WILLIAM & MARY
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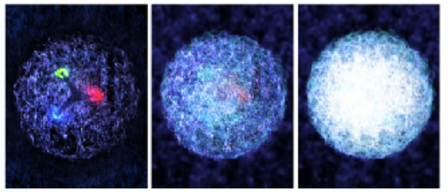
Baryon Spectroscopy at GlueX

Hao Li (W&M)
on behalf of the GlueX Collaboration

2024 Jefferson Lab Users Organization Annual Meeting (JLUO2024)

Baryon Spectroscopy at GlueX



Images courtesy of James LaPlante, Sputnik Animation in collaboration with the Massachusetts Institute of Technology Center for Art, Science & Technology and Jefferson Lab

p	$1/2^+$	****	$\Delta(1232)$	$3/2^+$	****	Σ^+	$1/2^+$	****
n	$1/2^+$	****	$\Delta(1600)$	$3/2^+$	***	Σ^0	$1/2^+$	****
$N(1440)$	$1/2^+$	****	$\Delta(1620)$	$1/2^-$	****	Σ^-	$1/2^+$	****
$N(1520)$	$3/2^-$	****	$\Delta(1700)$	$3/2^-$	****	$\Sigma(1385)$	$3/2^+$	****
$N(1535)$	$1/2^-$	****	$\Delta(1750)$	$1/2^+$	*	$\Lambda(1580)$	$3/2^-$	*
$N(1650)$	$1/2^-$	****	$\Delta(1900)$	$1/2^-$	**	$\Sigma(1620)$	$1/2^-$	*
$N(1675)$	$5/2^-$	****	$\Delta(1905)$	$5/2^+$	****	$\Sigma(1660)$	$1/2^+$	***
$N(1680)$	$5/2^+$	****	$\Delta(1910)$	$1/2^+$	****	$\Sigma(1670)$	$3/2^-$	****
$N(1700)$	$3/2^-$	***	$\Delta(1920)$	$3/2^+$	***	$\Sigma(1750)$	$1/2^-$	***
$N(1710)$	$1/2^+$	****	$\Delta(1930)$	$5/2^-$	***	$\Sigma(1775)$	$5/2^-$	****
$N(1720)$	$3/2^+$	****	$\Delta(1940)$	$3/2^-$	**	$\Lambda(1780)$	$3/2^+$	*
$N(1860)$	$5/2^+$	**	$\Delta(1950)$	$7/2^+$	****	$\Lambda(1880)$	$1/2^+$	**
$N(1875)$	$3/2^-$	***	$\Delta(2000)$	$5/2^+$	**	$\Sigma(1900)$	$1/2^-$	**
$N(1880)$	$1/2^+$	***	$\Delta(2150)$	$1/2^-$	*	$\Sigma(1910)$	$3/2^-$	***
$N(1895)$	$1/2^-$	****	$\Delta(2200)$	$7/2^-$	***	$\Sigma(1915)$	$5/2^+$	****
$N(1900)$	$3/2^+$	****	$\Delta(2300)$	$9/2^+$	**	$\Sigma(1940)$	$3/2^+$	*
$N(1990)$	$7/2^+$	**	$\Delta(2350)$	$5/2^-$	*	$\Lambda(2010)$	$3/2^-$	*
$N(2000)$	$5/2^+$	**	$\Delta(2390)$	$7/2^+$	*	$\Lambda(2030)$	$7/2^+$	****
$N(2040)$	$3/2^+$	*	$\Delta(2400)$	$9/2^-$	**	$\Sigma(2070)$	$5/2^+$	*
$N(2060)$	$5/2^-$	***	$\Delta(2420)$	$11/2^+$	****	$\Sigma(2080)$	$3/2^+$	*
$N(2100)$	$1/2^+$	***	$\Delta(2750)$	$13/2^-$	**	$\Sigma(2100)$	$7/2^-$	*
$N(2120)$	$3/2^-$	***	$\Delta(2950)$	$15/2^+$	**	$\Sigma(2110)$	$1/2^-$	*
$N(2190)$	$7/2^-$	****				$\Sigma(2230)$	$3/2^+$	*
$N(2220)$	$9/2^+$	****	Λ	$1/2^+$	****	$\Lambda(2250)$		**
$N(2250)$	$9/2^-$	****	$\Lambda(1380)$	$1/2^-$	**	$\Sigma(2455)$		*
$N(2300)$	$1/2^+$	**	$\Lambda(1405)$	$1/2^-$	****	$\Sigma(2620)$		*
$N(2570)$	$5/2^-$	**	$\Lambda(1520)$	$3/2^-$	****	$\Sigma(3000)$		*
$N(2600)$	$11/2^-$	***	$\Lambda(1600)$	$1/2^+$	***	$\Sigma(3170)$		*
$N(2700)$	$13/2^+$	**	$\Lambda(1670)$	$1/2^-$	****			
			$\Lambda(1690)$	$3/2^-$	****	Ξ^0	$1/2^+$	****
			$\Lambda(1710)$	$1/2^+$	*	Ξ^-	$1/2^+$	****
			$\Lambda(1800)$	$1/2^-$	***	$\Xi(1530)$	$3/2^+$	****
			$\Lambda(1810)$	$1/2^+$	***	$\Xi(1620)$		**
			$\Lambda(1820)$	$5/2^+$	****	$\Xi(1690)$		***
			$\Lambda(1830)$	$5/2^-$	****	$\Xi(1820)$	$3/2^-$	***
			$\Lambda(1890)$	$3/2^+$	****	$\Xi(1950)$		***
			$\Lambda(2000)$	$1/2^-$	*	$\Xi(2030)$	$\geq \frac{5}{2}$	***
			$\Lambda(2050)$	$3/2^-$	*	$\Xi(2120)$		*
			$\Lambda(2070)$	$3/2^+$	*	$\Xi(2250)$		**
			$\Lambda(2080)$	$5/2^-$	*	$\Xi(2370)$		**
			$\Lambda(2085)$	$7/2^+$	**	$\Xi(2500)$		*
			$\Lambda(2100)$	$7/2^-$	****			
			$\Lambda(2110)$	$5/2^+$	***	Ω^-	$3/2^+$	****
			$\Lambda(2325)$	$3/2^-$	*	$\Omega(2012)^-$	$?^-$	***
			$\Lambda(2350)$	$9/2^+$	***	$\Omega(2250)^-$		***
			$\Lambda(2585)$		*	$\Omega(2380)^-$		**
						$\Omega(2470)^-$		**

- Light baryons (u, d, s) have 6 families: $N, \Delta, \Lambda, \Sigma, \Xi, \Omega$
- Many excited baryon states predicted, few well-established, many's J^P to be determined [Phys. Rev. D 87, no. 7, 074504 (2013)][Phys. Rev. D 87, no. 5, 054506 (2013)]
- "Hybrid" baryon state, but unfortunately populate the same J^P values as conventional excited baryons [Phys. Rev. D 85, 054016 (2012)]
- Interaction dynamics and spin structure not well-understood in $N\bar{Y}, Y\bar{Y}$ system

GlueX Baryon Spectroscopy Program:

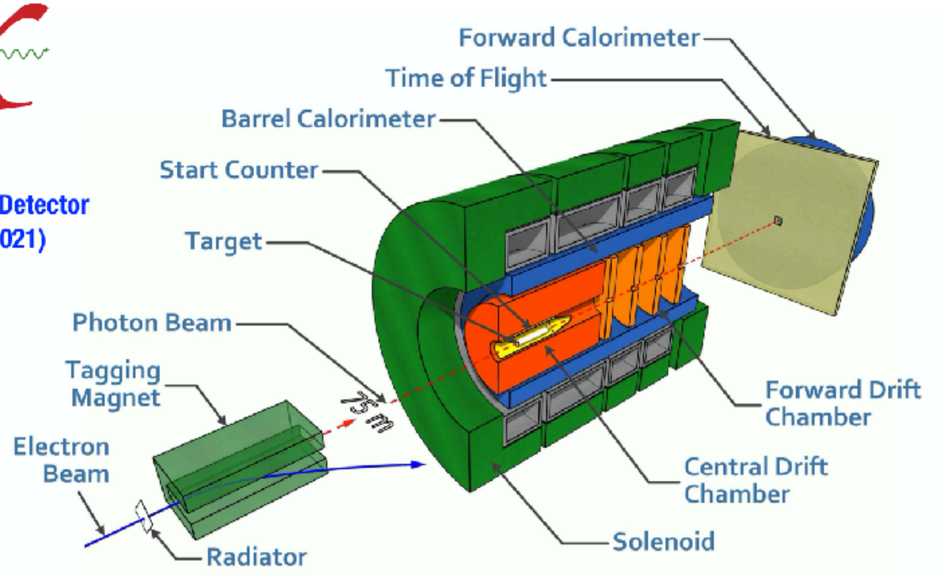
- Pole structure of $\Lambda(1405)$ from coupled-channel analysis in $N\bar{K}$ - $\Sigma\pi$ system
- Attractive dynamics and spin structure in photoproduced Baryon-antibaryon pairs: $N\bar{N}, Y\bar{Y}, N\bar{Y}, \cdots$
- Excited Cascades states

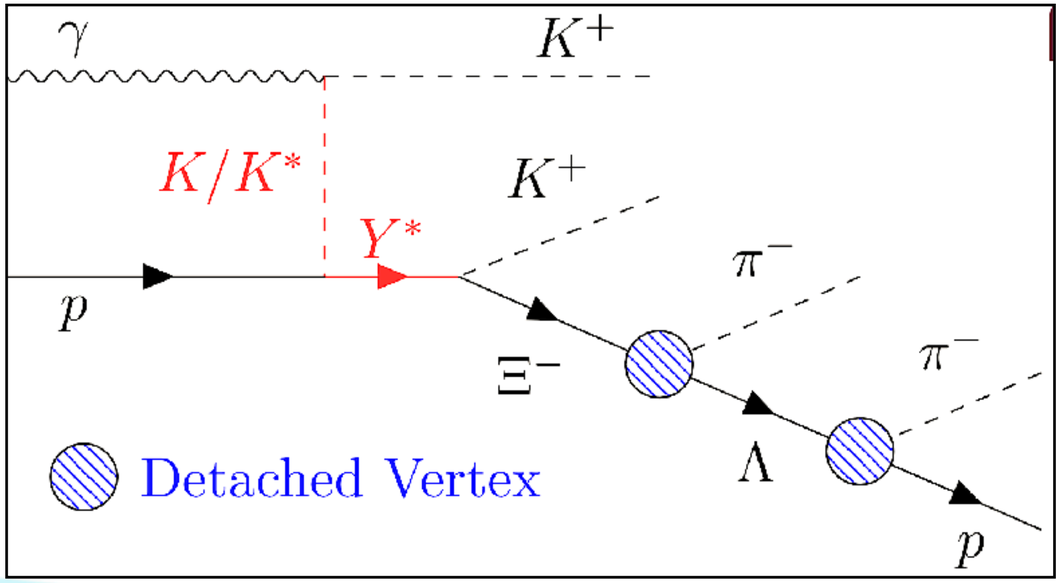
Baryon Spectroscopy via Photoproduction at GlueX

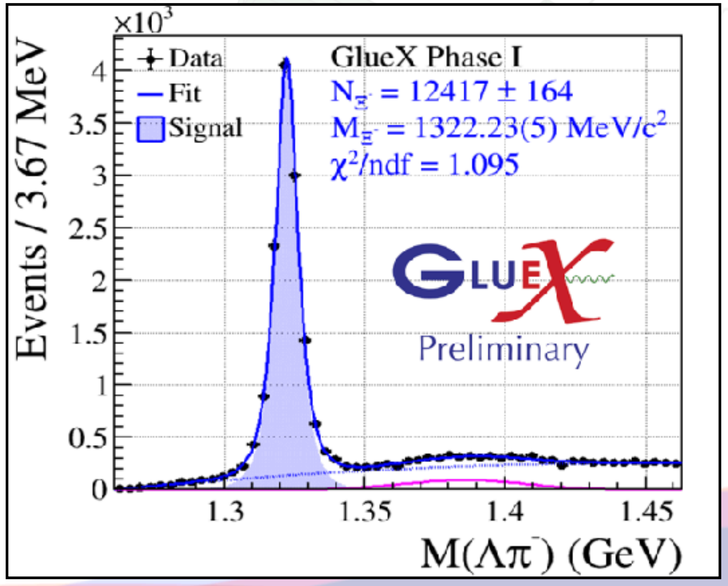
Large acceptance (near-hermetic) detector:

- Exclusive event reconstruction with charged and neutral tracks
- Linearly polarized photon —> moment analysis / partial wave analysis
- Capable of multi-stage detached vertices reconstruction

The GlueX Beamline and Detector
NIM A 987, 164807 (2021)

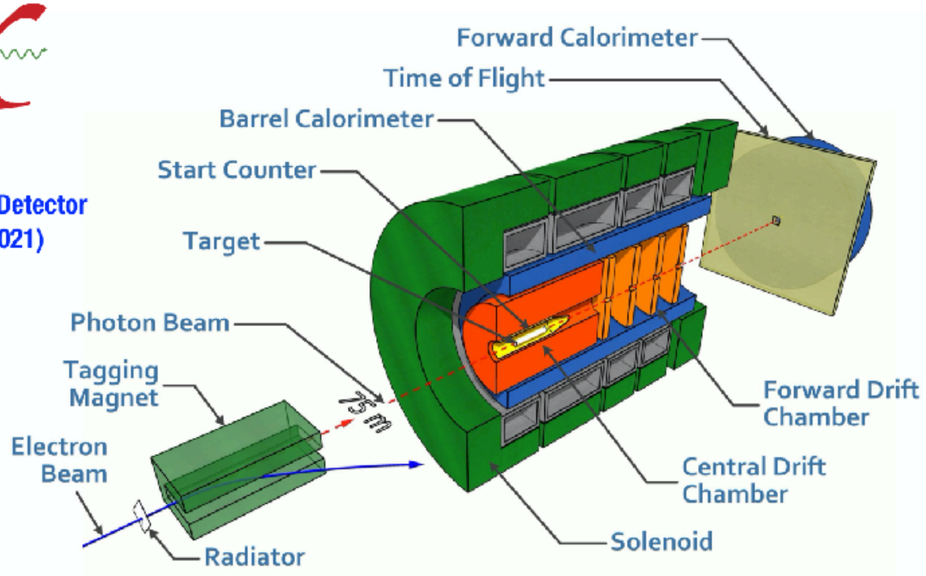




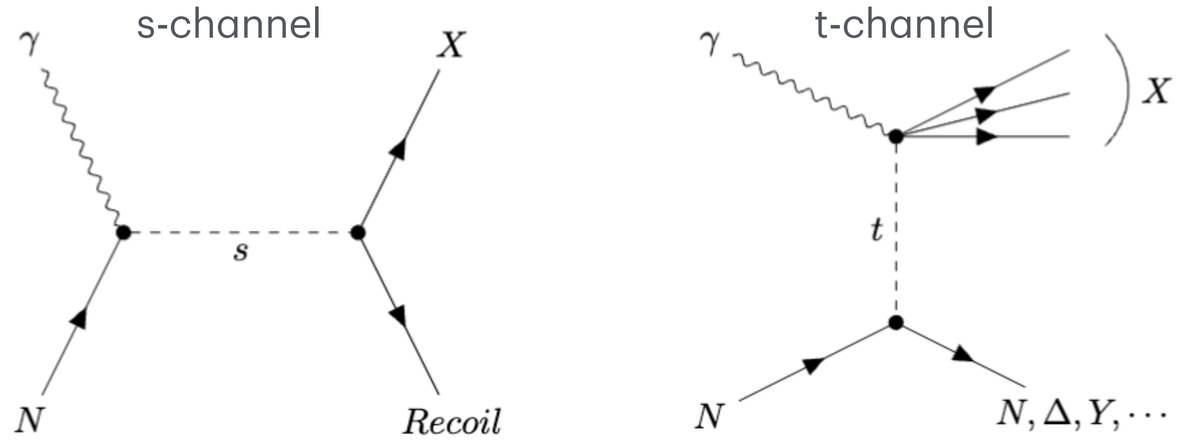


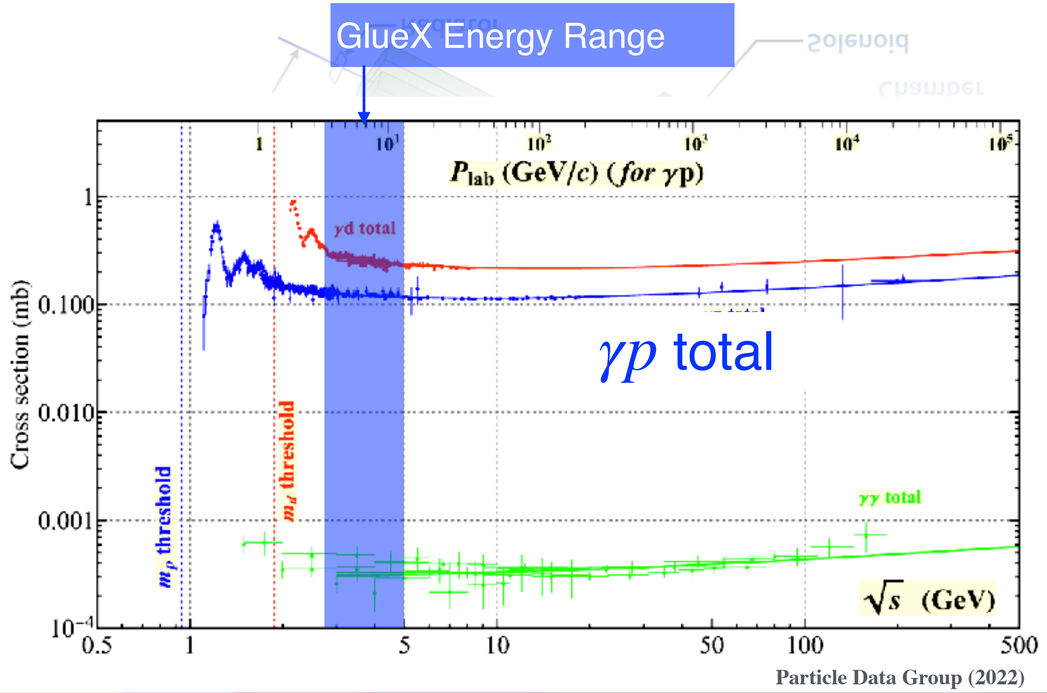
Baryon Spectroscopy via Photoproduction at GlueX

- World largest photoproduction dataset at $6 < E_\gamma < 11.4$ GeV
  - Phase-I dataset ~$439.6\ pb^{-1}$, Phase-II ongoing
- s-channel vanishes, t-channel dominates GlueX energies
  - Top vertex production recoiling against target proton (possibly excited) —> access to the near-threshold region of baryon production
  - Total cross section, differential cross section measurement —> study production mechanism —> extraction of physics

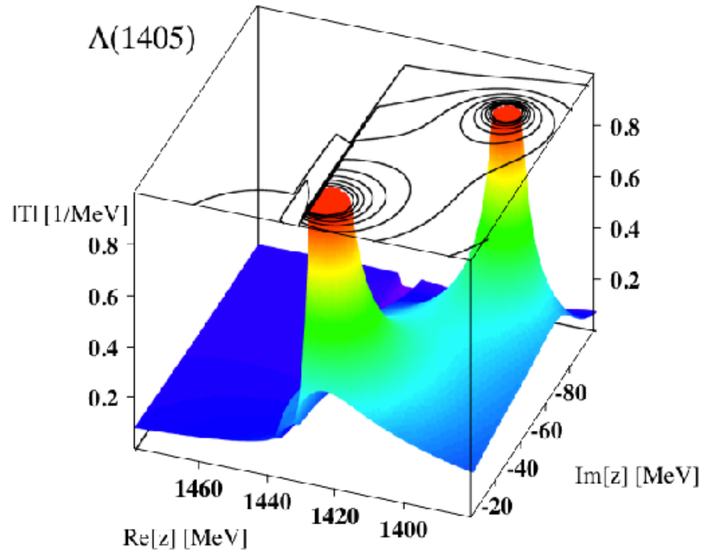


The GlueX Beamline and Detector
NIM A 987, 164807 (2021)



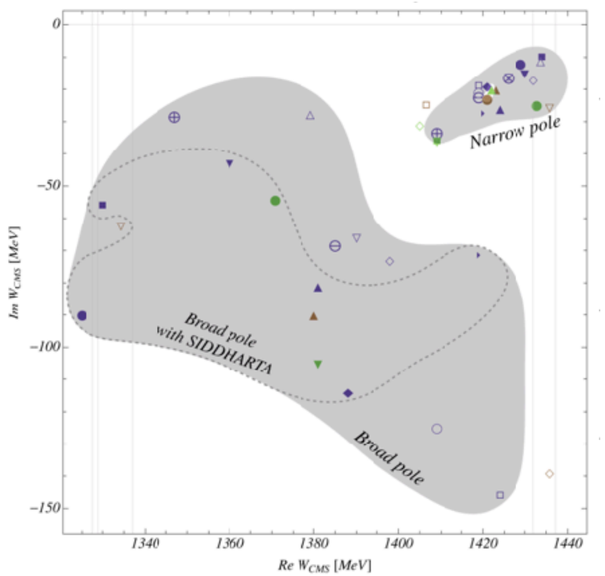


Pole structure of $\Lambda(1405)$ from coupled-channel analysis in $N\bar{K}$ - $\Sigma\pi$ system

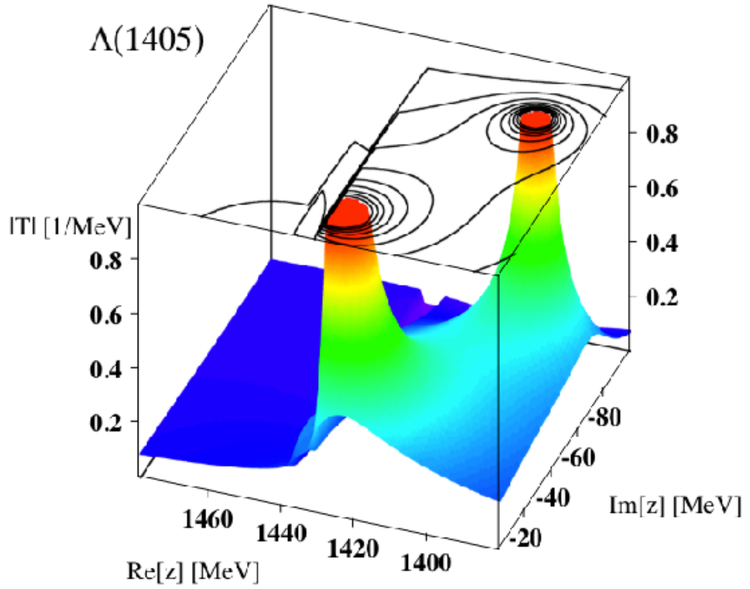


[Hyodo, T., & Jido, D. (2012). Prog. in Part. and Nucl. Phys, 67(1), 55-98.]

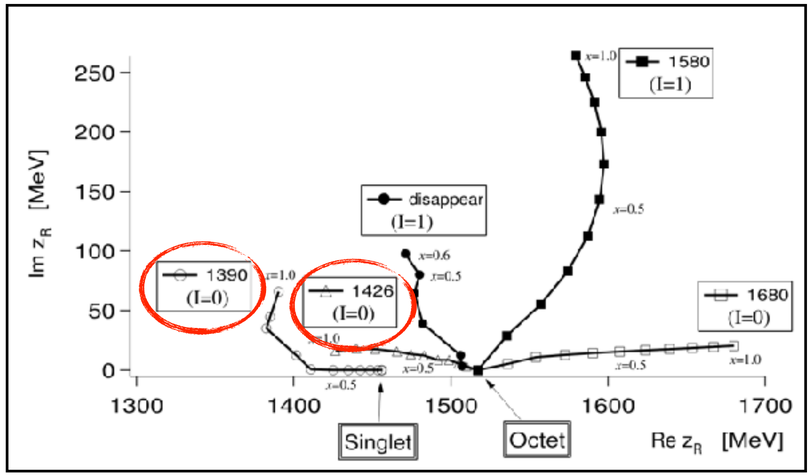
Pole Structure of $\Lambda(1405)$



Mai, Eur. Phys. J. 230 (2021)10.1140

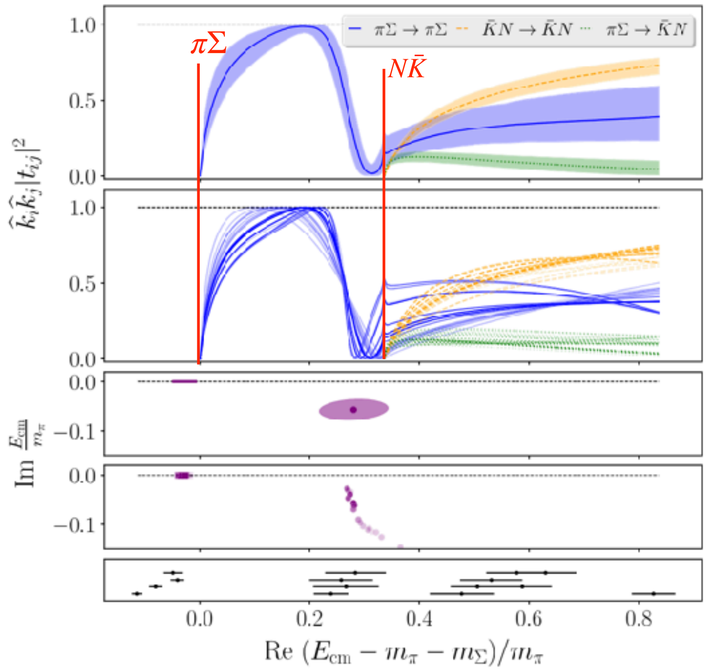


[Hyodo, T., & Jido, D. (2012). Prog. in Part. and Nucl. Phys, 67(1), 55-98.]



D. Jido, J.A Oller, E. Oset, A. Ramos, U-G Meissner Nucl. Phys. A 725 181 (2003)

- Chiral Unitary Approach: SU(3) breaking leads to two (I=0) poles:
  - higher pole (~1425 MeV) couples strongly to $N\bar{K}$
  - lower pole (~1390) couples mostly to $\Sigma\pi$
- LQCD: prediction in $N\bar{K}$ - $\Sigma\pi$ coupled-channel support second pole picture
- Most previous low-energy $N\bar{K}$ experiments not sensitive to $\Sigma\pi$; Some experiments consistent with one-pole solution [Physics Letters B 837 (2023): 137637] [EPJA 56 (2020)56:139]
- GlueX: the best data for clean photoproduction $\gamma p \to K^+\Lambda(1405) \to K^+\{\Sigma^0\pi^0\}$
  $\to K^+\{pK^-\}$

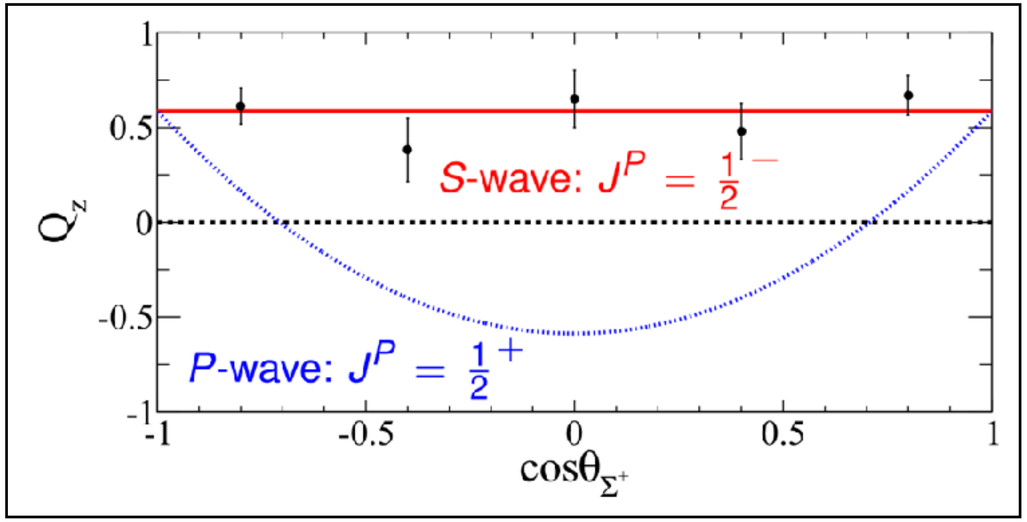


[J. Bulava et al., Phys Rev Lett 132, 051901 (2024)]

CLAS6 Results of $\Lambda(1405)$

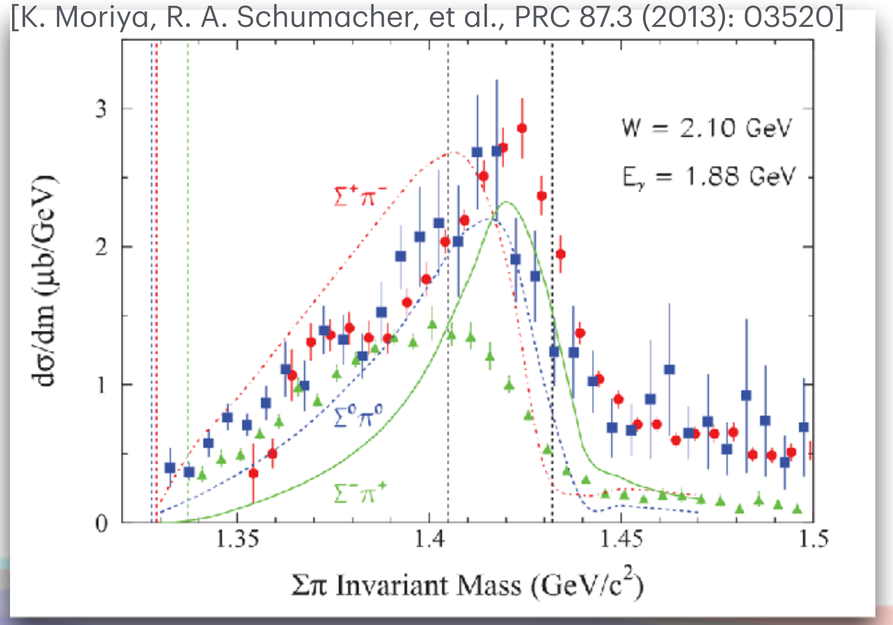
- "Measurement of the Σπ photoproduction line shapes near the $\Lambda(1405)$" *[K. Moriya, R. A. Schumacher, et al., PRC 87.3 (2013): 03520]*

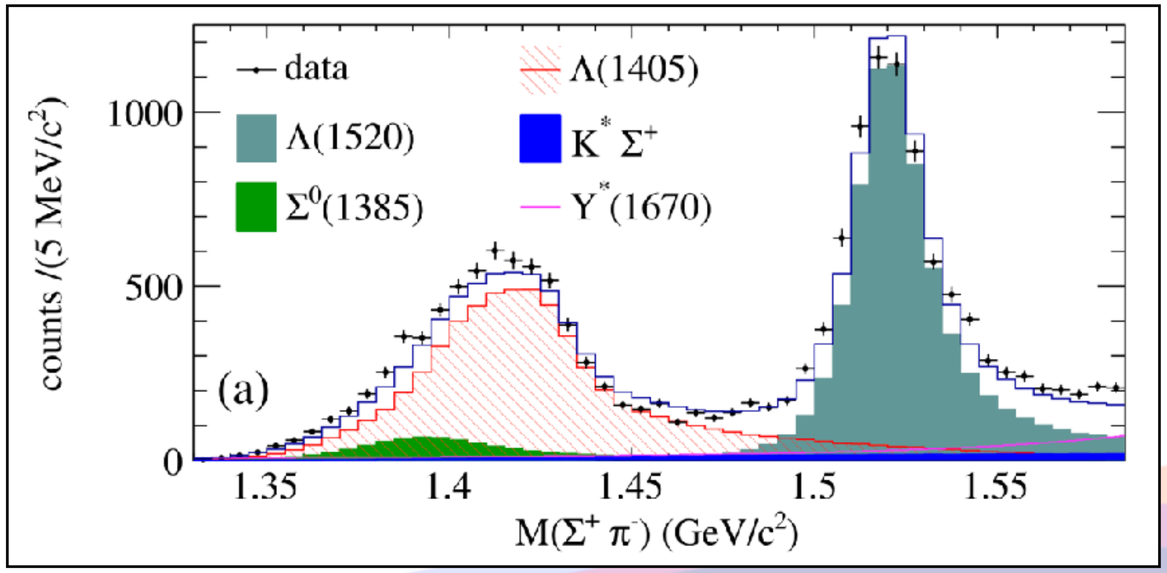
- "Spin and parity measurement of the Λ (1405) baryon" *[K. Moriya, R. A. Schumacher, et al., PRL 112.8 (2014): 082004]*



PRL 112.8 (2014): 082004

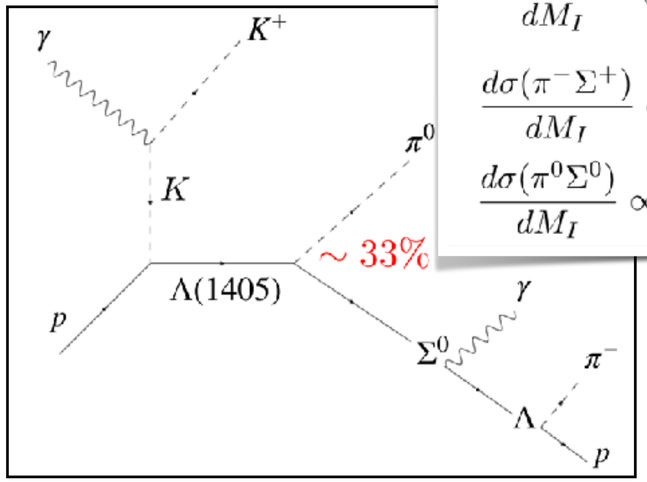
[K. Moriya, R. A. Schumacher, et al., PRC 87.3 (2013): 03520]





Measurement of $\Lambda(1405)$ Lineshape at GlueX

Reinhard Schumacher, Nilanga Wickramaarachchi, Peter Hurck

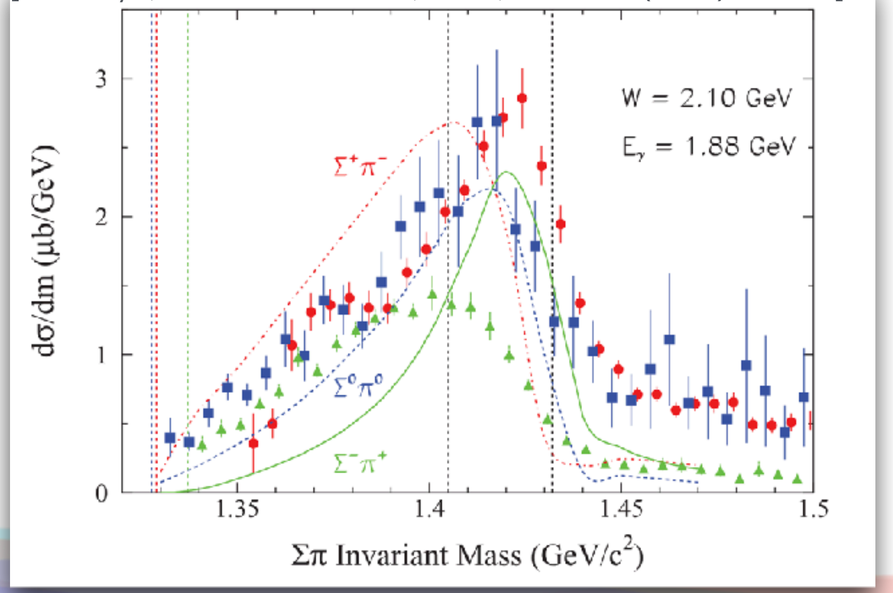


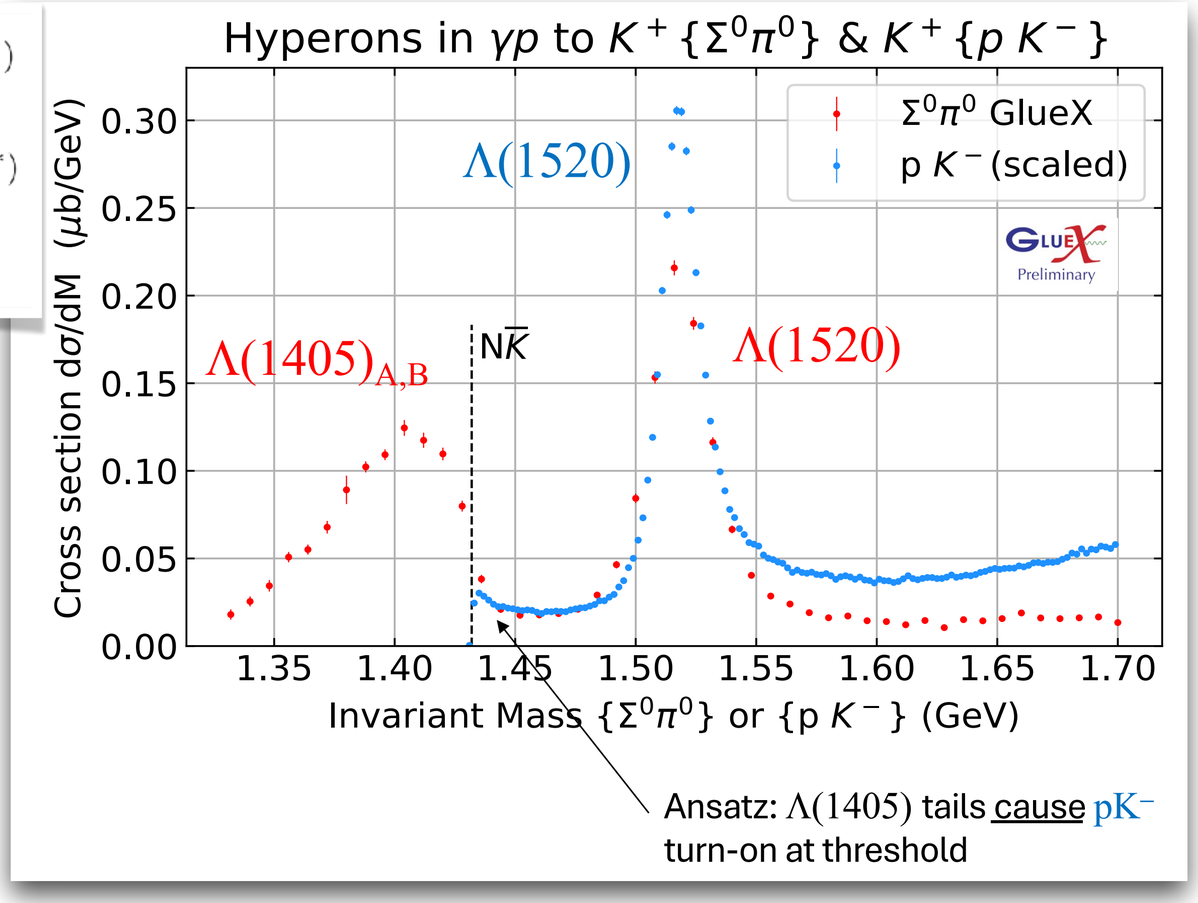
$$\frac{d\sigma(\pi^+\Sigma^-)}{dM_I} \propto \frac{1}{3}|T^{(0)}|^2 + \frac{1}{2}|T^{(1)}|^2 + \frac{2}{\sqrt{6}}\mathrm{Re}(T^{(0)}T^{(1)*})$$

$$\frac{d\sigma(\pi^-\Sigma^+)}{dM_I} \propto \frac{1}{3}|T^{(0)}|^2 + \frac{1}{2}|T^{(1)}|^2 - \frac{2}{\sqrt{6}}\mathrm{Re}(T^{(0)}T^{(1)*})$$

$$\frac{d\sigma(\pi^0\Sigma^0)}{dM_I} \propto \frac{1}{3}|T^{(0)}|^2$$

[K. Moriya, R. A. Schumacher, et al., PRC 87.3 (2013): 03520]



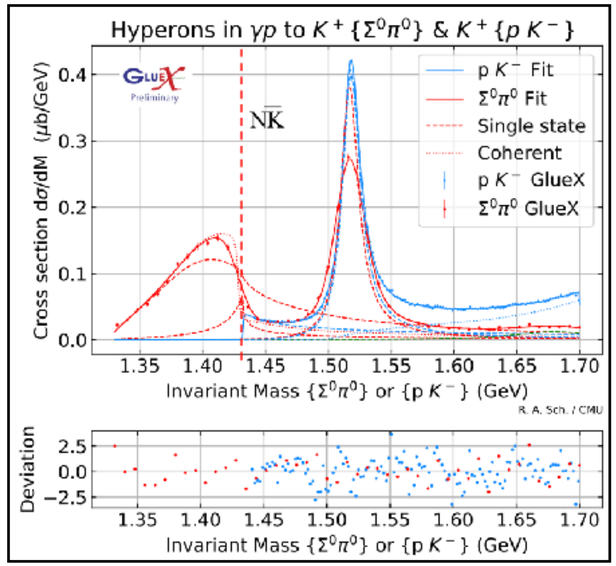


GlueX has the best dataset to analyze coupled-channel $N\bar{K}$ - $\Sigma\pi$:

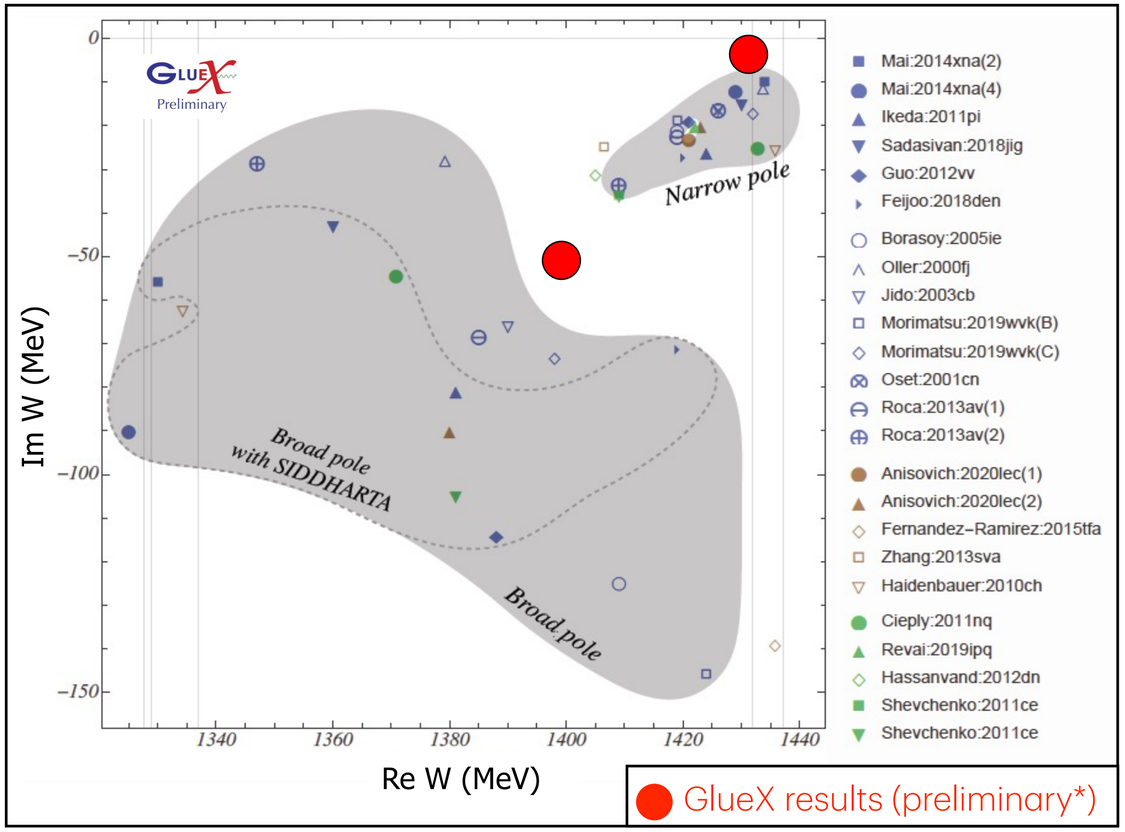
- $\Lambda(1405) \to \Sigma^0\pi^0$ is pure $I = 0$ with no contamination from $\Sigma^0(1385)$, differential cross section shows threshold effect
- $\Lambda(1405) \to pK^-$ shows instant turn-on at $N\bar{K}$ threshold

K-matrix Fitting of $\Lambda(1405)$ Lineshape at GlueX

Reinhard Schumacher, Nilanga Wickramaarachchi, Peter Hurck



- K-matrix formalism: a scattering theory approach that ensures unitarity in description of resonances and their interferences
- Each element of K-matrix describe one specific propagation from initial state to final state and a pole refers to the singularity of a propagator on the complex plane:
  - real part —> Resonance Mass
  - Imaginary part —> Resonance Width



*pole positions not finalized yet with systematics in progress

- First coupled-channel K-matrix fit on GlueX data, seems to favor the two-pole structure ansatz
- Planned for publication soon

Baryon-antibaryon Photoproduction

Hao Li, Reinhard Schumacher

Baryon-antibaryon Photoproduction

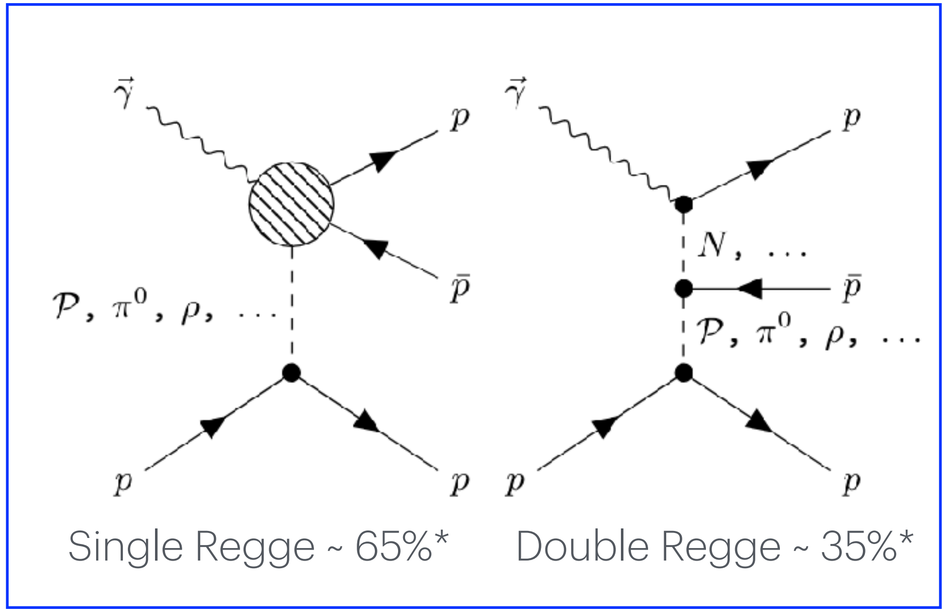
- Rich channels of **exclusive baryon-antibaryon photo-production**:

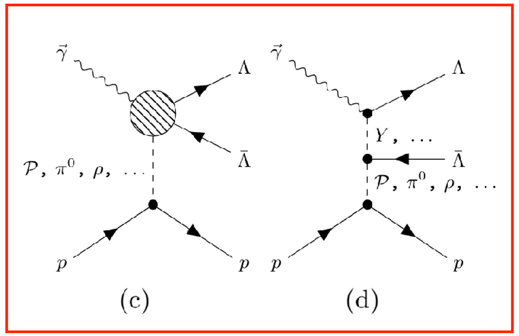
  $p\bar{p}$, $\Lambda\bar{\Lambda}$, $p\bar{\Lambda}$, $\Sigma^0\bar{\Sigma}^0$, $\Sigma^+\bar{\Sigma}^-$, $\Xi^0\bar{\Xi}^0$, ...

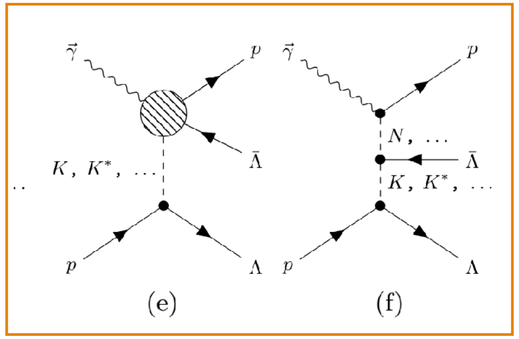
- **Single Regge**: "angular gap" between the baryon-antibaryon system and recoiling particle

- **Double Regge**: "flat" angular distribution for the particle produced off the middle vertex

- Unprecedented statistics to test Regge Modeling, without mesonic/ baryonic background.

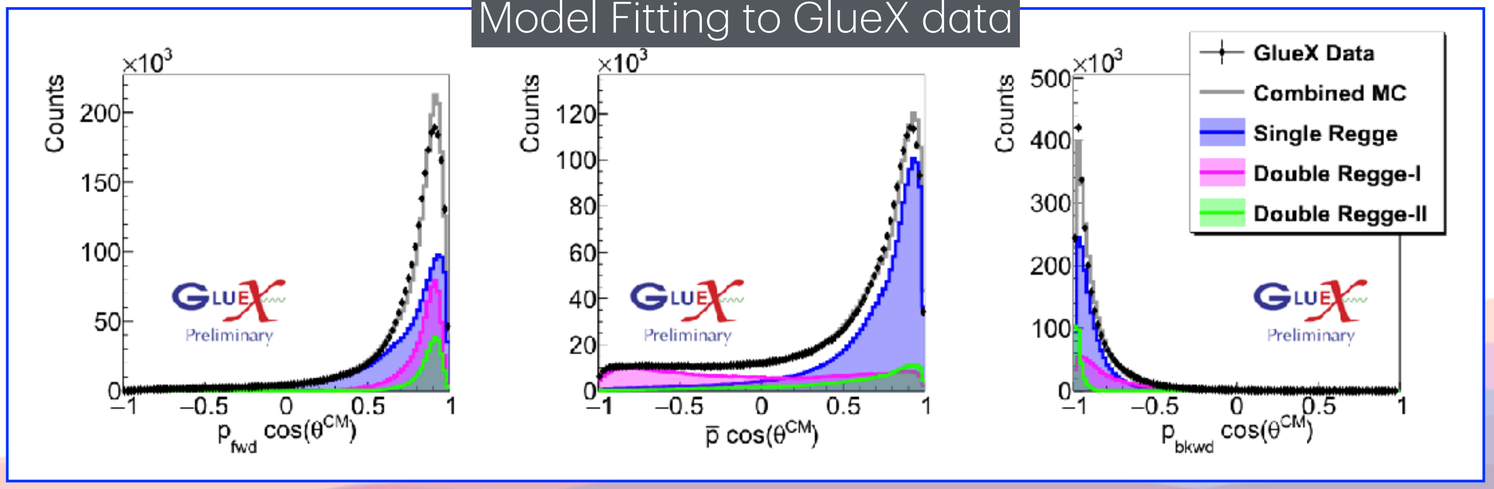




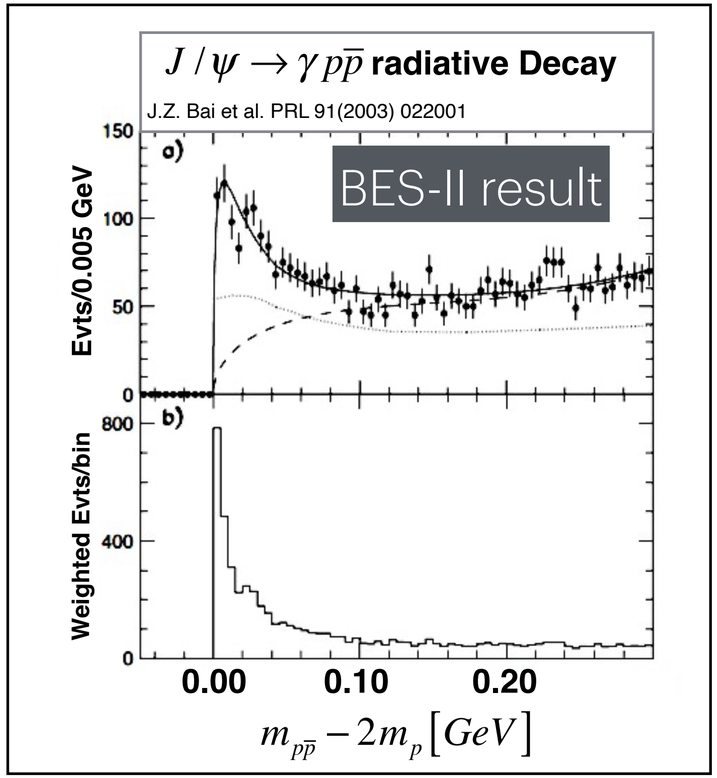


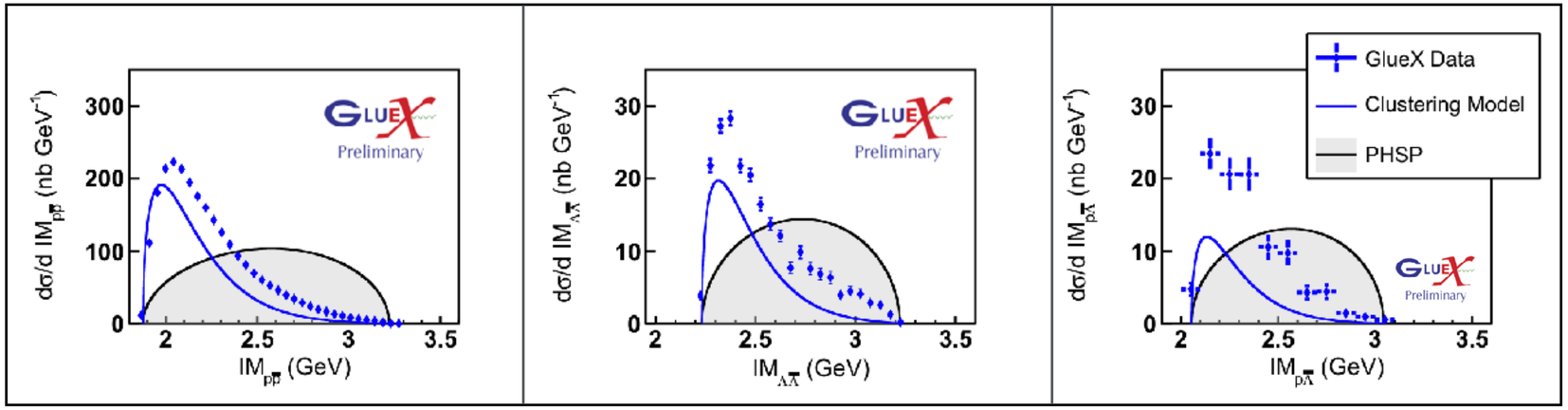
* Preliminary estimation based on incoherent intensity model fit over full range of kinematic region

Model Fitting to GlueX data



Threshold Enhancement: Invariant Mass of $p\bar{p}$, $\Lambda\bar{\Lambda}$, $p\bar{\Lambda}$

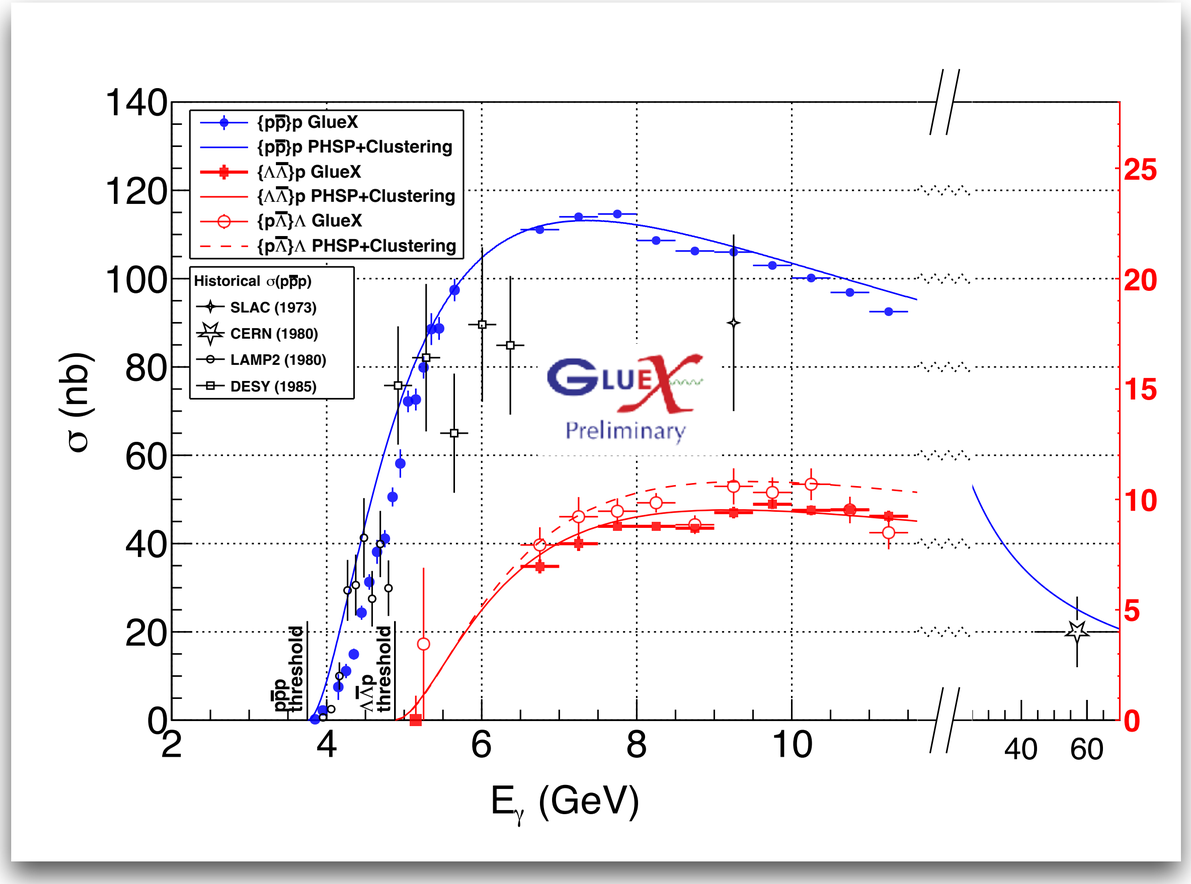




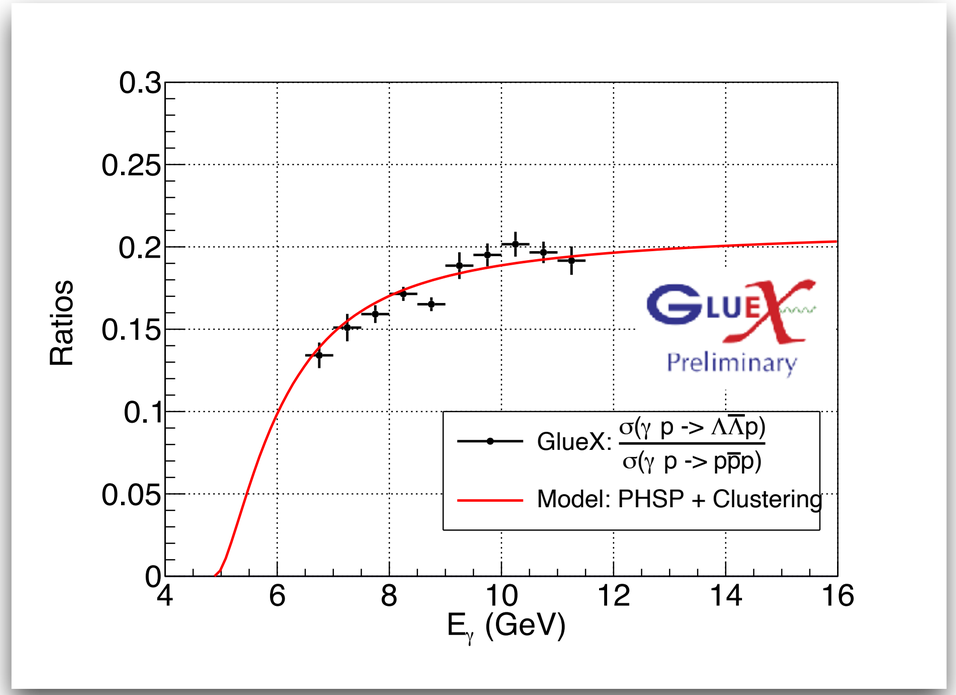
- Threshold enhancement $X(1835)$
  - First by BESII and confirmed by CLEO [Phys. Rev. D 82, 092002]
  - $I^G(J^{PC}) = ?^?(0^{-+})$ determined by BES-III [Phys. Rev. Lett. 108, 112003]

- Comparing to X(1835), broader threshold enhancement observed in $p\bar{p}$, $\Lambda\bar{\Lambda}$, $p\bar{\Lambda}$
  - Enhancement modeled as $\frac{d\sigma}{dm} \sim \exp\left(\frac{-(m - m_{\text{threshold}})}{c_m}\right)$
- Ongoing studies regarding baryon-antibaryon dynamics
  - Final-state Interaction (FSI) [Eur. Phys. J. A (2023) 59:136] [Eur. Phys. J. A (2024) 60:119],
  - Sub-threshold scalar meson $f_0(1370), f_0(1500), f_0(1710)$ with glue ball content [Phys. Rev. D 96, 054024]
  - Hyperon-antihyperon spin correlation [PRC 54.4 (1996): 1877][H Li, Hadron Spectroscopy with Strangeness 2024]

Total Cross-sections of $p\bar{p}$, $\Lambda\bar{\Lambda}$, $p\bar{\Lambda}$ photoproduction



- First measurement of photoproduction cross sections combining $N\bar{N}$, $Y\bar{Y}$, $N\bar{Y}$



- Non-strange/strange ratio related to probability $P(u\bar{u})/P(s\bar{s})$ in QCD hadronization
- Publication in preparation (under collaboration review)

Excited Cascades

Excited Hyperons

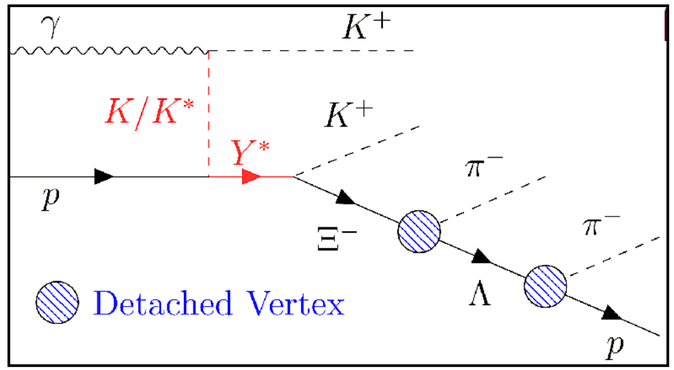
- Many excited Cascade states to be confirmed in the spectra predicted by quark model
- Many data points in PDG are from decades ago with limited statistics, some has unknown J^P yet to be determined
- Recent contribution from Belle[1,3] and BaBar[2] Collaboration (charmed baryon decay):
  1. $\Lambda_c^+ \to (\Sigma^+ K^-)_{\Xi(1690)} K^+$ [Phys. Lett. B 524, 33-43 (2002)]
  2. $\Lambda_c^+ \to (\Xi^- \pi^+)_{\Xi(1530)} K^+$ [Phys. Rev. D 78, 034008 (2008)]
  3. $\Xi_c^+ \to (\Xi^- \pi^+)_{\Xi(1620),\Xi(1690)} \pi^+$ [Phys. Rev. Lett. 122, 072501 (2019)]

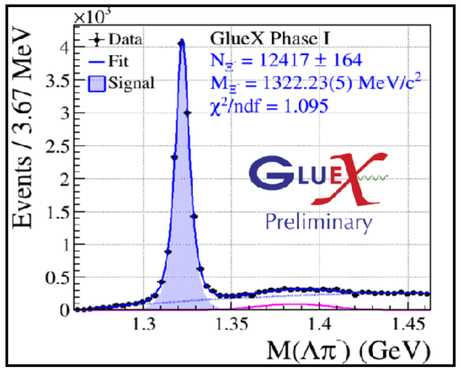
Particle	J^P	Overall status	Status as seen in — $\Xi\pi$	ΛK	ΣK	$\Xi(1530)\pi$
$\Xi(1318)$	$1/2+$	****				
$\Xi(1530)$	$3/2+$	****	****			
$\Xi(1620)$	$1/2^-$?	**	**			
$\Xi(1690)$	$1/2^-$?	***	**	***	**	
$\Xi(1820)$	$3/2-$	***	**	***	**	**
$\Xi(1950)$	$3/2^-$?	***	**	**		*
$\Xi(2030)$	$> 5/2$?	***		**	***	
$\Xi(2120)$		*		*		
$\Xi(2250)$		**				
$\Xi(2370)$		**				
$\Xi(2500)$		*		*	*	

Currently being investigated at GlueX

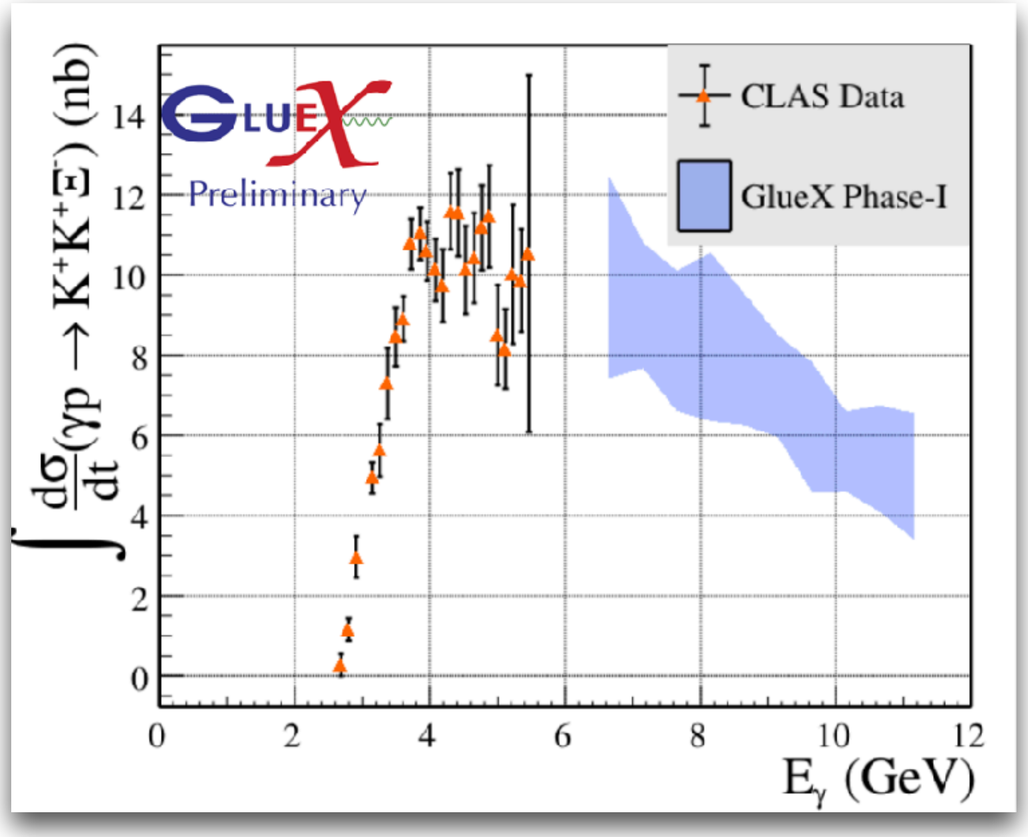
Particle Data Group

$\Xi^-(1320)$ Cross Section

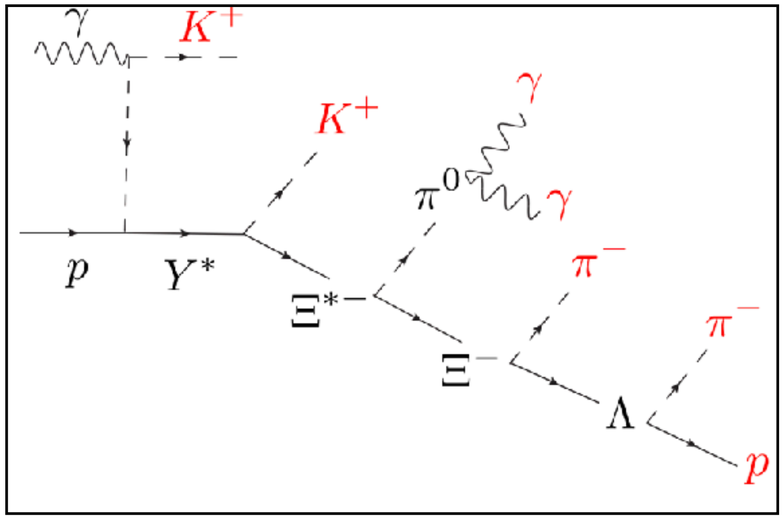


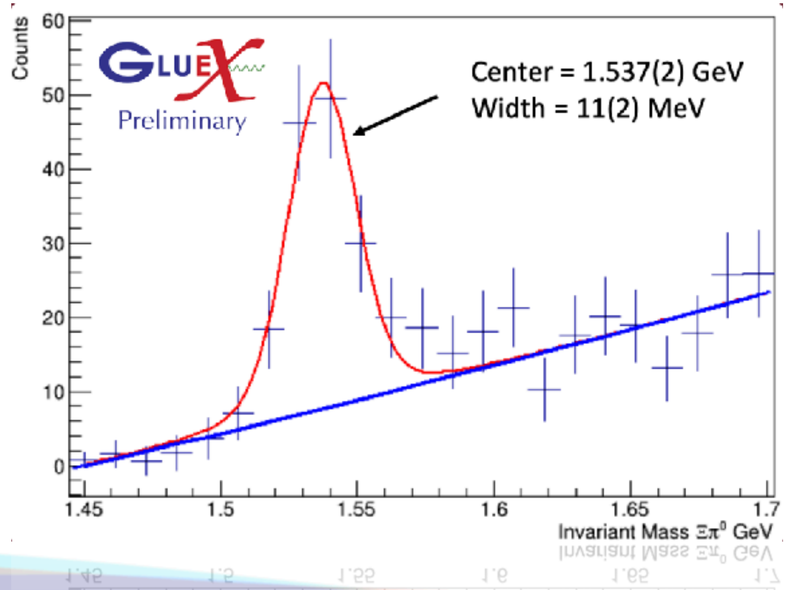


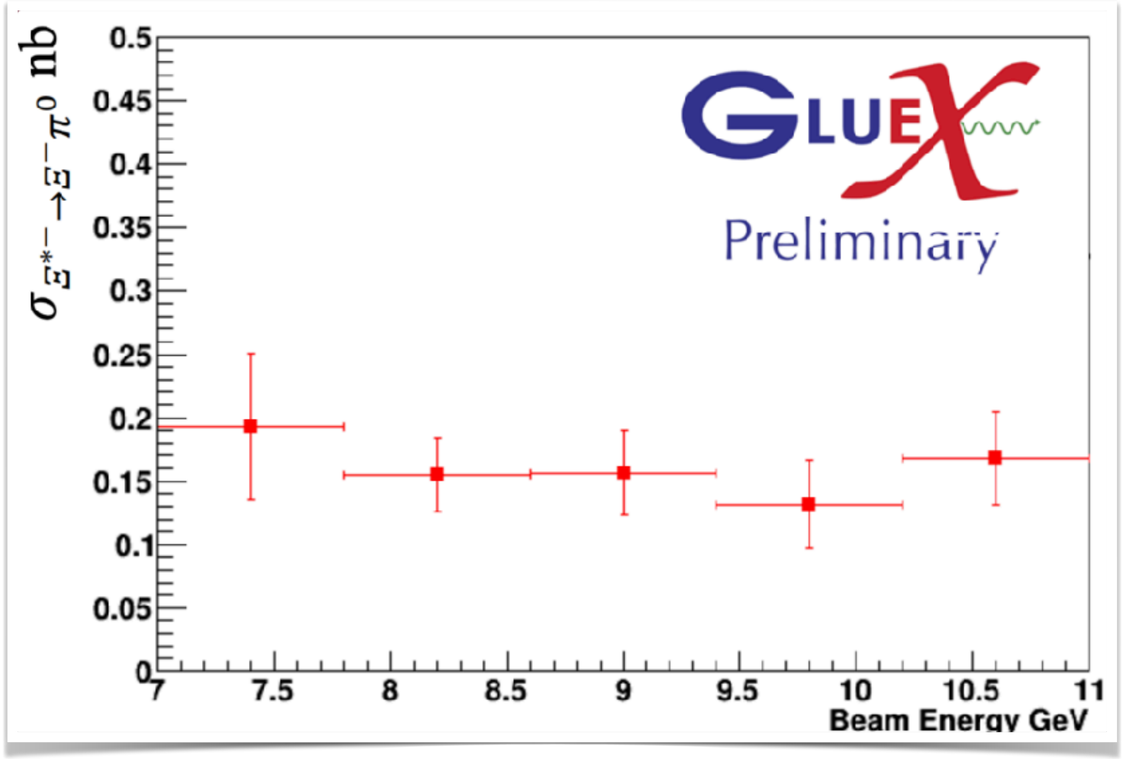
- Necessary building block for heavier excited cascade search, proof-of-principle for GlueX detected vertices reconstruction
- Total cross section compared with CLAS data only up to 5.4 GeV [Phys. Rev. C 98, 062201(R) (2018)]
- Good agreement with CLAS data and show cross section falls with increasing beam energy
- Analysis near finishing, overall scale to be finalized with ongoing systematics study



$\Xi^-(1530)$

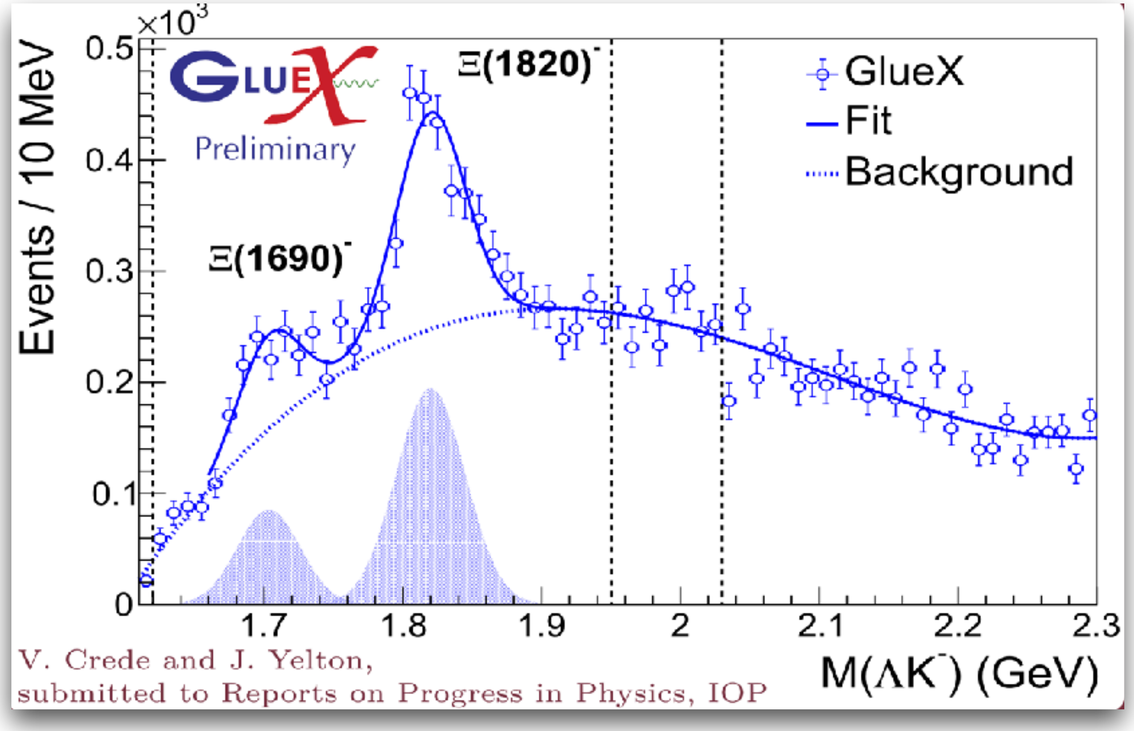




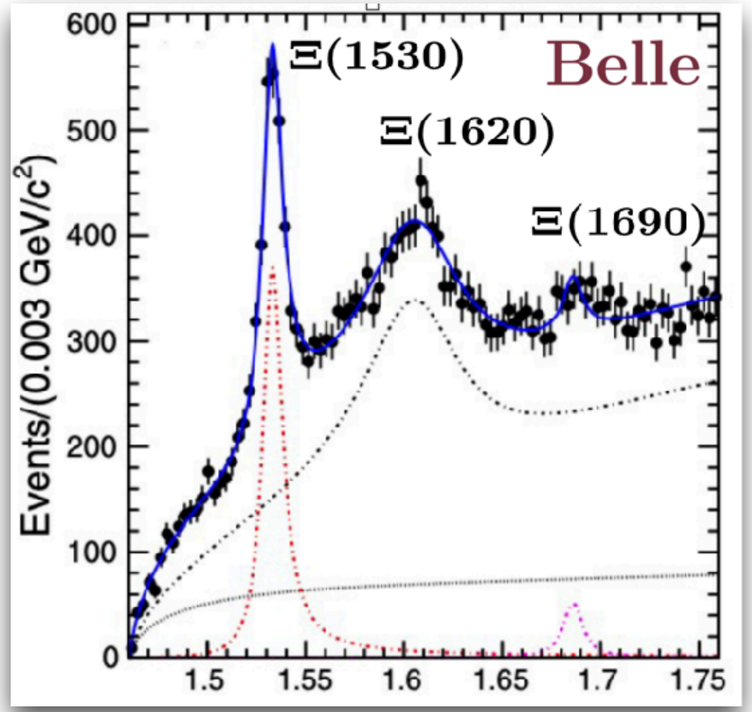


- 50% of the GlueX Phase-I data
- No significant energy dependence found in total cross section, surprisingly different from ground state $\Xi(1320)$

$\Xi^{*-}(1820)$



Phys. Rev. Lett. 122, 072501 (2019)



- Entire GlueX Phase-I data, much wider ΛK^- invariant mass than Belle
- First photoproduction measurement for $\Xi^{*-}(1690,1820) \rightarrow K^-\Lambda$
- Opportunity: more data coming in GlueX phase-II with better K/π separation

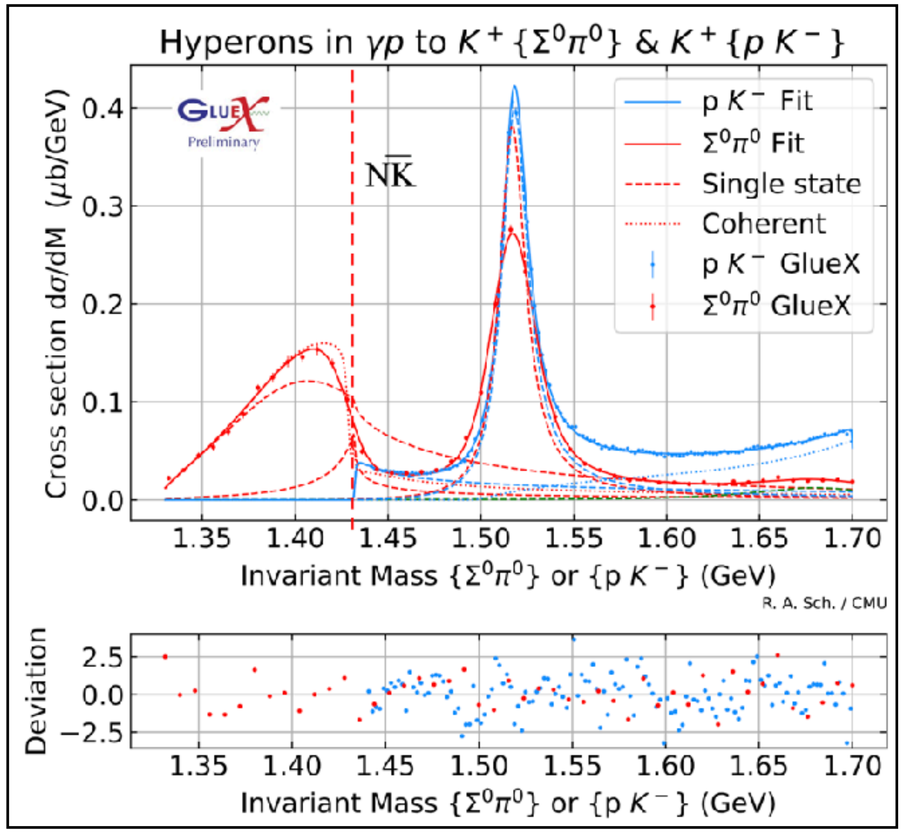
Summary

- **GlueX's coupled-channel measurement** of $N\bar{K}$ - $\Sigma\pi$ system is important to understand the confusing pole structure in $\Lambda(1405)$
- Photoproduction of $p\bar{p}$, $\Lambda\bar{\Lambda}$, $p\bar{\Lambda}$... systems provide rich data to study various aspect of **baryon-antibaryon dynamics**
- Investigation of the **excited cascades cross sections** will contribute important new dataset to the PDG and provide better understanding the role of **strangeness** in baryon sector

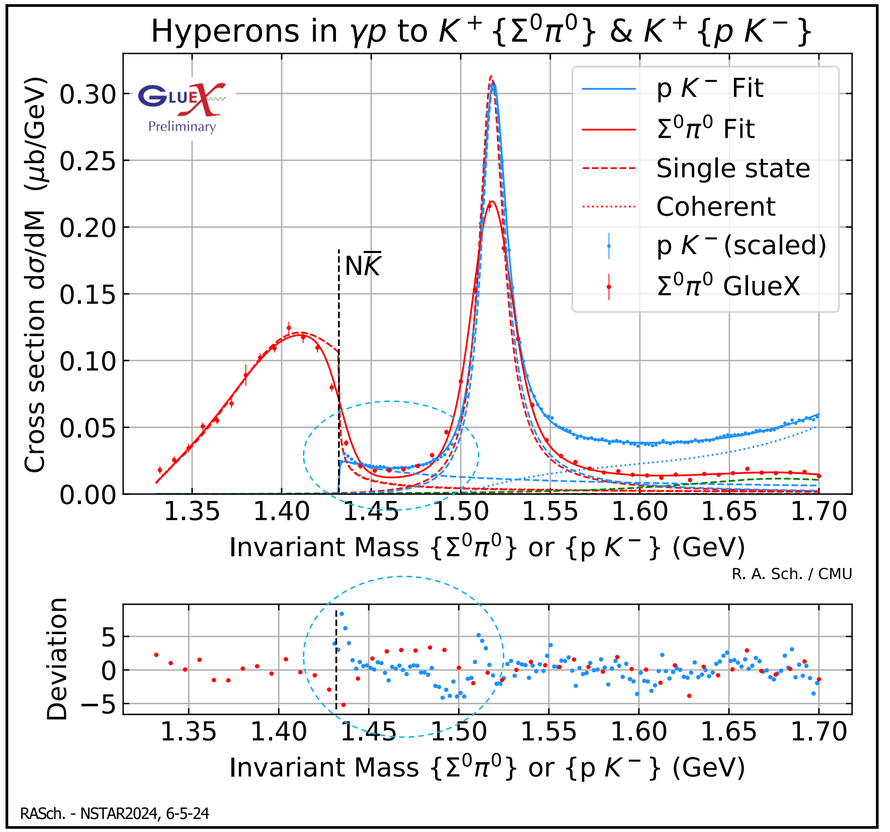
GlueX acknowledges the support of several funding agencies and computing facilities (http://gluex.org/thanks)

Backup Slides

K-matrix Fit of $\Lambda(1405)$ Lineshape at GlueX



Two-pole Fit



One-pole Fit

Event Reconstruction for $\gamma p \rightarrow \Lambda\bar{\Lambda}p$