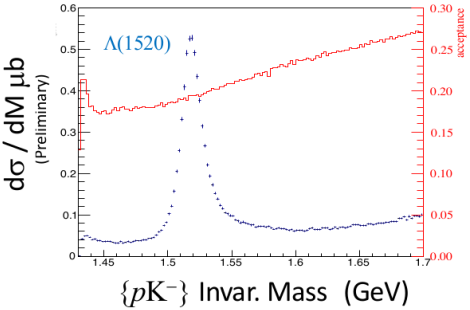


T. Hyodo and D. Jido, Prog.Part.Nucl.Phys. 67 (2012), 55-98



M. Mai, Eur.Phys.J.ST 230 (2021) 6, 1593-1607





GlueX has world's best data set to study Λ(1405) cleanly in photoproduction reactions:
$\gamma p \to K^+\Sigma^0\pi^0$ and also $\gamma p \to K^+pK^-$
$\to$ Allows to perform K-matrix fit to both final states together for the first time

$\Sigma^0\pi^0$

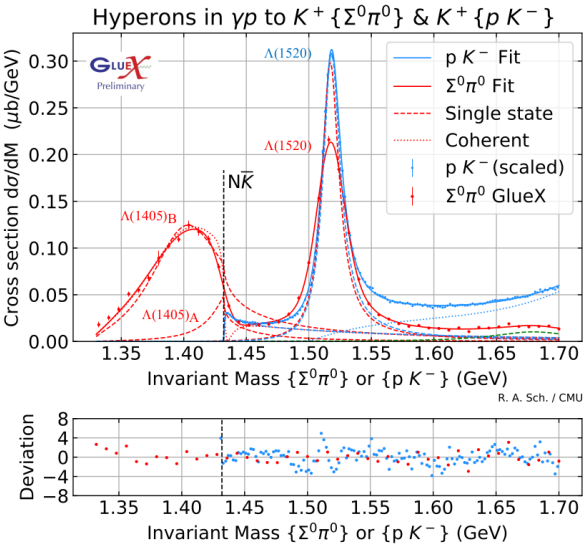
- Clean detection of Λ(1405) and Λ(1520)
- pK^- threshold effect is visible
- Average mass resolution 7.8 MeV

pK^-

- Λ(1405) tails cause pK^- turn-on at threshold
- Λ(1520) sits on top of Λ(1405) tails
- Average mass resolution 2 MeV

Two-pole ansatz

- Rescale pK^- using PDG branching and isospin factors of Λ(1520) to match the $\Sigma^0\pi^0$ scale
- K-matrix fits performed with two-pole ansatz and single-pole ansatz for Λ(1405)
- Fit results with **two-pole** ansatz:
  – Solid: fit to the data
  – Dashed: $\Sigma^0\pi^0$ - each A,B resonance separately; pK^- - coherent tail of $\Lambda(1405)_{A,B}$ states
- **Fit results with two-pole ansatz are superior!**
- GlueX (preliminary) Λ(1520):
  $(1516.5 \pm 0.3) - i(8.3 \pm 0.1)$ MeV
  → Good agreement with PDG



Two pole structure of Λ(1405)?

One-pole ansatz

- Rescale pK^- using PDG branching and isospin factors of Λ(1520) to match the $\Sigma^0\pi^0$ scale
- K-matrix fits performed with two-pole ansatz and single-pole ansatz for Λ(1405)
- Fit results with **one-pole** ansatz:
  – Solid: fit to the data
  – Dashed: $\Sigma^0\pi^0$ - single Λ(1405) resonance; pK^- - coherent tail of Λ(1405) state
- **Fit results with two-pole ansatz are superior!**
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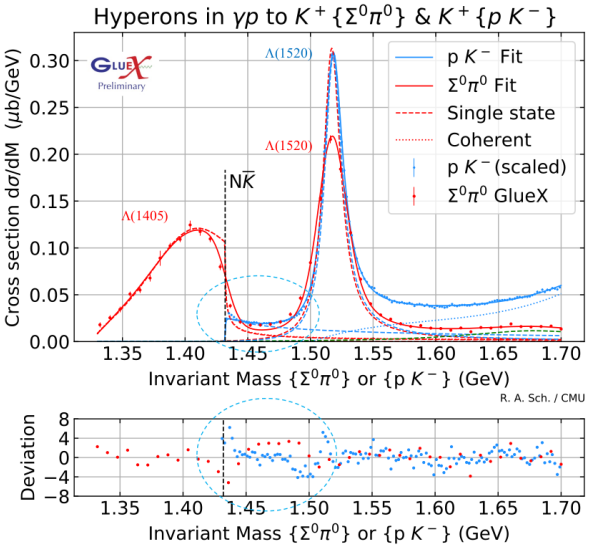
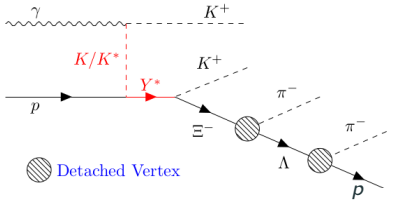
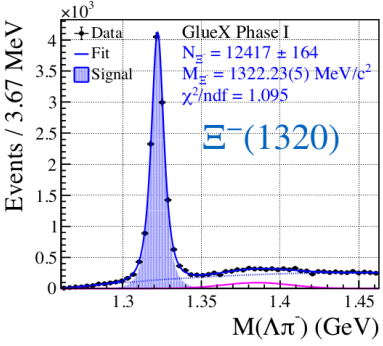
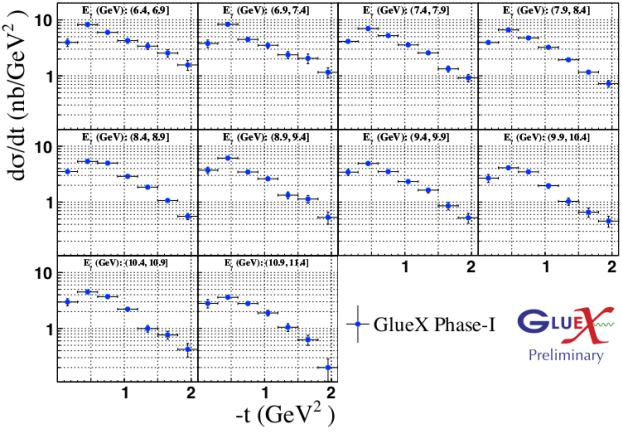


Ξ Photoproduction at GlueX - ground state $\Xi^-(1320)$

First step towards mapping the Cascade excitation spectrum and identifying possible intermediate hyperons Y^*







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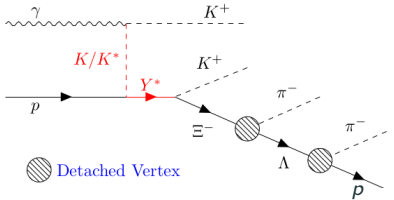
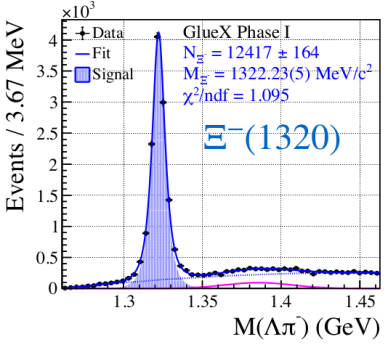
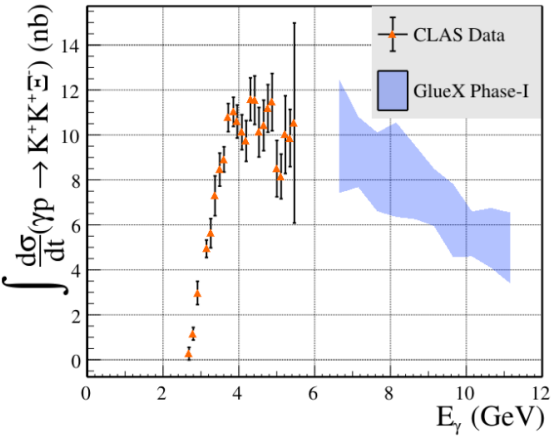




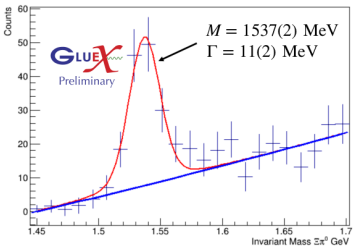
J. T. Goetz et al., (CLAS Collaboration), Phys. Rev. C 98, 062201(R) (2018)



Ξ Photoproduction at GlueX - $\Xi(1530)^-$, $\Xi(1690)^-$ and $\Xi(1820)^-$

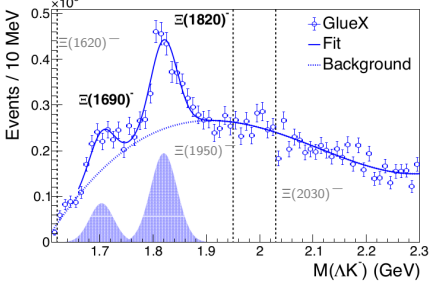
Strong evidence for $\Xi(1690)^-$, $\Xi(1820)^-$ in GlueX photoproduction data!

$\gamma p \to K^+K^+\Xi(1530)^-, \quad \Xi(1530)^- \to \Xi(1320)^-\pi^0$



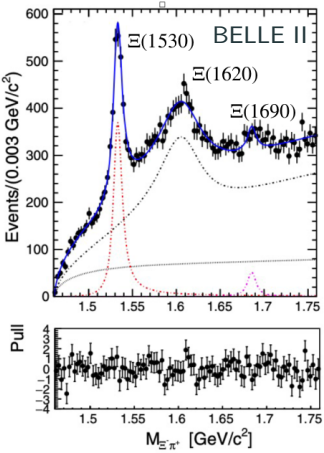
Particle	J^P	Overall status	Seen in $\Xi\pi$	Seen in ΛK
$\Xi(1318)$	1/2+	****		
$\Xi(1530)$	3/2+	****	****	
$\Xi(1620)$	1/2−?	**	**	
$\Xi(1690)$	1/2−?	***	**	***
$\Xi(1820)$	3/2−	***	**	***
$\Xi(1950)$	3/2−?	***	**	**
$\Xi(2030)$	5/2−?	***		**

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



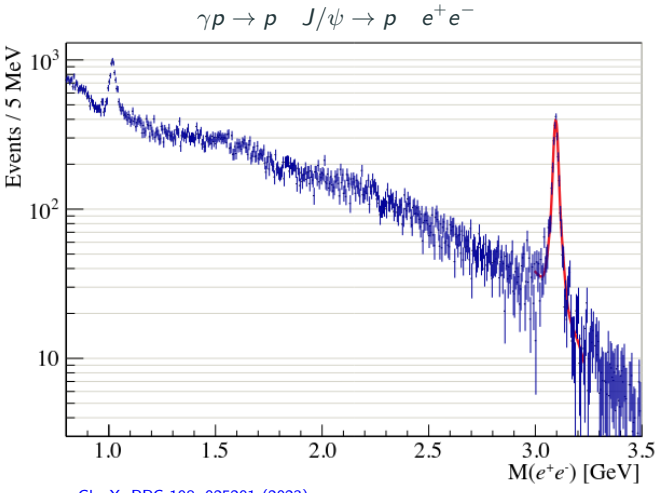
V. Crede and J. Yelton, accepted in Rep. Prog. Phys.

$\Xi_c^+ \to (\Xi^-\pi^+)\pi^+$



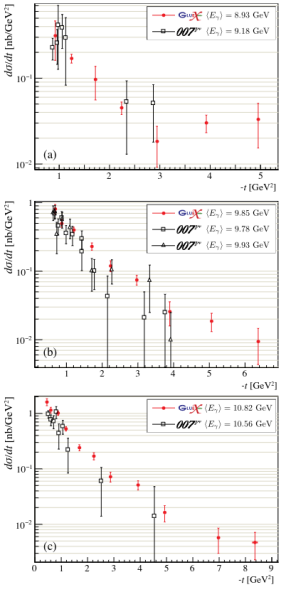
BELLE II: PRL 122, 072501 (2019)

J/ψ Photoproduction at GlueX

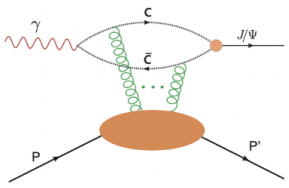


GlueX, PRC 108, 025201 (2023)

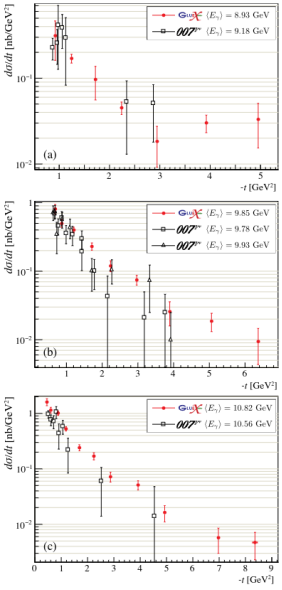
- First measurement: 469 ± 22 J/ψ's (GlueX, PRL 123 (2019) 7, 072001)
- Updated measurement: Full GlueX-I data: 2270 ± 58 J/ψ's (GlueX, PRC 108, 025201 (2023))
- J/ψ production near threshold ($E_\gamma = 8.2$ - 11.8 GeV)
  $\to$ probe of proton structure, search for P_c resonances, etc.



- $d\sigma/dt$ sensitive to proton gluonic form factors under certain assumptions
- Good agreement between GlueX and $J/\psi - 007$ (Hall C, JLab)
- Interesting enhancement at large $-t$ for low energy



J/ψ Photoproduction at GlueX - Differential and total cross section



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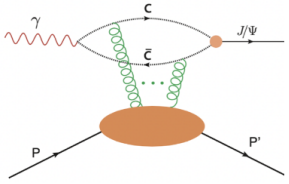
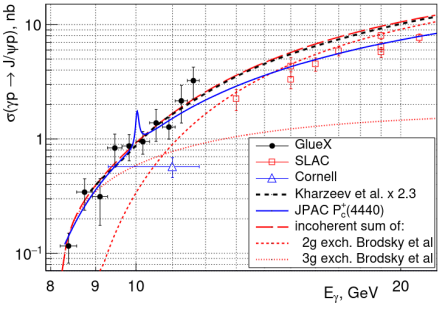


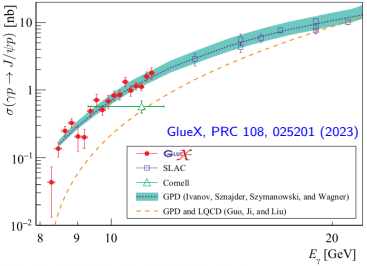
GlueX, PRL 123 (2019) 7, 072001



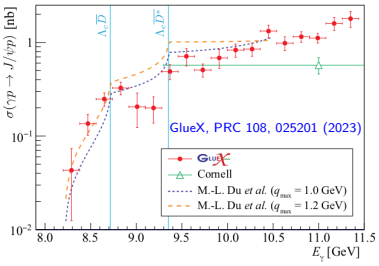
- 3g+2g exchange needed to describe data
- No clear evidence of narrow P_c states

J/ψ Photoproduction at GlueX - Different possible production mechanisms

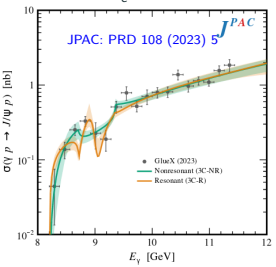
dip structure significance of 2.6σ

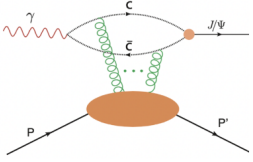


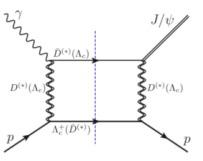
Cusps near open charm thresholds?

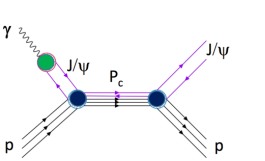


Resonant P_c contribution?





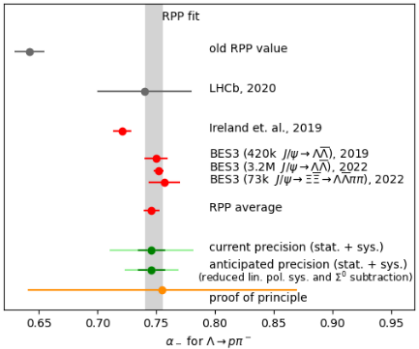




	$\mathcal{B}(P_c^+ \to J/\psi p)$ Upper Limits, %		$\sigma_{\max} \times \mathcal{B}(P_c^+ \to J/\psi p)$ Upper Limits, nb	
	p.t.p. only	total	p.t.p only	total
$P_c^+(4312)$	2.9	4.6	3.7	4.6
$P_c^+(4440)$	1.6	2.3	1.2	1.8
$P_c^+(4457)$	2.7	3.8	2.9	3.9

Outlook

Outlook for baryon spectroscopy at GlueX



Recently approved proposal at GlueX (arXiv:2405.01288):

- Measurement of the decay parameter α_- of the parity-violating weak decay $\Lambda \to p\pi^-$
- Measure pol. observables $P, \Sigma, T, O_x, O_z, C_x, C_z$ simultaneously for $\gamma p \to K^+\Lambda$ using **elliptically** (linear + circular) polarized photon beam (F. Afzal et al. (A2), Phys. Rev. Lett. 132, 121902 (2024))

- Investigating possibility of a **longitudinally polarized target** at GlueX (arXiv:2407.06429):
  - Measurement of high-energy contribution to the GDH sum rule (arXiv:2008.11059)
  - Measurement of almost complete set of pol. observables for 2-meson photoproduction (e.g. $K^+\Lambda\pi^0$) (LOI)
  - Measurement of A_{LL} for J/Ψ photoproduction (LOI)
- Planned measurements with a K_L **beam** in Hall D (arXiv:2008.08215)

Summary

- GlueX has measured a unique photoproduction data set with unprecedented statistical precision in its energy range
- GlueX can investigate excited baryons, ranging from "non-strange", "strange" to the threshold region of the "charm" sector
- t-dependence of the Δ^{++} SDMEs determined for the first time: SDMEs resolve sign ambiguity for two helicity amplitudes and provide important constraints for Regge models and ongoing amplitude analyses for the search of light-quark hybrid mesons
- GlueX data supports two-pole structure of $\Lambda(1405)$
- Strong evidence for $\Xi(1690)^-$ and $\Xi(1820)^-$ in the ΛK^- channel
- J/ψ photoproduction provides exciting opportunities for both hadron spectroscopy and hadron structure
  $\rightarrow$ More data will be taken in the future for GlueX-II and GlueX-III phase
- Exciting future opportunities at GlueX for baryon spectroscopy with elliptically polarized photon beam and perhaps with a longitudinally polarized target

- GlueX gratefully acknowledges the support of several funding agencies and computing facilities:

gluex.org/thanks/