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

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MENU 2019

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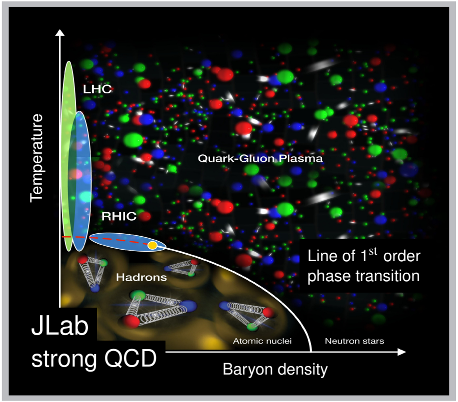
Outline

Outline

QCD Phases and the Study of Baryon Resonances

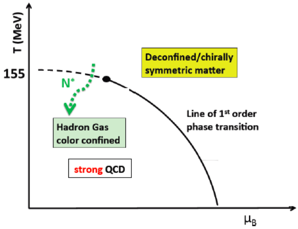


QGP

↓

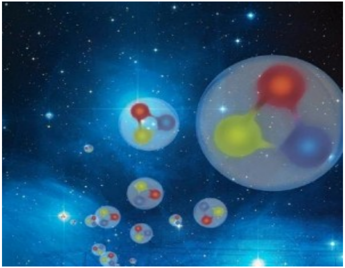
hadron phase

- 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)

Non-Perturbative QCD



How does QCD give rise to excited hadrons?

1. What is the origin of confinement?
2. How are confinement and chiral symmetry breaking connected?
3. What role do gluonic excitations play in the spectroscopy of light mesons, and can they help explain quark confinement?

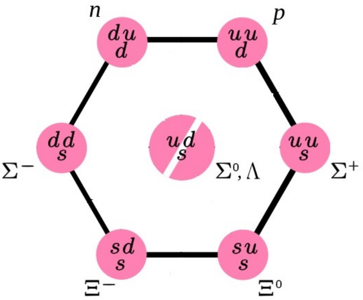
Baryons: What are the fundamental degrees of freedom inside a nucleon? Constituent quarks? How do the degrees change with varying quark masses?

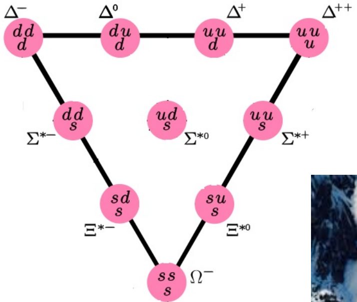
Mesons: What are the properties of the predicted states beyond simple quark-antiquark systems (hybrid mesons, glueballs, tetraquarks, ...)?

➜ Gluonic Excitations provide a measurement of the excited QCD potential.

Hybrid baryons are also possible ...

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.

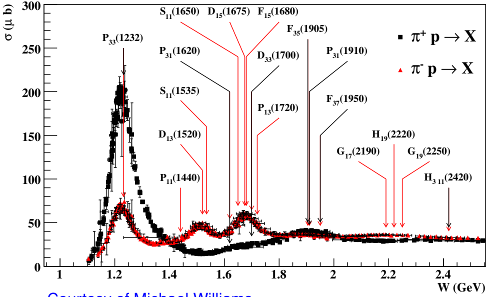
➜ We expect as many Ξ's as N^* & Δ^* states together. Moreover, their properties should be related.

Hadron Spectroscopy: The Light Flavors

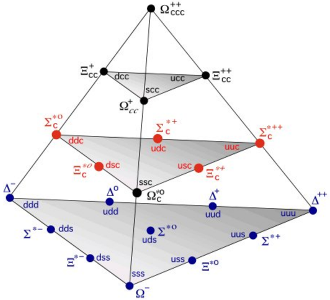
The strong coupling confines quarks and breaks chiral symmetry, and so defines the world of light hadrons.

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)

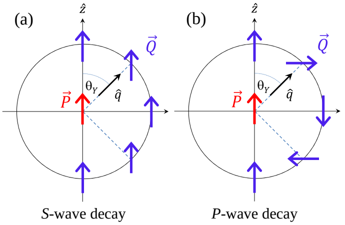
➜ many Ξ^* and Ω^*, etc.

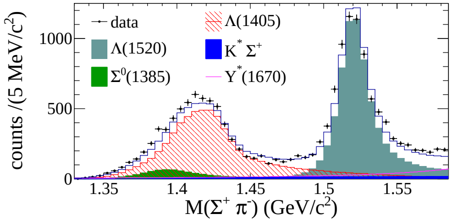
Spin and Parity Measurement of the Λ(1405) Baryon

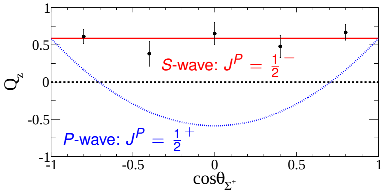
K. Moriya *et al.* [CLAS Collaboration], Phys. Rev. Lett. **112**, 082004 (2014)

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







From the Atomic Spectrum of Hydrogen ...

Development of the theory of atomic structure required

- Hydrogen Atom (ground state)
- Together with the emission (absorption) spectrum.

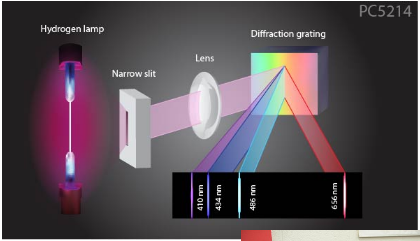
Bohr model ➜ QED

Understanding the nucleon requires

- proton (ground state)
- Together with its excitation spectrum.

Quark model ➜ strong QCD

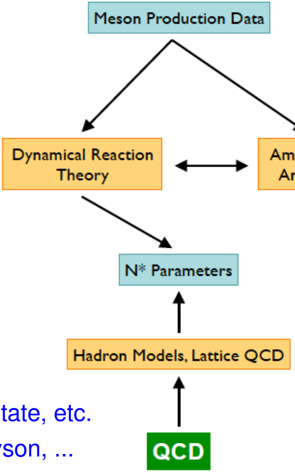
Atomic Spectrum of Hydrogen



Baryons are broad and overlapping ...

Extraction of Resonance Parameters in N^* Physics

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



Maid
Said
BnGa

Coupled Channels

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

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

✓ published

✓ acquired or under analysis

Tensor polarization, SDMEs

* published

Complete Experiments?

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

Voltaire

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

✓ published
✓ acquired or under analysis

Tensor polarization, SDMEs

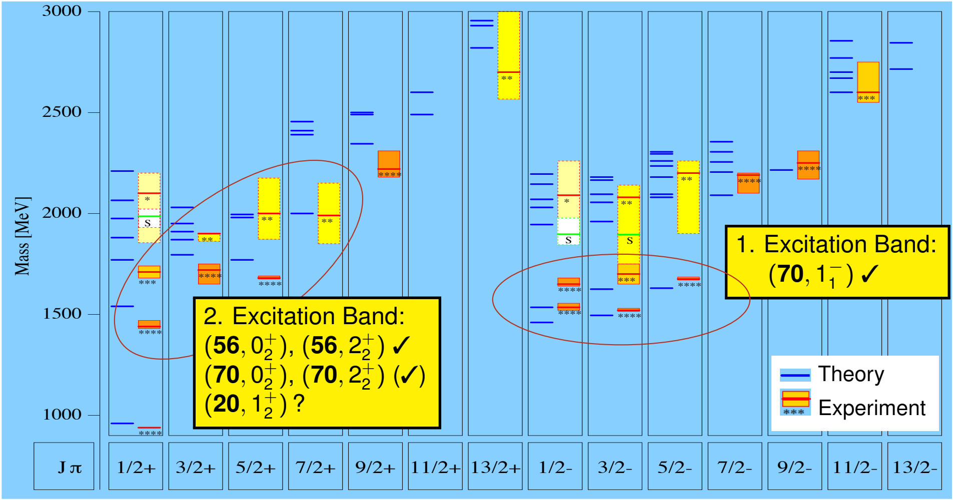
* published

In addition, two-meson reactions are being analyzed:

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

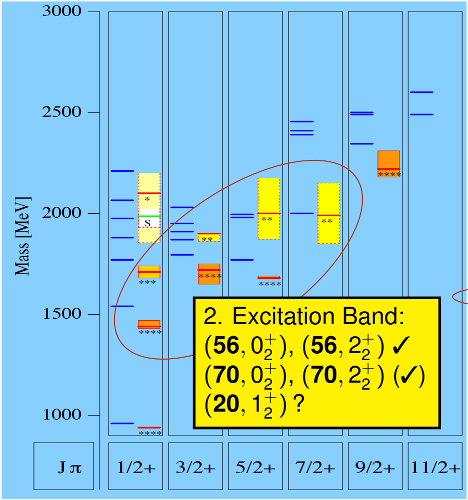
Outline

Spectrum of N^* Resonances



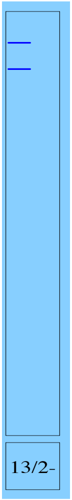
V. C. & W. Roberts, Rep. Prog. Phys. **76** (2013)

Spectrum of N^* Resonances



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

N^*	J^P $(L_{2I,2J})$	2010	2016
$N(1440)$	$1/2^+$ (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}	∗∗	



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

Decays observed in BnGa PWA into, e. g.

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

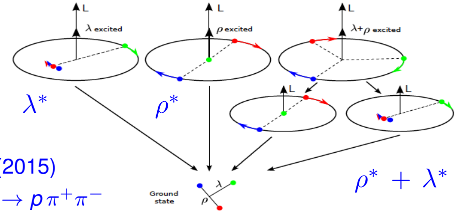
➜ Quartet of $(\mathbf{70}, 2_2^+)$ with $S = \frac{3}{2}$.

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

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

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

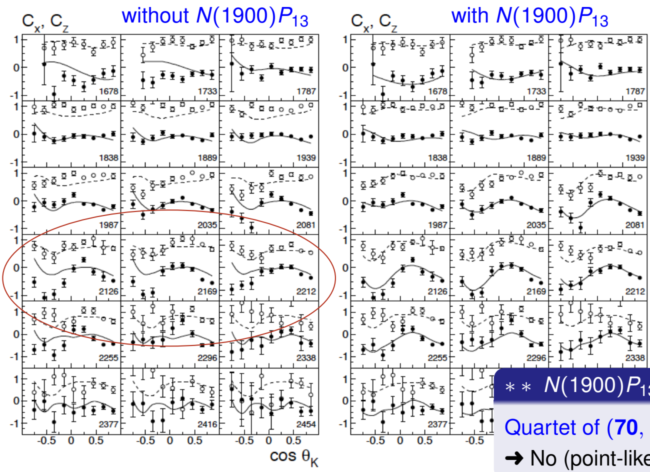


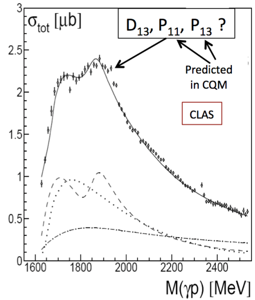
Sokhoyan, Gutz, V. C. *et al.*, EPJ A **51**, no. 8, 95 (2015)

➜ 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 $(\mathbf{70}, 2^+_2)$ with $S = \frac{3}{2}$

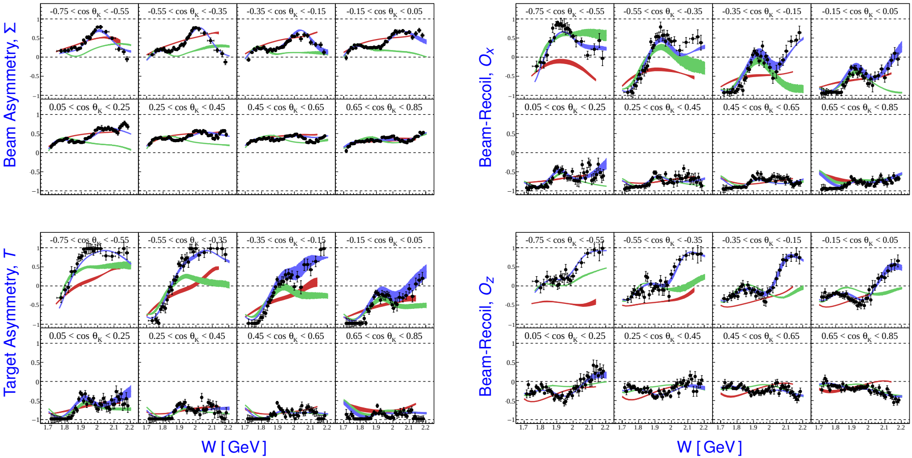
➜ No (point-like) quark-diquark oscillations!

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 in $\vec{\gamma} p \to K^+ \vec{\Lambda}$: O_x & O_z + T & Σ

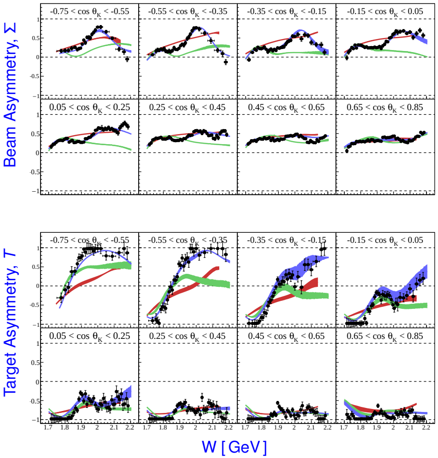
C. A. Paterson *et al.* [CLAS Collaboration], Phys. Rev. C **93**, 065201 (2016)



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

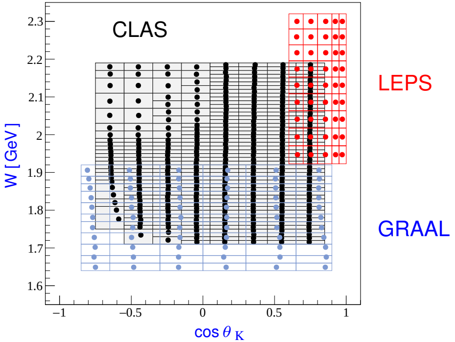
Polarization Observables in $\vec{\gamma} p \to K^+ \Lambda$

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



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

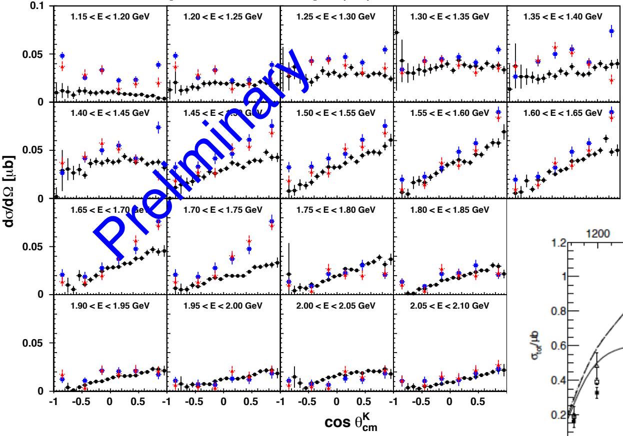
comparison of kinematic coverage



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

Cross Sections for $\gamma p \to K^0 \Sigma^+ \to p \pi^+ \pi^- \pi^0$

Z. Akbar *et al.* [CLAS Collaboration], in preparation.

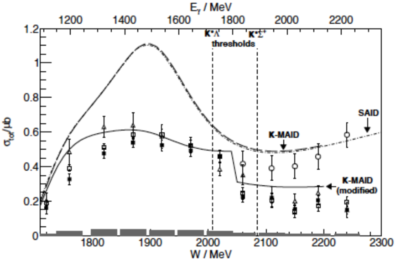


CLAS-g12 • CB-ELSA • CBELSA/TAPS •

New cross section results in 50-MeV-wide E_γ bins for

$1.15 < E_\gamma < 3.0$ GeV

Phys. Lett. B **713**, 180 (2012)



➜ In preparation for $K^0 \Sigma^+$: $E, \Sigma, T, C_x, C_z, O_x, O_z$

(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:

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

published (+ SDME's) $$- \Lambda_y(-T + \delta_l P \cos 2\phi)$$

in progress $$- \Lambda_z(-\delta_l G \sin 2\phi + \delta_\odot E)\}$$

$\phi = \Psi \equiv$ 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))

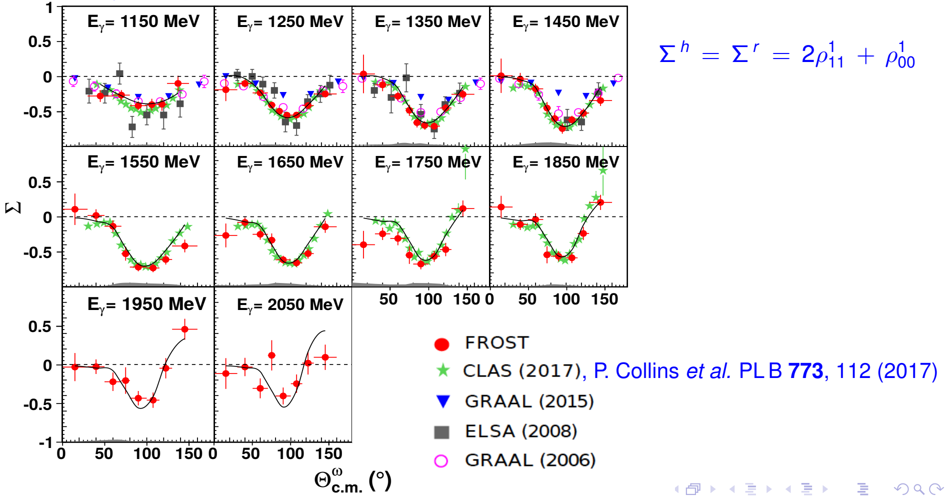
$$2\pi\, W^f(\Phi,\Psi) = 1 - \Sigma^f_\Phi \cos 2\Phi - P_\gamma \Sigma^f_b \cos 2\Psi + P_\gamma \Sigma^f_d \cos 2(\Phi - \Psi)$$

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

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

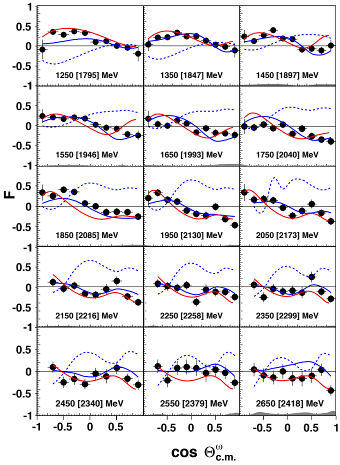
The Beam Asymmetry in $\vec{\gamma}\, p \to p\, \omega$ (CLAS-g9b)

P. Roy *et al.* [CLAS Collaboration], PR C **97**, 055202 (2018)



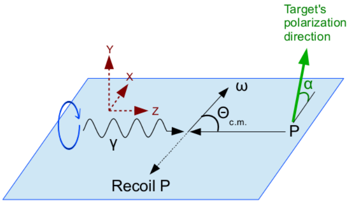
$$\Sigma^h = \Sigma^r = 2\rho^1_{11} + \rho^1_{00}$$

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



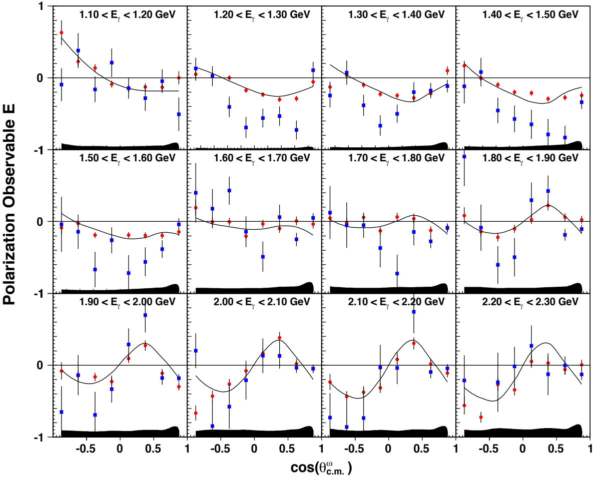
Polarized Cross Section

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



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

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



BnGa (coupled-channels) PWA

- Dominant $\mathbb{P}$ 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)

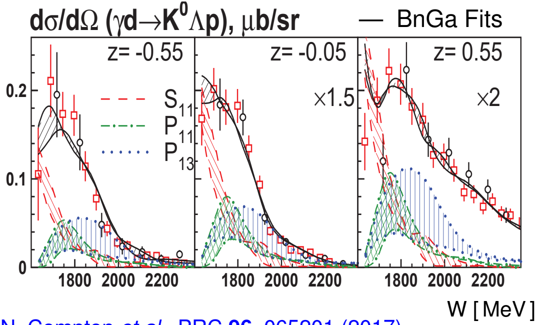
Z. Akbar *et al.* [CLAS Collaboration], PR C **96**, 065209 (2017)

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

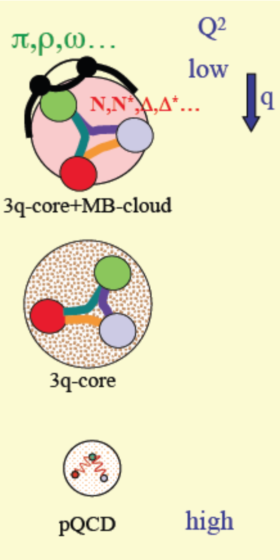
Decay modes of nucleon resonances
black: PDG 2004
red: PDG 2018
blue: BESIII resonances

****	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	$N\rho$	$N\omega$	$N\eta\prime$	$N_{1440}\pi$	$N_{1520}\pi$	$N_{1535}\pi$	$N_{1680}\pi$
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



The N^* program has two main components:

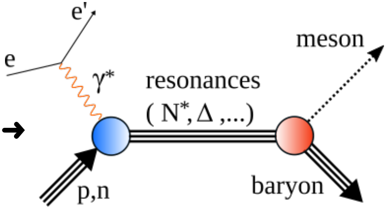
- Establish the systematics of the spectrum

  Provides information on the nature of the effective degrees of freedom in strong QCD.

- Probe resonance transitions at different distance scales (Q^2 dependence)

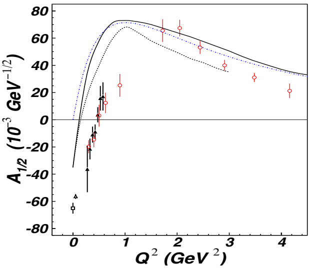
  Reveals the structure of N^* states.

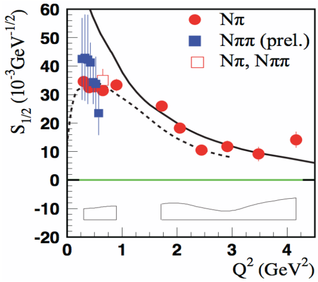
$A_{\frac{1}{2}}, A_{\frac{3}{2}}, S_{\frac{1}{2}}$ ➜



➜ D. Carman, Monday, Rangos 2

Helicity Amplitudes for the “Roper” Resonance





Data from CLAS

$A_{1/2}$ and $S_{1/2}$ amplitudes:

e.g. V. Mokeev *et al.*,

PRC **86**, 035203 (2012);

PRC **80**, 045212 (2009).

Quark-model calculations:

— - - q^3 radial excitation

— q^3G hybrid state

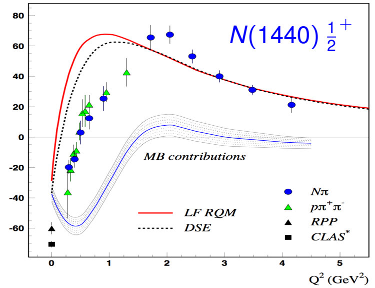
Consistency between both channels ($N\pi\pi$, $N\pi$): sign change, magnitude, ...

- At short distances (high Q^2), Roper behaves like radial excitation.
- Low-Q^2 behavior not well described by LF quark models
  ➜ ANL - Osaka achieves good description by adding meson-baryon interactions.
  DSE prediction: Mass of the quark core of the first radial excitation = 1.73 GeV.

➜ Gluonic excitation likely ruled out!

First Nucleon Excitations: Helicity Amplitude $A_{1/2}$

DSE: J. Segovia *et al.*, PR C **94** (2016) 042201

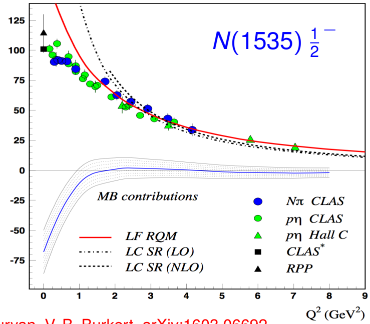


Non-quark contributions are significant at $Q^2 < 2.0$ GeV^2

➜ The 1st radial excitation of the q^3 core emerges as the probe penetrates the MB cloud.

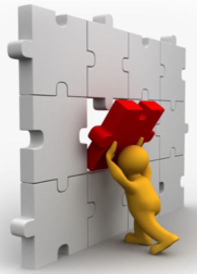
Non-quark contributions are significant at $Q^2 < 1.5$ GeV^2

➜ State consistent with the 1st orbital excitation of the nucleon.



— I. Aznauryan, V. B. Burkert, arXiv:1603.06692

Outline



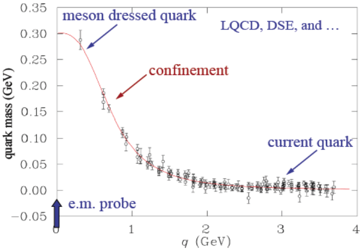
Open Issues in (Light) Baryon Spectroscopy

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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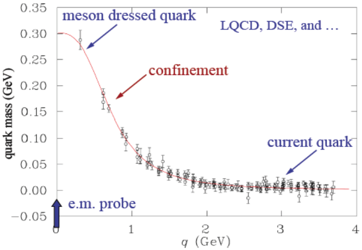

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Outlook

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

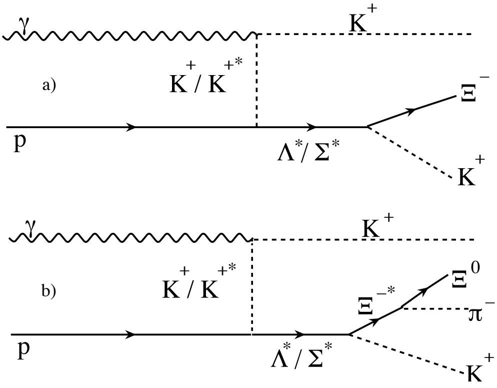
New era in the spectroscopy of strange baryons (GlueX, LHCb, PANDA, ...)

- 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



➜ Ashley Ernst, Friday, Rangos 2

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

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

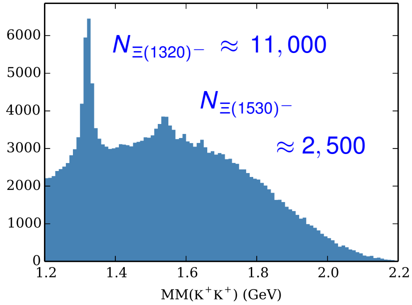
At other facilities (for comparison):

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

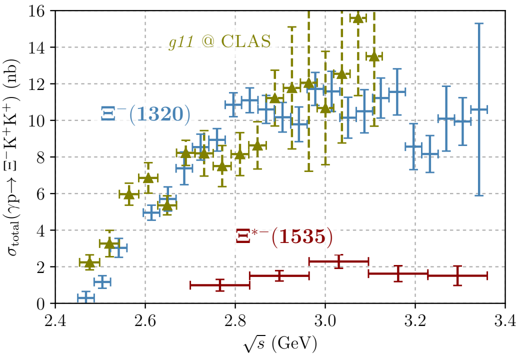
* W. Roberts *et al.*, Phys. Rev. C **71**, 055201 (2005)

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

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



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



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

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

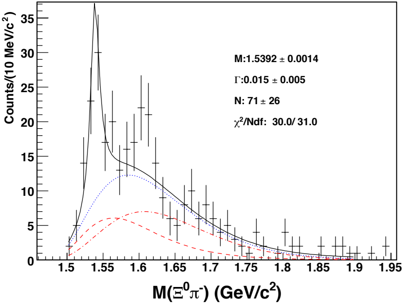
From the paper: *Although a small enhancement is observed in the $\Xi^0\pi^-$ invariant mass spectrum near the controversial 1-star $\Xi^-(1620)$ resonance, it is not possible to determine its exact nature without a full partial wave analysis.*
Phys. Rev. C **76**, 025208 (2007)

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

Plenary talks: Sean Dobbs, Monday
Annalisa D'Angelo, Thursday



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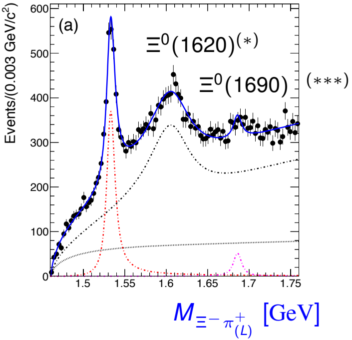
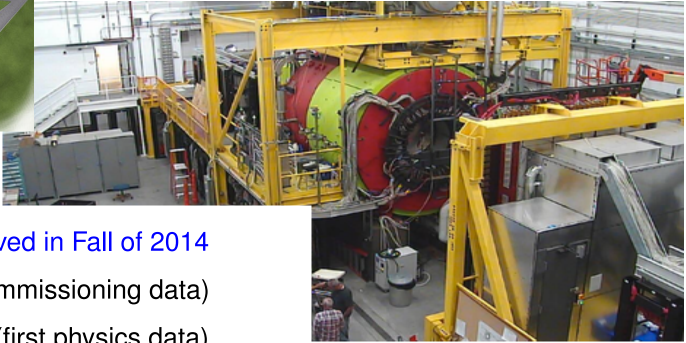
Belle: PRL **122**, 072501 (2019)



Jefferson Lab Upgrade to 12 GeV

Hall D



10.1 GeV achieved in Fall of 2014

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

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

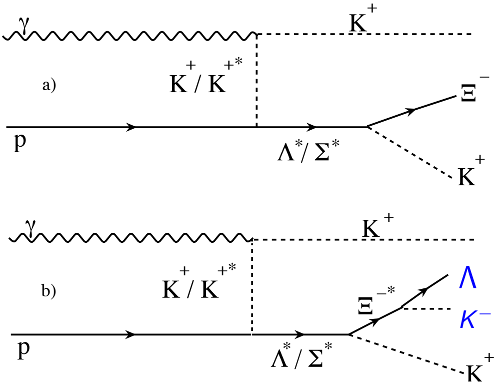
➜ Used for most physics analyses

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

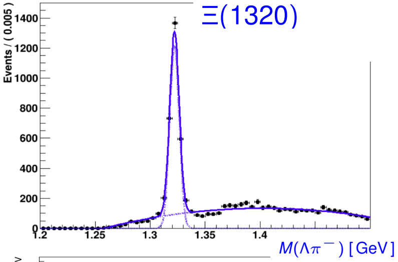
➜ GlueX Phase-I completed this Fall

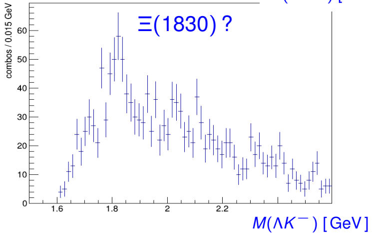
➜ Justin Stevens, Tuesday, Rangos 3

Possible Production Mechanisms



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





Courtesy of Ashley Ernst (FSU)

Acknowledgement

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