A fresh look at the excited baryon spectrum: What have we learned?

Volker Credé

Florida State University, Tallahassee, FL *

Excited QCD 2020

Krynica Zdrój, Poland

02/04/2020

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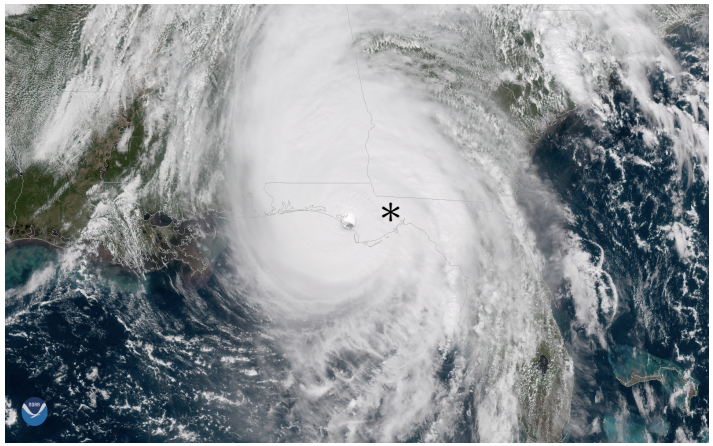

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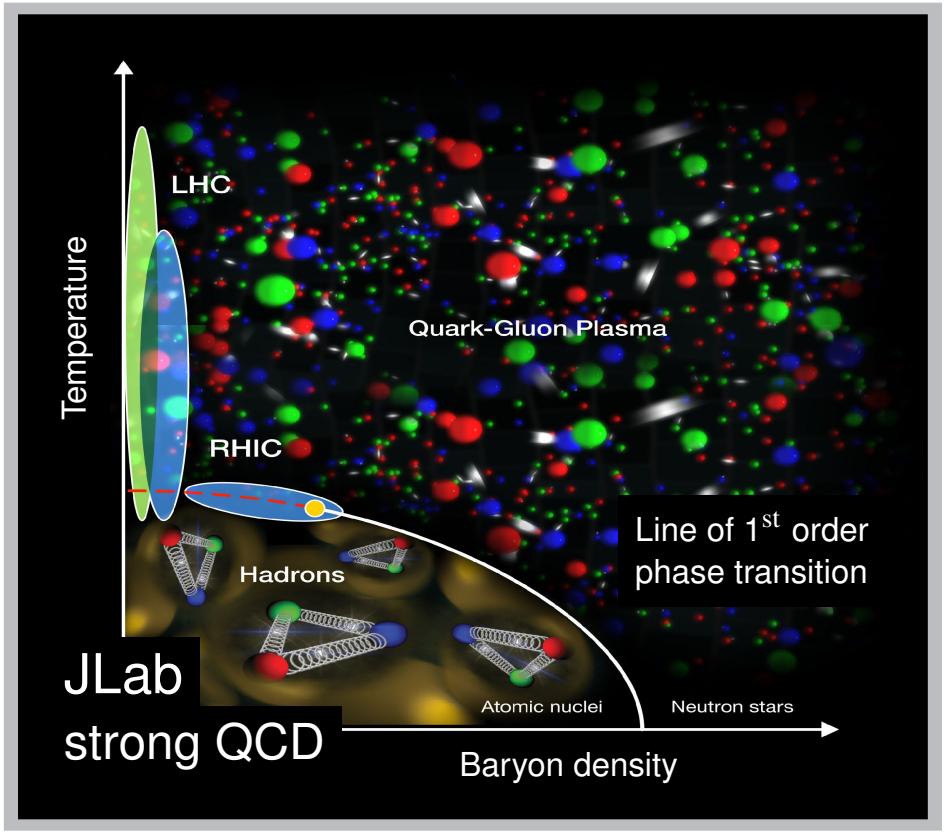
02/04/2020

Outline

Outline

QCD Phases and the Study of Baryon Resonances

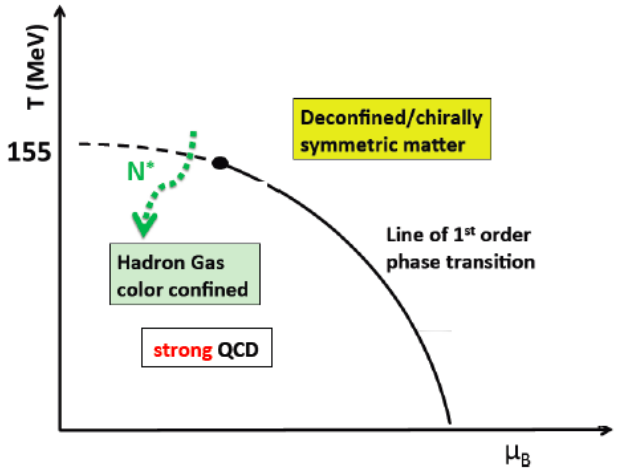


QGP

↓

hadron phase

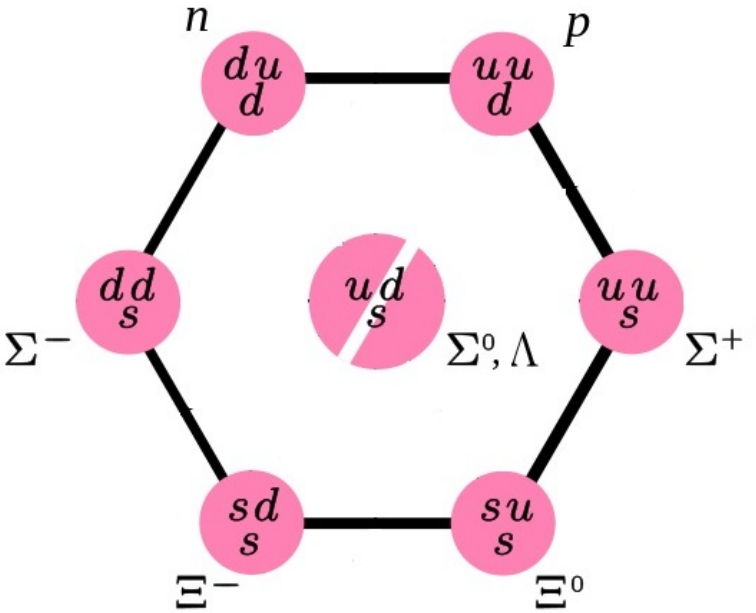
- Chiral symmetry is broken
- Quarks acquire mass
- Baryon resonances occur
- Color confinement emerges

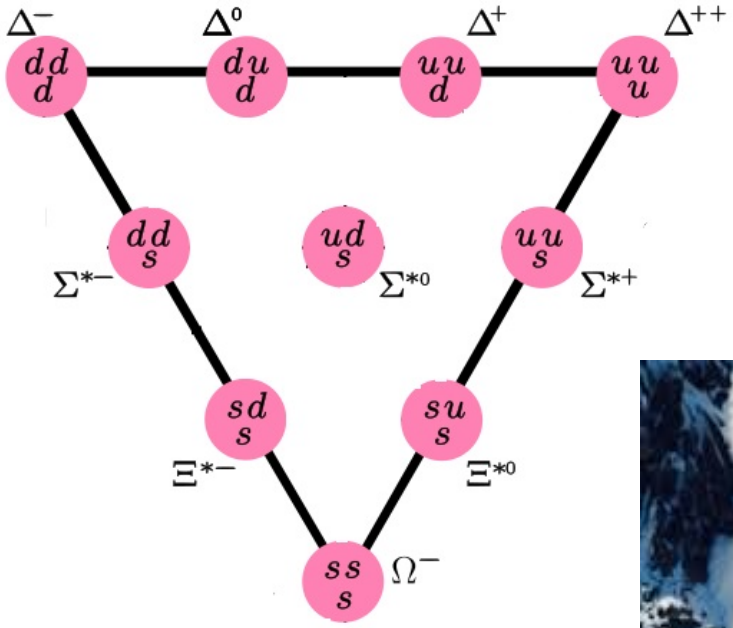


RPP (u, d, s, c) baryons not sufficient to describe freeze-out behavior.

(e. g. A. Bazavov *et al.*, PRL **113** (2014) 7, 072001)

Baryon Multiplets and N* / Hyperon Spectroscopy





The decuplets consist of Δ^*, Σ^*, Ξ^*, and Ω^* resonances, but also the octets consist of an Ξ^* state.

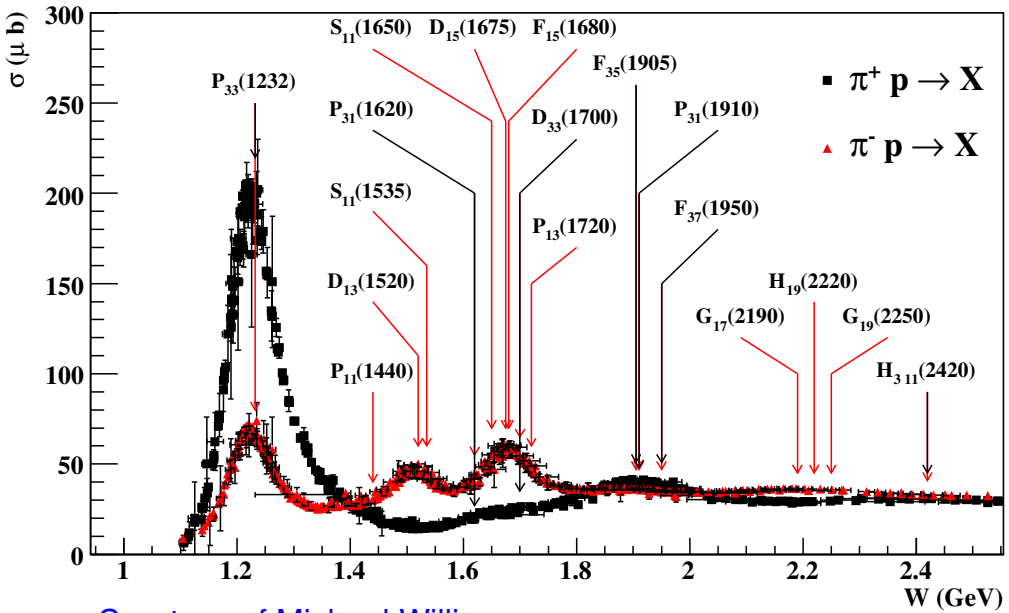
➜ We expect as many Ξ's as N^* & Δ^* states together. Moreover, their properties should be related.

Hadron Spectroscopy: The Light Flavors

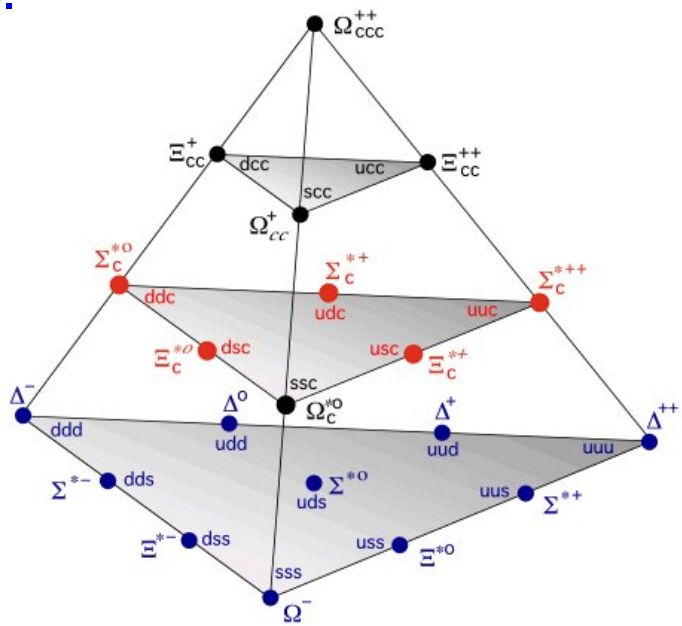
The strong coupling confines quarks and breaks chiral symmetry, and so defines the world of light hadrons.

Baryons are special because

Their structure is most obviously related to the color degree of freedom, e. g. $|\Delta^{++}\rangle = |u^{\uparrow}u^{\uparrow}u^{\uparrow}\rangle$.



Courtesy of Michael Williams



Many Y^* QN not measured:
(Quark model assignments)

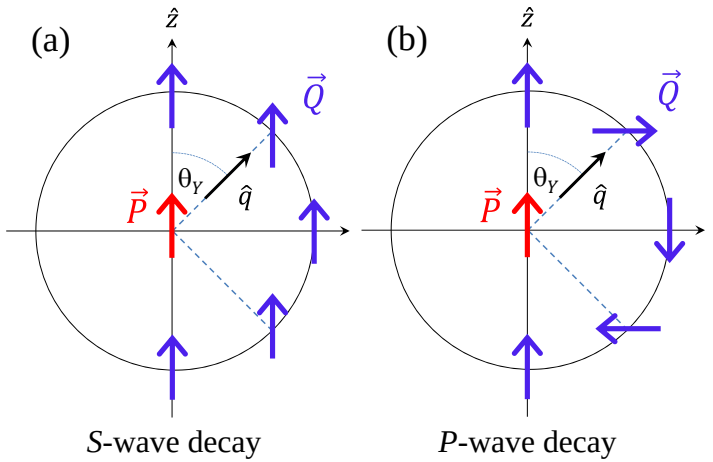
➜ many Ξ^* and Ω^*, etc.

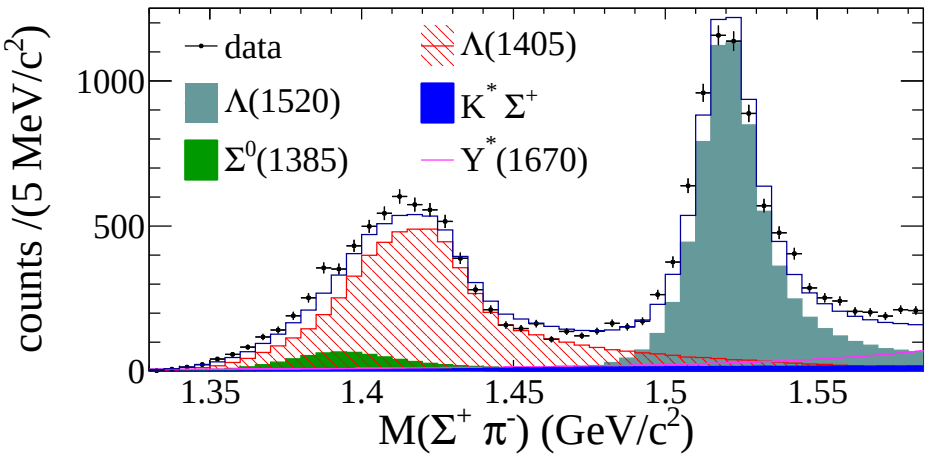
Spin and Parity Measurement of the Λ(1405) Baryon

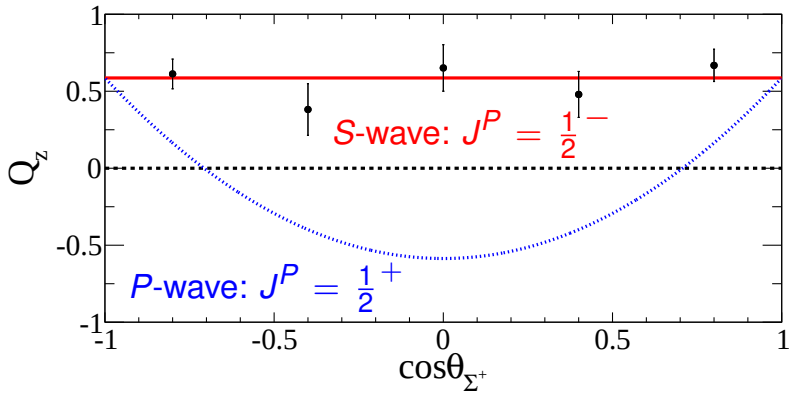
K. Moriya *et al.* [CLAS Collaboration], Phys. Rev. Lett. **112**, 082004 (2014)

Data for $\gamma p \to K^+\Lambda(1405)$ support $J^P = \frac{1}{2}^-$

- Decay distribution of $\Lambda(1405) \to \Sigma^+\pi^-$ consistent with $J = 1/2$.
- Polarization transfer, $\vec{Q}$, in $Y^* \to Y\pi$:
  - S-wave decay: $\vec{Q}$ independent of θ_Y





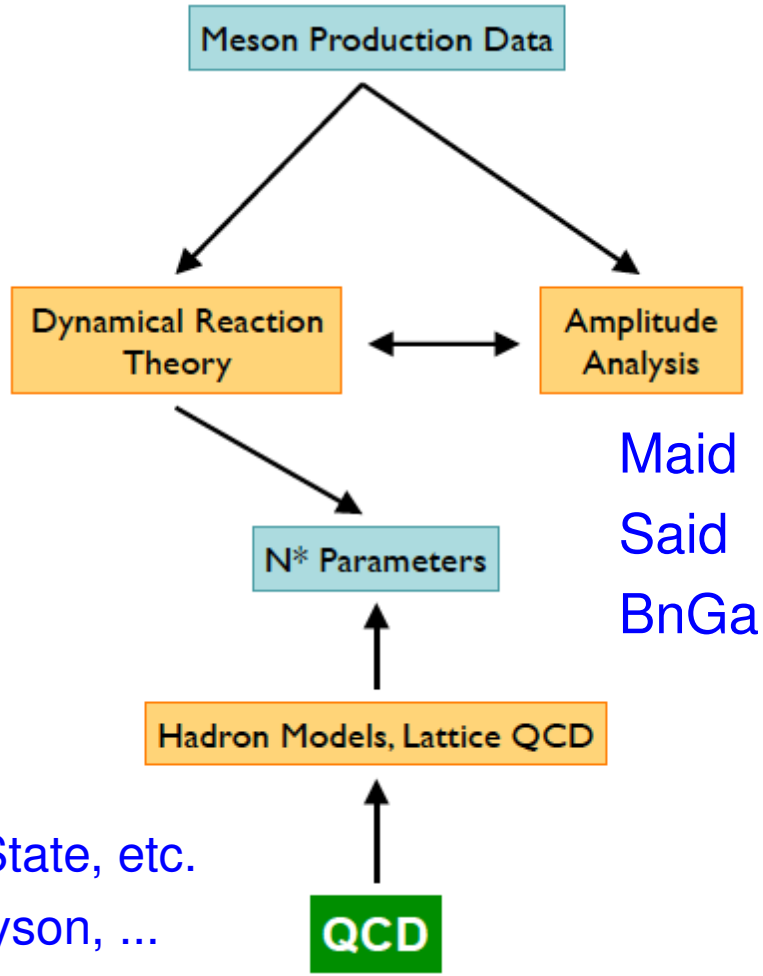


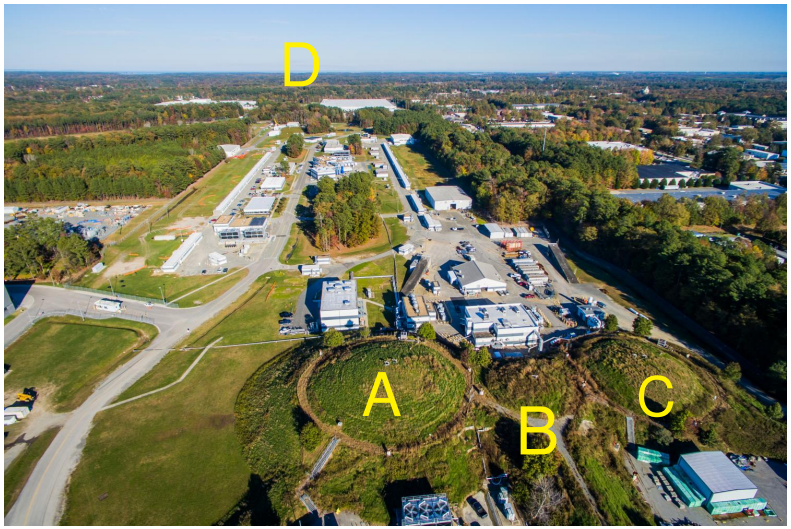
Extraction of Resonance Parameters in N^* Physics

- Double-polarization measurements
- Measurements off neutron and proton to resolve isospin contributions:
  1. $\mathcal{A}(\gamma N \to \pi,\ \eta,\ K)^{I=3/2} \iff \Delta^*$
  2. $\mathcal{A}(\gamma N \to \pi,\ \eta,\ K)^{I=1/2} \iff N^*$
- Re-scattering effects: Large number of measurements (and reaction channels) needed to extract full scattering amplitude.

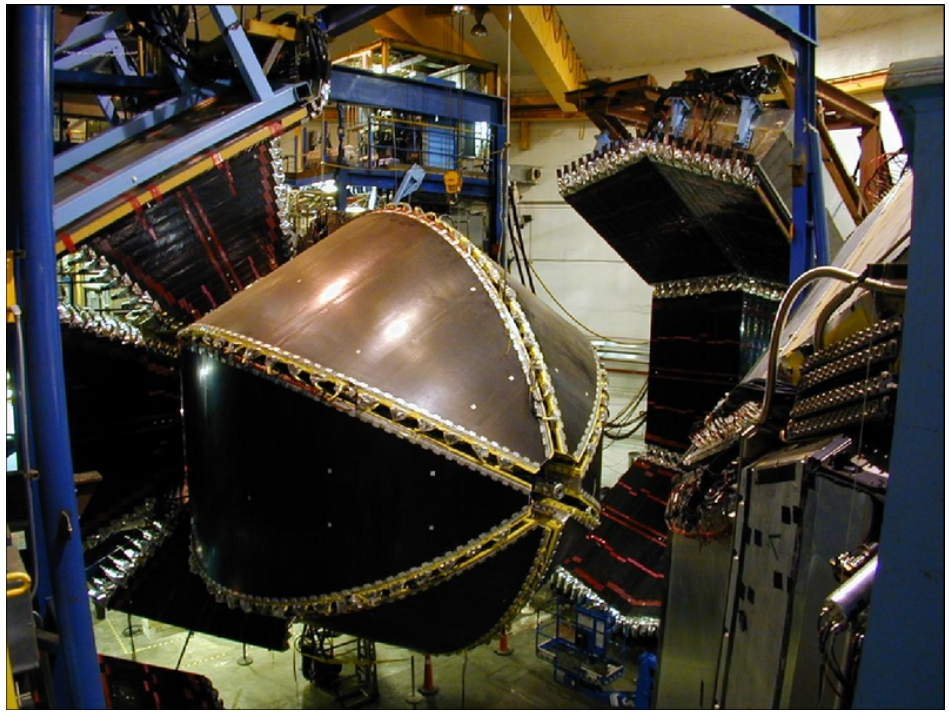
Coupled Channels

Jülich - GW, Gießen, Kent State, etc.
ANL - Osaka, Schwinger-Dyson, ...





CLAS (6 GeV) at JLab 1998 - 2012



Double-Polarization Experiments

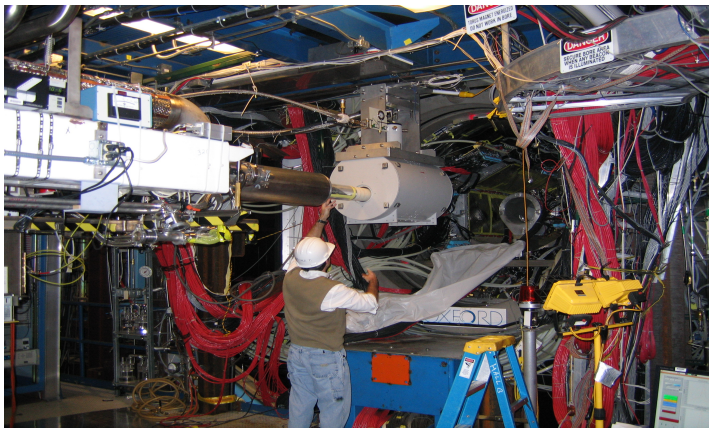


Photo-/electroproduction experiments in search for N^* states and measurement of the transition amplitudes.

← CLAS FROST

Table representing CLAS@JLab measurements

	σ	Σ	T	P	E	F	G	H	$T_{x'}$	$T_{z'}$	$L_{x'}$	$L_{z'}$	$O_{x'}$	$O_{z'}$	$C_{x'}$	$C_{z'}$
							Proton targets									
$p\,\pi^0$	✓	✓	✓	(✓)	✓	✓	✓	✓								
$n\,\pi^+$	✓	✓	✓	(✓)	✓	✓	✓	✓		✓	published					
$p\,\eta$	✓	✓	✓	(✓)	✓	✓	✓	✓		✓	acquired or under analysis					
$p\,\eta'$	✓	✓	✓	(✓)	✓	✓	✓	✓								
$p\,\omega\,(\phi)$	✓	✓	✓	(✓)	✓	✓	✓	✓			Tensor polarization, SDMEs					
$K^+\,\Lambda$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$K^+\,\Sigma^0$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$K^0\,\Sigma^+$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
							Neutron (deuteron) targets									
$p\,\pi^-$	✓	✓			✓		✓									
$K^+\,\Sigma^-$	✓	✓	✓	✓	✓	✓	✓									
$K^0\,\Lambda$	✓	✓	✓	✓	✓*	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$K^0\,\Sigma^0$	✓	✓	✓	✓	✓*	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Complete Experiments?

* published

"Uncertainty is an uncomfortable position. But Certainty is an absurd one."

Voltaire

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$n\,\pi^+$	✓	✓	✓	(✓)	✓	✓	✓	✓		✓						
$p\,\eta$	✓	✓	✓	(✓)	✓	✓	✓	✓		✓						
$p\,\eta'$	✓	✓	✓	(✓)	✓	✓	✓	✓								
$p\,\omega\,(\phi)$	✓	✓	✓	(✓)	✓	✓	✓	✓								
$K^+\,\Lambda$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$K^+\,\Sigma^0$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$K^0\,\Sigma^+$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
								Neutron (deuteron) targets								
$p\,\pi^-$	✓	✓			✓		✓									
$K^+\,\Sigma^-$	✓	✓	✓	✓	✓	✓	✓									
$K^0\,\Lambda$	✓	✓	✓	✓	✓*	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$K^0\,\Sigma^0$	✓	✓	✓	✓	✓*	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

✓ published
✓ acquired or under analysis

Tensor polarization, SDMEs

Complete Experiments?

* published

"Uncertainty is an uncomfortable position. But Certainty is an absurd one."

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Table representing CLAS@JLab measurements

	σ	Σ	T	P	E	F	G	H	$T_{x'}$	$T_{z'}$	$L_{x'}$	$L_{z'}$	$O_{x'}$	$O_{z'}$	$C_{x'}$	$C_{z'}$
						Proton targets										
$p\,\pi^0$	✓	✓	✓	(✓)	✓	✓	✓	✓								
$n\,\pi^+$	✓	✓	✓	(✓)	✓	✓	✓	✓								
$p\,\eta$	✓	✓	✓	(✓)	✓	✓	✓	✓								
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$p\,\omega\,(\phi)$	✓	✓	✓	(✓)	✓	✓	✓	✓								
$K^+\,\Lambda$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$K^+\,\Sigma^0$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$K^0\,\Sigma^+$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
						Neutron (deuteron) targets										
$p\,\pi^-$	✓	✓			✓		✓									
$K^+\,\Sigma^-$	✓	✓	✓	✓	✓	✓	✓									
$K^0\,\Lambda$	✓	✓	✓	✓	✓*	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$K^0\,\Sigma^0$	✓	✓	✓	✓	✓*	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

✓ published
✓ acquired or under analysis

Tensor polarization, SDMEs

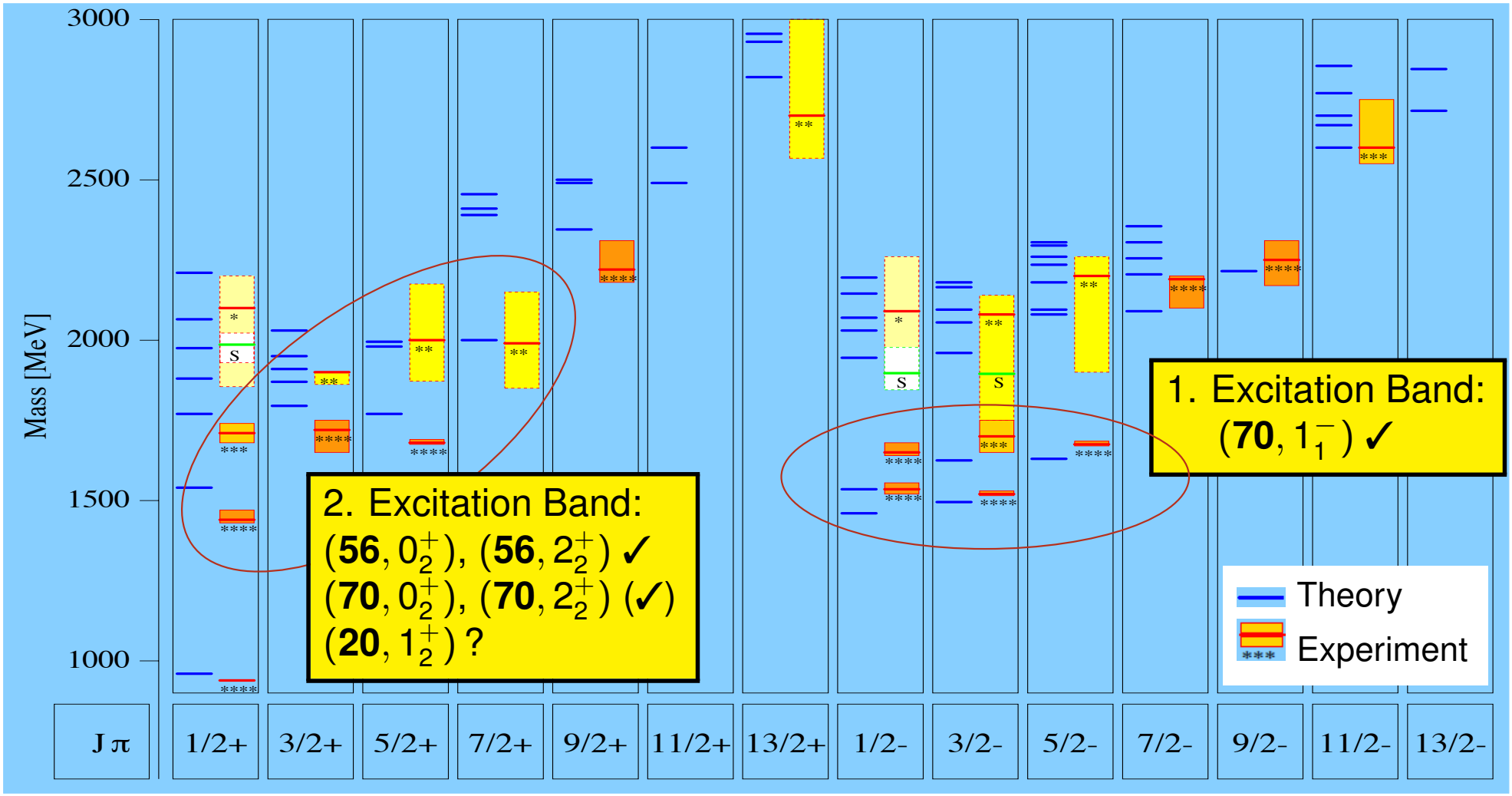
* published

In addition, two-meson reactions are being analyzed:

$\gamma p \to (p\,\rho) \to p\,\pi^+\pi^-$ (CLAS), $\gamma p \to p\,\pi^0\pi^0$, $p\,\pi^0\eta$, $p\,\pi^0\omega$ (ELSA, MAMI, etc.)

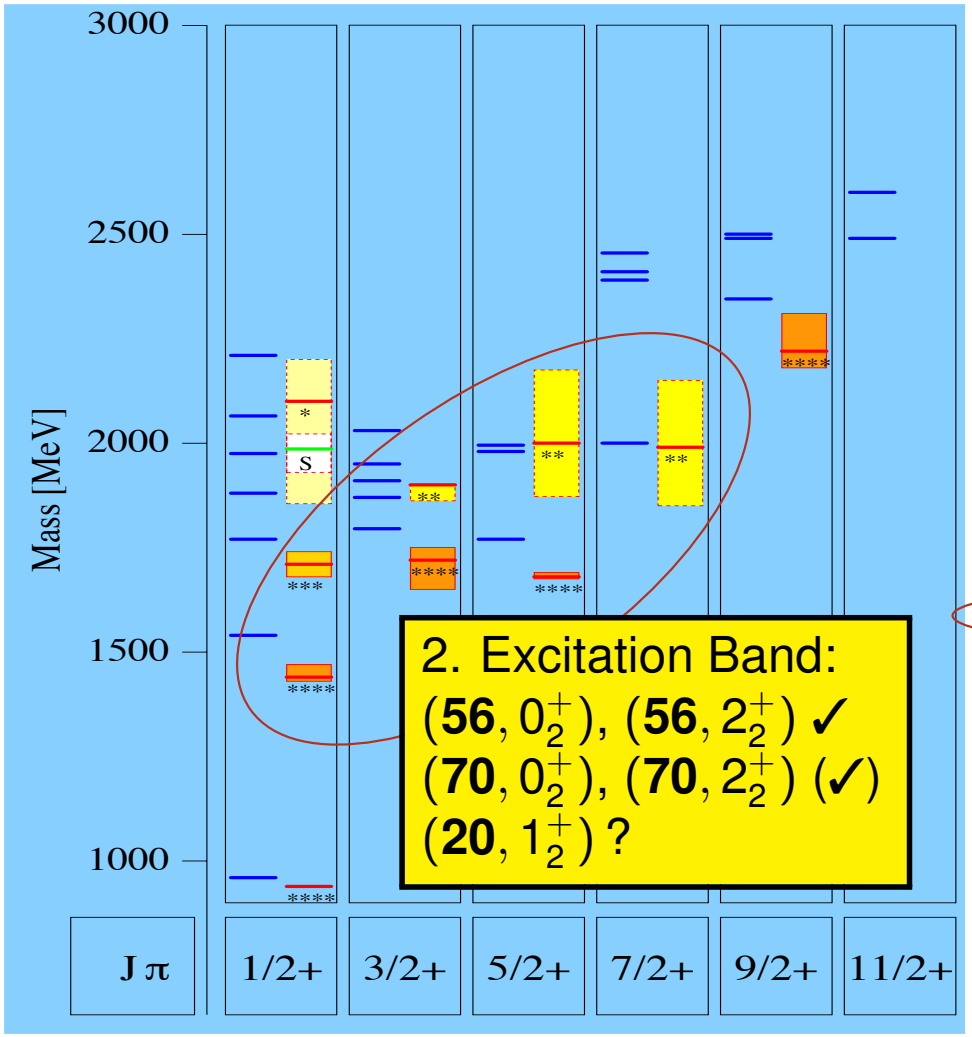
Outline

Spectrum of N^* Resonances



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

Spectrum of N^* Resonances



N^*	J^P $(L_{2I,2J})$	2010	2019
$N(1440)$	$1/2^+$ (P_{11})	****	****
$N(1520)$	$3/2^-$ (D_{13})	****	****
$N(1535)$	$1/2^-$ (S_{11})	****	****
$N(1650)$	$1/2^-$ (S_{11})	****	****
$N(1675)$	$5/2^-$ (D_{15})	****	****
$N(1680)$	$5/2^+$ (F_{15})	****	****
$N(1685)$			*
$N(1700)$	$3/2^-$ (D_{13})	***	***
$N(1710)$	$1/2^+$ (P_{11})	***	****
$N(1720)$	$3/2^+$ (P_{13})	****	****
$N(1860)$	$5/2^+$		**
$N(1875)$	$3/2^-$		***
$N(1880)$	$1/2^+$		***
$N(1895)$	$1/2^-$		****
$N(1900)$	$3/2^+$ (P_{13})	**	****
$N(1990)$	$7/2^+$ (F_{17})	**	**
$N(2000)$	$5/2^+$ (F_{15})	**	**
~~$N(2080)$~~	D_{13}	**	
~~$N(2090)$~~	S_{11}	*	
$N(2040)$	$3/2^+$		*
$N(2060)$	$5/2^-$		***
$N(2100)$	$1/2^+$ (P_{11})	*	***
$N(2120)$	$3/2^-$		***
$N(2190)$	$7/2^-$ (G_{17})	****	****
~~$N(2200)$~~	D_{15}	**	

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

Observation of Decay Cascades in $\gamma p \to p\pi^0\pi^0$

Decays observed in BnGa PWA into, e. g.

$$\left.\begin{array}{l} N(1880)\,1/2^+ \\ N(1900)\,3/2^+ \\ N(2000)\,5/2^+ \\ N(1990)\,7/2^+ \end{array}\right\} \begin{array}{l} N(1520)\pi \\ N(1535)\pi \\ N(1680)\pi \\ N\sigma\ (I=1) \end{array}$$

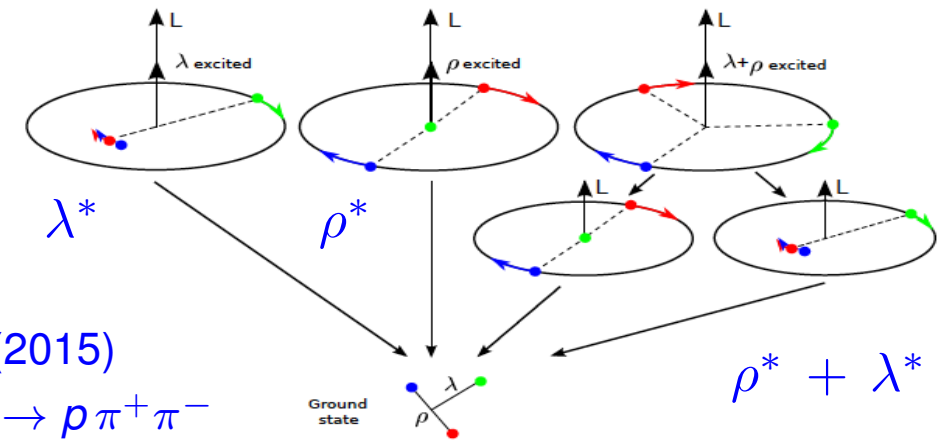
➜ Quartet of (**70**, 2_2^+) with $S = \frac{3}{2}$.

Observation of new decay modes in the decay of N^* resonances; weak at most in Δ^* decays.

Nucleon states with $S = \frac{3}{2}$ require spatial wave functions of mixed symmetry. For $L = 2$ the wave functions do have equal admixtures of $\mathcal{M}_S$ and

$$\mathcal{M}_A = [\phi_{0p}(\vec{\rho}) \times \phi_{0p}(\vec{\lambda})]^{(L=2)},$$

a component in which both the ρ and the λ oscillator are excited simultaneously.

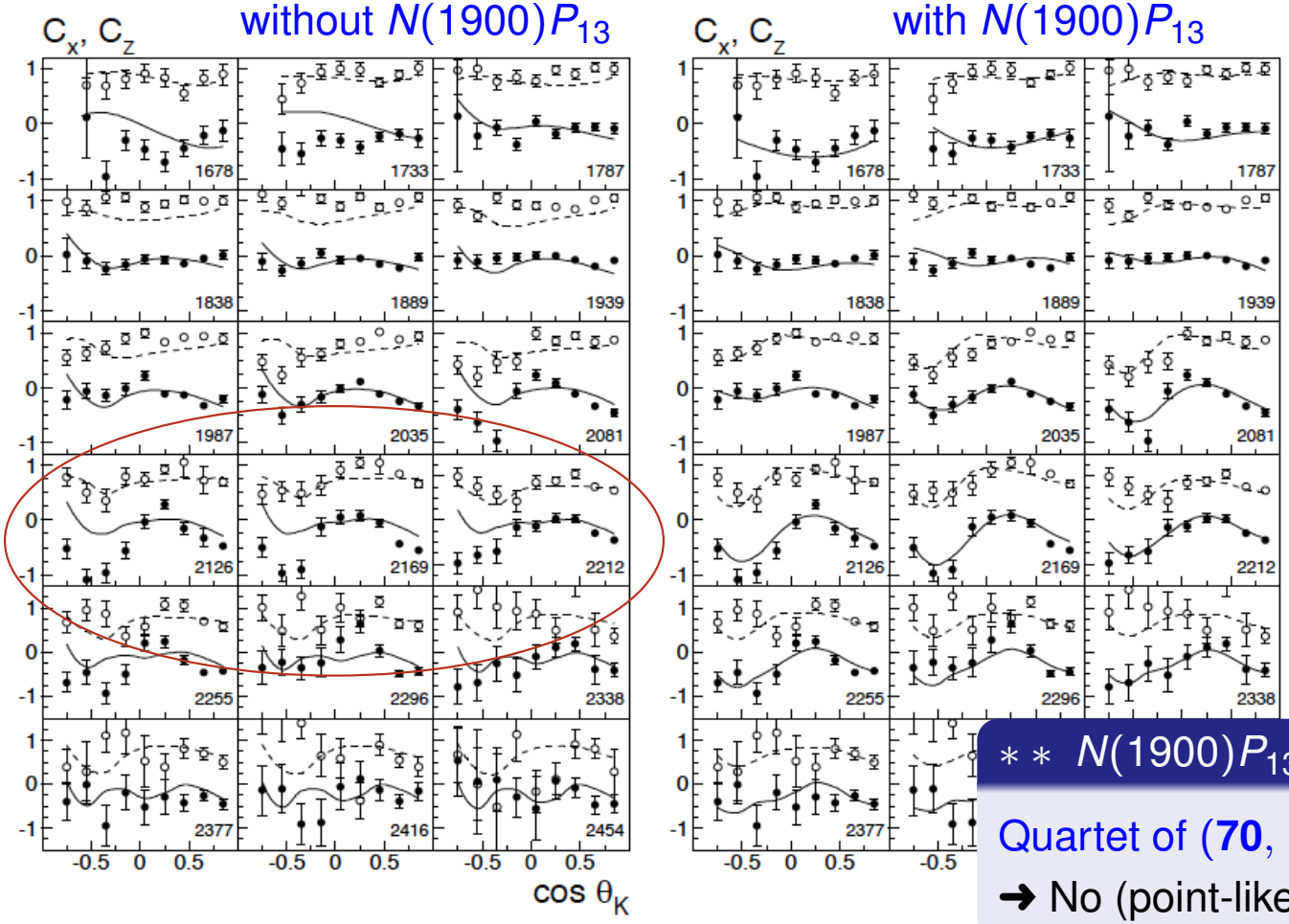


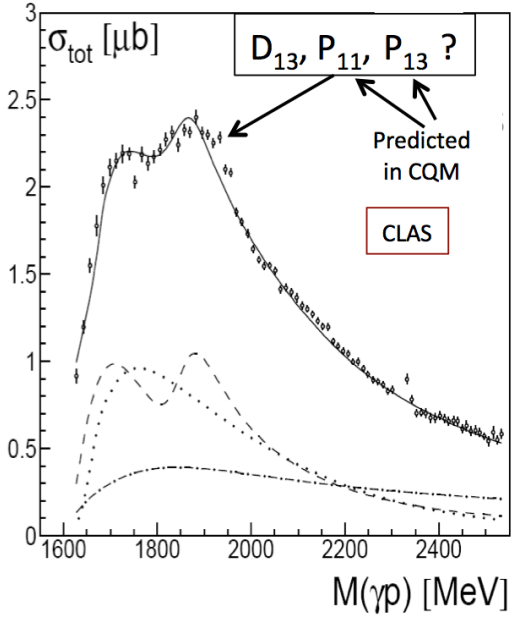
Sokhoyan, Gutz, V. C. *et al.*, EPJ A **51**, no. 8, 95 (2015)

➜ Refit includes CLAS cross-section data on $\gamma p \to p\pi^+\pi^-$

(E. Golovatch *et al.*, Phys. Lett. B **788**, 371 (2019))

Polarization Transfer in $\vec{\gamma}p \to K^+\vec{\Lambda}$: C_x & C_z





* * $N(1900)P_{13}$, $N(2000)F_{15}$, $N(1990)F_{17}$

Quartet of (**70**, 2_2^+) with $S = \frac{3}{2}$

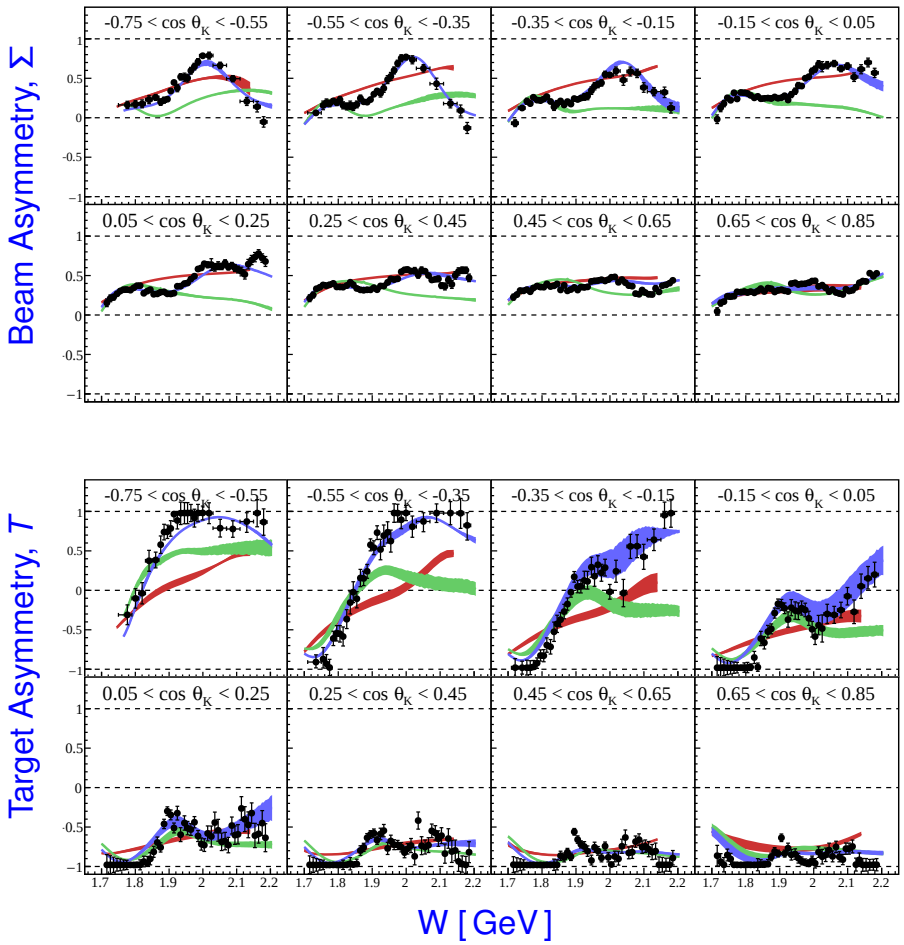
➜ No (point-like) quark-diquark oscillations!

R. Bradford *et al.* [CLAS Collaboration], PRC **75**, 035205 (2007)

Fits: BoGa-Model, V. A. Nikonov *et al.*, Phys. Lett. B **662**, 245 (2008)

Polarization Observables in $\vec{\gamma}p \to K^+\Lambda$ (g8b)

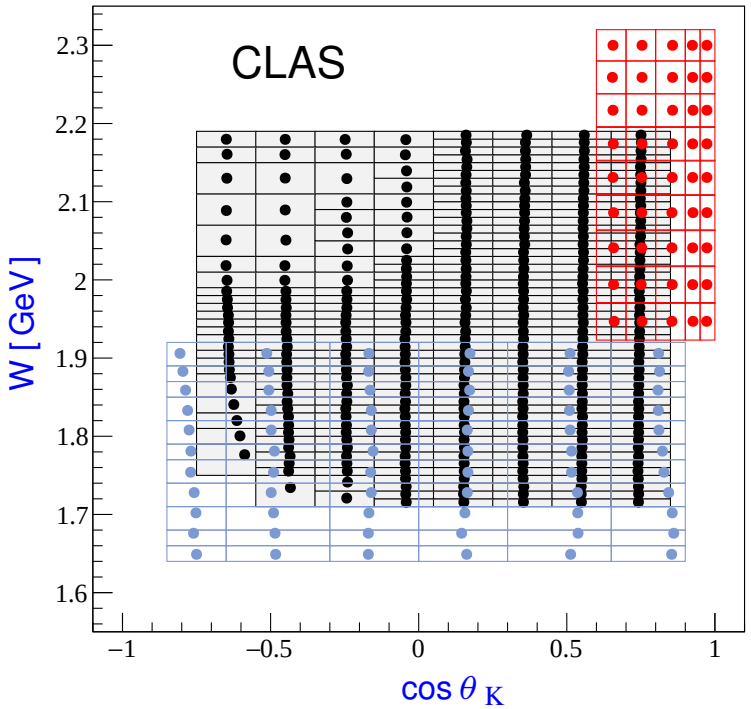
C. A. Paterson *et al.*, Phys. Rev. C **93**, 065201 (2016)



— ANL-Osaka — BnGa '14 — BnGa '14 refit

➜ Additional $N^*\ \frac{3}{2}^+$, $N^*\ \frac{5}{2}^+$ needed in BnGa refit.

comparison of kinematic coverage



(Complete) Experiments in $\gamma p \to p\omega$

- Event-based background subtraction (event-based dilution factors)
  ➜ $\gamma p \to p\pi^+\pi^-$ ✓ $\gamma p \to p\pi^+\pi^-(\pi^0)$ ✓
- In analogy to pseudoscalar mesons:

$$\frac{d\sigma}{d\Omega} = \sigma_0 \{ 1 - \delta_l \Sigma \cos 2\phi + \Lambda_x (-\delta_l H \sin 2\phi + \delta_\odot F) - \Lambda_y (-T + \delta_l P \cos 2\phi) - \Lambda_z (-\delta_l G \sin 2\phi + \delta_\odot E) \}$$

published (+ SDME's)

in progress

$\phi = \Psi \equiv$ Angle between $p\omega$ production plane and the photon polarization plane in the overall CM frame.

$\Phi \equiv$ Azimuthal angle of normal to the ω decay plane in helicity frame - quantization axis in the direction opposite the recoiling proton in the ω rest frame.

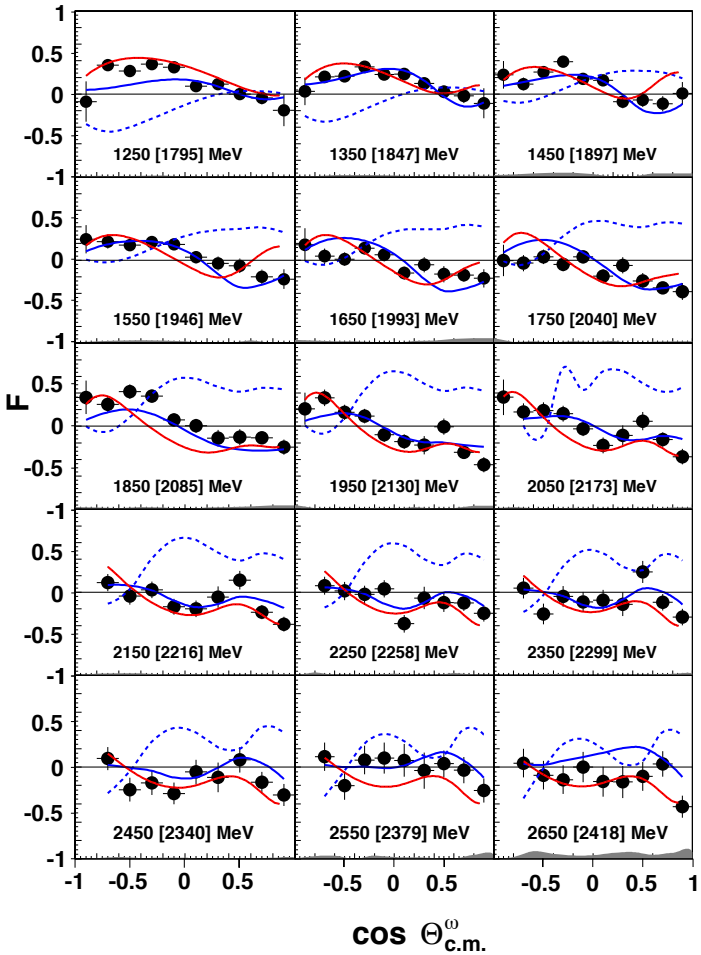
The ω is a vector meson (A. I. Titov and B. Kampfer, Phys. Rev. C 78, 038201 (2008))

$$2\pi W^f(\Phi,\Psi) = 1 - \Sigma^f_\Phi \cos 2\Phi - P_\gamma \Sigma^f_b \cos 2\Psi + P_\gamma \Sigma^f_d \cos 2(\Phi - \Psi)$$

$$\Sigma^h_b = \Sigma^r_b = 2\rho^1_{11} + \rho^1_{00} \qquad -\tfrac{1}{2}\Sigma^h_d = \Sigma^r_d = \rho^1_{1\,-1} \qquad -\tfrac{1}{2}\Sigma^h_\Phi = \Sigma^r_\Phi = -\rho^0_{1\,-1}$$

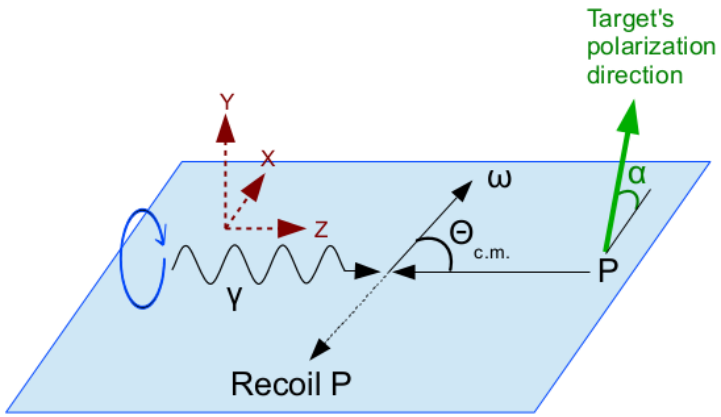
Pol. SDMEs: B. Vernarsky (CMU), PhD dissertation

F Observable in $\vec{\gamma}\,\vec{p} \to p\,\omega$ (CLAS g9b)



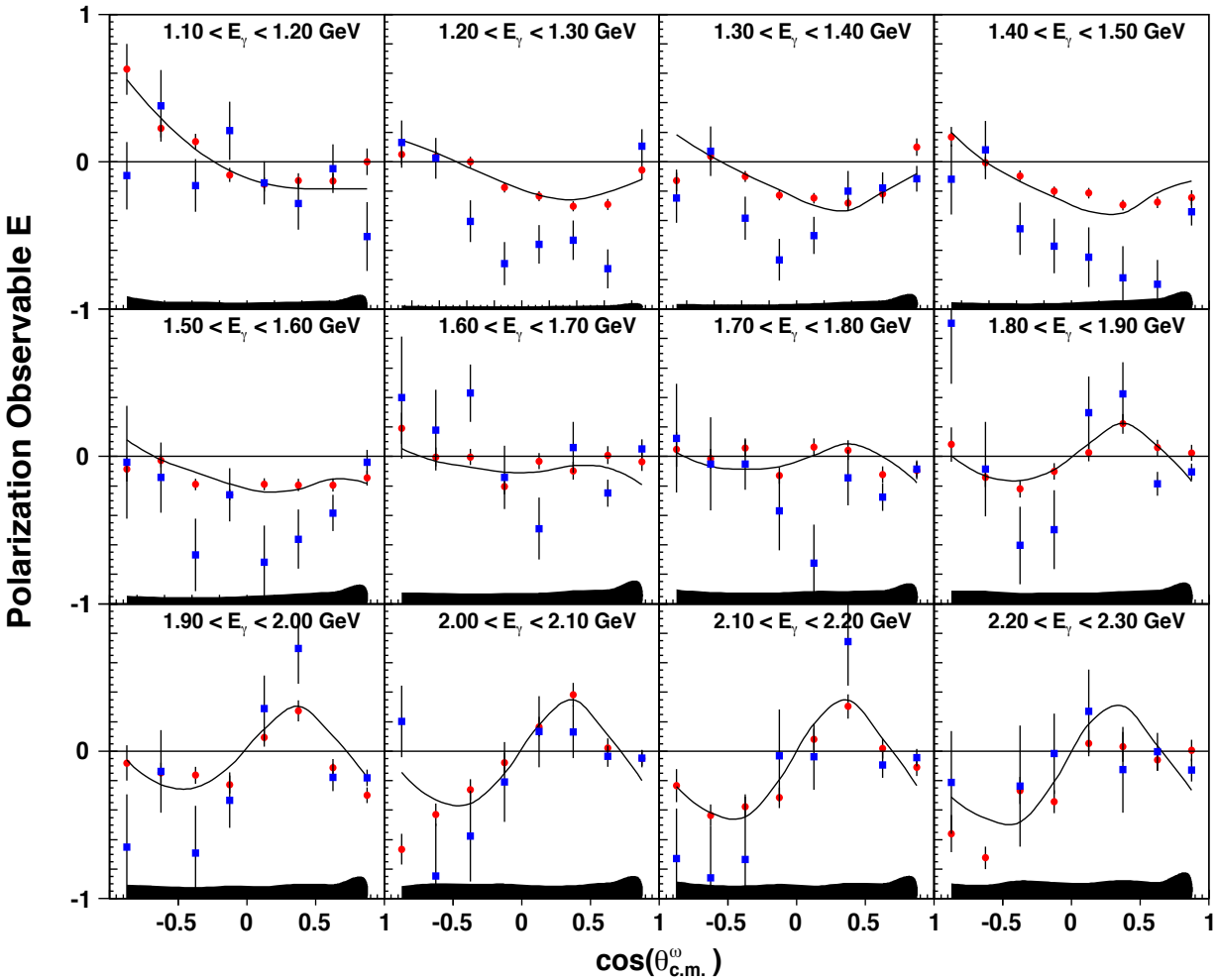
Polarized Cross Section

$$\frac{d\sigma}{d\Omega} = \sigma_0 \{ 1 - \delta_l \Sigma \cos 2\phi + \Lambda_x (-\delta_l H \sin 2\phi + \delta_\odot F) - \Lambda_y (-T + \delta_l P \cos 2\phi) - \Lambda_z (-\delta_l G \sin 2\phi + \delta_\odot E) \}$$



P. Roy *et al.* [CLAS Collaboration], PRL **122**, 162301 (2019)

Helicity Asymmetry in $\vec{\gamma}\vec{p} \to p\omega$ (CLAS g9a)



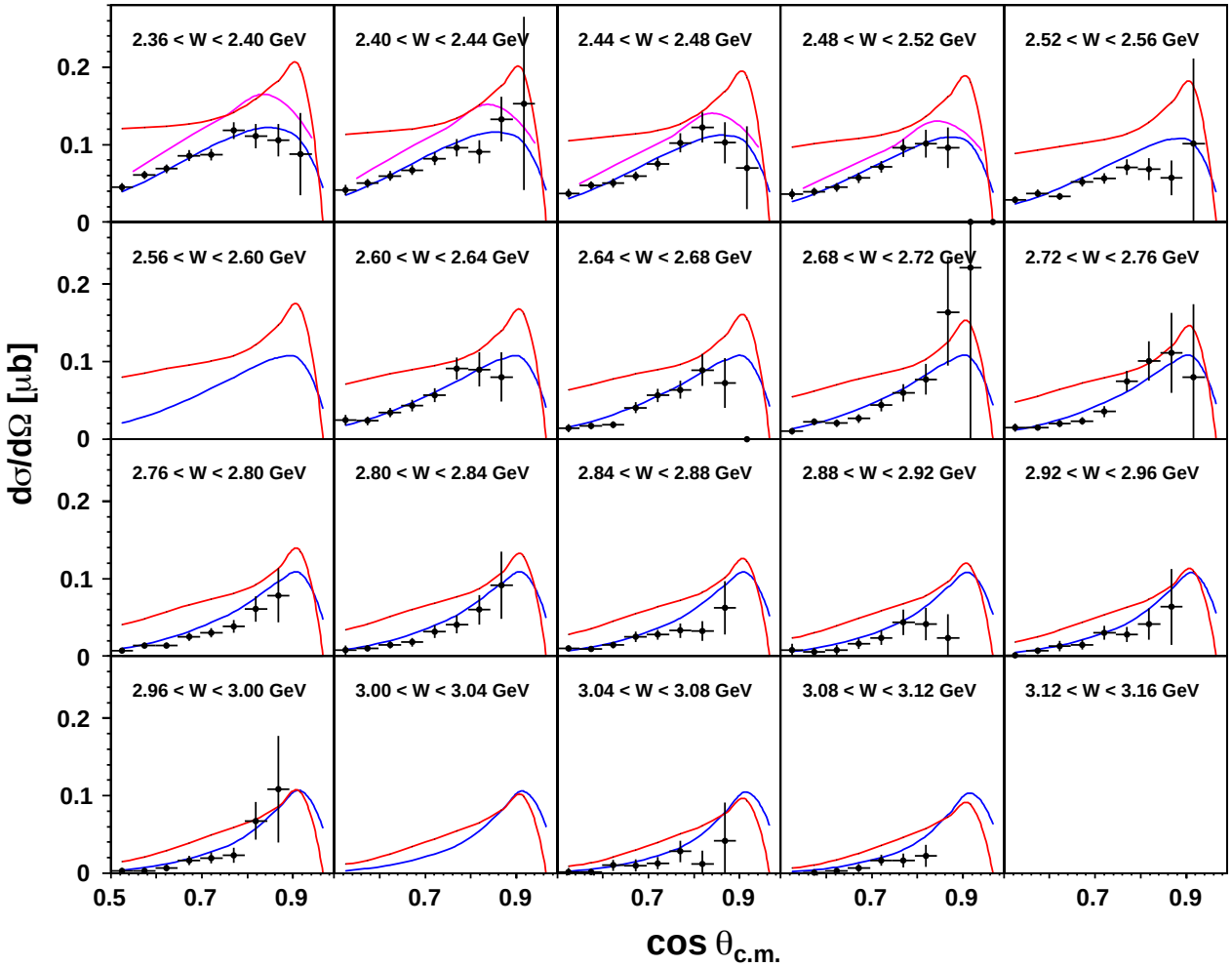
Z. Akbar *et al.* [CLAS Collaboration], PR C **96**, 065209 (2017)

BnGa (coupled-channels) PWA

- Dominant **P** exchange
- Complex $3/2^+$ wave
  1. $N(1720)$
  2. $W \approx 1.9$ GeV
- $N(1895)\,1/2^-$ (new state)
- $N(1680), N(2000)\,5/2^+$
- 7/2 wave > 2.1 GeV

- CLAS-g9a
- CBELSA/TAPS
  Phys. Lett. B **750**, 453 (2015)

Cross Sections for the Reaction $\gamma p \to p\eta \to p\pi^+\pi^-\pi^0$



New cross section results in 40-MeV-wide W bins for

$2.50 < E_\gamma < 4.72$ GeV, or

$2.36 < W < 3.12$ GeV

- JPAC, J. Nys *et al.*
- ηMAID 2018
- BnGa 2014-02

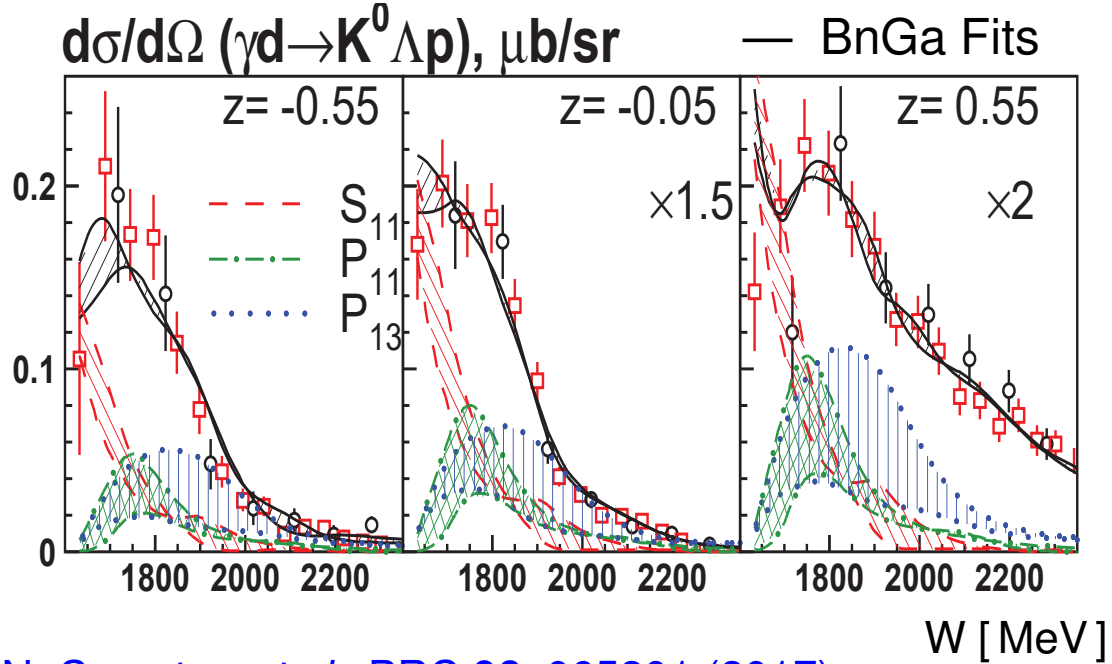
T. Hu *et al.* [CLAS Collaboration], paper under review.

Brief Summary of Measurements off Neutron (CLAS)

$\gamma n \to p \pi^-$ σ, E observable (P. T. Mattione *et al.*, Phys. Rev. C **96**, 035204 (2017))

$\gamma n \to K^0 \Sigma^0$ E observable (D. H. Ho *et al.*, Phys. Rev. C **98**, 045205 (2018))

$\gamma n \to K^0 \Lambda$ σ, E observable



N. Compton *et al.*, PRC **96**, 065201 (2017)

Summary of neutron results:

- No introduction of new resonances so far.
- Helicity amplitudes, $N(1900)\,\frac{3}{2}^+$, $N(1720)\,\frac{3}{2}^+$.
- Convergence of groups on $\gamma n N^*\,(A_n^h)$ for $N(2190)\,\frac{7}{2}^-$.

The impact of photoproduction on baryon resonances

Decay modes of nucleon resonances
black: PDG 2004
red: PDG 2018
blue: BESIII resonances

****	Existence is certain.
***	Existence is very likely.
**	Evidence of existence is fair.
*	Evidence of existence is poor.

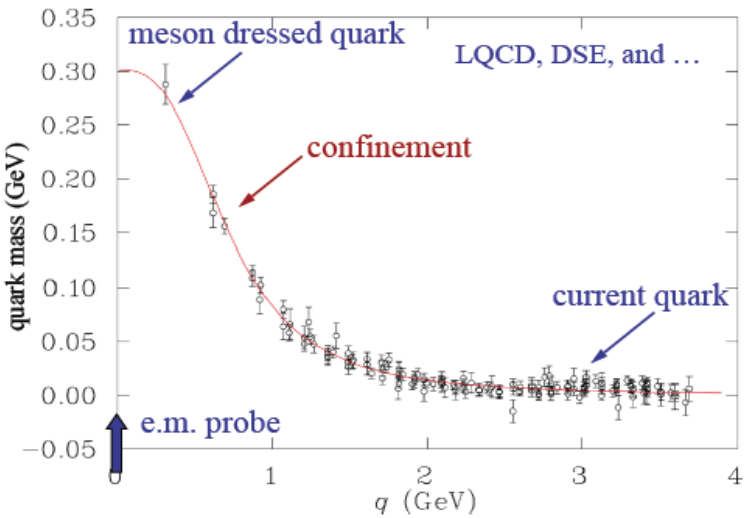
		overall	$N\gamma$	$N\pi$	$\Delta\pi$	$N\sigma$	$N\eta$	ΛK	ΣK	$N\rho$	$N\omega$	$N\eta'$	$N_{1440}\pi$	$N_{1520}\pi$	$N_{1535}\pi$	$N_{1680}\pi$
N	$1/2^+$	****														
$N(1440)$	$1/2^+$	****	****	****	****	***										
$N(1520)$	$3/2^-$	****	****	****	****	**	****									
$N(1535)$	$1/2^-$	****	****	****	***	*	****									
$N(1650)$	$1/2^-$	****	****	****	***	*	****	***					*			
$N(1675)$	$5/2^-$	****	****	****	****	***	*	*	*	**				*		
$N(1680)$	$5/2^+$	****	****	****	****	***	*			****						
$N(1700)$	$3/2^-$	***	**	***	***	*	*	**	*	*						
$N(1710)$	$1/2^+$	****	****	****	**		***	**	*	*	*				*	
$N(1720)$	$3/2^+$	****	*****	****	***	*	*	****	*	**	*					
$N(1860)$	$5/2^+$	**	*	**		*	*									
$N(1875)$	$3/2^-$	***	**	**	*	**	*	*	*	*	*	*	*			
$N(1880)$	$1/2^+$	***	**	*	**	*	*	**	**		**				*	
$N(1895)$	$1/2^-$	****	****	*	*	*	****	**	**	*	*	****	*			
$N(1900)$	$3/2^+$	****	****	**	**	*	*	**	**	*	*	**				
$N(1990)$	$7/2^+$	**	**	**	*	*	*	**	**							
$N(2000)$	$5/2^+$	**	**	**	**	*	*	*	*		*					
$N(2040)$	$3/2^+$	*		*												
$N(2060)$	$5/2^-$	***	***	**	*	*	*	*	*	*	*		*	*		*
$N(2100)$	$1/2^+$	***	**	***	**	**	*	*		*	*	**			***	
$N(2120)$	$3/2^-$	***	***	***	**	**		**	*		*	*	*	*	*	
$N(2190)$	$7/2^-$	****	****	****	****	**	*	**	*	*	*					
$N(2220)$	$9/2^+$	****	**	****			*	*	*							
$N(2250)$	$9/2^-$	****	**	****			*	*	*							
$N(2300)$	$1/2^+$	*		*												
$N(2570)$	$5/2^-$	*		*												
$N(2600)$	$11/2^-$	***		***												
$N(2700)$	$13/2^+$	**		**												

Based on results at Jefferson Lab, ELSA, MAMI, ...

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)



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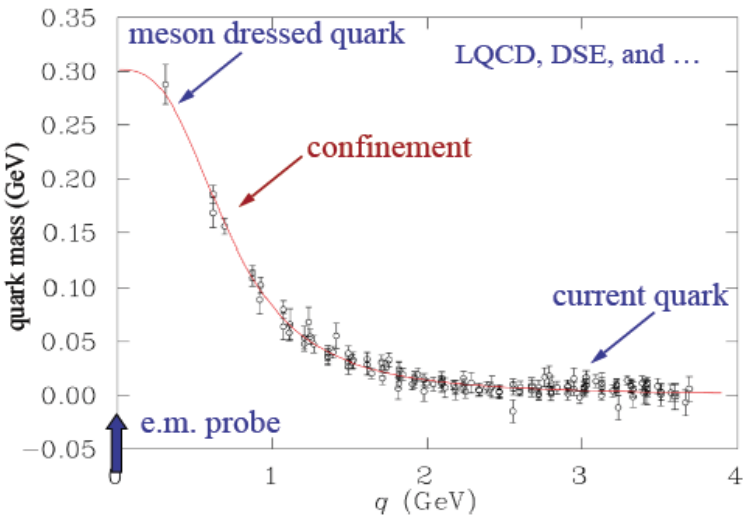


Outlook

Baryon Spectroscopy: Are we there, yet? Certainly not ...

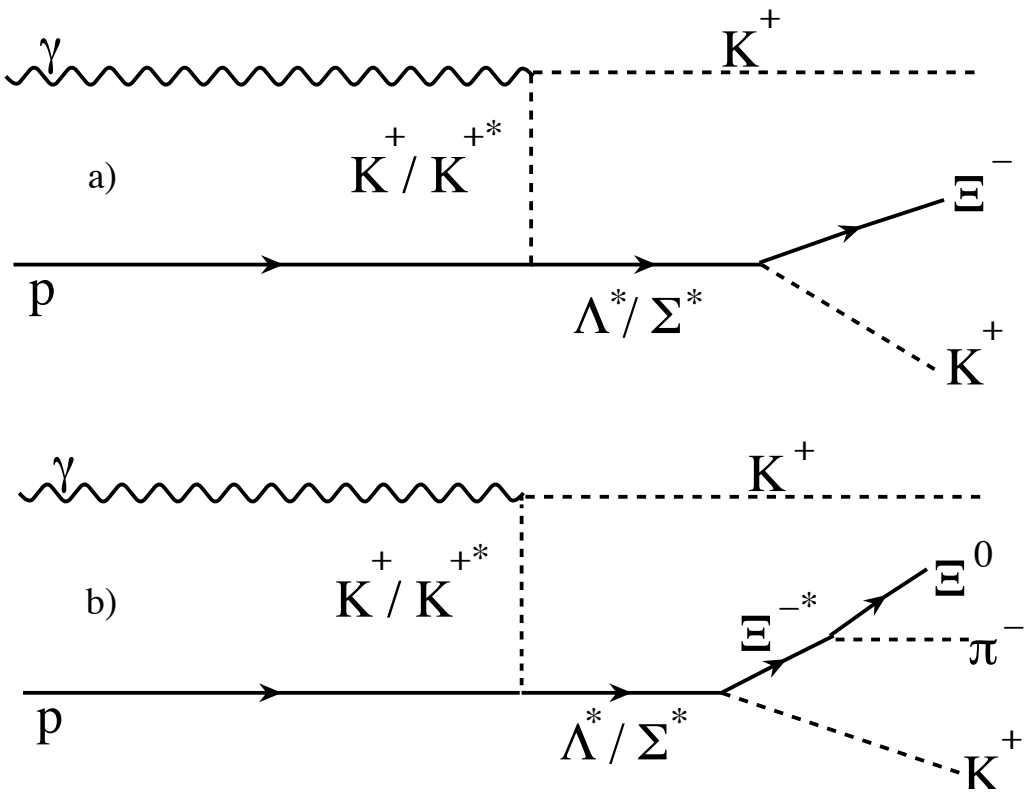
New era in the spectroscopy of strange baryons (GlueX, LHCb, PANDA, ...)

- Mapping out the spectrum of Ξ baryons is the primary motivation (including parity measurements); some hope for peak hunting.
- Ground-state Ξ in $\gamma p \to KK\,\Xi$ will allow the spectroscopy of Σ^* / Λ^* states.

The multi-strange baryons provide a missing link between the light-flavor and the heavy-flavor baryons. Also:

1. Do the lightest excited Ξ states in certain partial waves decouple from the $\Xi\pi$ channel, confirming the flavor independence of confinement?
2. Ξ baryons as a probe of excited hadron structure?
   ➜ Measurements of the isospin splittings in spatially excited Ξ states appear possible for the first time (similar to $n - p$ or $\Delta^0 - \Delta^{++}$).

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^*)

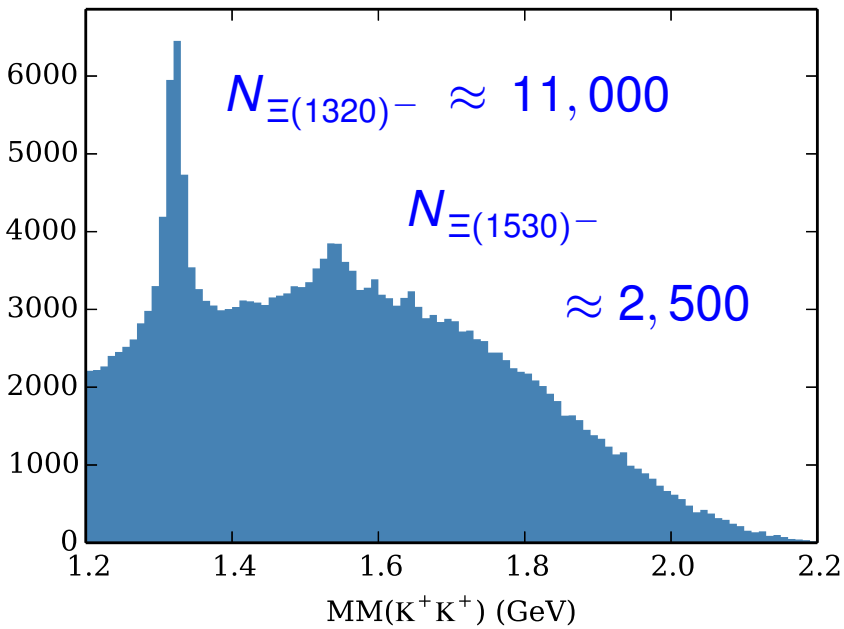
At other facilities (for comparison):

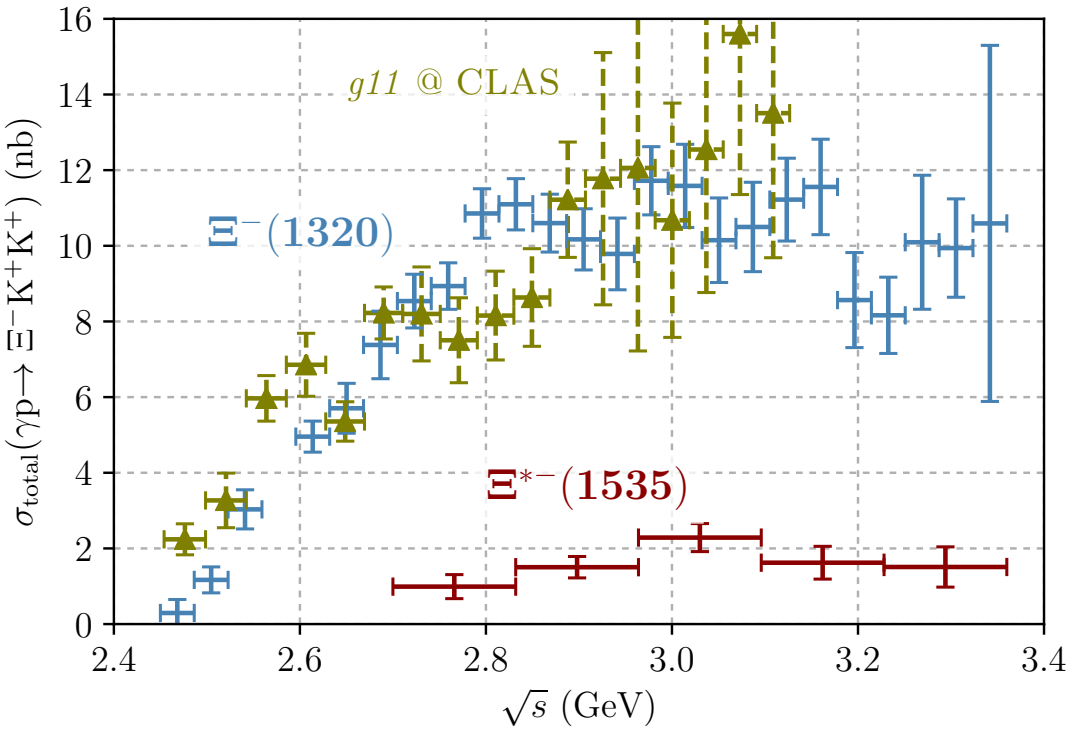
$K^- p \to K^+ \Xi^{*-}$	J-PARC
$K_L p \to K^+ \Xi^{*0}$	Hall D ?
$pp \to \Xi^* X$	LHCb
$\bar{p}p \to \Xi^* \bar{\Xi}$	$\bar{\text{P}}$ANDA
$e^+ e^- \to \Xi^* X$	Belle II, BES III

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

CLAS g12: Total Cross Sections of $(\Xi^-)^*$

$2.31 < \sqrt{s} < 3.4$ GeV





No statistically significant structures beyond Ξ(1530) peak: Different reaction (production) mechanism for Ξ^* states?

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

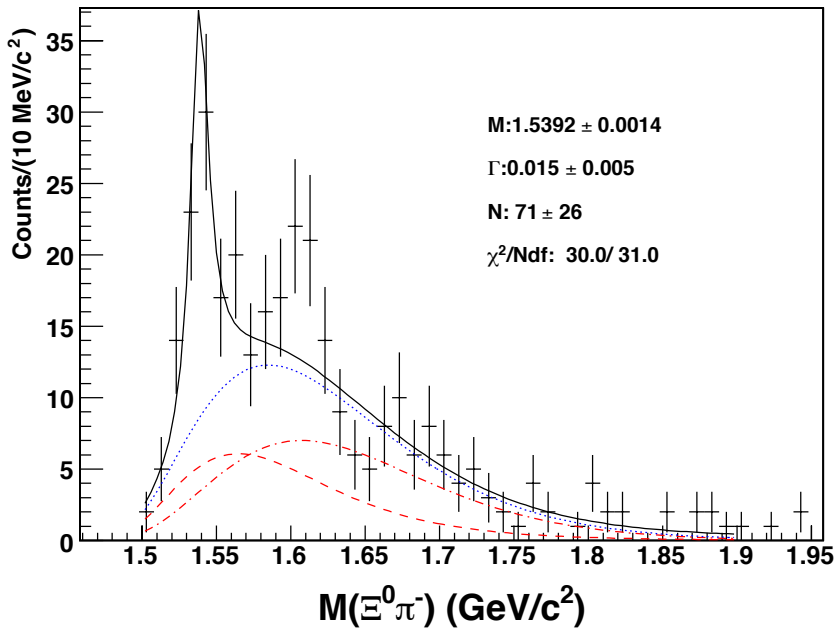
CLAS g11a: Excited States in $\gamma p \to K^+K^+\pi^-(X)$

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

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

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

➜ CLAS 12 and GlueX at Jefferson Lab



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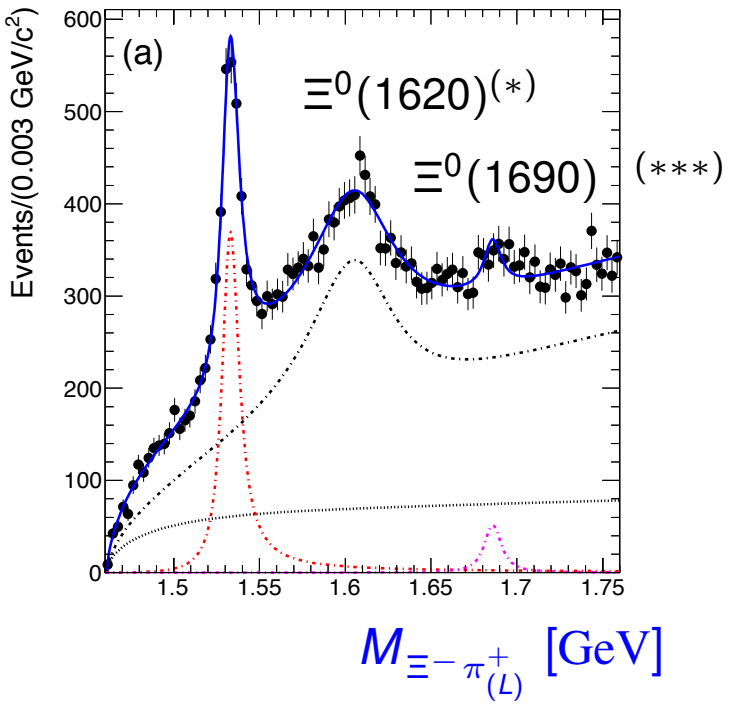
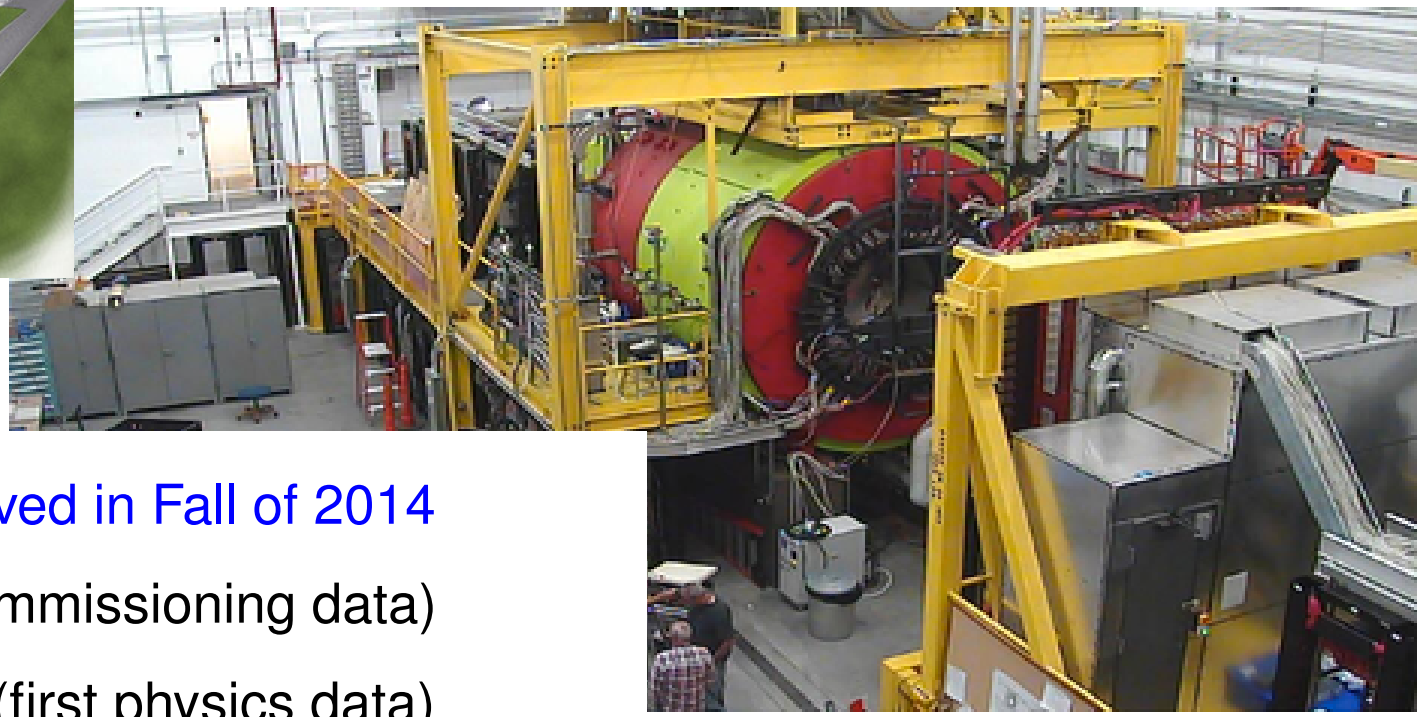
Belle: PRL **122**, 072501 (2019)



Hall D

Jefferson Lab Upgrade to 12 GeV



10.1 GeV achieved in Fall of 2014

2016: 2 pb^{-1} (commissioning data)

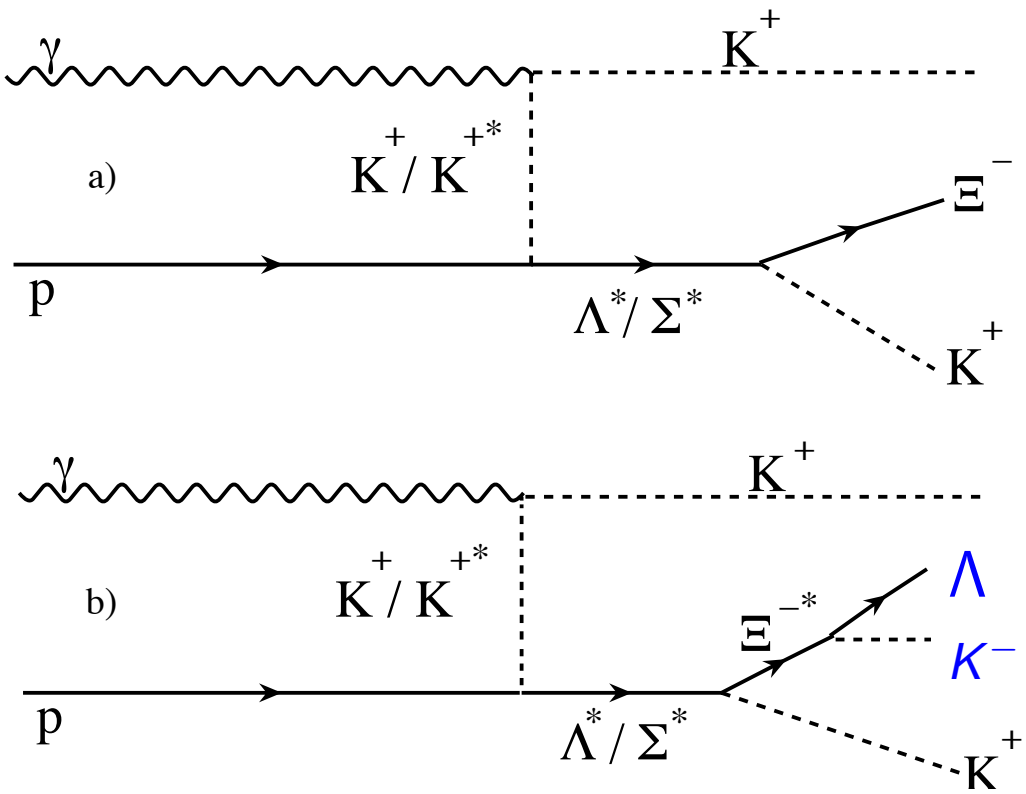
2017: 20.8 pb^{-1} (first physics data)

➜ Used for most physics analyses

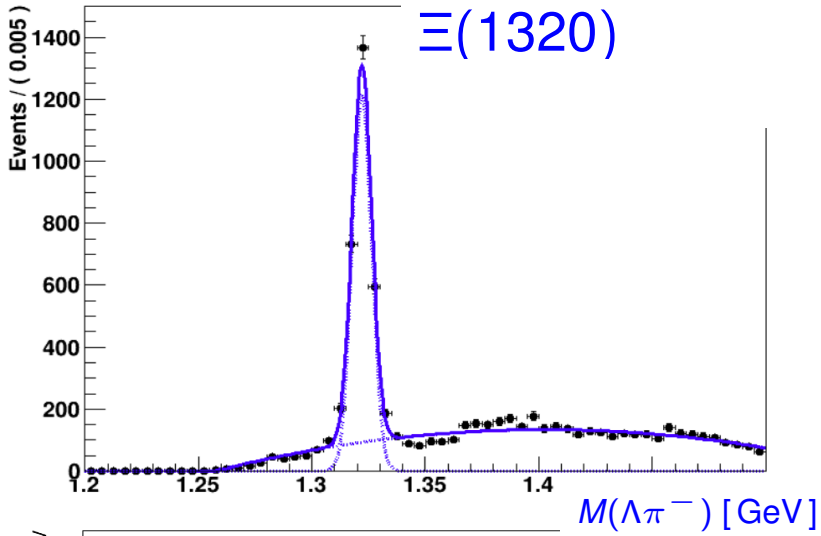
2018: 51 pb^{-1} (Spring data)

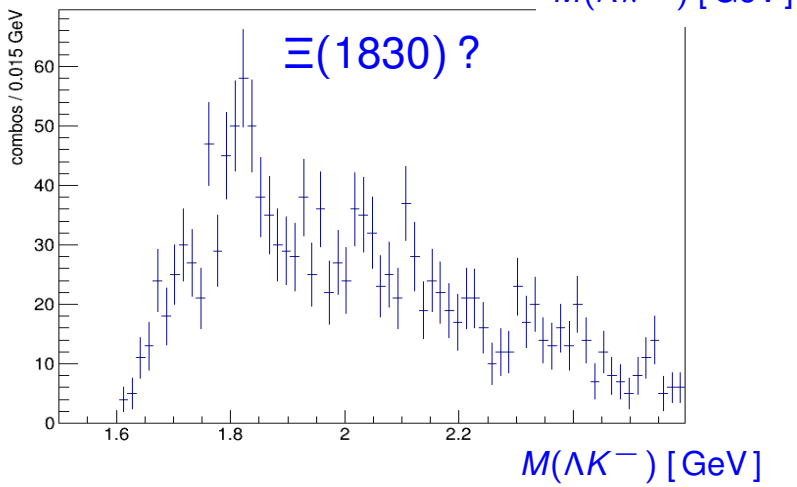
➜ GlueX Phase-I completed this Fall

Possible Production Mechanisms



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





Courtesy of Ashley Ernst (FSU)

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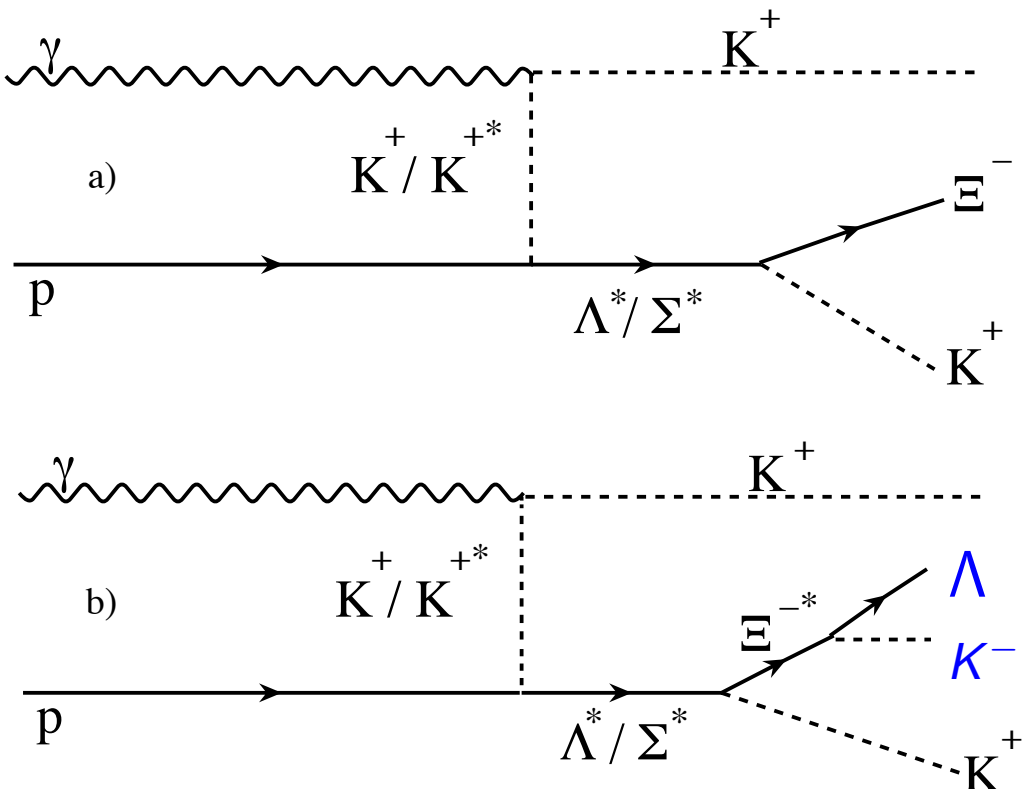
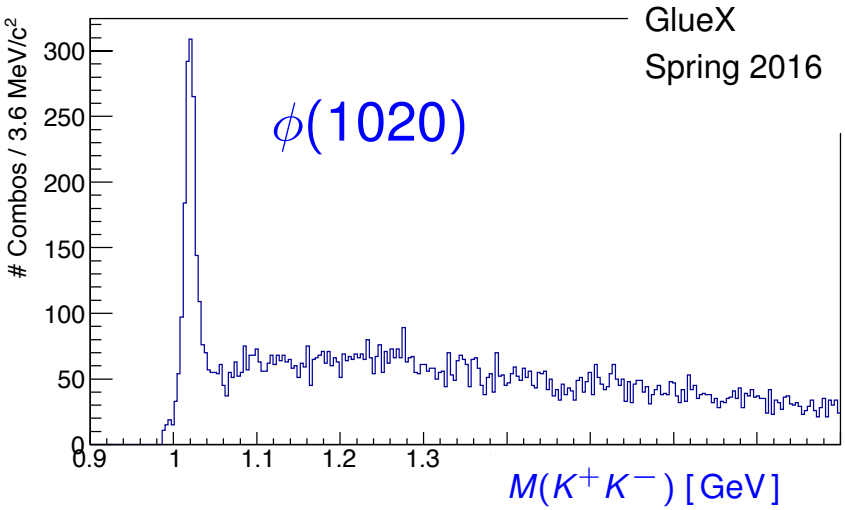
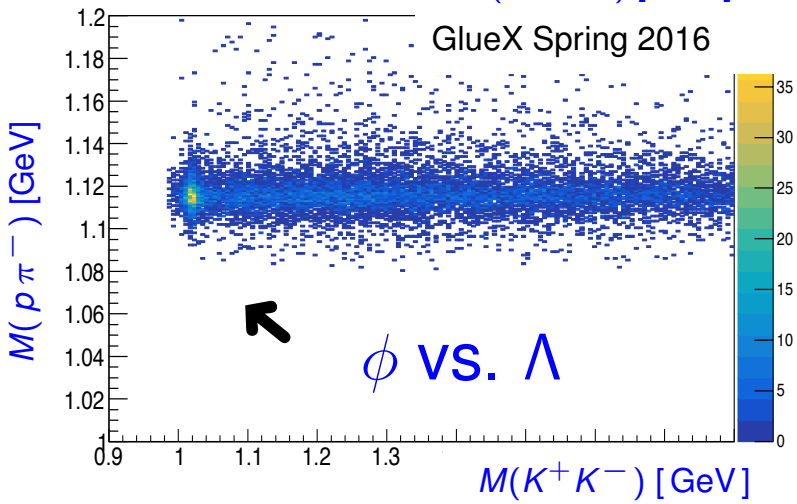


$\gamma p \to K^+ (\Lambda K^+ K^-)$

1) $K^+ (\Xi^{-*} K^+)$, 2) $K^+ (\Lambda \phi)$





Courtesy of Ashley Ernst (FSU)

Acknowledgement

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