



# ECT\*



EUROPEAN CENTRE FOR THEORETICAL STUDIES  
IN NUCLEAR PHYSICS AND RELATED AREAS  
TRENTO, ITALY

Institutional Member of the ESF Expert Committee NuPECC

## From Complete Photoproduction Reactions to Electroproduction of $N^*$ Resonances



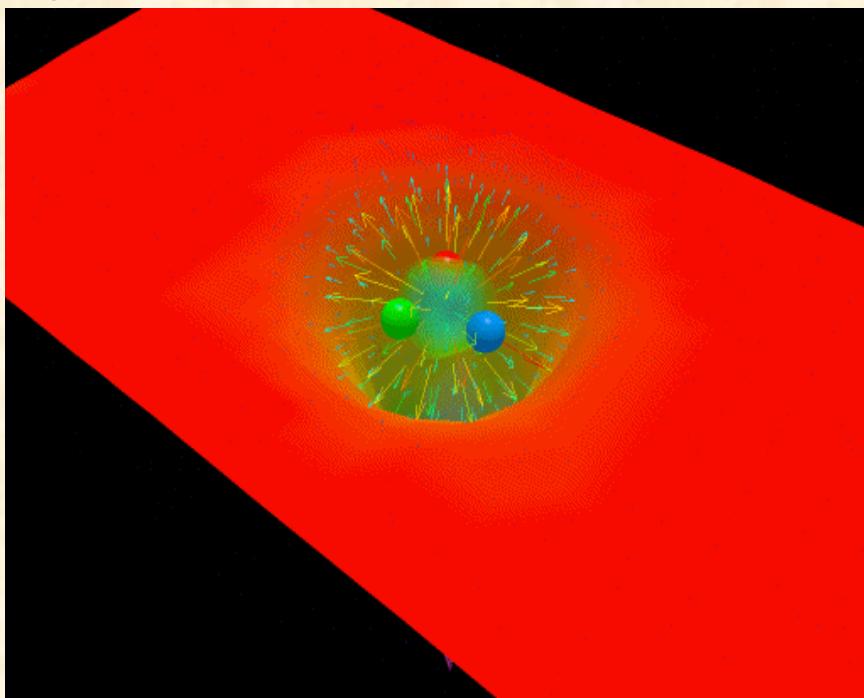
### Annalisa D'ANGELO

University of Rome “Tor Vergata” and INFN Rome Tor Vergata

# Baryon Spectroscopy reveals the workings of QCD

*“Nucleons are the stuff of which our world is made.  
As such they must be at the center of any discussion of  
why the world we actually experience has the character  
it does.”*

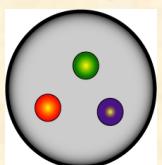
Nathan Isgur, NStar2000,  
Newport News, Virginia



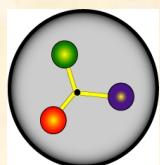
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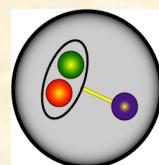
Nathan Isgur, NStar2000,  
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CQM



CQM+flux tubes



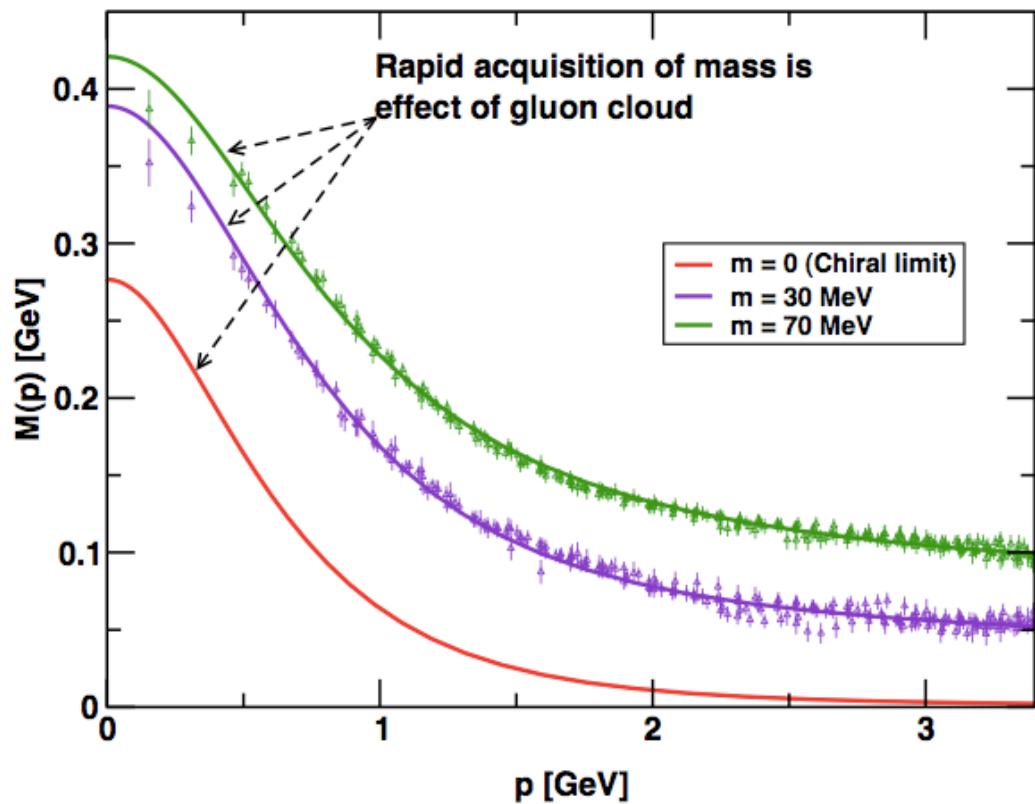
Quark-diquark  
clustering



Baryon-meson  
system

The  $N^*$  spectrum reflects the underlying degrees of freedom and the effective forces between them.

- Understanding the working of QCD: hadronic degrees of freedom.  
Connection between constituent and current quarks



▲ numerical simulations  
of unquenched lattice QCD  
(Bowman et al.)

Dyson-Swinger equation  
(Bhagwat et al.)

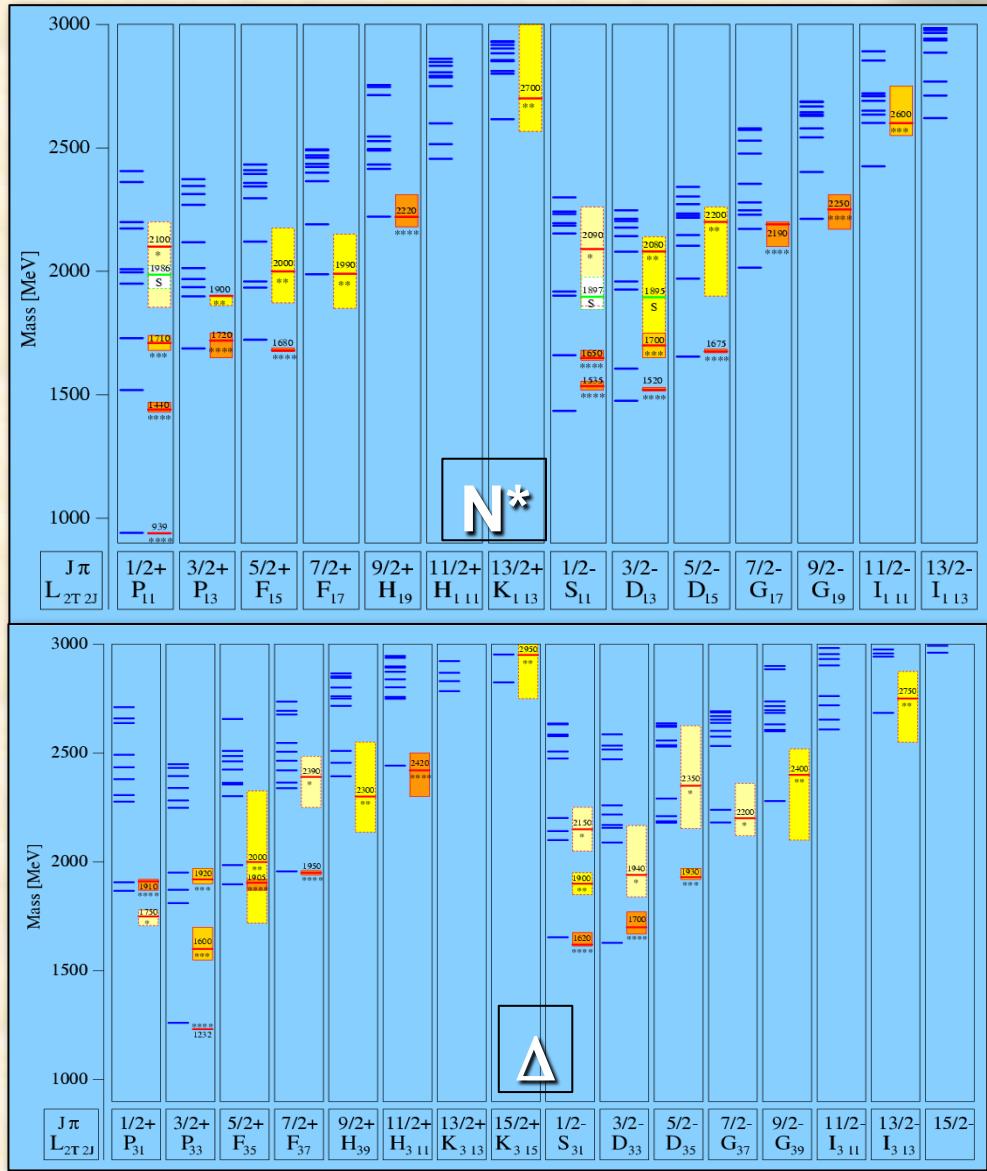
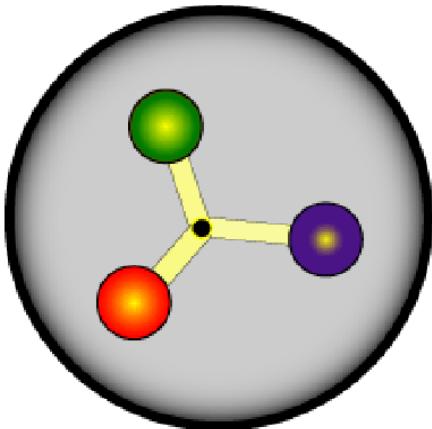
Current-quarks of perturbative QCD evolve into constituent quarks at low momentum

# QCD-inspired Constituent Quark Models

States classified by isospin,  
parity and spin within each  
oscillator band.

Thick  
segments:  
theoretical  
predictions

Shaded boxes:  
experimental  
results

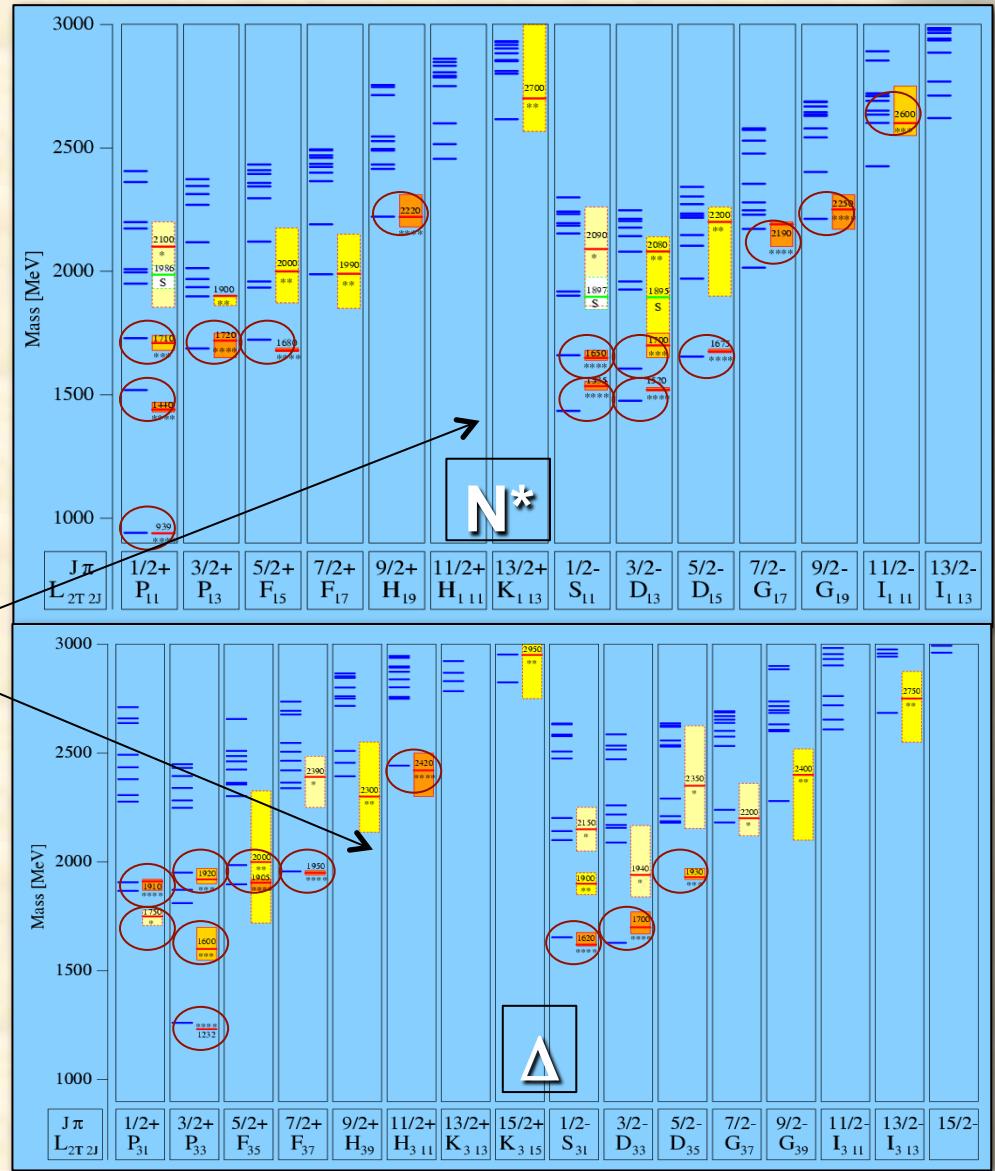


U. L\"oring, B. Metsch, H. Petry, Eur. Phys. J. A 10, 395 (2001).

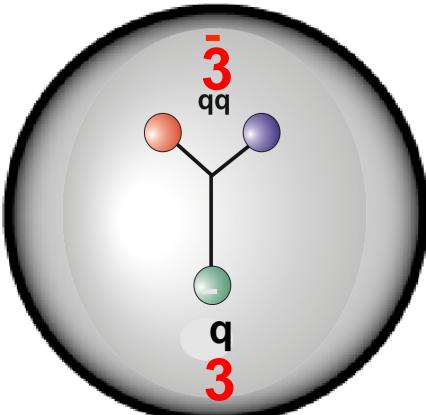
## QCD-inspired Constituent Quark Models

### Findings:

- Linear Regge trajectories
- Only lowest few in each band seen with 4★ or 3★ status
- $g(\pi N)$  couplings predicted to decrease rapidly with mass in each oscillator band
- Higher levels predicted to have larger couplings to  $K\Lambda$ ,  $K\Sigma$ ,  $\pi\pi N$ , ...



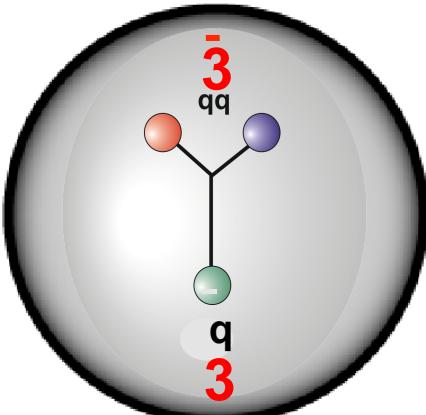
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- 2 quarks in nucleon assumed to be quasi-bound in a color isotriplet; diquark-quark is a net color isosinglet.
- all possible internal di-quark excitations  $\Leftrightarrow$  full spectrum of CQM
- internal di-quark excitations are frozen out (spin 0; isospin 0)  $\Leftrightarrow$  large reduction in the number of degrees of freedom  $\Leftrightarrow$  predicts less  $N^*$  states than seen in  $\pi N$

$N^*$	Status	$SU(6) \otimes U(3)$	Parity	$\Delta^*$	Status	$SU(6) \otimes U(3)$	Parity
$P_{13}(938)$	****	(56, 0 <sup>+</sup> )	+	$P_{33}(1232)$	****	(56, 0 <sup>+</sup> )	+
$S_{11}(1535)$	****	(70, 1 <sup>-</sup> )	-	$S_{31}(1620)$	****	(70, 1 <sup>-</sup> )	-
$S_{11}(1650)$	****	(70, 1 <sup>-</sup> )	-	$D_{13}(1700)$	***	(70, 1 <sup>-</sup> )	-
$D_{13}(1520)$	****	(70, 1 <sup>-</sup> )	-				
$D_{13}(1700)$	***	(70, 1 <sup>-</sup> )	-				
$D_{15}(1675)$	****	(70, 1 <sup>-</sup> )	-				
$P_{11}(1520)$	****	(56, 0 <sup>+</sup> )	+	$P_{31}(1875)$	****	(56, 2 <sup>+</sup> )	+
$P_{11}(1710)$	***	(70, 0 <sup>+</sup> )	+	$P_{31}(1835)$		(70, 0 <sup>+</sup> )	+
$P_{11}(1880)$		(70, 2 <sup>+</sup> )	+				
$P_{11}(1975)$		(20, 1 <sup>+</sup> )	+				
$P_{13}(1720)$	****	(56, 2 <sup>+</sup> )	+	$P_{33}(1600)$	***	(56, 0 <sup>+</sup> )	+
$P_{13}(1870)$	*	(70, 0 <sup>+</sup> )	+	$P_{33}(1920)$	***	(56, 2 <sup>+</sup> )	+
$P_{13}(1910)$		(70, 2 <sup>+</sup> )	+	$P_{33}(1985)$		(70, 2 <sup>+</sup> )	+
$P_{13}(1950)$		(70, 2 <sup>+</sup> )	+				
$P_{13}(2030)$		(20, 1 <sup>+</sup> )	+				
$F_{15}(1680)$	****	(56, 2 <sup>+</sup> )	+	$F_{35}(1905)$	****	(56, 2 <sup>+</sup> )	+
$F_{15}(2000)$	**	(70, 2 <sup>+</sup> )	+	$F_{35}(2000)$	**	(70, 2 <sup>+</sup> )	+
$F_{15}(1995)$		(70, 2 <sup>+</sup> )	+				
$F_{17}(1990)$	**	(70, 2 <sup>+</sup> )	+	$F_{37}(1950)$	****	(56, 2 <sup>+</sup> )	+

the challenge:  $\Leftrightarrow$  unravel the  $N^*$  spectrum

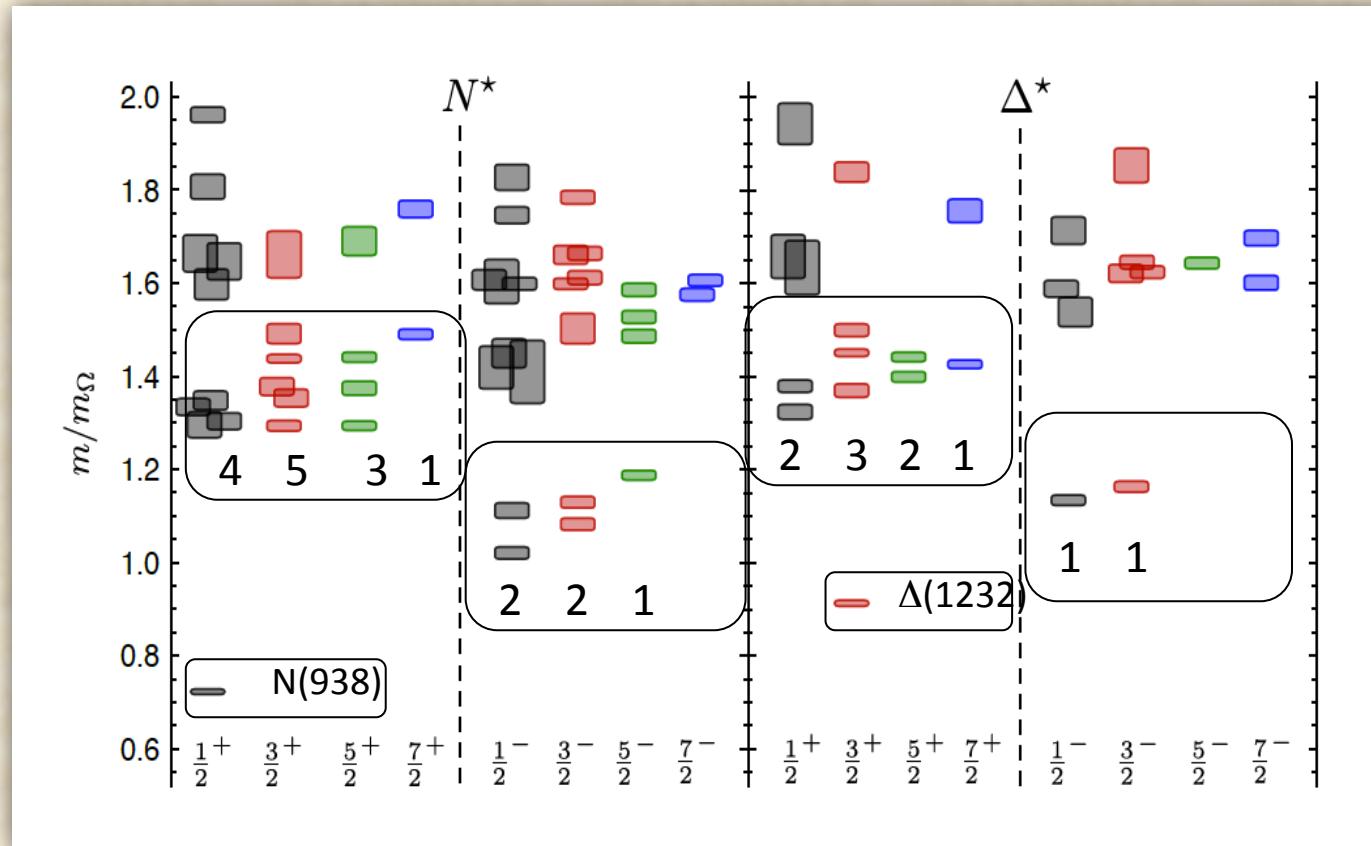


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- all possible internal di-quark excitations  $\Leftrightarrow$  full spectrum of CQM
- internal di-quark excitations are frozen out (spin 0; isospin 0)  $\Leftrightarrow$  large reduction in the number of degrees of freedom  $\Leftrightarrow$  used to predict less N\* states than seen in  $\pi N$  (Jacopo Ferretti)

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$P_{13}(1870)$	*	(70, 0 <sup>+</sup> )	+	$P_{33}(1920)$	***	(56, 2 <sup>+</sup> )	+
$P_{13}(1910)$		(70, 2 <sup>+</sup> )	+	$P_{33}(1985)$		(70, 2 <sup>+</sup> )	+
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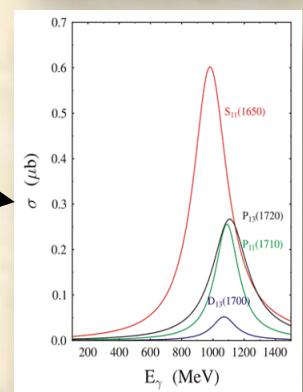
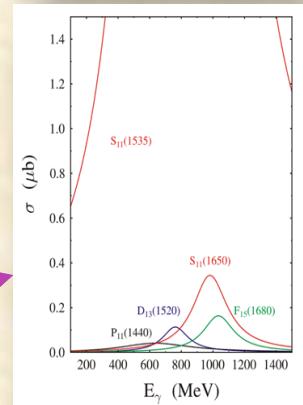
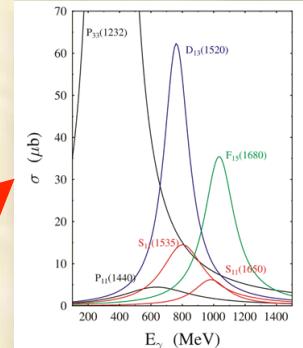
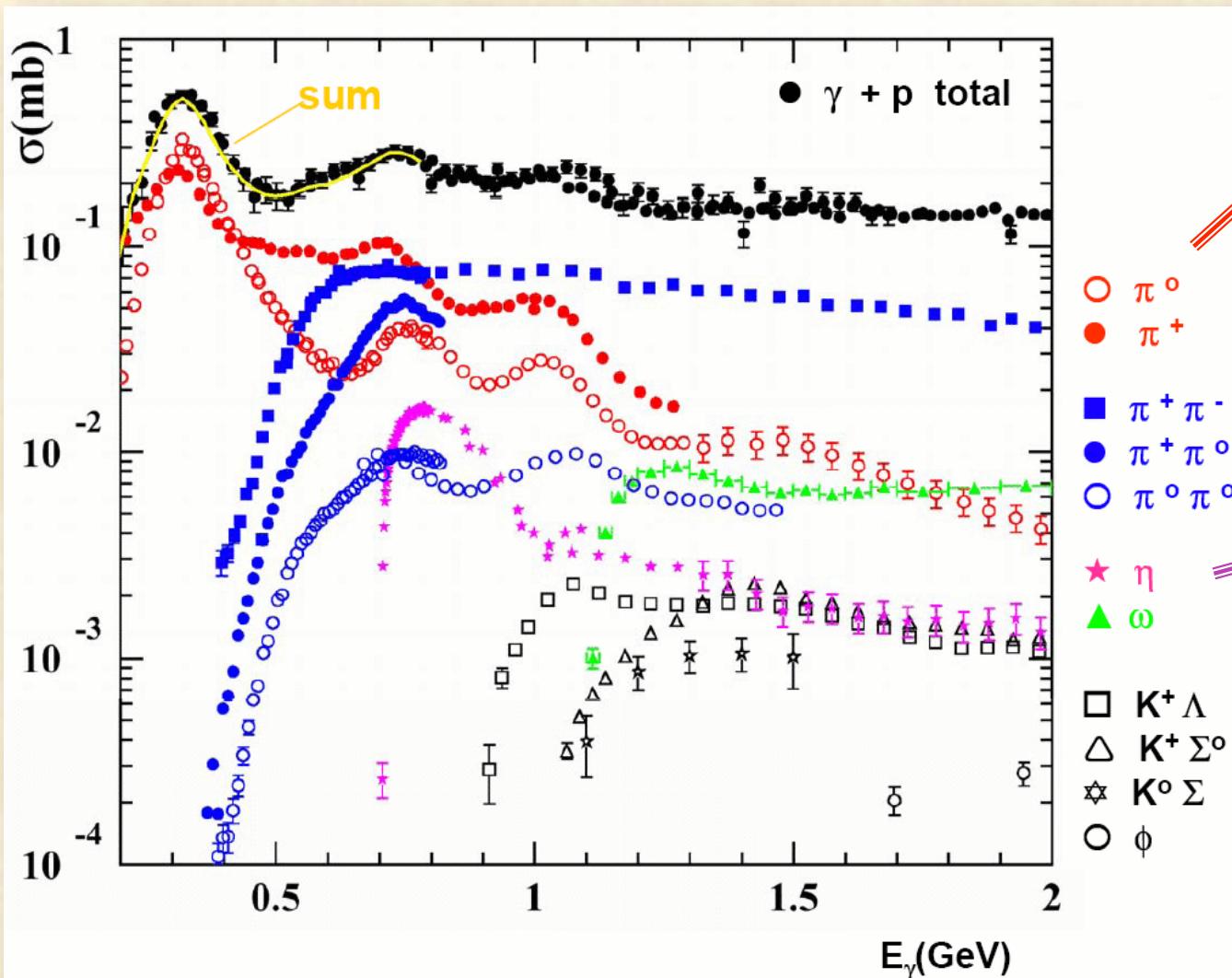
- Exhibits the  $SU(6) \times O(3)$ -symmetry features
- Counting of levels consistent with non-rel. quark model
- Striking similarity with quark model
- No parity doubling

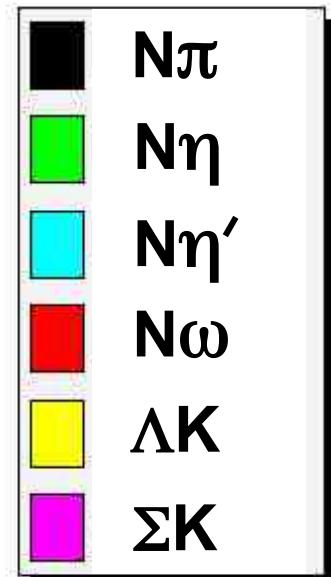
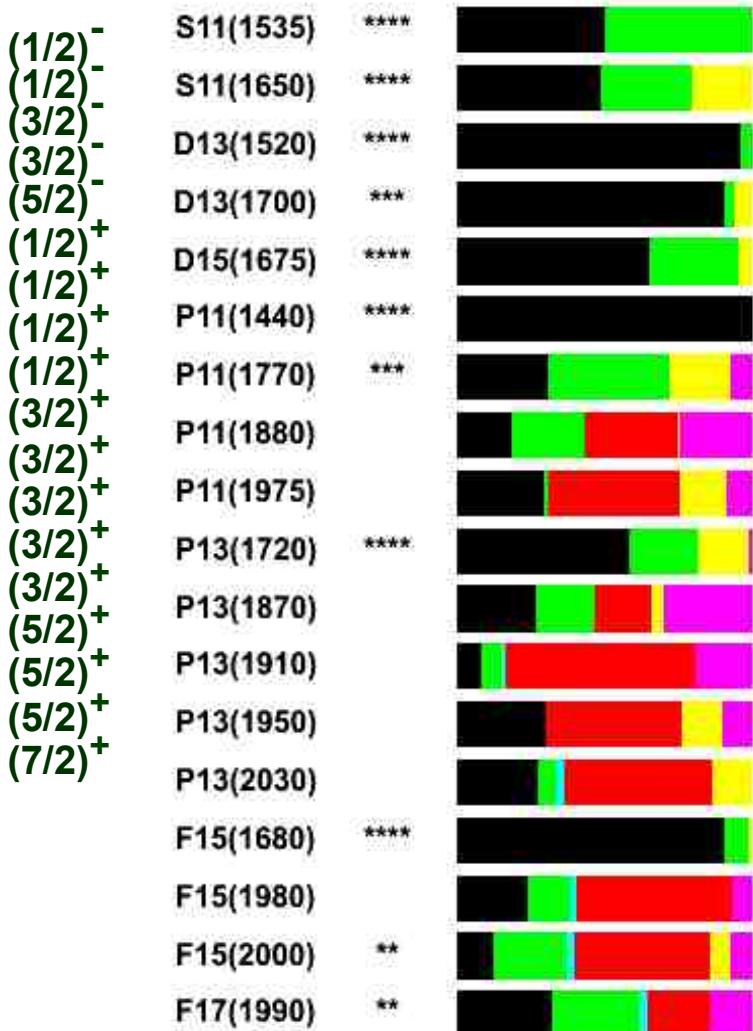


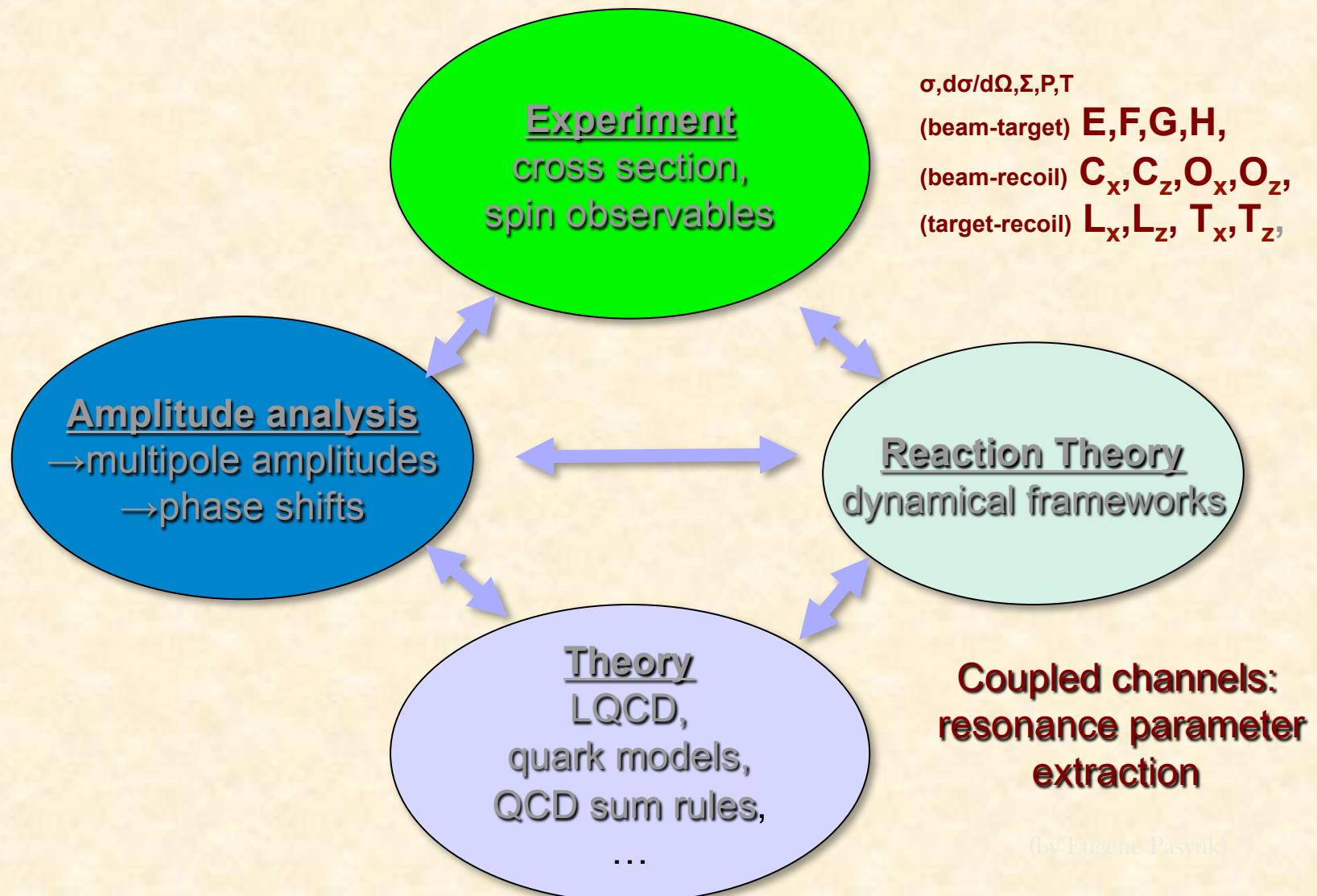
Robert G. Edwards, Jozef J. Dudek, David G. Richards, Stephen J. Wallace Phys.Rev. D84 (2011) 074508

Problems are not solved!

# Photonucleon cross sections

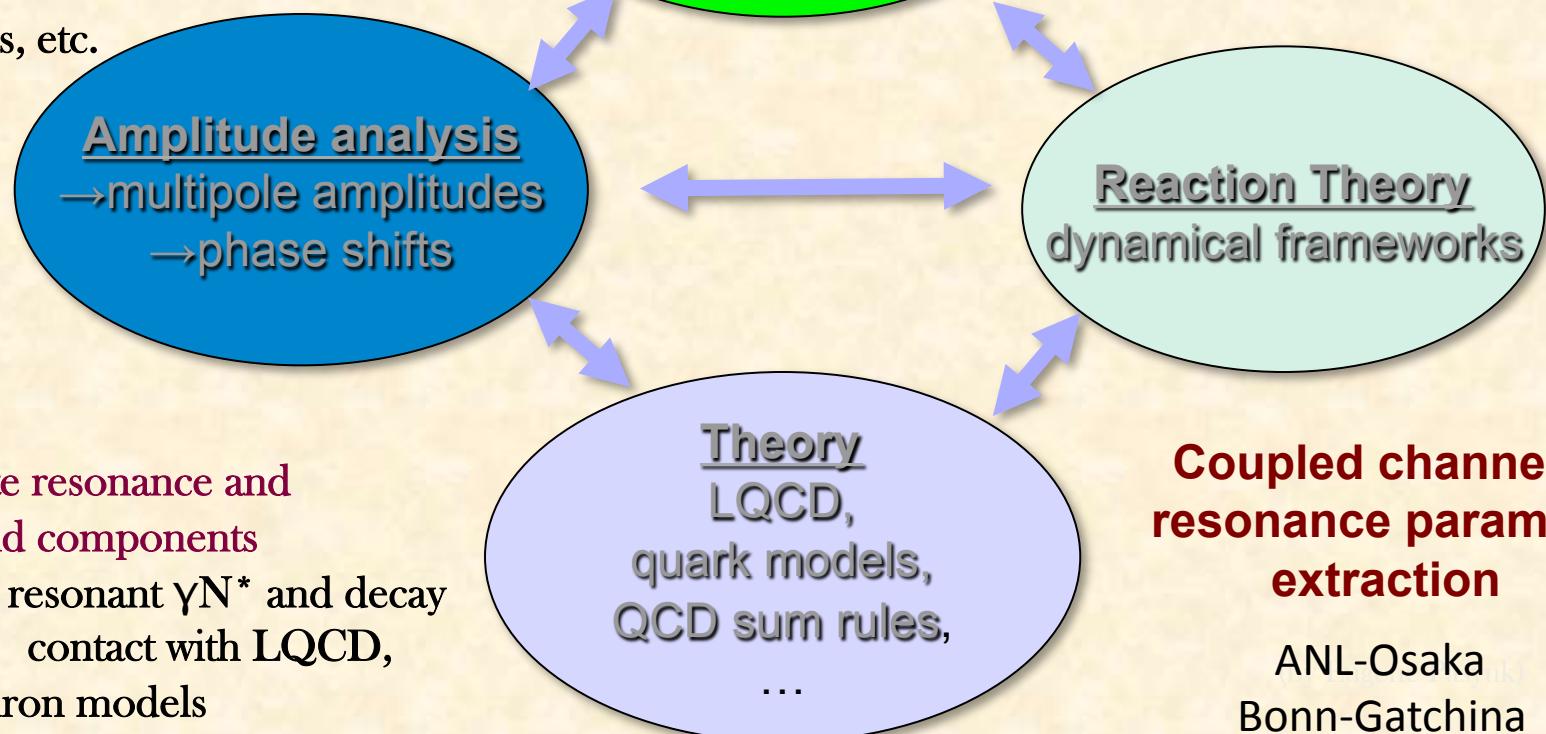






Idealized path to search for  $N^*$ ,  $\Delta^*$  states via meson photo-production:

(1) determine the production amplitude from experiment search for resonant structure:  
Argand circles, phase motion speed plots, etc.



(2) separate resonance and background components  
determine resonant  $\gamma N^*$  and decay couplings; contact with LQCD, DSE, Hadron models

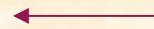
$\sigma, d\sigma/d\Omega, \Sigma, P, T$   
 (beam-target)  $E, F, G, H,$   
 (beam-recoil)  $C_x, C_z, O_x, O_z,$   
 (target-recoil)  $L_x, L_z, T_x, T_z,$

**Coupled channels:  
resonance parameter  
extraction**

ANL-Osaka  
Bonn-Gatchina

Idealized path to search for  $N^*$ ,  $\Delta^*$  states via meson photo-production:

(1) determine the production amplitude from experiment search for resonant structure:  
Argand circles, phase motion speed plots, etc.



Never been done after 50 years of experiments

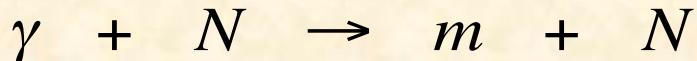
(2) separate resonance and background components  
determine resonant  $\gamma N^*$  and decay couplings; contact with LQCD, DSE, Hadron models



Without exp Amplitudes models have conjectured resonances and adjusted couplings to compare with limited data

(by Eugen Pasyuk)

## in pseudoscalar meson photoproduction



Spin states

$\pm 1$	$\pm \frac{1}{2}$	$0$	$\pm \frac{1}{2}$	
2	x	2	x	2

8 possible spin states  $\rightarrow$  4 independent complex amplitudes  
describe the transition matrix

$$F_\lambda = \vec{J} \cdot \varepsilon_\lambda = iF_1 \vec{\sigma} \cdot \hat{\varepsilon}_\lambda + F_2 (\hat{\sigma} \cdot \hat{q}) \hat{\sigma} \cdot (\hat{k} \times \hat{\varepsilon}_\lambda) + iF_3 (\hat{\sigma} \cdot \hat{k}) (\hat{q} \cdot \hat{\varepsilon}_\lambda) + iF_4 (\hat{\sigma} \cdot \hat{q}) (\hat{q} \cdot \hat{\varepsilon}_\lambda)$$

CGLN amplitudes in terms of Pauli matrixes:

are conveniently expanded into multipoles

$$F_1 = \sum_{l=0}^{l_{max}} [P'_{l+1}(x)E_{l+} + P'_{l-1}(x)E_{l-} + lP'_{l+1}(x)M_{l+} + (l+1)P'_{l-1}(x)M_{l-}]$$

$$F_2 = \sum_{l=0}^{l_{max}} [(l+1)P'_l(x)M_{l+} + lP'_l(x)M_{l-}],$$

$$F_3 = \sum_{l=0}^{l_{max}} [P''_{l+1}(x)E_{l+} + P''_{l-1}(x)E_{l-} - P''_{l+1}(x)M_{l+} + P''_{l-1}(x)M_{l-}],$$

$$F_4 = \sum_{l=0}^{l_{max}} [-P''_l(x)E_{l+} - P''_l(x)E_{l-} + P''_l(x)M_{l+} - P''_l(x)M_{l-}].$$

## in pseudoscalar meson photoproduction



Spin states

$$\begin{array}{ccc}
 \pm 1 & \pm \frac{1}{2} & 0 & \pm \frac{1}{2} \\
 & 2 & & x & 2 \\
 & x & 2 & &
 \end{array}$$

8 possible spin states → 4 independent complex amplitudes  
describe the transition matrix

Helicity amplitudes: amplitudes are expressed in terms of all independent photon and nucleons helicity states

$$\begin{aligned}
 H_1(\theta) &\equiv \langle +1 | J_{11} | -1 \rangle \\
 H_2(\theta) &\equiv \langle +1 | J_{11} | +1 \rangle \\
 H_3(\theta) &\equiv \langle -1 | J_{11} | -1 \rangle \\
 H_4(\theta) &\equiv \langle -1 | J_{11} | +1 \rangle
 \end{aligned}$$



$$\begin{aligned}
 H_1(\theta) &\equiv \frac{i}{\sqrt{2}} \sin \theta \sin\left(\frac{\theta}{2}\right) [F_3 - F_4] \\
 H_2(\theta) &\equiv -\frac{i}{\sqrt{2}} \sin\left(\frac{\theta}{2}\right) [F_1 + F_2 + (F_4 + F_3) \cos^2\left(\frac{\theta}{2}\right)] \\
 H_3(\theta) &\equiv +\frac{i}{\sqrt{2}} \sin \theta \cos\left(\frac{\theta}{2}\right) [F_3 + F_4] \\
 H_4(\theta) &\equiv -i\sqrt{2} \cos\left(\frac{\theta}{2}\right) [F_1 - F_2 + (F_4 - F_3) \sin^2\left(\frac{\theta}{2}\right)]
 \end{aligned}$$

# in pseudoscalar meson photoproduction



Spin states

$\pm 1$ $\frac{1}{2}$  $2 \quad \times \quad 2$	$0$ $\pm \frac{1}{2}$  $\times \quad 2$
--	--

8 possible spin states → 4 independent complex amplitudes  
describe the transition matrix

Helicity amplitudes: amplitudes are expressed in terms of all independent photon and nucleons helicity states

$$H_1(\theta) = \sum_J (2J+1) H_1^J d_{-\frac{1}{2} \frac{3}{2}}^J(\theta),$$

$$H_2(\theta) = \sum_J (2J+1) H_2^J d_{-\frac{1}{2} \frac{1}{2}}^J(\theta),$$

$$H_3(\theta) = \sum_J (2J+1) H_3^J d_{\frac{1}{2} \frac{3}{2}}^J(\theta),$$

$$H_4(\theta) = \sum_J (2J+1) H_4^J d_{\frac{1}{2} \frac{1}{2}}^J(\theta).$$

From decomposition into partial waves:

$$d^J_{\Lambda_f - \Lambda_i}(\theta)$$

$$\Lambda_i = \lambda - \lambda_1 \quad \Lambda_f = -\lambda_2$$

$$H_4 = N$$

no helicity flip

$$H_2, H_3 = S_1, S_2$$

single helicity flip

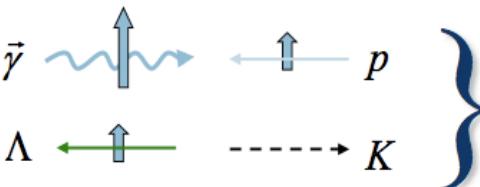
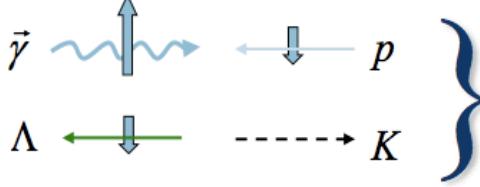
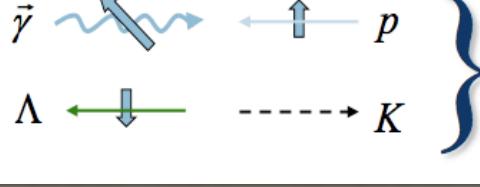
$$H_1 = D$$

double helicity flip

## in pseudoscalar meson photoproduction

**Transversity amplitudes:** are expressed in terms of linearly polarized photons and transversely polarized nucleons.

They are linear combinations of helicity amplitudes

	$b_1 = \frac{1}{2}[(S_1 + S_2) + i(N - D)]$
	$b_2 = \frac{1}{2}[(S_1 + S_2) - i(N - D)]$
	$b_3 = \frac{1}{2}[(S_1 - S_2) - i(N + D)]$
	$b_4 = \frac{1}{2}[(S_1 - S_2) + i(N + D)]$

# in pseudoscalar meson photoproduction

4 complex amplitudes



16 bilinear combinations



16 observables

## Complete experiment:

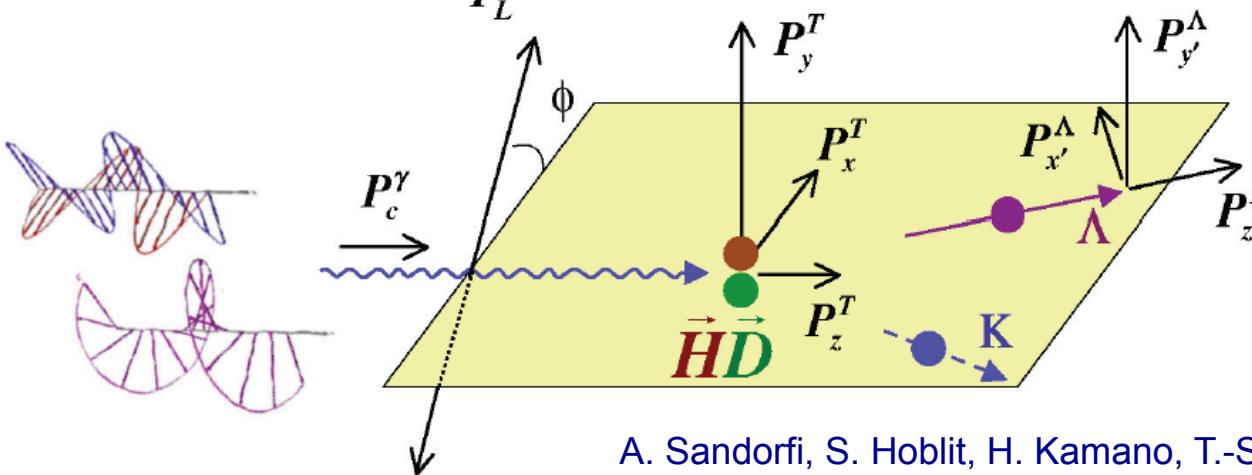
at least 8 carefully chosen observables are needed to extract the amplitudes

Symbol	Transversity representation	Experiment required	Type
$d\sigma/dt$	$ b_1 ^2 +  b_2 ^2 +  b_3 ^2 +  b_4 ^2$	$\{-; -; -\}$	$S$
$\Sigma d\sigma/dt$	$ b_1 ^2 +  b_2 ^2 -  b_3 ^2 -  b_4 ^2$	$\{L(\frac{1}{2}\pi, 0); -; -\}$	
$Td\sigma/dt$	$ b_1 ^2 -  b_2 ^2 -  b_3 ^2 +  b_4 ^2$	$\{-; y; -\}$	
$Pd\sigma/dt$	$ b_1 ^2 -  b_2 ^2 +  b_3 ^2 -  b_4 ^2$	$\{-; -; y\}$	
$Gd\sigma/dt$	$2 \operatorname{Im}(b_1 b_3^* + b_2 b_4^*)$	$\{L(\pm\frac{1}{4}\pi); z; -\}$	$BT$
$Hd\sigma/dt$	$-2 \operatorname{Re}(b_1 b_3^* - b_2 b_4^*)$	$\{L(\pm\frac{1}{4}\pi); x; -\}$	
$Ed\sigma/dt$	$-2 \operatorname{Re}(b_1 b_3^* + b_2 b_4^*)$	$\{C; z; -\}$	
$Fd\sigma/dt$	$2 \operatorname{Im}(b_1 b_3^* - b_2 b_4^*)$	$\{C; x; -\}$	
$O_x d\sigma/dt$	$-2 \operatorname{Re}(b_1 b_4^* - b_2 b_3^*)$	$\{L(\pm\frac{1}{4}\pi); -; x'\}$	$BR$
$O_z d\sigma/dt$	$-2 \operatorname{Im}(b_1 b_4^* + b_2 b_3^*)$	$\{L(\pm\frac{1}{4}\pi); -; z'\}$	
$C_x d\sigma/dt$	$2 \operatorname{Im}(b_1 b_4^* - b_2 b_3^*)$	$\{C; -; x'\}$	
$C_z d\sigma/dt$	$-2 \operatorname{Re}(b_1 b_4^* + b_2 b_3^*)$	$\{C; -; z'\}$	
$T_x d\sigma/dt$	$2 \operatorname{Re}(b_1 b_2^* - b_3 b_4^*)$	$\{-; x; x'\}$	$TR$
$T_z d\sigma/dt$	$2 \operatorname{Im}(b_1 b_2^* - b_3 b_4^*)$	$\{-; x; z'\}$	
$L_x d\sigma/dt$	$2 \operatorname{Im}(b_1 b_2^* + b_3 b_4^*)$	$\{-; z; x'\}$	
$L_z d\sigma/dt$	$2 \operatorname{Re}(b_1 b_2^* + b_3 b_4^*)$	$\{-; z; z'\}$	

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

Photon beam		Target			Recoil			Target - Recoil										
					$x'$	$y'$	$z'$	$x'$	$x'$	$x'$	$y'$	$y'$	$y'$	$z'$	$z'$			
		$x$	$y$	$z$				$x$	$y$	$z$	$x$	$y$	$z$	$x$	$y$			
unpolarized	$\sigma_0$				$T$			$P$		$T_{x'}$		$L_{x'}$		$\Sigma$		$T_z$		$L_z$
$P_L^\gamma \sin(2\phi_\gamma)$		$H$			$G$	$O_{x'}$		$O_{z'}$		$C_z$		$E$		$F$		$-C_x$		
$P_L^\gamma \cos(2\phi_\gamma)$	$-\Sigma$		$-P$			$-T$		$-L_z$		$T_z$		$-\sigma_0$		$L_x$		$-T_x$		
circular $P_c^\gamma$		$F$			$-E$	$C_{x'}$		$C_z$		$-O_z$		$G$		$-H$		$O_{x'}$		

## $P_L^\gamma$ (Over)complete experiments



16 different observables, each appearing twice:

- Single-pol observables can be measured from double-pol asymmetries
- Double-pol observables can be measured from triple-pol asymmetries

A. Sandorfi, S. Hoblit, H. Kamano, T.-S.H. Lee, J.Phys. 38 (2011) 053001

## in pseudoscalar meson photoproduction

$A^0$  and  $A^1$  are the components results from coupling of  $I=1/2$  with isoscalar and isovector components of the photon.

Their contributions appear in linear combinations that may be disentangled only by measurements on both the neutron and the proton.

$$\begin{aligned}
 A_{\gamma n \rightarrow \left( \begin{array}{c} \pi^0 n \\ K^0 \Sigma^0 \end{array} \right)} &= \pm \left[ \frac{1}{\sqrt{3}} A_{(K\Sigma)}^{(0)} + \frac{1}{3} A_{(K\Sigma)}^{(1)} \right]^{(I=\frac{1}{2})} + \frac{2}{3} A_{(K\Sigma)}^{(I=\frac{3}{2})} \\
 A_{\gamma n \rightarrow \left( \begin{array}{c} \pi^- p \\ K^+ \Sigma^- \end{array} \right)} &= \mp \sqrt{2} \left[ \frac{1}{\sqrt{3}} A_{(K\Sigma)}^{(0)} + \frac{1}{3} A_{(K\Sigma)}^{(1)} \right]^{(I=\frac{1}{2})} + \frac{\sqrt{2}}{3} A_{(K\Sigma)}^{(I=\frac{3}{2})} \\
 A_{\gamma n \rightarrow \left( \begin{array}{c} \eta n \\ K^0 \Lambda \end{array} \right)} &= + \left[ A_{(\eta N)}^{(0)} + \frac{1}{\sqrt{3}} A_{(\eta N)}^{(1)} \right]^{(I=\frac{1}{2})}.
 \end{aligned}$$

$$\begin{aligned}
 A_{\gamma p \rightarrow \left( \begin{array}{c} \pi^0 p \\ K^+ \Sigma^0 \end{array} \right)} &= \mp \left[ \frac{1}{\sqrt{3}} A_{(K\Sigma)}^{(0)} - \frac{1}{3} A_{(K\Sigma)}^{(1)} \right]^{(I=\frac{1}{2})} + \frac{2}{3} A_{(K\Sigma)}^{(I=\frac{3}{2})} \\
 A_{\gamma p \rightarrow \left( \begin{array}{c} \pi^+ n \\ K^0 \Sigma^+ \end{array} \right)} &= \pm \sqrt{2} \left[ \frac{1}{\sqrt{3}} A_{(K\Sigma)}^{(0)} - \frac{1}{3} A_{(K\Sigma)}^{(1)} \right]^{(I=\frac{1}{2})} + \frac{\sqrt{2}}{3} A_{(K\Sigma)}^{(I=\frac{3}{2})} \\
 A_{\gamma p \rightarrow \left( \begin{array}{c} \eta p \\ K^+ \Lambda \end{array} \right)} &= + \left[ A_{(\eta N)}^{(0)} - \frac{1}{\sqrt{3}} A_{(\eta N)}^{(1)} \right]^{(I=\frac{1}{2})}.
 \end{aligned}$$

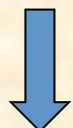
I. S. Barker, A. Donnachie, J. K. Storrow, Nucl. Phys. B95, 347 (1975).

- Tagged and polarized photon beam
- Large acceptance detector
- H and D polarized targets

Modern experiments are  
constructed to meet all above requirements:

GRAAL

$$E_\gamma = (500 - 1500) \text{ MeV}$$



BGO-OD&Crystal Barrel@BONN

$$E_\gamma = (500 - 3000) \text{ MeV}$$

CLAS in Hall-B

$$E_\gamma = (500 - 6000) \text{ MeV}$$

Crystal Ball@MAINZ

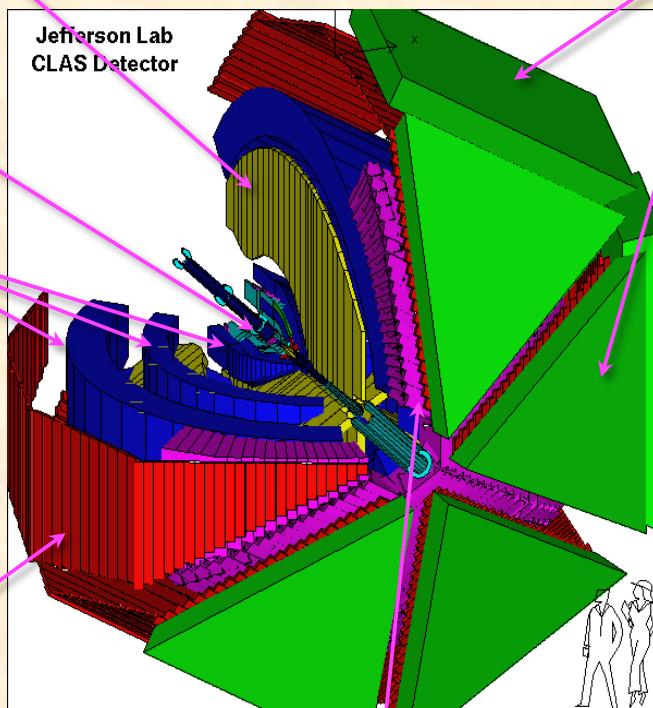
$$E_\gamma = (100 - 1500) \text{ MeV}$$

**target + start counter**



**Drift chambers  
35,000 cells**

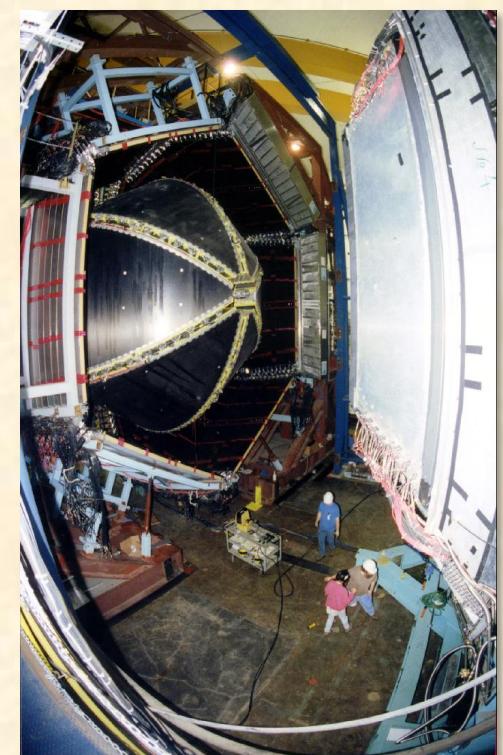
**Torus magnet  
6 superconducting coils**

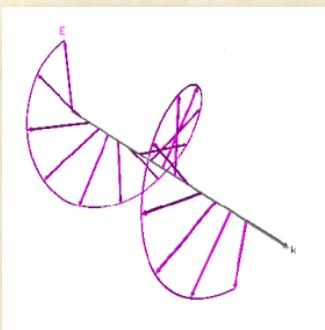


**Time-of-flight counters  
plastic scintillators, 684 photomultipliers**

**Gas Cherenkov counters  
e/π separation, 256 PMTs**

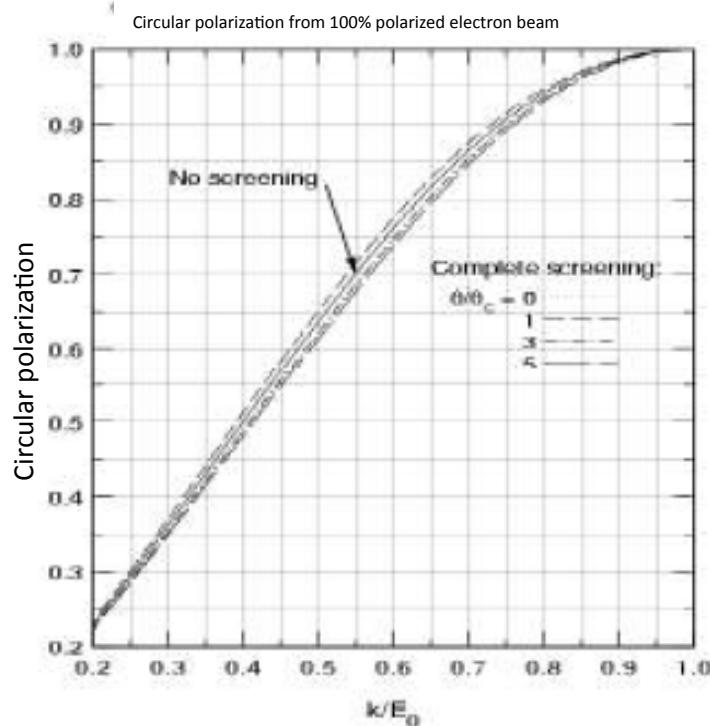
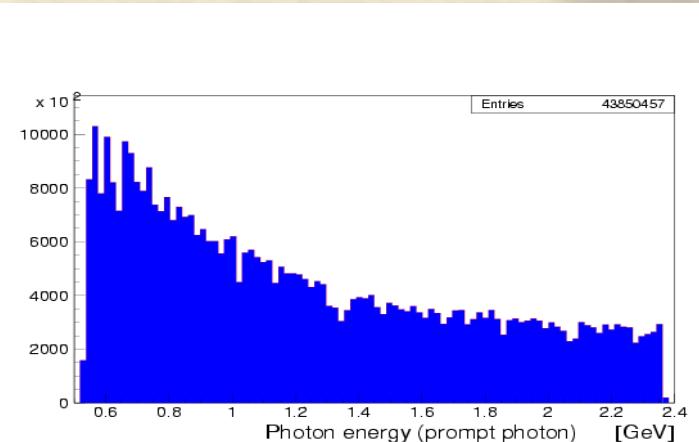
**Electromagnetic calorimeters  
Lead/scintillator, 1296 photomultipliers**

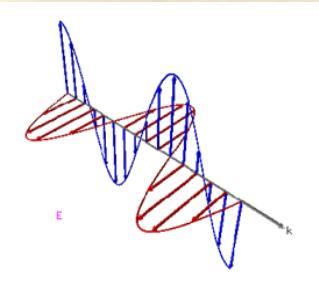




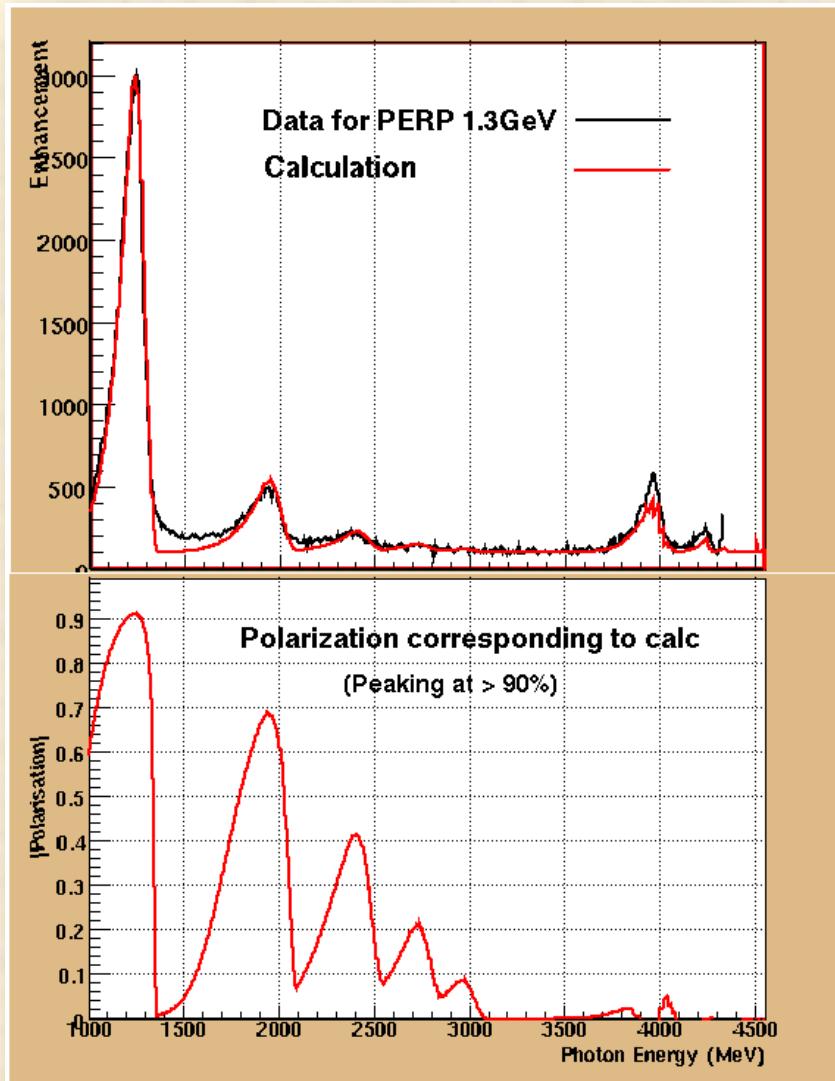
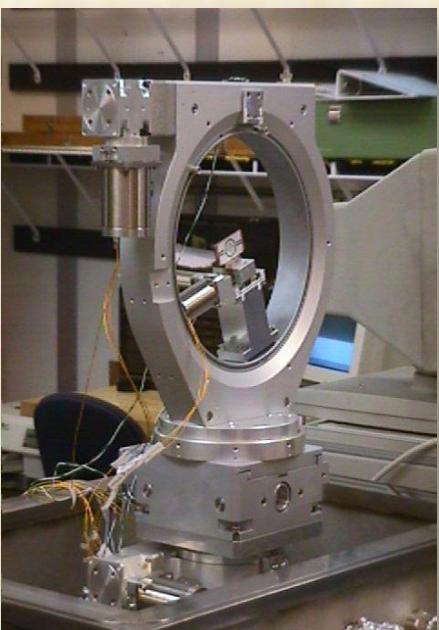
- Circularly polarized beam produced by longitudinally polarized electrons
- CEBAF electron beam polarization >85%
- tagged flux ~ 50 - 100MHz for  $k > 0.5 E_0$

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





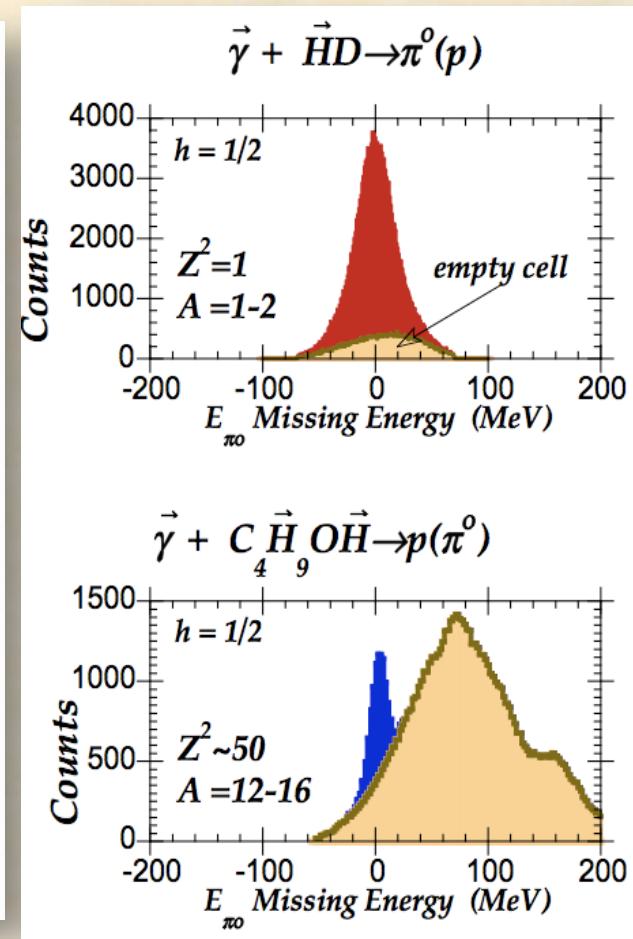
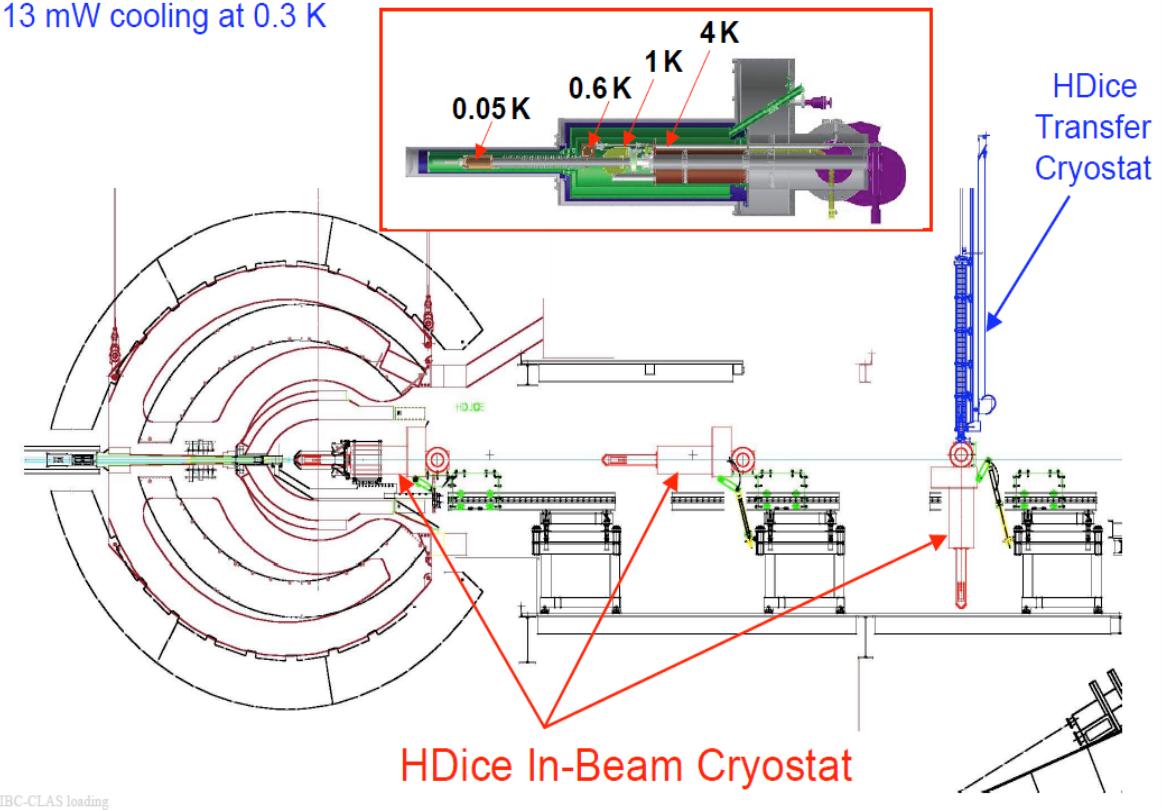
Linearly polarized photons: coherent bremsstrahlung on oriented diamond crystal

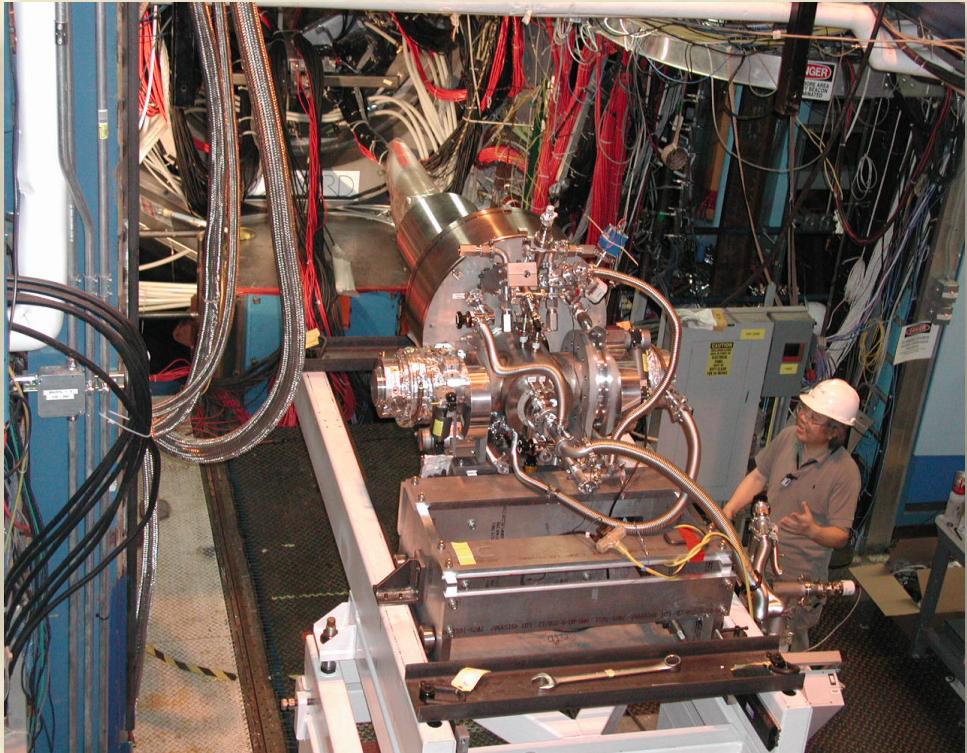
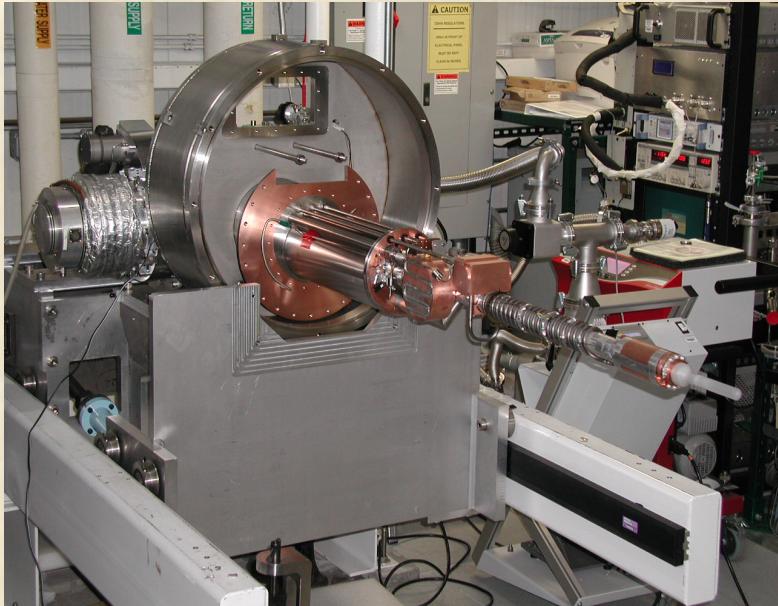


### HDIce Solid Deuterium-Hydride (HD) – a new class of polarized target

- Spin can be moved between H and D with RF transitions
- All material can be polarized with almost no background

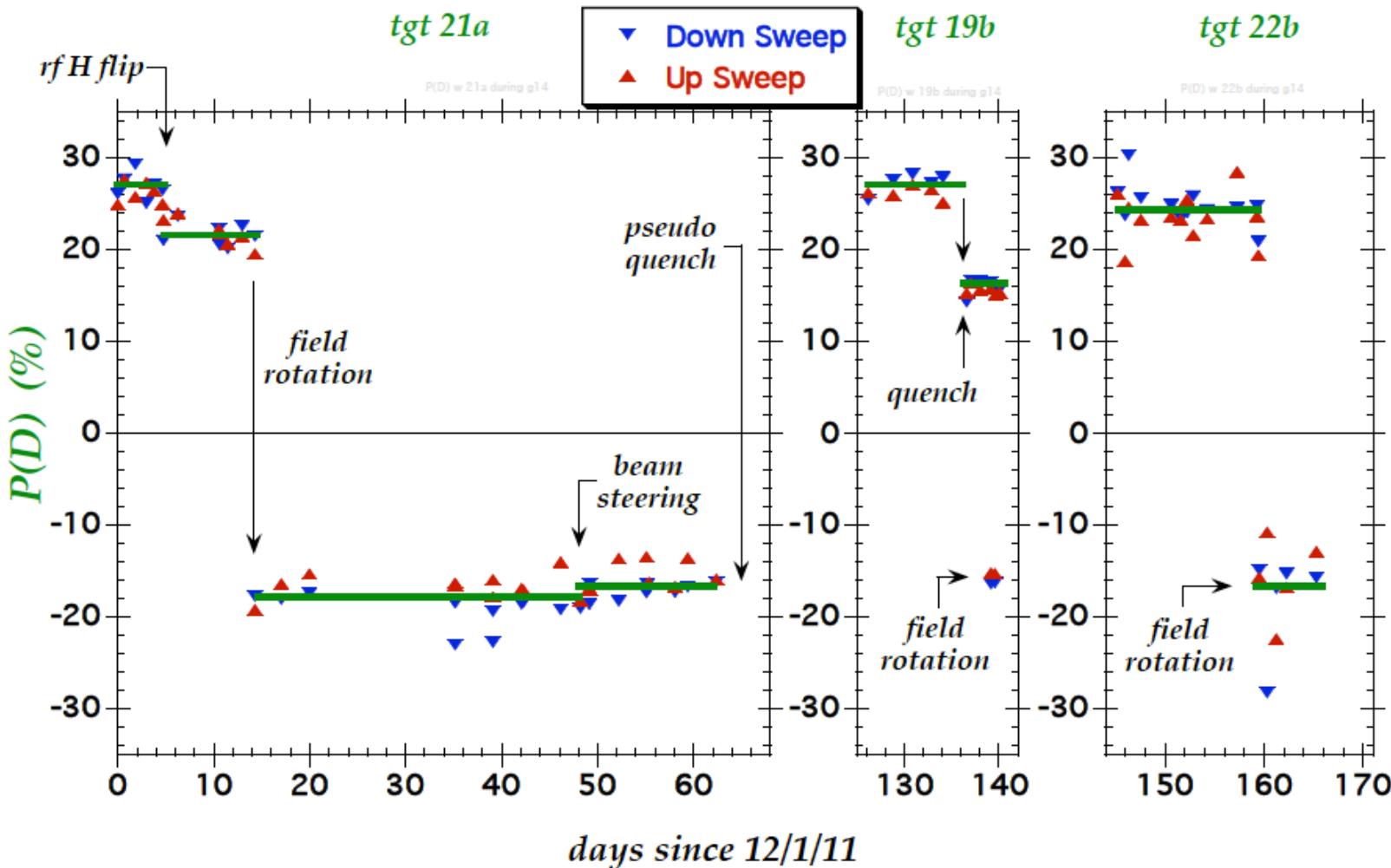
- designed for both  $\gamma$  (w Start Counter) and  $e^-$  (w mini-Torus) running
- 13 mW cooling at 0.3 K



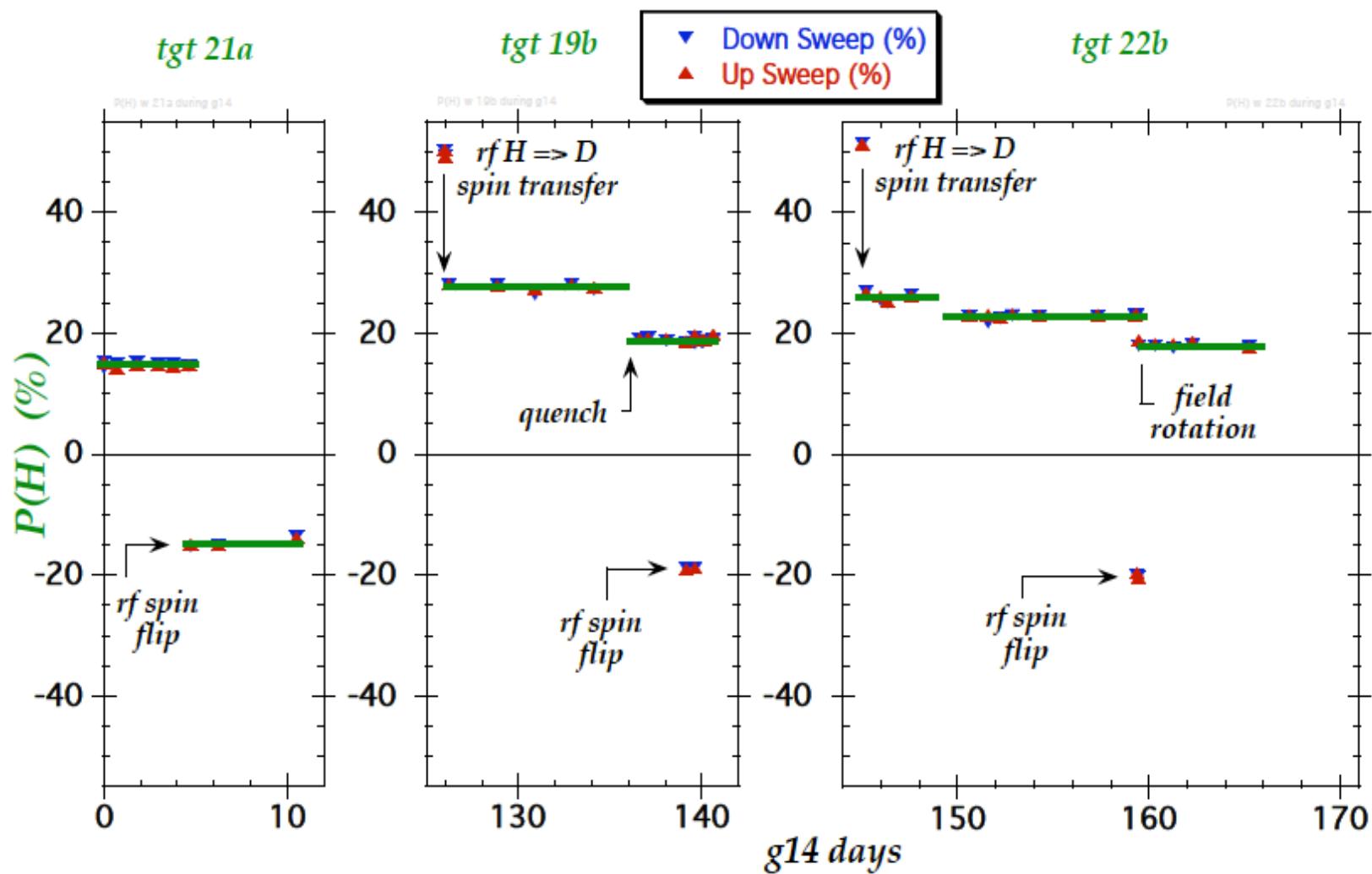


Longitudinal and Transverse Polarizations: > 60%  
Relaxation time: > 1 year  
Polarization procedure  $\approx$  3 months  
Data taking:  $\approx$  months  
Very complicated target transfer technology.



*H<sup>+</sup>D<sup>-</sup> polarization during g14*

### $\vec{H}$ D polarization during g14



	$\sigma$	$\Sigma$	T	P	E	F	G	H	$T_x$	$T_z$	$L_x$	$L_z$	$O_x$	$O_z$	$C_x$	$C_z$
--	----------	----------	---	---	---	---	---	---	-------	-------	-------	-------	-------	-------	-------	-------

**Proton target**

$p\pi^0$	✓	✓	✓			✓	✓	✓	✓							
$n\pi^+$	✓	✓	✓			✓	✓	✓	✓							
$p\eta$	✓	✓	✓			✓	✓	✓	✓							
$p\eta'$	✓	✓	✓			✓	✓	✓	✓							
$p\omega$	✓	✓	✓			✓	✓	✓	✓							
$K^+\Lambda$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$K^+\Sigma^0$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$K^{0*}\Sigma^+$	✓	✓									✓	✓				

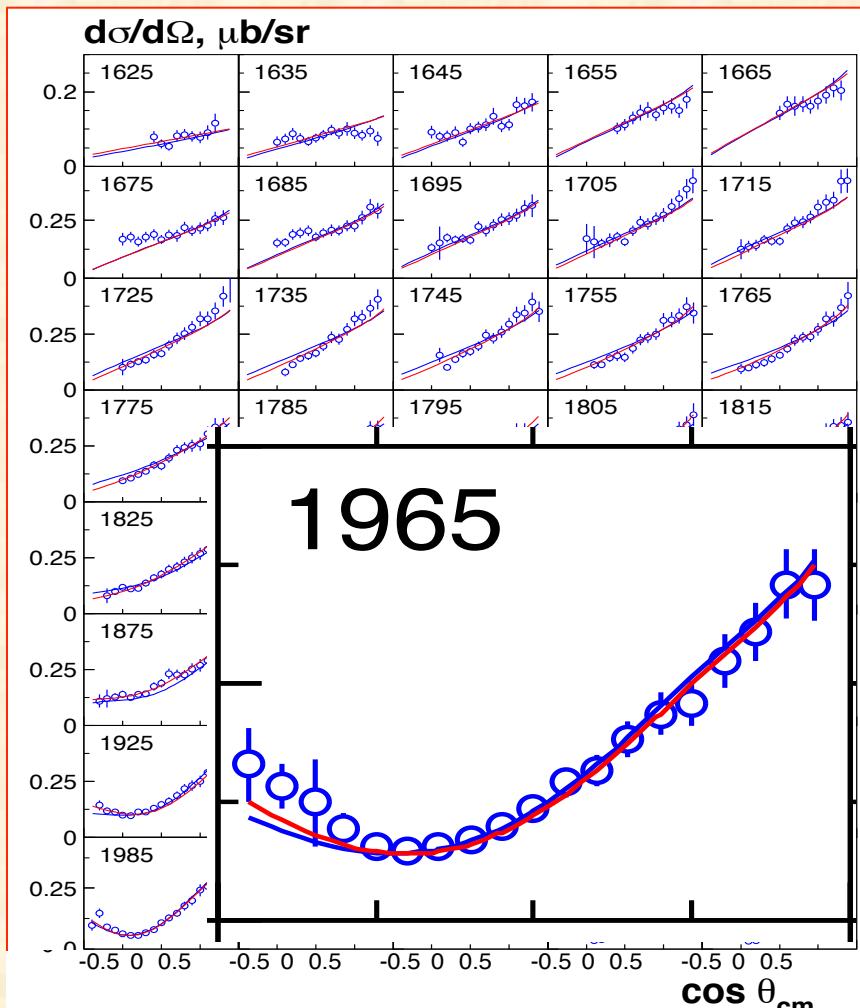
**Neutron target**

$p\pi^-$	✓	✓	✓			✓	✓	✓	✓							
$n\rho^0$	✓	✓	✓			✓	✓	✓	✓							
$K^-\Sigma^+$	✓	✓	✓			✓	✓	✓	✓							
$K^0\Lambda$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$K^0\Sigma^0$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$K^{0*}\Sigma^0$	✓	✓														

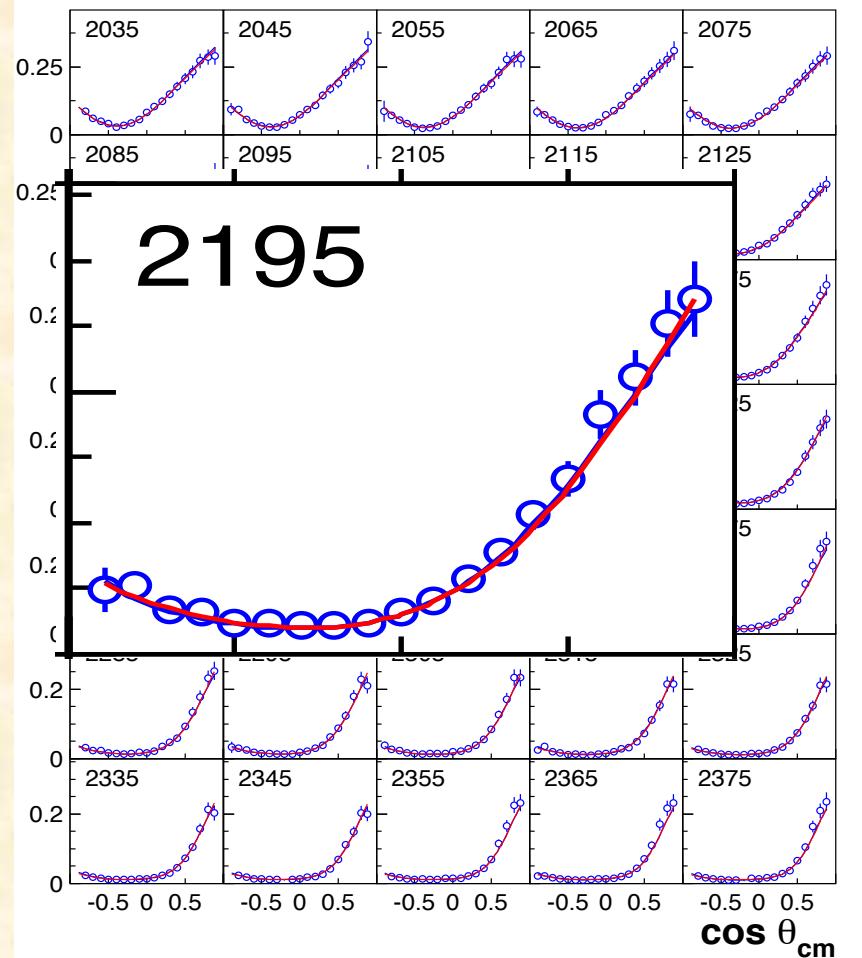
## Assessing the past:

**What did we learn up to now from meson photoproduction published data ?**

M. McCracken et al.(CLAS), Phys.RevC81,025201,2010

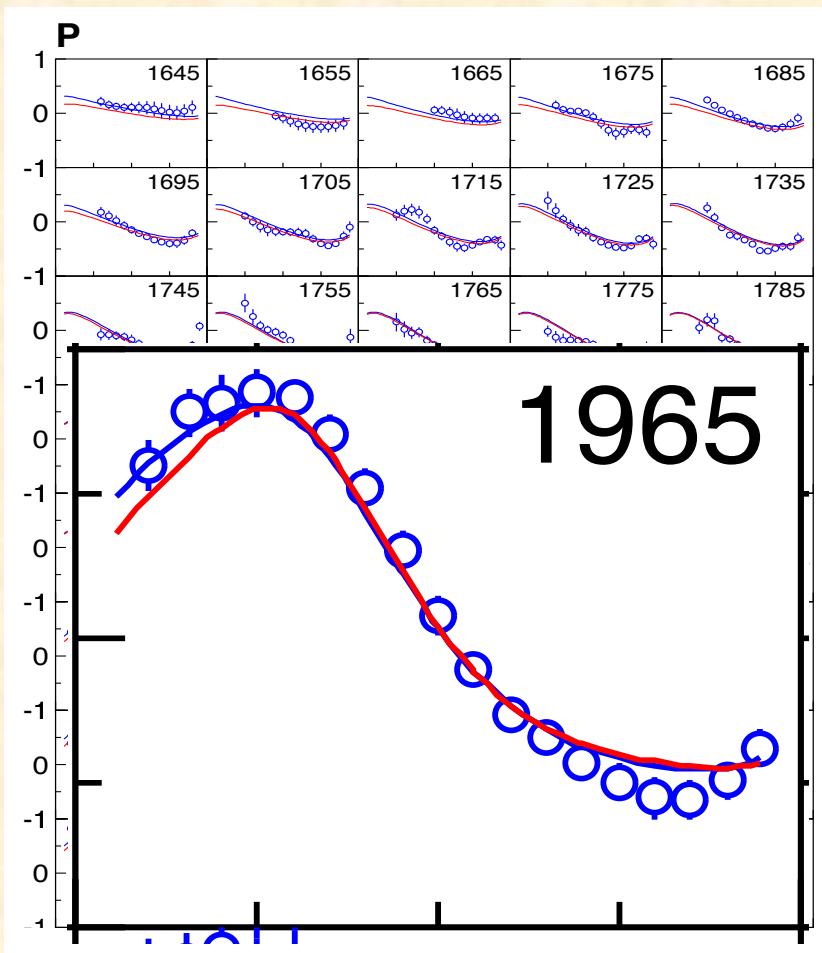


A.V. Anisovich et al, EPJ A48, 15 (2012)

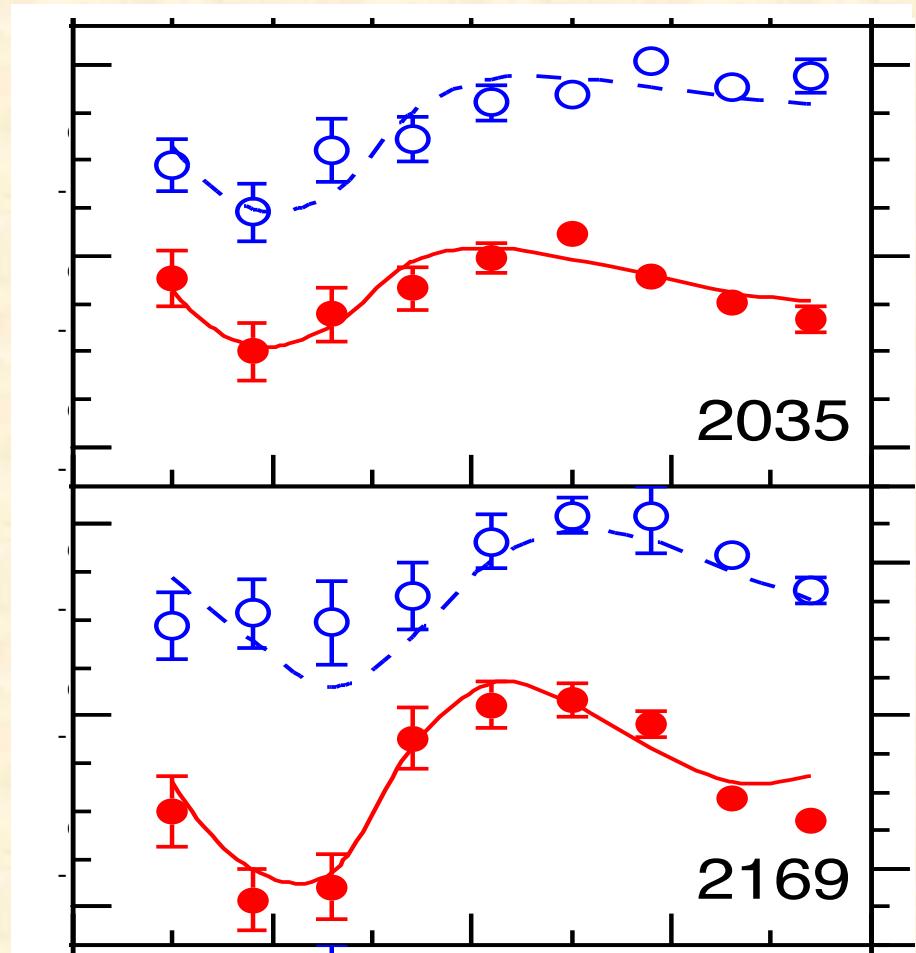


M. McCracken et al. (CLAS), Phys. Rev. C 81, 025201, 2010

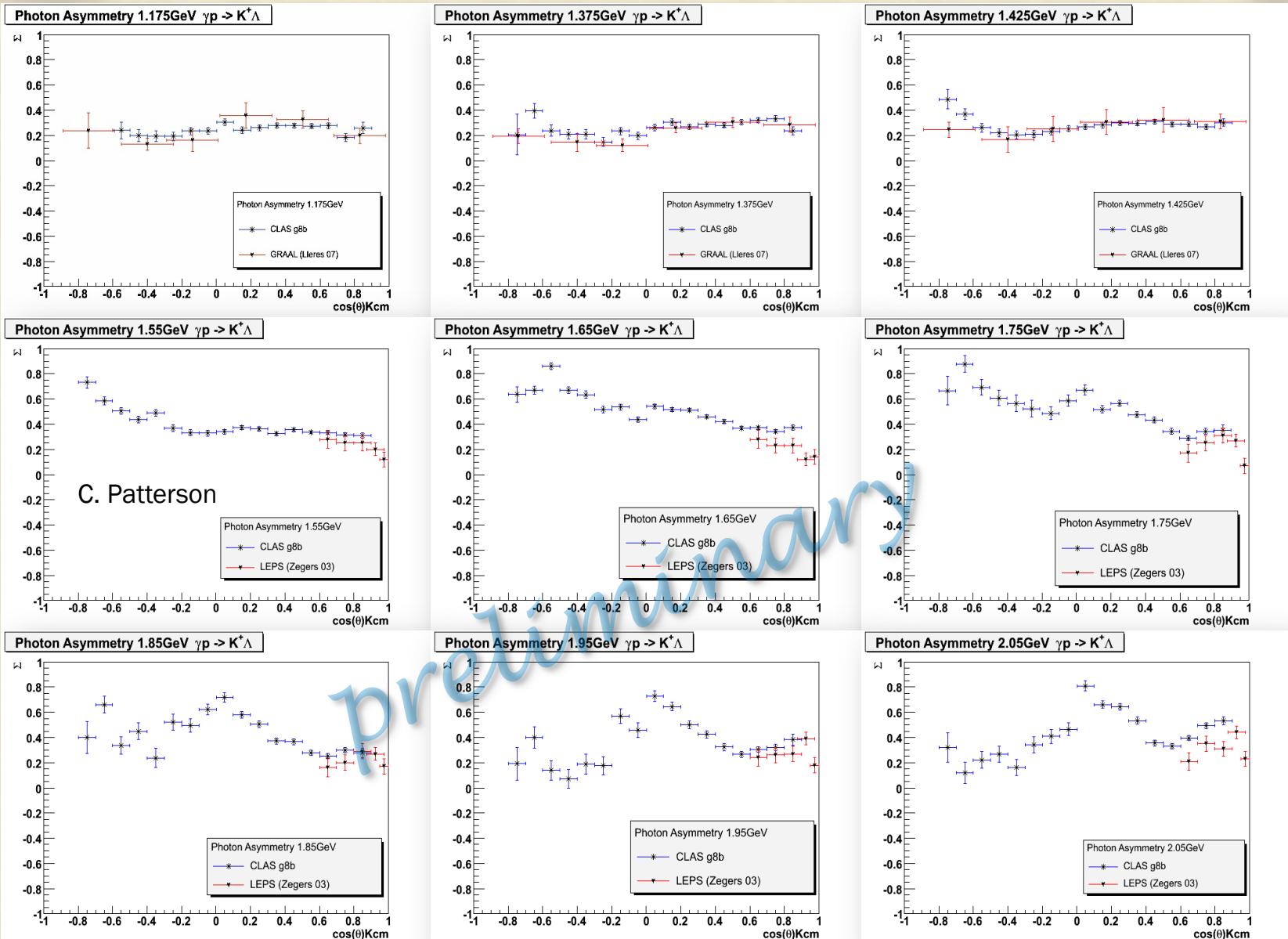
A.V. Anisovich et al., EPJ A 48, 15 (2012)



M. McCracken et al. (CLAS), Phys. Rev. C 81, 025201, 2010



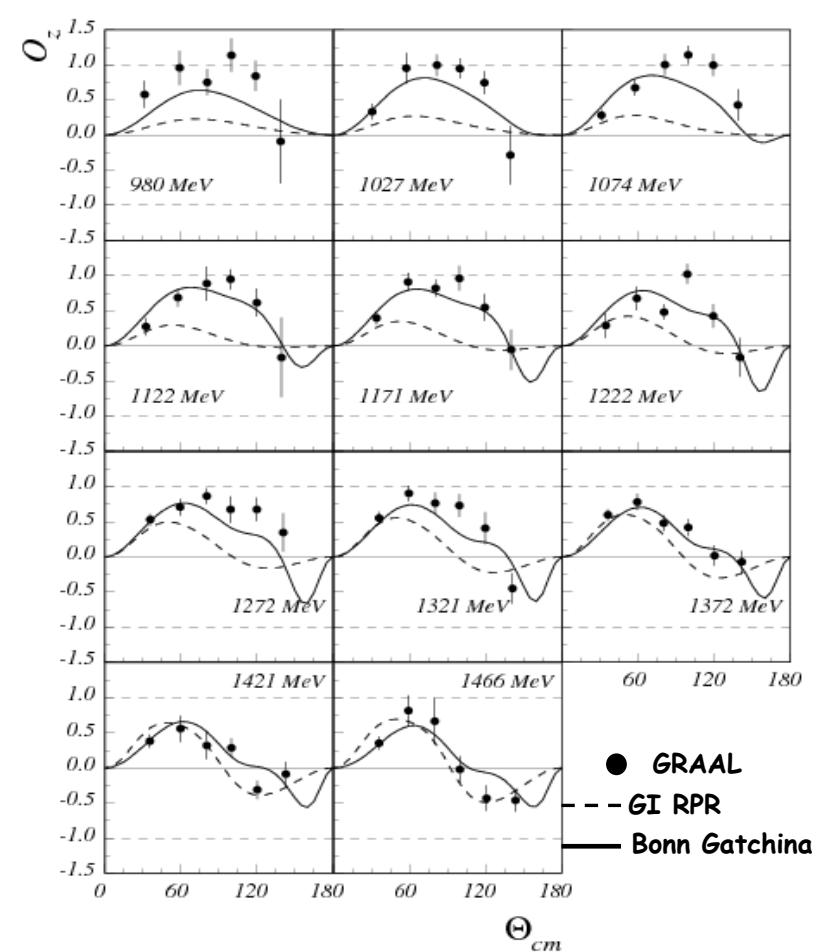
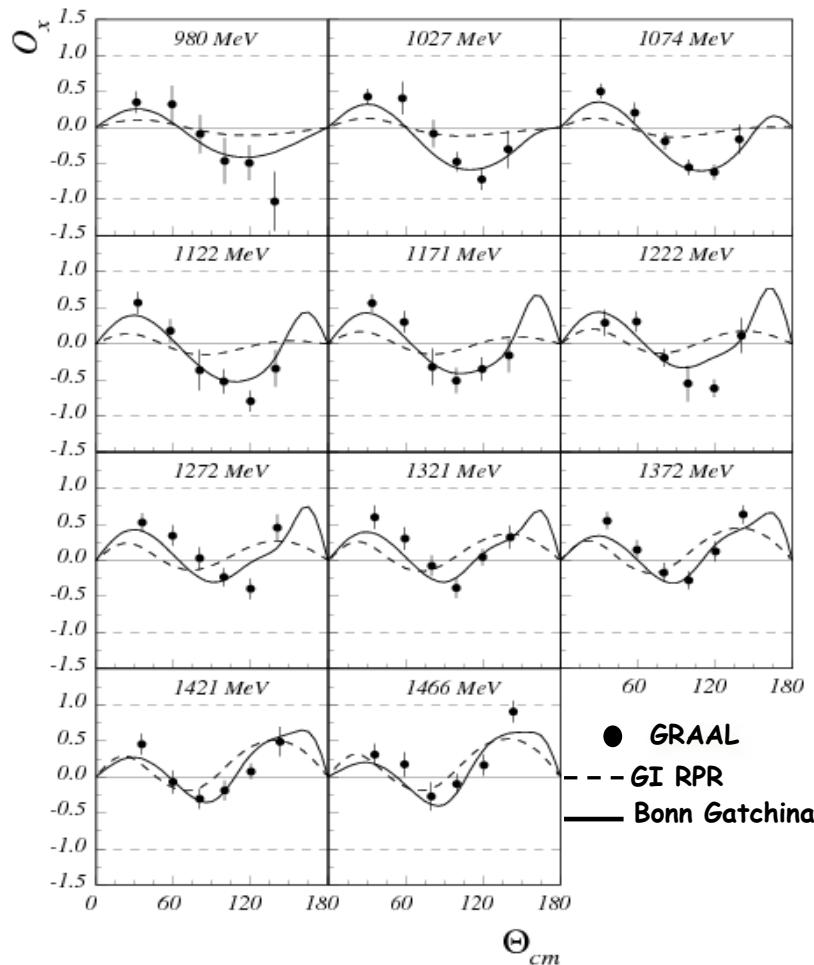
D. Bradford et al. (CLAS), Phys. Rev. C 75, 035205, 2007



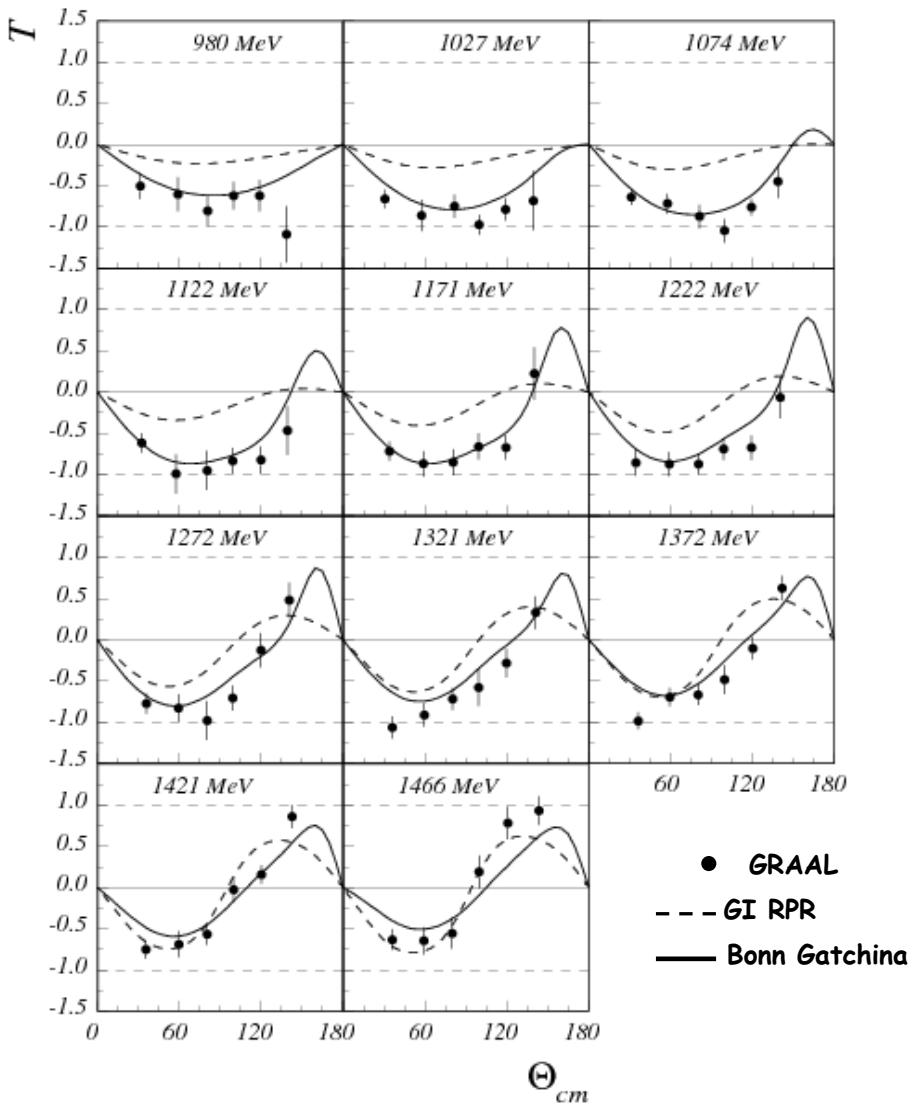
$$\frac{2N_+^{x'}}{N_+^{x'} + N_-^{x'}} = \left( 1 + \alpha \frac{2P_\gamma O_x}{\pi} \cos \theta_p^{x'} \right)$$

A.Lleres et al., EPJ A 39, 149-161 (2009)

$$\frac{2N_+^{z'}}{N_+^{z'} + N_-^{z'}} = \left( 1 + \alpha \frac{2P_\gamma O_z}{\pi} \cos \theta_p^{z'} \right)$$



A.Lleres et al., EPJ A 39, 149-161 (2009)



$$\frac{2N_+^{y'}}{N_+^{y'} + N_-^{y'}} = \left( 1 + \frac{2P_\gamma \Sigma}{\pi} \right) \left( \frac{1 + \alpha \frac{P\pi + 2P_\gamma T}{\pi + 2P_\gamma \Sigma} \cos \theta_p^{y'}}{1 + \alpha P \cos \theta_p^{y'}} \right)$$

From  $O_x$ ,  $O_z$  and  $T$  results:

- Ghent Isobar RPR Model:

$$S_{11}(1650) \quad P_{11}(1710) \quad P_{13}(1720)$$

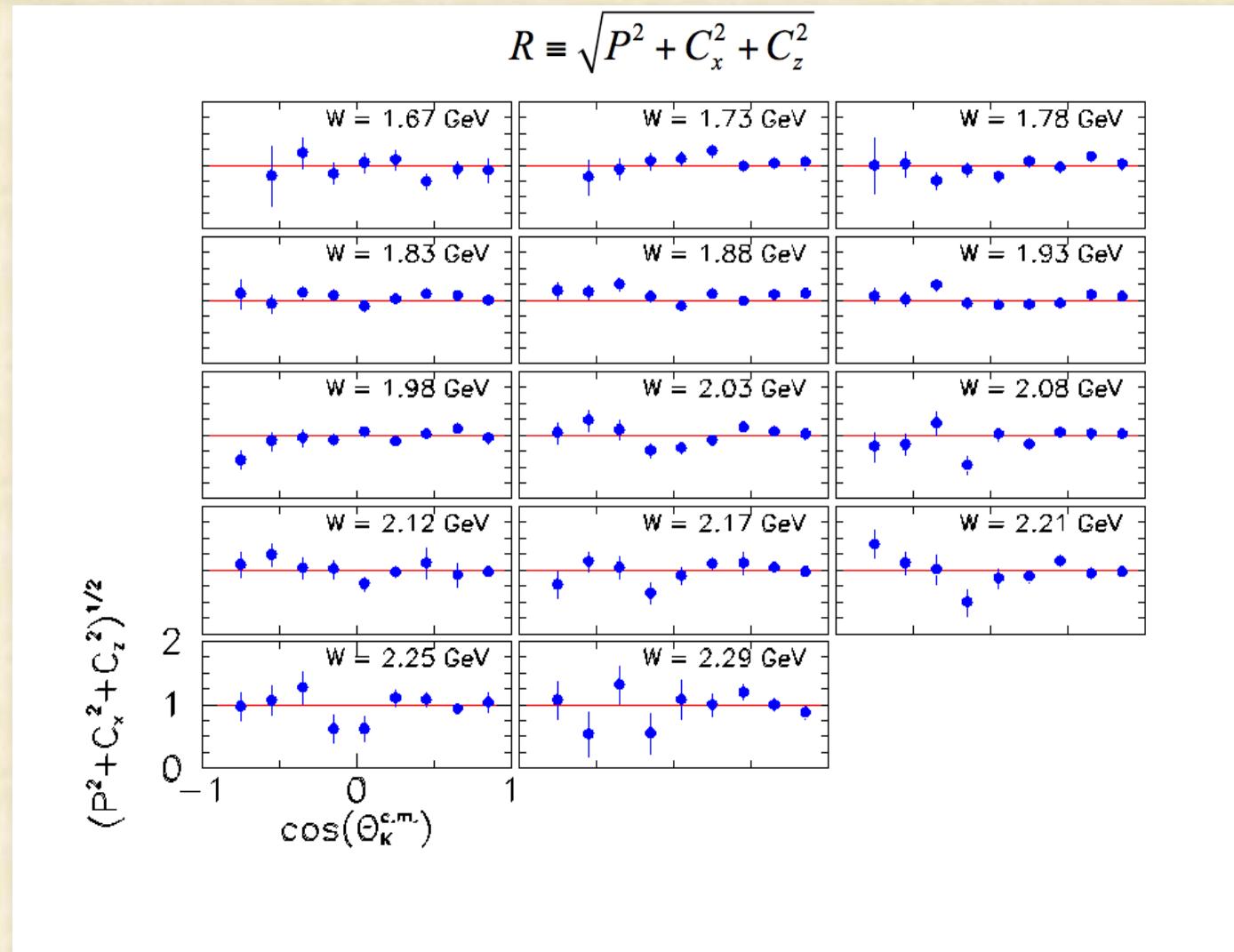
$$P_{13}(1900) \quad D_{13}(1900)$$

- Bonn Gatchina Model:

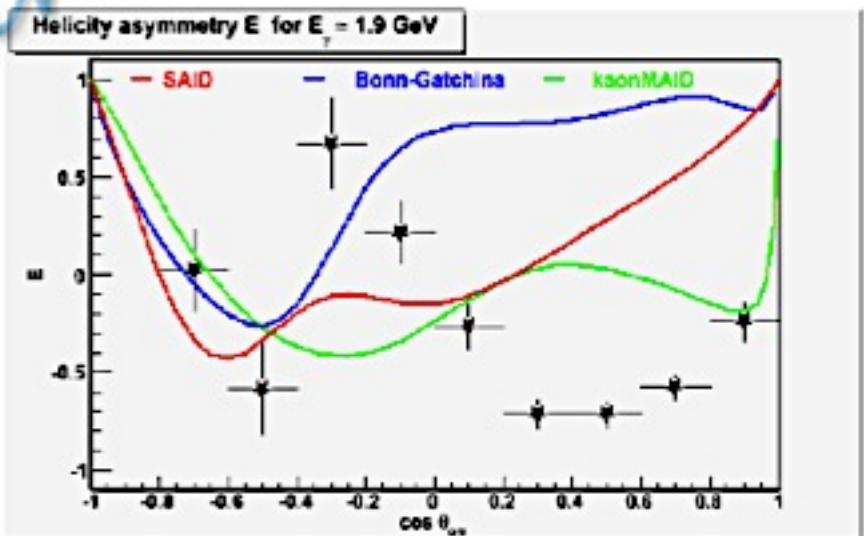
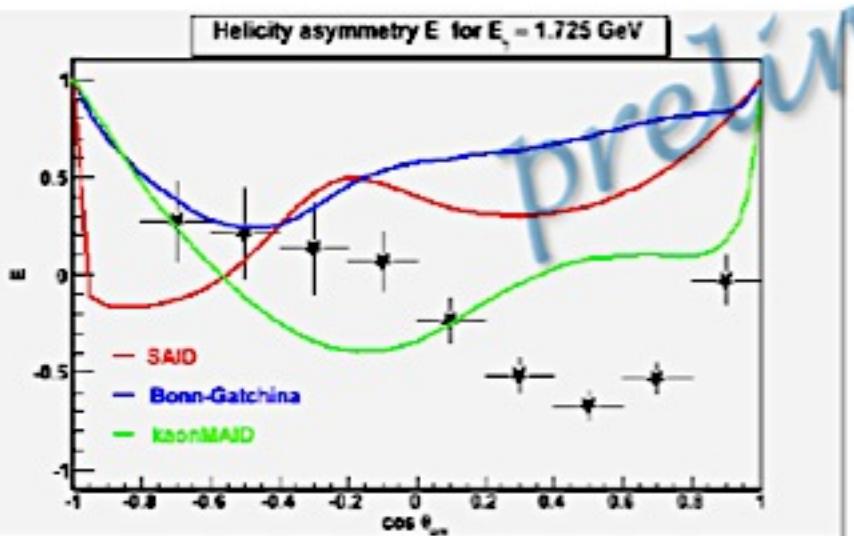
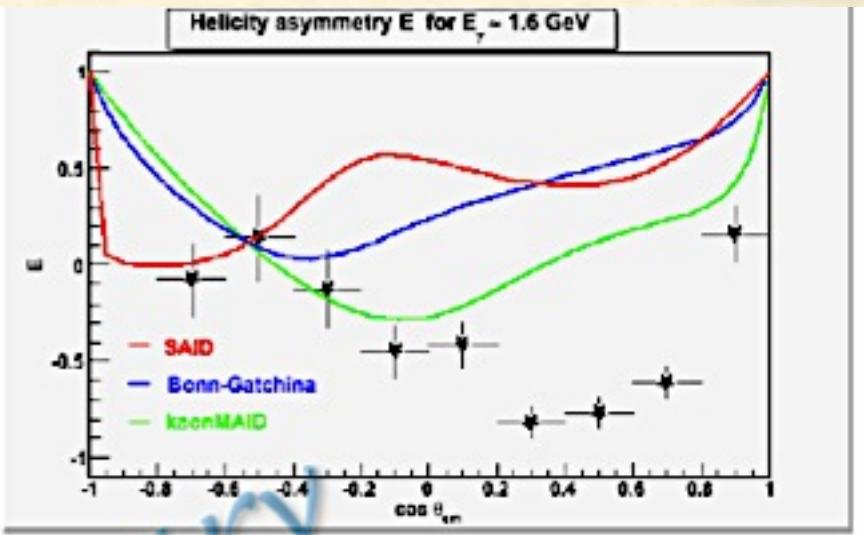
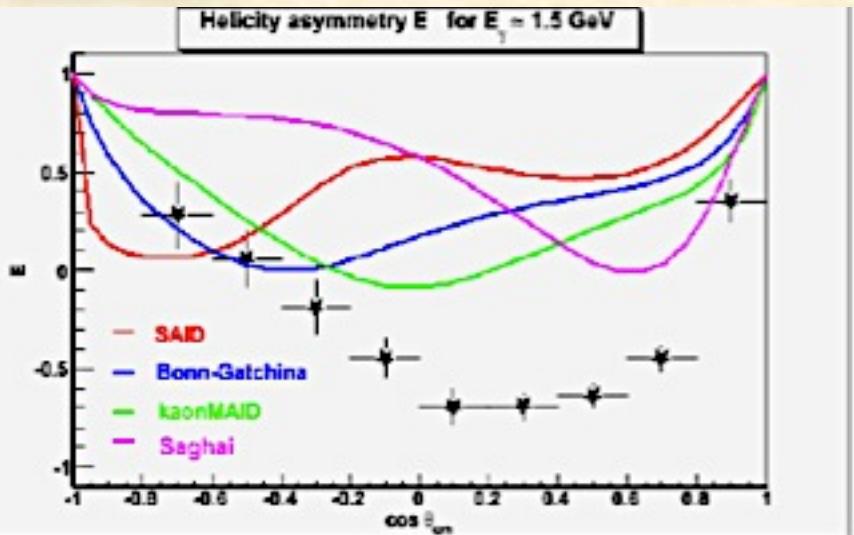
$$S_{11}(1535) \quad S_{11}(1650) \quad P_{13}(1720) \quad P_{11}(1840)$$

$$P_{13}(1900)$$

# R Values for the $\Lambda$



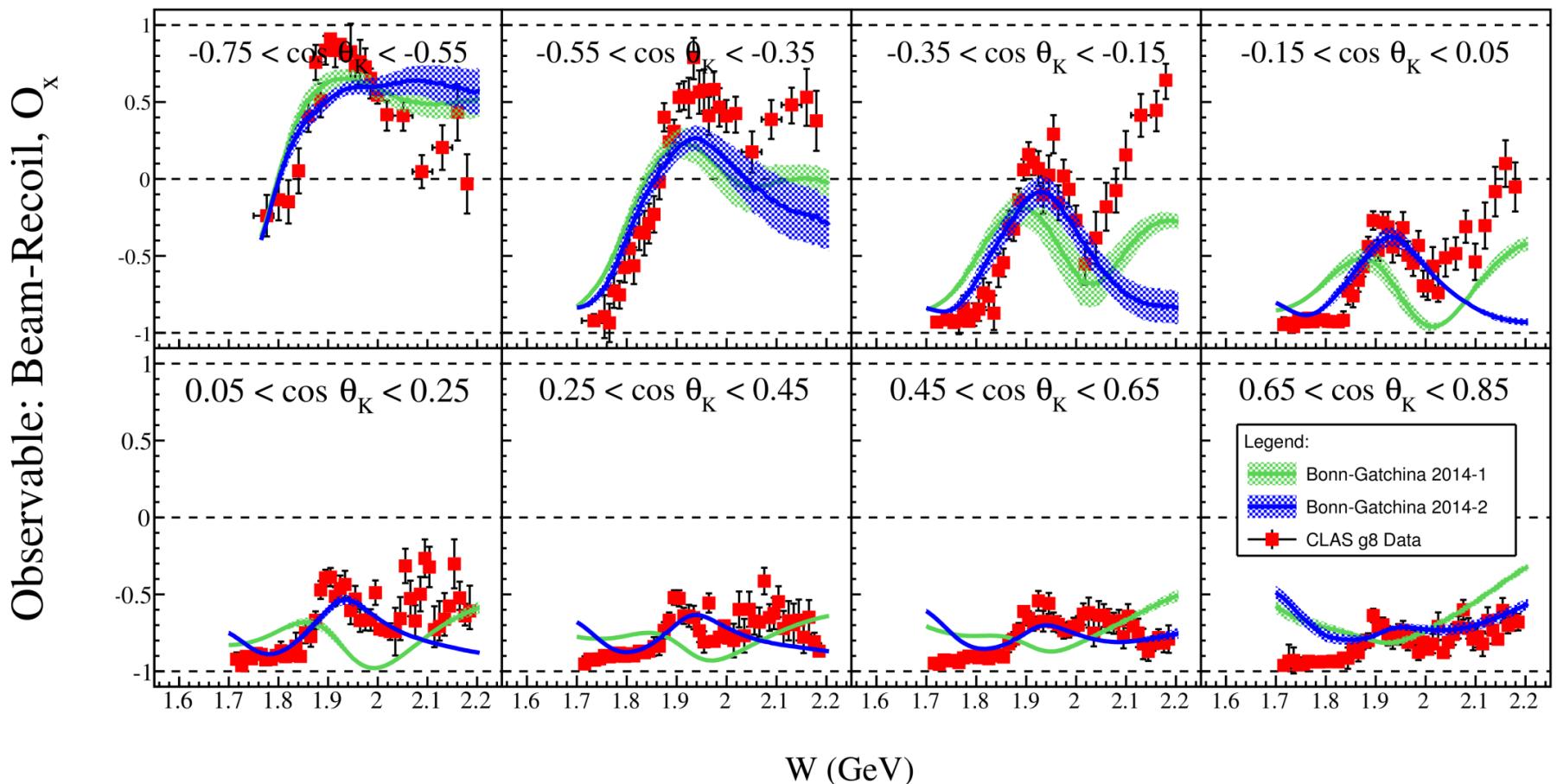
The  $\Lambda$  appears 100% polarized when created with a fully polarized beam.



L. Casey, Catholic Univ.

$\gamma + p \rightarrow K^+ \Lambda$ 

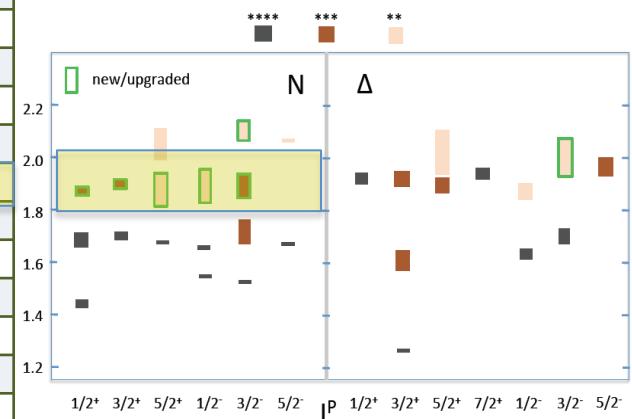
D. Ireland



N*	J <sup>P</sup> (L2I,2J)	2010	2014
p	1/2 <sup>+</sup> (P11)	****	****
n	1/2 <sup>+</sup> (P11)	****	****
N(1440)	1/2 <sup>+</sup> (P11)	****	****
N(1520)	3/2 <sup>-</sup> (D13)	****	****
N(1535)	1/2 <sup>-</sup> (S11)	****	****
N(1650)	1/2 <sup>-</sup> (S11)	****	****
N(1675)	5/2 <sup>-</sup> (D15)	****	****
N(1680)	5/2 <sup>+</sup> (F15)	****	****
<b>N(1685)</b>		*	
N(1700)	3/2 <sup>-</sup> (D13)	***	***
N(1710)	1/2 <sup>+</sup> (P11)	***	***
N(1720)	3/2 <sup>+</sup> (P13)	****	****
<b>N(1860)</b>	5/2 <sup>+</sup>		**
N(1875)	3/2 <sup>-</sup>		***
N(1880)	1/2 <sup>+</sup>		**
N(1895)	5/2 <sup>-</sup>		**
<b>N(1900)</b>	3/2 <sup>+</sup> (P13)	**	***
N(1900)	7/2 <sup>+</sup> (F17)	**	**
N(2000)	5/2 <sup>+</sup> (F15)	**	**
<b>N(2080)</b>	D 13	**	
<b>N(2090)</b>	S 11	*	
N(2040)	3/2 <sup>+</sup>		*
<b>N(2060)</b>	5/2 <sup>-</sup>		**
N(2100)	1/2 <sup>+</sup> (P11)	*	*
<b>N(2120)</b>	3/2 <sup>-</sup>		**
N(2190)	7/2 <sup>-</sup> (G17)	****	****
<b>N(2200)</b>	D 15	**	
N(2220)	9/2 <sup>+</sup> (H19)	****	****
N(2250)	9/2 <sup>-</sup> (G19)	****	****
N(2600)	11/2 <sup>-</sup> (I 1,11)	***	***
N(2700)	13/2 <sup>+</sup> (K 1,11)	**	**

$\Delta^*$	J <sup>P</sup> (L2I,2J)	2010	2014
$\Delta(1232)$	3/2 <sup>+</sup> (P33)	****	****
$\Delta(1600)$	3/2 <sup>+</sup> (P33)	***	***
$\Delta(1620)$	1/2 <sup>-</sup> (S31)	****	****
$\Delta(1700)$	3/2 <sup>-</sup> (D33)	****	****
$\Delta(1750)$	1/2 <sup>+</sup> (P31)	*	*
$\Delta(1900)$	1/2 <sup>-</sup> (S31)	**	**
$\Delta(1905)$	5/2 <sup>+</sup> (F35)	****	****
$\Delta(1910)$	1/2 <sup>+</sup> (F31)	****	****
$\Delta(1920)$	3/2 <sup>+</sup> (P33)	***	***
$\Delta(1930)$	5/2 <sup>-</sup> (D35)	***	***
<b><math>\Delta(1940)</math></b>	<b>3/2<sup>-</sup> (D33)</b>	*	**
$\Delta(1950)$	7/2 <sup>+</sup> (F37)	****	****
$\Delta(2000)$	5/2 <sup>+</sup> (F35)	**	**
$\Delta(2150)$	1/2 <sup>-</sup> (S31)	*	*
$\Delta(2200)$	7/2 <sup>-</sup> (G37)	*	*
$\Delta(2200)$	9/2 <sup>+</sup> (H39)	**	**
$\Delta(2350)$	5/2 <sup>-</sup> (D35)	*	*
$\Delta(2390)$	7/2 <sup>+</sup> (F37)	*	*
$\Delta(2400)$	9/2 <sup>-</sup> (G39)	**	**
$\Delta(2420)$	11/2 <sup>+</sup> (H3,11)	****	****
$\Delta(2750)$	13/2 <sup>-</sup> (I3,13)	**	**
$\Delta(2950)$	15/2 <sup>+</sup> (K 3,13)	**	**

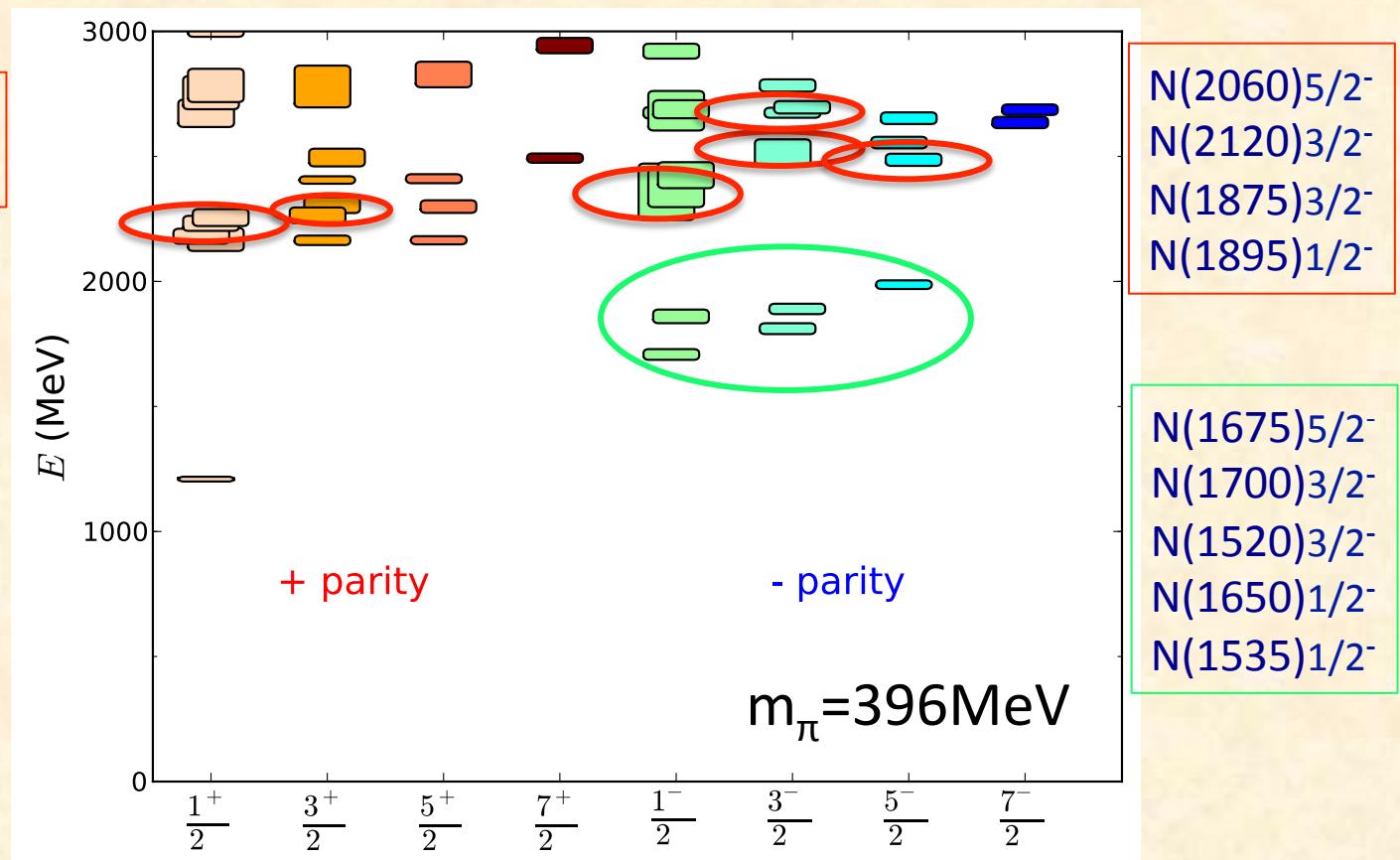
Photoproduction data  
from JLAB, ELSA,  
GRAAL, LEPS



Naming scheme  
has changed:  
 $L_{2I}2J(E) \rightarrow J^P(E)$

V. Crede & W. Roberts, arXiv:1302.7299

Projected new states constrained largely from meson photoproduction



New candidate states may be accommodated in LQCD projections

## On going analyses : g14

## On-going Analyses:

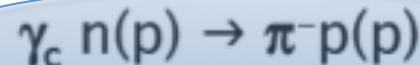
- T. Kageya (Jlab):  $\gamma_c n(p) \rightarrow \pi^- p(p)$
- H. Lu (CMU, U. Iowa):  $\gamma_L n(p) \rightarrow \pi^- p(p)$
- P. Peng (U. Virginia):  $\gamma_c p \rightarrow \pi^+ \pi^- p; \gamma_c n(p) \rightarrow \pi^+ \pi^- n(p)$
- J. Fleming (U. Edinburgh):  $\gamma_L p \rightarrow \pi^+ \pi^- p; \gamma_L n(p) \rightarrow \pi^+ \pi^- n(p)$   
 $\gamma_c n(p) \rightarrow K^+ \Sigma^-(p)$
- I. Zonta (U. Roma-II):  $\gamma_c n(p) \rightarrow \rho n(p) \rightarrow \pi^+ \pi^- n(p)$
- D. Ho (Carnegie-Mellon U.):  $\gamma_c n(p) \rightarrow K^0 \Lambda(p)$

⇒ some examples with  $\sim \frac{1}{3}$  to  $\frac{2}{3}$  data processed

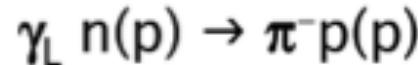
## On-going Analyses:

- T. Kageya (Jlab):
- H. Lu (CMU, U. Iowa):
- P. Peng (U. Virginia):
- J. Fleming (U. Edinburgh):  $\gamma_L p \rightarrow \pi^+ \pi^- p$ ;  $\gamma_L n(p) \rightarrow \pi^+ \pi^- n(p)$
- I. Zonta (U. Roma-II):
- D. Ho (Carnegie-Mellon U.):  $\gamma_c n(p) \rightarrow K^0 \Lambda(p)$

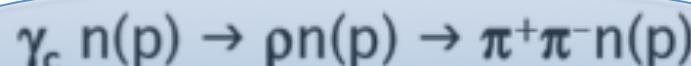
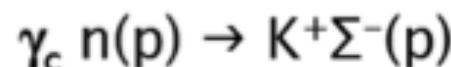
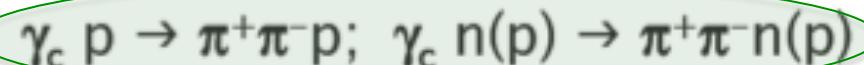
*Different bkg removal methods*



Empty cell  
Subtraction



Kinematical fitting

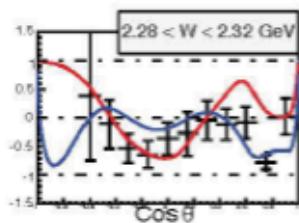
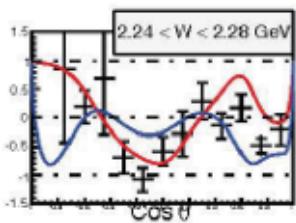
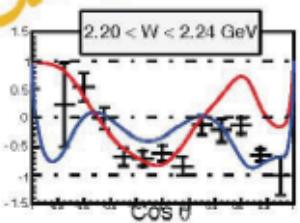
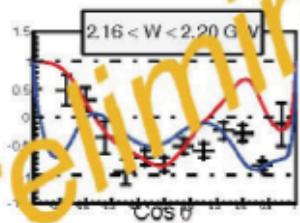
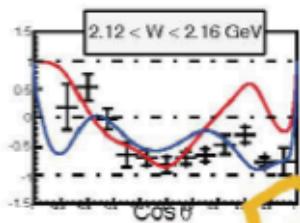
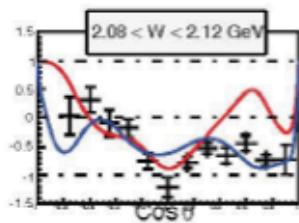
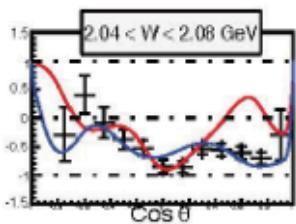
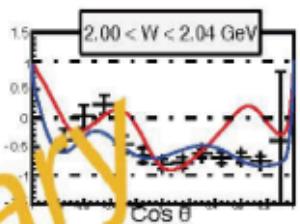
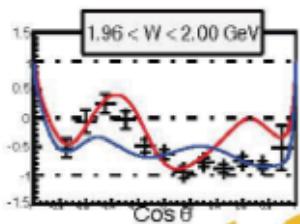
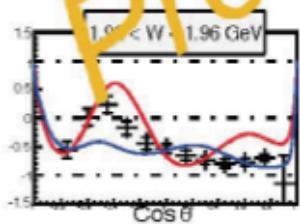
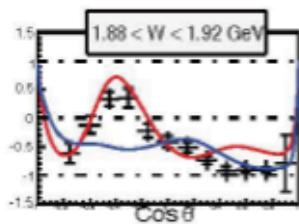
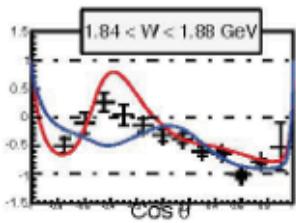
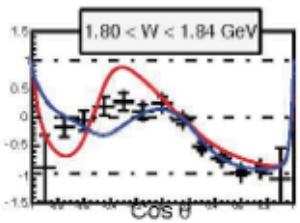
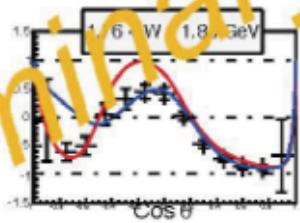
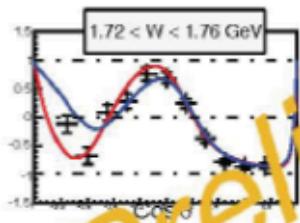
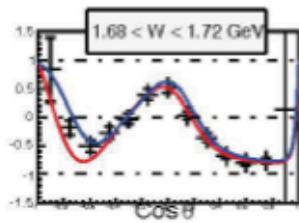
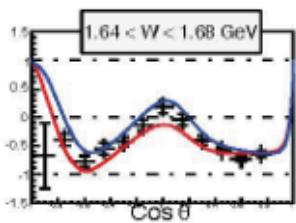
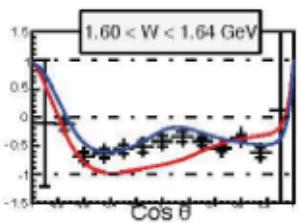
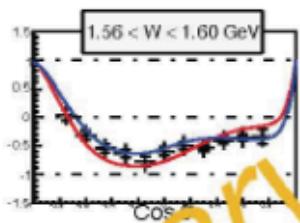
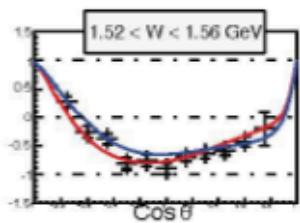
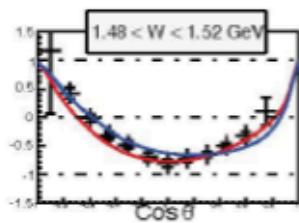


Empty cell  
Subtraction

Boosted Decision Trees

⇒ some examples with  $\sim \frac{1}{3}$  to  $\frac{2}{3}$  data processed

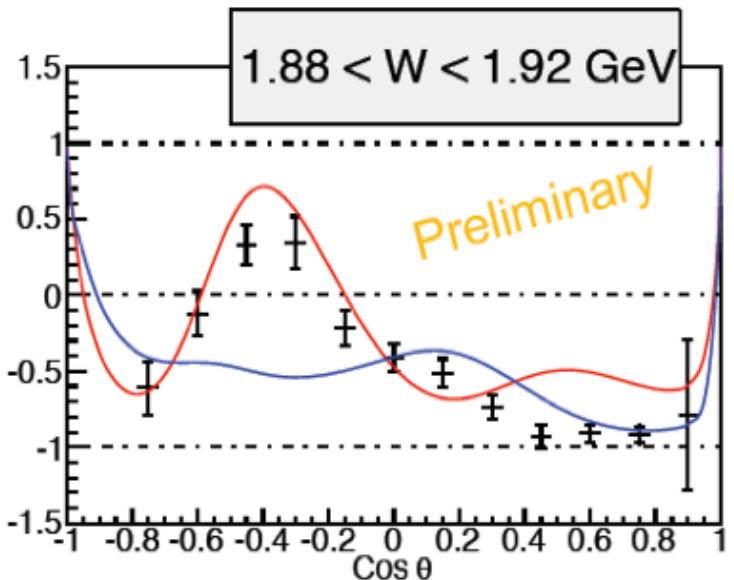
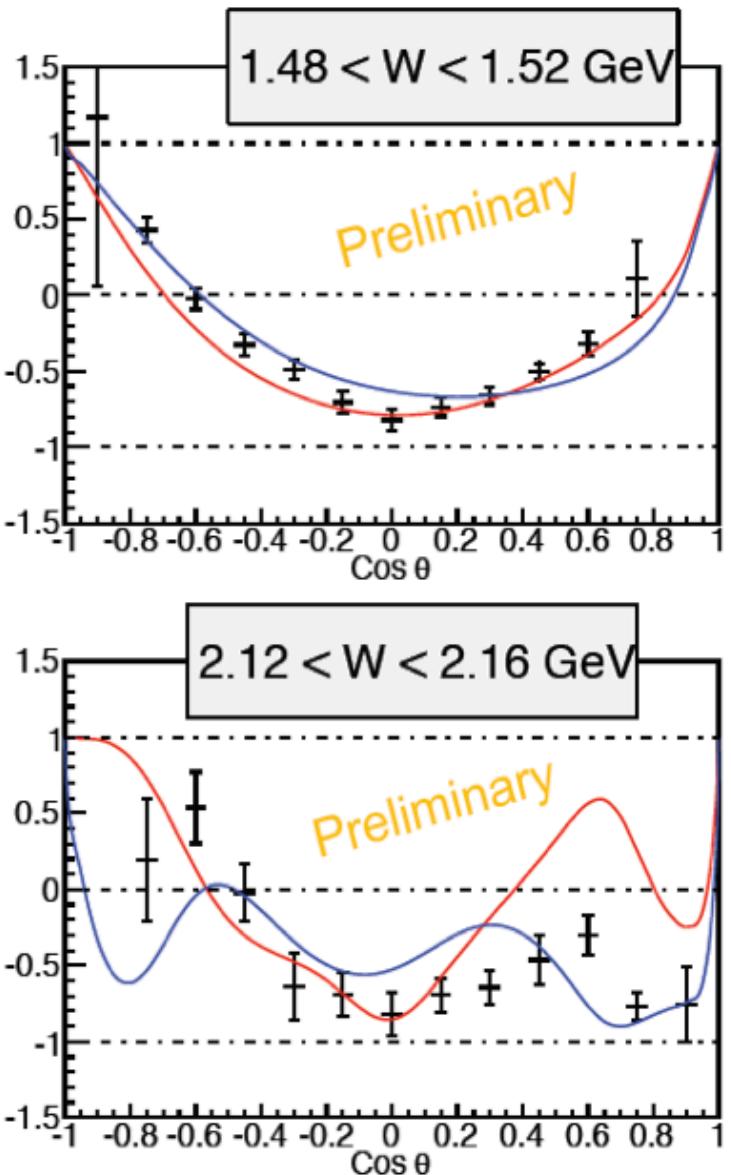
A.M. Sandorfi



SAID[CM12]  
BoGa[2012-02]

T. Kageya  
A.M. Sandorfi

$$E(\pi^- p) = \frac{\overleftarrow{\gamma}_c \overrightarrow{n}(p) - \overrightarrow{\gamma}_c \overleftarrow{n}(p)}{\overleftarrow{\gamma}_c \overrightarrow{n}(p) + \overrightarrow{\gamma}_c \overleftarrow{n}(p)}$$



Role of  $N(1900)3/2^+$  ?

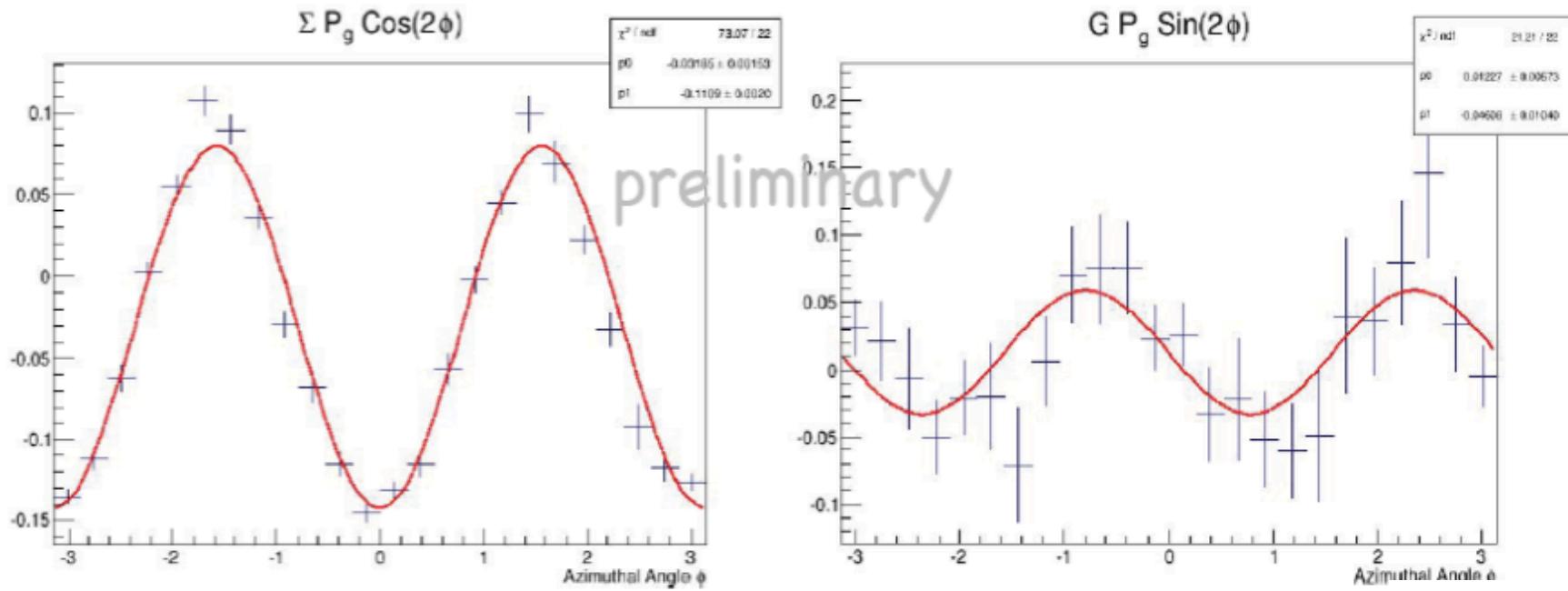
$$E(\pi^- p) = \frac{\overleftarrow{\gamma}_c \overrightarrow{n}(p) - \overrightarrow{\gamma}_c \overleftarrow{n}(p)}{\overleftarrow{\gamma}_c \overrightarrow{n}(p) + \overrightarrow{\gamma}_c \overleftarrow{n}(p)}$$

T. Kageya  
A.M. Sandorfi

PWA:  
SAID[CM12]  
BoGa[2012-02]

- linearly polarized beam from bremsstrahlung in diamond
- $d\sigma_{(B,T)} = \frac{1}{2} d\sigma_0 \left\{ 1 - \Sigma(\theta) \cdot P_L^\gamma \cos(2\varphi_\gamma) + G(\theta) \cdot P_L^\gamma \cdot P_z^T \cdot \sin(2\varphi_\gamma) \right\}$
- combine diff beam and target orientations to separate  $\Sigma$  and  $G$

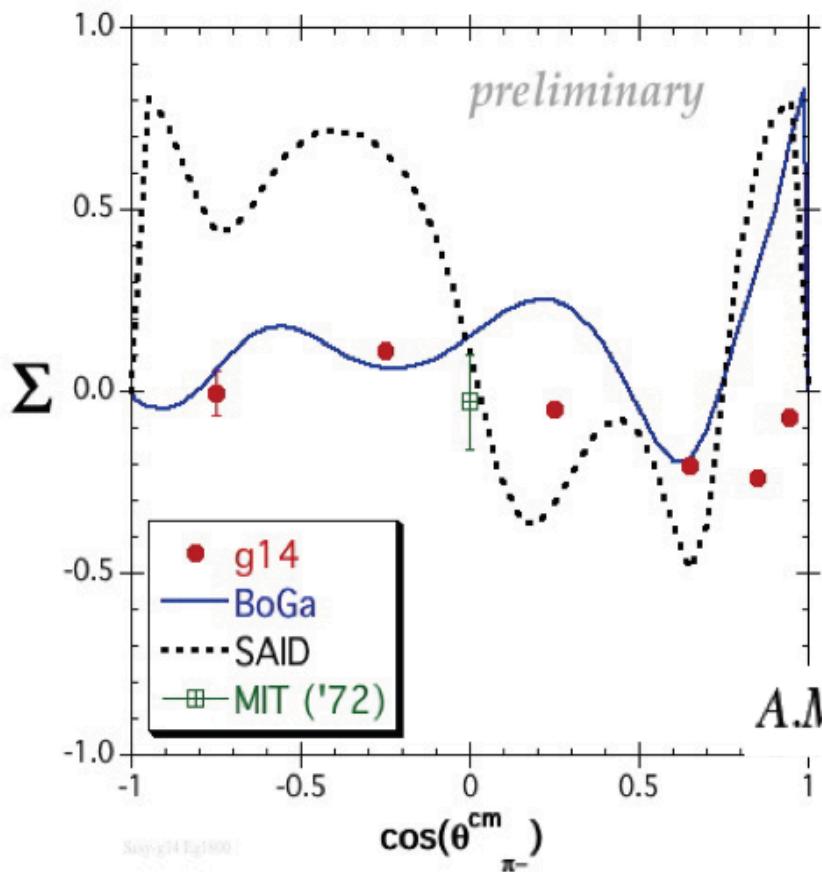
Haiyun Lu (CMU, U Iowa)



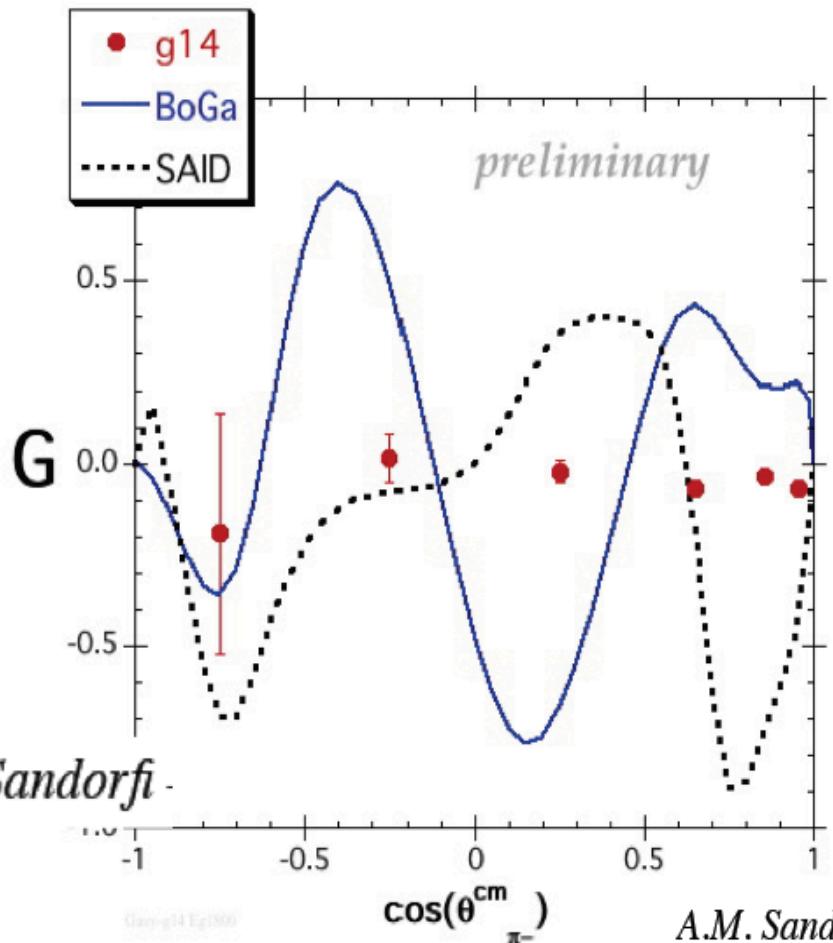
A.M. Sandorfi

- $d\sigma_{(B,T)} = \frac{1}{2}d\sigma_0 \left\{ 1 - \Sigma(\theta) \cdot P_L^\gamma \cos(2\phi_\gamma) + G(\theta) \cdot P_L^\gamma \cdot P_z^T \cdot \sin(2\phi_\gamma) \right\}$
- $E_\gamma \sim 1800 \text{ MeV} \Leftrightarrow W \sim 2060 \text{ MeV}$

Haiyun Lu (CMU, U Iowa)



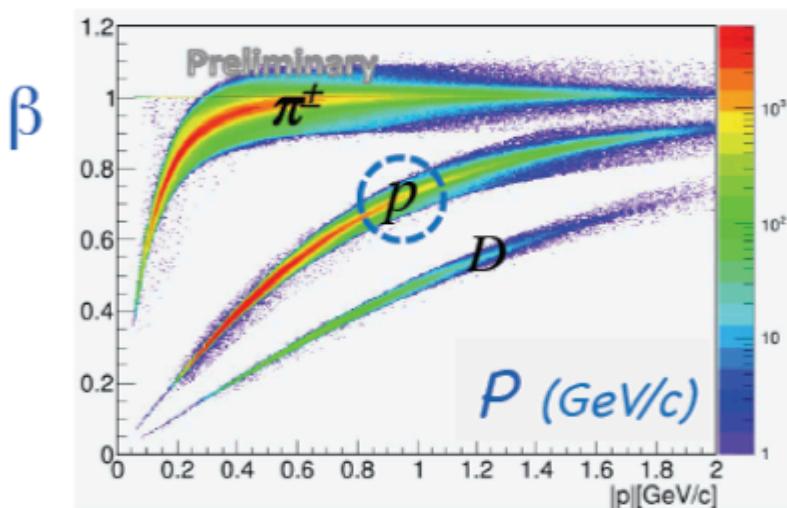
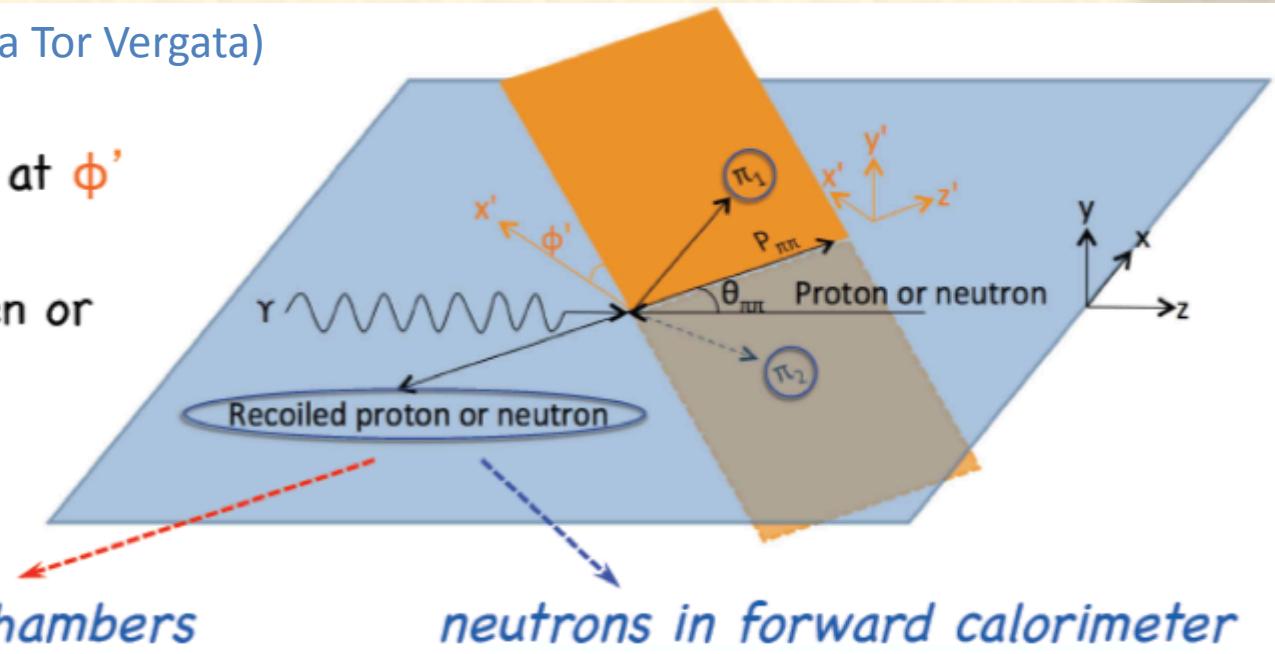
A.M. Sandorfi



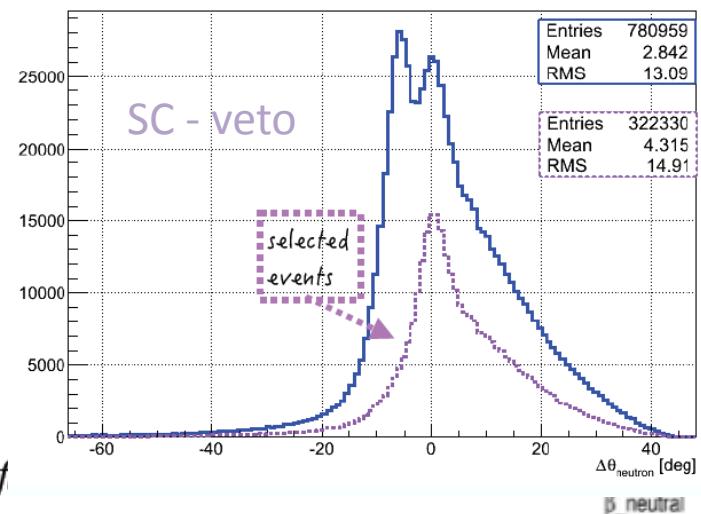
A.M. Sandorfi

P. Peng(UVa), I. Zonta (U. Roma Tor Vergata)

- elementary  $d^5\sigma$
- $\pi^+ \pi^-$  define a plane at  $\phi'$  wrt reaction plane
- observables are even or odd wrt  $\phi'$
- $P_{\pi\pi}(\theta_{\pi\pi}) = P_{\pi+} + P_{\pi-}$



A.M. Sandorf



- in the notation of Roberts and Oed, PR C71 (05) 055201
- 64 possible polarization observables;  $\geq 15$  needed to determine amplitude

$$\frac{d\sigma^{BT}}{d\Omega} = d\sigma_0 \left\{ \begin{aligned} & \left( 1 + \vec{\Lambda} \cdot \vec{P} \right) + \delta_{\odot} \left( I^{\odot} + \vec{\Lambda} \cdot \vec{P}^{\odot} \right) \\ & + \delta_L \left[ \sin(2\varphi_{\gamma}) \left( I^s + \vec{\Lambda} \cdot \vec{P}^s \right) + \cos(2\varphi_{\gamma}) \left( I^c + \vec{\Lambda} \cdot \vec{P}^c \right) \right] \end{aligned} \right\}$$

- $\delta_{\odot}, \delta_L$  : beam polarization ;
- $\vec{\Lambda}$  : target polarization

circularly polarized beam on a longitudinally polarized target

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

helicity difference    beam-helicity    beam-target

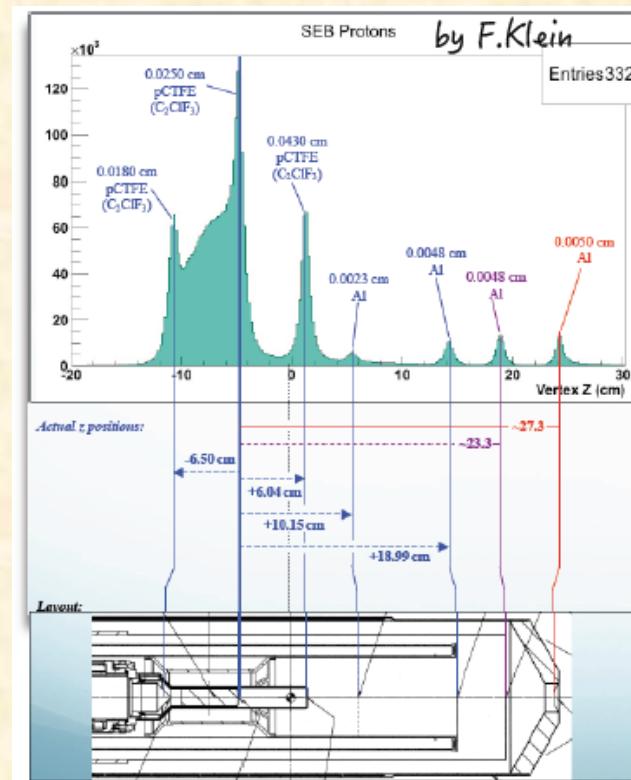
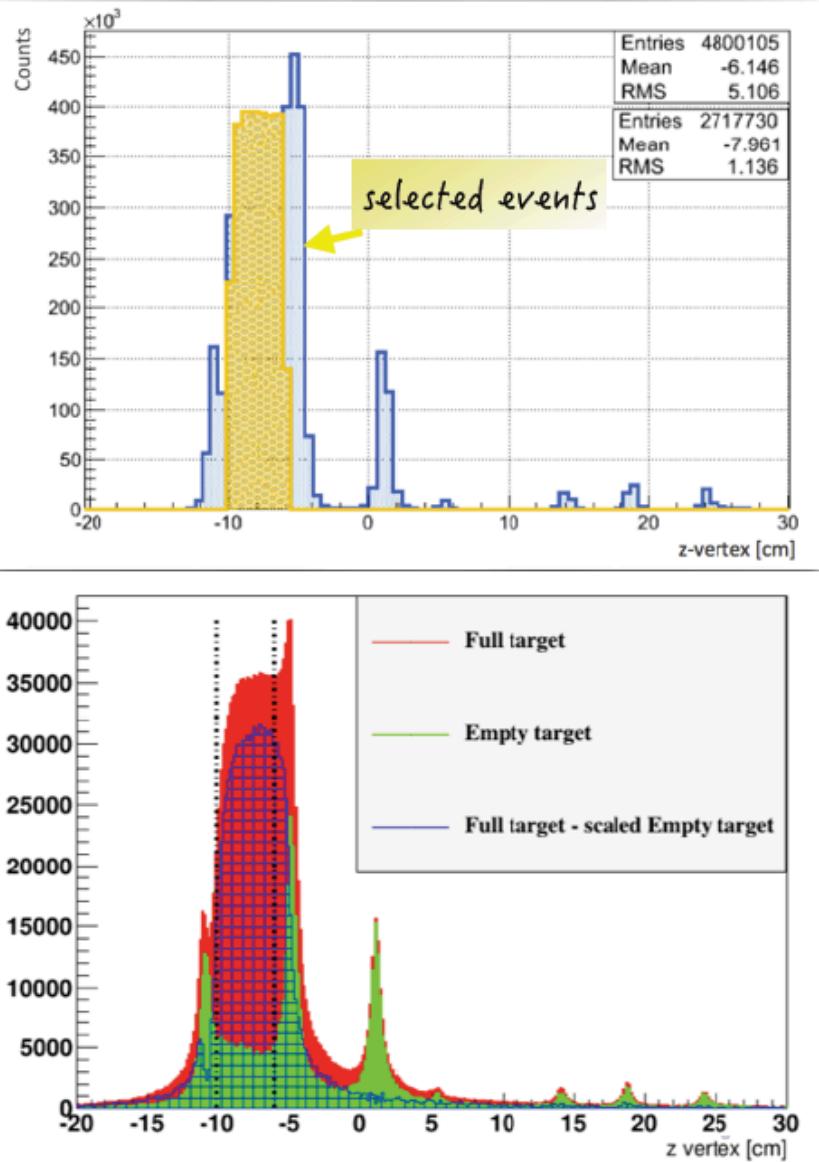
$$P_z = \frac{1}{\Lambda_z} \frac{[N(\rightarrow\Rightarrow) + N(\leftarrow\Rightarrow)] - [N(\rightarrow\Leftarrow) + N(\leftarrow\Leftarrow)]}{[N(\rightarrow\Rightarrow) + N(\leftarrow\Rightarrow)] + [N(\rightarrow\Leftarrow) + N(\leftarrow\Leftarrow)]}$$

$$I^{\odot} = \frac{1}{\delta_{\odot}} \frac{[N(\rightarrow\Rightarrow) + N(\rightarrow\Leftarrow)] - [N(\leftarrow\Rightarrow) + N(\leftarrow\Leftarrow)]}{[N(\rightarrow\Rightarrow) + N(\rightarrow\Leftarrow)] + [N(\leftarrow\Rightarrow) + N(\leftarrow\Leftarrow)]}$$

$$P_z^{\odot} = \frac{1}{\Lambda_z \delta_{\odot}} \frac{[N(\rightarrow\Rightarrow) + N(\leftarrow\Leftarrow)] - [N(\rightarrow\Leftarrow) + N(\leftarrow\Rightarrow)]}{[N(\rightarrow\Rightarrow) + N(\leftarrow\Leftarrow)] + [N(\rightarrow\Leftarrow) + N(\leftarrow\Rightarrow)]}$$

$P_z$  and  $I^{\odot}$  are odd functions of  $\phi'$

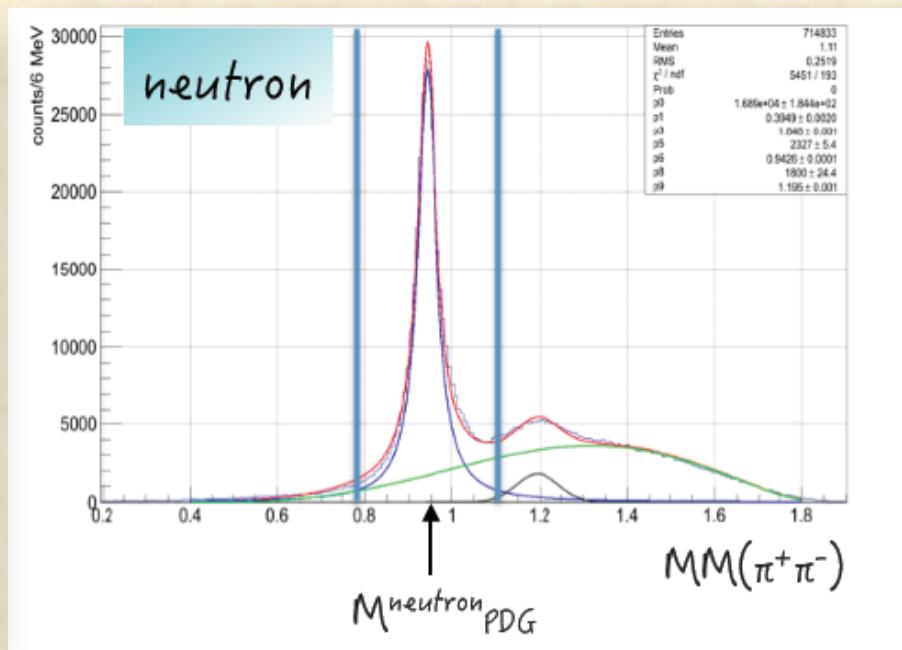
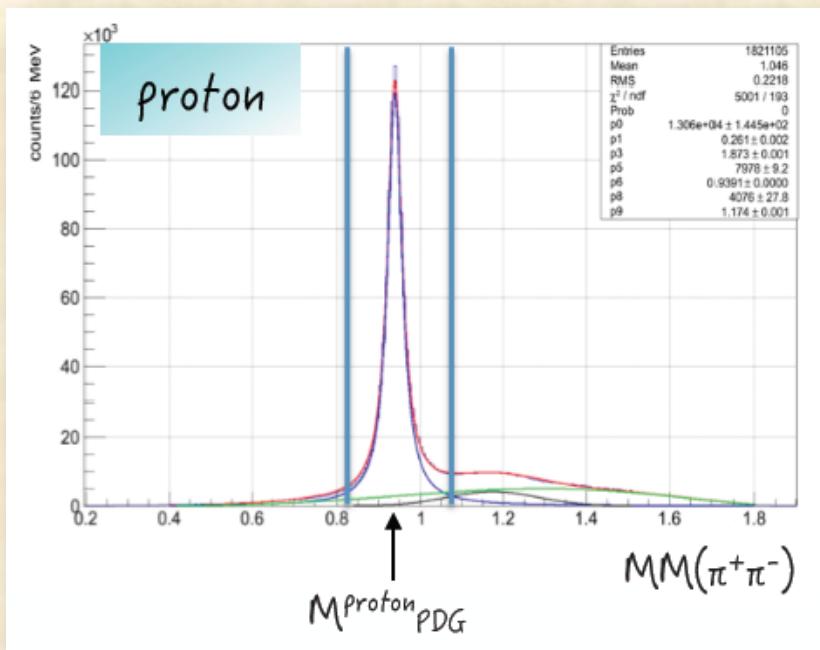
$\Rightarrow$  target orientation  $\rightarrow$  beam orientation



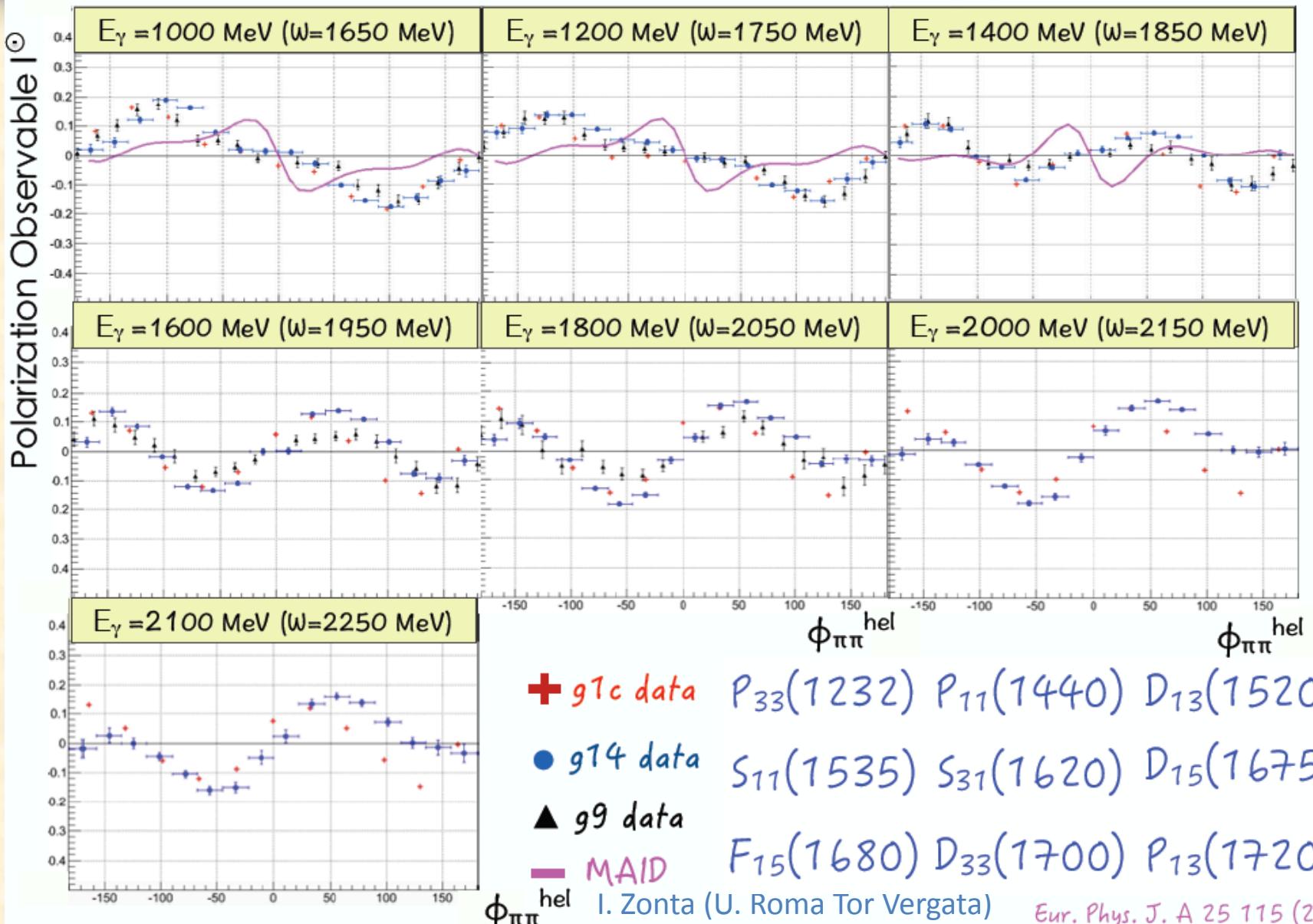
I. Zonta (U. Roma Tor Vergata)

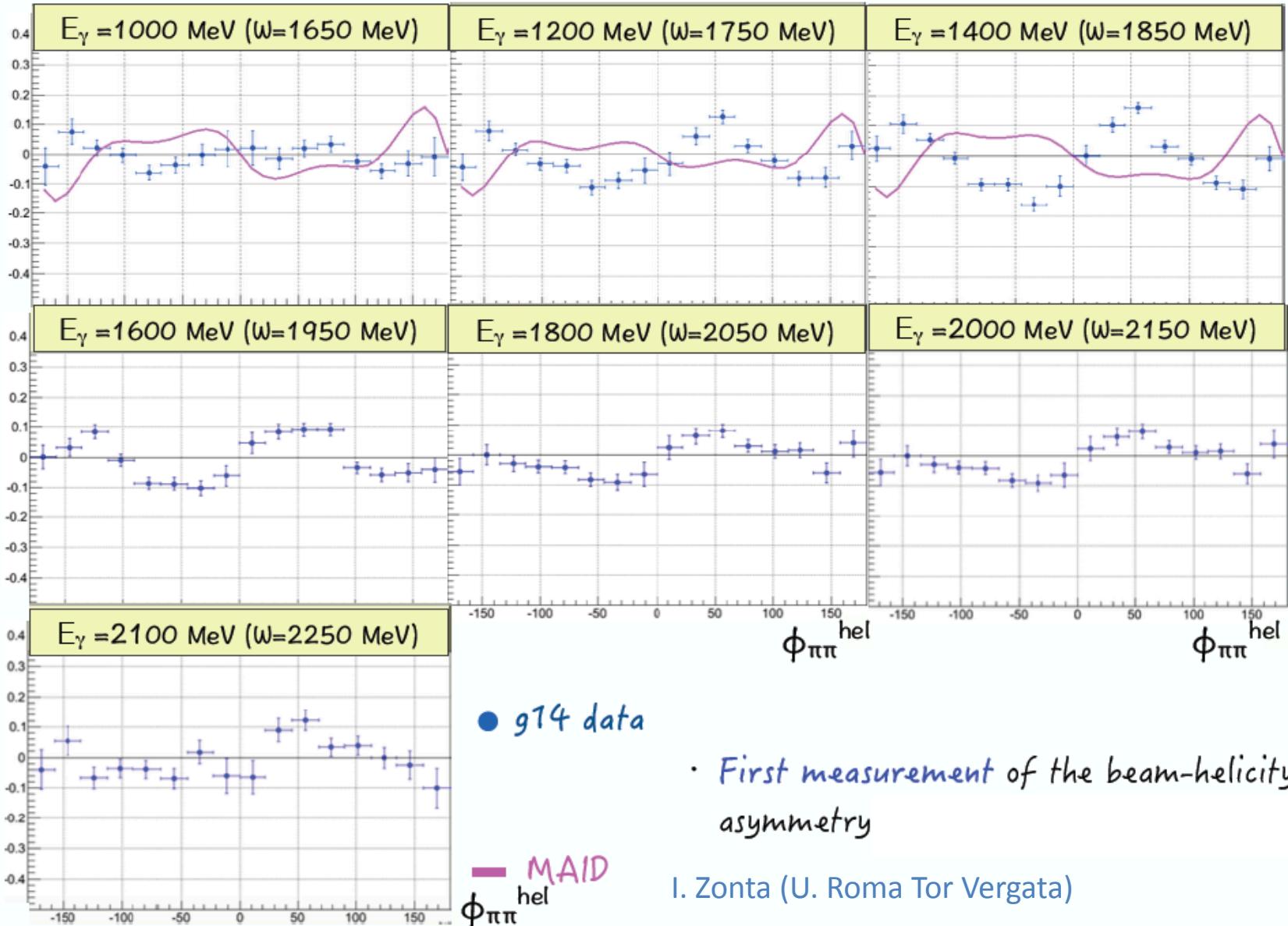
Events are selected using geometrical and kinematical cuts:

- Z Vertex cut to identify events in the HD volume
- Missing mass cut to identify (quasi) free target



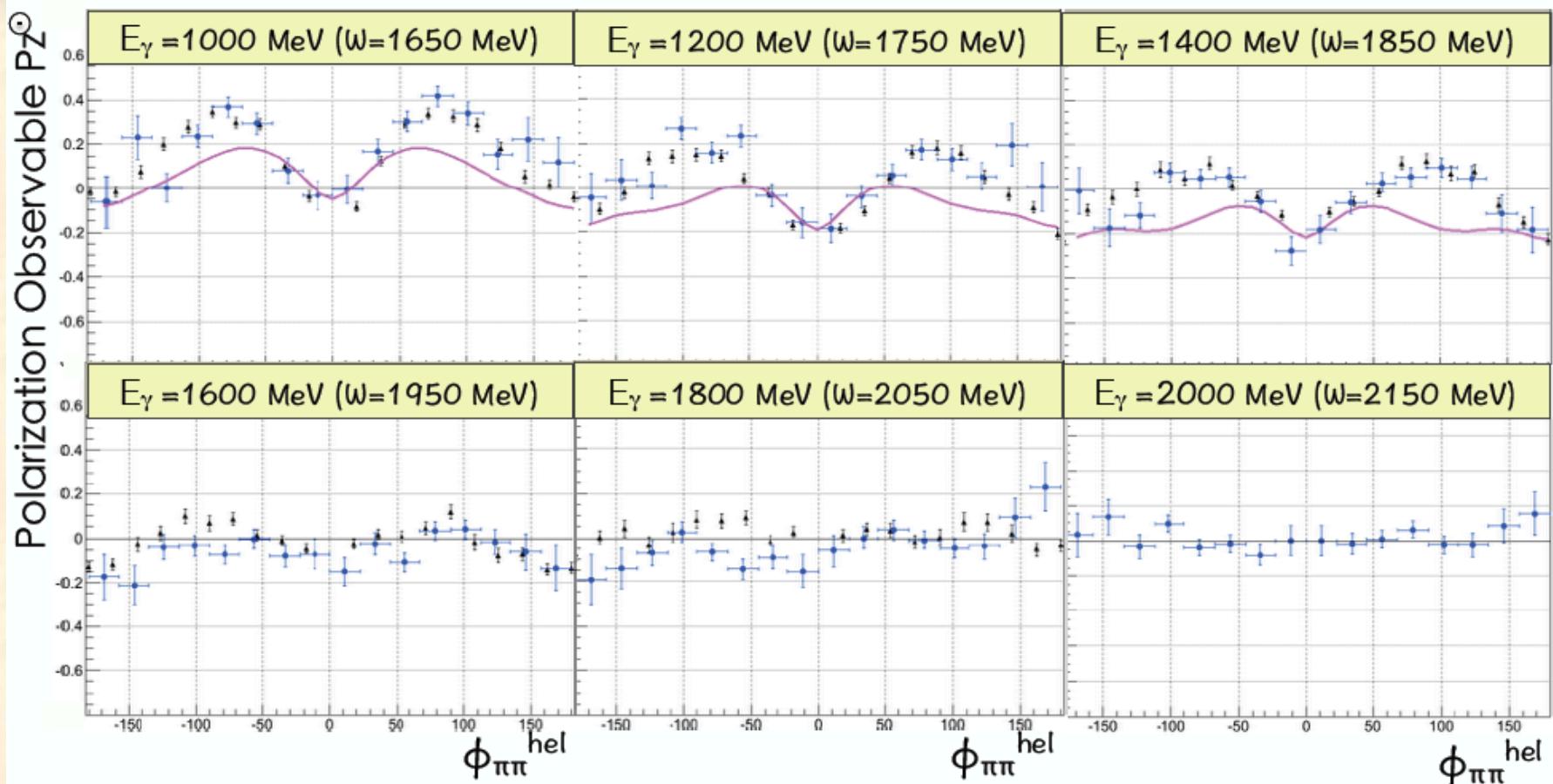
I. Zonta (U. Roma Tor Vergata)



Polarization Observable I<sup>⊕</sup>

- First measurement of the beam-helicity asymmetry

I. Zonta (U. Roma Tor Vergata)

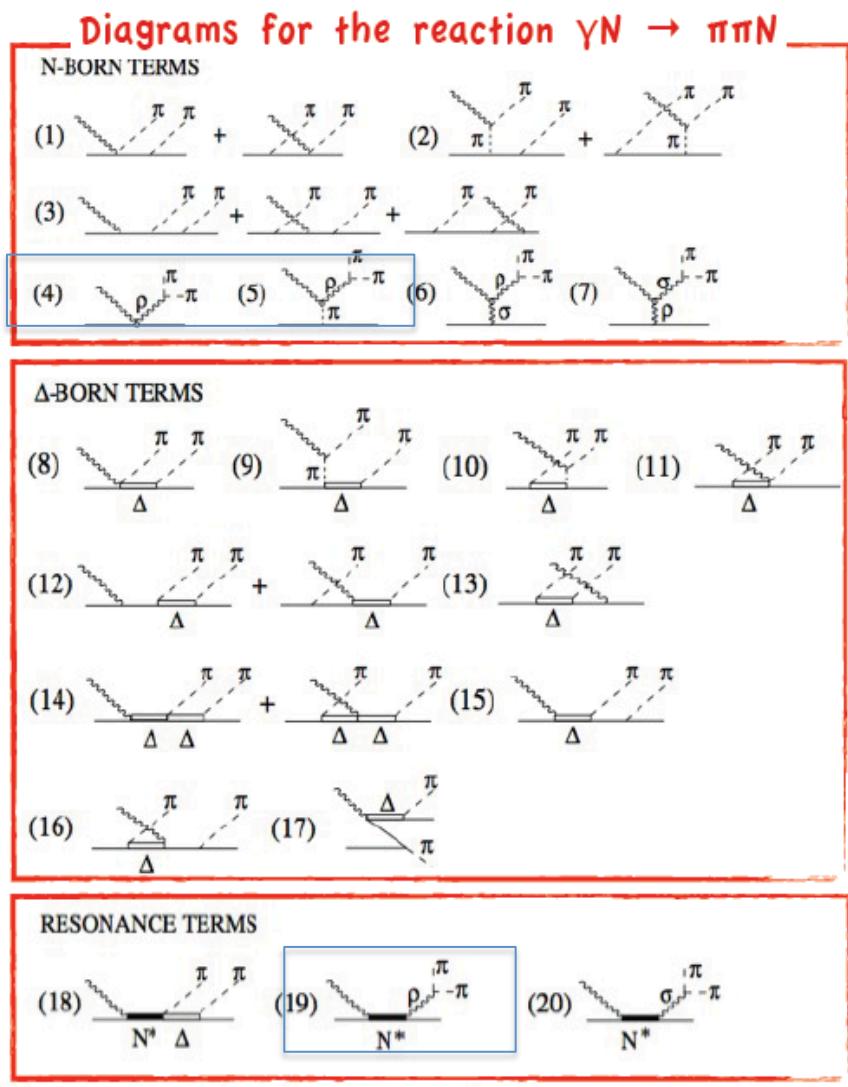
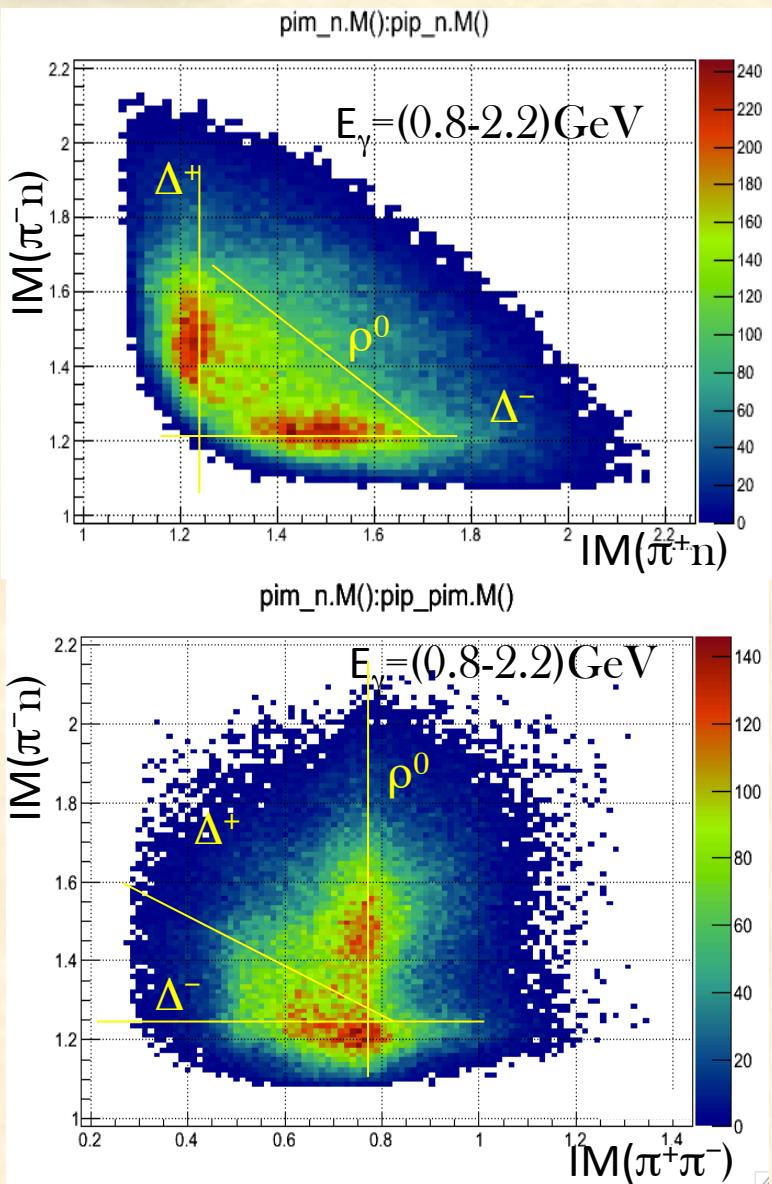


- *g14 data* HD-ICE target

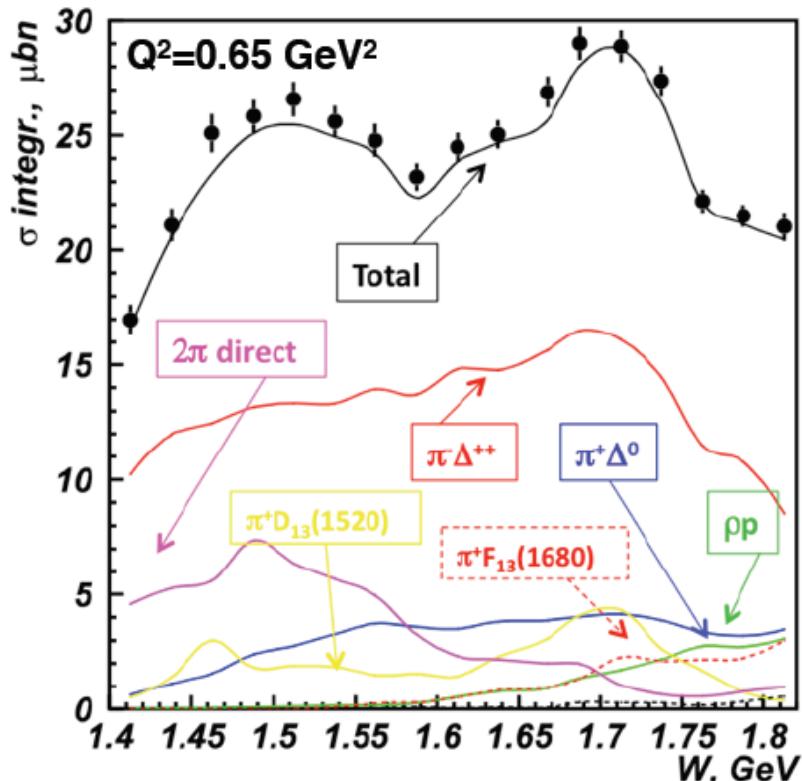
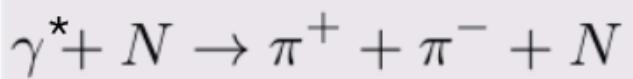
- ▲ *g9 data* FROST target

- *MAID* model

I. Zonta (U. Roma Tor Vergata)



A. Fix and H. Arenhovel, Eur.Phys.J. **A25** (2005) 115, nucl-th/0503042.



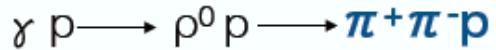
by V. Mokeev (JLab-Moscow model)

it's the final states of  
several possible reactions

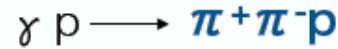
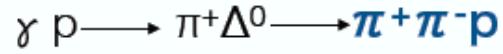
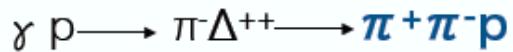
disentangled for  
electroproduction  
by V. Mokeev

1) **SELECTION:**  $|M(\pi^+\rho)| > 1.3 \text{ GeV}$  and  $|M(\pi^-\rho)| > 1.3 \text{ GeV}$

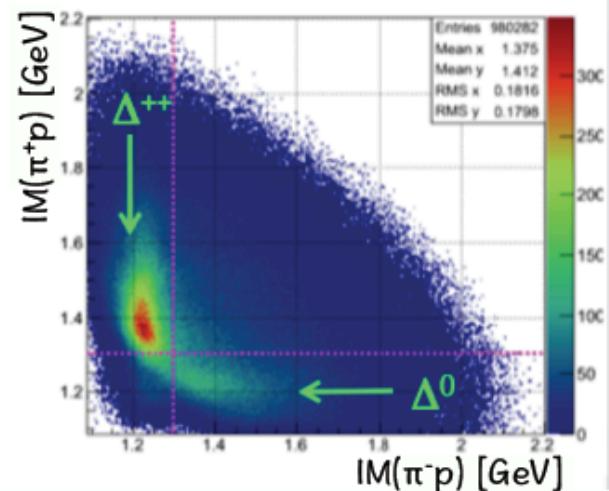
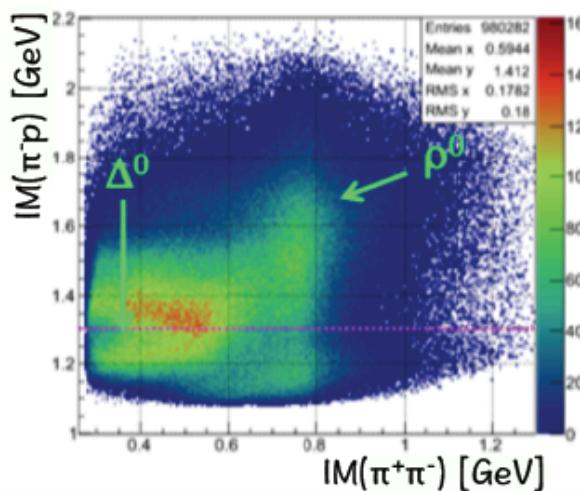
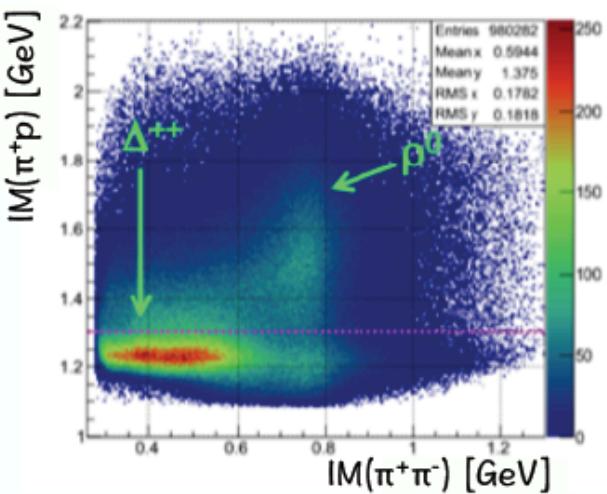
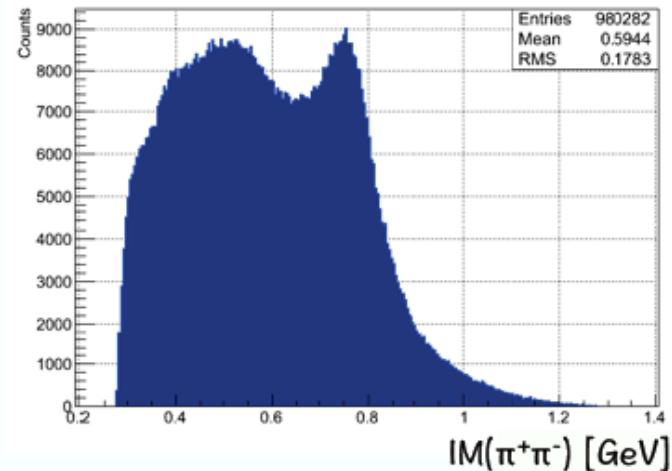
Goal → disentangle the reaction:

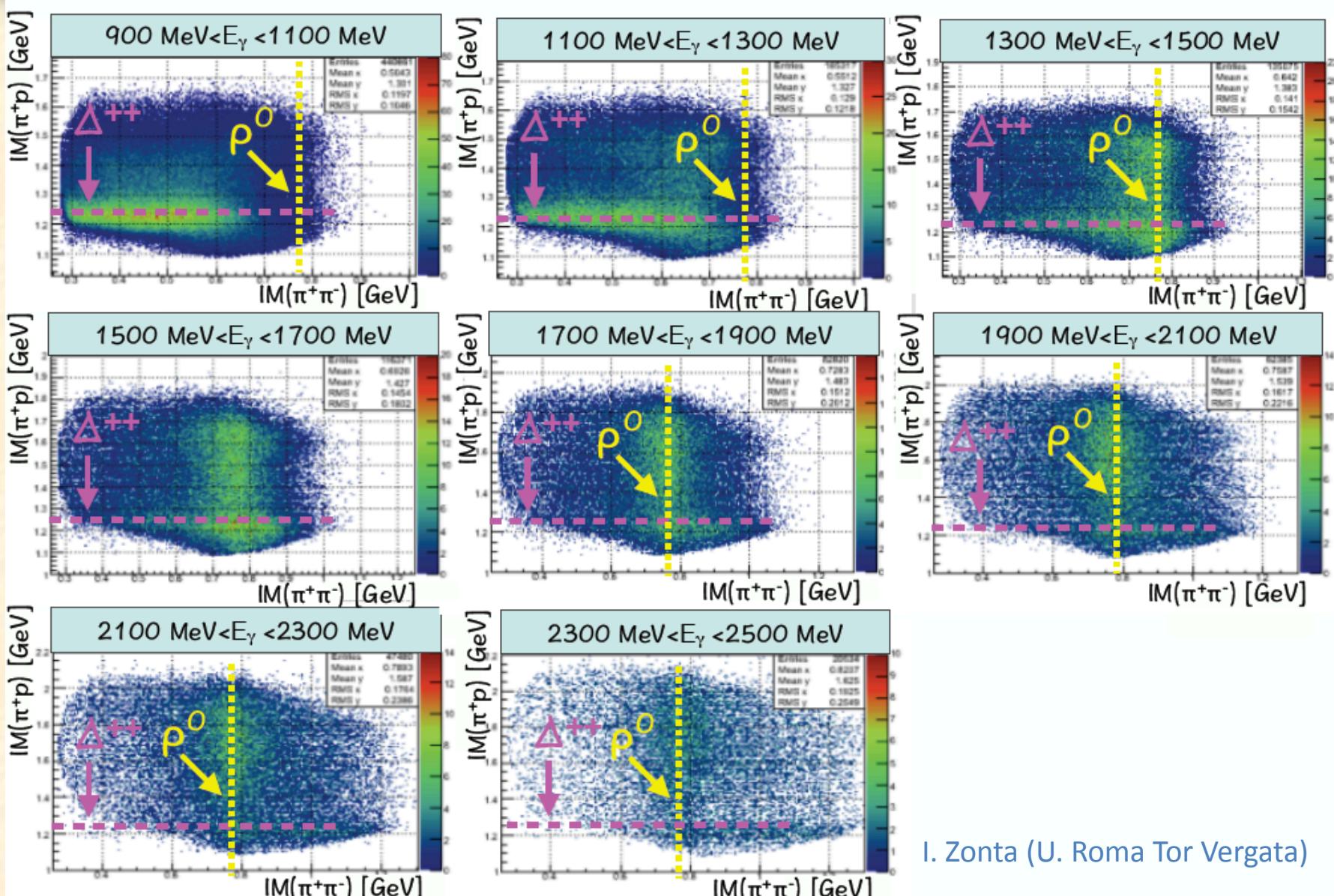


From the three concurrent reactions:

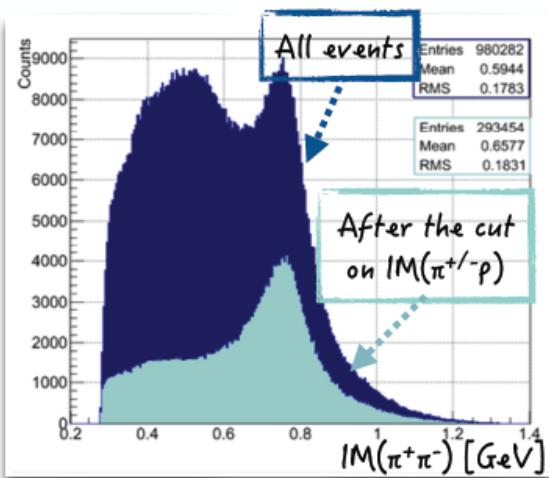


$|M(\pi^+ \pi^-)|$  spectrum

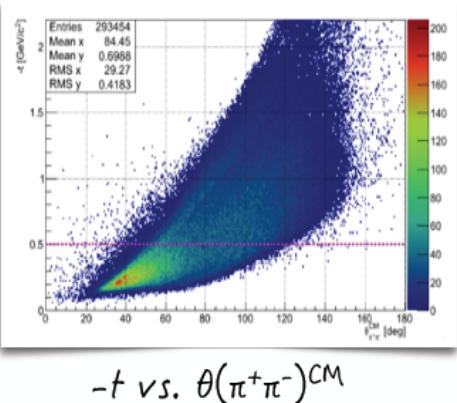




I. Zonta (U. Roma Tor Vergata)

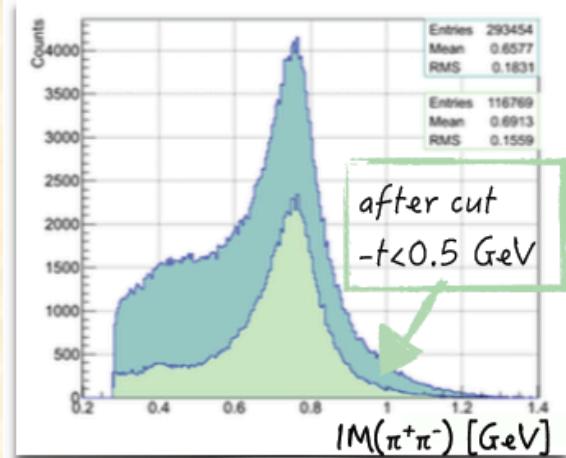


2) SELECTION: cut on  $-t < 0.5$  GeV

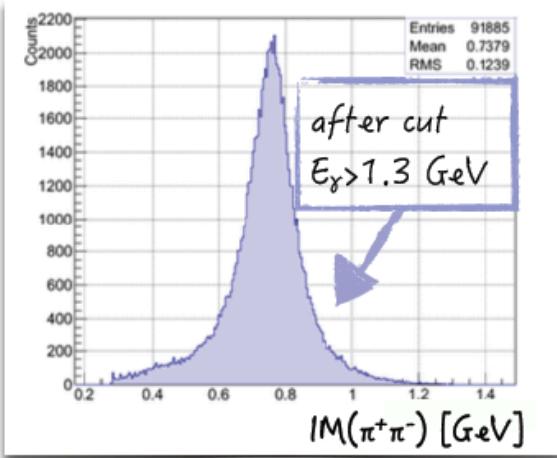


$-t$  vs.  $\theta(\pi^+\pi^-)$  CM

3) SELECTION: cut on  $E_\gamma > 1.3$  GeV

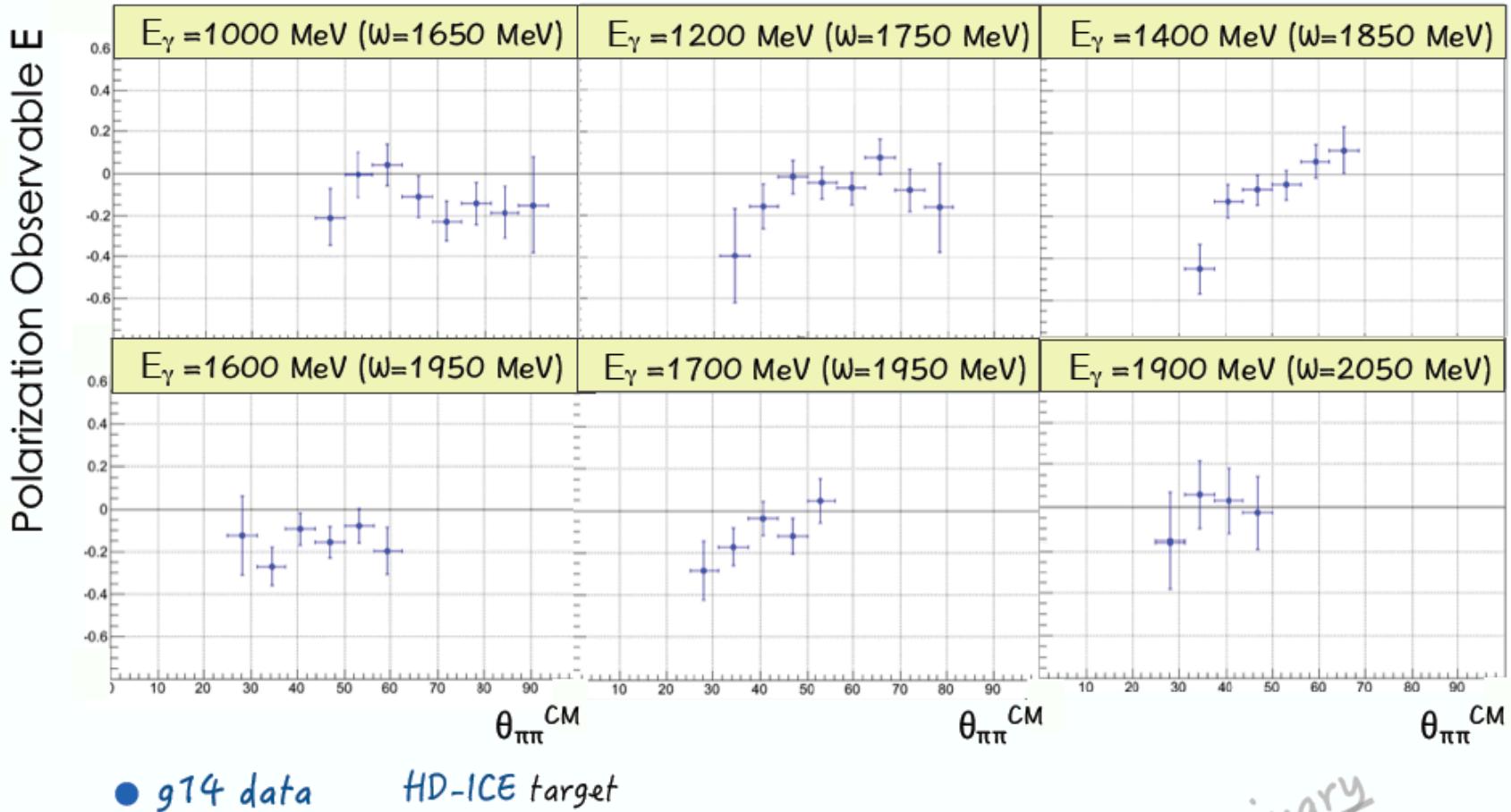


Final  $IM(\pi^+\pi^-)$  spectrum



## Events selection:

- $IM(p\pi^+) > 1.3$  GeV
- $IM(p\pi^-) > 1.3$  GeV
- $t < 0.5$  GeV
- $E_\gamma > 1.3$  GeV



● g14 data      HD-ICE target

- First measurement of the beam-target asymmetry

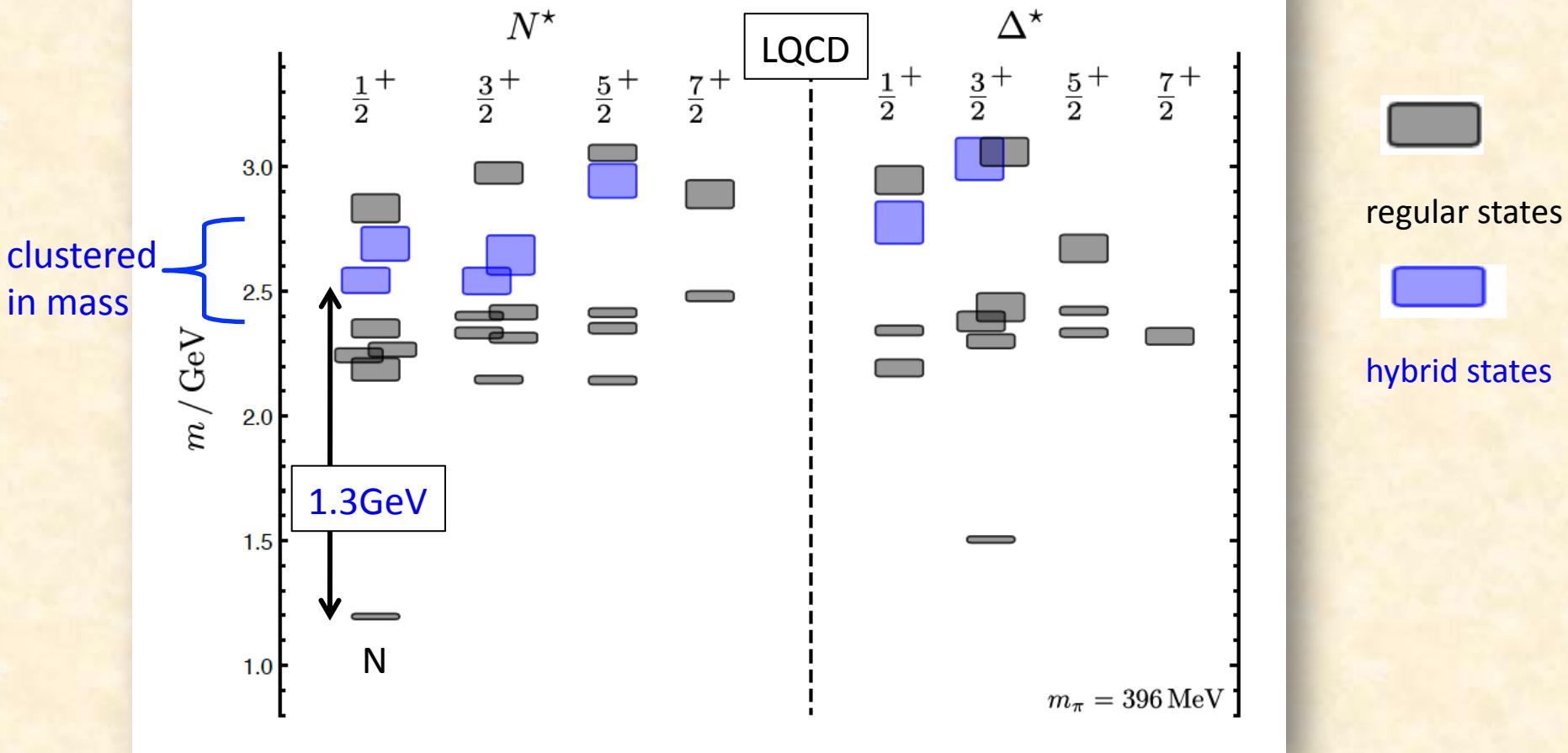
*Very preliminary*  
I. Zonta (U. Roma Tor Vergata)

# Future?

# Hybrid Baryons in LQCD

J.J. Dudek and R.G. Edwards, PRD85 (2012) 054016

T. Barnes and F.E. Close, PLB128, 277 (1983)

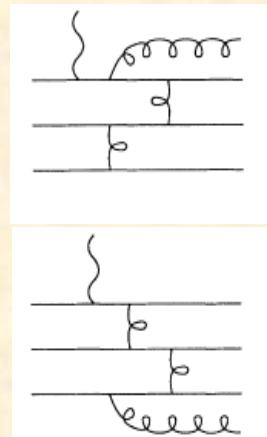
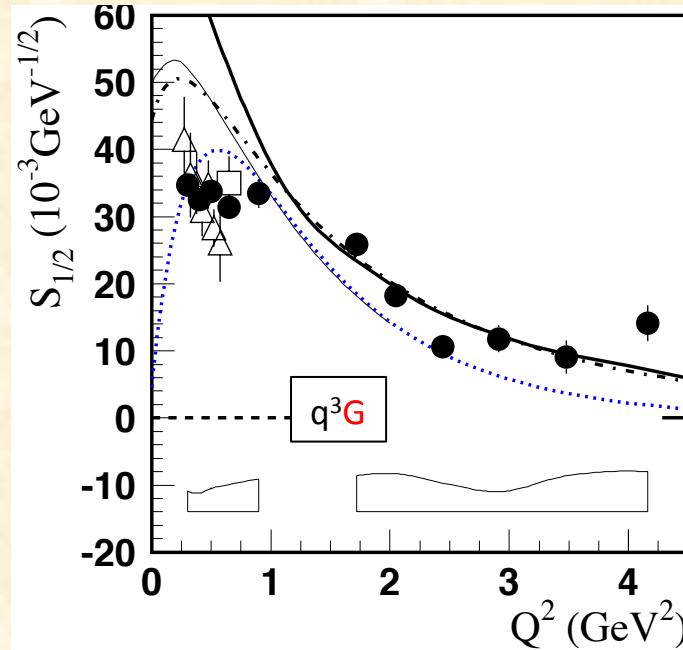
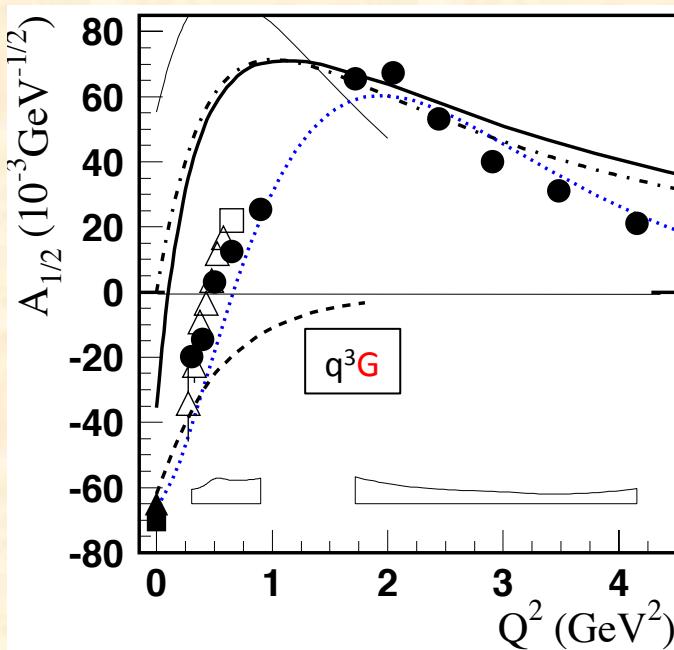


Hybrid states have same  $J^P$  values as  $Q^3$  baryons. How to identify them?

- Overpopulation of  $N1/2^+$  and  $N3/2^+$  states compared to QM projections?
- Transition form factors in electroproduction have different  $Q^2$  dependence

Z.P. Li, V.Burkert, Zh. Li, PRD46 (1992)70; C.E. Carlson, N. Mukhopadhyay, PRL 67, 3745, 1991

## Lowest mass QQQG state N1/2<sup>+</sup>



- $A_{1/2}$  dominant amplitude at high  $Q^2$  indicates radial QQQ excitation
- Significant meson-baryon coupling at small  $Q^2$

For hybrid “Roper”, transverse amplitude  $A_{1/2}(Q^2)$  drops off faster with  $Q^2$ , and  $S_{1/2}(Q^2) \sim 0$ .

- Thanks to precise new data, including double polarization data, the role of photoreaction data as been recognized for the first time by the PDG to impact the existing evidence of Nstar resonances, which seem to rule out di-quark models.
- Community achieved important milestone in the search for new baryon states from photoproduction – 6 new candidates, 2 almost certain in RPP 2012. Two further confirmations for  $N(1900)3/2^+$ .
- New results are about to come and are expected to further improve our knowledge of the baryonic excited states.

I would like to thank the HD-Ice group and CLAS collaboration for letting me present preliminary data

# The $P_{13}(1900)3/2^+$ State

- State solidly established in coupled-channel analysis making use of very precise  $K\Lambda$  data, resulting in \*\*\* assignment in PDG2012.
- State was confirmed in covariant isobar model analysis (*T. Mart & M. J. Kholili arXiv: 1208.2780*) of single channel analysis  $\gamma p \rightarrow K^+\Lambda$ .
- Confirmed in an effective Langrangian resonance model analysis (*O. V. Maxwell, PRC85,034611, 2012*) of photo- and electroproduction of single channel  $K^+\Lambda$  data.
- **State may be ready for promotion to \*\*\* assignment and to become the first baryon resonance observed and confirmed in electromagnetic meson production.**

