CLAS Excited Baryon Program

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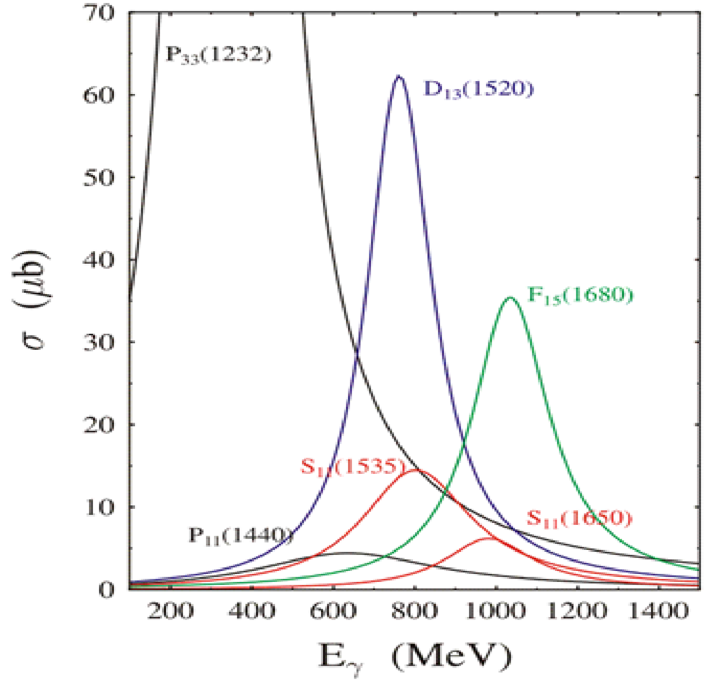
Outline

- **Motivations**
- Helicity amplitudes
- Experimental facilities
- Reactions and results

Nucleon resonances

- As a three-quark system, the nucleon has a specific excitation spectrum comprised of nucleon resonances.
- This nucleon resonance spectrum has been found to have many broad overlapping states, making disentangling the spectrum difficult. ☹

$$\gamma\, p \longrightarrow \pi^+\, n$$

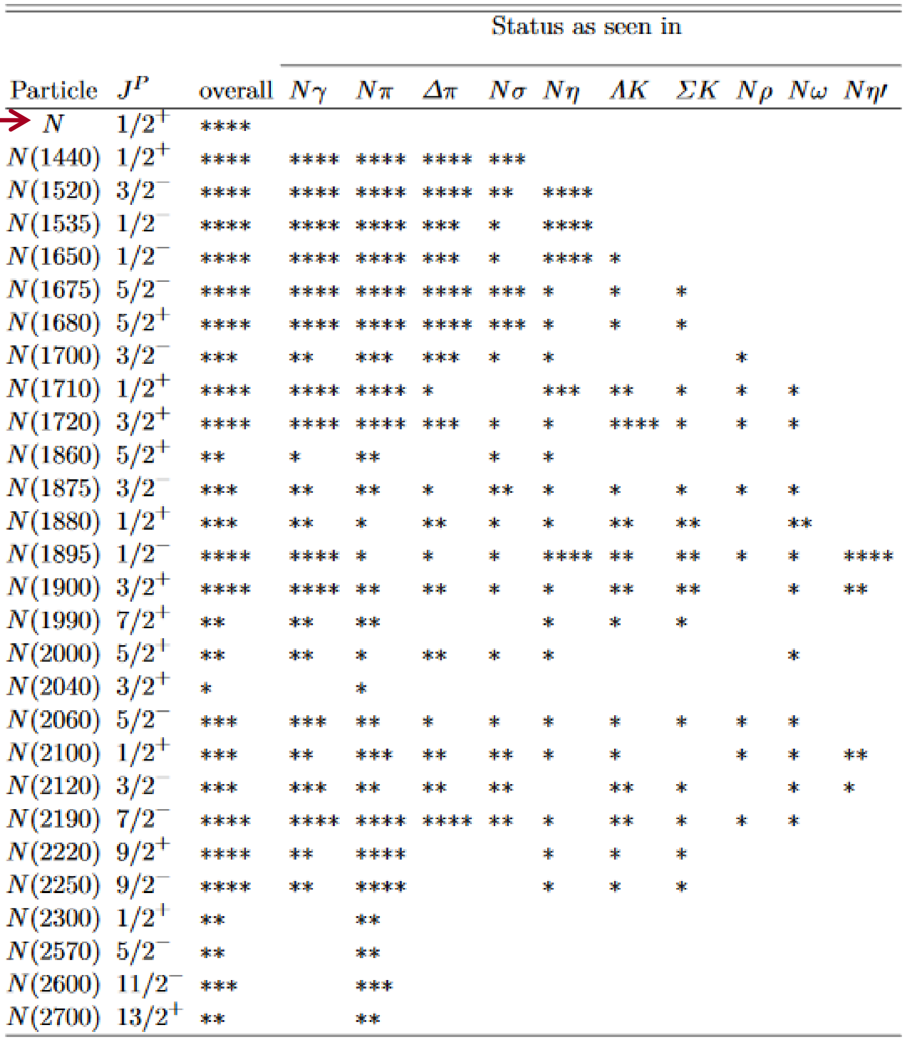


How well do we know the nucleon resonance spectrum?

Nucleon resonances are rated using the “star” system:

*	Poor evidence of existence
**	Fair evidence of existence
***	Likely evidence of existence, or certain and properties need work
****	Existence is certain and properties well explored

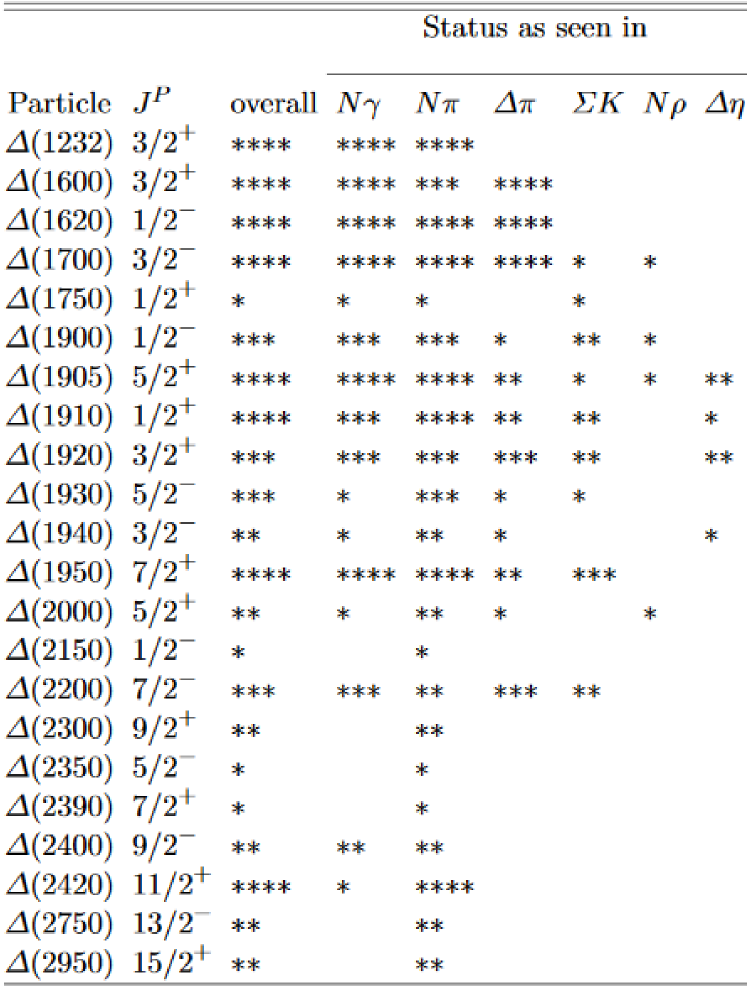
Resonance status for N^* and Δ^*



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

27 N^* states:

- 13 with ****
- 7 with ***
- 6 with **
- 1 with *



			Status as seen in					
Particle	J^P	overall	$N\gamma$	$N\pi$	$\Delta\pi$	ΣK	$N\rho$	$\Delta\eta$
$\Delta(1232)$	$3/2^+$	****	****	****				
$\Delta(1600)$	$3/2^+$	****	****	***	****			
$\Delta(1620)$	$1/2^-$	****	****	****	****			
$\Delta(1700)$	$3/2^-$	****	****	****	****	*	*	
$\Delta(1750)$	$1/2^+$	*	*	*		*		
$\Delta(1900)$	$1/2^-$	***	***	***	*	**	*	
$\Delta(1905)$	$5/2^+$	****	****	****	**	*	*	**
$\Delta(1910)$	$1/2^+$	****	***	****	**	**		*
$\Delta(1920)$	$3/2^+$	***	***	***	***	**		**
$\Delta(1930)$	$5/2^-$	***	*	***	*	*		
$\Delta(1940)$	$3/2^-$	**	*	**	*			*
$\Delta(1950)$	$7/2^+$	****	****	****	**	***		
$\Delta(2000)$	$5/2^+$	**	*	**	*		*	
$\Delta(2150)$	$1/2^-$	*		*				
$\Delta(2200)$	$7/2^-$	***	***	**	***	**		
$\Delta(2300)$	$9/2^+$	**		**				
$\Delta(2350)$	$5/2^-$	*		*				
$\Delta(2390)$	$7/2^+$	*		*				
$\Delta(2400)$	$9/2^-$	**	**	**				
$\Delta(2420)$	$11/2^+$	****	*	****				
$\Delta(2750)$	$13/2^-$	**		**				
$\Delta(2950)$	$15/2^+$	**		**				

22 Δ^* states:

- 8 with ****
- 4 with ***
- 6 with **
- 4 with *

Resonance status for N^* and Δ^*

Nucleon →

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

27 N^* states:

- 13 with ****
- 7 with ***
- 6 with **
- 1 with *

In 2013

26 N^* states:

- 10 with ****
- 5 with ***
- 8 with **
- 3 with *

			Status as seen in					
Particle	J^P	overall	$N\gamma$	$N\pi$	$\Delta\pi$	ΣK	$N\rho$	$\Delta\eta$
$\Delta(1232)$	$3/2^+$	****	****	****				
$\Delta(1600)$	$3/2^+$	****	****	***	****			
$\Delta(1620)$	$1/2^-$	****	****	****	****			
$\Delta(1700)$	$3/2^-$	****	****	****	****	*	*	
$\Delta(1750)$	$1/2^+$	*	*	*		*		
$\Delta(1900)$	$1/2^-$	***	***	***	*	**	*	
$\Delta(1905)$	$5/2^+$	****	****	****	**	*	*	**
$\Delta(1910)$	$1/2^+$	****	***	****	**	**		*
$\Delta(1920)$	$3/2^+$	***	***	***	***	**		**
$\Delta(1930)$	$5/2^-$	***	*	***	*	*		
$\Delta(1940)$	$3/2^-$	**	*	**	*			*
$\Delta(1950)$	$7/2^+$	****	****	****	**	***		
$\Delta(2000)$	$5/2^+$	**	*	**	*		*	
$\Delta(2150)$	$1/2^-$	*		*				
$\Delta(2200)$	$7/2^-$	***	***	**	***	**		
$\Delta(2300)$	$9/2^+$	**		**				
$\Delta(2350)$	$5/2^-$	*		*				
$\Delta(2390)$	$7/2^+$	*		*				
$\Delta(2400)$	$9/2^-$	**	**	**				
$\Delta(2420)$	$11/2^+$	****	*	****				
$\Delta(2750)$	$13/2^-$	**		**				
$\Delta(2950)$	$15/2^+$	**		**				

22 Δ^* states:

- 8 with ****
- 4 with ***
- 6 with **
- 4 with *

In 2013

22 Δ^* states:

- 7 with ****
- 3 with ***
- 7 with **
- 5 with *

Resonance status for N^* and Δ^*

Nucleon →

			Status as seen in									
Particle	J^P	overall	$N\gamma$	$N\pi$	$\Delta\pi$	$N\sigma$	$N\eta$	ΛK	ΣK	$N\rho$	$N\omega$	$N\eta'$
N	$1/2^+$	****										
$N(1440)$	$1/2^+$	****	****	****	****	***						
$N(1520)$	$3/2^-$	****	****	****	****	**	****					
$N(1535)$	$1/2^-$	****	****	****	***	*	****					
$N(1650)$	$1/2^-$	****	****	****	***	*	****	*				
$N(1675)$	$5/2^-$	****	****	****	****	***	*	*	*			
$N(1680)$	$5/2^+$	****	****	****	****	***	*	*	*			
$N(1700)$	$3/2^-$	***	**	***	***	*	*			*		
$N(1710)$	$1/2^+$	****	****	****	*		***	**	*	*	*	
$N(1720)$	$3/2^+$	****	****	****	***	*	*	****	*	*	*	
$N(1860)$	$5/2^+$	**	*	**		*	*					
$N(1875)$	$3/2^-$	***	**	**	*	**	*	*	*	*	*	
$N(1880)$	$1/2^+$	***	**	*	**	*	*	**	**		**	
$N(1895)$	$1/2^-$	****	****	*	*	*	****	**	**	*	*	****
$N(1900)$	$3/2^+$	****	****	**	**	*	*	**	**		*	**
$N(1990)$	$7/2^+$	**	**	**			*	*	*			
$N(2000)$	$5/2^+$	**	**	*	**	*	*				*	
$N(2040)$	$3/2^+$	*		*								
$N(2060)$	$5/2^-$	***	***	**	*	*	*	*	*	*	*	
$N(2100)$	$1/2^+$	***	**	***	**	**	*	*		*	*	**
$N(2120)$	$3/2^-$	***	***	**	**	**		**	*		*	*
$N(2190)$	$7/2^-$	****	****	****	****	**	*	**	*	*	*	
$N(2220)$	$9/2^+$	****	**	****			*	*	*			
$N(2250)$	$9/2^-$	****	**	****			*	*	*			
$N(2300)$	$1/2^+$	**		**								
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$N(2600)$	$11/2^-$	***		***								
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Particle	J^P	overall	$N\gamma$	$N\pi$	$\Delta\pi$	ΣK	$N\rho$	$\Delta\eta$
$\Delta(1232)$	$3/2^+$	****	****	****				
$\Delta(1600)$	$3/2^+$	****	****	***	****			
$\Delta(1620)$	$1/2^-$	****	****	****	****			
$\Delta(1700)$	$3/2^-$	****	****	****	****	*	*	
$\Delta(1750)$	$1/2^+$	*	*	*		*		
$\Delta(1900)$	$1/2^-$	***	***	***	*	**	*	
$\Delta(1905)$	$5/2^+$	****	****	****	**	*	*	**
$\Delta(1910)$	$1/2^+$	****	***	****	**	**		*
$\Delta(1920)$	$3/2^+$	***	***	***	***	**		**
$\Delta(1930)$	$5/2^-$	***	*	***	*	*		
$\Delta(1940)$	$3/2^-$	**	*	**	*			*
$\Delta(1950)$	$7/2^+$	****	****	****	**	***		
$\Delta(2000)$	$5/2^+$	**	*	**	*		*	
$\Delta(2150)$	$1/2^-$	*		*				
$\Delta(2200)$	$7/2^-$	***	***	**	***	**		
$\Delta(2300)$	$9/2^+$	**		**				
$\Delta(2350)$	$5/2^-$	*		*				
$\Delta(2390)$	$7/2^+$	*		*				
$\Delta(2400)$	$9/2^-$	**	**	**				
$\Delta(2420)$	$11/2^+$	****	*	****				
$\Delta(2750)$	$13/2^-$	**		**				
$\Delta(2950)$	$15/2^+$	**		**				

27 N^* states:
- 13 with ****
- 7 with ***
- 6 with **
- 1 with *

In 2013

26 N^* states:
- 10 with ****
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22 Δ^* states:
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In 2013

22 Δ^* states:
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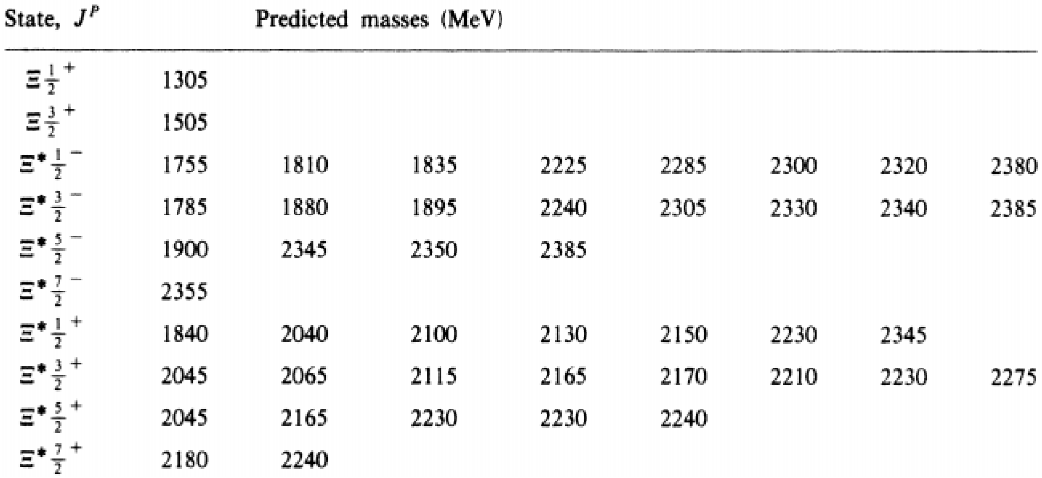
- **Are there missing states?**

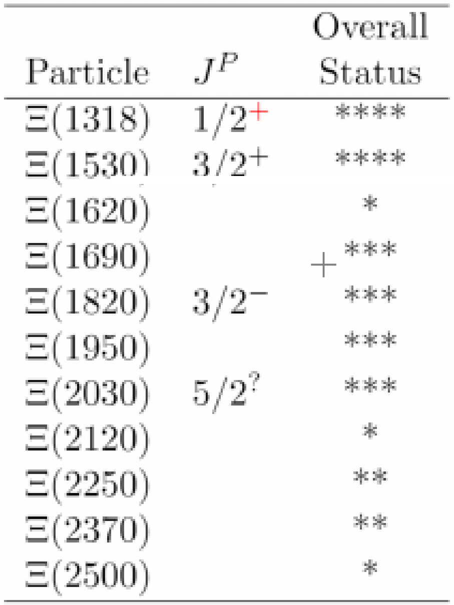
Resonance status for Ξ^*



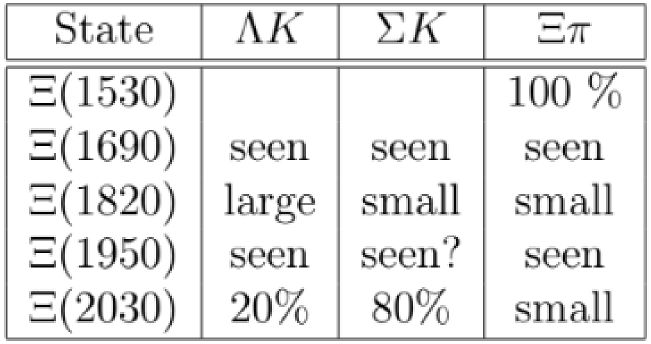
State, J^P	Predicted masses (MeV)							
$\Xi\frac{1}{2}^+$	1305							
$\Xi\frac{3}{2}^+$	1505							
$\Xi^*\frac{1}{2}^-$	1755	1810	1835	2225	2285	2300	2320	2380
$\Xi^*\frac{3}{2}^-$	1785	1880	1895	2240	2305	2330	2340	2385
$\Xi^*\frac{5}{2}^-$	1900	2345	2350	2385				
$\Xi^*\frac{7}{2}^-$	2355							
$\Xi^*\frac{1}{2}^+$	1840	2040	2100	2130	2150	2230	2345	
$\Xi^*\frac{3}{2}^+$	2045	2065	2115	2165	2170	2210	2230	2275
$\Xi^*\frac{5}{2}^+$	2045	2165	2230	2230	2240			
$\Xi^*\frac{7}{2}^+$	2180	2240						

- List of Cascade Baryons predicted by Capstick and Isgur with mass less than 2.4 GeV/c^2

PDG



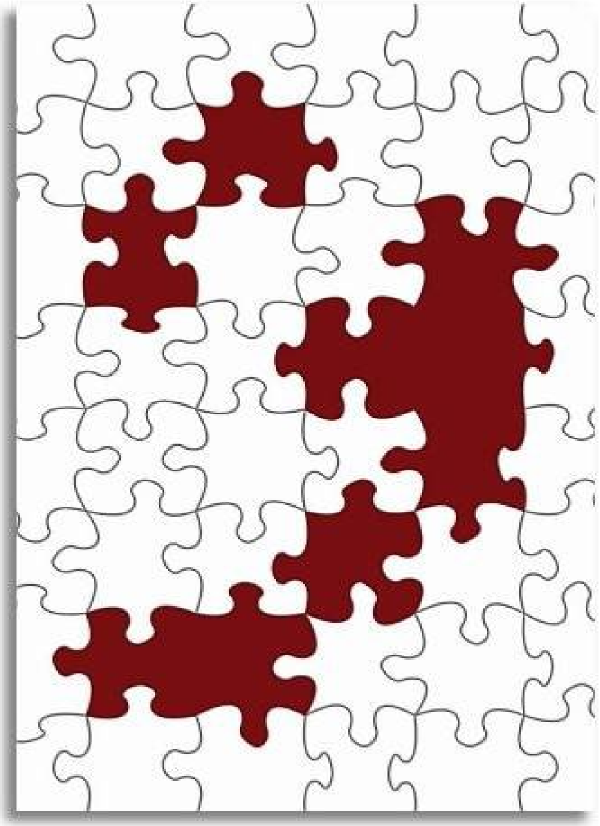
Particle	J^P	Overall Status
$\Xi(1318)$	$1/2^+$	****
$\Xi(1530)$	$3/2^+$	****
$\Xi(1620)$		*
$\Xi(1690)$		+ ***
$\Xi(1820)$	$3/2^-$	***
$\Xi(1950)$		***
$\Xi(2030)$	$5/2^?$	***
$\Xi(2120)$		*
$\Xi(2250)$		**
$\Xi(2370)$		**
$\Xi(2500)$		*



State	ΛK	ΣK	$\Xi\pi$
$\Xi(1530)$			100 %
$\Xi(1690)$	seen	seen	seen
$\Xi(1820)$	large	small	small
$\Xi(1950)$	seen	seen?	seen
$\Xi(2030)$	20%	80%	small

So, where are the resonances?

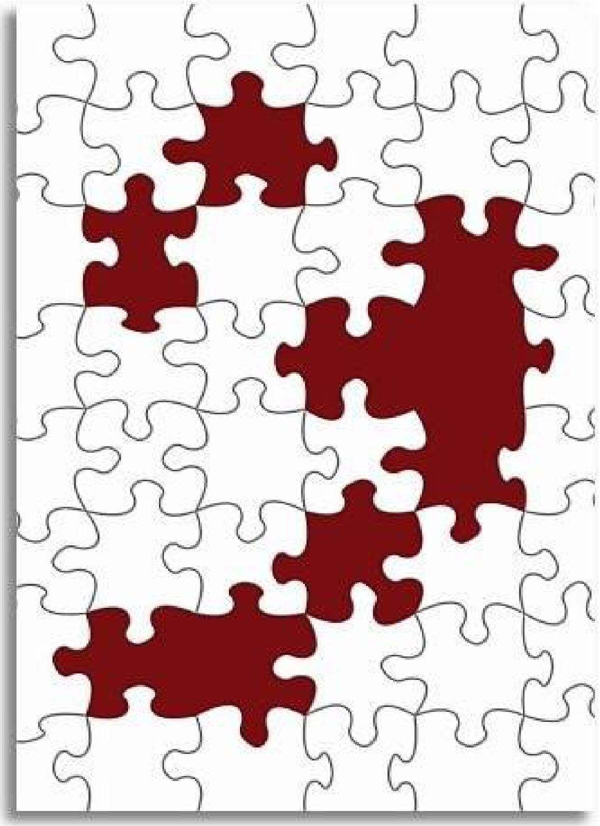
- Masses, widths, and coupling constants not well known for many resonances



So, where are the resonances?

- Masses, widths, and coupling constants not well known for many resonances

- Many models exist to “predict” the nucleon resonance spectrum - quark model, Goldstone-boson exchange, diquark and collective models, instanton-induced interactions, flux-tube models, lattice QCD - **BUT**…

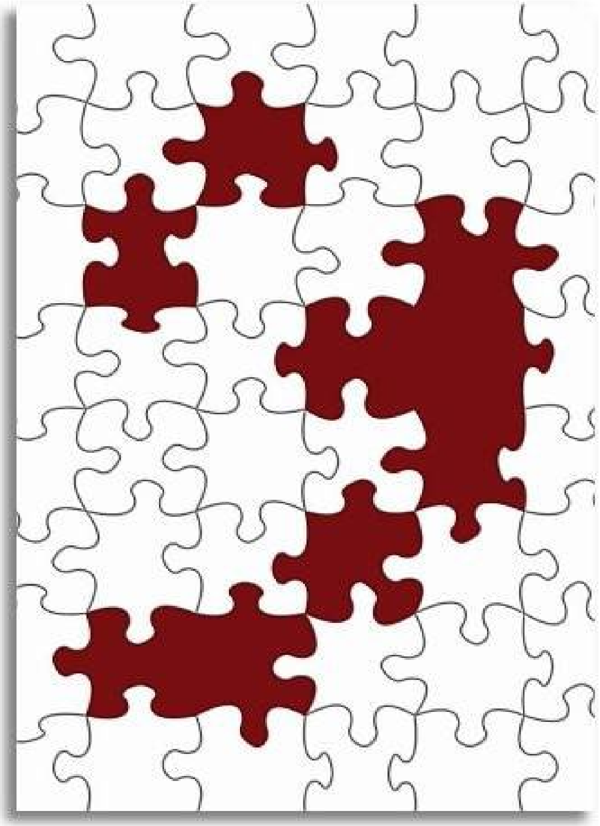


So, where are the resonances?

- Masses, widths, and coupling constants not well known for many resonances

- Many models exist to "predict" the nucleon resonance spectrum - quark model, Goldstone-boson exchange, diquark and collective models, instanton-induced interactions, flux-tube models, lattice QCD - **BUT**…

- **THE BIG PUZZLE: Most models predict many more resonance states than have been observed.**



Outline

- Motivations
- **Helicity amplitudes**
- Experimental facilities
- Reactions and results

Helicity amplitudes for $\gamma + p \rightarrow p + pseudoscalar$

- 8 helicity states: 4 initial, 2 final → 4·2 = 8
- Amplitudes are complex but parity symmetry reduces independent numbers to 8
- Overall phase unobservable → 7 independent numbers

- **HOWEVER**, not all possible observables are linearly independent and it turns out that there must be a minimum of 8 observables / experiments

Initial helicity

$$A = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}$$

Final helicity

helicity +1 photons (ε₊):

$$A_{\varepsilon_+} = \begin{array}{cc} & \begin{array}{cc} \frac{3}{2} & \frac{1}{2} \end{array} \\ \begin{array}{c} \frac{1}{2} \\ \frac{-1}{2} \end{array} & \begin{bmatrix} H_1 & H_2 \\ H_3 & H_4 \end{bmatrix} \end{array}$$

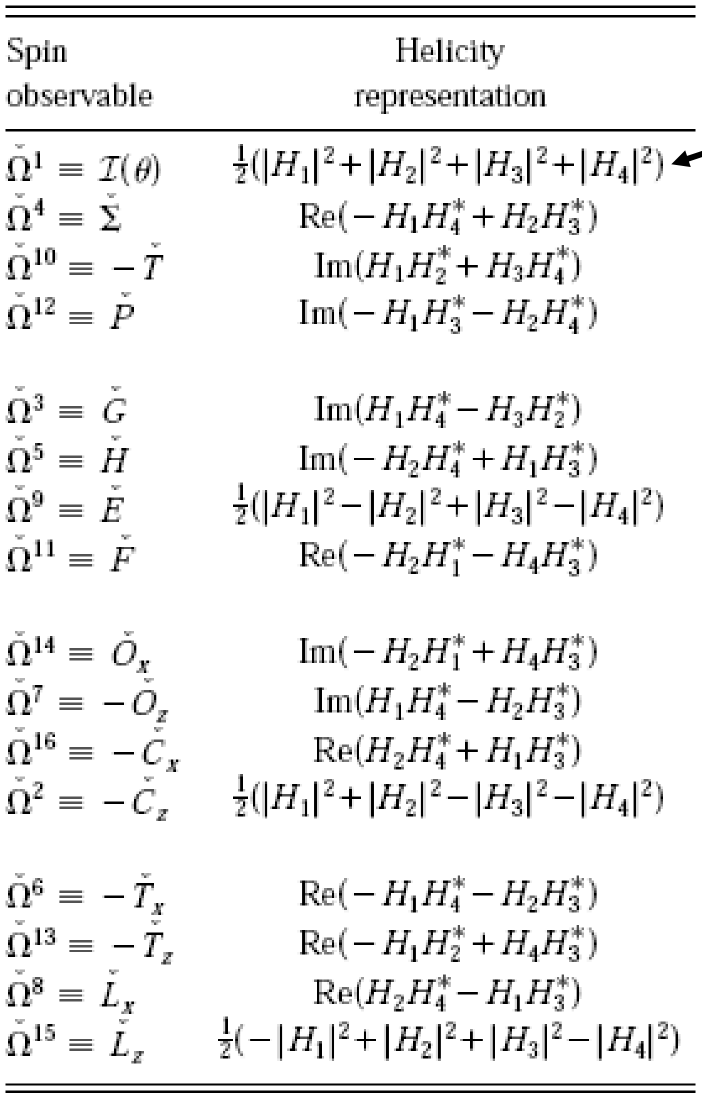
$$\left(A_{-\mu,-\lambda} = -e^{(\lambda-\mu)\pi} A_{\mu,\lambda} \right)$$

Parity symmetry →

helicity -1 photons (ε₋):

$$A_{\varepsilon_-} = \begin{array}{cc} & \begin{array}{cc} \frac{-1}{2} & \frac{-3}{2} \end{array} \\ \begin{array}{c} \frac{1}{2} \\ \frac{-1}{2} \end{array} & \begin{bmatrix} H_4 & -H_3 \\ -H_2 & H_1 \end{bmatrix} \end{array}$$

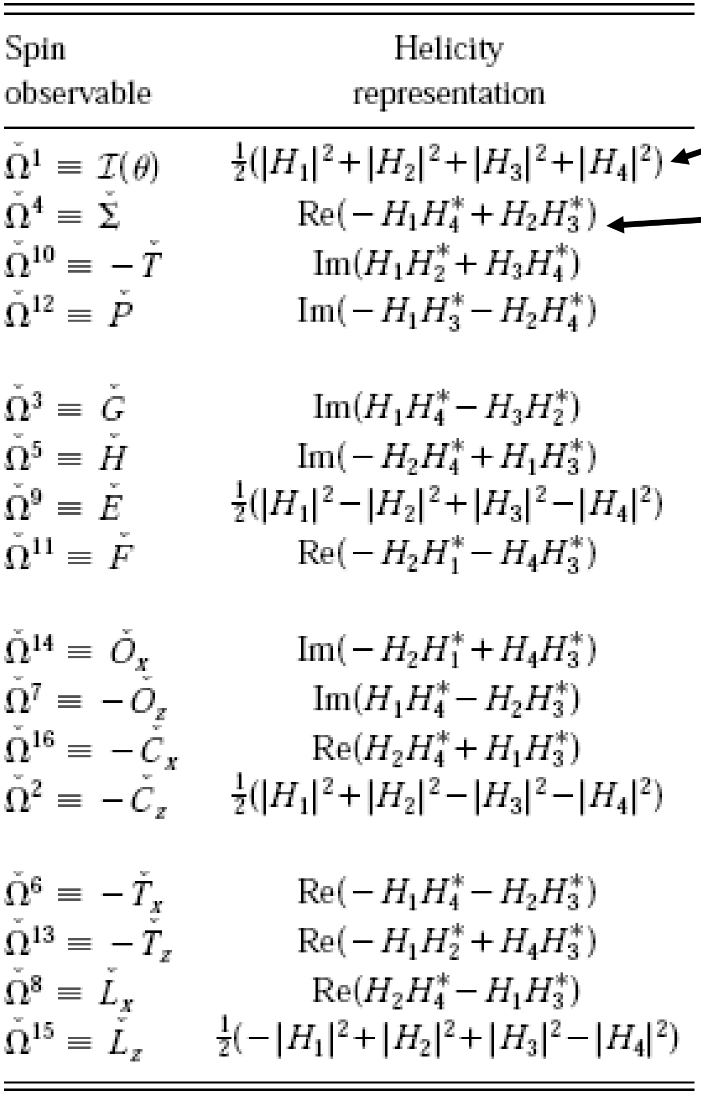
Linkage between helicity amplitudes and the observables for single pseudoscalar photoproduction



Spin observable	Helicity representation
$\check{\Omega}^1 \equiv \check{\mathcal{I}}(\theta)$	$\frac{1}{2}(\lvert H_1\rvert^2+\lvert H_2\rvert^2+\lvert H_3\rvert^2+\lvert H_4\rvert^2)$
$\check{\Omega}^4 \equiv \check{\Sigma}$	$\mathrm{Re}(-H_1H_4^*+H_2H_3^*)$
$\check{\Omega}^{10} \equiv -\check{T}$	$\mathrm{Im}(H_1H_2^*+H_3H_4^*)$
$\check{\Omega}^{12} \equiv \check{P}$	$\mathrm{Im}(-H_1H_3^*-H_2H_4^*)$
$\check{\Omega}^3 \equiv \check{G}$	$\mathrm{Im}(H_1H_4^*-H_3H_2^*)$
$\check{\Omega}^5 \equiv \check{H}$	$\mathrm{Im}(-H_2H_4^*+H_1H_3^*)$
$\check{\Omega}^9 \equiv \check{E}$	$\frac{1}{2}(\lvert H_1\rvert^2-\lvert H_2\rvert^2+\lvert H_3\rvert^2-\lvert H_4\rvert^2)$
$\check{\Omega}^{11} \equiv \check{F}$	$\mathrm{Re}(-H_2H_1^*-H_4H_3^*)$
$\check{\Omega}^{14} \equiv \check{O}_x$	$\mathrm{Im}(-H_2H_1^*+H_4H_3^*)$
$\check{\Omega}^7 \equiv -\check{O}_z$	$\mathrm{Im}(H_1H_4^*-H_2H_3^*)$
$\check{\Omega}^{16} \equiv -\check{C}_x$	$\mathrm{Re}(H_2H_4^*+H_1H_3^*)$
$\check{\Omega}^2 \equiv -\check{C}_z$	$\frac{1}{2}(\lvert H_1\rvert^2+\lvert H_2\rvert^2-\lvert H_3\rvert^2-\lvert H_4\rvert^2)$
$\check{\Omega}^6 \equiv -\check{T}_x$	$\mathrm{Re}(-H_1H_4^*-H_2H_3^*)$
$\check{\Omega}^{13} \equiv -\check{T}_z$	$\mathrm{Re}(-H_1H_2^*+H_4H_3^*)$
$\check{\Omega}^8 \equiv \check{L}_x$	$\mathrm{Re}(H_2H_4^*-H_1H_3^*)$
$\check{\Omega}^{15} \equiv \check{L}_z$	$\frac{1}{2}(-\lvert H_1\rvert^2+\lvert H_2\rvert^2+\lvert H_3\rvert^2-\lvert H_4\rvert^2)$

Differential cross section

Linkage between helicity amplitudes and the observables for single pseudoscalar photoproduction



Spin observable	Helicity representation
$\check{\Omega}^1 \equiv \mathcal{I}(\theta)$	$\frac{1}{2}(\lvert H_1\rvert^2+\lvert H_2\rvert^2+\lvert H_3\rvert^2+\lvert H_4\rvert^2)$
$\check{\Omega}^4 \equiv \check{\Sigma}$	$\mathrm{Re}(-H_1H_4^*+H_2H_3^*)$
$\check{\Omega}^{10} \equiv -\check{T}$	$\mathrm{Im}(H_1H_2^*+H_3H_4^*)$
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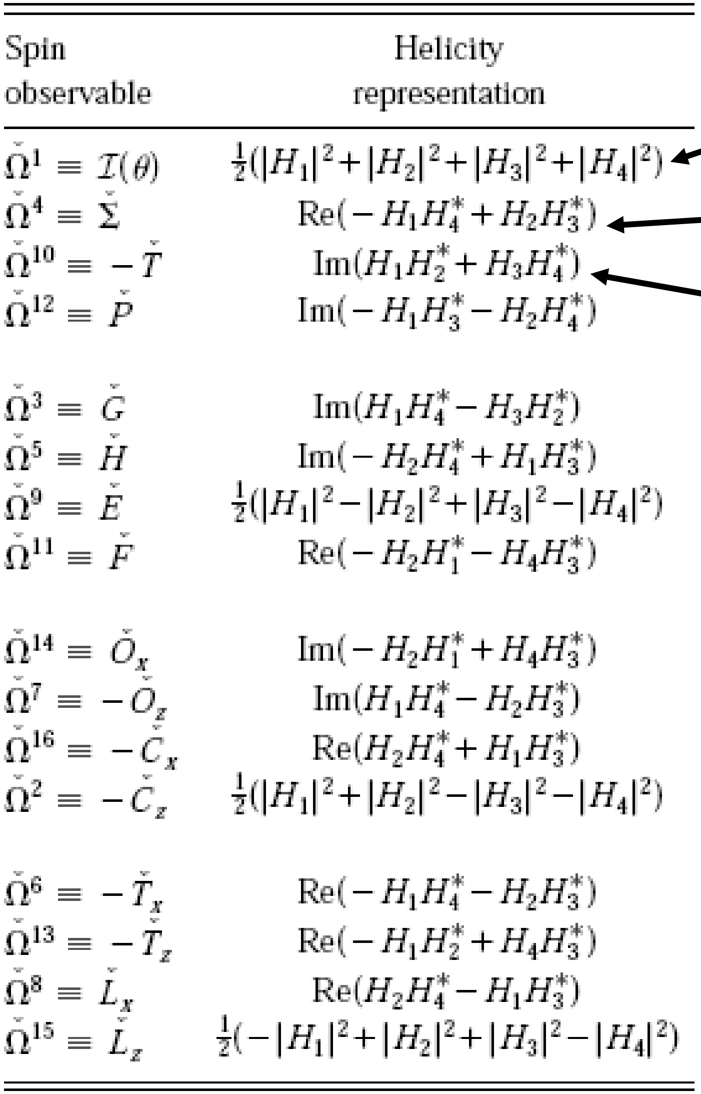
Differential cross section

Beam polarization Σ

Linkage between helicity amplitudes and the observables for single pseudoscalar photoproduction



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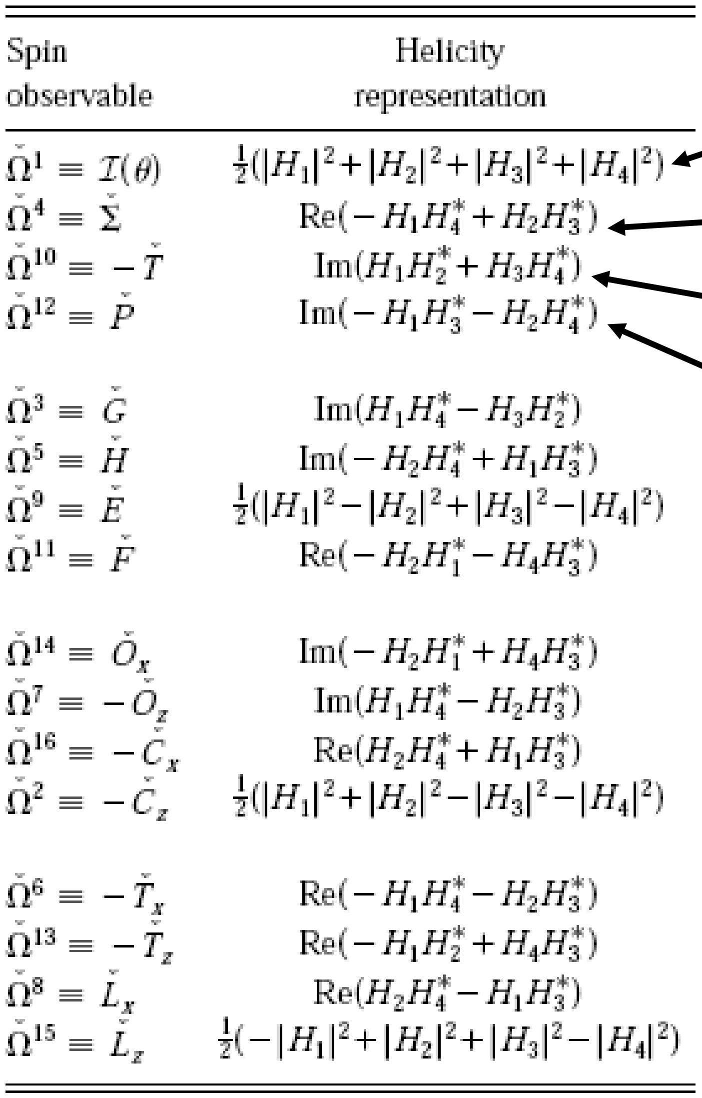
Differential cross section

Beam polarization Σ

Target asymmetry T

Linkage between helicity amplitudes and the observables for single pseudoscalar photoproduction



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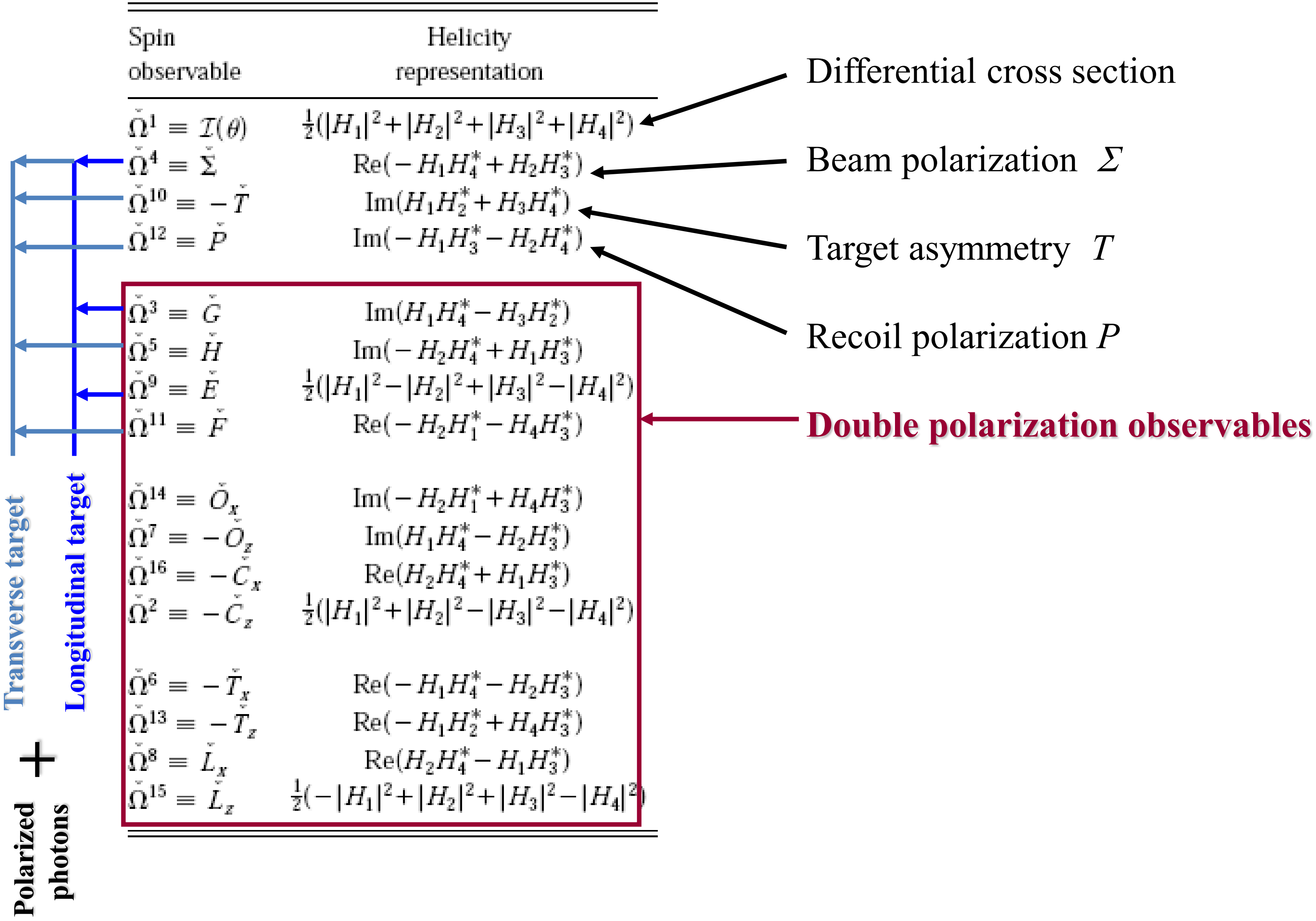
Differential cross section

Beam polarization Σ

Target asymmetry T

Recoil polarization P

Linkage between helicity amplitudes and the observables for single pseudoscalar photoproduction



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Differential cross section

Beam polarization Σ

Target asymmetry T

Recoil polarization P

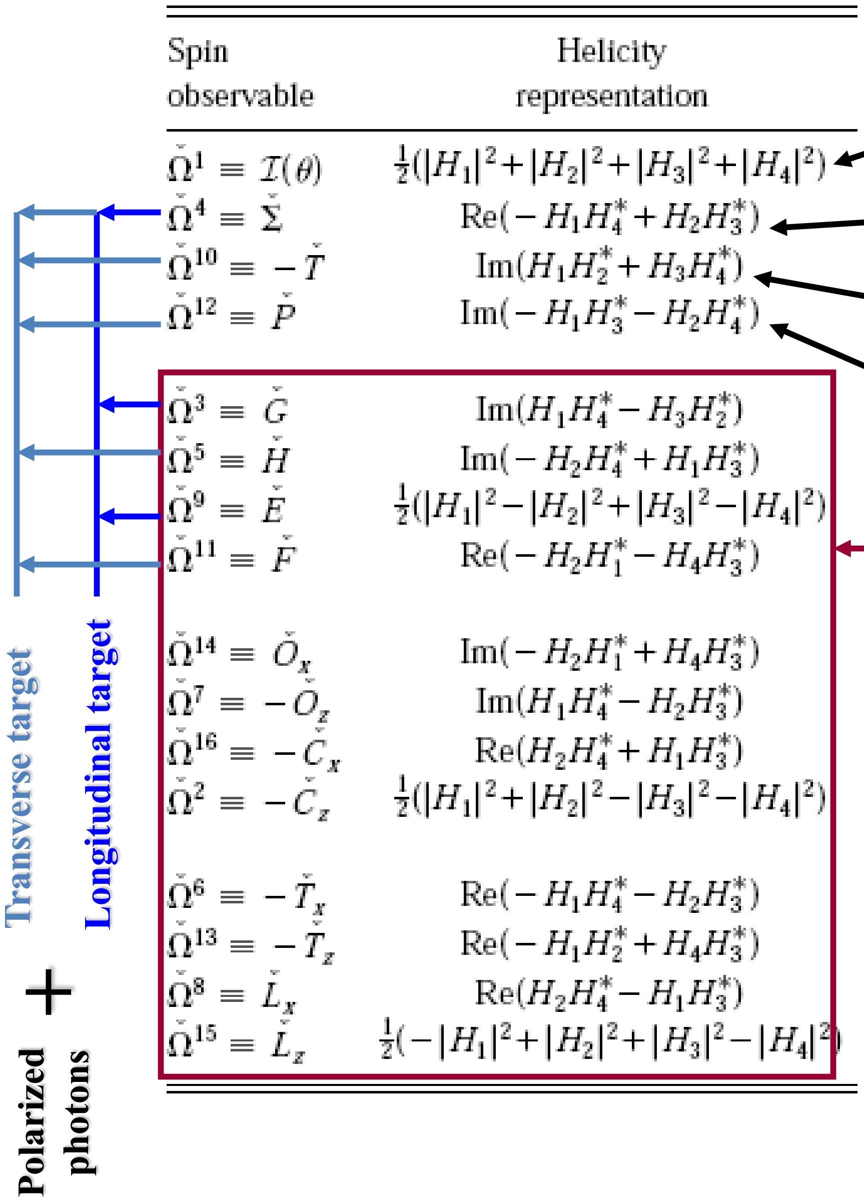
Double polarization observables

Transverse target

Longitudinal target

+ Polarized photons

Linkage between helicity amplitudes and the observables for single pseudoscalar photoproduction



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Recoil polarization P

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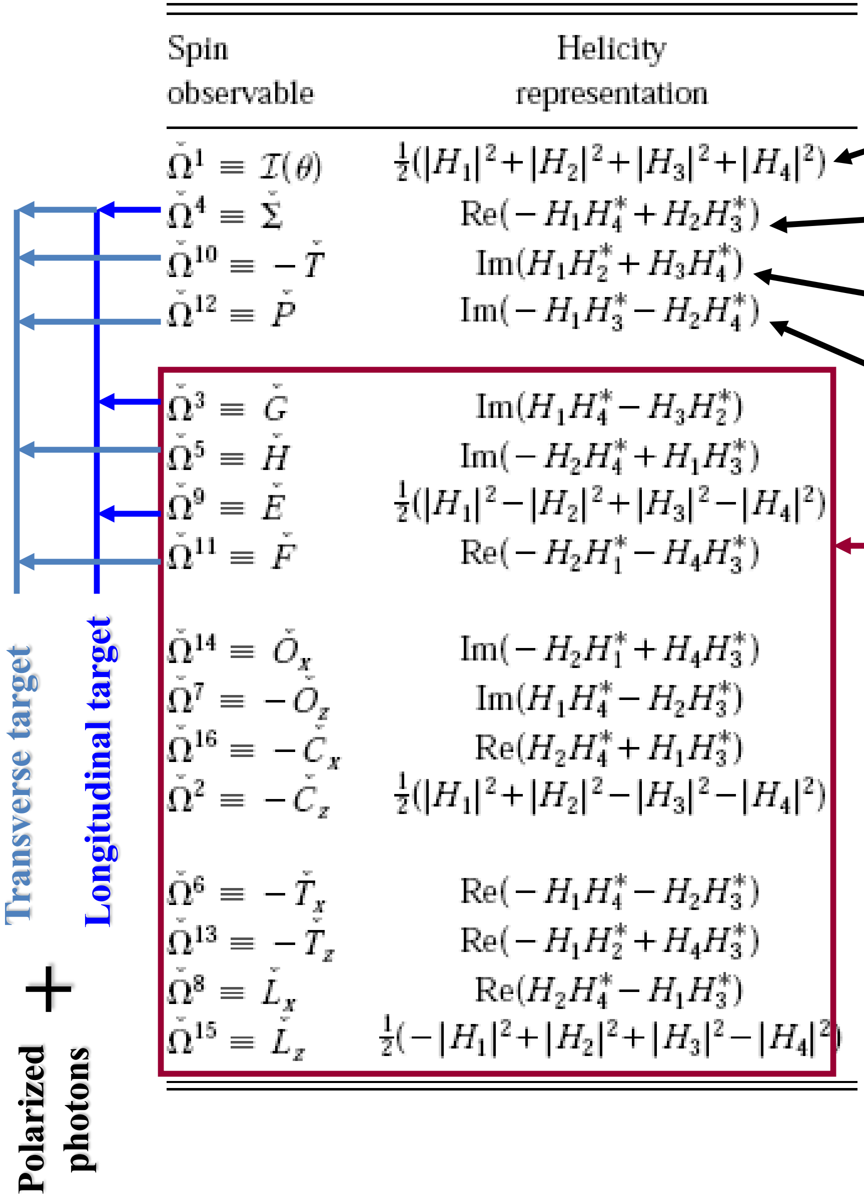
- Need **at least** 4 of the double observables from at least 2 groups for a “complete experiment”

Linkage between helicity amplitudes and the observables for single pseudoscalar photoproduction



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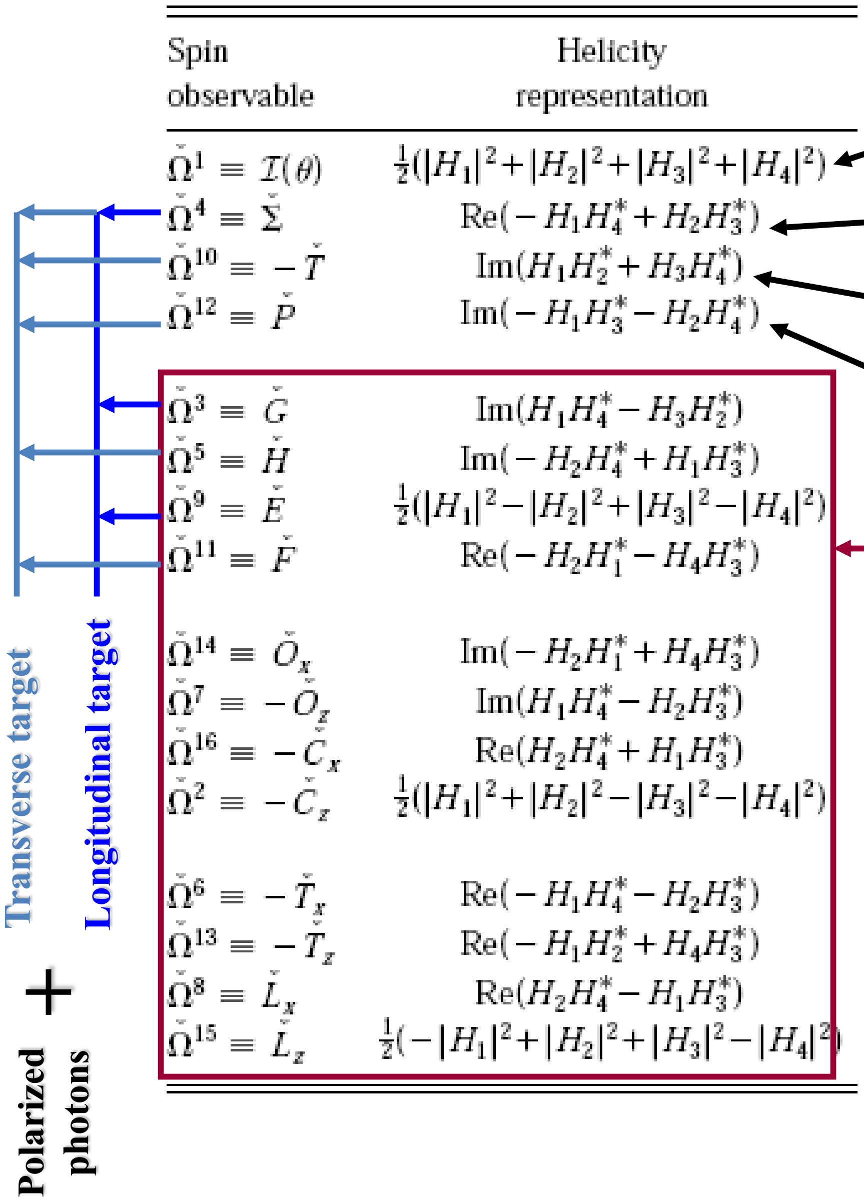
Linkage between helicity amplitudes and the observables for single pseudoscalar photoproduction



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- Need **at least** 4 of the double observables from at least 2 groups for a "complete experiment"
- $\pi^0 p$, $\pi^+ n$, and $\eta\, p$ will be nearly complete
- $K^+ \Lambda$ will be complete!

So, finding missing resonances requires lots of different observables.

Cross sections are not enough!

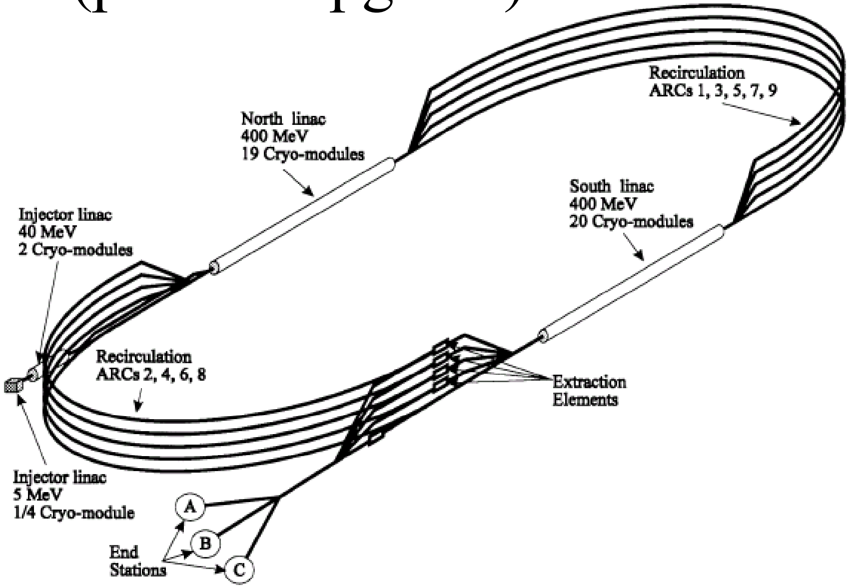
Outline

- Motivations
- Helicity amplitudes
- **Experimental facilities**
- Reactions and results

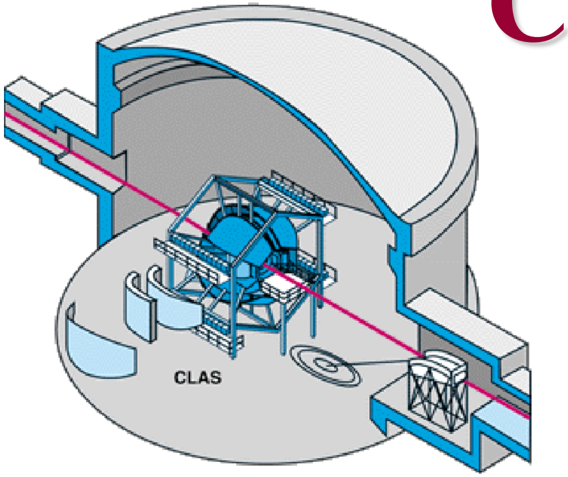
Experimental facilities:

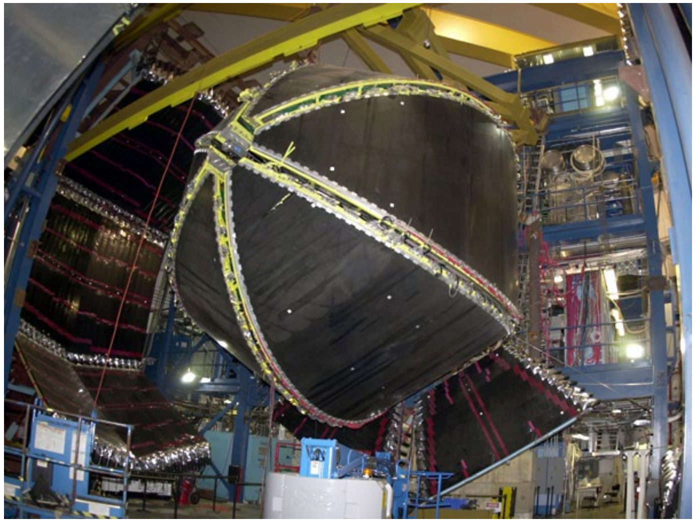
- The Thomas Jefferson National Accelerator Facility (Jefferson Laboratory = JLab).
- Continuous Electron Beam Accelerator Facility (CEBAF)

- Racetrack design
- Energies up to 6 GeV (prior to upgrade)



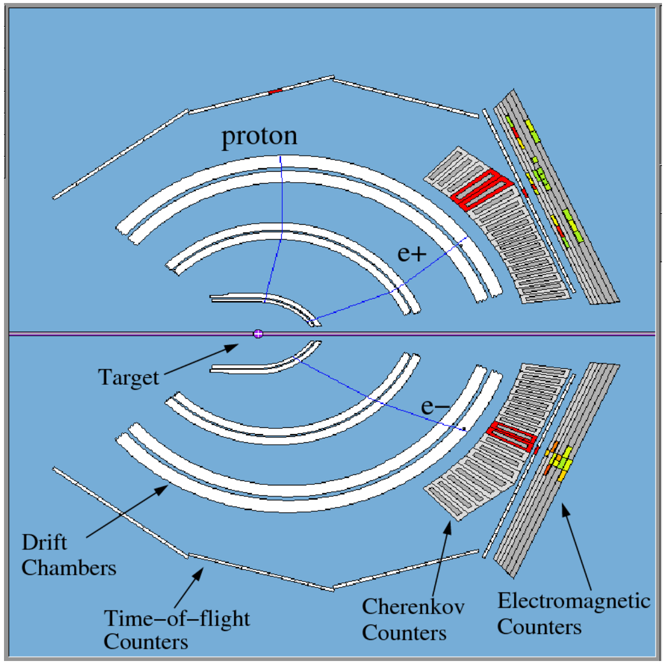
CLAS (1997-2012)



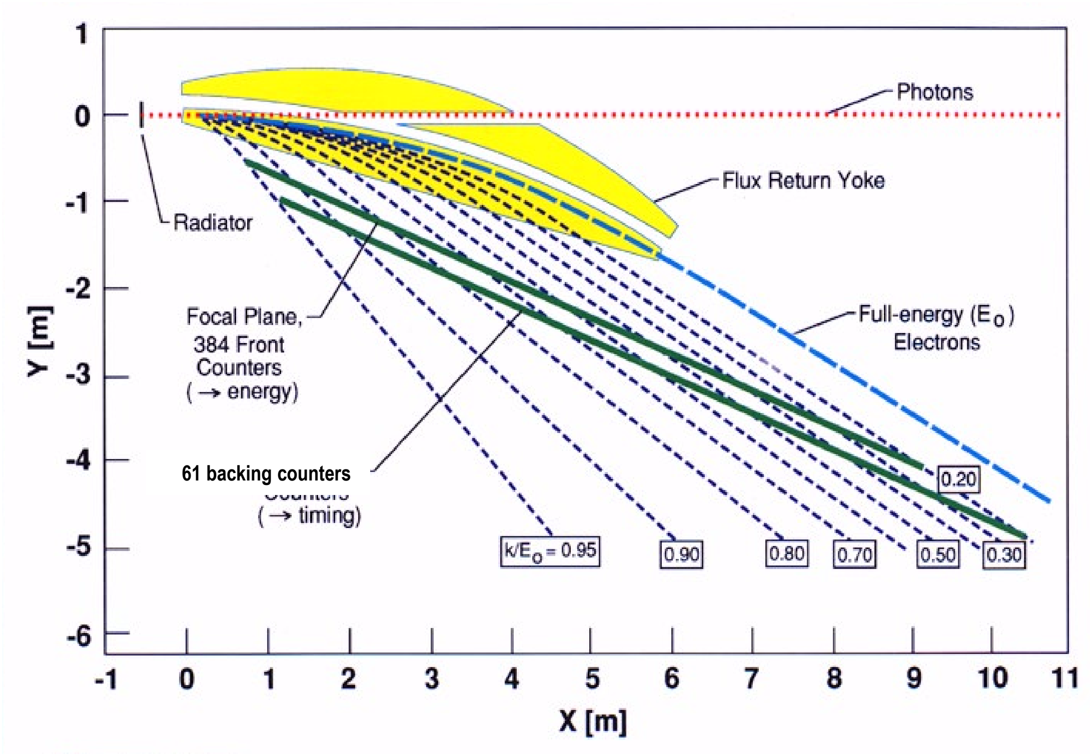


Lest we forget:

- CLAS was very good for detecting charged particles
- CLAS had a rather large acceptance



Bremsstrahlung photon tagger (also deceased)



- Jefferson Lab Hall B bremsstrahlung photon tagger had:
  - E_γ = 20-95% of E_0
  - E_γ up to ~5.5 GeV

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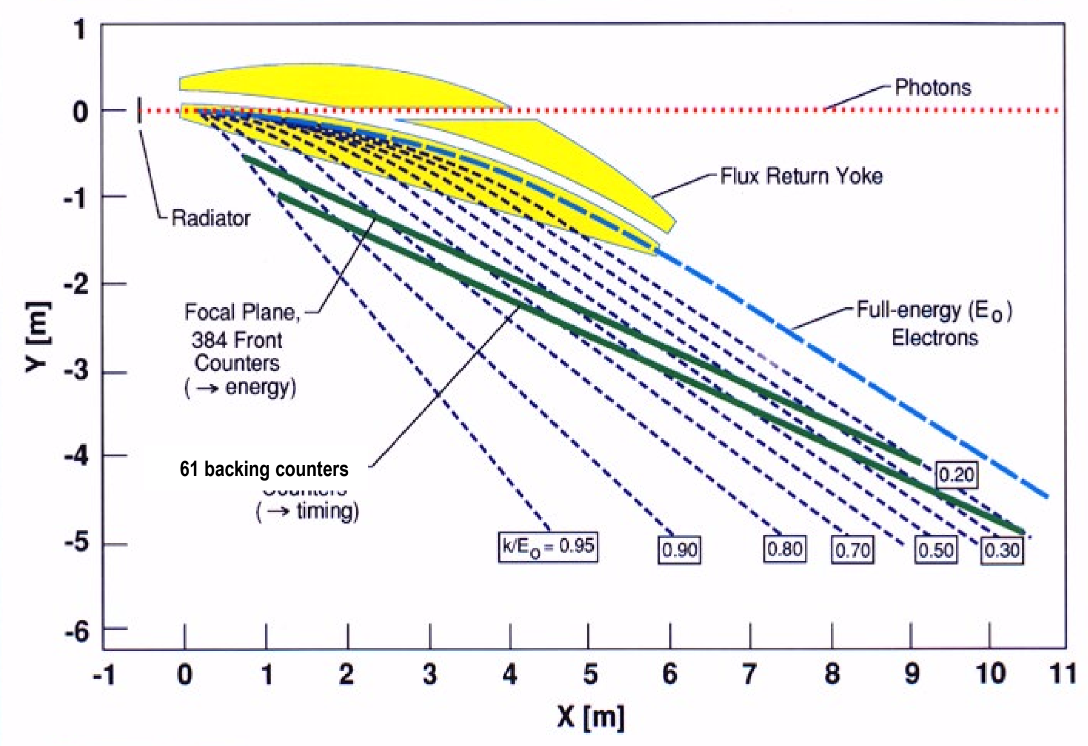

- Jefferson Lab Hall B bremsstrahlung photon tagger had:
  - E_γ = 20-95% of E_0
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  - **Circular polarized photons with longitudinally polarized electrons**

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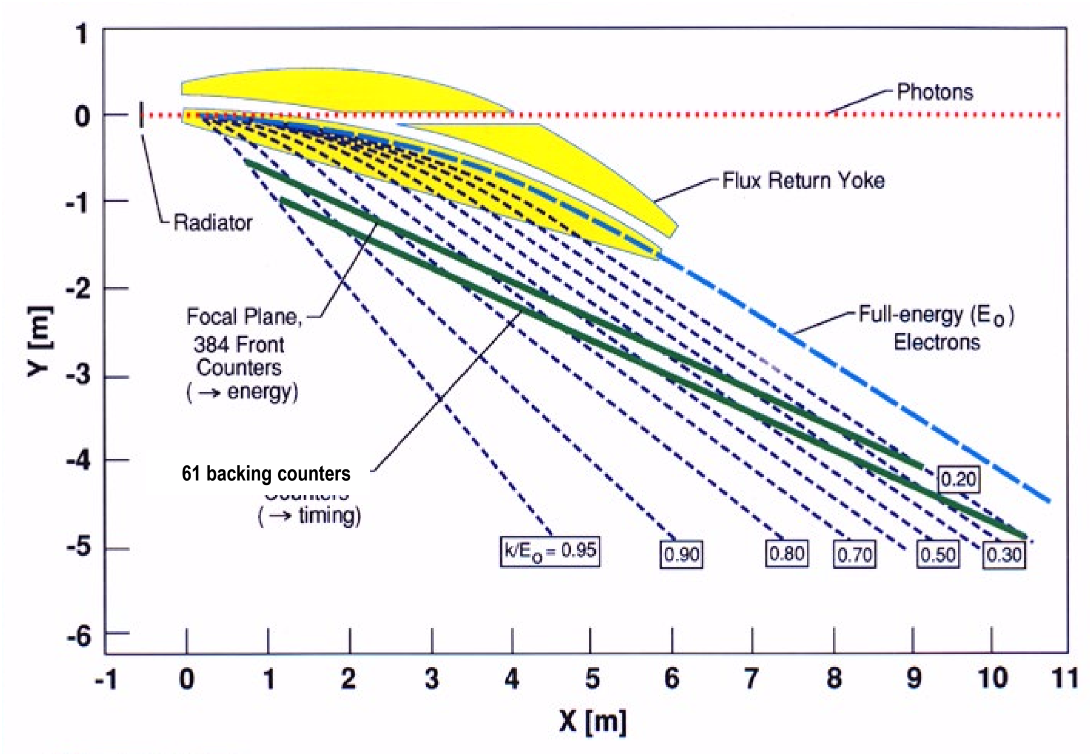
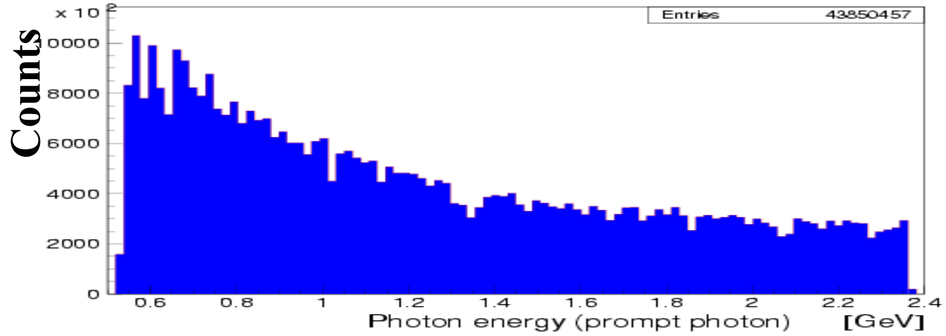
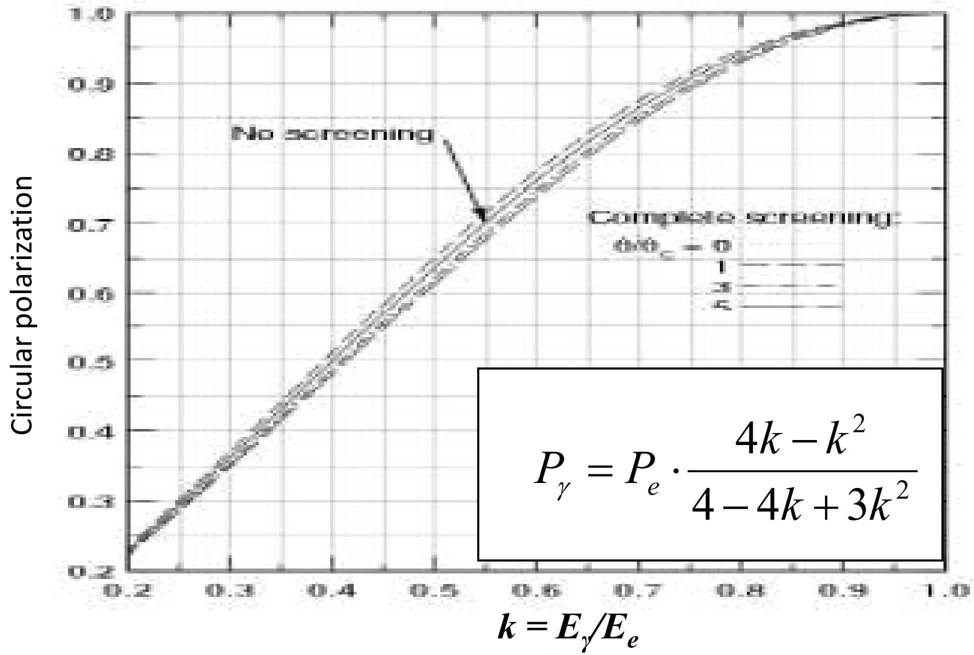


- Jefferson Lab Hall B bremsstrahlung photon tagger had:
  - E_γ = 20-95% of E_0
  - E_γ up to ~5.5 GeV
  - **Circular polarized photons with longitudinally polarized electrons**
  - **Oriented diamond crystal for linearly polarized photons**

Circular beam polarization



Circular polarization from 100% polarized electron beam

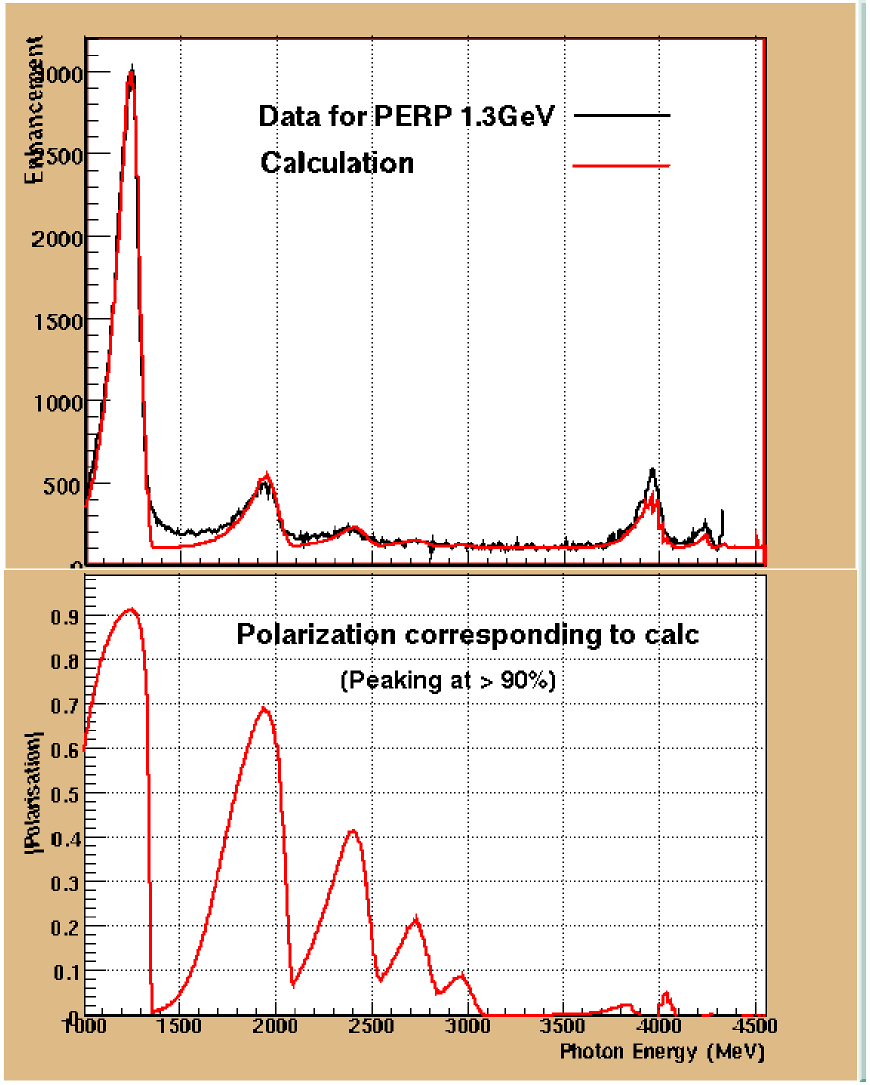


$$P_\gamma = P_e \cdot \frac{4k - k^2}{4 - 4k + 3k^2}$$

H. Olsen and L.C. Maximon, Phys. Rev. 114, 887 (1959)

- Circular photon beam from longitudinally-polarized electrons
- Incident electron beam polarization > 85%

Linearly polarized photons



- Coherent bremsstrahlung from 50-μ oriented diamond

- Two linear polarization states (vertical & horizontal)

- Analytical QED coherent bremsstrahlung calculation fit to actual spectrum (Livingston/Glasgow)

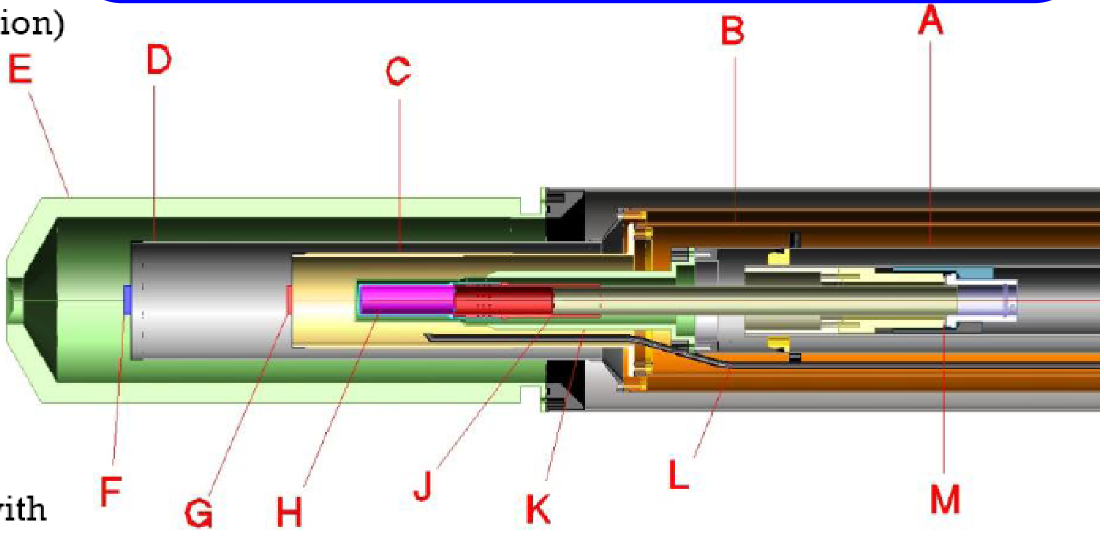
- Vertical 1.3 GeV edge shown

FROST target

- Butanol composition: C_4H_9OH
- C and O are even-even nuclei → No polarization of the bound nucleons

The FroST target and its components:

A: Primary heat exchanger
B: 1 K heat shield
C: Holding coil
D: 20 K heat shield
E: Outer vacuum can (Rohacell extension)
F: CH2 target
G: Carbon target
H: Butanol target
J: Target insert
K: Mixing chamber
L: Microwave waveguide
M: Kapton coldseal

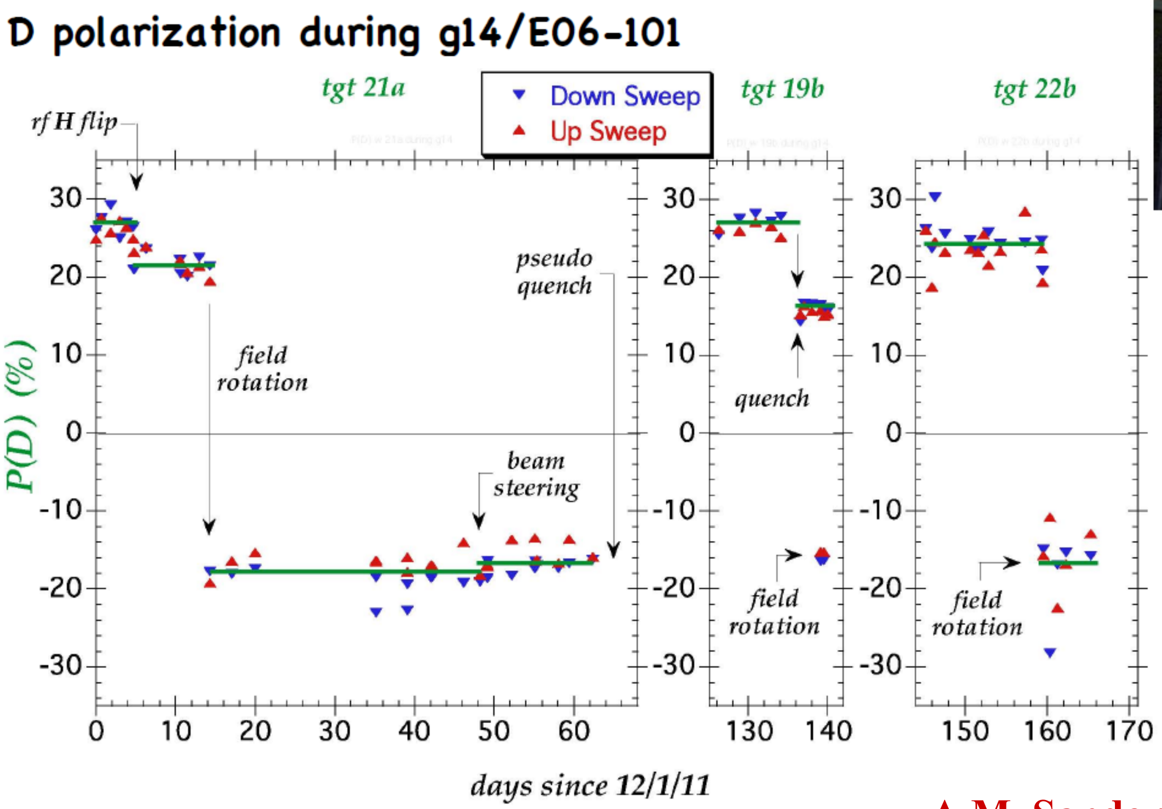


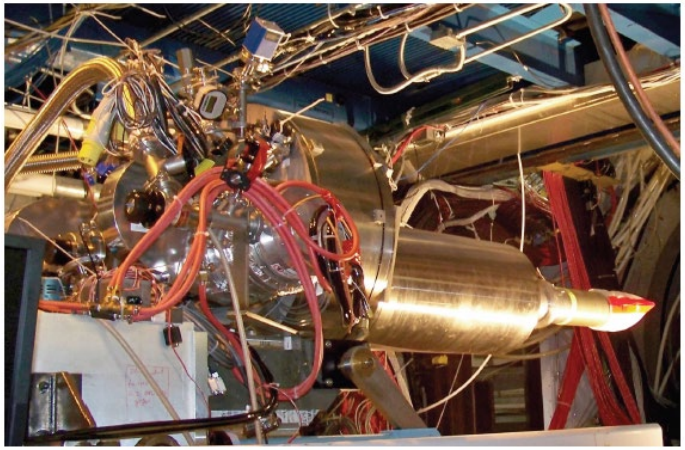
Performance Specs:

Base Temp: 28 mK w/o beam, 30 mK with
Cooling Power: 800 µW @ 50 mK, 10 mW @ 100 mK, and 60 mW @ 300 mK
Polarization: +82%, -90%
1/e Relaxation Time: 2800 hours (+Pol), 1600 hours (-Pol)
Roughly 1% polarization loss per day.

- Carbon target used to represent bound nucleon contribution of butanol

HD-ICE target





- Deuteron target

A.M. Sandorfi

Outline

- Motivations
- Helicity amplitudes
- Experimental facilities
- **Reactions and results**

Pion photoproduction

Isospin combinations for reactions involving π^0 and π^+

- Differing isospin compositions for N^* and Δ^+ for the $\pi^0\, p$ and $\pi^+\, n$ final states
- The $\pi^0\, p$ and $\pi^+\, n$ final states can help distinguish between the Δ and N^*

$$\pi^0 + p : \sqrt{2/3}\,\overset{\overset{\Delta^+}{\downarrow}}{\left|I = \tfrac{3}{2}, I_3 = \tfrac{1}{2}\right\rangle} - \sqrt{1/3}\,\overset{\overset{N^*}{\downarrow}}{\left|I = \tfrac{1}{2}, I_3 = \tfrac{1}{2}\right\rangle}$$

$$\pi^+ + n : \sqrt{1/3}\left|I = \tfrac{3}{2}, I_3 = \tfrac{1}{2}\right\rangle + \sqrt{2/3}\left|I = \tfrac{1}{2}, I_3 = \tfrac{1}{2}\right\rangle$$

Isospin photo-couplings

- Using both proton and neutron targets allows decomposition of iso-singlet and iso-vector photo-couplings C^0, C^1

Example:

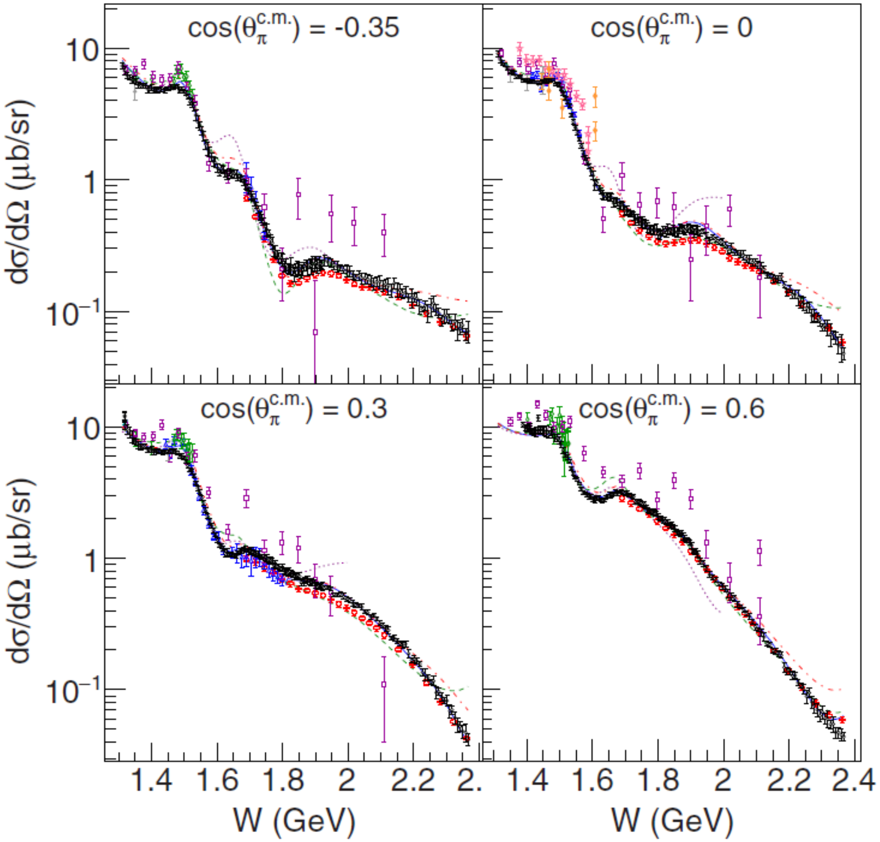
$$\gamma p \rightarrow n\pi^+: \qquad \pm\sqrt{\tfrac{2}{3}}\left[C^0 \ominus \sqrt{\tfrac{1}{3}}C^1\right]N^* + \tfrac{\sqrt{2}}{3}C\Delta^*$$

$$\gamma n \rightarrow p\pi^-: \qquad \mp\sqrt{\tfrac{2}{3}}\left[C^0 \oplus \sqrt{\tfrac{1}{3}}C^1\right]N^* + \tfrac{\sqrt{2}}{3}C\Delta^*$$

Observable: σ

G13

Reaction: $\gamma\, n \rightarrow p\, \pi^-$



- First-ever determination of the excited neutron multipoles for: *N*(1440)1/2$^+$, *N*(1535)1/2$^-$, *N*(1650)1/2-, and *N*(1720)3/2$^+$

Jefferson Lab

P.T. Mattione, *et al.*, (CLAS Collaboration), Phys. Rev. C 96, 035204 (2017)

Observable: Σ

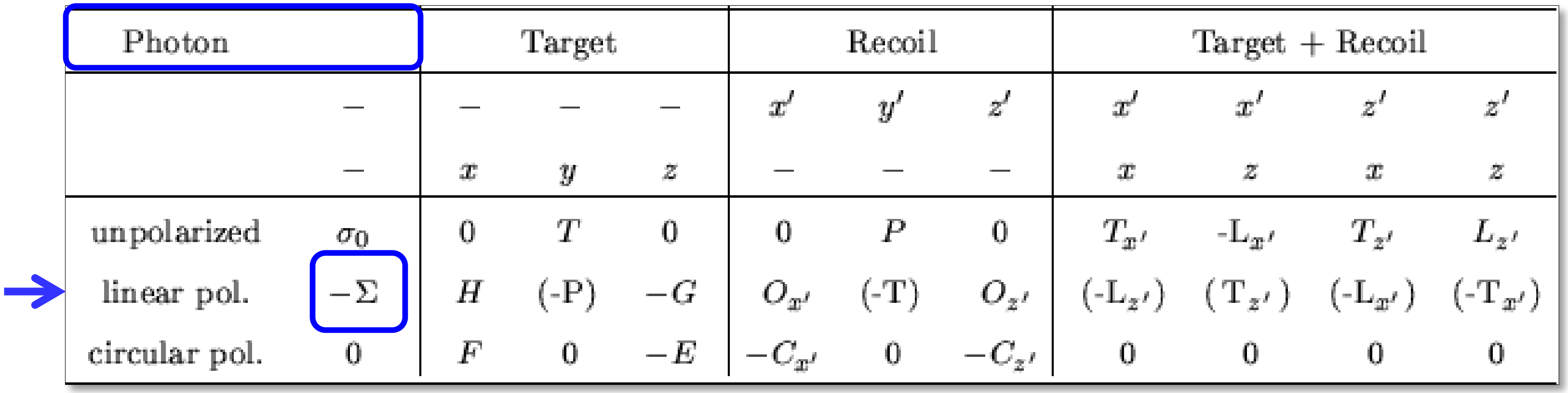
Reactions: $\gamma\, p \rightarrow p\, \pi^0$ and $\gamma\, p \rightarrow n\, \pi^+$

Configuration:

- **Linear photon polarization**
- No target polarization
- No recoil polarization

Experiments:

- g8b → proton reactions
- g13 → neutron reactions

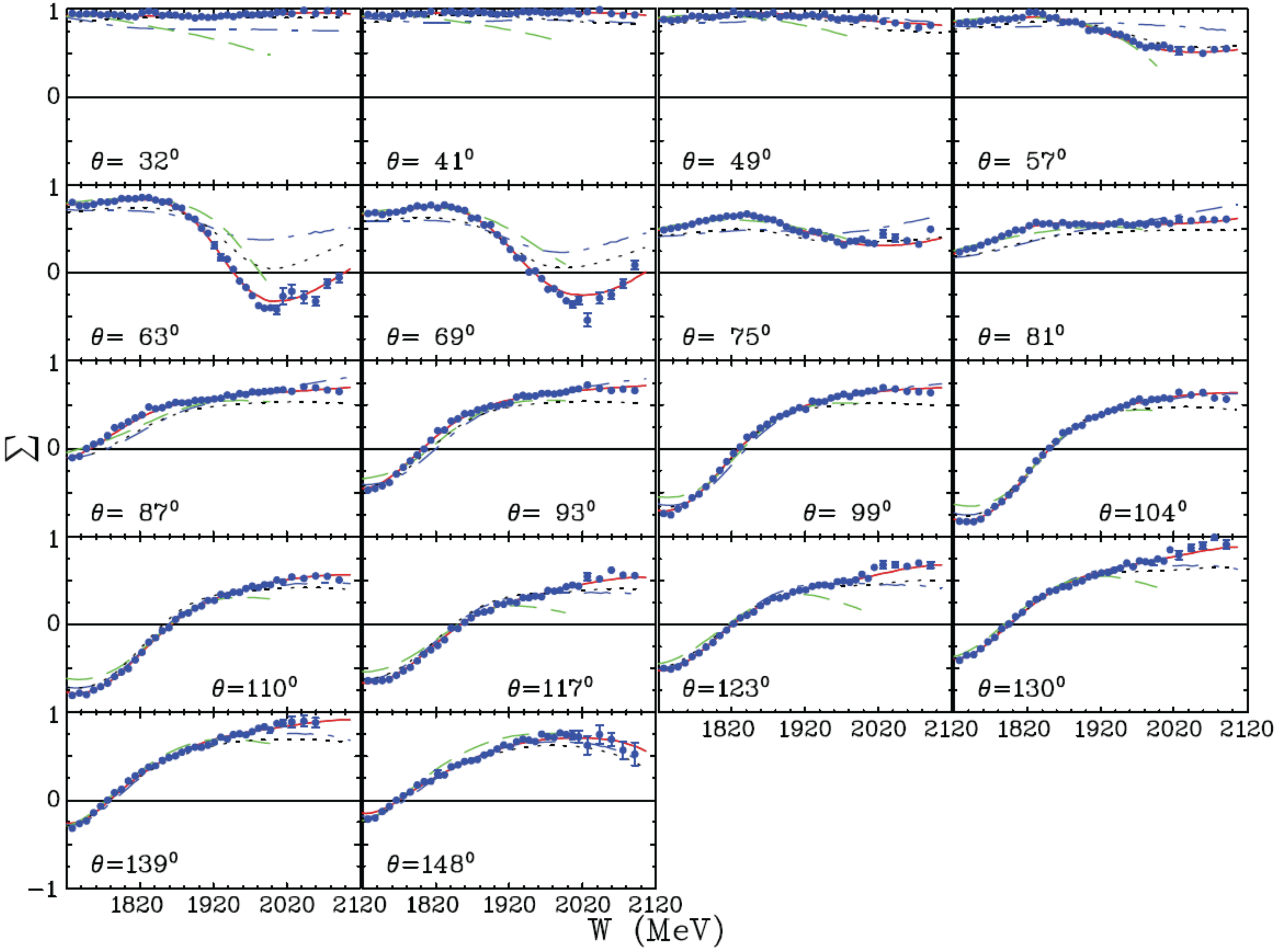


Photon		Target			Recoil			Target + Recoil			
	–	–	–	–	x'	y'	z'	x'	x'	z'	z'
	–	x	y	z	–	–	–	x	z	x	z
unpolarized	σ_0	0	T	0	0	P	0	$T_{x'}$	-$L_{x'}$	$T_{z'}$	$L_{z'}$
linear pol.	$-\Sigma$	H	(-P)	$-G$	$O_{x'}$	(-T)	$O_{z'}$	(-$L_{z'}$)	($T_{z'}$)	(-$L_{x'}$)	(-$T_{x'}$)
circular pol.	0	F	0	$-E$	$-C_{x'}$	0	$-C_{z'}$	0	0	0	0

Σ for $\gamma\, p \rightarrow p\, \pi^0$

G8b

RED: SAID fit

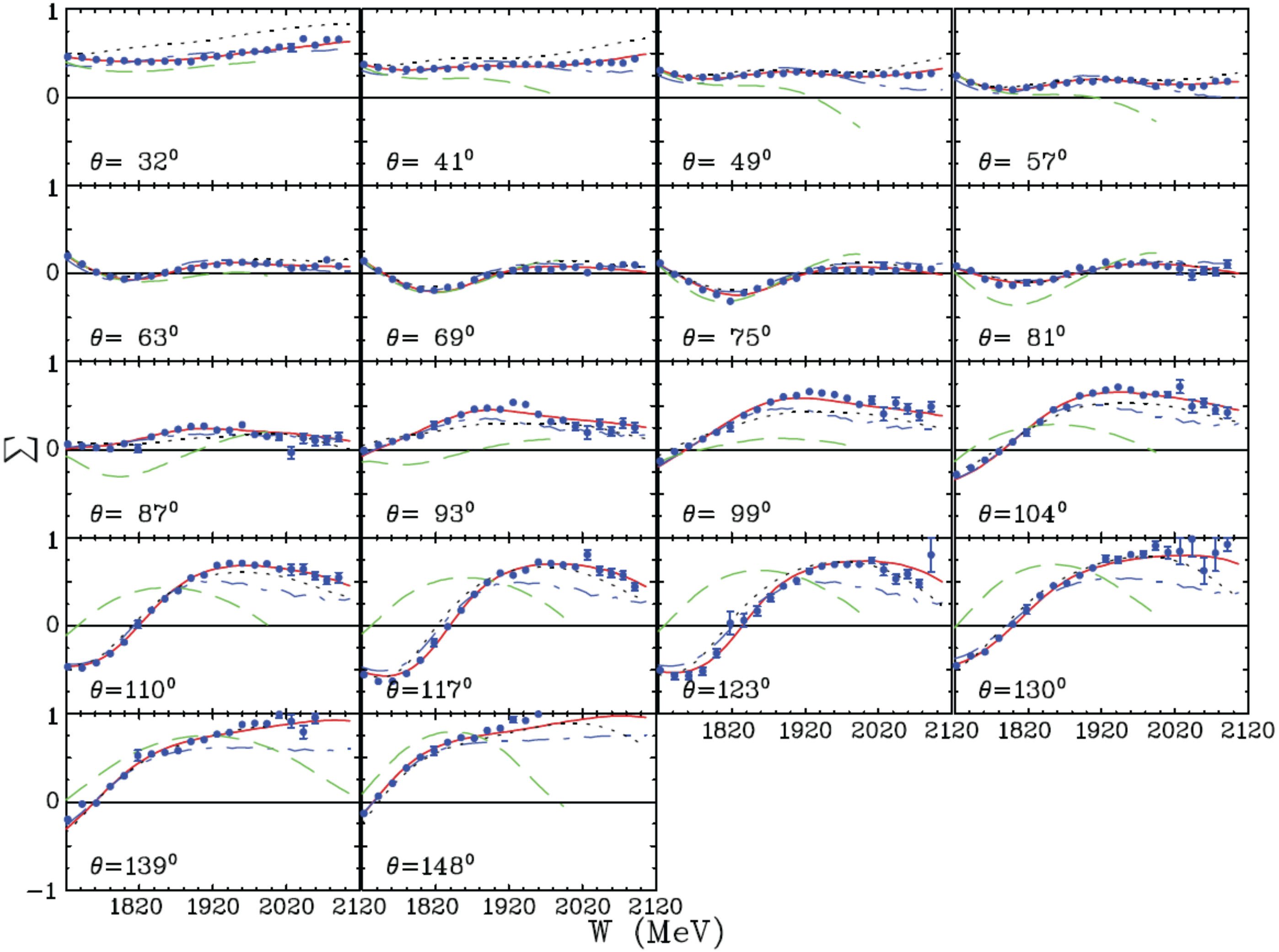


M. Dugger, *et al.*, (CLAS Collaboration), Phys. Rev. C88, 065203 (2013))

Σ for $\gamma\, p \rightarrow n\, \pi^+$

G8b

RED: SAID fit



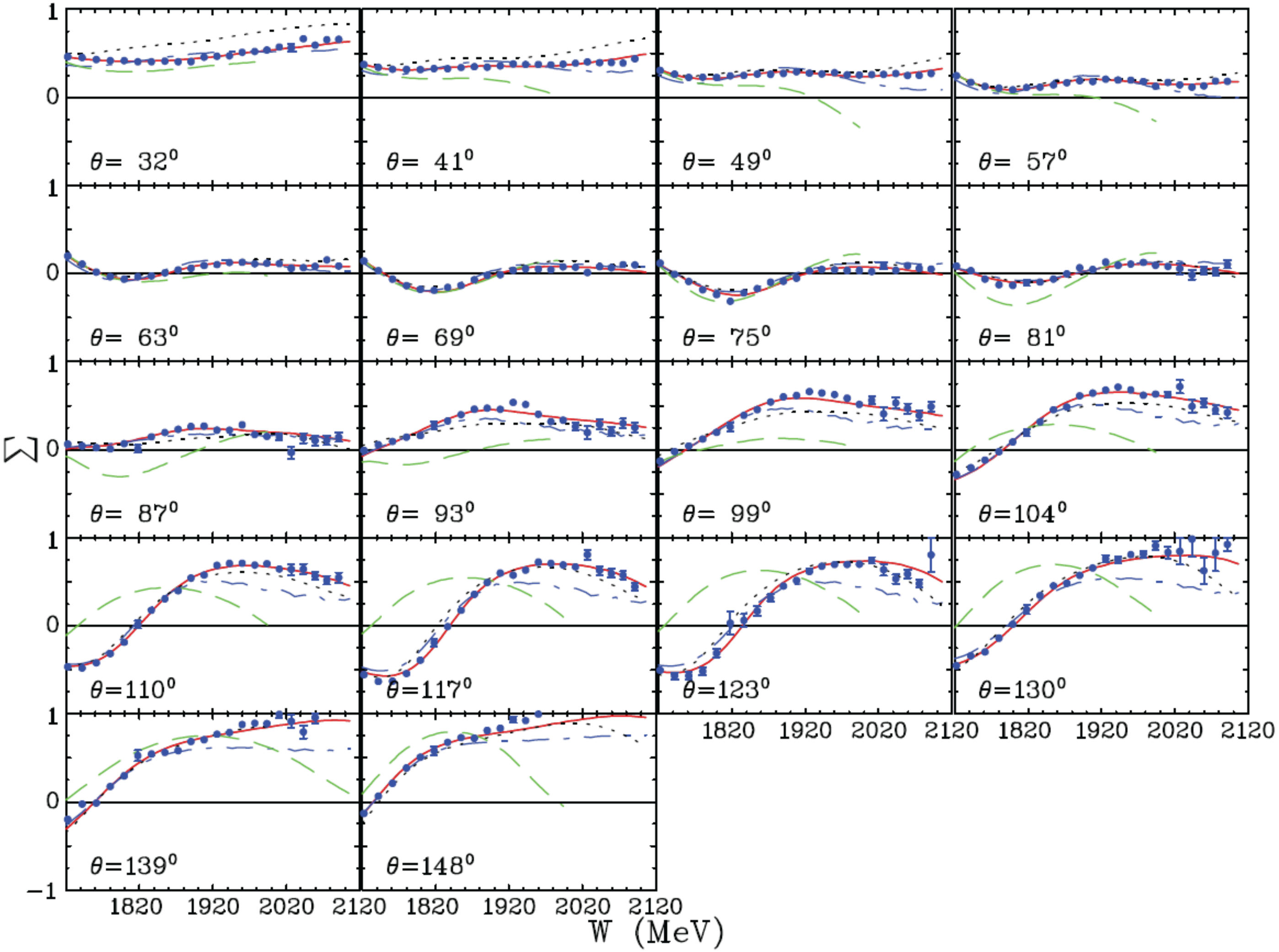
- Data for both reactions more than doubled the world database

M. Dugger, *et al.*, (CLAS Collaboration), Phys. Rev. C88, 065203 (2013)

Σ for $\gamma\, p \rightarrow n\, \pi^+$

G8b

RED: SAID fit



- Largest change from fits to prior Σ data for pions found in resonance couplings of $\Delta(1700)3/2^-$ and $\Delta(1905)5/2^+$

M. Dugger, *et al.*, (CLAS Collaboration), Phys. Rev. C88, 065203 (2013)

Observable: *G*

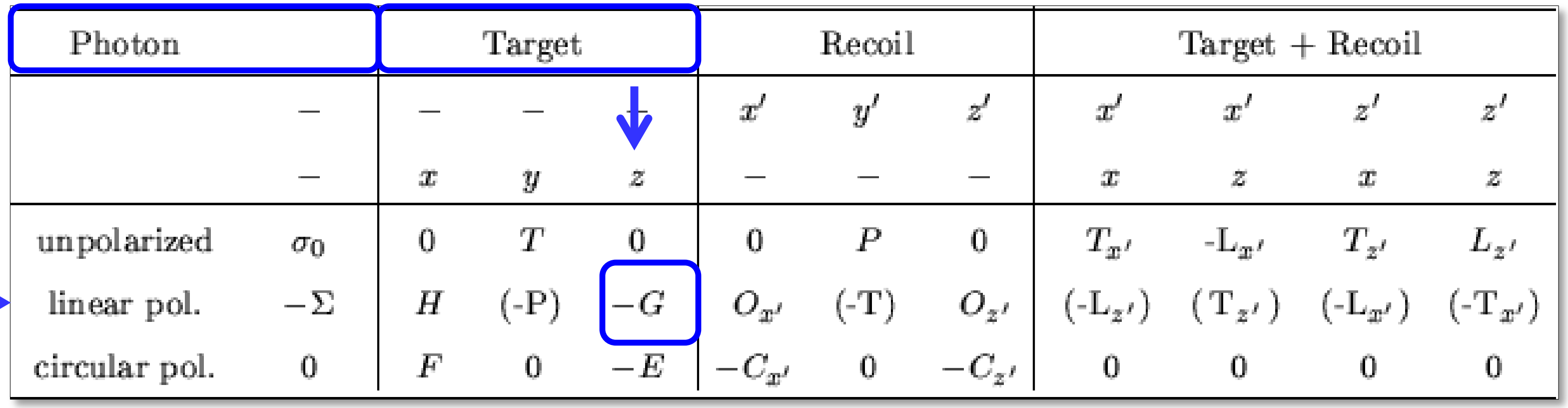
Reactions: $\gamma\, p \rightarrow p\, \pi^0$ and $\gamma\, p \rightarrow n\, \pi^+$

Configuration:

- **Linear photon polarization**
- **Longitudinal target polarization**
- No recoil polarization

Experiment:

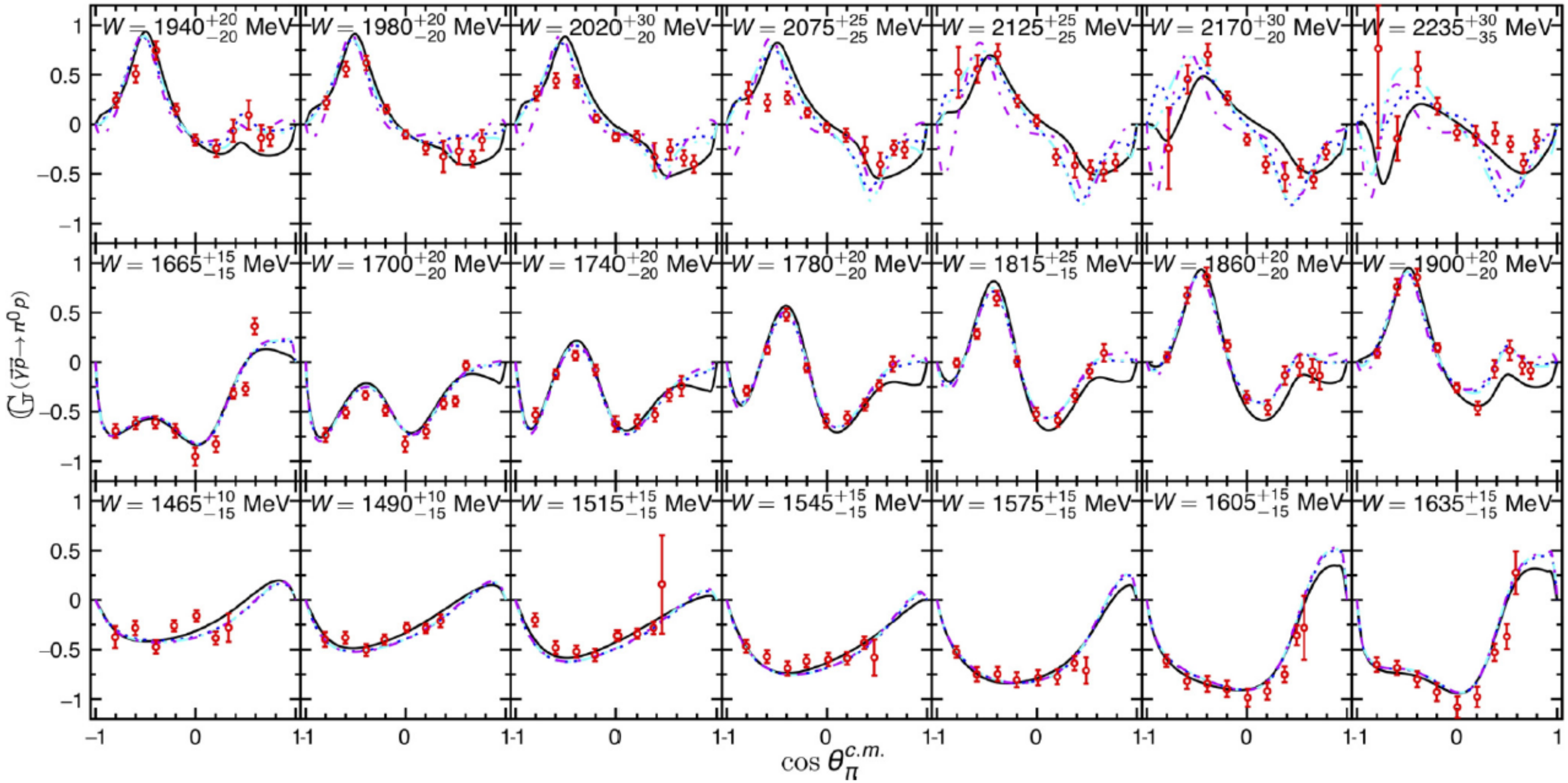
- g9b: FROST



Photon		Target			Recoil			Target + Recoil			
	–	–	–	–	x'	y'	z'	x'	x'	z'	z'
	–	x	y	z	–	–	–	x	z	x	z
unpolarized	σ_0	0	T	0	0	P	0	$T_{x'}$	$-L_{x'}$	$T_{z'}$	$L_{z'}$
linear pol.	$-\Sigma$	H	(-P)	$\boxed{-G}$	$O_{x'}$	(-T)	$O_{z'}$	$(-L_{z'})$	$(T_{z'})$	$(-L_{x'})$	$(-T_{x'})$
circular pol.	0	F	0	$-E$	$-C_{x'}$	0	$-C_{z'}$	0	0	0	0

G for $\gamma\, p \rightarrow p\, \pi^0$

G9b: FROST



SAID: Solid black lines

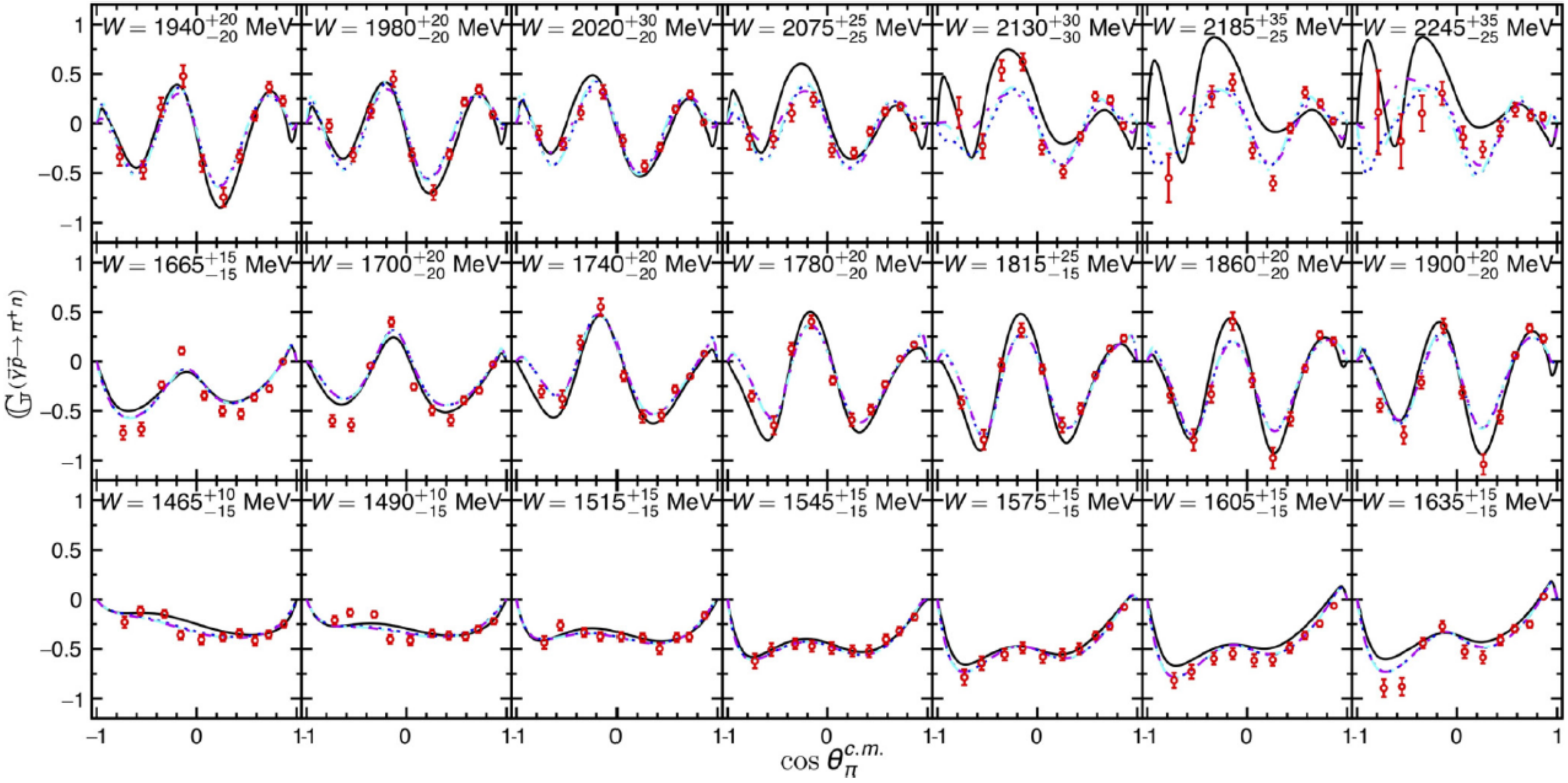
Bonn-Gatchina: Dotted lines of various colors

N. Zachariou, *et al.*, (CLAS Collaboration), Phys. Lett. B817, 136304 (2021)

UNIVERSITY of York

G for $\gamma\, p \rightarrow n\, \pi^+$

G9b: FROST



Bonn-Gatchina analysis (dotted) sees important contribution from *N*(2190)7/2$^-$ and *Δ*(2200)7/2$^-$

N. Zachariou, *et al.*, (CLAS Collaboration), Phys. Lett. B817, 136304 (2021)

Observables: *T* and *F*

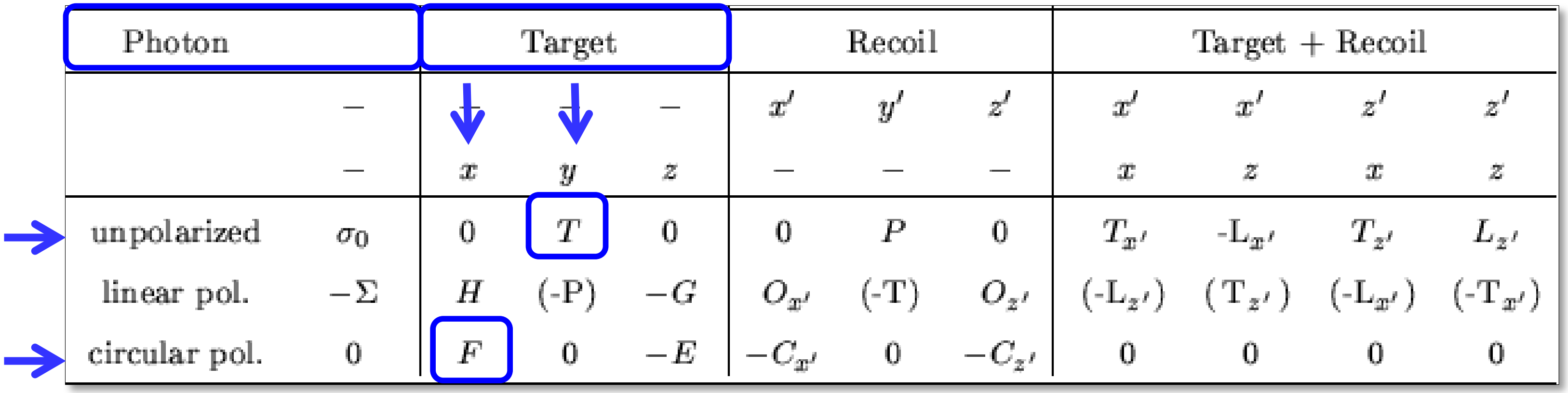
Reaction: $\gamma\, p \rightarrow n\, \pi^+$

Configuration:

- **Circular photon polarization**
- **Transverse target polarization**
- Unpolarized photon (by adding circular beams)
- No recoil polarization

Experiment:

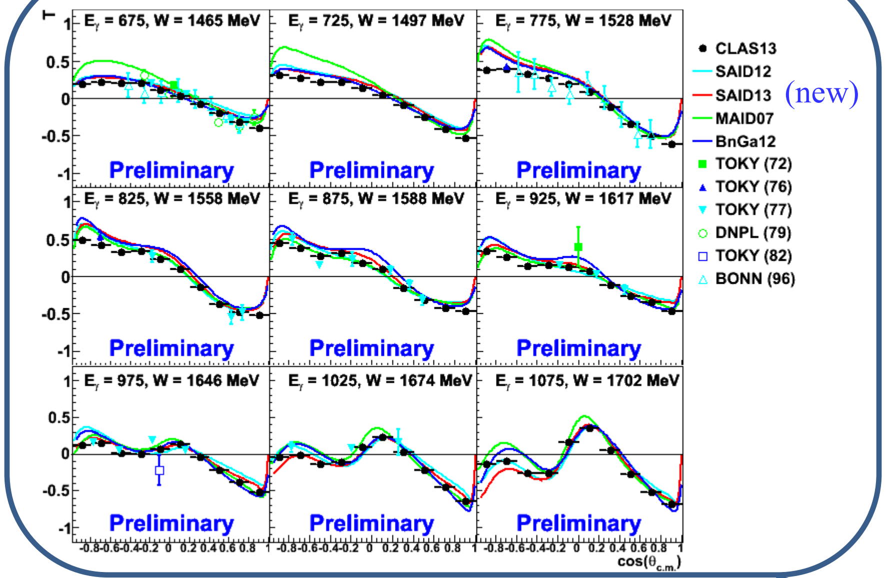
- g9b: FROST

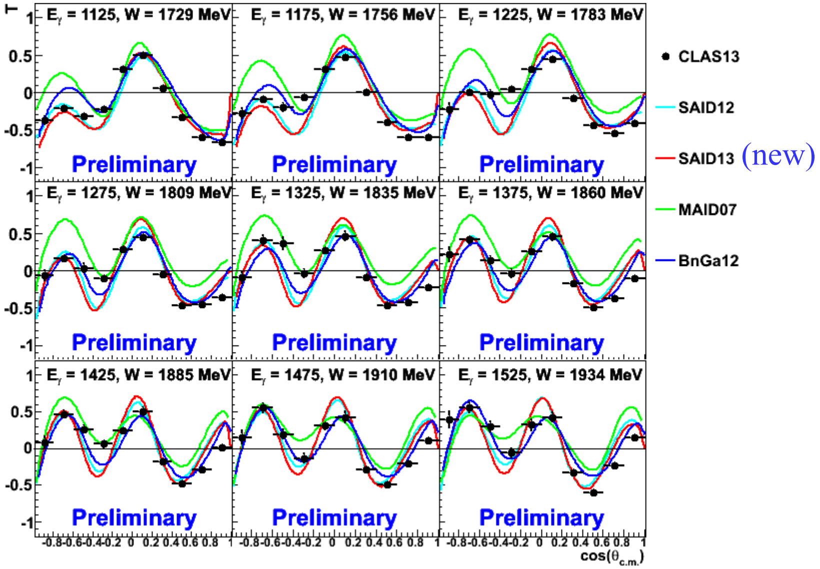


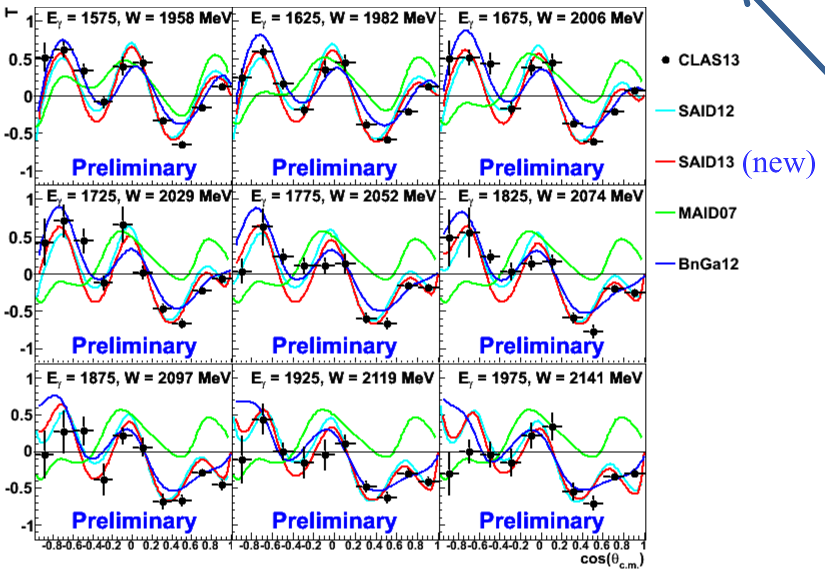
Photon		Target			Recoil			Target + Recoil			
	—	—	—	—	x'	y'	z'	x'	x'	z'	z'
	—	x	y	z	—	—	—	x	z	x	z
unpolarized	σ_0	0	T	0	0	P	0	$T_{x'}$	-$L_{x'}$	$T_{z'}$	$L_{z'}$
linear pol.	$-\Sigma$	H	(-P)	$-G$	$O_{x'}$	(-T)	$O_{z'}$	(-$L_{z'}$)	($T_{z'}$)	(-$L_{x'}$)	(-$T_{x'}$)
circular pol.	0	F	0	$-E$	$-C_{x'}$	0	$-C_{z'}$	0	0	0	0

T for $\gamma\, p \rightarrow n\, \pi^+$

G9b: FROST



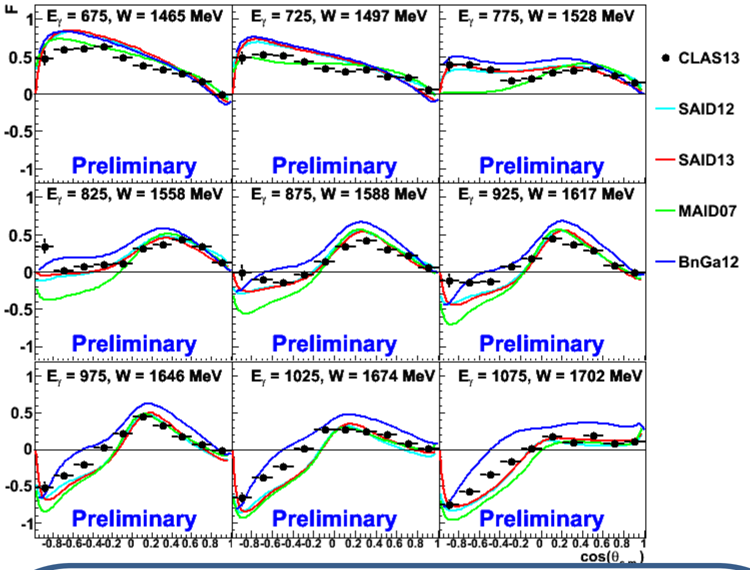


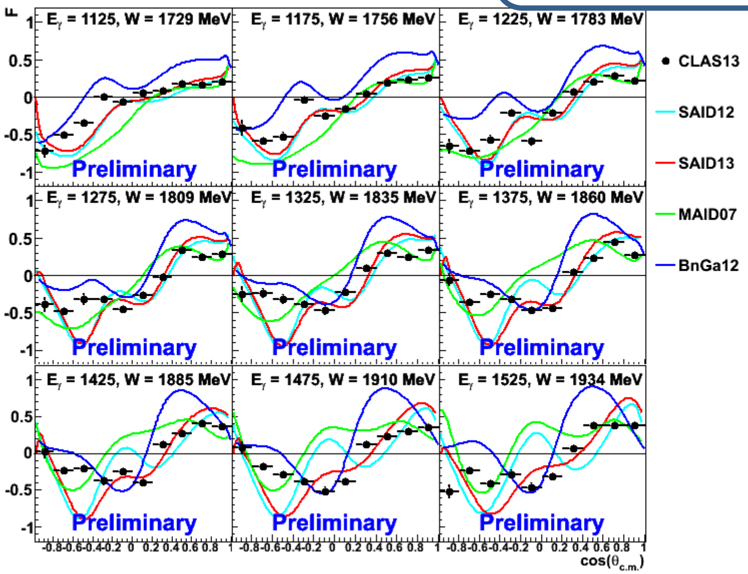


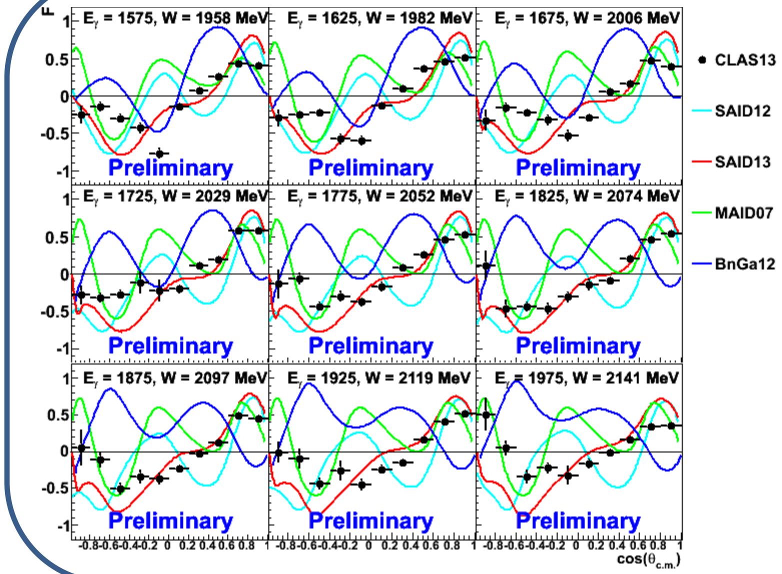
- Early stage results
- CLAS results agree well with previous data

F for $\gamma\, p \rightarrow n\, \pi^+$

G9b: FROST







- Early stage results
- Predictions get worse at higher energies

ARIZONA STATE UNIVERSITY

Observable: *E*

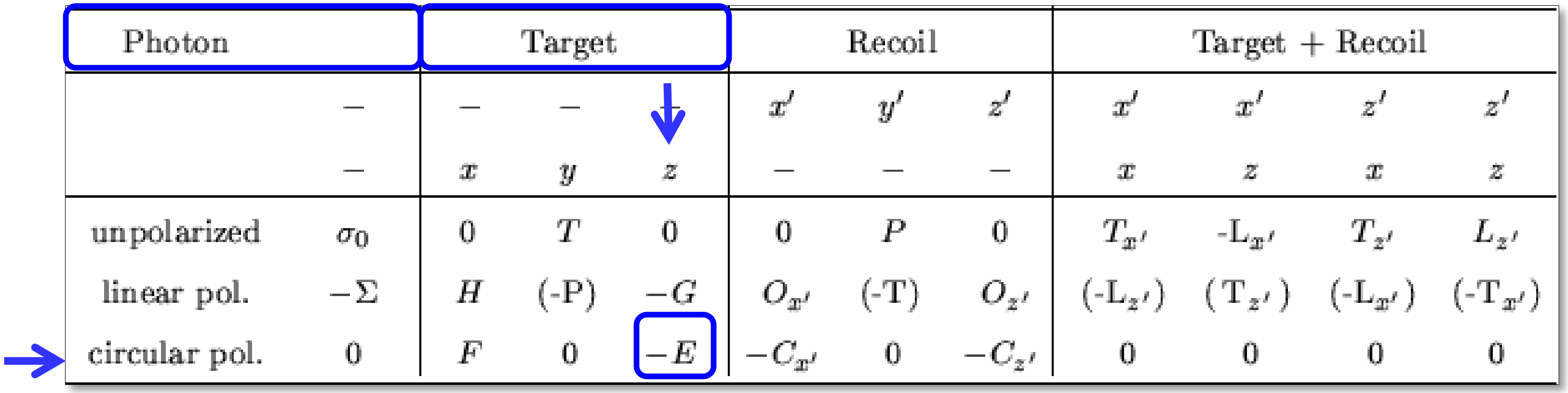
Reactions: $\gamma\, p \to n\, \pi^+,\, p\, \pi^0$ and $\gamma\, n \to p\, \pi^-$

Configuration:

- **Circular photon polarization**
- **Longitudinal Target polarization**
- No recoil polarization

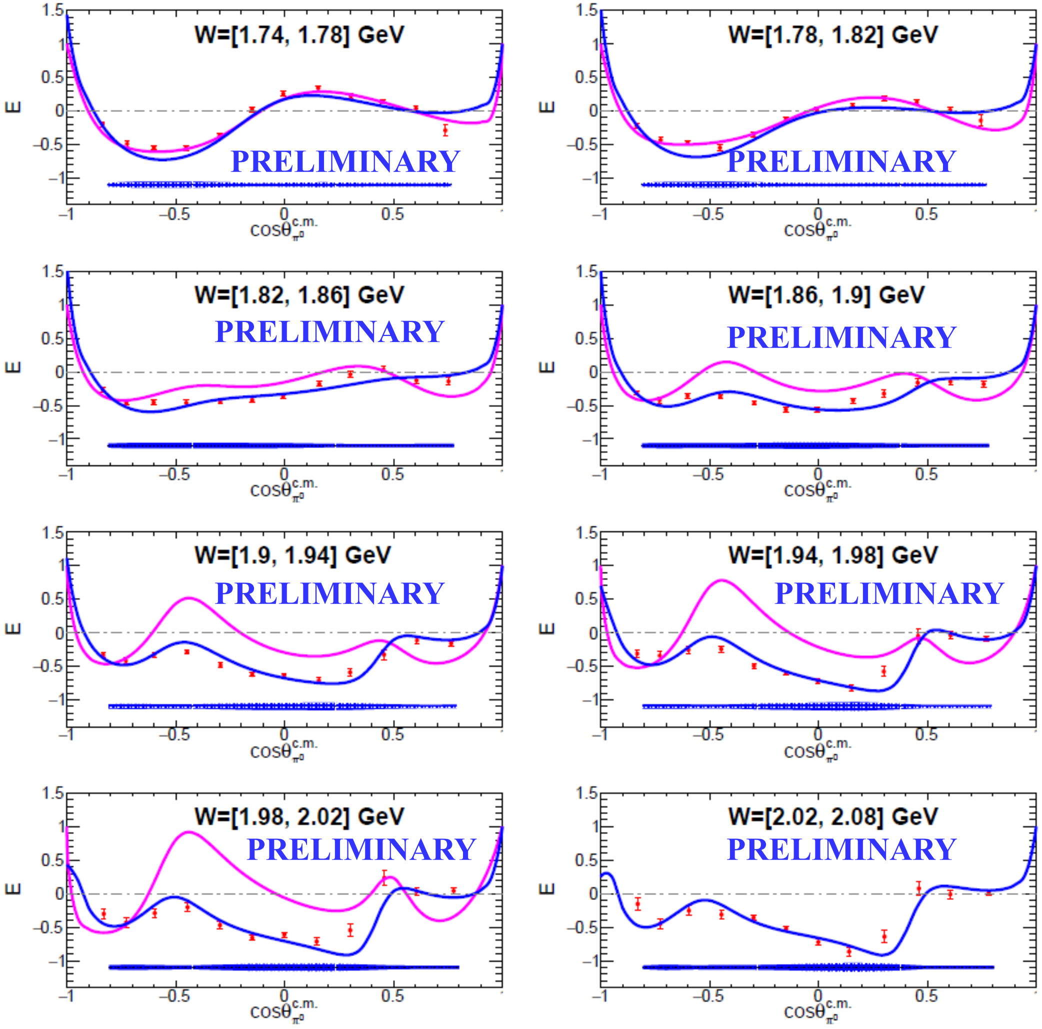
Experiments:

- g9a: FROST → proton reactions
- g14: HDICE → neutron reactions



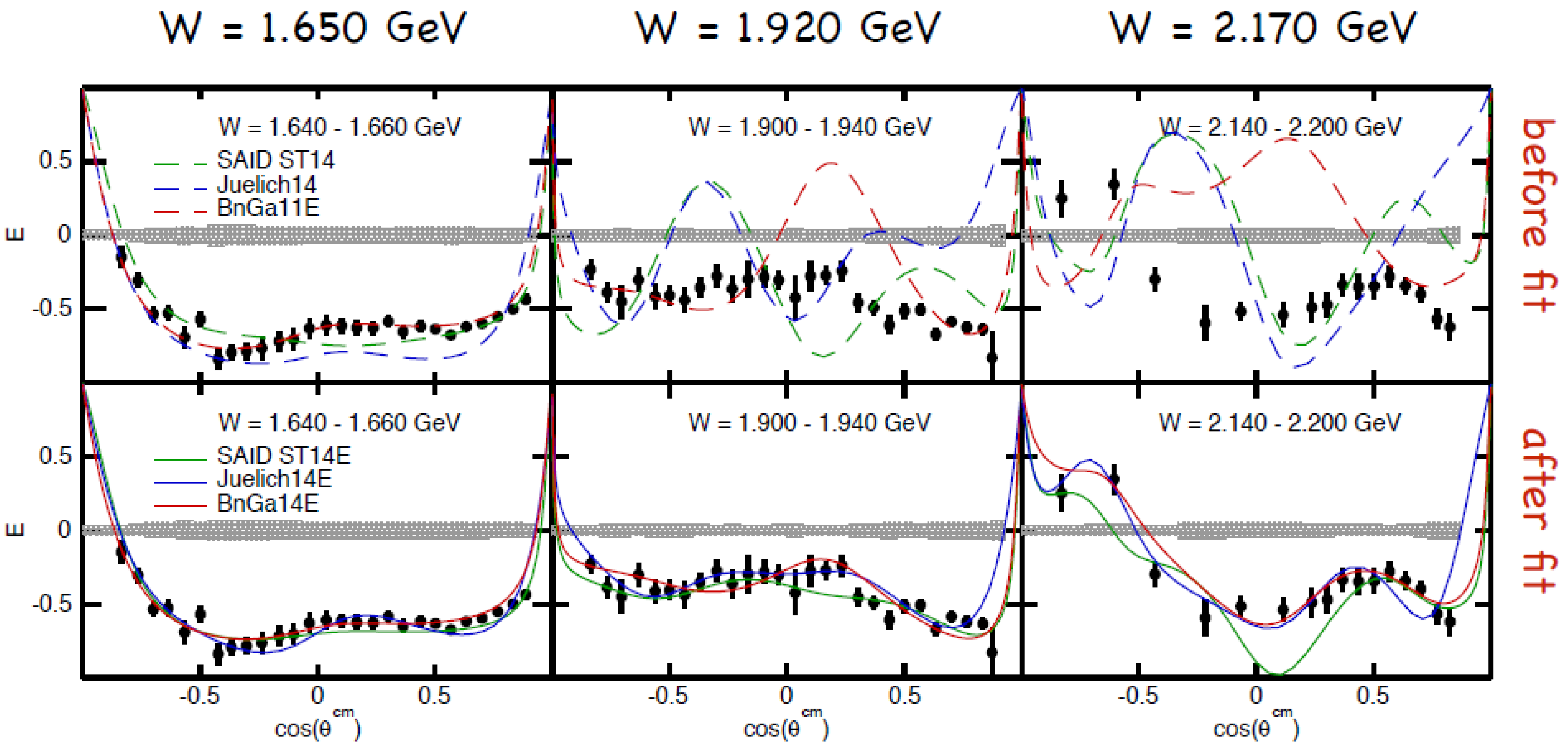
Photon		Target			Recoil			Target + Recoil			
	—	—	—	—	x'	y'	z'	x'	x'	z'	z'
	—	x	y	z	—	—	—	x	z	x	z
unpolarized	σ_0	0	T	0	0	P	0	$T_{x'}$	$-L_{x'}$	$T_{z'}$	$L_{z'}$
linear pol.	$-\Sigma$	H	(-P)	$-G$	$O_{x'}$	(-T)	$O_{z'}$	$(-L_{z'})$	$(T_{z'})$	$(-L_{x'})$	$(-T_{x'})$
circular pol.	0	F	0	$-E$	$-C_{x'}$	0	$-C_{z'}$	0	0	0	0

E for $\gamma\, p \rightarrow p\, \pi^0$



- Sample of results taken from analysis note
- **Blue** lines: SAID
- **Magenta** lines: MAID

Selected results of FROST Experiment $\vec{\gamma}\vec{p} \rightarrow \pi^+ n$

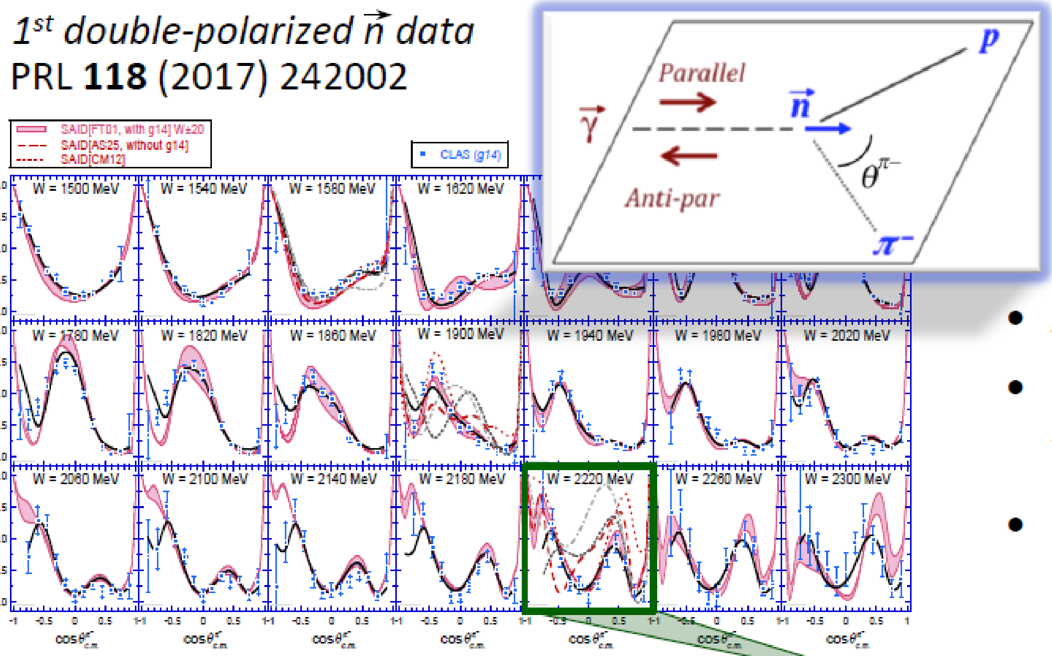


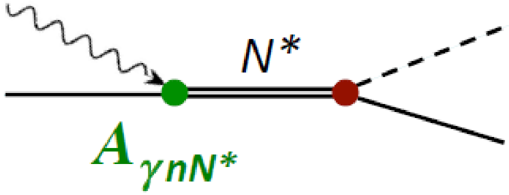
- FROST experiment produced 900 data points of the **double-polarization observable E** in π^+ photoproduction with circularly polarized beam on longitudinally polarized protons for W = 1240 - 2260 MeV.
- Significant improvements of the description of the data in SAID, Jülich, and BnGa partial-wave analyses after fitting.
- New evidence found in this data for a Δ(2200)7/2⁻ resonance (BnGa analysis).

S. Strauch et al. (CLAS Collaboration), Phys. Lett. B **750**, 53 (2015) and A.V. Anisovich et al., arXiv:1503.05774.

g14 beam-target helicity asymmetries for $\gamma n \rightarrow \pi^- p$ and N states excited from the neutron*

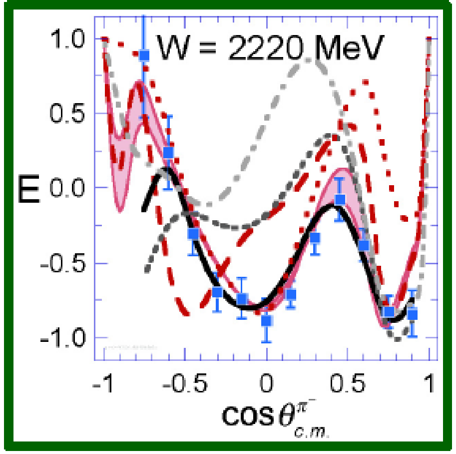
- *1st double-polarized $\vec{n}$ data*
  PRL **118** (2017) 242002



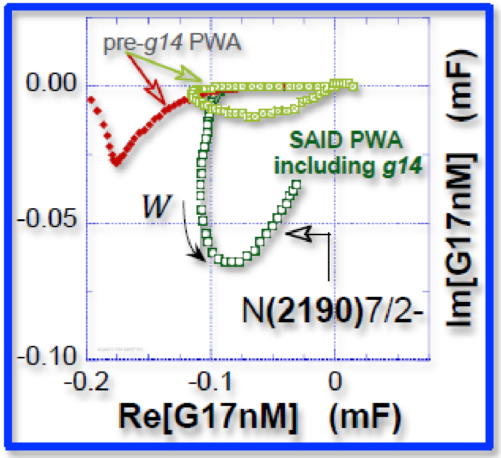


- E&M interaction is not isospin symmetric
- γnN^* and γpN^* couplings are different ⇔ probes of dynamics in N* excitation
- *eg. SAID Partial Wave Analysis (PWA):*
  $A_{\gamma n}^{1/2}$ [N(2190)7/2-] ➔ **-16 ±5** (10^{-3} GeV$^{-1/2}$)
  $A_{\gamma n}^{3/2}$ [N(2190)7/2-] ➔ **-35 ±5** (10^{-3} GeV$^{-1/2}$)

- very little previous spin-dependent γ n data exists
- for invariant masses (W) over 1800 MeV, predictions from previous Partial Wave Analyses (PWA) fail badly
- $\vec{\gamma}\vec{n}$ data probes N* states



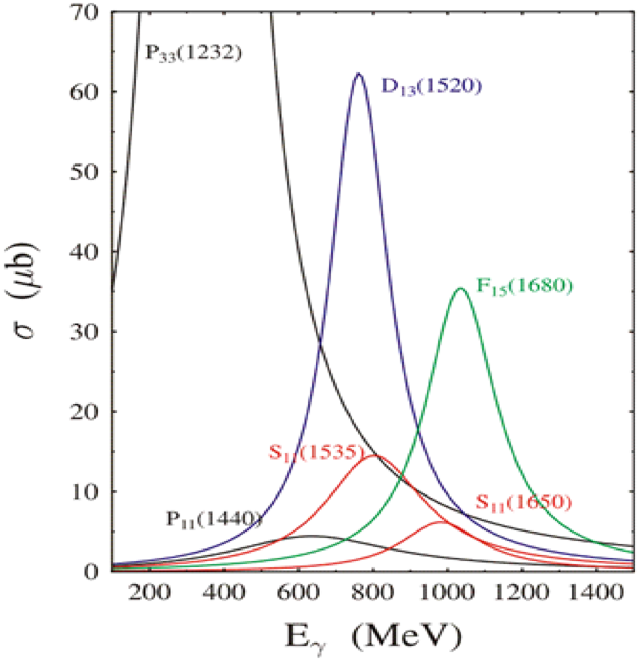
➔ PWA ➔



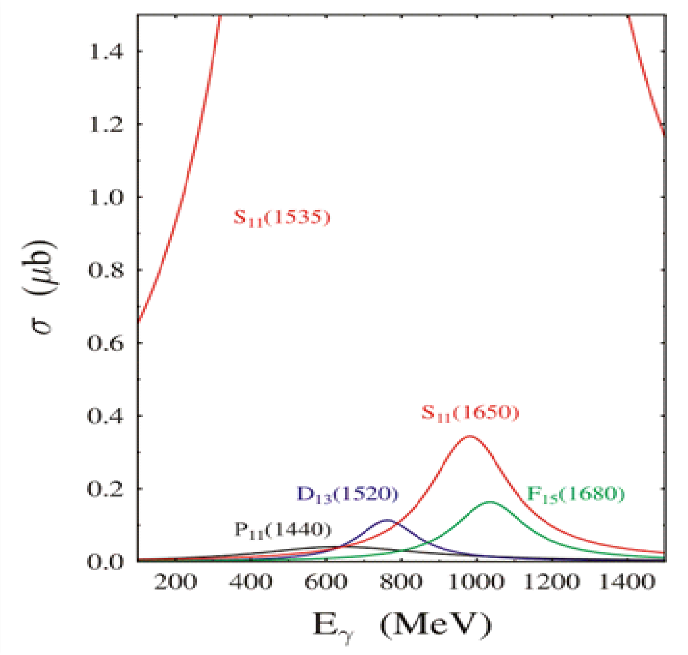
“Isospin filters”

- The *ηp, ωp* and $K^+\Lambda$ systems have isospin ½ and limit one-step excited states of the proton to be isospin ½. The final states *ηp, ωp,* and $K^+\Lambda$ act as **isospin filters** to the resonance spectrum.

$\gamma\, p \longrightarrow \pi^+\, n$

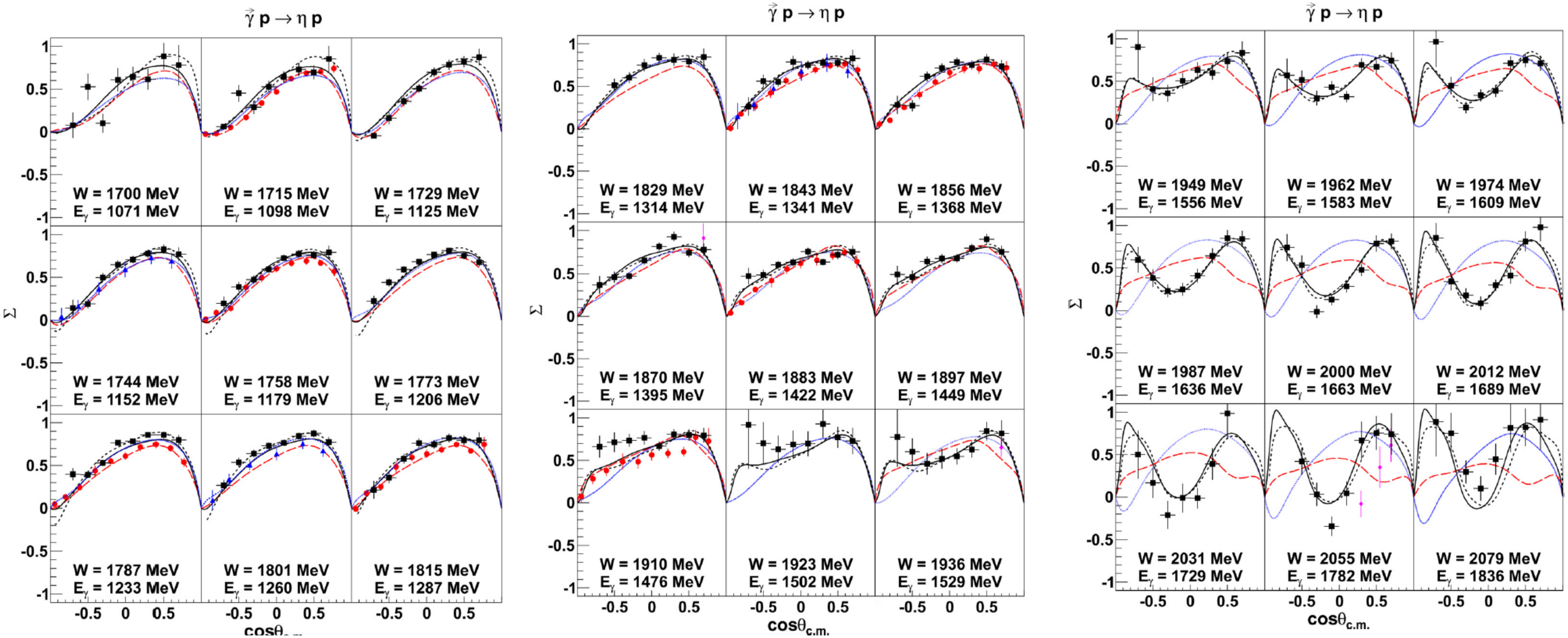


$\gamma\, p \longrightarrow \eta\, p$



Σ for η

G8b



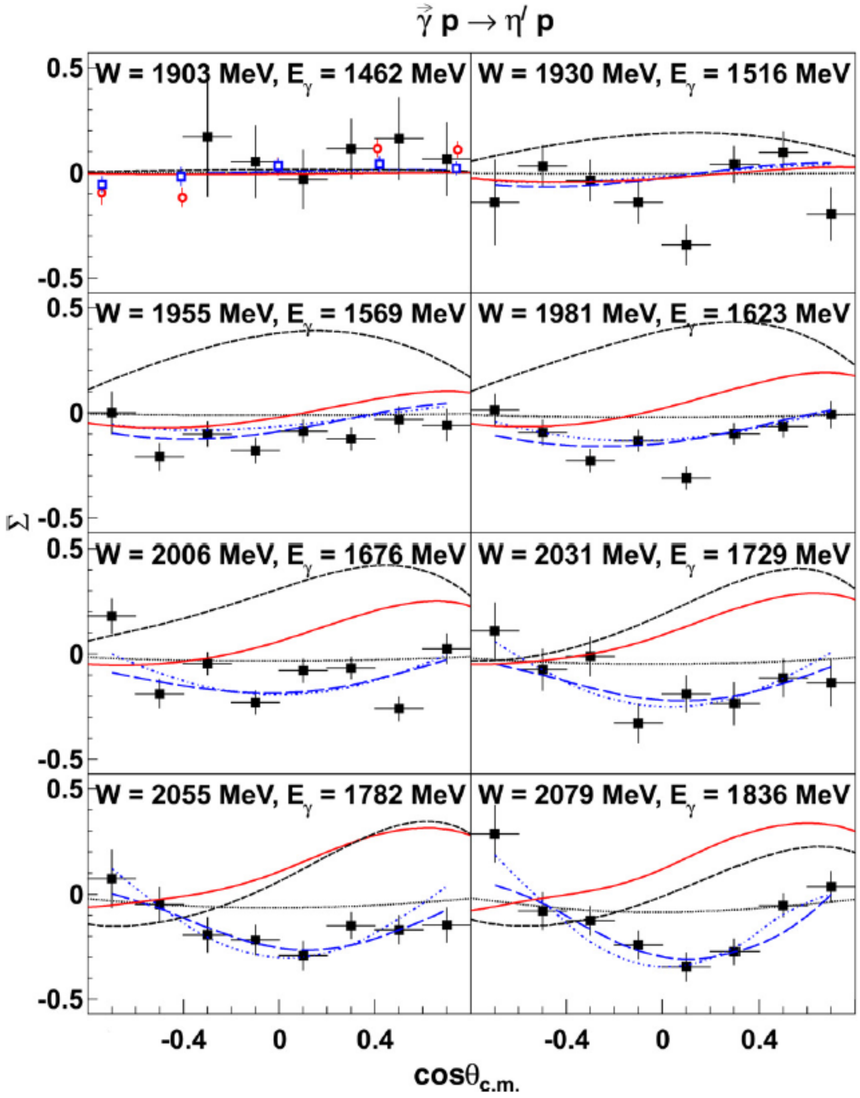
- Fit to Julich Bonn model (black line) with presence of *N*(1900)3/2$^-$ (solid) and without (dashed)

- The inclusion of the *N*(1900)3/2+ was found to be important by Bonn-Gatchina for *KΛ* and *KΣ* photoproduction

P. Collins, *et al.*, (CLAS Collaboration), Phys. Lett. B 771, 213-221 (2017)

Σ for η'

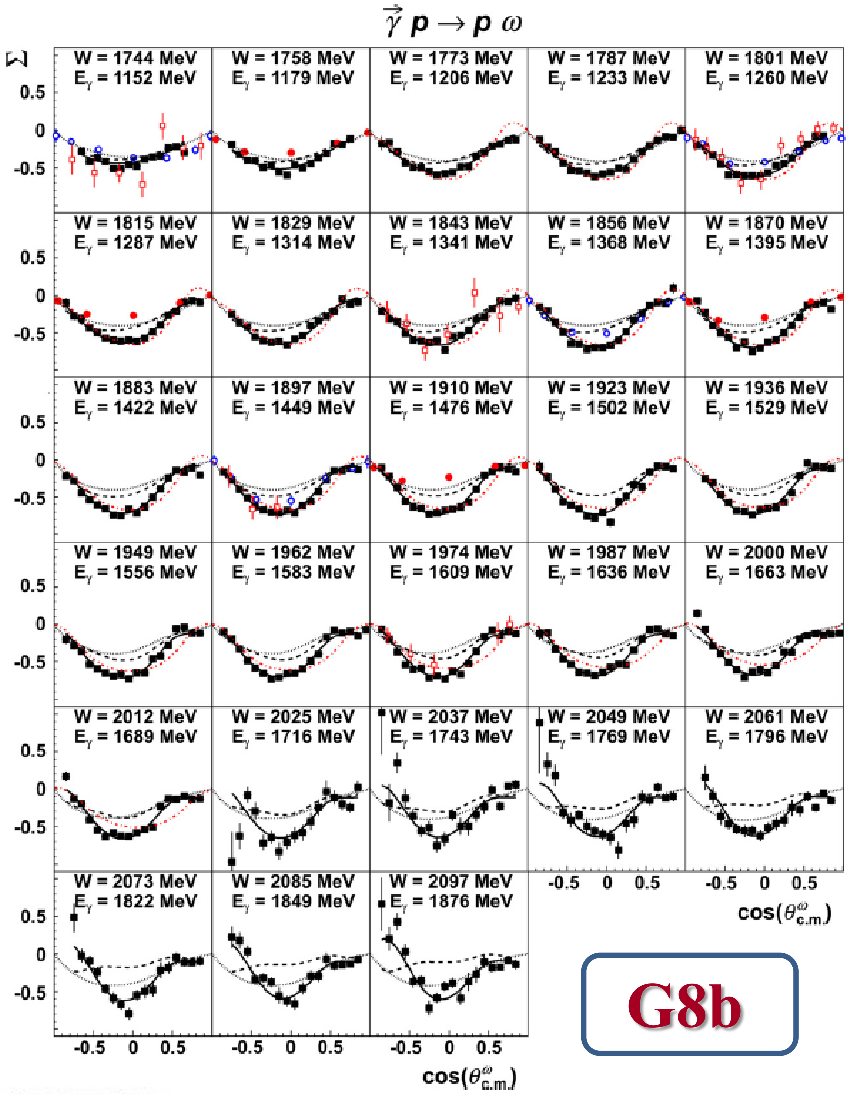
G8b



- Fit to Bonn-Gatchina model (blue lines) indicates presence of *N*(1895)1/2$^-$, *N*(2100)1/2$^+$, *N(*2120)3/2$^-$ and strong presence of *N*(1900)1/2$^-$

P. Collins, *et al.*, (CLAS Collaboration), Phys. Lett. B 771, 213-221 (2017)

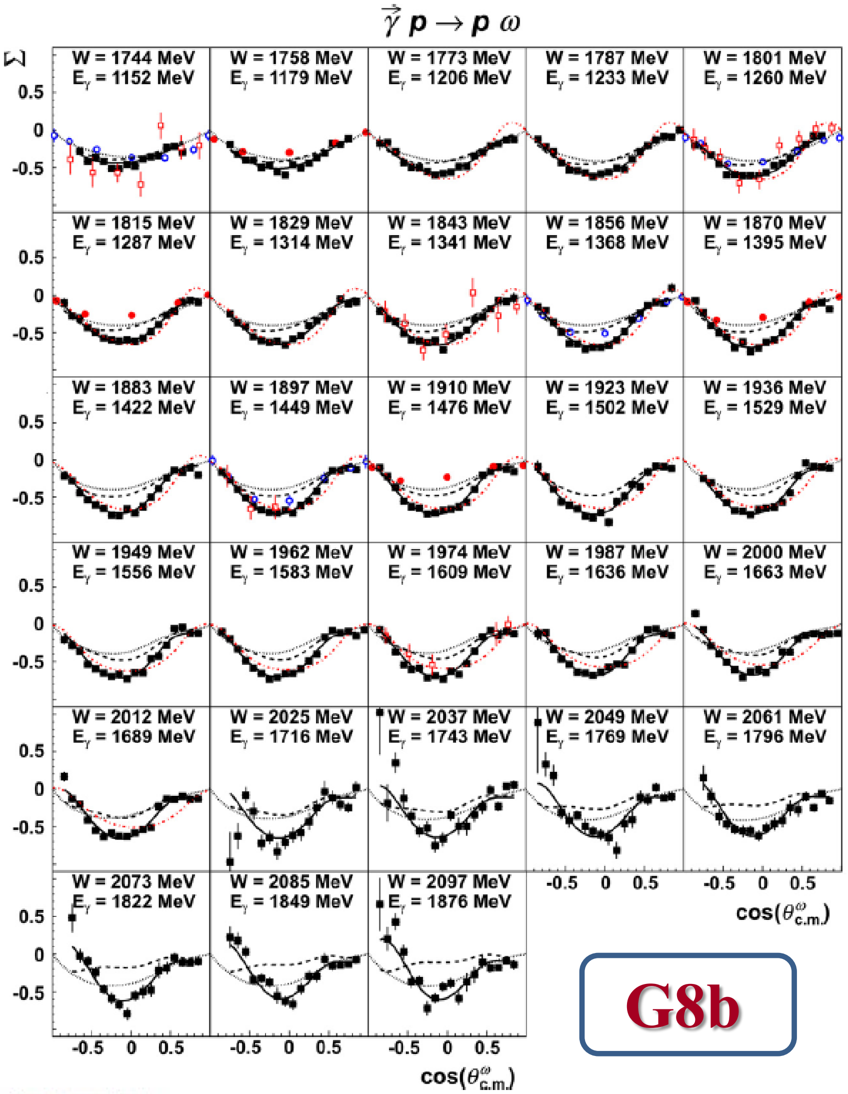
Σ for ω

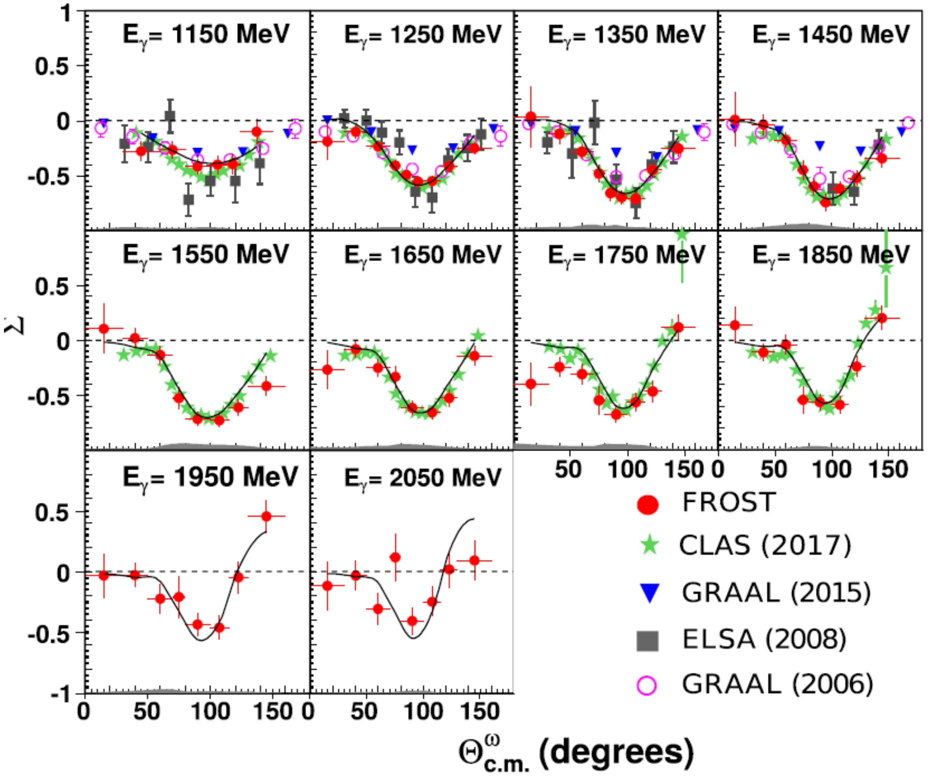


G8b

P. Collins, *et al.*, (CLAS Collaboration), Phys. Lett. B 773, 112-120 (2017)

Σ for *ω*





G8b

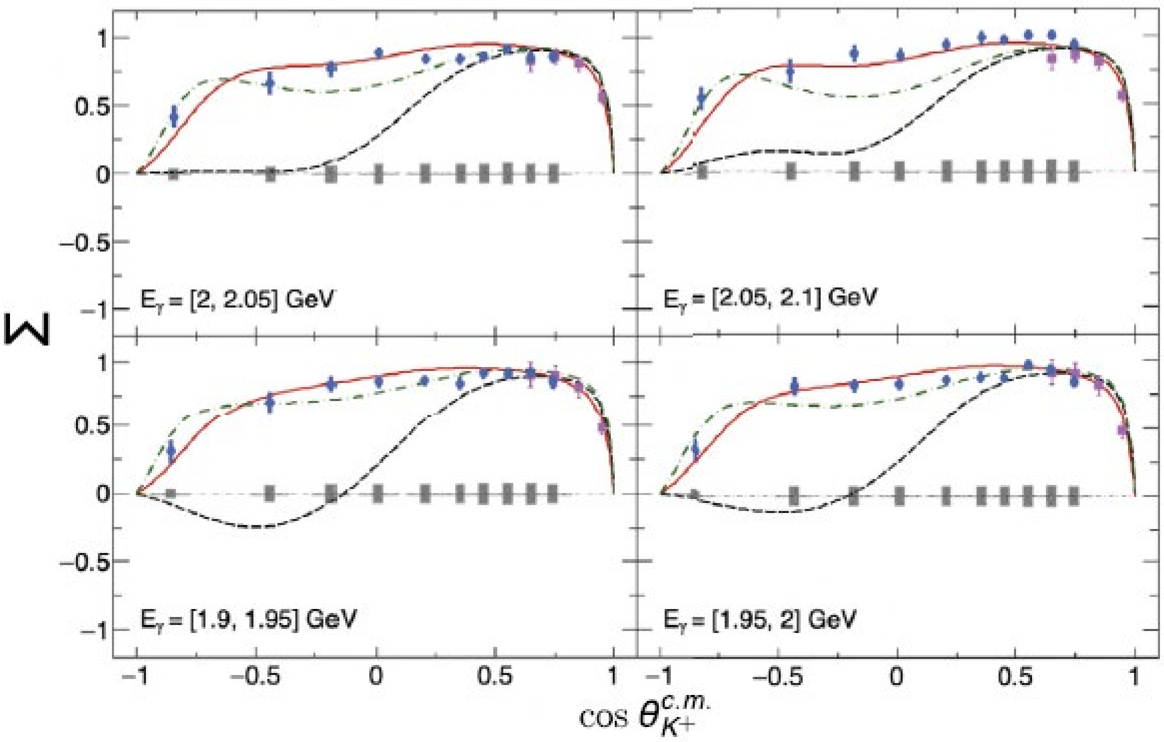
G9a: FROST

P. Roy, *et al.*, (CLAS Collaboration), Phys. Rev. C 97, 055202 (2018)

P. Collins, *et al.*, (CLAS Collaboration), Phys. Lett. B 773, 112-120 (2017)

Beam asymmetries for $\gamma\, n \rightarrow K^+ \Sigma^-$

G13



Red: Full solution (Bonn-Gatchina)

Black: Contribution of $N(1720)3/2^+$ removed

Green: Contribution of $N(1720)3/2^+$ and $\Delta(1900)1/2^-$ removed

N. Zachariou, *et al.*, (CLAS Collaboration), Phys. Lett. B 827, 136985 (2022)

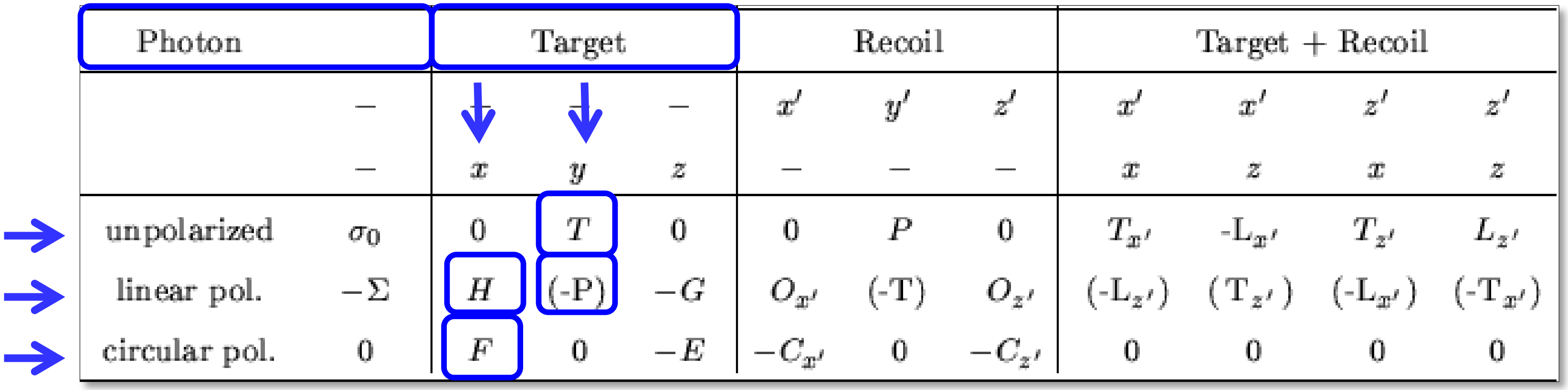
Observable: *T, F, P* and *H*

Reaction: $\gamma p \rightarrow p\omega$

Configuration:

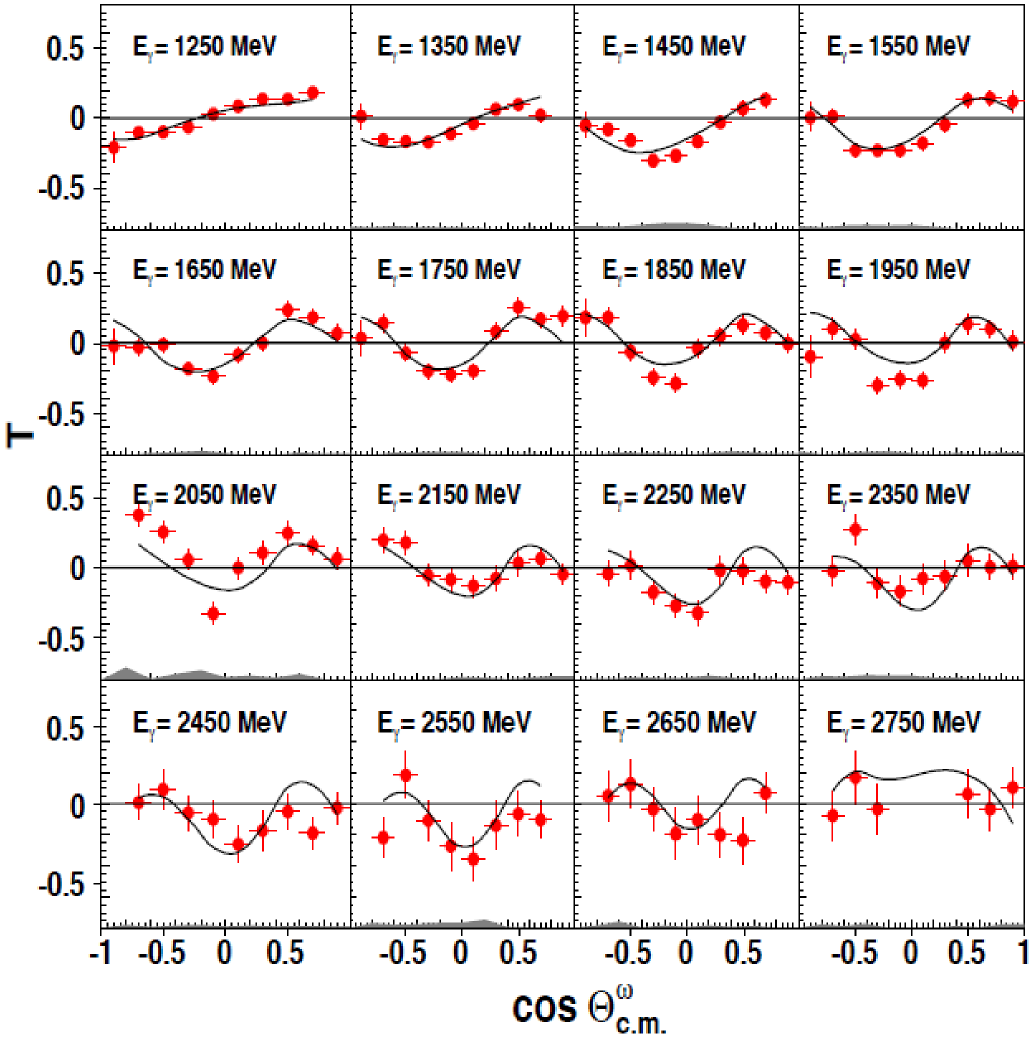
- **Circular photon polarization**
- **Transverse target polarization**
- **Unpolarized photon** (by adding circular beams)
- No recoil polarization

Experiment:
- g9b: FROST



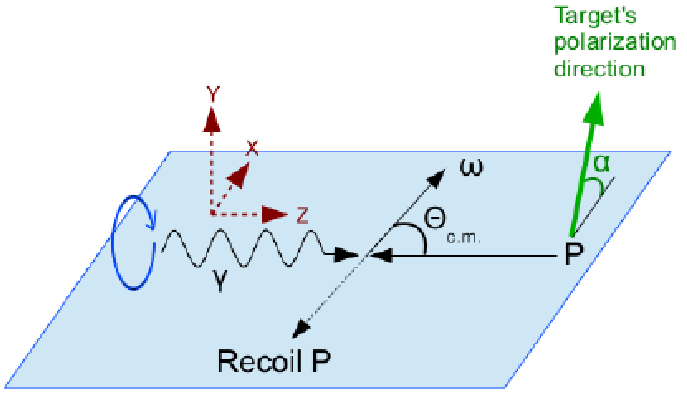
Photon		Target			Recoil			Target + Recoil			
	—	—	—	—	x'	y'	z'	x'	x'	z'	z'
	—	x	y	z	—	—	—	x	z	x	z
unpolarized	σ_0	0	T	0	0	P	0	$T_{x'}$	-$L_{x'}$	$T_{z'}$	$L_{z'}$
linear pol.	$-\Sigma$	H	(-P)	$-G$	$O_{x'}$	(-T)	$O_{z'}$	(-$L_{z'}$)	($T_{z'}$)	(-$L_{x'}$)	(-$T_{x'}$)
circular pol.	0	F	0	$-E$	$-C_{x'}$	0	$-C_{z'}$	0	0	0	0

Target Asymmetry T in $\gamma \vec{p} \to p\omega$ (CLAS g9b)



Polarized Cross Section

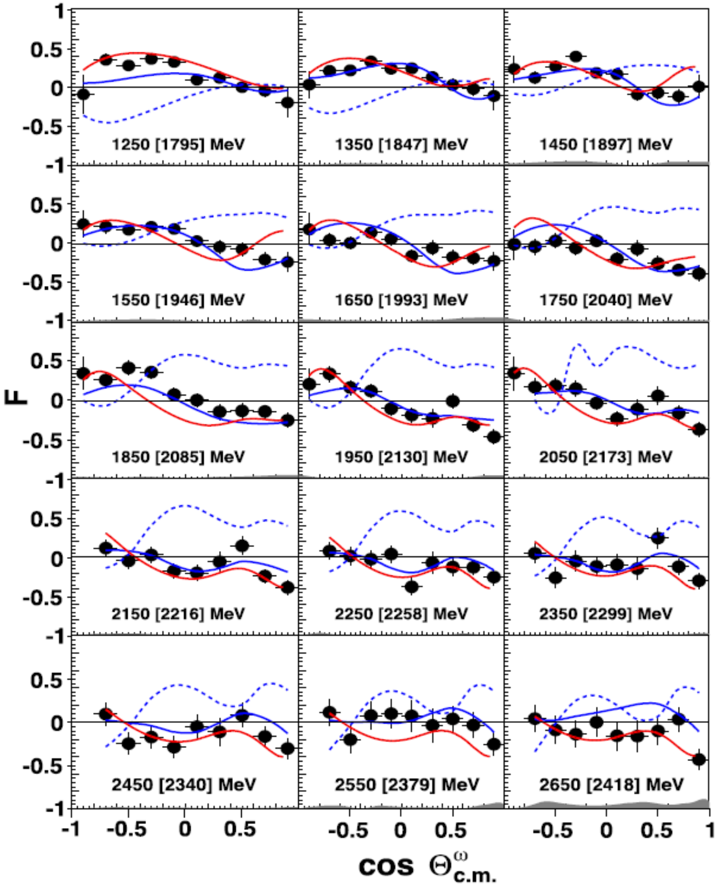
$$\frac{d\sigma}{d\Omega} = \sigma_0 \{ 1 - \delta_l \Sigma \cos 2\phi + \Lambda_x (-\delta_l H \sin 2\phi + \delta_\odot F) - \Lambda_y (-T + \delta_l P \cos 2\phi) - \Lambda_z (-\delta_l G \sin 2\phi + \delta_\odot E) \}$$

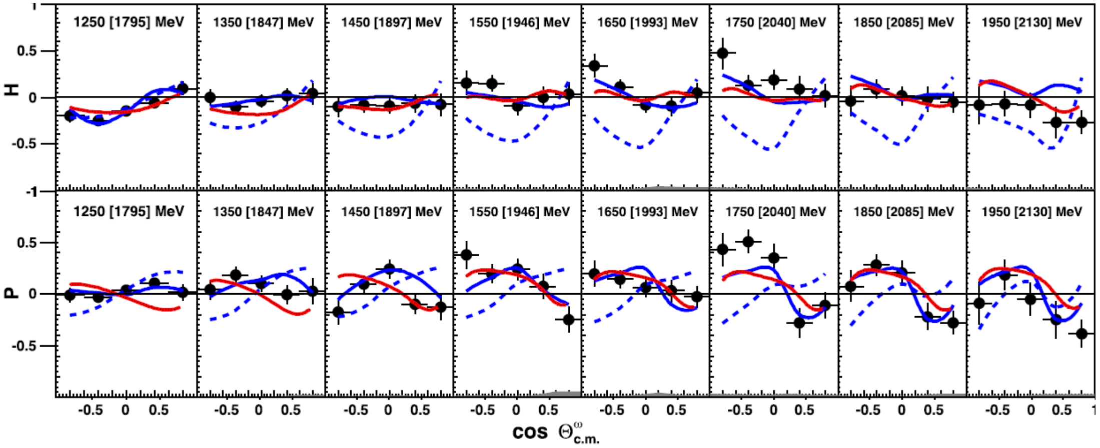


P. Roy *et al.* [CLAS Collaboration], Phys. Rev. C **97**, no. 5, 055202 (2018)

P. Roy, Z. Akbar, V. Credé *et al.* Published on 4 May 2018

F, *P* and *H* for *ω*





- Red : Wei
- Blue : Bon-Gatchina, where dashed = old
- Indicates notable contributions from *N*(1875)3/2$^-$, *N*(2120)3/2$^-$ and *N*(1880)1/2$^+$

P. Roy, *et al.*, (CLAS Collaboration), Phys. Rev. Lett. 122, 162301 (2019)

Observable: *E*

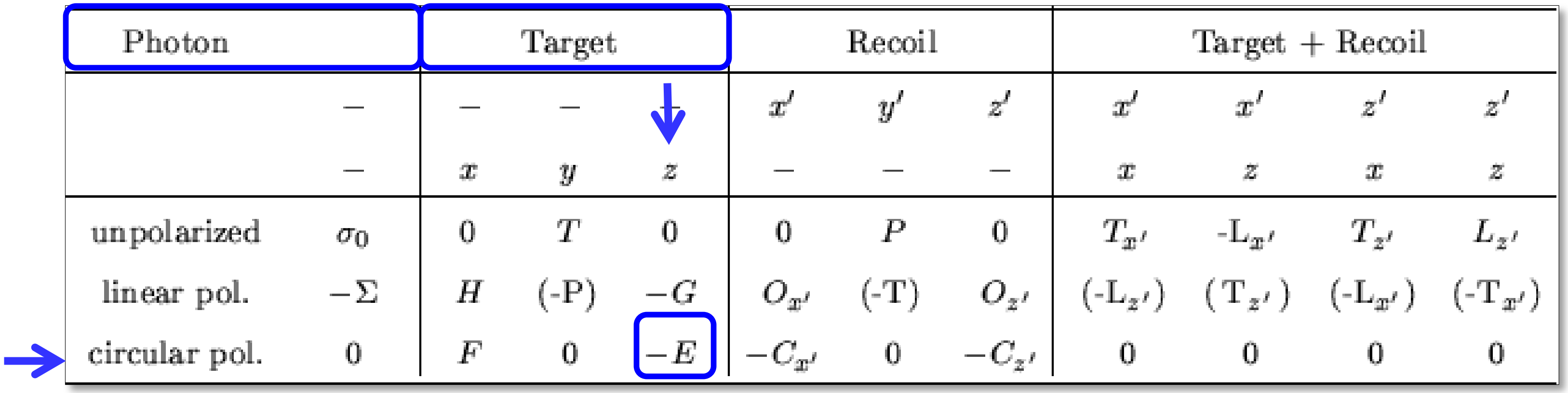
Reactions: $\gamma\, p \rightarrow p\, \omega$, $p\, \eta$ and $\gamma\, n \rightarrow K^+ \Sigma^-$

Configuration:

- **Circular photon polarization**
- **Longitudinal Target polarization**
- No recoil polarization

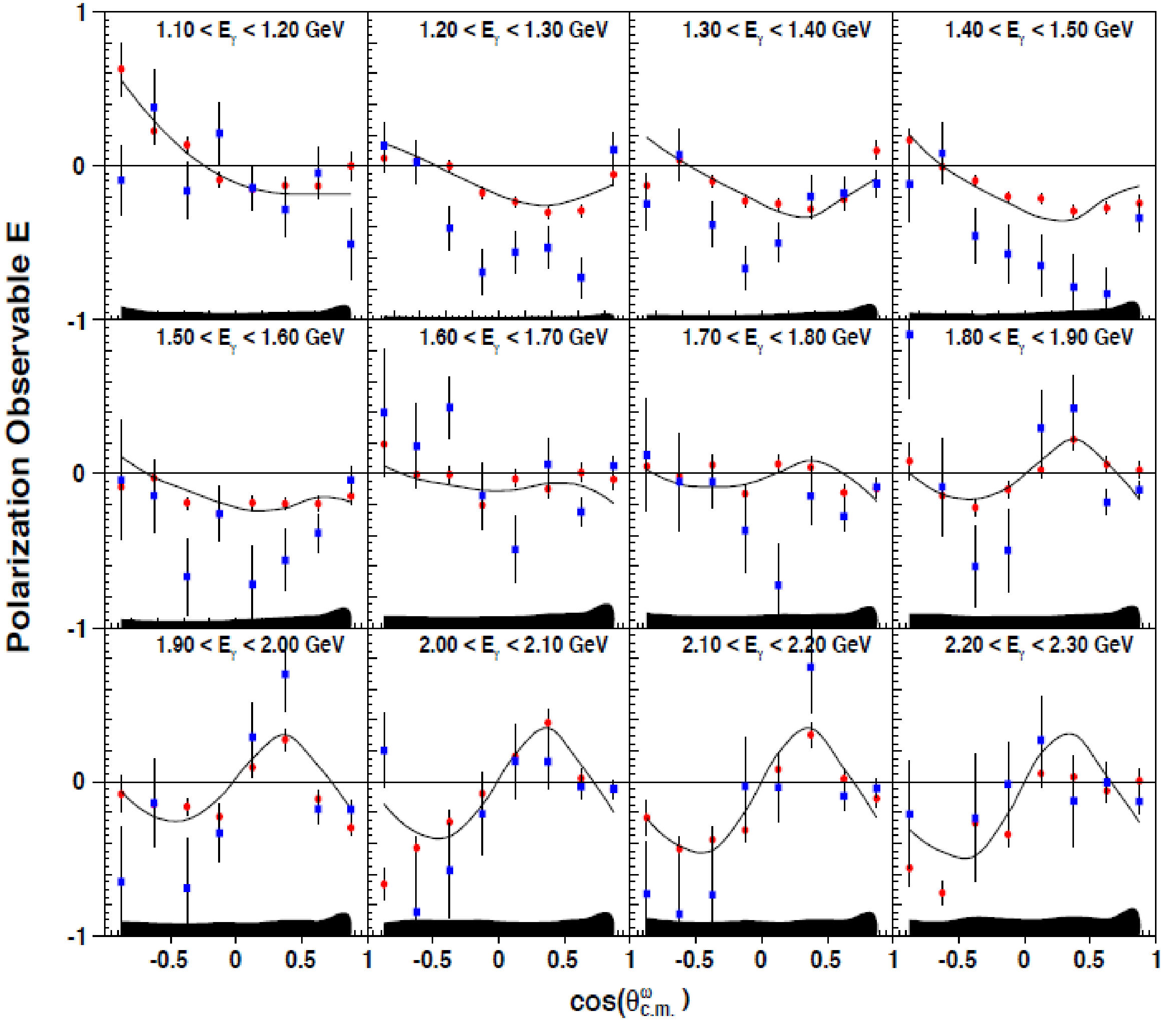
Experiment:

- g9b: FROST
- g14: HD-ICE



Photon		Target			Recoil			Target + Recoil			
	—	—	—	—	x'	y'	z'	x'	x'	z'	z'
	—	x	y	z	—	—	—	x	z	x	z
unpolarized	σ_0	0	T	0	0	P	0	$T_{x'}$	-$L_{x'}$	$T_{z'}$	$L_{z'}$
linear pol.	$-\Sigma$	H	(-P)	$-G$	$O_{x'}$	(-T)	$O_{z'}$	(-$L_{z'}$)	($T_{z'}$)	(-$L_{x'}$)	(-$T_{x'}$)
circular pol.	0	F	0	$\boxed{-E}$	$-C_{x'}$	0	$-C_{z'}$	0	0	0	0

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



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

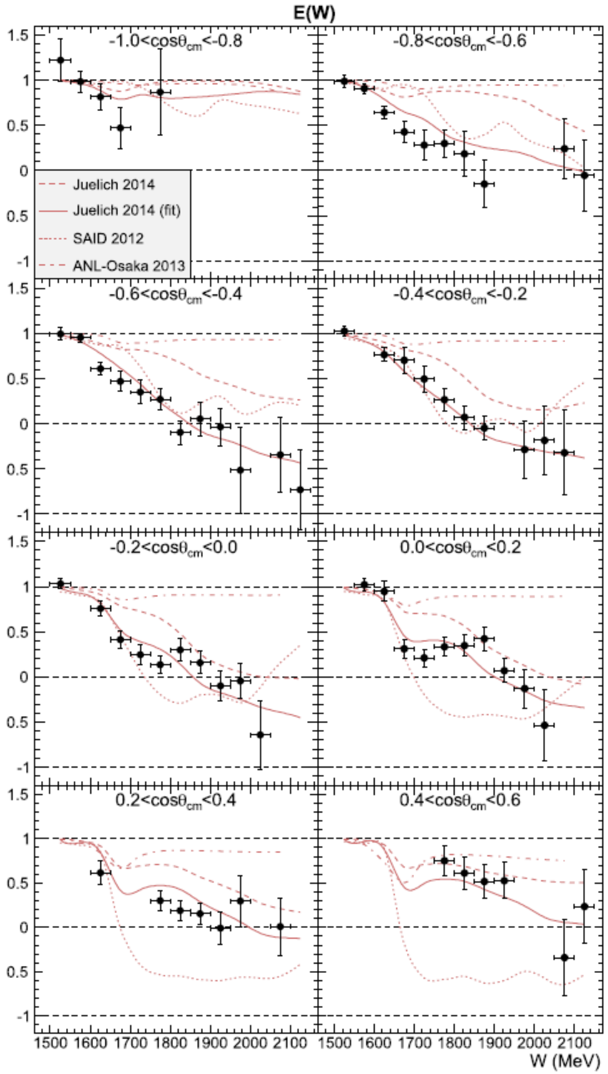
● CLAS-g9a

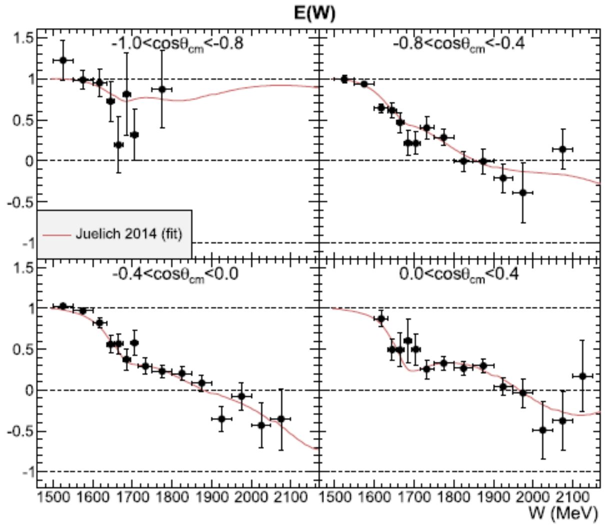
■ CBELSA/TAPS
Phys. Lett. B **750**, 453 (2015)

Z. Akbar *et al.* [CLAS Collaboration], Phys. Rev. C **96**, no. 6, 065209 (2017)

Z. Akbar, P. Roy, V. Credé *et al.* Published on 28 December 2017

E for η





G9a: FROST

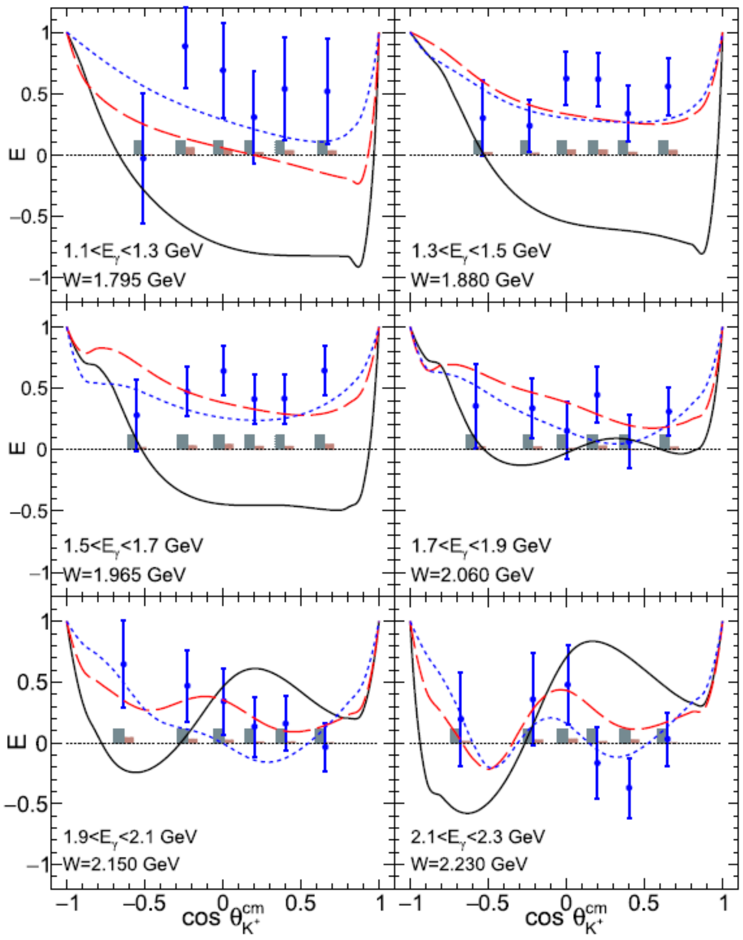
- Fit to Julich-Bonn model (red lines) does not indicate the need for a narrow resonance ~1.7 GeV

- Structure near ~1.7 GeV appears to be interference of E_0^+ and M_2^+ multipoles

I. Senderovich, *et al.*, (CLAS Collaboration), Phys. Lett. B 755, 64-69 (2016)

E for $\gamma\, n \rightarrow K^+ \Sigma^-$

G14: HD-ICE



Red: Bonn-Gatchina prior to fit

Blue: Full fit including “missing” D_{13}

Black: Full fit without D_{13}

N. Zachariou, *et al.*, (CLAS Collaboration), Phys. Lett. B 808, 135662 (2020)

UNIVERSITY of York

Self-analyzing reaction $K^+ Y$ (hyperon)

- The weak decay of the hyperon allows the extraction of the hyperon polarization by looking at the decay distribution of the baryon in the hyperon center of mass system:

$$I(\cos\theta) = \tfrac{1}{2}\left(1 + \alpha P_Y \cos\theta\right)$$

where I is the decay distribution of the baryon, α is the weak decay asymmetry ($\alpha_\Lambda = 0.642$ and $\alpha_{\Sigma 0} = -⅓\, \alpha_\Lambda$), and P_Y is the hyperon polarization.

- We can obtain recoil polarization information without a recoil polarimeter and the reaction is said to be **“self-analyzing”**

Observables: Σ, T, O_x, O_z

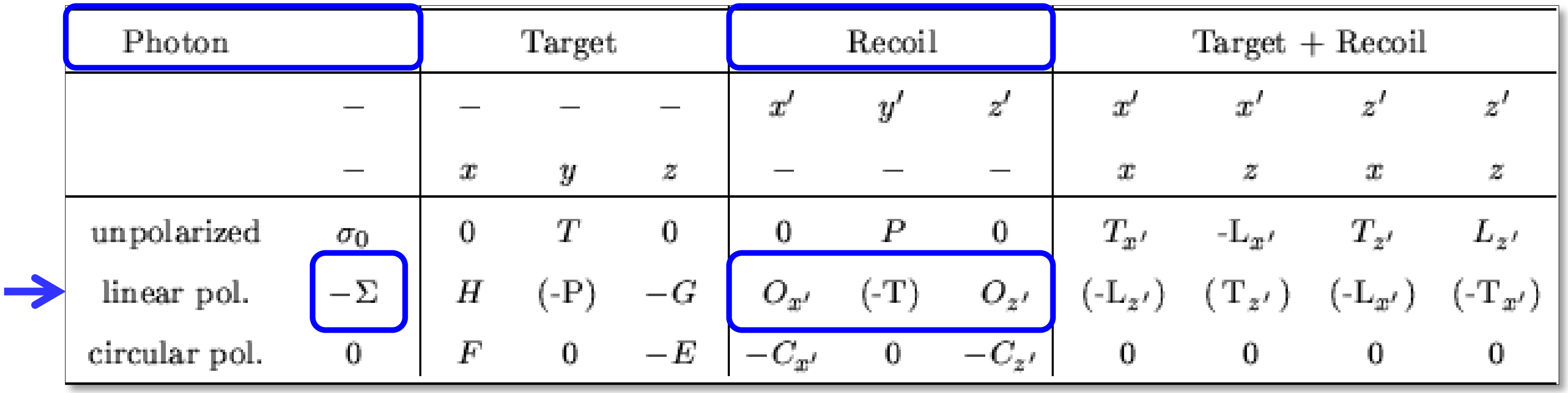
Reaction: $\gamma p \rightarrow K^+\Lambda,\ K^+\Sigma$

Configuration:

- **Linear photon polarization**
- **Recoil polarization self analyzed**
- No target polarization

Experiments:

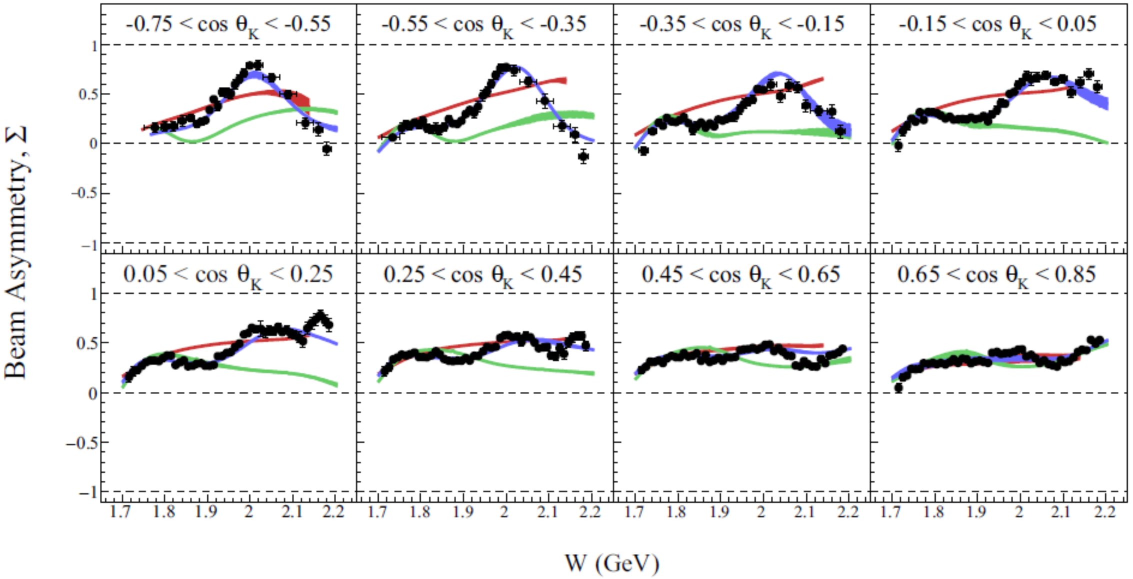
- g8b → proton reactions
- g13 → neutron reactions

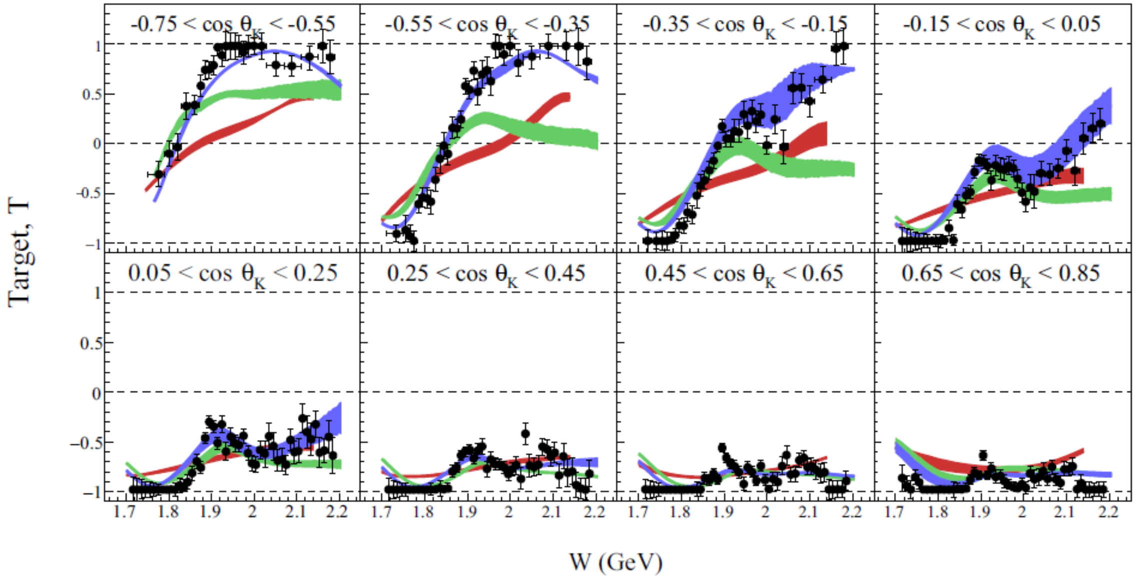


Photon		Target			Recoil			Target + Recoil			
	–	–	–	–	x'	y'	z'	x'	x'	z'	z'
	–	x	y	z	–	–	–	x	z	x	z
unpolarized	σ_0	0	T	0	0	P	0	$T_{x'}$	-$L_{x'}$	$T_{z'}$	$L_{z'}$
linear pol.	$-\Sigma$	H	(-P)	$-G$	$O_{x'}$	(-T)	$O_{z'}$	(-$L_{z'}$)	($T_{z'}$)	(-$L_{x'}$)	(-$T_{x'}$)
circular pol.	0	F	0	$-E$	$-C_{x'}$	0	$-C_{z'}$	0	0	0	0

Σ ,T for $\gamma\, p \rightarrow K^+ \Lambda$

G8b





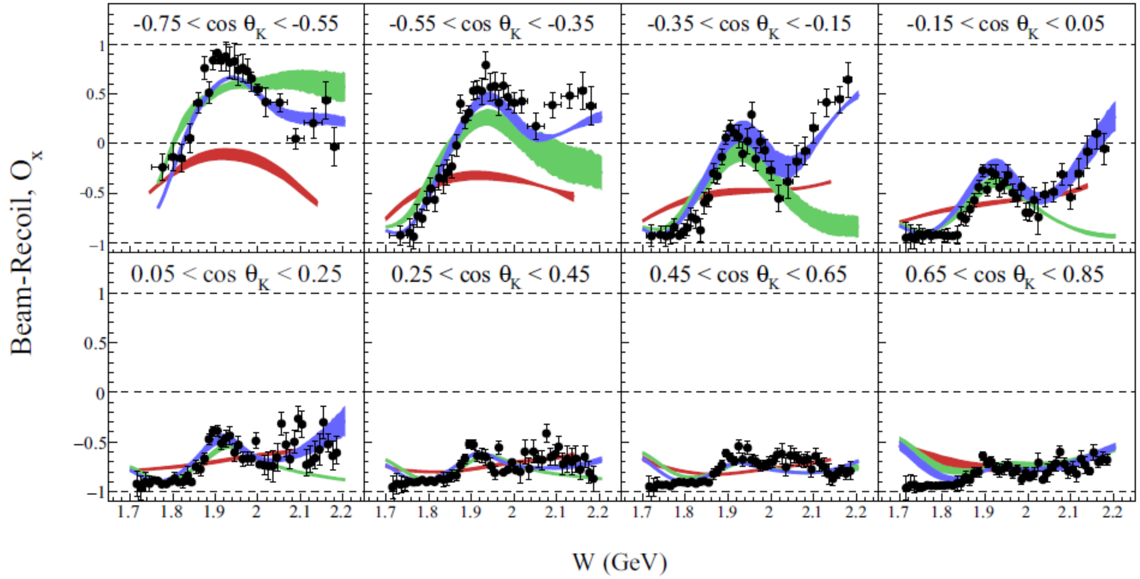
- Blue lines represent fits to Bonn-Gatchina model

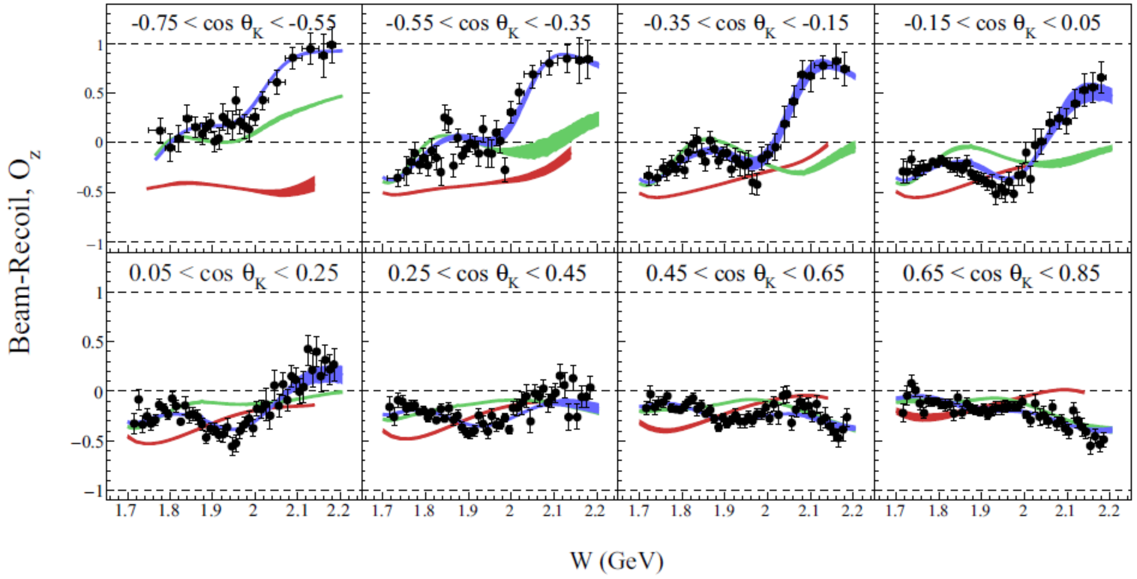
- Other lines represent various predictions

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

O_x, O_z for $\gamma\, p \to K^+ \Lambda$

G8b



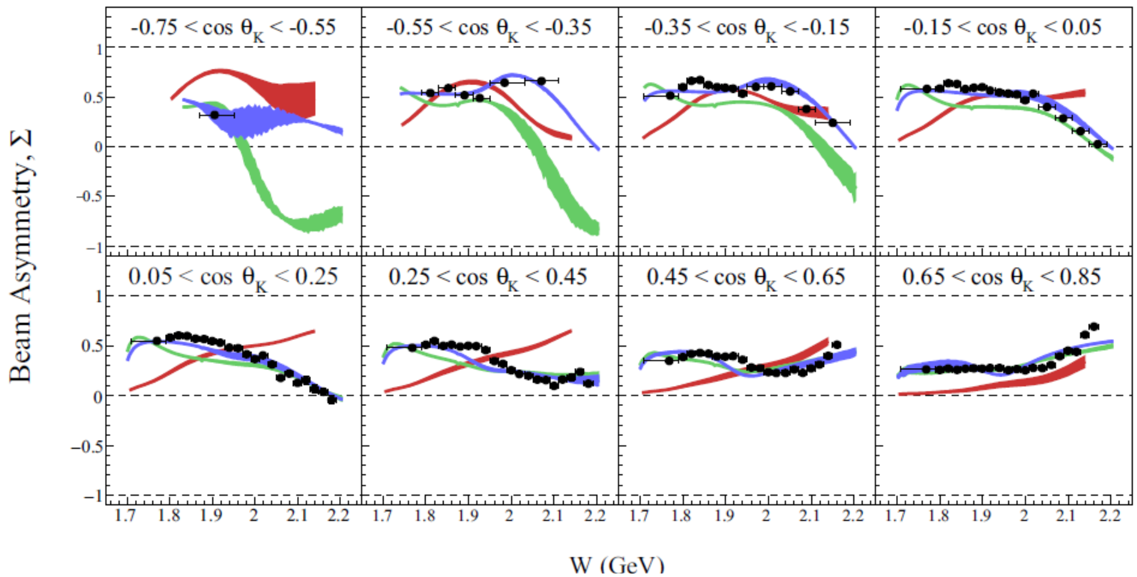


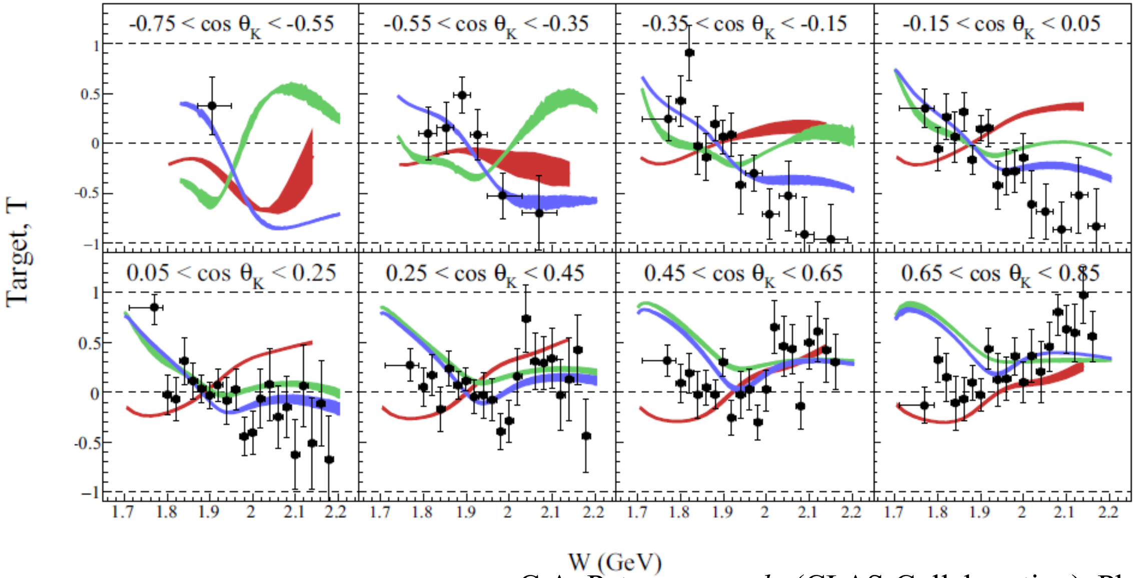
- Blue lines represent fits to Bonn-Gatchina model
- Other lines represent various predictions

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

Σ ,T for $\gamma\, p \rightarrow K^+\, \Sigma^0$

G8b





- Blue lines represent fits to Bonn-Gatchina model

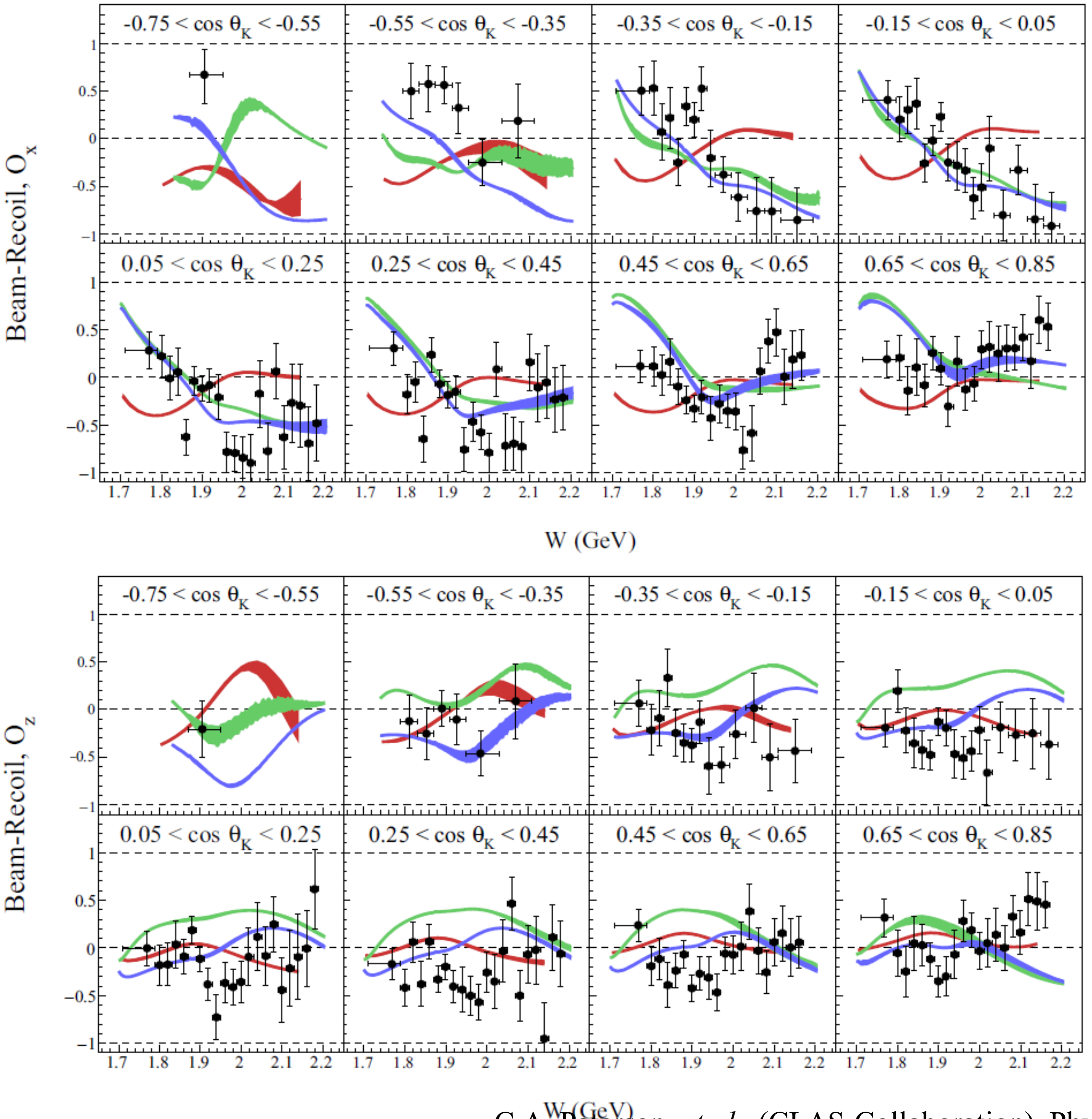
- Other lines represent various predictions

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

University of Glasgow

O_x, O_z for $\gamma\, p \rightarrow K^+\, \Sigma^0$

G8b



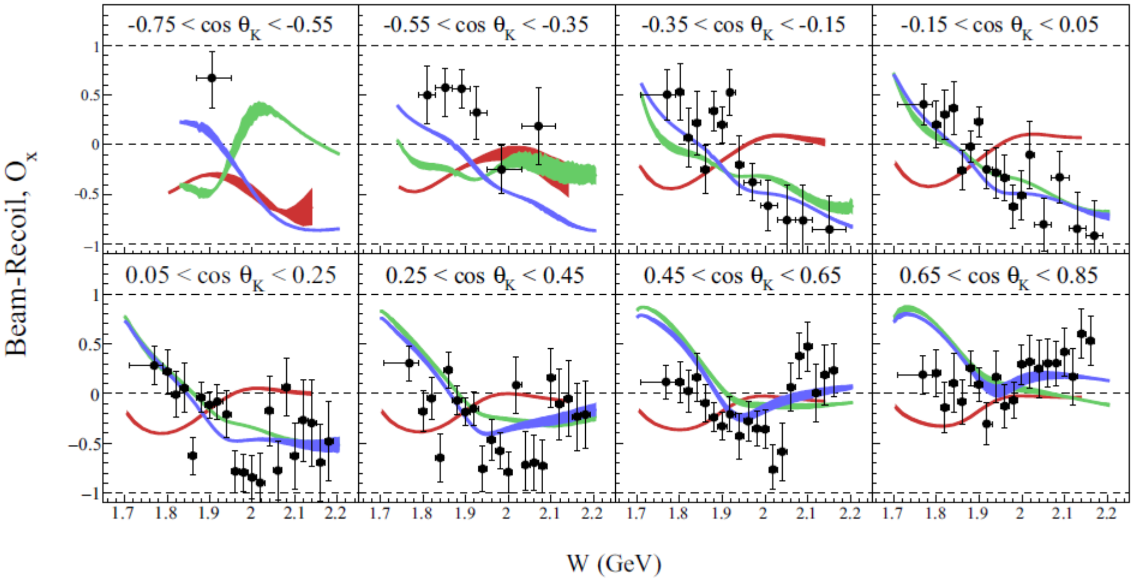
- Blue lines represent fits to Bonn-Gatchina model
- Other lines represent various predictions

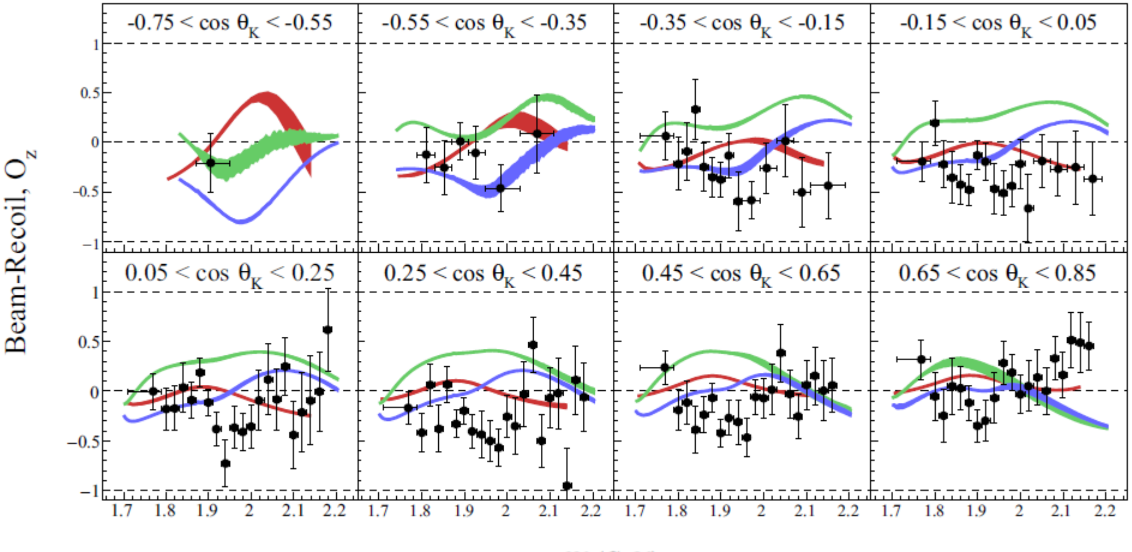
C.A. Paterson, *et al.*, (CLAS Collaboration), Phys. Rev. C 93, 065201 (2016)

University of Glasgow

O_x, O_z for $\gamma\, p \rightarrow K^+ \Sigma^0$

G8b



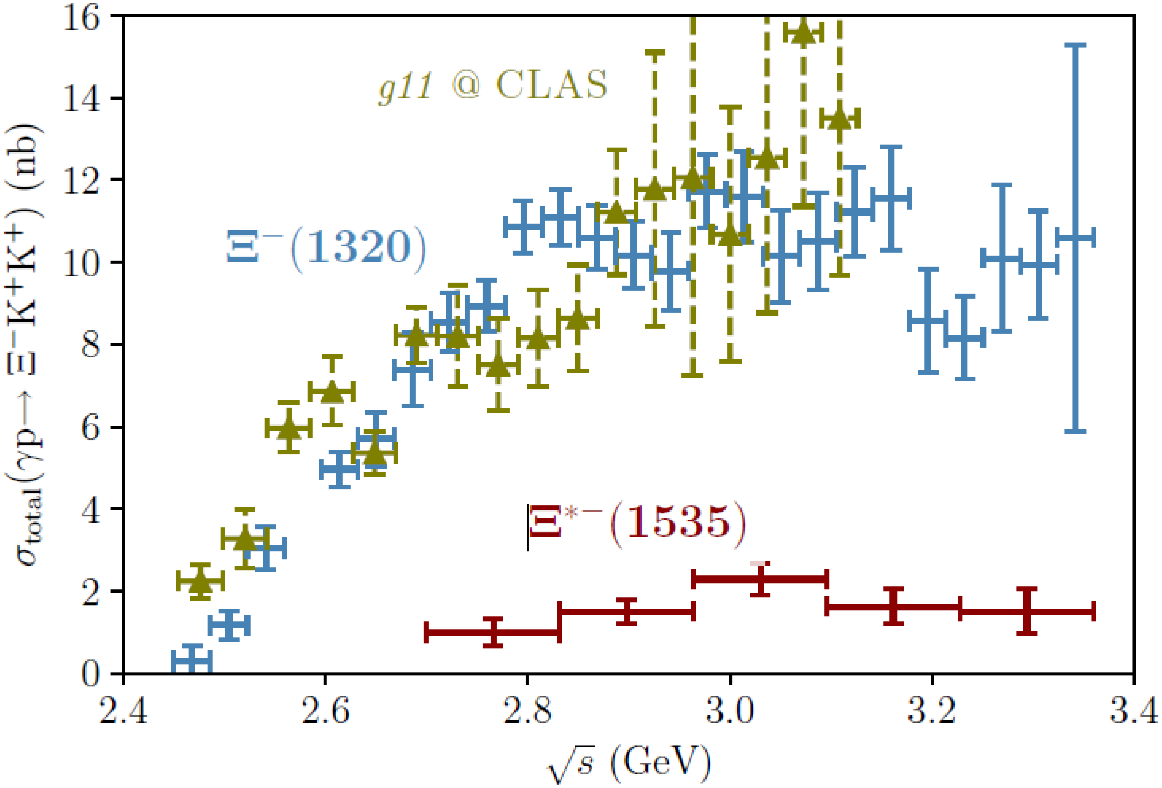


- Indicates some evidence for additional $N^*(3/2^+)$ and $N^*(5/2^+)$ resonances of undetermined mass

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

Ξ photoproduction

σ for *γ p* → *K*⁺ *K*⁺ *Ξ*⁻



- All data from CLAS (G11, and G12)
- First total cross sections or photoproduction of these states above *W*=2.8 GeV

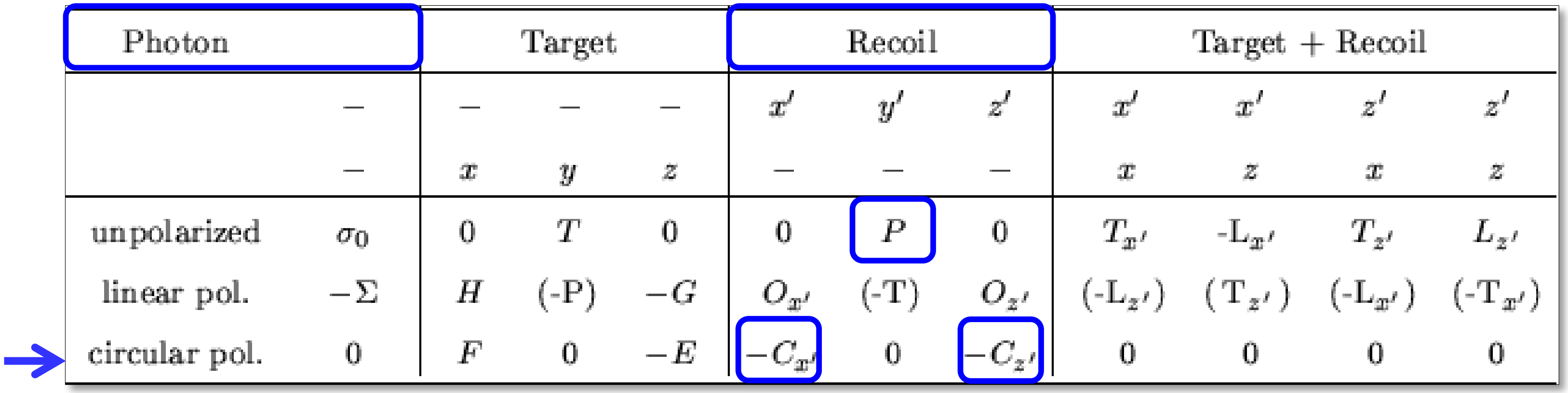
J.T. Goetz, *et al.*, (CLAS Collaboration), Phys. Rev. C 98, 062201(R) (2018)

Observables: P, C_x, C_z

Reaction: $\gamma p \rightarrow K^+K^+\Xi^-$

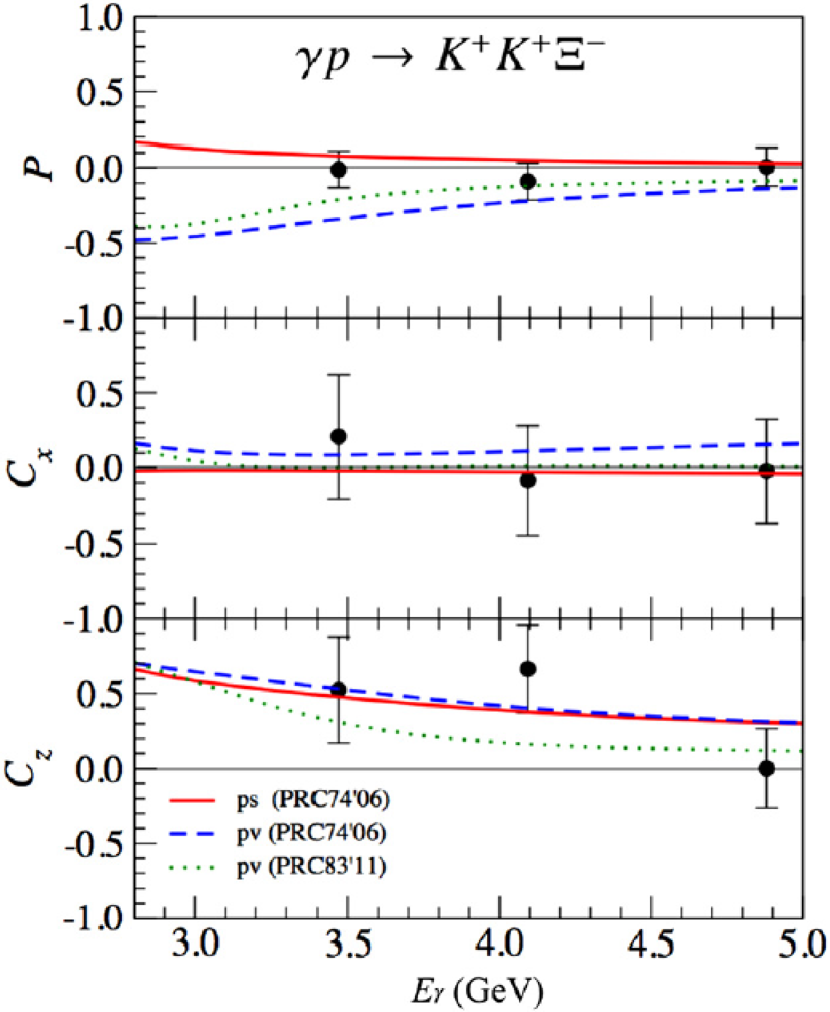
Configuration:

- **Circular photon polarization**
- **Recoil polarization self analyzed**
- No target polarization



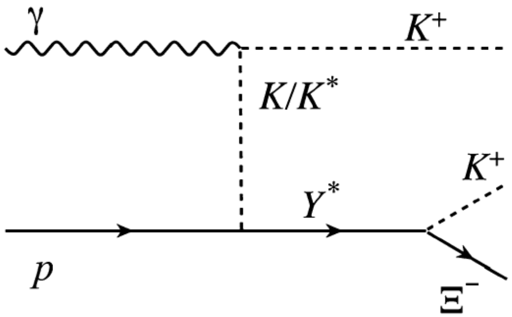
Photon		Target			Recoil			Target + Recoil			
	$-$	$-$	$-$	$-$	x'	y'	z'	x'	x'	z'	z'
	$-$	x	y	z	$-$	$-$	$-$	x	z	x	z
unpolarized	σ_0	0	T	0	0	$\boxed{P}$	0	$T_{x'}$	-$L_{x'}$	$T_{z'}$	$L_{z'}$
linear pol.	$-\Sigma$	H	(-P)	$-G$	$O_{x'}$	(-T)	$O_{z'}$	(-$L_{z'}$)	($T_{z'}$)	(-$L_{x'}$)	(-$T_{x'}$)
circular pol.	0	F	0	$-E$	$\boxed{-C_{x'}}$	0	$\boxed{-C_{z'}}$	0	0	0	0

P, C_x, C_z for $\gamma\, p \rightarrow K^+ K^+ \Xi^-$



- First-time measurement

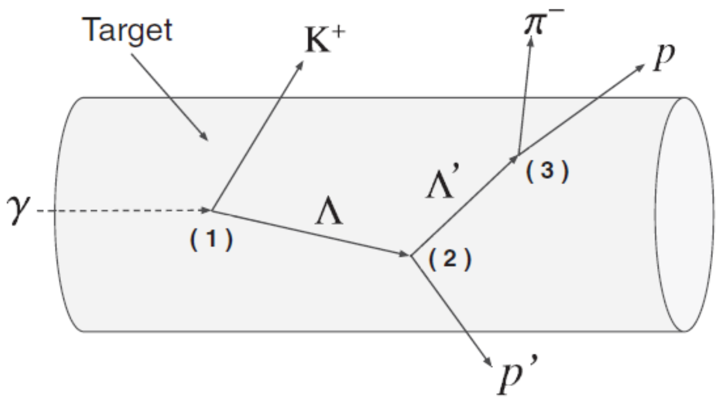
- Coupling:
  - ps = pseudoscalar
  - pv = pseudovector

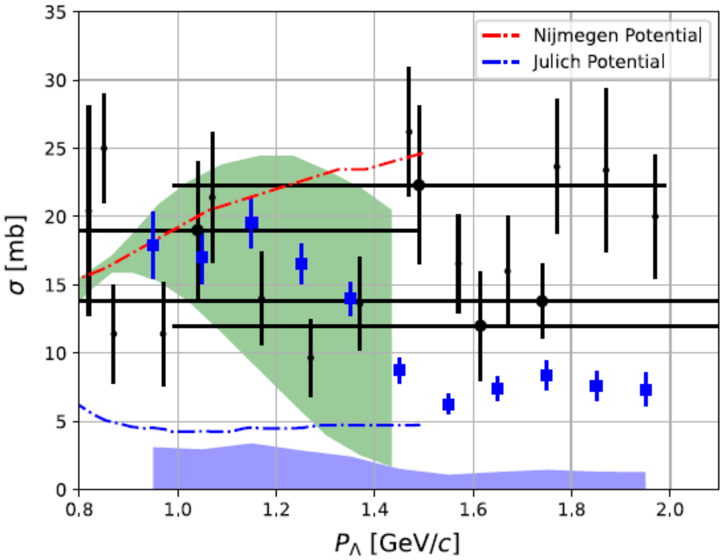


- Green dotted includes *Σ*(2030) contribution

J. Bono, *et al.*, (CLAS Collaboration), Phys. Lett. B 783, 280-286 (2018)

$p\Lambda$ elastic scattering: $p\Lambda \rightarrow p\Lambda$





- **Black** circles: previous world data (bubble chambers)
- **Blue** squares: CLAS results
- Momentum range important to neutron star physics

J. Rowley, *et al.*, (CLAS Collaboration), Phys. Rev. Lett. 127, 272303 (2021)

Status of meson photoproduction

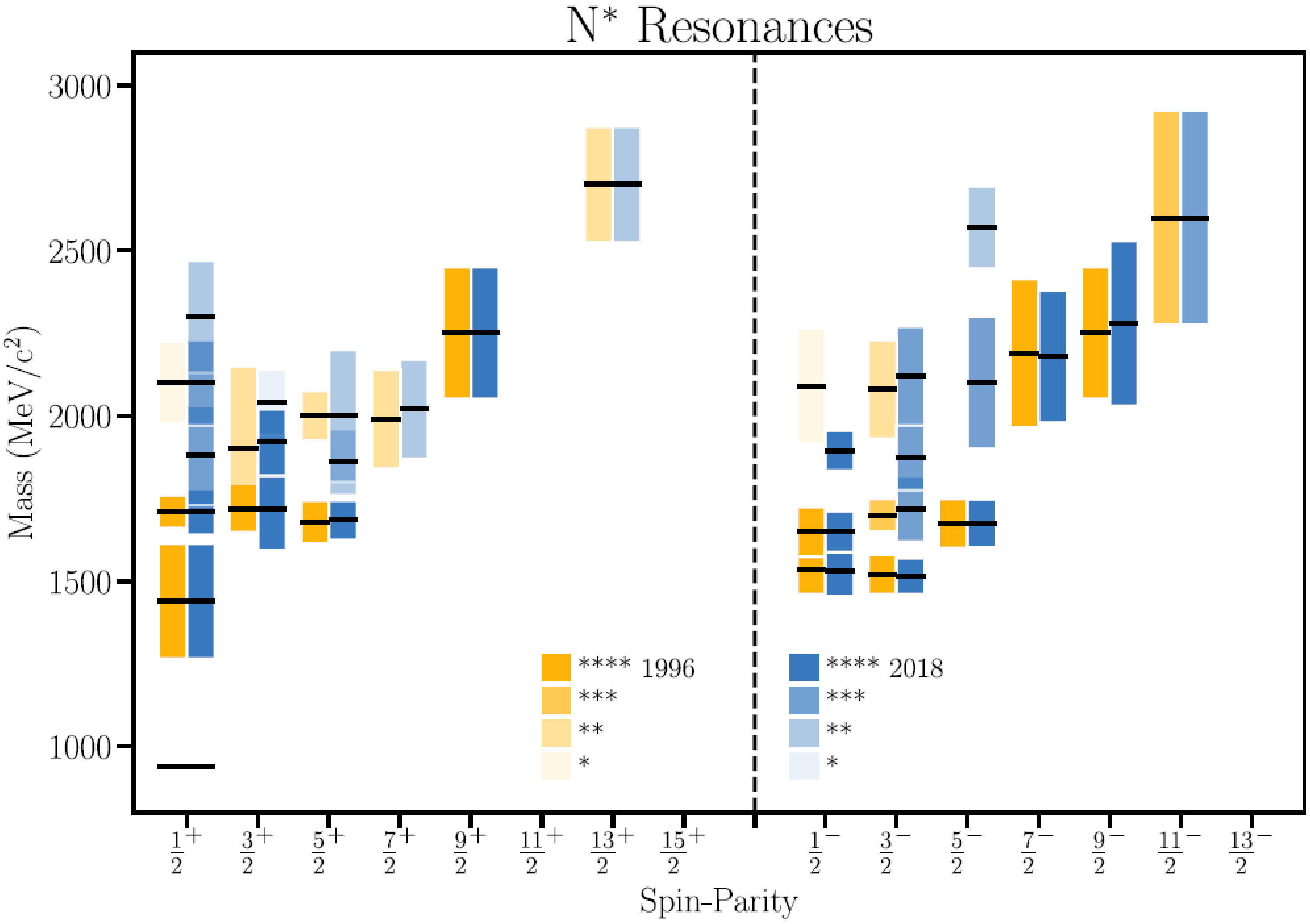
	σ	Σ	T	P	E	F	G	H	T_x	T_z	L_x	L_z	O_x	O_z	C_x	C_z
Proton target																
$p\pi^0$	✔	✔	✓	✓	✓	✓	✓	✓								
$n\pi^+$	✔	✔	✓	✓	✔	✓	✓	✓								
$p\eta$	✔	✔	✓	✓	✔	✓	✓	✓								
$p\eta'$	✔	✔	✓	✓	✓	✓	✓	✓								
$p\omega$	✔	✔	✔	✔	✔	✔	✓	✔								
$K^+\Lambda$	✔	✔	✔	✔	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔	✔	✔
$K^+\Sigma^0$	✔	✔	✔	✔	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔	✔	✔
$K^0\Sigma^+$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
“Neutron” target																
$p\pi^-$	✔	✓	✓	✓	✓	✓	✓	✓								
$K^+\Sigma^-$	✔	✓	✓	✓	✓	✓	✓	✓								
$K^0\Lambda$	✔	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$K^0\Sigma^0$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

✔ - published ✓ - acquired

Not shown in table:

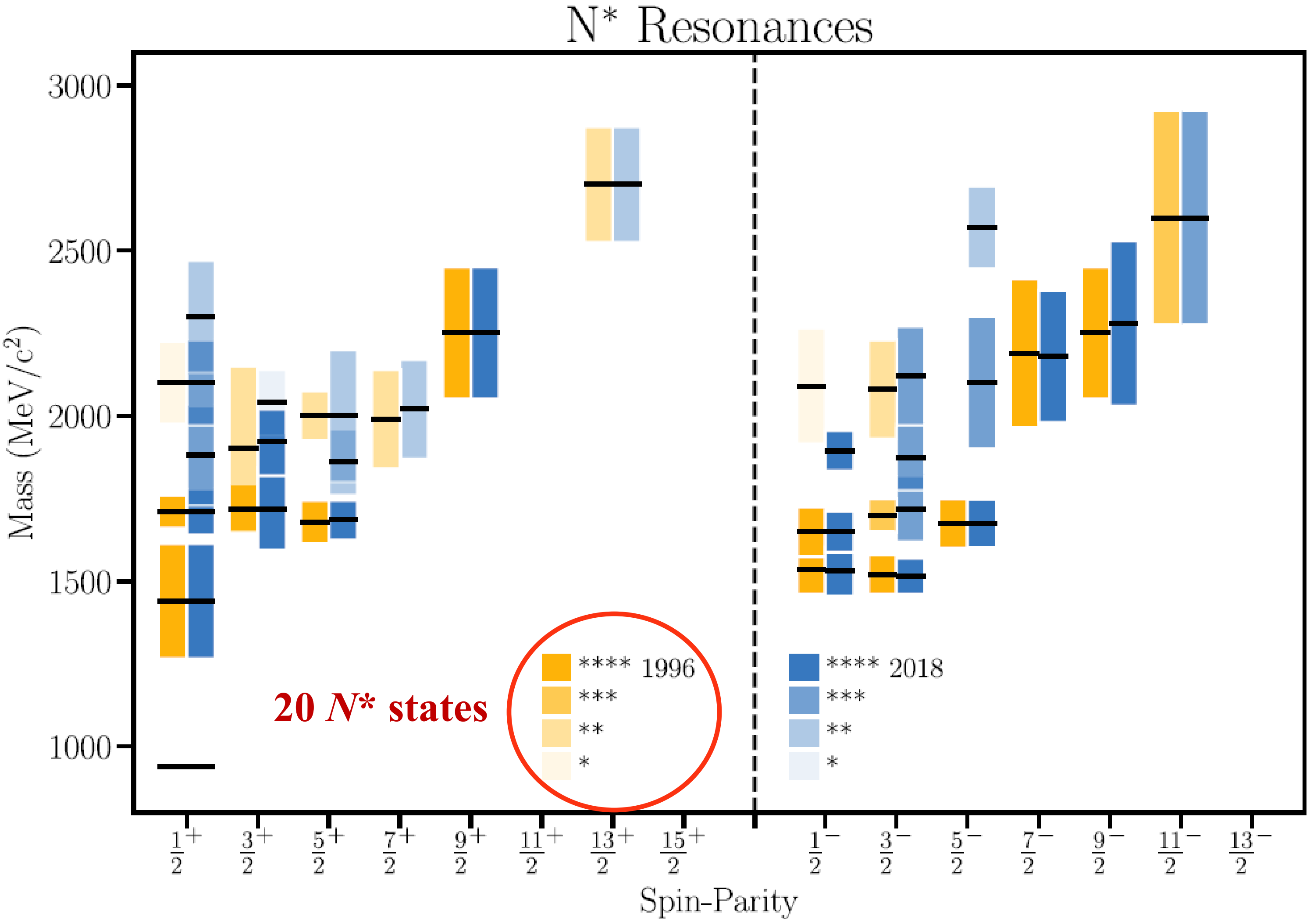
- $\pi\pi$ photoproduction observables or
- Ξ states
- $p\Lambda$ scattering

Changes to PDG from 1996 to 2018



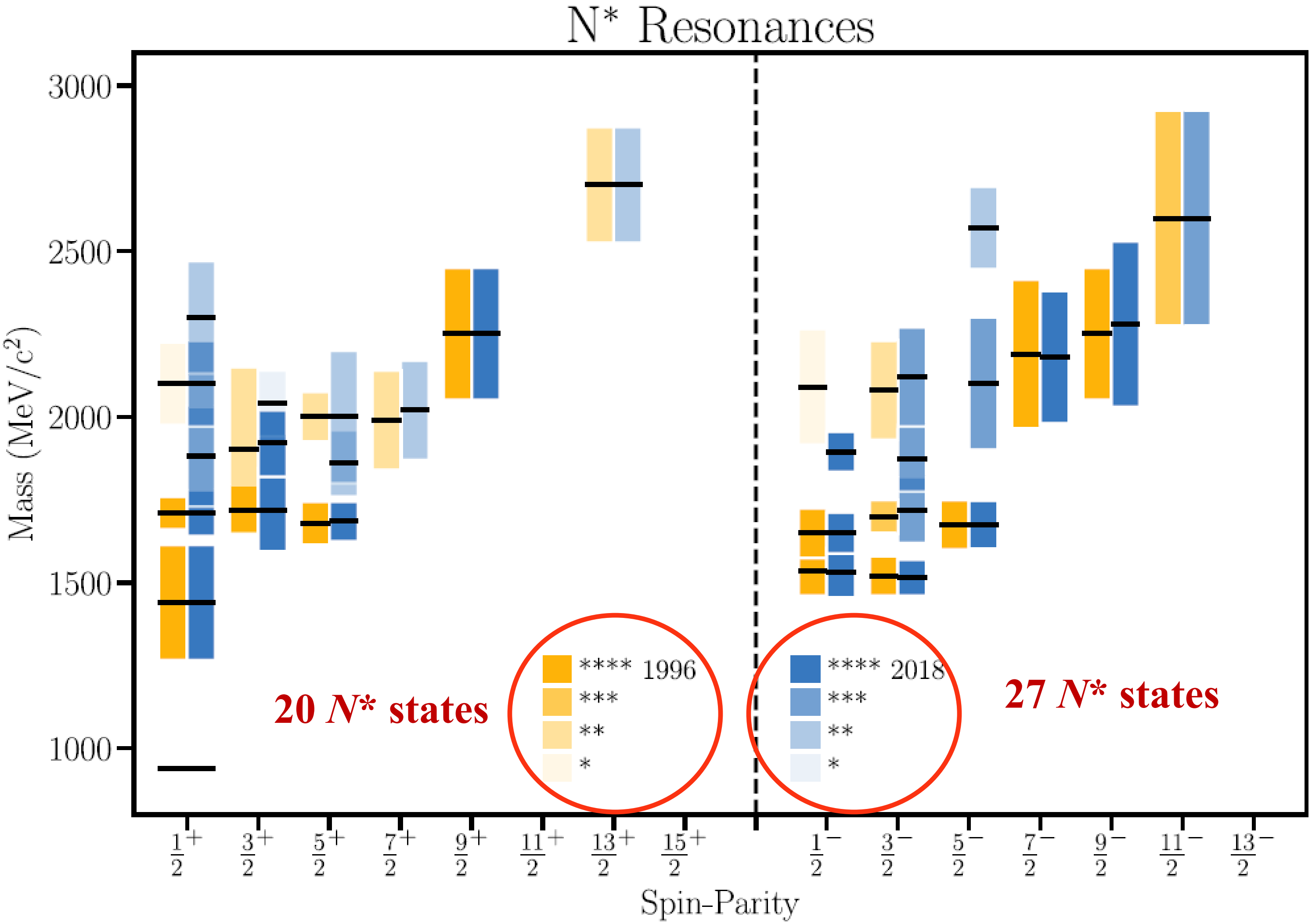
D.G. Ireland, E. Pasyuk, I. Strakovsky, Progress in Particle and Nuclear Physics 111 103752 (2020)

Changes to PDG from 1996 to 2018



D.G. Ireland, E. Pasyuk, I. Strakovsky, Progress in Particle and Nuclear Physics 111 103752 (2020)

Changes to PDG from 1996 to 2018

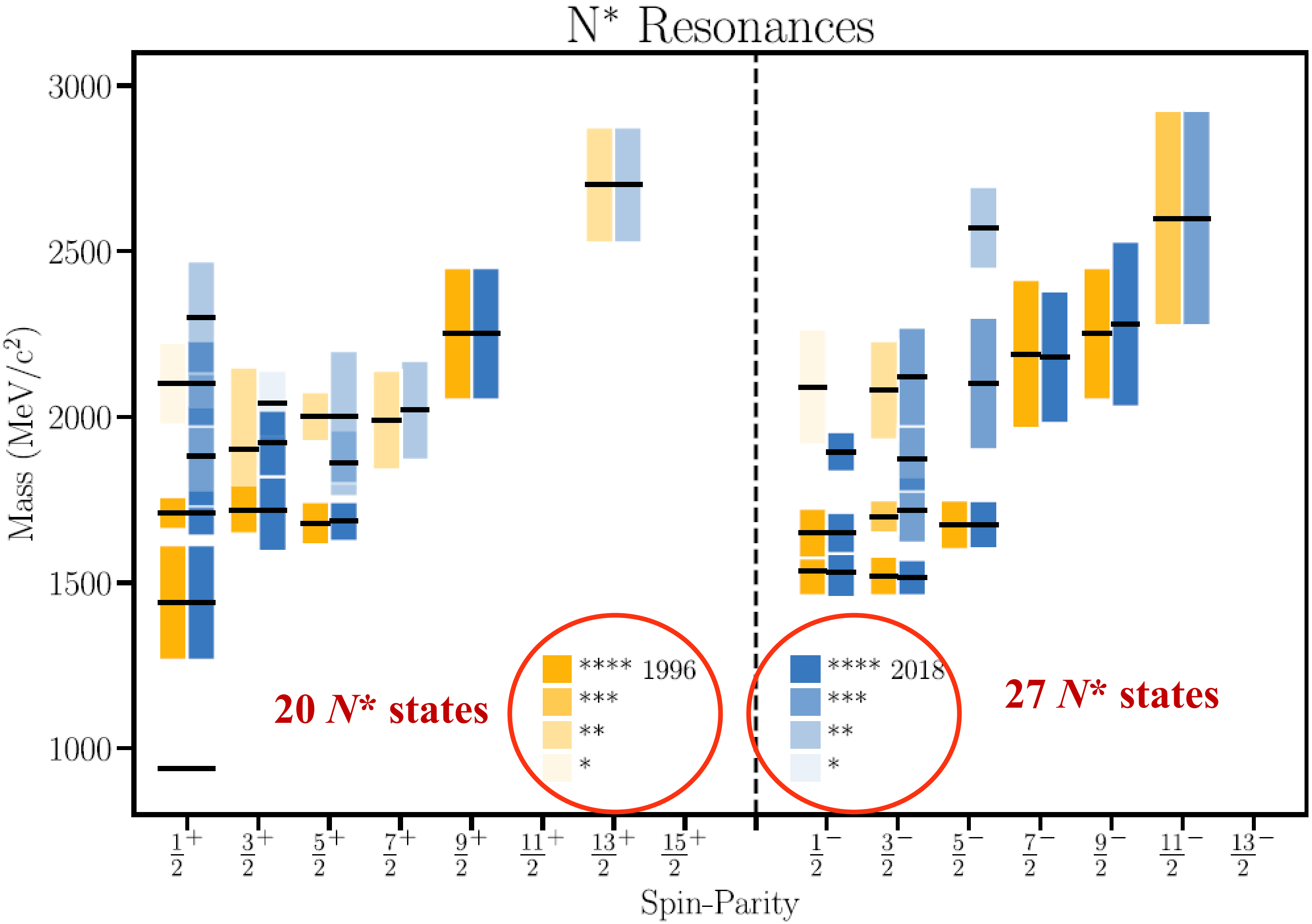


20 *N states**

27 *N states**

D.G. Ireland, E. Pasyuk, I. Strakovsky, Progress in Particle and Nuclear Physics 111 103752 (2020)

Changes to PDG from 1996 to 2018



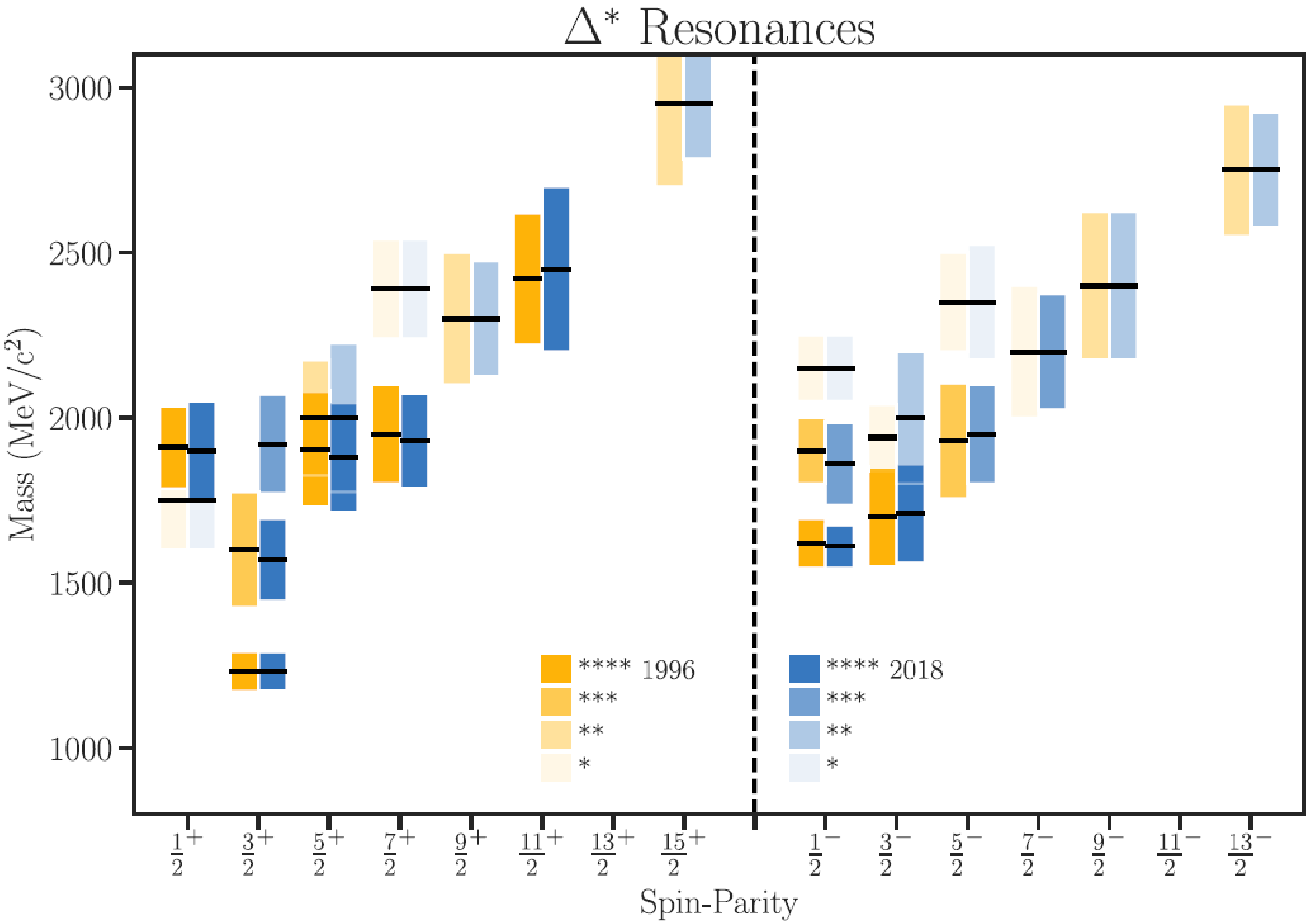
20 *N states**

27 *N states**

Along with additional new states, "old" states have been measured better and PDG properties have changed

D.G. Ireland, E. Pasyuk, I. Strakovsky, Progress in Particle and Nuclear Physics 111 103752 (2020)

Changes to PDG from 1996 to 2018



States have been measured better and PDG properties have changed

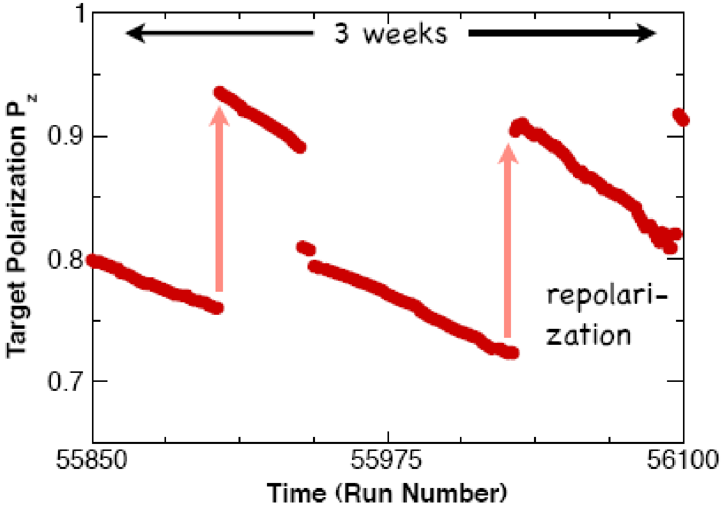
D.G. Ireland, E. Pasyuk, I. Strakovsky, Progress in Particle and Nuclear Physics 111 103752 (2020)

Frost target

- Brute force polarization requires large magnet

- Instead use “trick” (Dynamic Nuclear Polarization):
  - Dope butanol with paramagnetic radical TEMPO
  - Polarize unpaired TEMPO electrons to 99.999% with B = 5 T and T = 0.3 K
  - Transfer electron polarization to free protons with microwaves at ~140 GHz
  - Remove microwaves
  - Cool to T = 3 mK and use B=0.5T holding field
  - Put target in CLAS and run experiment

Performance: target polarization



- Frozen spin butanol (C_4H_9OH)
- $P_z \approx 80\%$
- Target depolarization: $\tau \approx 100$ days

- For g9a (longitudinal orientation) 10% of allocated time was used polarizing target

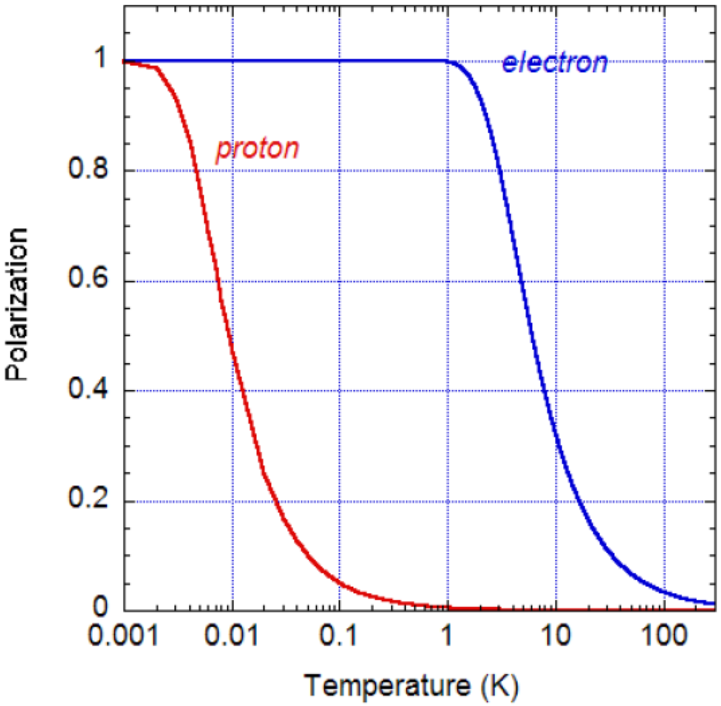
- For g9b (transverse orientation) 5% of allocated time was used polarizing target

Frost target

Brute Force Polarization

$$P = \tanh\left(\frac{\vec{\mu}\cdot\vec{B}}{kT}\right) \longrightarrow$$ maximize B, minimize T

5 Tesla



Disadvantages:

1. Requires very large magnet
2. Low temperatures mean low luminosity
3. Polarization can take a very long time

We need a trick!

Slide from Chris Keith

Frost target

The Trick -- **D**ynamic **N**uclear **P**olarization

Use brute force to polarize free electrons in the target material.
Use microwaves to "transer" this polarization to nuclei. Mutual electron-nucleus spin flips re-arrange the nuclear Zeeman populations to favor one spin state over the other.

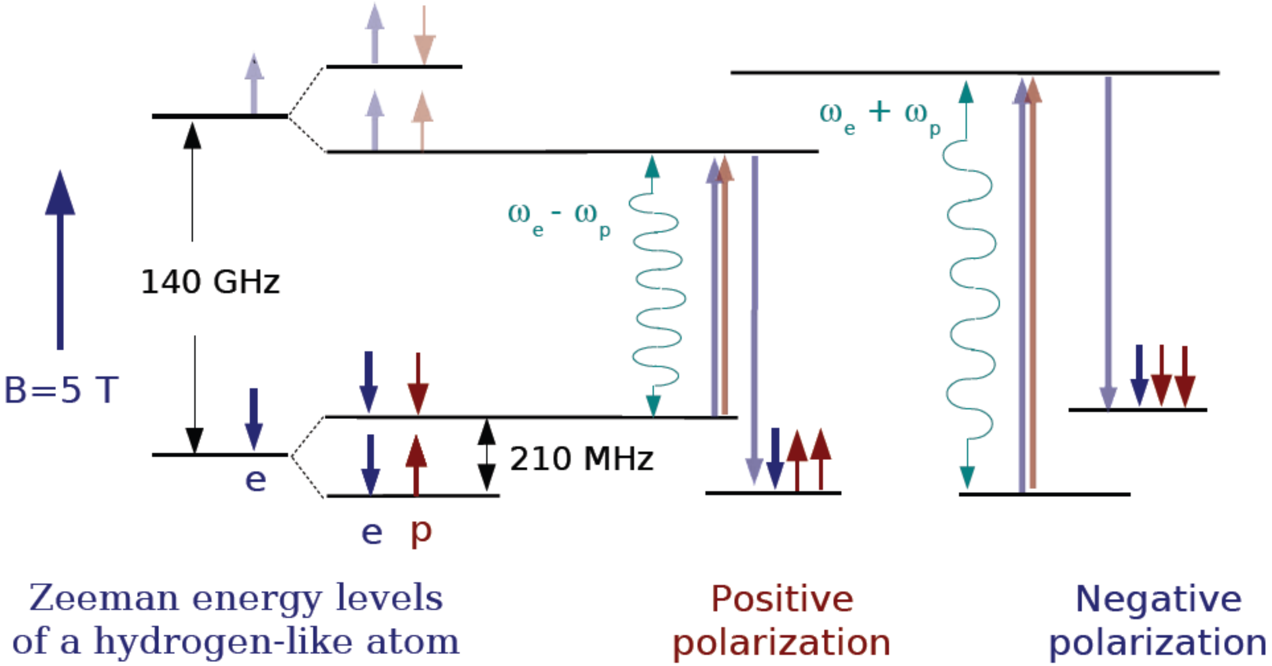
For best results, DNP is performed at *B/T* conditions where electron t_1 is short (ms) and nuclear t_1 is long (minutes)

JLab: $B = 5$ *Tesla*
$T = 1$ *Kelvin*

Slide from Chris Keith

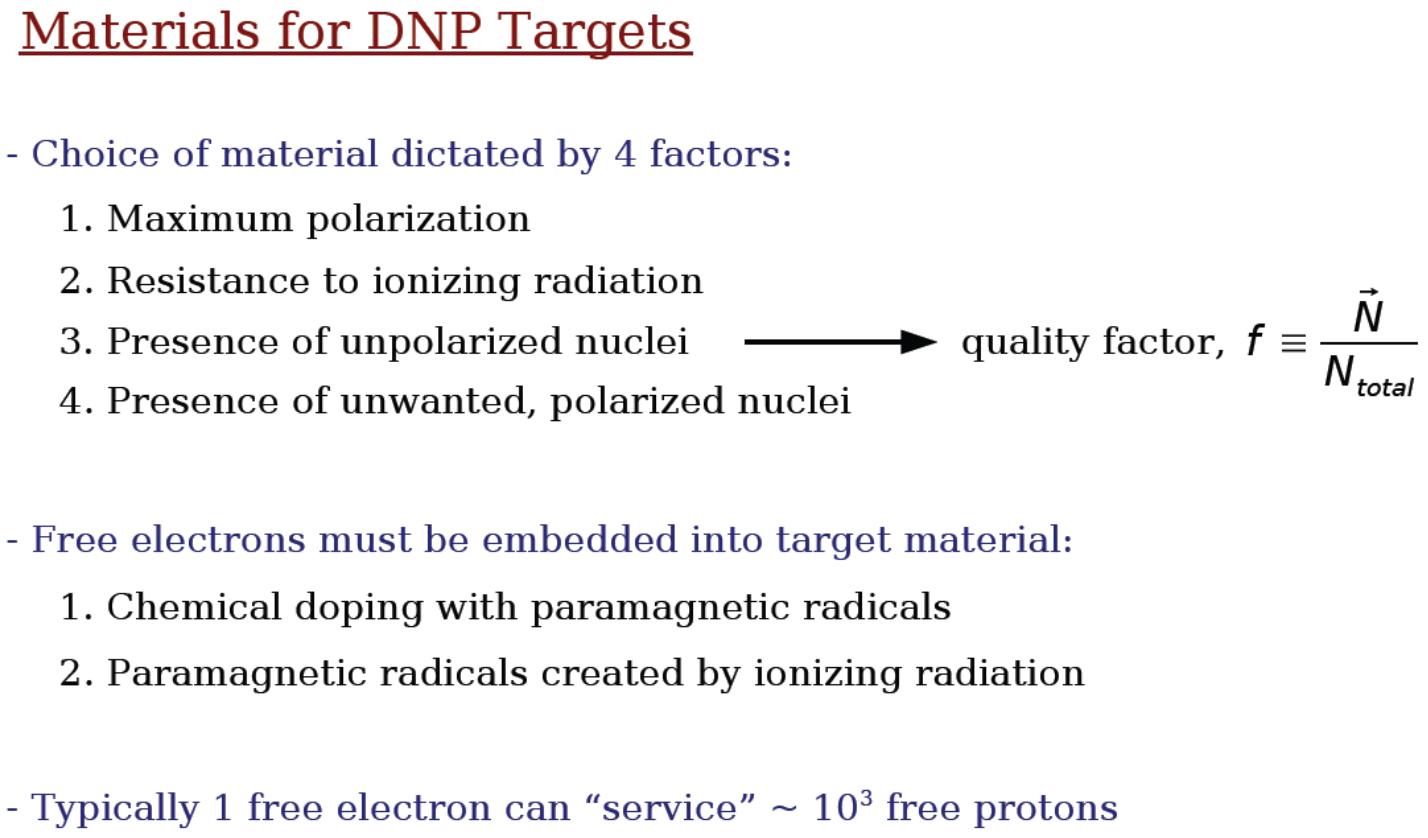
Frost target

The Resolved Solid Effect



Slide from Chris Keith

Frost target



Materials for DNP Targets

- Choice of material dictated by 4 factors:

1. Maximum polarization
2. Resistance to ionizing radiation
3. Presence of unpolarized nuclei $\longrightarrow$ quality factor, $f \equiv \frac{\vec{N}}{N_{total}}$
4. Presence of unwanted, polarized nuclei

- Free electrons must be embedded into target material:

1. Chemical doping with paramagnetic radicals
2. Paramagnetic radicals created by ionizing radiation

- Typically 1 free electron can “service” ~ 10^3 free protons

Slide from Chris Keith

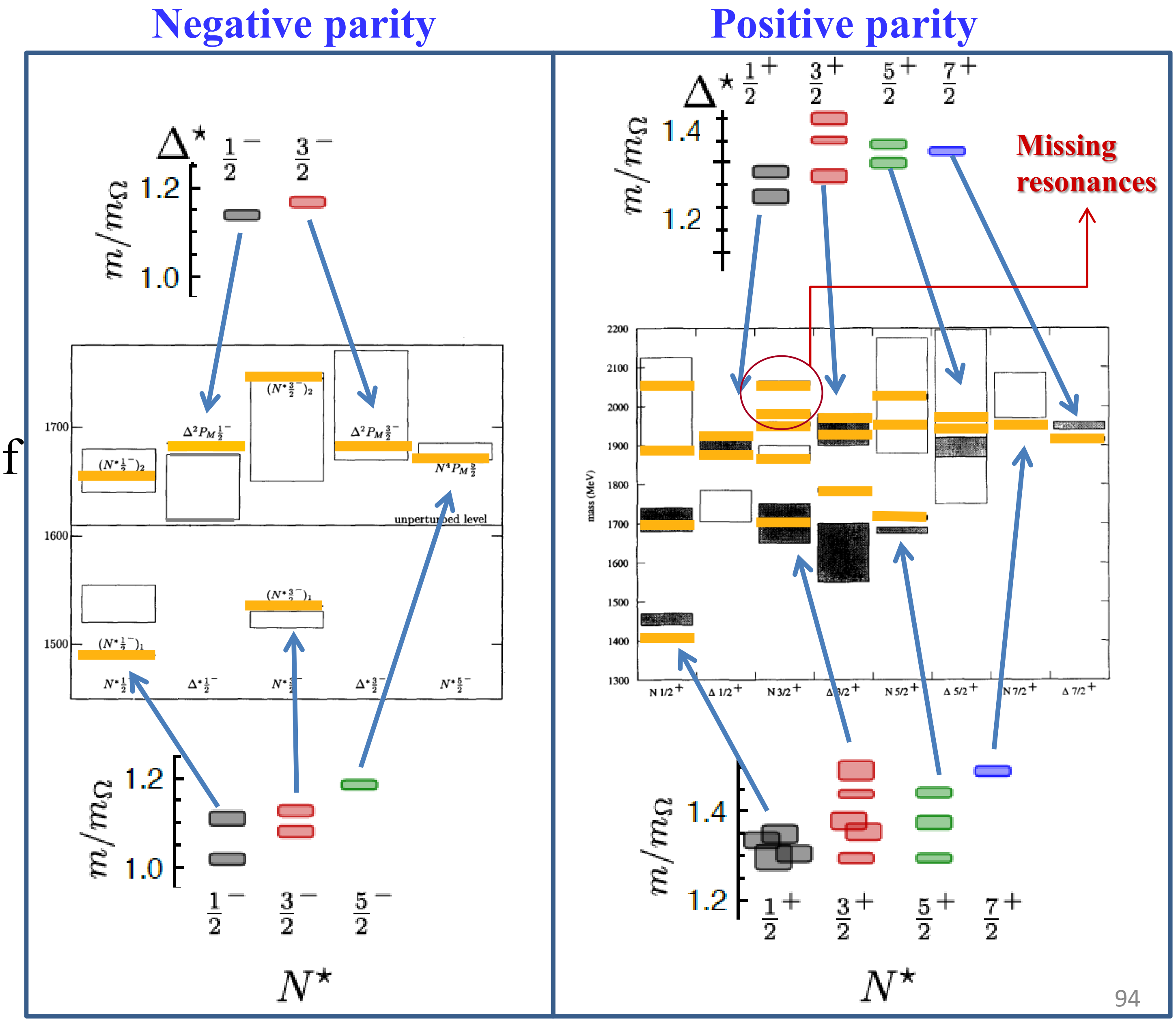
Materials for DNP Targets, examples

Name	Dopant	f	Rad. Resistance
Polyethelyne, C_2H_4	chemical	0.12	low
Polystyrene, C_8H_8	chemical	0.07	low
Propandiol, $C_3H_6(OH)_2$	chemical	0.11	moderate
Butanol, C_4H_9OH	chemical	0.13	moderate
Ammonia, $^{15}NH_3$	radiation	0.17	high
Lithium Hydride, ^{7}LiH	radiation	0.12	very high

Slide from Chris Keith

Low-lying Resonance States

Lattice QCD is consistent with non-relativistic quark model for number of low-lying states



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

Circular beam and longitudinal target:
$\delta_l = \Lambda_x = \Lambda_y = 0$

The differential cross section for $\gamma p \rightarrow p\pi^+\pi^-$

(without measuring the polarization of the recoiling nucleon)

$$\frac{d\sigma}{dx_i} = \sigma_0 \{ (1 + \vec{\Lambda}_i \cdot \boxed{\vec{\mathbf{P}}}) + \delta_\odot (\mathbf{I}^\odot + \vec{\Lambda}_i \cdot \boxed{\vec{\mathbf{P}}^\odot})$$

G9a: FROST

Next slides

$$+ \delta_l [\sin 2\beta (\mathbf{I}^s + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}^s) + \cos 2\beta (\mathbf{I}^c + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}^c)] \}$$

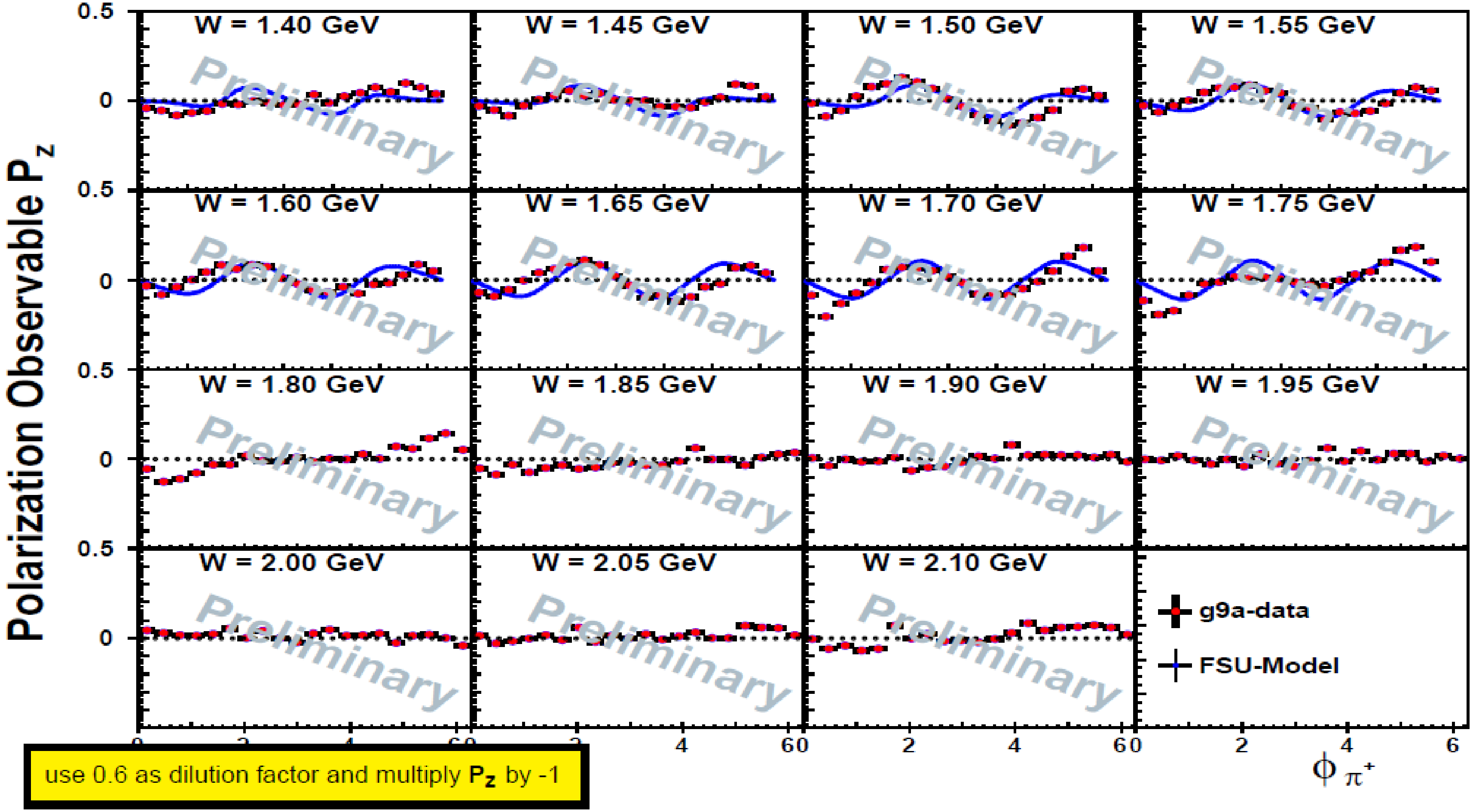
- σ_0: The unpolarized cross section
- β: The angle between the direction of polarization and the x-axis
- $\delta_{\odot, l}$: The degree of polarizaton of the photon beam $\Rightarrow \delta_\odot$, and δ_l
- $\vec{\Lambda}_i$: The polarization of the initial nucleon $\Rightarrow (\Lambda_x, \Lambda_y, \Lambda_z)$
- $\mathbf{I}^{\odot, s, c}$: The observable arising from use of polarized photons $\Rightarrow \mathbf{I}^\odot, \mathbf{I}^s, \mathbf{I}^c$
- $\vec{\mathbf{P}}$: The polarization observable $\Rightarrow (\mathbf{P_x}, \mathbf{P_y}, \mathbf{P_z})\ (\mathbf{P}_x^\odot, \mathbf{P}_y^\odot, \mathbf{P}_z^\odot)\ (\mathbf{P}_x^s, \mathbf{P}_y^s, \mathbf{P}_z^s)\ (\mathbf{P_x^c}, \mathbf{P_y^c}, \mathbf{P_z^c})$

15 Observables

P^z for $p\ \pi^+\ \pi^-$

G9a: FROST

● FSU-model calculation by Winston Roberts



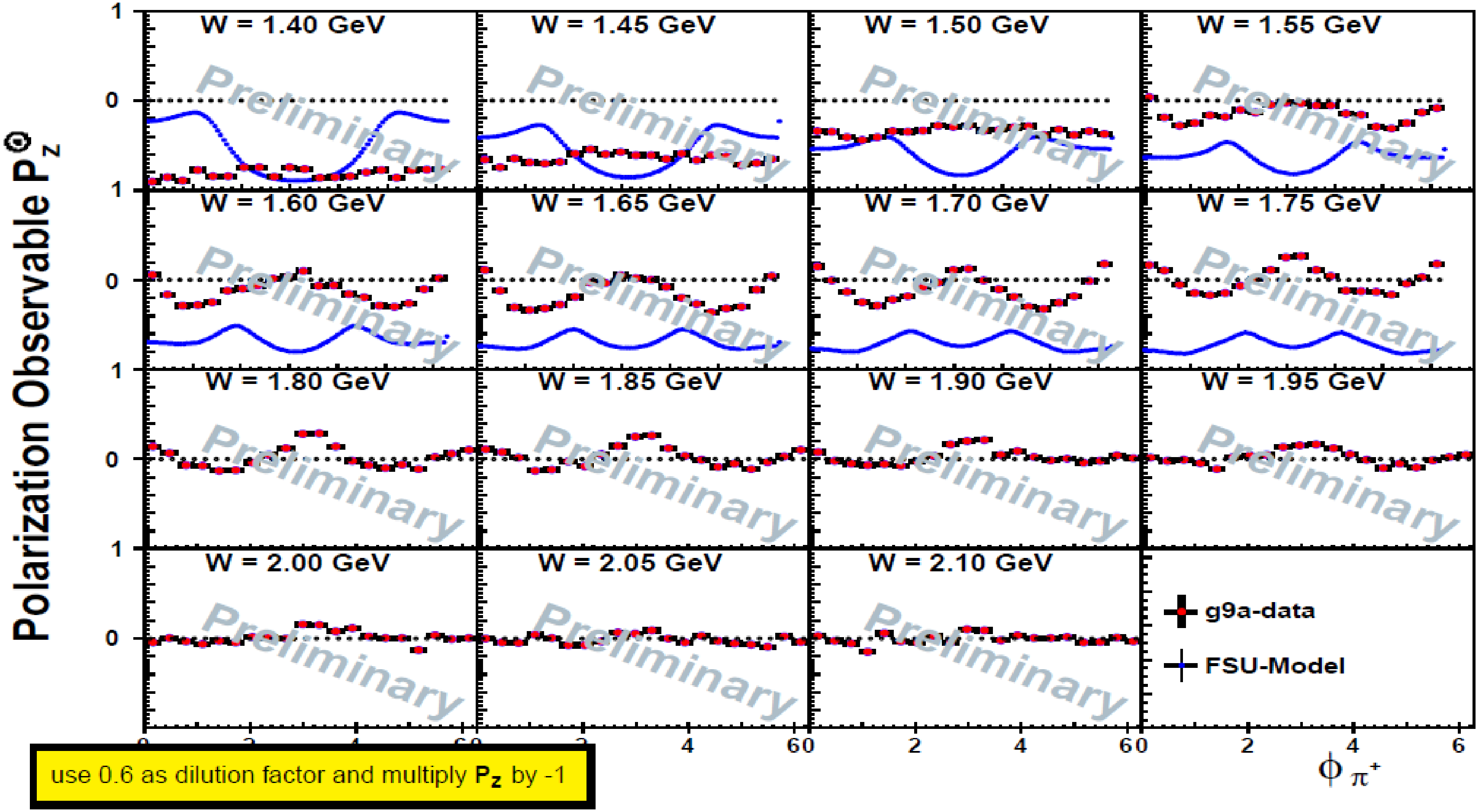
use 0.6 as dilution factor and multiply P_z by -1

ARIZONA STATE UNIVERSITY

$P^{\odot}$ for $p\ \pi^{+}\ \pi^{-}$

G9a: FROST

- FSU-model calculation by Winston Roberts



use 0.6 as dilution factor and multiply P_z by -1

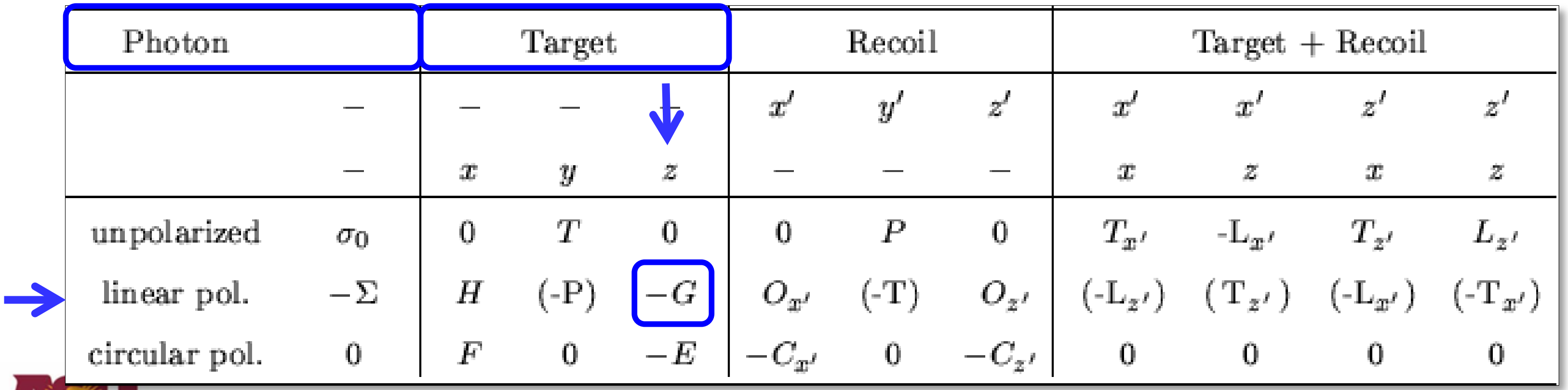
Observable

Configuration:

- **Linear photon polarization**
- **Longitudinal Target polarization**
- No recoil polarization

Experiment:

- g9a: FROST



Photon		Target			Recoil			Target + Recoil			
	–	–	–		x'	y'	z'	x'	x'	z'	z'
	–	x	y	z	–	–	–	x	z	x	z
unpolarized	σ_0	0	T	0	0	P	0	$T_{x'}$	$-L_{x'}$	$T_{z'}$	$L_{z'}$
linear pol.	$-\Sigma$	H	$(-P)$	$\boxed{-G}$	$O_{x'}$	$(-T)$	$O_{z'}$	$(-L_{z'})$	$(T_{z'})$	$(-L_{x'})$	$(-T_{x'})$
circular pol.	0	F	0	$-E$	$-C_{x'}$	0	$-C_{z'}$	0	0	0	0

Isospin photo-couplings for $\gamma p \rightarrow n\pi^+$ and $\gamma n \rightarrow p\pi^-$

γp
- Iso-singlet $A^0\left|I=0, I_3=0\right\rangle\left|I=\tfrac{1}{2}, I_3=\tfrac{1}{2}\right\rangle = A^0\left|I=\tfrac{1}{2}, I_3=\tfrac{1}{2}\right\rangle$
- Iso-vector $A^1\left|I=1, I_3=0\right\rangle\left|I=\tfrac{1}{2}, I_3=\tfrac{1}{2}\right\rangle = A^1\left\lfloor\sqrt{2/3}\left|I=\tfrac{3}{2}, I_3=\tfrac{1}{2}\right\rangle \ominus \sqrt{1/3}\left|I=\tfrac{1}{2}, I_3=\tfrac{1}{2}\right\rangle\right\rfloor$

γn
- Iso-singlet $A^0\left|I=0, I_3=0\right\rangle\left|I=\tfrac{1}{2}, I_3=\tfrac{-1}{2}\right\rangle = A^0\left|I=\tfrac{1}{2}, I_3=\tfrac{-1}{2}\right\rangle$
- Iso-vector $A^1\left|I=1, I_3=0\right\rangle\left|I=\tfrac{1}{2}, I_3=\tfrac{-1}{2}\right\rangle = A^1\left\lfloor\sqrt{2/3}\left|I=\tfrac{3}{2}, I_3=\tfrac{-1}{2}\right\rangle \oplus \sqrt{1/3}\left|I=\tfrac{1}{2}, I_3=\tfrac{-1}{2}\right\rangle\right\rfloor$

$$\gamma p \rightarrow n\pi^+: \quad \pm\sqrt{\tfrac{2}{3}}\left\lfloor A^0 \ominus \sqrt{\tfrac{1}{3}}A^1\right\rfloor N^* + \frac{\sqrt{2}}{3}A^1\Delta^*$$

$$\gamma n \rightarrow p\pi^-: \quad \mp\sqrt{\tfrac{2}{3}}\left\lfloor A^0 \oplus \sqrt{\tfrac{1}{3}}A^1\right\rfloor N^* + \frac{\sqrt{2}}{3}A^1\Delta^*$$

- Using both proton and neutron targets allows decomposition of iso-singlet and iso-vector photo-couplings
- The sings in ○ ○ will give interference terms