RESULTS FROM POLARIZED EXPERIMENTS FROM LEGS AND GRAAL

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Outline

- Introduction: missing resonances and hadronic degrees of freedom
- The Legs and Graal Experimental set-ups.
- Results for Σ beam polarization asymmetries at Graal:

$$\begin{cases} \vec{\gamma} + n \to \pi^0 + n \\ \vec{\gamma} + n \to \pi^- + p \\ \vec{\gamma} + N \to \omega + N \end{cases}$$

- Results for O_x and O_y double polarization asymmetries for $k^+ \Lambda$ photoproduction on the proton at Graal.
- Results on E and G double polarization asymmetries at Legs:

$$\begin{cases} \vec{\gamma} + \vec{HD} \to \pi^0 p \\ \vec{\gamma} + \vec{HD} \to \pi^+ n \end{cases}$$

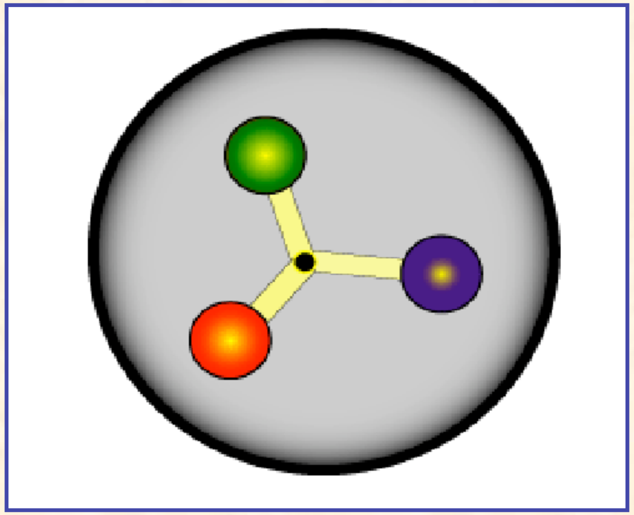
- Conclusions

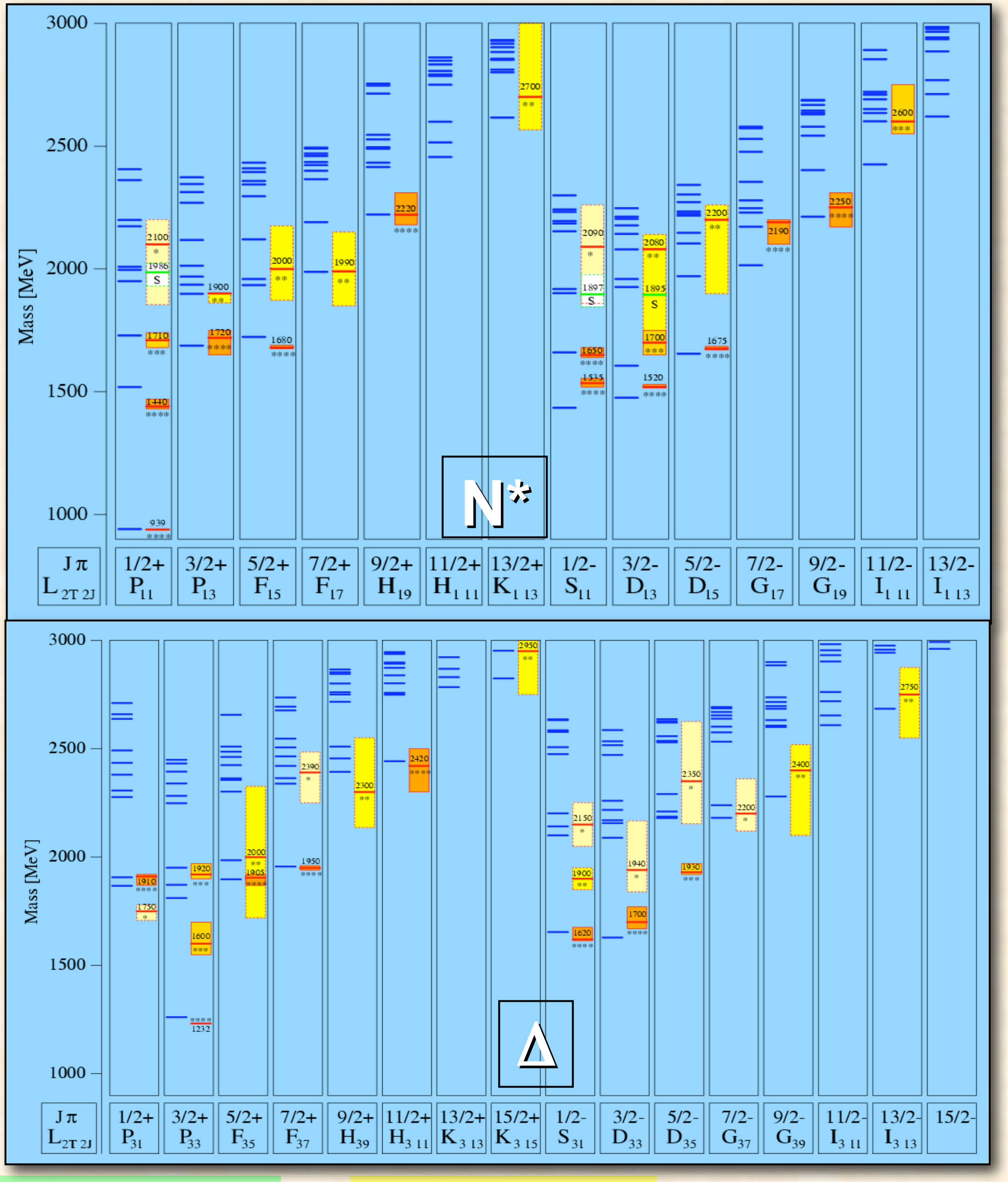
QCD-inspired Constituent Quark Models

- 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.

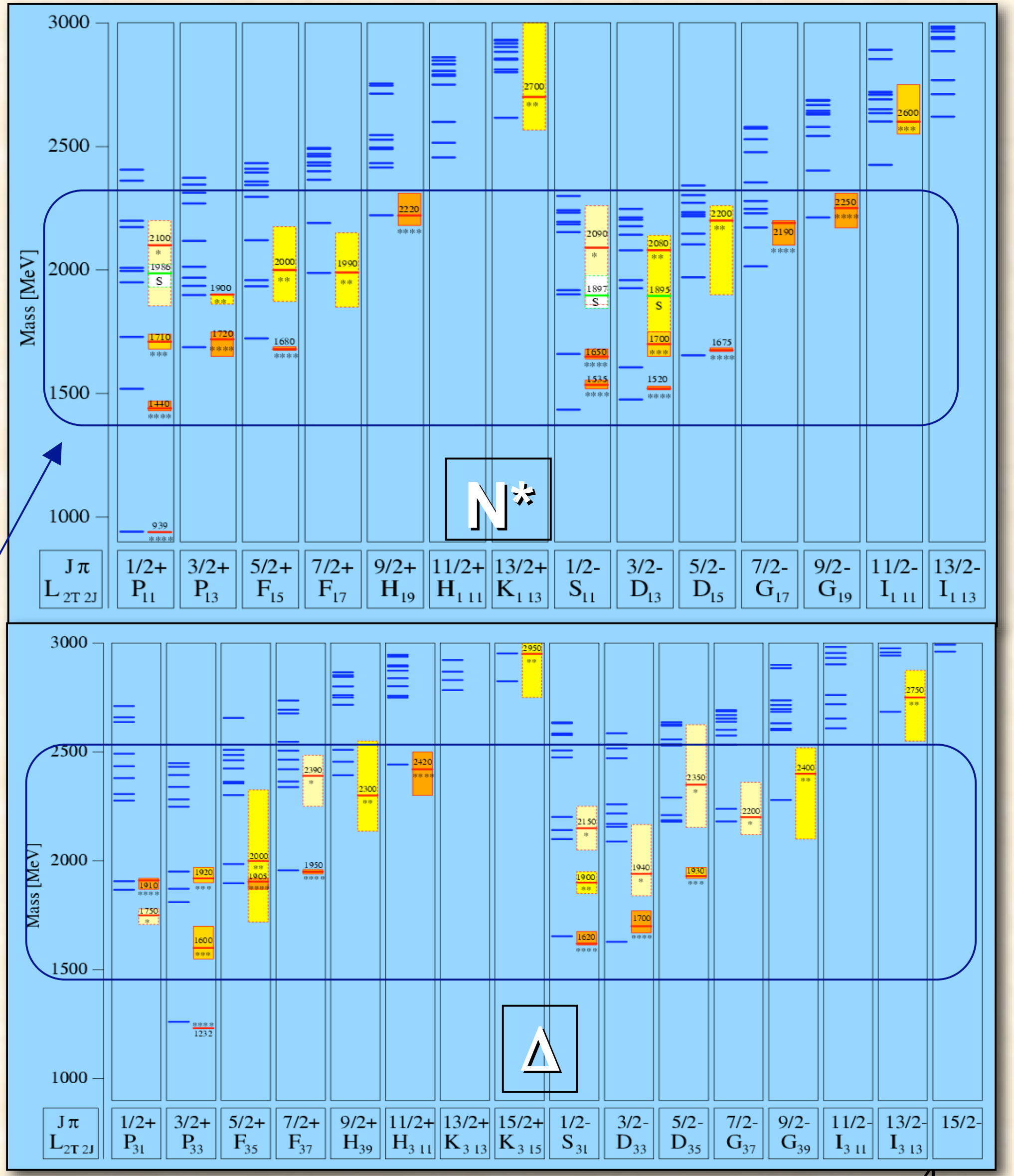
- Asymmetry of the baryon wave function is guaranteed by color, but color degrees of freedom are integrated out and play no dynamical role.

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

- only lowest few in each band seen (in πN) 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, ...

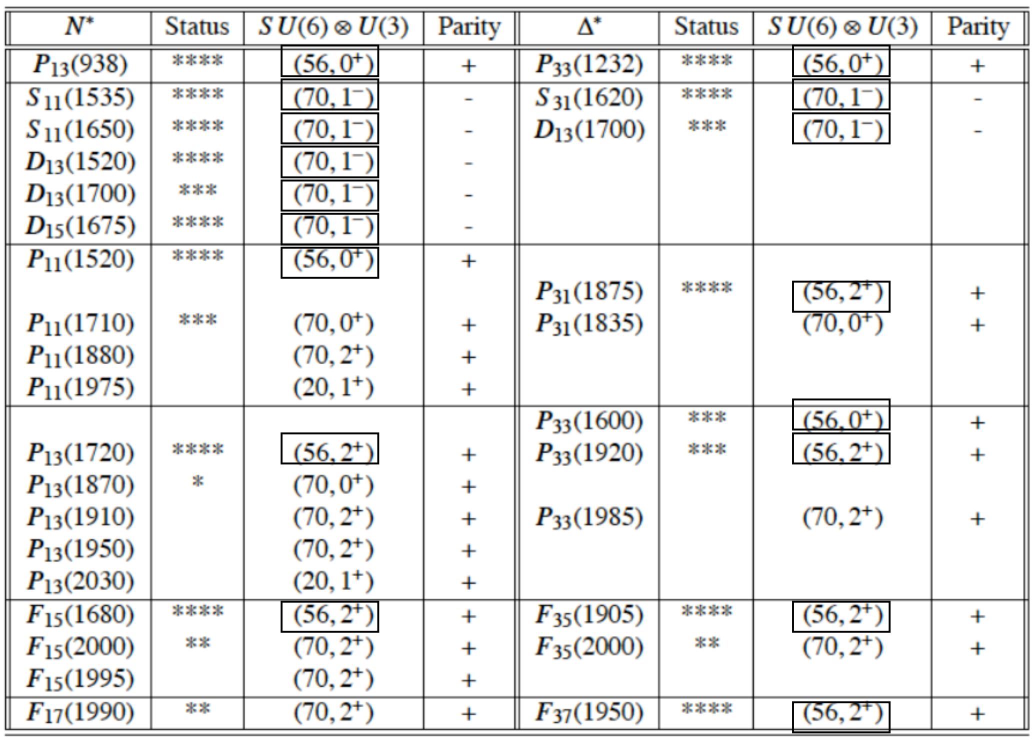


QCD-inspired di- Quark Models

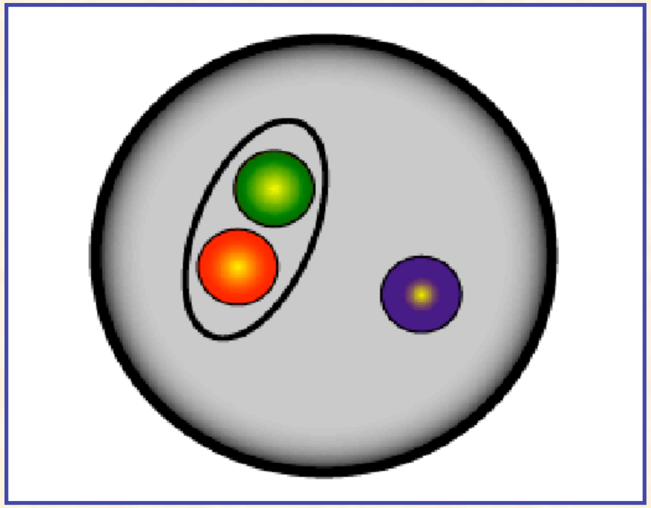
- 2 quarks in nucleon assumed to be quasi-bound in a color isotriplet; diquark-quark is a net color isosinglet.

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



the challenge: ⇔ unravel the N* spectrum

Experimental Requirements

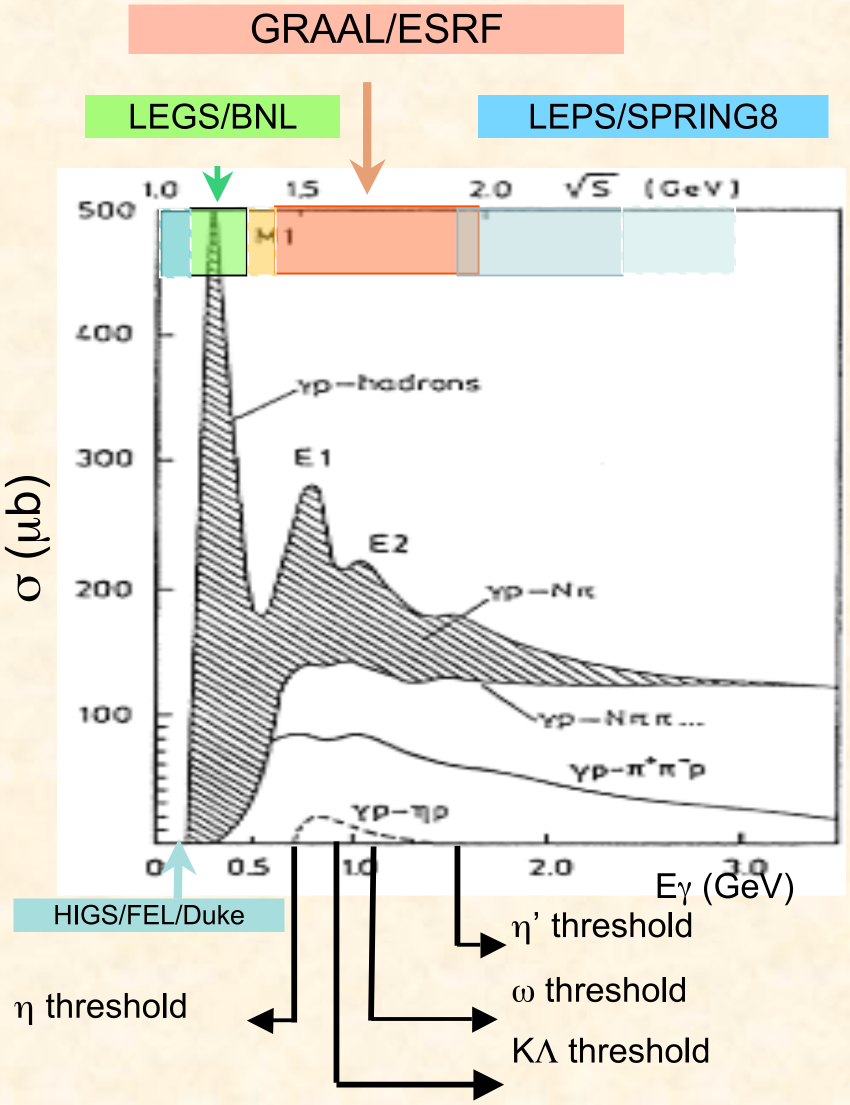
- ☐ Tagged and polarized photon beam
- ☐ Large acceptance detector
- ☐ H and D polarized targets

Both Legs and Graal experiment were constructed to meet all above requirements

in the energy ranges:

E_γ = (180 - 450)MeV and E_γ = (500 - 1500)MeV

Polarized photon beams: Compton backscattering



GRAAL/ESRF

LEGS/BNL

LEPS/SPRING8

HIGS/FEL/Duke

η threshold

η' threshold

ω threshold

$K\Lambda$ threshold

- Hiγs → below π threshold
- Legs → $\Delta_{33}(1232)$ resonance region

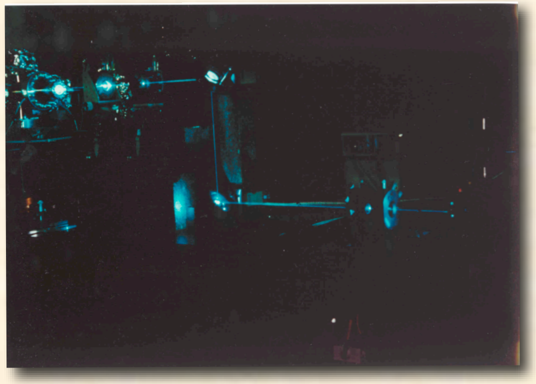
- Graal → E_γ = .6-1.5 GeV / W=1.4-1.9 GeV Region of the second and third baryon resonances η, K, ω, thresholds

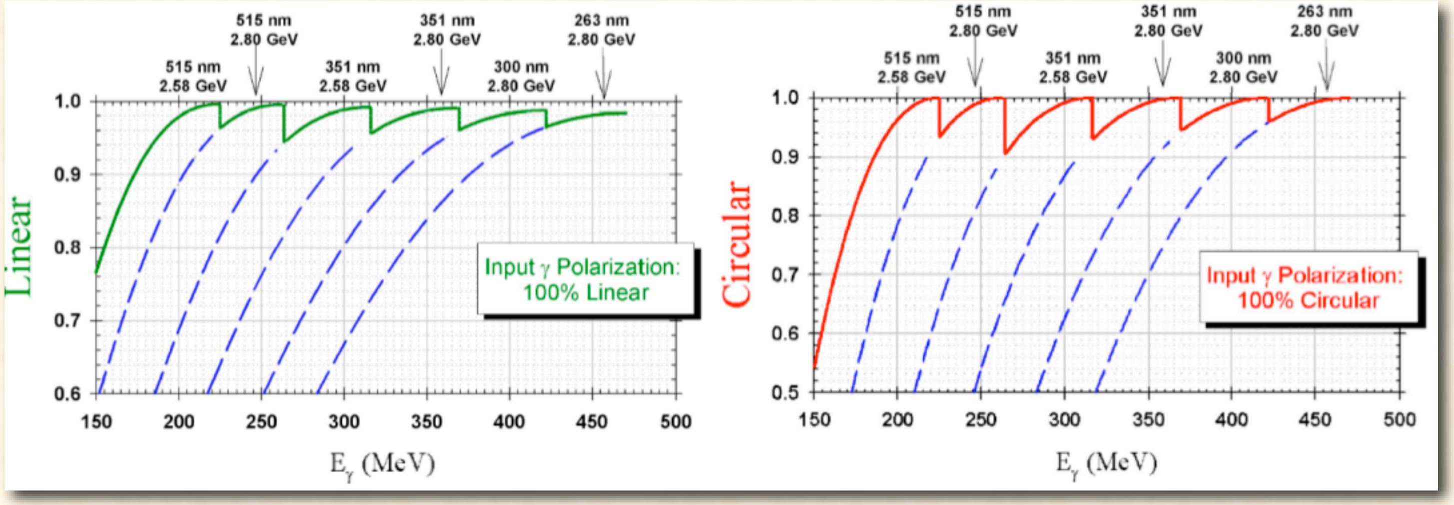
- Leps → E_γ = 1.5-2.5 GeV

η' ϕ thresholds

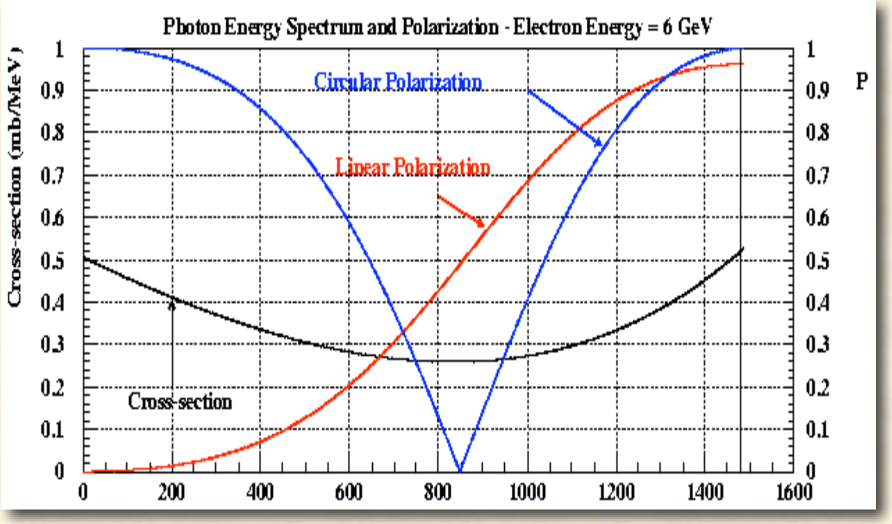
Polarized photon beams: Compton backscattering and Bremsstrahlung

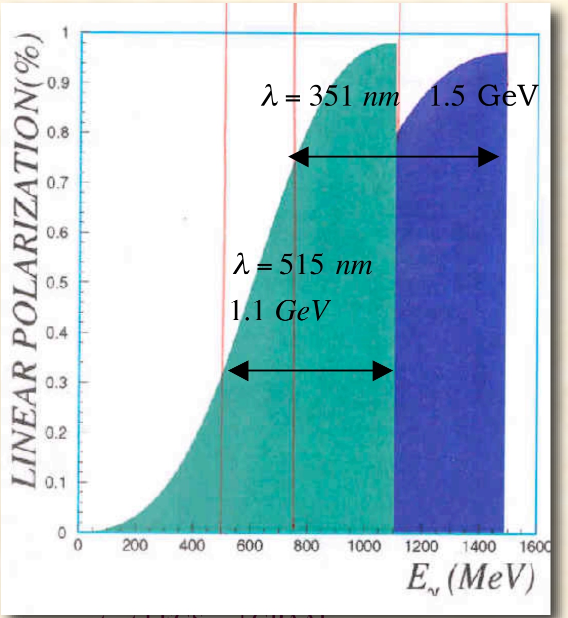
LEGS beam polarization



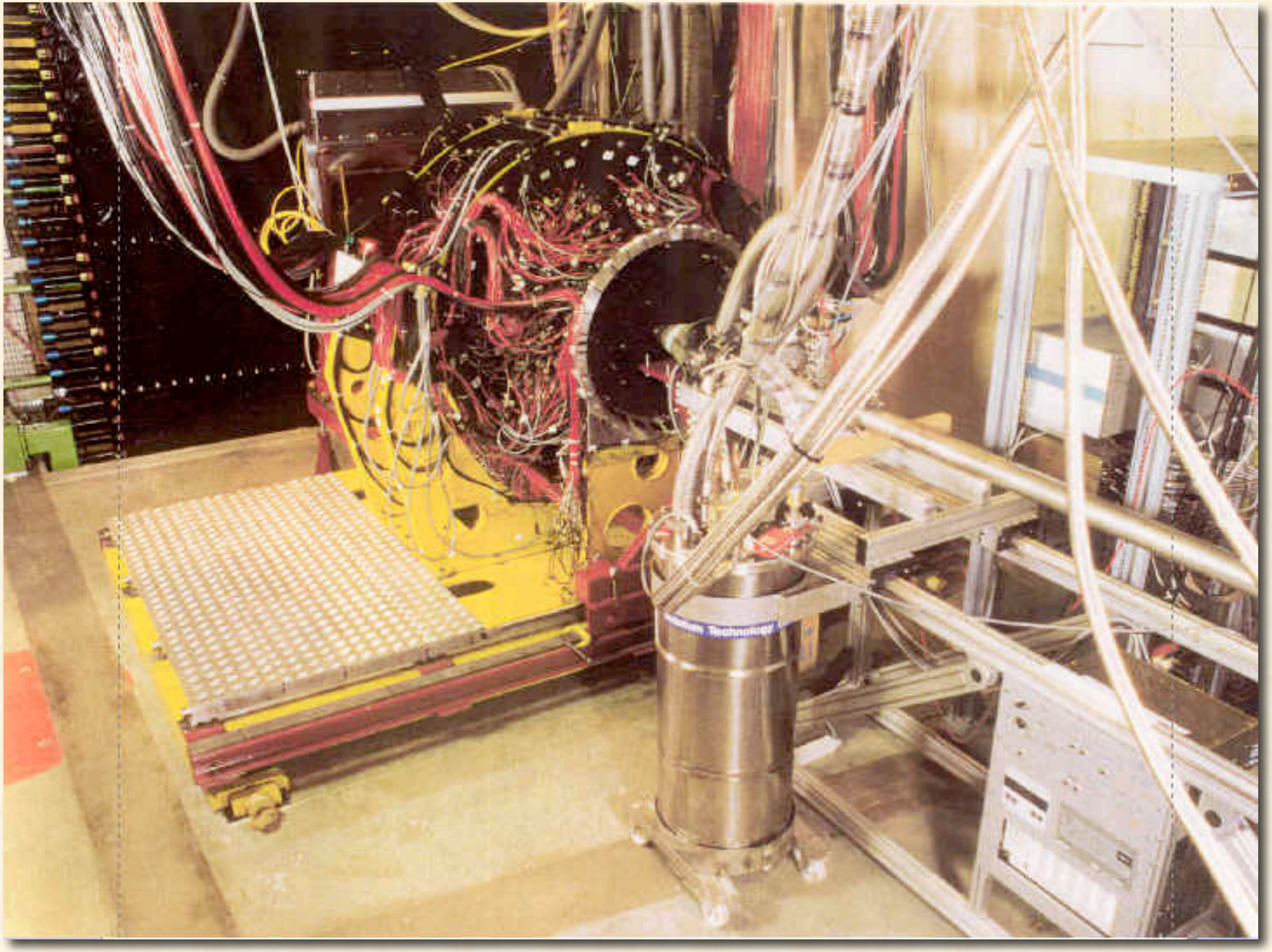


GRAAL beam polarization





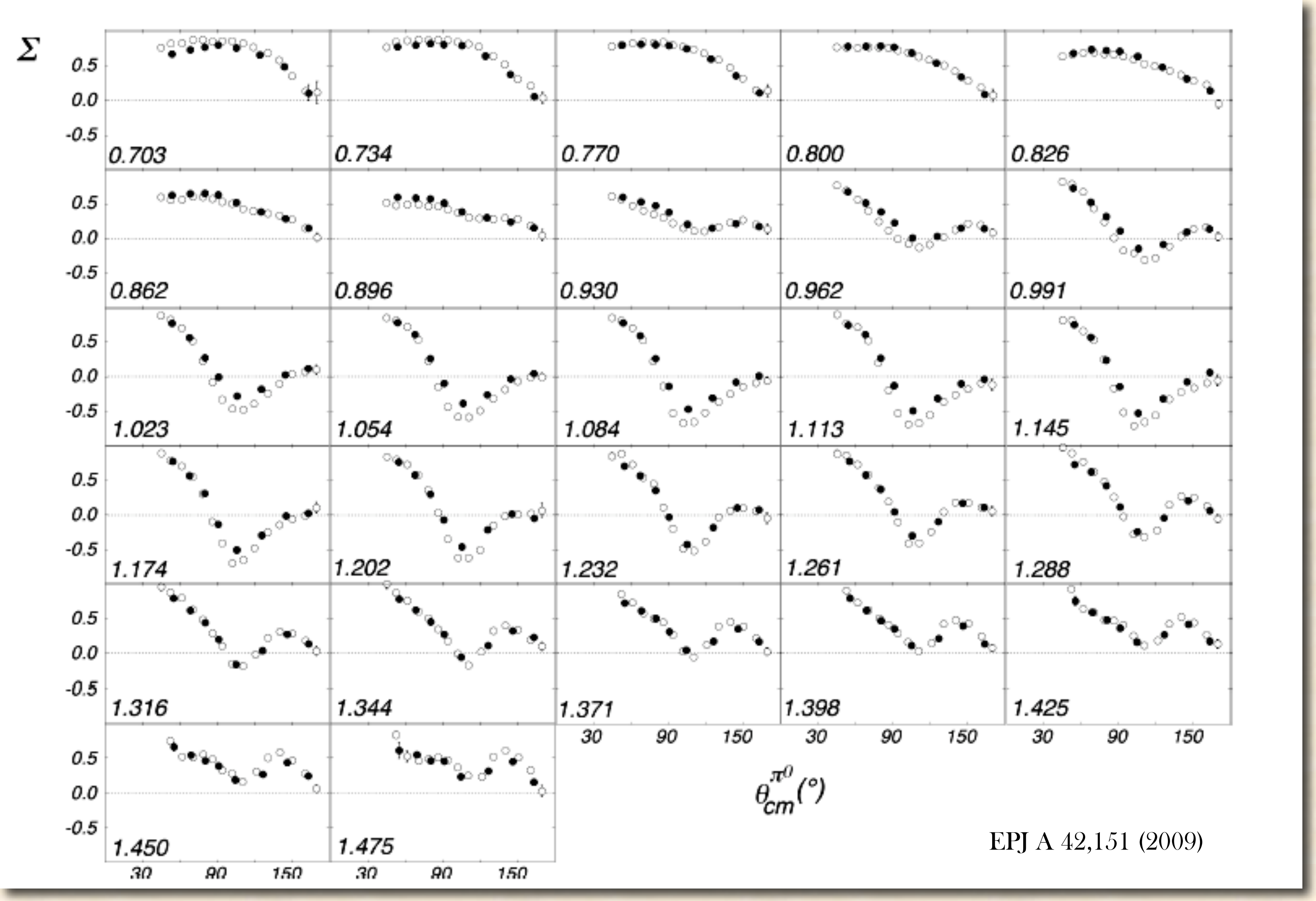
The Graal detector: Lagranγe



Large Acceptance Graal Apparatus for Nuclear γ Experiments

Σ measurements at Graal on proton and deuteron targets

○ $\vec{\gamma} + p \to \pi^0 + p$ ● $\vec{\gamma} + p(+n) \to \pi^0 + p(+n)$

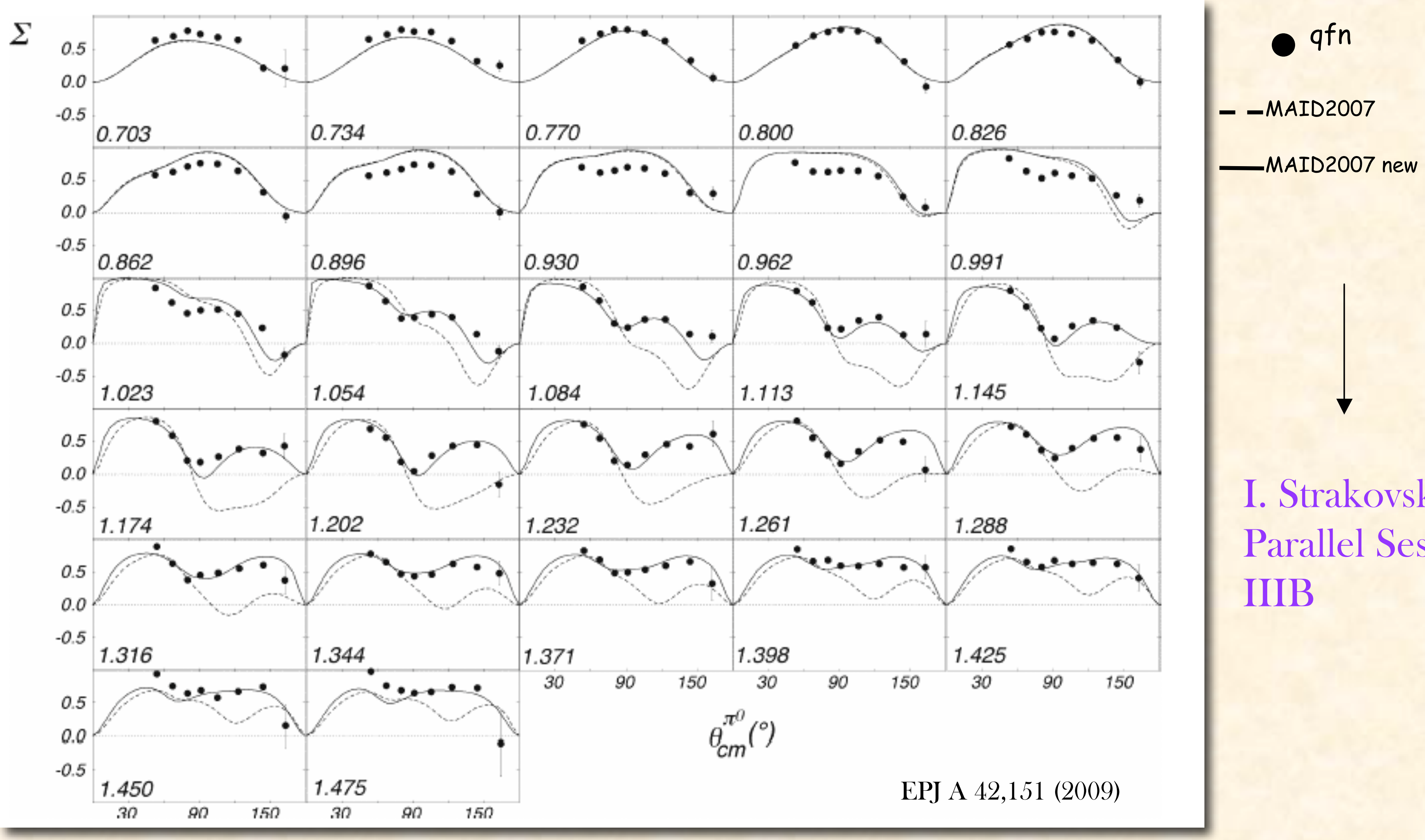


EPJ A 42,151 (2009)

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

Σ measurements at GRAAL deuteron target

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



EPJ A 42,151 (2009)

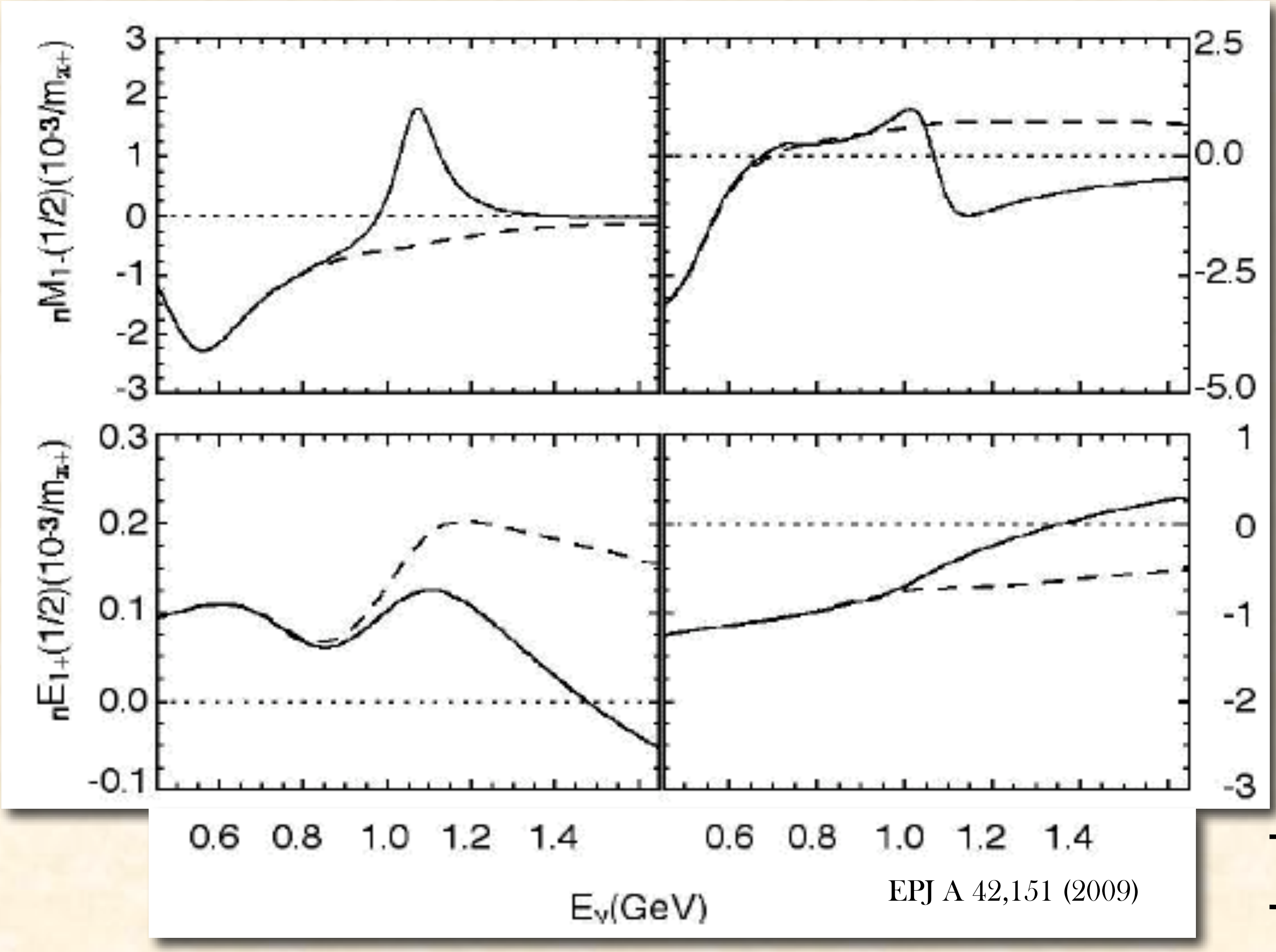
I. Strakovsky Parallel Session IIIB

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

Σ for π^0 photoproduction on qfn
Multipole extraction in MAID2007

Immaginary part

Real part



EPJ A 42,151 (2009)

Second P_{11}(1700) resonance

$\boxed{P_{11}(1700)}$

$\Gamma_{tot} = 70 MeV$

$\beta_\pi = 0.1$

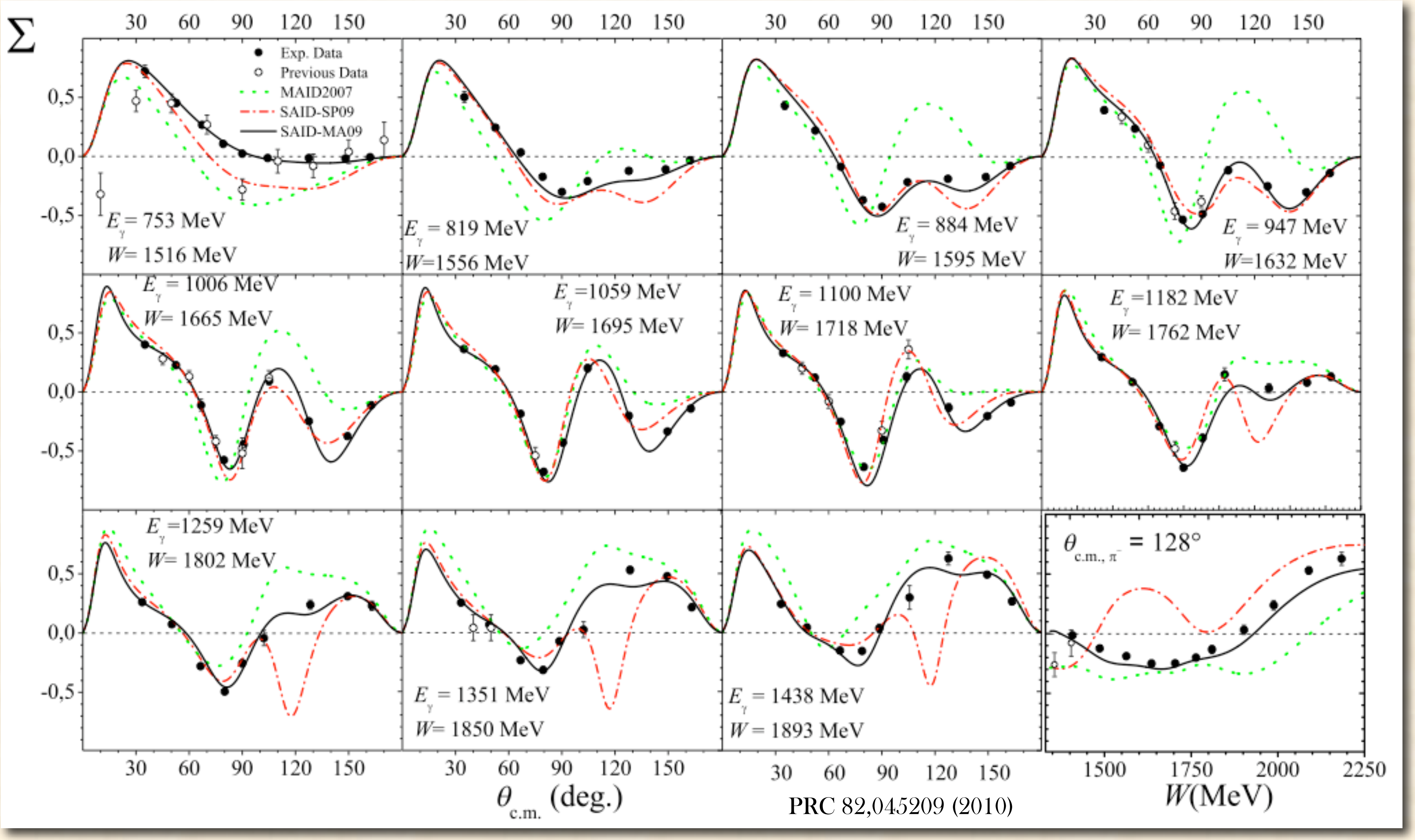
$\boxed{P_{13}(1720)}$

modified photo-couplings

- - - MAID2007 qfn

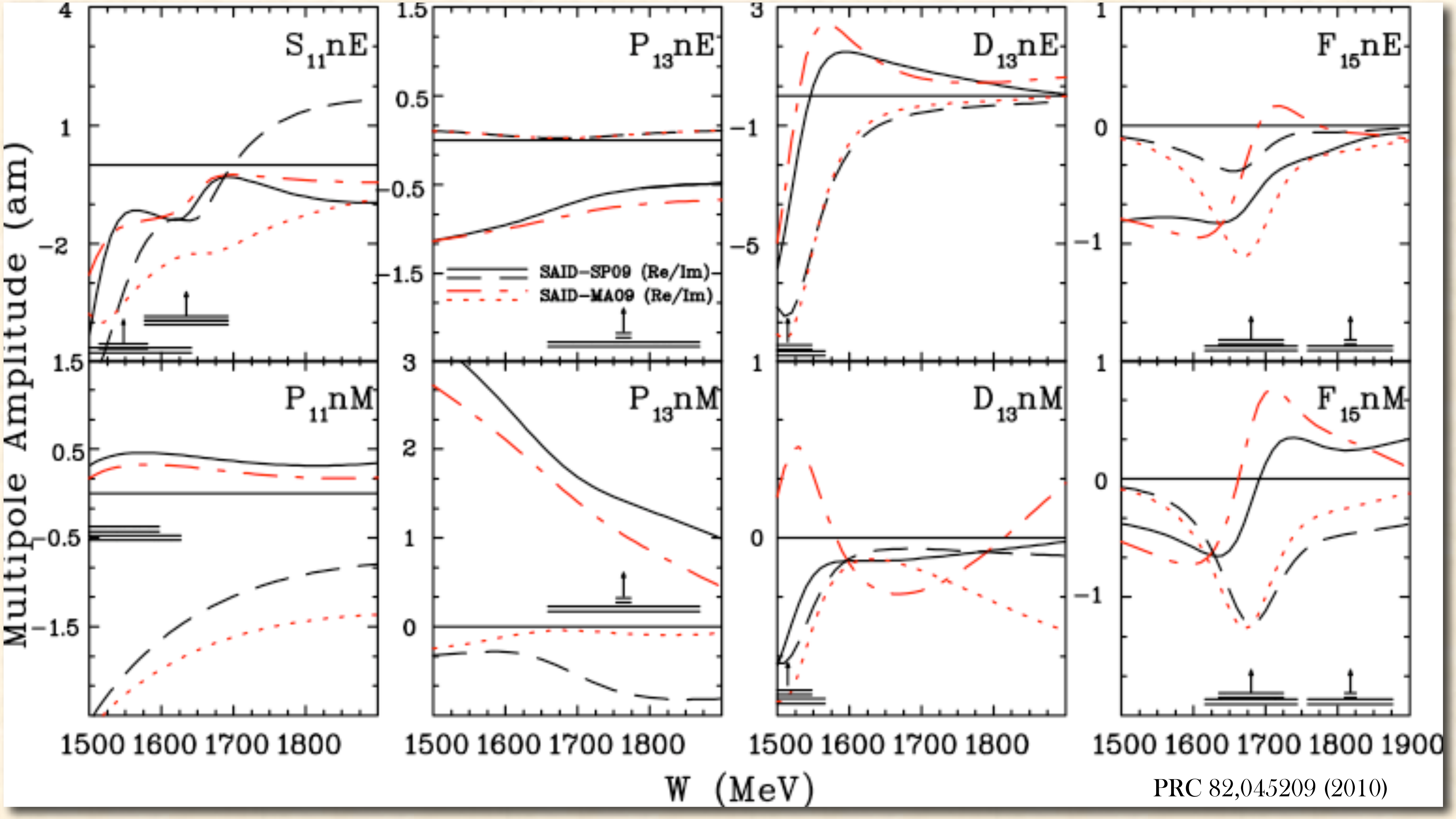
—— mod MAID2007 qfn

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



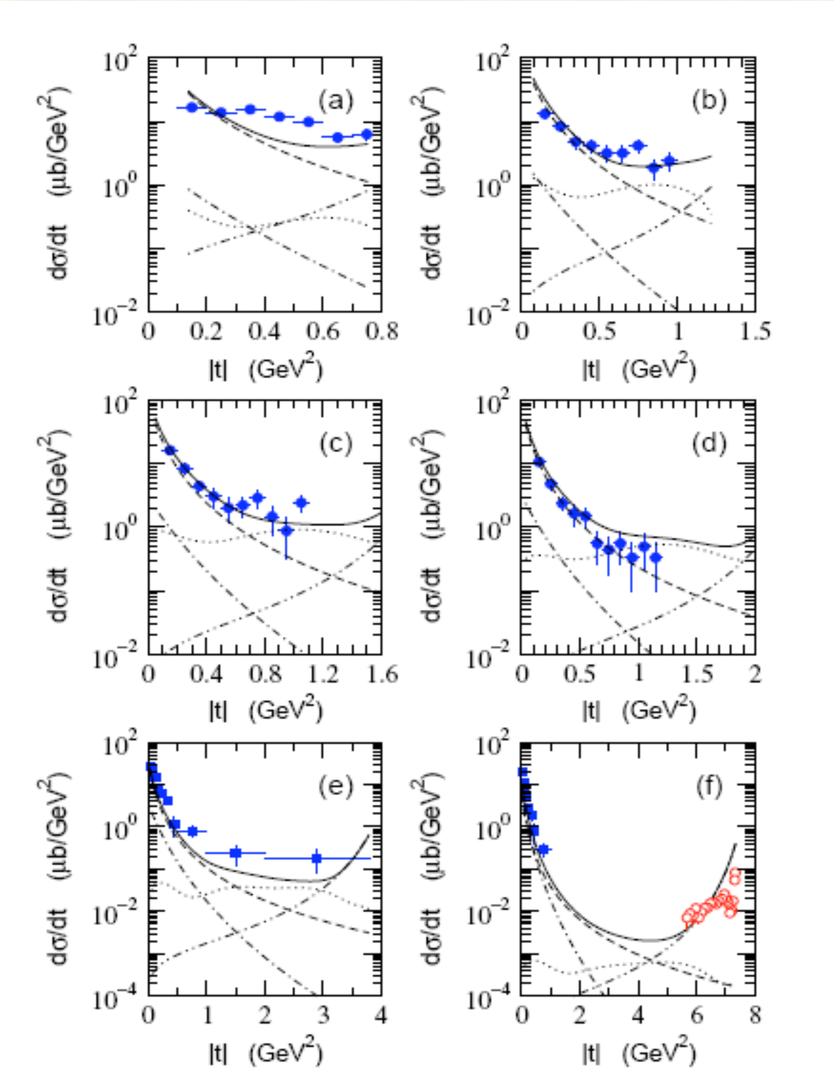
PRC 82,045209 (2010)

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



PRC 82,045209 (2010)

$\vec{\gamma} + p \to \omega + p$: Differential Cross-Section



Oh,Titov,Lee
PRC63 (2001) 025201

Low *t* diffractive behavior:

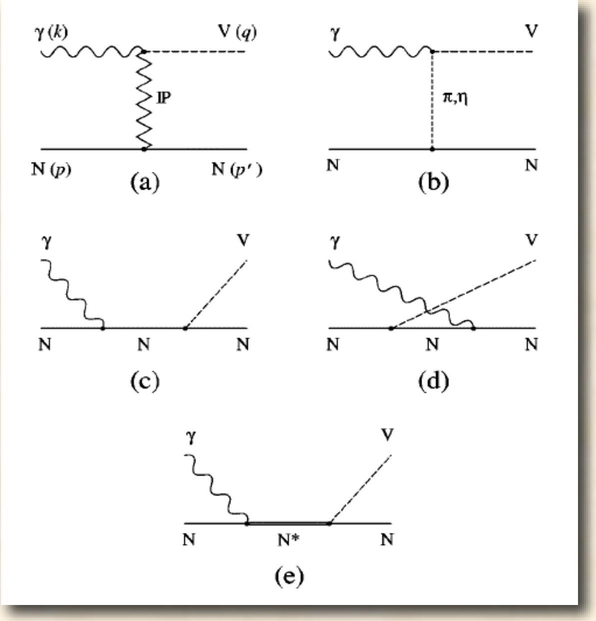
Vector Dominance Model (1960), J.J.Sakurai

→ Pomeron exchange

→ π^0/η exchange

} *t*-channel

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

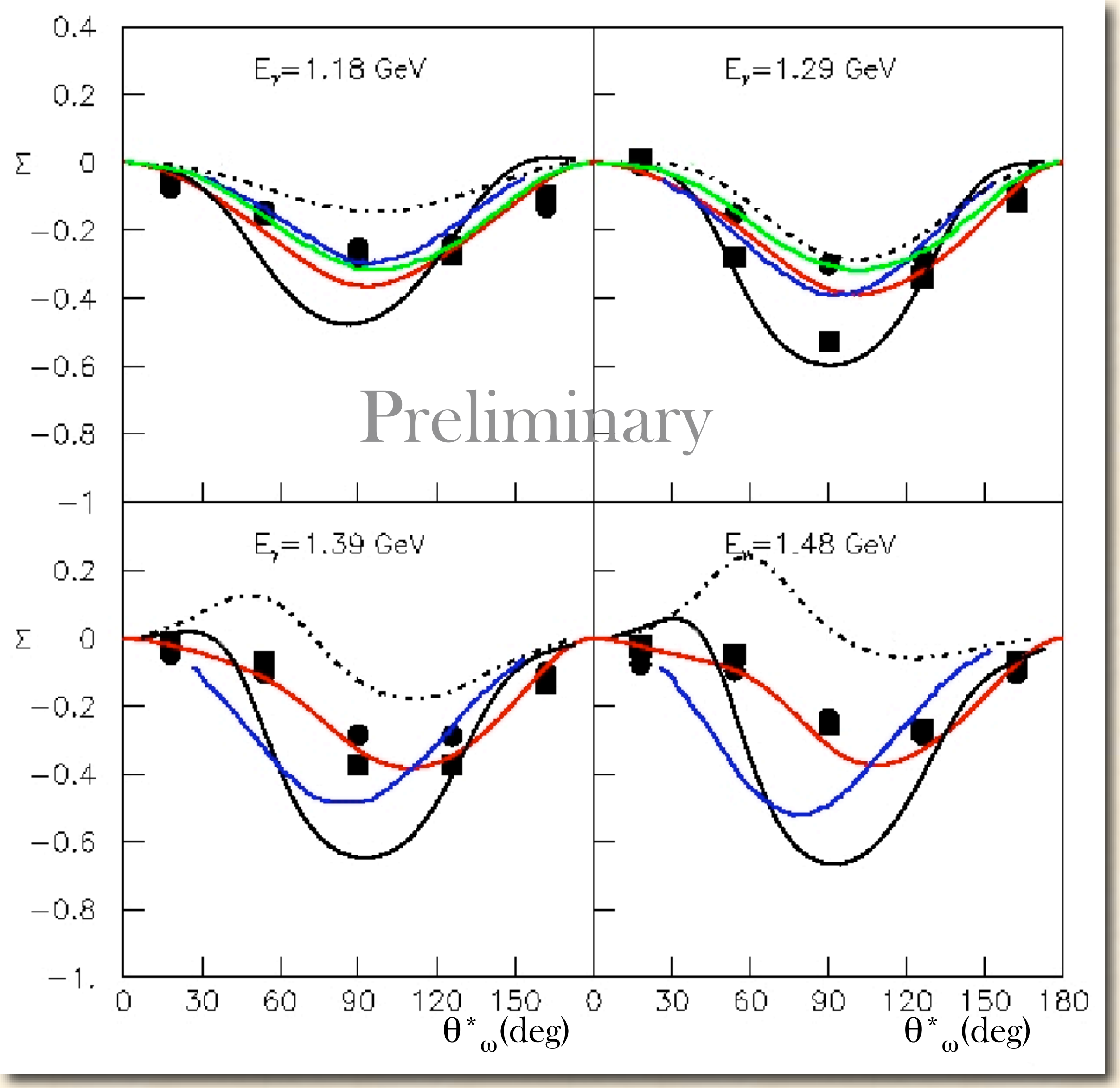


Large t behavior : s- and u-channel contributions

→ intermediate resonant states (N*).

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

Σ results on $\vec{\gamma} + p \rightarrow \omega + p$ at GRAAL : $\omega \rightarrow \pi^0\gamma$ and $\omega \rightarrow \pi^+\pi^-\pi^0$



Q. Zhao
s and u-channel
including $P_{13}(1720)$
PRC63(2001)025203

Bonn-Gatchina
dominant $P_{13}(1720)$
Eur. Phys.J.A 25(2005)427

Giessen model
PRC71(2005)055206

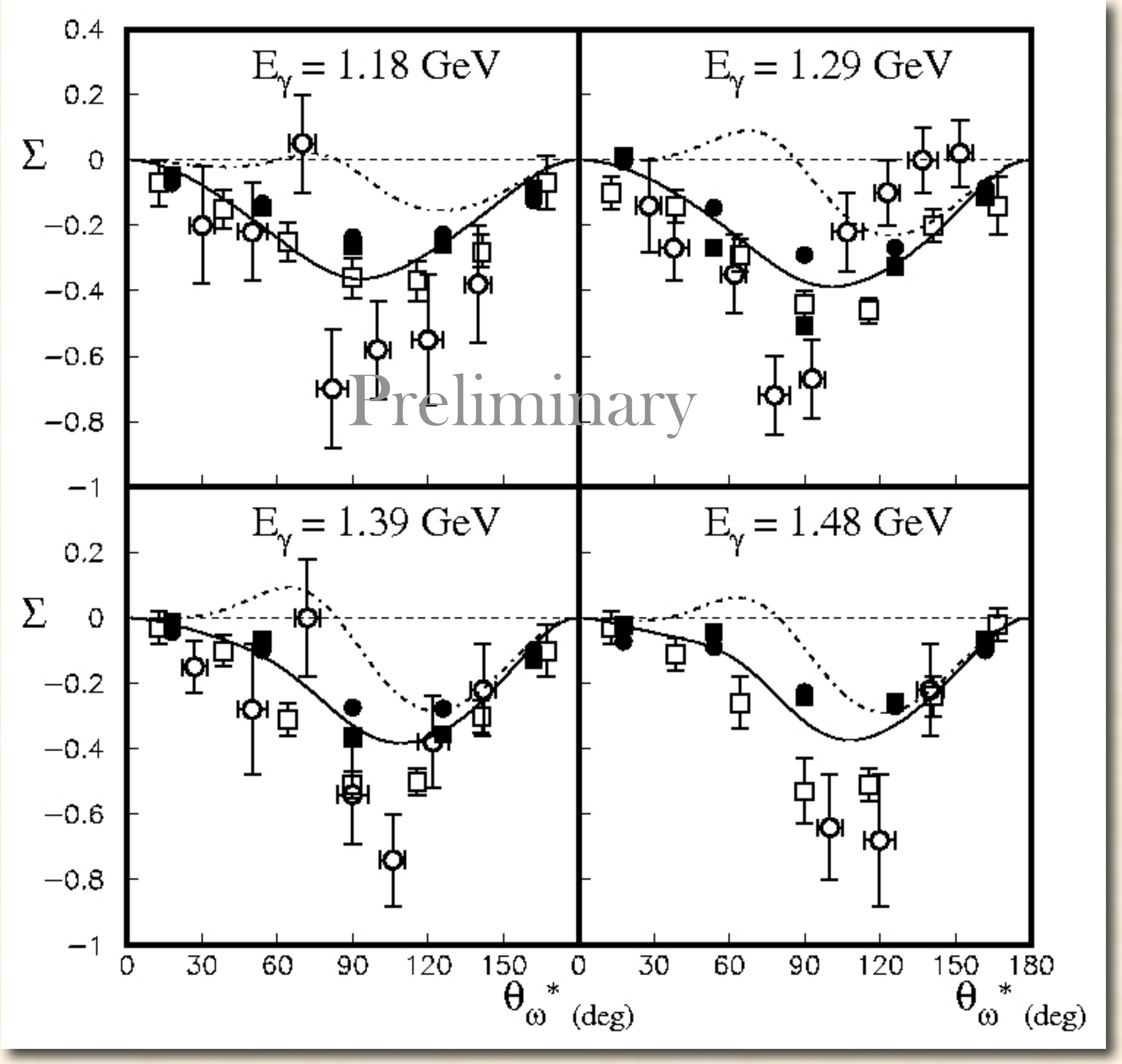
Oh,Titov and Lee
PRC66 (2002)015204

M. Paris
PRC79 (2009) 025208

● $\omega \rightarrow \pi^0\gamma$

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

Σ results on $\vec{\gamma} + p \rightarrow \omega + p$ at GRAAL : $\omega \rightarrow \pi^0\gamma$ and $\omega \rightarrow \pi^+\pi^-\pi^0$



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

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

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

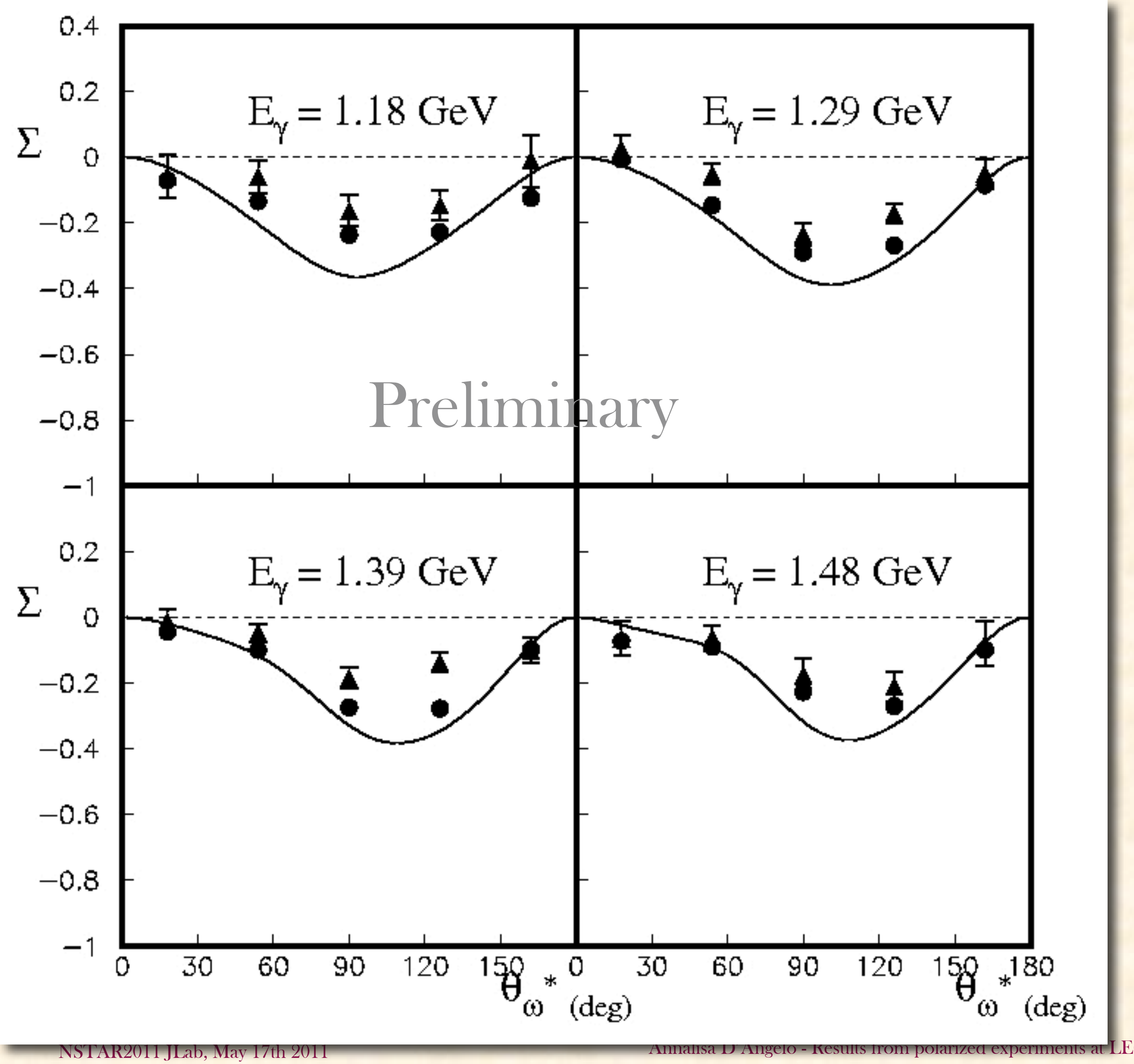
□ PRL96(06) $\omega \rightarrow \pi^+\pi^-\pi^0$

Zhao model

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

– · – s and u-channel no $P_{13}(1720)$

Σ results on $\vec{\gamma} + p \rightarrow \omega + p$ and $\vec{\gamma} + p\ (+n) \rightarrow \omega + p\ (+n)$ at GRAAL



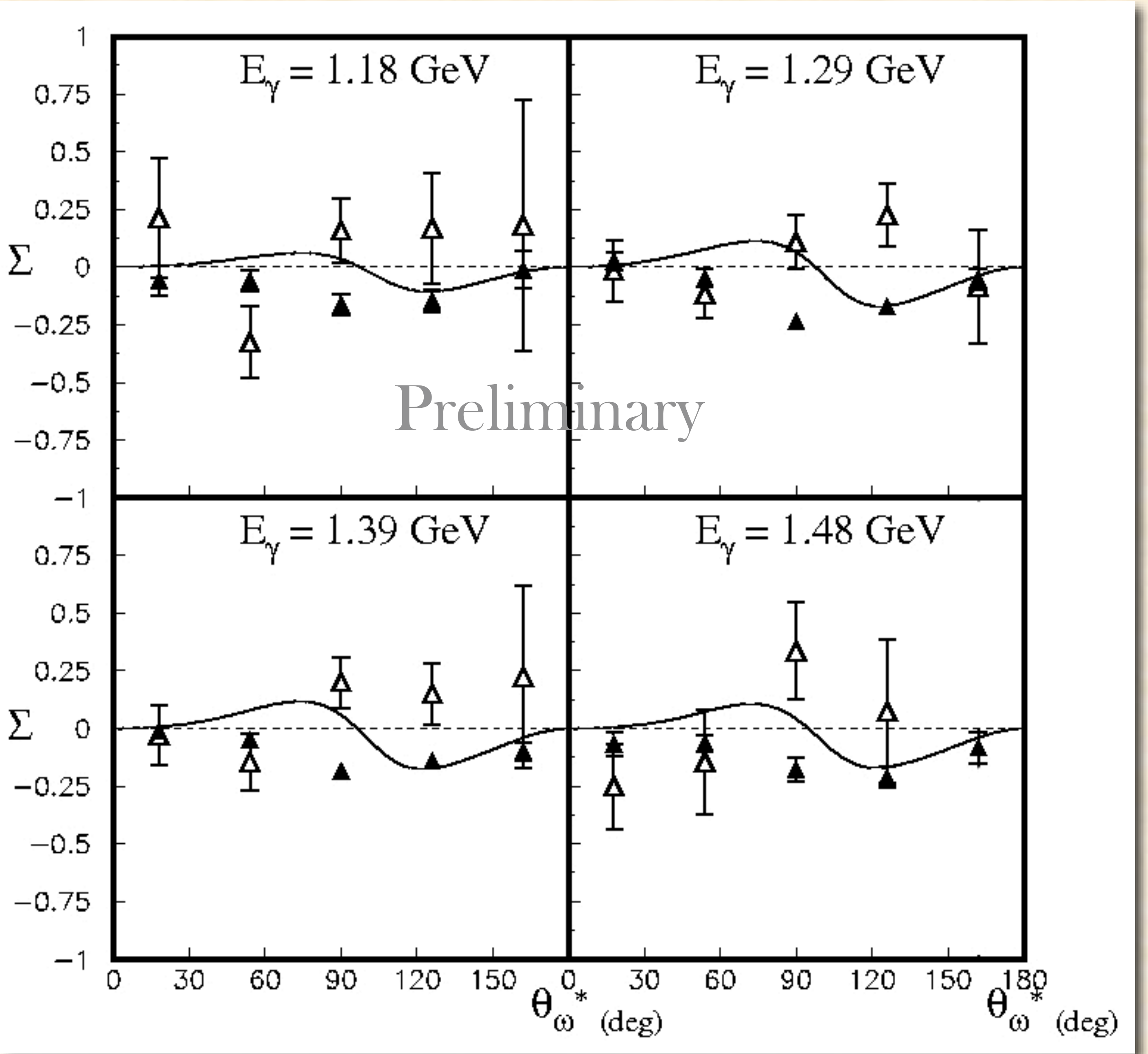
Zhao model

— s and u-channel including P_{13}(1720)

● $\omega \rightarrow \pi^0\gamma$ free- proton

▲ $\omega \rightarrow \pi^0\gamma$ Quasi-free- proton

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

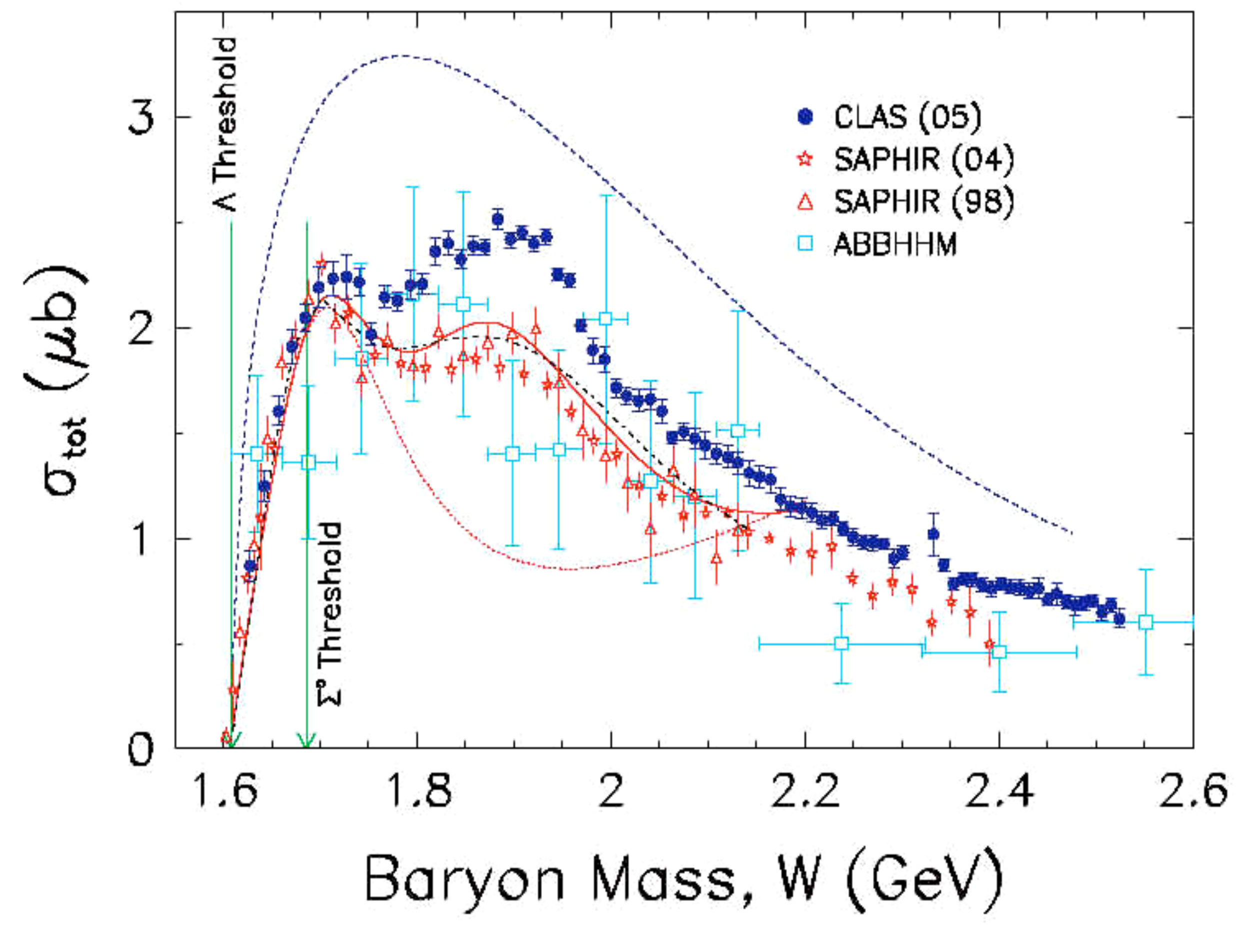


—— Zhao model

△ $\omega \rightarrow \pi^0\gamma$ quasi-free- neutron

▲ $\omega \rightarrow \pi^0\gamma$ quasi-free- proton

$\vec{\gamma} + p \rightarrow k^{+} + \Lambda$: Total Cross-Section



– – – – – Regge model calculation

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

—— KAON-Maid with $D_{13}(1895)$

— · — · · Saclay dynamical coupled channel

Cross section data show a structure at W=1900 MeV.

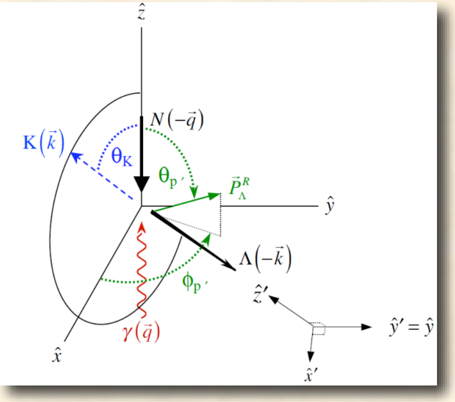
Coupled–channel analysis finds that $S_{11}(1650)$, $P_{11}(1710)$ and $P_{13}(1720)$ have the most significant decay widths in the k+Λ channel.

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

S_{11} (1800) and P_{13} (1900)

also seem to play a role

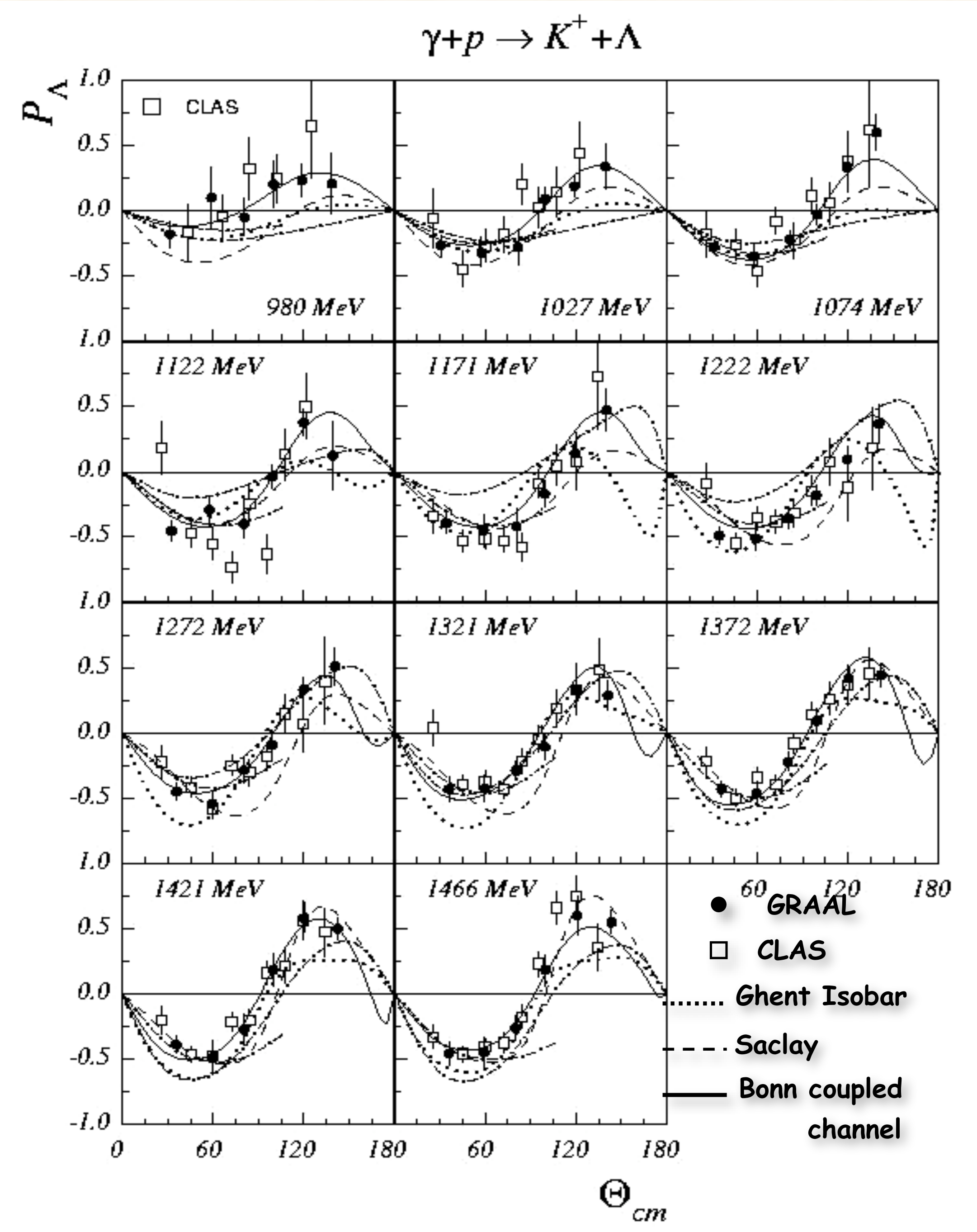
Polarization observables in $\vec{\gamma} + p \rightarrow k^{+} + \vec{\Lambda}$



Weak Λ decay is self-analyzing

Photon beam		***Target***			***Recoil***		
					x'	*y'*	*z'*
		x	*y*	*z*			
unpolarized	**σ_0**		***T***			***P***	
linearly P_γ	**Σ**	***H***	***–P***	***–G***	***$O_{x'}$***	***–T***	***$O_{z'}$***
circular P_γ		***F***		***–E***	**$-C_{x'}$**		**$C_{z'}$**

PΛ in: $\vec{\gamma} + p \rightarrow k^+ + \vec{\Lambda}$ at Graal



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:

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

- Ghent Isobar Model:

  $\boxed{D_{13}(1900)}$

- Reggeized Model:

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

- Bonn Coupled Channel Model:

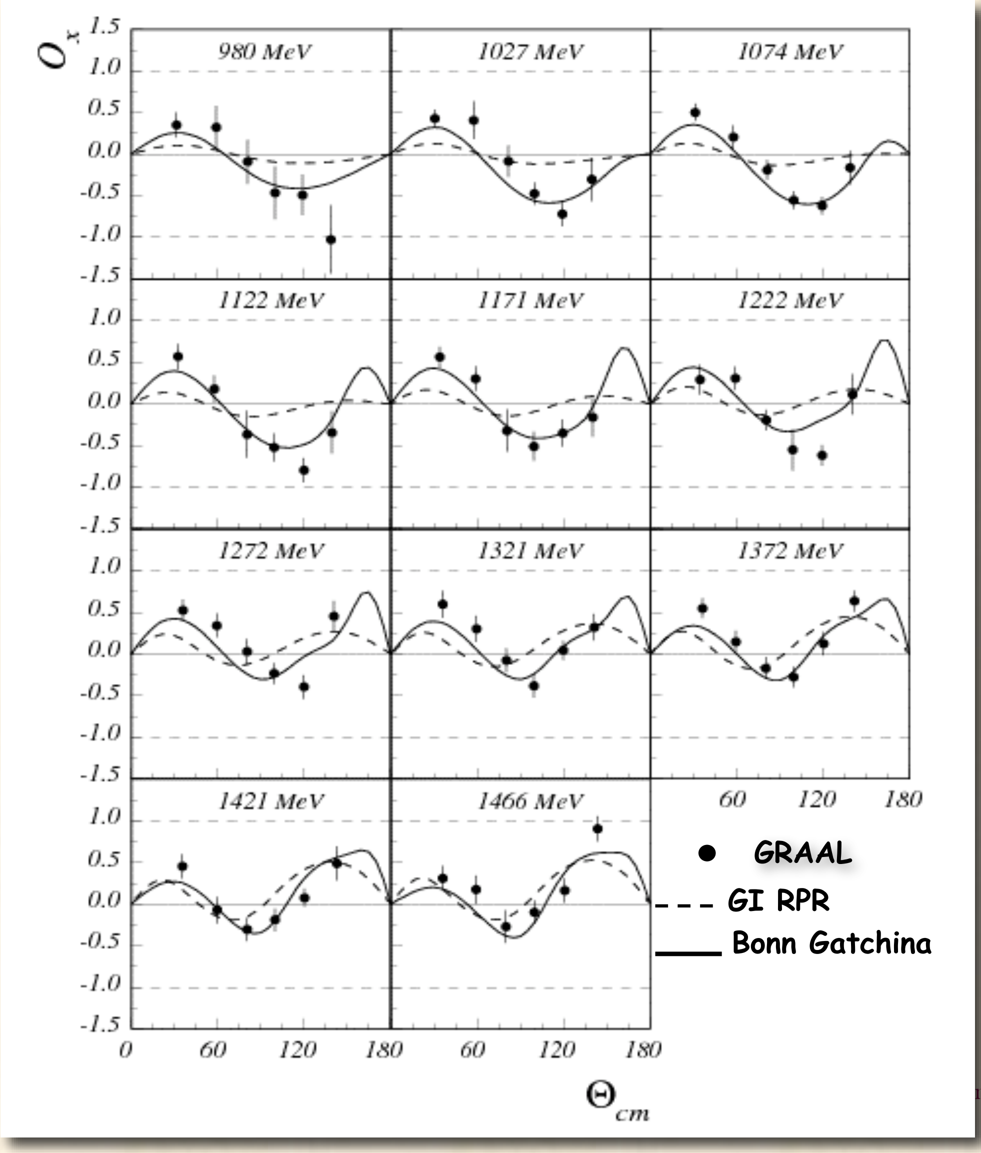
  $\boxed{D_{13}(1875)}$

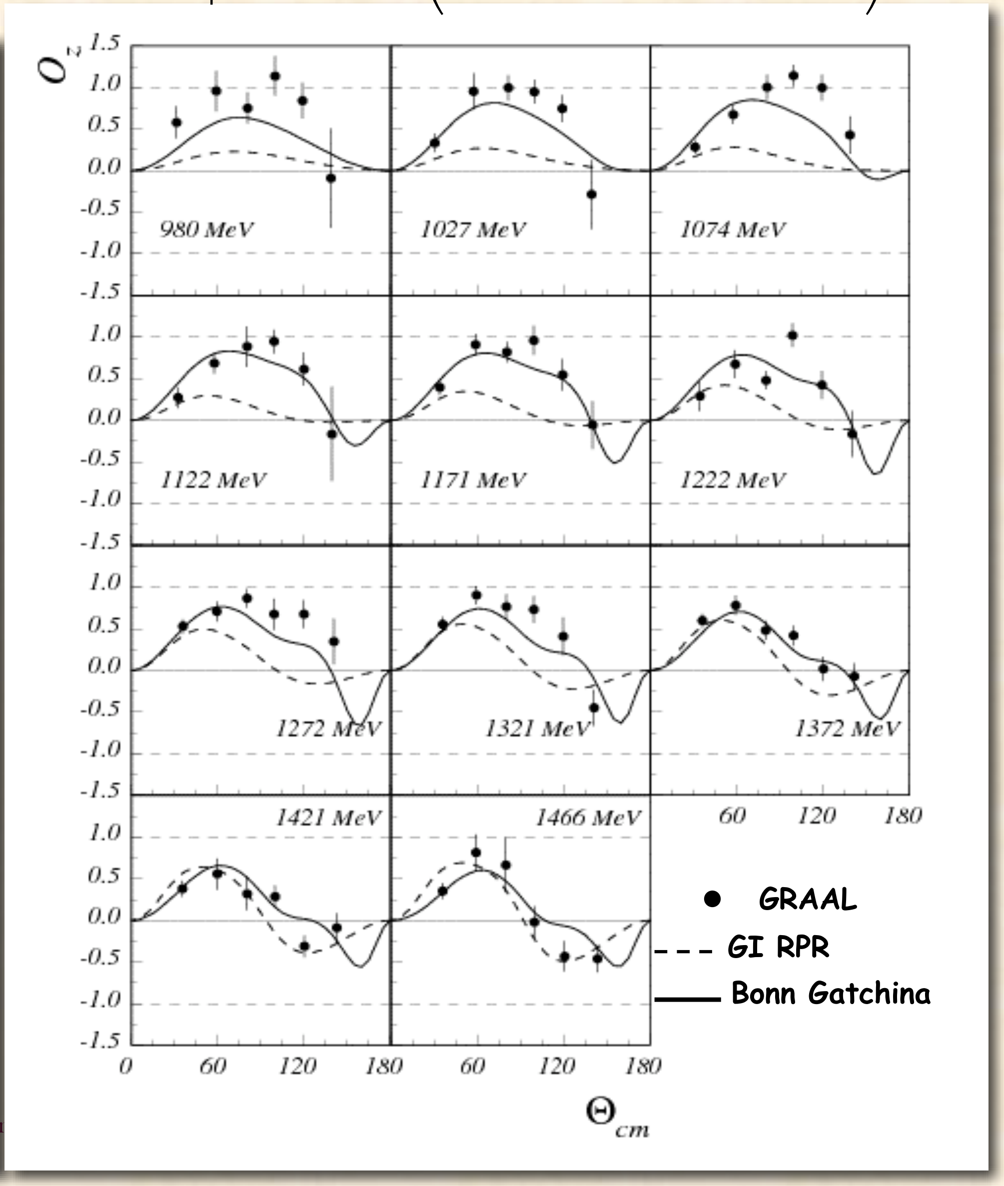
Double Polarization Observables in K+Λ Photoproduction

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

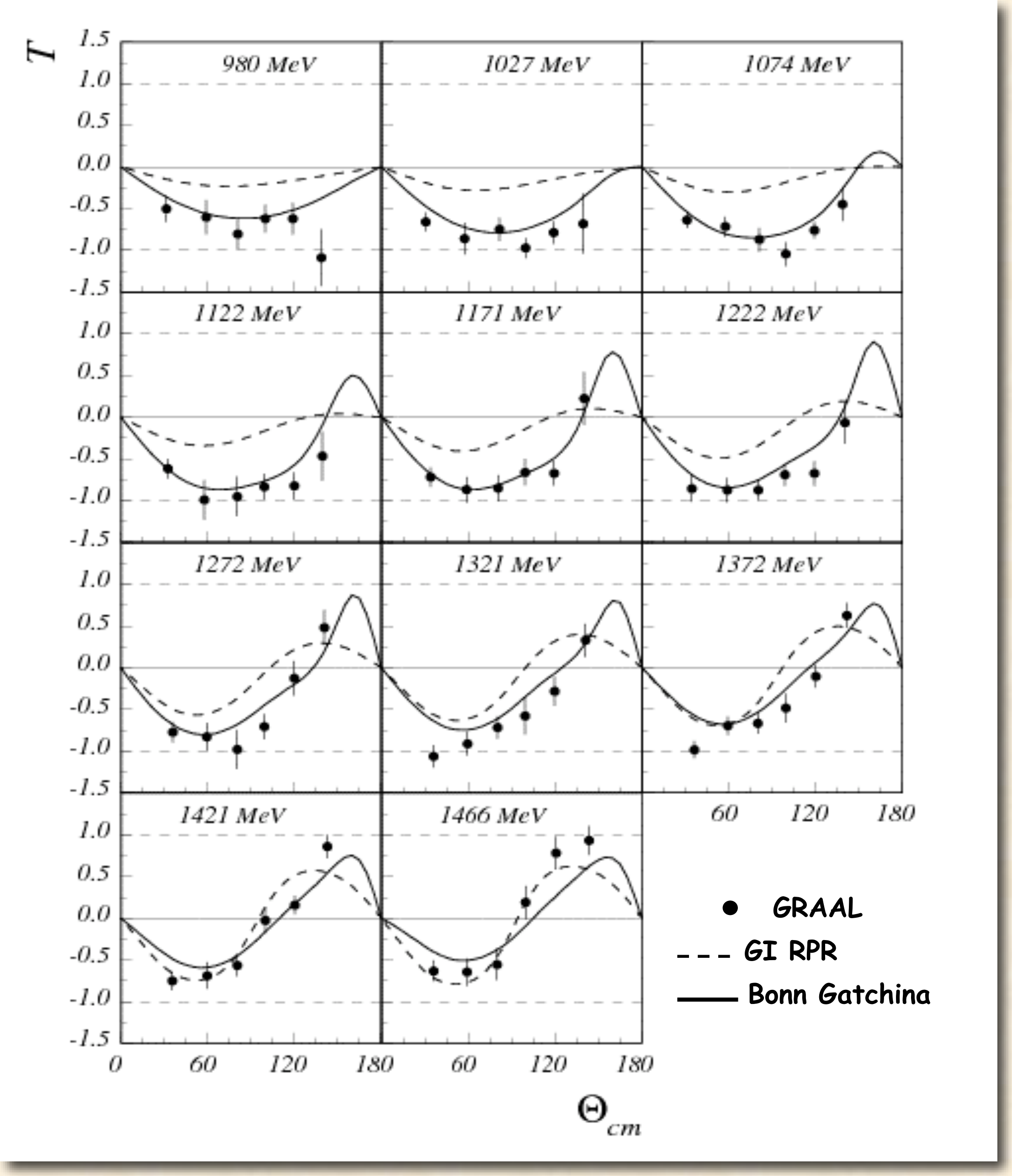
$$\frac{2N_+^{x'}}{N_+^{x'}+N_-^{x'}} = \left(1+\alpha\frac{2P_\gamma O_x}{\pi}\cos\theta_p^{x'}\right)$$

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





T in K$^+\Lambda$ Photoproduction



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

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

From O$_x$, O$_z$ and T results:

- Ghent Isobar RPR Model:

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

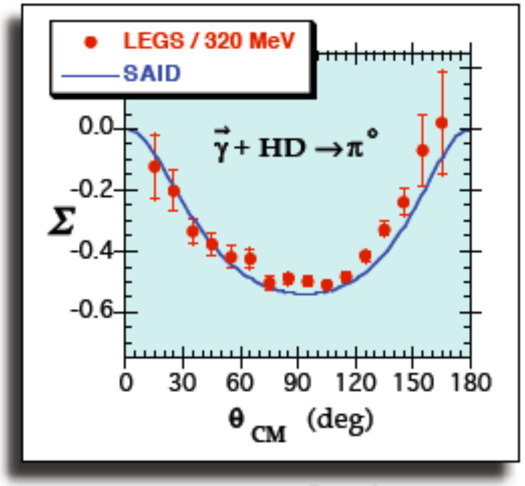
$$\boxed{P_{13}(1900)}\quad \boxed{D_{13}(1900)}$$

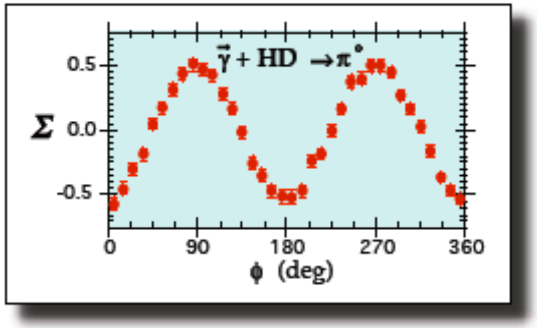
- Bonn Gatchina Model:

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

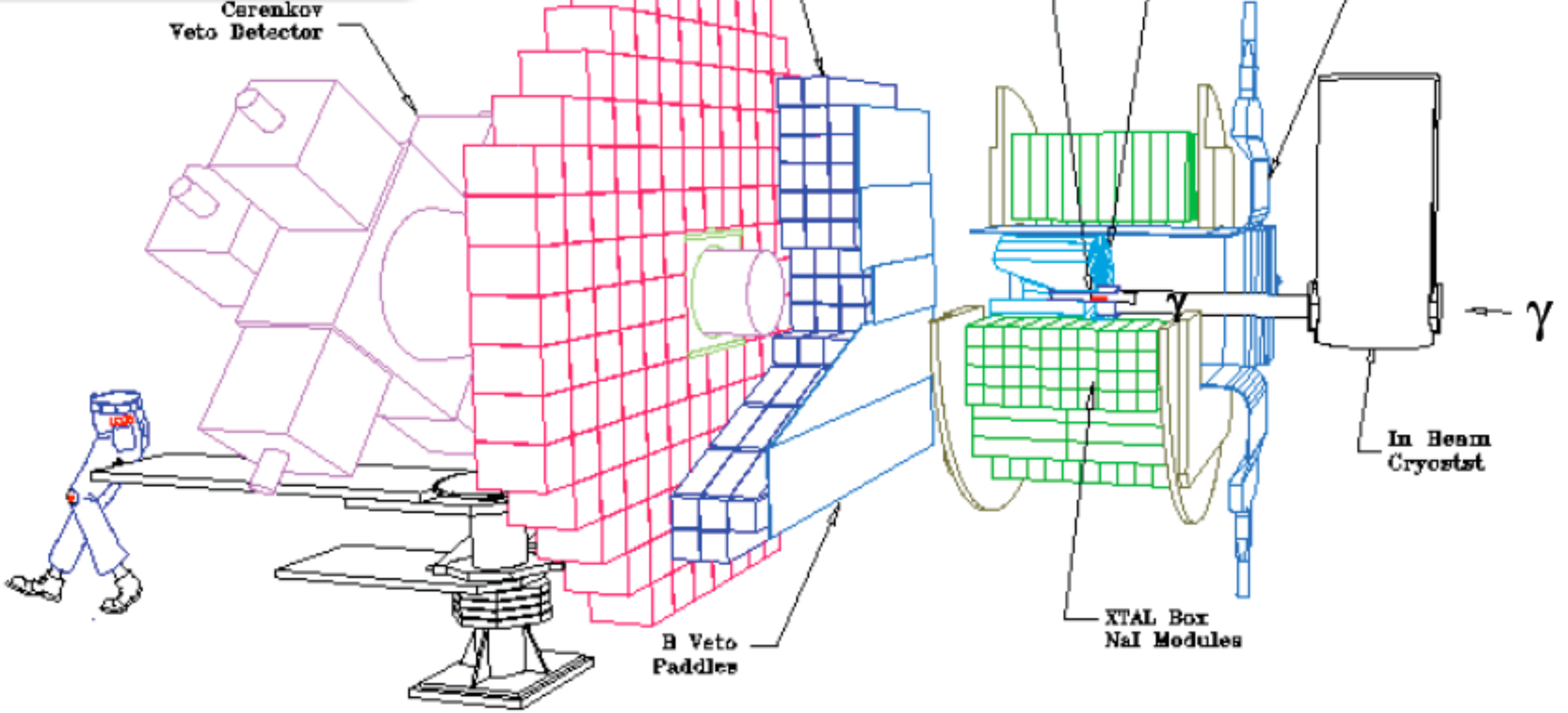
$$\boxed{P_{13}(1900)}$$

LEGS Spin ASYmmetry Array (SASY)

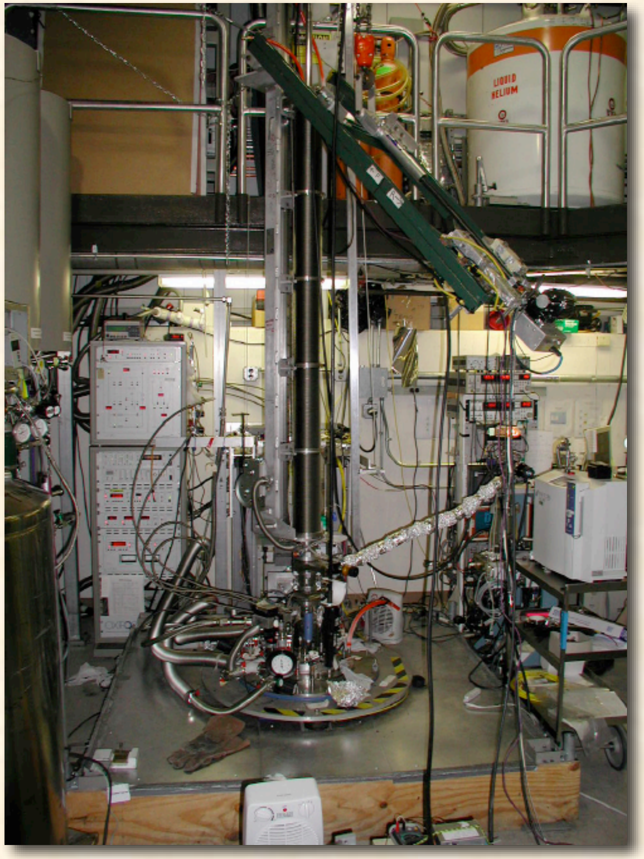


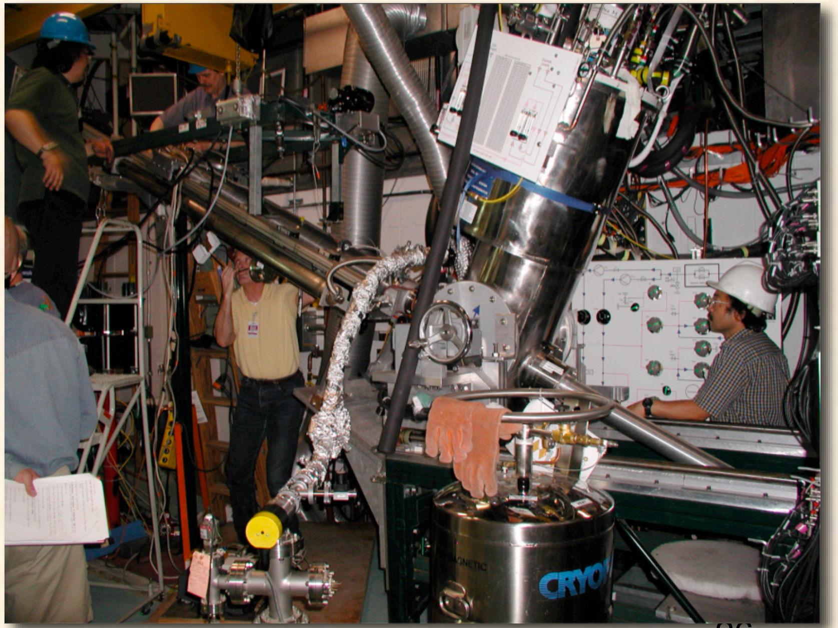


~ 4π acceptance for π^0



Polarized targets: frozen spin HD target at LEGS

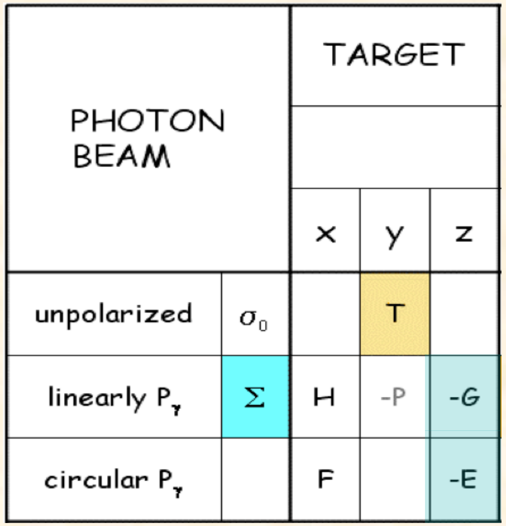




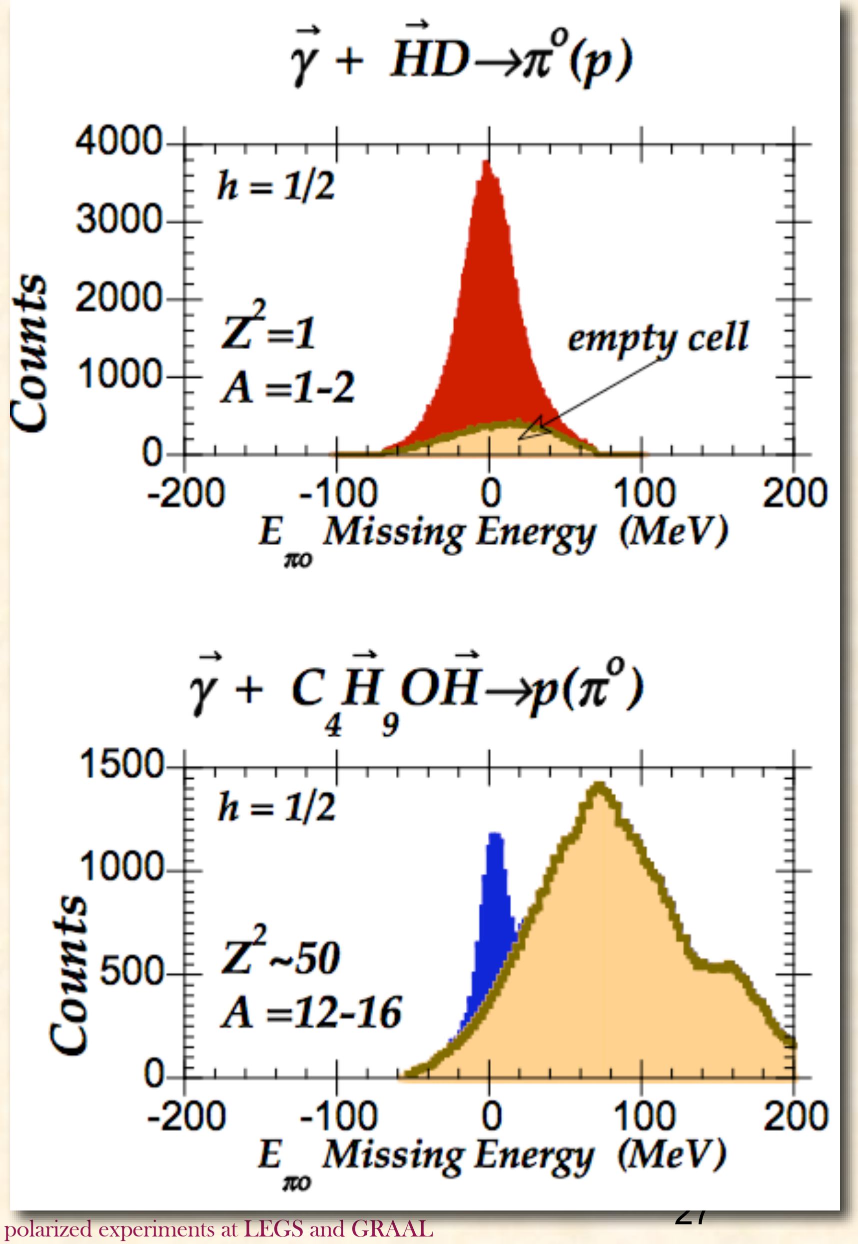
Longitudinal and Transverse Polarizations: > 60%
Relaxation time: > 1 year
Polarization procedure ≈ 3 months
Data taking: ≈ months
Very complicated target transfer technology.

Polarized targets: frozen spin HD target at LEGS

Very clean signal/background separation



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



Longitudinal and Transverse Polarizations: > 60%
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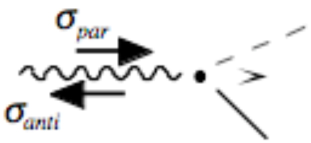
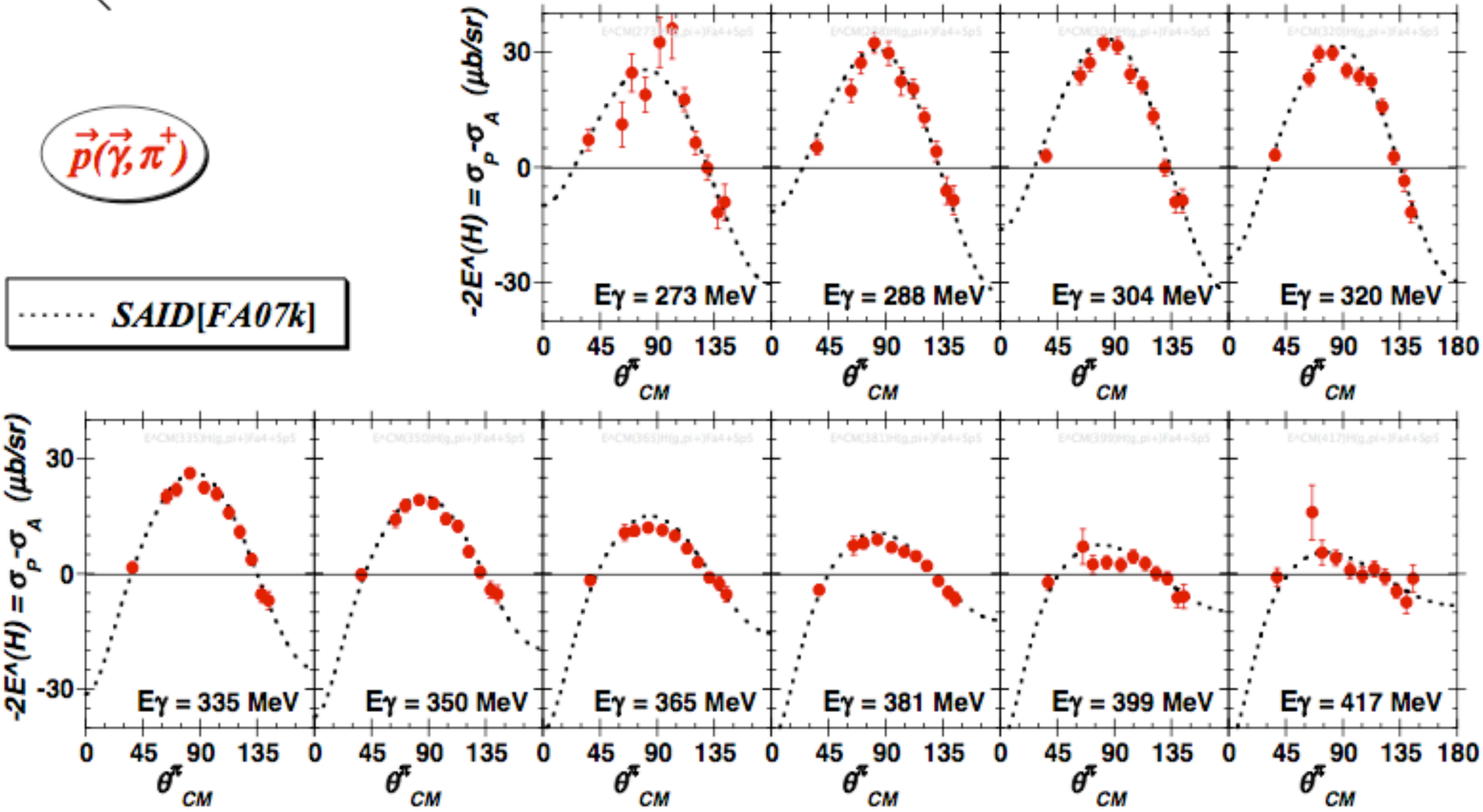
π^0 photoproduction at LEGS: longitudinally polarized photons on longitudinally polarized target :

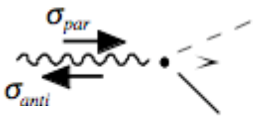
$$\hat{E} = E \times \frac{d\sigma}{d\Omega_0}$$



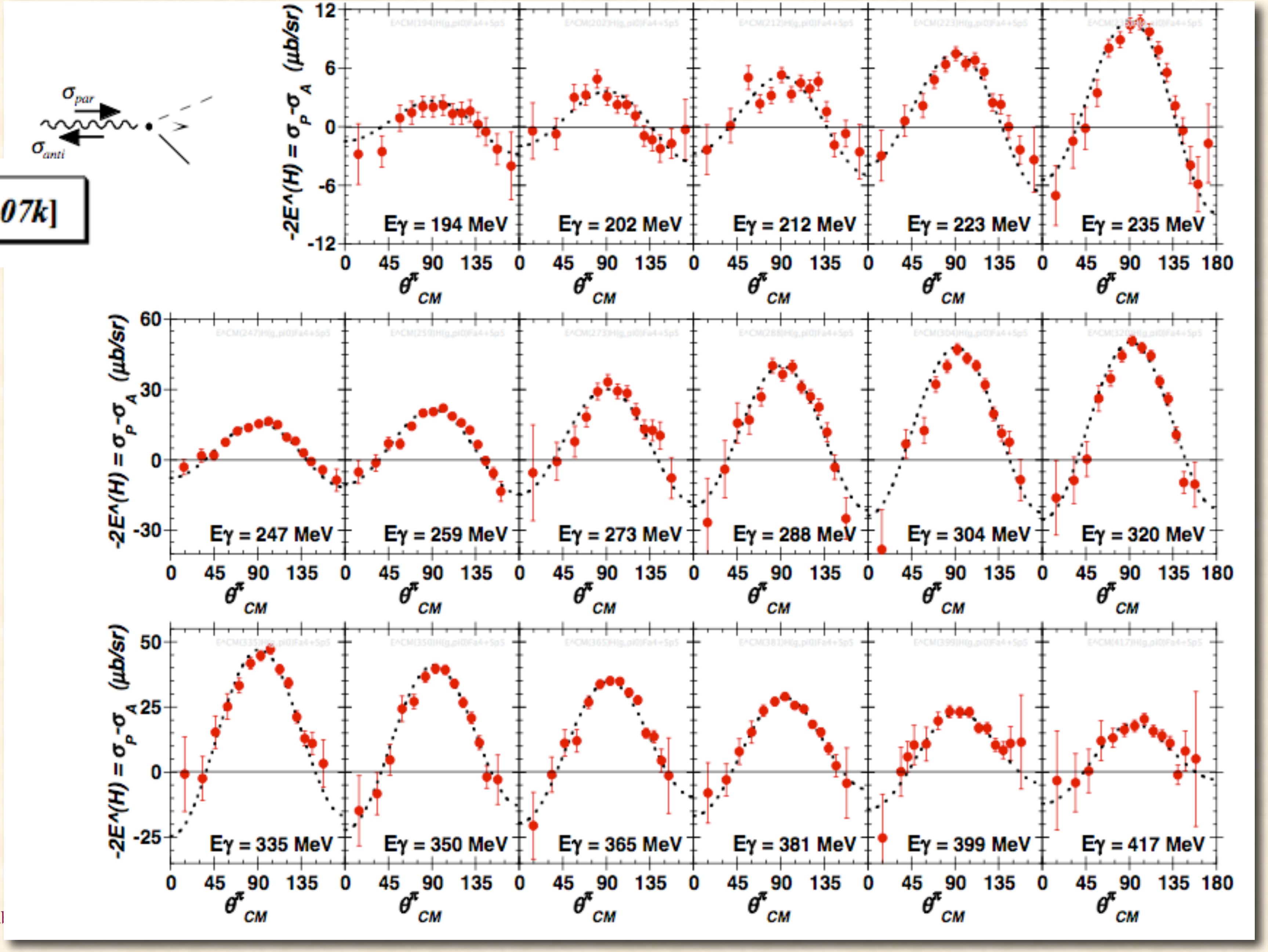


π^0 photoproduction at LEGS: longitudinally polarized photons on longitudinally polarized target : $\hat{E} = E \times \frac{d\sigma}{d\Omega_0}$

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



······ **SAID[FA07k]**



Extraction of observable G
linearly polarized photons on longitudinally polarized targets

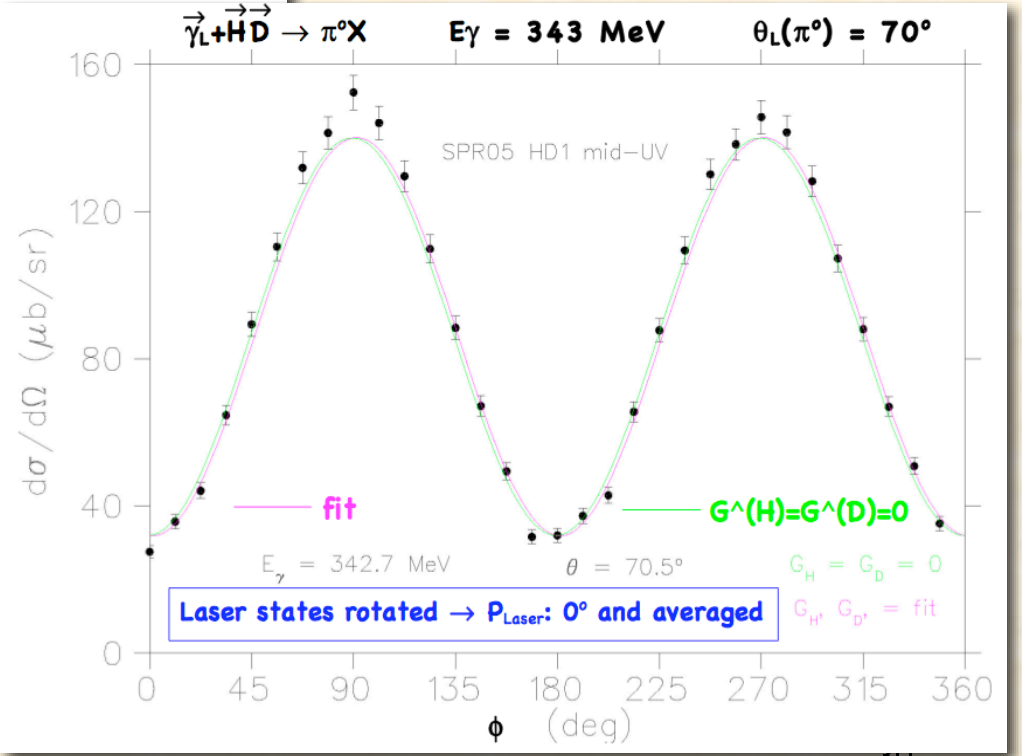
$$d\sigma = d\sigma_o(HD) + P_\gamma^L \cdot \left[\hat{\Sigma}(HD) + \tfrac{1}{\sqrt{2}} P_D^T \cdot T_{20}^L(D)\right] \cdot \cos 2\phi$$

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

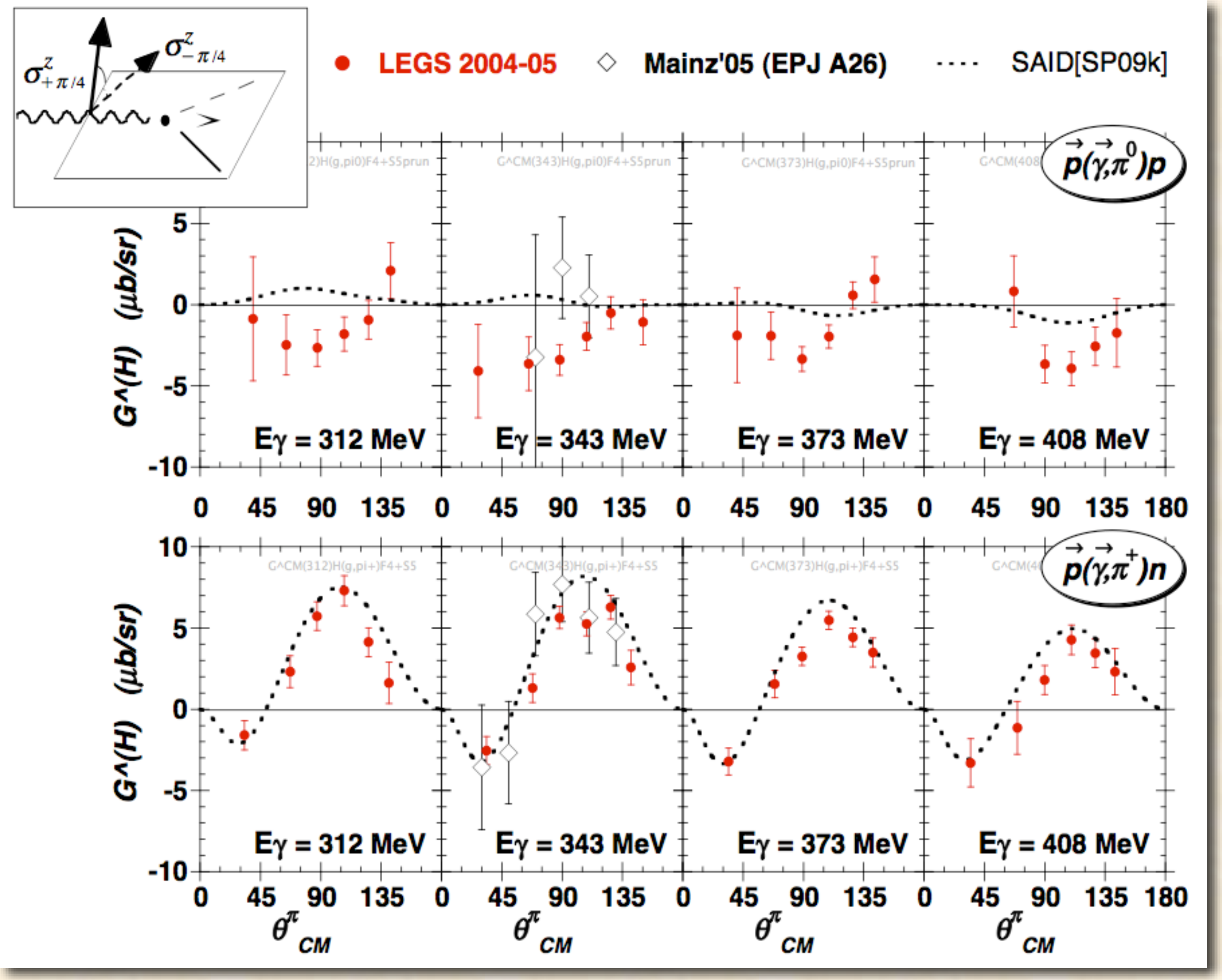
$$- P_\gamma^C \cdot \left[P_H \cdot \hat{E}(H) + P_D^V \cdot \hat{E}(D)\right] + \tfrac{1}{\sqrt{2}} P_D^T \cdot T_{20}^0(D)$$

ϕ-fits

from $\int d\phi$ fits



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



$$\hat{G} = G \times \frac{d\sigma}{d\Omega_0}$$

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

Under investigation.

D-wave component under $P_{33}(1232)$ larger than expected.

Conclusions

- Σ asymmetry for π^0 and π^- production on quasi-free neutrons provided new challenging constraints on $P_{11}(1700)$ and $P_{13}(1720)$ properties.

- Σ asymmetry for ω photoproduction on the nucleon is a benchmark prediction for most existing models - sensitive to $P_{13}(1720)$ resonance.

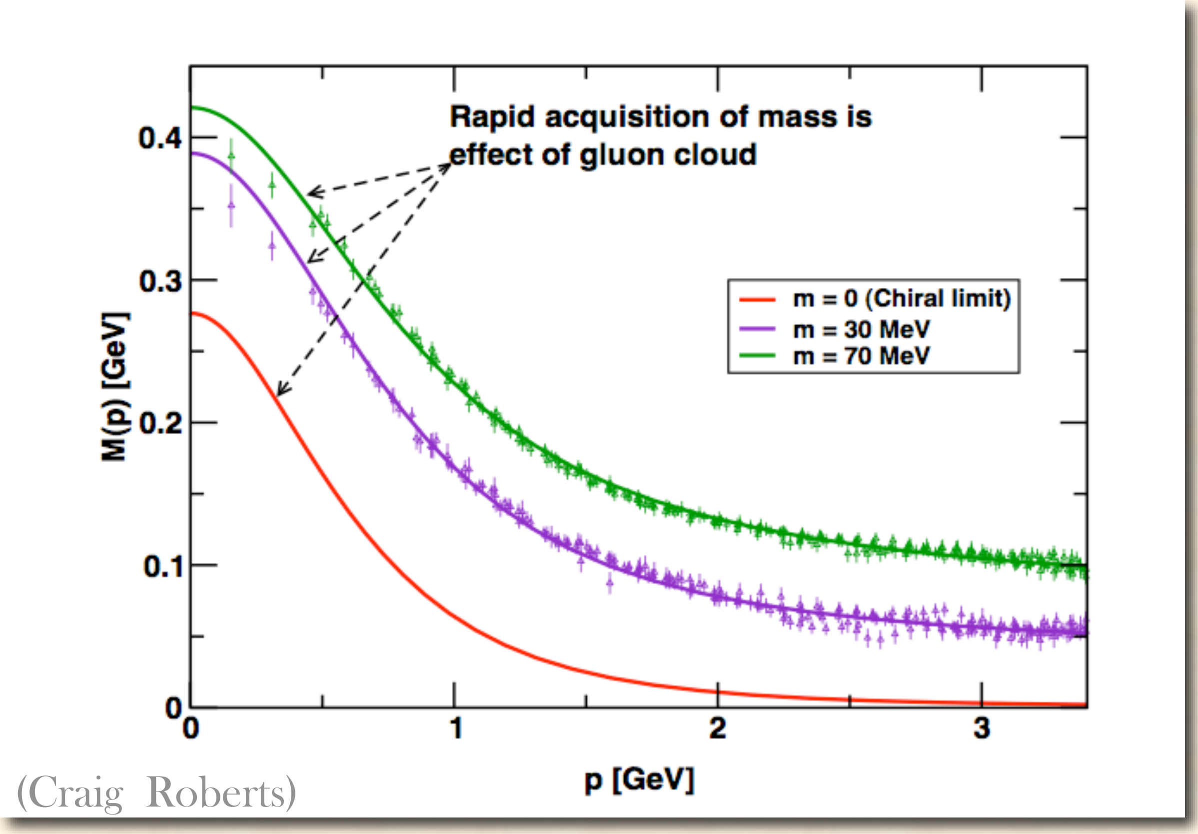
- Double polarization observables in $k^+ \Lambda$ photoproduction are mostly consistent with Bonn-Gatchina CC-PWA predictions - the role of the "missing" D_{13}(1900) is still uncertain.

- First results on G double polarization observable at LEGS suggest a strong D-wave component in the Δ resonance.

- The next step is performing complete experiments.

Backup slides

Hadron Models: connection between constituent and current quarks



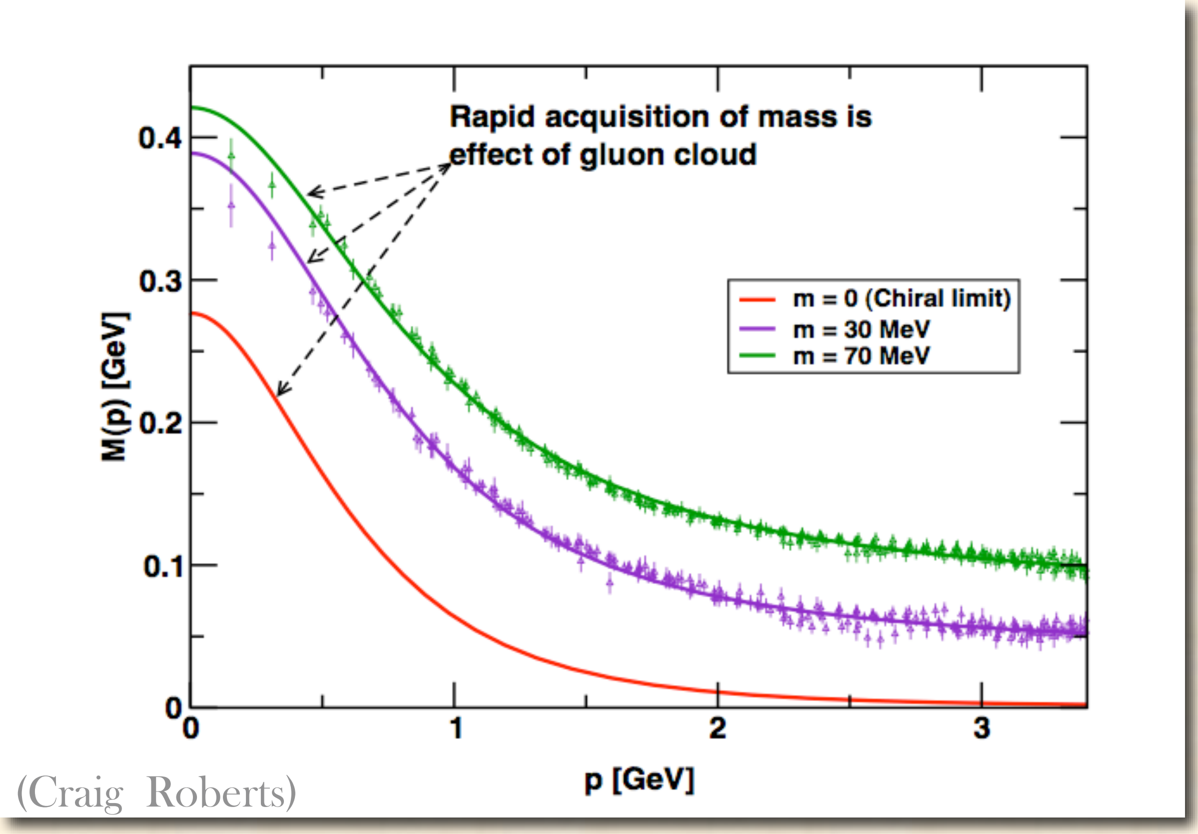
(Craig Roberts)

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

— Dyson-Swinger equation
(Bhagwat et al.)

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

Hadron Models: connection between constituent and current quarks



(Craig Roberts)

▲ ▲ numerical simulations of unquenched lattice QCD
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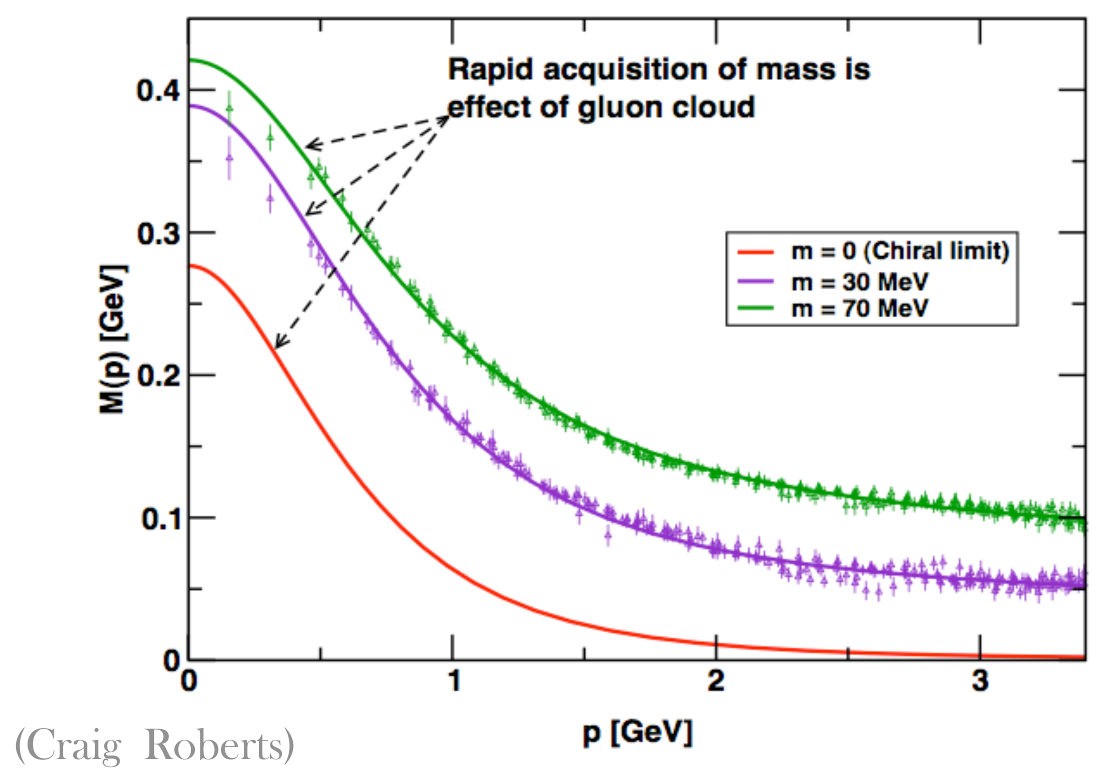
— Dyson-Swinger equation
— (Bhagwat et al.)
—

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
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(Bhagwat et al.)

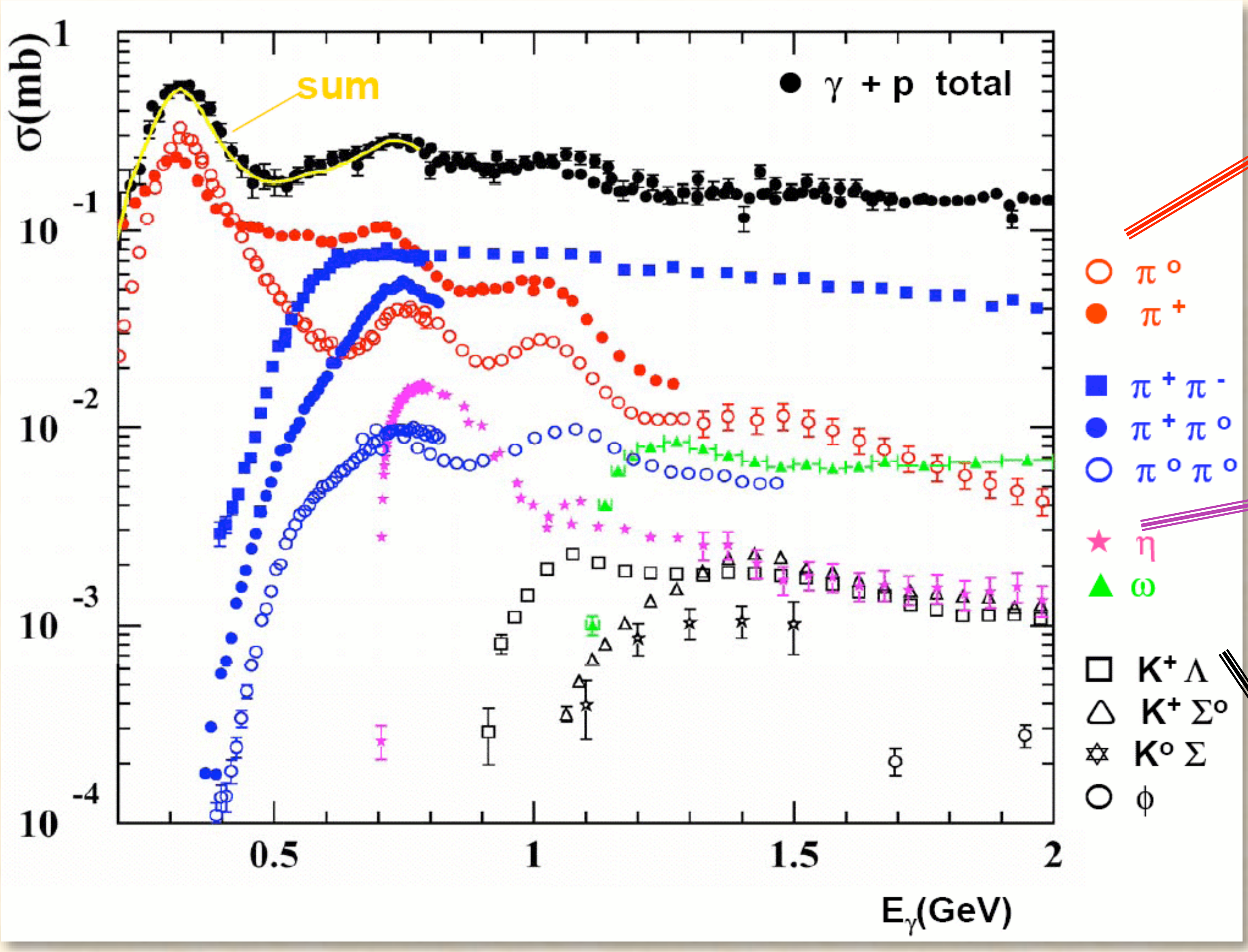
The interaction that describes color-singlet mesons also generates axial-vector isotriplet quark-quark correlations with significant attraction :

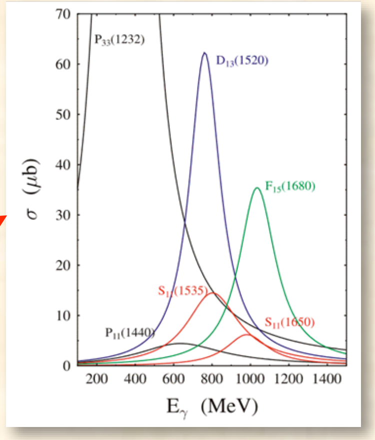
$m[ud]_0 = 0.74 - 0.82$ GeV

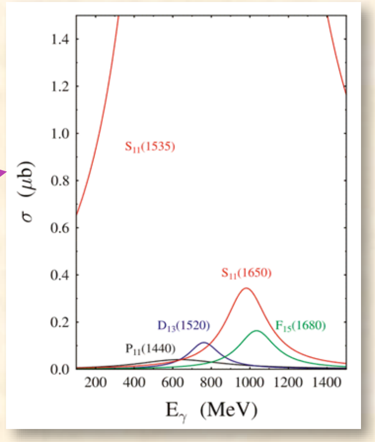
$m[ud]_1 = m[uu]_1 = m[dd]_1 = 0.95 - 1.02$ GeV

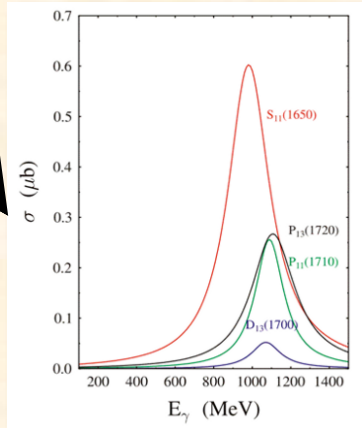
di-Quarks →

Photonuclear cross sections

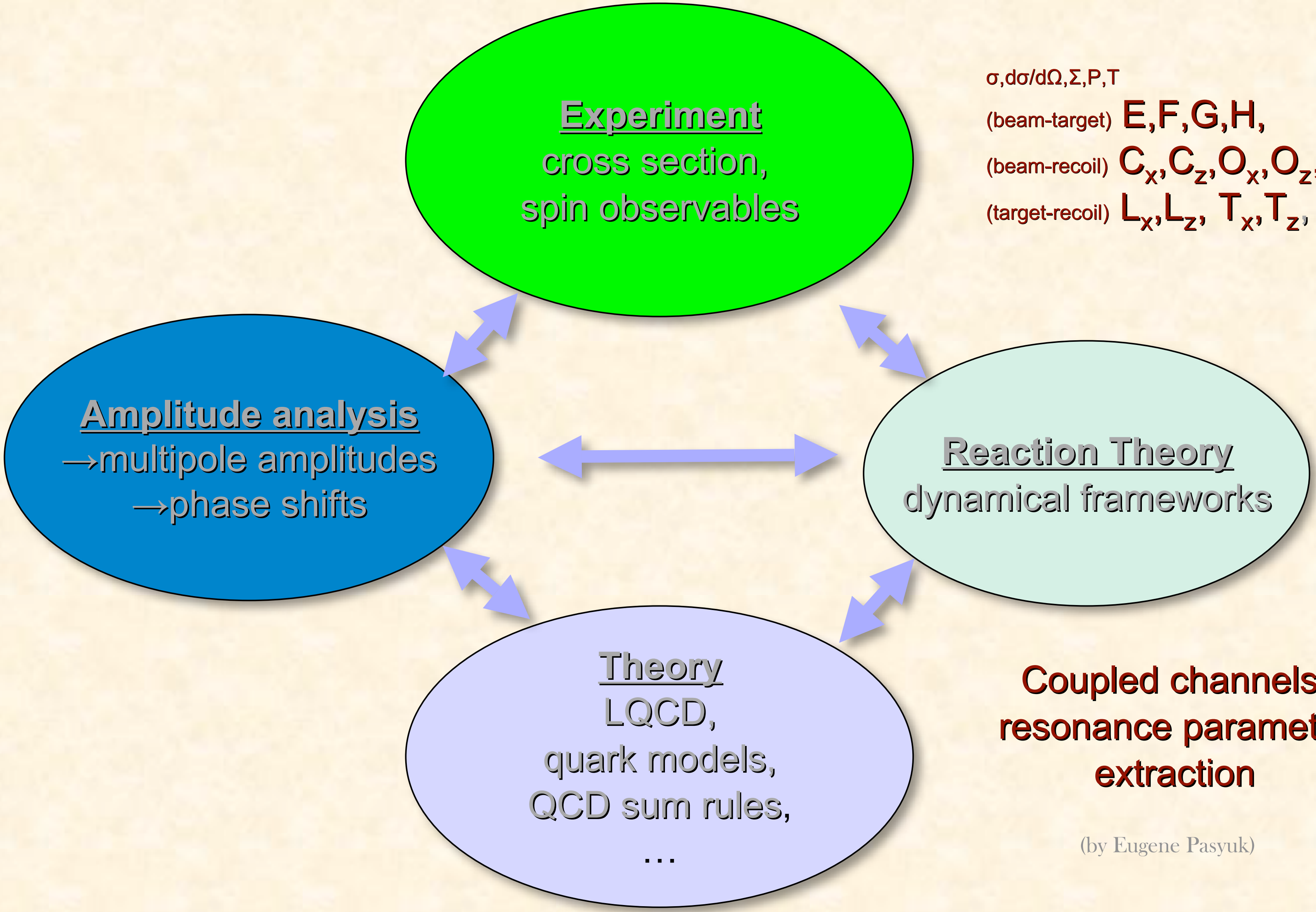








From the Experiment to Theory



Experiment
cross section,
spin observables

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

Amplitude analysis
→multipole amplitudes
→phase shifts

Reaction Theory
dynamical frameworks

Theory
LQCD,
quark models,
QCD sum rules,
…

Coupled channels:
resonance parameter
extraction

(by Eugene Pasyuk)

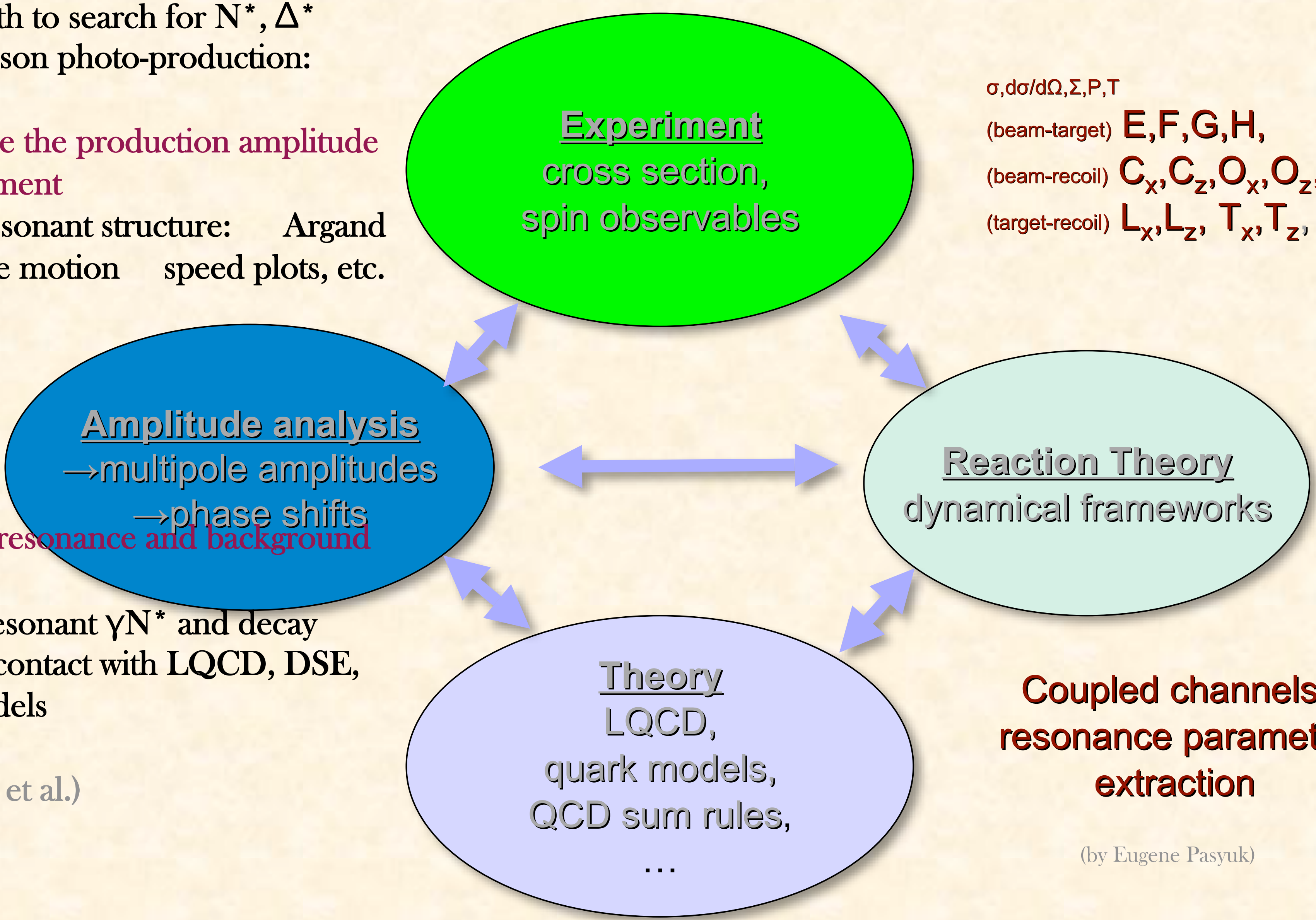
From the Experiment to Theory

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

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

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

(A. Sandorfi et al.)



Experiment
cross section,
spin observables

Amplitude analysis
→multipole amplitudes
→phase shifts

Reaction Theory
dynamical frameworks

Theory
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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 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

(A. Sandorfi et al.)

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