Helicity Asymmetry Measurement for π^0 Photoproduction on the CLAS Frozen Spin Target

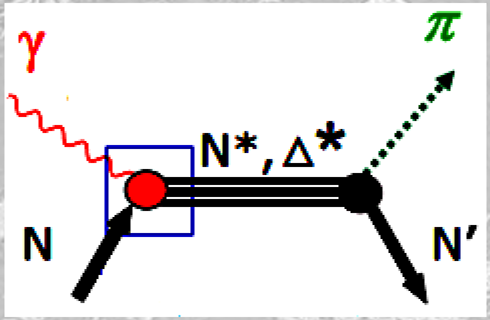
Diane Schott, William Briscoe, Igor Strakovsky

The George Washington University

For CLAS Collaboration

- Single Pion photoproduction.
- Experimental Facilities at JLab Hall B.
  - CLAS.
  - Photon Tagger.
  - Circular polarized beam.
  - Linearly polarized beam.
  - FROST.
- The Experiment.
- Double Polarized measurements for $\vec{\gamma}\vec{p}\to\pi^0 p$.
- Summary.

Single Pion Photo Production



Status of Non-strange Resonances: PDG14

K.A. Olive *et al* (PDG) Chin Phys C **38**, 090001 (2014)

- More than half of states have **poor evidence**.
- Most of **QCD** models predict more states than observed.
- **Where are missing resonances**?

GW SAID Contribution

I = 1/2

Particle J^P	Status overall	Status πN	Status γN	Status as seen in — $N\eta$	$N\sigma$	$N\omega$	ΛK	ΣK	$N\rho$	$\Delta\pi$
N $1/2^+$	****									
$N(1440)$ $1/2^+$	****	****	****		***				*	***
$N(1520)$ $3/2^-$	****	****	****	***					***	***
$N(1535)$ $1/2^-$	****	****	****	****					**	*
$N(1650)$ $1/2^-$	****	****	***	***			***	**	**	***
$N(1675)$ $5/2^-$	****	****	***	*			*		*	***
$N(1680)$ $5/2^+$	****	****	****	*	**				***	***
$N(1685)$ $?^?$	*									
$N(1700)$ $3/2^-$	***	***	**	*			*	*	*	***
$N(1710)$ $1/2^+$	***	***	***	***		**	***	**	*	**
$N(1720)$ $3/2^+$	****	****	***	***			**	**	**	*
$N(1860)$ $5/2^+$	**	**							*	*
$N(1875)$ $3/2^-$	***	*	***			**	***	**		***
$N(1880)$ $1/2^+$	**	*	*		**		*			
$N(1895)$ $1/2^-$	**	*	**	**			**	*		
$N(1900)$ $3/2^+$	***	**	***	**		**	***	**	*	**
$N(1990)$ $7/2^+$	**	**	**					*		
$N(2000)$ $5/2^+$	**	*	**	**			**	*	**	
$N(2040)$ $3/2^+$	*									
$N(2060)$ $5/2^-$	**	**	**	*				**		
$N(2100)$ $1/2^+$	*									
$N(2150)$ $3/2^-$	**	**	**				**			**
$N(2190)$ $7/2^-$	****	****	***				**		*	
$N(2220)$ $9/2^+$	****	****								
$N(2250)$ $9/2^-$	****	****								
$N(2600)$ $11/2^-$	***	***								
$N(2700)$ $13/2^+$	*	**								

26 N*
11 ****
5 ***
7 **
3 *

I = 3/2

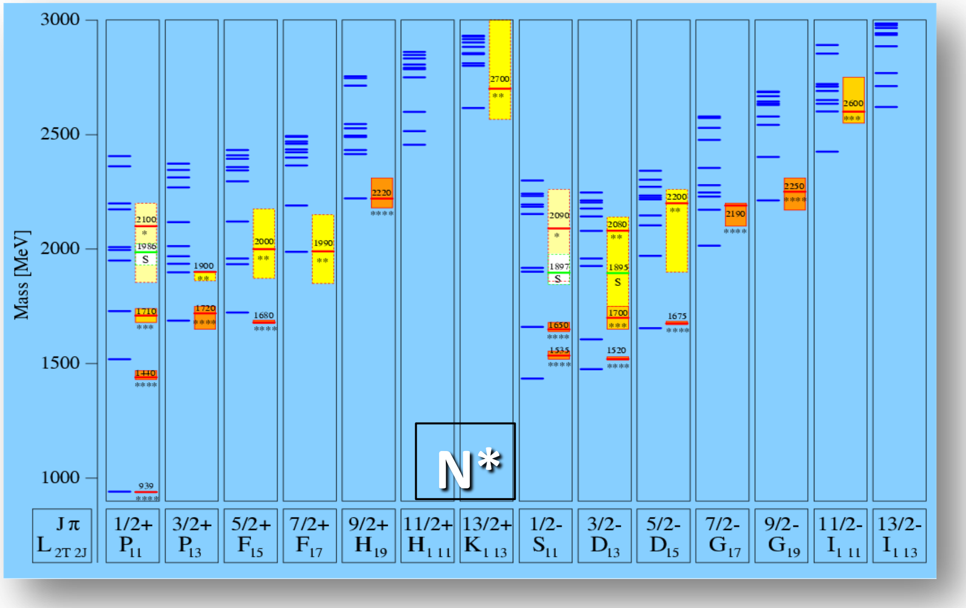
Particle J^P	Status overall	Status πN	Status γN	Status as seen in — $N\eta$	$N\sigma$	$N\omega$	ΛK	ΣK	$N\rho$	$\Delta\pi$
$\Delta(1232)$ $3/2^+$	****	****	****	F						
$\Delta(1600)$ $3/2^+$	***	***	***	o					*	***
$\Delta(1620)$ $1/2^-$	****	****	***		r				***	***
$\Delta(1700)$ $3/2^-$	****	****	****		b				**	***
$\Delta(1750)$ $1/2^+$	*	*			i					
$\Delta(1900)$ $1/2^-$	**	**	**			d		**	**	**
$\Delta(1905)$ $5/2^+$	****	****	****			d		***	**	**
$\Delta(1910)$ $1/2^+$	****	****	**				e	*	*	**
$\Delta(1920)$ $3/2^+$	***	***	**				n	***		**
$\Delta(1930)$ $5/2^-$	***	***								
$\Delta(1940)$ $3/2^-$	**	*	**	F				(seen	in	$\Delta\eta$)
$\Delta(1950)$ $7/2^+$	****	****	****	o				***	*	***
$\Delta(2000)$ $5/2^+$	**				r					**
$\Delta(2150)$ $1/2^-$	*	*			b					
$\Delta(2200)$ $7/2^-$	*	*			i					
$\Delta(2300)$ $9/2^+$	**	**				d				
$\Delta(2350)$ $5/2^-$	*	*				d				
$\Delta(2390)$ $7/2^+$	*	*					e			
$\Delta(2400)$ $9/2^-$	**	**					n			
$\Delta(2420)$ $11/2^+$	****	****								
$\Delta(2750)$ $13/2^-$	**	**								
$\Delta(2950)$ $15/2^+$	[illegible]	**								

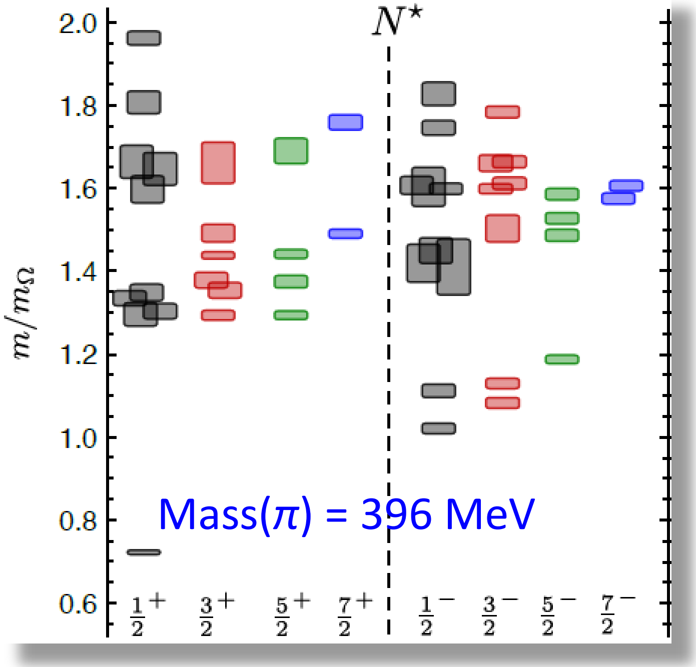
22 Δ*
7 ****
3 ***
7 **
5 *

BnGa Additional States

The latest GWU analysis (ARNDT 06) finds no evidence for this resonance.

Baryon Resonance Spectrum





Mass(π) = 396 MeV

R.G. Edwards *et al.* Phys Rev D **84,** 074508 (2011)

- Masses, widths, and coupling constants not well known for many resonances.
- Most models predict more resonance states than observed.

Baryon Resonances

- The **three light quarks** can arranged in **6** baryonic families, **N***, **Δ***, Λ*, Σ*, Ξ*, and Ω*.
- The number of family members that can exist is not arbitrary.
- Rather, the following proportionally is expected when the **$SU(3)_F$** symmetry of **QCD** is the controlling symmetry:

2 N*, **1 Δ***, 3 Λ*, 3 Σ*, 3 Ξ*, and 1 Ω*

  - The number of experimentally identified resonances of each baryon family is **26 N***, **22 Δ*** and so on.
  - **Constituent quark** models predict the existence of no less than **64 N*** and **22 Δ*** states with mass **<** **3** GeV^2.

- The seriousness of the ``**missing-states**" problem is obvious from these numbers.
- Recently, the **hypothesis** of a very **small** **πN** coupling of missing states should await the results of more realistic, coupled-channel calculations.

Ben Nefkens, πN Newsletter, **14**, 150 (1997)

Isospin Combinations for Reactions involving π^0 and π^+

- Differing isospin for **N*** and Δ^+ for π^0**p** and π^+**n** states.
- The π^0**p** and π^+**n** final states can help distinguish between the Δ^+ and **N***.

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

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

JLab Hall B

Experimental Facilities

CEBAF Large Acceptance Spectrometer 1997-2012

Torus Magnet

6 superconducting coils

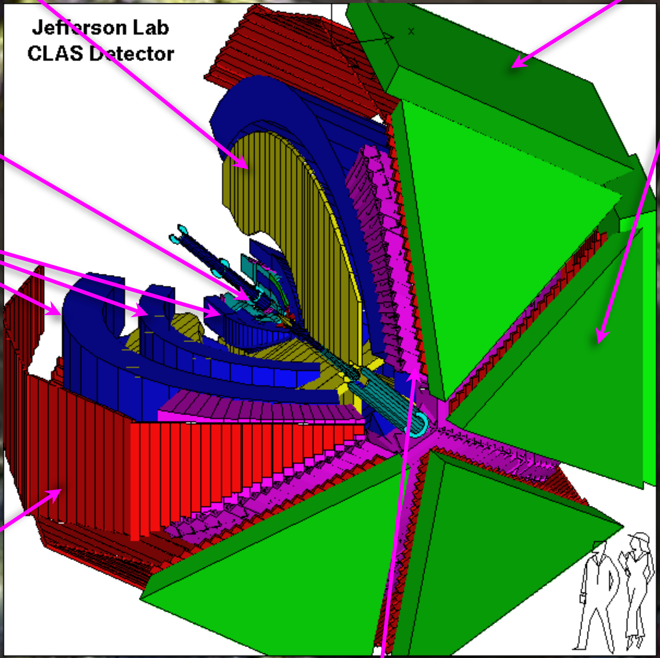
Electromagnetic calorimeters

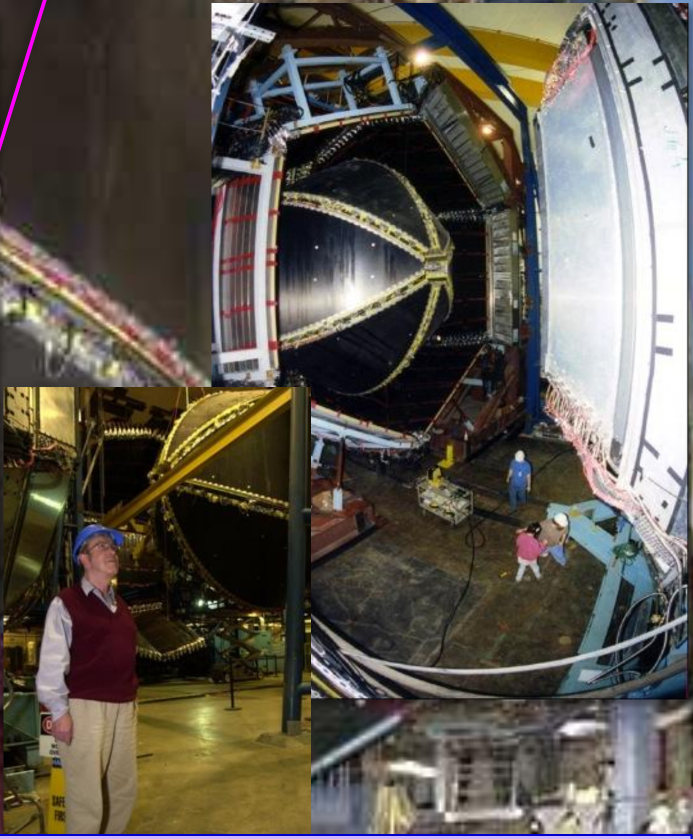
Lead/Scintillator, 1296 photomultipliers

Target + Start Counter

Drift Chambers

35,000 cells





Time-of-Flight Counters

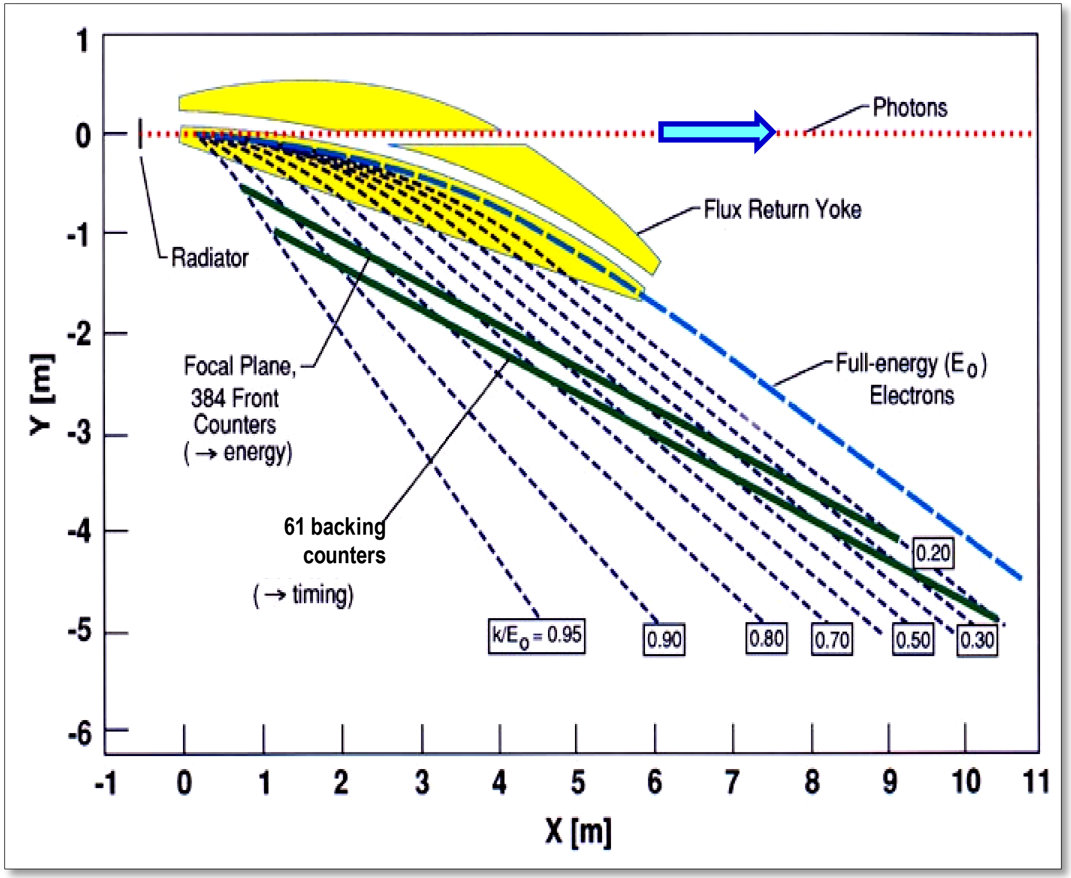
plastic scintillators, 684 photomultipliers

Gas Cherenkov Counters

e/π separation, 256 PMTs

B. A. Mecking *et al*. Nucl Instrum Meth A 503, 513 (2003)

Hall B Photon Tagger



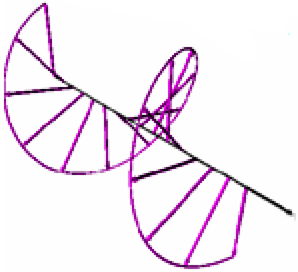
JLab Hall B Bremsstrahlung Photon Tagger had:

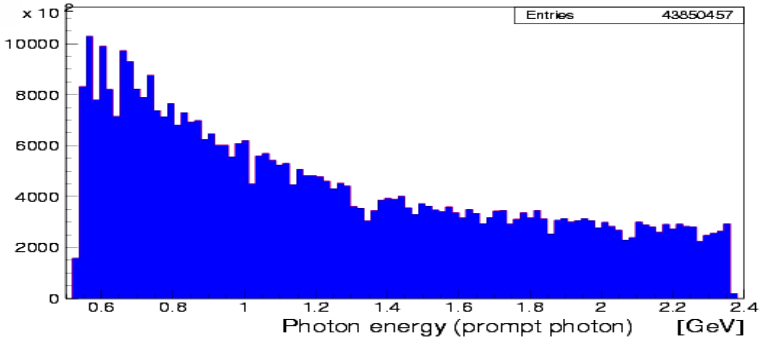
- E_γ = (**0.20–0.95**) x E_0
- E_γ up to ~**5.8 GeV**
- $\Delta E/E$ ~ 10^{-3} x E_0
- **Circular** polarized photons with longitudinally polarized electrons.
- Oriented diamond crystal for **linearly** polarized photons.

- **Tagger** was built by the **GW**, **CUA, and ASU** nuclear physics groups.

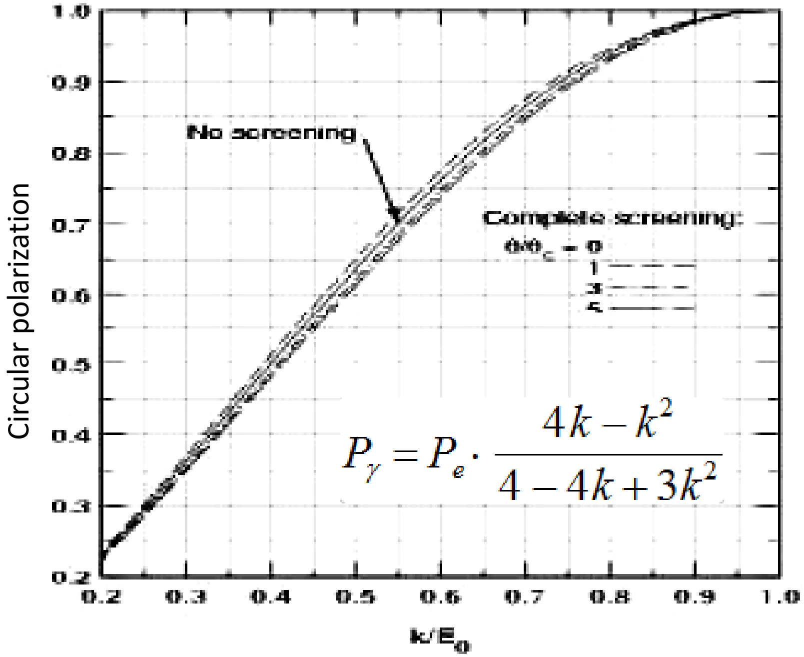
D. Sober *et al.* Nucl Instrum Meth A **440**, 263 (2000)

Circular Photon Beam Polarization





Circular polarization from 100% polarized electron beam

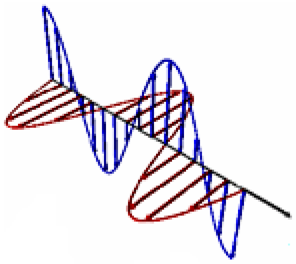


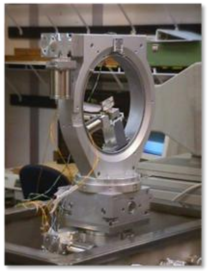
$$P_\gamma = P_e \cdot \frac{4k - k^2}{4 - 4k + 3k^2}$$

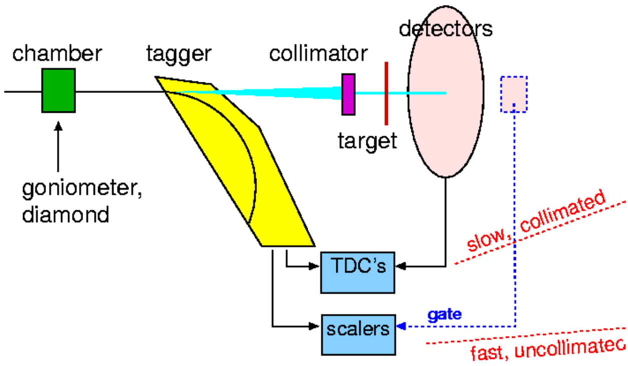
- **Circular** polarized **photons** with longitudinally polarized electrons.
- CEBAF **electron beam** polarization >**85%**.
- Tagged flux ~**50** – **100** MHz for **k > 0.5 E$_0$**

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

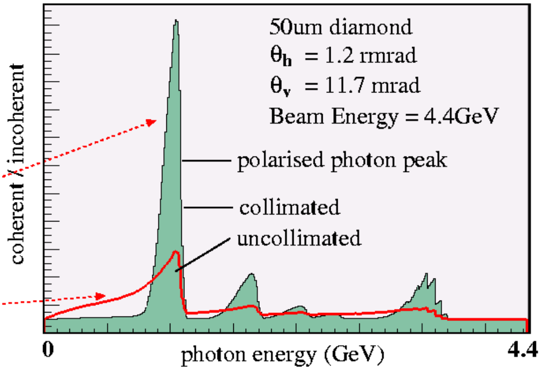
Linearly Polarized Photons



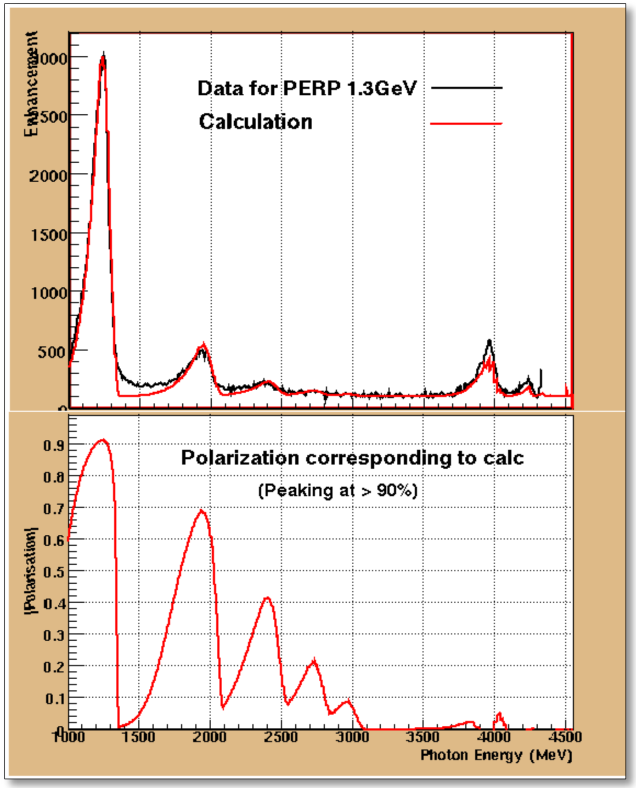




tagged photon facility



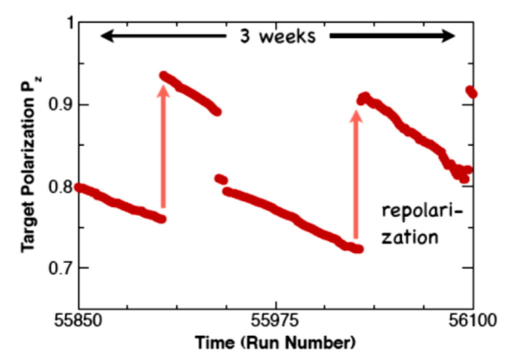
simulated coherent brem. spectrum

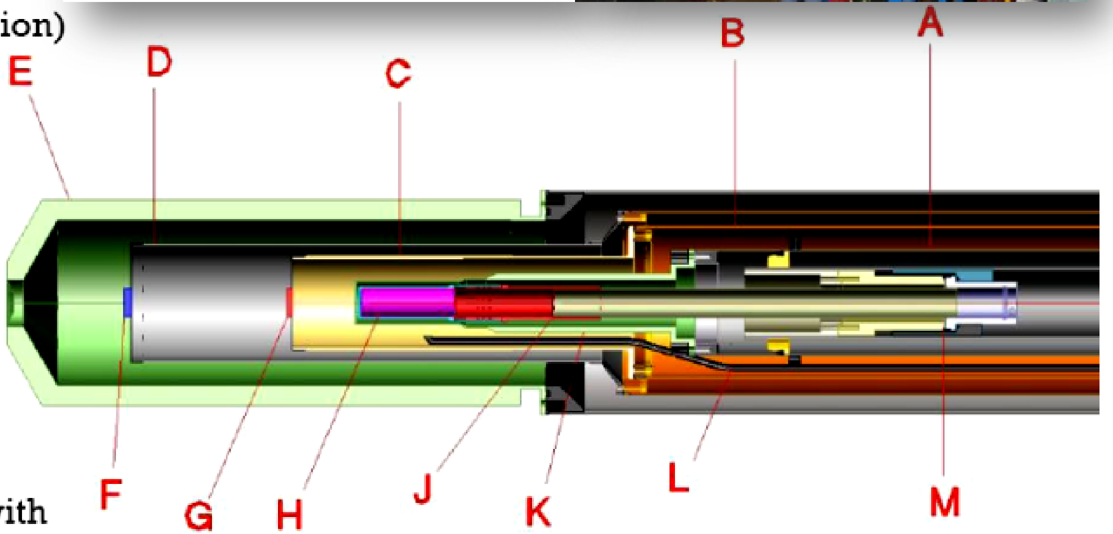


- **Linearly polarized photons**: coherent bremsstrahlung on oriented diamond **crystal** (**50** μm).
- Two **linear** polarized states (**parallel** & **perpendicular**).
- Analytical **QED** coherent bremsstrahlung calculation fit to actual spectrum (**Ken Livingston**/Glasgow U.)
- Perpendicular **1.3 GeV** edge shown.

FroST Target

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.

C. Keith *et al*. Nucl Instrum Meth A **684**, 27 (2012)

The Experiment

Battle Plan for Observables

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		$-H$		$O_{x'}$	

Lorenzo Zana (**6D2**)

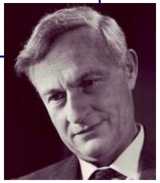
FroST

Photon beam	Target		
	x	y	z
Unpolarized	0	T	0
Linearly polarized	H	(-P)	-G
Circularly polarized	F	0	-E

g9b g9a

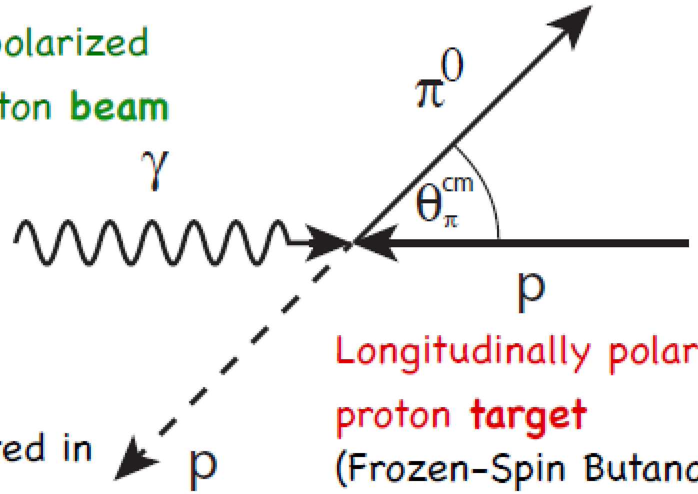
Nov '07 to Feb '08

- Every observable can be measured in at least **two** different experiments.
- They are not all independent.
  There are relations between the known as **Fierz** identities.



The Experiment

W = 1325 – 2075 MeV ΔW = 50 MeV
Cosθ = -0.8 – 0.8 $n_{\cos\theta}$ = 16



Circularly polarized tagged photon **beam**

Longitudinally polarized proton **target**
(Frozen-Spin Butanol Target)

p reconstructed in the **CLAS detector**

	beam spin	target spin
N_+^p :	⇄	⇄
N_-^p :	⇆	⇄

Polarized cross section

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

Maximum likelihood estimator

$$\hat{E}=-\frac{1}{P_zP_\odot}\left(\frac{N_+^p-N_-^p}{N_+^p+N_-^p}\right)$$

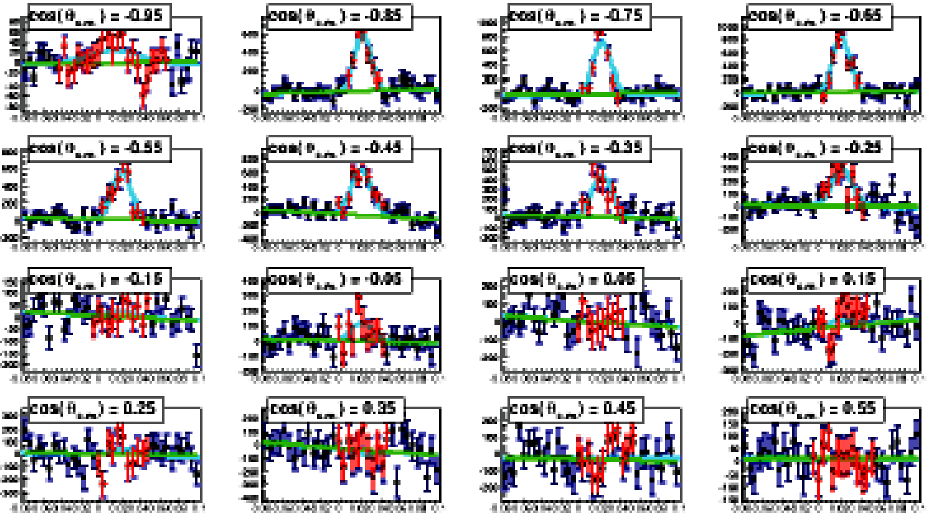
Courtesy of Steffen Strauch

Yields

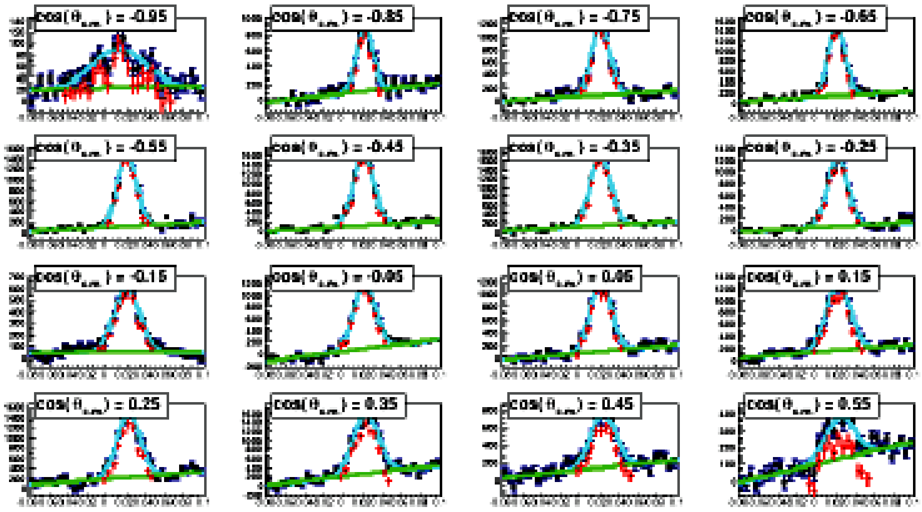
- Gaussian + polynomial to fit **peak**, yield is **2 σ**
- W = 1475 MeV.

$$E = -\frac{1}{P_Z^T P_C^\gamma}\left(\frac{N_+ - N_-}{N_+ + N_-}\right)$$

Numerator



Denominator



Polarized Measurements

for $\gamma p \rightarrow \pi^+ n$ & for $\gamma p \rightarrow \pi^0 p$

Double Polarization Observable $\mathcal{E}$ for $\pi^+ n$

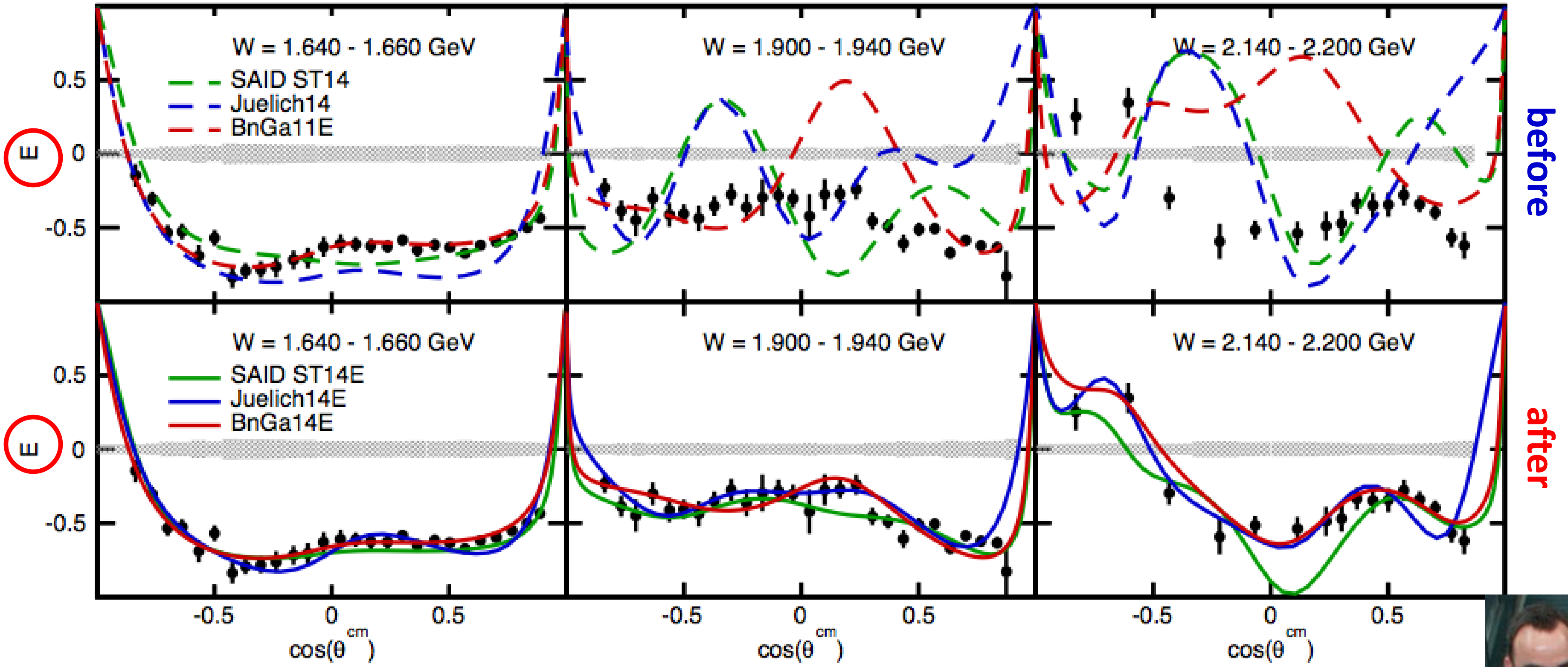
$$\boxed{\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_0 \left(1 - P_z P_\odot E\right)}$$

$W = 1240 - 2260$ MeV

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

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

W = 1650 MeV **W = 1920 MeV** **W = 2170 MeV**



S. Strauch *et al.* (CLAS) to be published in Phys Lett B (2015) ; arXiv:1503.05163 [nucl–ex]

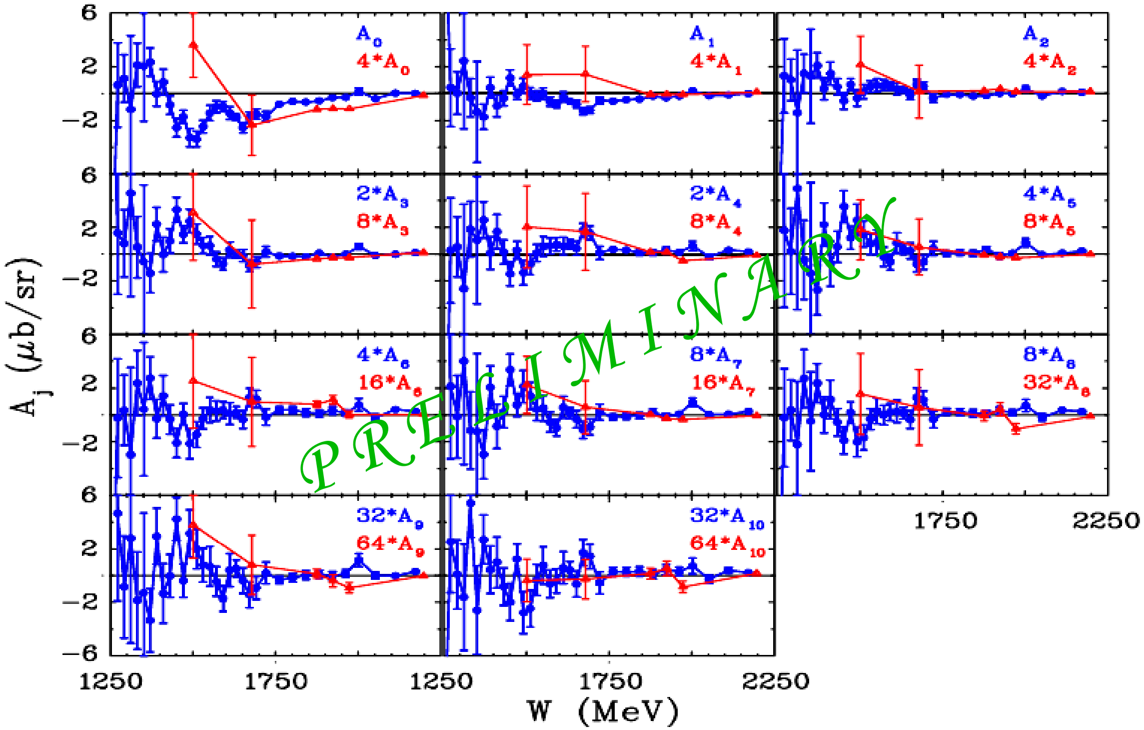
Courtesy of Steffen Strauch, CIPANP 2015

Legendre Polynomial Fit

- Beyond the **SAID PWA**, we plan the **Legendre analysis** for **CLAS E** measurements for both $\gamma p \rightarrow \pi^+ p$ and $\gamma p \rightarrow \pi^0 p$ as we did recently for the **CLAS** Σ data

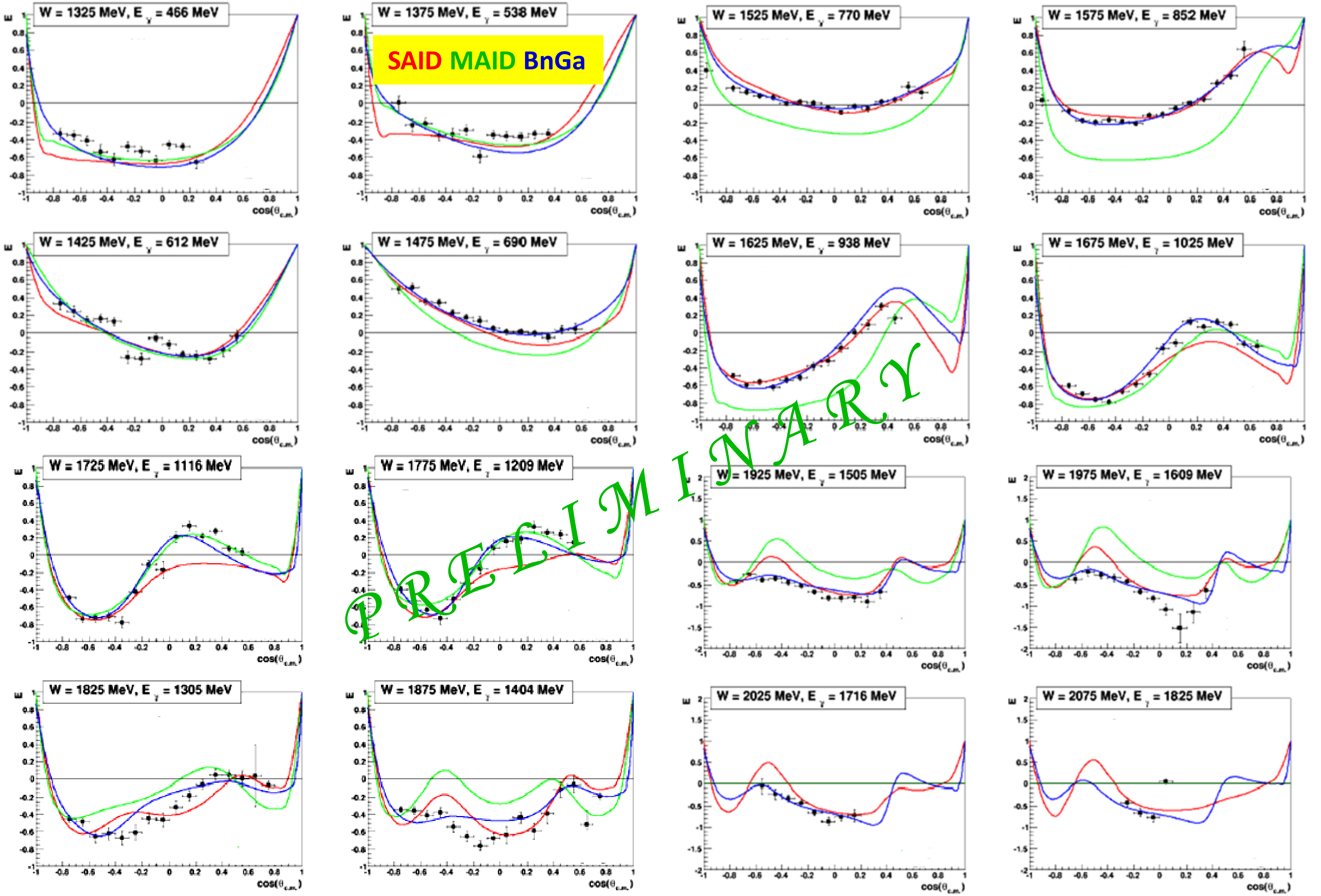
M. Dugger *et al*. (CLAS) Phys Rev C **88**, 065203 (2013).

- Unfortunately, recent **CBELSA E** for $\gamma p \rightarrow \pi^0 p$ is insufficient for that because of so broad energy binning (Δ**W** = 300 – 500 MeV).



- S. Strauch *et al*. (**CLAS**) to be published in Phys Lett B (2015) ; arXiv:1503.05163 [nucl–ex]
- M. Gottschall *et al*. (**CBELSA**/**TAPS**) Phys Rev Lett **112**, 012003 (2014)

Double Polarization Observable E for $\pi^0 p$



- Predictions are good for low energies while high energies are waiting for fit.

Summary

- Spin observables will tremendously aid in determining resonance parameters and finding ``**missing resonances**" (if they exist).
- Photon experiments in **Hall B** with **FroST** **at JLab** have acquired hundreds of data points unprecedented statistical quality and covering many reactions.
- For most reaction channels, we will have data sufficient for a nearly **complete experiments**.
- Evidence of **new states** found in **coupled-channel** analyses.
- Data for some reactions and some observables are nearing the **publication stage**, but much work remains.
- High level **analysis tools** (**SAID**, MAID, Juelich, BnGa) are in great demand.

Thank you for the invitation
and your attention

Work in Progress

igor@gwu.edu

Direct Amplitude Reconstruction in Pion Photo Production

$$\gamma \quad N \rightarrow N \quad \pi$$

spin: $1 \quad \frac{1}{2} \rightarrow \frac{1}{2} \quad 0$

helicities: $2 \times 2 \times 2 \,/\, 2 =$ ④

parity conservation

- In **particle physics**, **helicity** is the projection of the spin $\vec{S}$ onto the direction of momentum, $\hat{p}$:

$$h = \vec{J}\cdot\hat{p} = \vec{L}\cdot\hat{p} + \vec{S}\cdot\hat{p} = \vec{S}\cdot\hat{p}$$

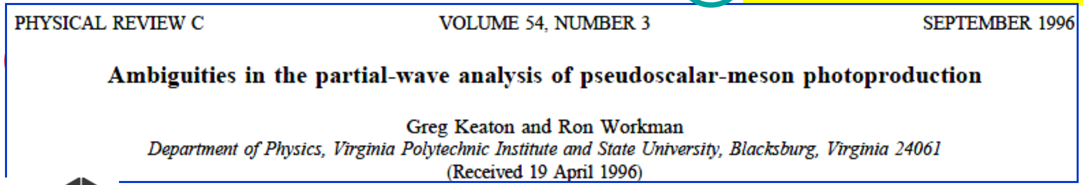
$$\hat{p} = \frac{\vec{p}}{|\vec{p}|}$$

Therefore, there are ④ independent invariant amplitudes

- In order to **determine** the pion photoproduction amplitude [**4 modules** and **3 relative phases**], one has to carry out ⑦ **independent** measurements at **fixed** **(W, t)** or **(E_γ, θ)**.

⑧

- This extra observable is necessary to eliminate a **sign ambiguity**.



PHYSICAL REVIEW C VOLUME 54, NUMBER 3 SEPTEMBER 1996

Ambiguities in the partial-wave analysis of pseudoscalar-meson photoproduction

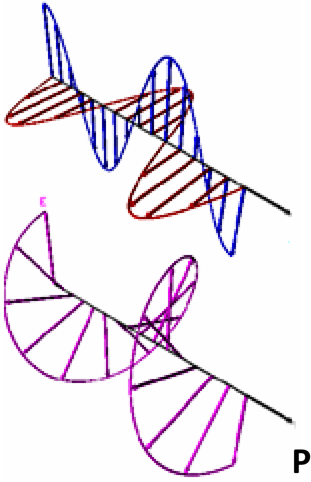
Greg Keaton and Ron Workman

Department of Physics, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061

(Received 19 April 1996)

Complete Experiment in Pion PhotoProduction

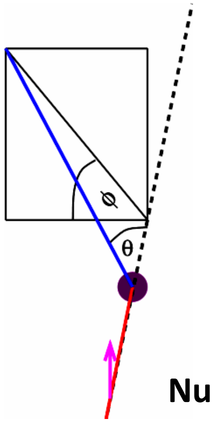
- There are 16 non-redundant observables.
- They are **not completely independent** from each other.



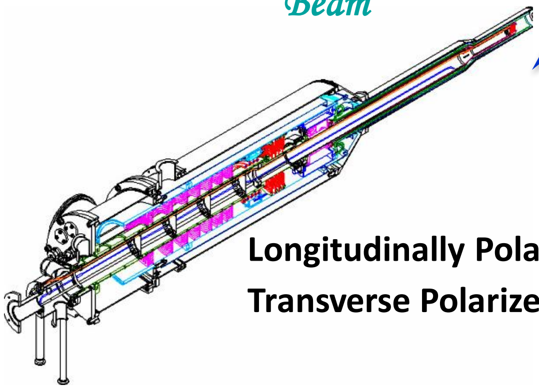
Linear Polarized *Beam*

Circular Polarized *Beam*

$$\vec{\gamma}\ \vec{N} \rightarrow \vec{N}\ \pi$$



Nucleon *Recoil* **Polarization**



Longitudinally Polarized Nucleon *Target*

Transverse Polarized Nucleon *Target*

1 **un-pol** measurement: **dσ/dΩ**

3 **single** pol measurements: **Σ**, **T**, **P**

12 **double** pol measurements: **E**, **F**, **G**, **H**, **Cx**, **Cz**, **Ox**, **Oz**, **Lx**, **Lz**, **Tx**, **Tz**

18 **triple** polarization asymmetries

[9 for linear pol beam]

[9 for circular pol beam]

13 of them are non-vanishing

Q: *Can we avoid?* A: *NO!*

A. Sandorfi *et al*. AIP Conf. Proc. **1432**, 219 (2012).
K. Nakayama, private communication, 2014.