Jefferson Lab
Thomas Jefferson National Accelerator Facility

INFN Istituto Nazionale di Fisica Nucleare

ELBA XII Workshop

The Baryon Spectroscopy Experimental Program

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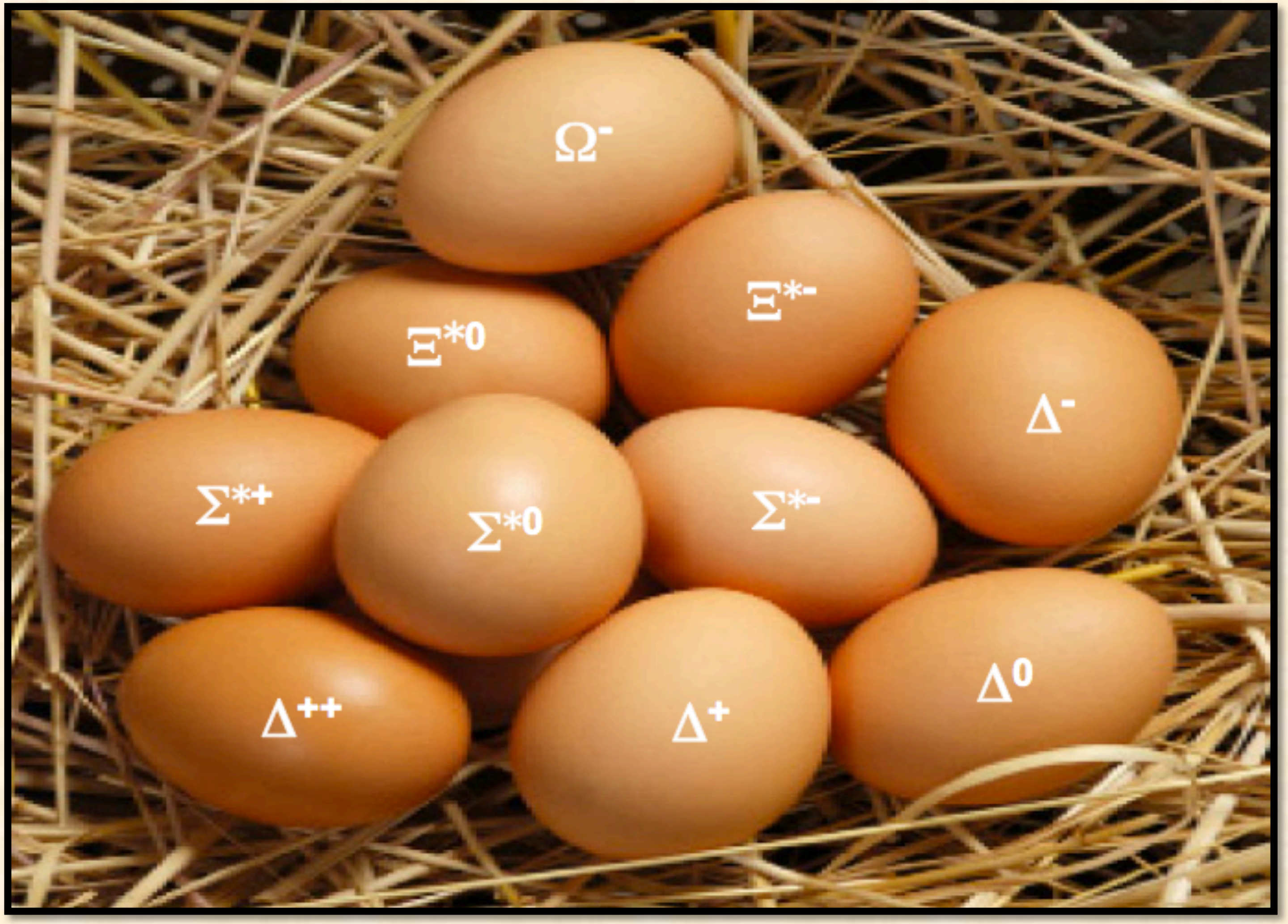
Motivation



Baryons

Motivation

- Understanding the working of QCD:

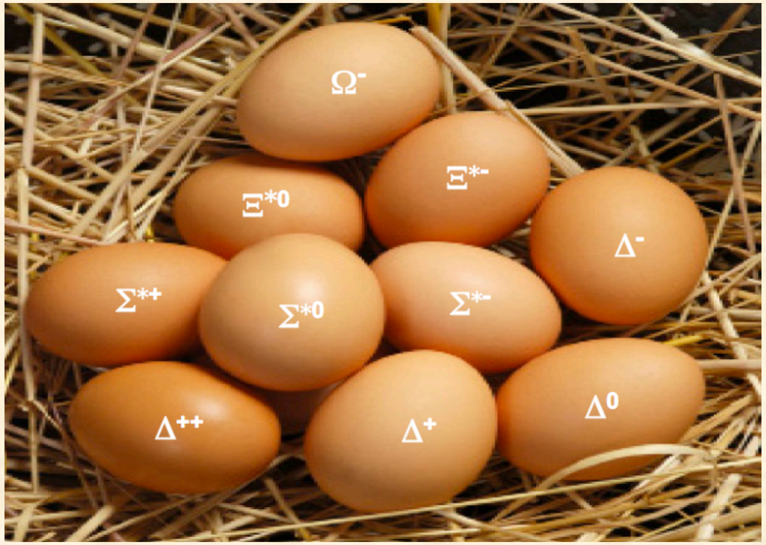
$$\mathcal{L}_{QCD} = \sum_{q=u,d,s,c,b} \bar{q}\,(i\gamma_\mu D^\mu - m_q)\,q - \frac{1}{4}\mathcal{F}^{\mu\nu}\mathcal{F}_{\mu\nu}$$

Outline

- Motivation: understanding the working of QCD

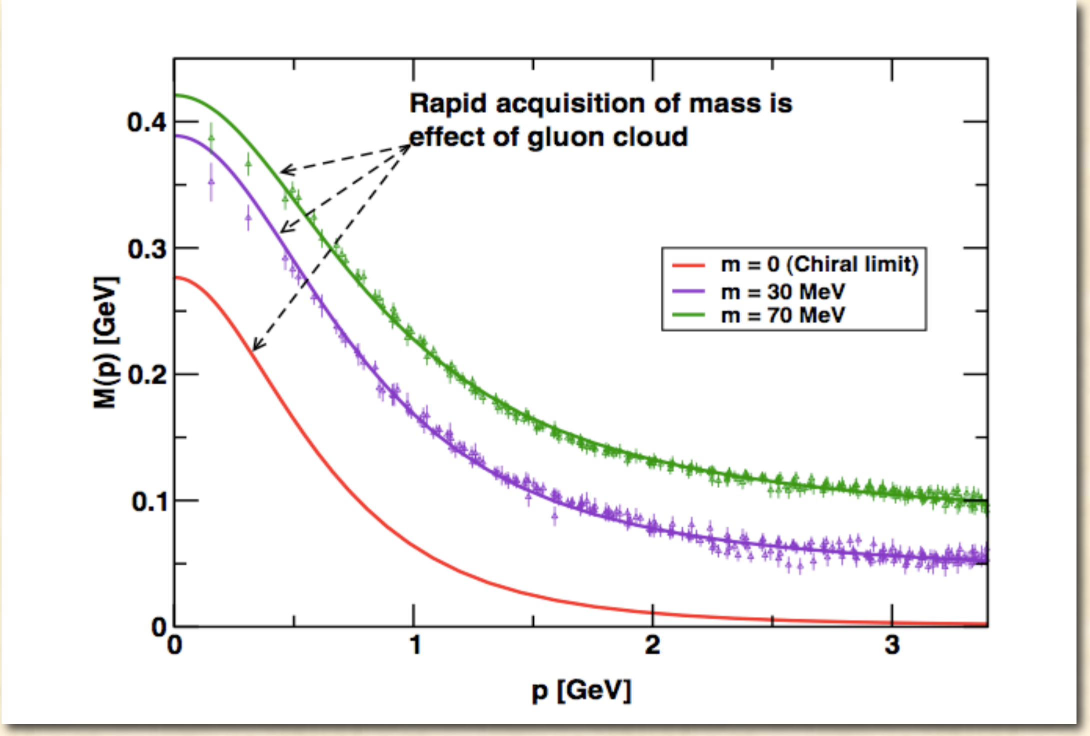
$$\mathcal{L}_{QCD} = \sum_{q=u,d,s,c,b} \bar{q}\,(i\gamma_\mu D^\mu - m_q)\,q - \frac{1}{4}\mathcal{F}^{\mu\nu}\mathcal{F}_{\mu\nu}$$

- Hadronic degrees of freedom.
- The experimental tools: beam, target, detector.
- Selected experimental results.
- Outlook and conclusions.



Motivation

- 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.)

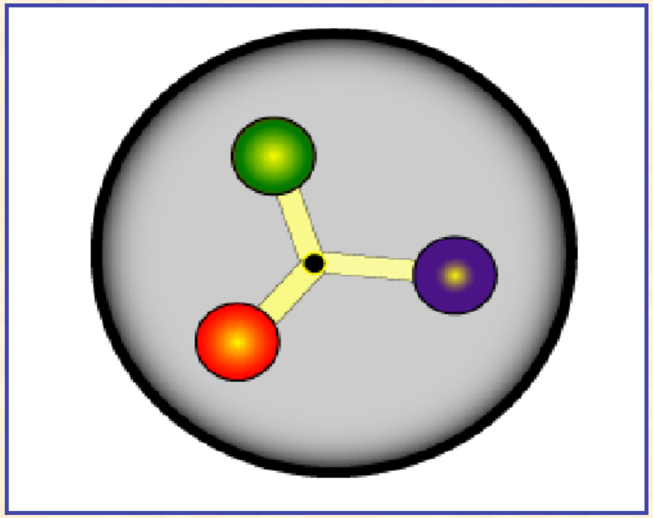
Current-quarks of perturbative QCD evolve into constituent quarks at low momentum
⟶ the constituent quark mass arises from low momentum gluons attaching them selves to current quarks. *Field excitation generates mass from nothing: mass is field energy.*

QCD -inspired Constituent Quark Models

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

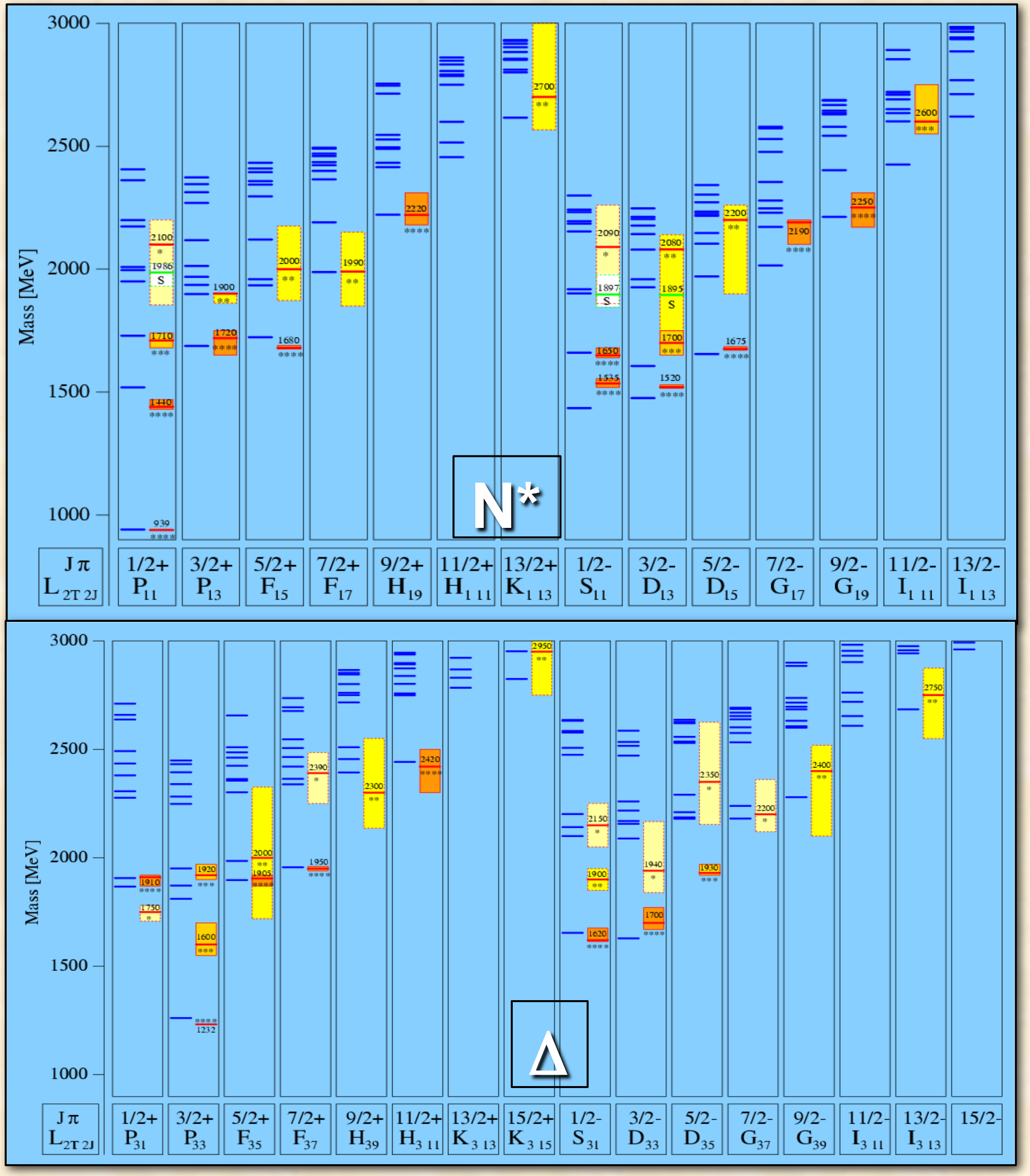
- Asymmetry of the baryon wave function is guaranteed by color, but color degrees of freedom are integrated out and play no dynamical role.

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



Shaded boxes: experimental results

Thick segments: theoretical predictions



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

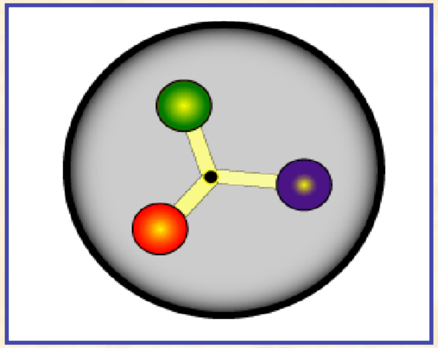
(in πN) with 4★ or 3★ status

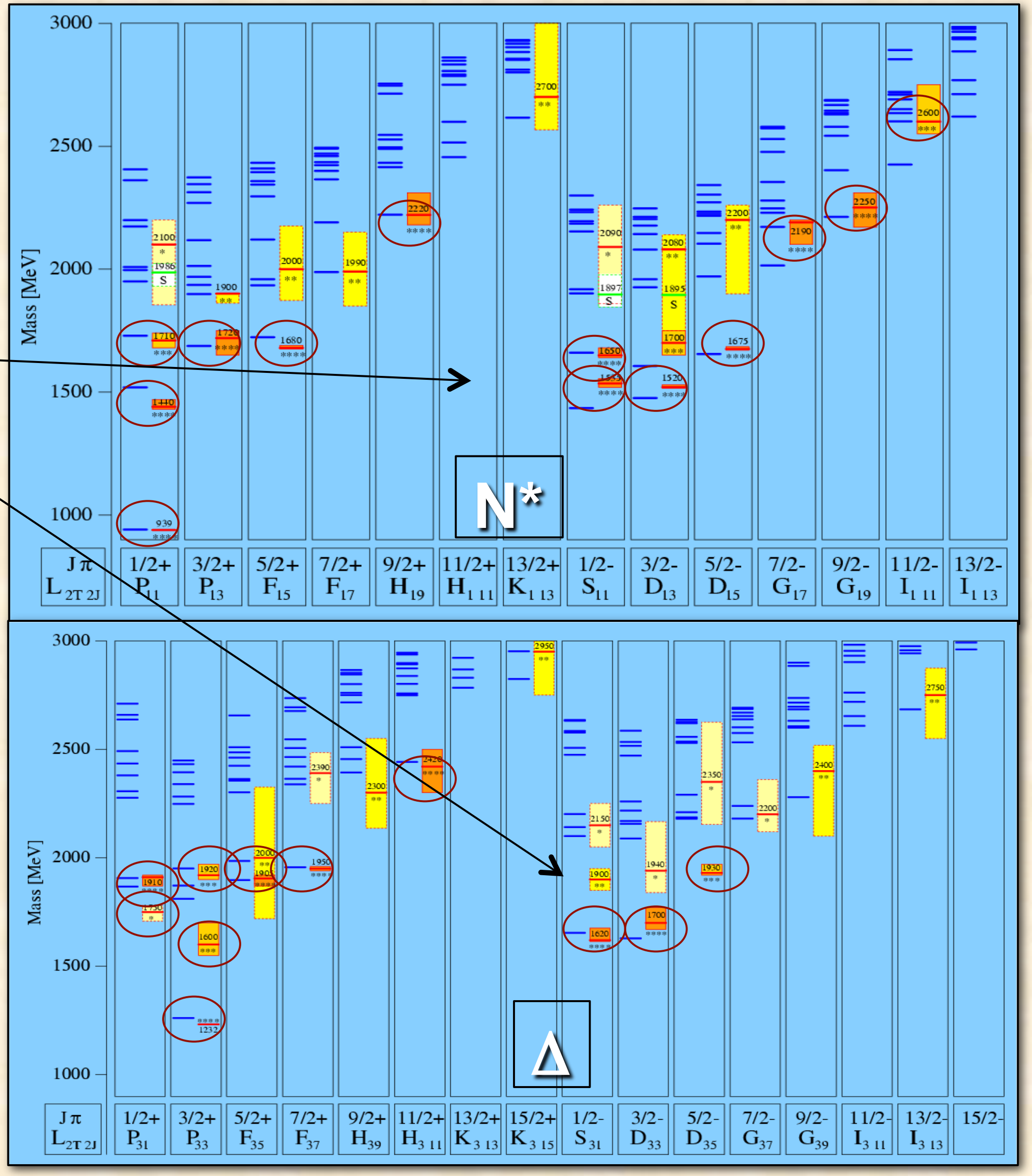
- g(πN) couplings predicted to decrease rapidly with mass in each oscillator band
- higher levels predicted to ha

couplings to KΛ, KΣ, ππN, ...

Shaded boxes: experimental results

Thick segments: theoretical predictions





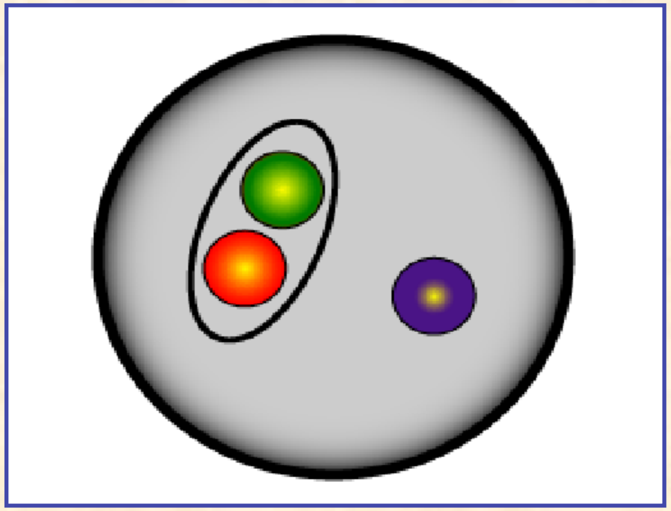
U. L¨oring, B. Metsch, H. Petry, Eur. Phys. J. A 10, 395 (2001).

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

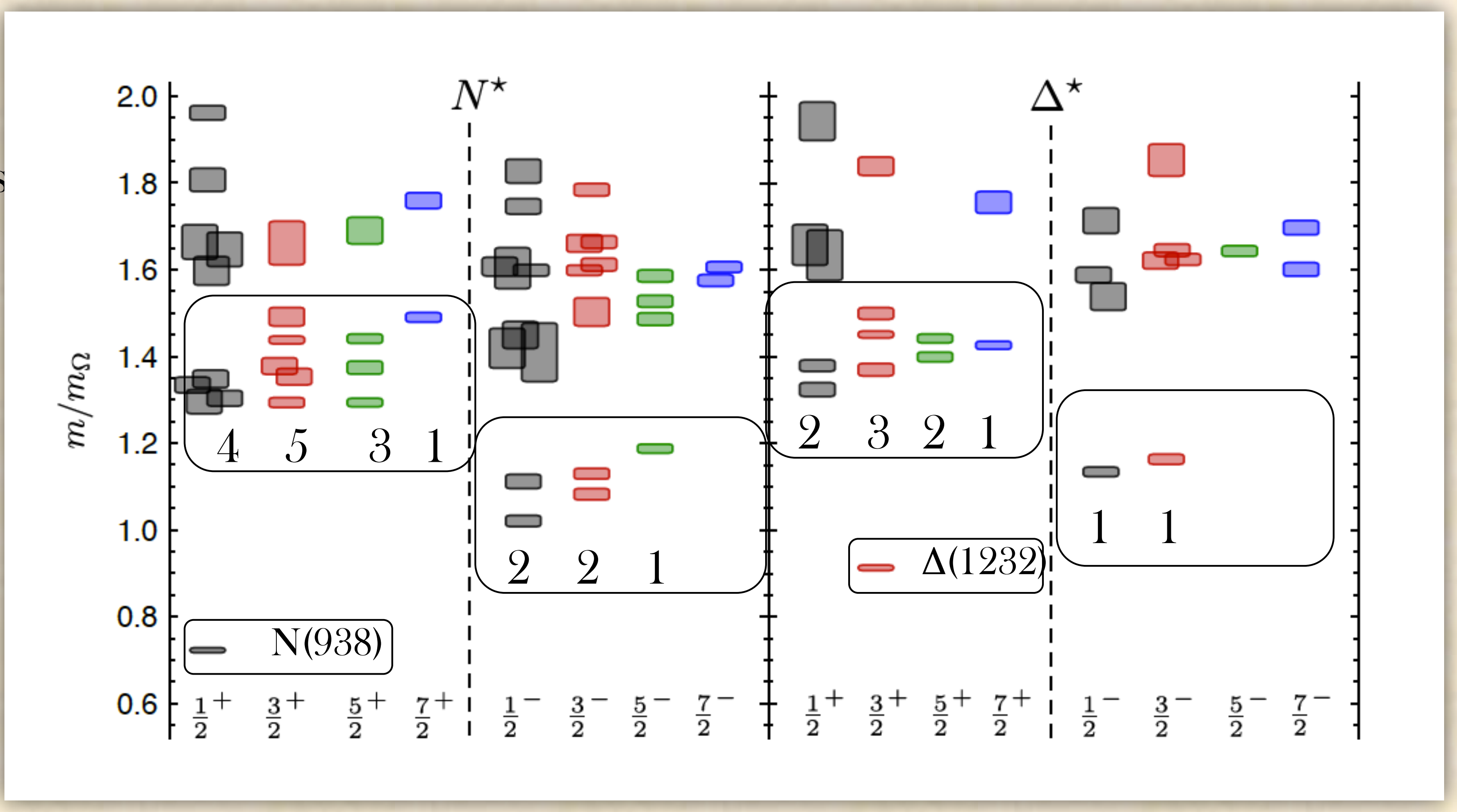


N^*	Status	$SU(6) \otimes U(3)$	Parity	Δ^*	Status	$SU(6) \otimes U(3)$	Parity
$P_{13}(938)$	****	$(56,0^+)$	+	$P_{33}(1232)$	****	$(56,0^+)$	+
$S_{11}(1535)$	****	$(70,1^-)$	-	$S_{31}(1620)$	****	$(70,1^-)$	-
$S_{11}(1650)$	****	$(70,1^-)$	-	$D_{13}(1700)$	***	$(70,1^-)$	-
$D_{13}(1520)$	****	$(70,1^-)$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

the challenge: ⇔ unravel the N* spectrum

Excited Baryons from L QCD

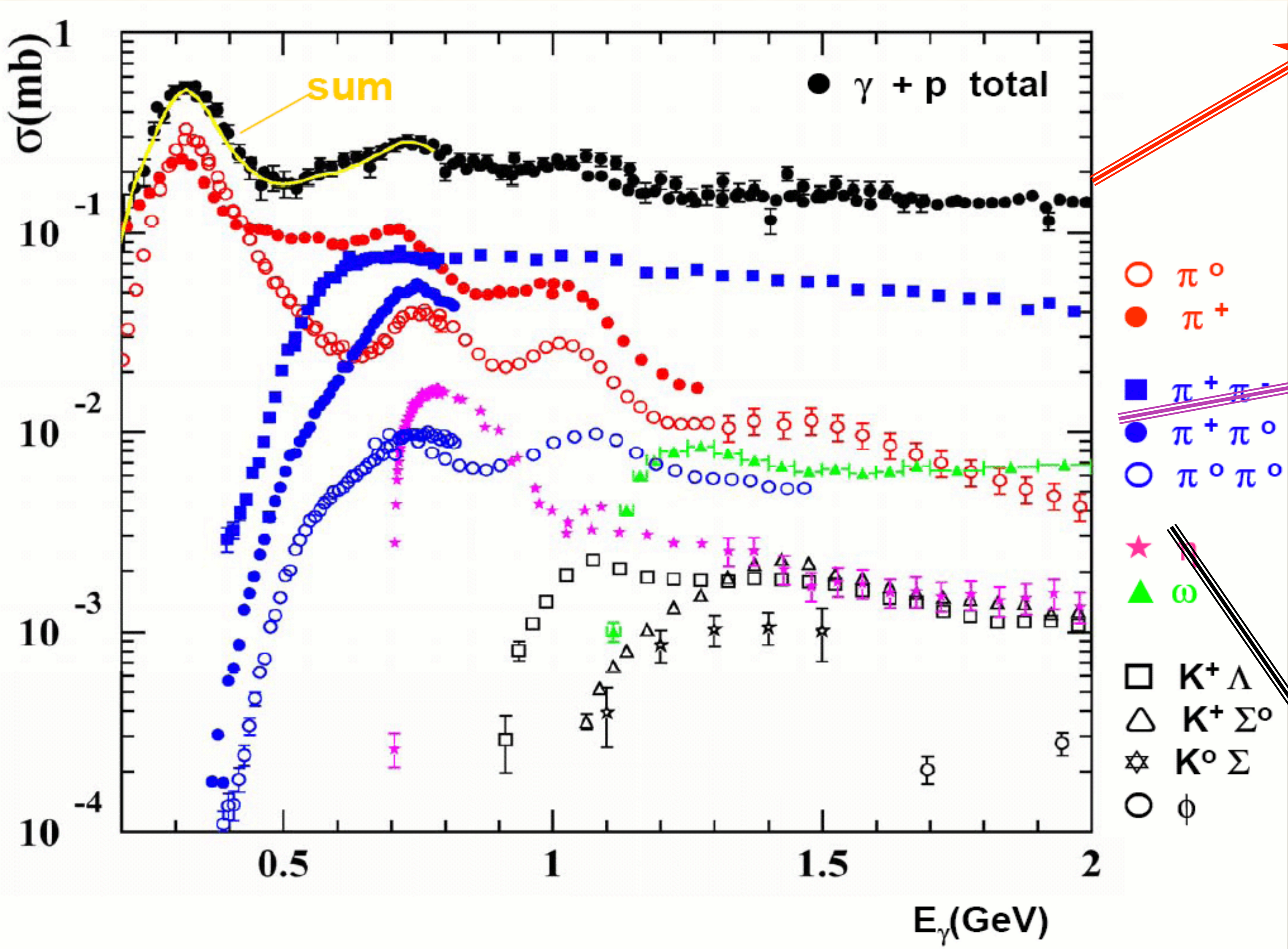
- Exhibits the features SU(6)O(3)-symmetry
- Counting of levels consistent with non-rel. quark model
- Striking similarity With quark model
- No parity doubling

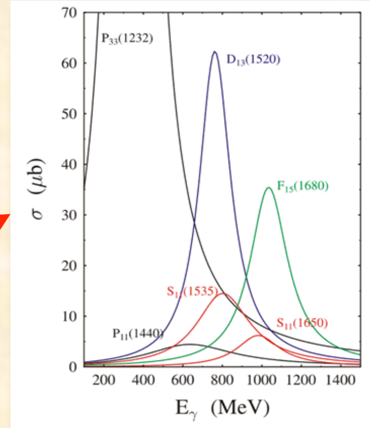


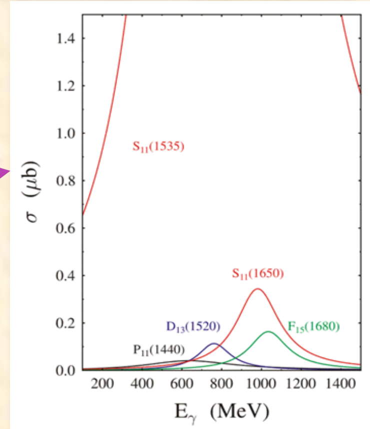
Robert G. Edwards, Jozef J. Dudek, David G. Richards, Stephen J. Wallace **Phys.Rev. D84 (2011) 074508**

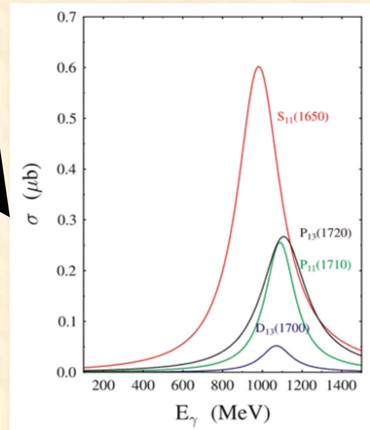
Problems are not solved!

Photonuclear cross sections



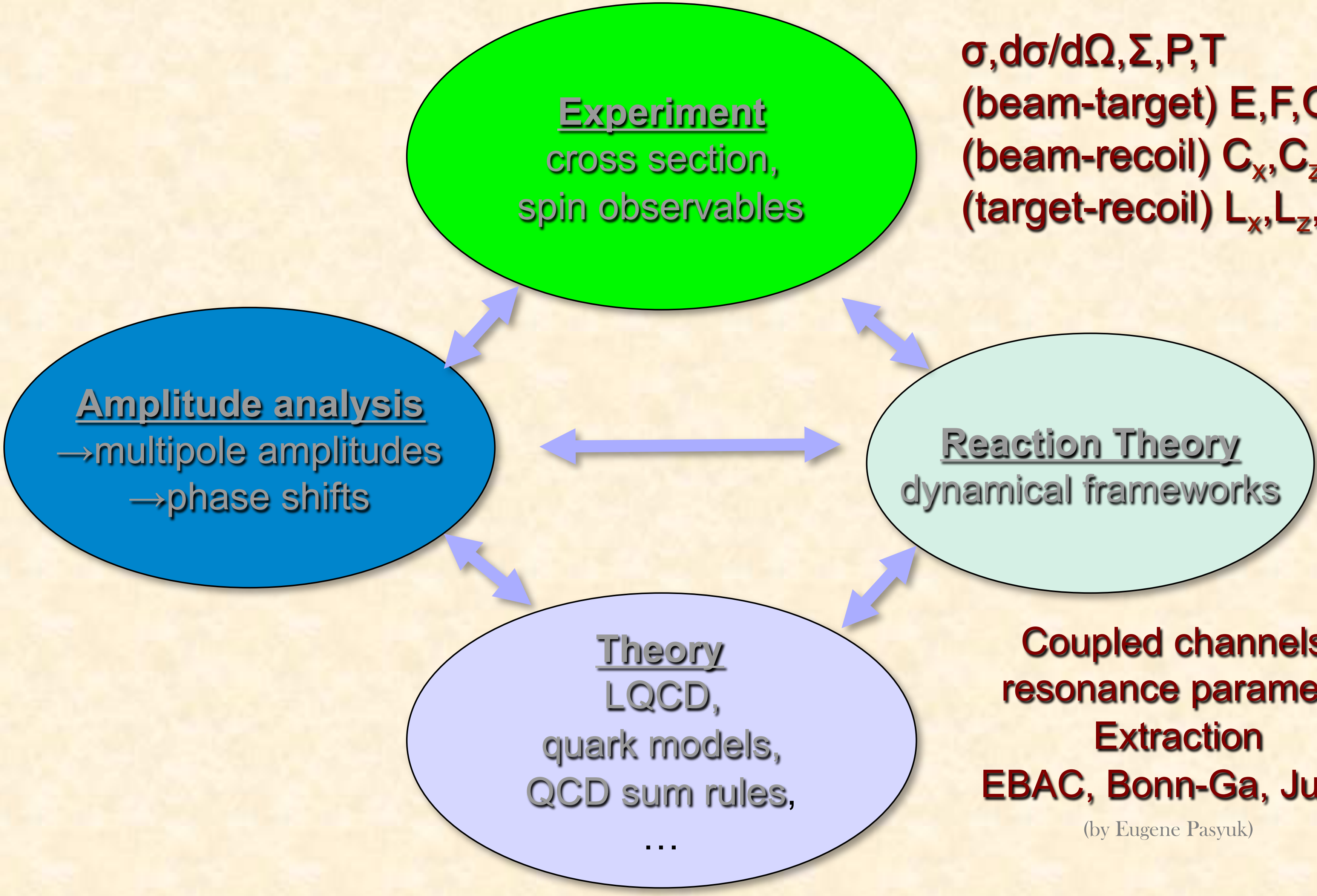






From the Experiment to Theory

σ,$d\sigma/d\Omega$,Σ,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
EBAC, Bonn-Ga, Julich

(by Eugene Pasyuk)

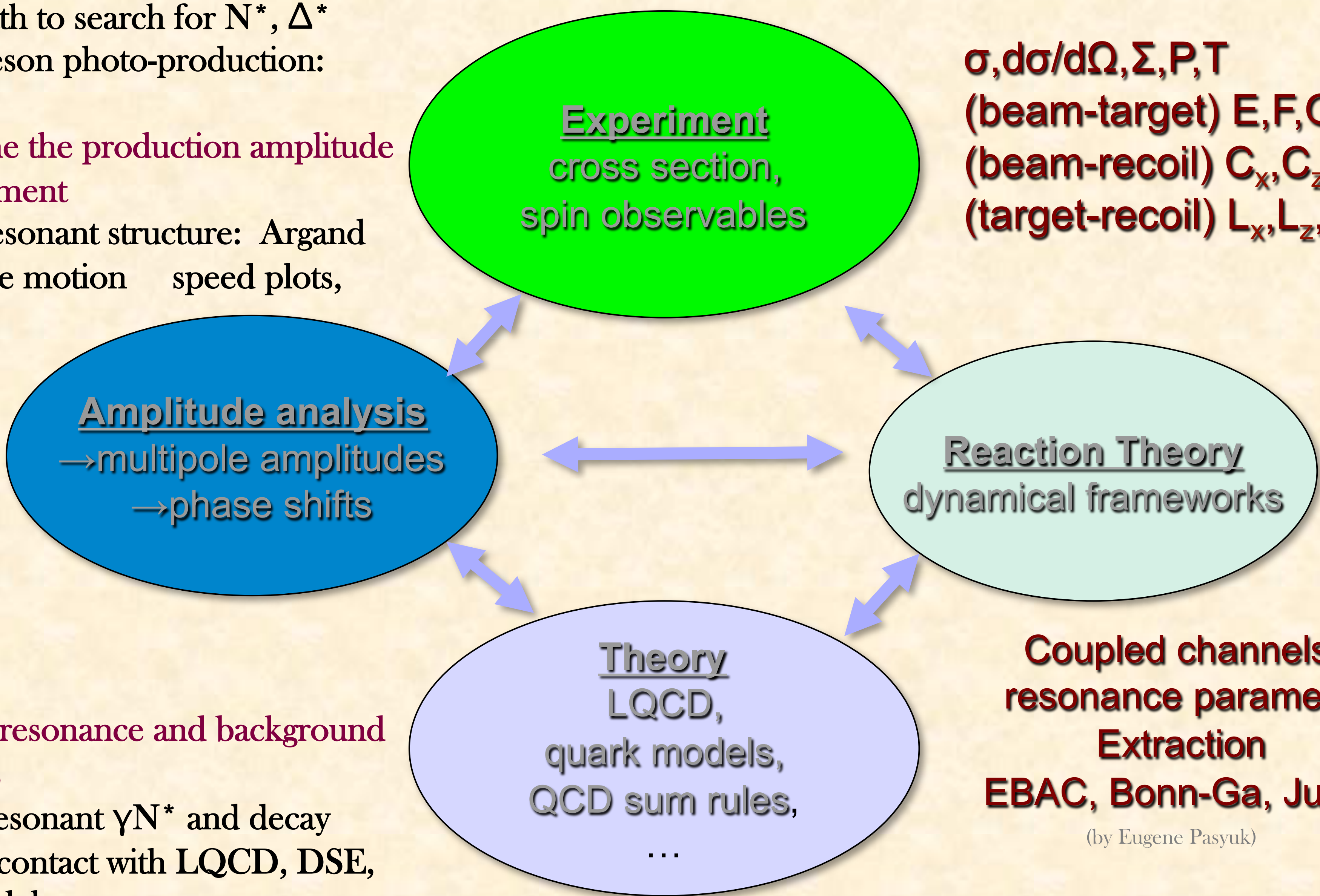
From the Experiment to Theory

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.



σ,$d\sigma/d\Omega$,Σ,P,T
(beam-target) E,F,G,H,
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(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
EBAC, Bonn-Ga, Julich

(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**

Complete experiments in pseudoscalar meson photoproduction

$$\gamma \quad + \quad N \quad \longrightarrow \quad m \quad + \quad N$$

Spin states

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

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 →

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

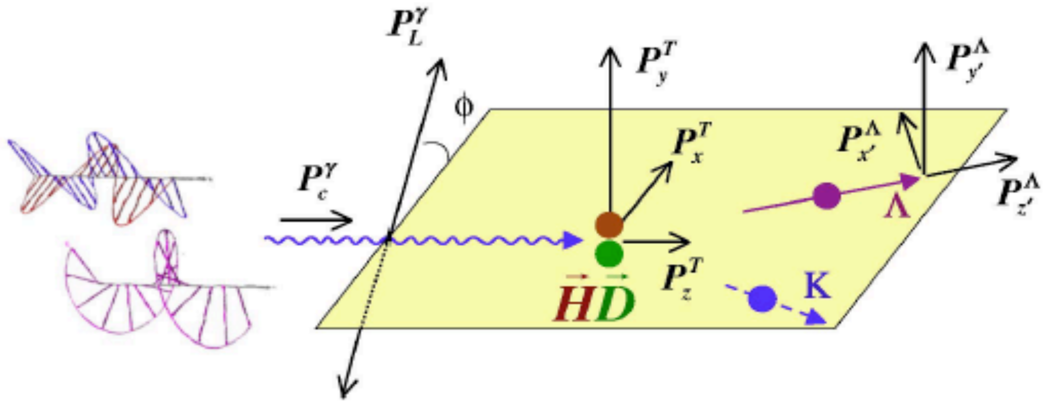
$$F_2 = \sum_{l=0}^{l_{max}}[(l+1)P'_l(x)M_{l+} + lP'_l(x)M_{l-}]\,,$$

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

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

Polarization observables in $J^{\pi} = 0^{-}$ meson photo-production : (SHKL, J Phys G38 (11) 053001)

Photon beam		Target			Recoil			Target - Recoil								
					x'	y'	z'	x'	x'	x'	y'	y'	y'	z'	z'	z'
		x	y	z				x	y	z	x	y	z	x	y	z
unpolarized	σ_0		T			P		$T_{x'}$		$L_{x'}$		Σ		$T_{z'}$		$L_{z'}$
$P_L^{\gamma}\ \sin(2\phi_{\gamma})$		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^{γ}		F		$-E$	$C_{x'}$		$C_{z'}$		$-O_{z'}$		G		$-H$		$O_{x'}$	



16 different observables, each appearing twice:

- ***single-pol observables can be measured from double-pol asy***
- ***double-pol observables can be measured from triple-pol asy***

0- N Pol Obsv table-v9 w plane

Experimental Requirements

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

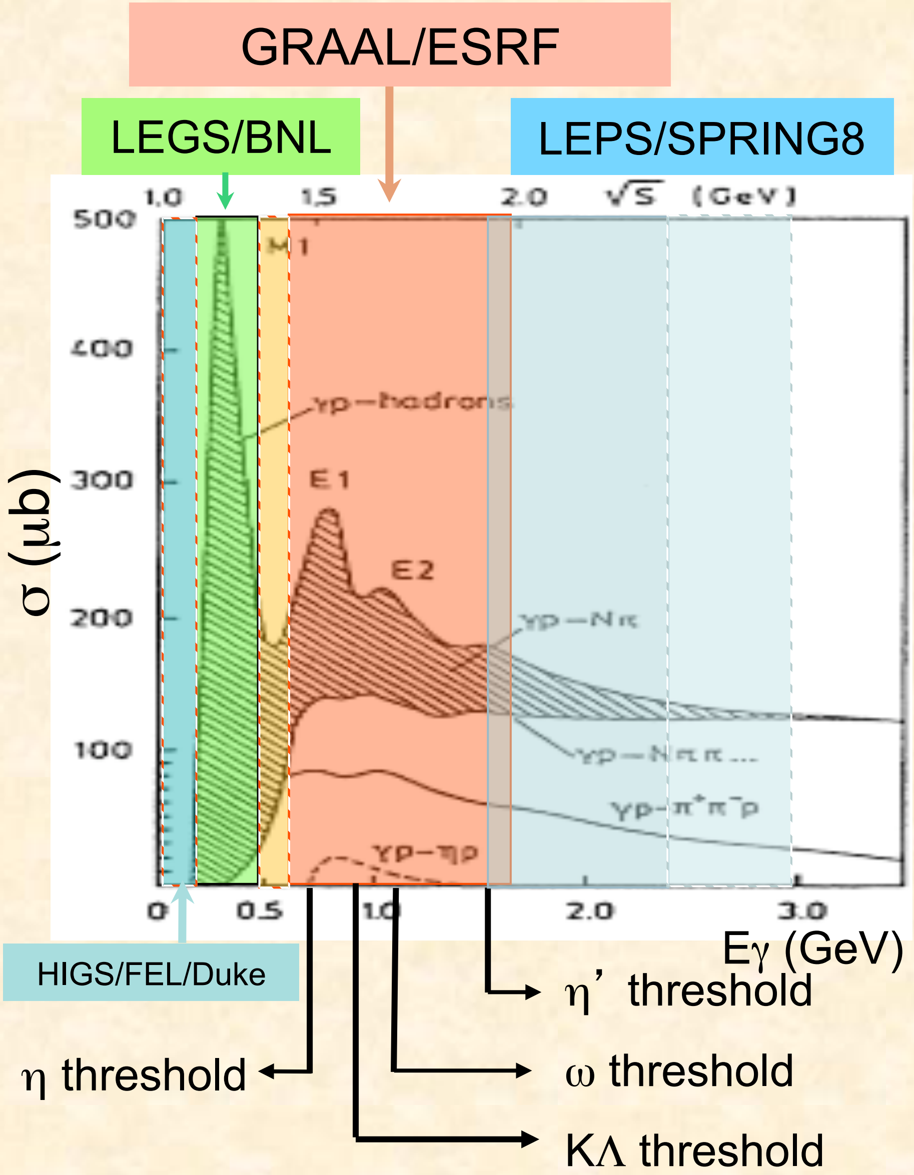
Modern experiments are
constructed to meet all above requirements:

GRAAL $E\gamma = (500 - 1500)$ MeV and CLAS in Hall-B $E\gamma = (500 - 6000)$ MeV

↓

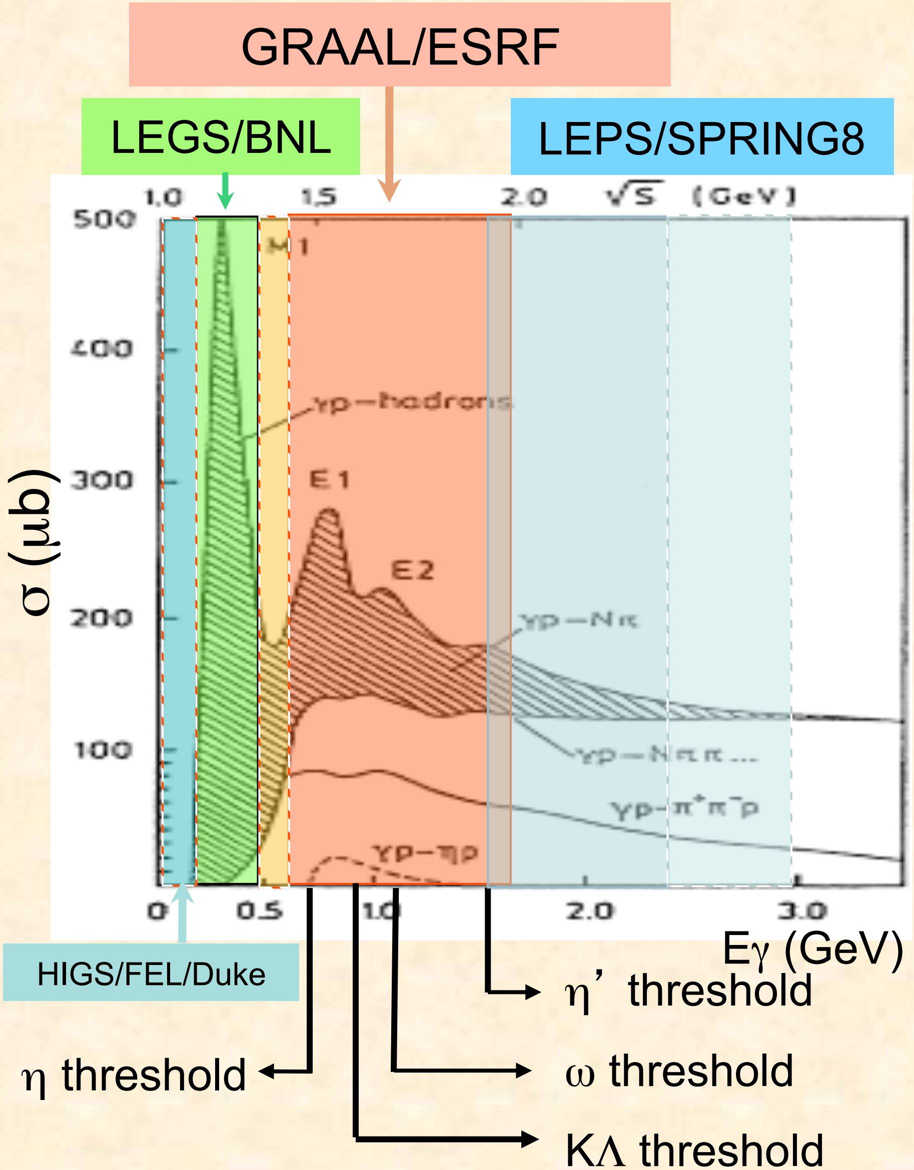
Crystal Barrel@BONN $E\gamma = (500 - 3000)$ MeV and Crystal Ball@MAINZ $E\gamma = (100 - 1500)$ MeV

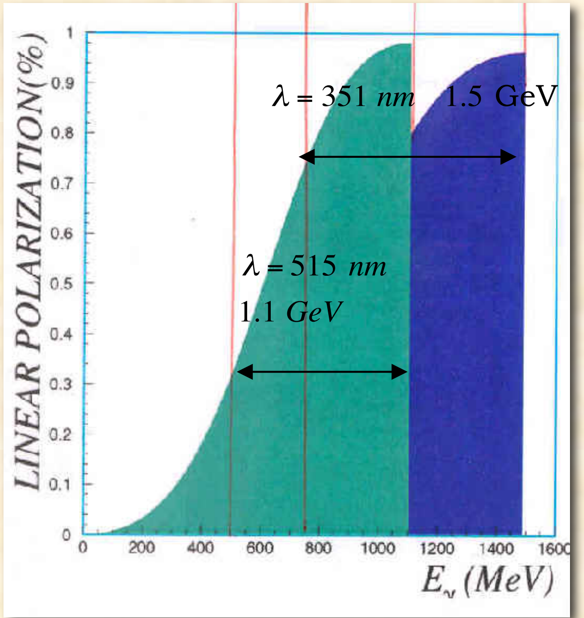
Polarized photon beams: Compton Backscattering

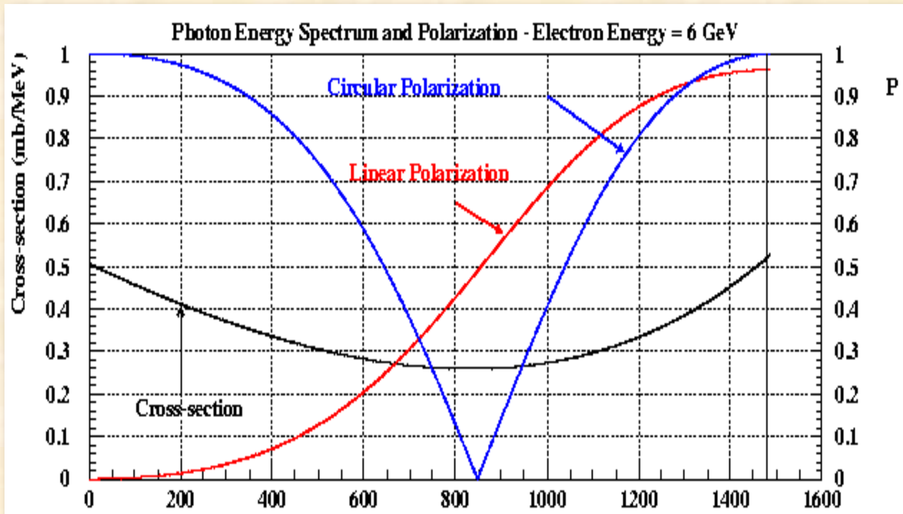


- Hiγs → below π threshold
- Legs → $\Delta_{33}(1232)$ resonance region
- Graal → E_γ = .6-1.5 GeV / W=1.4-1.9 GeV
  Region of the second and third baryon resonances η, K, ω, thresholds
- Leps → E_γ = 1.5-2.5 GeV
  η' ϕ thresholds

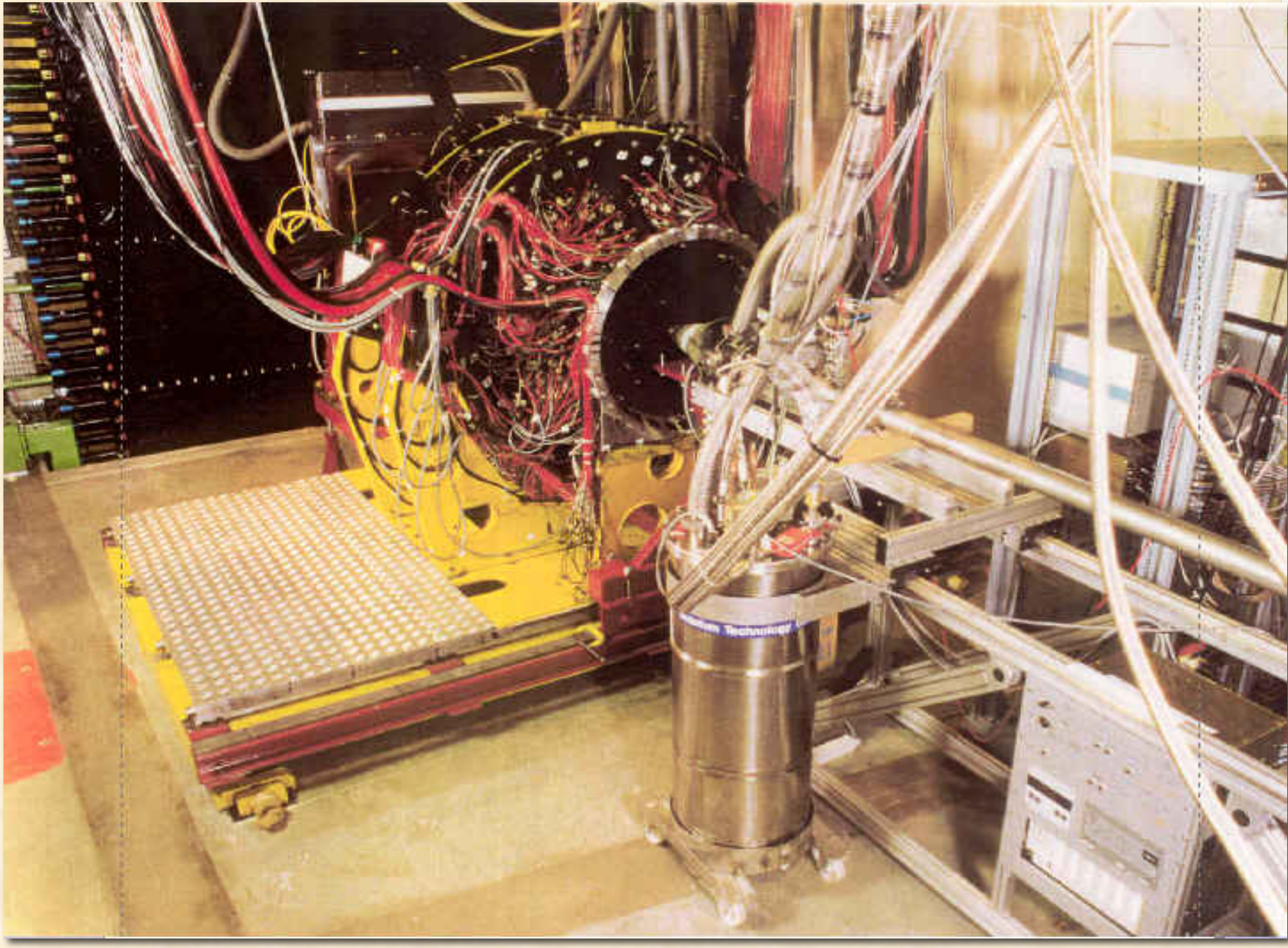
Polarized photon beams: Compton Backscattering



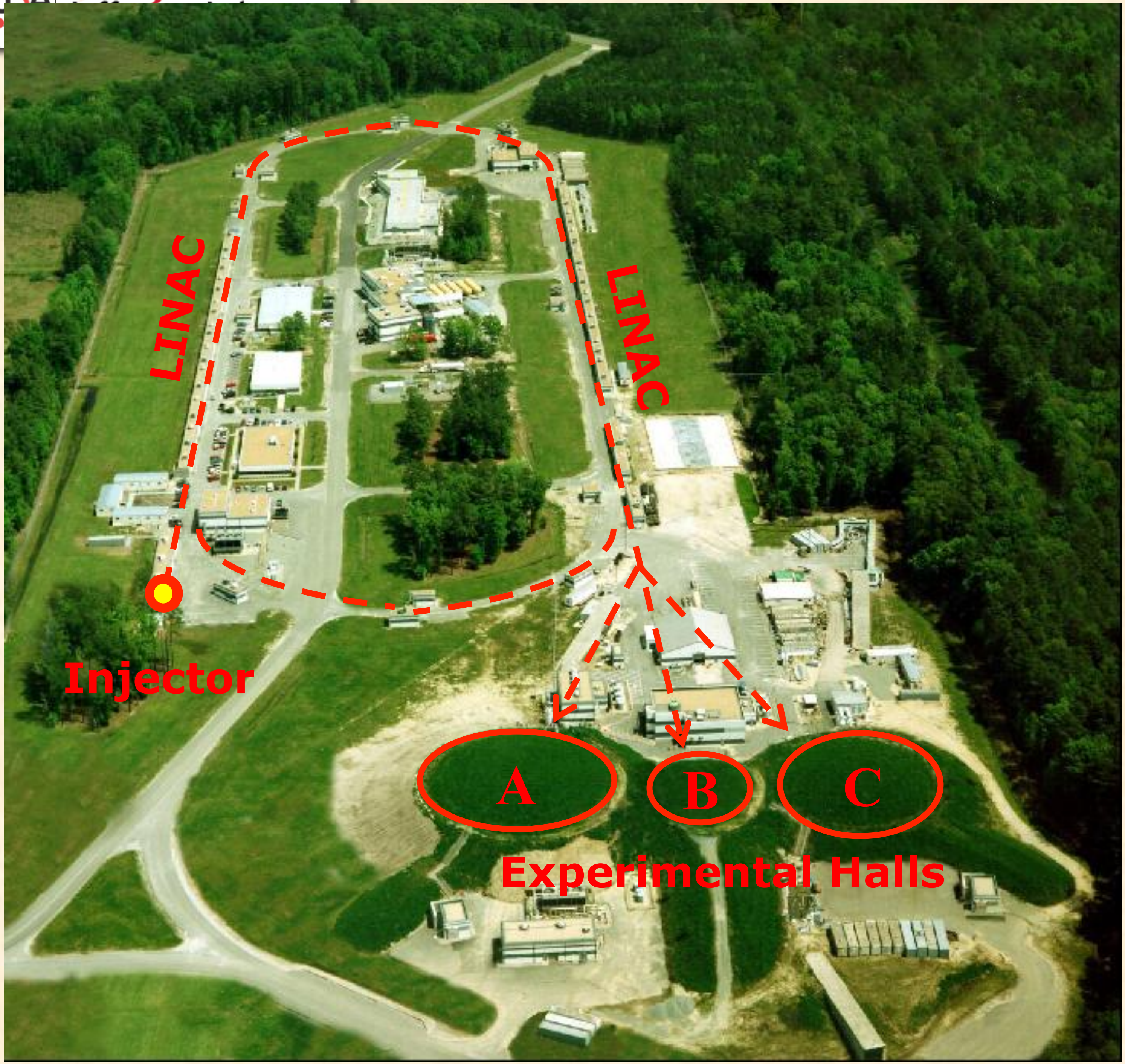




The Graal detector: Lagranγe



Large Acceptance Graal Apparatus for Nuclear γ Experiments



CEBAF

**Continuous
Electron
Beam
Accelerator
Facility**

- E: 0.75 –6 GeV
- I_{max}: 200mA
- Duty Cycle: ~ 100%
- $\sigma(E)/E$: 2.5x10^{-5}
- Polarization: ≥85%
- Simultaneous distribution to 3 experimental Halls

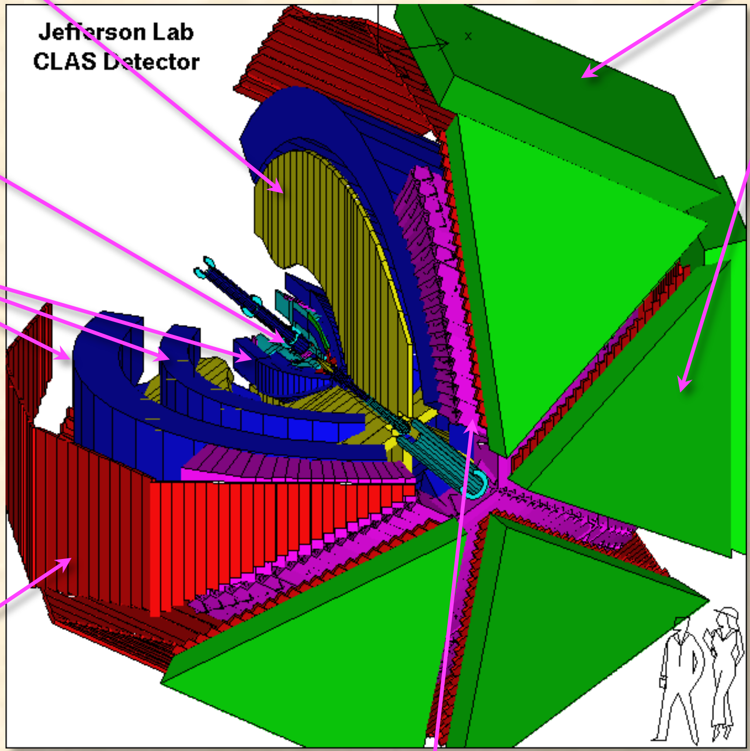
CEBAF Large Acceptance Spectrometer

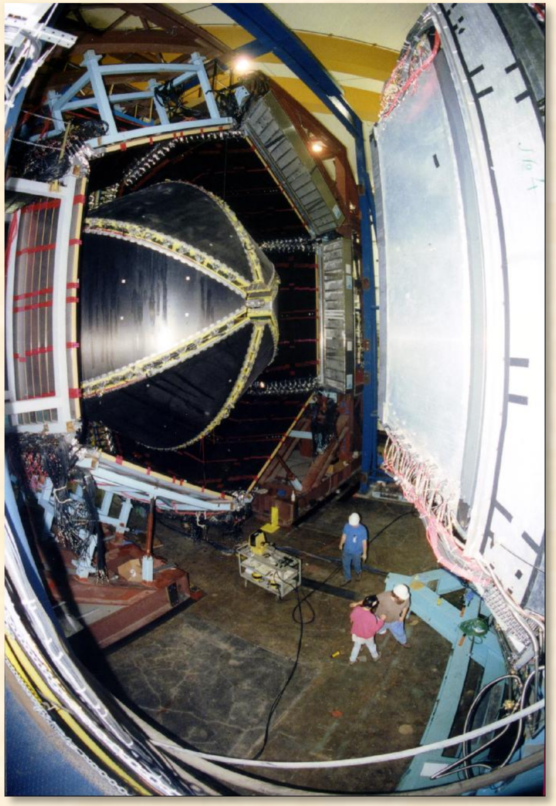
Torus magnet
6 superconducting coils

Electromagnetic calorimeters
Lead/scintillator, 1296 photomultipliers

target + start counter

Drift chambers
35,000 cells

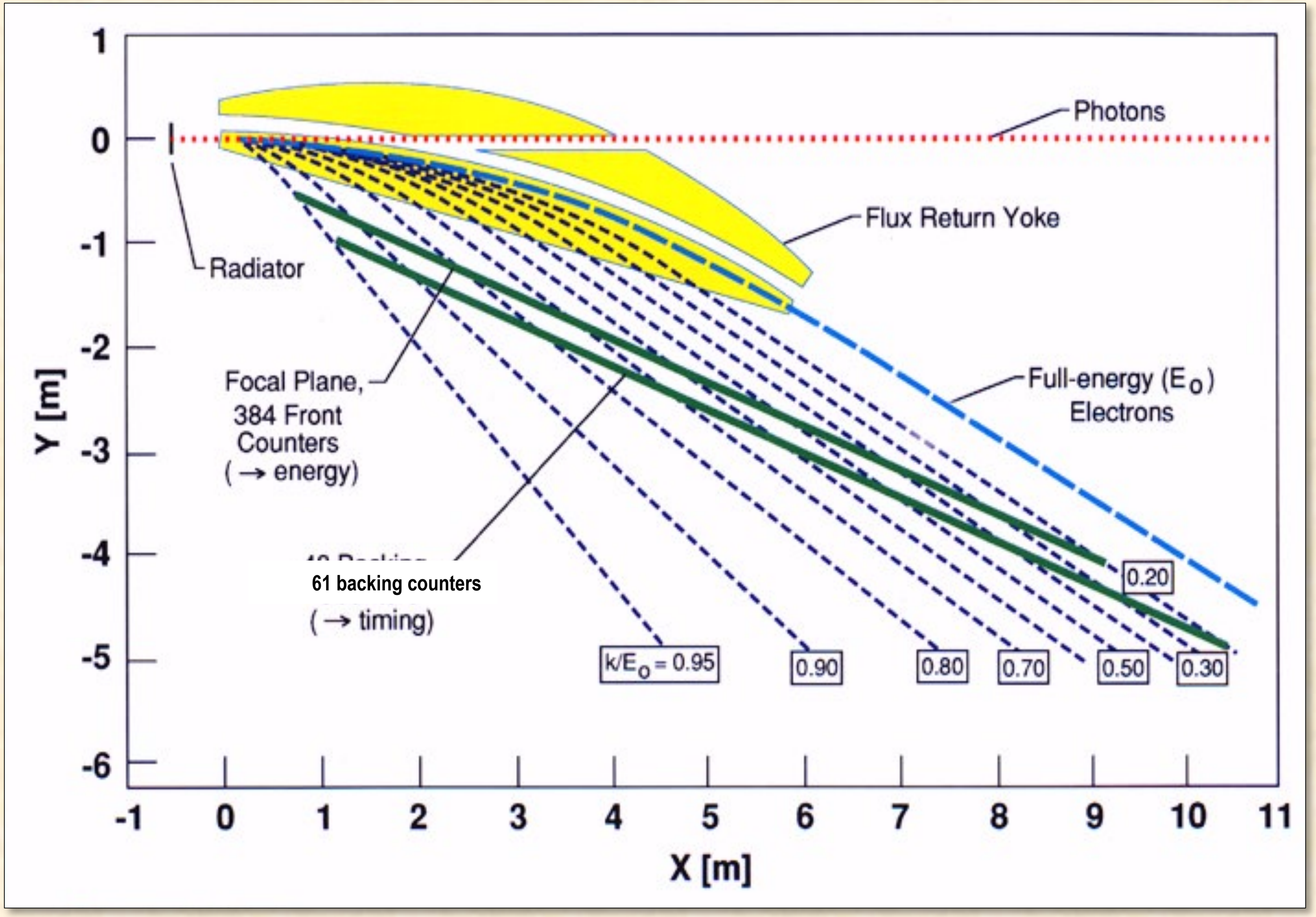




Time-of-flight counters
plastic scintillators, 684 photomultipliers

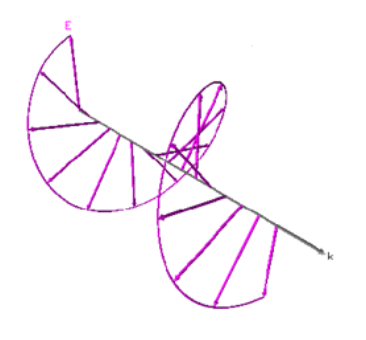
Gas Cherenkov counters
e/π separation, 256 PMTs

Hall B Photon Tagger



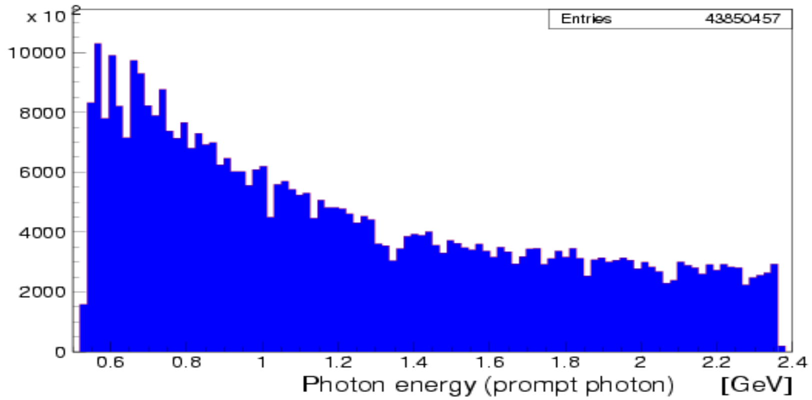
- E_γ = 20-95% of E_0
- E_γ up to ~5.8 GeV
- dE/E ~10^{-3} of E_0

Circularly polarized photons

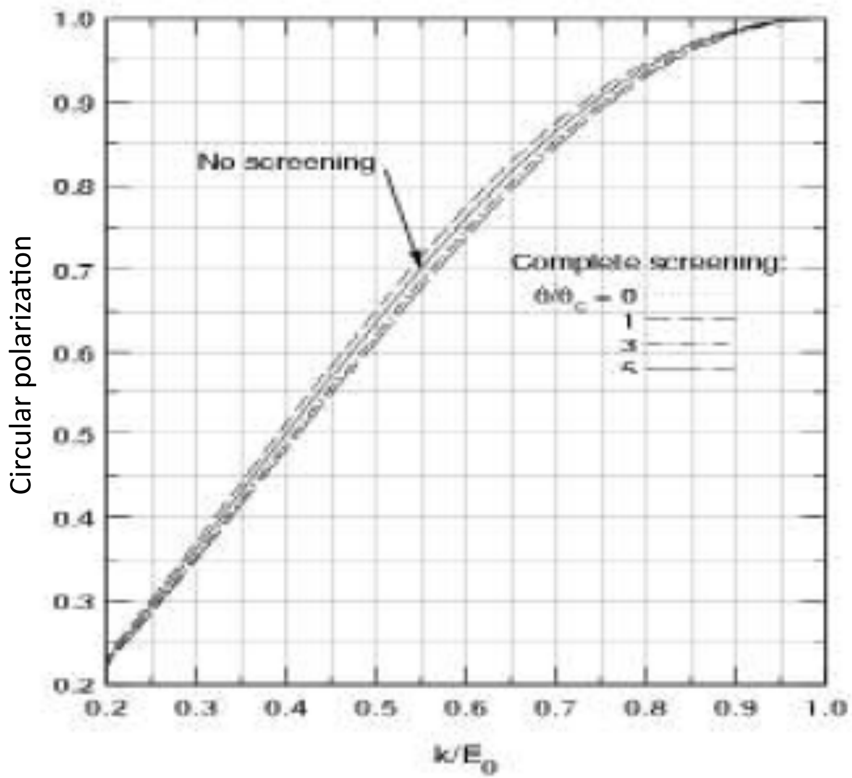


- Circularly polarized beam produced by longitudinally polarized electrons
- CEBAF electron beam polarization >85%
- tagged flux ~ 50 - 100MHz for k>0.5 E_0

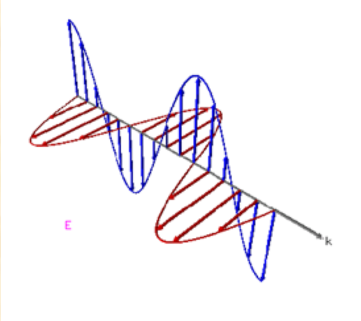
$$P_\gamma = P_e \cdot \frac{4k - k^2}{4 - 4k + 3k^2}$$



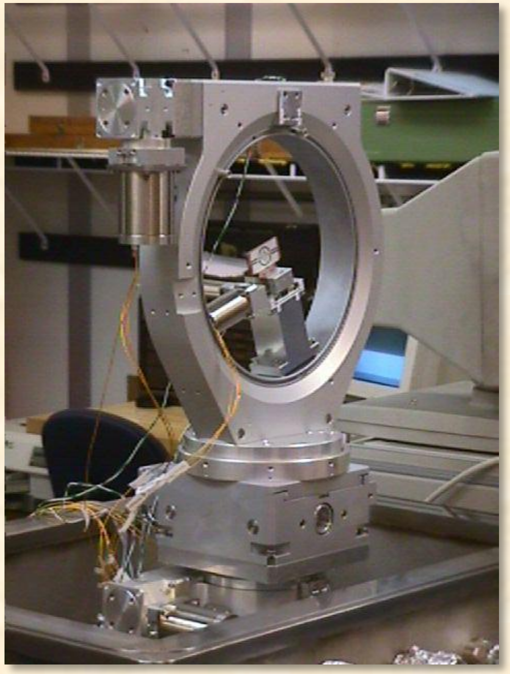
Circular polarization from 100% polarized electron beam

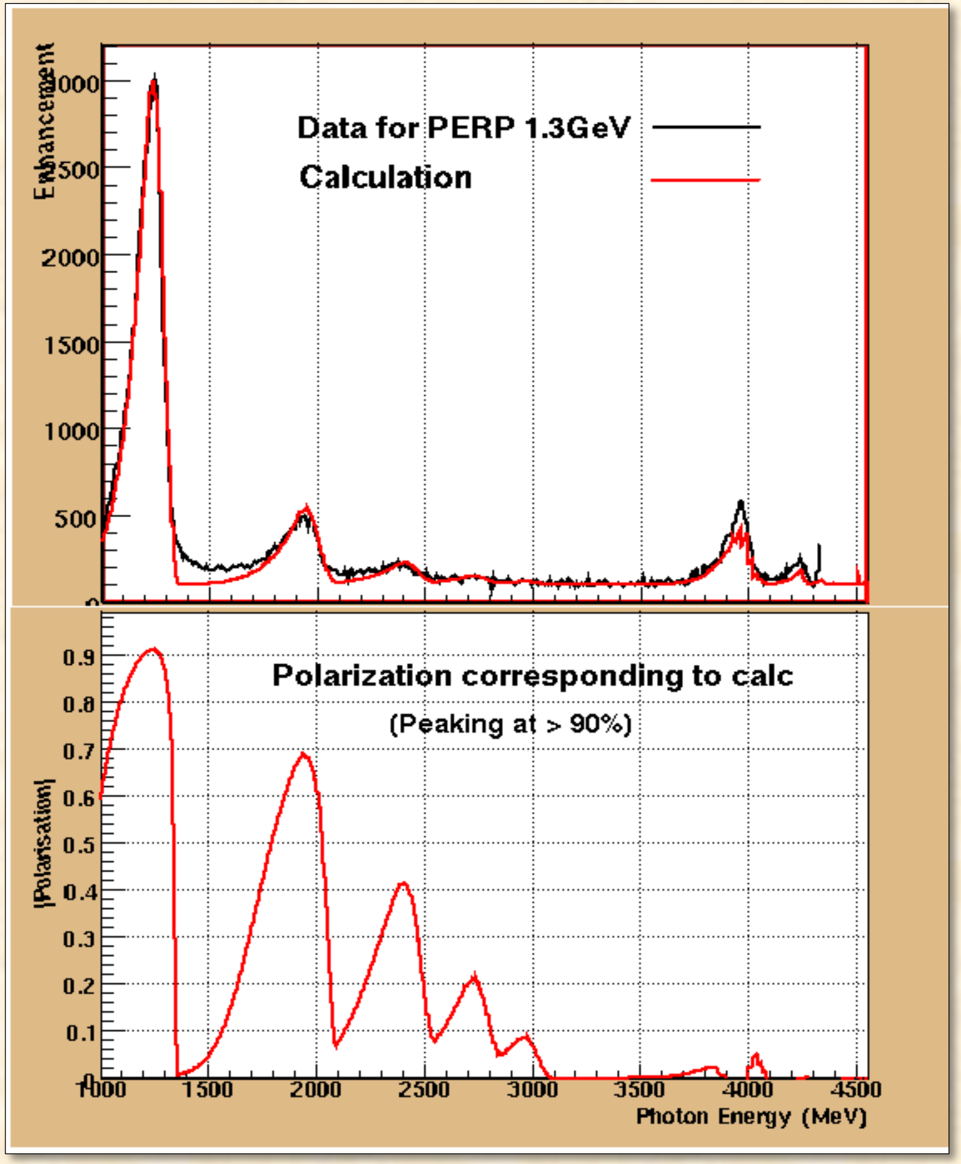


Linearly polarized photons

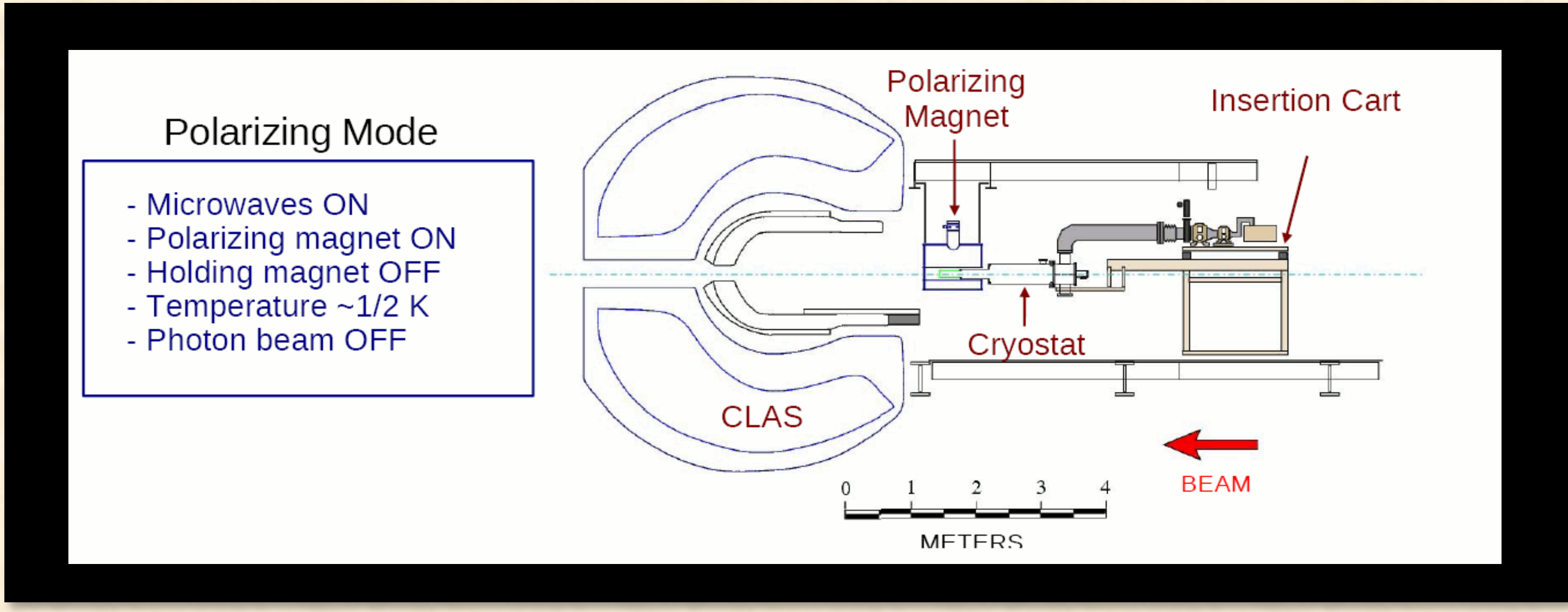


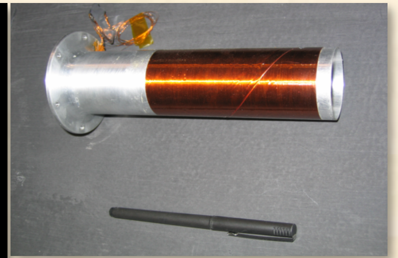
Linearly polarized photons: coherent bremsstrahlung on oriented diamond crystal

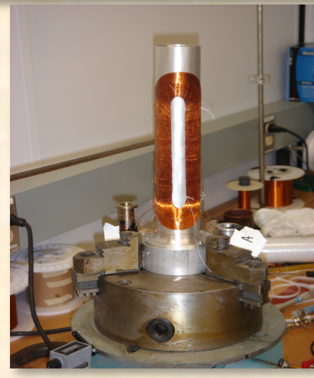


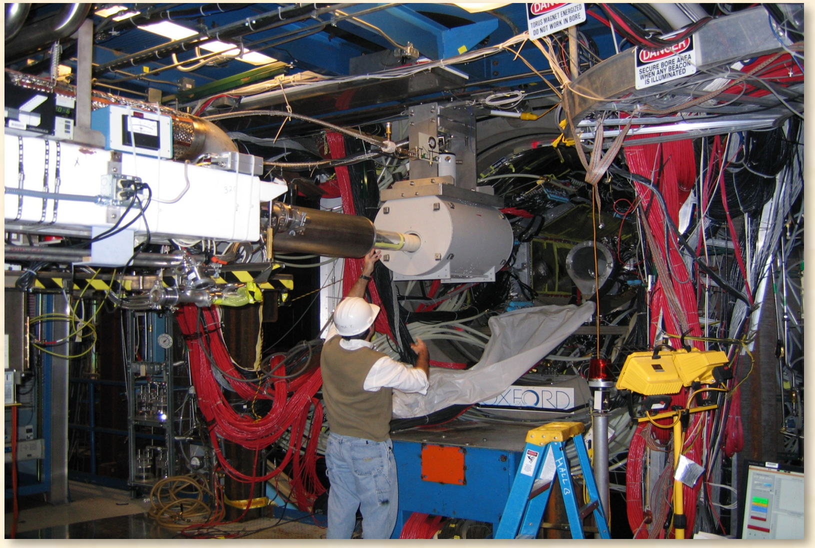


Polarized targets: frozen spin butanol FROST at CLAS





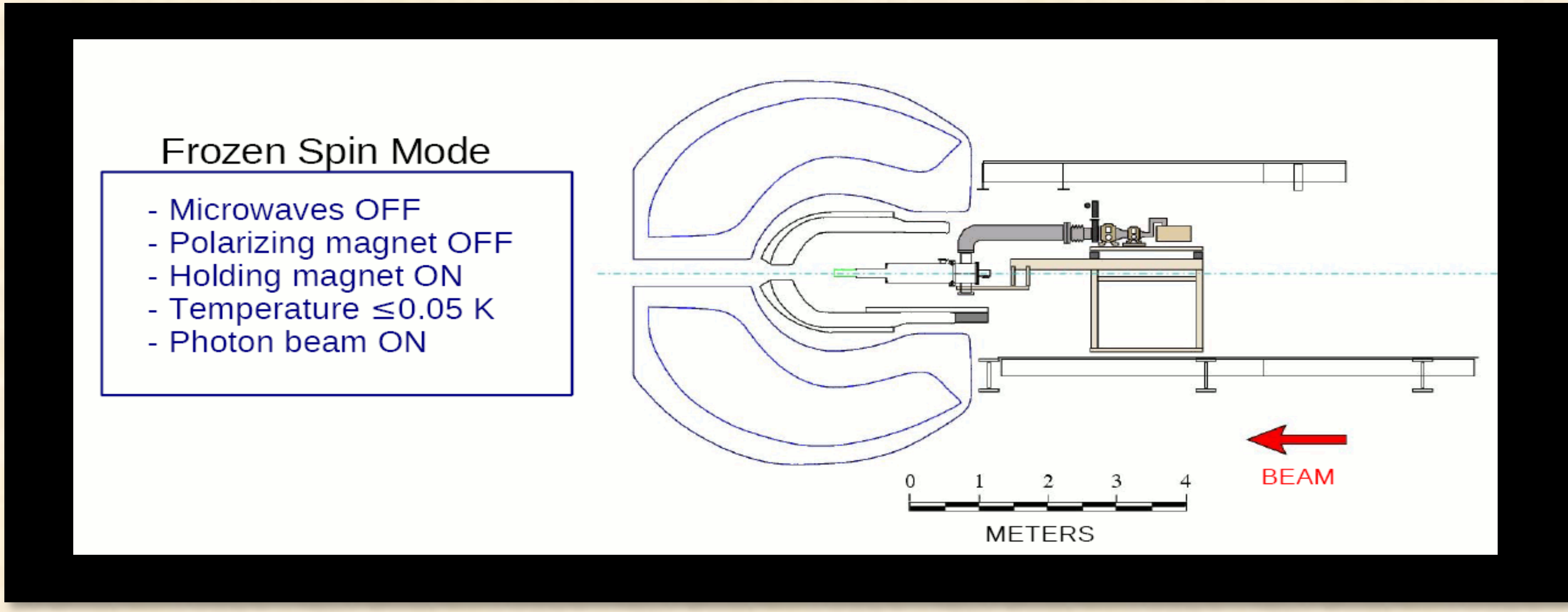


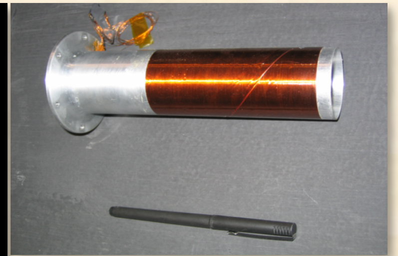


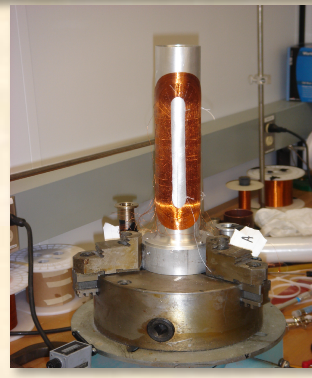
Longitudinal Polarization: above 80%
Relaxation time: > 2000 hours
Polarization procedure< 6 hours
Data taking: 5-6 days

Very reliable.

Polarized targets: frozen spin butanol FROST at CLAS







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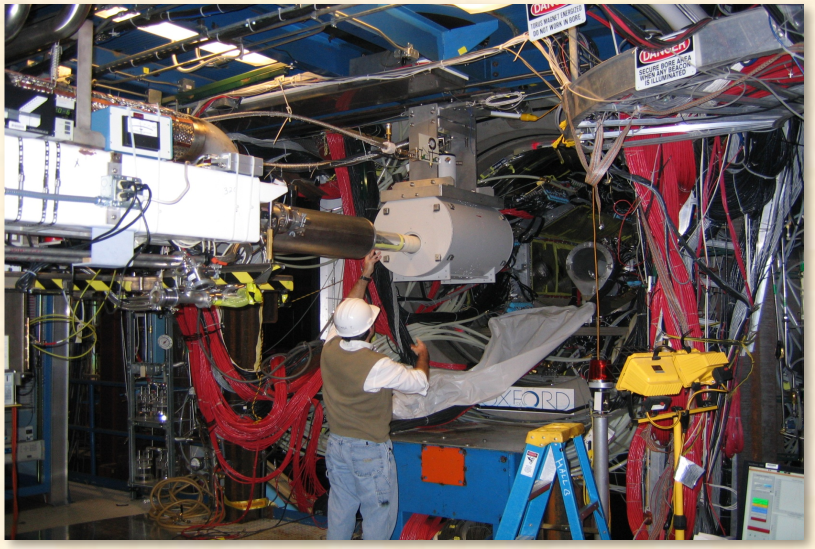

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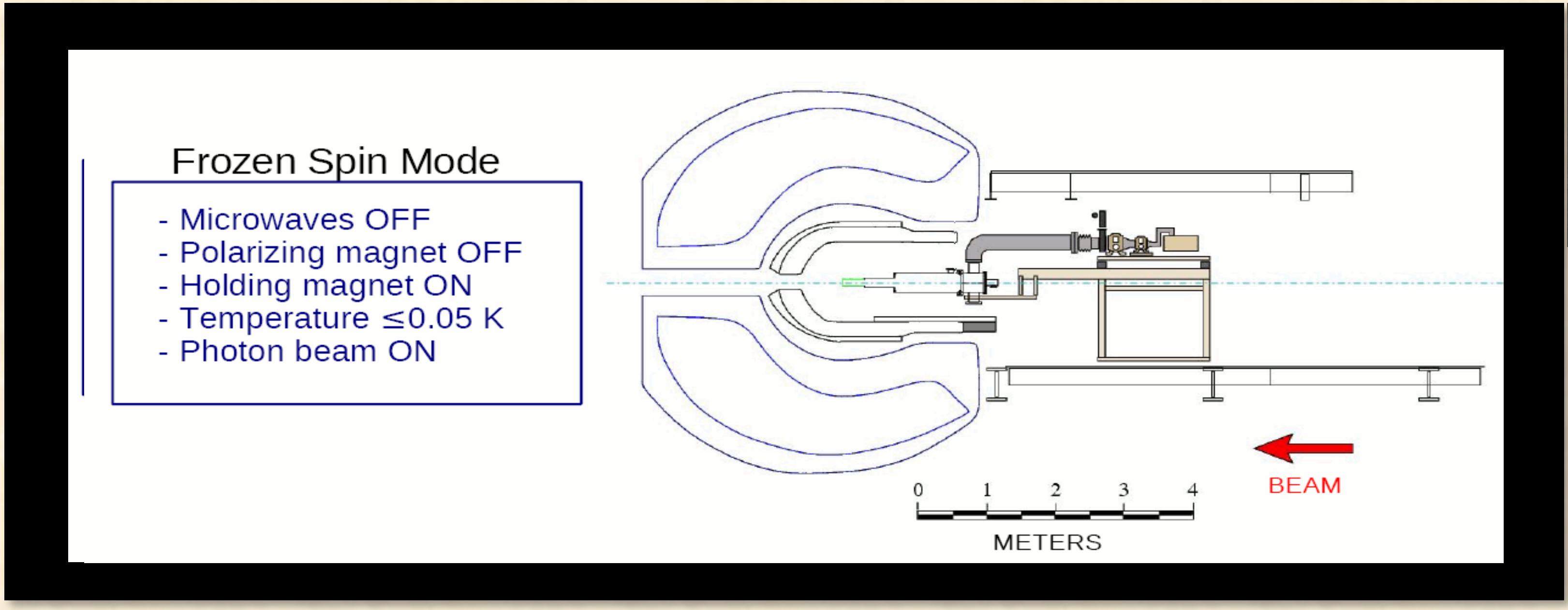
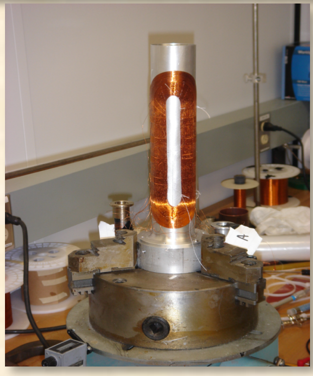
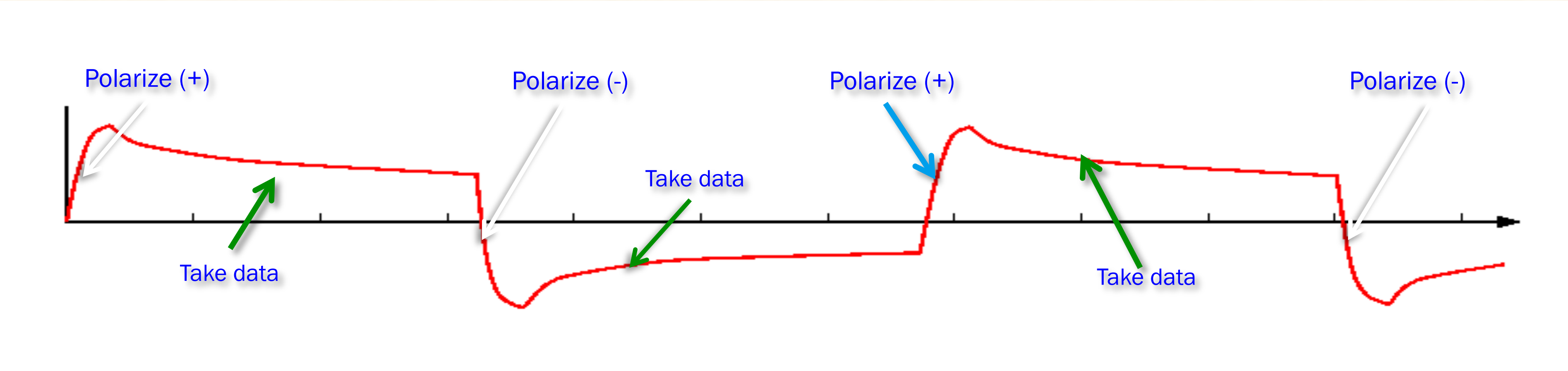




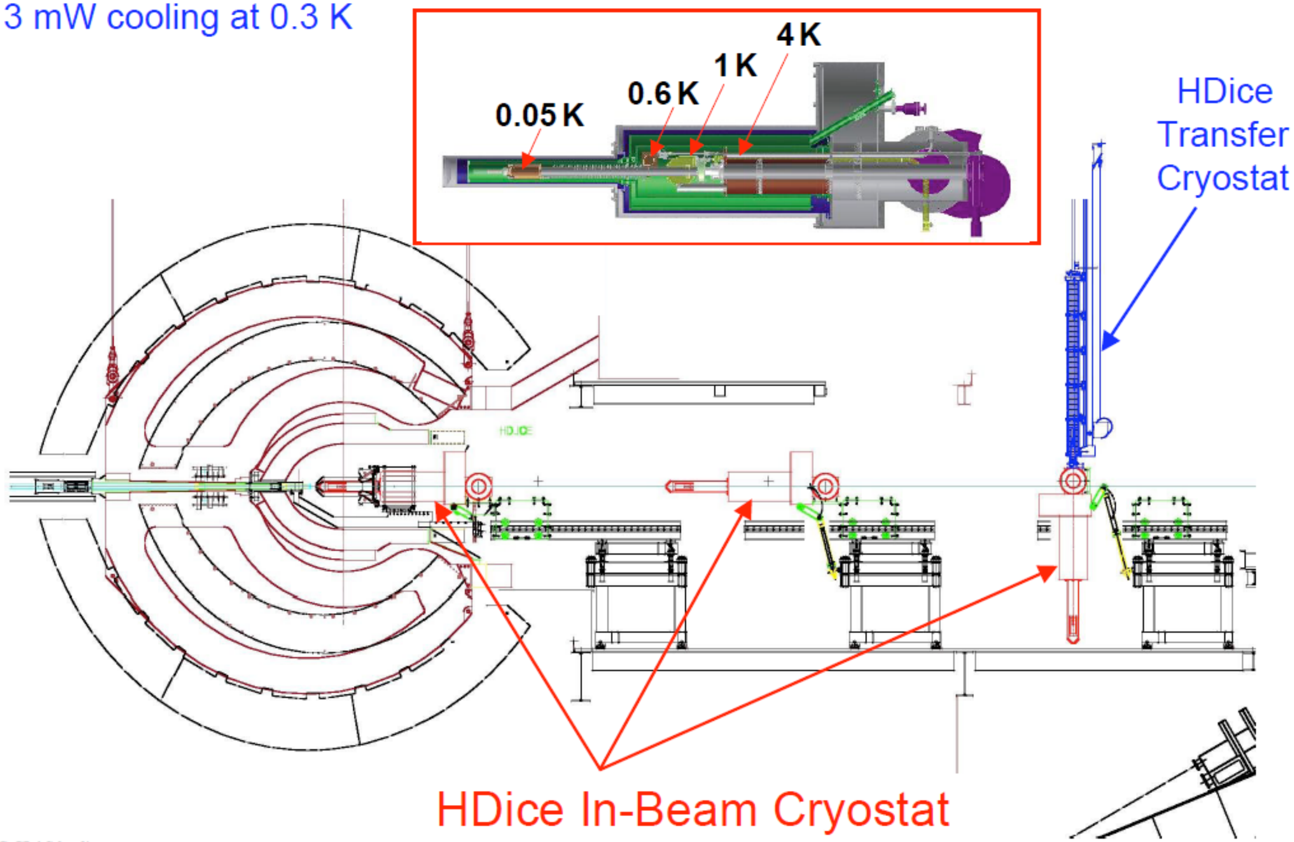


HDIce polarized target

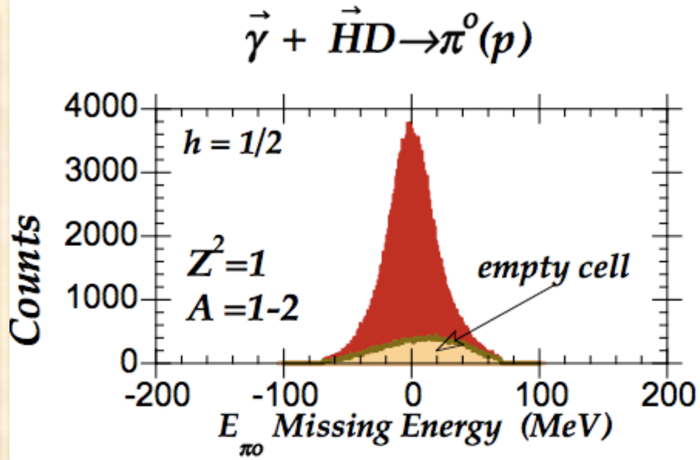
HDIce Solid Deuterium-Hydride (HD) – a new class of polarized target

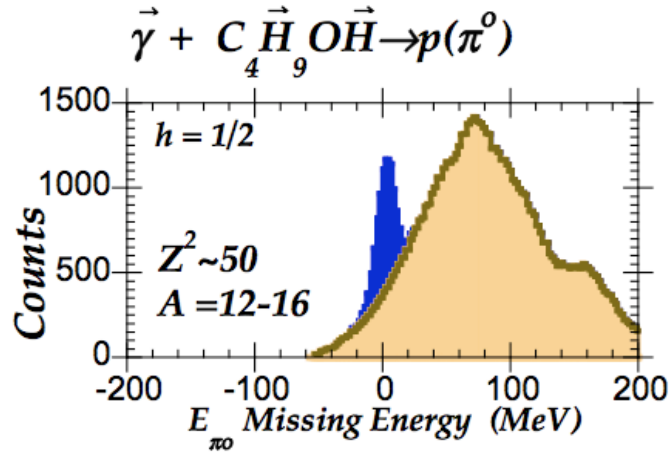
- Spin can be moved between H and D with RF transitions
- All material can be polarized with almost no background

- designed for both γ (w Start Counter) and e⁻ (w mini-Torus) running
- 13 mW cooling at 0.3 K

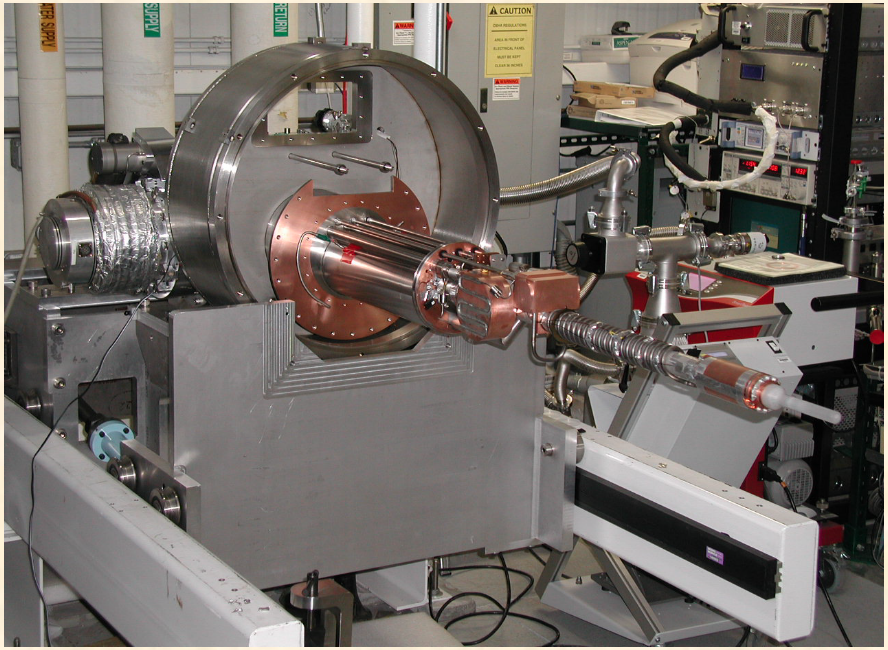


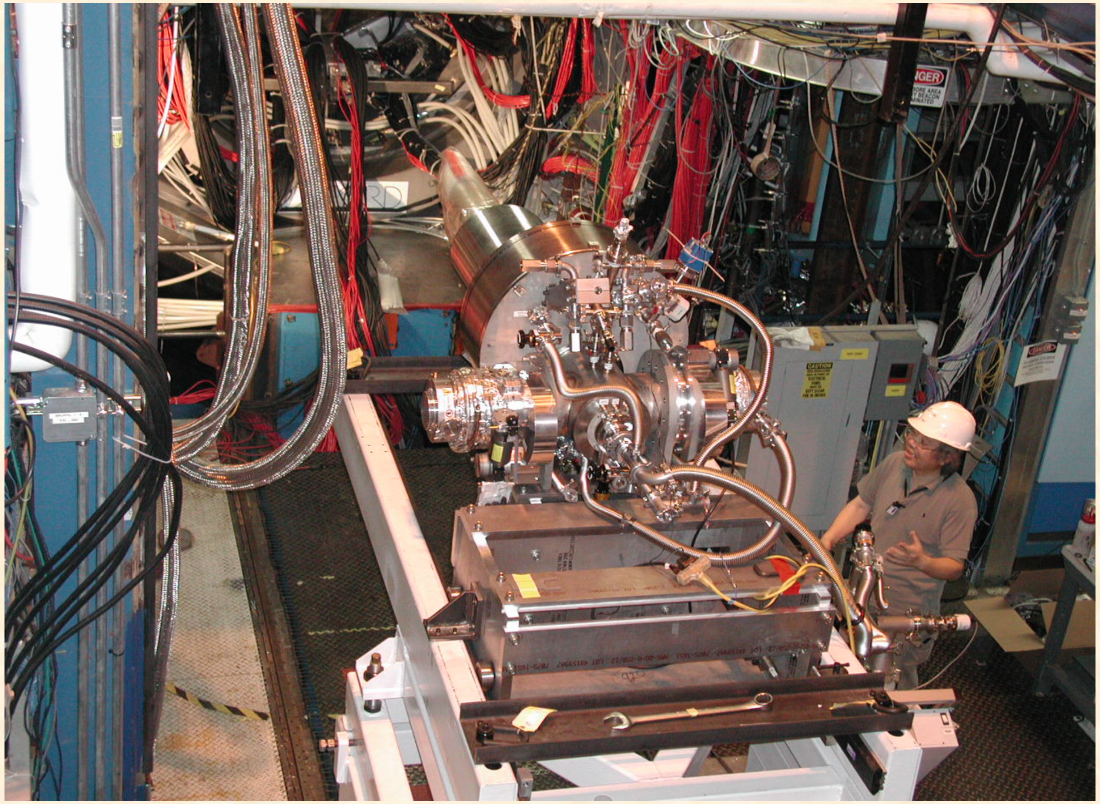
HDice IBC-CLAS loading





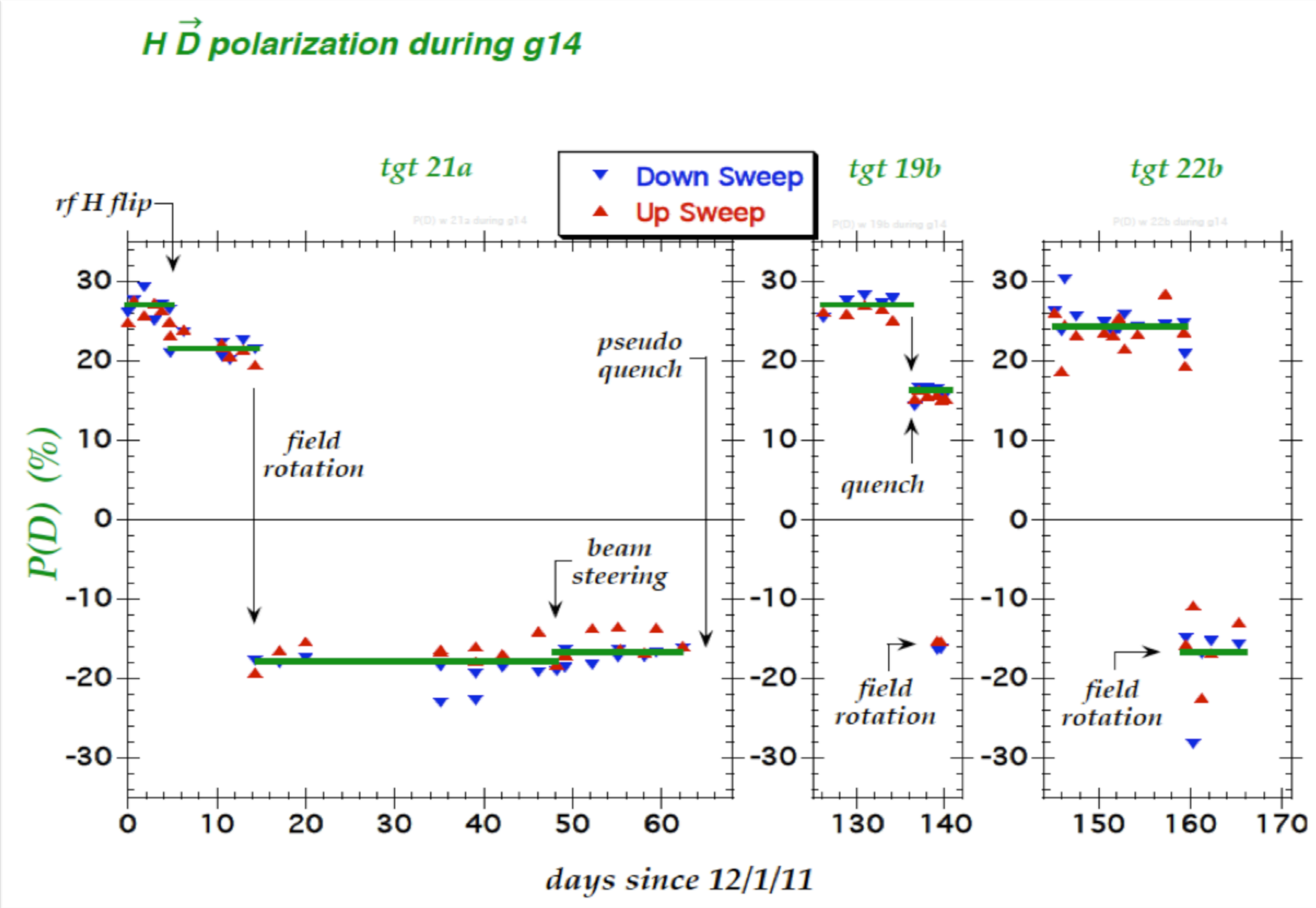
HD-Ice





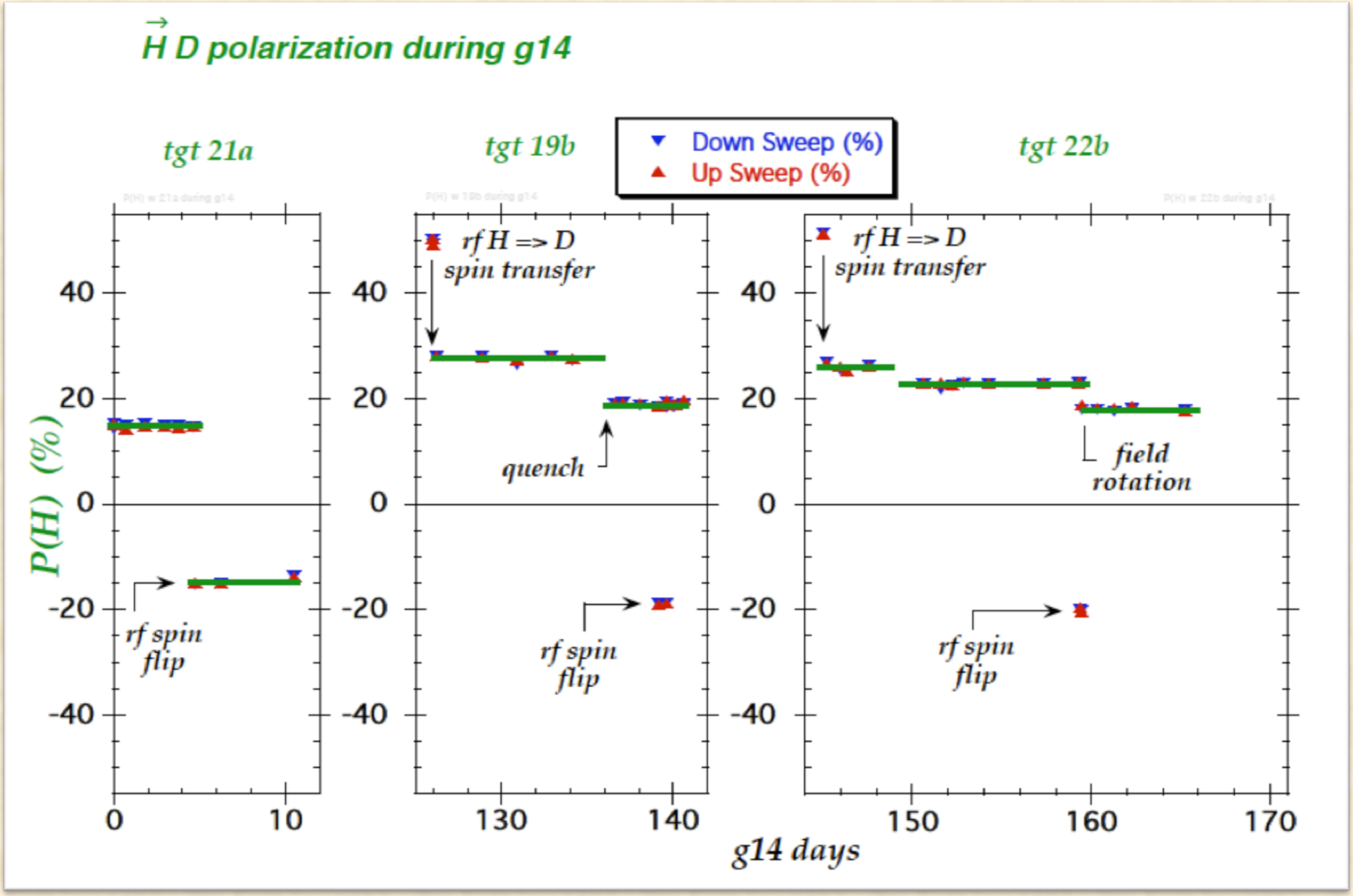
Longitudinal and Transverse Polarizations: > 60%
Relaxation time: > 1 year
Polarization procedure ≈ 3 months
Data taking: ≈ months
Very complicated target transfer technology.

HD-Ice



H $\vec{D}$ polarization during g14
tgt 21a
tgt 19b
tgt 22b
Down Sweep
Up Sweep
rf H flip
field rotation
pseudo quench
beam steering
quench
field rotation
field rotation
P(D) (%)
days since 12/1/11

HD-Ice



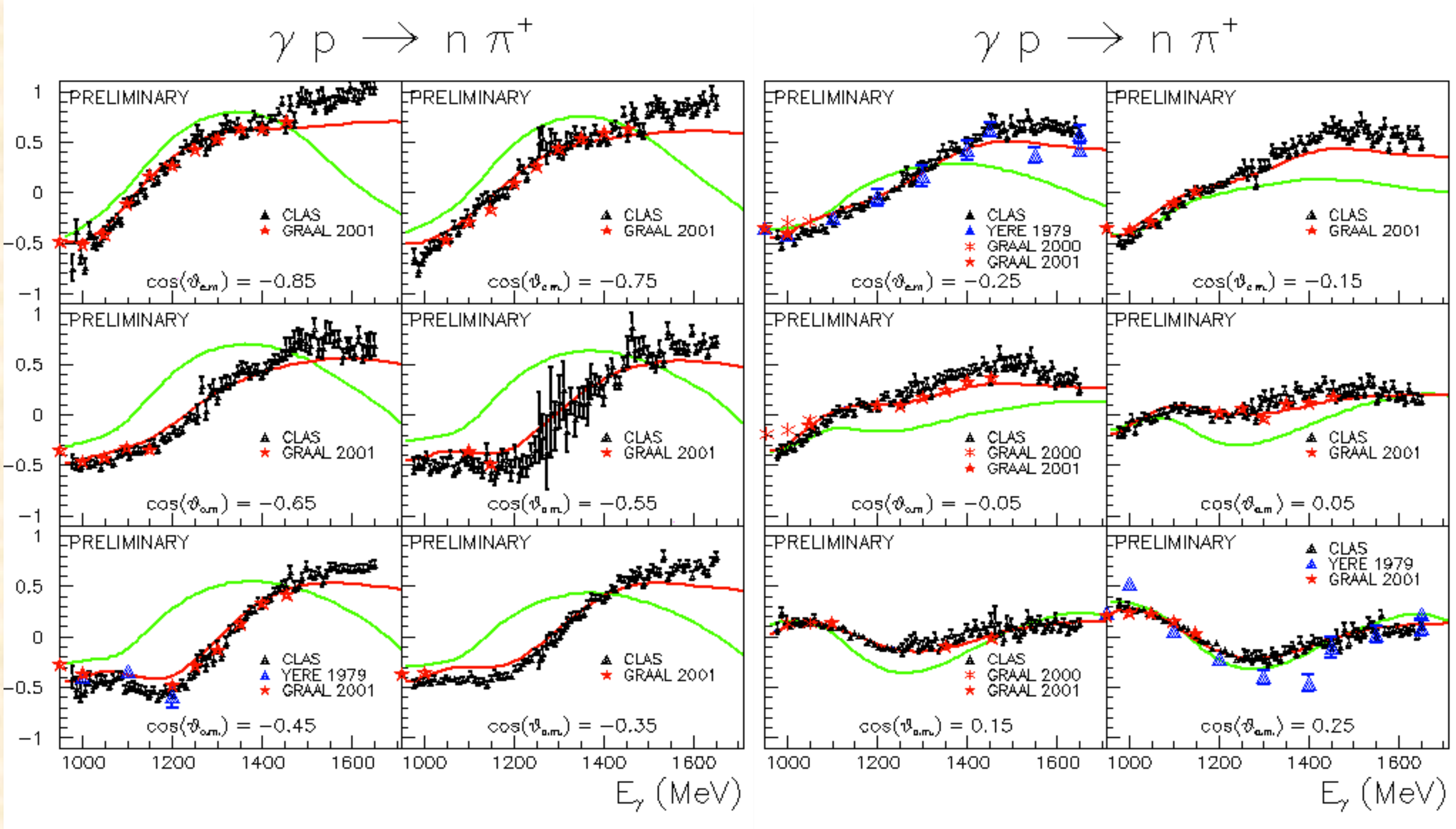
$\vec{H}D$ polarization during g14
tgt 21a
tgt 19b
tgt 22b
Down Sweep (%)
Up Sweep (%)
rf H => D
spin transfer
quench
field
rotation
rf spin
flip
P(H) (%)
40
20
0
-20
-40
0
10
130
140
150
160
170
g14 days

Measured Reaction Channels

- $\gamma p \rightarrow \pi^0 p$, $\pi^+ n$
- $\gamma p \rightarrow \eta p$
- $\gamma p \rightarrow \eta' p$
- $\gamma p \rightarrow KY$ ($K^+\Lambda$, $K^+\Sigma^0$, $K^0\Sigma^+$)
- $\gamma p \rightarrow \pi^+\pi^- p$ ωp, ρp, ϕp

- $\gamma n \rightarrow \pi^+\pi^- n$
- $\gamma n \rightarrow \eta n$
- $\gamma n \rightarrow \pi^- p$
- $\gamma n \rightarrow \pi^+\pi^- n$
- $\gamma n \rightarrow \Sigma^- K^+$, ΛK^0
- $\gamma n \rightarrow \omega n$

$\gamma p \rightarrow \pi^+ n$ Photon asymmetry Σ

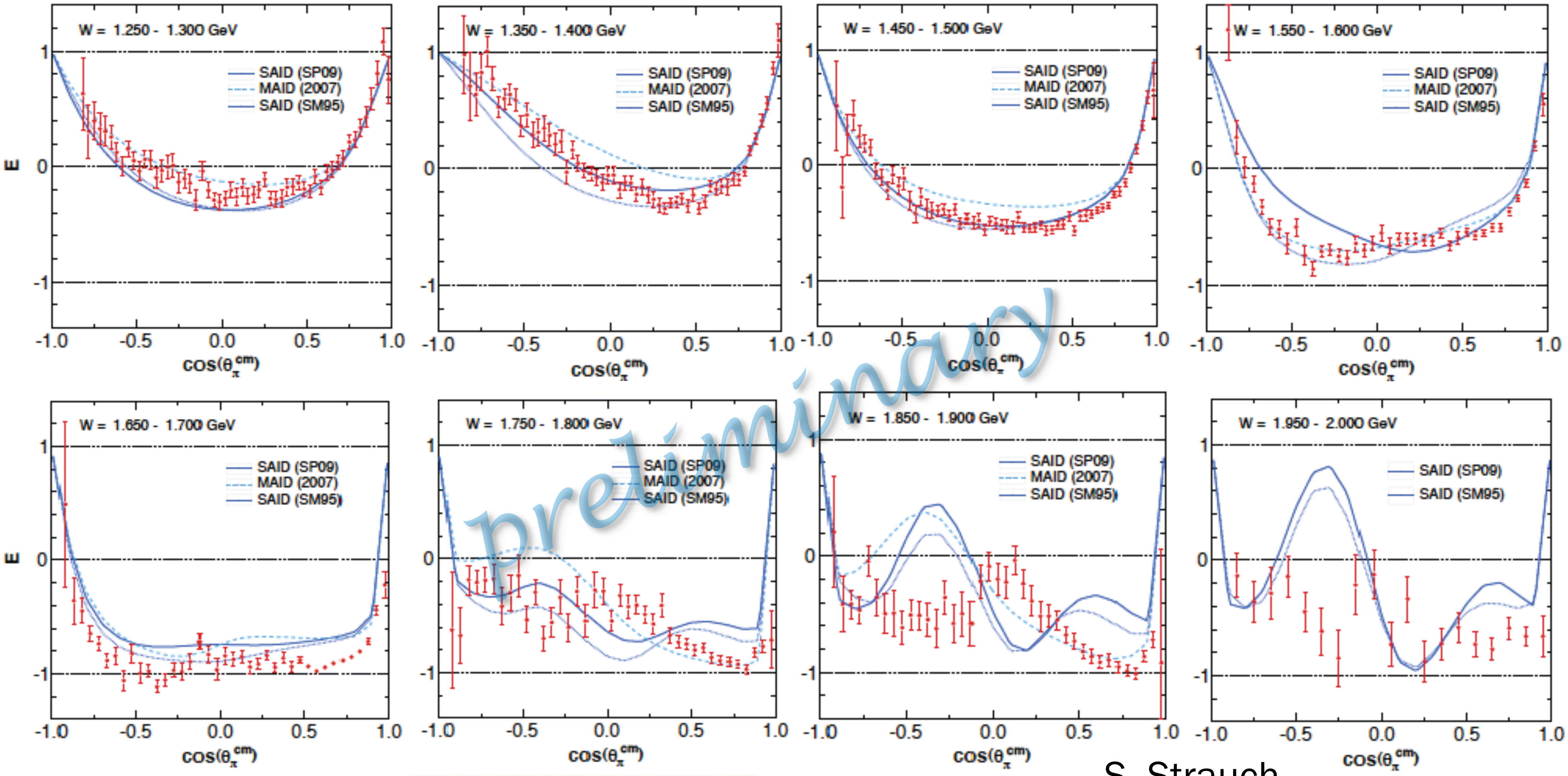


MAID 2007

SAID 2009

$\gamma p \rightarrow \pi^+ n$ Helicity asymmetry E

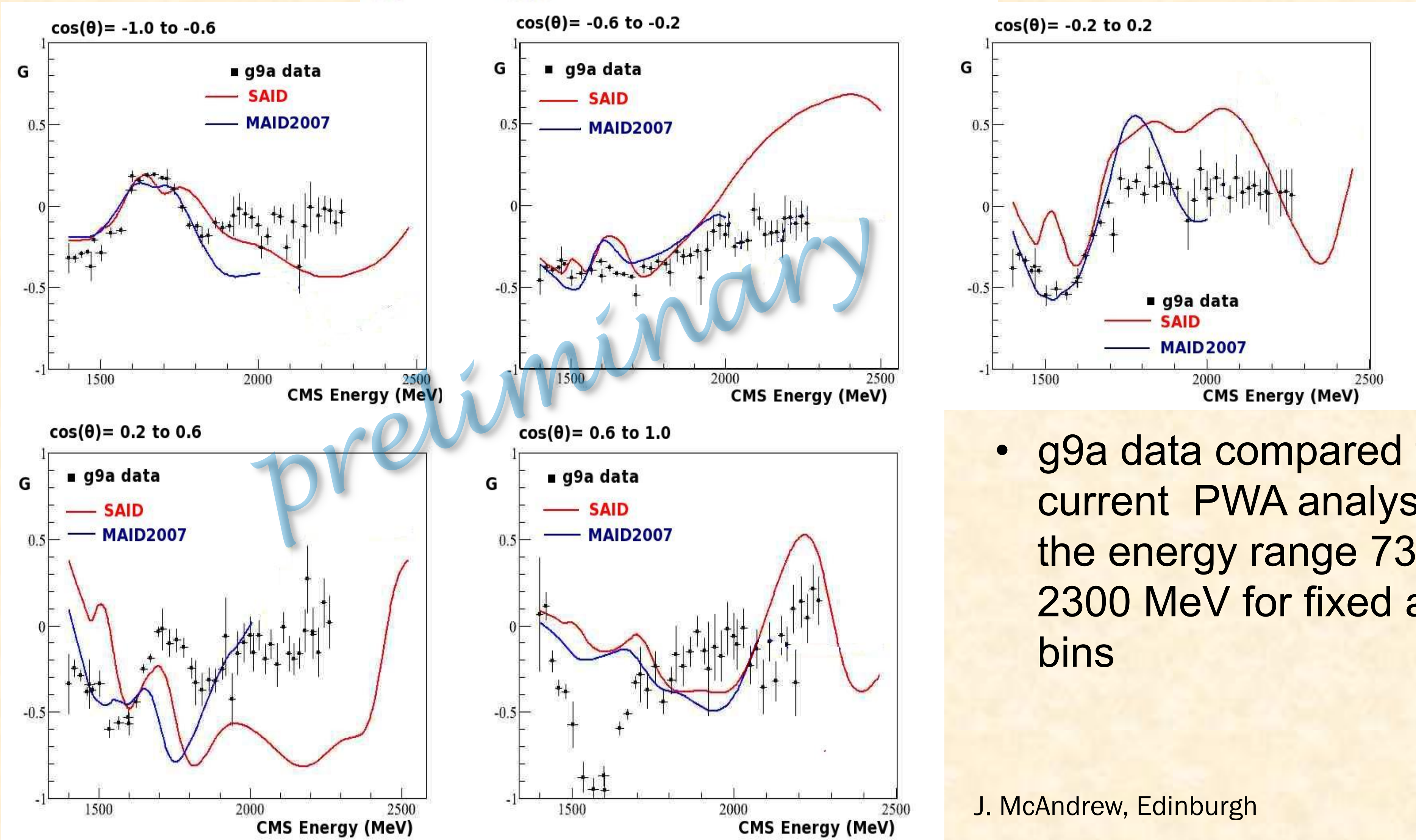
circularly polarized beam – longitudinally polarized target (g9a-FROST)



S. Strauch

$\gamma p \rightarrow \pi^+ n$ Helicity asymmetry G

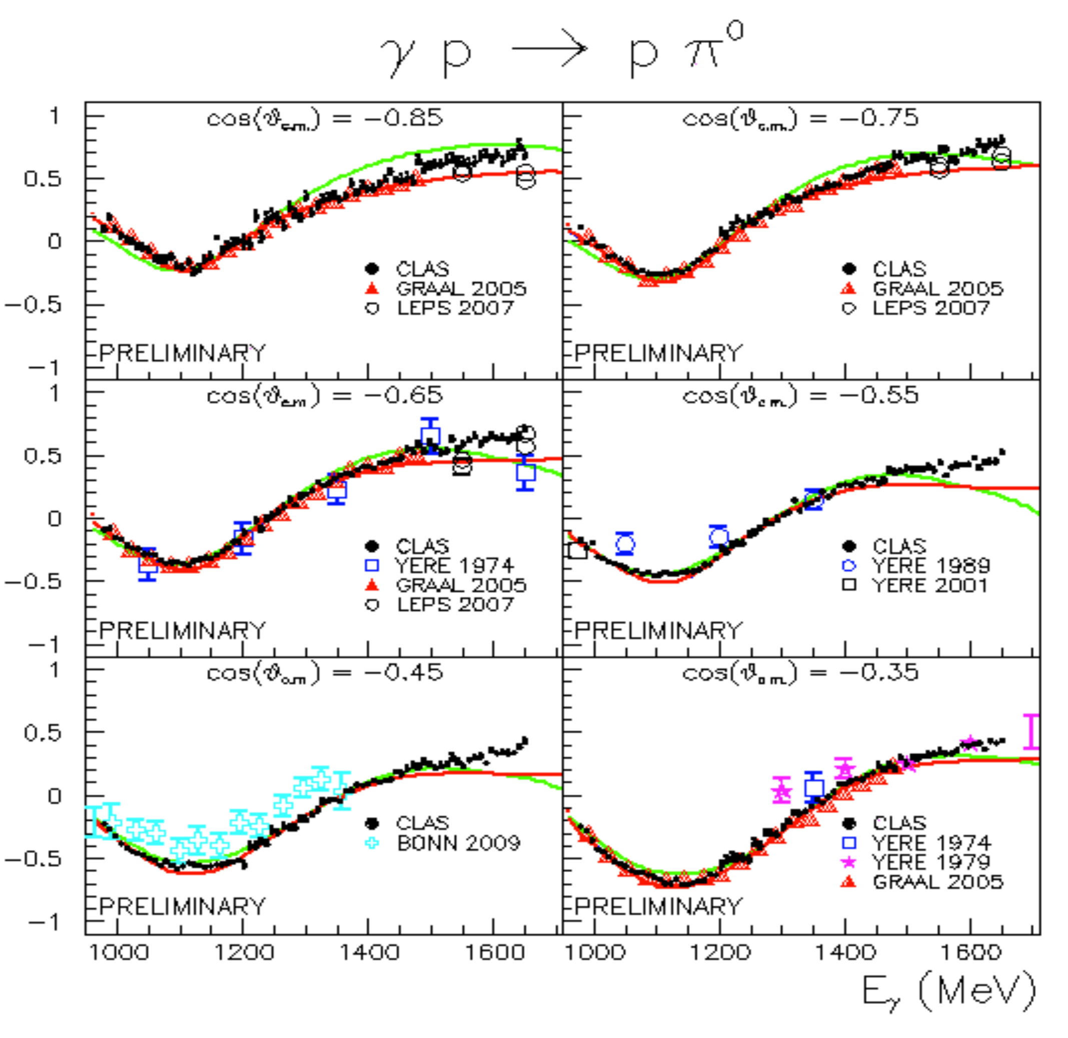
$$\frac{d\sigma}{d\Omega}(\theta,\phi) = \frac{d\sigma}{d\Omega}(\theta)[1 - p_T \Sigma \cos(2\phi) + p_z p_T G \sin(2\phi)]$$

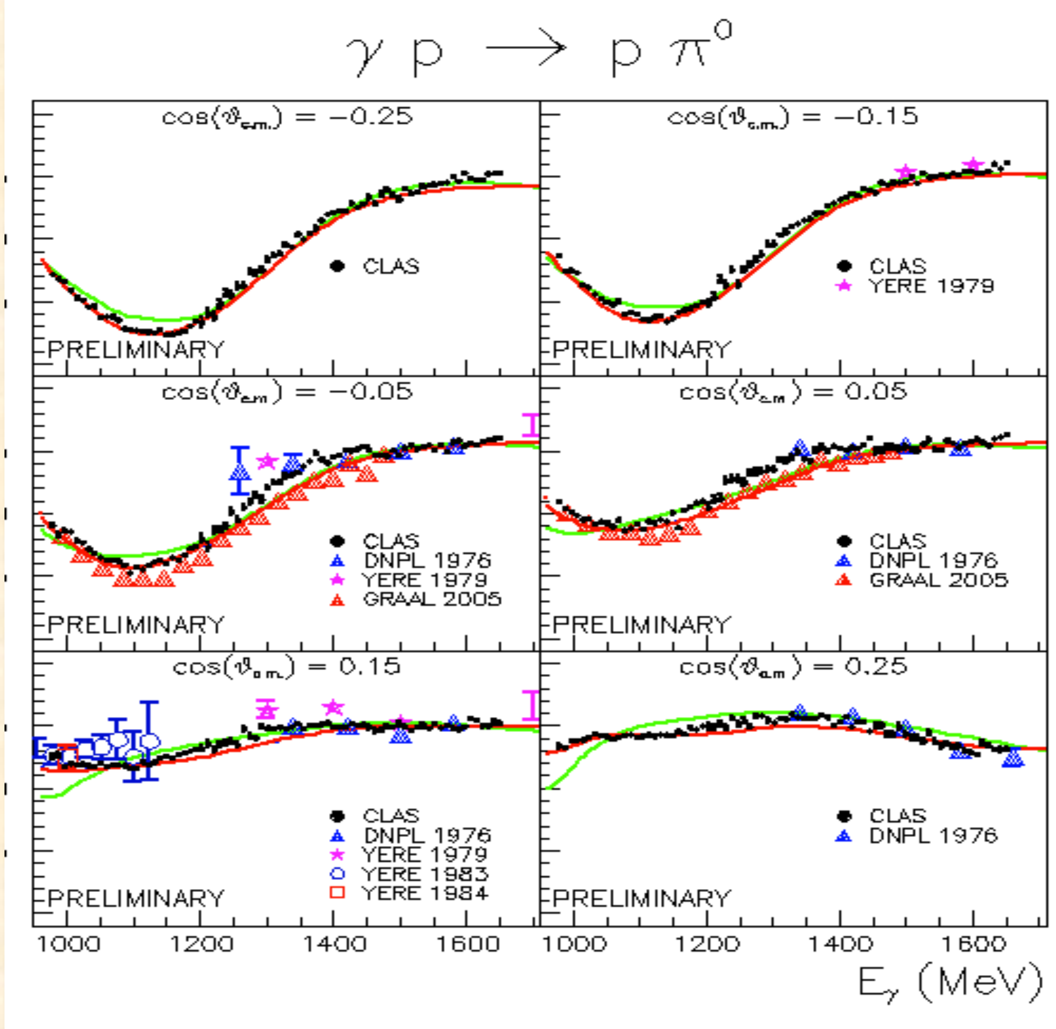


- g9a data compared to current PWA analyses in the energy range 730 – 2300 MeV for fixed angular bins

J. McAndrew, Edinburgh

$\gamma p \rightarrow \pi^0 p$ Photon asymmetry Σ





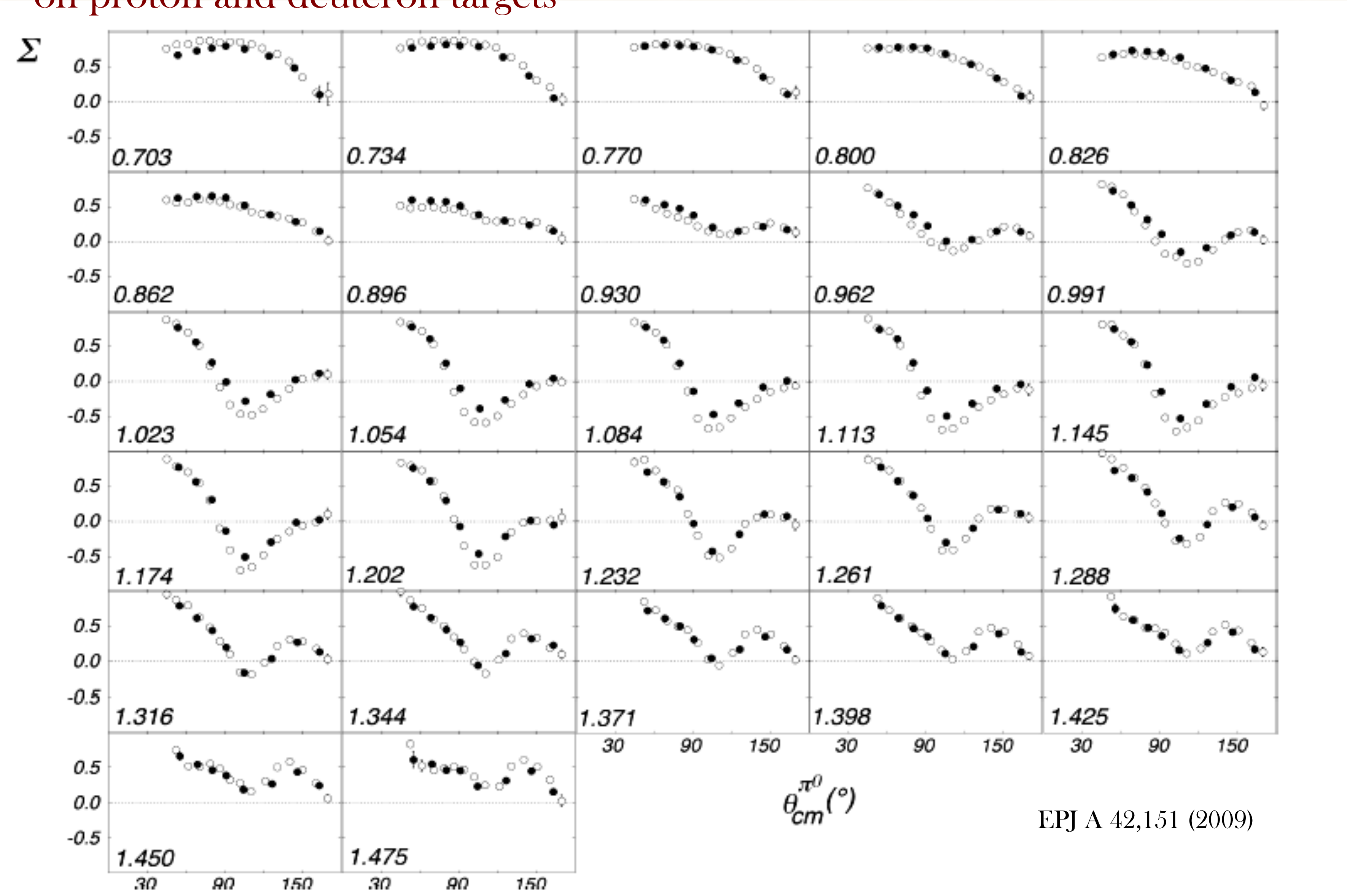
MAID 2007

SAID 2009

M. Dugger

Σ measurements at Graal on proton and deuteron targets

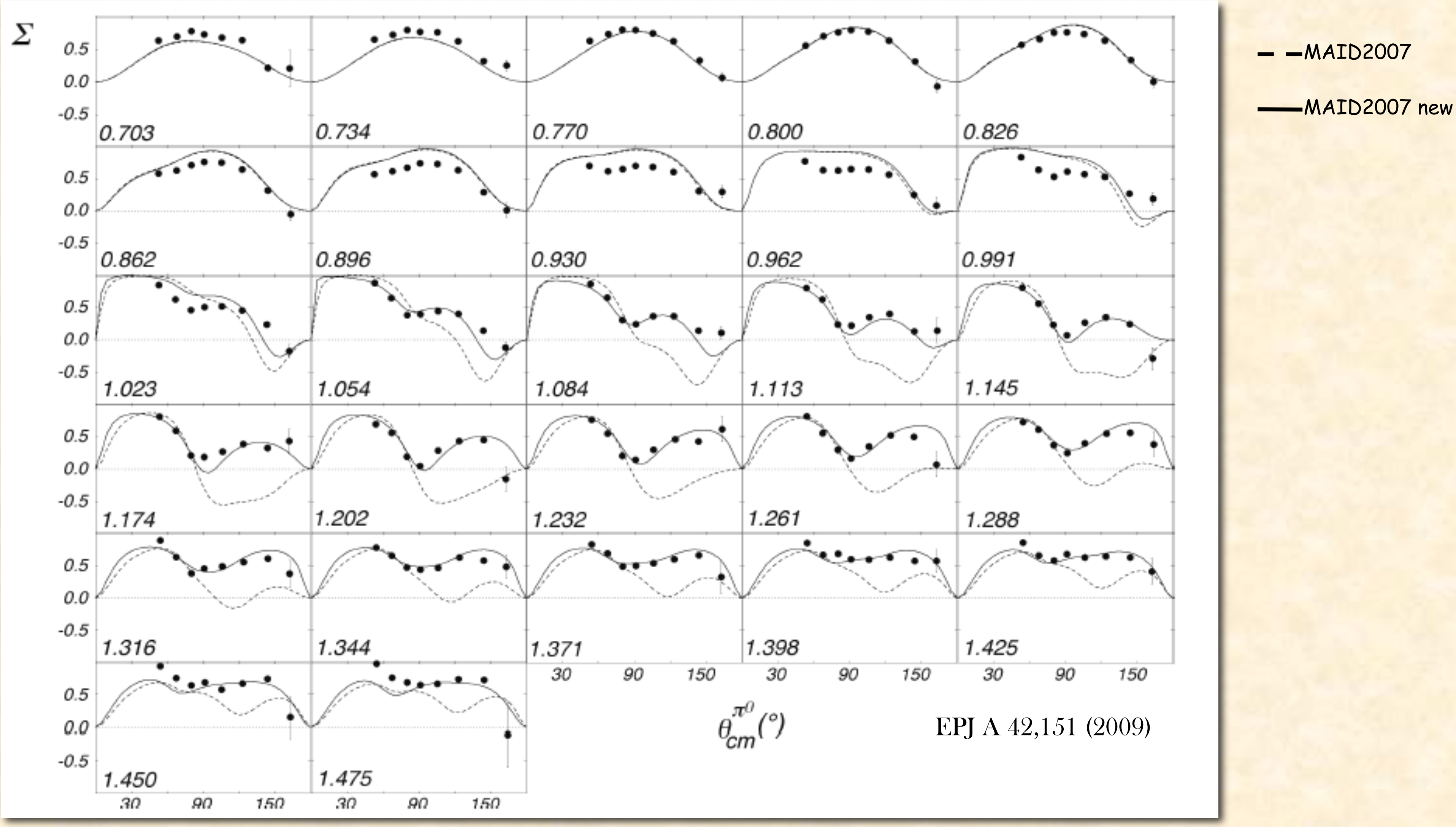
○ $\vec{\gamma}+p \rightarrow \pi^0+p$ ● $\vec{\gamma}+p\ (+n) \rightarrow \pi^0+p\ (+n)$



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

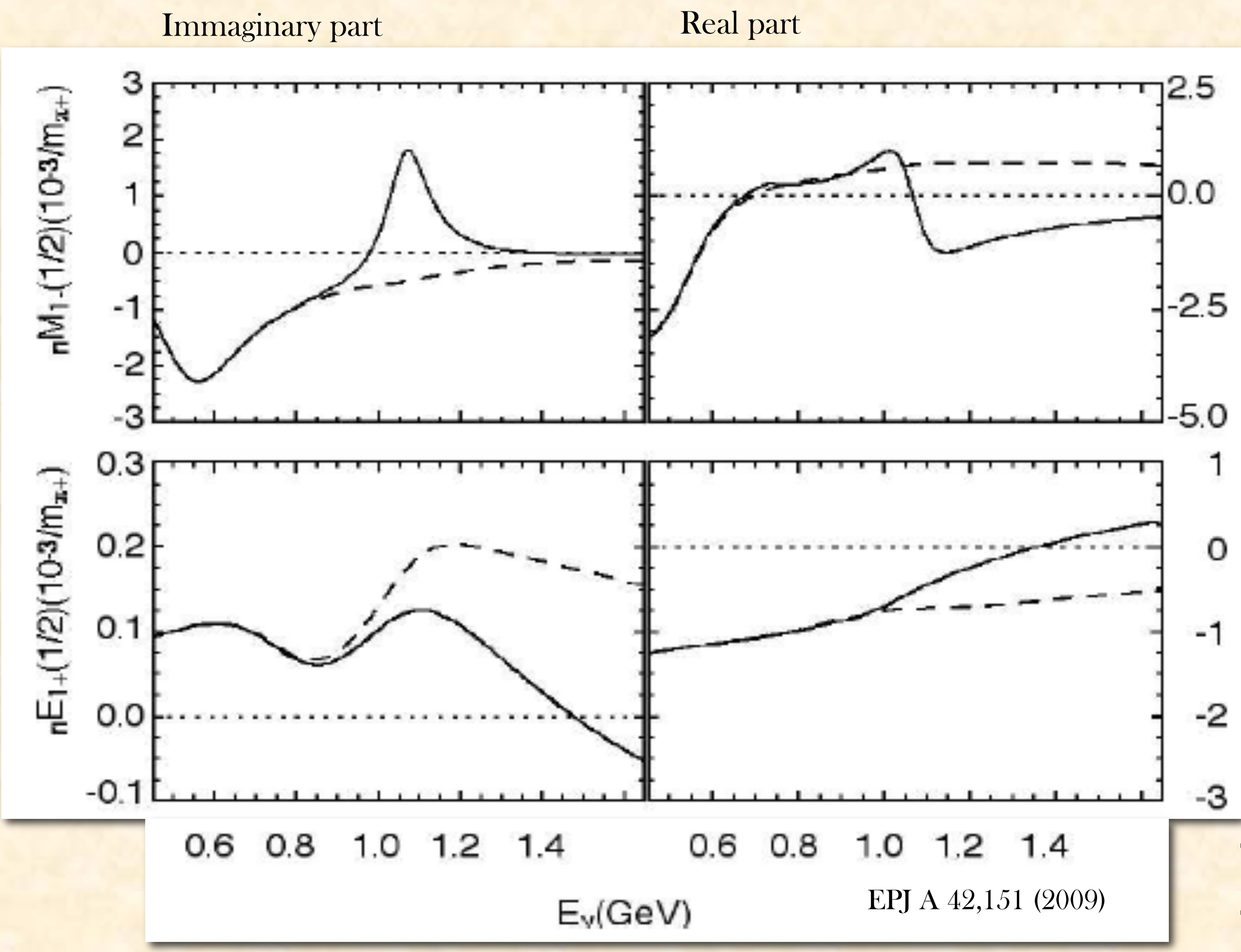
Σ measurements at GRAAL deuteron target

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



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

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



EPJ A 42,151 (2009)

Second $P_{11}(1700)$ resonance

$P_{11}(1700)$

$\Gamma_{tot} = 70\,MeV$

$\beta_\pi = 0.1$

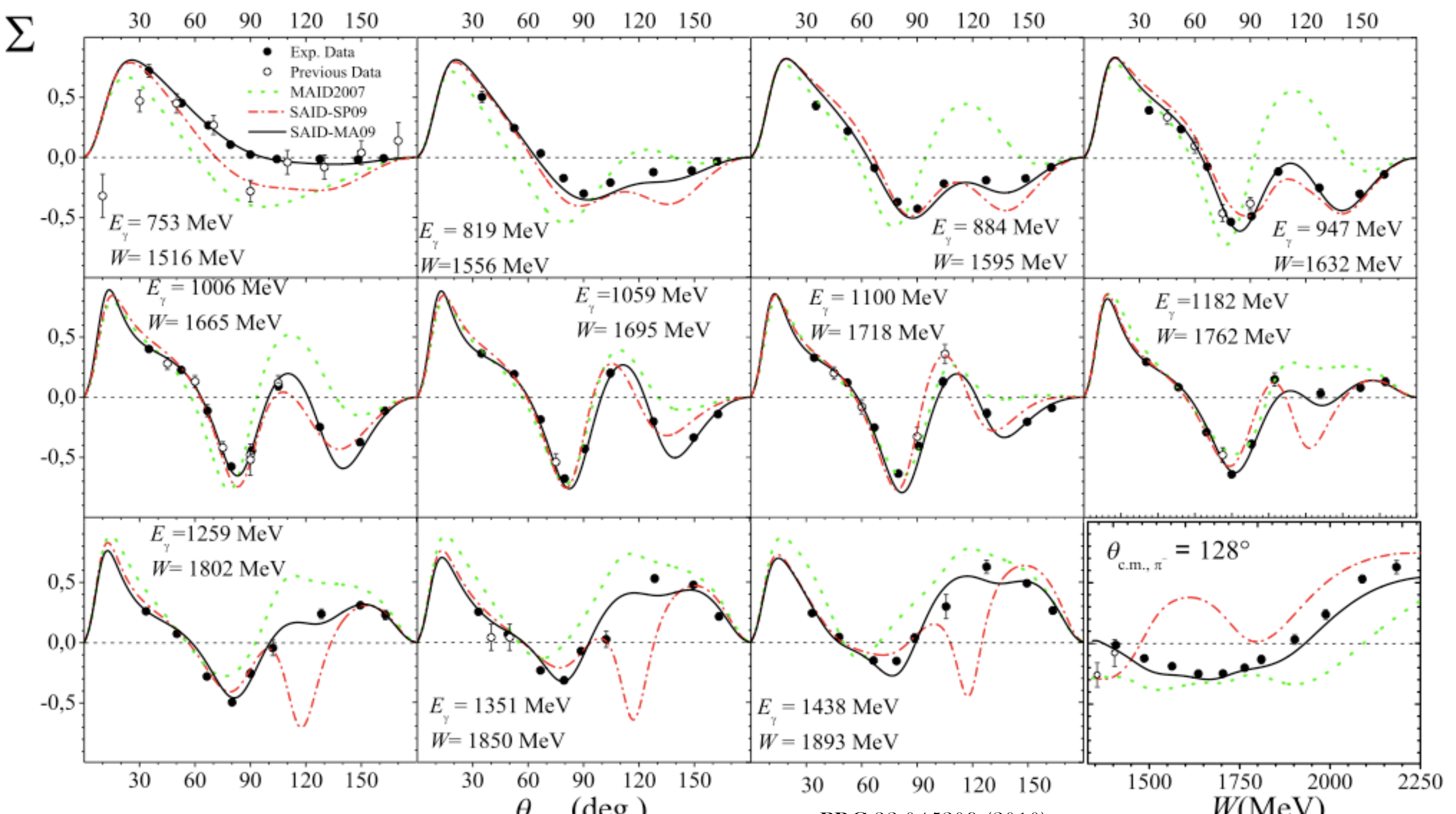
$P_{13}(1720)$

modified photo-couplings

- - - MAID2007 qfn

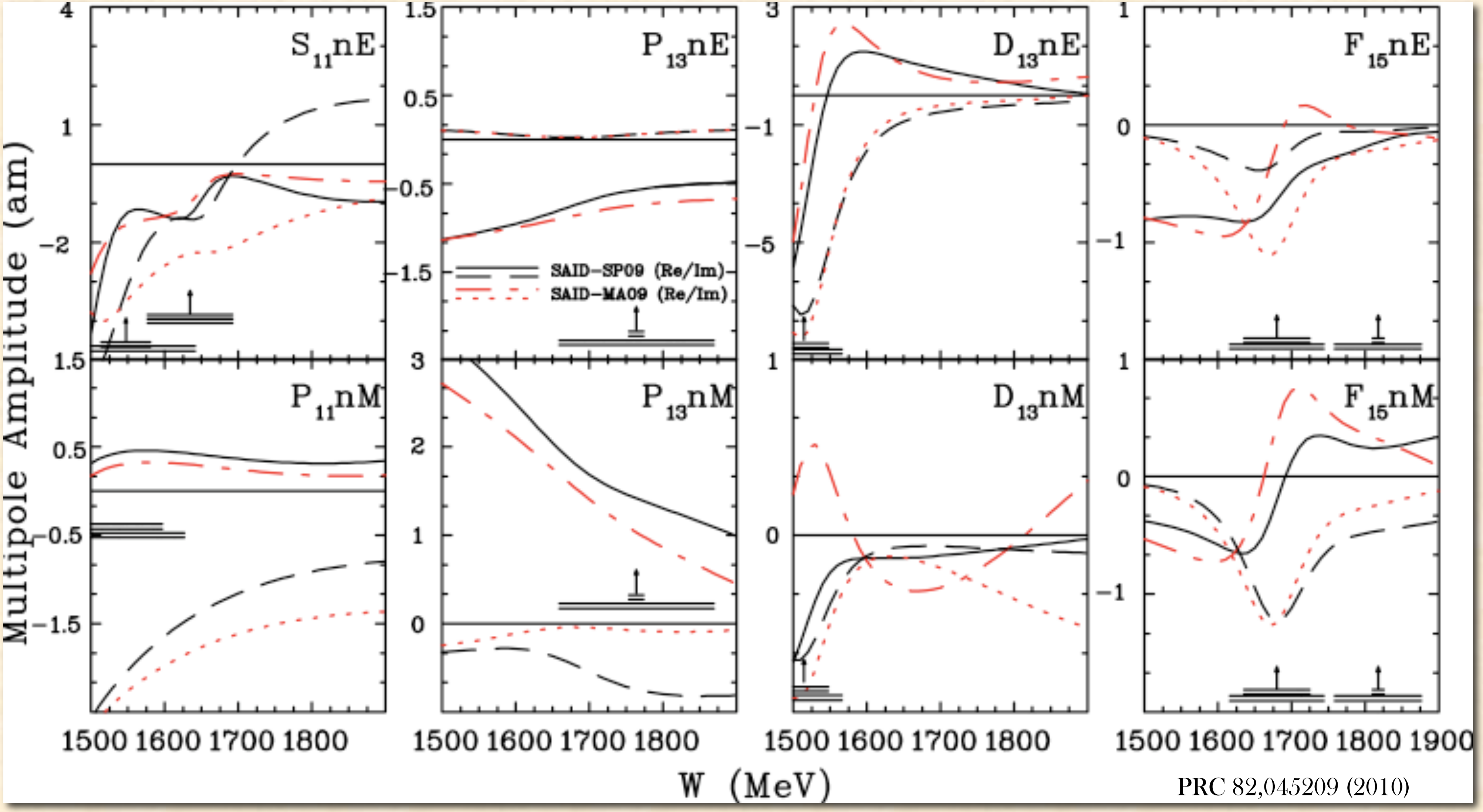
—— mod MAID2007 qfn

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



PRC 82,045209 (2010)

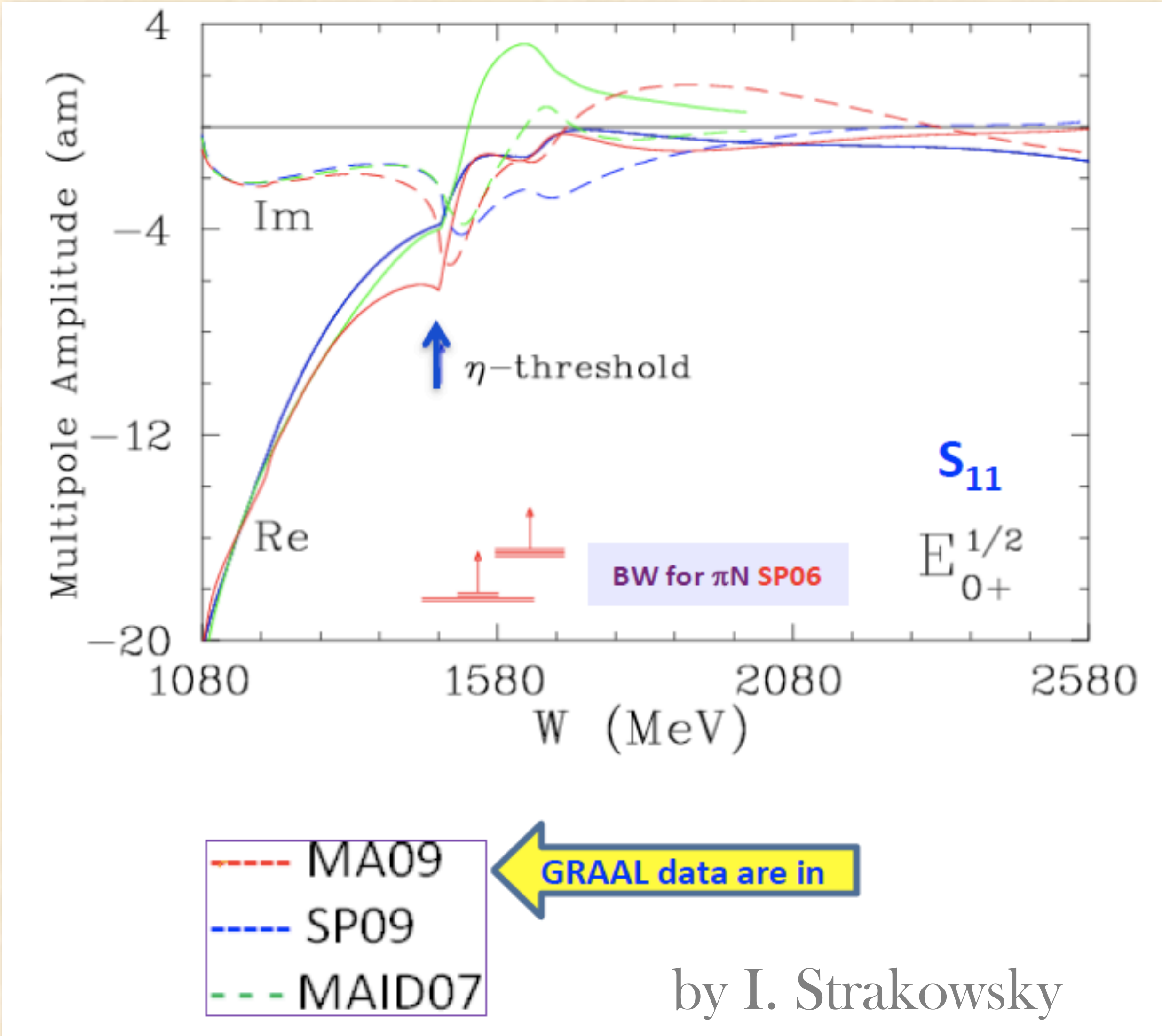
Multipole modifications due to Σ results on $\vec{\gamma} + n\ (+p) \rightarrow \pi^- + p\ (+p)$ at GRAAL



PRC 82,045209 (2010)

by I. Strakowsky

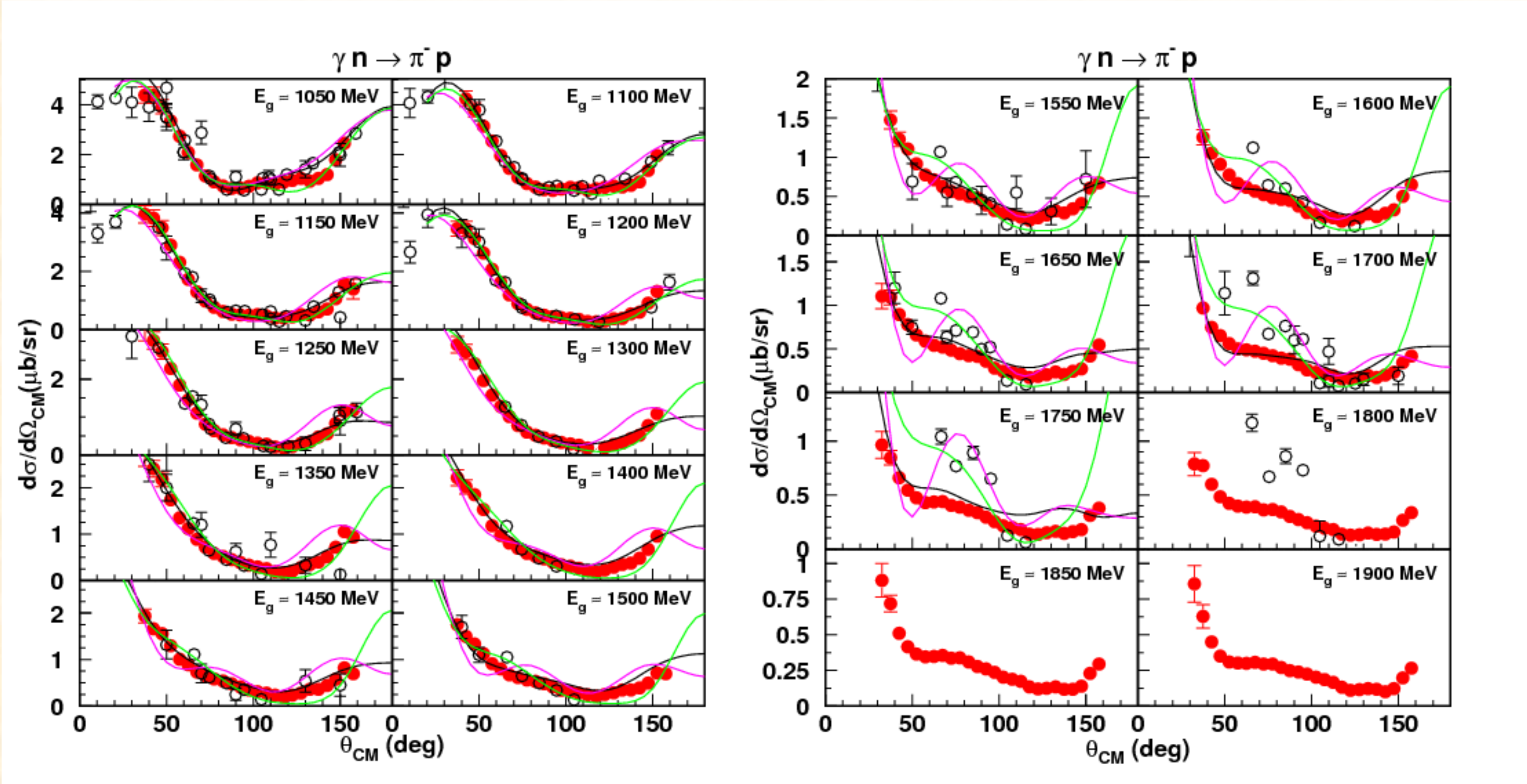
Multipole modifications due to Σ results on $\vec{\gamma} + n\ (+p) \rightarrow \pi^- + p\ (+p)$ at GRAAL



The η cusp is visible

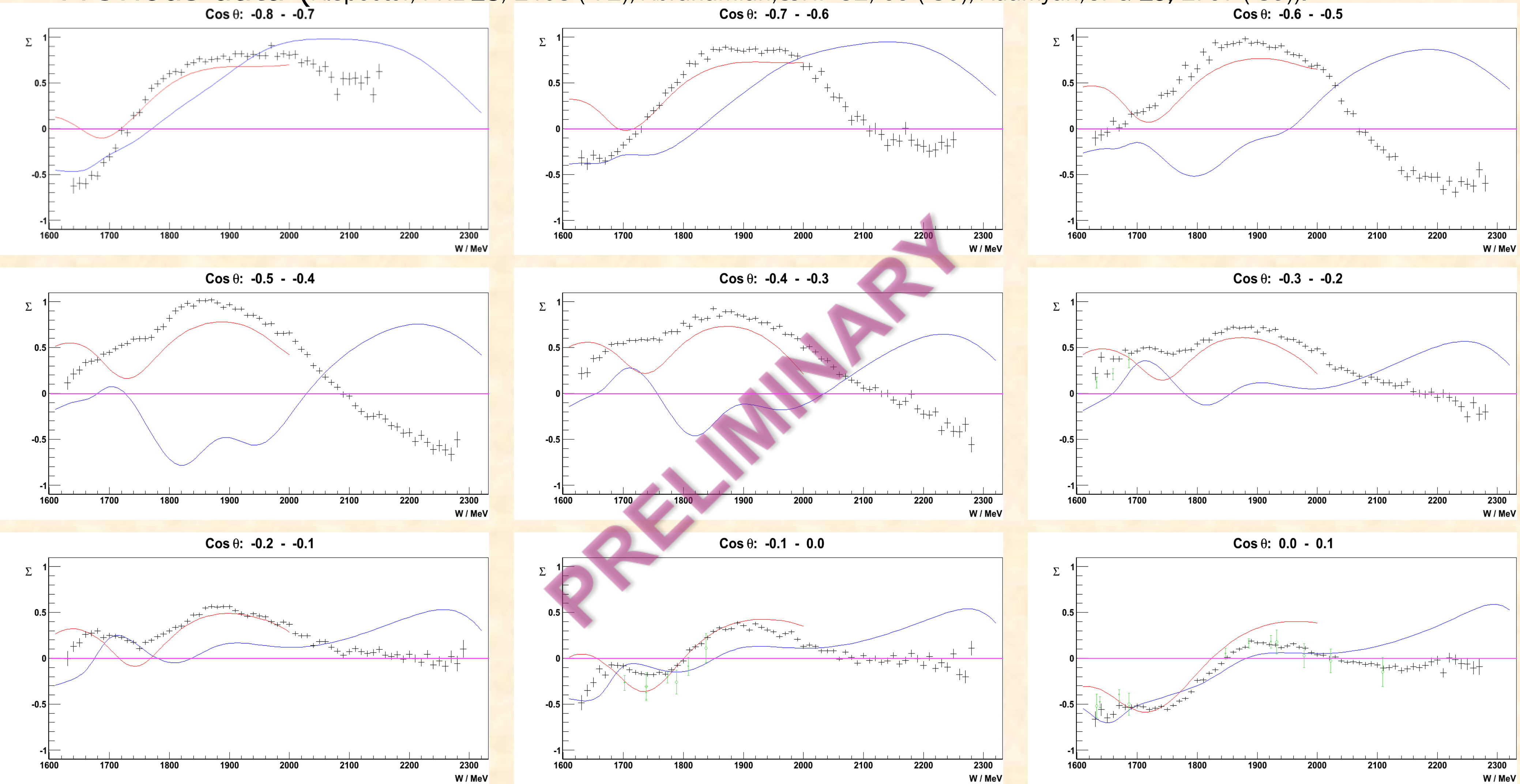
PRC 82,045209 (2010)

CLAS G10: $\gamma n \rightarrow \pi^- p$



CLAS Photon asymmetry Σ $\gamma n \to \pi^- p$

- Previous data (Alspector, PRL **28**, 1403 ('72), Abrahamian,SJNP 32, 69 ('80), Adamyan, JPG **15**, 1797 ('89)).

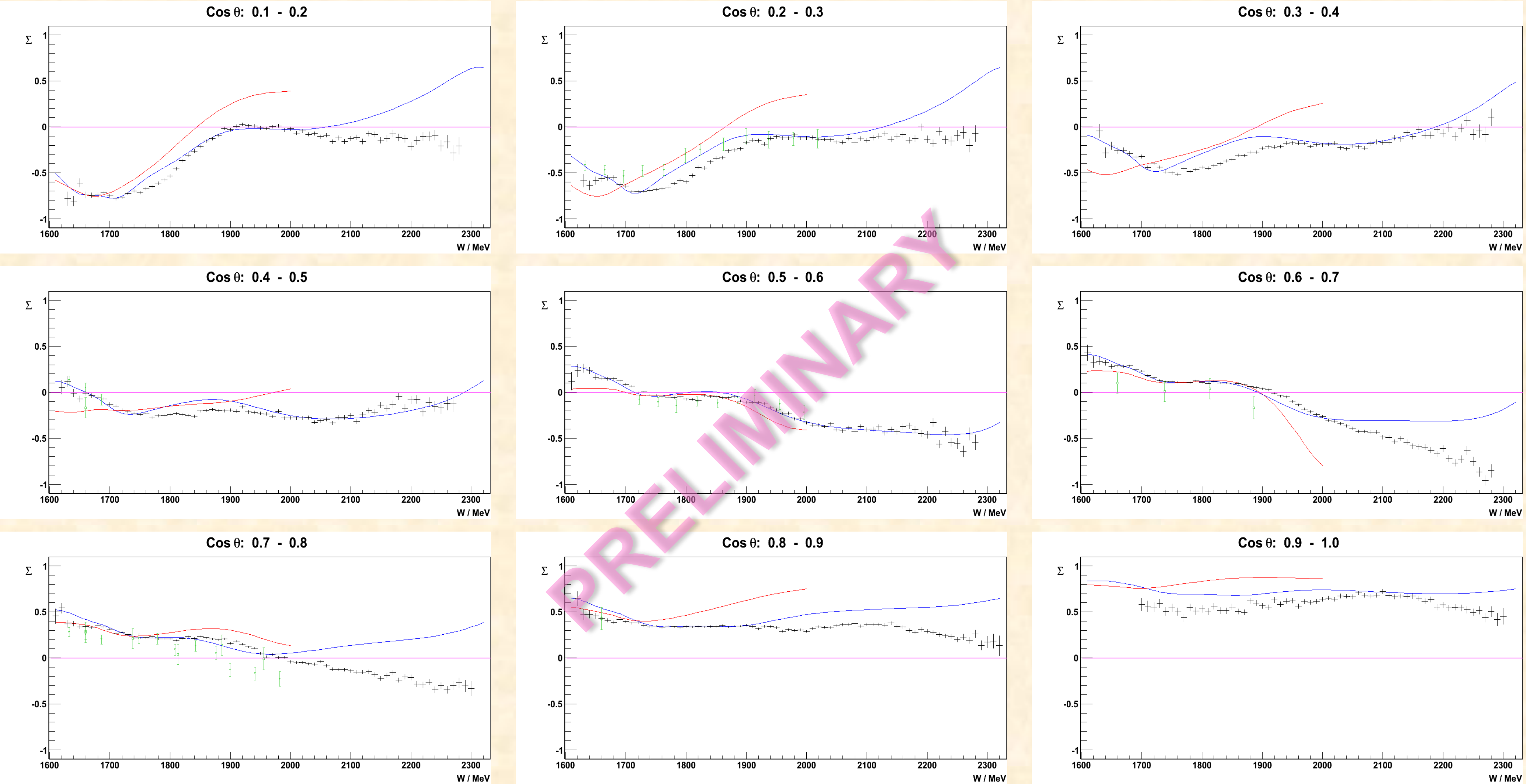


MAID 07 SAID 09

Daria Sokhan

CLAS Photon asymmetry $\gamma n \rightarrow \pi^- p$

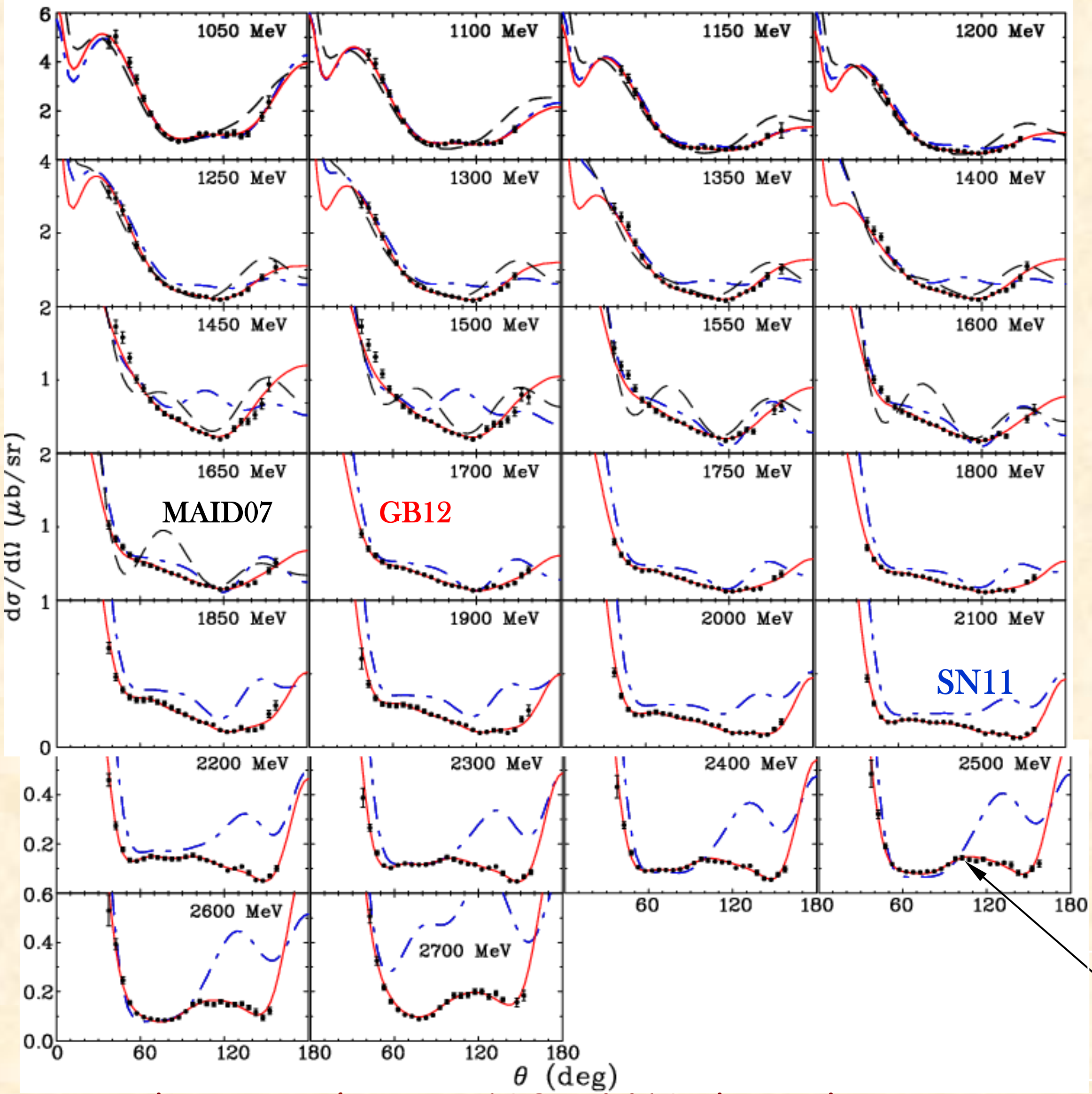
- Previous data (Alspector, PRL **28**, 1403 ('72), Abrahamian,SJNP 32, 69 ('80), Adamyan, JPG **15**, 1797 ('89)).



MAID 07 SAID 09

Daria Sokhan

$\gamma n \to \pi^- p$ from CLAS



W. Chen, *et al*, arXiv:1203.4412 [hep-ph]

Systematics:

Exp: 6-9%

FSI: 2-3%

χ^2/dp = 45636/626 = 72.9 [SN11 – no fit]

χ^2/dp = 1580/626 = 2.5 [GB12 – fit]

New SAID fit

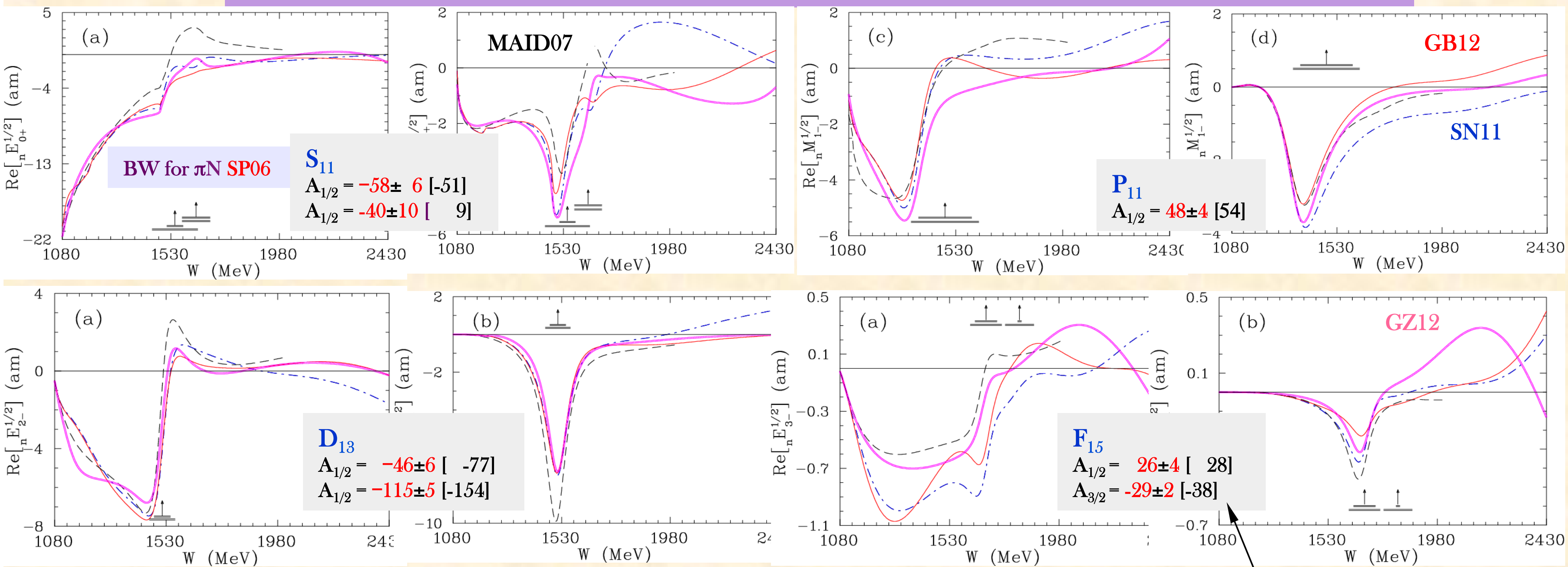
- CLAS data appear to have fewer angular structures than the earlier fits.

by I. Strakowsky

Neutron Multipoles from GB12

[W. Chen, *et al*, arXiv:1203.4412 [hep-ph]]

- Overall: the difference between MAID07 and SAID-GB12 is rather small but... Resonances may be essentially different



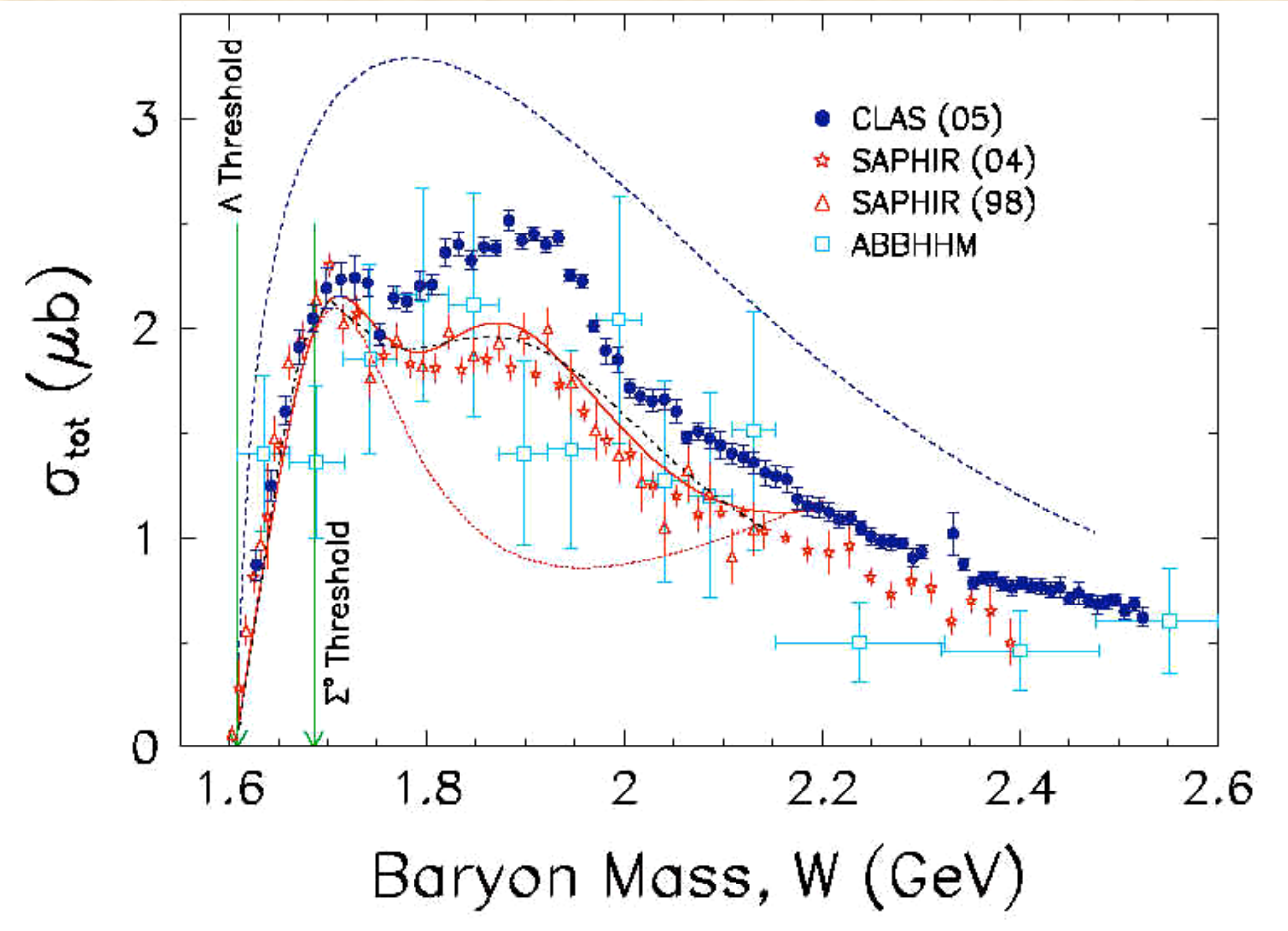
MAID07

- Significant changes have occurred at high energies
- Comparisons to earlier SAID fits and fit from the Mainz group show that the new GB12 solution is much more satisfactory at higher energies

MAID07: D. Drechsel, *et al,* Eur Phys J A 34, 69 (2007)

by I. Strakowsky

$\gamma + p \rightarrow K^+ + \Lambda$: Total Cross-Section



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 $+\Lambda$ channel.
S_{11} (1800) and P_{13} (1900) also seem to play a role

- "missing" $D_{13}(1895)$ (Mart&Bennhold)
- $P_{13}(1900)$ (Nikonov et al.)
- P_{11} (1900) (Ghent model)
- KKN bound state

Martinez Torres et al. arXiv:09023633[nucl-th]

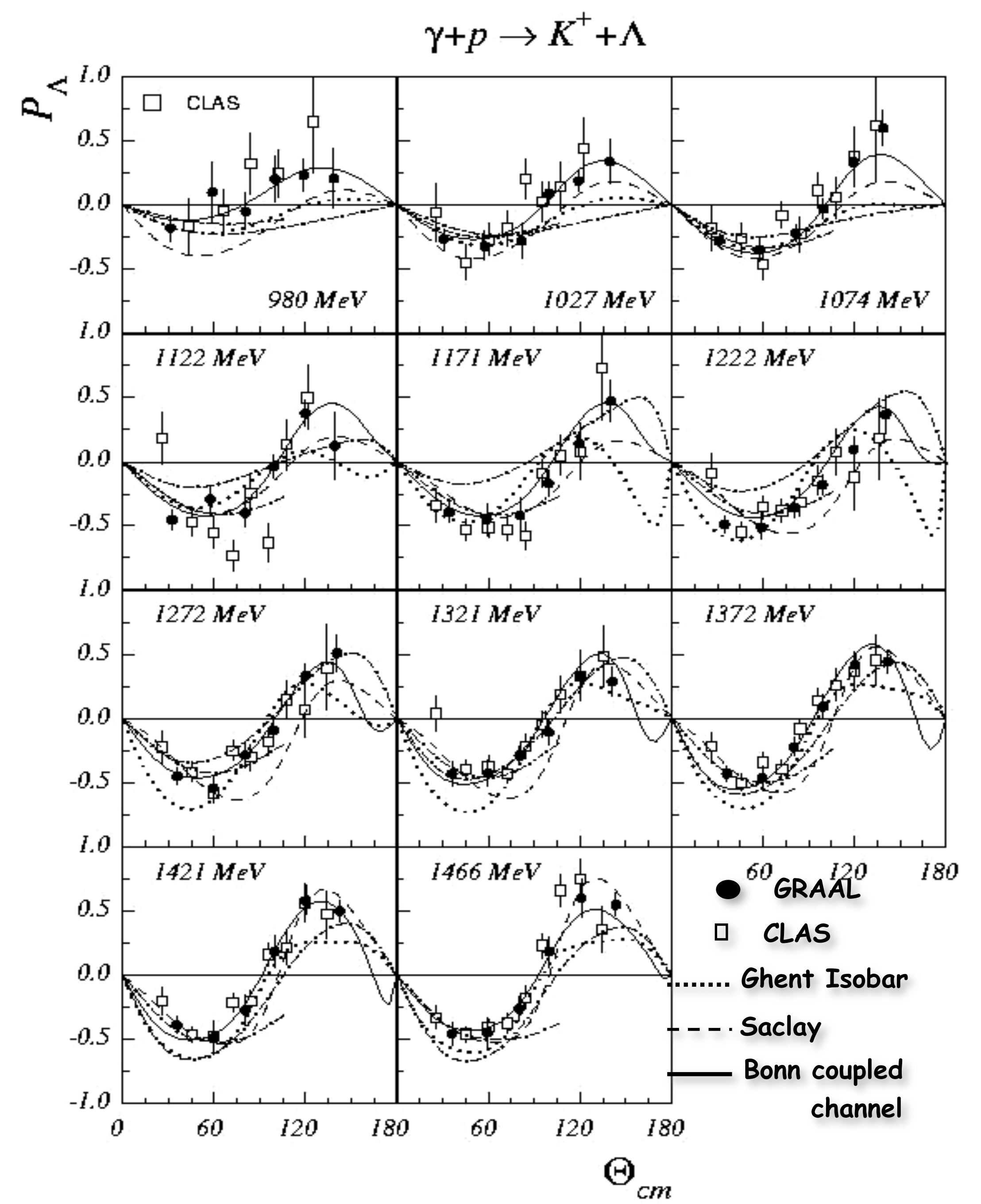
- - - - - Regge model calculation

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

——— KAON-Maid with $D_{13}(1895)$

— · — · · Saclay dynamical coupled channel

P_Λ in: $\gamma + p \rightarrow K^+ + \Lambda$ 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:

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

- Ghent Isobar Model:

  $D_{13}(1900)$

- Reggeized Model:

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

- Bonn Coupled Channel Model:

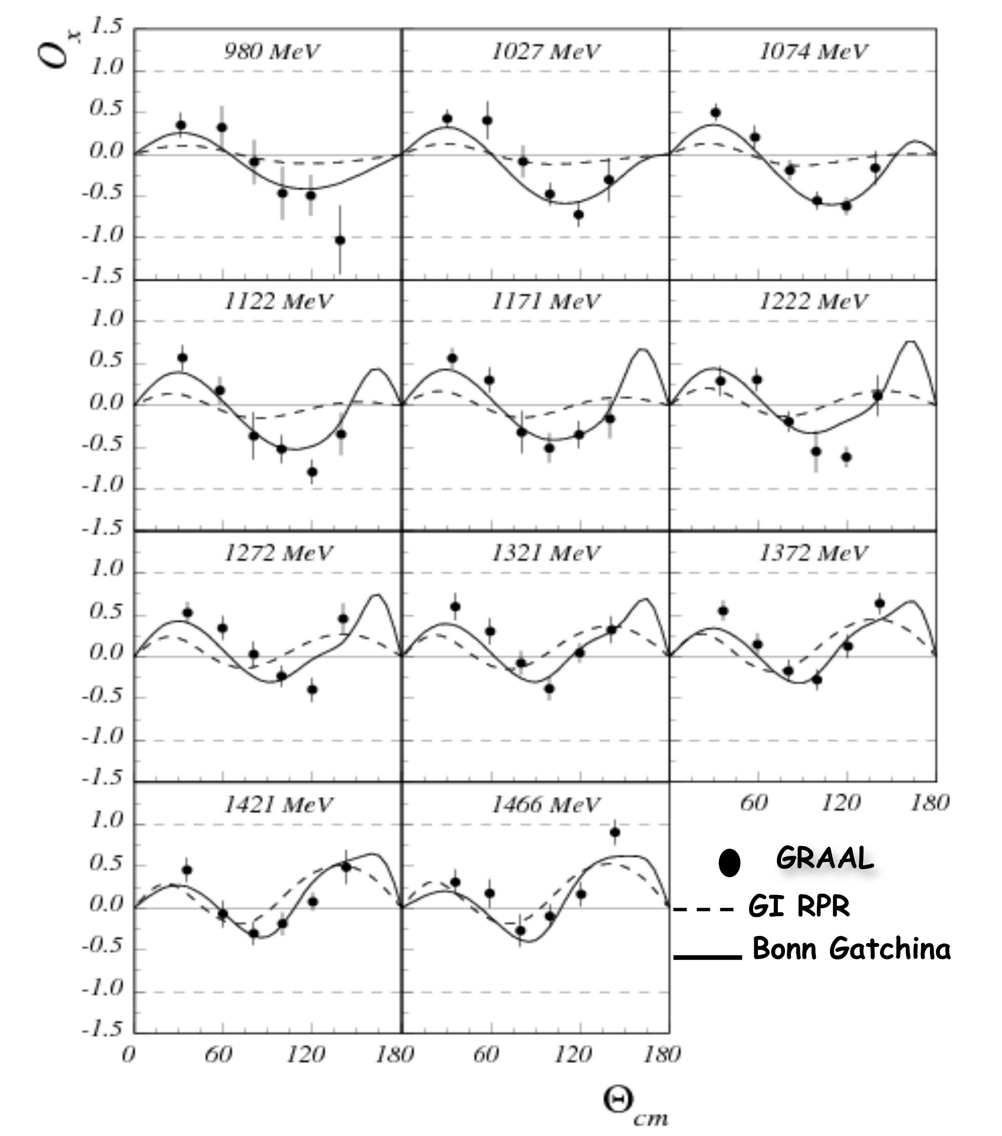
  $D_{13}(1875)$

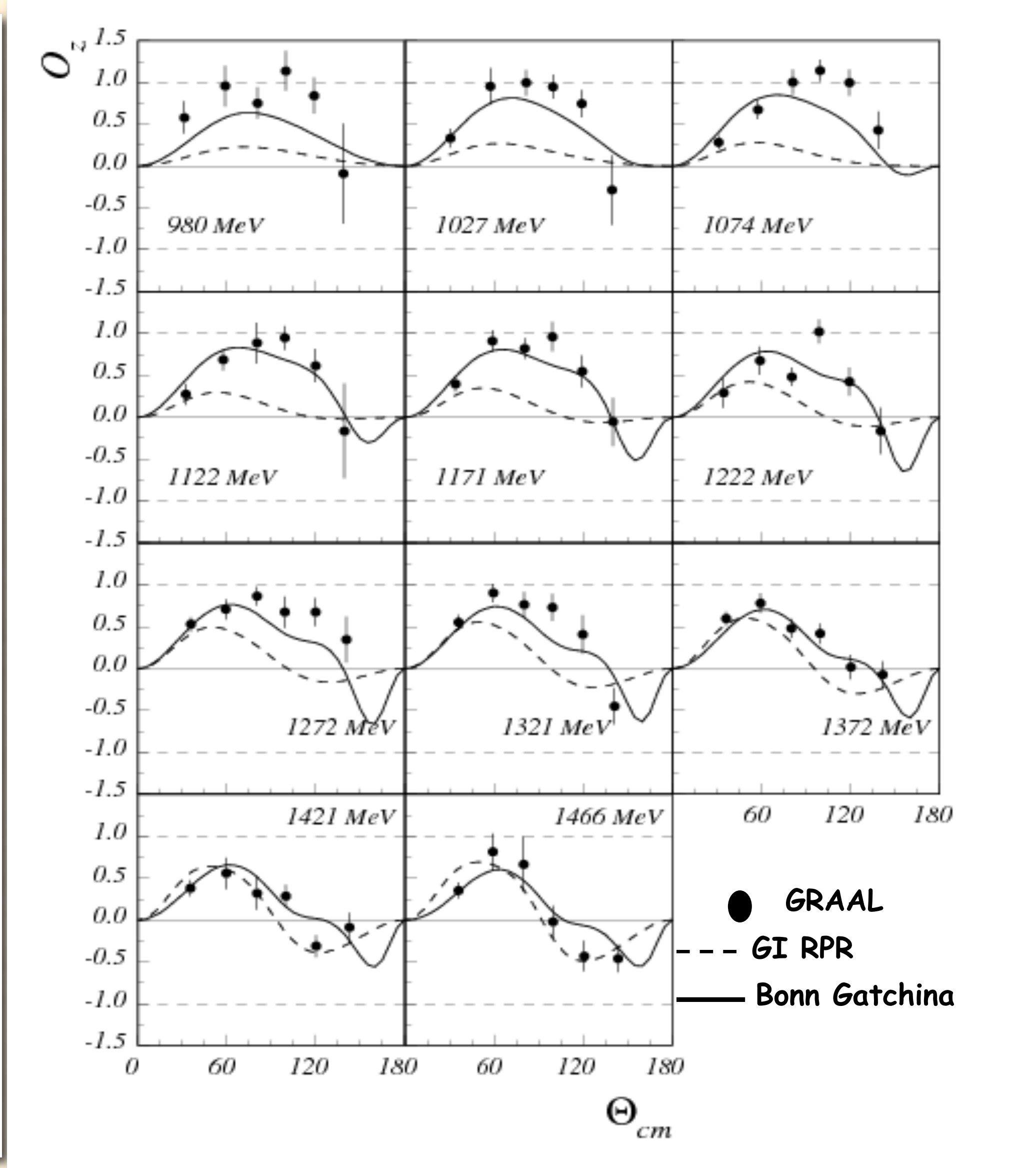
Double Polarization Observables in K+Λ Photoproduction

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

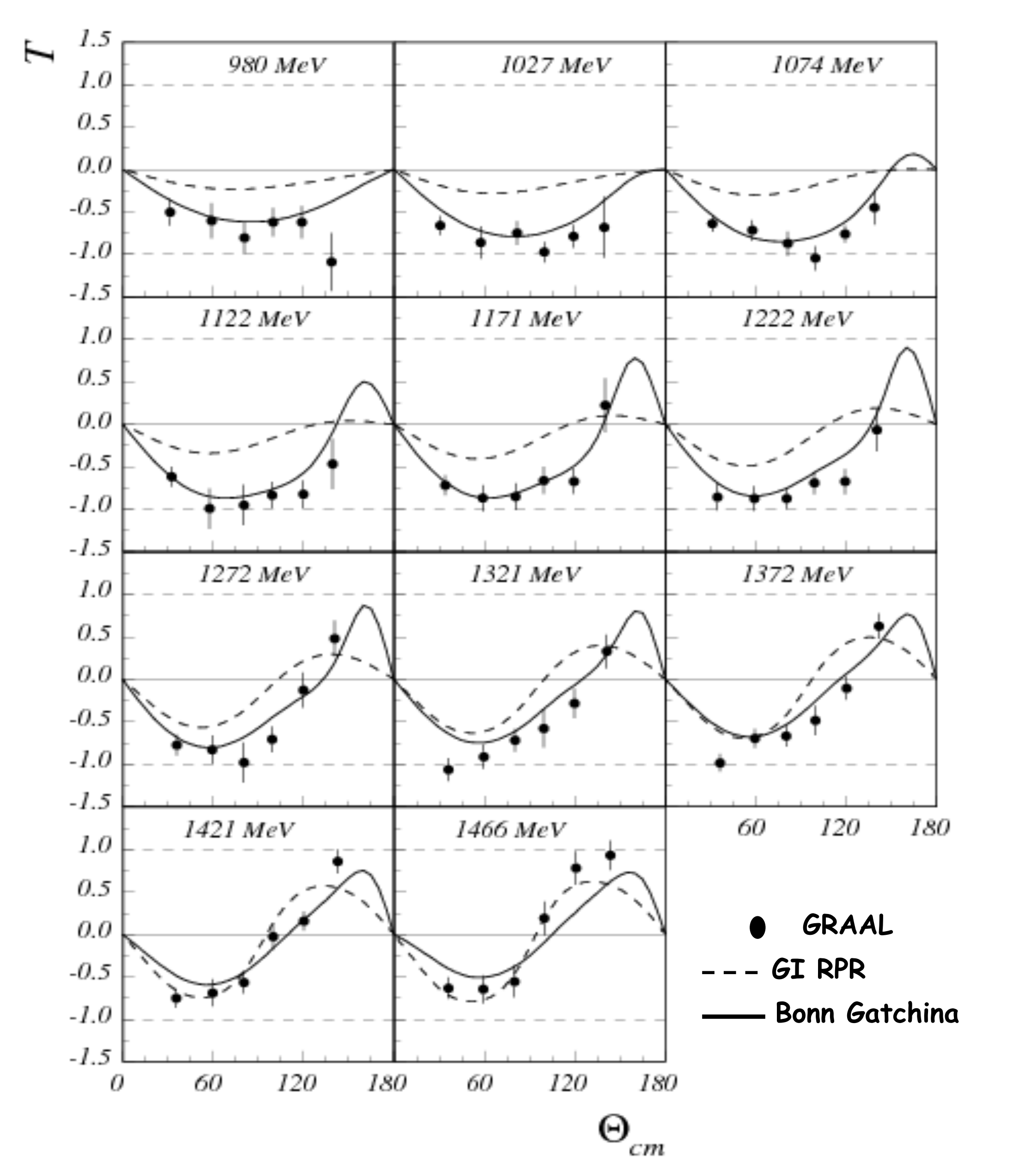
$$\frac{2N_+^{x'}}{N_+^{x'}+N_-^{x'}}=\left(1+\alpha\frac{2P_\gamma O_x}{\pi}\cos\theta_p^{x'}\right)$$

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





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:

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

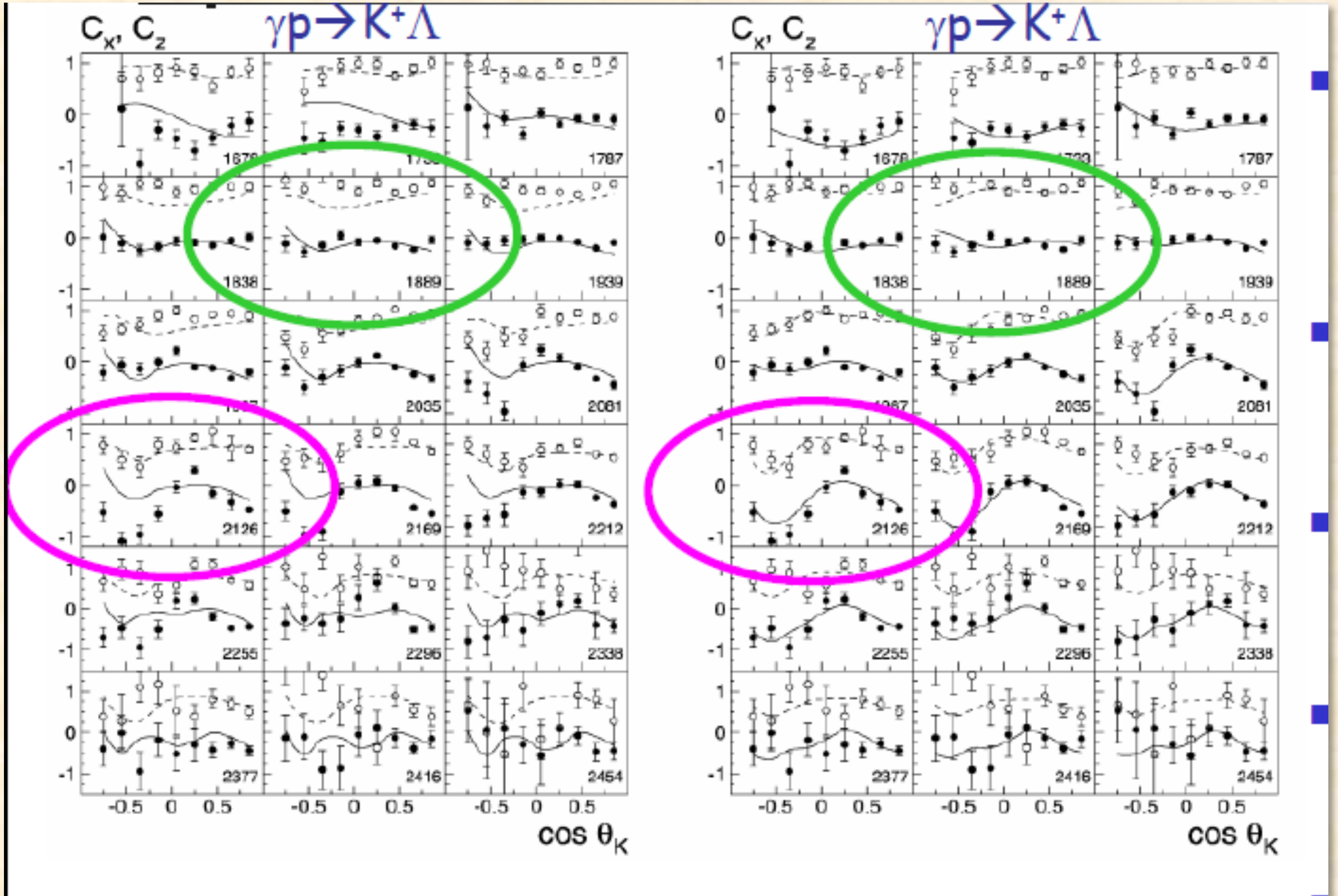
$P_{13}(1900)$ $D_{13}(1900)$

- Bonn Gatchina Model:

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

$P_{13}(1900)$

γp→K⁺Λ: Cx/Cz



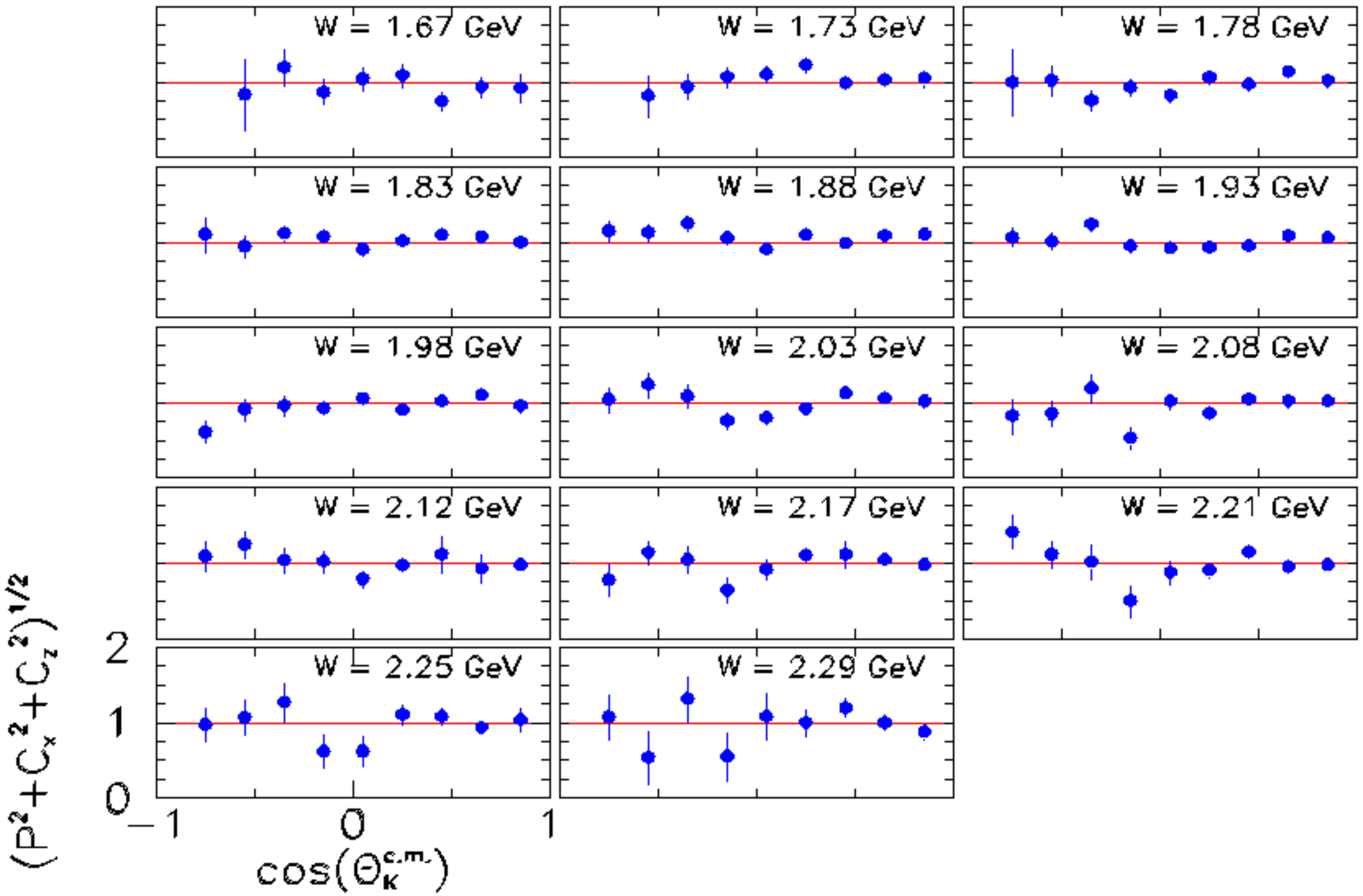
C_xC_z without N*(1900)P_{13} C_xC_z with N*(1900)P_{13}

- Nikonov *et al*'.'s refit of Bonn-Gachina multi-coupled-channel isobar model
- mix includes: S11 wave, P13(1720), P13(1900), P11(1840)
- $K^+\Sigma^0$cross sections also better described with P13(1900)
- Promote this "missing" resonance from ** to **** status.
- P13(1900) is found in qqq quark models, but not in quark-diquark models

Bradford et al.

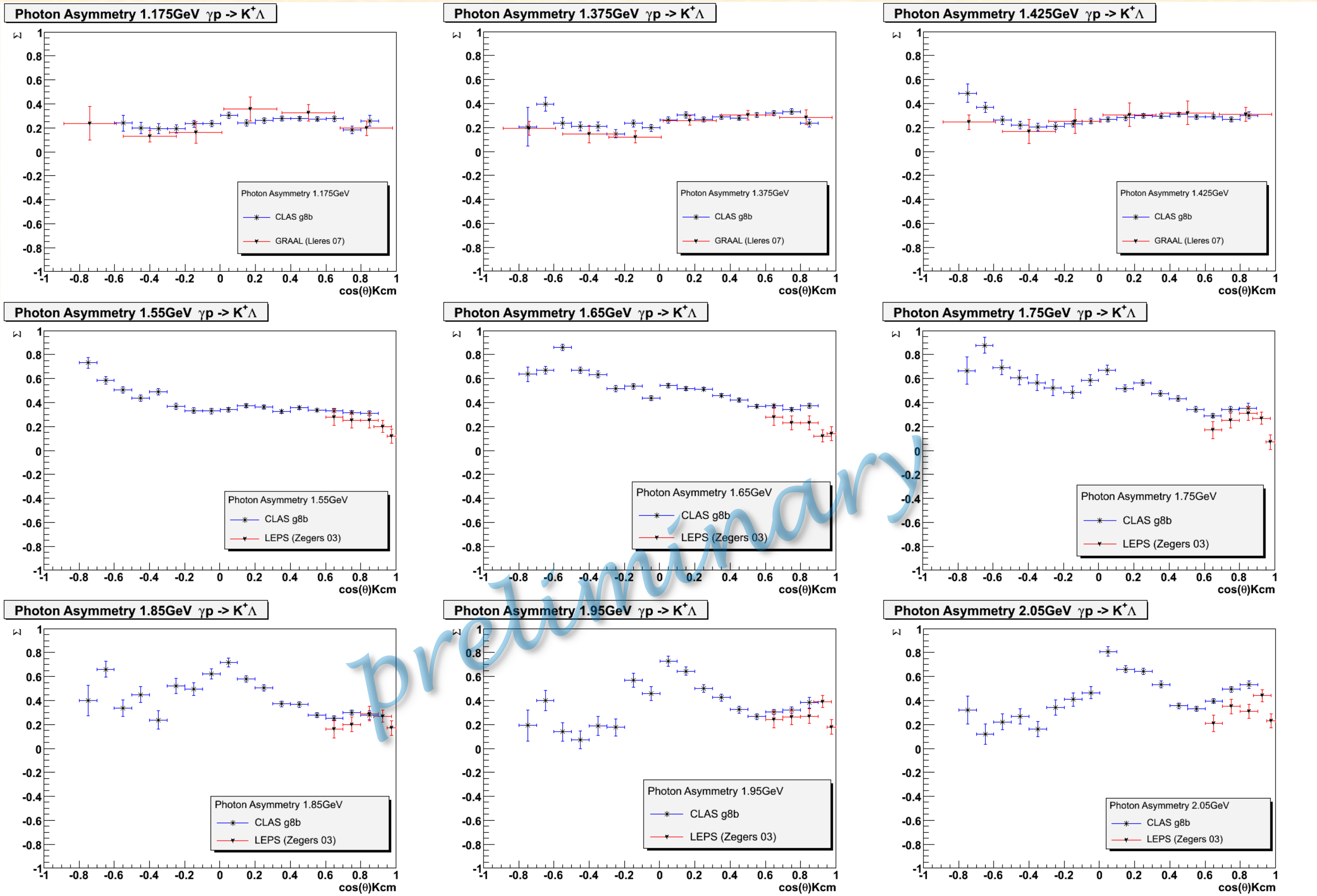
R Values for the Λ

$$R \equiv \sqrt{P^2 + C_x^2 + C_z^2}$$



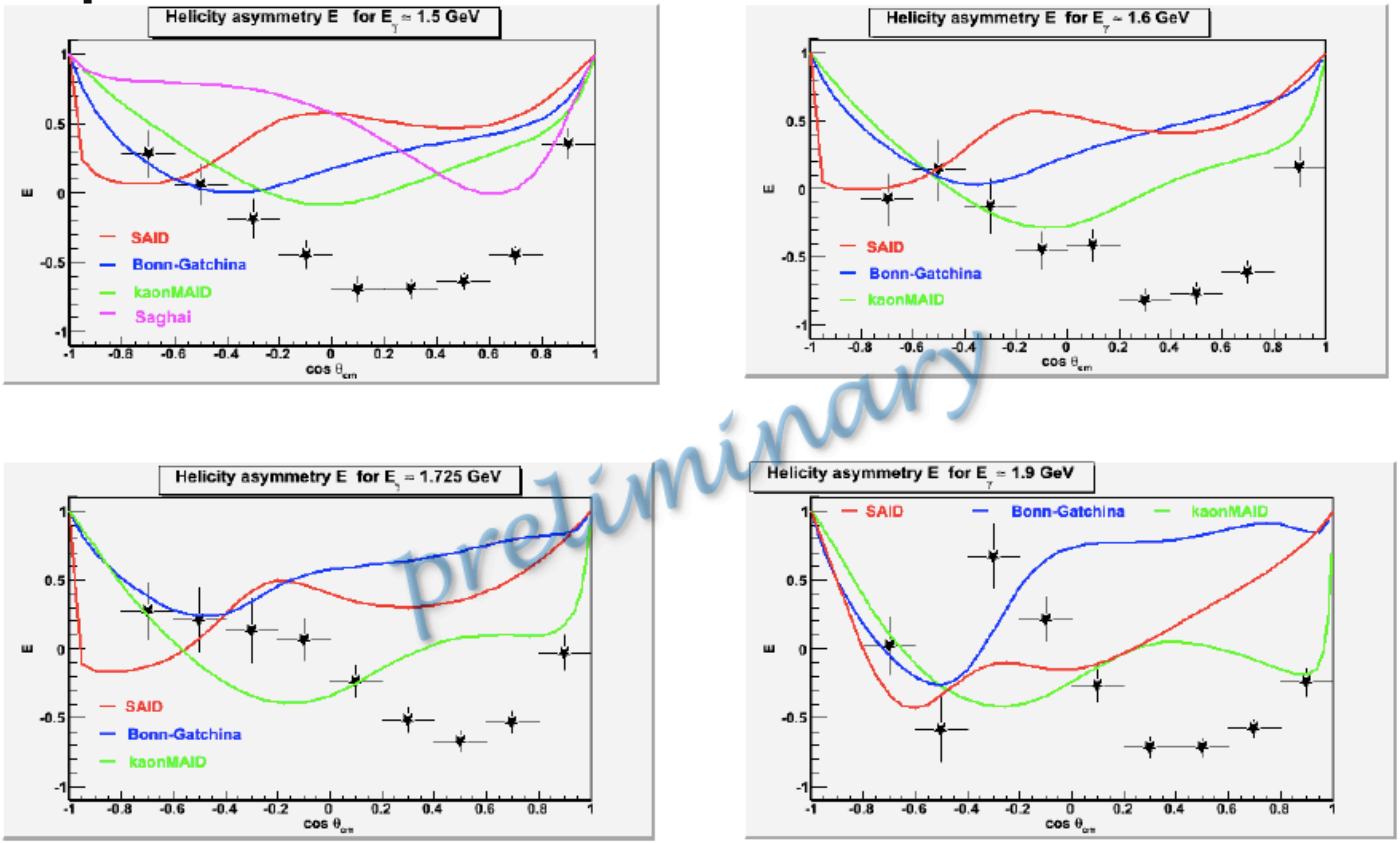
The Λ appears 100% polarized when created with a fully polarized beam.

$\gamma p \rightarrow K^+\Lambda$ Photon Asymmetry Σ



C. Patterson

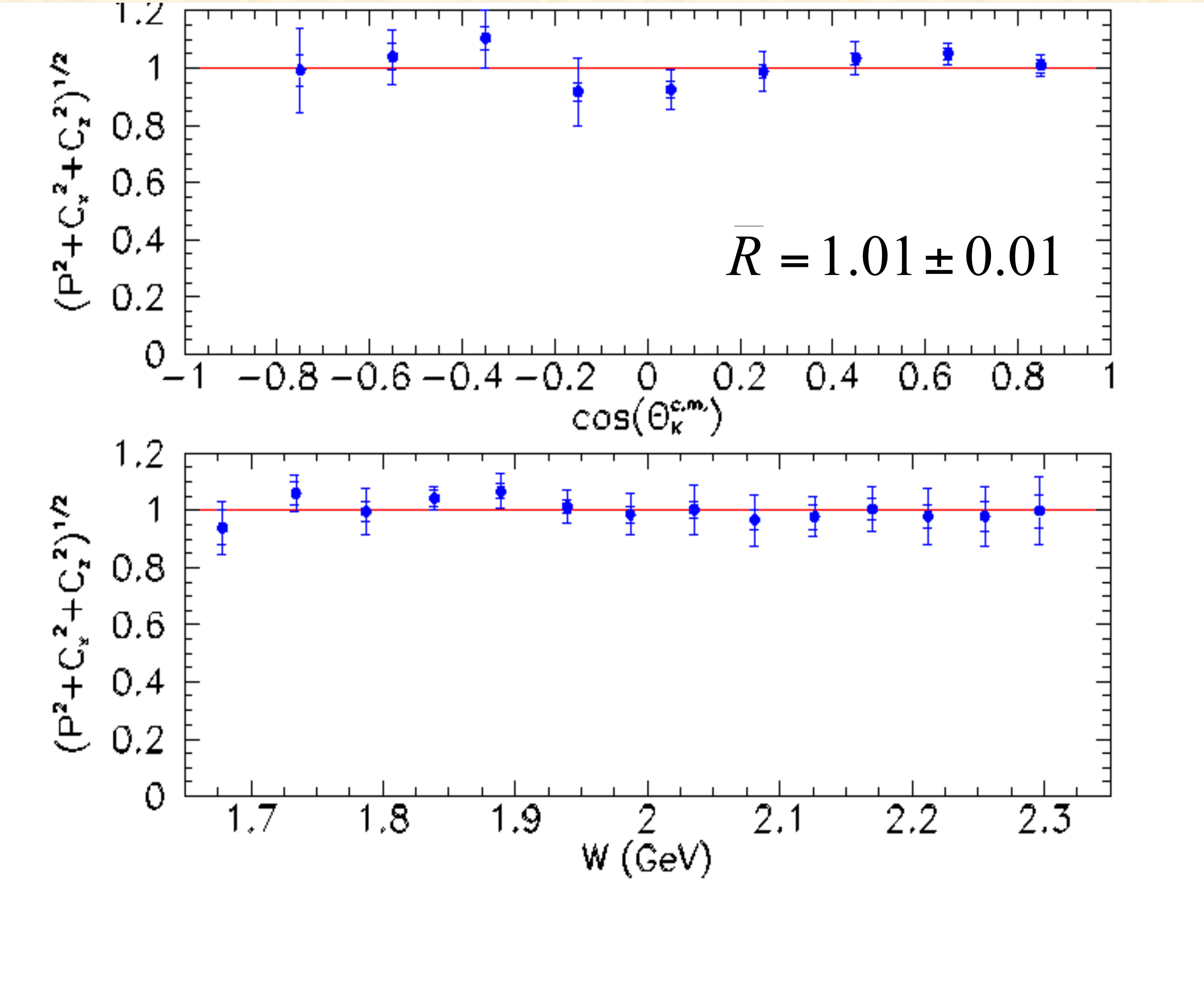
$K^+\Lambda$ Helicity Asymmetry E



R. A. Schumacher, Carnegie Mellon University, ECT*, 9-26-2011

L. Casey, Catholic U.

Average R values



- Energy and angle averages are consistent with unity.
- No model predicted this CLAS result.

New results from PDG

J. Beringer et al. (Particle Data Group), Phys. Rev. D86, 010001 (2012).

Resonance	Rating	N_{pp}	Resonance	Rating	N_{pp}	Resonance	Rating	N_{pp}
$N(1440)1/2^+$	****	13	$N(1520)3/2^-$	****	17	$N(1535)1/2^-$	****	15
$N(1650)1/2^-$	****	18	$N(1675)5/2^-$	****	14	$N(1680)5/2^+$	****	17
$N(1685)$	*		$N(1700)3/2^-$	***	15	$N(1710)1/2^+$	***	14
$N(1720)3/2^+$	****	17	$N(1860)5/2^+$	**	9	$N(1875)3/2^-$	***	16
$N(1880)1/2^+$	**	20	$N(1895)1/2^-$	**	17	$N(1900)3/2^+$	***	18
$N(1990)7/2^+$	**	9	$N(2000)5/2^+$	**	11	$N(2040)3/2^+$	*	
$N(2060)5/2^-$	**	13	$N(2100)1/2^+$	*		$N(2150)3/2^-$	**	11
$N(2190)7/2^-$	****	11	$N(2220)7/2^-$	****	7	$N(2250)9/2^-$	****	
$N(2600)11/2^-$	***		$N(2700)13/2^+$	**				
$\Delta(1232)$	****	8	$\Delta(1600)3/2^+$	***	12	$\Delta(1620)1/2^-$	****	10
$\Delta(1700)3/2^-$	****	11	$\Delta(1750)1/2^+$	*		$\Delta(1900)1/2^-$	**	13
$\Delta(1905)5/2^+$	****	11	$\Delta(1910)1/2^+$	****	13	$\Delta(1920)3/2^+$	***	21
$\Delta(1930)5/2^-$	***		$\Delta(1940)3/2^-$	*	5	$\Delta(1950)7/2^+$	****	13
$\Delta(2000)5/2^+$	**		$\Delta(2150)1/2^-$	*		$\Delta(2200)7/2^-$	*	
$\Delta(2300)9/2^+$	**		$\Delta(2350)3/2^-$	*		$\Delta(2390)7/2^+$	*	
$\Delta(2420)11/2^+$	****		$\Delta(2400)9/2^-$	****		$\Delta(2750)13/2^-$	**	
$\Delta(2950)15/2^+$	**							

E.g.: V. Kuznetsov et al., Phys. Lett. B 647, 23 (2007); V. Kuznetsov et al., Phys. Rev. C 83, 022201 (2011); I. Jaegle et al., Eur. Phys. J. A 47, 89 (2011).
M. Ablikim et al. [BES Collaboration], Phys. Rev. D 80, 052004 (2009).

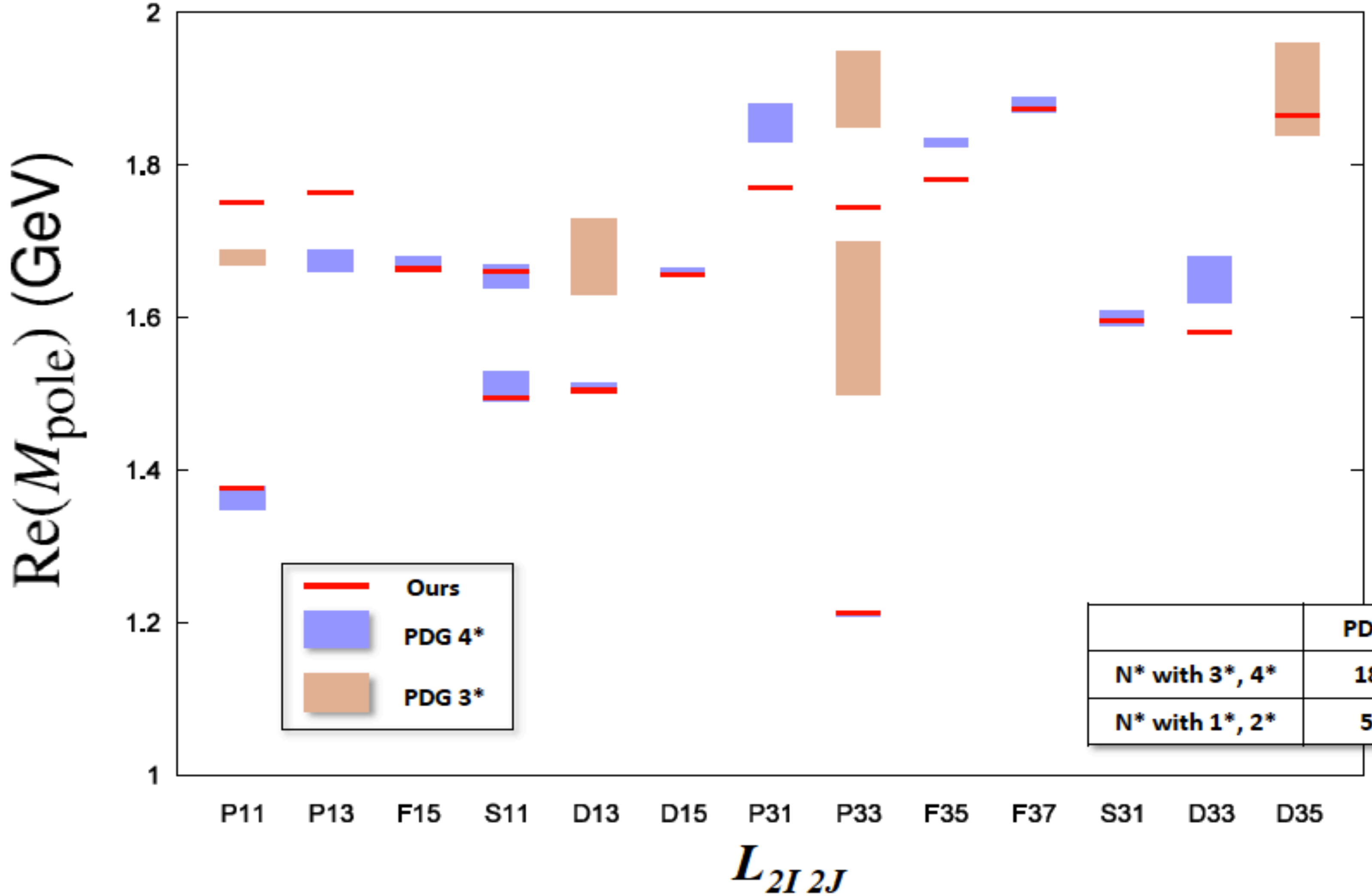
A. V. Anisovich, R. Beck, E. Klempt, V. A. Nikonov, A. V. Sarantsev and U. Thoma, Eur. Phys. J. A 48, 15 (2012); BonnGa

Spectrum of N* resonances

Kamano, Nakamura, Lee, Sato ,2012

EBAC

Real parts of N* pole values



	PDG	Ours
N* with 3*, 4*	18	16
N* with 1*, 2*	5	

	σ	Σ	T	P	E	F	G	H	T_x	T_z	L_x	L_z	O_x	O_z	C_x	C_z
Proton target																
$p\pi^0$	✔ (red)	✔ (green)	✔ (green)		✔ (green)	✔ (green)	✔ (green)	✔ (green)								
$n\pi^+$	✔ (red)	✔ (green)	✔ (green)		✔ (green)	✔ (green)	✔ (green)	✔ (green)								
$p\eta$	✔ (red)	✔ (green)	✔ (green)		✔ (green)	✔ (green)	✔ (green)	✔ (green)								
$p\eta'$	✔ (red)	✔ (green)	✔ (green)		✔ (green)	✔ (green)	✔ (green)	✔ (green)								
$p\omega$	✔ (red)	✔ (green)	✔ (green)		✔ (green)	✔ (green)	✔ (green)	✔ (green)								
$K^+\Lambda$	✔ (red)	✔ (green)	✔ (green)	✔ (red)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (red)	✔ (red)
$K^+\Sigma^0$	✔ (red)	✔ (green)	✔ (green)	✔ (red)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (red)	✔ (red)
$K^{0*}\Sigma^+$	✔ (red)	✔ (green)									✔ (green)	✔ (green)				
Neutron target																
$p\pi^-$	✔ (red)	✔ (green)	✔ (green)		✔ (green)	✔ (green)	✔ (green)	✔ (green)								
$p\rho^-$	✔ (green)	✔ (green)	✔ (green)		✔ (green)	✔ (green)	✔ (green)	✔ (green)								
$K^-\Sigma^+$	✔ (red)	✔ (green)	✔ (green)		✔ (green)	✔ (green)	✔ (green)	✔ (green)								
$K^0\Lambda$	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)
$K^0\Sigma^0$	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)
$K^{0*}\Sigma^0$	✔ (green)	✔ (green)														

✔ (red) - published, ✔ (green) - acquired, ✔ (blue) - planned

Conclusions

- For the first time a "complete experiment" has been performed for pseudoscalar meson photoproduction both on the proton and the neutron.

- For the first time the role of photoreaction data as been recognized by the PDG to impact the existing evidence of Nstar resonances, which seem to rule out di-quark models.

- For the first time EBAC had produced its own baryon spectrum.

I would like to thank the CLAS collaboration for letting me present preliminary data and Eugene Pasyuk for providing and letting me use his slides.

Backup slides

η' photoproduction at CLAS

1968: 11 events from the ABBHHM bubble chamber experiment

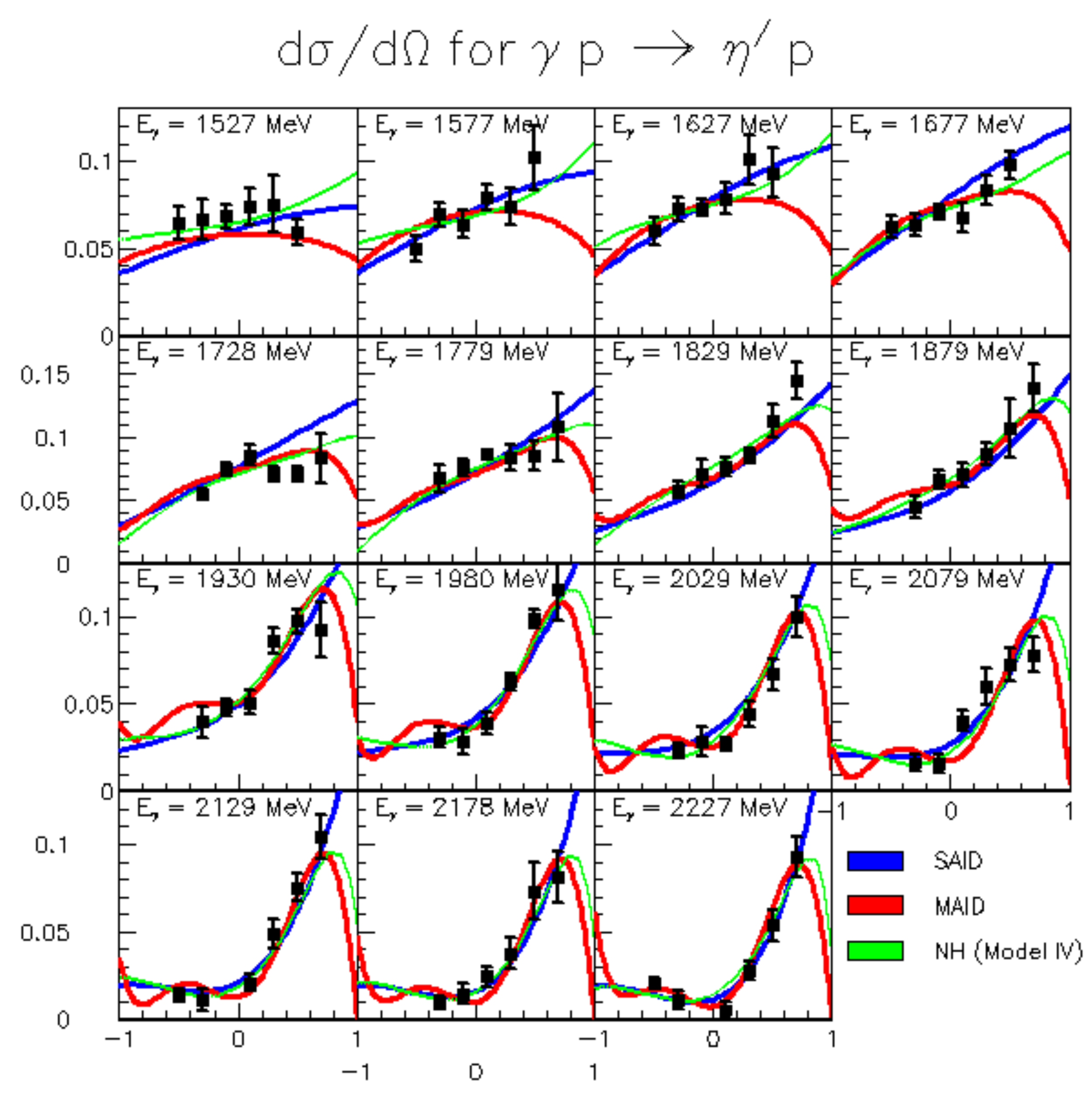
1976: 7 events from the AHHM streamer chamber experiment

1998: 250 events from the SAPHIR collaboration (first differential cross sections)

2006: over 2×10^5 events from the CLAS collaboration

2009: another few orders of magnitude from CLAS g11 data set

$\gamma p \rightarrow \eta' p$



- First CLAS data

SAID

MAID

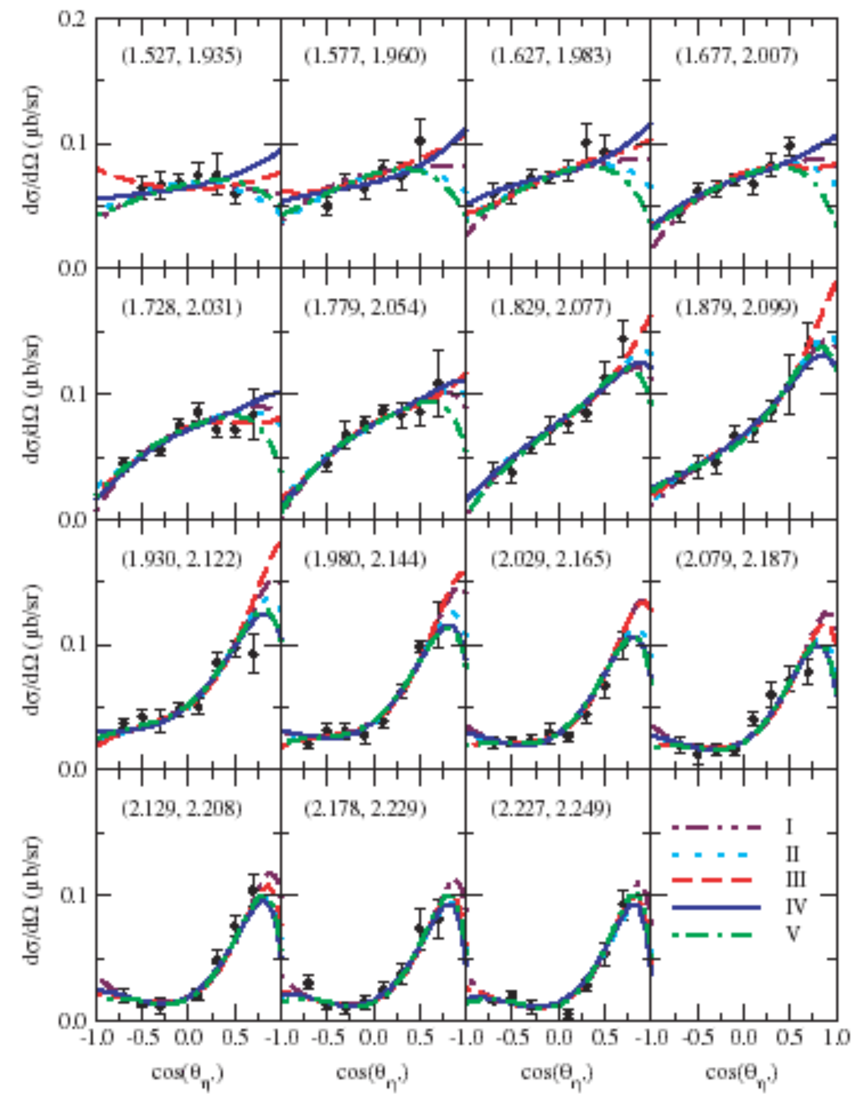
NH (K.Nakayama and H. Haberzettl)

M. Dagger et al. PRL **96**, 062001 (2006)

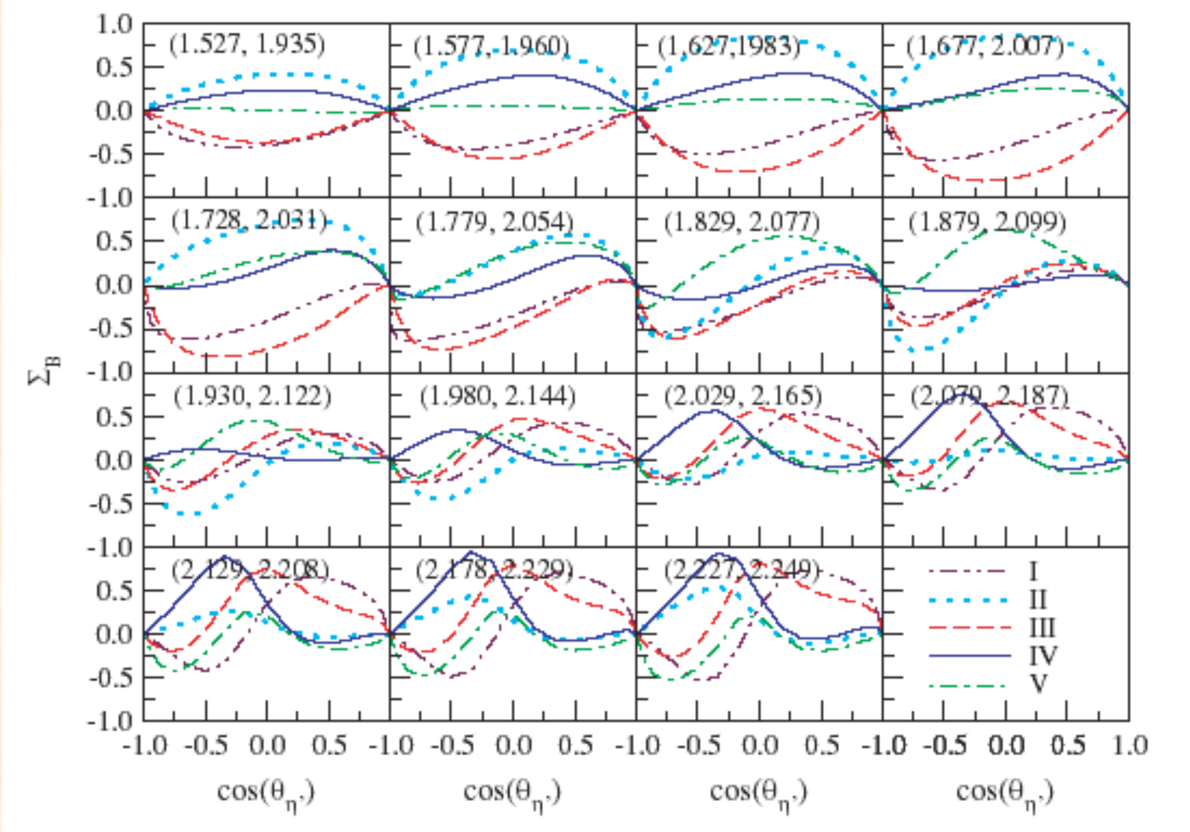
Variants of NH model

I	II	III	IV	V
		$S_{11}(1535)$	$S_{11}(1535)$	$S_{11}(1535)$
		$S_{11}(1650)$		$S_{11}(1650)$
$S_{11}(2090)$	$S_{11}(2090)$	$S_{11}(2090)$	$S_{11}(2090)$	$S_{11}(2090)$
		$P_{11}(1710)$	$P_{11}(1710)$	$P_{11}(1710)$
$P_{11}(2100)$	$P_{11}(2100)$	$P_{11}(2100)$	$P_{11}(2100)$	$P_{11}(2100)$
		$P_{11}(2400)$		
				$P_{13}(1720)$
$P_{13}(1900)$	$P_{13}(1900)$	$P_{13}(1900)$		$P_{13}(1900)$
				$D_{13}(1520)$
$D_{13}(1700)$	$D_{13}(1700)$	$D_{13}(1700)$	$D_{13}(1700)$	$D_{13}(1700)$
	$D_{13}(2080)$	$D_{13}(2080)$	$D_{13}(2080)$	$D_{13}(2080)$
$g_{\eta' NN} = 0.43$	$g_{\eta' NN} = 0.25$	$g_{\eta' NN} = 1.33$	$g_{\eta' NN} = 0.002$	$g_{\eta' NN} = 1.91$

γp→η′p



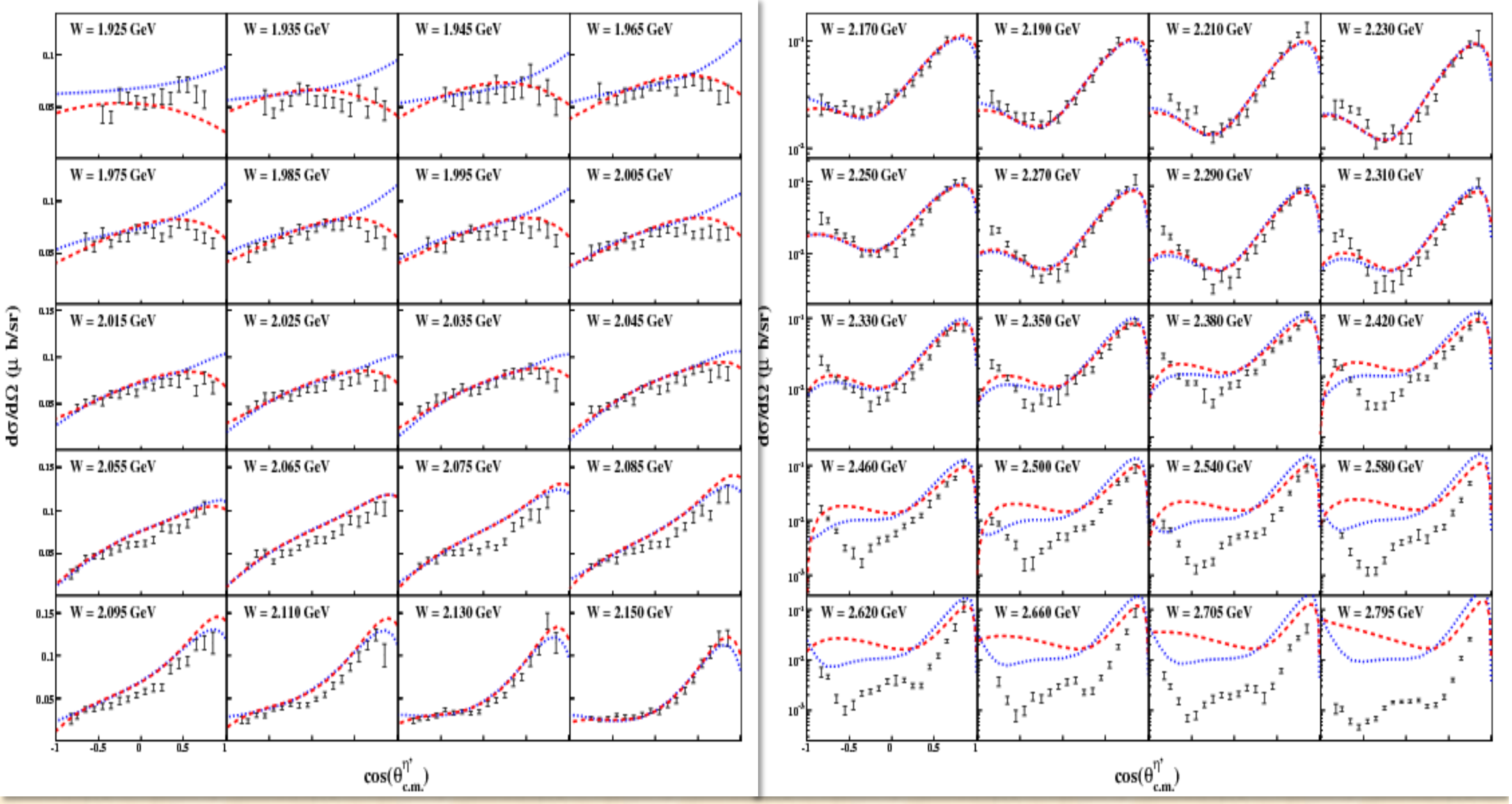
M. Dugger et al. PRL **96**, 062001 (2006)



K. Nakayama and H. Haberzettl, Phys. Rev. C 73, 045211 (2006).

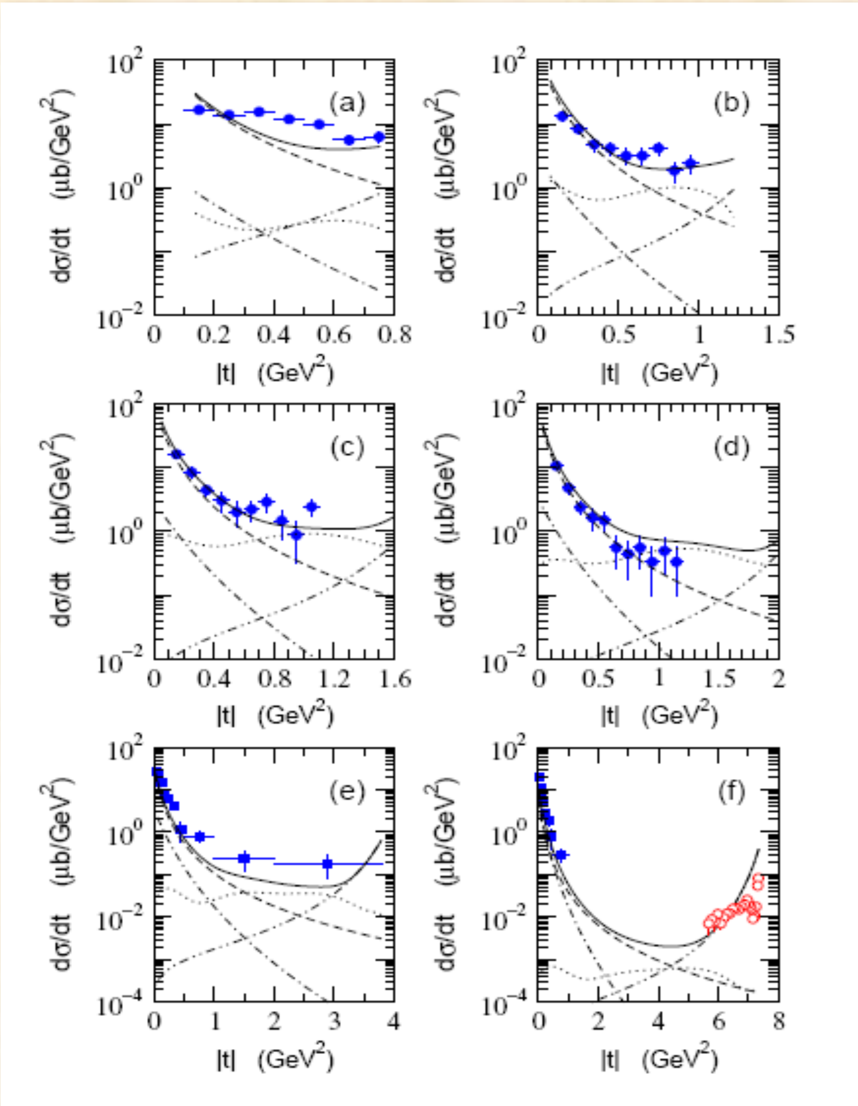
- Different versions of the model yield similar results for cross section, but quite different predictions for beam asymmetry

$\gamma p \rightarrow \eta' p$



M. Williams et al. PRC 80, 045213 (2009)

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

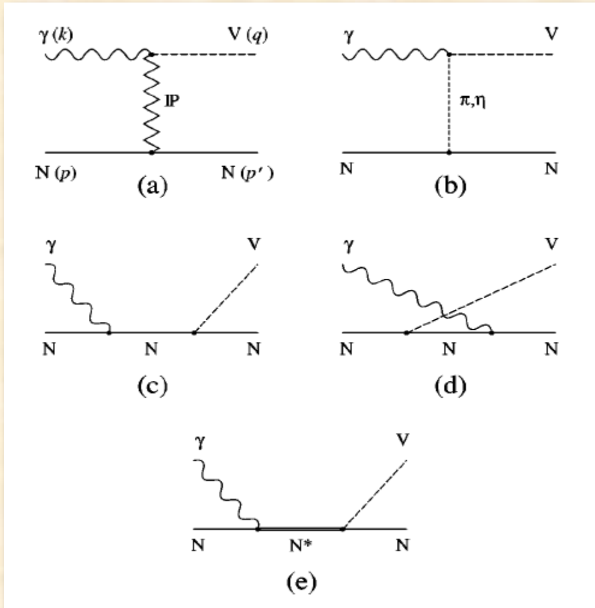


Oh,Titov,Lee
PRC63 (2001) 025201

Low *t* diffractive behavior:

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

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

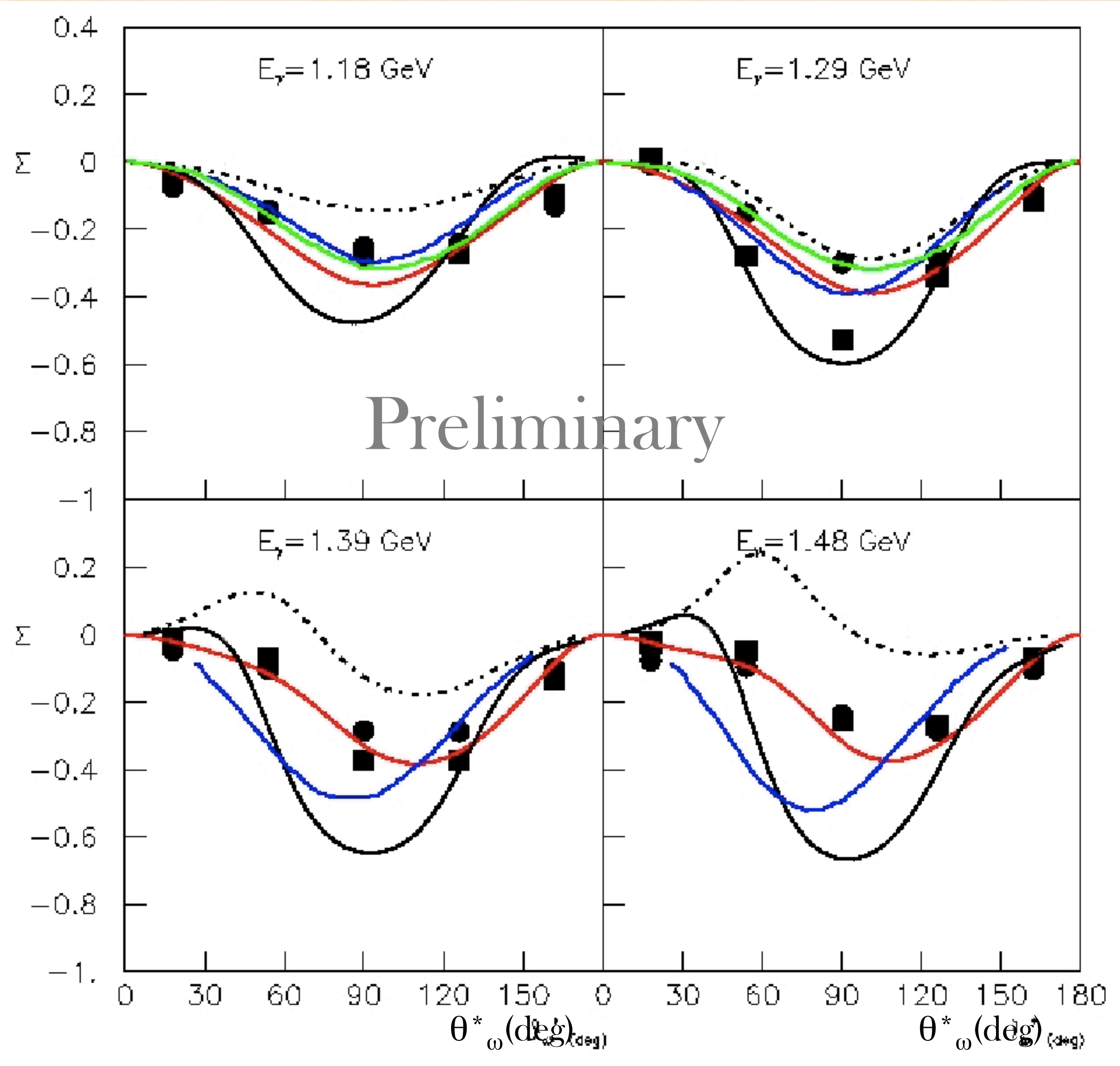


Eγ=(a) 1.23GeV
(b) 1.45GeV
(c) 1.68GeV
(d) 1.92GeV
(e) 2.80GeV
(f) 4.70 GeV

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 $\vec{\gamma} + p \to \omega + p$ at GRAAL: $\omega \to \pi^0\gamma$ and $\omega \to \pi^+\pi^-\pi^0$



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

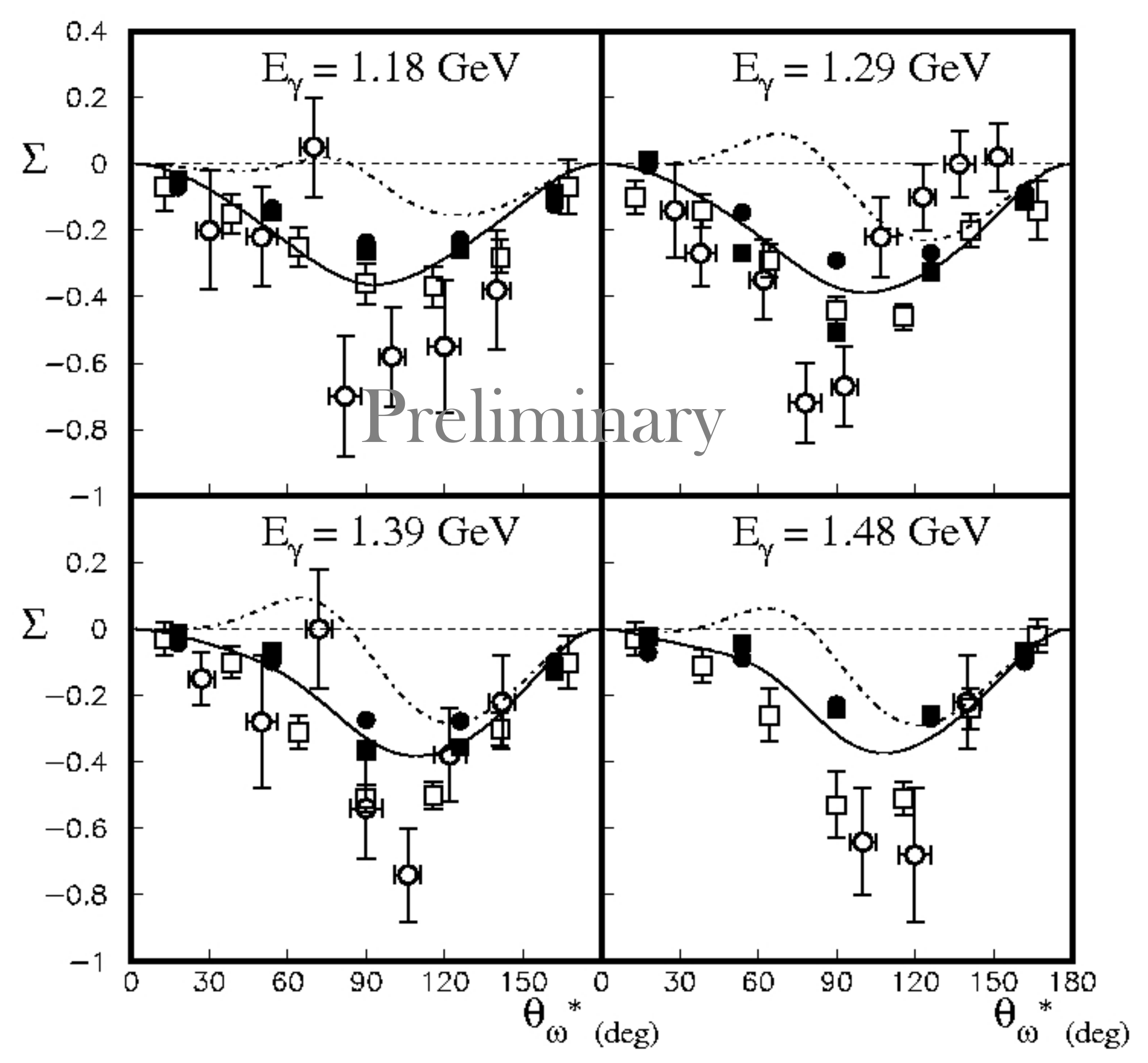
Oh,Titov and Lee
PRC66 (2002)015204

M. Paris
PRC79 (2009) 025208

● $\omega \to \pi^0\gamma$

■ $\omega \to \pi^+\pi^-\pi^0$

Σ results on $\gamma + p \rightarrow \omega + p$ 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 $\omega \rightarrow \pi^0\gamma$

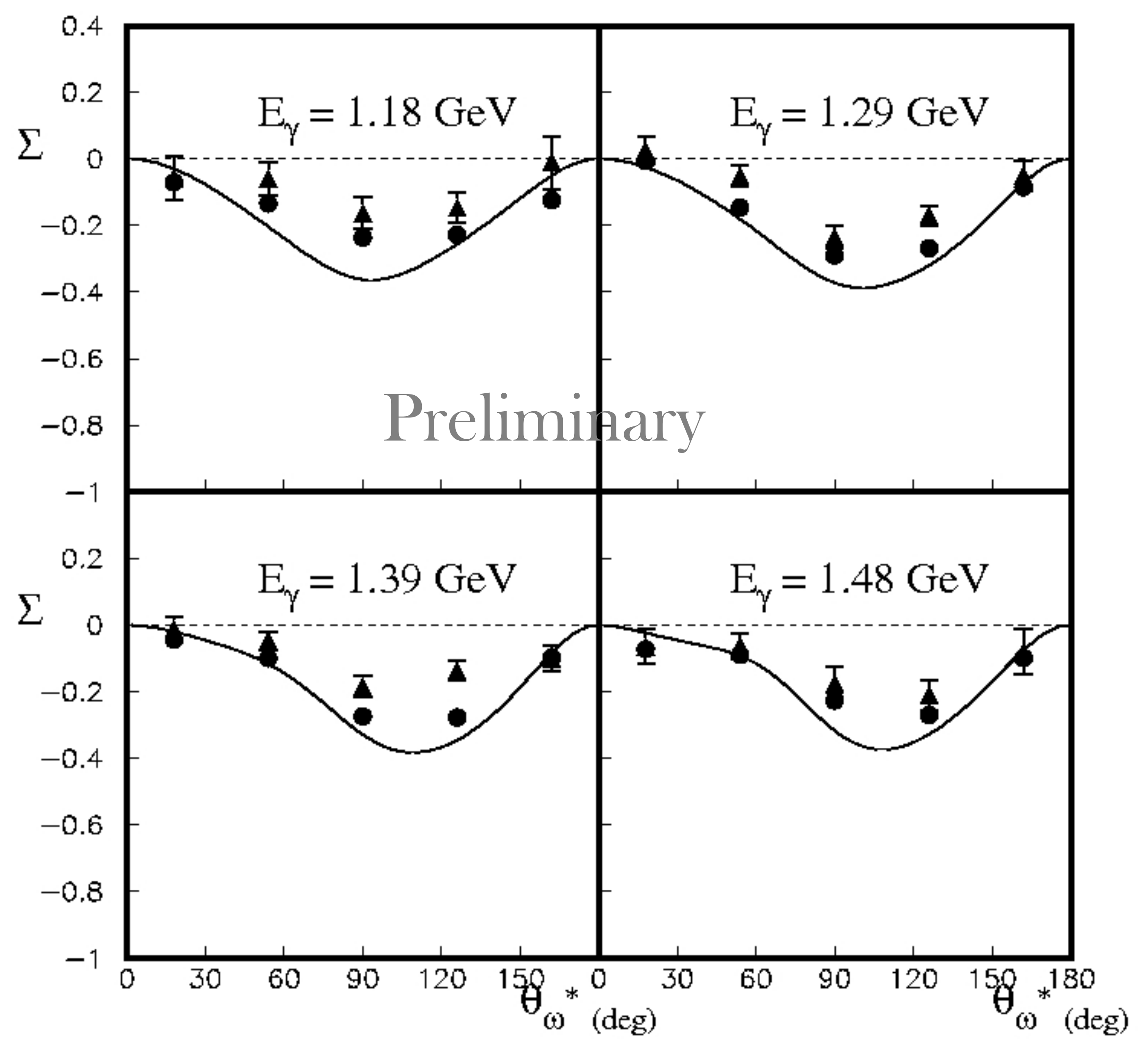
PRL96(06) $\omega \rightarrow \pi^+\pi^-\pi^0$

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