The Study of Excited Baryons: What is next?

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Future Directions in Spectroscopy Analysis

Jefferson Laboratory

11/20/2014

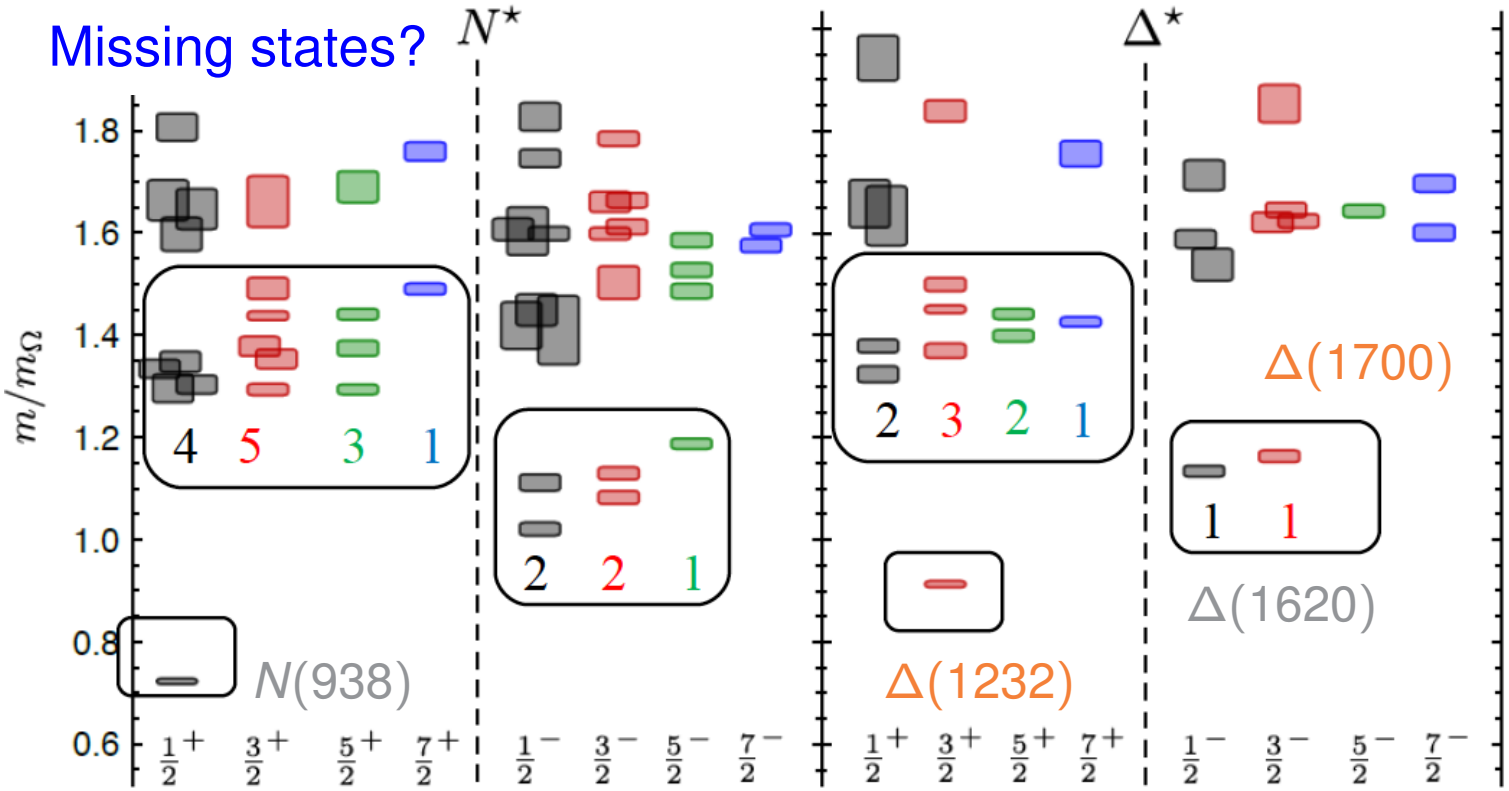
Outline

Outline

Baryon Spectroscopy from Lattice QCD

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

Missing states?

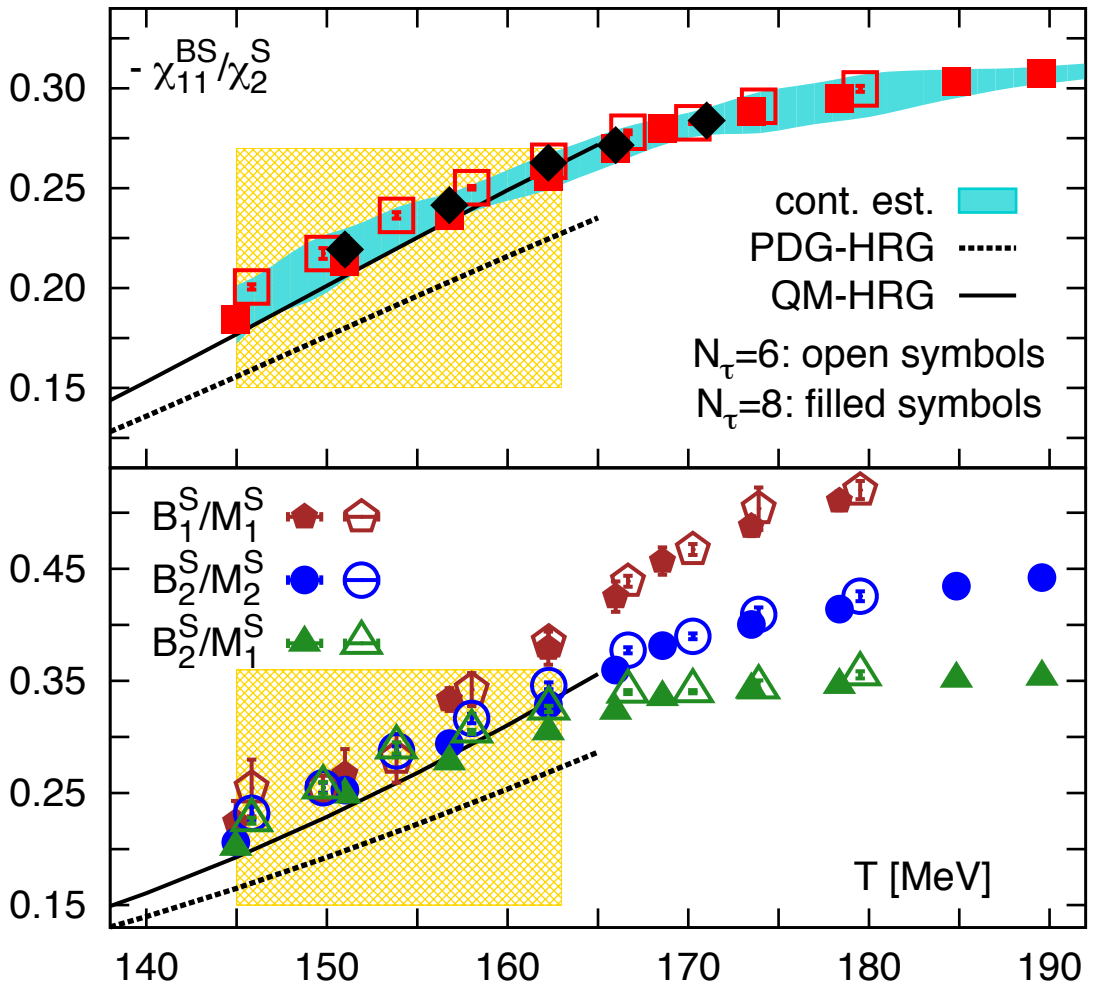


$m_\pi = 396$ MeV

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

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

Evidence for *Missing* Strange Baryons



Comparison with two hadron resonance gas models:

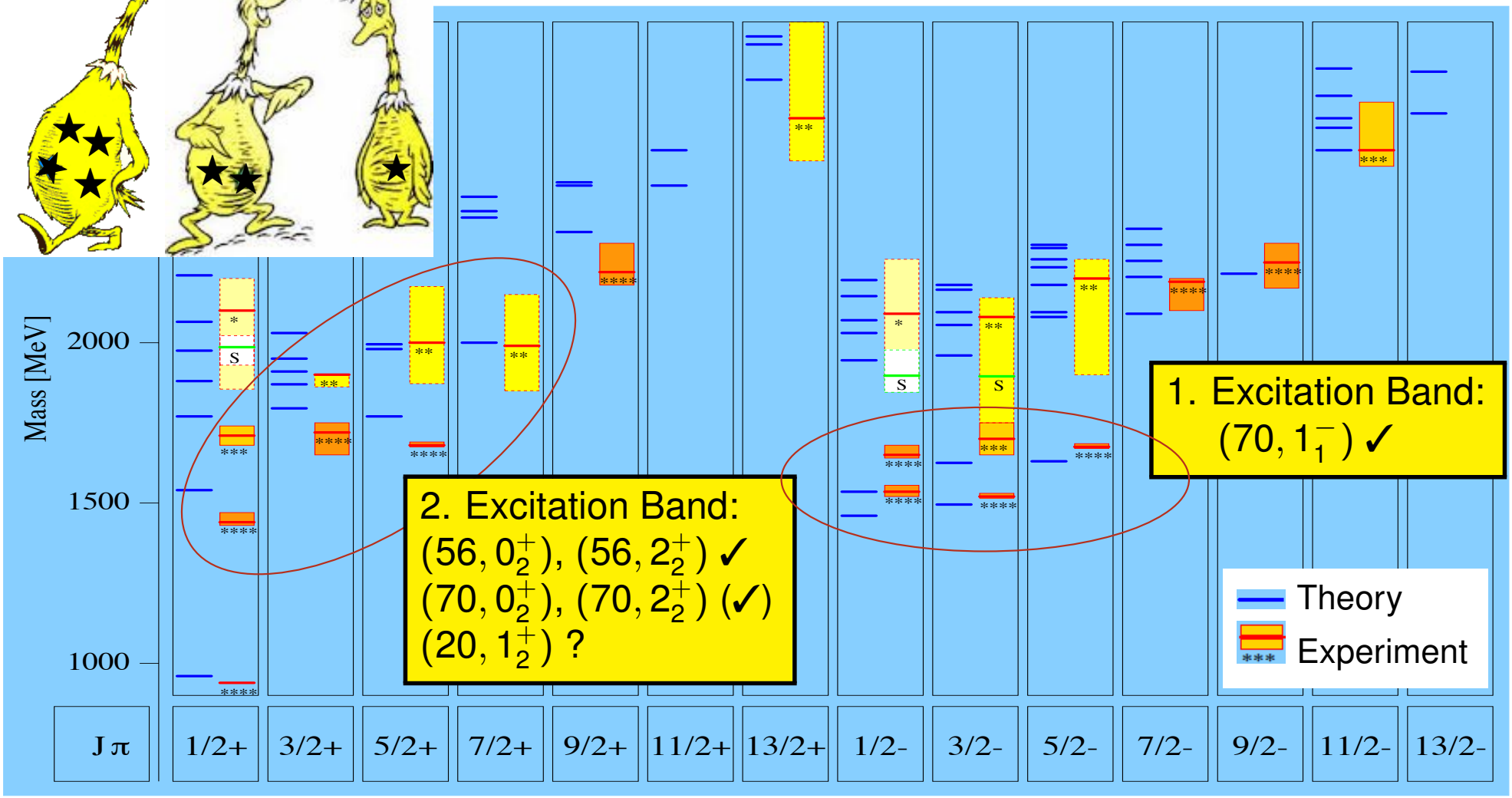
- PDG-HRG
- QM-HRG

"These results do provide evidence for the existence of additional strange baryons and their thermodynamic importance."

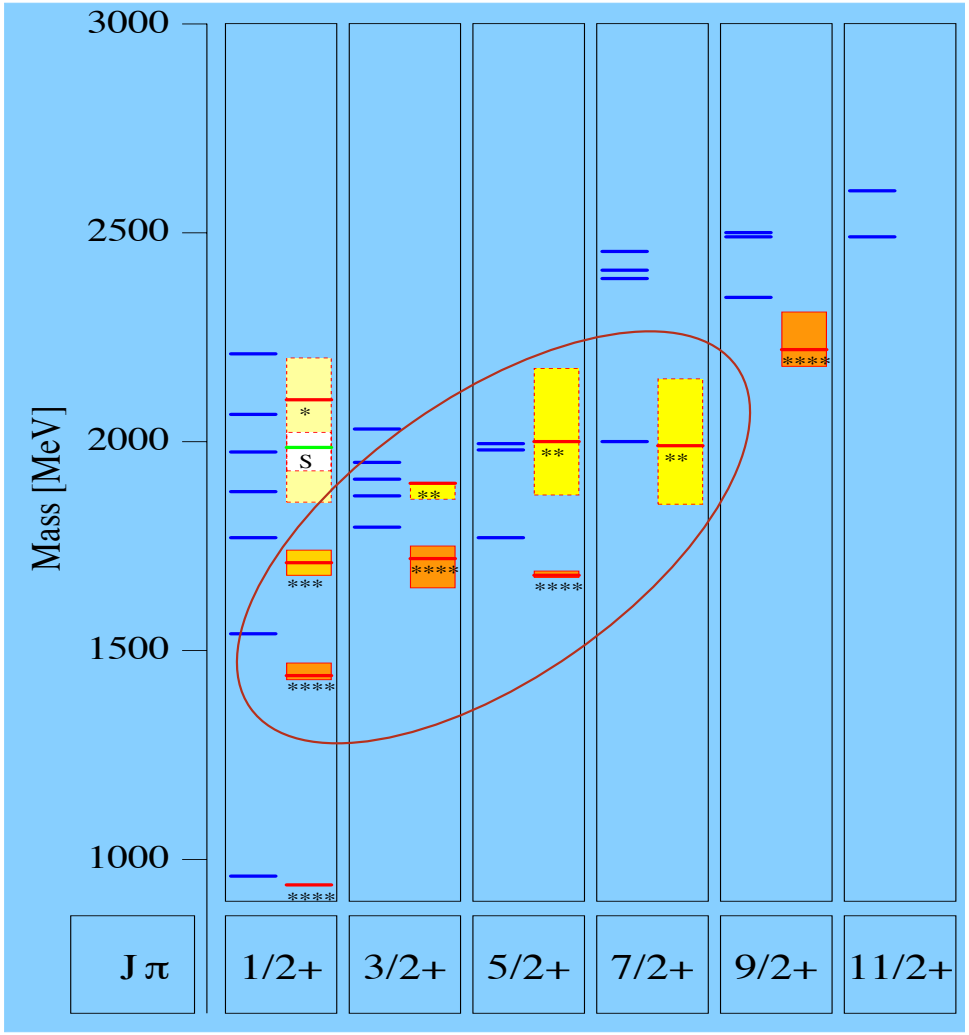
A. Bazavov *et al.*, Phys. Rev. Lett. **113**, 072001 (2014)

Spectrum of N^* Resonances (PDG < 2012)

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

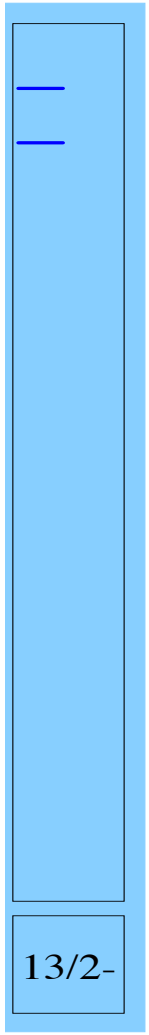


Spectrum of N^* Resonances

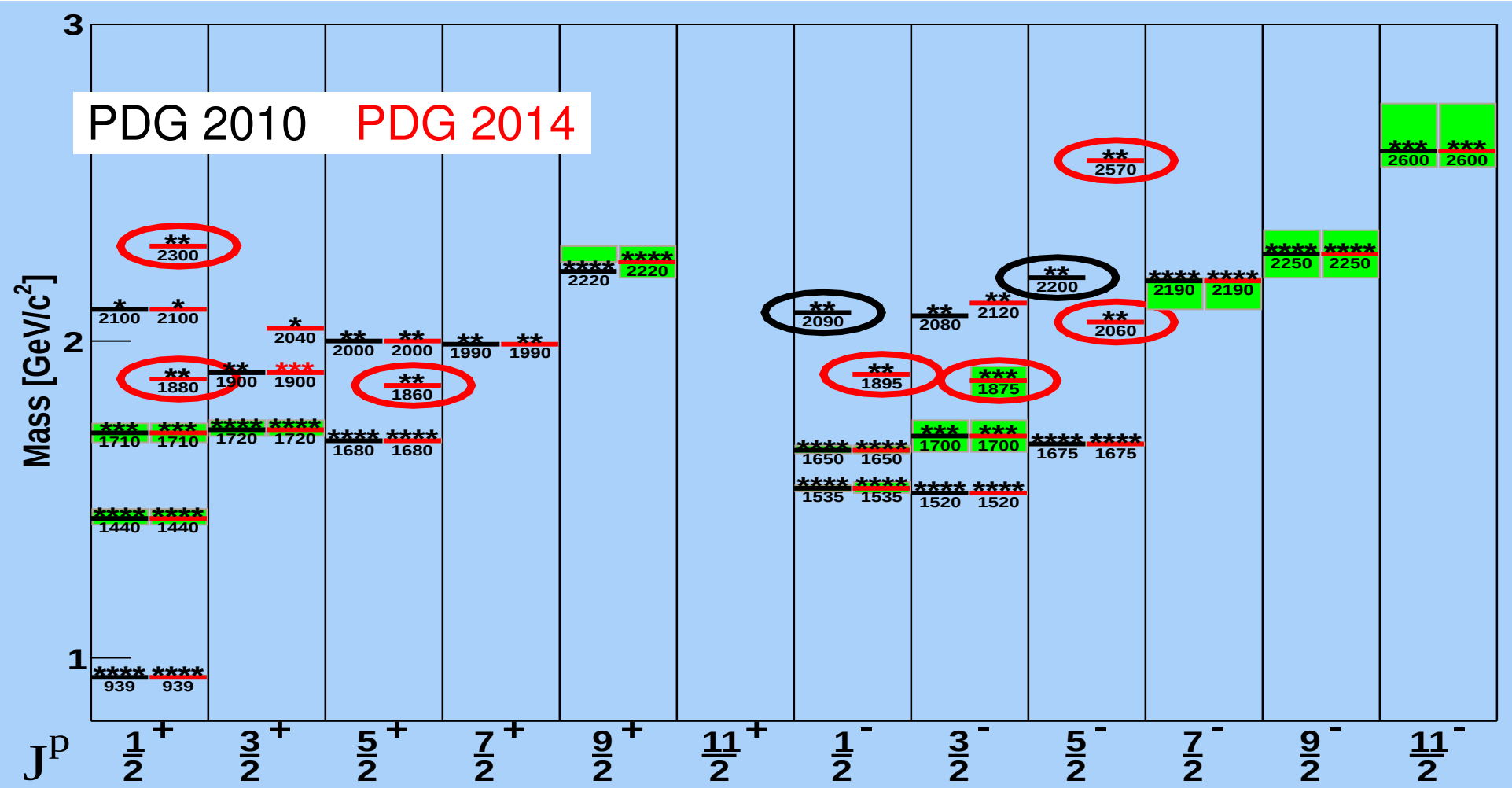


V. C. & W. Roberts, Rep. Prog. Phys. **76** (2013)

N^*	J^P $(L_{2I,2J})$	2010	2012
$N(1440)$	$1/2^+$ (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}	**	
$N(2220)$	$9/2^+$ (H_{19})	* * **	* * **



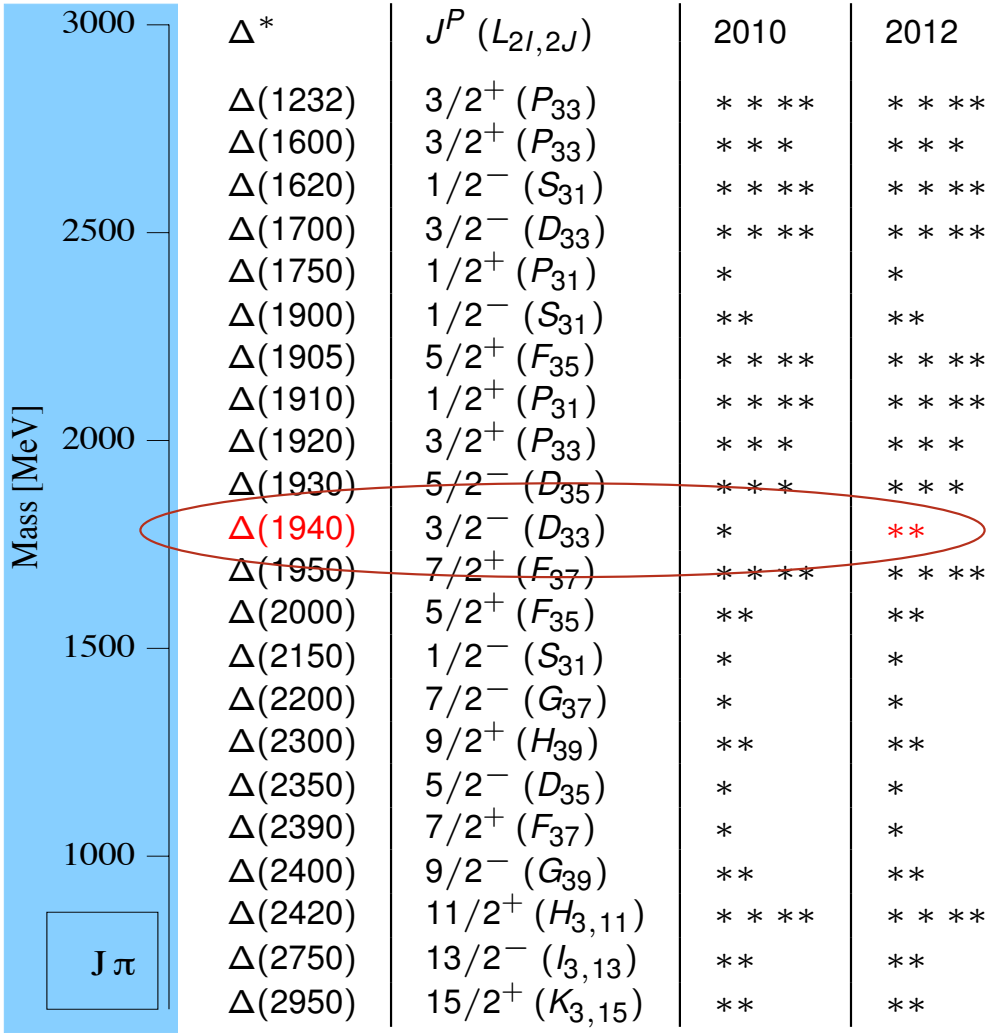
The Experimental N^* Spectrum: Recent Changes

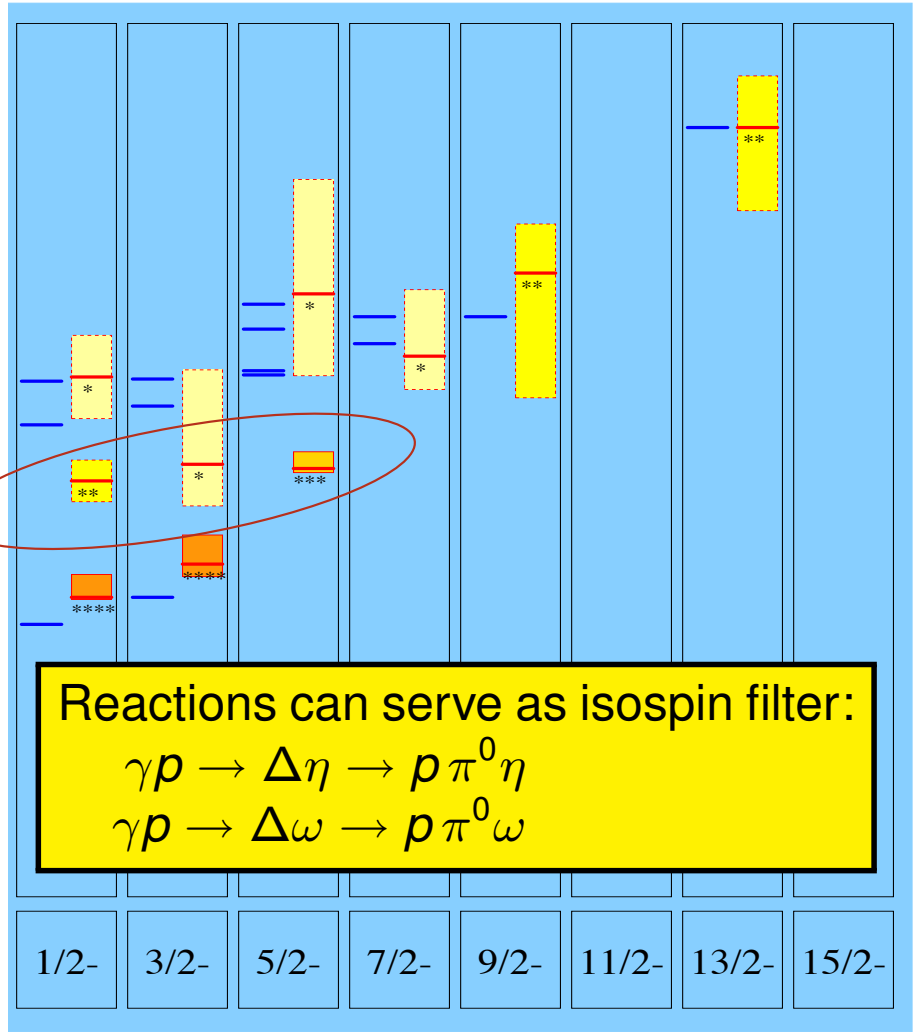


Courtesy of Andrew Wilson, FSU & U. of Bonn (HISKP)

Spectrum of Δ^* Resonances

Δ^*	J^P $(L_{2I,2J})$	2010	2012
$\Delta(1232)$	$3/2^+$ (P_{33})	* * **	* * **
$\Delta(1600)$	$3/2^+$ (P_{33})	* * *	* * *
$\Delta(1620)$	$1/2^-$ (S_{31})	* * **	* * **
$\Delta(1700)$	$3/2^-$ (D_{33})	* * **	* * **
$\Delta(1750)$	$1/2^+$ (P_{31})	*	*
$\Delta(1900)$	$1/2^-$ (S_{31})	**	**
$\Delta(1905)$	$5/2^+$ (F_{35})	* * **	* * **
$\Delta(1910)$	$1/2^+$ (P_{31})	* * **	* * **
$\Delta(1920)$	$3/2^+$ (P_{33})	* * *	* * *
$\Delta(1930)$	$5/2^-$ (D_{35})	* * *	* * *
$\Delta(1940)$	$3/2^-$ (D_{33})	*	**
$\Delta(1950)$	$7/2^+$ (F_{37})	* * **	* * **
$\Delta(2000)$	$5/2^+$ (F_{35})	**	**
$\Delta(2150)$	$1/2^-$ (S_{31})	*	*
$\Delta(2200)$	$7/2^-$ (G_{37})	*	*
$\Delta(2300)$	$9/2^+$ (H_{39})	**	**
$\Delta(2350)$	$5/2^-$ (D_{35})	*	*
$\Delta(2390)$	$7/2^+$ (F_{37})	*	*
$\Delta(2400)$	$9/2^-$ (G_{39})	**	**
$\Delta(2420)$	$11/2^+$ $(H_{3,11})$	* * **	* * **
$\Delta(2750)$	$13/2^-$ $(I_{3,13})$	**	**
$\Delta(2950)$	$15/2^+$ $(K_{3,15})$	**	**





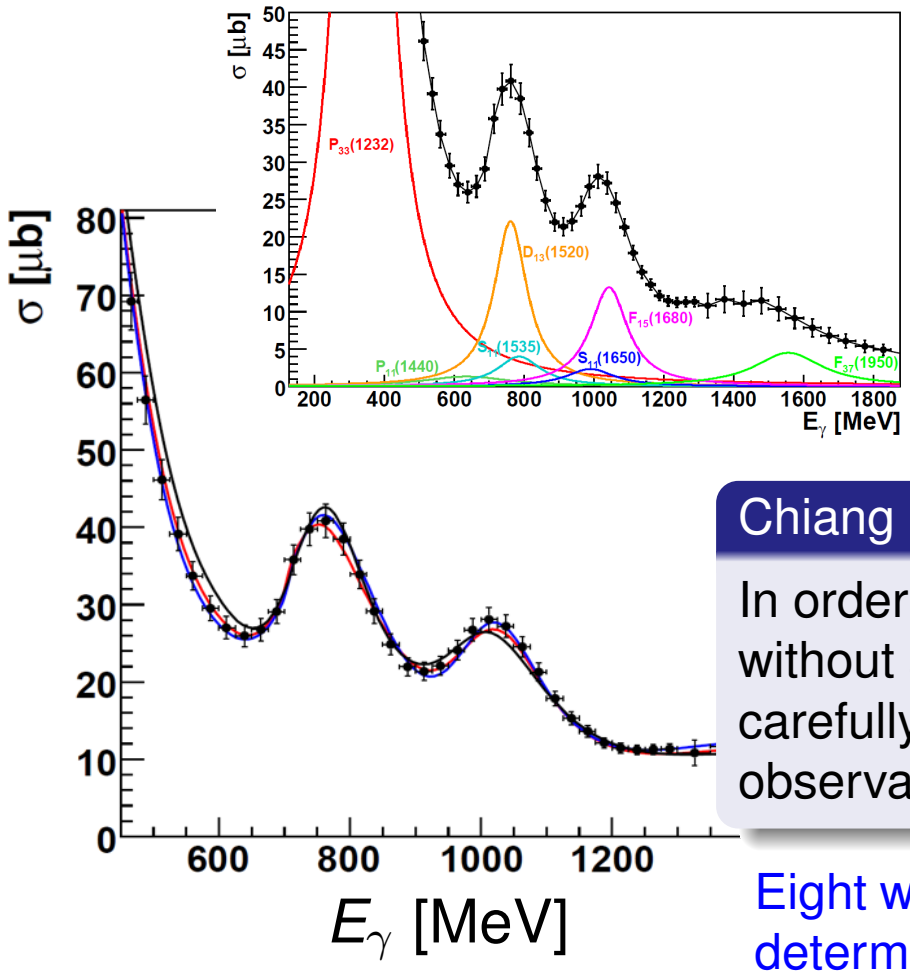
Reactions can serve as isospin filter:

$\gamma p \to \Delta\eta \to p\pi^0\eta$

$\gamma p \to \Delta\omega \to p\pi^0\omega$

Outline

Observables in Single-Meson Photoproduction



$\gamma p \to p\pi^0$

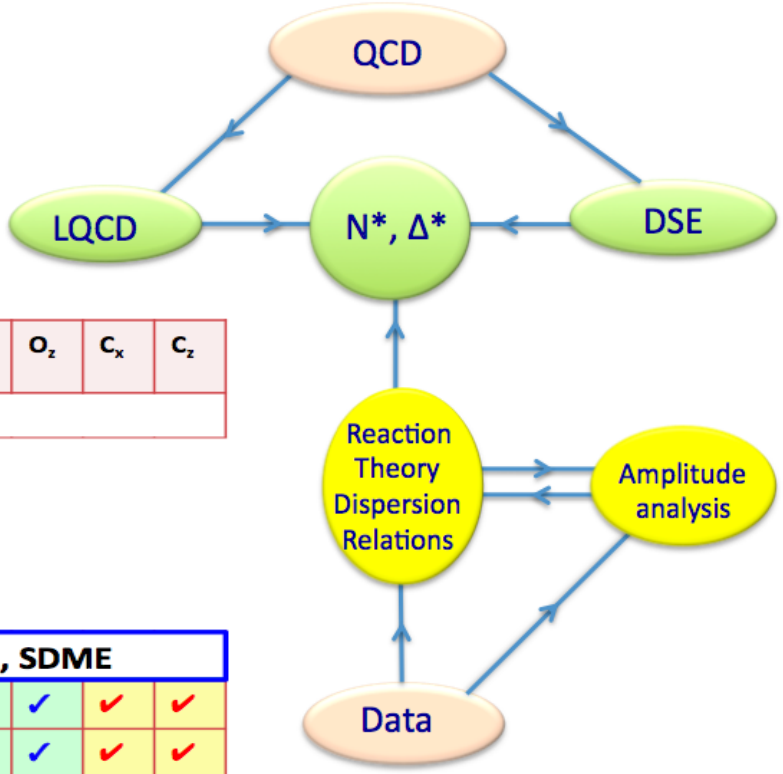
For single-meson production:

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

Chiang & Tabakin, Phys. Rev. C55, 2054 (1997)

In order to determine the full scattering amplitude without ambiguities, one has to carry out eight carefully selected measurements: <u>four</u> double-spin observables along with <u>four</u> single-spin observables.

Eight well-chosen measurements are needed to fully determine production amplitudes F_1, F_2, F_3, and F_4.



Observables	σ	Σ	T	P	E	F	G	H	T_x	T_z	L_x	L_z	O_x	O_z	C_x	C_z
✔ published	✔ acquired or under analysis															
$p\pi^0$	✔	✔	✓	(✓)	✓	✓	✓	✓								
$n\pi^+$	✔	✔	✓	(✓)	✓	✓	✓	✓								
$p\eta$	✔	✓	✓	(✓)	✓	✓	✓	✓								
$p\eta'$	✔	✓	✓	(✓)	✓	✓	✓	✓								
$p\omega/\phi$	✔	✓	✓	(✓)	✓	✓	✓	✓								
$K^+\Lambda$	✔	✓	✓	✔	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔
$K^+\Sigma^0$	✔	✓	✓	✔	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔
$K^{0*}\Sigma^+$	✔	✓									✓	✓				
$p\pi^-$	✔	✓		(✓)	✓	✓	✓									
$p\rho^-$	✓	✓		(✓)	✓	✓	✓									
$K^-\Sigma^+$	✓	✓		(✓)	✓	✓	✓									
$K^0\Lambda$	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
$K^0\Sigma^0$	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
$K^{0*}\Sigma^0$	✓	✓									✓	✓				

Proton targets

Tensor polarization, SDME

Neutron targets

Need more observables on:

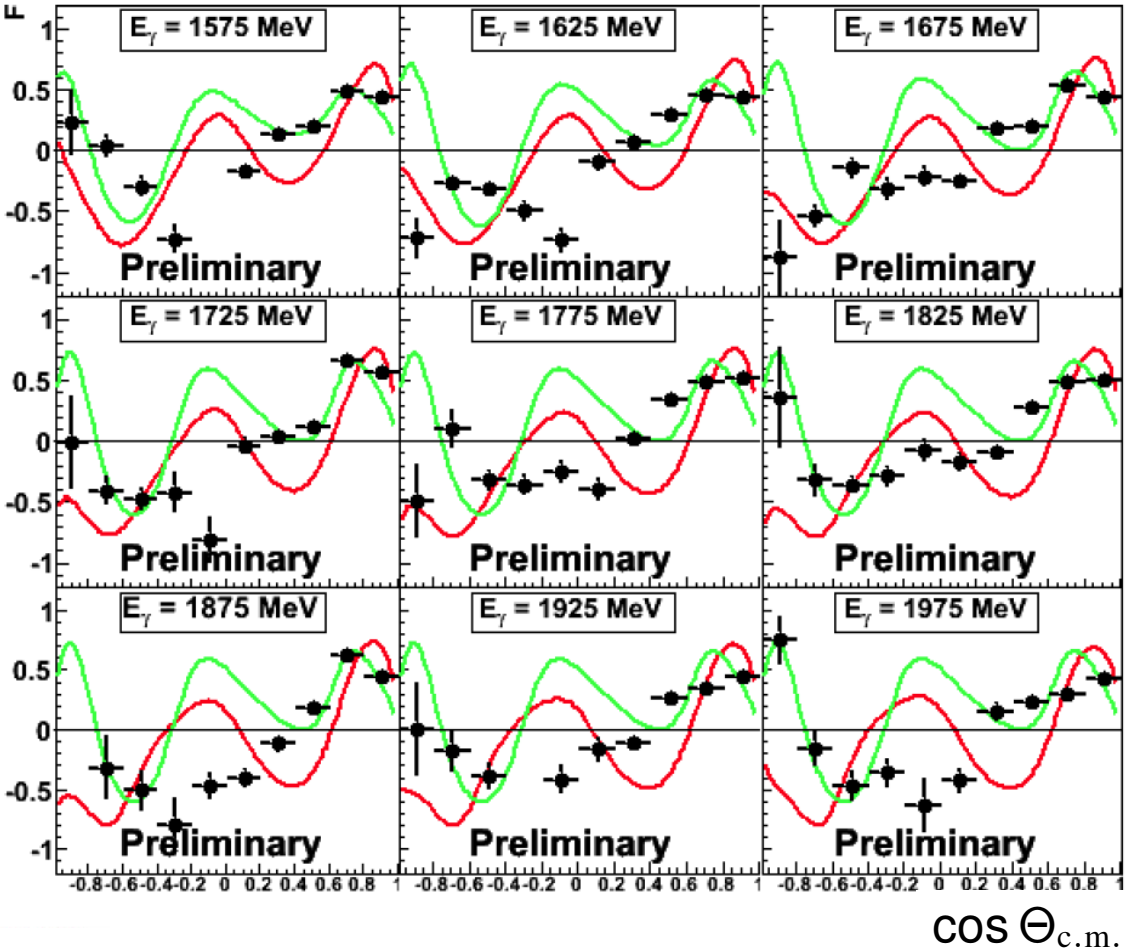
$$\gamma p \to p\pi\pi,\ p\pi\eta$$

$$\gamma p \to p\pi\omega,\ \ldots$$

Table representing CLAS@JLab measurements.

Observable F in $\vec{\gamma}\,\vec{p} \to n\,\pi^+$ (CLAS FROST-g9b)

– MAID 07 – SAID 12 BoGa not shown



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

Transv. target pol. & circ. beam pol.

- Early-stage analysis
- Reasonable agreement among predictions for $W < 1.7$ GeV

➜ Much to learn at the higher energies

M. Dugger (ASU), CLAS g9b run group

Complete Experiment in $\gamma\, p \to p\,\omega$

$\gamma p \to p\,\omega \to p\,\pi^+\pi^-\pi^0_{\rm miss}$ ➜ same final state as $\gamma p \to p\,\pi^+\pi^-$

Analysis in basically three steps:

- Kinematics & Event Selection ($p\,\pi^+\pi^-$)

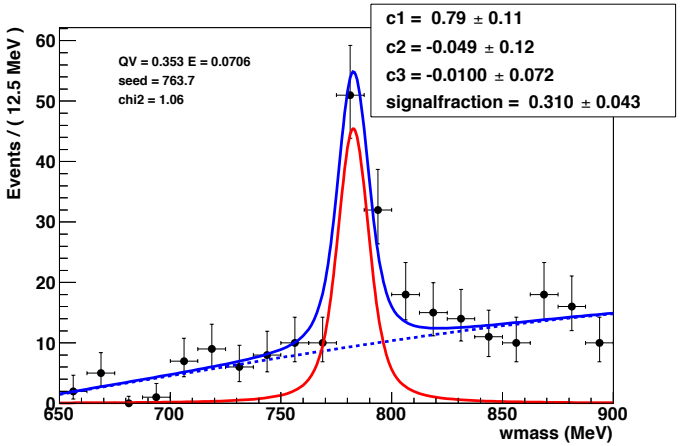
	lin. pol.	circ. pol.
g9a	USC (✓)	FSU ✓, CU (✓)
g9b	FSU ✓	USC (✓)

- Event-based background subtraction
  ➜ $p\,\pi^+(\pi^-)$, $p\,(\pi^+)\pi^-$, $p\,\pi^+\pi^-$ ✓
  $p\,\pi^+\pi^-(\pi^0)$ ✓ $p\,\pi^+\pi^-(\eta)$?

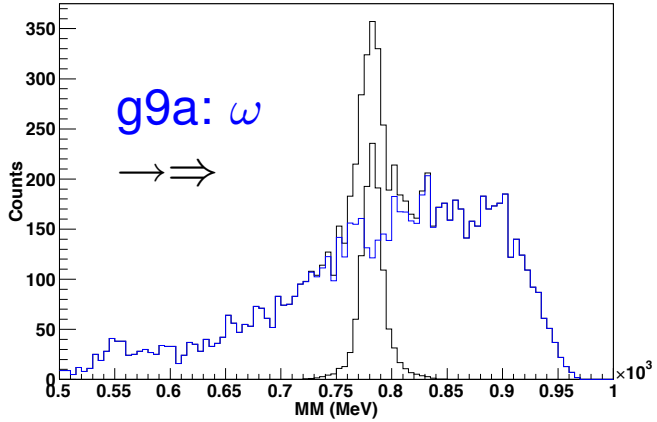
- Physics: $$\frac{d\sigma}{d\Omega} = \sigma_0 \{ 1 - \delta_l \Sigma \cos 2\phi + \Lambda_x (-\delta_l H \sin 2\phi + \delta_\odot F) - \Lambda_y (-T + \delta_l P \cos 2\phi) - \Lambda_z (-\delta_l G \sin 2\phi + \delta_\odot E) \}$$

published (+ SDME's)

in progress

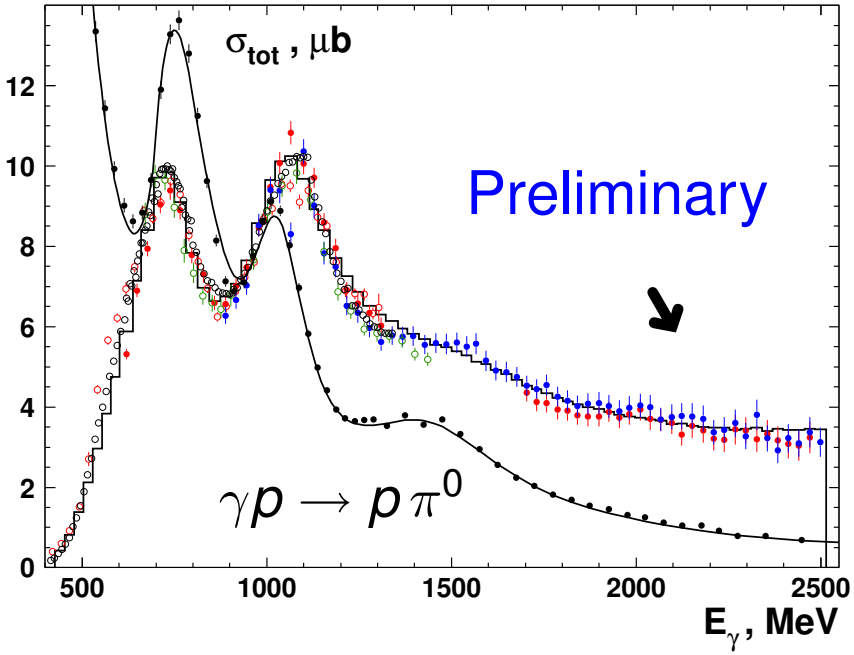


$E_\gamma \in [1.4, 1.5]$ GeV



Courtesy of Priyashree Roy (FSU)

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



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

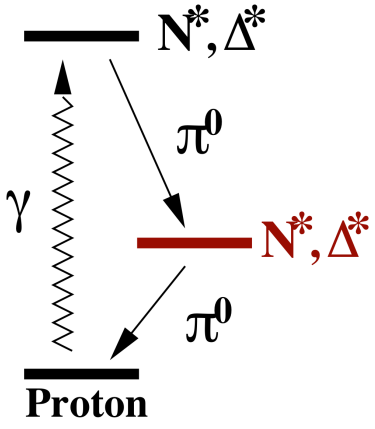
—— Bonn-Gatchina PWA

V. Sokhoyan, E. Gutz, V. C. *et al.* @ELSA

Cross Section and Polarization Observables

(W. Roberts *et al.*, PRC **71**, 055201 (2005))

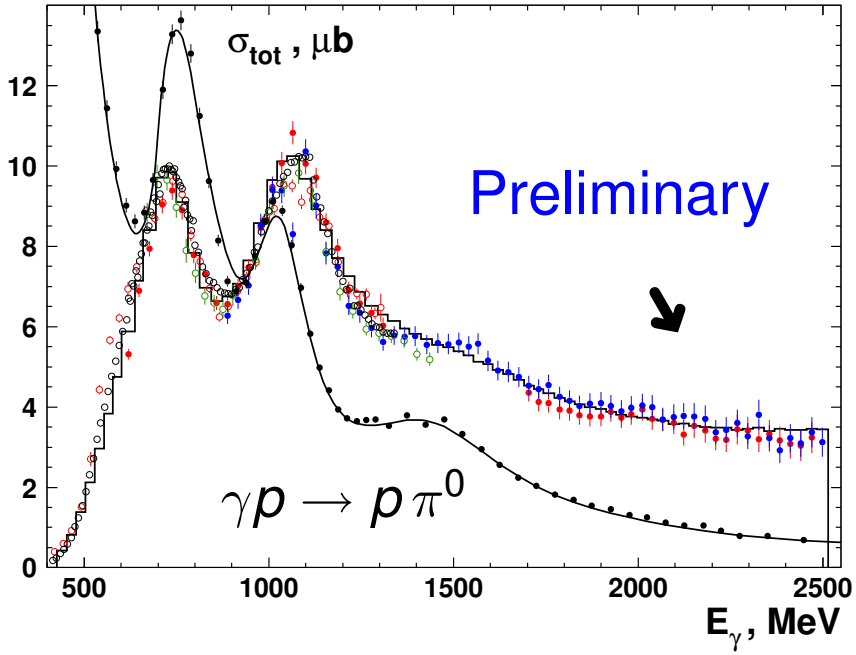
$$
\begin{aligned}
I = I_0 \{ & (1 + \vec{\Lambda}_i \cdot \vec{P}) \\
& + \delta_\odot (I^\odot + \vec{\Lambda}_i \cdot \vec{P}^\odot) \\
& + \delta_l [\sin 2\beta (I^s + \vec{\Lambda}_i \cdot \vec{P}^s) + \\
& \qquad \cos 2\beta (I^c + \vec{\Lambda}_i \cdot \vec{P}^c)] \}
\end{aligned}
$$

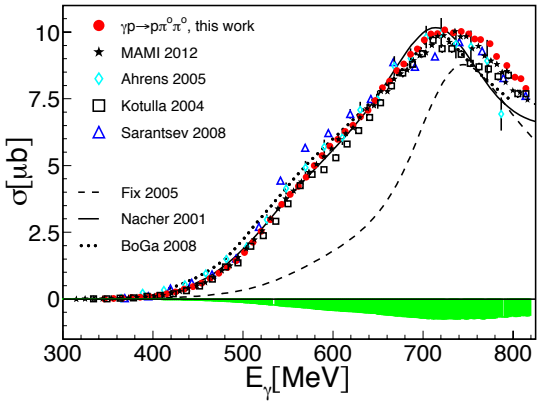


➜ Search for states in decay cascades!

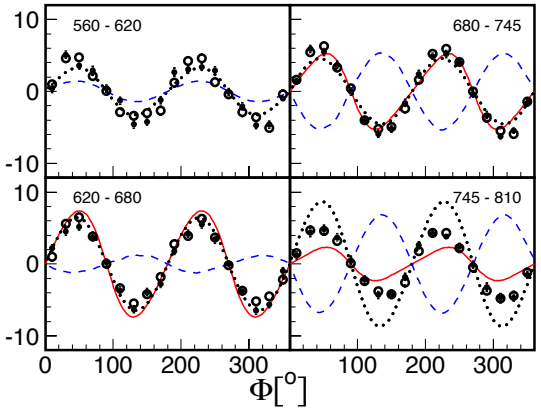
Observation of Decay Cascades in $\gamma\, p \to p\, \pi^0 \pi^0$

F. Zehr *et al.*, Eur. Phys. J. A **48**, 98 (2012) @MAMI





Cross Sections

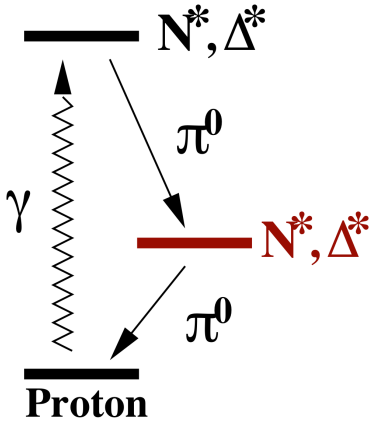


Beam Asymmetry, $I^{\odot}$

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

—— Bonn-Gatchina PWA

V. Sokhoyan, E. Gutz, V. C. *et al.* @ELSA



➜ Search for states in decay cascades!

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

Decays observed in PWA into, e. g.

$N(1880)\, 1/2^+$	$N(1520)\pi$
$N(1900)\, 3/2^+$	$N(1535)\pi$
$N(2000)\, 5/2^+$	$N(1680)\pi$
$N(1990)\, 7/2^+$	$N\sigma\ (I = 1)$

➜ 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.

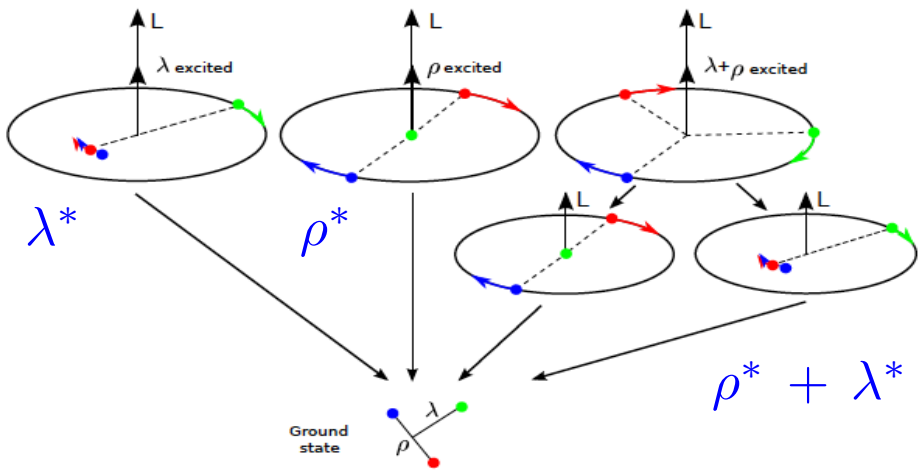
—— Bonn-Gatchina PWA

V. Sokhoyan, E. Gutz, V. C. *et al.* @ELSA

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

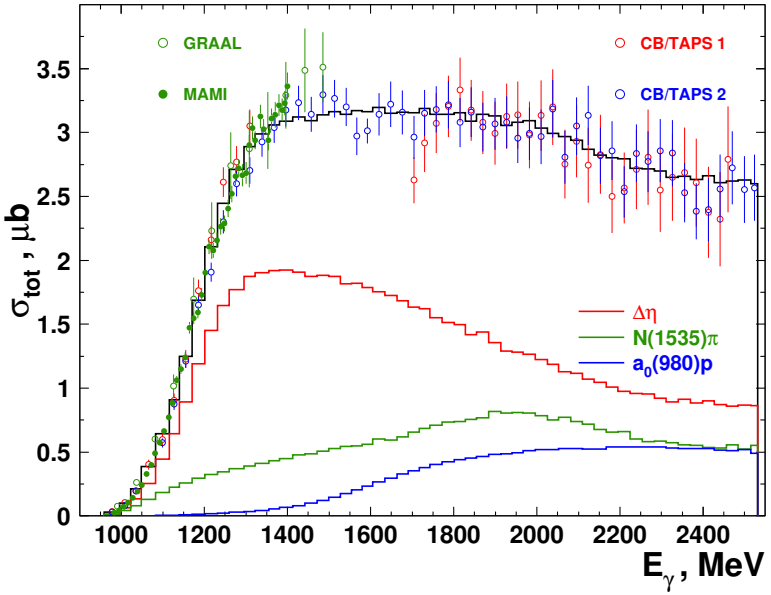
$$\mathcal{M}_{\mathcal{A}} = [\phi_{0p}(\vec{\rho}) \times \phi_{0p}(\vec{\lambda})]^{(L=2)},$$

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



High Statistics Study of the Reaction $\gamma p \to p\pi^0\eta$

E. Gutz, V. C. *et al.* [CBELSA/TAPS Collaboration], Eur. Phys. J. A **50**, 74 (2014)



Dominant Isobars

$\Delta(1232)\eta$, $N(1535)\,\frac{1}{2}^-\pi$, $pa_0(980)$

Observation of some

$\Delta^* \to N(1535)\,\frac{1}{2}^-\pi \to p\pi\eta$

Bonn-Gatchina

$\Delta(1700)\,\frac{3}{2}^-$

$\Delta(1600)\,\frac{3}{2}^+$

$\Delta(1920)\,\frac{3}{2}^+$

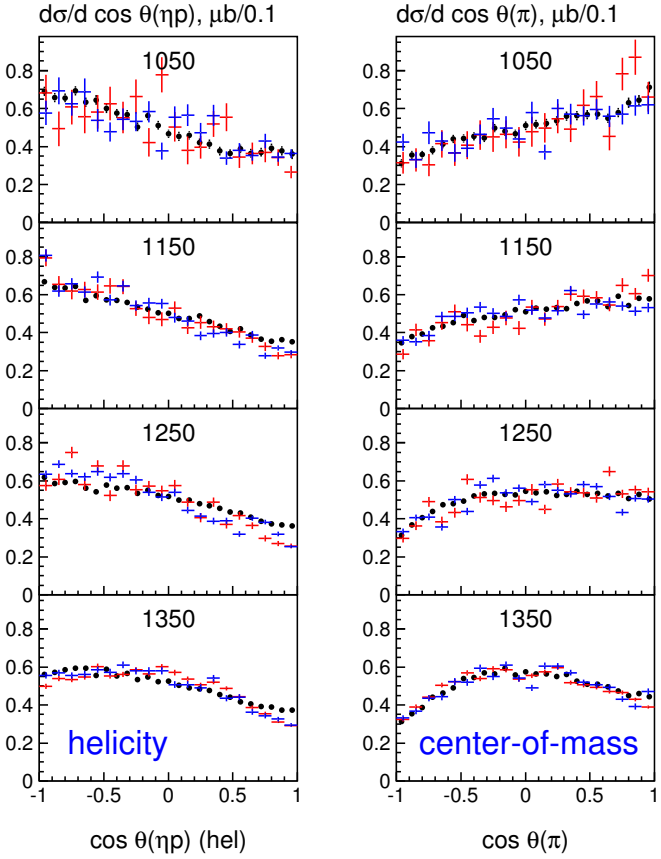
$\Delta(1940)\,\frac{3}{2}^-$

$\Delta(1905)\,\frac{5}{2}^+$

$\Delta(2360)\,\frac{3}{2}^-$

$N(1880)\,\frac{1}{2}^+$

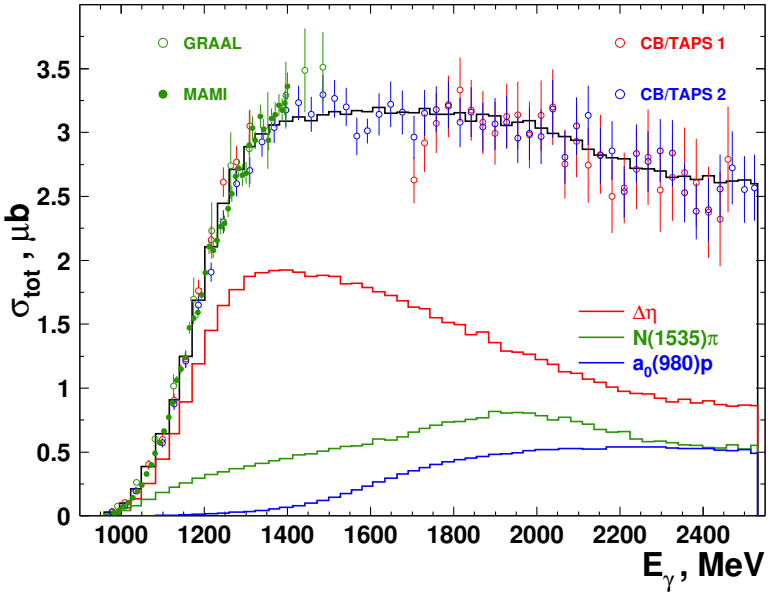
$N(2200)\,\frac{3}{2}^+$

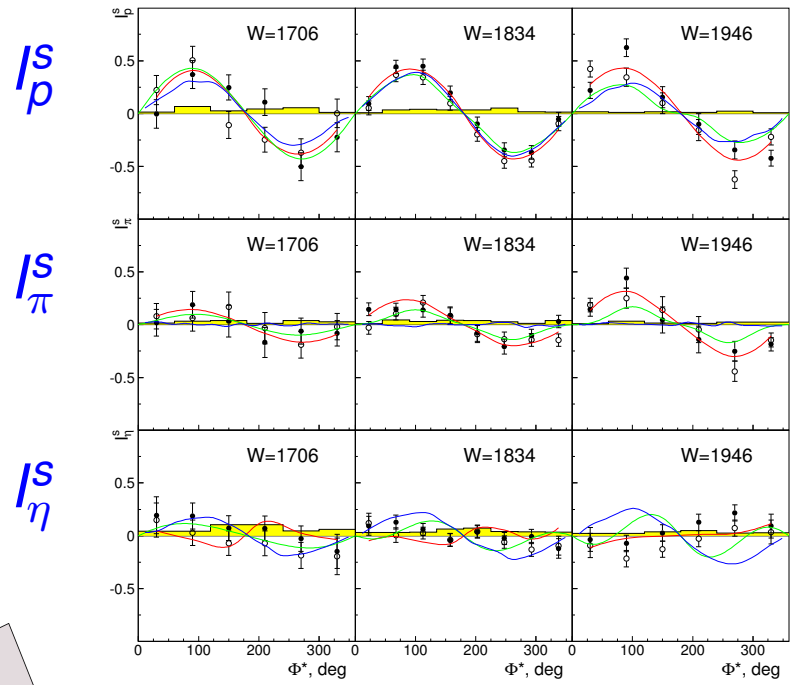


V. L. Kashevarov *et al.*, EPJ A **42**, 141 (2009) @MAMI

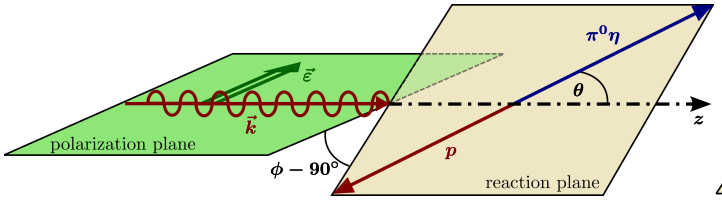
High Statistics Study of the Reaction $\vec{\gamma}p \to p\pi^0\eta$

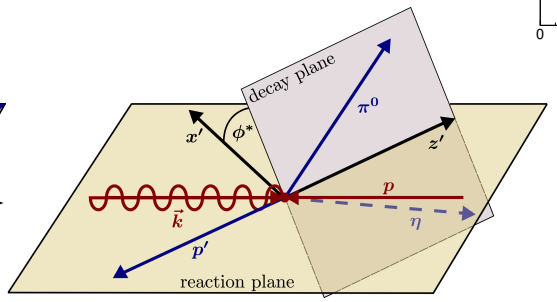
E. Gutz, V. C. *et al.* [CBELSA/TAPS Collaboration], Eur. Phys. J. A **50**, 74 (2014)





Linear Beam Polarization

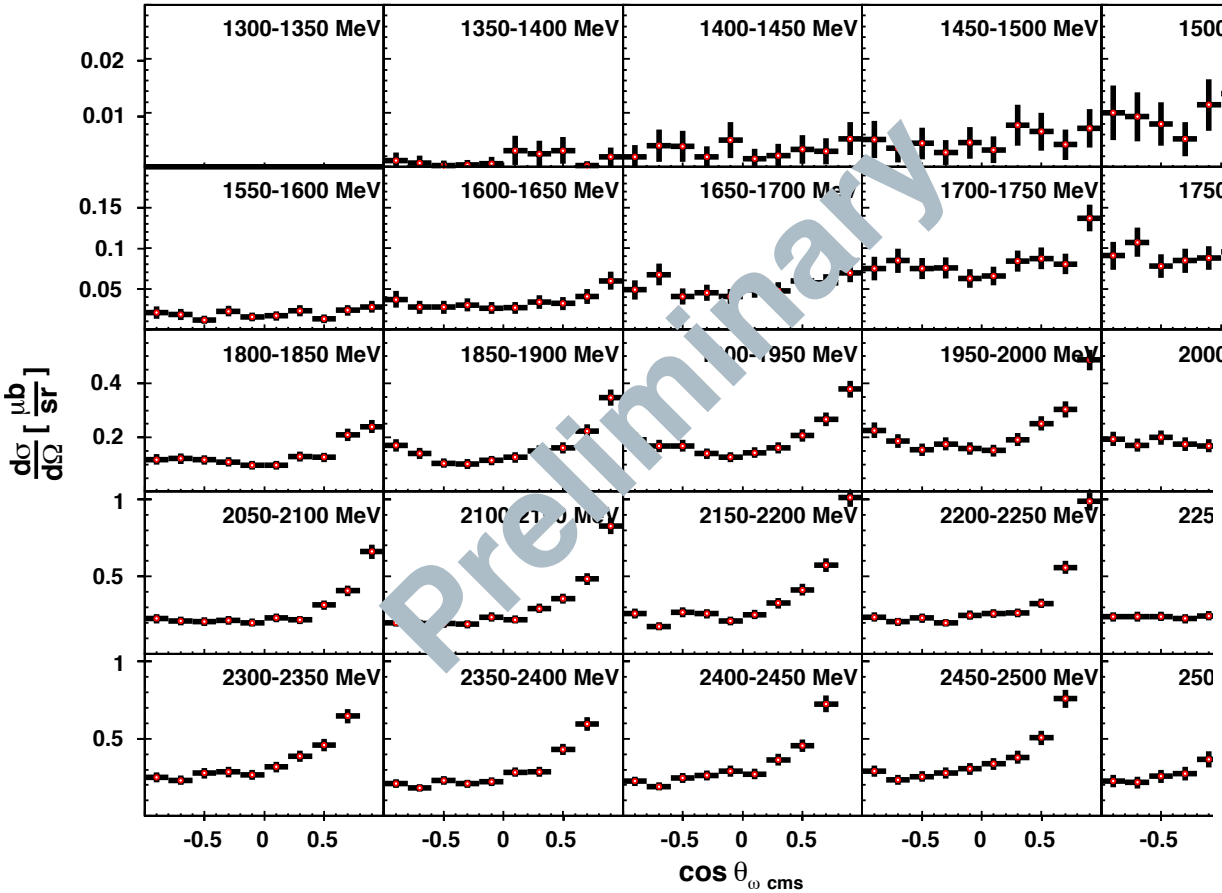


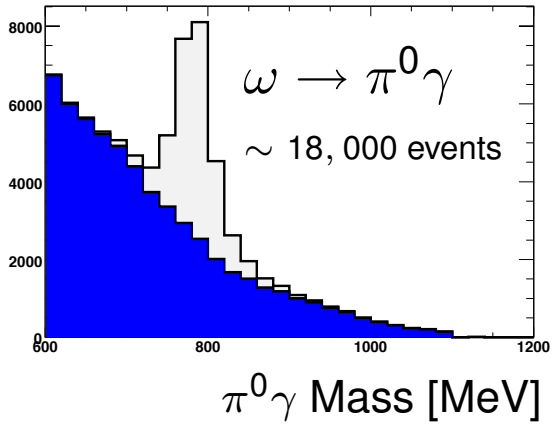


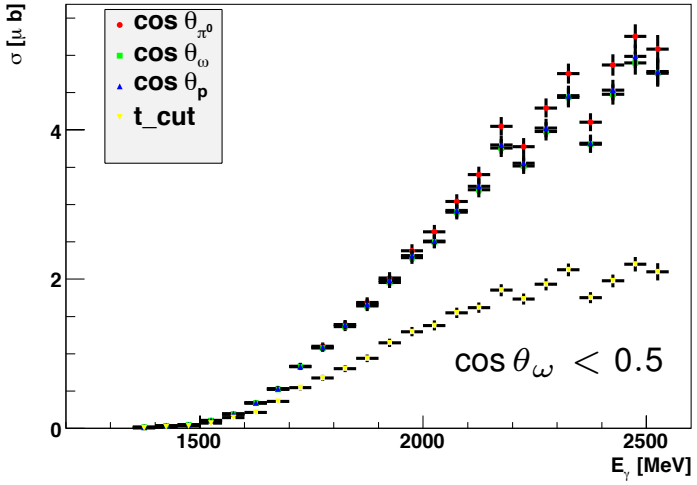
Bonn-Gatchina
A. Fix *et al.*
M. Döring *et al.*

Isospin Filter: $\gamma p \to \Delta^* \ (I = 3/2) \ \to \Delta\,\omega \to p\,\pi^0\omega$

Preliminary Differential Cross Sections for $\gamma p \to p\,\pi^0\omega$

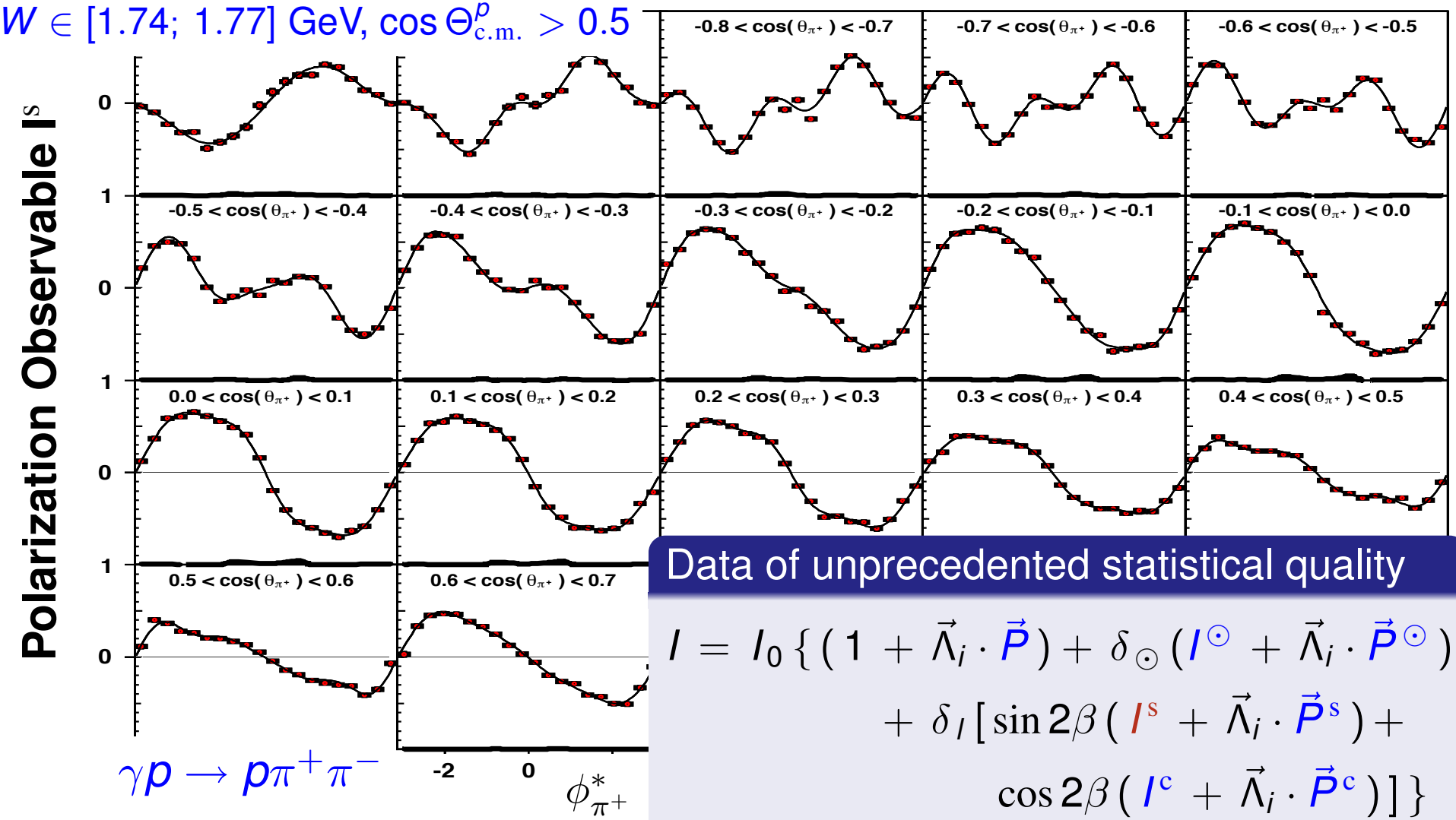






A. Wilson, Florida State University, PhD thesis (2013)

$W \in [1.74;\ 1.77]$ GeV, $\cos\Theta^{p}_{\mathrm{c.m.}} > 0.5$

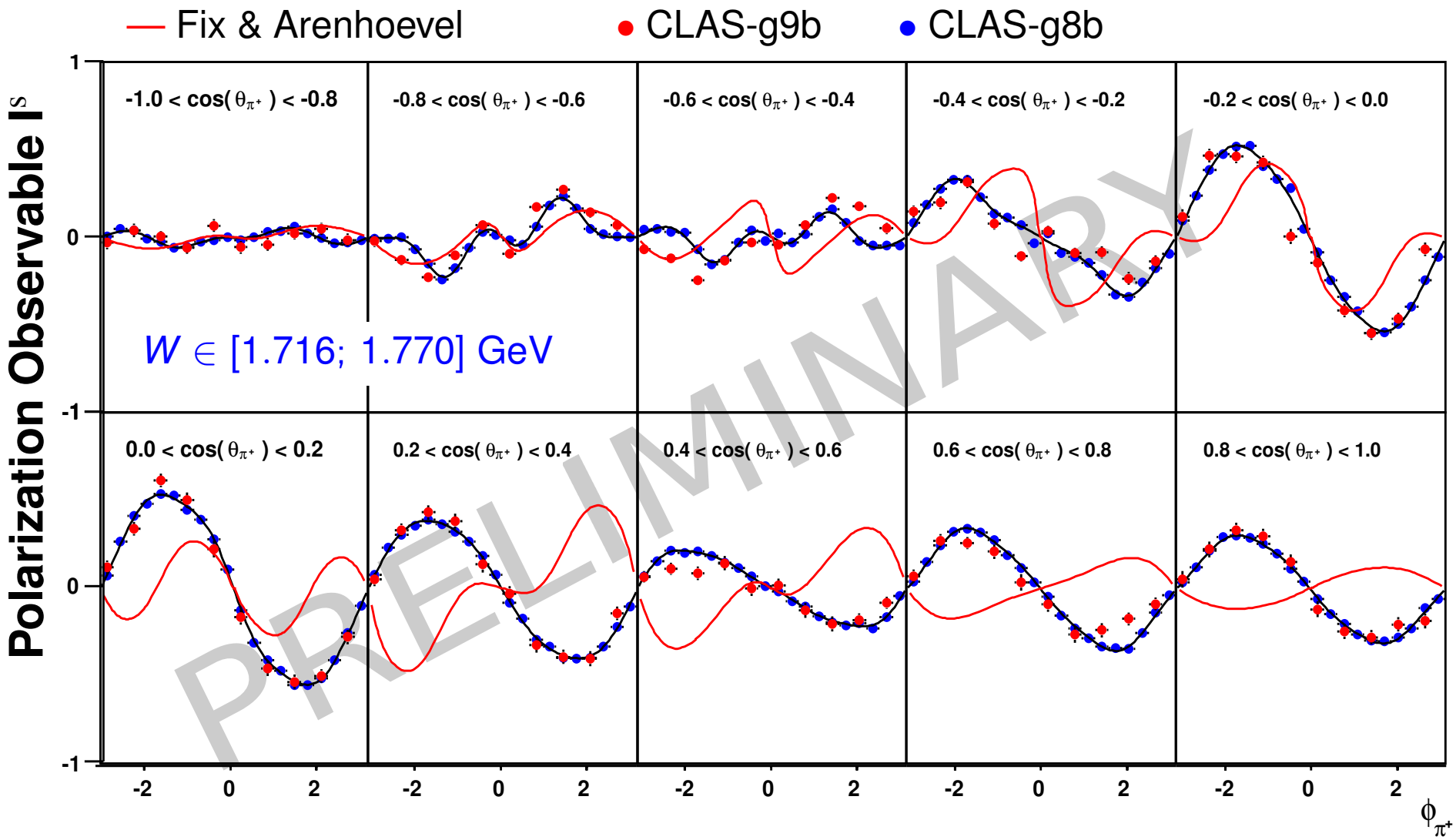


$\gamma p \to p\pi^+\pi^-$

Data of unprecedented statistical quality

$$I = I_0\{(1 + \vec{\Lambda}_i \cdot \vec{P}) + \delta_\odot (I^\odot + \vec{\Lambda}_i \cdot \vec{P}^\odot) + \delta_l [\sin 2\beta (I^s + \vec{\Lambda}_i \cdot \vec{P}^s) + \cos 2\beta (I^c + \vec{\Lambda}_i \cdot \vec{P}^c)]\}$$

Charles Hanretty (FSU), approved by CLAS collaboration



Priyashree Roy (Florida State), CLAS g9b (FROST)

How do we publish these results?

The interpretation of many observables is far behind the experimental analysis, in particular for 2-meson reactions. How do we proceed?

- Wait?
- Publish results without any direct physics conclusion? Reviewers usually ask what the impact of the new data is.

How do we preserve the data for future analysis?

- Events? Simple projections are not suitable for $p\pi\pi$, $p\pi\eta$ (5-dim.)

What else is needed for future analyses?

- Polarized cross sections? Requires Monte Carlo simulations (also for event-based PWA), which is not a standard tool for the people doing “baryon” polarization experiments.

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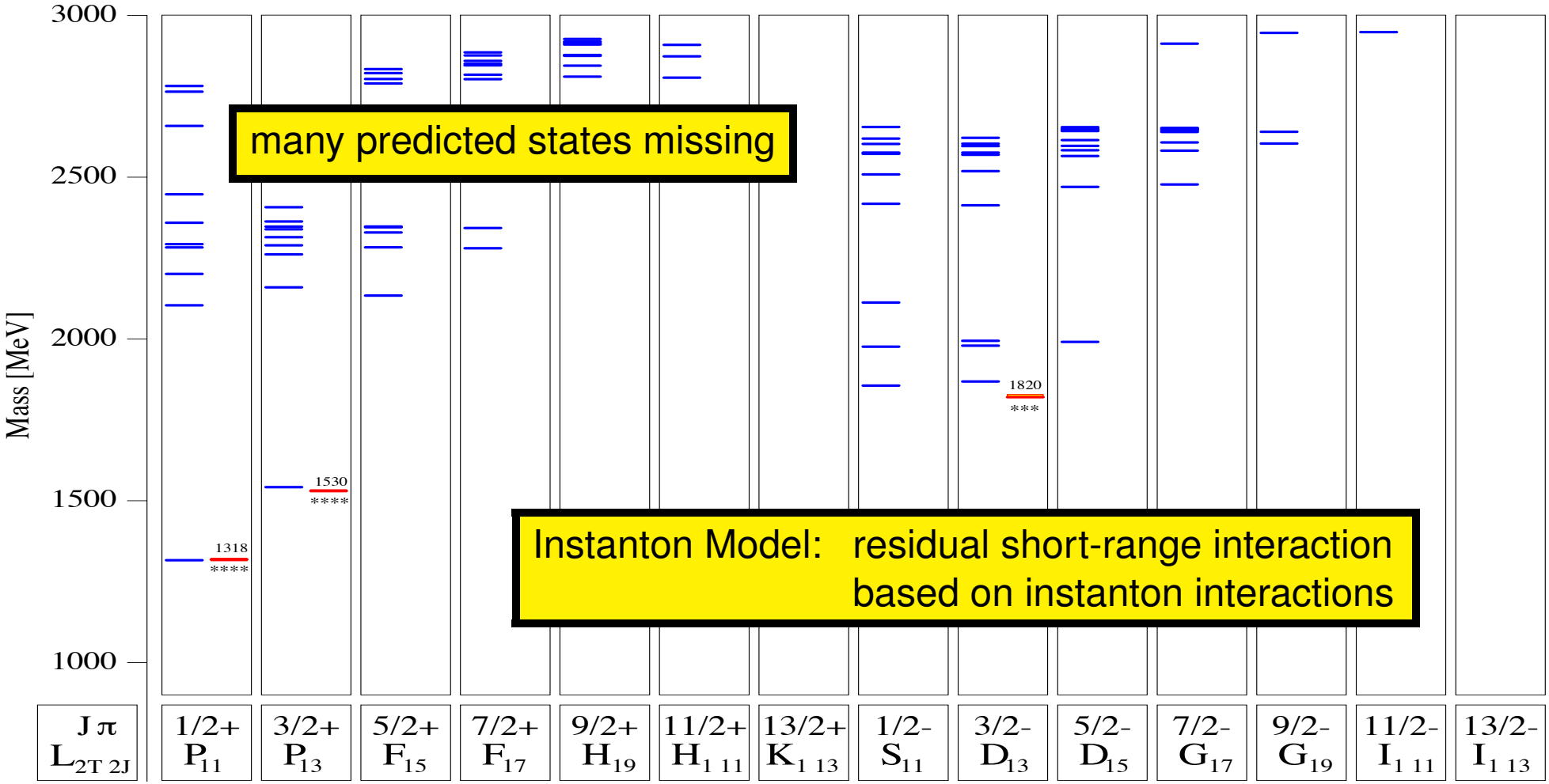
Outline

Cascade Resonances: Status of 2001

U. Loering, B. Ch. Metsch, H. R. Petry, Eur. Phys. J. **A10** (2001) 447-486

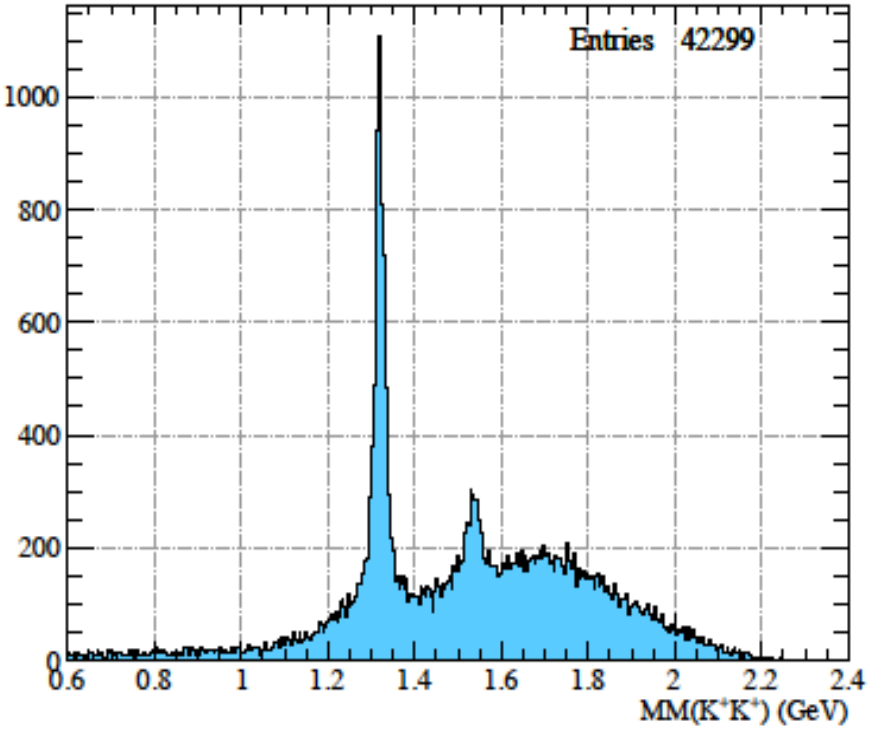


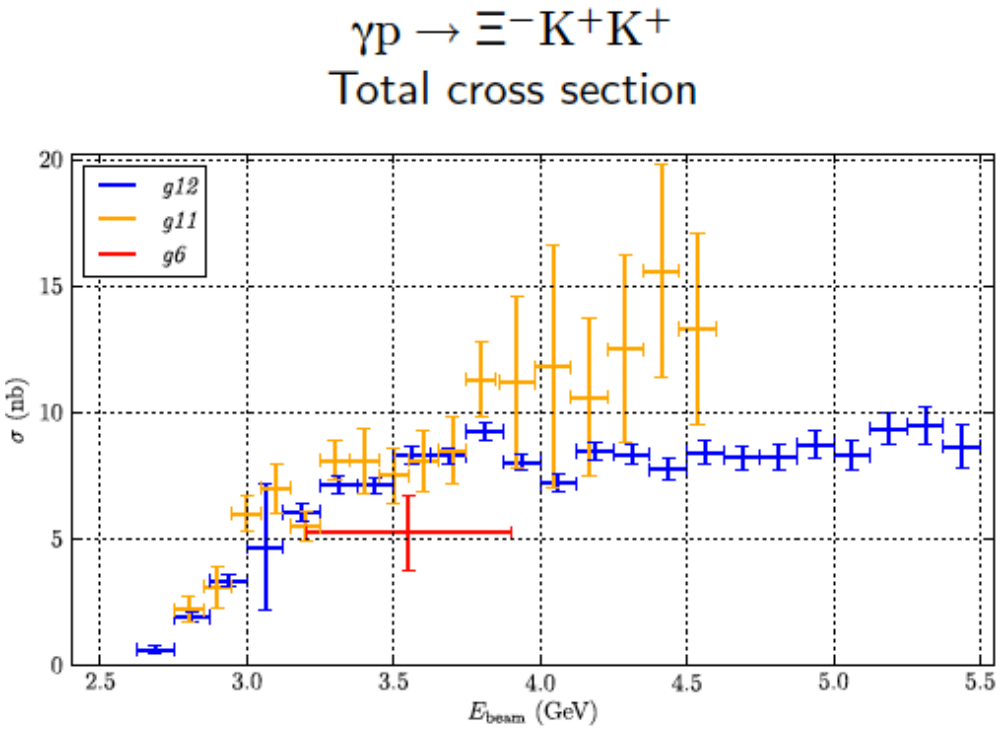
many predicted states missing

Instanton Model: residual short-range interaction based on instanton interactions

CLAS g12 (prel.): Total Cross Section of Ξ^-

Johann Goetz (CLAS Collaboration), UCLA, Ph.D. Thesis





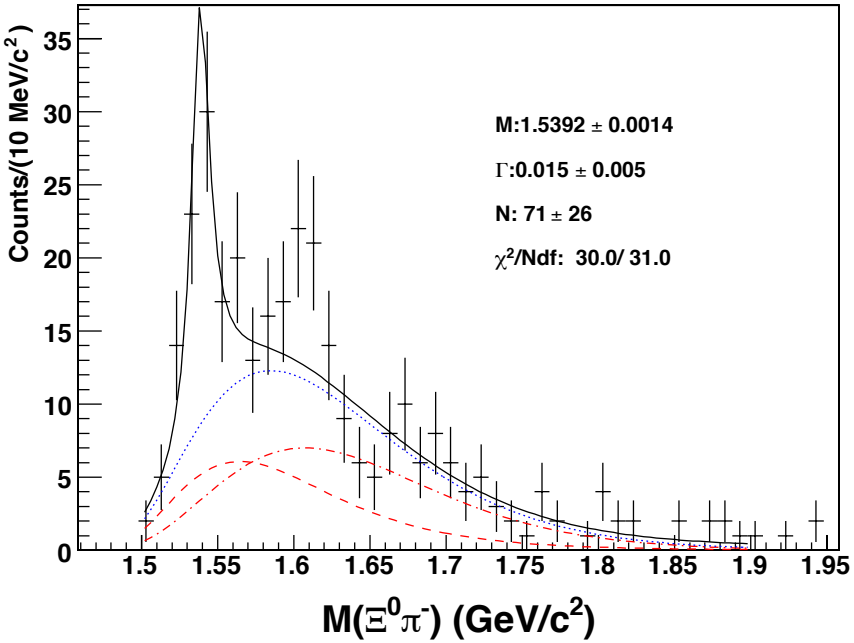
Upper Limits (integrated over 3.5-5.4 GeV):

(1) $\Xi(1620)$: 0.78 nb (2) $\Xi(1690)$: 0.97 nb (3) $\Xi(1820)$: 1.09 nb

CLAS g11: Excited States in $\gamma p \to K^+ K^+ \pi^- (X)$

1. Only $\Xi(1530)$ statistically significant
2. $\Xi(1620)$ signal "plausible", but simulated K^{*0} events also peak in 1600 MeV/c^2 region ($\gamma p \to K^+ K^{*0} \Xi^0$, $K^{*0} \to K^+ \pi^-$)

"... it is not possible to determine its exact nature without a full PWA."

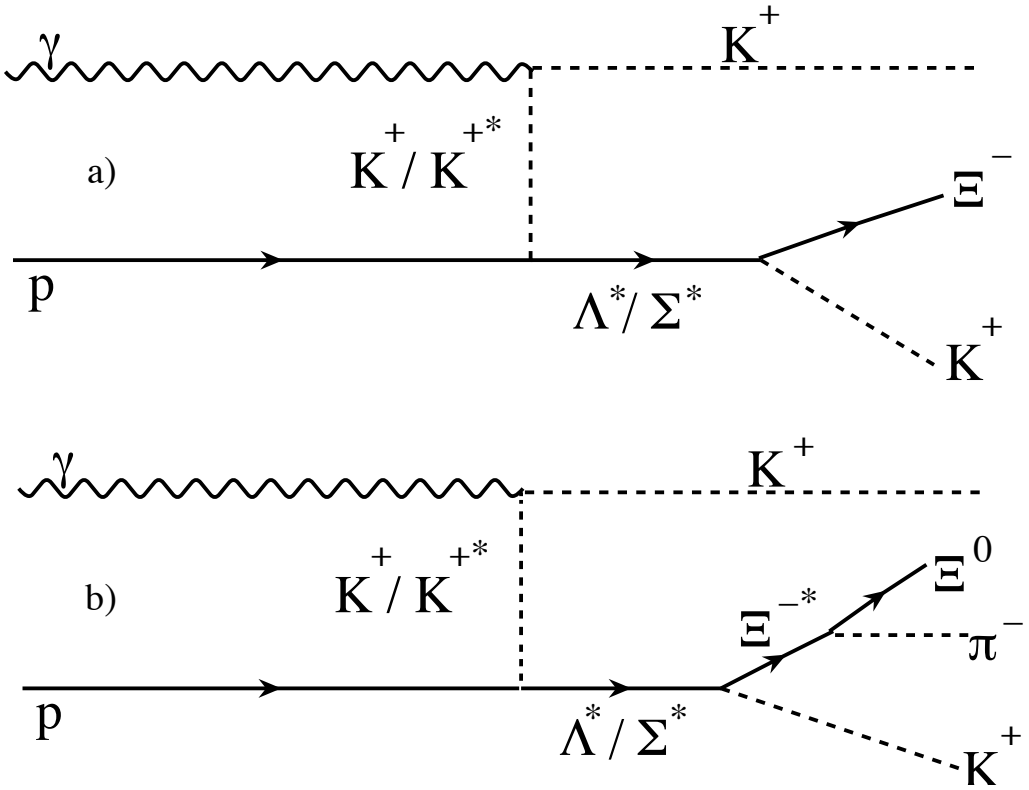


Need high-statistics, high-energy data from an experiment designed to see Ξ states

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

➜ GlueX, CLAS12, ...

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^*)

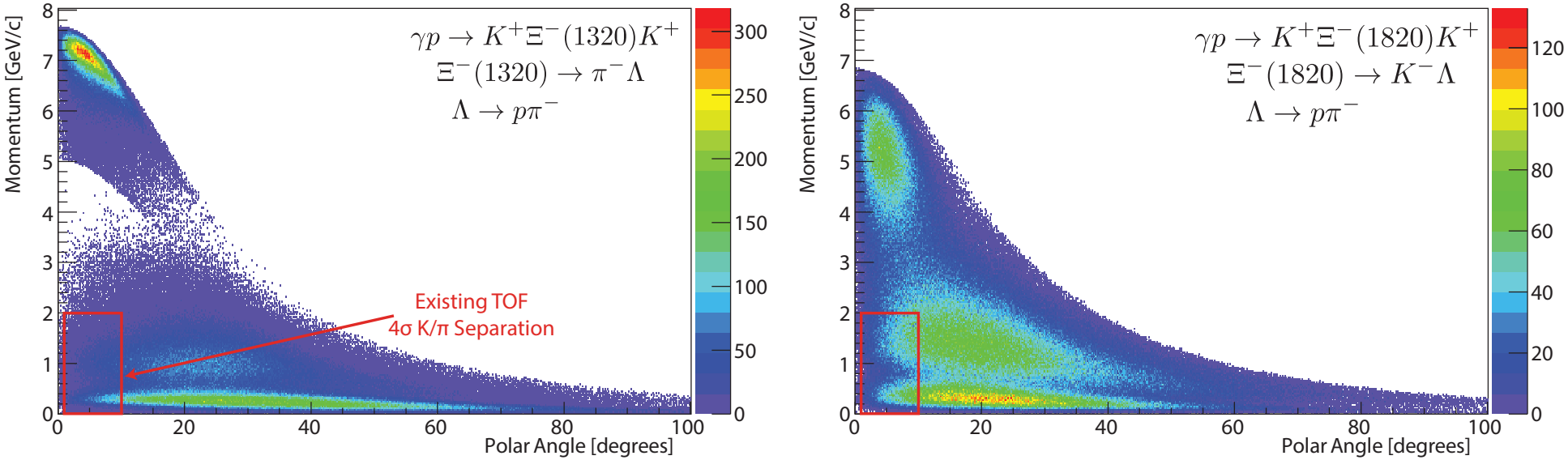
Production of excited states via a

1. forward-going K^0 meson
   ➜ $K^0\,(\Xi^-\,\pi^+)\,K^+$, etc.
2. forward-going K^+ meson
   ➜ $K^+\,(\Xi^-\,\pi^+)\,K^0$,
   $K^+\,(\Xi^0\,\pi^-)\,K^+$, etc.

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

Ξ Spectroscopy with the GlueX Detector

GlueX Proposal on "Decays to Strange Final States" (JLab PAC 39 & 42)



Efficiency should be adequate for conducting a study of excited Ξ states with the baseline detector:

- Detailed studies of the production, especially of the ground state Ξ's, and a parity measurement * will likely require enhanced kaon identification in the forward direction ➜ Components of the BaBar DIRC for GlueX.

* e.g. Nakayama *et al.*, Phys. Rev. C **85**, 042201 (2012)

Outline

Summary and Outlook

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

Data-taking in low-energy photoproduction is almost over

(polarization experiments for "complete experiments")

- The job to extract (and study) baryon resonances has only just begun.
- The experimental (data analysis) community slowly moves on.

  How do we archive the data for later analysis?

  Example 2-meson channels: Extraction of observables is happening now, but the extraction of physics will likely happen years later.

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.