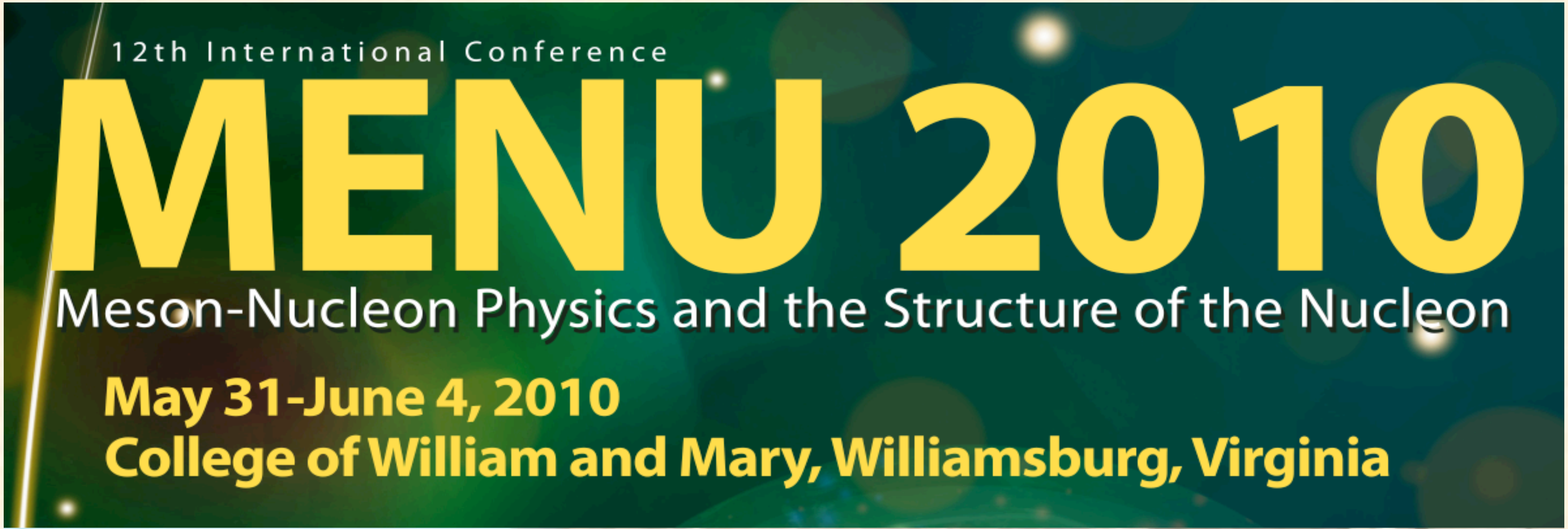

COMPLETE PHOTOPRODUCTION EXPERIMENTS

Annalisa D'ANGELO

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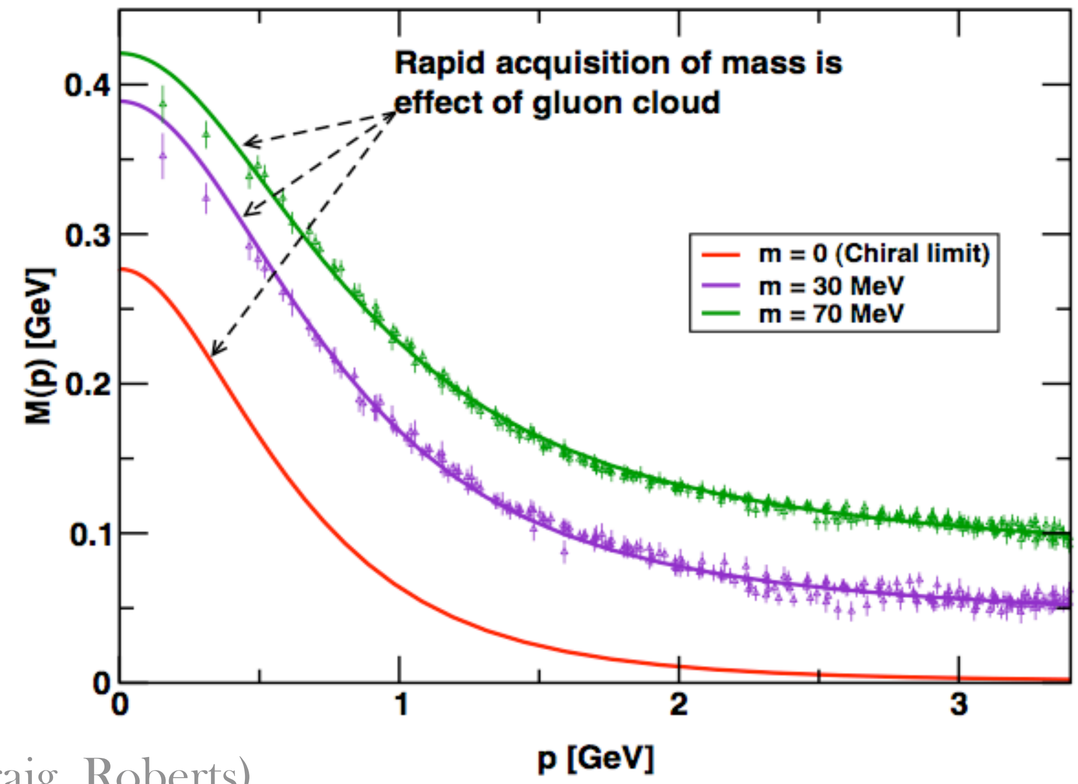
Outline

- Introduction: missing resonances and hadronic degrees of freedom
- Pseudoscalar meson photoproduction: spin and isospin dependent amplitudes extraction
- Results from Legs and Graal
- Vector meson photoproduction: spin density matrix
- Conclusions

Hadron Models: connection between constituent and current quarks



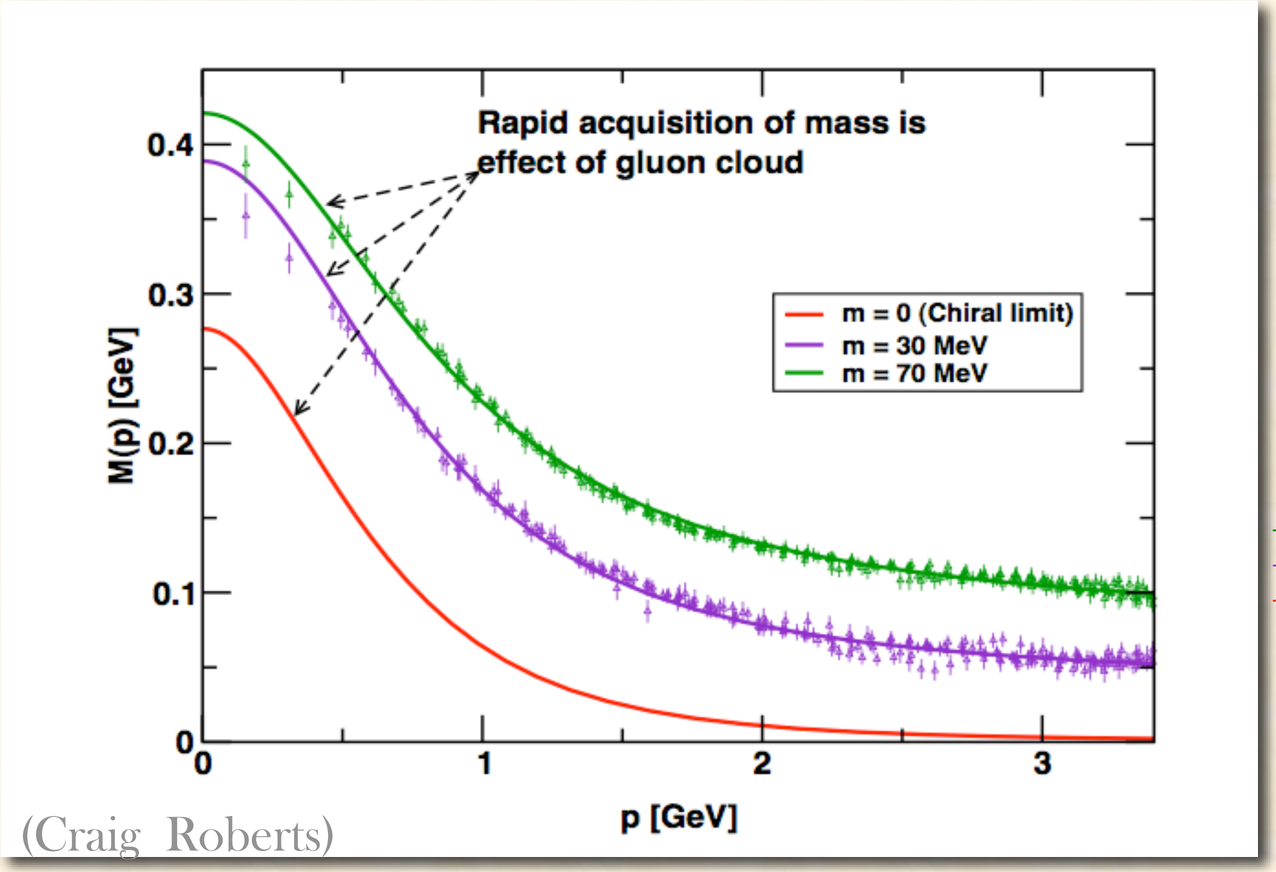
(Craig Roberts)

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

Dyson-Swinger equation (Bhagwat et al.)

Current-quarks of perturbative QCD evolve into constituent quarks as low momentum → the constituent quark mass arises from low momentum gluons that attaching them selves to current quarks.

Hadron Models: connection between constituent and current quarks



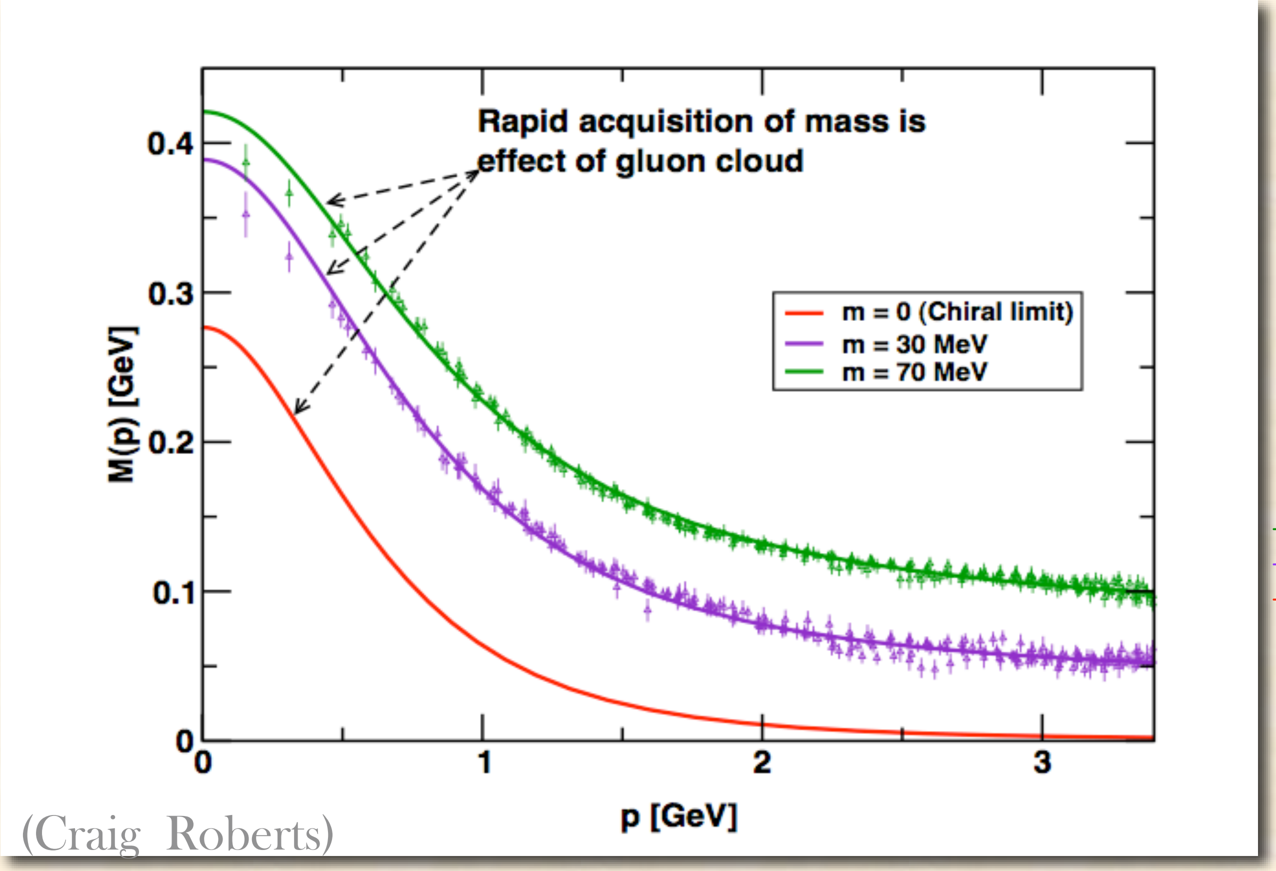
▲ ▲ numerical simulations of unquenched lattice QCD (Bowman et al.)

Dyson-Swinger equation (Bhagwat et al.)

This effect is a dynamical chiral symmetry breaking (DCSB): a non-perturbative QCD effect that occurs also at the chiral limit

→ *generates mass from nothing*

Hadron Models: connection between constituent and current quarks



(Craig Roberts)

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

Dyson-Swinger equation (Bhagwat et al.)

The interaction that describes color-singlet mesons also generates axial-vector isotriplet quark-quark correlations with significant attraction :

$m[ud]_0 = 0.74 - 0.82$ GeV

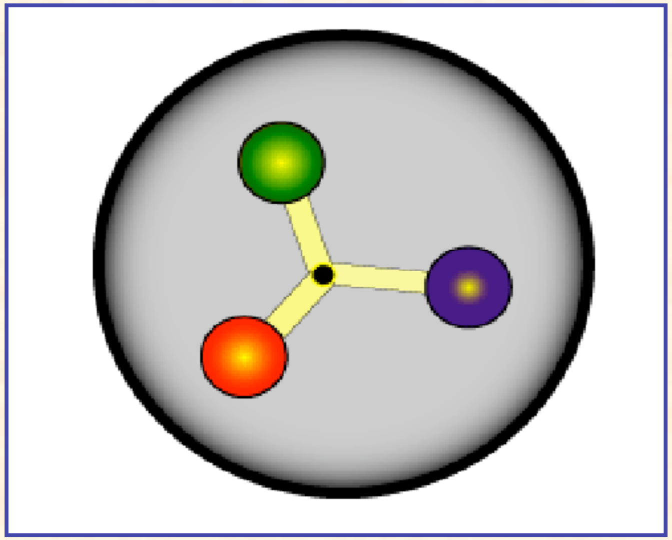
$m[ud]_1 = m[uu]_1 = m[dd]_1 = 0.95 - 1.02$ GeV ⟶ **di-Quarks**

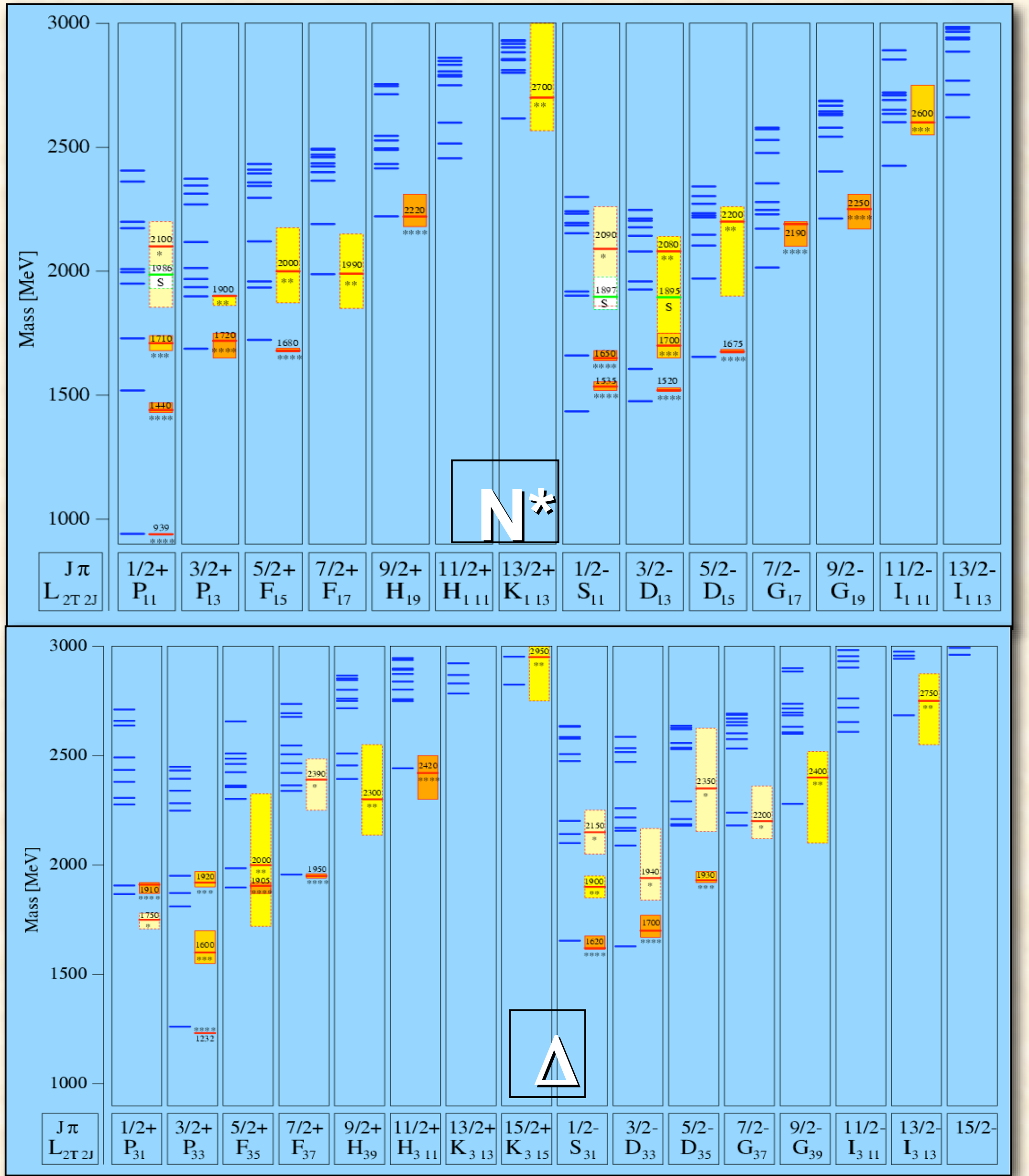
QCD-inspired Constituent Quark Models

- Chiral symmetry breaking of the QCD Lagrangian generates Constituent Q with effective masses - confirmed by LQCD and DSE calculations.

- Asymmetry of the baryon wave function is guaranteed by color, but color degrees of freedom are integrated out and play no dynamical role.

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





Shaded boxes: experimental results

Thick segments: theoretical predictions

(by S. Capstick)

QCD -inspired Constituent Quark Models

• Chiral symmetry breaking of the QCD Lagrangian generates Constituent Q with effective masses - confirmed by LQCD and DSE calculations.

•Asymmetry of the baryon wave function is guaranteed by color, but color degrees of freedom are integrated out and play no dynamical role.

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

• Only lowest few have been seen in each band (in πN) with 4★ or 3★ status

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

			Status as seen in —						
Particle	$L_{2I\cdot 2J}$	Overall status	$N\pi$	$N\eta$	ΛK	ΣK	$\Delta\pi$	$N\rho$	$N\gamma$
$N(939)$	P_{11}	****							
$N(1440)$	P_{11}	****	****	*			***	*	***
$N(1520)$	D_{13}	****	****	***			****	****	****
$N(1535)$	S_{11}	****	****	****			*	**	***
$N(1650)$	S_{11}	****	****	*	***	**	***	**	***
$N(1675)$	D_{15}	****	****	*	*		****	*	****
$N(1680)$	F_{15}	****	****	*			****	****	****
$N(1700)$	D_{13}	***	***	*	**	*	**	*	**
$N(1710)$	P_{11}	***	***	**	**	*	**	*	***
$N(1720)$	P_{13}	****	****	*	**	*	*	**	**
$N(1900)$	P_{13}	**	**					*	
$N(1990)$	F_{17}	**	**	*	*	*			*
$N(2000)$	F_{15}	**	**	*	*	*	*	**	
$N(2080)$	D_{13}	**	**	*	*				*
$N(2090)$	S_{11}	*	*						
$N(2100)$	P_{11}	*	*	*					
$N(2190)$	G_{17}	****	****	*	*	*		*	*
$N(2200)$	D_{15}	**	**	*	*				
$N(2220)$	H_{19}	****	****	*					
$N(2250)$	G_{19}	****	****	*					
$N(2600)$	$I_{1\,11}$	***	***						
$N(2700)$	$K_{1\,13}$	**	**						
$\Delta(1232)$	P_{33}	****	****	F					****
$\Delta(1600)$	P_{33}	***	***	o			***	*	**
$\Delta(1620)$	S_{31}	****	****	r			****	****	***
$\Delta(1700)$	D_{33}	****	****	b		*	***	**	***
$\Delta(1750)$	P_{31}	*	*	i					
$\Delta(1900)$	S_{31}	**	**	d		*	*	**	*
$\Delta(1905)$	F_{35}	****	****	d		*	**	**	***
$\Delta(1910)$	P_{31}	****	****	e		*	*	*	*
$\Delta(1920)$	P_{33}	***	***	n		*	**		*
$\Delta(1930)$	D_{35}	***	***			*			**
$\Delta(1940)$	D_{33}	*	*	F					
$\Delta(1950)$	F_{37}	****	****	o		*	****	*	****
$\Delta(2000)$	F_{35}	**		r			**		
$\Delta(2150)$	S_{31}	*	*	b					
$\Delta(2200)$	G_{37}	*	*	i					
$\Delta(2300)$	H_{39}	**	**	d					
$\Delta(2350)$	D_{35}	*	*	d					
$\Delta(2390)$	F_{37}	*	*	e					
$\Delta(2400)$	G_{39}	**	**	n					
$\Delta(2420)$	$H_{3\,11}$	****	****						*
$\Delta(2750)$	$I_{3\,13}$	**	**						
$\Delta(2950)$	$K_{3\,15}$	**	**						

QCD -inspired Constituent Quark Models

• Chiral symmetry breaking of the QCD Lagrangian generates Constituent Q with effective masses - confirmed by LQCD and DSE calculations.

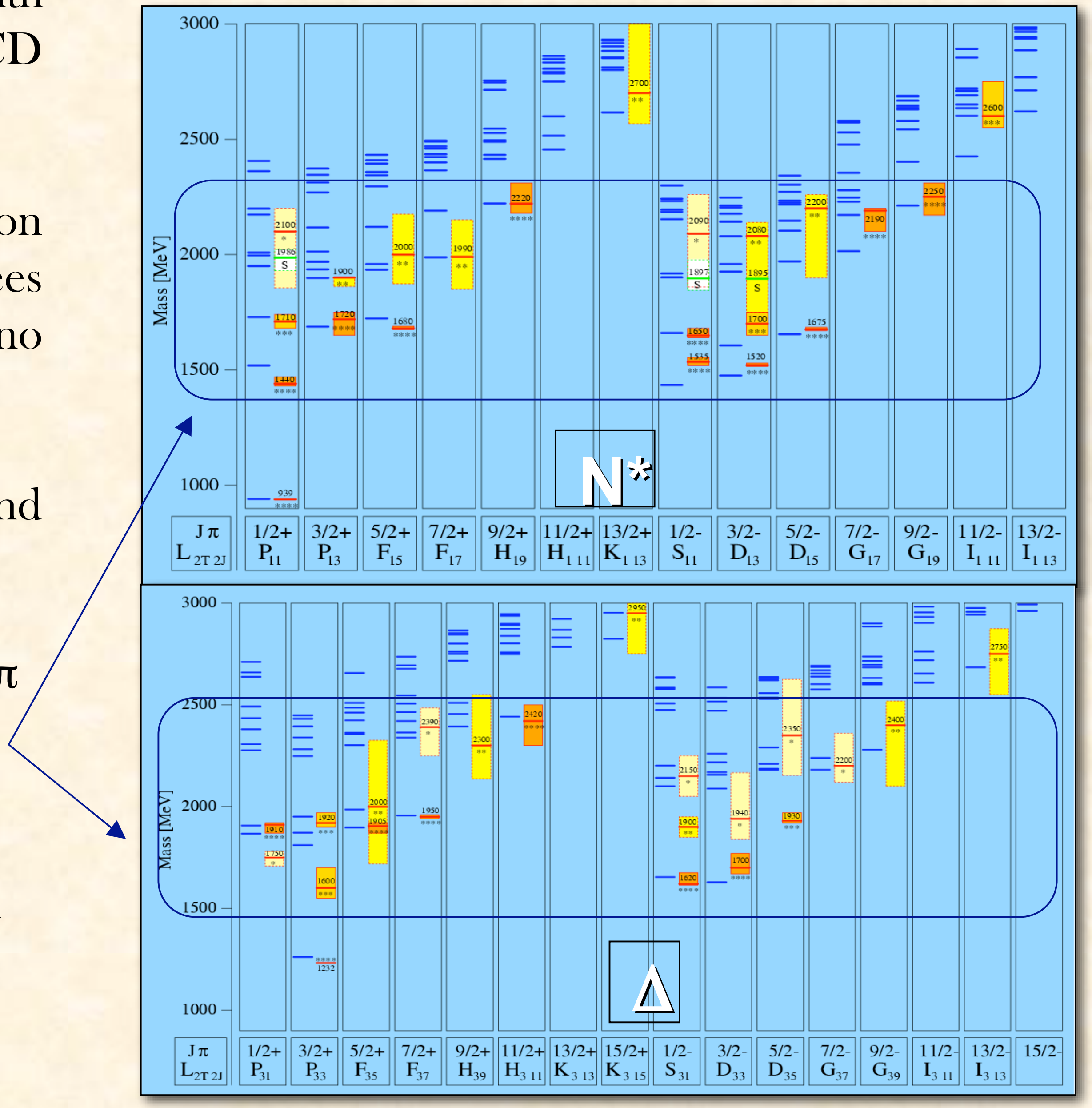
•Asymmetry of the baryon wave function is guaranteed by color, but color degrees of freedom are integrated out and play no dynamical role.

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

• only lowest few in each band seen (in π N) with 4★ or 3★ status

• g(πN) couplings predicted to decrease rapidly with mass in each oscillator band

• higher levels predicted to have larger couplings to KΛ, KΣ, ππN, ...



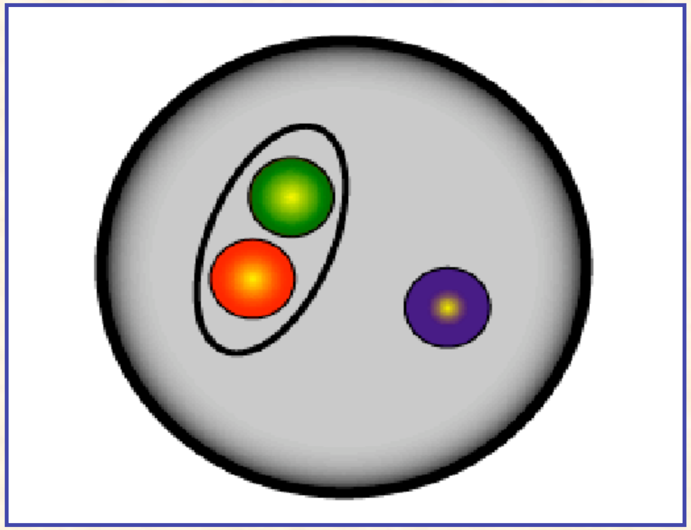
QCD -inspired di- Quark Models

- 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 ⇔ full spectrum of CQM

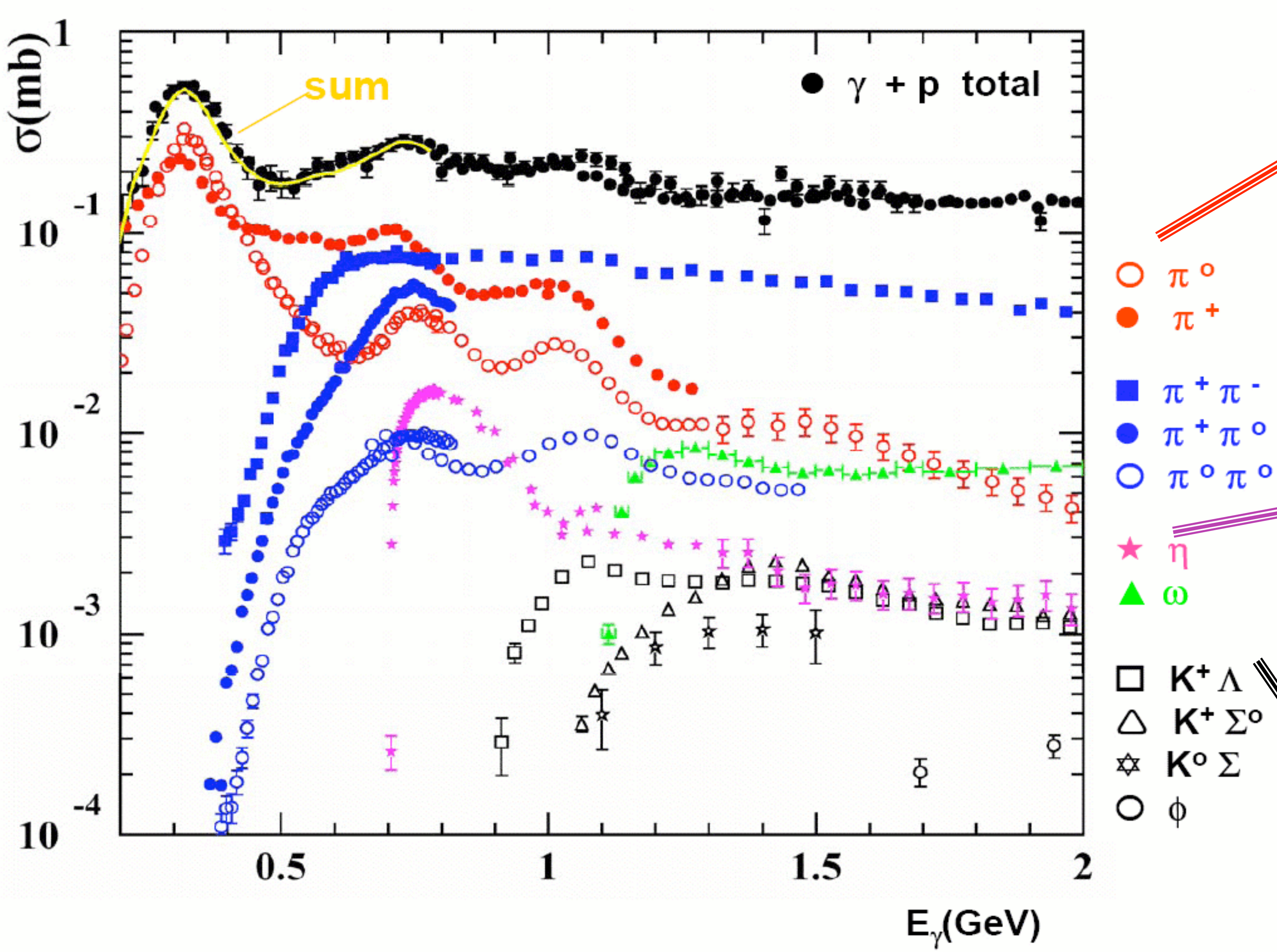
- internal di-quark excitations are frozen out (spin 0; isospin 0) ⇔ large reduction in the number of degrees of freedom ⇔ predicts less N^* states than seen in πN

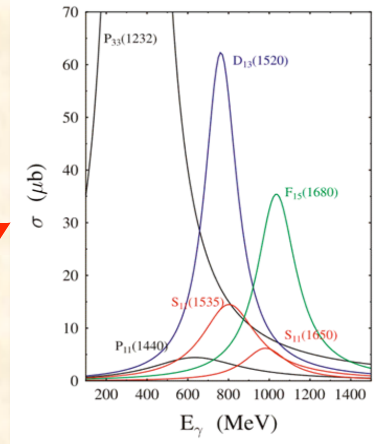
N^*	Status	$SU(6)\otimes U(3)$	Parity	Δ^*	Status	$SU(6)\otimes U(3)$	Parity
$P_{13}(938)$	****	$(56,0^+)$	+	$P_{33}(1232)$	****	$(56,0^+)$	+
$S_{11}(1535)$	****	$(70,1^-)$	-	$S_{31}(1620)$	****	$(70,1^-)$	-
$S_{11}(1650)$	****	$(70,1^-)$	-	$D_{13}(1700)$	***	$(70,1^-)$	-
$D_{13}(1520)$	****	$(70,1^-)$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

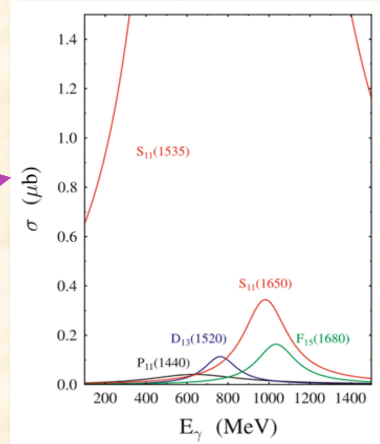


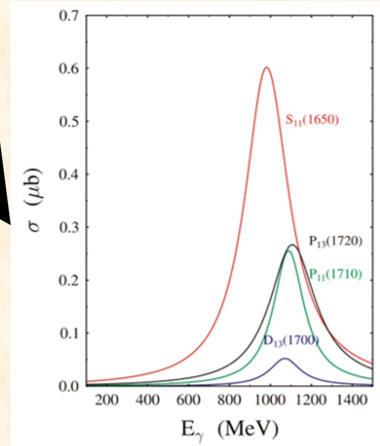
the challenge: ⇔ unravel the N^* spectrum

Photonuclear cross sections

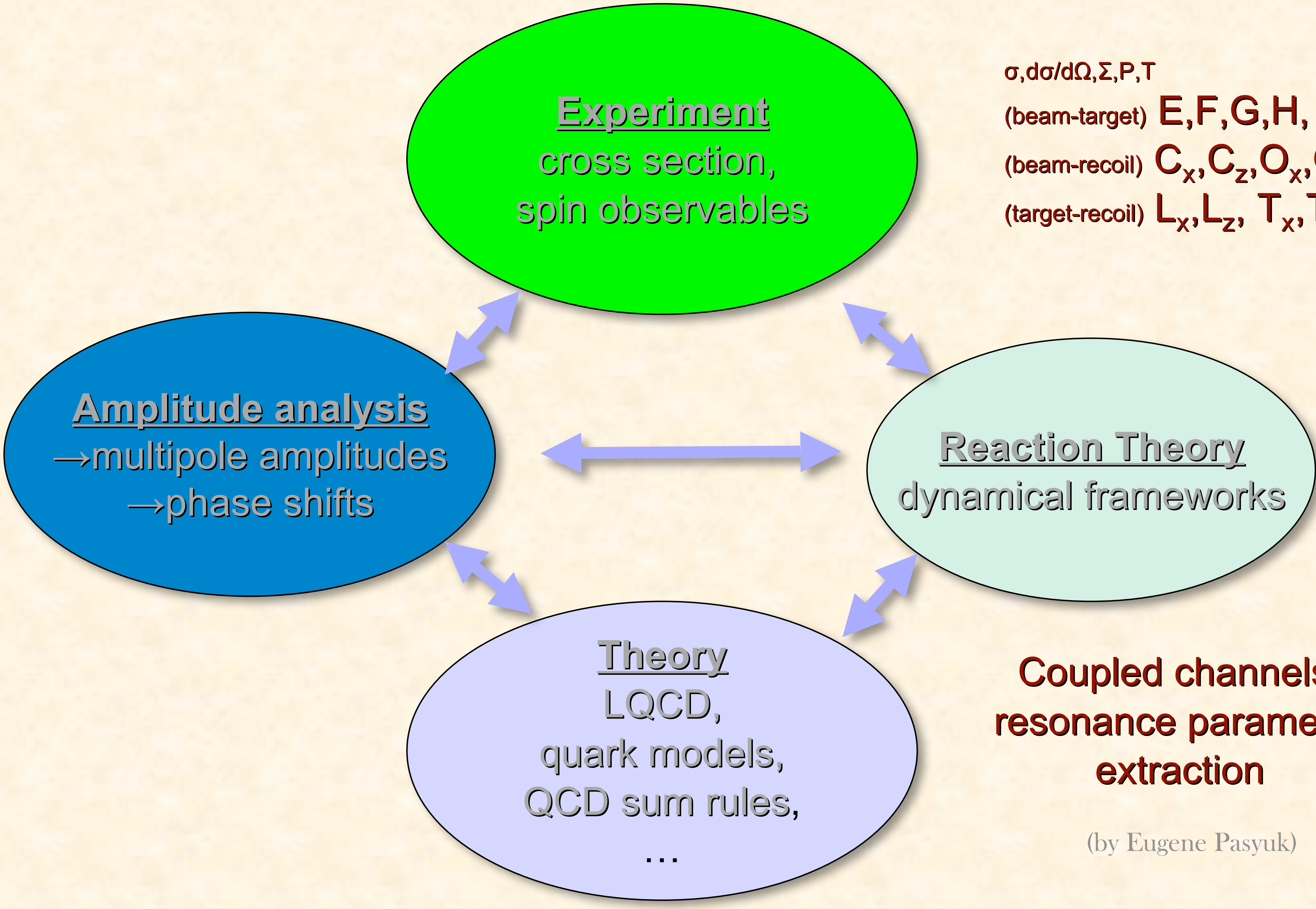








From the Experiment to Theory



$\sigma, d\sigma/d\Omega, \Sigma, P, T$

(beam-target) $E, F, G, H,$

(beam-recoil) $C_x, C_z, O_x, O_z,$

(target-recoil) $L_x, L_z, T_x, T_z,$

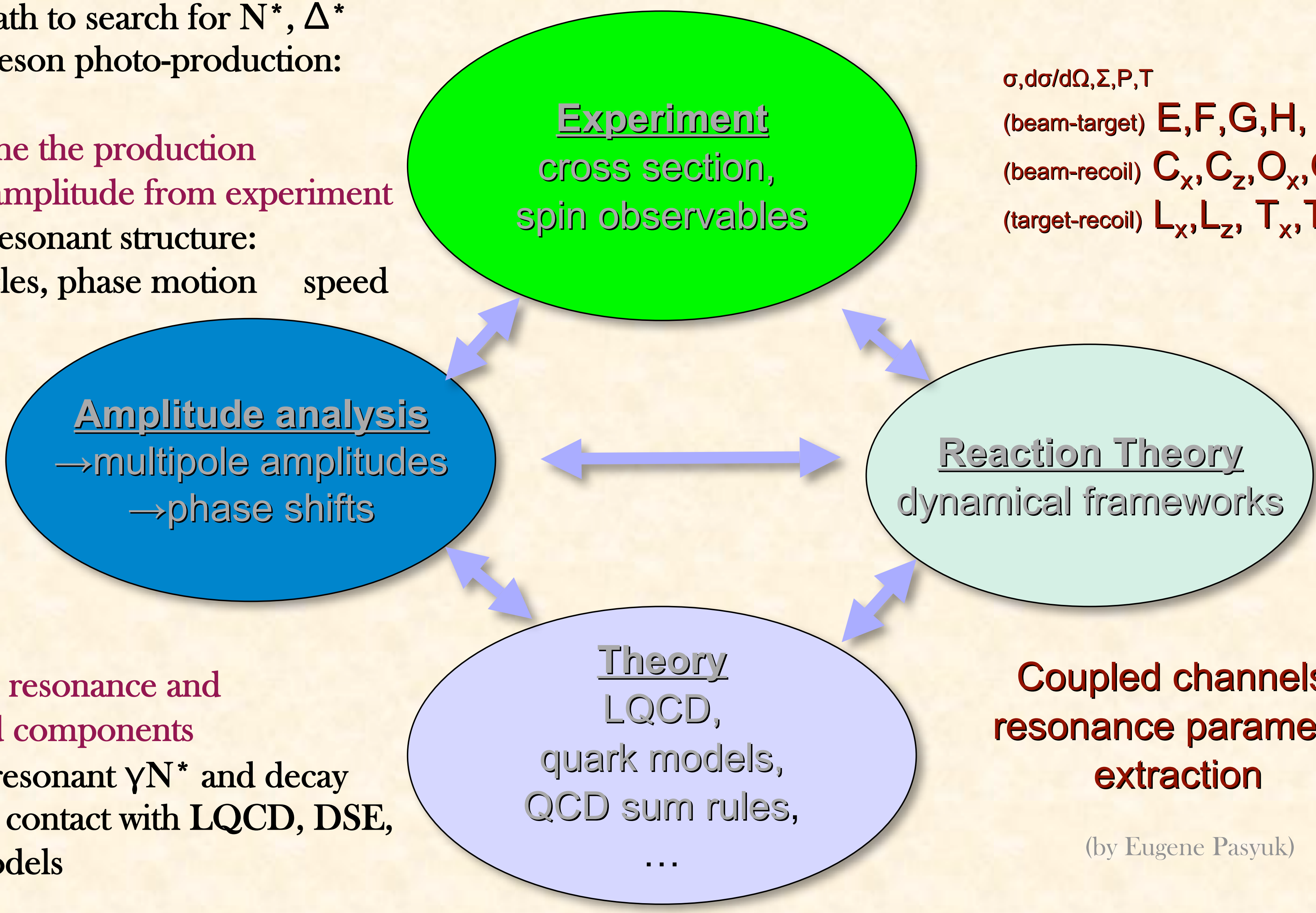
Coupled channels:
resonance parameter
extraction

(by Eugene Pasyuk)

From the Experiment to Theory

Idealized path to search for N*, Δ* states via meson photo-production:

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



$\sigma, d\sigma/d\Omega, \Sigma, P, T$
(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,

(2) separate resonance and background components
determine resonant γN* and decay couplings; contact with LQCD, DSE, Hadron models

Coupled channels: resonance parameter extraction

(by Eugene Pasyuk)

(A. Sandorfi et al.)

From the Experiment to Theory

Idealized path to search for N*, Δ* states via meson photo-production:

(1) determine the production amplitude 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 γN* and decay couplings; contact with LQCD, DSE, Hadron models

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

(A. Sandorfi et al.)

Complete experiments in pseudoscalar meson photoproduction

$$\gamma \quad + \quad N \quad \rightarrow \quad m \quad + \quad N$$

Spin states	± 1	$\pm\frac{1}{2}$	0	$\pm\frac{1}{2}$
	2	x 2		x 2

8 possible spin states → 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 →

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

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

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

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

Complete experiments in pseudoscalar meson photoproduction

$$\gamma \quad + \quad N \quad \rightarrow \quad m \quad + \quad N$$

Spin states $\quad \pm 1 \quad \pm\frac{1}{2} \quad\quad 0 \quad\quad \pm\frac{1}{2}$

$2 \quad x \quad 2 \quad\quad\quad x \quad 2$

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

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

→

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

Complete experiments in pseudoscalar meson photoproduction

$$\gamma \quad + \quad N \quad \rightarrow \quad m \quad + \quad N$$

Spin states $\pm 1 \quad \pm\frac{1}{2} \qquad 0 \qquad \pm\frac{1}{2}$

$2 \quad x \quad 2 \qquad\qquad x \quad 2$

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

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

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

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

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

From decomposition into partial waves:

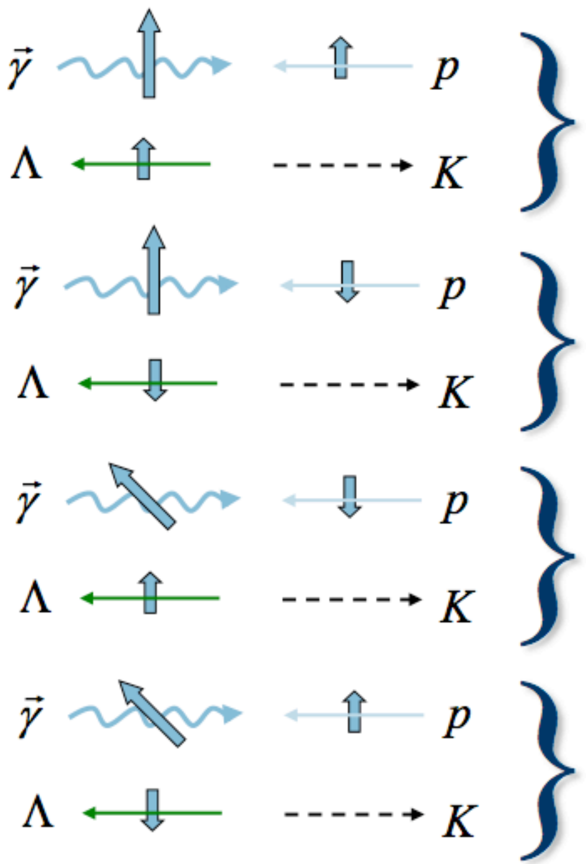
$$d^J{}_{\Lambda_f - \Lambda_i}(\theta) \qquad \Lambda_i = \lambda - \lambda_1 \qquad \Lambda_f = -\lambda_2$$

$H_4 = N$	no helicity flip
$H_2, H_3 = S_1, S_2$	single helicity flip
$H_1 = D$	double helicity flip

Complete experiments 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



$$b_1 = {}^1/_2[(S_1 + S_2) + i(N - D)]$$

$$b_2 = {}^1/_2[(S_1 + S_2) - i(N - D)]$$

$$b_3 = {}^1/_2[(S_1 - S_2) - i(N + D)]$$

$$b_4 = {}^1/_2[(S_1 - S_2) + i(N + D)]$$

(D. Ireland)

Polarization observables 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

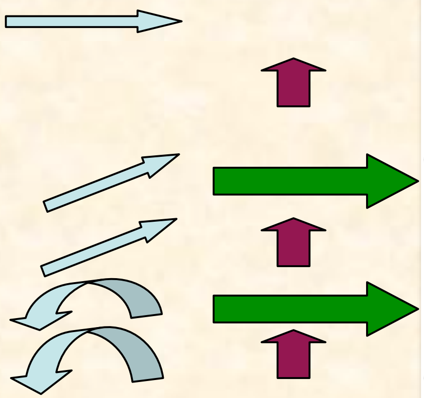
$\gamma p \rightarrow \pi p$

Recoil Beam Target

High statistics - no recent recoil polarization measurements

↓

Talk by Wei Luo



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

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

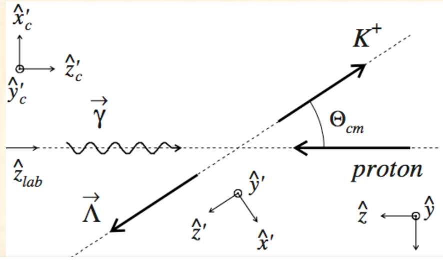
Target

Transverse polarization Lomgitudinal polarization

Beam

Linear polarization at 90° Linear polarization at 45° Circular polarization

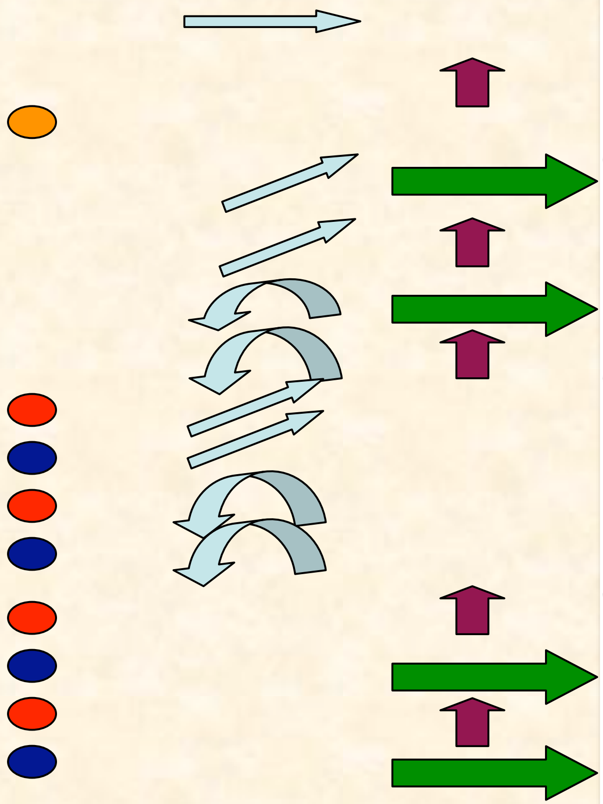
Polarization observables in pseudoscalar meson photoproduction



Weak Λ decay is self-analyzing

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

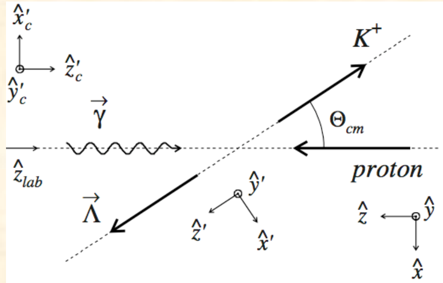
Recoil Beam Target



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
$\Sigma d\sigma/dt$	$\lvert b_1\rvert^2 + \lvert b_2\rvert^2 - \lvert b_3\rvert^2 - \lvert b_4\rvert^2$	$\{L(\frac{1}{2}\pi,0);-;-\}$	
$T d\sigma/dt$	$\lvert b_1\rvert^2 - \lvert b_2\rvert^2 - \lvert b_3\rvert^2 + \lvert b_4\rvert^2$	$\{-;y;-\}$	
$P d\sigma/dt$	$\lvert b_1\rvert^2 - \lvert b_2\rvert^2 + \lvert b_3\rvert^2 - \lvert b_4\rvert^2$	$\{-;-;y\}$	
$G d\sigma/dt$	$2\ \mathrm{Im}(b_1 b_3^* + b_2 b_4^*)$	$\{L(\pm\frac{1}{4}\pi);z;-\}$	BT
$H d\sigma/dt$	$-2\ \mathrm{Re}(b_1 b_3^* - b_2 b_4^*)$	$\{L(\pm\frac{1}{4}\pi);x;-\}$	
$E d\sigma/dt$	$-2\ \mathrm{Re}(b_1 b_3^* + b_2 b_4^*)$	$\{C;z;-\}$	
$F d\sigma/dt$	$2\ \mathrm{Im}(b_1 b_3^* - b_2 b_4^*)$	$\{C;x;-\}$	
$O_x d\sigma/dt$	$-2\ \mathrm{Re}(b_1 b_4^* - b_2 b_3^*)$	$\{L(\pm\frac{1}{4}\pi);-;x'\}$	BR
$O_z d\sigma/dt$	$-2\ \mathrm{Im}(b_1 b_4^* + b_2 b_3^*)$	$\{L(\pm\frac{1}{4}\pi);-;z'\}$	
$C_x d\sigma/dt$	$2\ \mathrm{Im}(b_1 b_4^* - b_2 b_3^*)$	$\{C;-;x'\}$	
$C_z d\sigma/dt$	$-2\ \mathrm{Re}(b_1 b_4^* + b_2 b_3^*)$	$\{C;-;z'\}$	
$T_x d\sigma/dt$	$2\ \mathrm{Re}(b_1 b_2^* - b_3 b_4^*)$	$\{-;x;x'\}$	TR
$T_z d\sigma/dt$	$2\ \mathrm{Im}(b_1 b_2^* - b_3 b_4^*)$	$\{-;x;z'\}$	
$L_x d\sigma/dt$	$2\ \mathrm{Im}(b_1 b_2^* + b_3 b_4^*)$	$\{-;z;x'\}$	
$L_x d\sigma/dt$	$2\ \mathrm{Re}(b_1 b_2^* + b_3 b_4^*)$	$\{-;z;z'\}$	

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

Polarization observables in pseudoscalar meson photoproduction



Weak Λ decay is self-analyzing

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

$$\begin{aligned}
d\sigma \;=\; & d\sigma_0 + \hat{\Sigma}[-P_L^\gamma \cos(2\phi_\gamma)] + \hat{T}[P_y^T] + \hat{P}[P_{y'}^R] \\
& + \hat{E}[-P_c^\gamma P_z^T] + \hat{G}[P_L^\gamma P_z^T \sin(2\phi_\gamma)] + \hat{F}[P_c^\gamma P_x^T] + \hat{H}[P_L^\gamma P_x^T \sin(2\phi_\gamma)] \\
& + \hat{C}_{x'}[P_c^\gamma P_{x'}^R] + \hat{C}_{z'}[P_c^\gamma P_{z'}^R] + \hat{O}_{x'}[P_L^\gamma P_{x'}^R \sin(2\phi_\gamma)] + \hat{O}_{z'}[P_L^\gamma P_{z'}^R \sin(2\phi_\gamma)] \\
& + \hat{L}_{x'}[P_z^T P_{x'}^R] + \hat{L}_{z'}[P_z^T P_{z'}^R] + \hat{T}_{x'}[P_x^T P_{x'}^R] + \hat{T}_{z'}[P_x^T P_{z'}^R].
\end{aligned}$$

Complete measurements are presently possible at CLAS and BONN

F, H and T observables require transversely polarized targets

Isospin dependence of reaction amplitudes 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.

$$A_{\gamma n\to\begin{pmatrix}\pi^0 n\\ K^0\Sigma^0\end{pmatrix}} = \pm\left[\frac{1}{\sqrt{3}}A^{(0)}_{\begin{pmatrix}\pi N\\ K\Sigma\end{pmatrix}} + \frac{1}{3}A^{(1)}_{\begin{pmatrix}\pi N\\ K\Sigma\end{pmatrix}}\right]^{(I=\frac{1}{2})} + \frac{2}{3}A^{(I=\frac{3}{2})}_{\begin{pmatrix}\pi N\\ K\Sigma\end{pmatrix}}$$

$$A_{\gamma n\to\begin{pmatrix}\pi^- p\\ K^+\Sigma^-\end{pmatrix}} = \mp\sqrt{2}\left[\frac{1}{\sqrt{3}}A^{(0)}_{\begin{pmatrix}\pi N\\ K\Sigma\end{pmatrix}} + \frac{1}{3}A^{(1)}_{\begin{pmatrix}\pi N\\ K\Sigma\end{pmatrix}}\right]^{(I=\frac{1}{2})} + \frac{\sqrt{2}}{3}A^{(I=\frac{3}{2})}_{\begin{pmatrix}\pi N\\ K\Sigma\end{pmatrix}}$$

$$A_{\gamma n\to\begin{pmatrix}\eta n\\ K^0\Lambda\end{pmatrix}} = +\left[A^{(0)}_{\begin{pmatrix}\eta N\\ K\Lambda\end{pmatrix}} + \frac{1}{\sqrt{3}}A^{(1)}_{\begin{pmatrix}\eta N\\ K\Lambda\end{pmatrix}}\right]^{(I=\frac{1}{2})}.$$

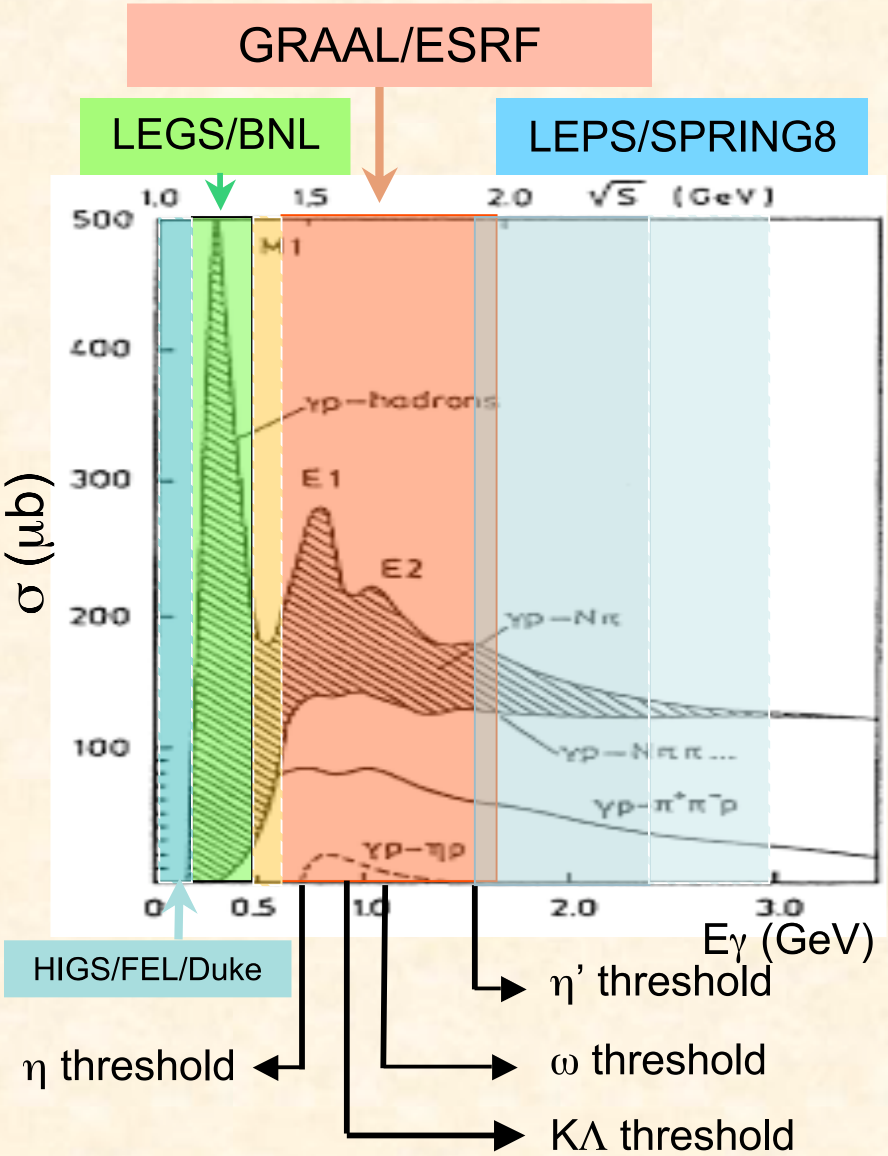
$$A_{\gamma p\to\begin{pmatrix}\pi^0 p\\ K^+\Sigma^0\end{pmatrix}} = \mp\left[\frac{1}{\sqrt{3}}A^{(0)}_{\begin{pmatrix}\pi N\\ K\Sigma\end{pmatrix}} - \frac{1}{3}A^{(1)}_{\begin{pmatrix}\pi N\\ K\Sigma\end{pmatrix}}\right]^{(I=\frac{1}{2})} + \frac{2}{3}A^{(I=\frac{3}{2})}_{\begin{pmatrix}\pi N\\ K\Sigma\end{pmatrix}}$$

$$A_{\gamma p\to\begin{pmatrix}\pi^+ n\\ K^0\Sigma^+\end{pmatrix}} = \pm\sqrt{2}\left[\frac{1}{\sqrt{3}}A^{(0)}_{\begin{pmatrix}\pi N\\ K\Sigma\end{pmatrix}} - \frac{1}{3}A^{(1)}_{\begin{pmatrix}\pi N\\ K\Sigma\end{pmatrix}}\right]^{(I=\frac{1}{2})} + \frac{\sqrt{2}}{3}A^{(I=\frac{3}{2})}_{\begin{pmatrix}\pi N\\ K\Sigma\end{pmatrix}}$$

$$A_{\gamma p\to\begin{pmatrix}\eta p\\ K^+\Lambda\end{pmatrix}} = +\left[A^{(0)}_{\begin{pmatrix}\eta N\\ K\Lambda\end{pmatrix}} - \frac{1}{\sqrt{3}}A^{(1)}_{\begin{pmatrix}\eta N\\ K\Lambda\end{pmatrix}}\right]^{(I=\frac{1}{2})}.$$

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

Polarized photon beams: Compton backscattering and Bremsstrahlung



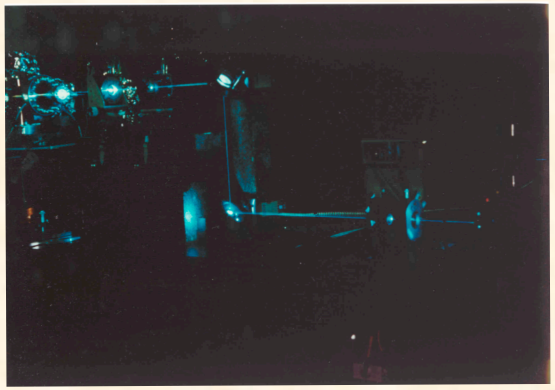
•Hiγs → below π threshold

•Legs → $\Delta_{33}(1232)$ resonance region

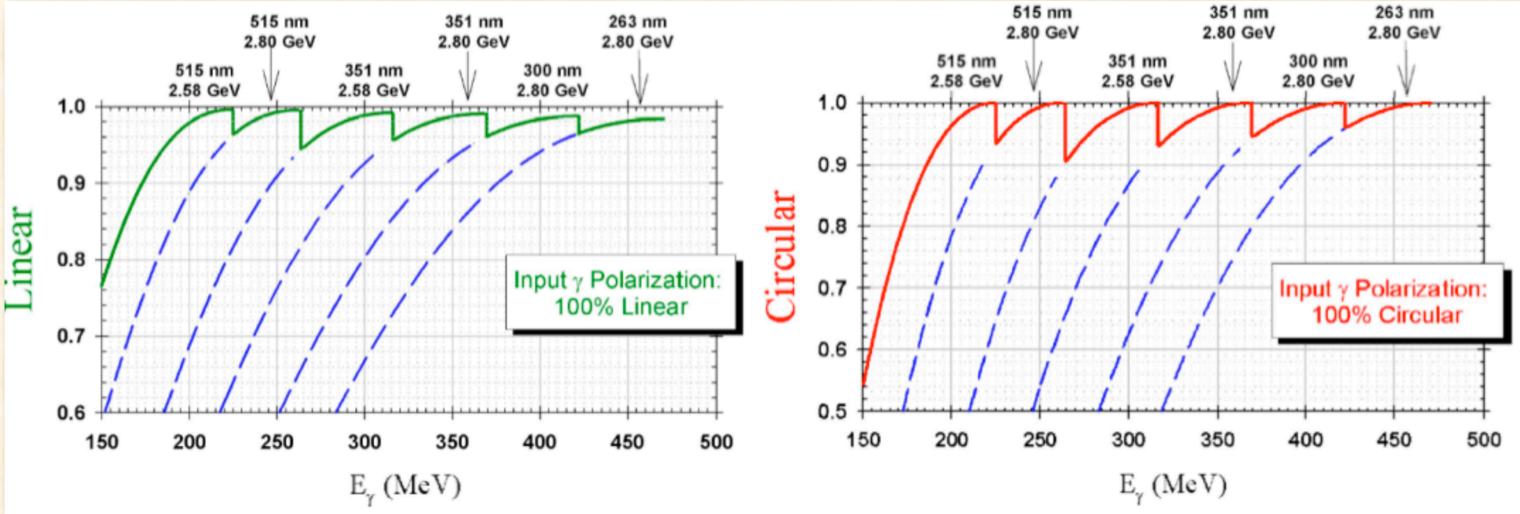
•Graal → E_γ = .6-1.5 GeV / W=1.4-1.9 GeV
Region of the second and third
baryon resonances η, K, ω, thresholds

•Leps → E_γ = 1.5-2.5 GeV
η' ϕ thresholds

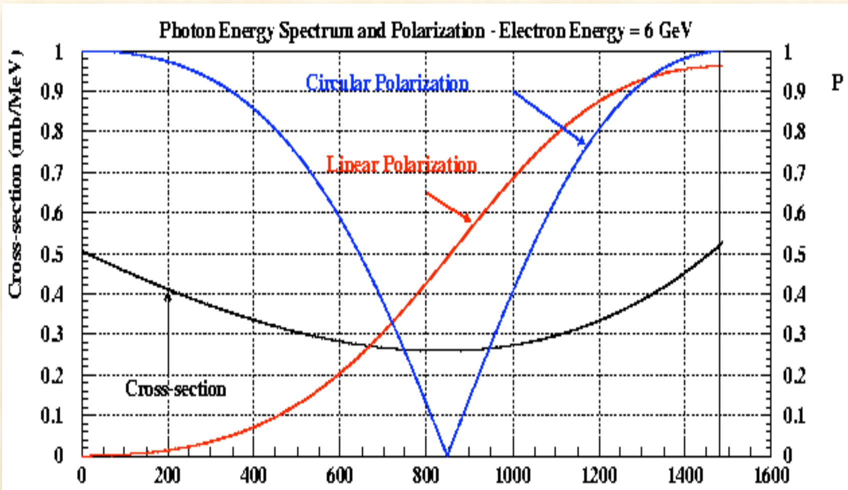
Polarized photon beams: Compton backscattering and Bremsstrahlung

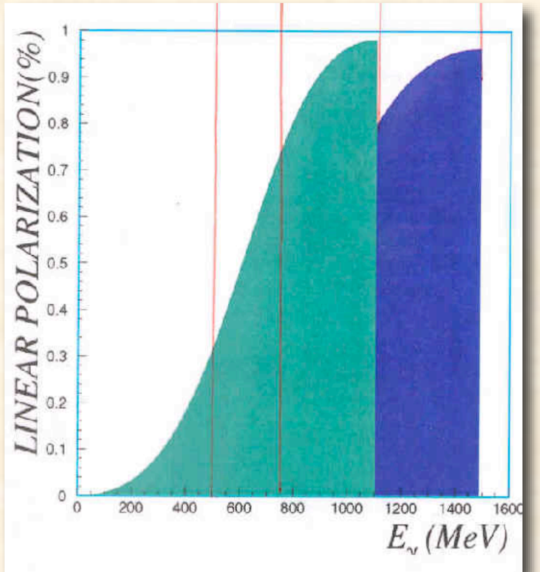


LEGS beam polarization



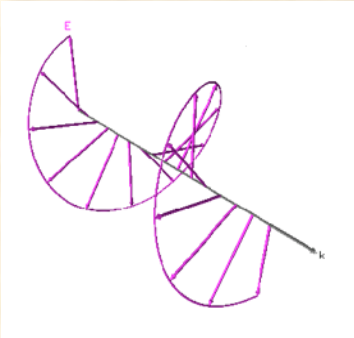
GRAAL beam polarization

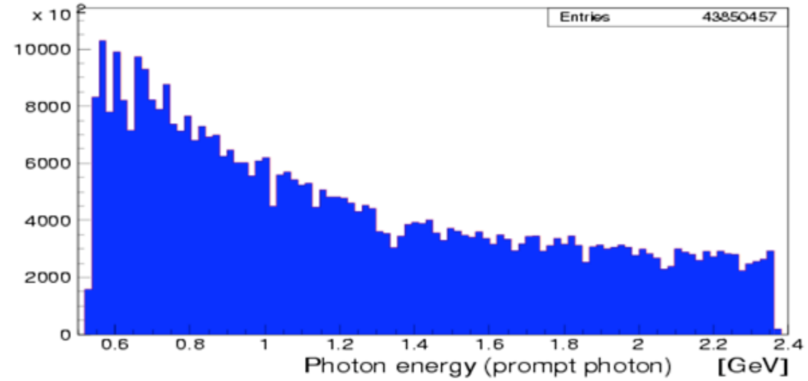




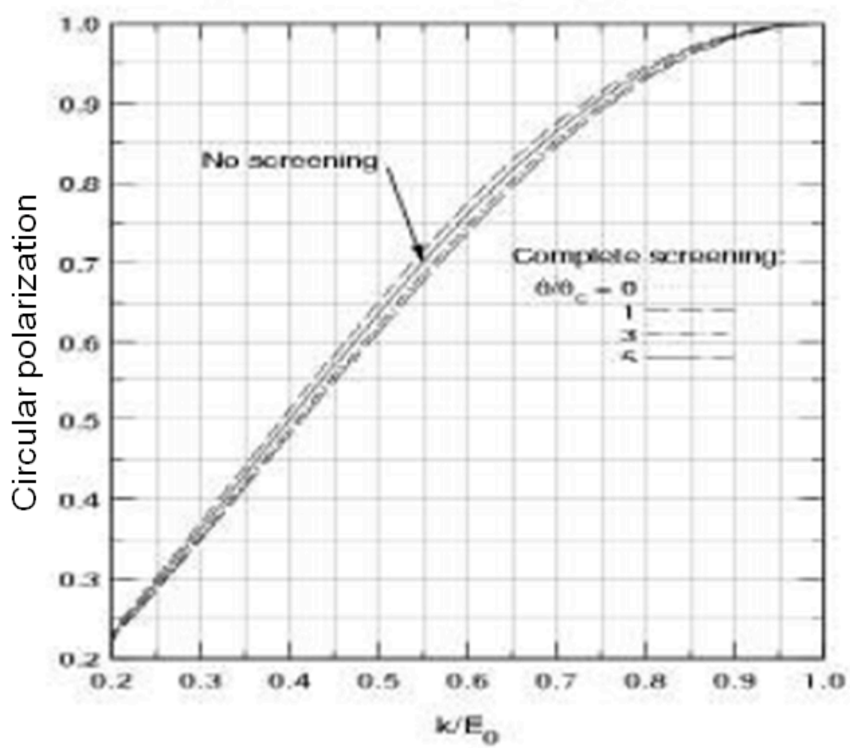
Polarized photon beams: Compton backscattering and Bremsstrahlung

Mami at Mainz
Elsa at Bonn
Clas at Jlab





Circular polarization from 100% polarized electron beam

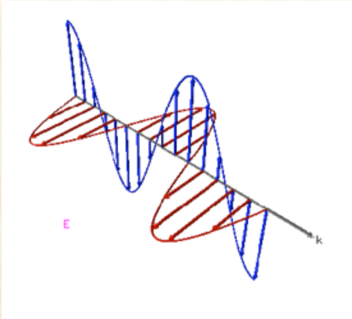


- Circularly polarized beam produced by longitudinally polarized electrons
- CEBAF electron beam polarization >85%

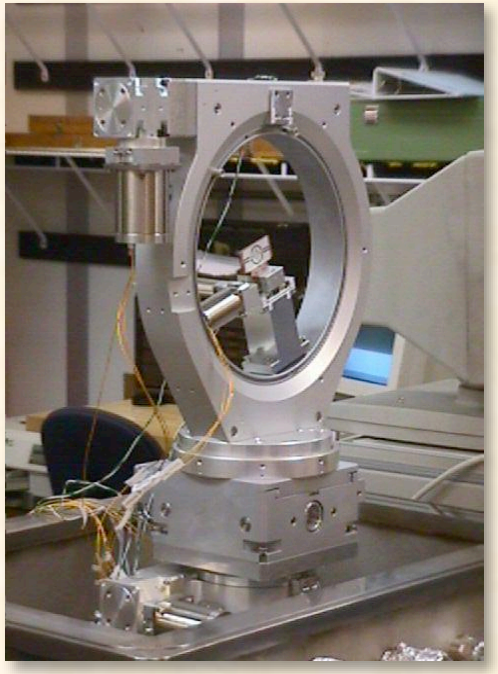
$$P_\gamma = P_e \cdot \frac{4k - k^2}{4 - 4k + 3k^2}$$

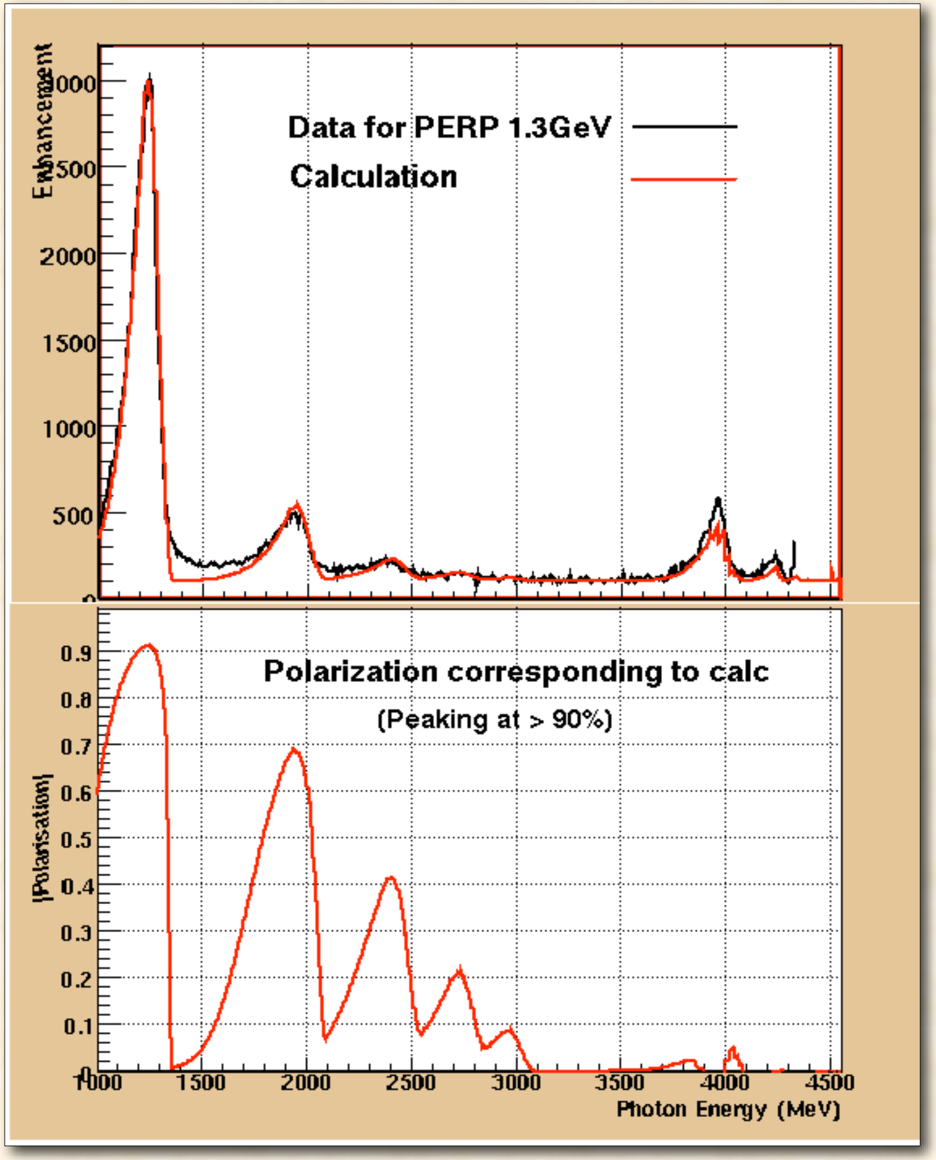
Polarized photon beams: Compton backscattering and Bremsstrahlung

Mami at Mainz
Elsa at Bonn
Clas at Jlab

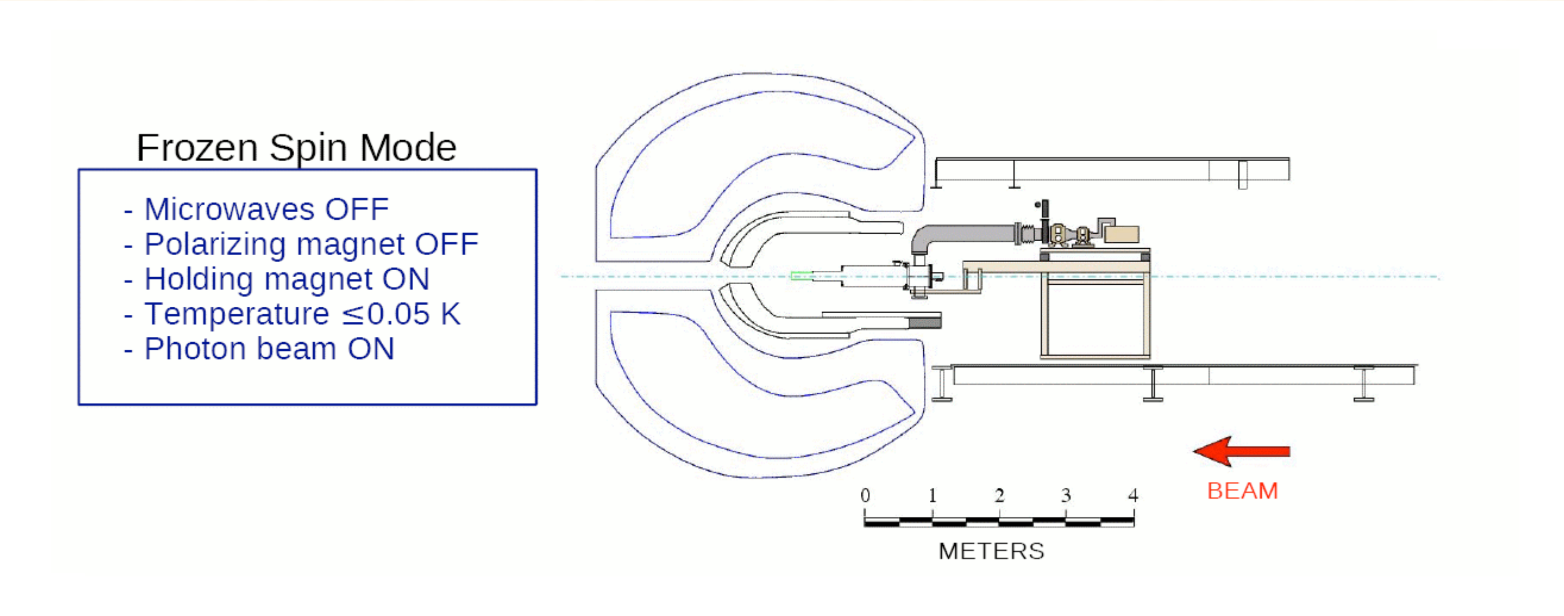


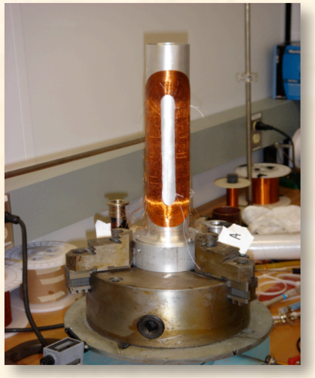
Linearly polarized photons: coherent bremsstrahlung on oriented diamond crystal

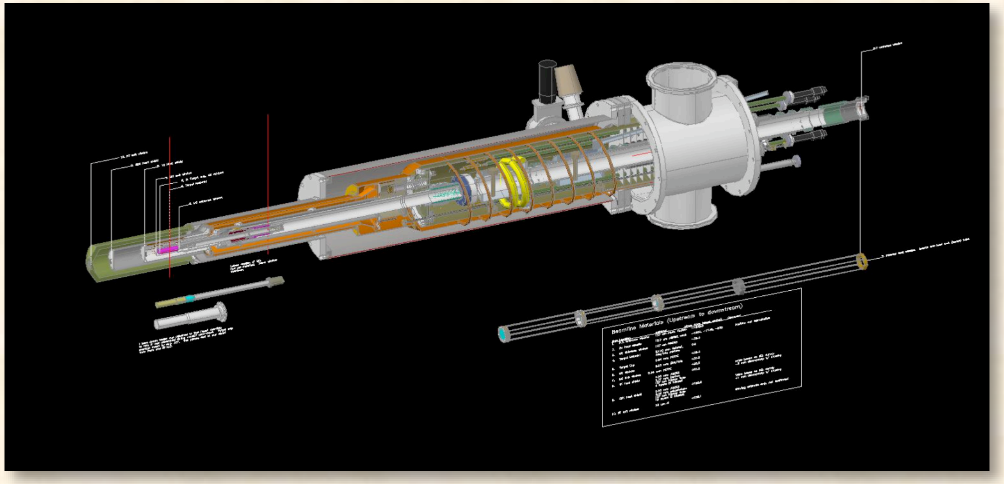


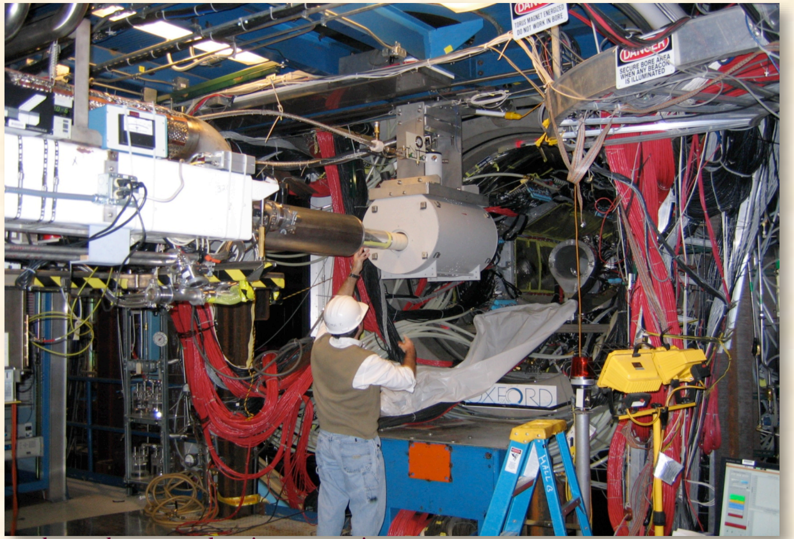


Polarized targets: frozen spin butanol FROST at CLAS

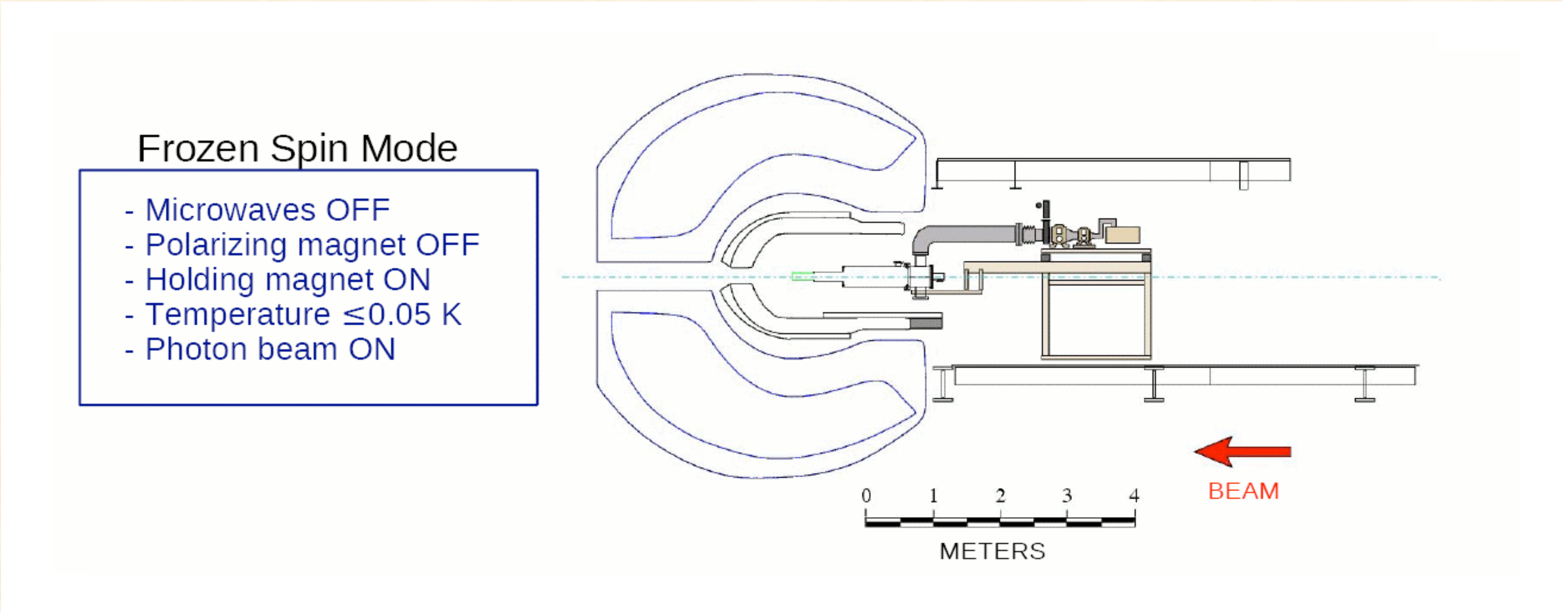


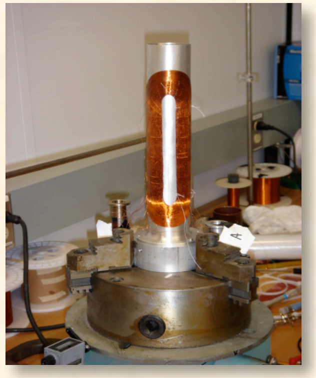






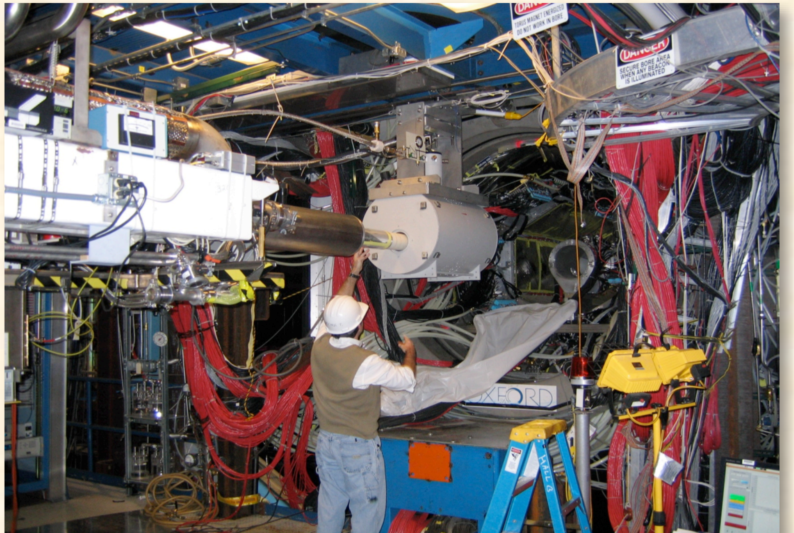
Polarized targets: frozen spin butanol FROST at CLAS



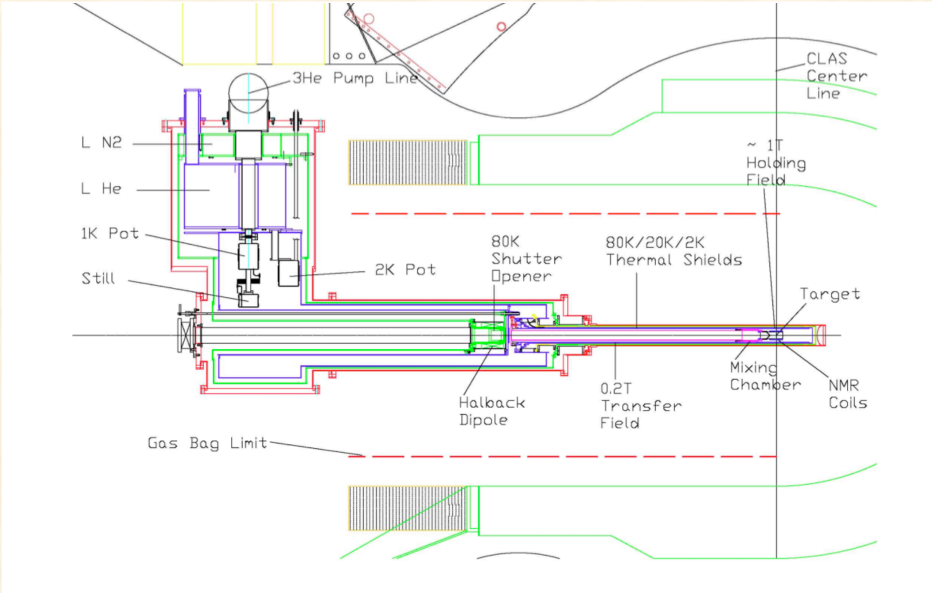


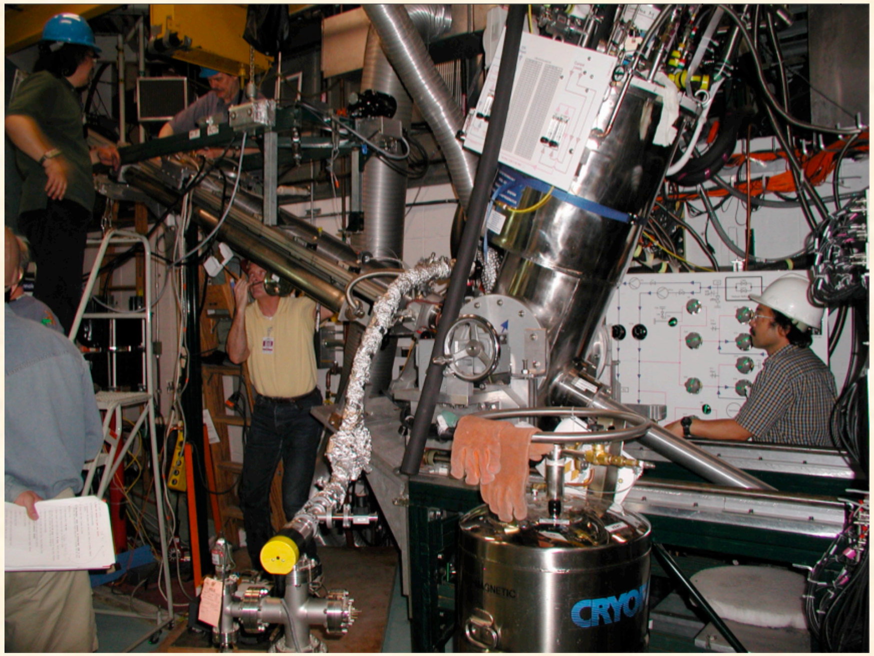
Longitudinal Polarization: above 80%
Relaxation time: > 2000 hours
Polarization procedure< 6 hours
Data taking: 5-6 days

Very reliable.



Polarized targets: frozen spin HD target at LEGS and CLAS





Longitudinal and Transverse Polarizations: > 60%
Relaxation time: > 1 year
Polarization procedure ≈ 3 months
Data taking: ≈ months

Very complicated.

Polarized targets: frozen spin HD target at LEGS

Very clean signal/background separation

PHOTON BEAM		TARGET x	TARGET y	TARGET z
unpolarized	σ_0		T	
linearly P_γ	Σ	H	-P	-G
circular P_γ		F		-E

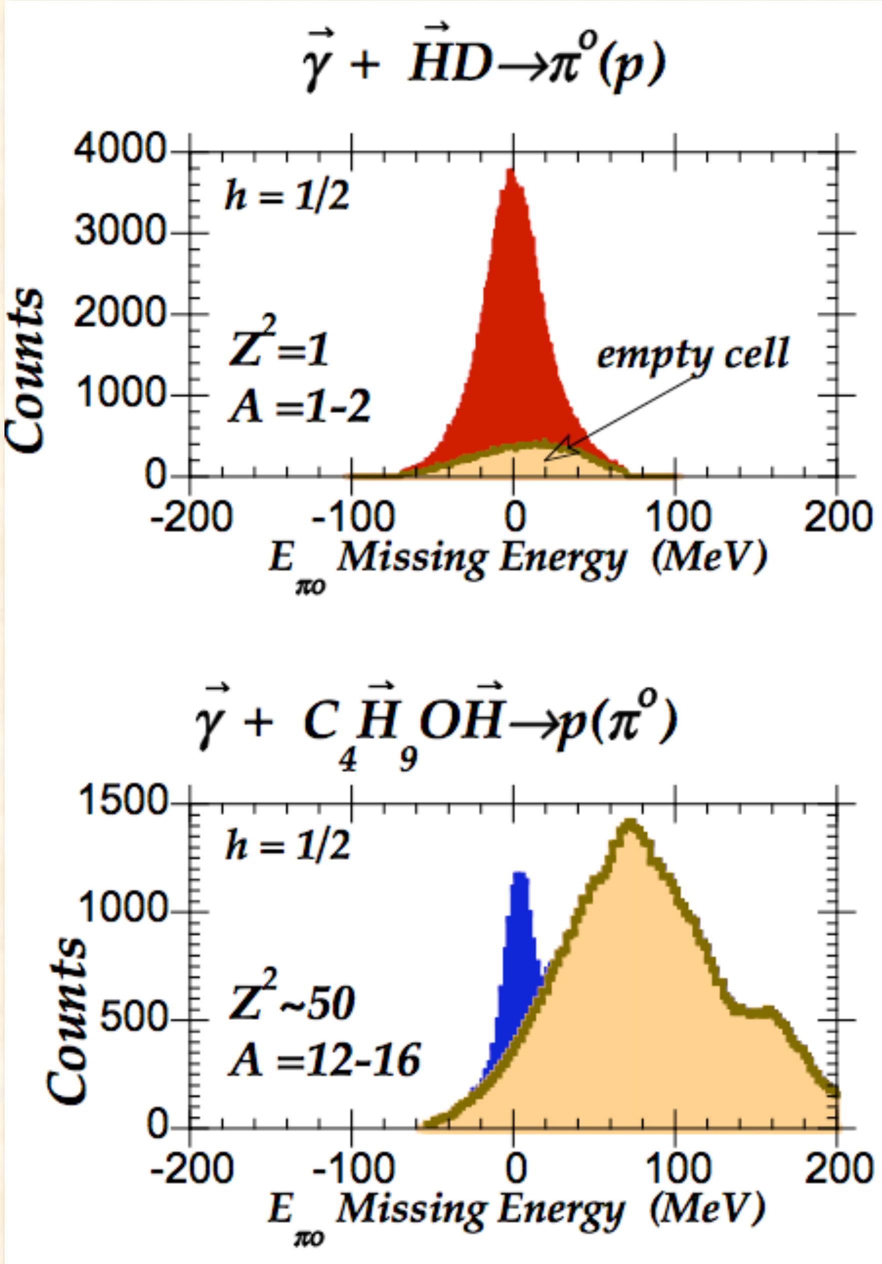
Longitudinal and Transverse Polarizations: > 60%

Relaxation time: > 1 year

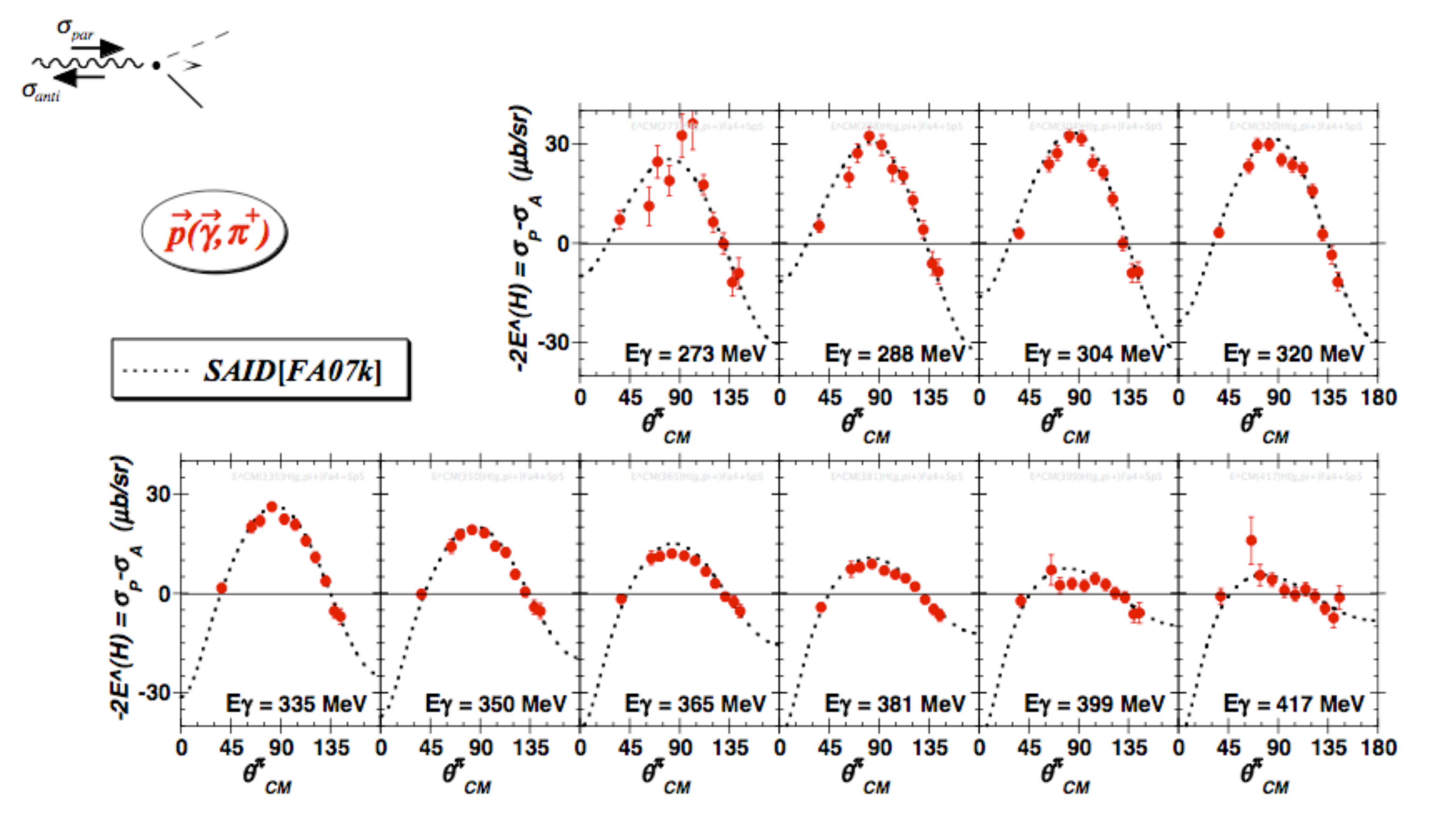
Polarization procedure ≈ 3 months

Data taking: ≈ months

Very complicated.

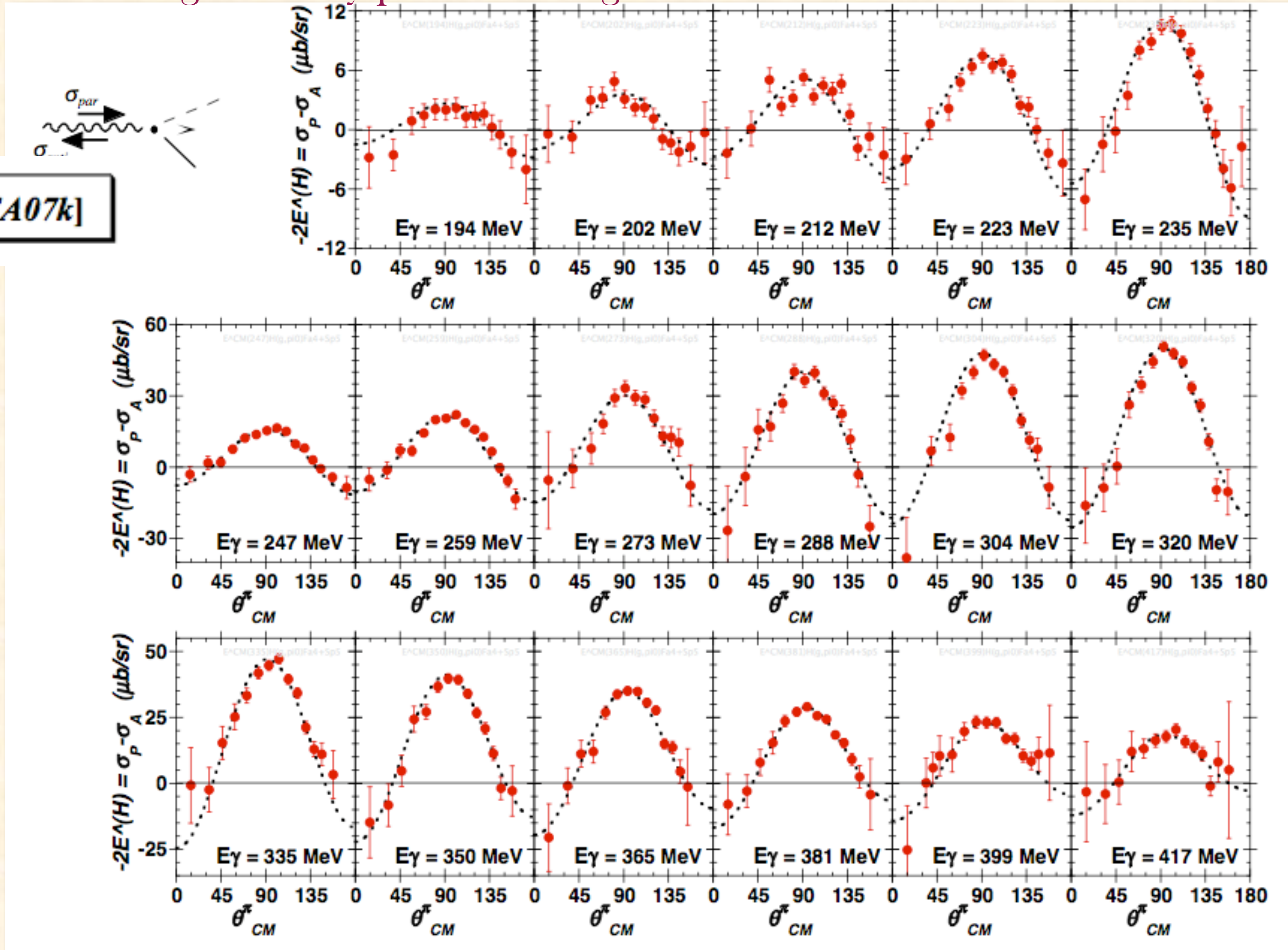


π^+ photoproduction at LEGS: longitudinally polarized photons on longitudinally polarized target : E

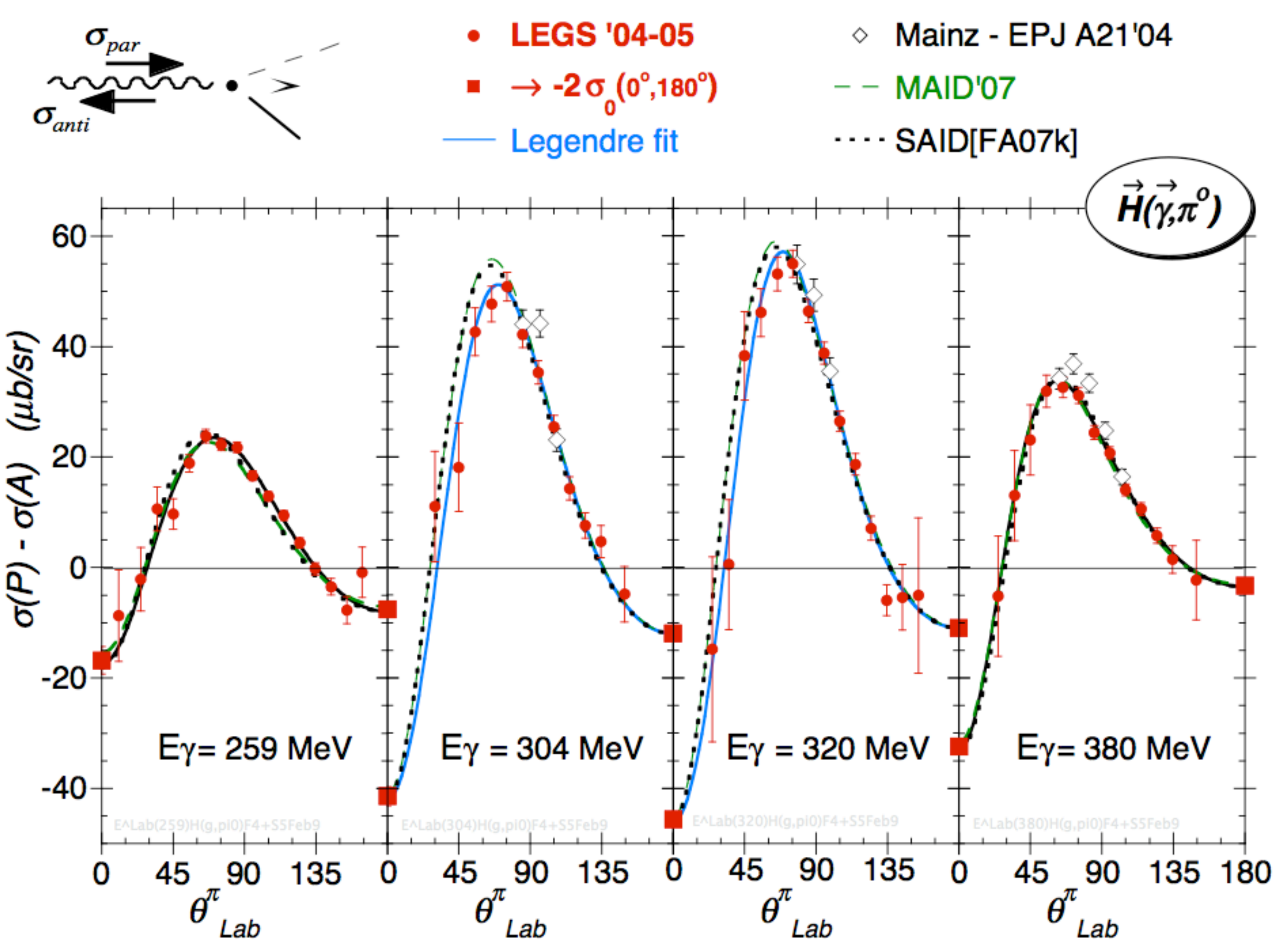


π^0 photoproduction at LEGS: longitudinally polarized photons on longitudinally polarized target : E

$\vec{p}(\vec{\gamma},\pi^0)$



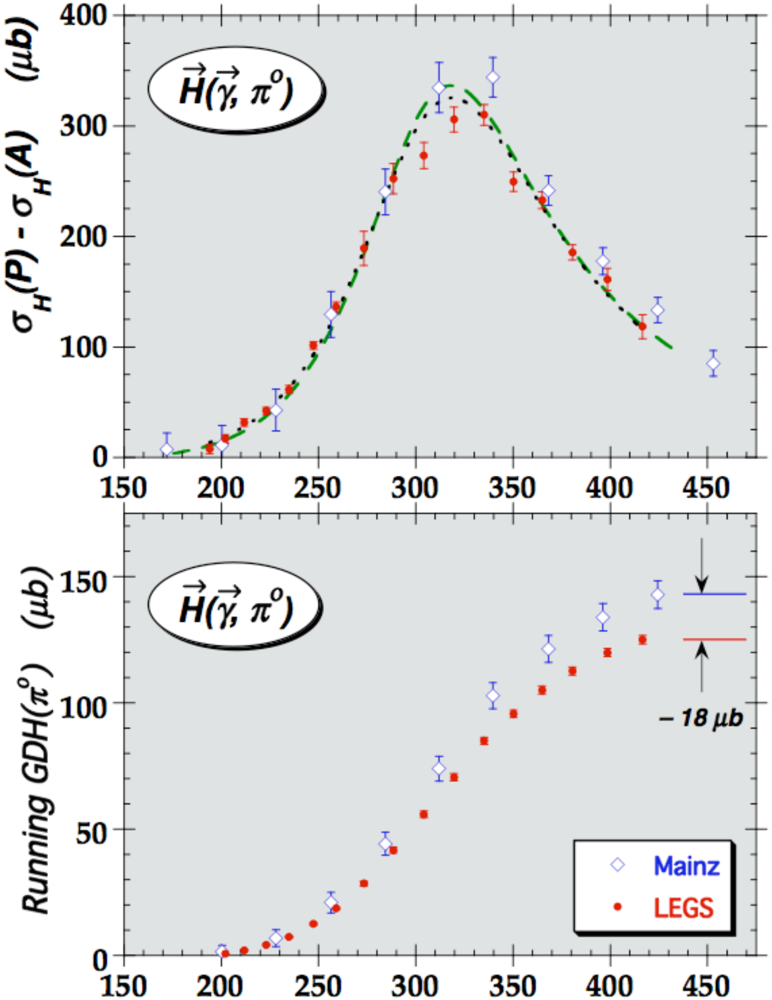
π^0 photoproduction at LEGS: longitudinally polarized photons on longitudinally polarized target : E comparison with MAINZ



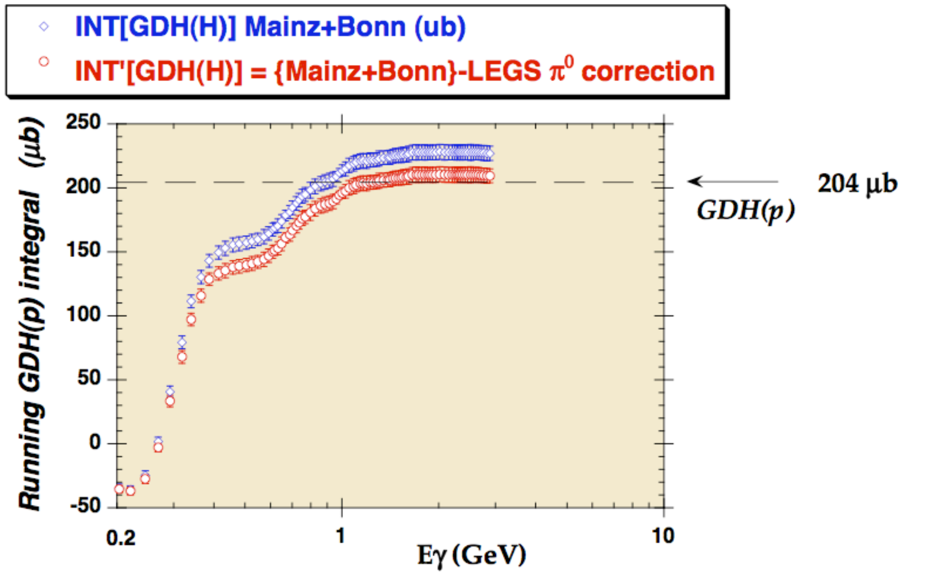
π^0 photoproduction at LEGS: longitudinally polarized photons on longitudinally polarized target : contribution to DHG sum rule

arXiv-0808.2183

PRL 102, 172002 (09)



$$\textit{Running } INT_{GDH}(E_\gamma) = \int^{E_\gamma} \frac{\sigma(P) - \sigma(A)}{E} \, dE = 4S\pi^2\alpha\left(\frac{\kappa}{m}\right)^2$$



GDHp [combined Mainz+Bonn+LEGS] = 208 ±6(stat) ± 14(sys) μb

PRL **102**, 172002(09)

Extraction of observable G
linearly polarized photons on longitudinally polarized targets

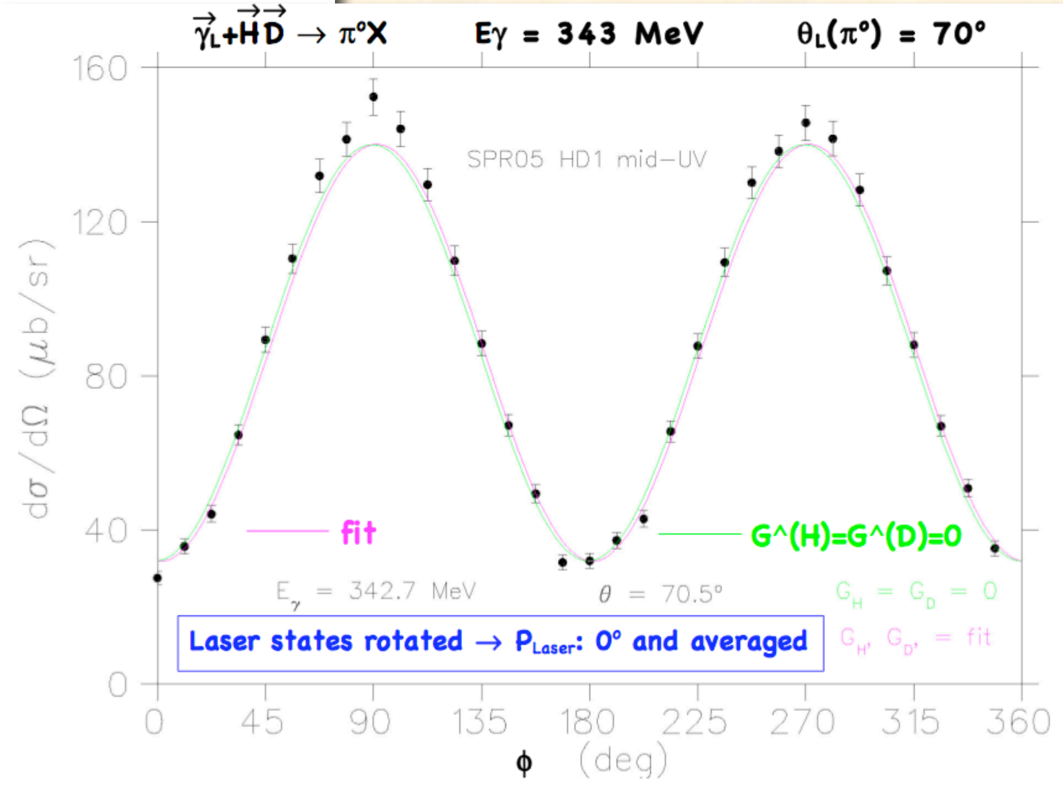
$$d\sigma = d\sigma_o(HD) + P_\gamma^L \cdot \left[\hat{\Sigma}(HD) + \tfrac{1}{\sqrt{2}} P_D^T \cdot T_{20}^L(D) \right] \cdot \cos 2\phi$$

$$+ P_\gamma^L \cdot \left[P_H \cdot \hat{G}(H) + P_D^V \cdot \hat{G}(D) \right] \cdot \sin 2\phi$$

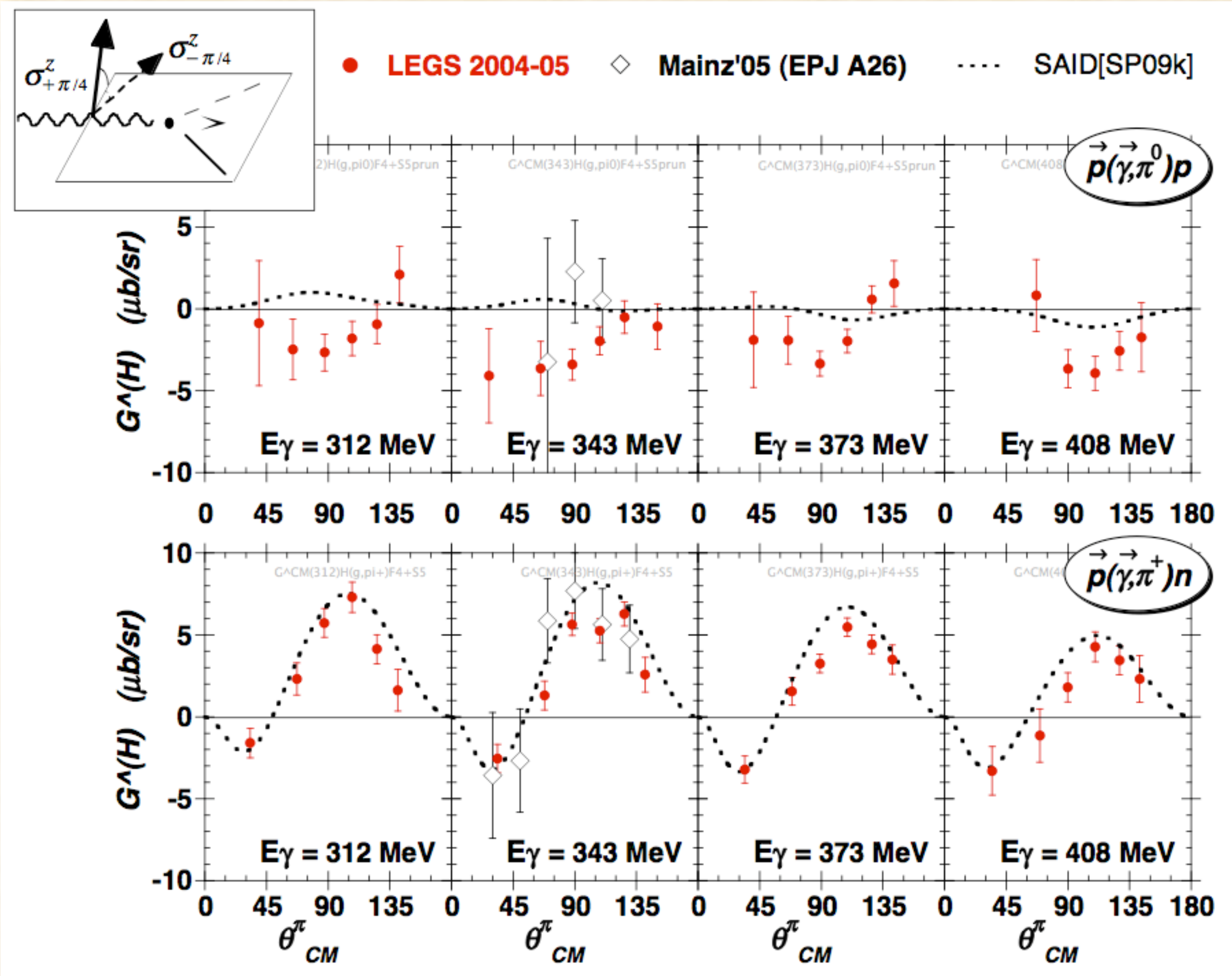
$$- P_\gamma^C \cdot \left[P_H \cdot \hat{E}(H) + P_D^V \cdot \hat{E}(D) \right] + \tfrac{1}{\sqrt{2}} P_D^T \cdot T_{20}^0(D)$$

ϕ-fits

from $\int d\phi$ fits



G asymmetry from π^+ and π^0 photoproduction on the proton at LEGS



Surprise: opposite sign and one order of magnitude larger than expected.

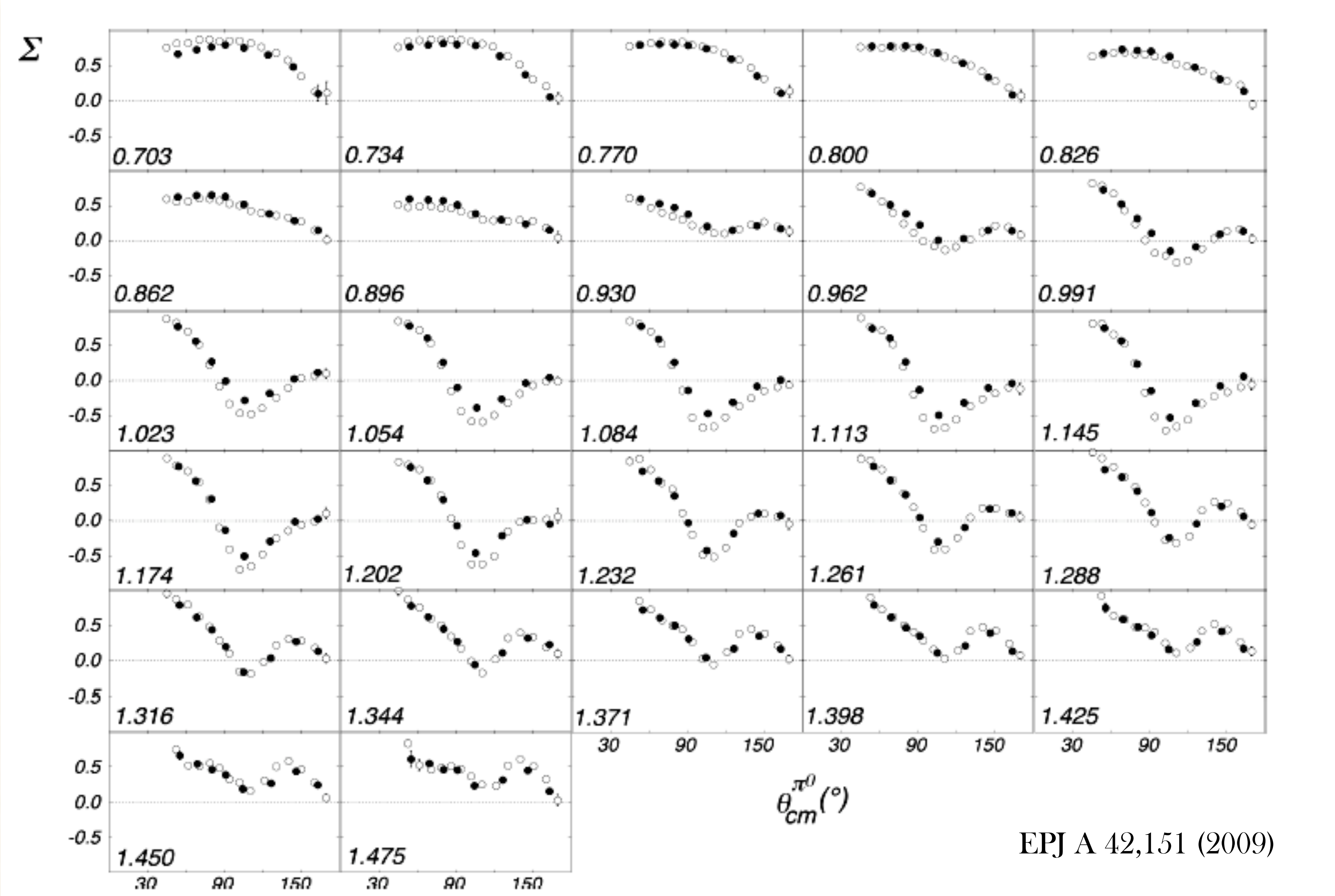
Under investigation.

Large D-wave component under $P_{33\Delta}(1232)$

Need a *complete* set of observables

Σ measurements at GRAAL on proton and deuteron targets

$\vec{\gamma}+p \rightarrow \pi^0+p$ $\vec{\gamma}+p(+n) \rightarrow \pi^0+p+(n)$

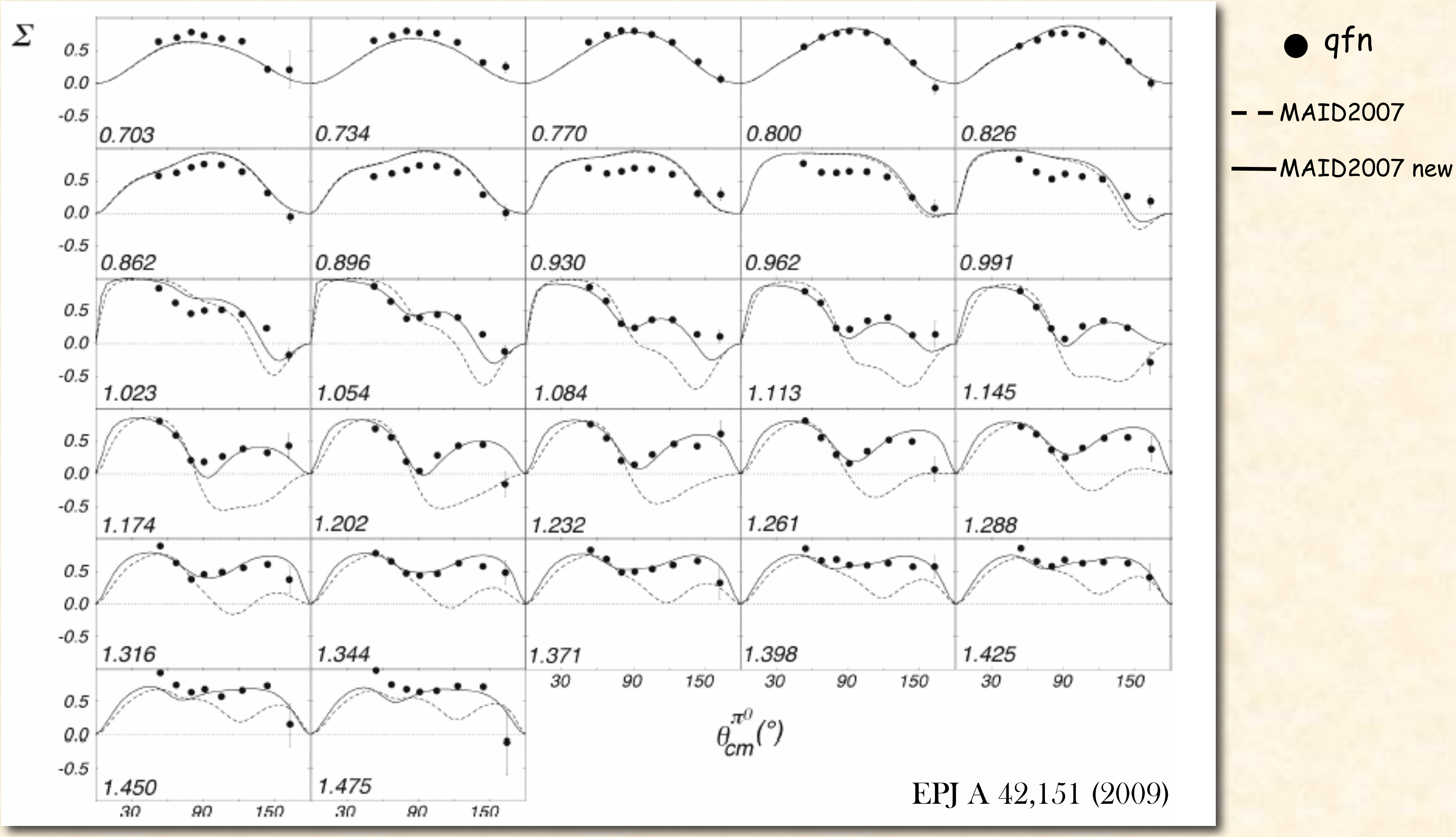


EPJ A 42,151 (2009)

Very nice agreement between free and quasi-free results on the proton

Σ measurements at GRAAL deuteron target

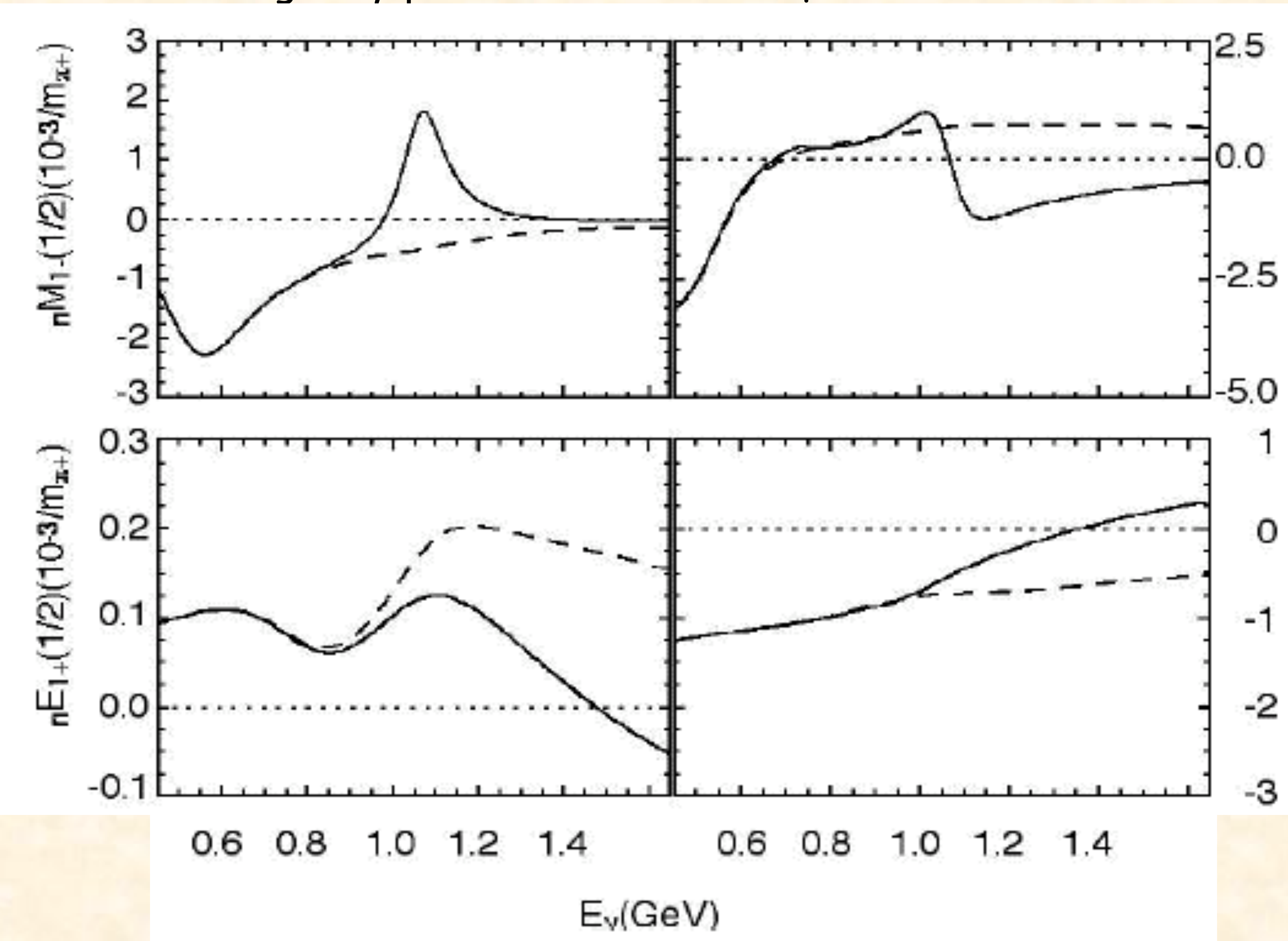
$\vec{\gamma}+n(+p)\rightarrow\pi^0+n+(p)$



We may assume that results from quasi-free neutrons may represent the free neutron response → final state interactions and re-scattering are negligible)

Σ in π^0 Photoproduction on qfn
Multipole extraction in MAID2007

Immaginary part Real part



Second $P_{11}(1700)$ resonance

$P_{11}(1700)$

$\Gamma_{tot} = 70 MeV$

$\beta_\pi = 0.1$

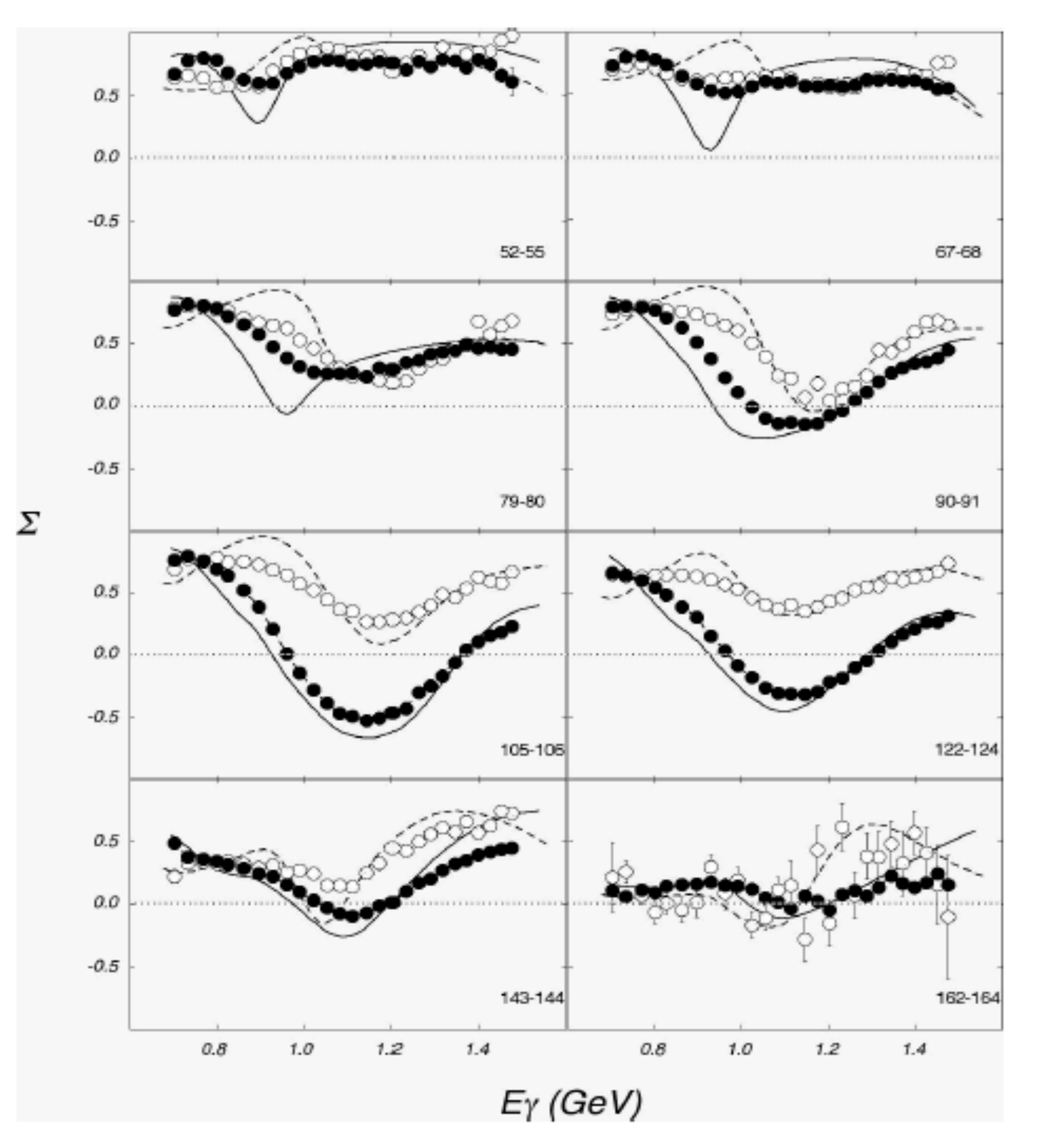
$P_{13}(1720)$

modified photo-couplings

- - - MAID2007 qfn

—— mod MAID2007 qfn

Σ in π^0 photoproduction on qfp and qfn



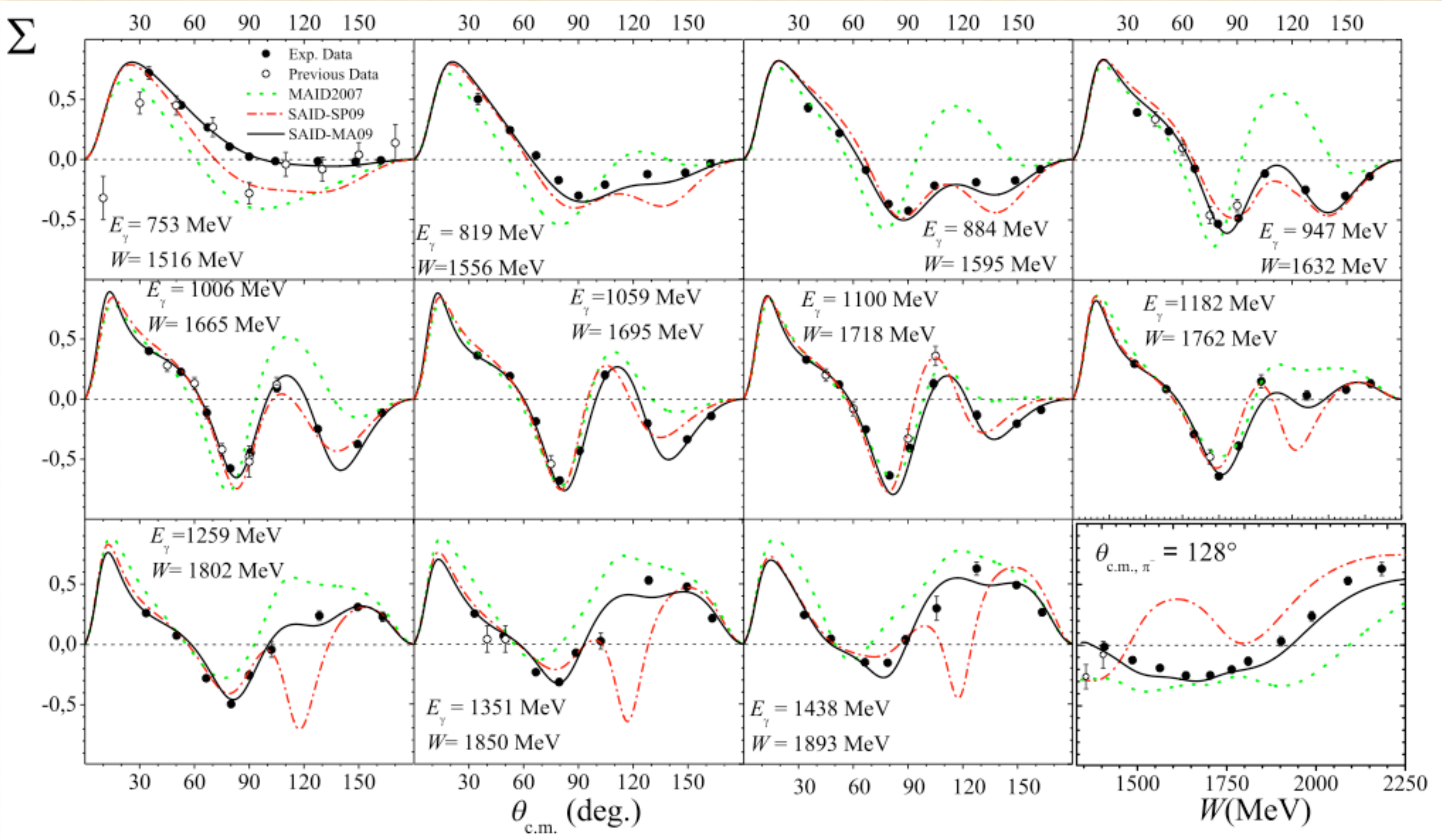
○ qfn
● qfp
- - MAID2007 "new" for neutron
— MAID2007 "new" for proton

New data are coming from CLAS

↓

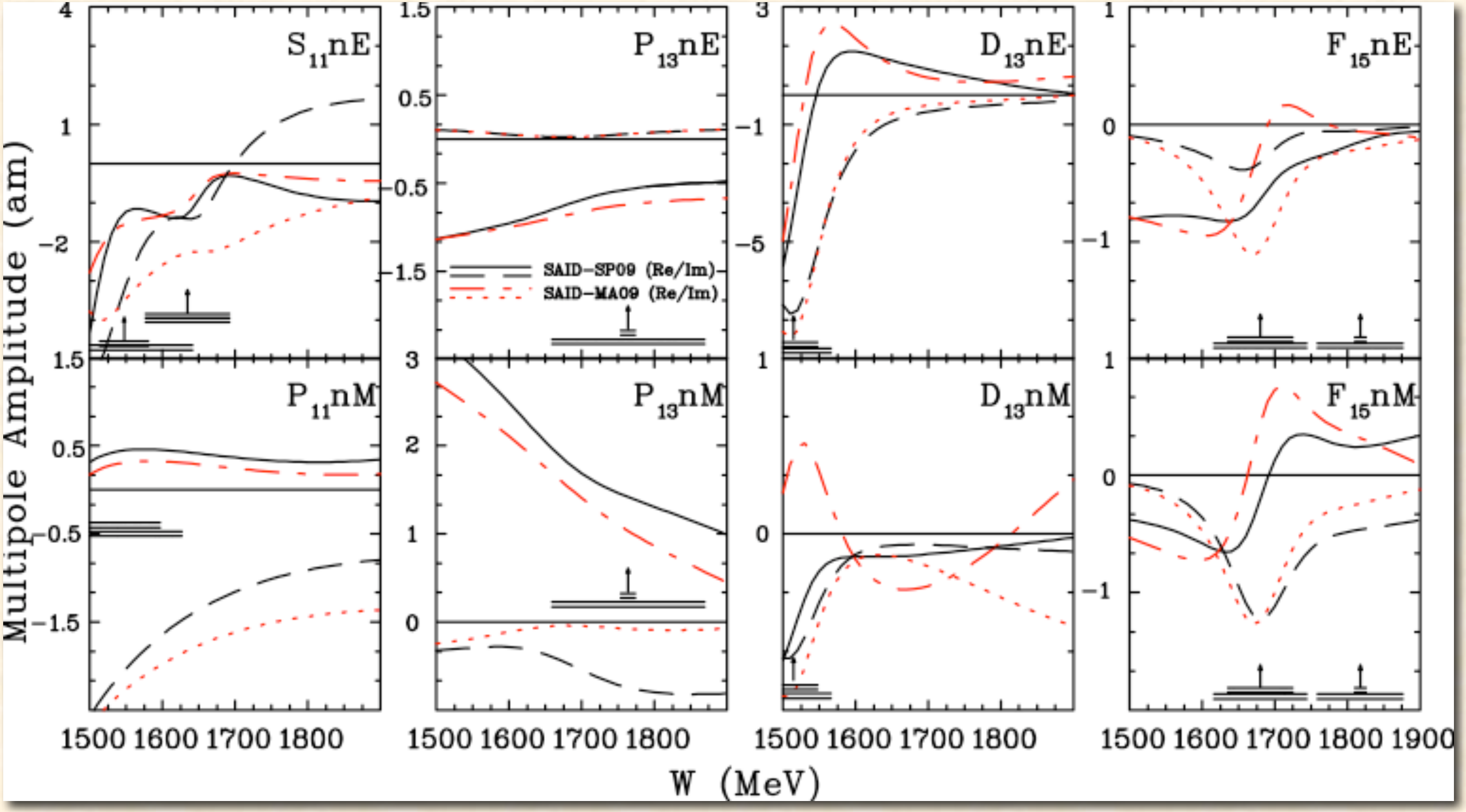
Micheal Dugger (session 2E)

Σ results on $\vec{\gamma}+n(+p)\rightarrow\pi^{-}+p+(p)$ at GRAAL



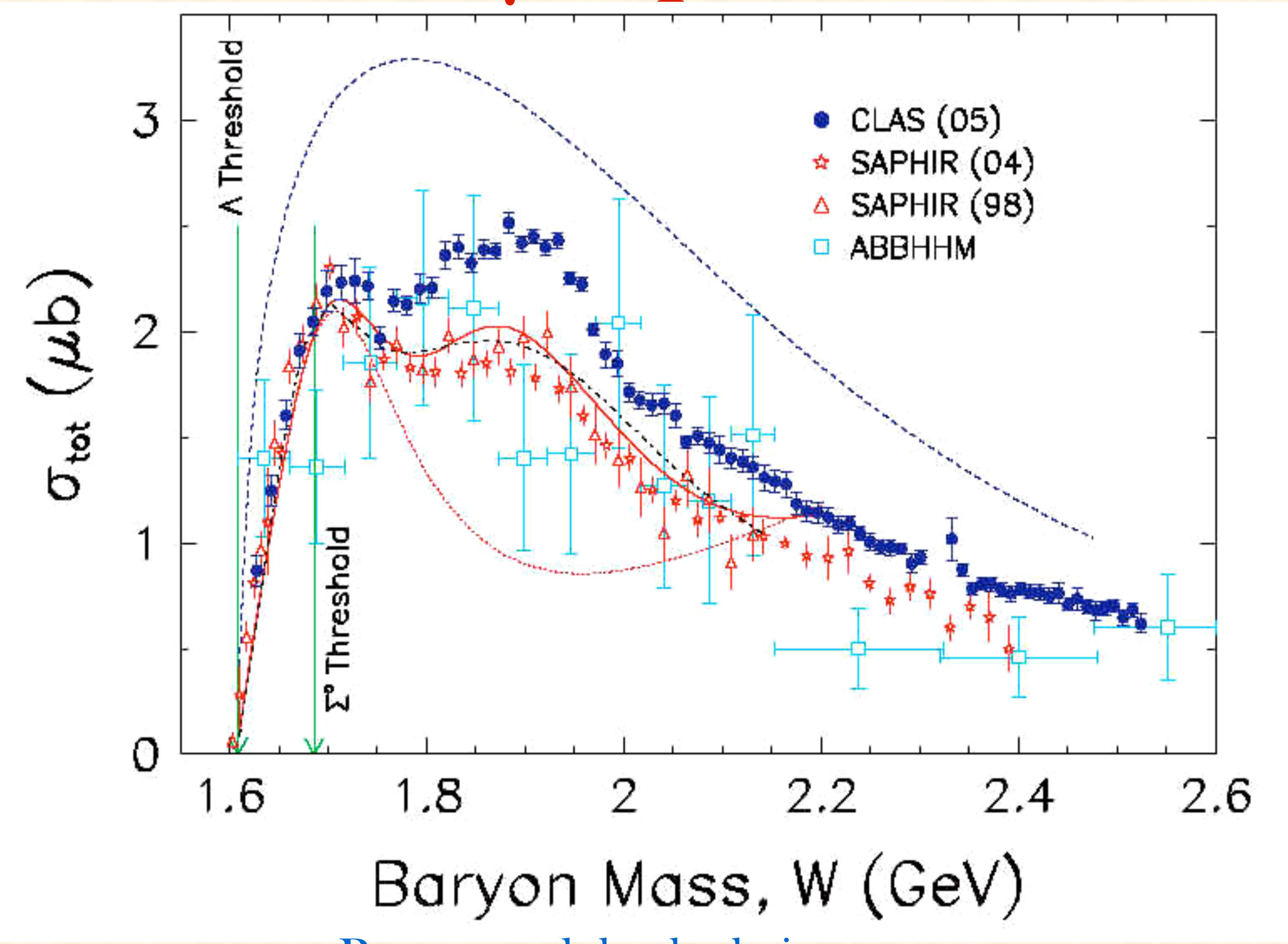
New data are coming from CLAS → Micheal Dugger (session 2E)

Multipole modifications due to Σ results on $\gamma+n(+p)\rightarrow\pi^{-}+p+(p)$ at GRAAL



New data are coming from CLAS → Micheal Dugger (session 2E)

$\gamma + p \rightarrow k^{+} + \Lambda$



Cross section data show a structure at W=1900 MeV

Coupled –channel analysis finds that S11(1650), P11(1710) and P13(1720) have the most significant decay widths in the k+Λ channel

Isobar model requires the inclusion of a "missing" $D_{13}(1895)$ resonance to reproduce the cross section data.

- - - - - Regge model calculation

.... KAON-Maid without $D_{13}(1895)$

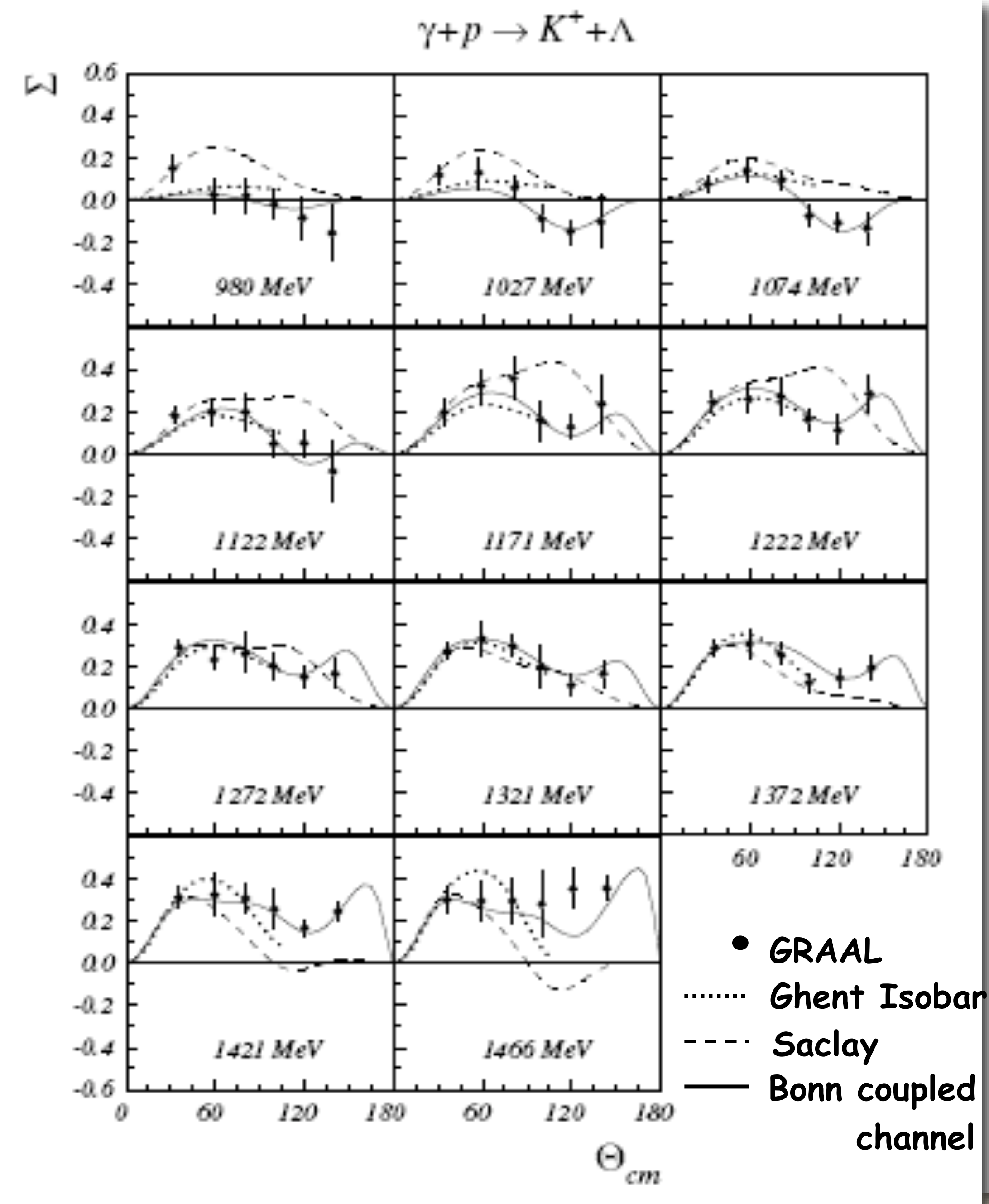
——— KAON-Maid with $D_{13}(1895)$

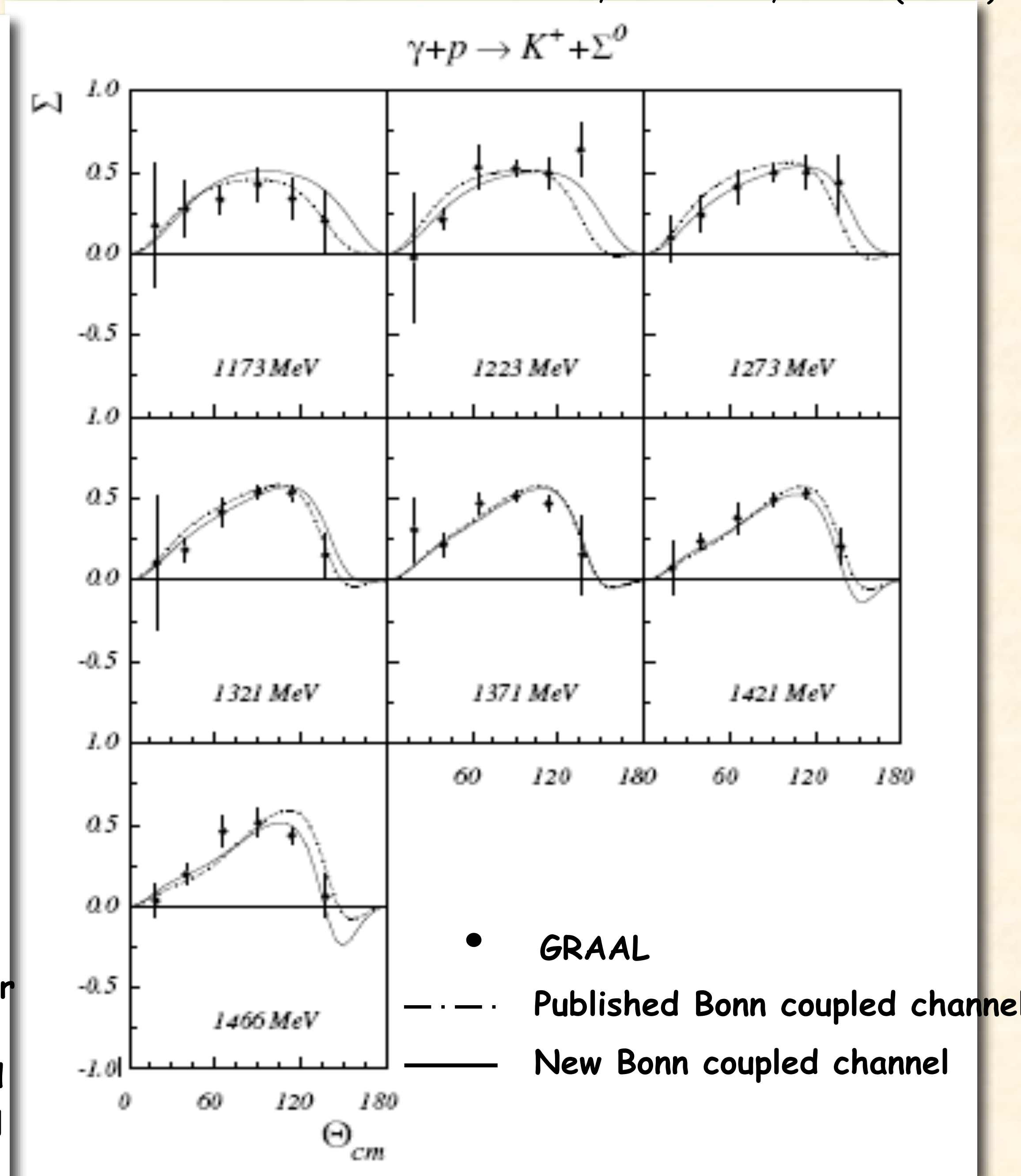
— · — · - Saclay dynamical coupled channel

S_{11} (1800) and P_{13} (1900) also seem to play a role

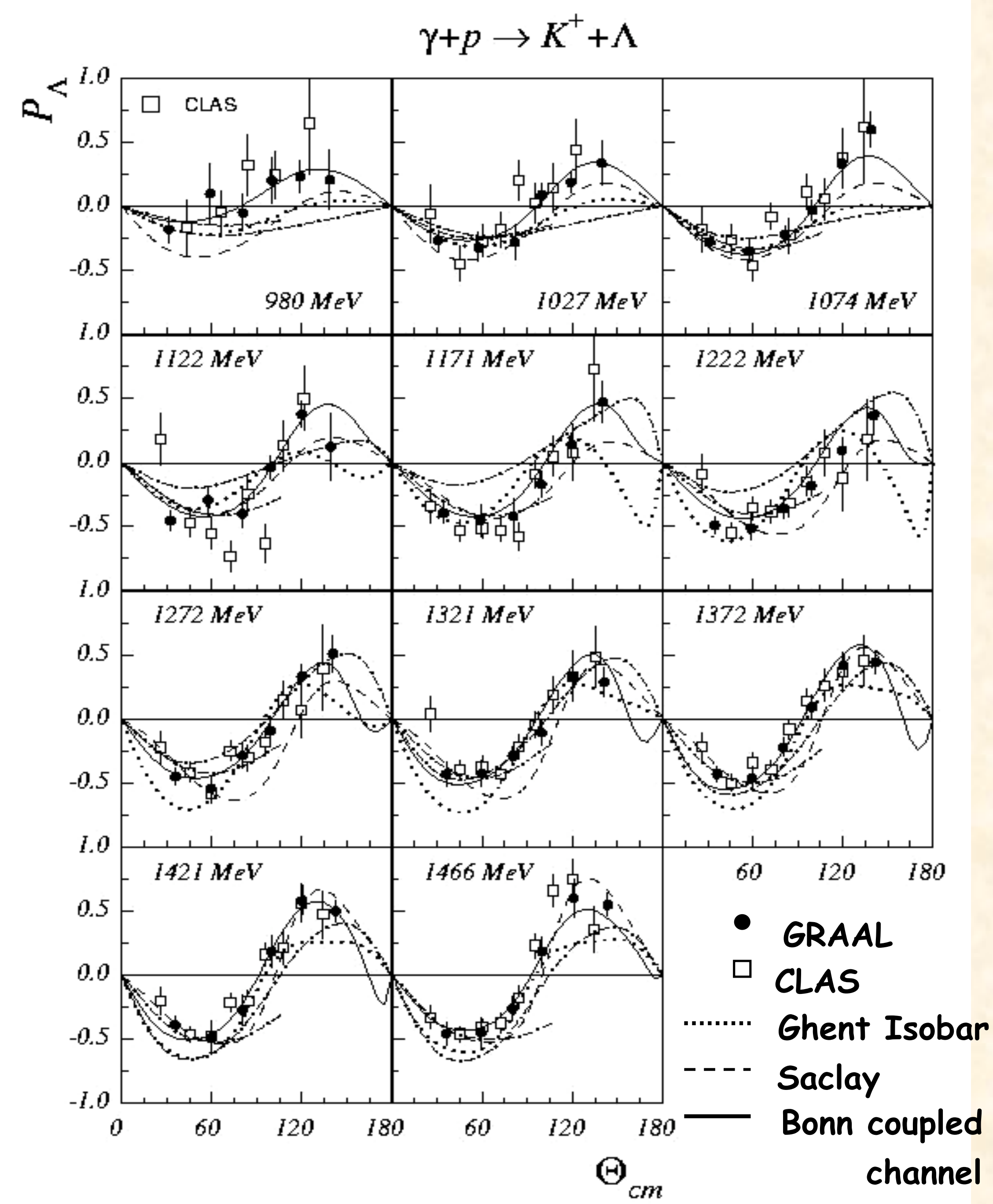
Σ in $K^+\Lambda$ and $K^+\Sigma^0$ Photoproduction

A.Lleres et al., EPJ A **31**, 79-93 (2007)





PΛ in K⁺Λ Photoproduction



A.Lleres et al., EPJ A **31**, 79-93 (2007)

$$W(\cos\theta_p) = \frac{1}{2}\left(1 + \alpha\left|\vec{P}_\Lambda\right|\cos\theta_p\right)$$

$$P_\Lambda = \frac{2}{\alpha}\,\frac{N_{(\cos\theta_p>0)} - N_{(\cos\theta_p<0)}}{N_{(\cos\theta_p>0)} + N_{(\cos\theta_p<0)}}$$

$$\alpha = 0.642 \pm 0.013$$

From Σ and P measurements:

- Saclay Model:

  $S_{11}(1700)$ $P_{13}(1800)$ $D_{13}(1850)$

- Ghent Isobar Model:

  $D_{13}(1900)$

- Reggeized Model:

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

- Bonn Coupled Channel Model:

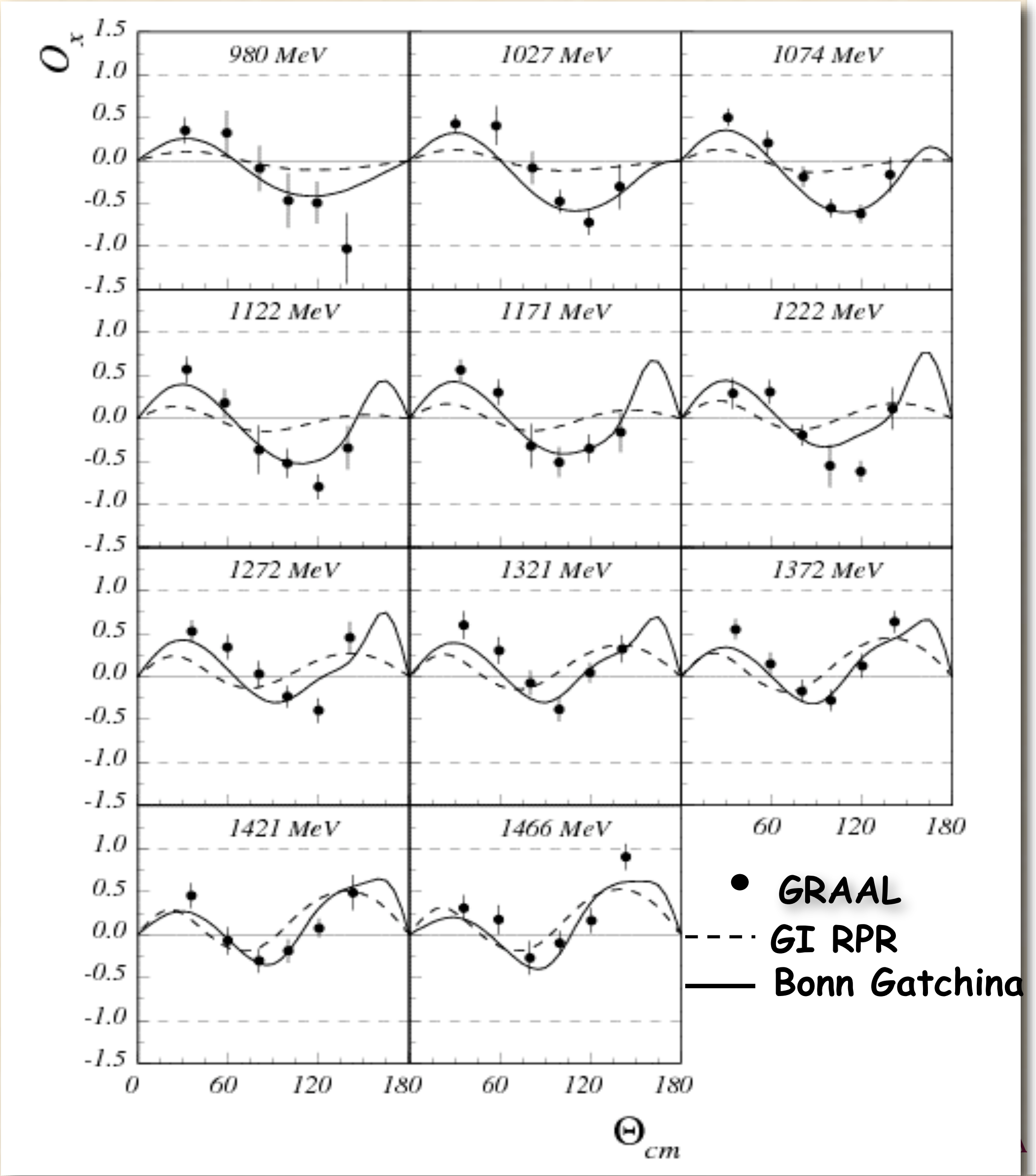
  $D_{13}(1875)$

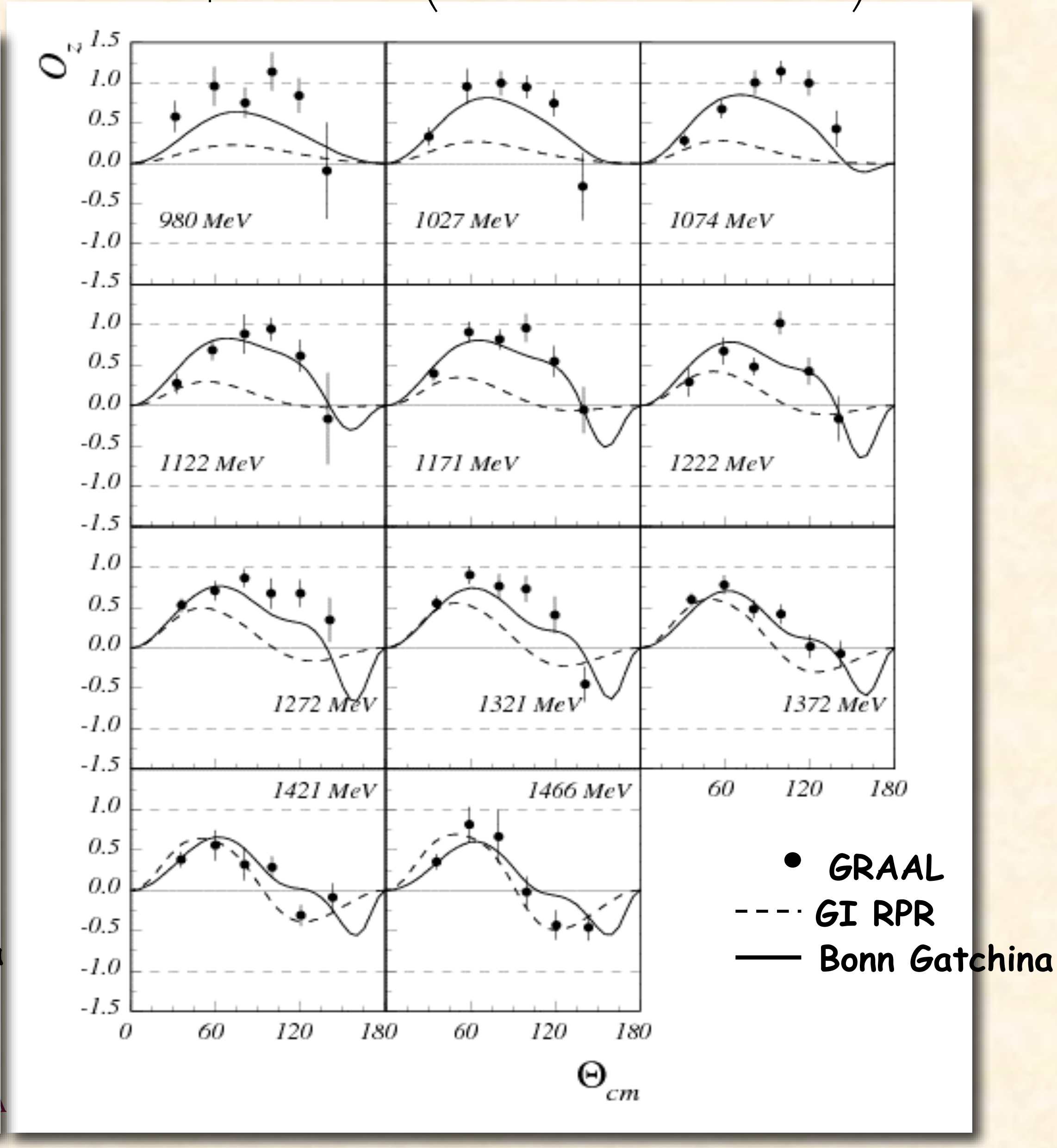
Double Polarization Observables in K+Λ Photoproduction

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

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

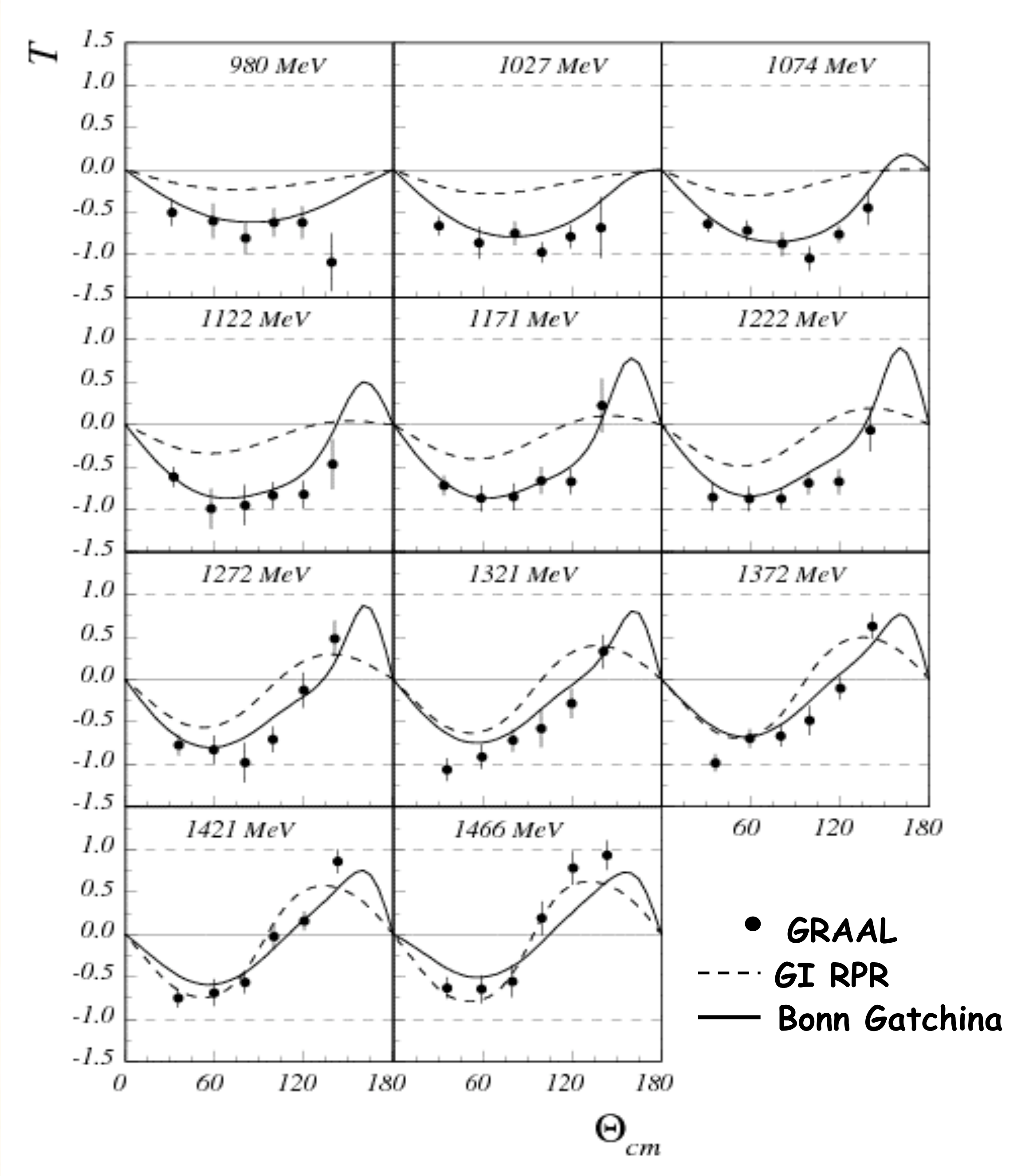
$$\frac{2N_+^{z'}}{N_+^{z'}+N_-^{z'}} = \left(1+\alpha\frac{2P_\gamma O_z}{\pi}\cos\theta_p^{z'}\right)$$





T in $K^+\Lambda$ Photoproduction

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:

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

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

- Bonn Gatchina Model:

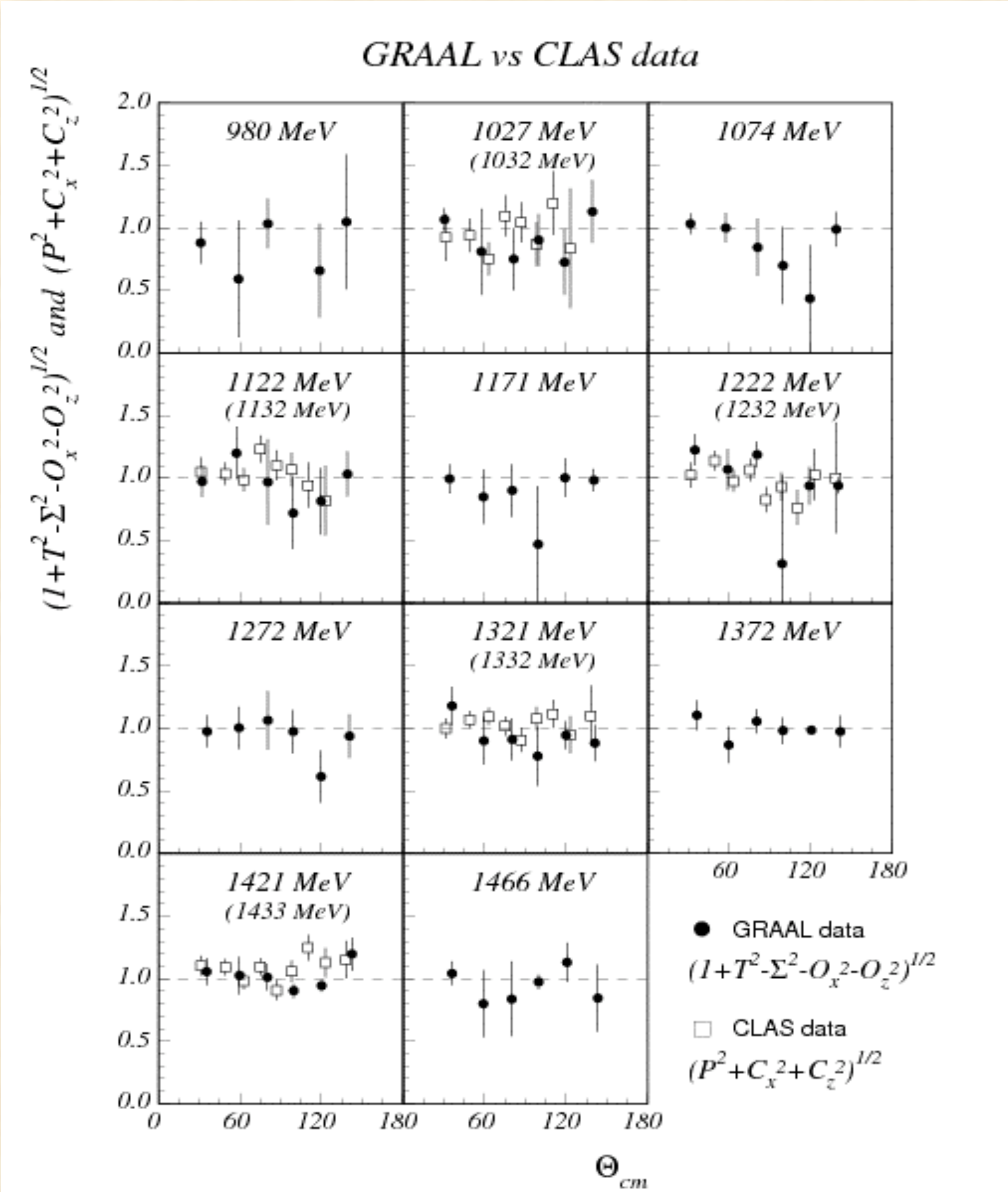
$S_{11}(1535)\, S_{11}(1650)\, P_{13}(1720)\, P_{11}(1840)$

$P_{13}(1900)$

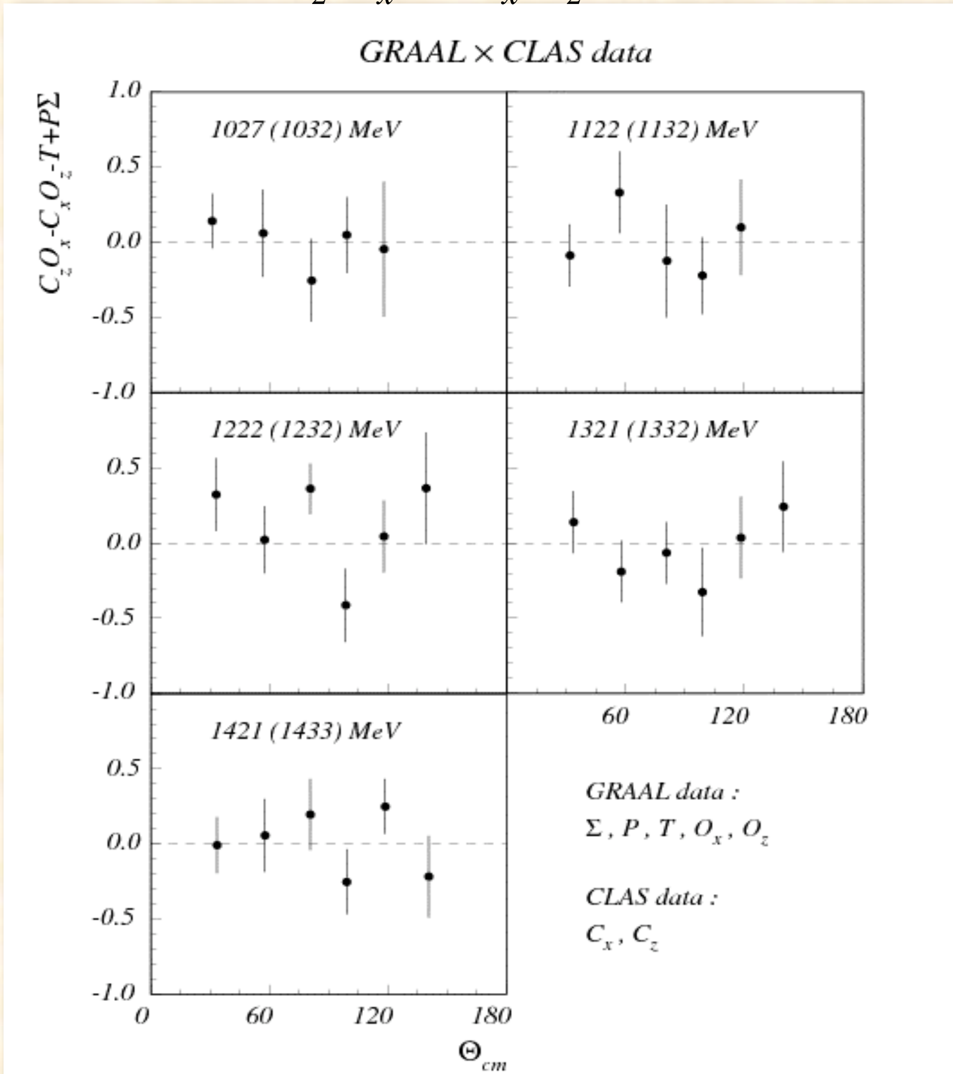
Comparison with CLAS

$$1+T^2-\Sigma^2-O_x^2-O_z^2=P^2+C_x^2+C_z^2$$

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

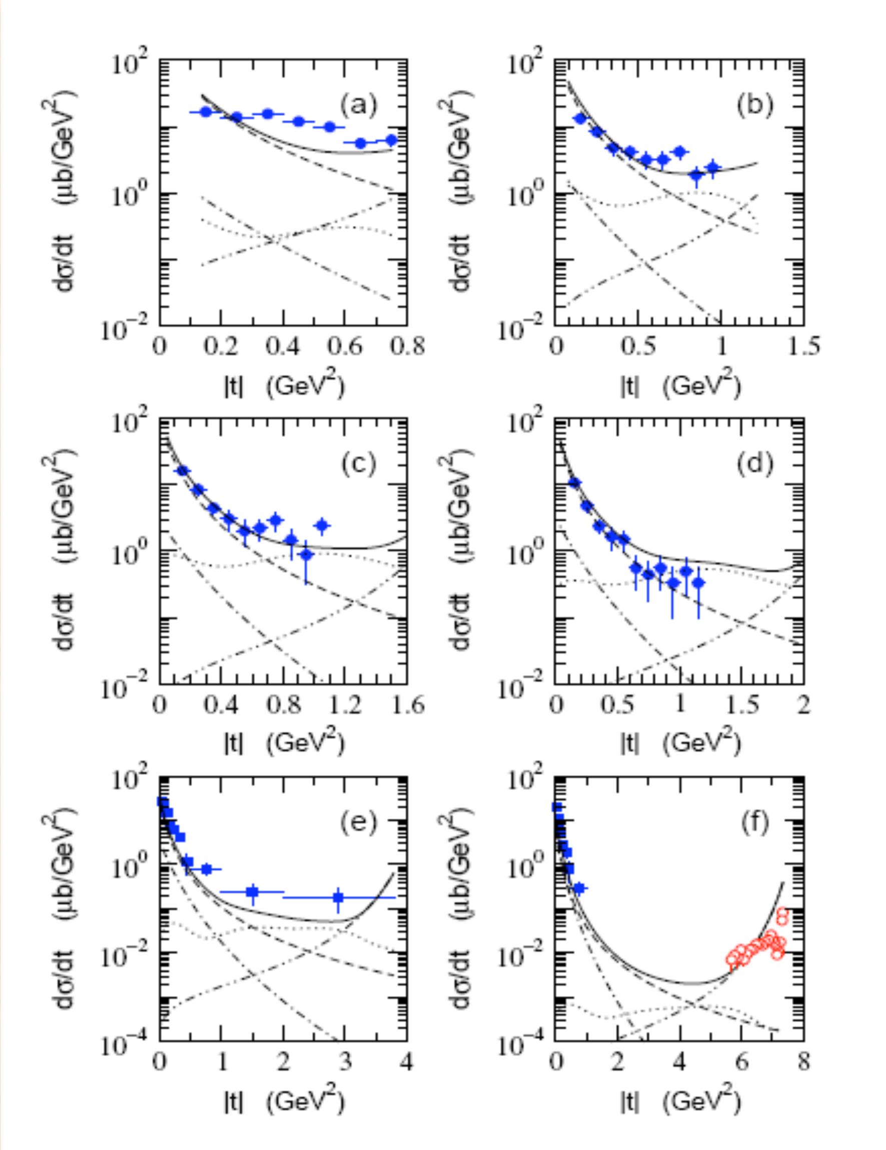


$$C_zO_x-C_xO_z=T-P\Sigma$$



More data have been obtained at CLAS

ω Photoproduction on the Proton: Differential Cross-Section



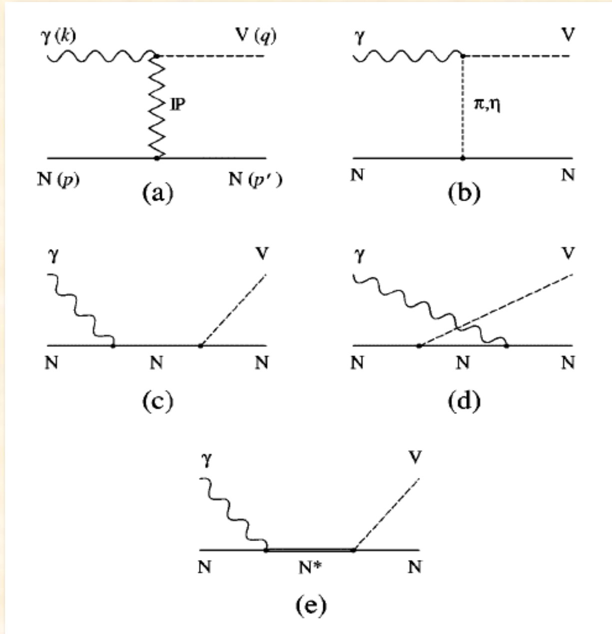
Eγ=(a) 1.23GeV, (b) 1.45GeV,
(c) 1.68GeV, (d) 1.92GeV,
(e) 2.80GeV, (f) 4.70 GeV

Oh, Titov and Lee, NSTAR 2001

Low *t* diffractive behavior:

Vector Dominance Model (1960), J.J.Sakurai

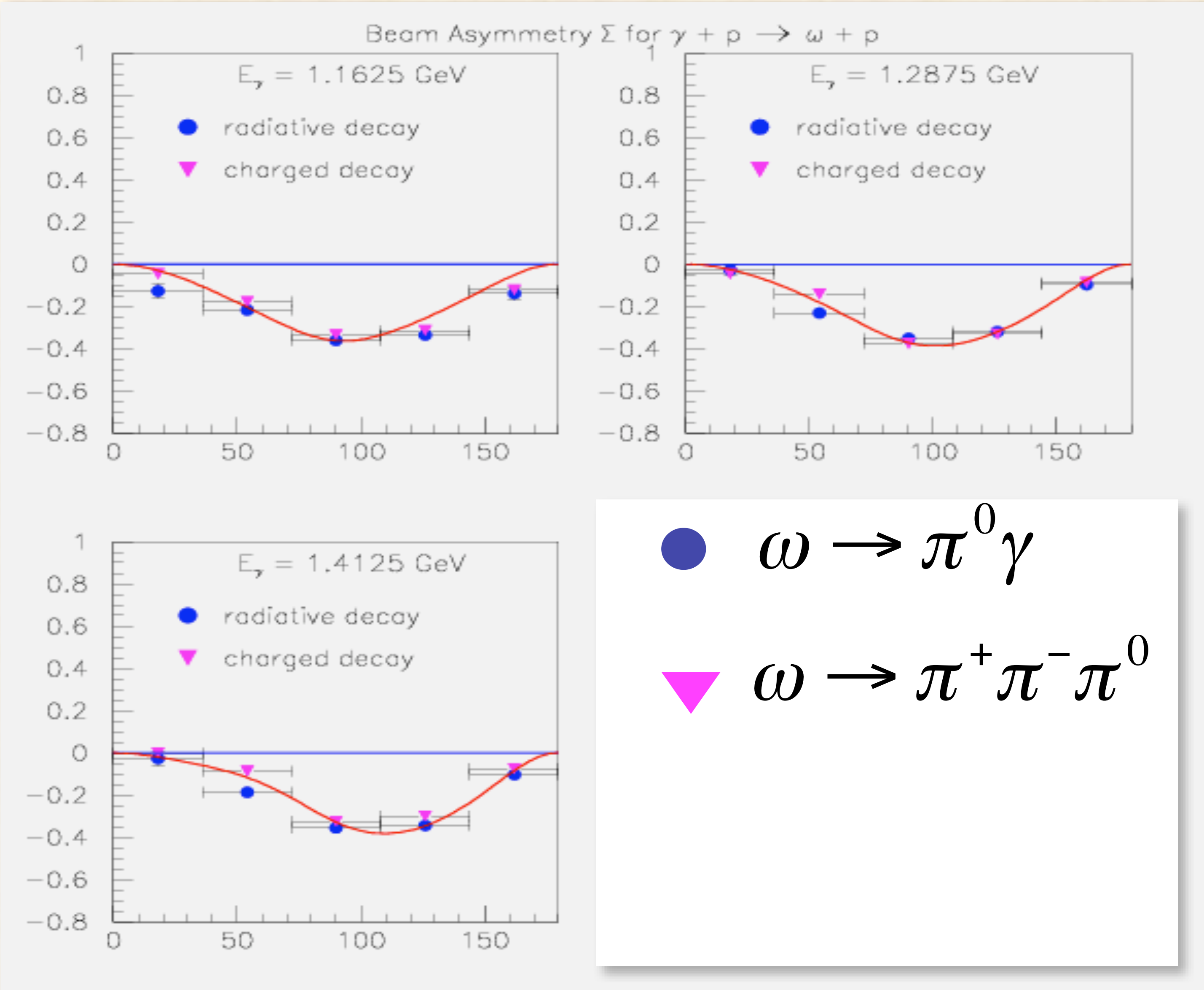
→ Pomeron exchange
→ π^0/η exchange
} *t*-channel



Large t behavior : s- and u-channel contributions
→ intermediate resonant states (N*).

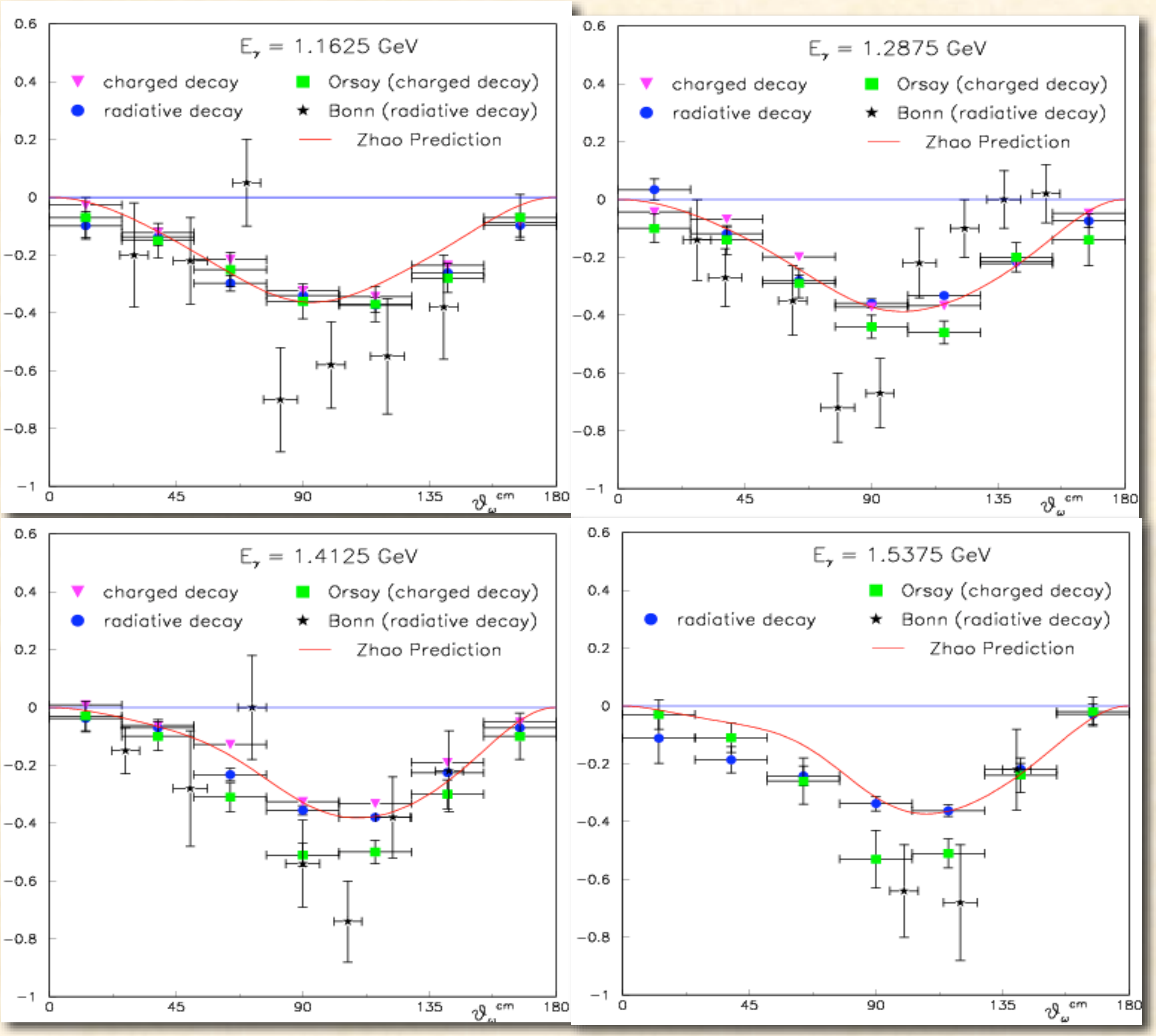
- - - - - - pseudo-scalar meson exchange
— · — · — Pomeron exchange
— · · — · · direct and crossed nucleon terms
.... N^* excitation

Beam Asymmetry: Comparison Between the Two Decay Modes



s and u-channel
including $P_{13}(1720)$
Q. Zhao

Σ Beam Asymmetry in ω Photoproduction on Free-Proton



Zhao model
s and u-channel
including $P_{13}(1720)$

J. Ajaka et al, Physical Review Letters **96**, 132003

F. Klein et al, Physical Review D **78** 117101

charged decay

radiative decay

Vector meson photoproduction

$$\gamma \quad + \quad N \quad \rightarrow \quad \text{v} \quad + \quad N$$

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

$$2 \quad \text{x} \quad 2 \quad \text{x} \quad 3 \quad \text{x} \quad 2$$

24 possible spin states → 12 independent complex amplitudes describe the transition matrix

At least 34 well chosen measurements are necessary to perform a complete experiment

↓

Additional information comes from the decay distribution of the vector meson

$$\rho(V)_{\lambda_V \lambda'_V} = \frac{1}{N} \sum_{\lambda_{N'} \lambda_\gamma, \lambda_N \lambda'_\gamma} T_{\lambda_V \lambda_{N'}, \lambda_\gamma \lambda_N} \, \rho(\gamma)_{\lambda_\gamma \lambda'_\gamma} \, T^*_{\lambda_V \lambda_{N'}, \lambda'_\gamma \lambda_N}$$

Vector meson photoproduction

$$\rho(V)_{\lambda_V \lambda'_V} = \frac{1}{N} \sum_{\lambda_{N'}\lambda_\gamma, \lambda_N \lambda'_\gamma} T_{\lambda_V \lambda_{N'}, \lambda_\gamma \lambda_N} \, \rho(\gamma)_{\lambda_\gamma \lambda'_\gamma} \, T^*_{\lambda_V \lambda_{N'}, \lambda'_\gamma \lambda_N}$$

$$\rho(\gamma) = \frac{1}{2}\left(I + \vec{P}_\gamma \cdot \vec{\sigma}\right)$$

$$\rho(V)_{\lambda_V \lambda'_V} = \frac{1}{N} \sum_{\lambda_{N'}, \lambda_\gamma, \lambda_N, \lambda'_\gamma} T_{\lambda_V \lambda_{N'}, \lambda_\gamma \lambda_N} \, \frac{1}{2}\left[I + \vec{P}_\gamma \cdot \vec{\sigma}\right] T^*_{\lambda_V \lambda_{N'}, \lambda'_\gamma \lambda_N}$$

$$\rho(V) = \rho^0 + \sum_{1=1}^{3} P^\alpha_\gamma \rho^a$$

$$\rho^0_{\lambda_v \lambda'_v} = \frac{1}{2N} \sum_{\lambda_\gamma \lambda_f \lambda_i} T_{\lambda_v \lambda_f, \lambda_\gamma \lambda_i} T^*_{\lambda'_v \lambda_f, \lambda_\gamma \lambda_i},$$

No photon polarization

$$\rho^1_{\lambda_v \lambda'_v} = \frac{1}{2N} \sum_{\lambda_\gamma \lambda_f \lambda_i} T_{\lambda_v \lambda_f, -\lambda_\gamma \lambda_i} T^*_{\lambda'_v \lambda_f, \lambda_\gamma \lambda_i},$$

$$\rho^2_{\lambda_v \lambda'_v} = \frac{i}{2N} \sum_{\lambda_\gamma \lambda_f \lambda_i} \lambda_\gamma T_{\lambda_v \lambda_f, -\lambda_\gamma \lambda_i} T^*_{\lambda'_v \lambda_f, \lambda_\gamma \lambda_i}$$

Linearly polarized photons

$$\rho^3_{\lambda_v \lambda'_v} = \frac{i}{2N} \sum_{\lambda_\gamma \lambda_f \lambda_i} \lambda_\gamma T_{\lambda_v \lambda_f, \lambda_\gamma \lambda_i} T^*_{\lambda'_v \lambda_f, \lambda_\gamma \lambda_i}.$$

Circularly polarized photons

Vector meson photoproduction

$$\rho(V)_{\lambda_V\lambda'_V} = \frac{1}{N}\sum_{\lambda_{N'}\lambda_\gamma,\lambda_N\lambda'_\gamma} T_{\lambda_V\lambda_{N'},\lambda_\gamma\lambda_N}\,\rho(\gamma)_{\lambda_\gamma\lambda'_\gamma}\,T^*_{\lambda_V\lambda_{N'},\lambda'_\gamma\lambda_N}$$

$$\rho(\gamma) = \frac{1}{2}\left(I + \vec{P}_\gamma\cdot\vec{\sigma}\right)$$

$$\rho(V)_{\lambda_V\lambda'_V} = \frac{1}{N}\sum_{\lambda_{N'},\lambda_\gamma,\lambda_N,\lambda'_\gamma} T_{\lambda_V\lambda_{N'},\lambda_\gamma\lambda_N}\,\frac{1}{2}\left[I + \vec{P}_\gamma\cdot\vec{\sigma}\right]T^*_{\lambda_V\lambda_{N'},\lambda'_\gamma\lambda_N}$$

$$\rho(V) = \rho^0 + \sum_{1=1}^{3} P_\gamma^\alpha \rho^a$$

$\omega\rightarrow\pi^+\pi^-\pi^0$

No photon polarization

$$W^0(\cos\theta,\phi) = C^2\frac{3}{4\pi}[\frac{1}{2}(1-\rho^0_{00}) + \frac{1}{2}(3\rho^0_{00}-1)\cos^2\theta - \mathrm{Re}\,\rho^0_{10}\sqrt{2}\sin 2\theta\cos\phi - \mathrm{Re}\,\rho^0_{1-1}\sin^2\theta\cos 2\phi]$$

$$W^1(\cos\theta,\phi) = C^2\frac{3}{4\pi}[\rho^1_{11}\sin^2\theta + \rho^1_{00}\cos^2\theta - \mathrm{Re}\,\rho^1_{10}\sqrt{2}\sin 2\theta\cos\phi - \mathrm{Re}\,\rho^1_{1-1}\sin^2\theta\cos 2\phi]$$

$$W^2(\cos\theta,\phi) = C^2\frac{3}{4\pi}[\sqrt{2}\,\mathrm{Im}\,\rho^2_{10}\sin 2\theta\sin\phi + \mathrm{Im}\,\rho^2_{1-1}\sin 2\theta\sin\phi]$$

Linearly polarized photons

$$W^3(\cos\theta,\phi) = C^2\frac{3}{4\pi}[\sqrt{2}\,\mathrm{Im}\,\rho^3_{10}\sin 2\theta\sin\phi + \mathrm{Im}\,\rho^3_{1-1}\sin 2\theta\sin\phi]$$

Circularly polarized photons

Vector meson photoproduction

$$\rho(V)_{\lambda_V \lambda'_V} = \frac{1}{N} \sum_{\lambda_{N'}\lambda_\gamma, \lambda_N \lambda'_\gamma} T_{\lambda_V \lambda_{N'}, \lambda_\gamma \lambda_N}\, \rho(\gamma)_{\lambda_\gamma \lambda'_\gamma}\, T^*_{\lambda_V \lambda_{N'}, \lambda'_\gamma \lambda_N}$$

$$\rho(\gamma) = \frac{1}{2}\left(I + \vec{P}_\gamma \cdot \vec{\sigma}\right)$$

$$\rho(V)_{\lambda_V \lambda'_V} = \frac{1}{N} \sum_{\lambda_{N'}, \lambda_\gamma, \lambda_N, \lambda'_\gamma} T_{\lambda_V \lambda_{N'}, \lambda_\gamma \lambda_N}\, \frac{1}{2}\left[I + \vec{P}_\gamma \cdot \vec{\sigma}\right] T^*_{\lambda_V \lambda_{N'}, \lambda'_\gamma \lambda_N}$$

$$\rho(V) = \rho^0 + \sum_{1=1}^{3} P_\gamma^\alpha \rho^a$$

$\omega \rightarrow \pi^0 \gamma$

No photon polarization

$$W^0(\cos\phi, \theta) = C^2 \frac{3}{8\pi}\{\frac{1}{2}(1+\cos^2\theta) + \left(\frac{1}{2} - \frac{3}{2}\cos^2\theta\right)\rho^0_{00} + \sqrt{2}\sin 2\theta \cos\phi\,(\mathrm{Re}\,\rho^0_{10}) + \rho^0{}_{1-1}\sin^2\theta\cos 2\phi\}$$

$$W^1(\cos\theta, \phi) = C^2 \frac{3}{8\pi}\{\rho^1{}_{11}(1+\cos^2\theta) + \rho^1_{00}\sin^2\theta + \sqrt{2}\sin 2\theta\cos\phi\,(\mathrm{Re}\,\rho^1_{10}) + \rho^0{}_{1-1}\sin^2\theta\cos 2\phi$$

$$W^2(\cos\phi, \theta) = \sqrt{2}\sin 2\theta \sin\phi\,\mathrm{Im}\,\rho^2_{10} + \mathrm{Im}\,\rho^2_{1-1}\sin^2\theta$$

$$W^3(\cos\phi, \theta) = \sqrt{2}\sin 2\theta \sin\phi\,\mathrm{Im}\,\rho^3_{10} + \mathrm{Im}\,\rho^3_{1-1}\sin^2\theta$$

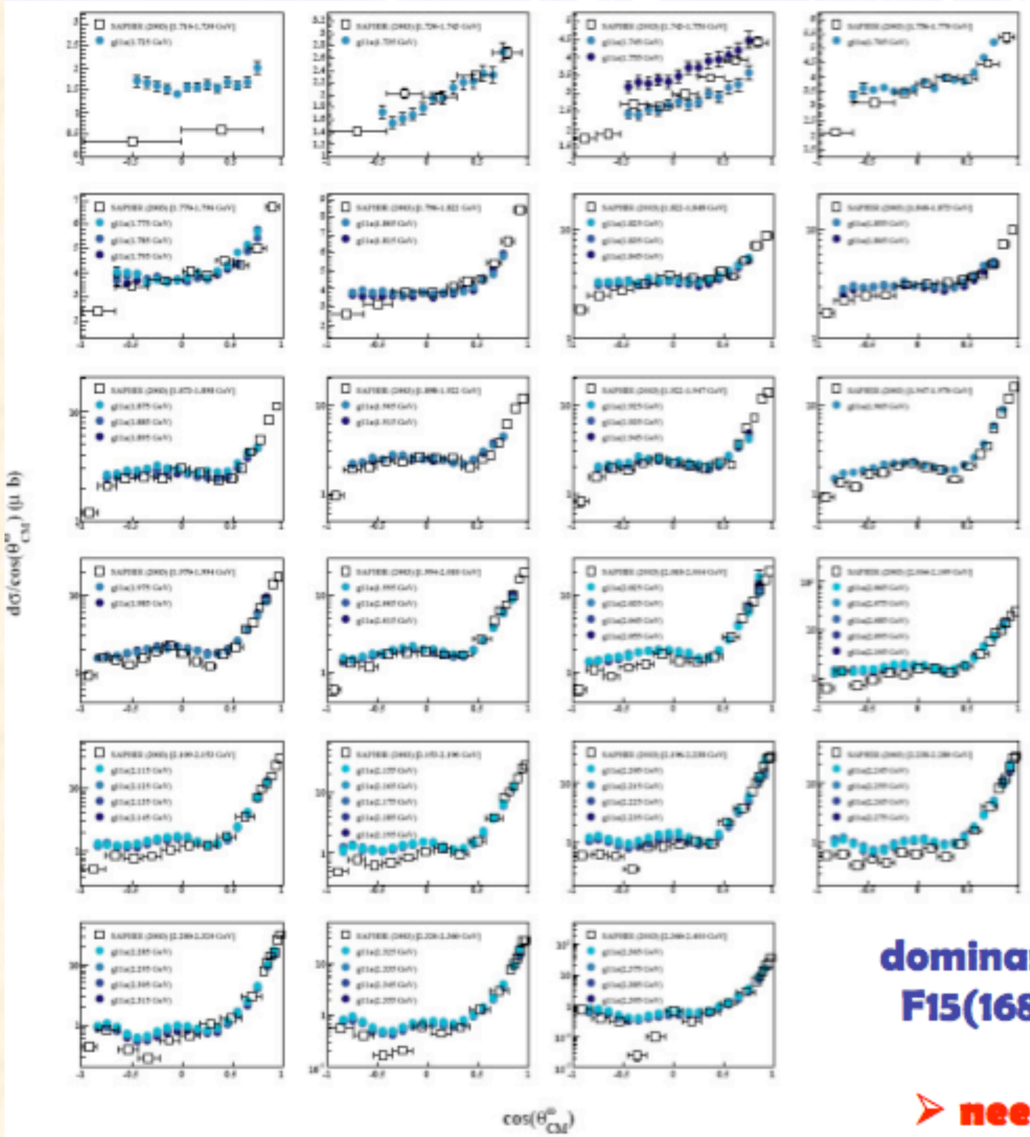
← Linearly polarized photons

Circularly polarized photons

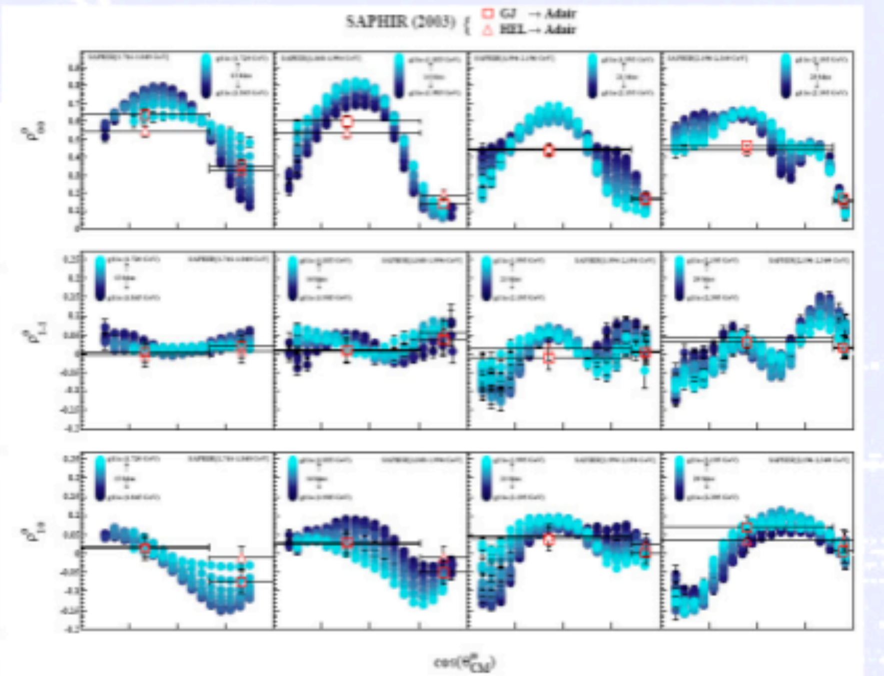
ω photoproduction at CLAS

γp→ωp (event-based PWA)

(M.Williams et al, submitted to PRC)

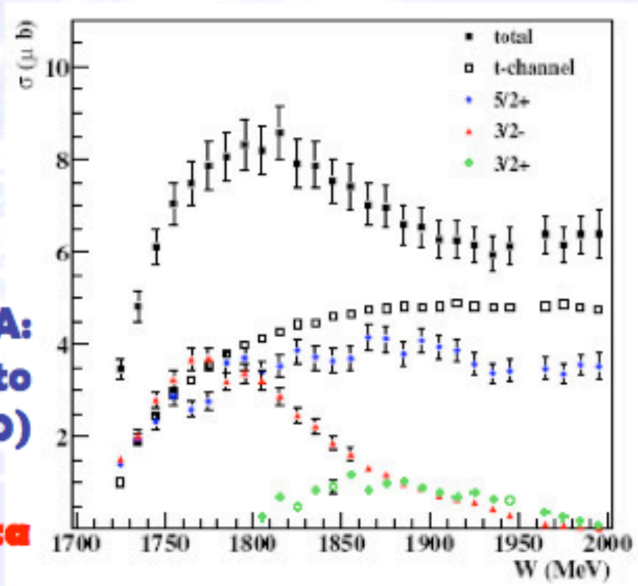


spin density matrix



PWA:
dominant coupling to
F15(1680), D13(1700)

➢ need polar.data



Conclusions

- Existing results on pseudo-scalar meson (and vector meson) photo production have shown that reliable extraction of Baryon resonance properties require the experimental determination of a complete set of Observables requiring both beam and target and polarization measurements.

- A large effort is going on in world facilities to perform this goal

- After 50 years of activity the goal is close to be met.

  Within two years we will have the first complete experiment!