Developing Ideas for Baryon Spectroscopy using Proton Beams at FAIR

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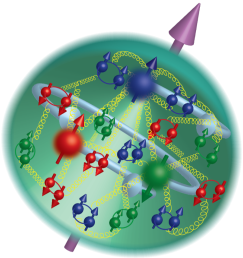
Florida State University, Tallahassee, Florida

QCD at FAIR Workshop 2024

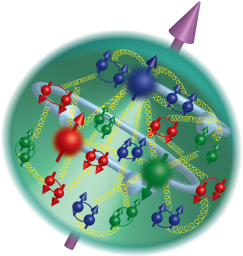
GSI Darmstadt, Germany

11/12/2024

Outline



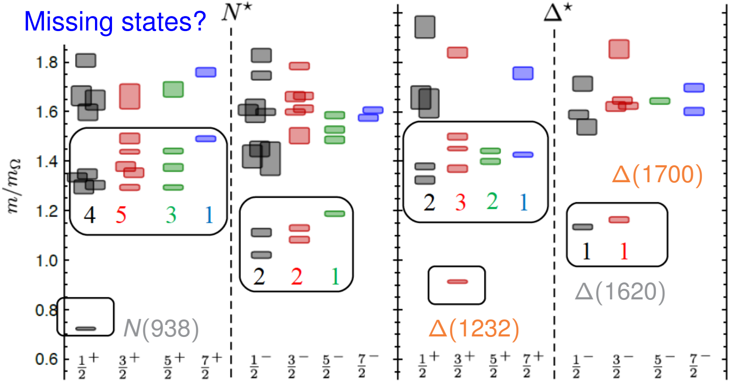
Outline



The N^* and Δ^* Spectrum from Lattice QCD

R. Edwards *et al.*, Phys. Rev. D **84**, 074508 (2011); Phys. Rev. D **87**, 054506 (2013)

Missing states?



$m_\pi = 396$ MeV

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

➜ Counting of levels consistent with non-rel. quark model, no parity doubling.

Spectrum of N^* Resonances

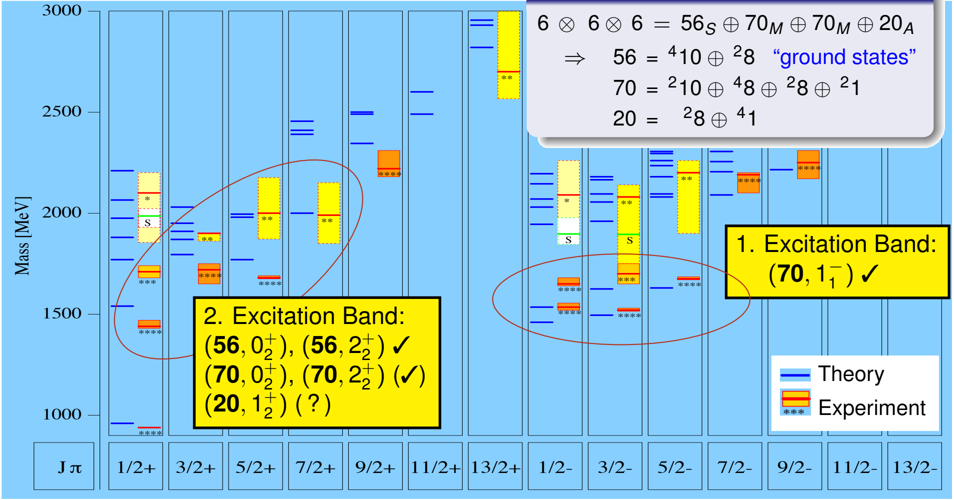
SU(6) ($^{2S+1}$multiplets; u, d, s, spin)

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

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

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

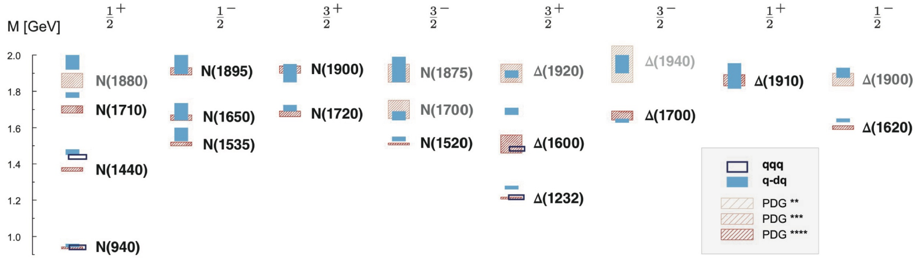
$$20 = {}^2 8 \oplus {}^4 1$$



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

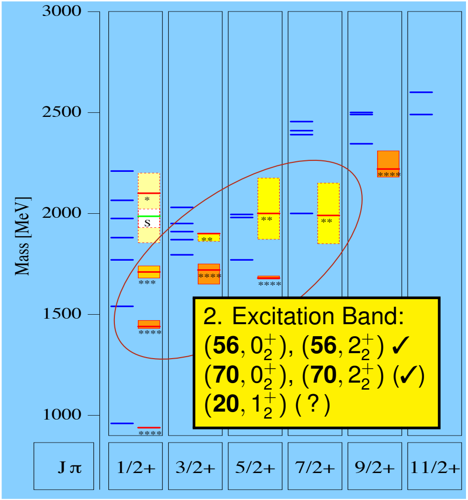
Diquark clustering in baryons?

Barabanov et al., Prog. Part. Nucl. Phys. 116 (2021)



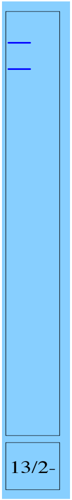
Eichmann, Fischer, Sanchis-Alepuz, PRD **94** (2016)

Spectrum of N^* Resonances

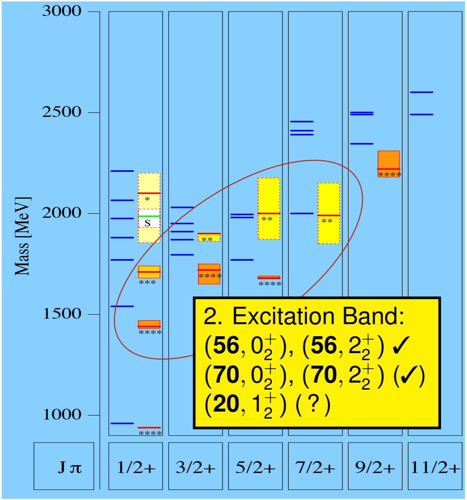


V. C. & W. Roberts, Rep. Prog. Phys. **76** (2013)

N^*	J^P $(L_{2I,2J})$	2010	2024
$N(1440)$	$1/2^+$ (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}	*	
$N(2040)$	$3/2^+$		*
$N(2080)$	$5/2^-$		* * *
$N(2100)$	$1/2^+$ (P_{11})	*	* * *
$N(2120)$	$3/2^-$		* * *
$N(2190)$	$7/2^-$ (G_{17})	* * * *	* * * *
~~$N(2200)$~~	D_{15}	* *	



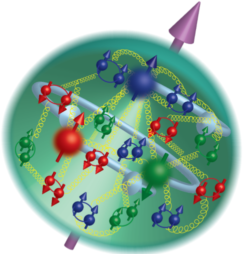
Spectrum of N^* Resonances



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

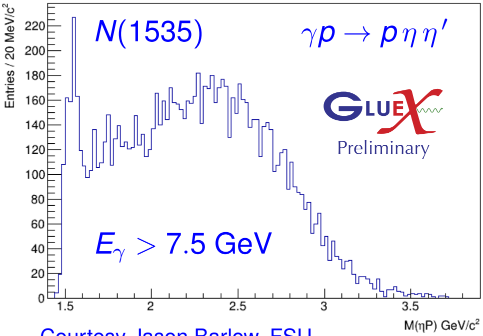
Outline



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.



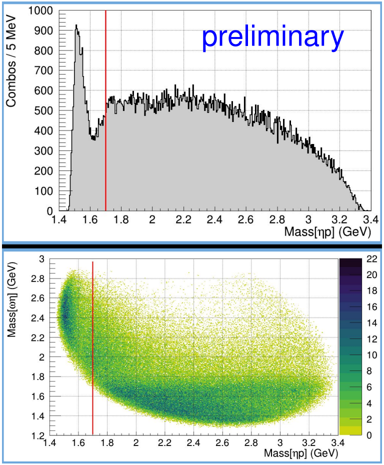
Courtesy Jason Barlow, FSU

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

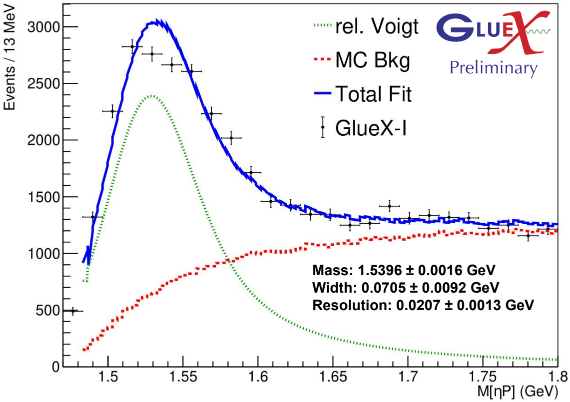
Data selection:

- General cuts to improve overall event kinematics (CL, missing mass, etc.).
- $8.2\ \text{GeV} < E_\gamma < 8.8\ \text{GeV}$
- $-t < 0.6\ \text{GeV}^2$
- 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.

N^* Spectroscopy at GlueX

V. C. *et al.* [GlueX], Few Body Syst. **64** (2023) 2, 32



Courtesy Edmundo Barriga, FSU

N(1535) BREIT-WIGNER WIDTH

VALUE (MeV)		DOCUMENT ID		TECN	COMMENT
125 to 175 (≈ 150) OUR ESTIMATE					
147 ± 5	[6]	HUNT	19	DPWA	Multichannel
163 ± 25		KASHEVAROV	17	DPWA	$\gamma p \to \eta p, \eta' p$
120 ± 10		SOKHOYAN	15A	DPWA	Multichannel
131 ± 12	[6]	SHKLYAR	13	DPWA	Multichannel
188.4 ± 3.8	[6]	ARNDT	06	DPWA	$\pi N \to \pi N, \eta N$
240 ± 80		CUTKOSKY	80	IPWA	$\pi N \to \pi N$
120 ± 20		HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
128 ± 14		ANISOVICH	12A	DPWA	Multichannel
141 ± 4	[6]	SHRESTHA	12A	DPWA	Multichannel
182 ± 25		BATINIC	10	DPWA	$\pi N \to N\pi, N\eta$
129 ± 8		PENNER	02C	DPWA	Multichannel
95 ± 25		BAI	01B	BES	$J/\psi \to p\bar{p}\eta$
143 ± 18		THOMPSON	01	CLAS	$\gamma^* p \to p\eta$

Description with rel. Voigtian

Barrier factor of $L = 1$

$\eta\omega$ MC background

$M_{\eta\omega} < 2$ GeV/c^2

➜ $\Gamma = 70.5 \pm 9.2$ MeV

How do we study baryons experimentally?

Light-flavor baryons are typically studied in fixed-target experiments (nuclear physics), heavy-flavor baryons are studied at colliders (high-energy physics).

1. Fixed-Target Experiments

   Photo-/electroproduction, e. g. Jefferson Lab, ELSA, MAMI, etc.

   e. g. $\gamma N\,(\mathrm{e}^-\,N) \to (\mathrm{e}^-)\,N^*/\Delta^*$

   $\gamma N\,(\mathrm{e}^-\,N) \to (\mathrm{e}^-)\,K\,Y^*\;(Y^{ast} = \Lambda^*, \Sigma^*)$

   $\pi\,/\,K$-induced production, e. g. HADES@GSI, J-PARC

   e. g. $\pi N \to N^*/\Delta^*$

   ➜ pp reactions at FAIR (new idea) ?

2. Collider Experiments

   at e^+e^- machines, e. g. BES III, Belle, BaBar, etc.

   e. g. $\Xi_c^+\,(\Lambda_c^+) \to [\Xi^-\pi^+]_{\Xi^*}\,\pi^+\,(K^+)$ or $e^+e^- \to J/\psi \to N^*\bar{N}$

   at pp machines, e. g. LHC

   e. g. $\Xi_b^{*\,-} \to \Xi_b^-\,\pi^+\pi^-$ (LHCb, CMS)

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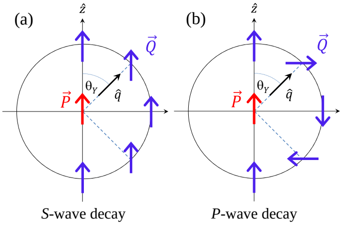
   at pp machines, e. g. LHC

   e. g. $\Xi_b^{*\,-} \to \Xi_b^-\,\pi^+\pi^-$ (LHCb, CMS)

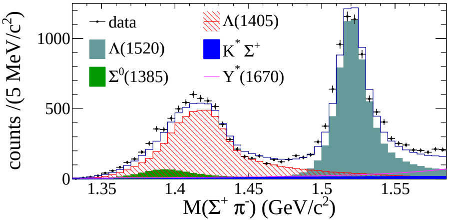
Spin and Parity Measurement of the $\Lambda(1405)$ Baryon

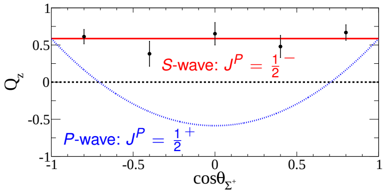
K. Moriya *et al.* [CLAS Collaboration], Phys. Rev. Lett. **112**, 082004 (2014)

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

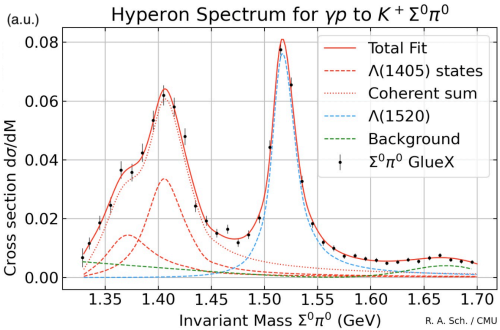




The Λ(1405) Baryons at GlueX

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 $\Lambda(1405) \to \Sigma^0\pi^0$



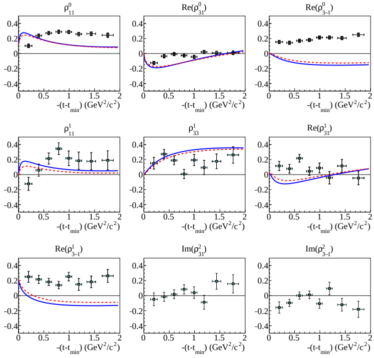
Different attempts at describing $\Sigma^0\pi^0$ mass distribution over the months.

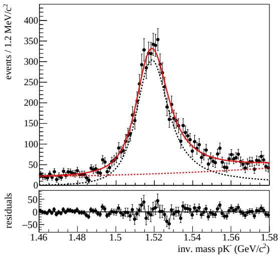
↓

However, preliminary fit results consistently support two-pole structure.

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

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





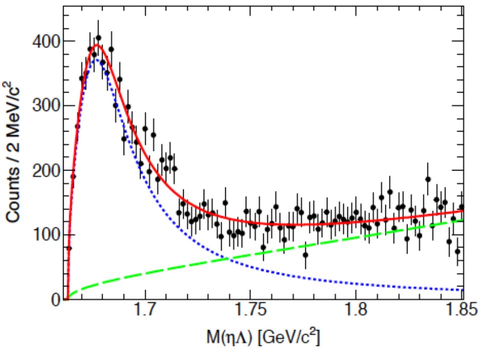
$-(t - t_0) \in [\,0.3, 0.5\,]$ GeV^2

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)

$\Lambda_c^+ \to \Lambda(1670)\pi^+$



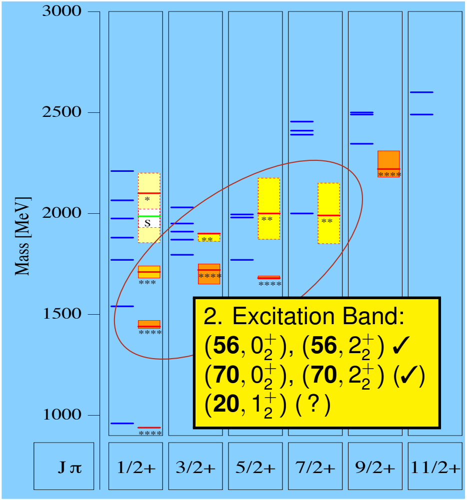
Λ(1670) WIDTH

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

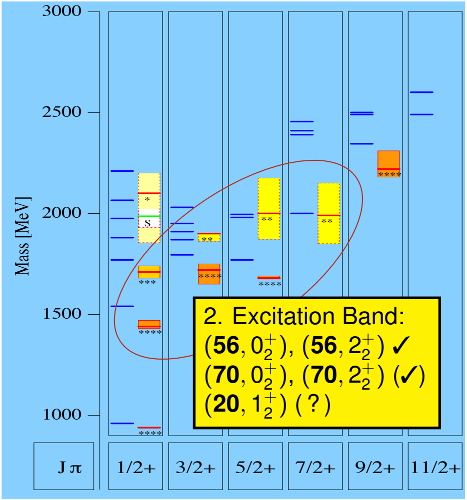
Spectrum of N^* Resonances



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

Spectrum of N^* Resonances



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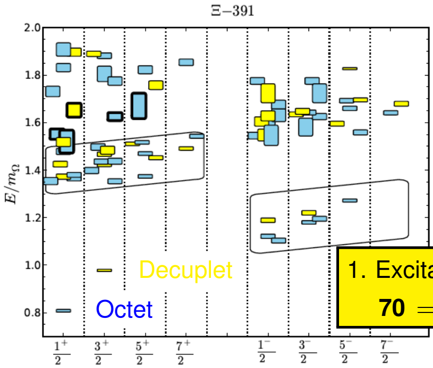
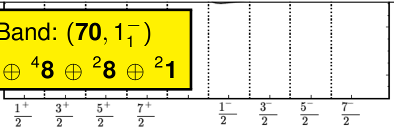
			$\frac{3}{2}^-$	$N(1520)$	$\Lambda(1690)$	$\Sigma(1670)$	$\Xi(1820)$	$\Lambda(1520)$
		$\frac{3}{2}$	$\frac{1}{2}^-$	$N(1650)$	$\Lambda(1800)$	$\Sigma(1750)$		–
			$\frac{3}{2}^-$	$N(1700)$				–
			$\frac{5}{2}^-$	$N(1675)$	$\Lambda(1830)$	$\Sigma(1775)$		–
2	$(56, 0_2^+)$	$\frac{1}{2}$	$\frac{1}{2}^+$	$N(1440)$	$\Lambda(1600)$	$\Sigma(1660)$		–
	$(70, 0_2^+)$	$\frac{1}{2}$	$\frac{1}{2}^+$	$N(1710)$	$\Lambda(1810)^\dagger$	$\Sigma(1770)^\dagger$		
		$\frac{3}{2}$	$\frac{3}{2}^+$					–
	$(56, 2_2^+)$	$\frac{1}{2}$	$\frac{3}{2}^+$	$N(1720)^\dagger$	$\Lambda(1890)^\dagger$	$\Sigma(1840)^\dagger$		–
			$\frac{5}{2}^+$	$N(1680)$	$\Lambda(1820)^\dagger$	$\Sigma(1915)^\dagger$		–
	$(70, 2_2^+)$	$\frac{1}{2}$	$\frac{3}{2}^+$					
			$\frac{5}{2}^+$	$N(1860)$				
		$\frac{3}{2}$	$\frac{1}{2}^+$	$N(1880)$				–
			$\frac{3}{2}^+$	$N(1900)^\dagger$		$\Sigma(2080)^\dagger$		–
			$\frac{5}{2}^+$	$N(2000)$	$\Lambda(2110)^\dagger$	$\Sigma(2070)^\dagger$		–
			$\frac{7}{2}^+$	$N(1990)$	$\Lambda(2020)$	$\Sigma(2030)^\dagger$		–
	$(20, 1_2^+)$	$\frac{1}{2}$	$\frac{1}{2}^+$	$N(2100)^\dagger$				
			$\frac{3}{2}^+$	$N(2040)^\dagger$				
			$\frac{5}{2}^+$	–	–	–	–	

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

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





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

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

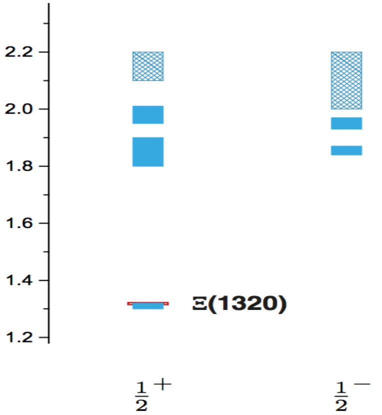
$\mathbf{70} = {}^2\mathbf{10} \oplus {}^4\mathbf{8} \oplus {}^2\mathbf{8} \oplus {}^2\mathbf{1}$

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.

The Ξ^* Spectrum in a Dyson-Schwinger Approach

C. Fischer *et al.*, PoS Hadron 2017 (2018) 007



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

PDG 2022 Mini-Review

Ξ Resonances

Revised 2004 by C.G. Wohl, (LBNL).

The accompanying table gives our evaluation of the present status of the Ξ resonances. Not much is known about Ξ resonances. This is because (1) they can only be produced as a part of a final state, and so the analysis is more complicated than if direct formation were possible, (2) the production cross sections are small (typically a few μb), and (3) the final states are topologically complicated and difficult to study with electronic techniques. Thus early information about Ξ resonances came entirely from bubble chamber experiments, where the numbers of events are small, and only in the 1980's did electronic experiments make any significant contributions. However, nothing of significance on Ξ resonances has been added since our 1988 edition.

PDG 2023 Mini-Review

Ξ Resonances

Revised 2023 by V. Crede (FSU), U. Thoma (U. Bonn)

Most of our present knowledge of Ξ resonances stems from the low-statistics data samples recorded in the 1960s–1980s using K^- beams and in the 1980s and 1990s using hyperon (Σ^-, Ξ^-) beams. This is because (1) they could only be produced as a part of a final state, and so the analysis is more complicated than if direct formation were possible, (2) the production cross sections are small (typically a few μb), and (3) the final states are topologically complicated and difficult to study with electronic techniques. Thus, early information about Ξ resonances came entirely from bubble chamber experiments, where the numbers of events are small, and only in the 1980s did electronic experiments make any significant contributions.

In recent years, significant contributions have come from collider experiments. Excited Ξ baryons are produced and have been studied in the decay of the charmed Λ_c^+ into $(\Sigma^+ K^-)_{\Xi(1690)} K^+$ by the Belle Collaboration [1] and into $(\Xi^- \pi^+)_{\Xi^*} K^+$ by the BaBar Collaboration [2]. Belle measures the decay $\Xi_c^+ \to (\Xi^- \pi^+)_{\Xi^*} \pi^+$ [3] with unprecedented statistical quality.

Ξ Resonances using K^- Beams

VOLUME 51, NUMBER 11 PHYSICAL REVIEW LETTERS 12 SEPTEMBER 1983

Existence of Ξ Resonances above 2 GeV

C. M. Jenkins, J. R. Albright, R. N. Diamond, H. Fenker,[a] J. H. Goldman, S. Hagopian, V. Hagopian, and W. Morris[b]
Florida State University, Tallahassee, Florida 32306

and

L. Kirsch, R. Poster, and P. Schmidt[c]
Brandeis University, Waltham, Massachusetts 02154

and

S. U. Chung, R. C. Fernow, H. Kirk, S. D. Protopopescu, and D. P. Weygand
Brookhaven National Laboratory, Upton, New York 11973

and

B. T. Meadows
University of Cincinnati, Cincinnati, Ohio 45221

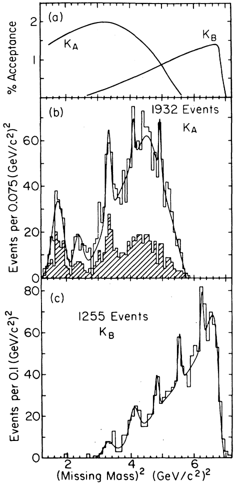
and

Z. Bar-Yam, J. Dowd, W. Kern, and M. Winik[d]
Southern Massachusetts University, North Dartmouth, Massachusetts 02747
(Recieved 30 June 1983)

Ξ^{*-} production was studied in the reaction $K^- + p \to K^+_{slow} + X^-$ at 5 GeV/c. The slow K^+ was electronically detected, while the X^- was observed as a missing mass, thus allowing for observation of all Ξ^* independent of decay mode. The observed Ξ states were $\Xi(1320)$, $\Xi(1530)$, $\Xi(1820)$, $\Xi(2030)$, $\Xi(2250)$, $\Xi(2370)$, and $\Xi(2500)$. These data establish and confirm the existence of $\Xi(2250)$ and indicate a peculiar production-cross-section behavior for the $\Xi^*(2370)$.

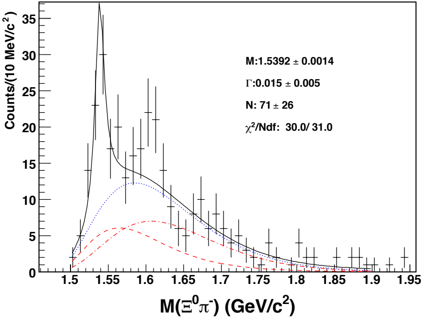
PACS numbers: 14.20.Jn, 13.75.Jz

$K^- p \to K^+ X^-$ ➜

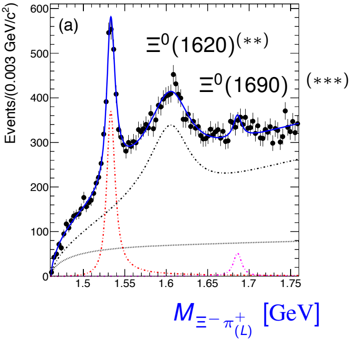


Excited Ξ^* States: 1500 - 1750 Mass Region

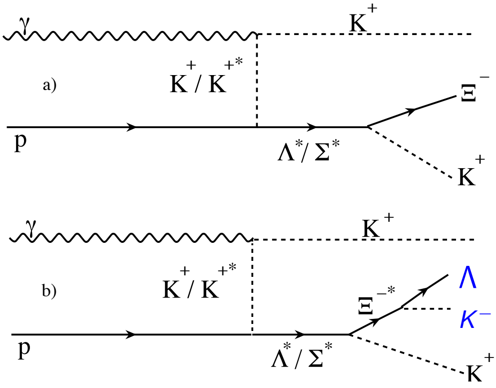
From the paper: *Although a small enhancement is observed in the $\Xi^0\pi^-$ invariant mass spectrum near the controversial 1-star $\Xi^-(1620)$ resonance, it is not possible to determine its exact nature without a full partial wave analysis.*
[CLAS], Phys. Rev. C **76**, 025208 (2007)



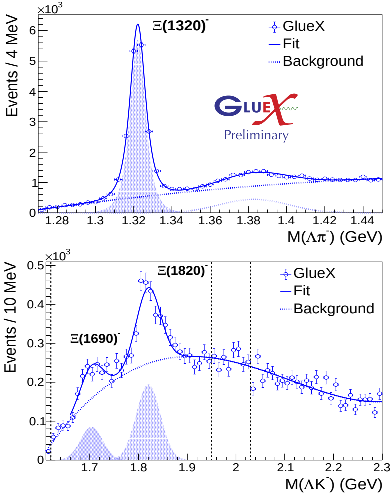
Belle: PRL **122**, 072501 (2019)



Possible Production Mechanisms

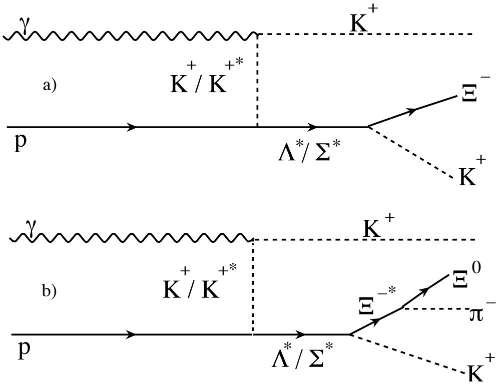


$\gamma p \rightarrow K^+ (K^+ \Xi^{-*}) \rightarrow K^+ (p \pi^- K^-) K^+$



Courtesy of Jesse Hernandez, Chandra Akondi (FSU)

Possible Production Mechanisms



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

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

At other facilities (for comparison):

$K^- p \rightarrow K^+ \Xi^{*-}$	J-PARC (2029?)
$K_L p \rightarrow K^+ \Xi^{*0}$	Hall D (2026/30?)
$p\,p \rightarrow \Xi^* X$	LHCb, FAIR ?
$\bar{p}\,p \rightarrow \Xi^* \bar{\Xi}$	$\overline{\text{P}}$ANDA ?
$e^+ e^- \rightarrow \Xi^* X$	Belle II, BES III

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

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?

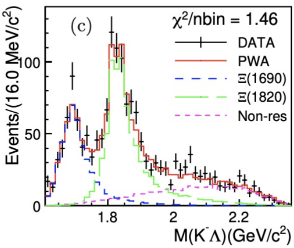
N	(D, L_N^P)	S	J^P	Octet Members				Singlets
0	$(56, 0_0^+)$	$\frac{1}{2}$	$\frac{1}{2}^+$	$N(939)$	$\Lambda(1116)$	$\Sigma(1193)$	$\Xi(1318)$	—
1	$(70, 1_1^-)$	$\frac{1}{2}$	$\frac{1}{2}^-$	$N(1535)$	$\Lambda(1670)$	$\Sigma(1620)$	$\Xi(1620)^\dagger$	$\Lambda(1405)$
			$\frac{3}{2}^-$	$N(1520)$	$\Lambda(1690)$	$\Sigma(1670)$	$\Xi(1820)$	$\Lambda(1520)$
		$\frac{3}{2}$	$\frac{1}{2}^-$	$N(1650)$	$\Lambda(1800)$	$\Sigma(1750)$	$\Xi(1690)^\dagger$	—
			$\frac{3}{2}^-$	$N(1700)$				—
			$\frac{5}{2}^-$	$N(1675)$	$\Lambda(1830)$	$\Sigma(1775)$	$\Xi(2030)^\dagger$	—

Open Questions

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

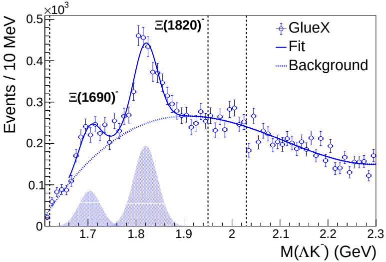
- What about the properties of the Ξ(1620) / Ξ(1690) states?

BES III, PRD **109**, 072008 (2024)



$\Gamma_{\Xi(1690)} = 81^{+10}_{-9} \pm 20$ MeV ?

$\Gamma_{\Xi(1820)} = 73^{+6}_{-5} \pm 9$ MeV ?



GlueX

Rept. Prog. Phys. 87 (2024) 10, 106301

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 (fairly broad) Ξ(1620) more than one state? Is a possible Ξ(1620) doublet the doubly strange partner of the Λ(1405) doublet?
- Where is the $\Omega\,\frac{1}{2}^-$ partner of the Δ(1620)?

N	$(D,\, L_N^P)$	Spin, S	J^P	Decuplet Members			
0	$(56,\, 0_0^+)$	$\frac{3}{2}$	$\frac{3}{2}^+$	$\Delta(1232)$	$\Sigma(1385)$	$\Xi(1530)$	$\Omega(1672)$
1	$(70,\, 1_1^-)$	$\frac{1}{2}$	$\frac{1}{2}^-$ $\frac{3}{2}^-$	$\Delta(1620)$ $\Delta(1700)$			$\Omega(2012)^\dagger$

Open Questions

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

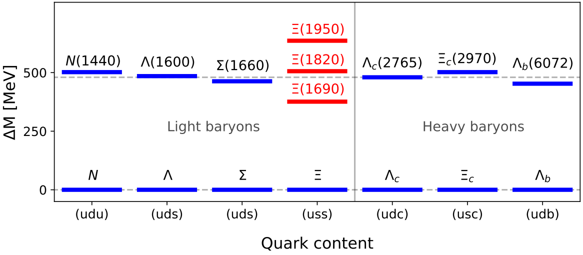
- What about the properties of the Ξ(1620) / Ξ(1690) states?
- Is the (fairly broad) Ξ(1620) more than one state? Is a possible Ξ(1620) doublet the doubly strange partner of the Λ(1405) doublet?
- Where is the $\Omega\ \frac{1}{2}^-$ partner of the Δ(1620)?

N	$(D,\ L_N^P)$	Spin, S	J^P	Decuplet Members			
0	$(56,\ 0_0^+)$	$\frac{3}{2}$	$\frac{3}{2}^+$	$\Delta(1232)$	$\Sigma(1385)$	$\Xi(1530)$	$\Omega(1672)$
1	$(70,\ 1_1^-)$	$\frac{1}{2}$	$\frac{1}{2}^-$ $\frac{3}{2}^-$	$\Delta(1620)$ $\Delta(1700)$			$\Omega(2012)^\dagger$

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 (fairly broad) Ξ(1620) more than one state? Is a possible Ξ(1620) doublet the doubly strange partner of the Λ(1405) doublet?
- Where is the radial excitation of the Ξ(1320)?



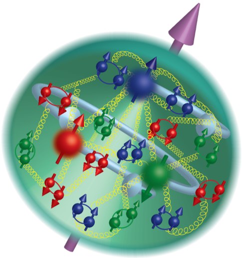
Radial Excitations
(Roper-like states)

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

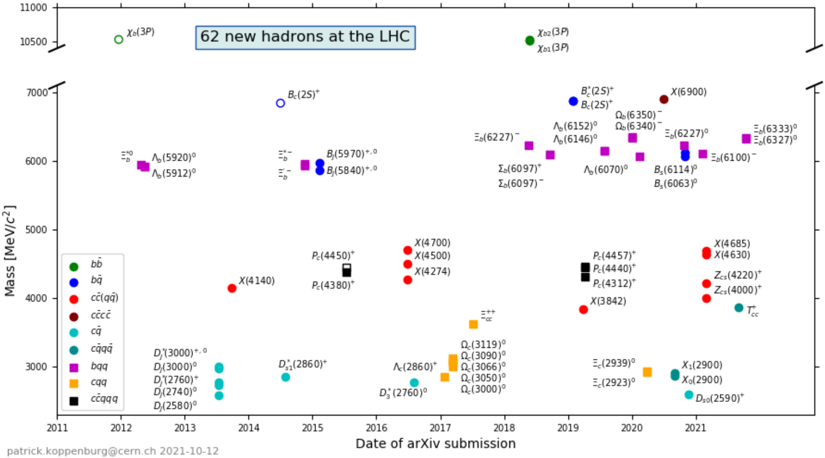
Arifi *et al.*, PRD **105**, 094006

Outline

1. A (very) brief introduction
   - The Experimental Status of the Spectrum
2. Spectroscopy of Baryon Resonances
   - $N^{\star}$ Spectroscopy: Measurements at GlueX
   - The Study of Strangeness -1 Hyperons
   - Spectroscopy of Ξ Resonances
3. Heavy-Flavor Resonances
4. Summary and Conclusions



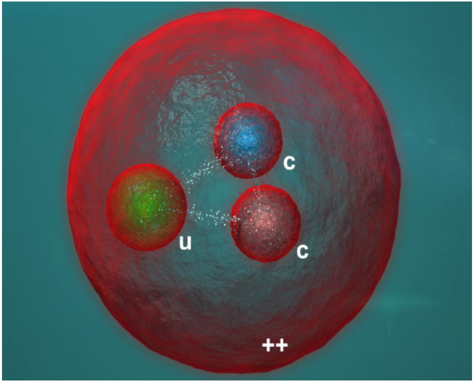
Peak Hunting for Heavy-Flavor States

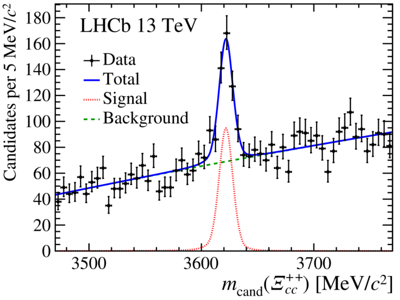


https://www.nikhef.nl/ pkoppenb/particles.html

Doubly-Heavy (Charmed) Resonances

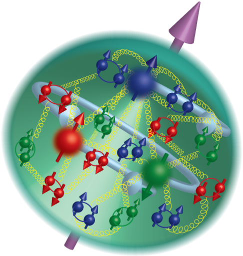
2017: The LHCb (Large Hadron Collider beauty) collaboration at CERN's Large Hadron Collider in Switzerland has reported the observation of a doubly charmed particle, $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$.





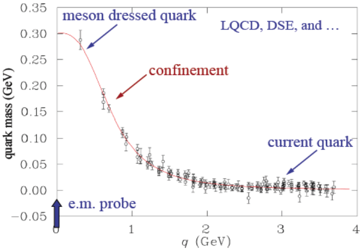
R. Aaij *et al.*, PRL **119** (2017) 112001

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)



Summary and Conclusions

A “low”-energy p beam on a fixed target would be a novel spectroscopy tool:

- Photoproduction at $8-9$ GeV seems to be able to produce isolated N^* peaks in t-channel prroduction. Would this be possible in pp reactions?
- Spectroscopy of Λ^* and Σ^* resonances ideal for K_L - and K^- - beam facilities. Jefferson Lab, J-PARC, and FAIR appear to have a similar timeline, i.e., first physics runs around 2027 / 2028.

  J-PARC also plans to study Ω and charmed baryons.
- Spectroscopy of (low-mass) Ξ resonances important to understand the systematics of the baryon spectrum.
  1. What about the $\Xi(1620)$ / $\Xi(1690)$ states?
  2. Is $\Xi(1620)$ the doubly strange partner of the $\Lambda(1405)$?

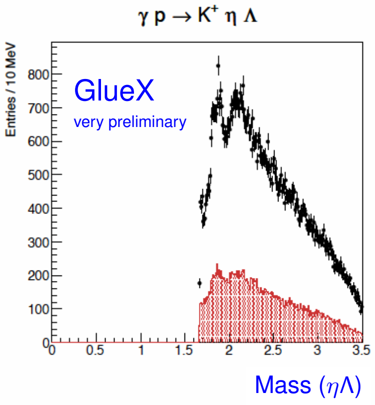
➜ Selling point for hadron spectroscopy with proton beams is charmonium production & study of hyperons in decay of excited charmed hadrons, e.g. in the reaction $pp \to \Lambda_c^+ p \bar{D}^0$.

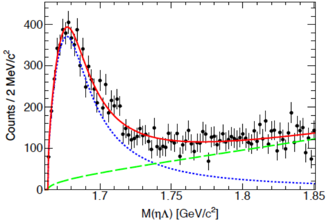
Backup Slides

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)

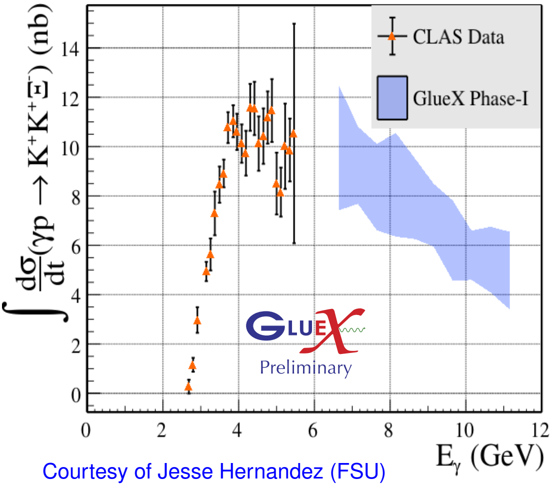




Resonances	Mass [MeV/c^2]	Width [MeV]
$\Lambda(1670)$	$1674.3 \pm 0.8 \pm 4.9$	$36.1 \pm 2.4 \pm 4.8$
$\Sigma(1385)^+$	$1384.8 \pm 0.3 \pm 1.4$	$38.1 \pm 1.5 \pm 2.1$

all PDG listings based on PWA

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



Courtesy of Jesse Hernandez (FSU)

Measurements of

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

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

Courtesy of Jesse Hernandez (FSU)