SPIN2014
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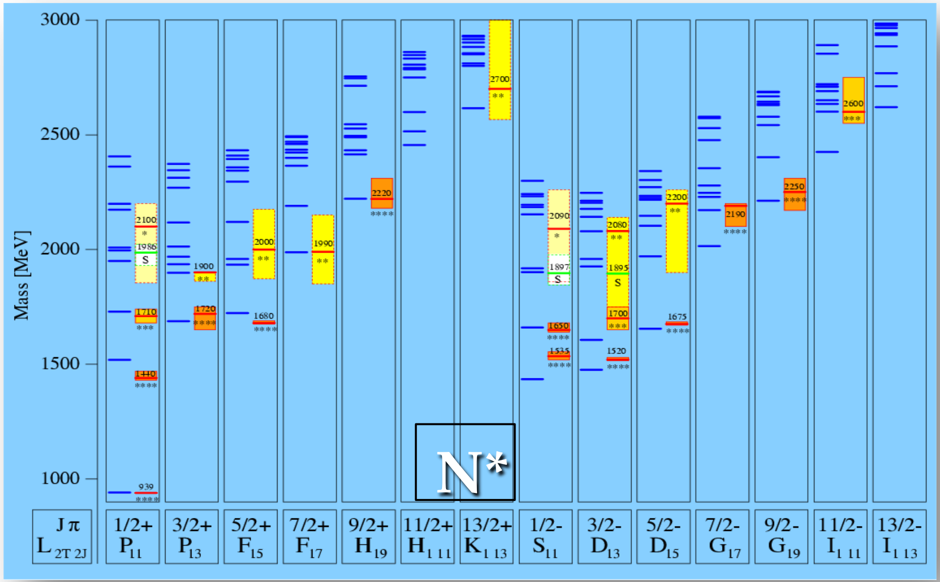
Double polarization experiments in meson photoproduction at Jefferson Lab

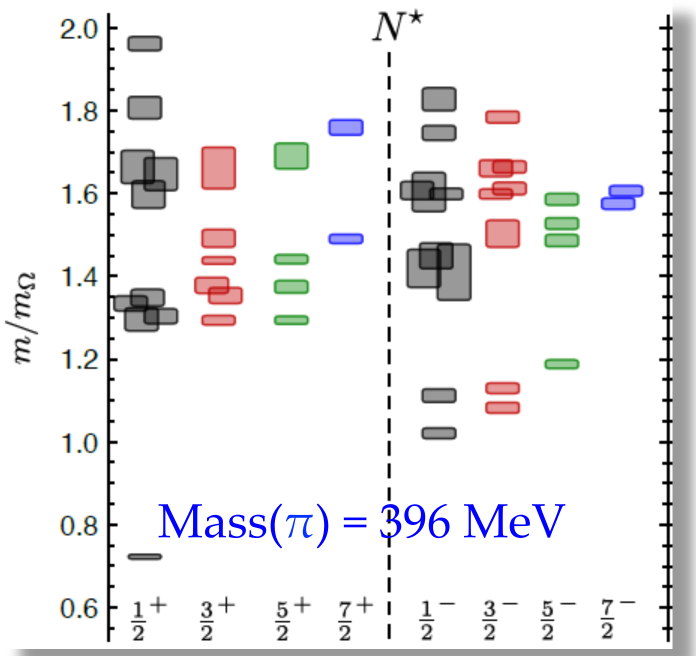
Eugene Pasyuk
Jefferson Lab

Outline

- Introduction and formalism
- Experimental tools
- Selected results
- Summary

Baryon Resonance Spectrum

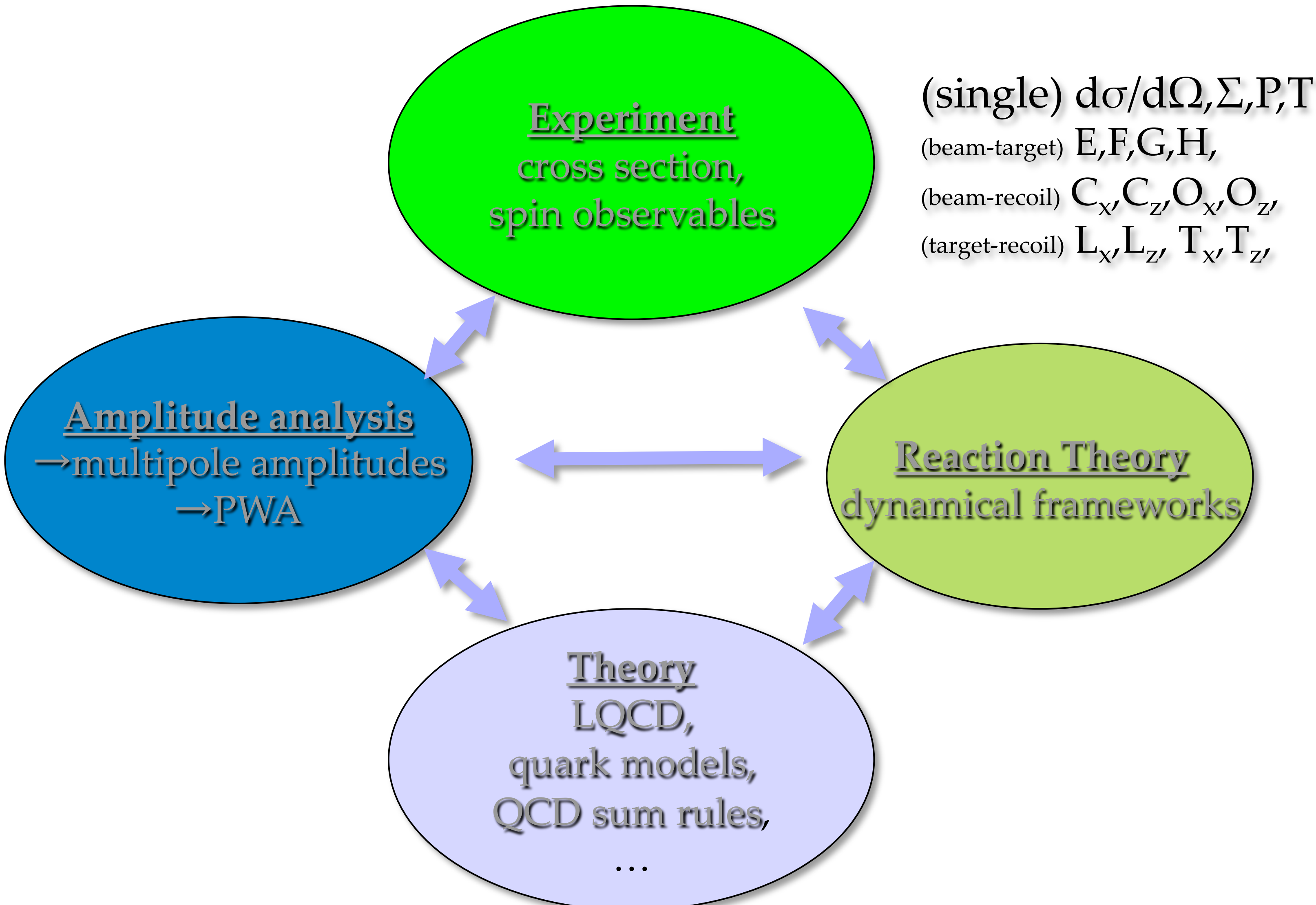




R.G. Edwards *et al*. Phys. Rev. D84 074508 (2011)

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

From the Experiment to Theory

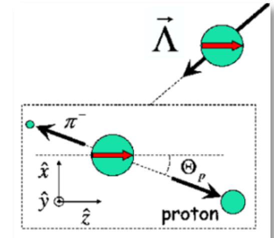


Polarization observables in pseudoscalar meson production

4 Complex amplitudes: **16** real polarization observables.

Complete measurement from **8** carefully chosen observables.

πN has large cross section but in **KY** recoil is **self-analysing**



πN: recoil targ γ

KY: γ targ recoil

Symbol	Transversity representation	Experiment required	Type
$d\sigma/dt$	$\lvert b_1\rvert^2+\lvert b_2\rvert^2+\lvert b_3\rvert^2+\lvert b_4\rvert^2$	$\{-;-;-\}$	S
$\Sigma d\sigma/dt$	$\lvert b_1\rvert^2+\lvert b_2\rvert^2-\lvert b_3\rvert^2-\lvert b_4\rvert^2$	$\{L(\frac{1}{2}\pi,0);-;-\}$	
$T d\sigma/dt$	$\lvert b_1\rvert^2-\lvert b_2\rvert^2-\lvert b_3\rvert^2+\lvert b_4\rvert^2$	$\{-;y;-\}$	
$P d\sigma/dt$	$\lvert b_1\rvert^2-\lvert b_2\rvert^2+\lvert b_3\rvert^2-\lvert b_4\rvert^2$	$\{-;-;y\}$	
$G d\sigma/dt$	$2\,\mathrm{Im}(b_1b_3^*+b_2b_4^*)$	$\{L(\pm\frac{1}{4}\pi);z;-\}$	BT
$H d\sigma/dt$	$-2\,\mathrm{Re}(b_1b_3^*-b_2b_4^*)$	$\{L(\pm\frac{1}{4}\pi);x;-\}$	
$E d\sigma/dt$	$-2\,\mathrm{Re}(b_1b_3^*+b_2b_4^*)$	$\{C;z;-\}$	
$F d\sigma/dt$	$2\,\mathrm{Im}(b_1b_3^*-b_2b_4^*)$	$\{C;x;-\}$	
$O_x d\sigma/dt$	$-2\,\mathrm{Re}(b_1b_4^*-b_2b_3^*)$	$\{L(\pm\frac{1}{4}\pi);-;x'\}$	BR
$O_z d\sigma/dt$	$-2\,\mathrm{Im}(b_1b_4^*+b_2b_3^*)$	$\{L(\pm\frac{1}{4}\pi);-;z'\}$	
$C_x d\sigma/dt$	$2\,\mathrm{Im}(b_1b_4^*-b_2b_3^*)$	$\{C;-;x'\}$	
$C_z d\sigma/dt$	$-2\,\mathrm{Re}(b_1b_4^*+b_2b_3^*)$	$\{C;-;z'\}$	
$T_x d\sigma/dt$	$2\,\mathrm{Re}(b_1b_2^*-b_3b_4^*)$	$\{-;x;x'\}$	TR
$T_z d\sigma/dt$	$2\,\mathrm{Im}(b_1b_2^*-b_3b_4^*)$	$\{-;x;z'\}$	
$L_x d\sigma/dt$	$2\,\mathrm{Im}(b_1b_2^*+b_3b_4^*)$	$\{-;z;x'\}$	
$L_z d\sigma/dt$	$2\,\mathrm{Re}(b_1b_2^*+b_3b_4^*)$	$\{-;z;z'\}$	

I. S. Barker, A. Donnachie, J. K. Storrow, Nucl. Phys. B95 347 (1975).

circ polarized photons

longitudinally polarized target

linearly polarized photons

transversely polarized target

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 observables

Beam-Target

Beam-Recoil

Target-Recoil

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

Experiments

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
- They are not all independent. There are relations between the known as Fierz identities.

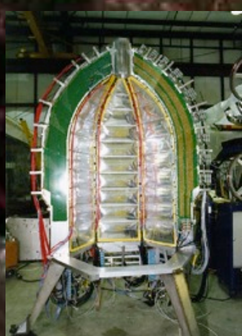
CEBAF Large Acceptance Spectrometer 1997-2012

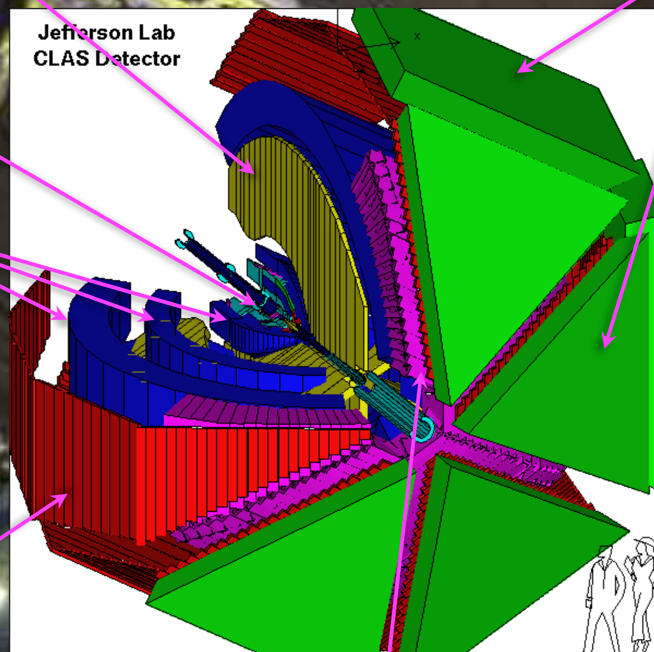
Torus magnet
6 superconducting coils

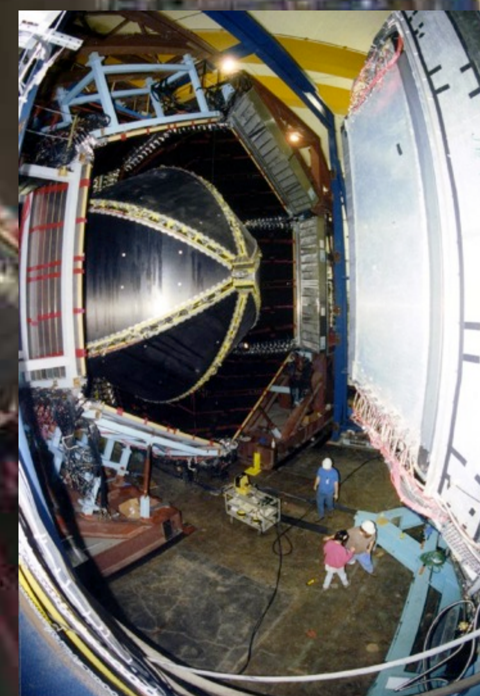
Electromagnetic calorimeters
Lead/scintillator, 1296 photomultipliers

target + start counter

Drift chambers
35,000 cells



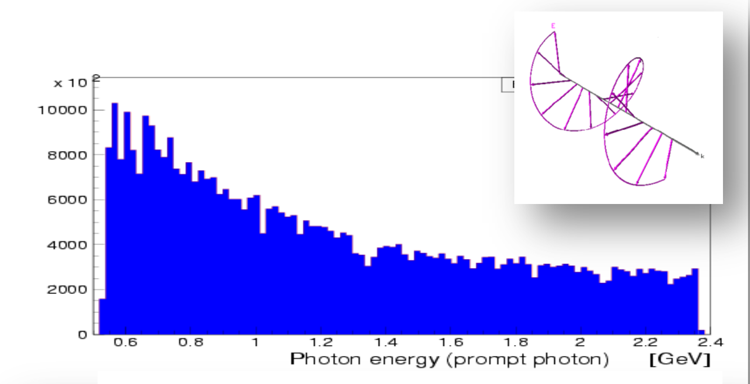




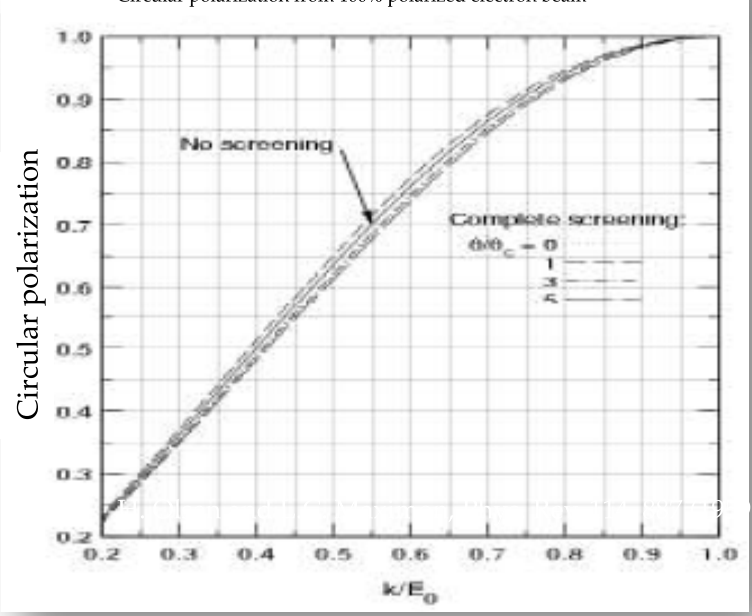
Time-of-flight counters
plastic scintillators, 684 photomultipliers

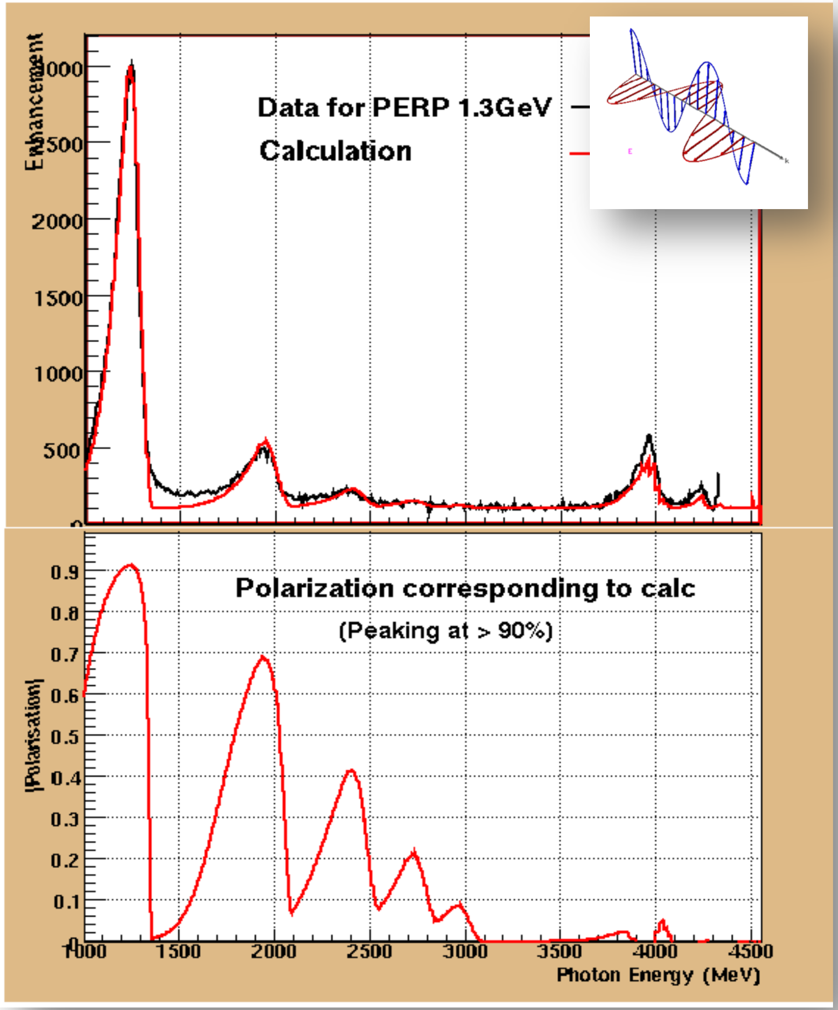
Gas Cherenkov counters
e/π separation, 256 PMTs

Polarized pohoton beam



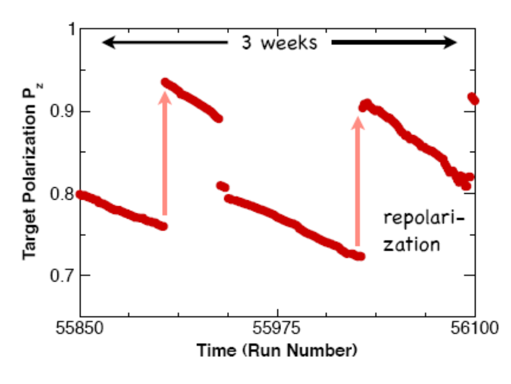
Circular polarization from 100% polarized electron beam





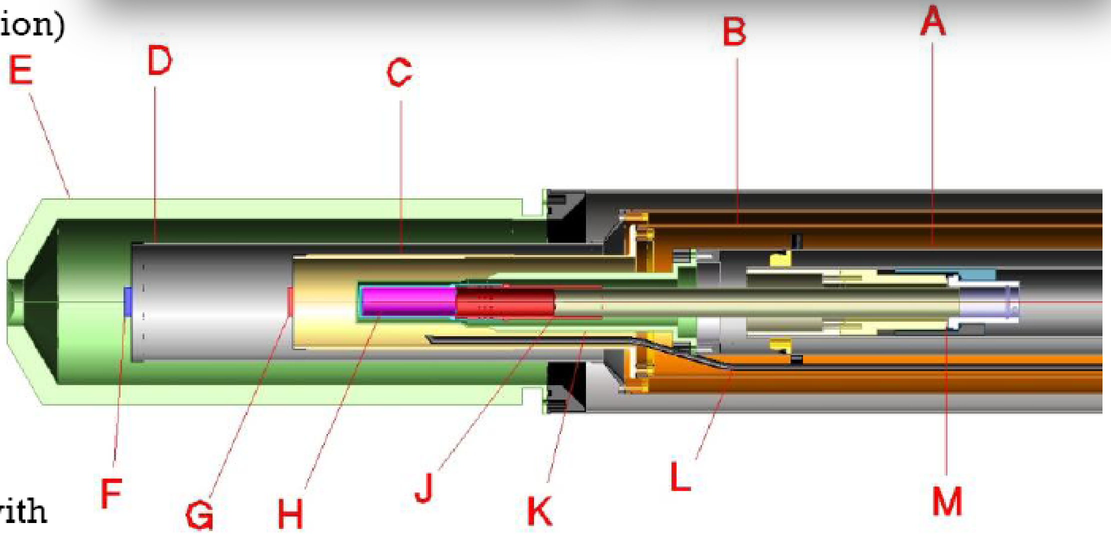
Circularly polarized beam produced by longitudinally polarized electrons

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



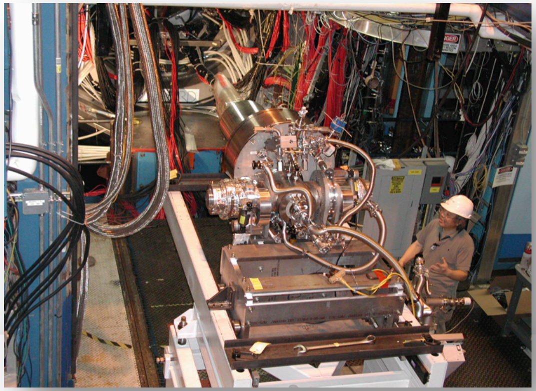
Performance Specs:

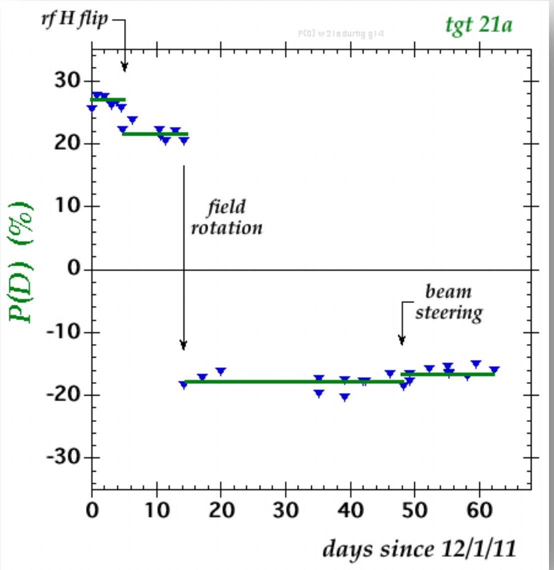
Base Temp: 28 mK w/o beam, 30 mK with
Cooling Power: 800 μW @ 50 mK, 10 mW @ 100 mK, and 60 mW @ 300 mK
Polarization: +82%, -90%
1/e Relaxation Time: 2800 hours (+Pol), 1600 hours (-Pol)
Roughly 1% polarization loss per day.

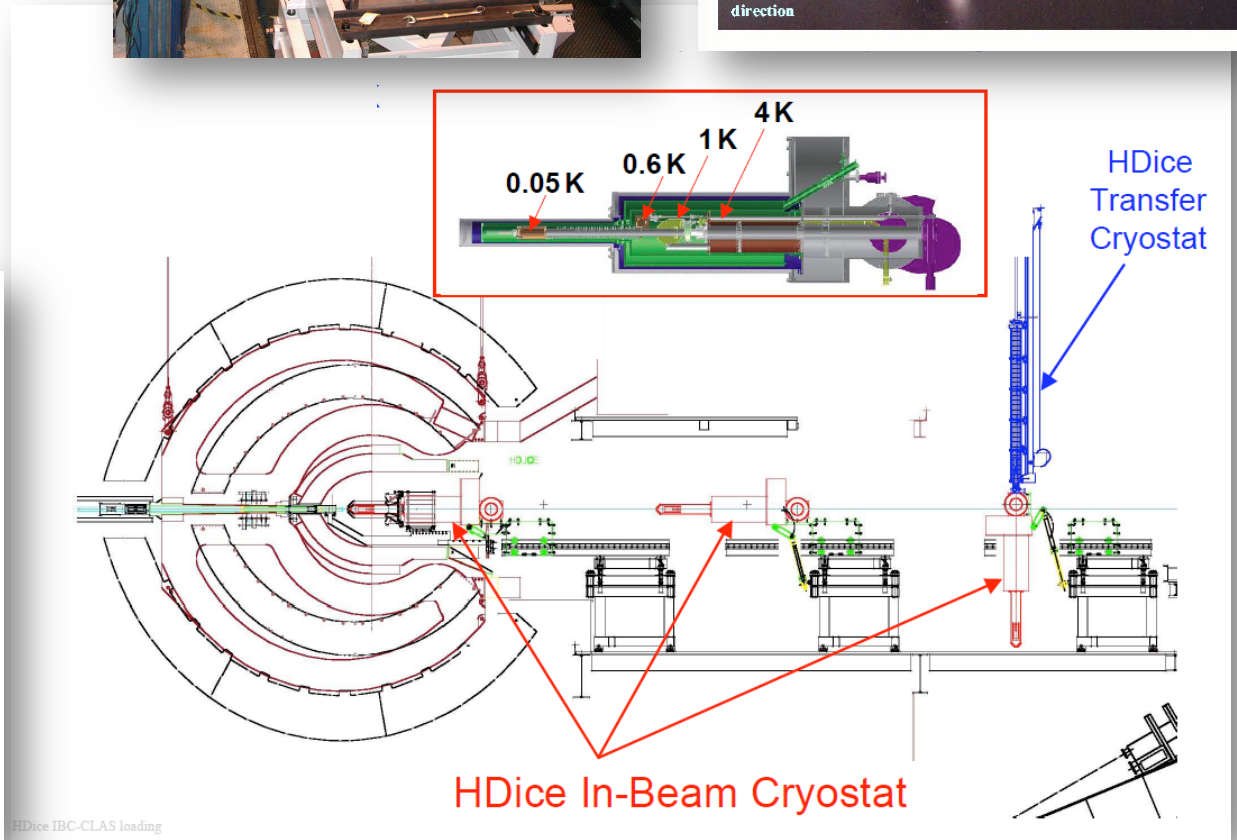
HDIce polarized target

- 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

(X. Wei, Parallel VII S10)







What we measure with CLAS

- $\gamma p \to \pi^0 p,\ \pi^+ n$
- $\gamma p \to \eta p$
- $\gamma p \to \eta' p$
- $\gamma p \to KY\ (K^+\Lambda,\ K^+\Sigma^0,\ K^0\Sigma^+)$
- $\gamma p \to \pi^+\pi^- p\ \ \omega p,\ \rho p,\ \phi p$
- ....

- $\gamma n \to \pi^- p$
- $\gamma n \to \pi^+\pi^- n$
- $\gamma n \to \Sigma^- K^+,\ \Lambda K^0$
- .....

CLAS Experiments: g1c, g11

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		$-H$		$O_{x'}$	

- unpolarized target
- g1c – circularly polarized beam
- g11 – unpolarized beam, high statistics

CLAS Experiments: g8b

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		$-H$		$O_{x'}$	

- linearly polarized beam

CLAS Experiments: g9a

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		$-H$		$O_{x'}$	

- Longitudinally polarized target

CLAS Experiments: g9b

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		$-H$		$O_{x'}$	

- transversely polarized target

CLAS Experiments: deuteron target

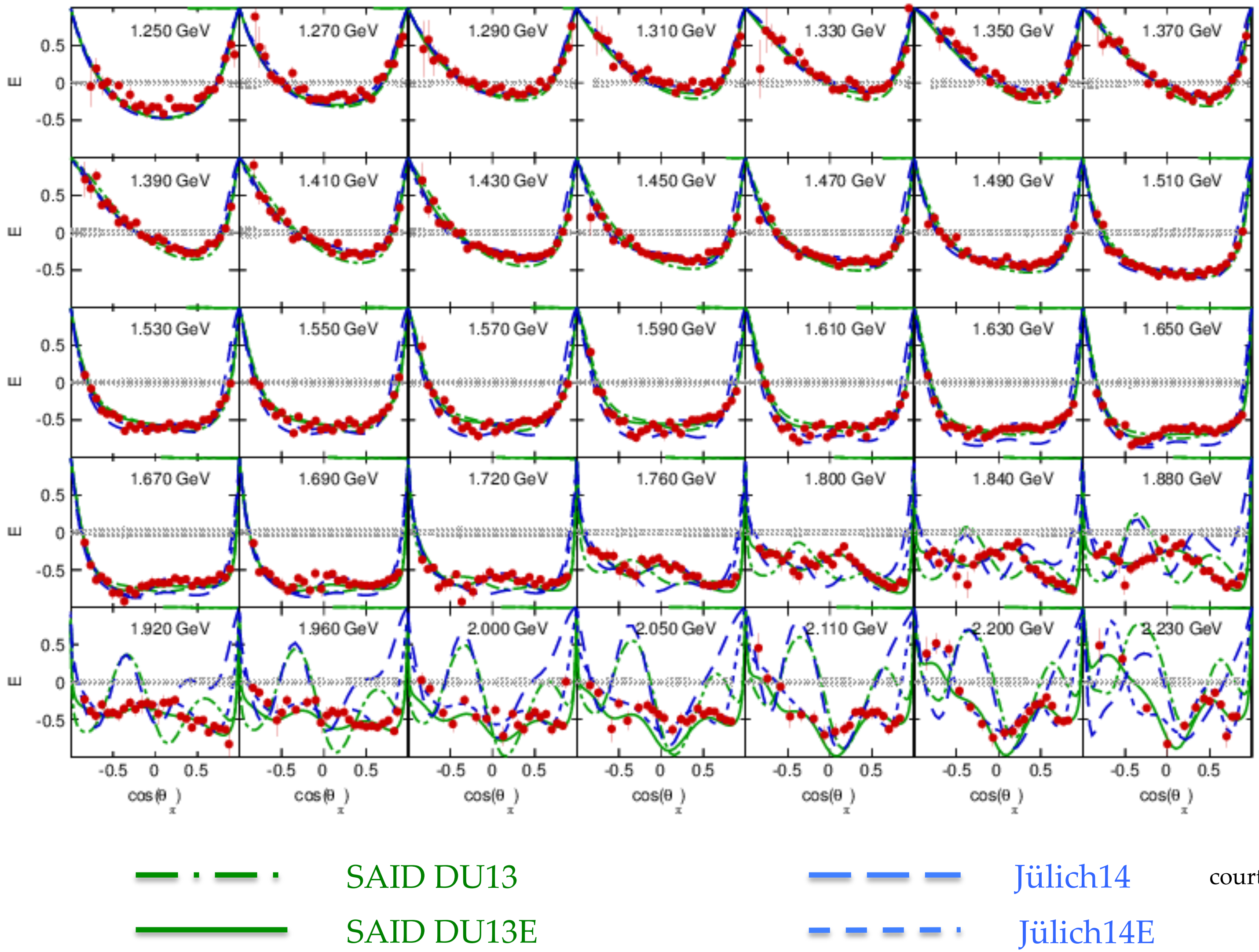
- g10 unpolarized beam, unpolarized deuterium target
- g13 circularly and linearly polarized beam on unpolarized deuterium target
- g14 circularly and linearly polarized beam on longitudinally polarized HD target   (A. Sandorfi, Parallel VI S6)

Single pion production

• • •

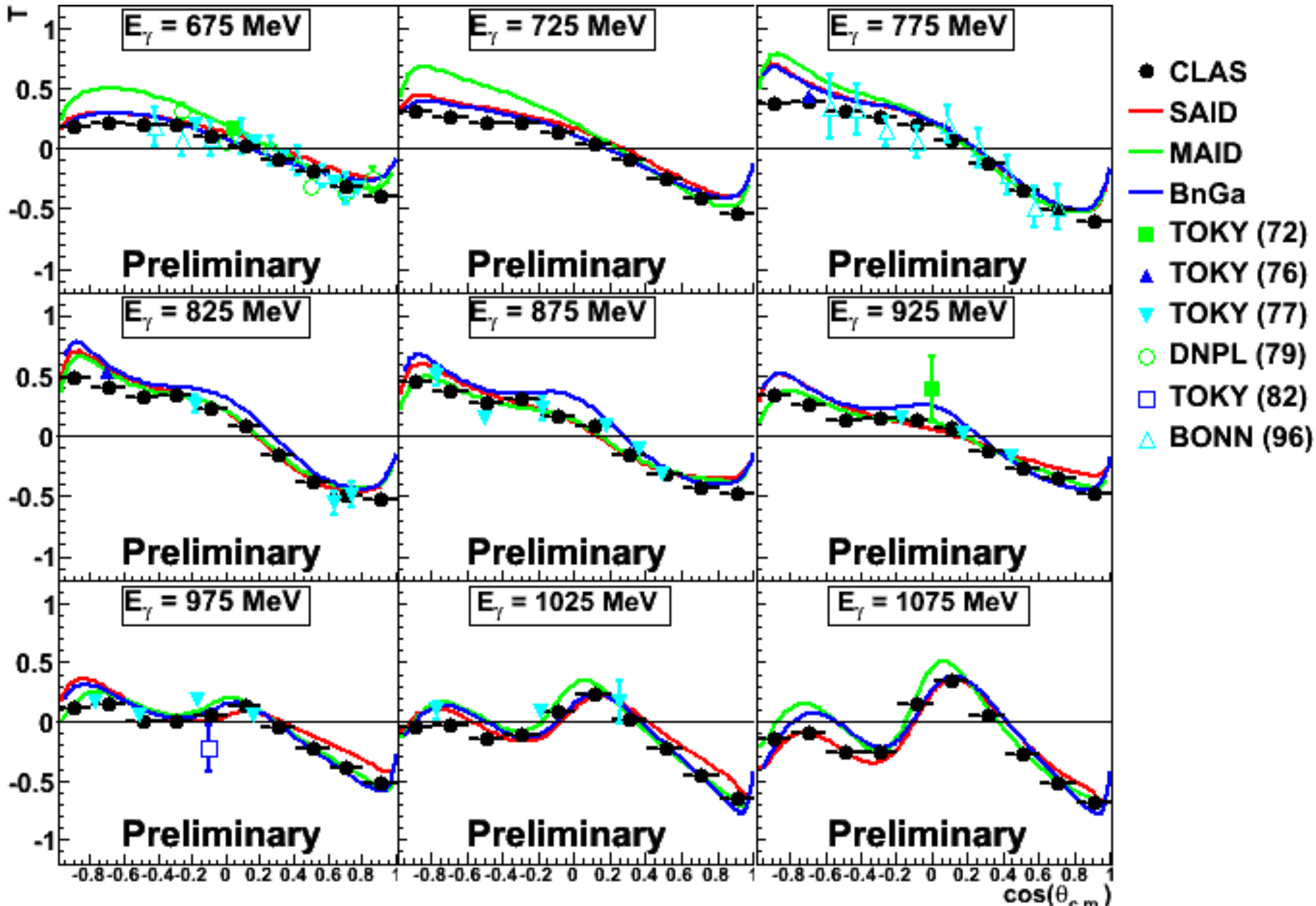
$\gamma p \to \pi^+ n$

E for $\gamma p \rightarrow n \pi^+$



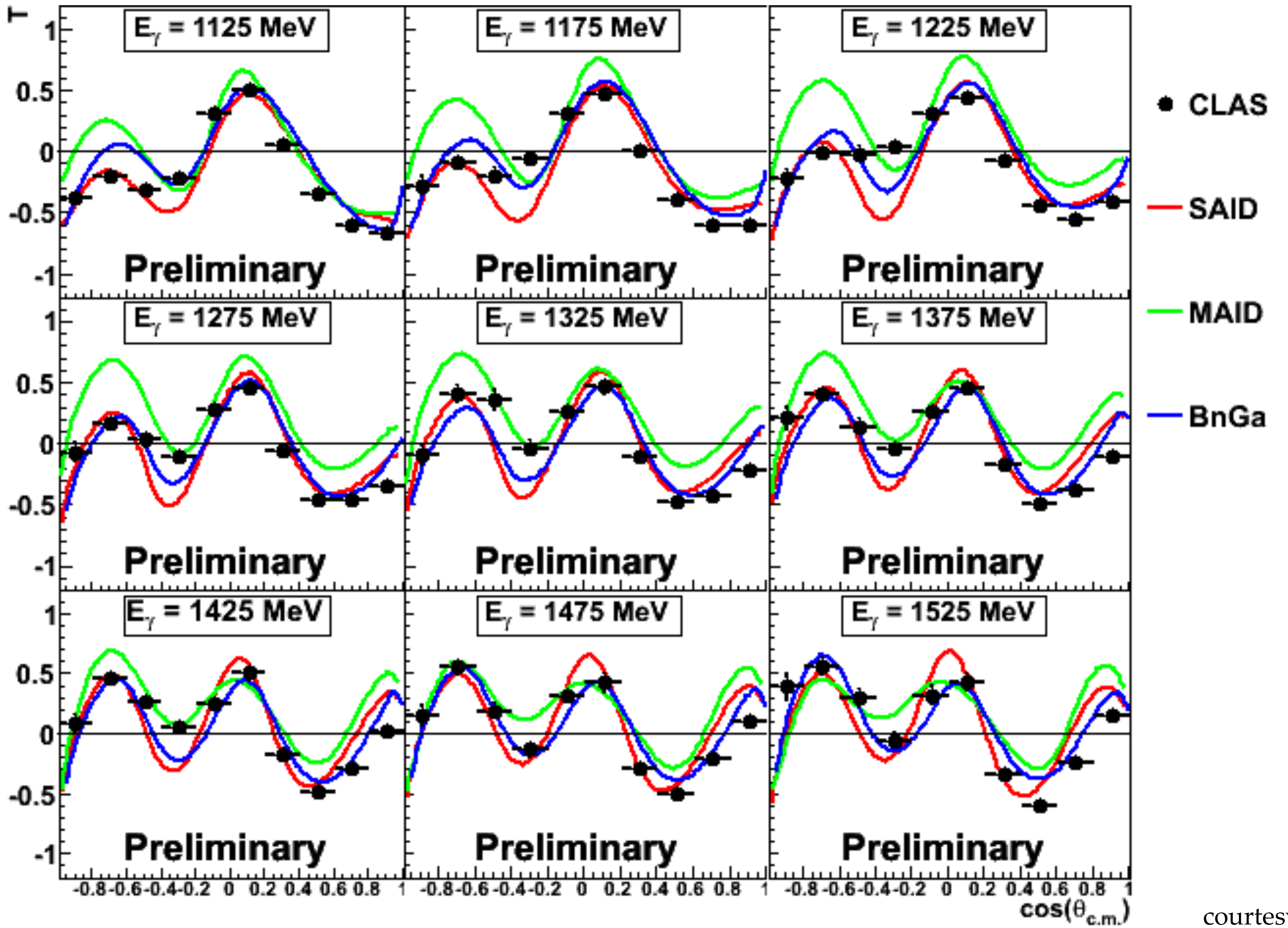
courtesy S. Strauch, USC

T for $\gamma p \rightarrow n\pi^+$ E_γ = 675 to 1075 MeV



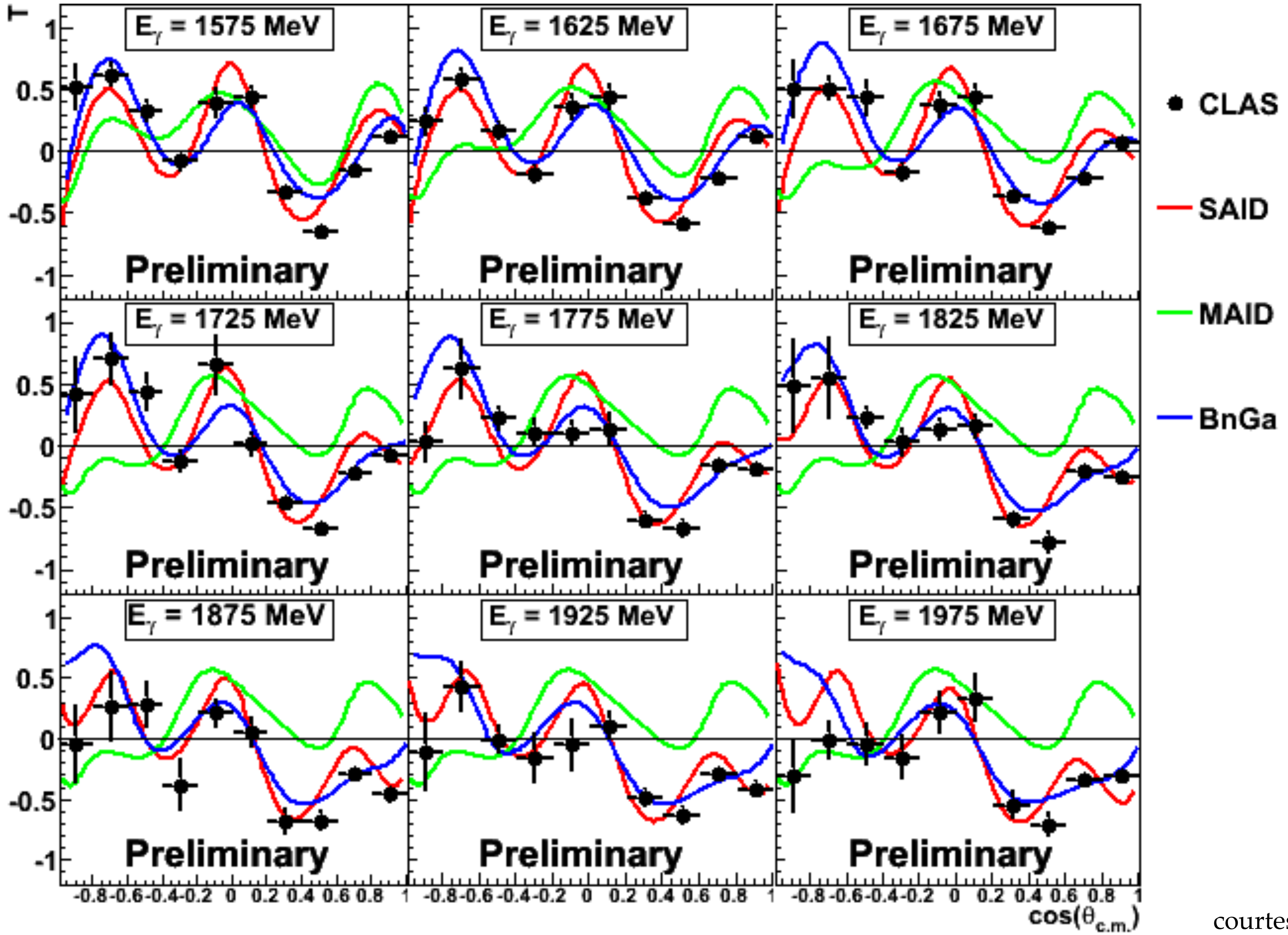
courtesy M. Dugger, ASU

T for $\gamma p \rightarrow n\pi^+$ E_γ = 1125 to 1525 MeV



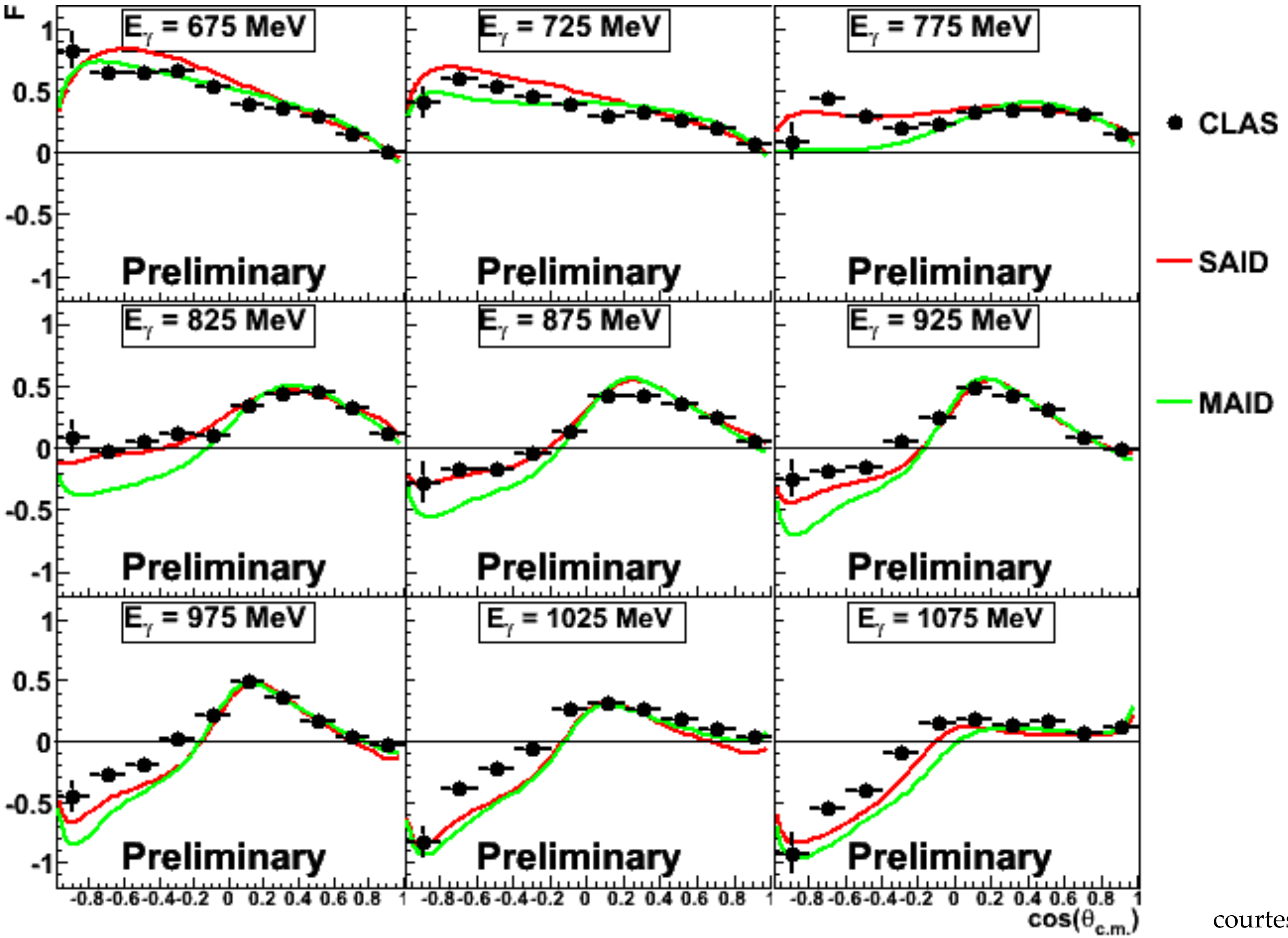
courtesy M. Dugger, ASU

T for $\gamma p \rightarrow n\pi^+$ E_γ = 1575 to 1975 MeV



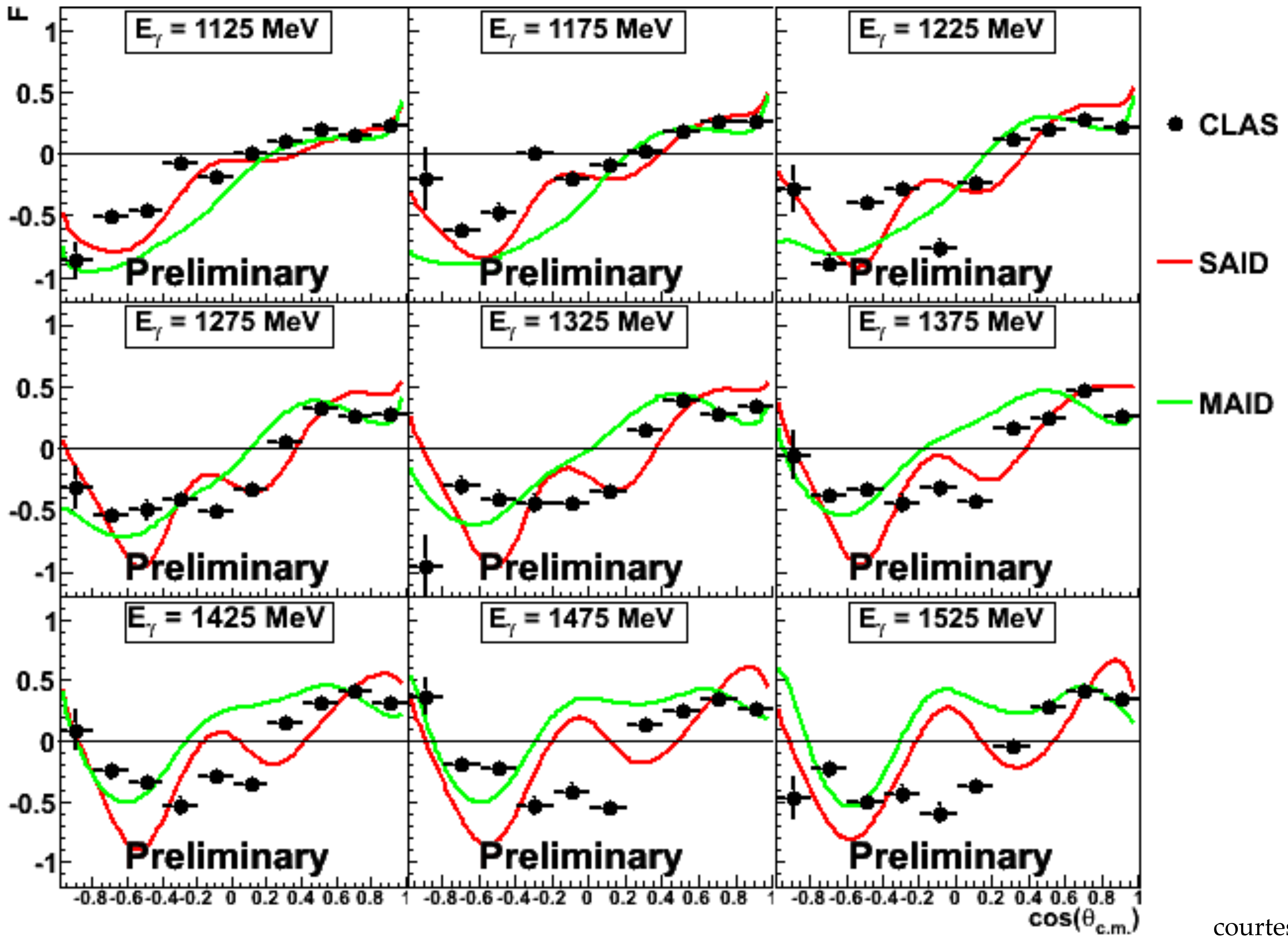
courtesy M. Dugger, ASU

F for $\gamma p \to n\pi^+$ (E_γ = 675 to 1075 MeV)



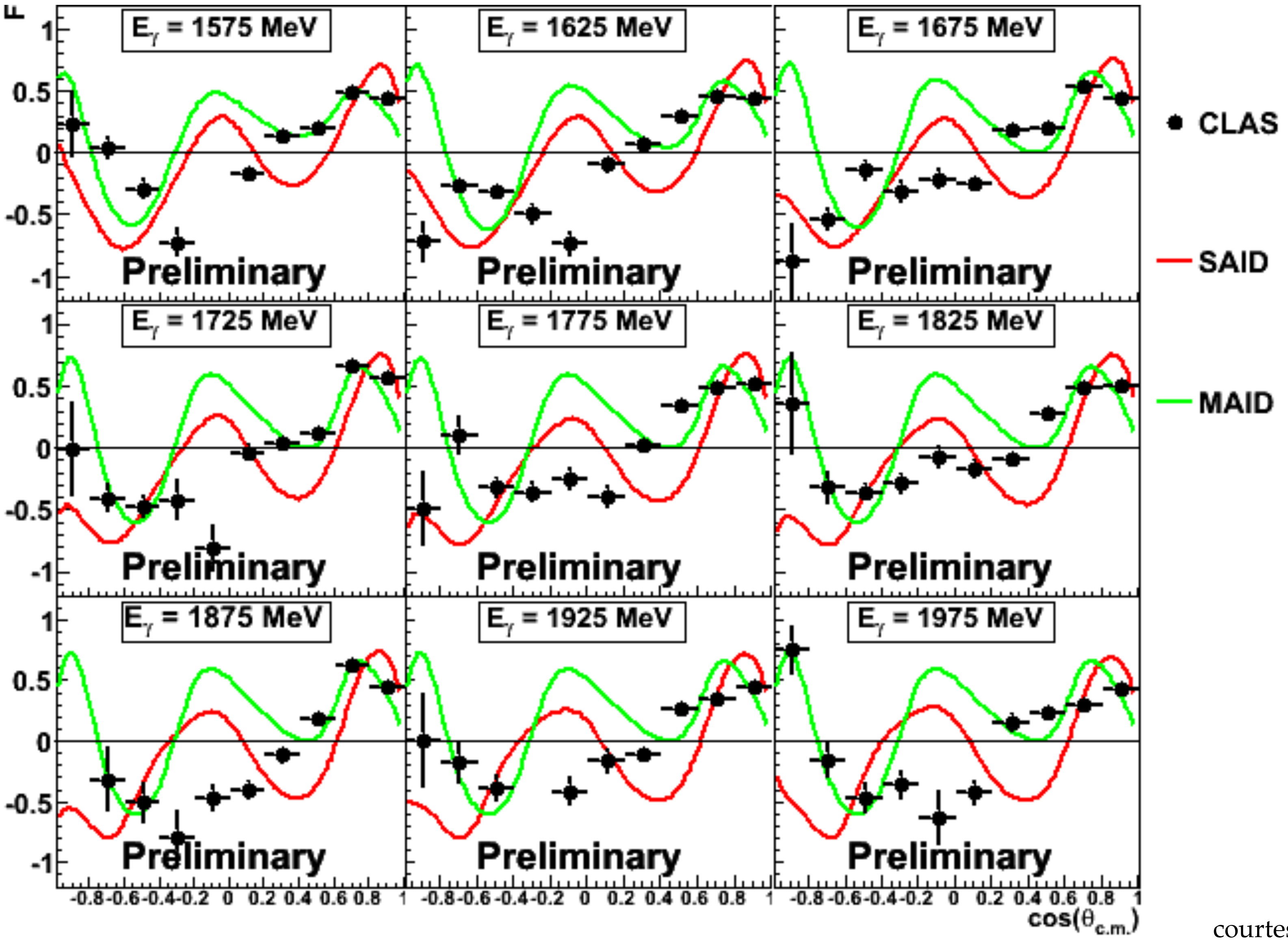
courtesy M. Dugger, ASU

F for $\gamma p \to n \pi^+$ E_γ = 675 to 1075 MeV



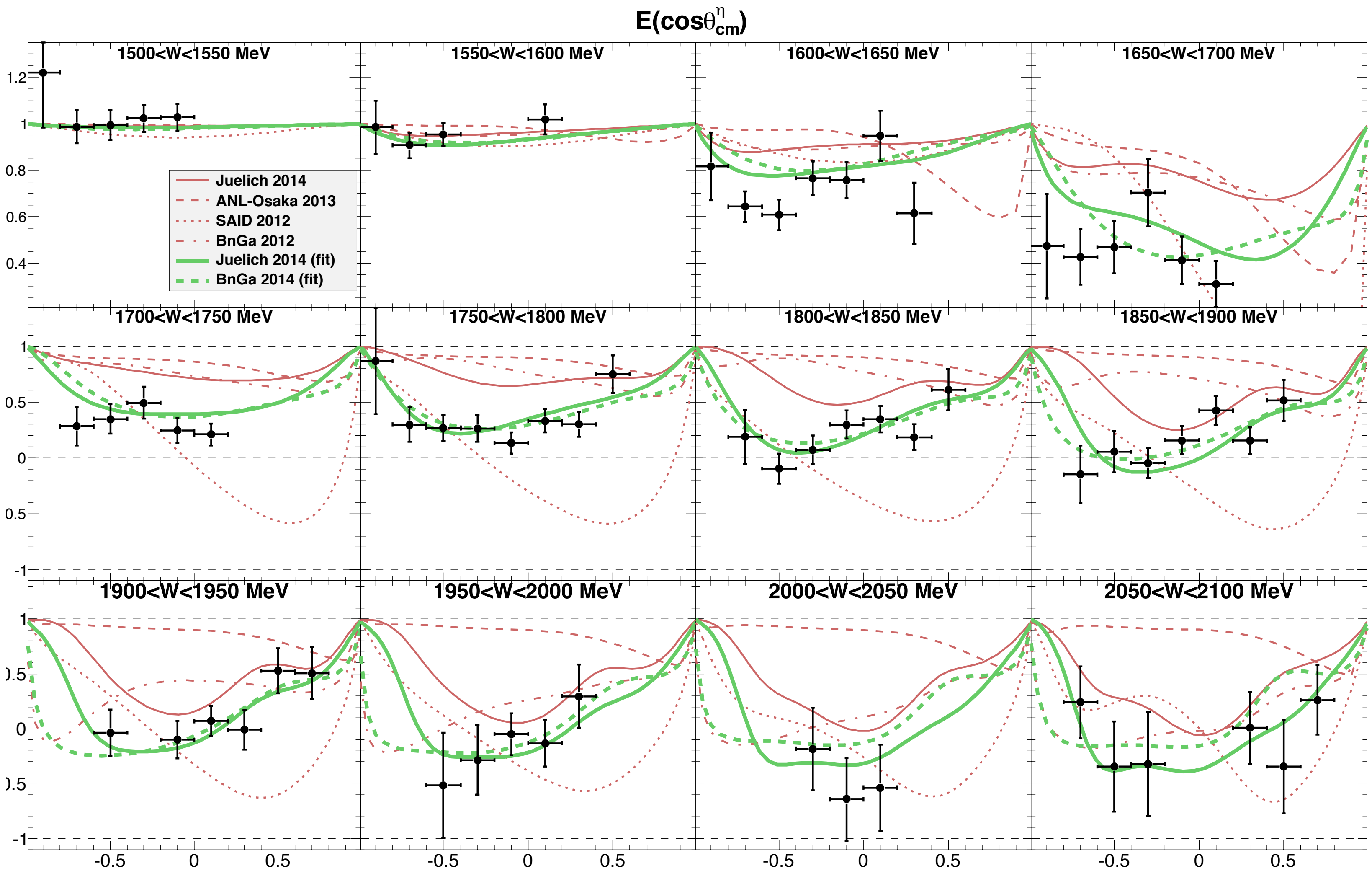
courtesy M. Dugger, ASU

F for $\gamma p \rightarrow n \pi^+$ E_γ = 1575 - 1975 MeV



courtesy M. Dugger, ASU

E for γ p → p η



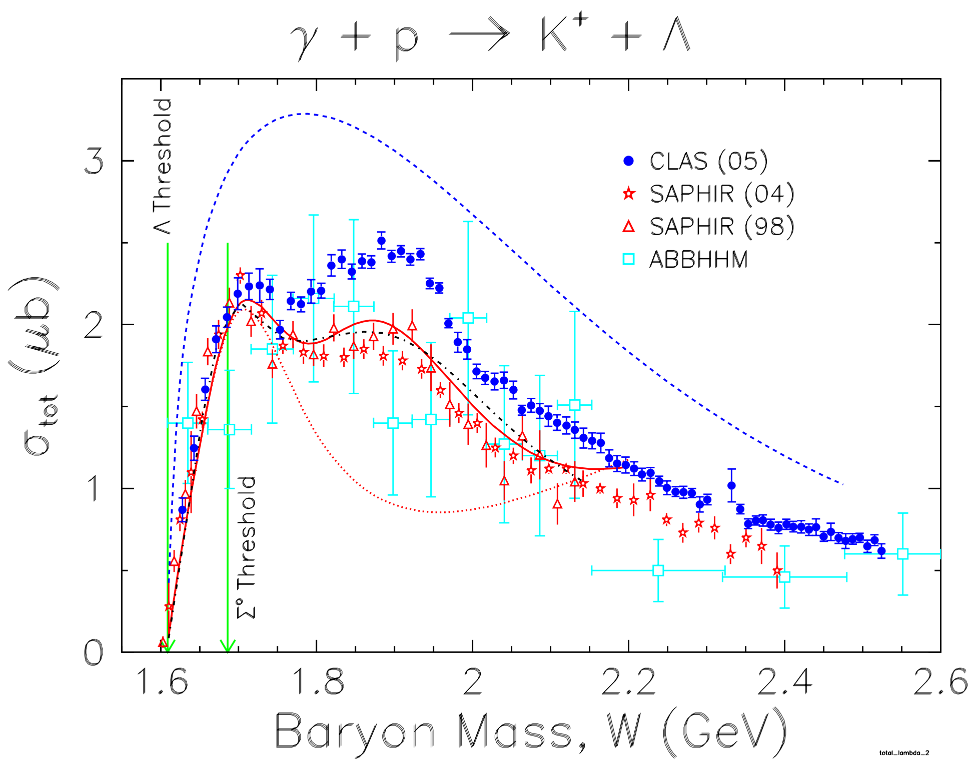
courtesy I. Senderovich, ASU

Kaon production

• • •

$\gamma p \rightarrow K^+ \Lambda, K^+ \Sigma^0$

What is this Bump?



SAPHIR data (1998) triggered discussionon "missing" D_{13}:

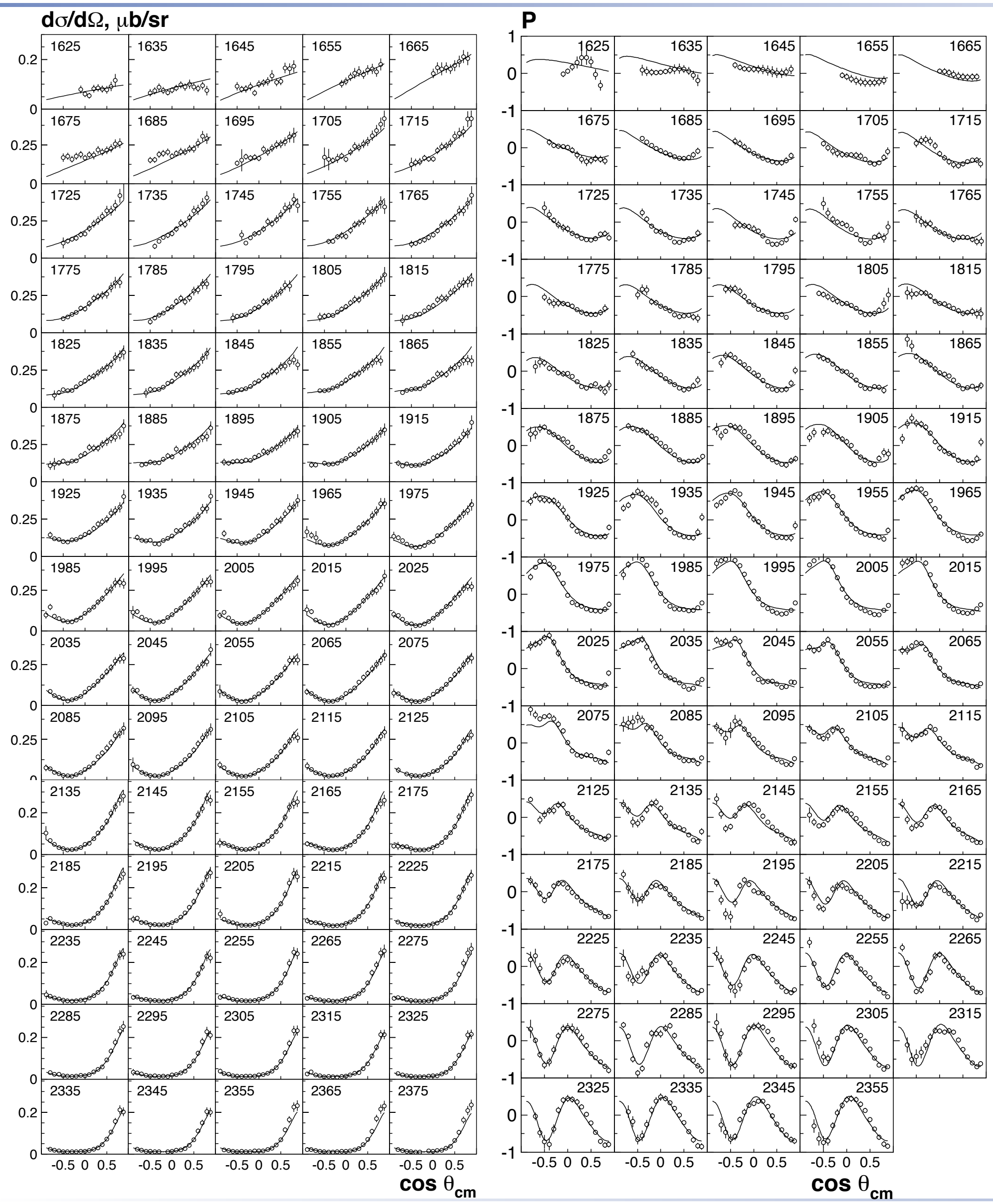
$D_{13}(1890)$?, $P_{11}(1840)$? $D_{13}(1900)$?... lots of other interpretations

CLAS got into the game

First CLAS measurements (g1c): $d\sigma/d\Omega$, P, C_x, C_z

Confirmed bump around 1.9 GeV

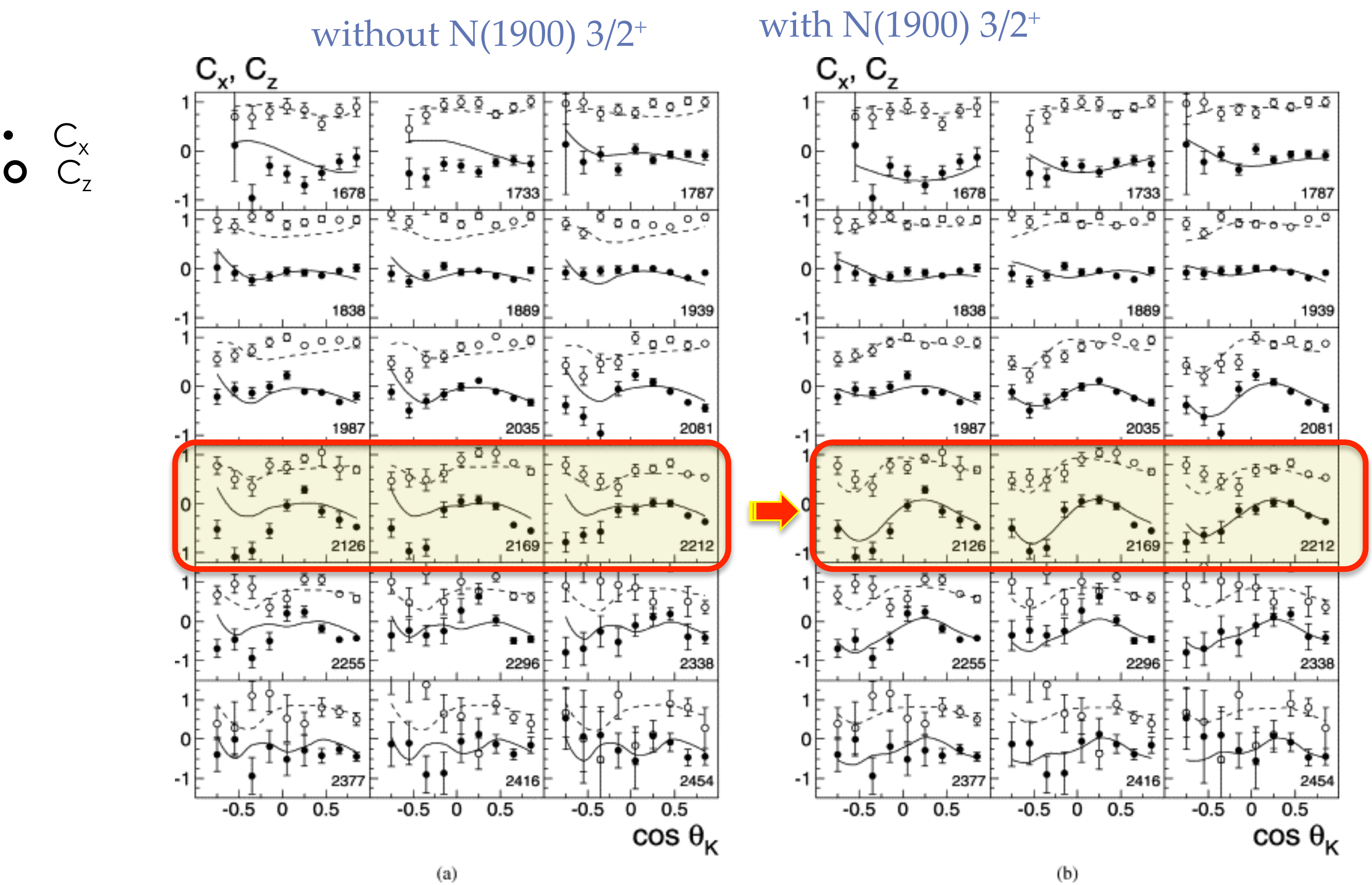
g11 cross sections and *P*



data: CLAS g11

fit: BoGa

Polarization transfer Cx, Cz



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

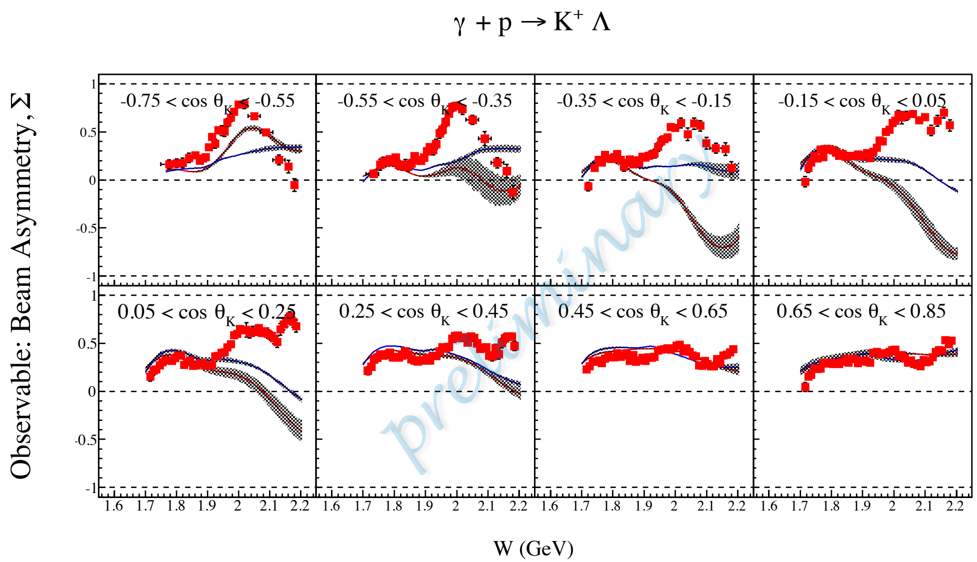
N*	$J^P(L_{2I,2J})$	2010	2012
N(1440)	$1/2^+$ (P11)	****	****
N(1520)	$3/2^-$ (D13)	****	****
N(1535)	$1/2^-$ (S11)	****	****
N(1650)	1/2- (S11)	****	****
N(1675)	5/2- (D15)	****	****
N(1680)	5/2+ (F15)	****	****
N(1685)			*
N(1700)	3/2- (D13)	***	***
N(1710)	1/2+ (P11)	***	***
N(1720)	3/2+ (P13)	****	****
N(1860)	5/2+		**
N(1875)	3/2-		***
N(1880)	1/2+		**
N(1895)	1/2-		**
N(1900)	3/2+ (P13)	**	***
N(1990)	7/2+ (F17)	**	**
N(2000)	5/2+ (F15)	**	**
~~N(2080)~~	~~D13~~	**	
~~N(2090)~~	~~S11~~	*	
N(2040)	3/2+		*
N(2060)	5/2-		**
N(2100)	1/2+ (P11)		*
N(2120)	3/2-		**
N(2190)	7/2- (G17)		
~~N(2200)~~	~~D15~~	**	
N(2220)	9/2+ (H19)	****	****

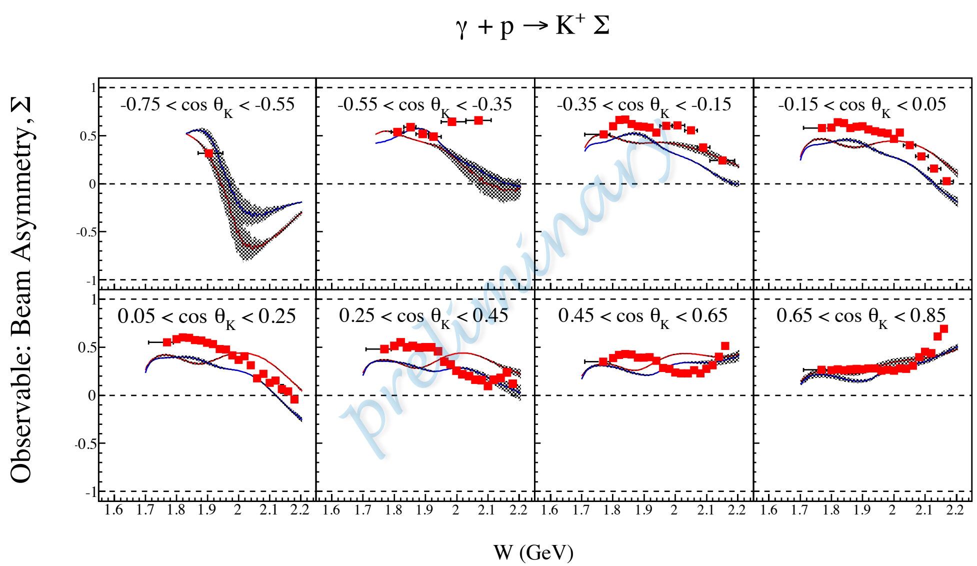
- Major revision of the baryon table to large extent driven by new photoproducton data, particularly CLAS data.
- Them “bump” origin seems to be settled being attributed to N(1900) 3/2+
- Other new states still require more confirmation

Energy dependence: Σ

BoGa2011-1

BoGa2011-1



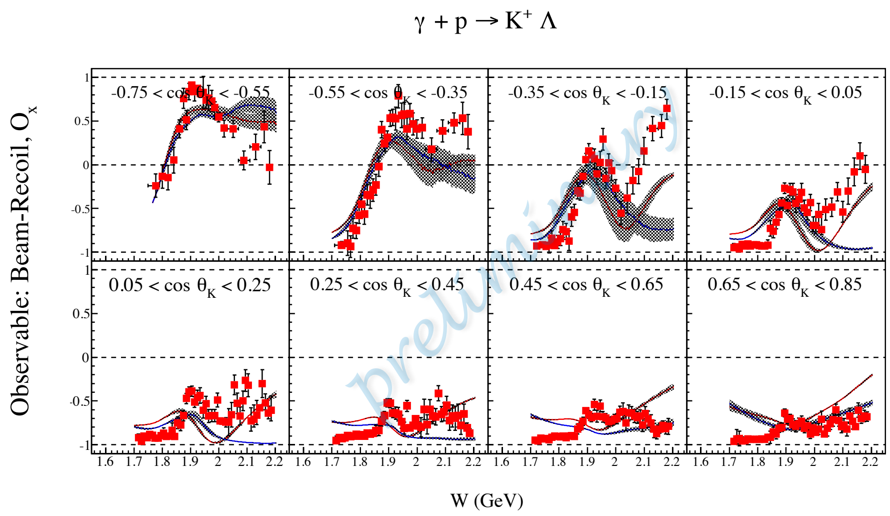


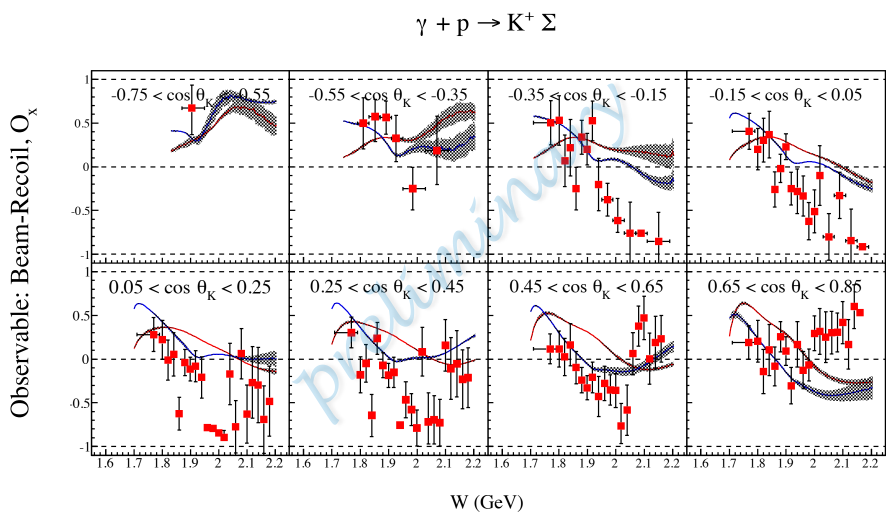
courtesy D. Ireland, UGlasgow

Energy dependence: Ox

BoGa2011-1

BoGa2011-1



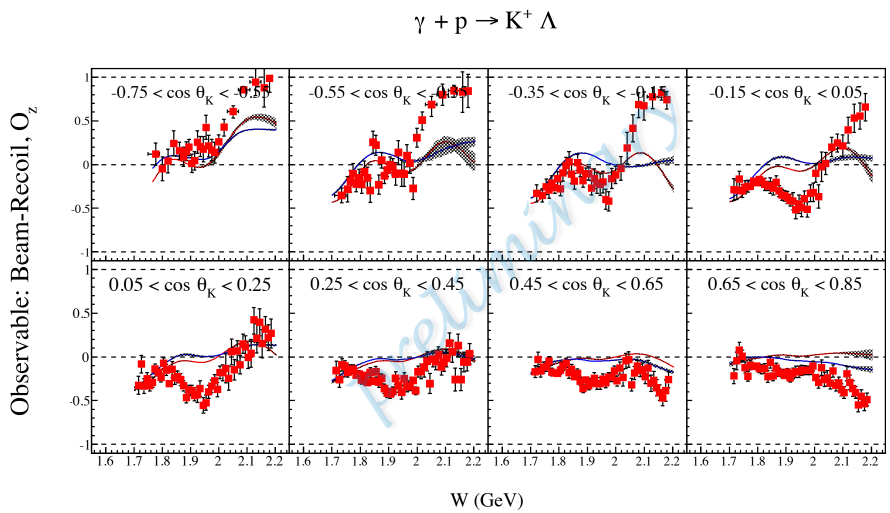


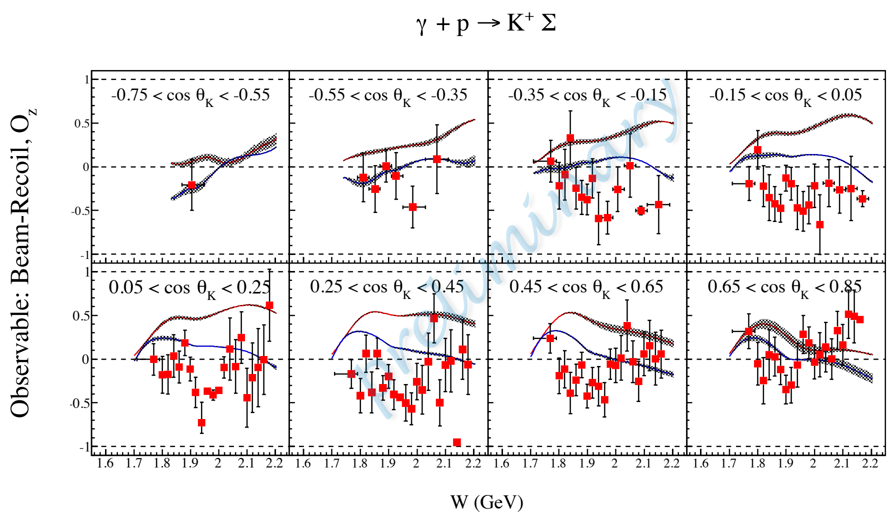
courtesy D. Ireland, UGlasgow

Energy dependence: Oz

BoGa2011-1

BoGa2011-1



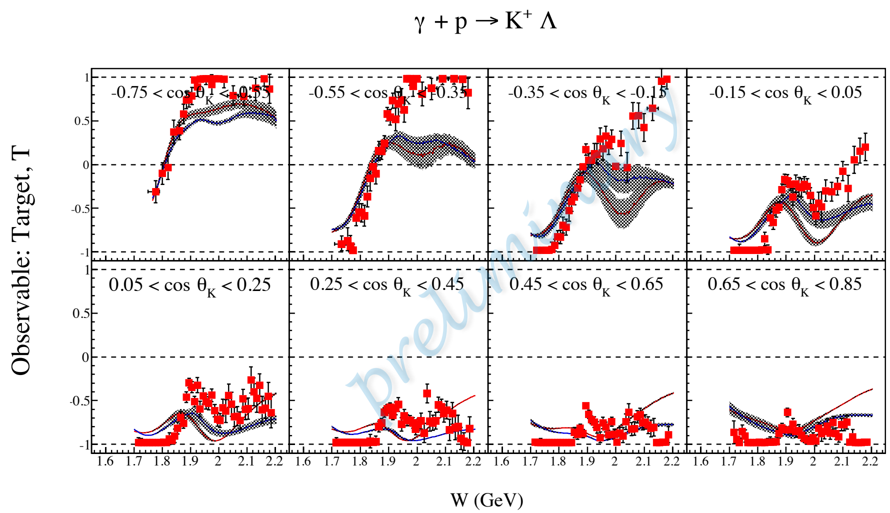


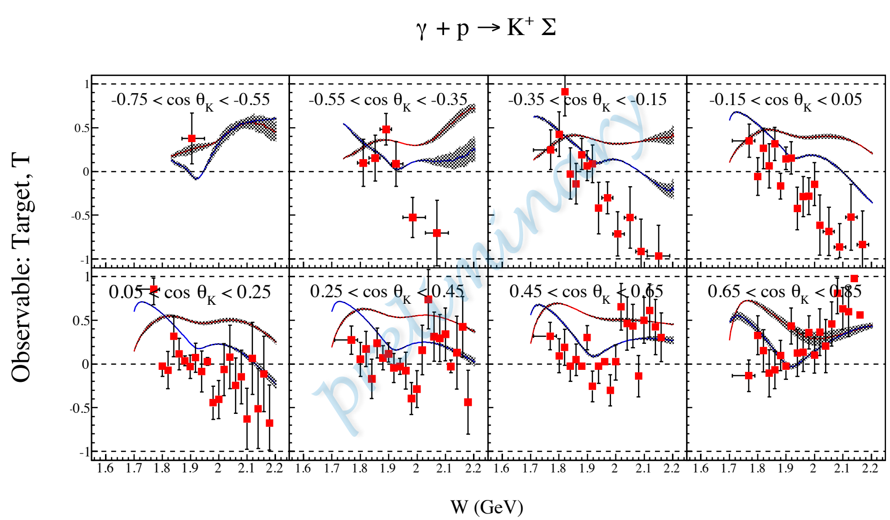
courtesy D. Ireland, UGlasgow

Energy dependence: *T*

BoGa2011-1

BoGa2011-1





courtesy D. Ireland, UGlasgow

Two pion production

• • •

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

Spin dependent cross section for $\gamma p \to p \pi^+ \pi^-$

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

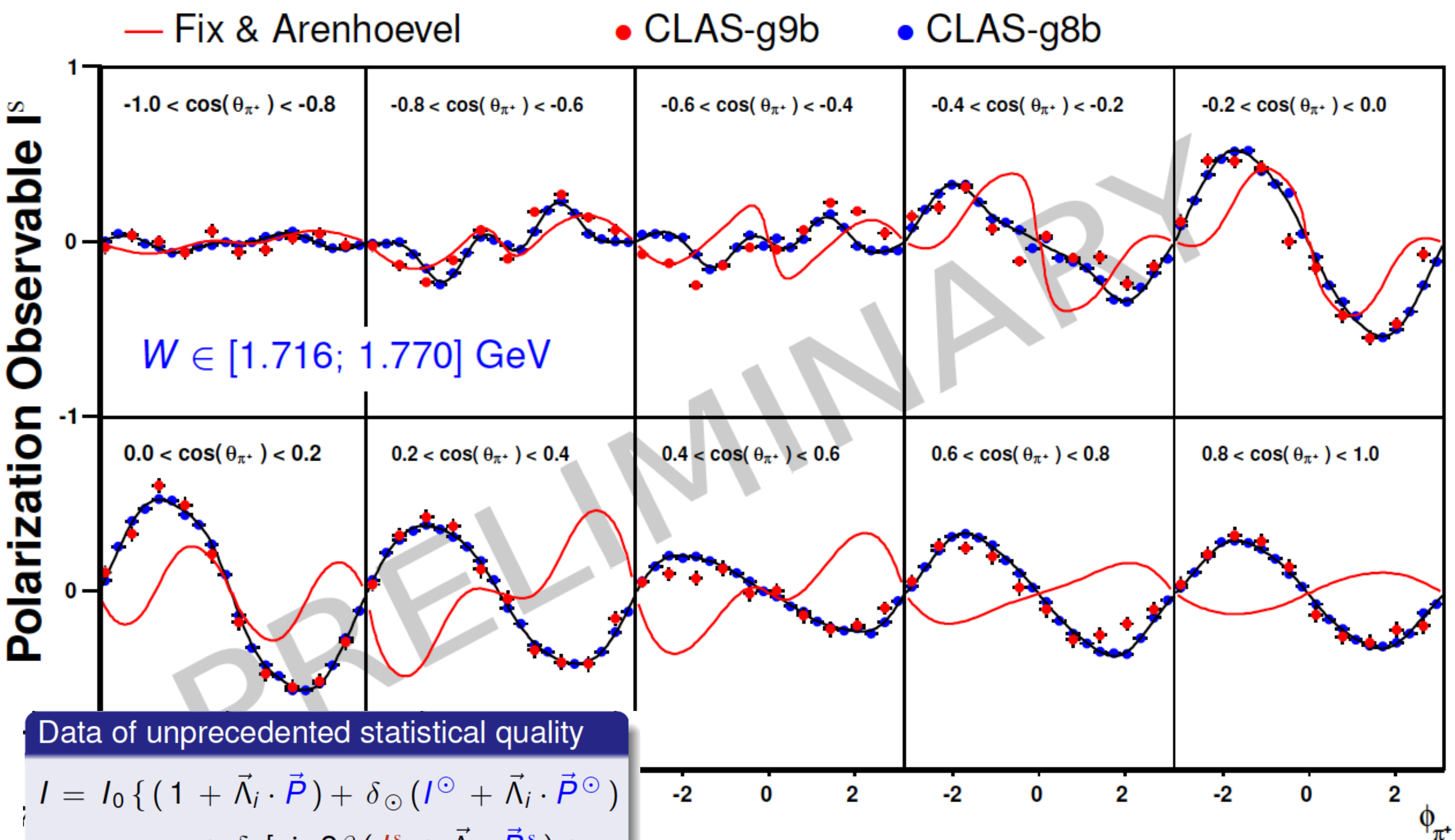
(without measuring the polarization of the recoiling nucleon)

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

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

- σ_0: The unpolarized cross section
- β: The angle between the direction of polarization and the x-axis
- x_i: The kinematic variables
- $\delta_{\odot, l}$: 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 $\Rightarrow (\mathbf{P_x}, \mathbf{P_y}, \mathbf{P_z})$ $(\mathbf{P}_x^\odot, \mathbf{P}_y^\odot, \mathbf{P}_z^\odot)$ $(\mathbf{P}_x^s, \mathbf{P}_y^s, \mathbf{P}_z^s)$ $(\mathbf{P_x^c}, \mathbf{P_y^c}, \mathbf{P_z^c})$

I^S for $p\pi^+\pi^-$



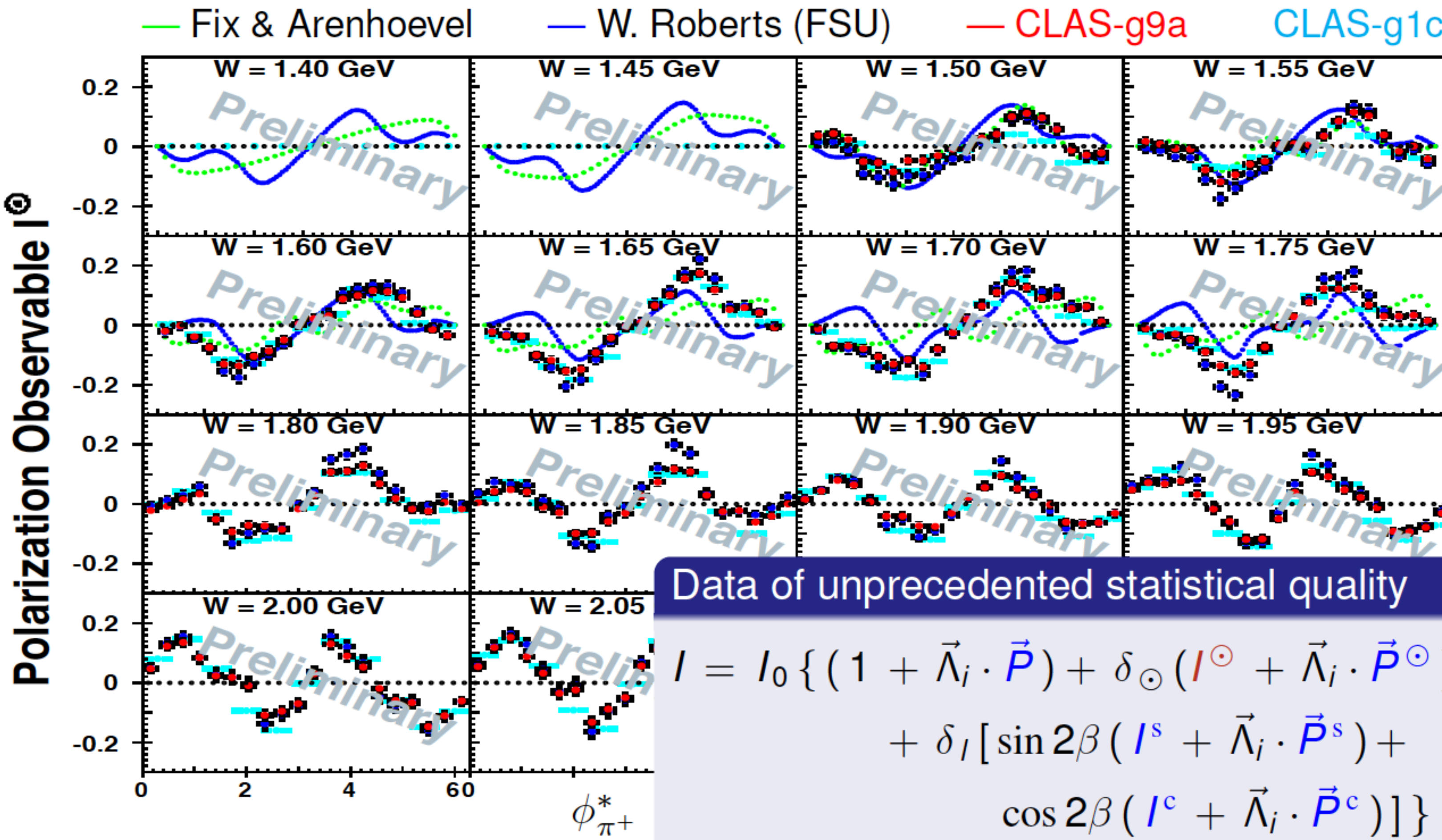
Data of unprecedented statistical quality

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

Charles Hanretty (FSU), g8b

Priyashree Roy (FSU), CLAS g9b (FROST)

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

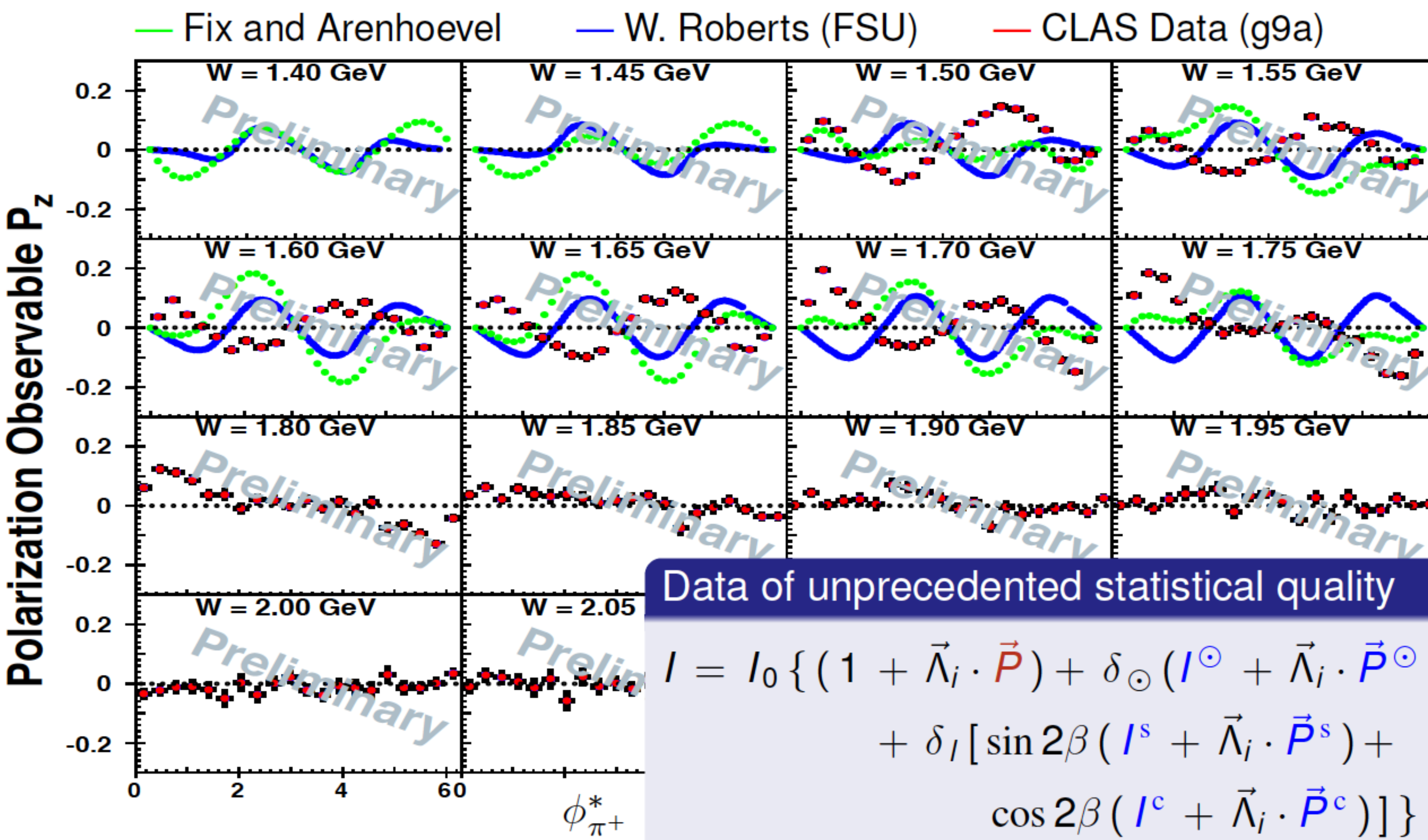


Data of unprecedented statistical quality

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

Sungkyun Park (FSU), under collaboration review

P_z for $p\pi^+\pi^-$

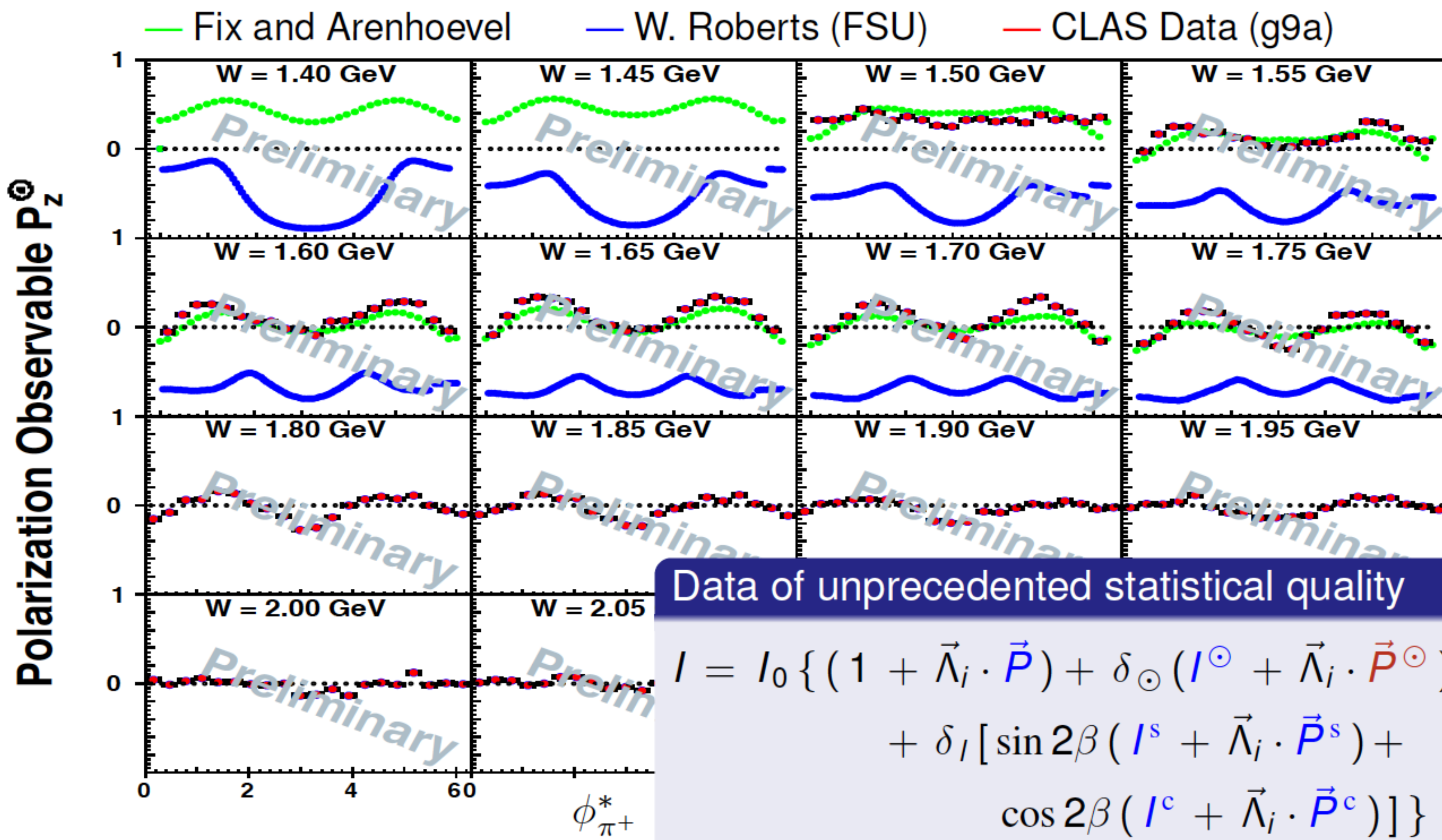


Data of unprecedented statistical quality

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

Sungkyun Park (FSU), under collaboration review

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



Data of unprecedented statistical quality

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

Summary

- Polarization measurements in photoproduction proved themeselves to be a critical piece for understanding of the nucleon resonance spectrum.
- More interesting data are on the way for strange and non-strange meson production both on proton and deuteron targets.
- High level analysis tools are in great demand.