Advances in N* spectroscopy from Exclusive Photoproduction at CLAS

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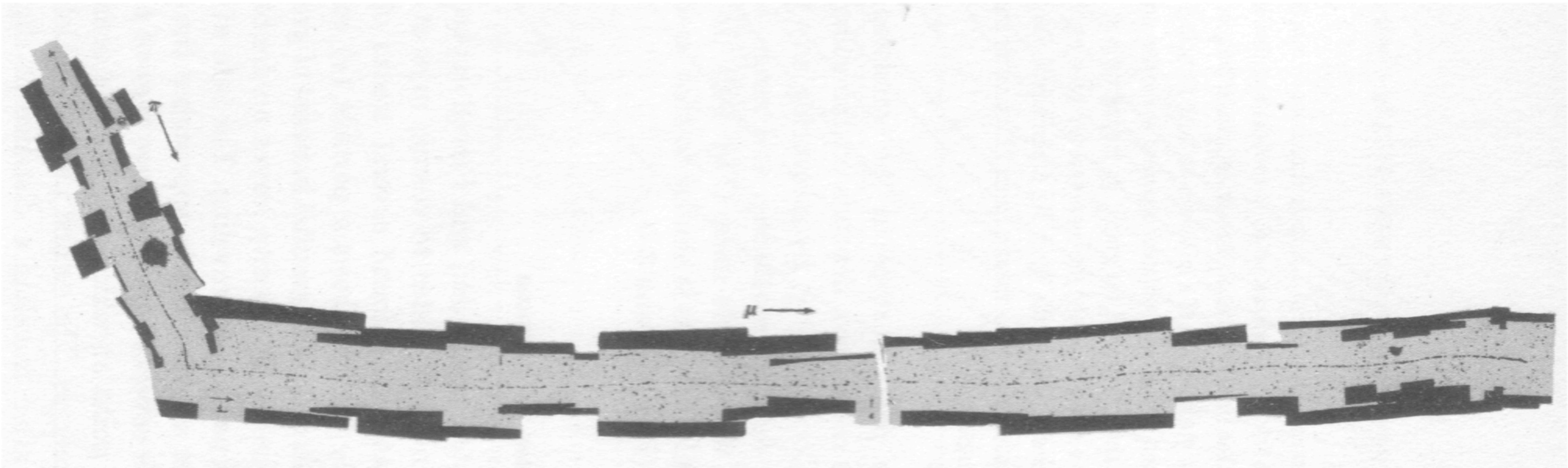
Outline

- History
- Experimental tools
- Some formalism
- Selected results
- Summary

1947: Discovery of pion



Photomicrograph showing a π meson (π) coming to rest in a nuclear emulsion and a μ meson (μ) arising from the end of the π-meson track. (From C. M. G. Lattes, H. Muirhead, G. Occhialini, and C. F. Powell, *Nature*, vol. 160, p. 453, 1947.)

1949: First pion photoproduction experiment

December 2, 1949, Vol. 110 SCIENCE

Production of Mesons by X-Rays

Edwin M. McMillan, Jack M. Peterson, and R. Stephen White[1]

Radiation Laboratory, Department of Physics, University of California, Berkeley

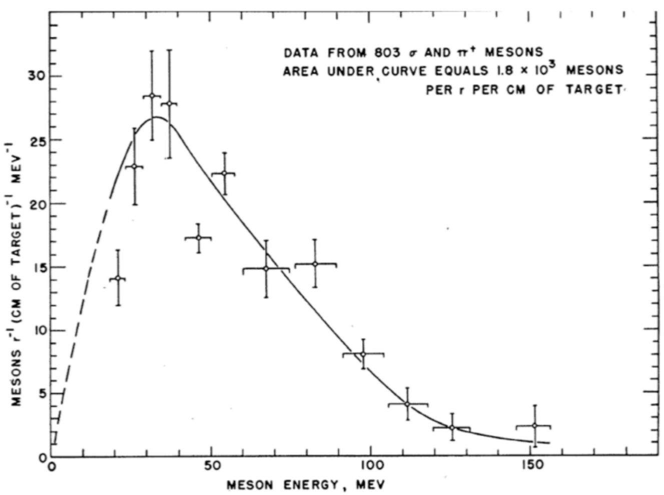


FIG. 4. Distribution of meson energies from x-ray energy of 335 Mev. The apparent lower limit on the energy is caused by the fact that the energies are computed as if the mesons originated in the center of the carbon block. The dotted line is simply a guess as to the trend of the distribution at low energies, which was used in the integration leading to the total cross section.

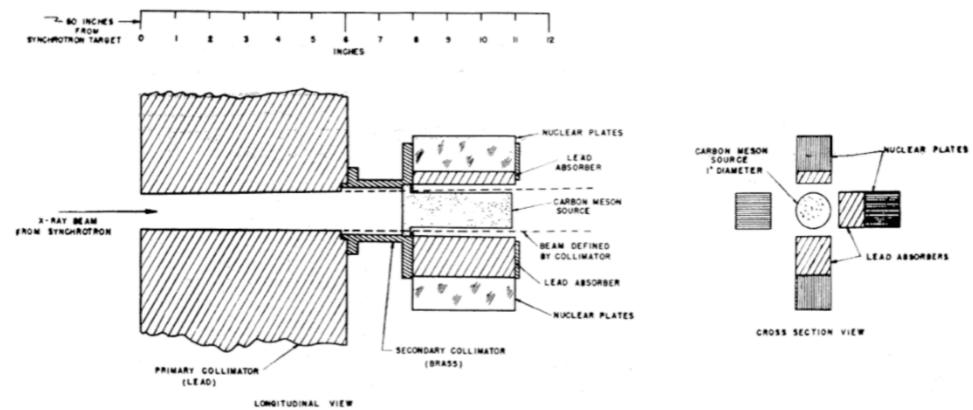


FIG. 1. Drawing of experimental arrangement (Geometry 4).

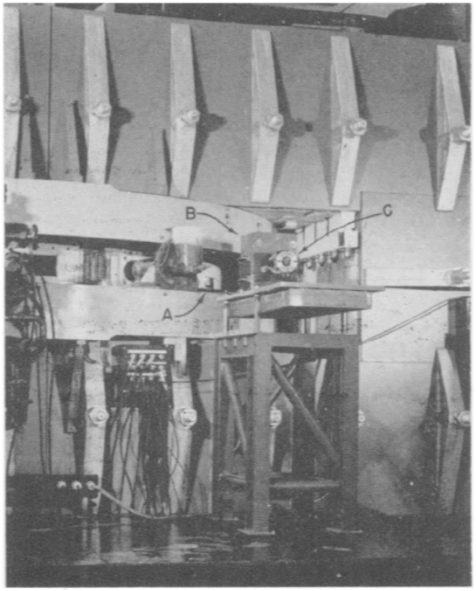


FIG. 2. Photograph of experimental arrangement (Geometry 4). The x-ray beam emerges from the synchrotron through the rectangular hole (A). The 6-inch-thick lead collimator is at B. C is the plate holder.

1952: Discovery of Δ resonance

Physical Review **85,** 936 (1952)

produced in pairs by the decay of the neutral pions, the cross sections for the processes (1) and (2) would be $(10\pm4)\times10^{-27}$ and $(20\pm5)\times10^{-27}$ cm². The cross section obtained for the charge exchange process is not very sensitive to the angular distribution adopted. It would be $(29\pm7)\times10^{-27}$ cm² for a $\cos^2\theta$-distribution and $(18\pm4)\times10^{-27}$ cm² for a $\sin^2\theta$-distribution.

* Research sponsored by the ONR and AEC.

Total Cross Sections of Positive Pions in Hydrogen*

H. L. Anderson, E. Fermi, E. A. Long,† and D. E. Nagle
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois

(Received January 21, 1952)

In a previous letter,[1] measurements of the total cross sections of negative pions in hydrogen were reported. In the present letter, we report on similar experiments with positive pions.

The experimental method and the equipment used in this

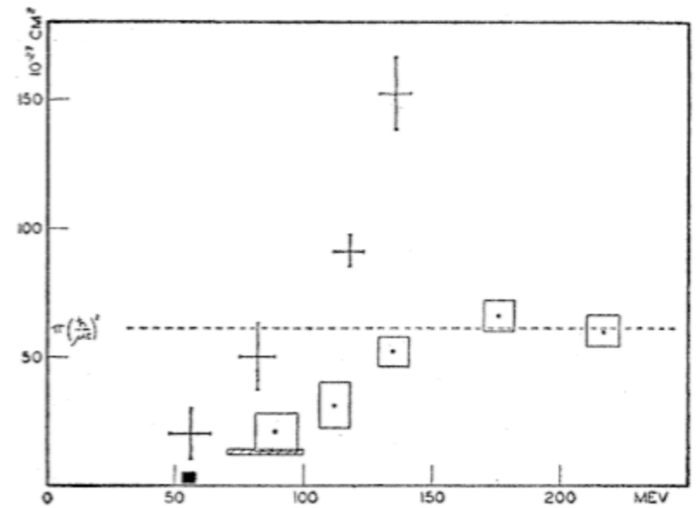


Fig. 1. Total cross sections of negative pions in hydrogen (sides of the rectangle represent the error) and positive pions in hydrogen (arms of the cross represent the error). The cross-hatched rectangle is the Columbia result. The black square is the Brookhaven result and does not include the charge exchange contribution.

processes should be (9:2:1), a set of values which is compatible with the experimental observations. It is more difficult, at present,

This event marks the beginning of baryon resonance era

1982: Baryon spectroscopy is 30 years old

PHYSICS REPORTS (Review Section of Physics Letters) 96, Nos. 2 & 3 (1983) 71–204. North-Holland Publishing Company

BARYON SPECTROSCOPY

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and

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Received 29 September 1982

Preface

In 1952 Fermi and coworkers (Andersen et al. [1952]) discovered the first baryon resonance – the $\Delta(1238)$. Since then, hundreds of resonances have been identified and nuclear democracy has given way to fundamental quarks. Baryon spectroscopy is now thirty years old and perhaps approaching a mid-life crisis. For it is inevitable in such a fast-moving field as high energy particle physics, that experiments have moved on beyond the resonance region to higher energies and different priorities. Thus it is probably no exaggeration to say that we now have essentially *all* the experimental data relevant to the low-energy baryon spectrum, that we are *ever* likely to obtain. It is therefore timely to review both the accumulated mass of resonance data, together with the techniques used in its analysis, and also our theoretical framework for understanding the results. The latter is inevitably based on quarks and, by and large, on a very simple, phenomenological, nonrelativistic potential model. Nonetheless, the advent of Quantum-Chromo-Dynamics (QCD) has inspired some rethinking of the original quark model, as originated and developed by Zweig, Greenberg, Dalitz and others, and now appears to culminate in a very successful variant due to Isgur, Karl and co-workers. Needless to say, the phenomenal phenomenological success of this model does not mean that all is understood!

1997: known nucleon resonances

Table 1. The status of the N and Δ resonances. Only those with an overall status of *** or **** are included in the main Baryon Summary Table.

Particle	$L_{2I\cdot 2J}$	Overall status	Status as seen in — $N\pi$	$N\eta$	ΛK	ΣK	$\Delta\pi$	$N\rho$	$N\gamma$
$N(939)$	P_{11}	****							
$N(1440)$	P_{11}	****	****	*			***	*	***
$N(1520)$	D_{13}	****	****	*			****	****	****
$N(1535)$	S_{11}	****	****	****			*	**	***
$N(1650)$	S_{11}	****	****	*	***	**	***	**	***
$N(1675)$	D_{15}	****	****	*	*		****	*	****
$N(1680)$	F_{15}	****	****				****	****	****
$N(1700)$	D_{13}	***	***	*	**	*	**	*	**
$N(1710)$	P_{11}	***	***	**	**	*	**	*	***
$N(1720)$	P_{13}	****	****	*	**	*	*	**	**
$N(1900)$	P_{13}	**	**					*	
$N(1990)$	F_{17}	**	**	*	*	*			*
$N(2000)$	F_{15}	**	**	*	*	*	*	**	
$N(2080)$	D_{13}	**	**	*	*				*
$N(2090)$	S_{11}	*	*						
$N(2100)$	P_{11}	*	*	*					
$N(2190)$	G_{17}	****	****	*	*	*		*	*
$N(2200)$	D_{15}	**	**	*	*				
$N(2220)$	H_{19}	****	****	*					
$N(2250)$	G_{19}	****	****	*					
$N(2600)$	$I_{1\,11}$	***	***						
$N(2700)$	$K_{1\,13}$	**	**						

Particle	$L_{2I\cdot 2J}$	Overall status	Status as seen in — $N\pi$	$N\eta$	ΛK	ΣK	$\Delta\pi$	$N\rho$	$N\gamma$
$\Delta(1232)$	P_{33}	****	****	F					****
$\Delta(1600)$	P_{33}	***	***	o			***	*	**
$\Delta(1620)$	S_{31}	****	****	r			****	****	***
$\Delta(1700)$	D_{33}	****	****	b		*	***	**	***
$\Delta(1750)$	P_{31}	*	*	i					
$\Delta(1900)$	S_{31}	**	**	d		*	*	**	*
$\Delta(1905)$	F_{35}	****	****	d		*	**	**	***
$\Delta(1910)$	P_{31}	****	****	e		*	*	*	*
$\Delta(1920)$	P_{33}	***	***	n		*	**		*
$\Delta(1930)$	D_{35}	***	***			*			**
$\Delta(1940)$	D_{33}	*	*	F					
$\Delta(1950)$	F_{37}	****	****	o		*	****	*	****
$\Delta(2000)$	F_{35}	**		r				**	
$\Delta(2150)$	S_{31}	*	*	b					
$\Delta(2200)$	G_{37}	*	*	i					
$\Delta(2300)$	H_{39}	**	**	d					
$\Delta(2350)$	D_{35}	*	*	d					
$\Delta(2390)$	F_{37}	*	*	e					
$\Delta(2400)$	G_{39}	**	**	n					
$\Delta(2420)$	$H_{3\,11}$	****	****						*
$\Delta(2750)$	$I_{3\,13}$	**	**						
$\Delta(2950)$	$K_{3\,15}$	**	**						

**** Existence is certain, and properties are at least fairly well explored.
*** Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, *etc.* are not well determined.
** Evidence of existence is only fair.
* Evidence of existence is poor.

R.M. Barnett *et al.*, Physical Review **D54**, 1 (1996) and 1997 off-year partial update for the 1998 edition
December 18, 1997 15:23

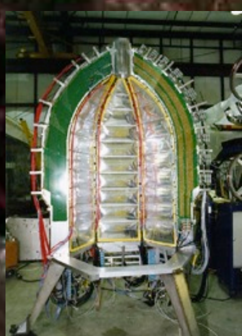
CEBAF Large Acceptance Spectrometer 1997-2012

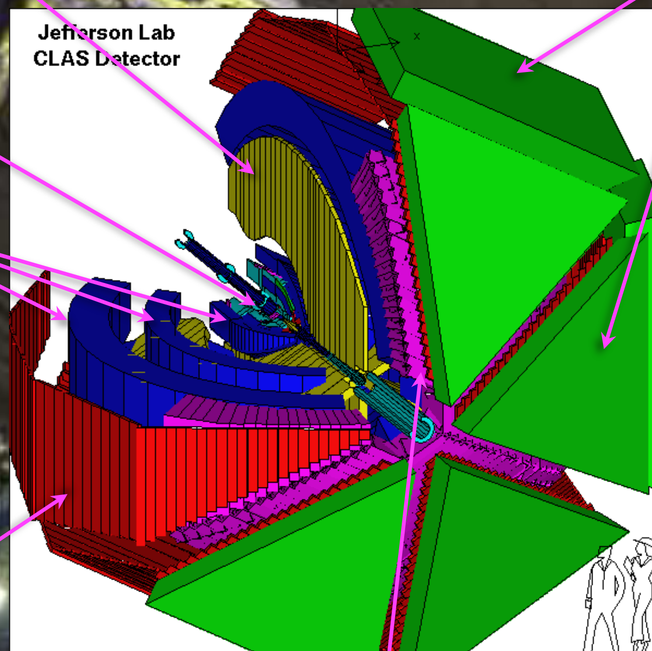
Torus magnet
6 superconducting coils

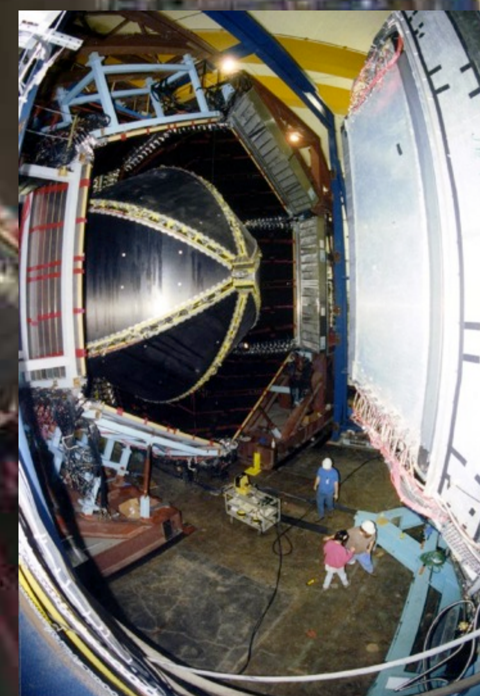
Electromagnetic calorimeters
Lead/scintillator, 1296 photomultipliers

target + start counter

Drift chambers
35,000 cells



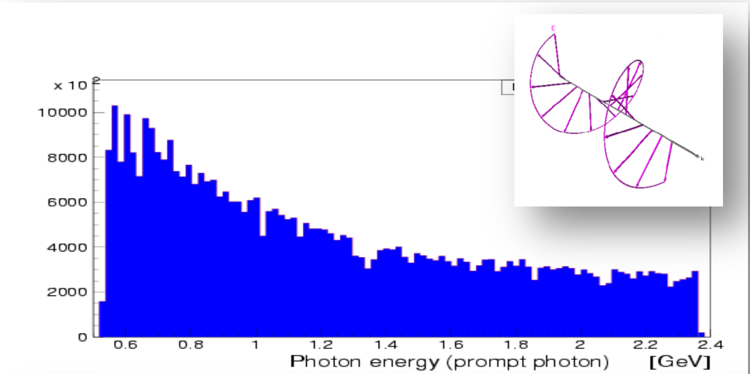




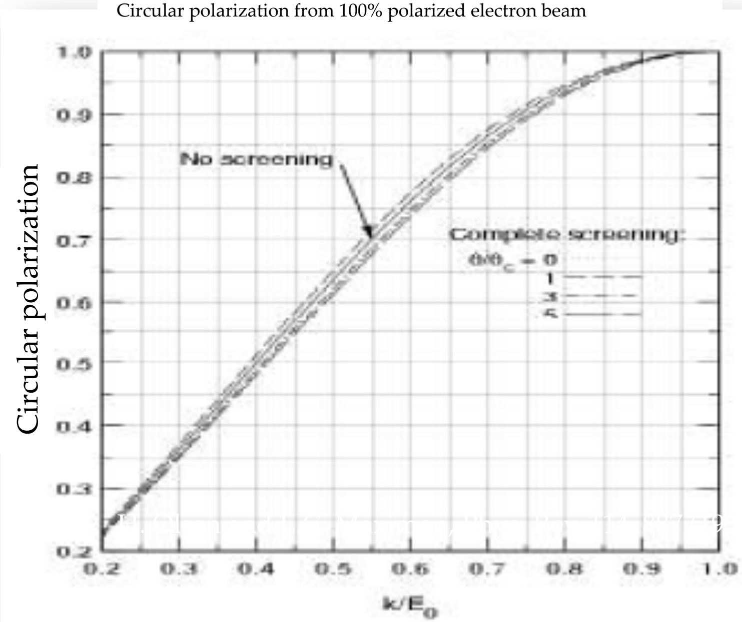
Time-of-flight counters
plastic scintillators, 684 photomultipliers

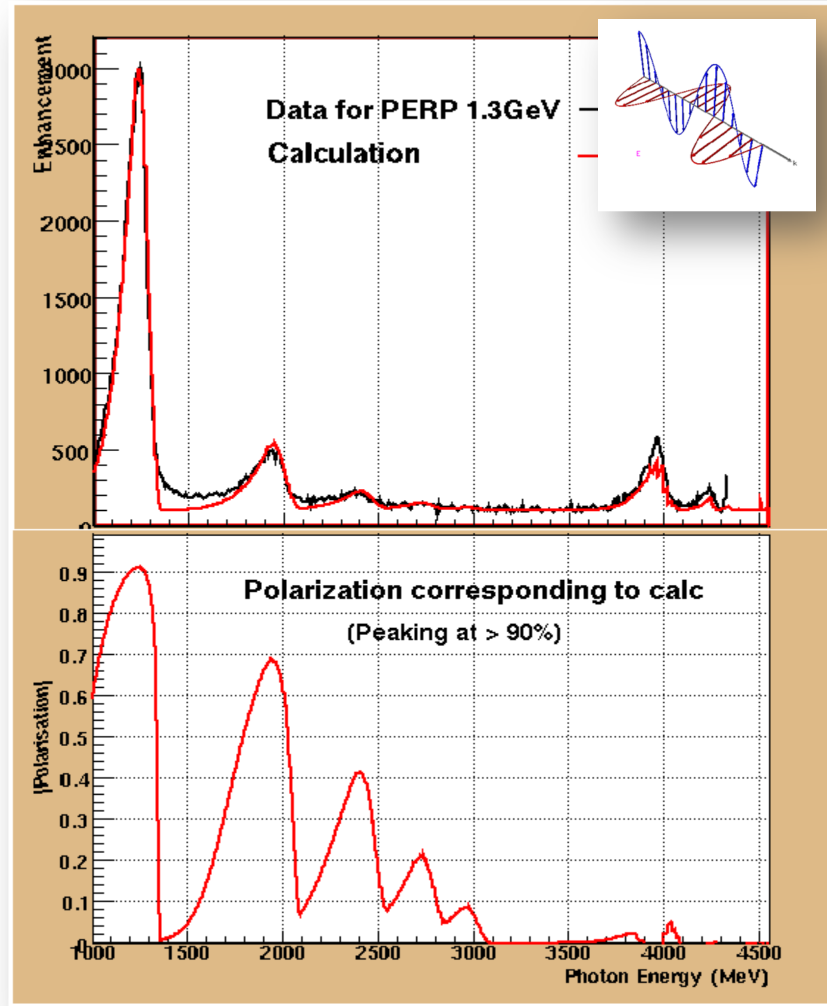
Gas Cherenkov counters
e/π separation, 256 PMTs

Polarized pohoton beam



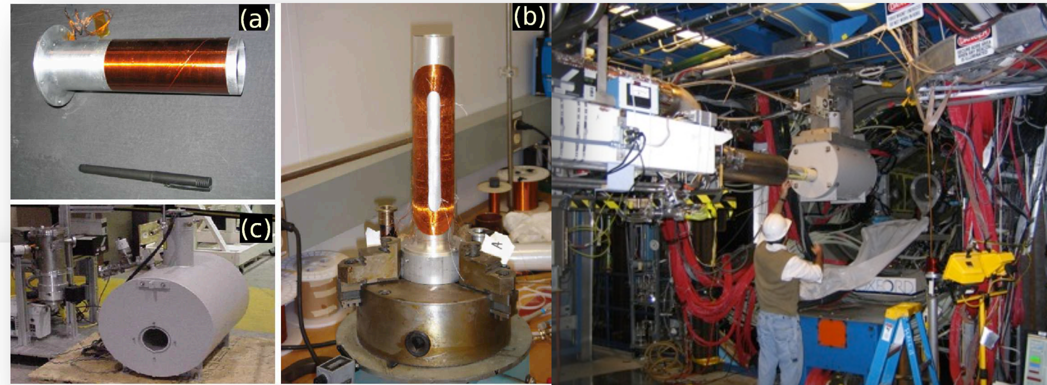
Circular polarization from 100% polarized electron beam





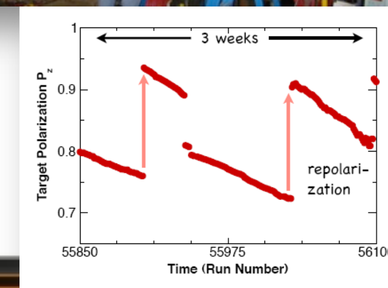
Circularly polarized beam produced by longitudinally polarized electrons

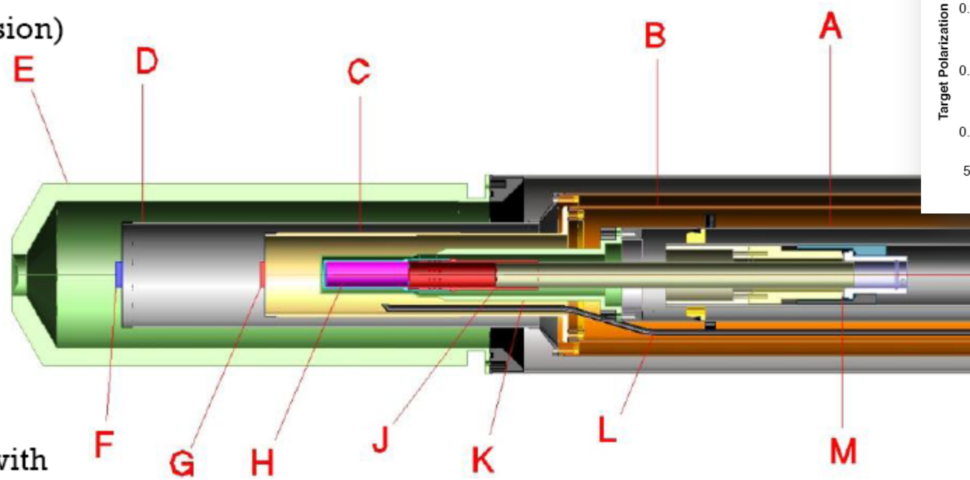
Linearly polarized photons: coherent bremsstrahlung on oriented diamond crystal



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



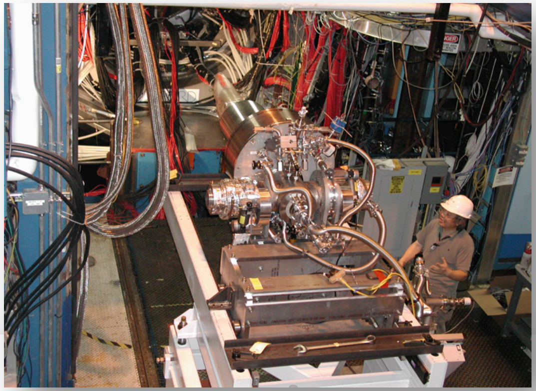


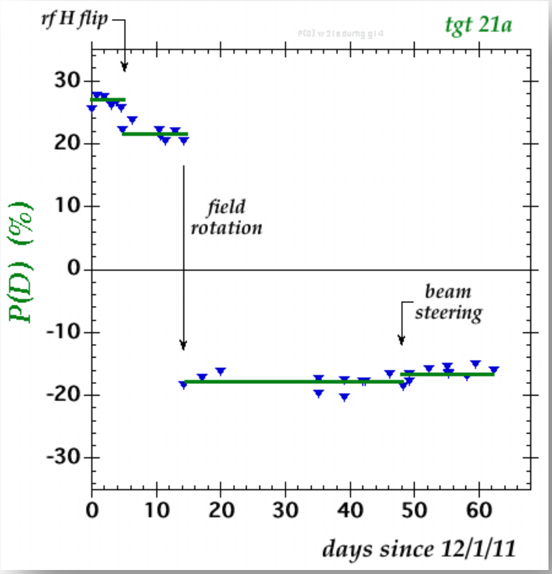
Performance Specs:

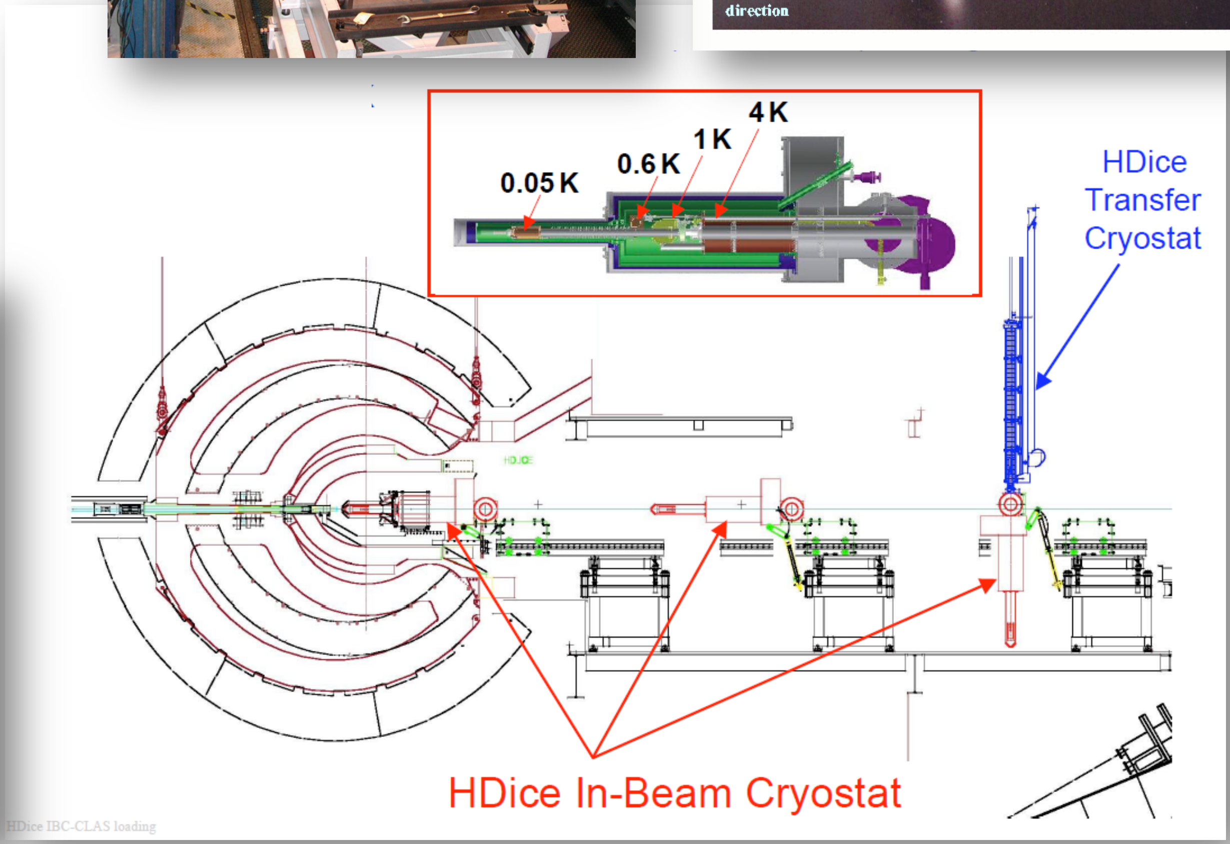
Base Temp: 28 mK w/o beam, 30 mK with
Cooling Power: 800 μW @ 50 mK, 10 mW @ 100 mK, and 60 mW @ 300 mK
Polarization: +82%, -90%
1/e Relaxation Time: 2800 hours (+Pol), 1600 hours (-Pol)
Roughly 1% polarization loss per day.

HDIce polarized target

- Polarized at very high magnetic field and very low temperature
- Transferred to in-beam cryostat
- Spin can be moved between H and D with RF transitions
- All material can be polarized with small background







General spin dependent cross section

$$
\begin{aligned}
d\sigma^{B,T,R}(\vec{P}^{\gamma},\vec{P}^{T},\vec{P}^{R}) = \frac{1}{2}\{ & d\sigma_0[1 - P_L^{\gamma} P_y^{T} P_{y'}^{R} \cos(2\phi_\gamma)] \\
& + \Sigma[-P_L^{\gamma}\cos(2\phi_\gamma) + P_y^{T} P_{y'}^{R}] \\
& + T[P_y^{T} - P_L^{\gamma} P^{R}_{y'} \cos(2\phi_\gamma)] \\
& + P[P^{R}_{y'} - P_L^{\gamma} P_y^{T} \cos(2\phi_\gamma)] \\
& + E[-P_c^{\gamma} P_z^{T} + P_L^{\gamma} P_x^{T} P_{y'}^{R} \sin(2\phi_\gamma)] \\
& + G[P_L^{\gamma} P_z^{T} \sin(2\phi_\gamma) + P_c^{\gamma} P_x^{T} P_{y'}^{R}] \\
& + F[P_c^{\gamma} P_x^{T} + P_L^{\gamma} P_z^{T} P_{y'}^{R} \sin(2\phi_\gamma)] \\
& + H[P_L^{\gamma} P_x^{T} \sin(2\phi_\gamma) - P_c^{\gamma} P_x^{T} P_{y'}^{R}] \\
& + C_{x'}[P_c^{\gamma} P_{x'}^{R} - P_L^{\gamma} P_y^{T} P_{z'}^{R} \sin(2\phi_\gamma)] \\
& + C_{z'}[P_c^{\gamma} P_{z'}^{R} - P_L^{\gamma} P_y^{T} P_{x'}^{R} \sin(2\phi_\gamma)] \\
& + O_{x'}[P_L^{\gamma} P_{x'}^{R} \sin(2\phi_\gamma) + P_L^{\gamma} P_y^{T} P_{z'}^{R}] \\
& + O_{z'}[P_L^{\gamma} P_{z'}^{R} \sin(2\phi_\gamma) - P_c^{\gamma} P_y^{T} P_{x'}^{R}] \\
& + L_{x'}[P_z^{T} P_{x'}^{R} + P_L^{\gamma} P_x^{T} P_{x'}^{R} \cos(2\phi_\gamma)] \\
& + L_{z'}[P_z^{T} P_{z'}^{R} - P_L^{\gamma} P_x^{T} P_{z'}^{R} \cos(2\phi_\gamma)] \\
& + T_{x'}[P_x^{T} P_{x'}^{R} + P_L^{\gamma} P_z^{T} P_{z'}^{R} \cos(2\phi_\gamma)] \\
& + T_{z'}[P_z^{T} P_{z'}^{R} - P_L^{\gamma} P_z^{T} P_{x'}^{R} \cos(2\phi_\gamma)]\}
\end{aligned}
$$

Single spin (terms Σ, T, P)

Beam-Target (terms E, G, F, H)

Beam-Recoil (terms $C_{x'}$, $C_{z'}$, $O_{x'}$, $O_{z'}$)

Target-Recoil (terms $L_{x'}$, $L_{z'}$, $T_{x'}$, $T_{z'}$)

- Every observable can be measured in at least two different experiments.

A. M. Sandorfi, S. Hoblit, H. Kamano, T.-S. H. Lee J.Phys.G38:053001,2011

Measurements

Beam		Target			Recoil			Target + Recoil								
					x'	y'	z'	x'	x'	x'	y'	y'	y'	z'	z'	z'
		x	y	z				x	y	z	x	y	z	x	y	z
unpolarized	$d\sigma_0$		T			P		$T_{x'}$		$L_{x'}$		Σ		$T_{z'}$		$L_{z'}$
$P_L^\gamma \sin(2\varphi_\gamma)$		H		G	$O_{x'}$		$O_{z'}$		$C_{z'}$		E		F		$-C_{x'}$	
$P_L^\gamma \cos(2\varphi_\gamma)$	Σ		$-P$			$-T$		$-L_{x'}$		$T_{z'}$		$-d\sigma_0$		$L_{x'}$		$-T_{x'}$
circular P_c^γ	$d\sigma_0$	F		$-E$	$C_{x'}$		$C_{z'}$		$-O_{z'}$		G		$-H$		$O_{x'}$	

- Every observable can be measured in at least two different experiments configurations.
- **η, η′** and **ω** are isospin filtered channels, not coupled directly to **Δ**
- It is important to measure both **$K^+\Lambda$** and **$K^+\Sigma^0$**: isospin filter
- It is also important to do measurement on both proton and neutron target
- **There is no such things as redundant data!**

See also B5: 11:20 Dave Ireland, “Evaluating Polarization Data”

CLAS experiments with proton target

- Unpolarized target (liquid hydrogen)
    - g1c – circularly polarized beam
    - g11 – unpolarized beam, high statistics
    - g8b – linearly polarized beam
- FROST polarized target (butanol)
    - g9a – circularly and linearly polarized beam on longitudinally polarized target
    - g9b – circularly and linearly polarized beam on transversely polarized target

CLAS Experiments with deuteron target

- g10 unpolarized beam, unpolarized deuterium target
- g13 circularly and linearly polarized beam on unpolarized deuterium target
- g14 circularly and linearly polarized beam on longitudinally polarized HD target

Final states measured in photoproduction with CLAS

	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																
$p\pi^0$	✔ (red)	✔ (red)	✔ (green)	✔ (green)	✔ (red)	✔ (green)	✔ (green)	✔ (green)								
$n\pi^+$	✔ (red)	✔ (red)	✔ (green)	✔ (green)	✔ (red)	✔ (green)	✔ (green)	✔ (green)								
$p\eta$	✔ (red)	✔ (red)	✔ (green)	✔ (green)	✔ (red)	✔ (green)	✔ (green)	✔ (green)								
$p\eta'$	✔ (red)	✔ (red)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)								
$p\omega$	✔ (red)	✔ (red)	✔ (yellow)	✔ (green)	✔ (yellow)	✔ (green)	✔ (green)	✔ (green)	SDME							
$p\pi^+\pi^-$	✔ (yellow)	64 beam-target asymmetries														
$K^+\Lambda$	✔ (red)	✔ (green)	✔ (red)	✔ (red)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (red)	✔ (red)	✔ (red)	✔ (red)
$K^+\Sigma^0$	✔ (red)	✔ (green)	✔ (red)	✔ (red)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (red)	✔ (red)	✔ (red)	✔ (red)
$K^{0*}\Sigma^+$	✔ (red)															
$K^0\Sigma^+$	✔ (red)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)								
"Neutron" target																
$p\pi^-$	✔ (red)	✔ (yellow)			✔ (red)		✔ (green)									
$K^+\Sigma^-$	✔ (red)	✔ (green)														
$K^0\Lambda$	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)
$K^0\Sigma^0$	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)

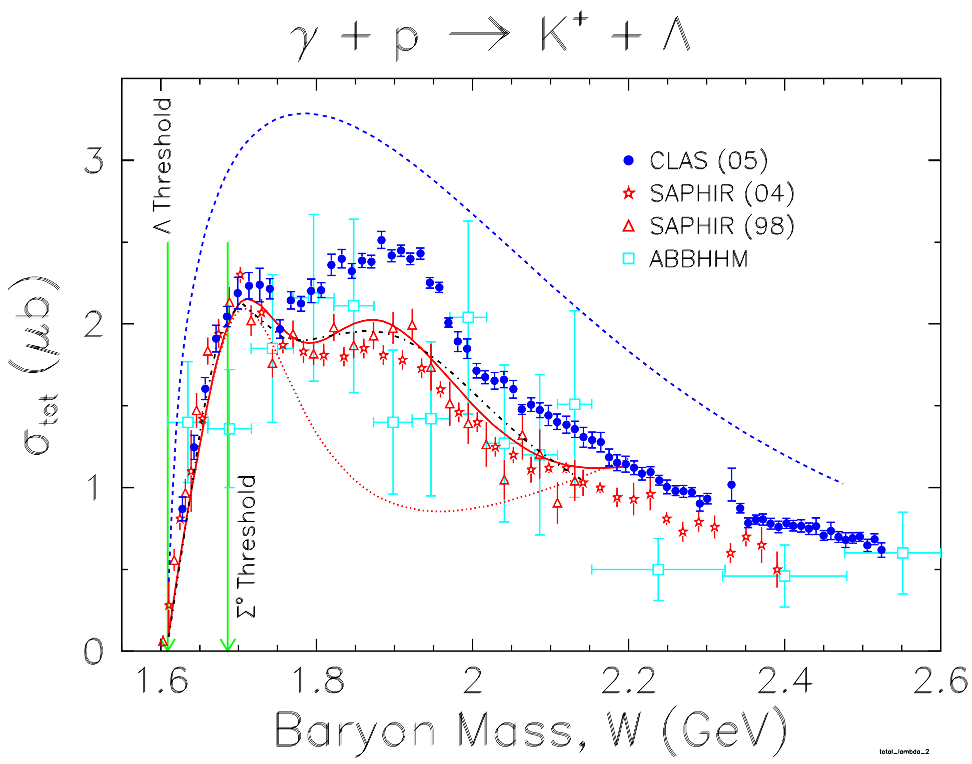
✔ (red) - published ✔ (yellow) - analysis complete ✔ (green) - acquired

$\gamma p \rightarrow KY$

…

	Total	CLAS
$\gamma p \rightarrow K^+\Lambda$	9026	6046
$\gamma p \rightarrow K^+\Sigma^0$	6876	4343
$\gamma p \rightarrow K^0\Sigma^+$	304	48

Bump?



SAPHIR data (1998) triggered discussion of "missing" resonances.

D_{13}(1890)?, P_{11}(1840)? D_{13}(1900)?... lots of other interpretations

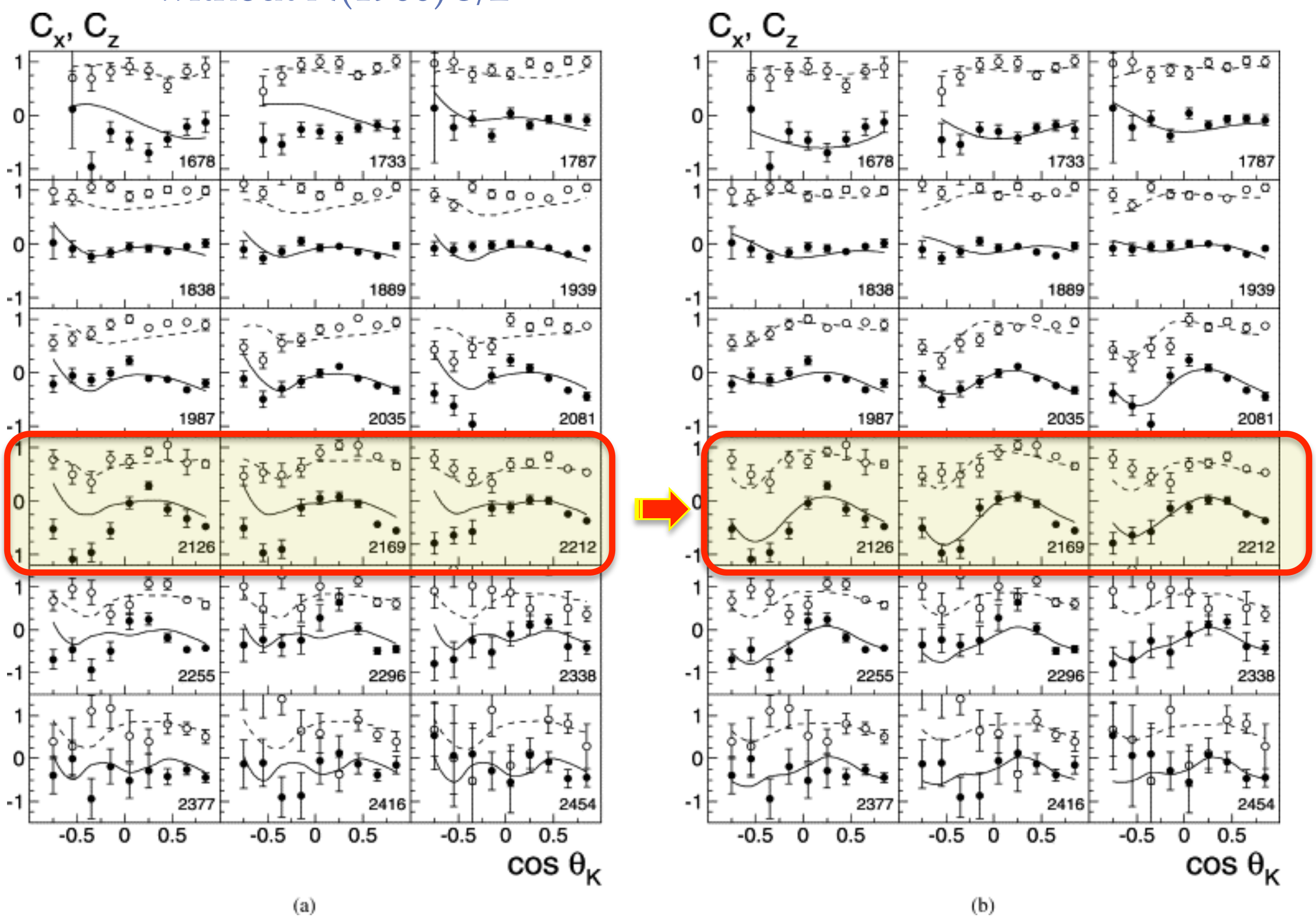
CLAS got into the game

First CLAS measurements (g1c): ***dσ/dΩ, P, Cx, Cz***

Confirmed bump around 1.9 GeV

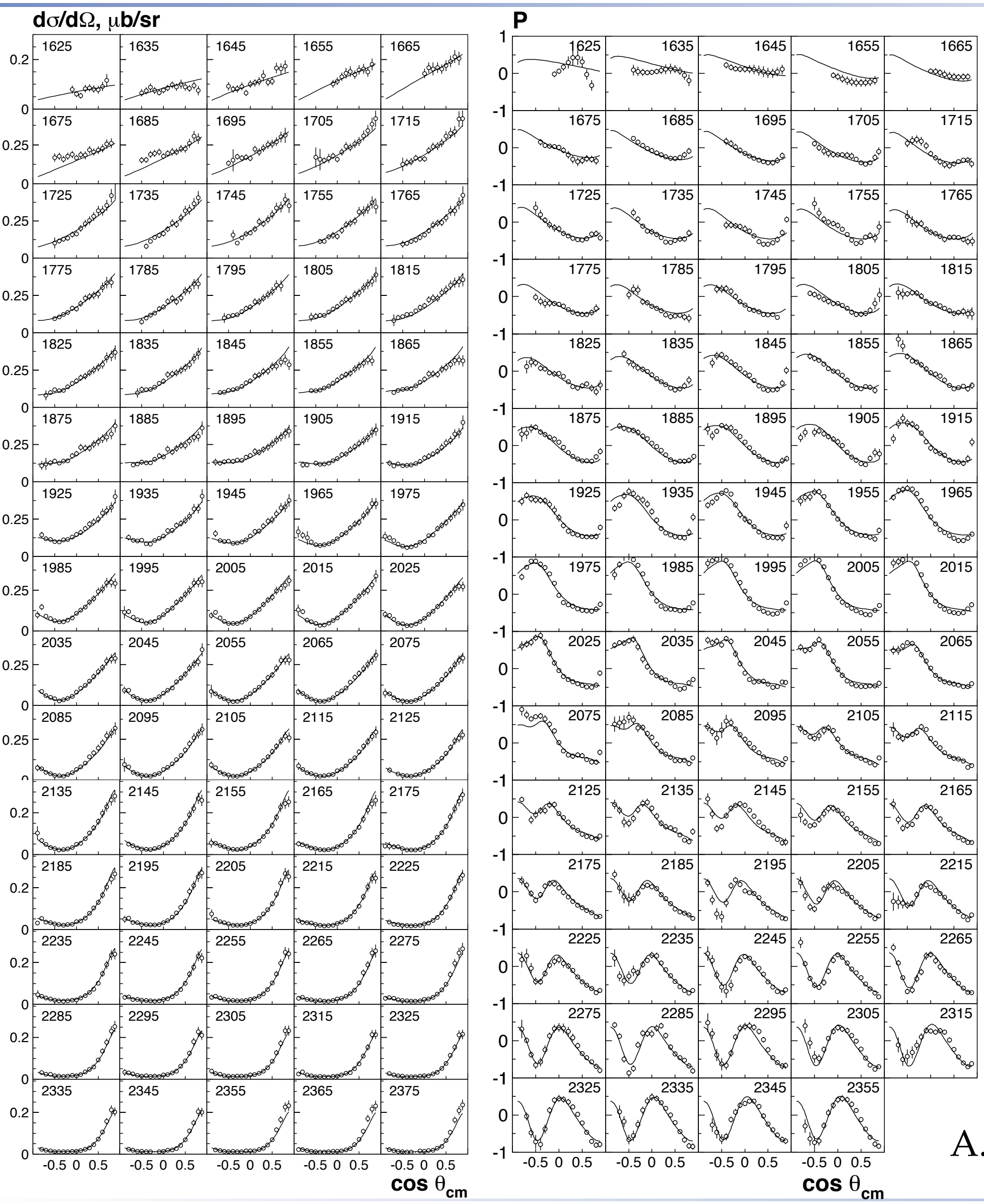
Polarization transfer C_x and C_z

without N(1900) 3/2+ with N(1900) 3/2+

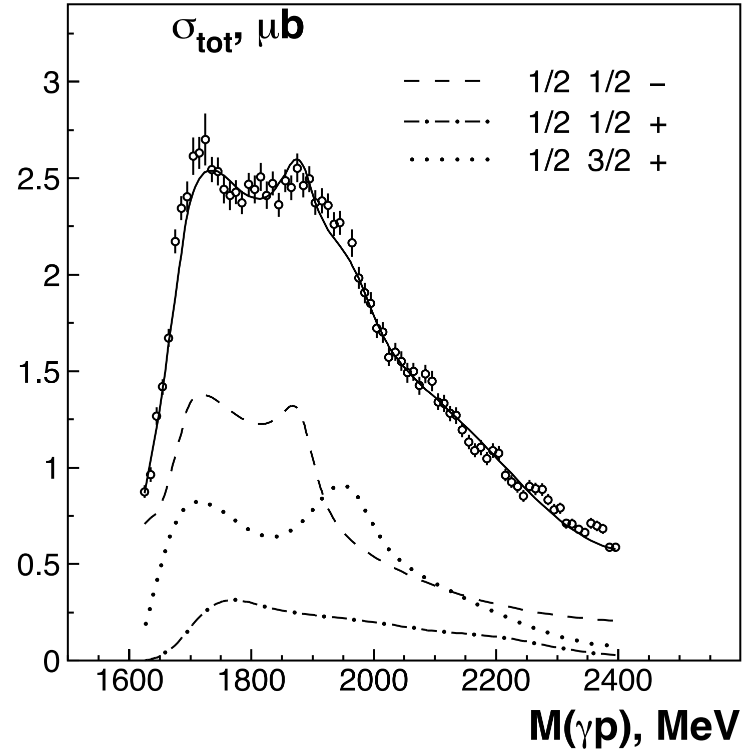


Fits: BnGa-Model, V. A. Nikonov et al., Phys. Lett. B 662, 245 (2008)

g11 cross sections and *P*



CLAS g11 data

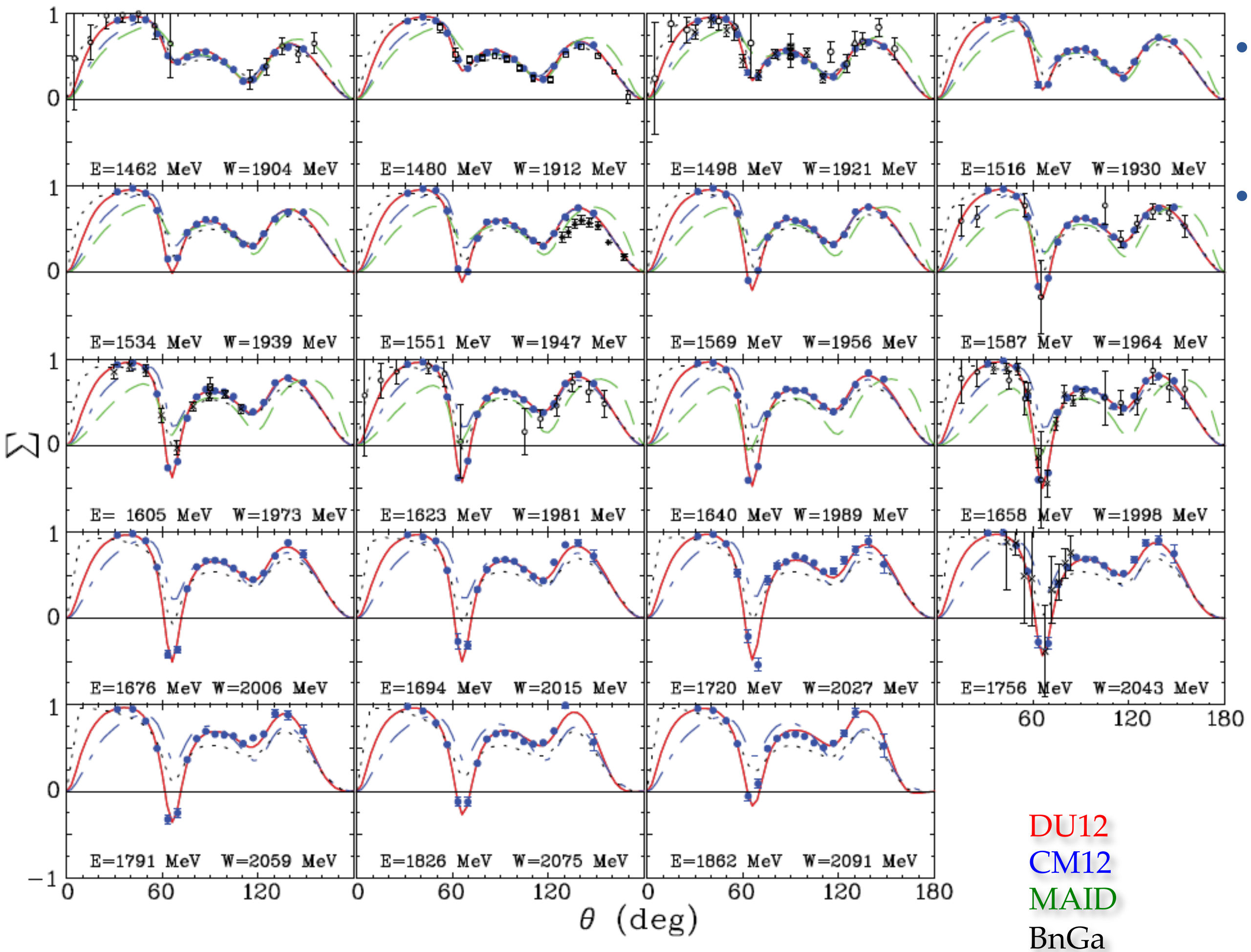


A.V. Anisovich *et al.* EPJ. A (2011) 47: 27

More on strangeness production

- A2: 14:50 Colin Gleason, "Determination of the Hyperon Induced Polarization and Polarization Transfer Coefficients for Quasi-Free Hyperon Photoproduction off the Bound Neutron"
- A3: 16:50 Natalie Walford, "Polarization Observables in $\gamma p \rightarrow K^+\Lambda$ and $K^+\Sigma^0$ Using Circularly Polarized Photons on a Polarized Frozen Spin Target"
- A3: 17:10 Shankar Adhikari, "Measurement of polarization observables for Lambda in the reaction $\gamma p \rightarrow K^+\Lambda$"
- A4: 10:00 Tongtong Cao, "Determination of the Polarization Observables C_x, C_z, and P for the Quasi-Free Mechanism in the reaction $\gamma d \rightarrow K^+\Lambda n$"

Σ asymmetry for π^+ and π^0 on proton



- CLAS: M. Dugger *et al.*, Phys Rev C **88**, 065203 (2013).
- 700 π^0 and 386 π^+ data points

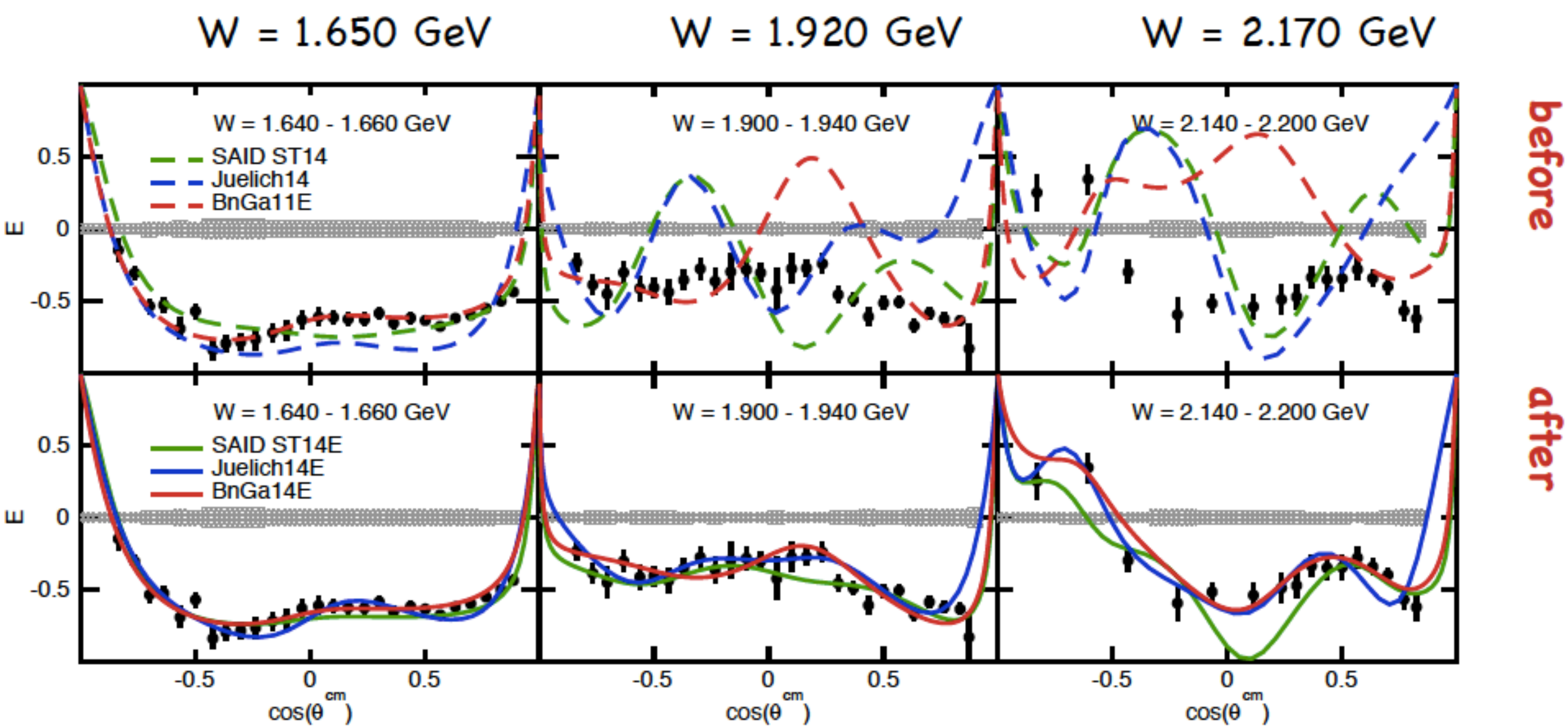
E asymmetry for $\gamma p \to p\pi^+$

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_0 \left(1 - P_z P_\odot E\right)$$

$W = 1240 - 2260$ MeV

$-0.9 \le \cos(\theta_\pi^{cm}) \le +0.9$

$$\vec{\gamma}\vec{p} \to \pi^+ n$$



S. Strauch, et al., PLB 750 (2015) 53.

Partial restoration of chiral symmetry at high mass?

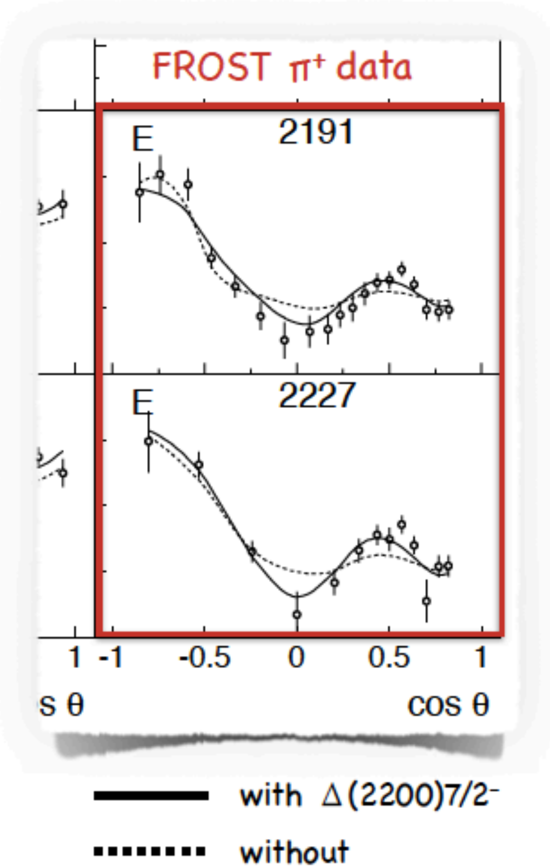
Parity partner of Δ(1950)7/2⁺ is poorly known

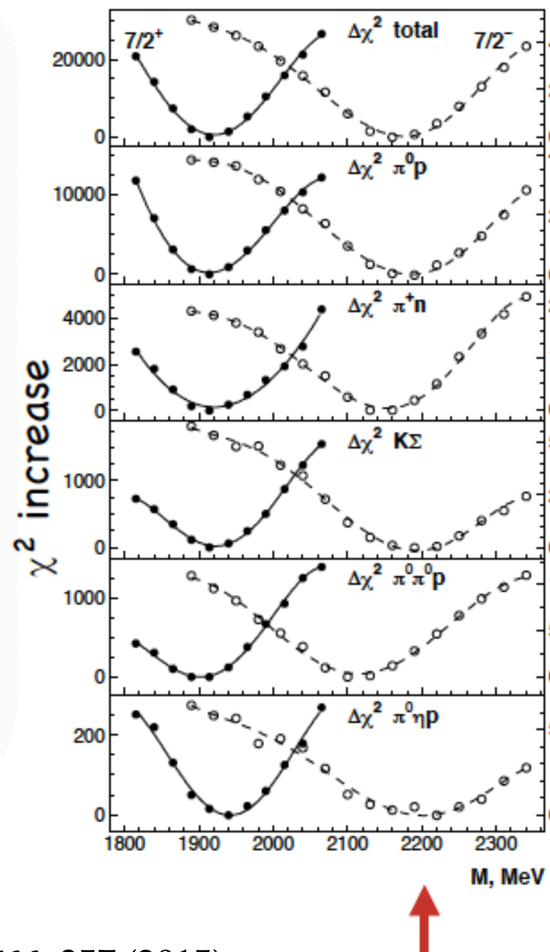
Δ(1950)7/2⁺ *****
Δ(2200)7/2⁻ *

New evidence for Δ(2200)7/2⁻ in the BnGa analysis of data from CLAS and CB/ELSA :

M(Δ7/2⁻) = 2180 MeV
M(Δ7/2⁺) = 1950 MeV

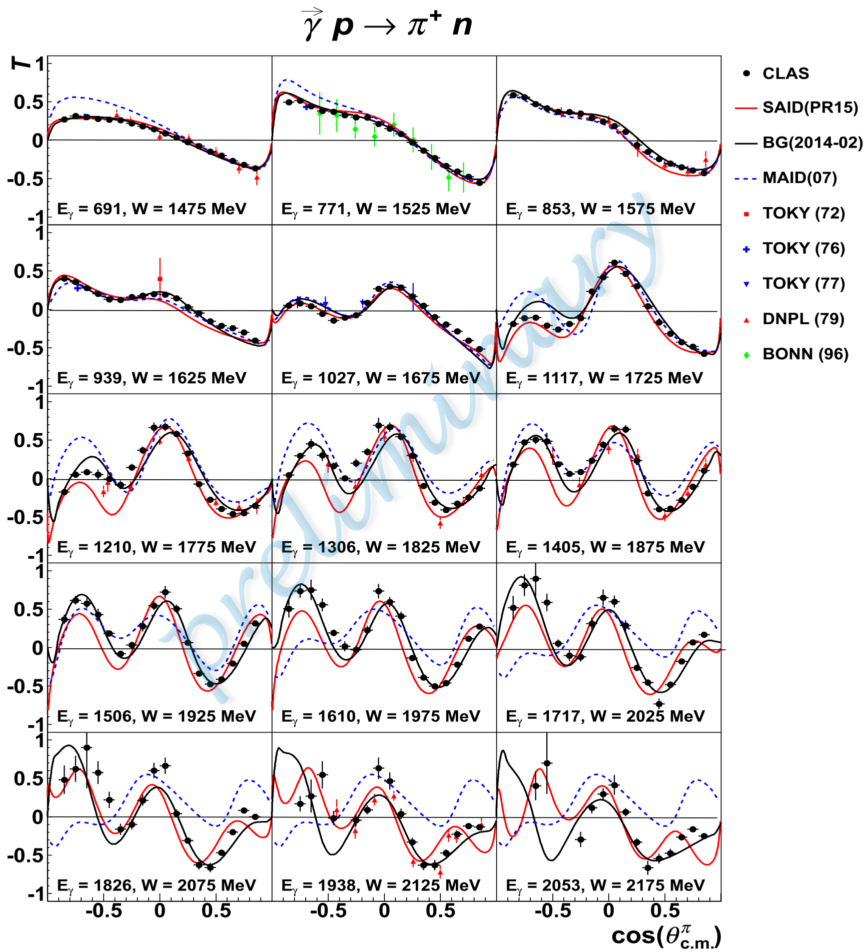
2180 ≠ 1950

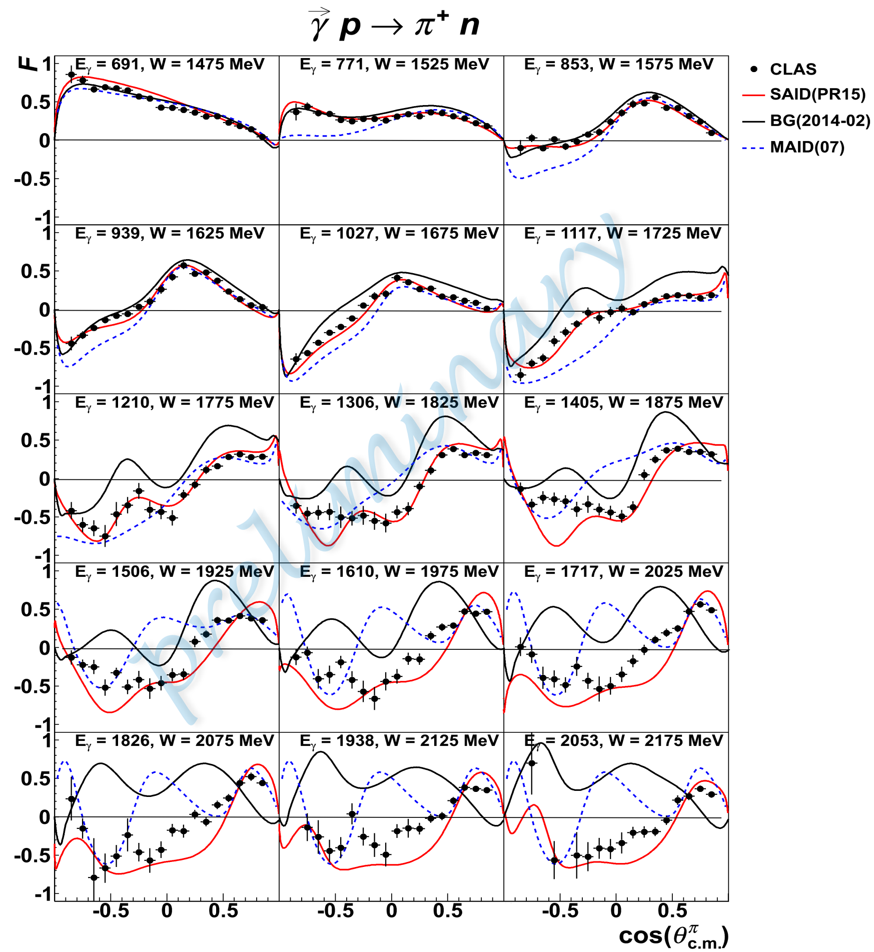




A.V. Anisovich et al., PLB **766**, 357 (2015)

T and F asymmetries in the $\gamma p \to \pi^+ p$





courtesy of M. Dugger (ASU)

See also A3: 17:50 Hao Jiang, "Polarization Observables T and F in the $\gamma p \to \pi^+ p$ Reaction"

$\gamma d \rightarrow \pi^- p(p)$ cross sections

Need measurements for both proton and neutron targets to disentangle different isospin contributions
(neutron measurements sorely lacking)

CLAS "g13" experiment: $\gamma d \rightarrow \pi^- p(p)$

8400 bins *g13 triples world data base!*

E_γ: [0.445 – 2.510 GeV]

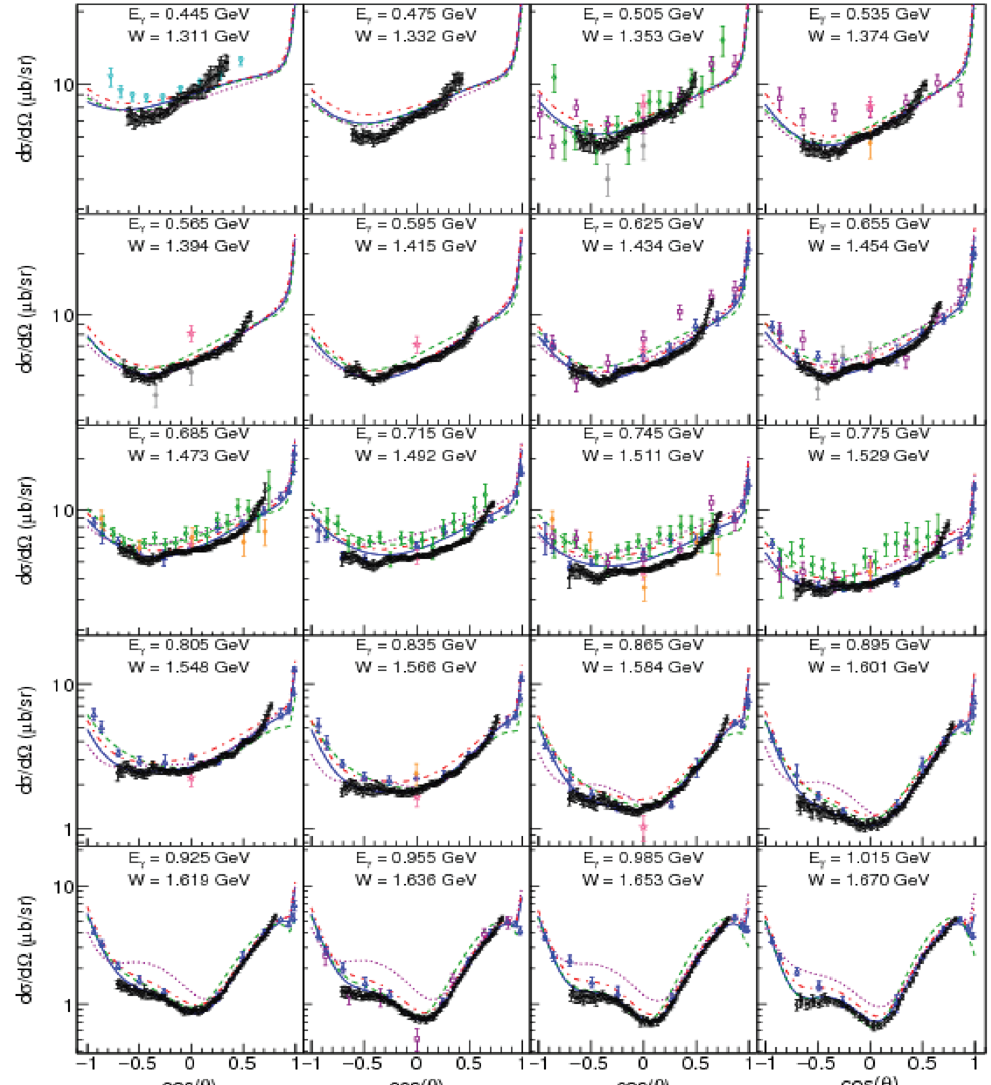
$\cos\theta_\pi^{cm}$: [-0.72 – 0.92]

FSI corrections applied to extract γn from γd

This first determination of neutron couplings at the pole positions significantly improves the world data

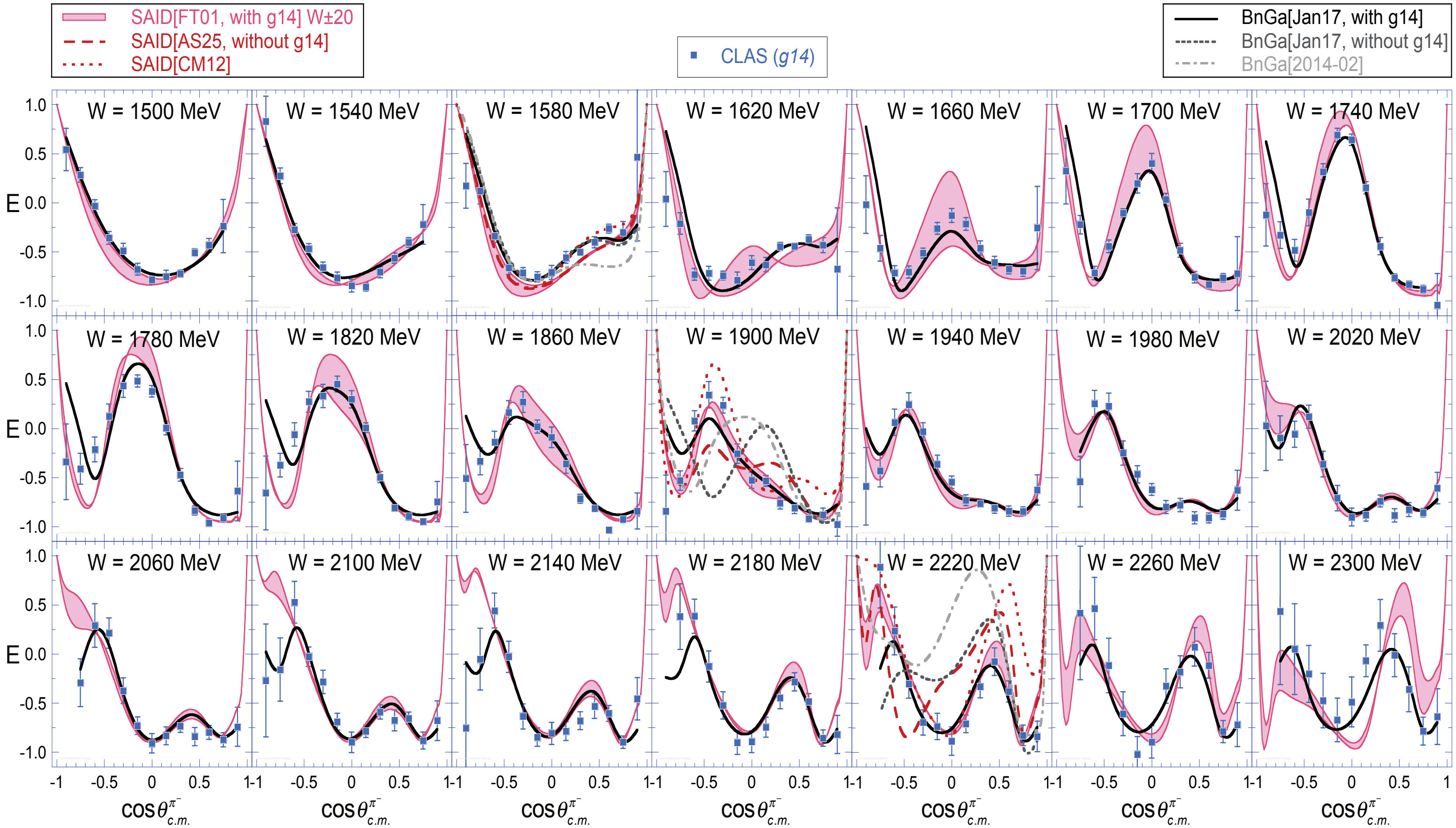
amplitudes [$GeV^{-1/2}$]

Resonance	Coupling	SAID Fits Modulus, phase	PDG 2016 BW
$N(1440)1/2^+$	$A_{1/2}(n)$	0.065±0.005, 5º±3º	0.040±0.010
$N(1535)1/2^-$	$A_{1/2}(n)$	-0.055±0.005, 5º±2º	-0.075±0.020
$N(1650)1/2^-$	$A_{1/2}(n)$	0.014±0.002, -30º±10º	-0.050±0.020
$N(1720)3/2^+$	$A_{1/2}(n)$	-0.016±0.006, 10º±5º	-0.080±0.050
$N(1720)3/2^+$	$A_{3/2}(n)$	0.017±0.005, 90º±10º	-0.140±0.065



P.T. Mattione et al. (CLAS Collaboration), arXiv:1706:01963, (2017) submitted to PRC

$\gamma d \to \pi p(p)$ E asymmetry



- P3: 08:30 Andrew Sandorfi, "Spin Asymmetries and Helicity Amplitudes from Pion Production from Polarized Neutrons at Jefferson Lab"
- A2: 15:10 Haiyun Lu, "Beam-Target Asymmetry for $\gamma n(p) \to \pi^- p(p)$ in N* Resonance Region"

$\gamma d \rightarrow \pi p(p)$ Σ asymmetry

Over 1200 data-points in the range:

$$-0.9 < \cos\theta_{CM} < 1$$

$$1620 < W(MeV/c^2) < 2370$$

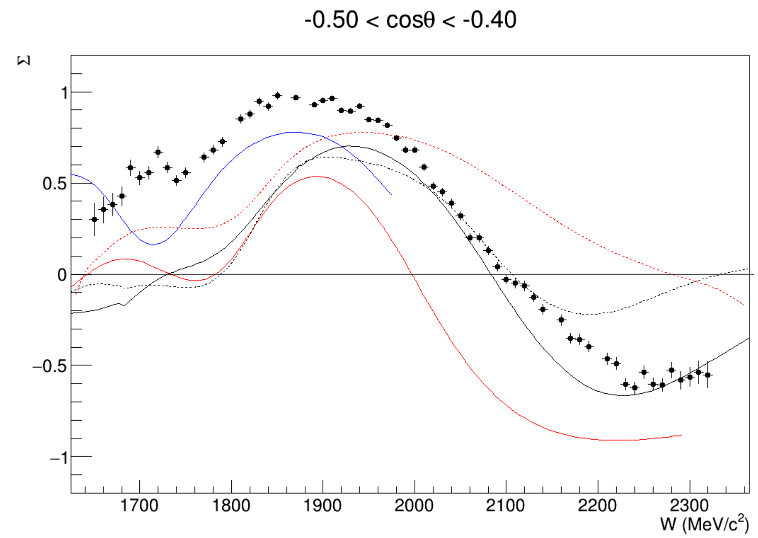
MAID 2007

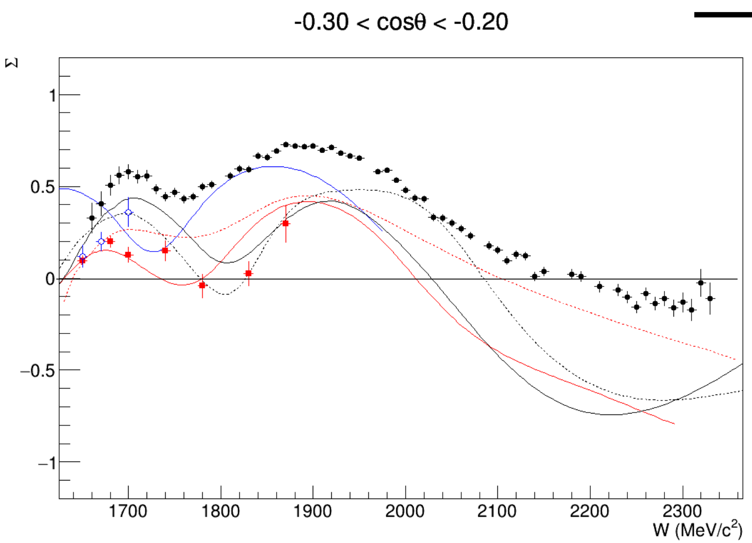
SAID CM12

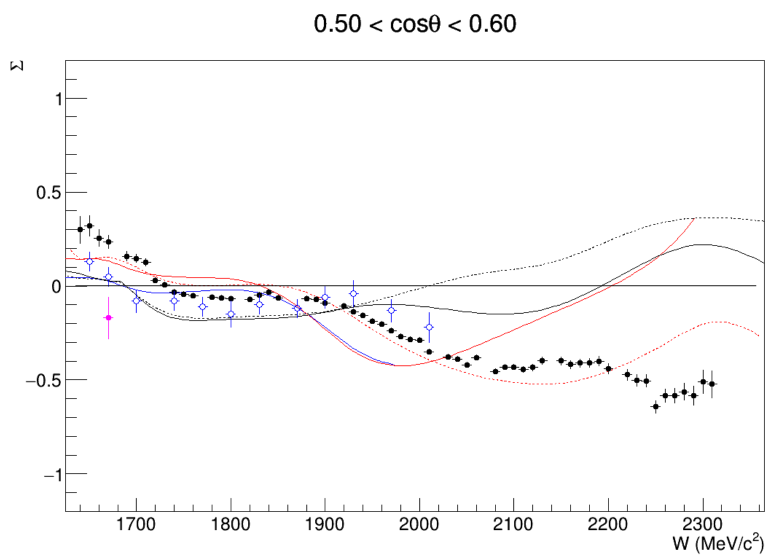
SAID MA27

BG2011 - free n

BG2014 - free n







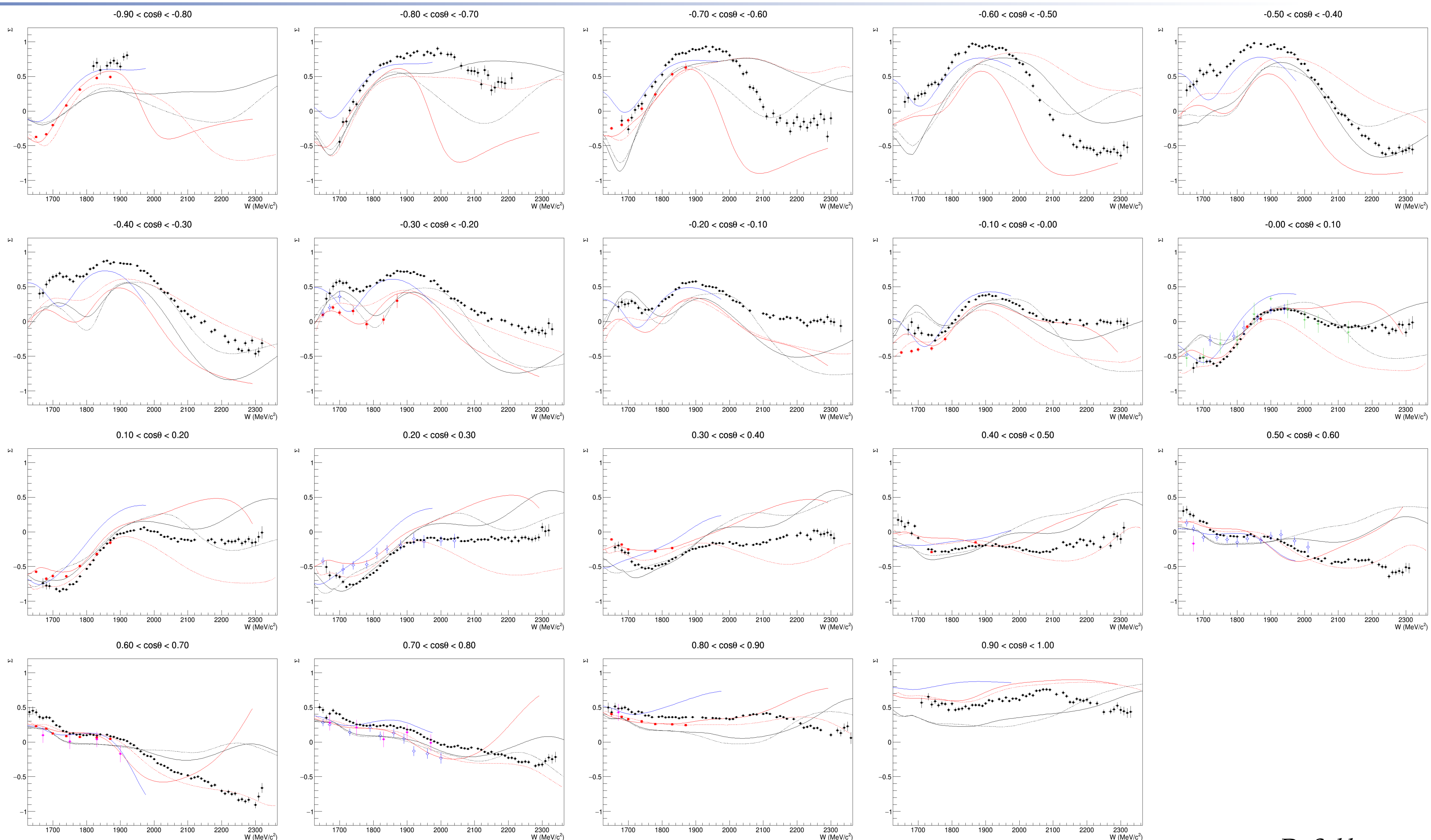
G. Mandaglio, PRC82, 045209 (2010)

F. Adamian, J. Phys. G15, 1797 (1989)

L. Abrahamian, EFI-389-47-79-YEREVAN (1979)

courtesy D. Sokhan

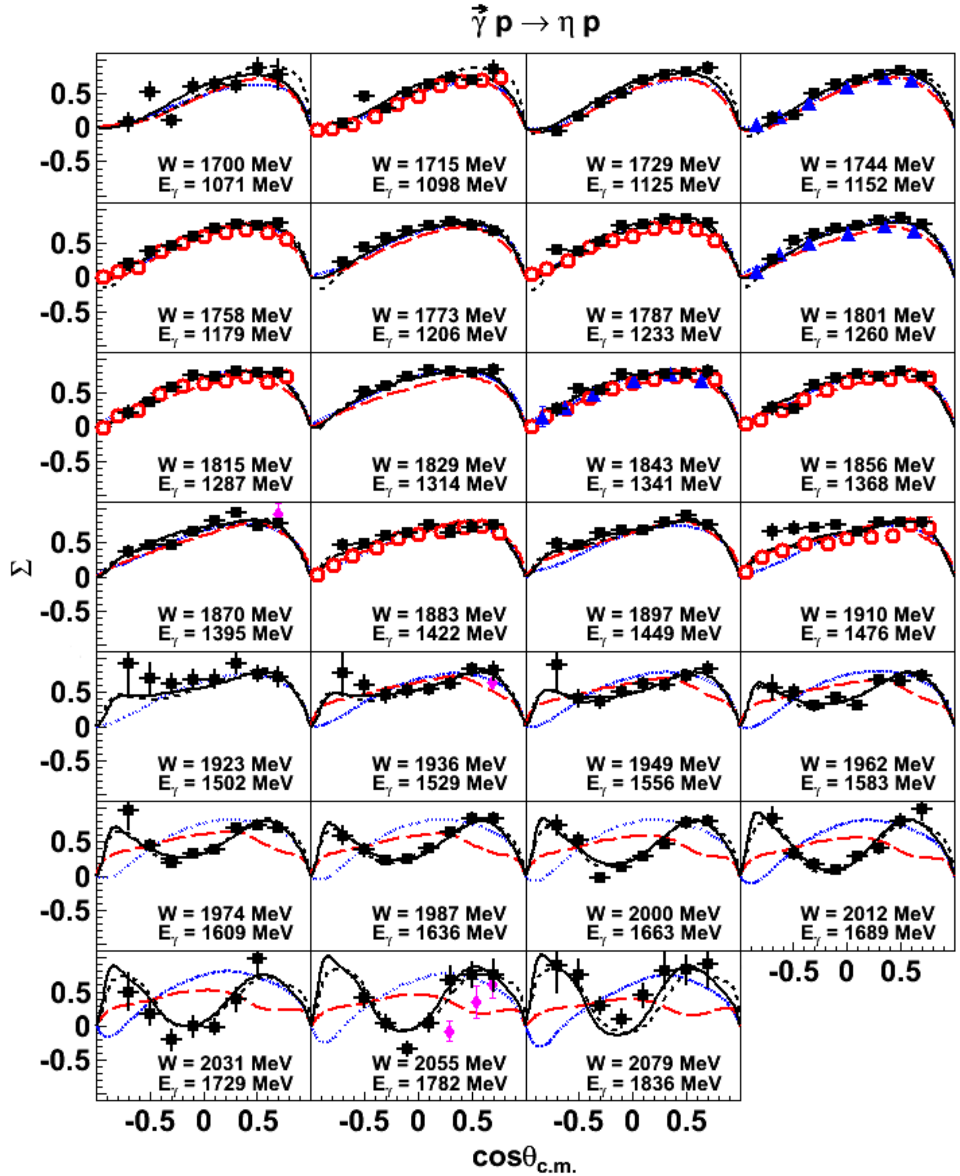
$\gamma d \to \pi p(p)$ Σ asymmetry



courtesy D. Sokhan

Bin size in : 0.1, from -0.9 (top left) to 1 (bottom right), W on the x-axis.

η photoproduction results

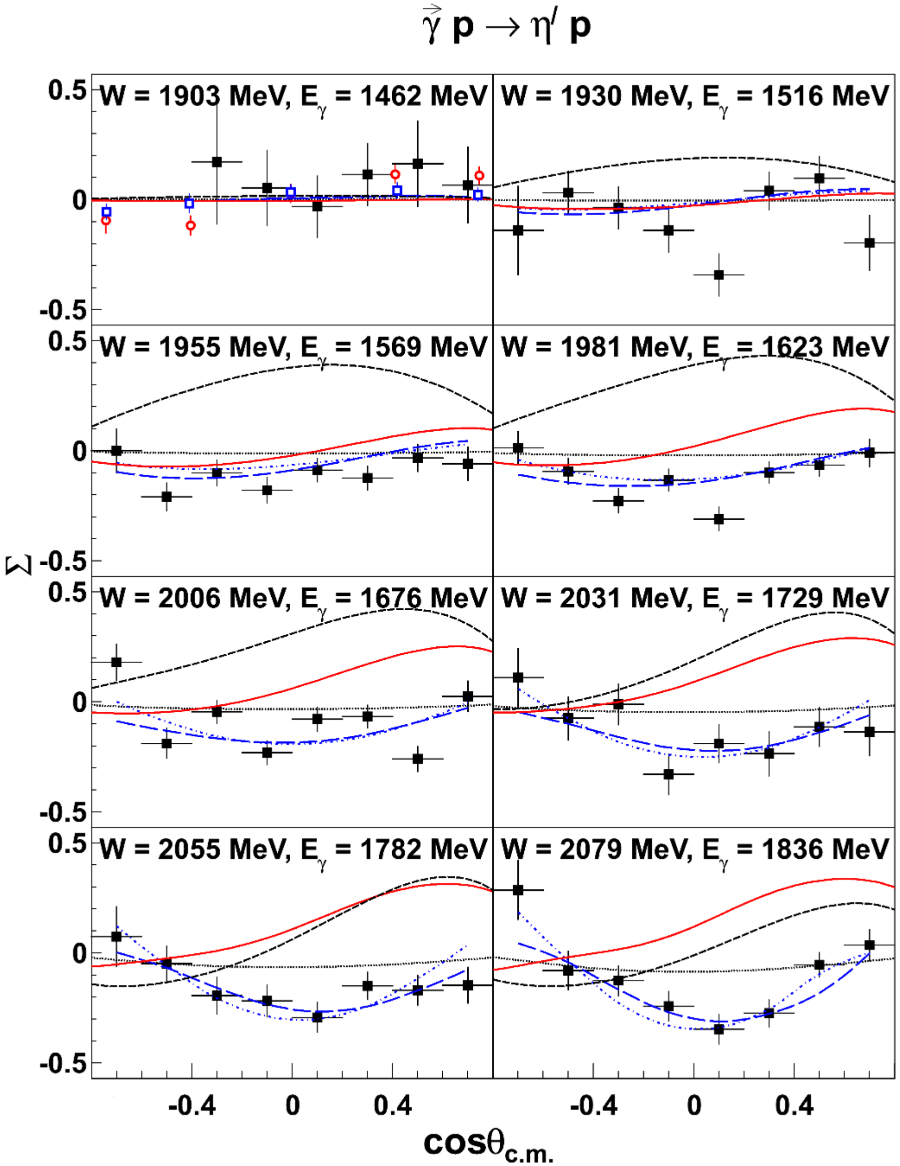


- ■ CLAS: P. Collins *et al.*, Phys Lett B **771**, 213 (2017) - 266 points distributed over 27 *W* bins
- ▲ CB-ELSA/TAPS (2007)
- ○ GRAAL (2015)
- ◆ Vartapetian, Piliposian (1980)

- SAID (blue dotted line) and ETA-MAID (red dashed line) do not predict the structure in Σ above *W*=1.96 GeV.
- How important is the N(1900)3/2$^+$ state in *η* photoproduction?
- Fits to these new data gave sizeable changes in the contributions from N(1720)3/2$^+$ and N(1900)3/2$^+$.
- Are those changes significant for Σ?
  - Not really. Compare black dashed and black solid lines.
  - So may be Σ is not the best observable to test how important the N(1900)3/2$^+$ is.
- Stay tuned: More work is in progress.

courtesy of B.G. Ritchie, ASU

η' photoproduction results



■ CLAS P. Collins *et al.*, Phys Lett B **771**, 213 (2017)
- 62 points distributed over 8 *W* bins

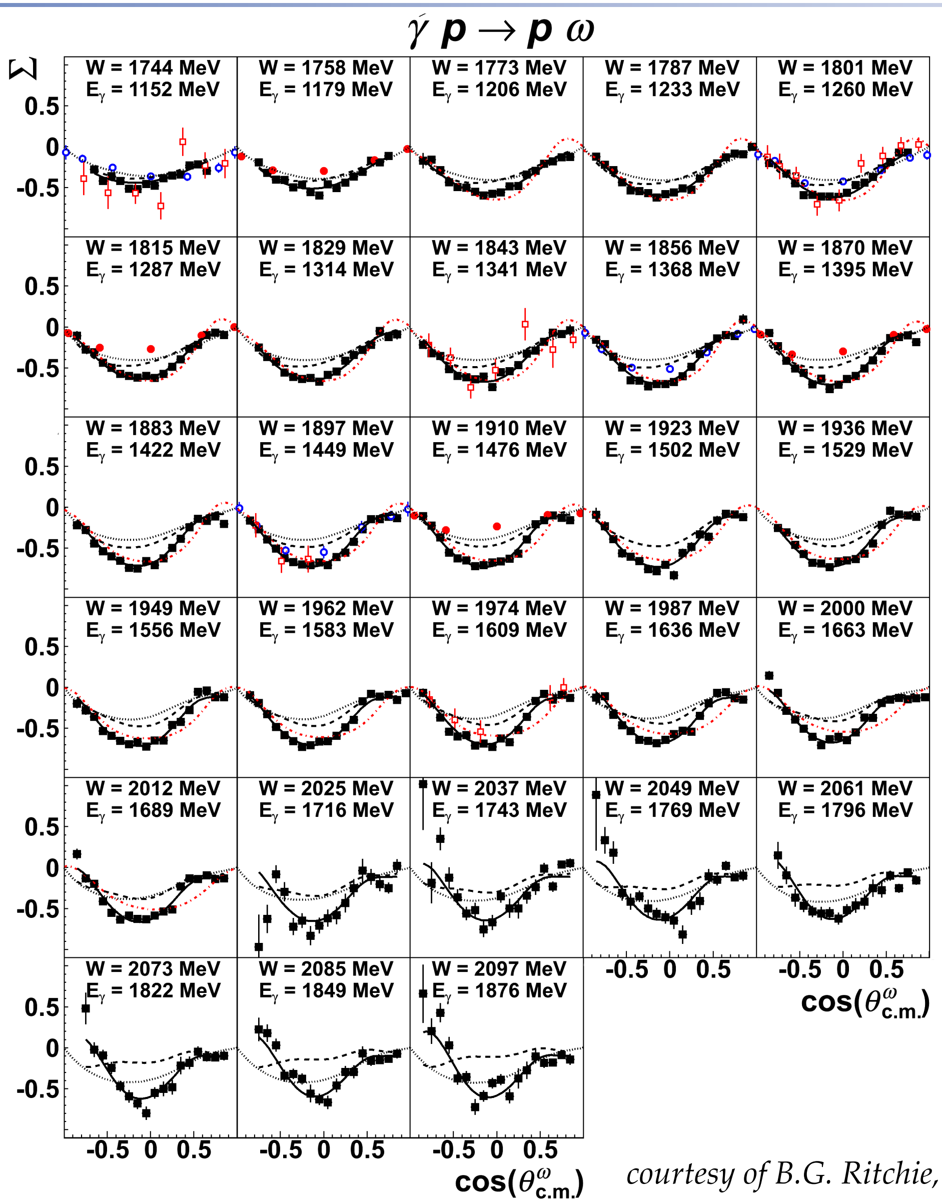
○ GRAAL, 1.461 GeV

□ GRAAL, 1.480 GeV

- Asymmetry is small
- SAID (black dotted line), ETA-MAID (red solid line), and NH (black dashed line) don't work so well.
- New fits with BnGa model work well
  - Two solutions give comparable fits
  - *N*(1900)3/2+ is important! May push this state to "****"
  - Statistically significant η' branches for *N*(1895)1/2$^-$, *N*(1900)3/2$^+$, *N*(2100)1/2$^+$, and *N*(2120)3/2$^-$
- Stay tuned: More work in progress (Anisovich *et al.*, submitted to PLB).

courtesy of B.G. Ritchie, ASU

ω photoproduction results

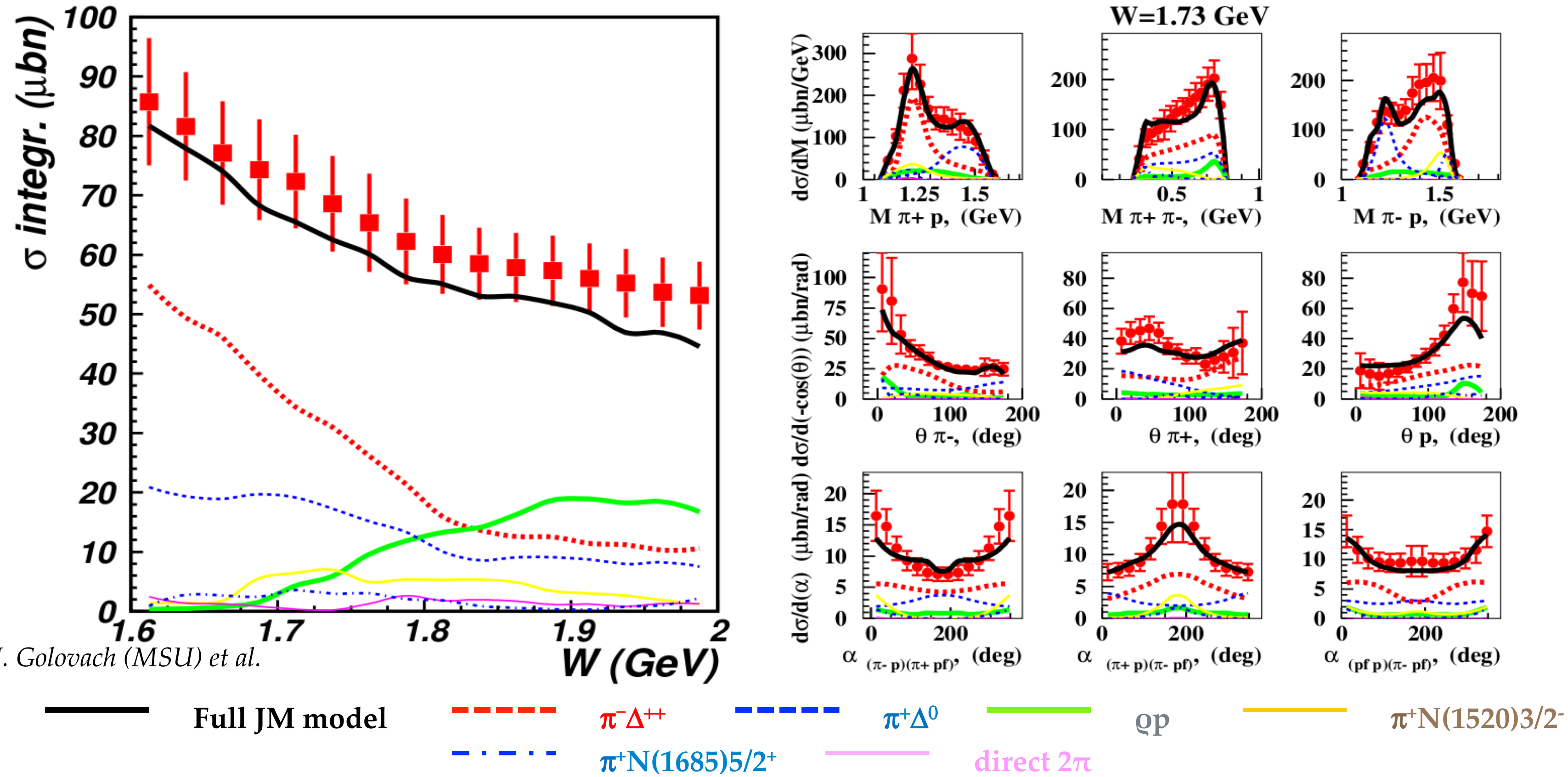


courtesy of B.G. Ritchie, ASU

- ■ CLAS P. Collins *et al.*, just have been accepted to PLB **773**, 112 (2017) https://doi.org/10.1016/j.physletb.2017.08.015
  - 547 data points distributed over 28 *W* bins
- ○ GRAAL (2006)
- ● GRAAL (2015)
- □ CB-ELSA/TAPS (2015)

- BnGa fit with (black solid line) and without (black dashed line) incorporating these new data
- Close to threshold the process is dominated by $3/2^+$ and $5/2^+$ partial waves associated with $N(1720)3/2^+$ and $N(1680)5/2^+$
- More about ω:
  - A3: 16:30 Zulkaida Akbar, "Photo-production of $\pi^+\pi^-\pi^0$ Using CLAS at Jefferson Laboratory"
  - P5: 09:00 Volker Crede, "Understanding the Spectrum of Excited Nucleons using CLAS at Jefferson Lab"

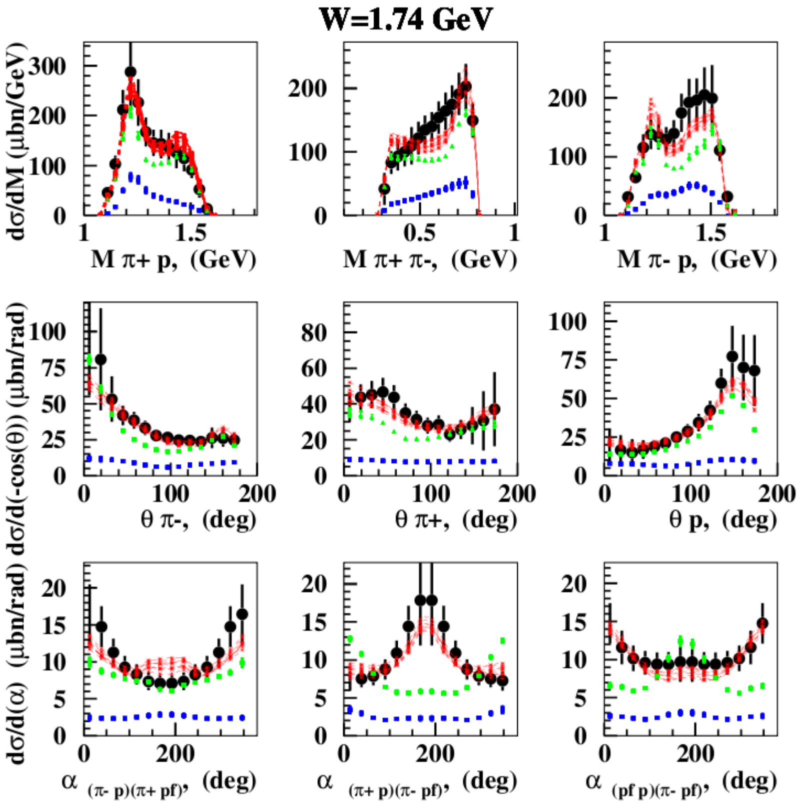
$\gamma p \to p\pi^+\pi^-$



E.N. Golovach (MSU) et al.

- Nine independent one-fold differential and fully integrated cross sections at 1.6 GeV <W< 2.0 GeV have become available for the first time .
- Successful data description achieved within the framework of the meson-baryon reaction model JM allowed us to establish all essential mechanisms contributing to $\pi^+\pi^-p$ photoproduction off protons.

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



resonant (•) on-resonant (•) Full model (•) contributions from the data fit within the framework of the JM model

Resonance	$A_{1/2}$, GeV$^{-1/2}$ *1000, $\pi^+\pi^-p$ / $N\pi$	$A_{3/2}$, GeV$^{-1/2}$ *1000 $\pi^+\pi^-p$ / $N\pi$
$N(1650)1/2^-$	61±8 / 53±16	
$N(1680)5/2^+$	-28±4 / -15±6	128±11 / 133±12
$N'(1720)3/2^+$	37±7 / N/A	-40±7 / N/A
$N(1720)3/2^+$	81±12 / 97±3	-34±8 / -39±3
$\Delta(1620)1/2^-$	29±6 / 27±11	
$\Delta(1700)3/2^-$	87±19 / 104±15	87±16 / 85±22
$\Delta(1905)5/2^+$	19±8 / 26±11	-43±17 / -45±20
$\Delta(1950)7/2^+$	-70±14 / -76±12	-118±19 / -97±10

- Photocouplings of the resonances with dominant $N\pi\pi$ decays (colored boxes in the table) were determined from $\pi^+\pi^-p$ photoproduction off protons data for the first time.
- Consistent results on photocouplings of resonances with masses above 1.6 GeV from analyses of $N\pi$ and $\pi^+\pi^-p$ channels validates a reliable extraction of these quantities in a nearly model independent way.

2017 vs. 1997

		overall	$N\gamma$	$N\pi$	$N\eta$	$N\sigma$	$N\omega$	ΛK	ΣK	$N\rho$	$\Delta\pi$
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+	**		**							

Taken out:
N(2080)D13
N(2090)S11
N(2200)D15

Summary

- The field of the N* physics is still very much alive!
- There is significant progress in N* physics over the last 20 years.
- CLAS photoproduction experiments played major role in it.
- There is no redundant data. Any data are useful.
- Precision and consistency of the experimental data is of critical importance.
- More interesting data are on the way for strange and non-strange meson production both on proton and deuteron targets.

CLAS meson photoproduction talks at NSTAR2017

- P3: 08:30 Andrew Sandorfi, "Spin Asymmetries and Helicity Amplitudes from Pion Production from Polarized Neutrons at Jefferson Lab"
- P5: 09:00 Volker Crede, "Understanding the Spectrum of Excited Nucleons using CLAS at Jefferson Lab"
- A2: 14:00 Paul Mattione, "$\gamma n \rightarrow p\ \pi^-$ Cross Section Measurement at CLAS"
- A2: 14:50 Colin Gleason, "Determination of the Hyperon Induced Polarization and Polarization--Transfer Coefficients for Quasi-Free Hyperon Photoproduction off the Bound Neutron"
- A2: 15:10 Haiyun Lu, "Beam-Target Asymmetry for $\gamma n(p) \rightarrow \pi^- p(p)$ in N* Resonance Region"
- A3: 16:30 Zulkaida Akbar, "Photo-production of $\pi^+\pi^-\pi^0$ Using CLAS at Jefferson Laboratory"
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- A3: 17:30 Lelia Net, "Polarization observables in double charged pion photo-production with circularly polarized photons off transversely polarized protons"
- A3: 17:50 Hao Jiang, "Polarization Observables T and F in the $\gamma p \rightarrow \pi^0 p$ Reaction"
- B5: 11:20 Dave Ireland, "Evaluating Polarization Data"
- A4: 10:00 Tongtong Cao, "Determination of the Polarization Observables Cx, Cz, and Py for the Quasi-Free Mechanism in the reaction $\gamma d \rightarrow K^+\Lambda n$"