EINN2013

10TH EUROPEAN RESEARCH CONFERENCE ON
"ELECTROMAGNETIC INTERACTIONS WITH NUCLEONS AND NUCLEI"

Baryon Spectroscopy: an overview

Annalisa D'ANGELO

University of Rome "Tor Vergata" and INFN Rome Tor Vergata

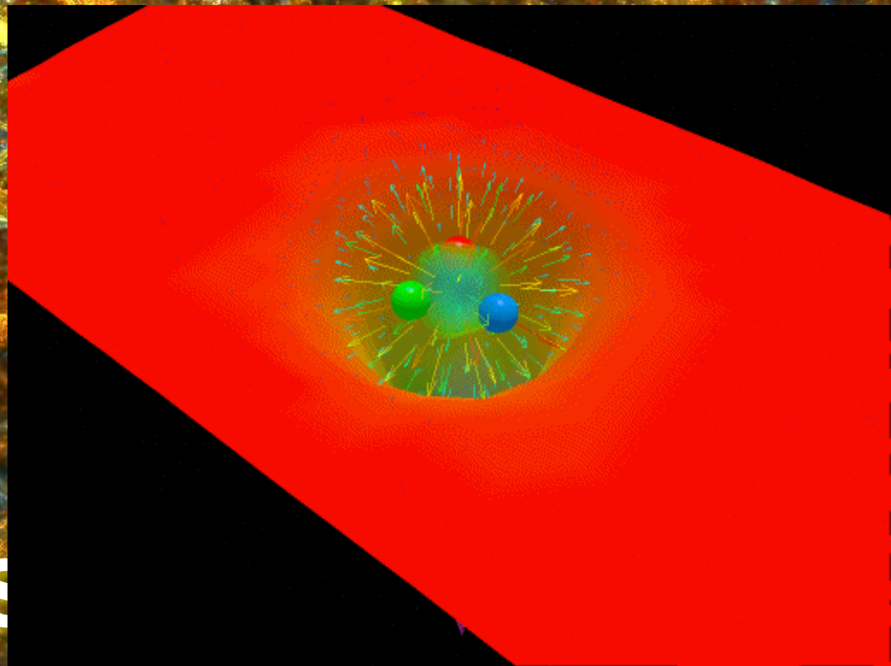
substituting

Volker Burkert
Hall-B leader at JLab

INFN Istituto Nazionale di Fisica Nucleare

JSA Jefferson Lab Thomas Jefferson National Accelerator Facility

Baryon Spectroscopy



reveals ... of QCD

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

color wave-functions

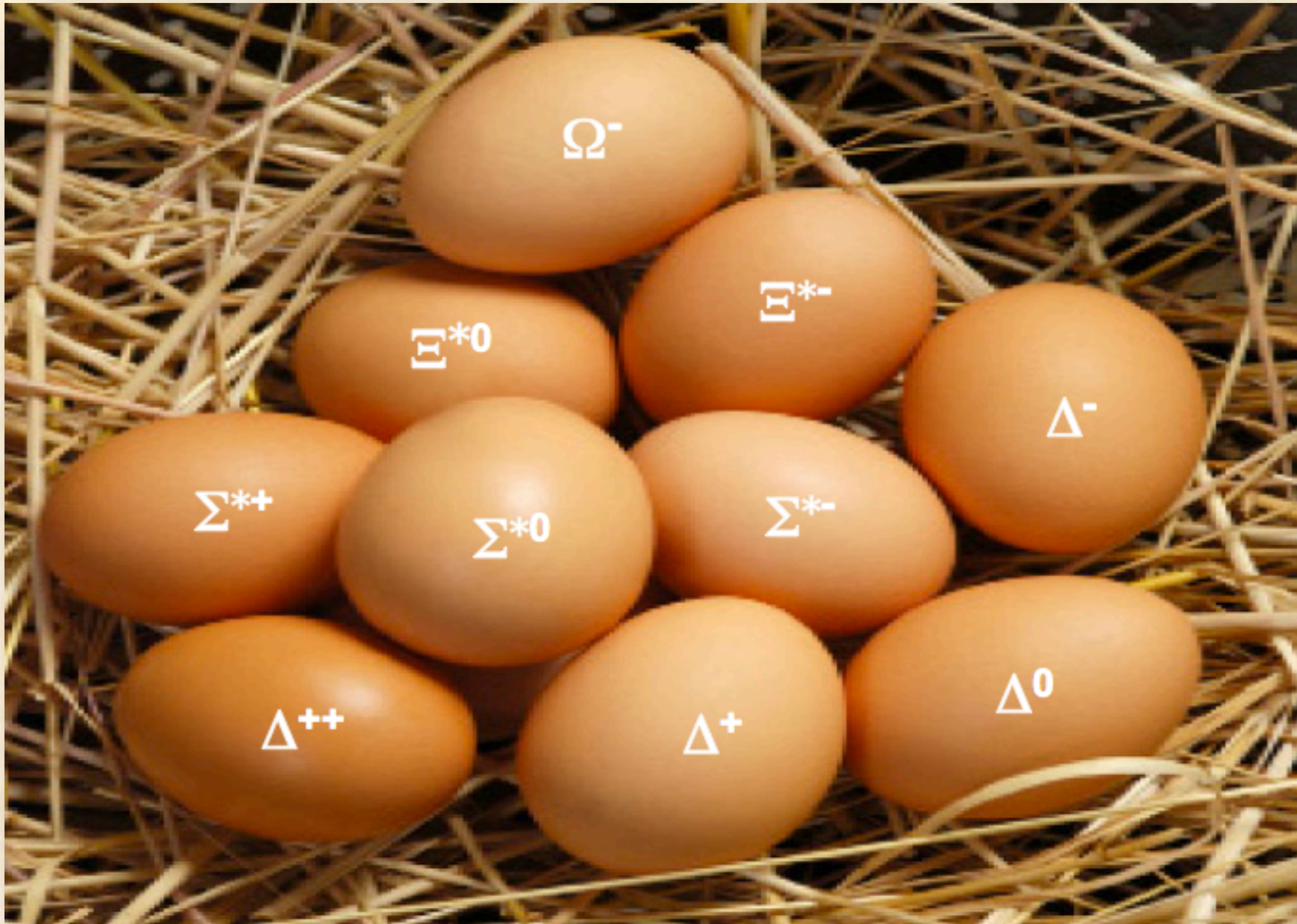
$$p^{+} = \frac{1}{\sqrt{N_c}}\left[\, u\bar{d} + u\bar{d} + u\bar{d} + u\bar{d} + \ldots \,\right]$$

$N_c = 3$

$$p = \frac{1}{\sqrt{6}}\left[\, uud + uud + uud - uud - uud - uud \,\right]$$

Motivation

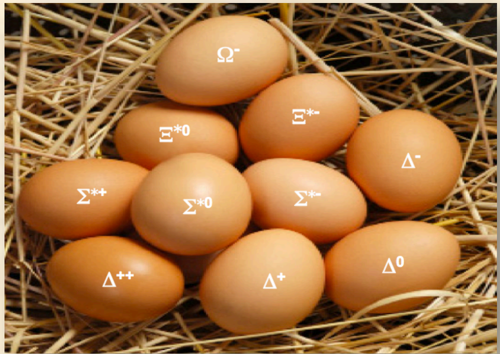
- Understanding the working of QCD: non-perturbative low energy scale (≈ GeV)



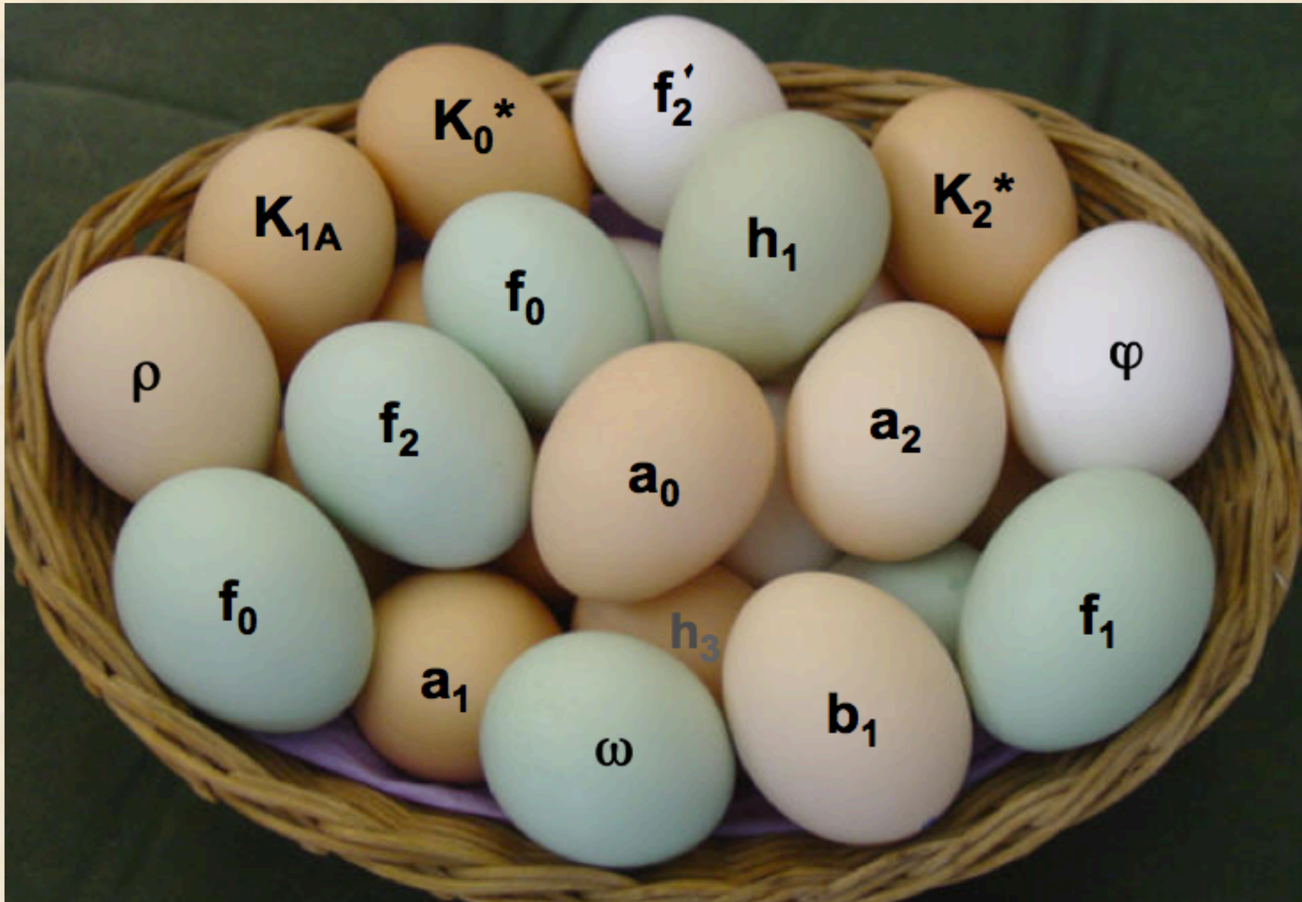
Baryons

Motivation

- Understanding the working of QCD: non-perturbative low energy scale (≈ GeV)



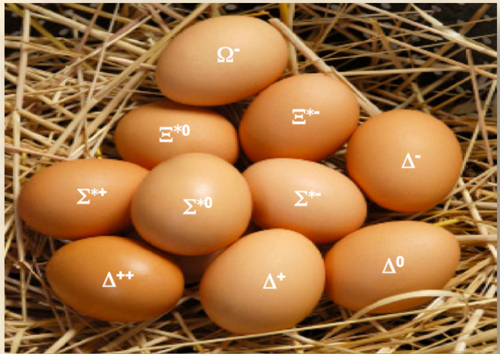
Baryons



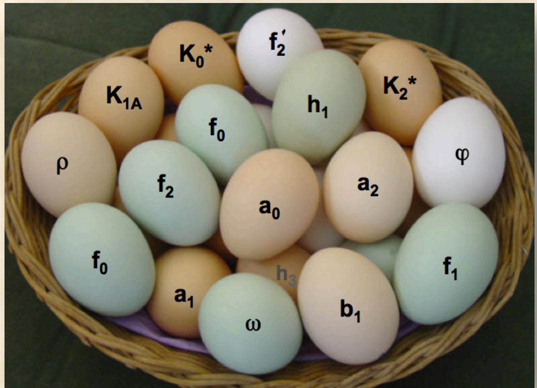
Mesons

Motivation

- Understanding the working of QCD: non-perturbative low energy scale (≈ GeV)



Baryons



Mesons

Exotics

Motivation

- Understanding the working of QCD: non-perturbative low energy scale (≈ GeV)

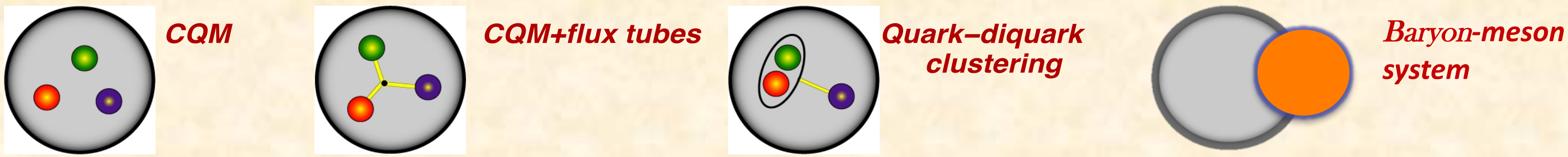
hadronic degrees of freedom

Why do we study N*'s?

"Nucleons are the stuff of which our world is made. As such they must be at the center of any discussion of why the world we actually experience has the character it does. I am convinced that completing this chapter in the history of science is one of the most interesting and fruitful areas of physics for at least the next 30 years. " *Nathan Isgur, NStar2000, Newport News, Virginia.*

• Only now do we have experimental, phenomenological, and theoretical tools to fully explore baryon spectrum and structure.

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

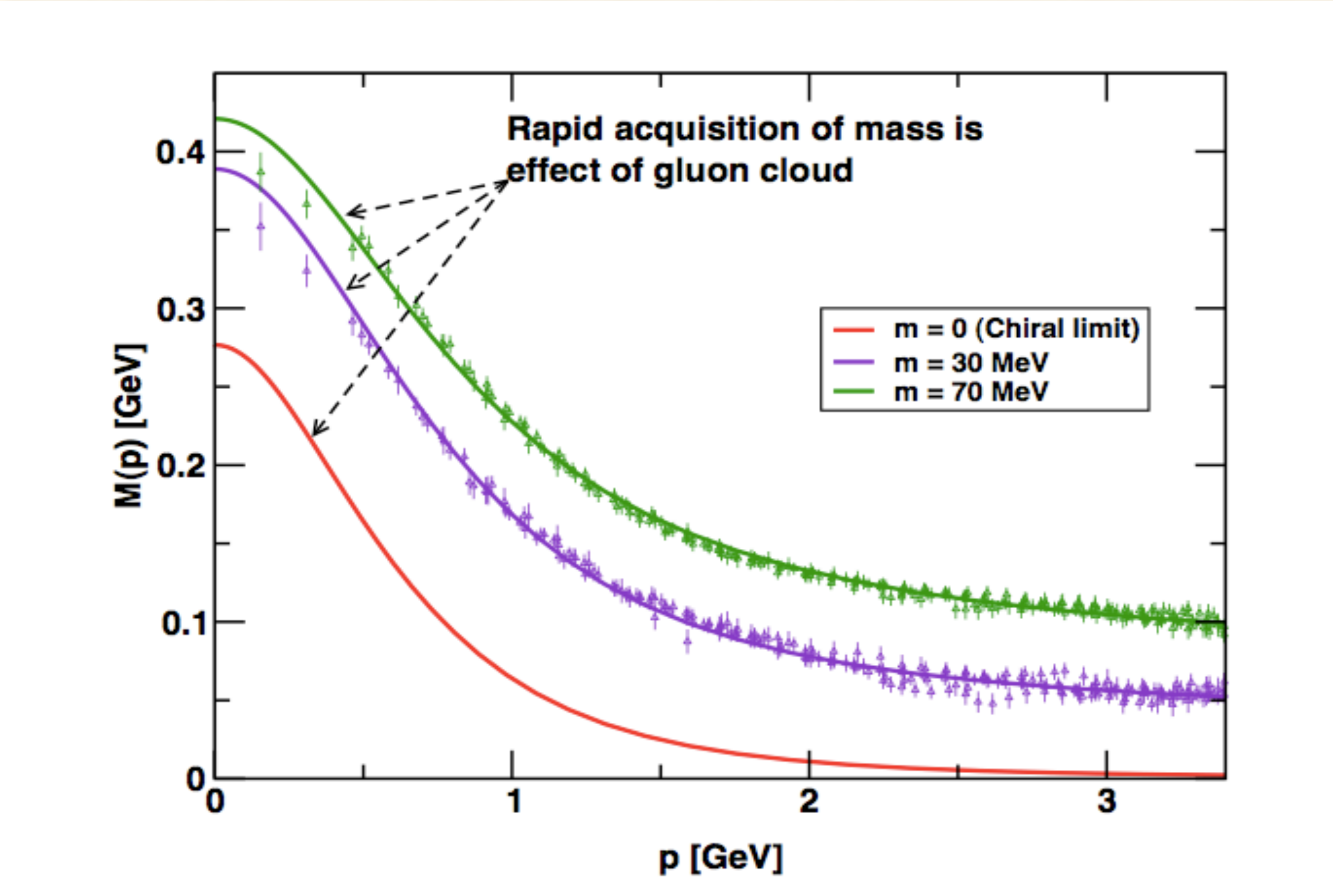


- Vigorous experimental program needed along two avenues
  - Search for undiscovered states in photoproduction (ELSA, GRAAL, JLab, MAMI)
  - Identify the relevant degrees of freedom for prominent states versus distance scale in meson electroproduction (JLab/JLab12)
- New developments in theory connect to QCD – LQCD, DSE/QCD, AdS/QCD

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.)

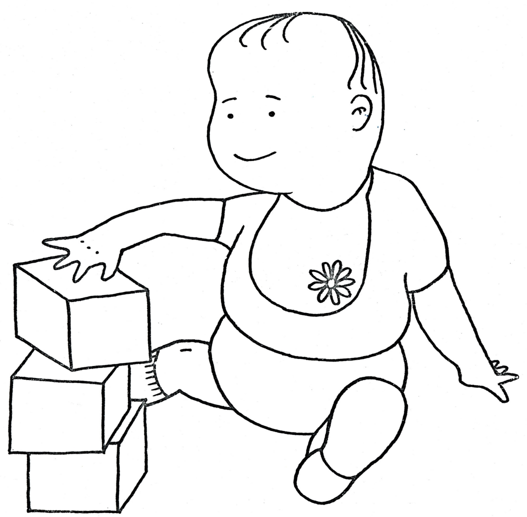
Dyson-Swinger equation (Bhagwat et al.)

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

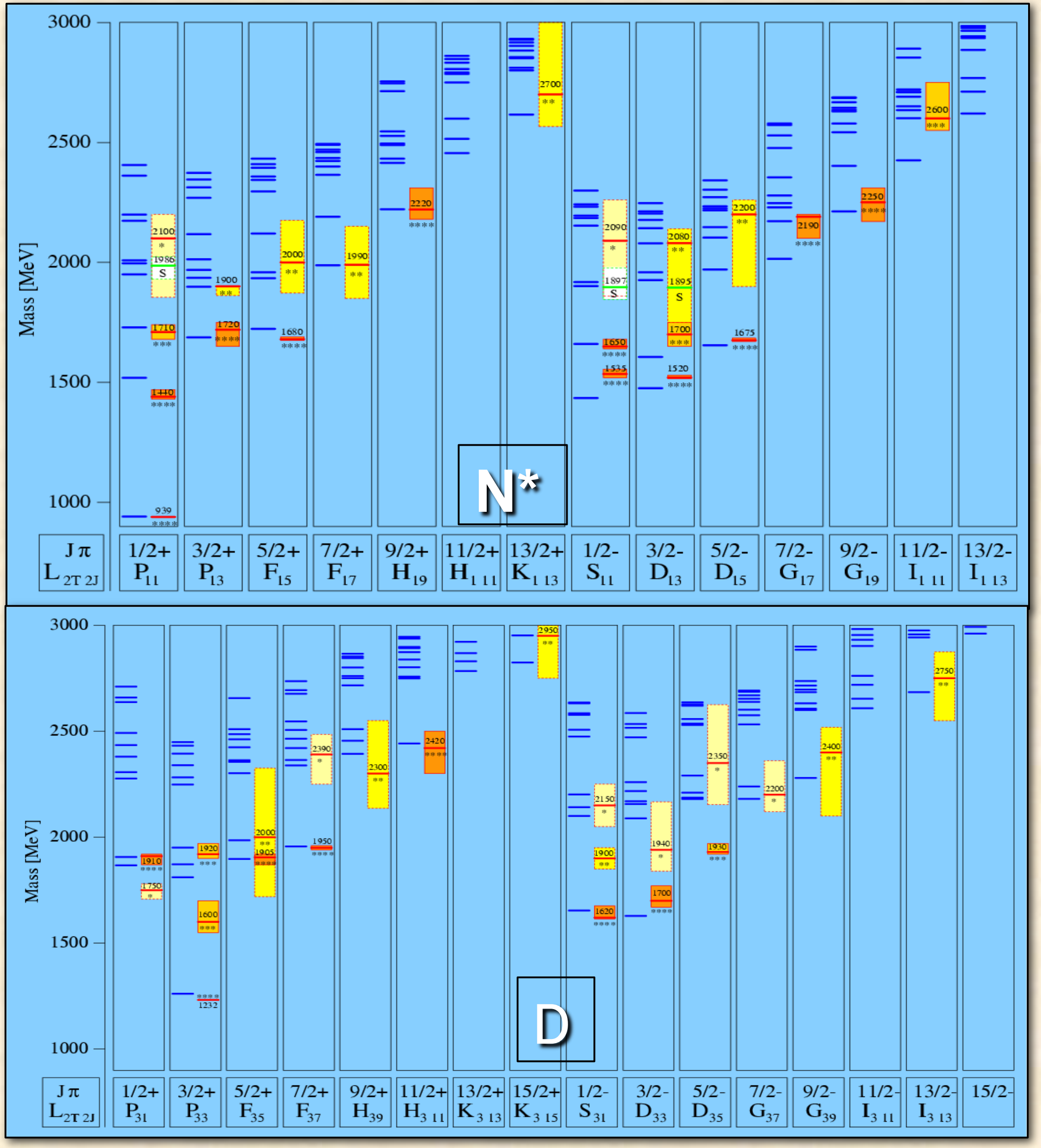
Nucleon model states (p N couplings)

QCD-inspired Constituent Quark Models

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



Infant Quark Model



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

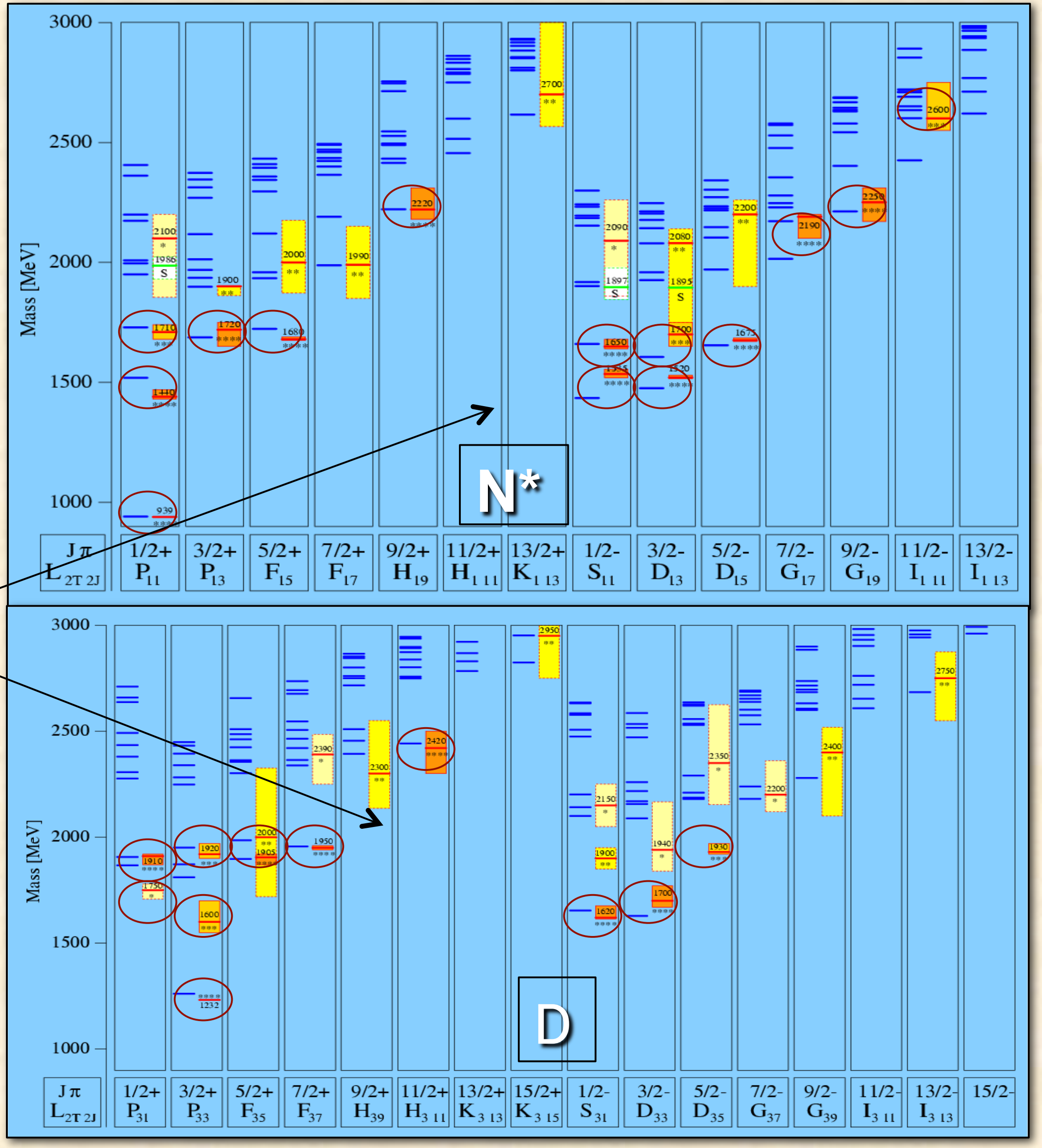
Nucleon model states (p N couplings)

QCD-inspired
Constituent Quark Models

Findings:

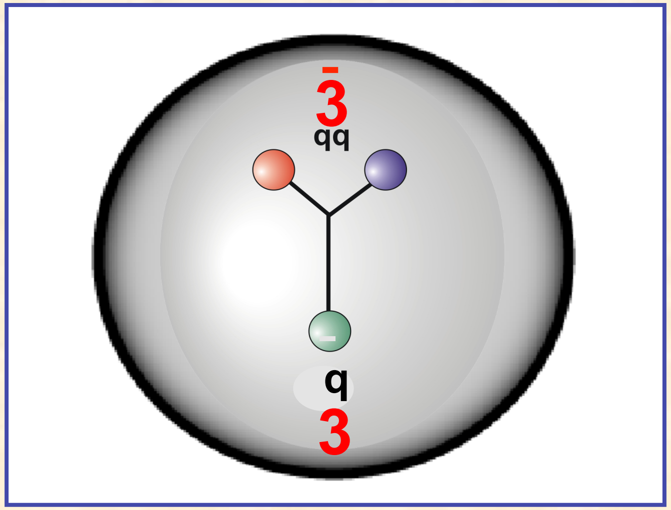
- Linear Regge trajectories
- Only lowest few in each band seen with 4★ or 3★ status
- g(πN) couplings predicted to decrease rapidly with mass in each oscillator band
- Higher levels predicted to have

larger couplings to KΛ, KΣ, ππN, …



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

QCD-inspired di-Quark Models



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

- **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**

the challenge: ⇔ unravel the N* spectrum

- **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 [illegible]N**

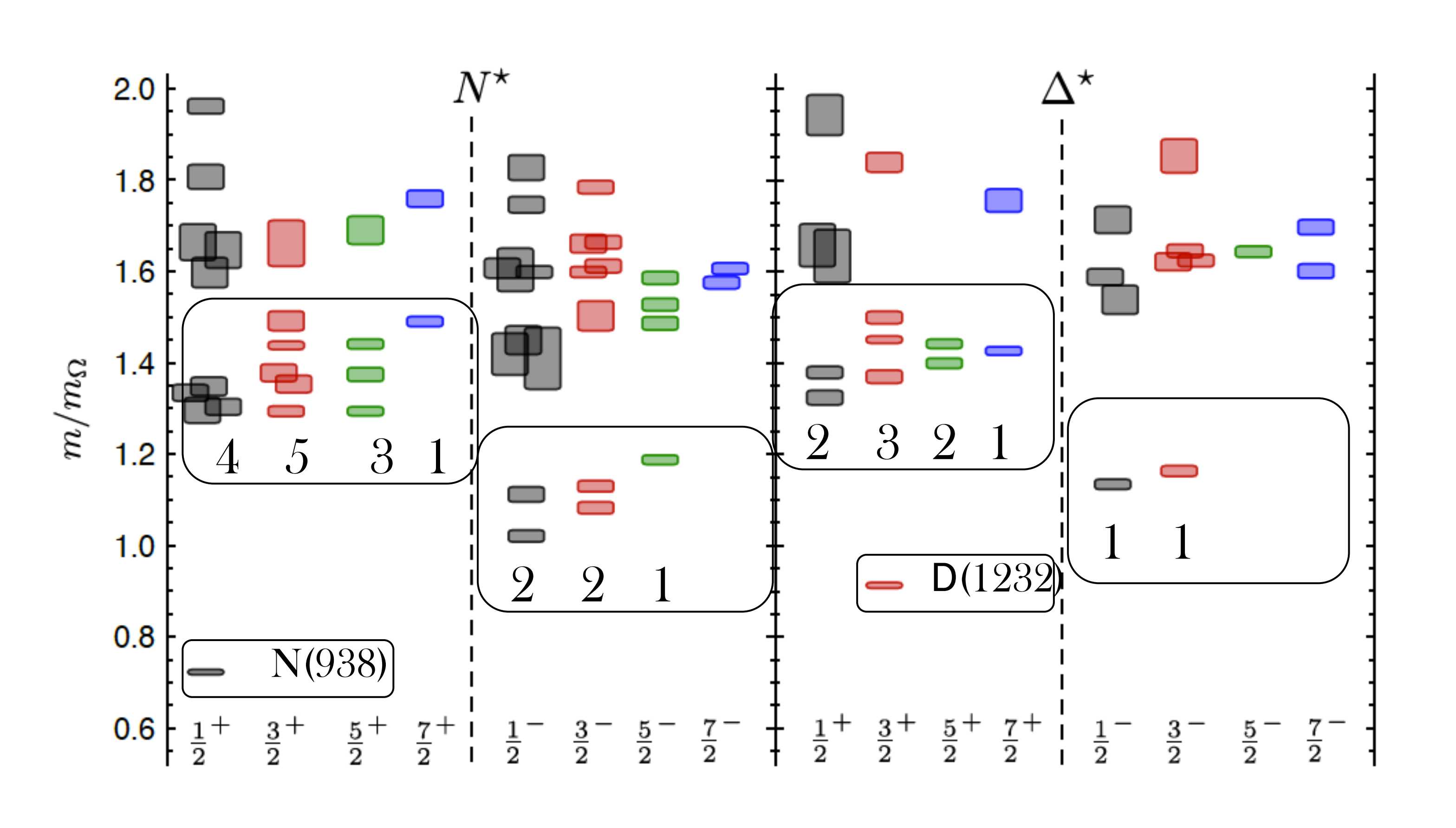
Excited Baryons from L QCD

- Exhibits the SU(6) ×O(3)-symmetry features

•Counting of levels consistent with non-rel. quark model

•Striking similarity with quark model

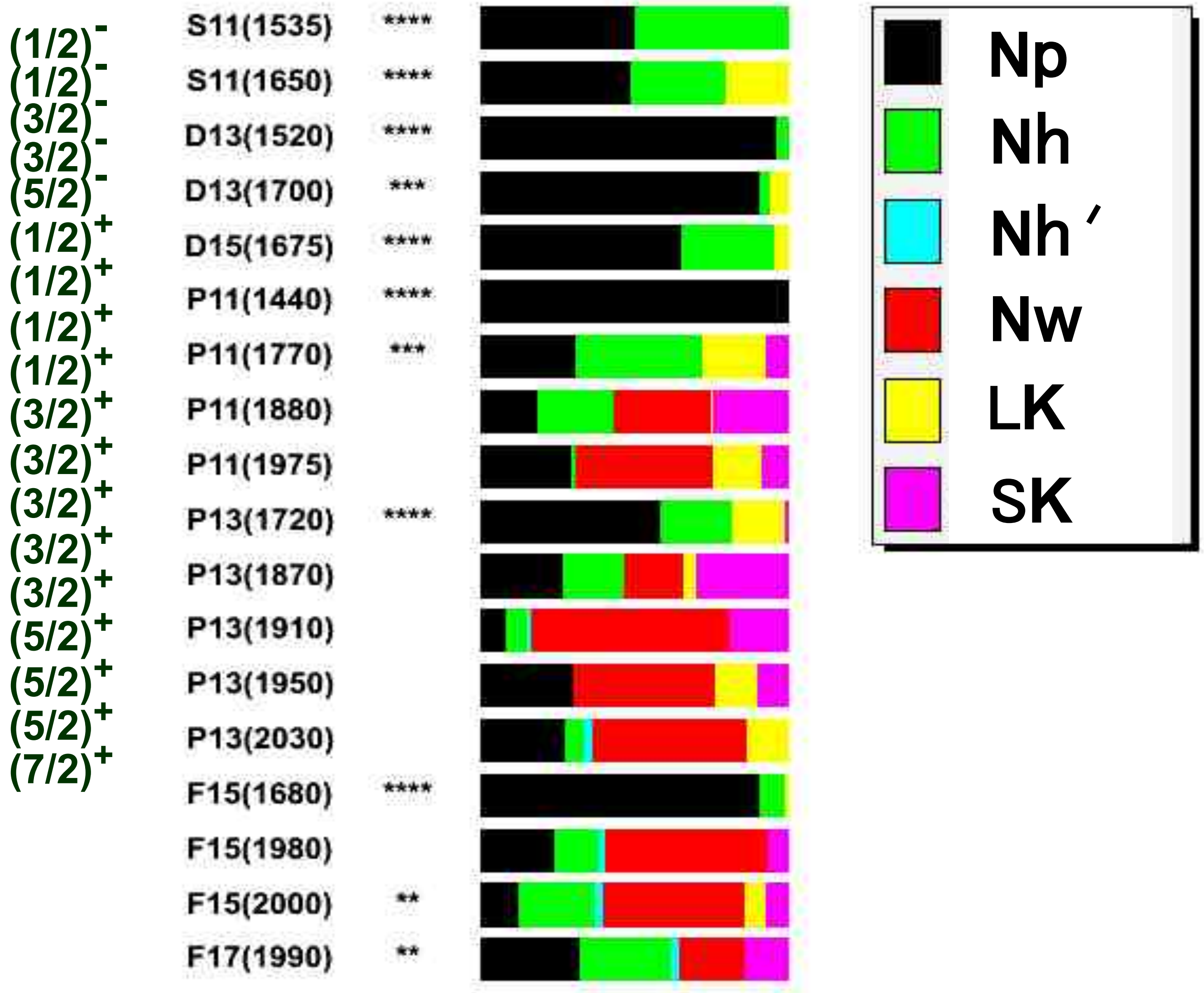
•No parity doubling



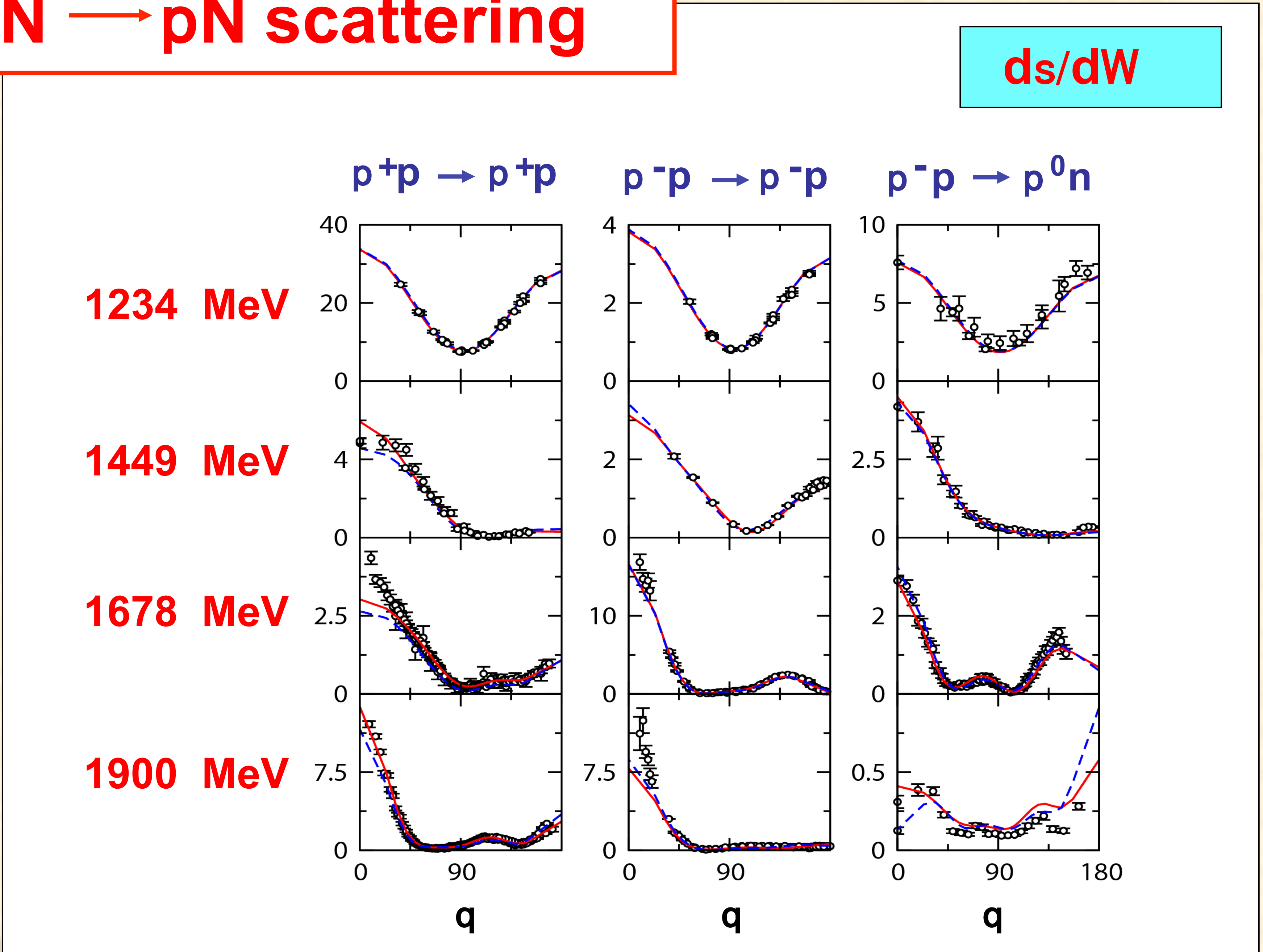
Robert G. Edwards, Jozef J. Dudek, David G. Richards, Stephen J. Wallace **Phys.Rev. D84 (2011) 074508**

Problems are not solved!

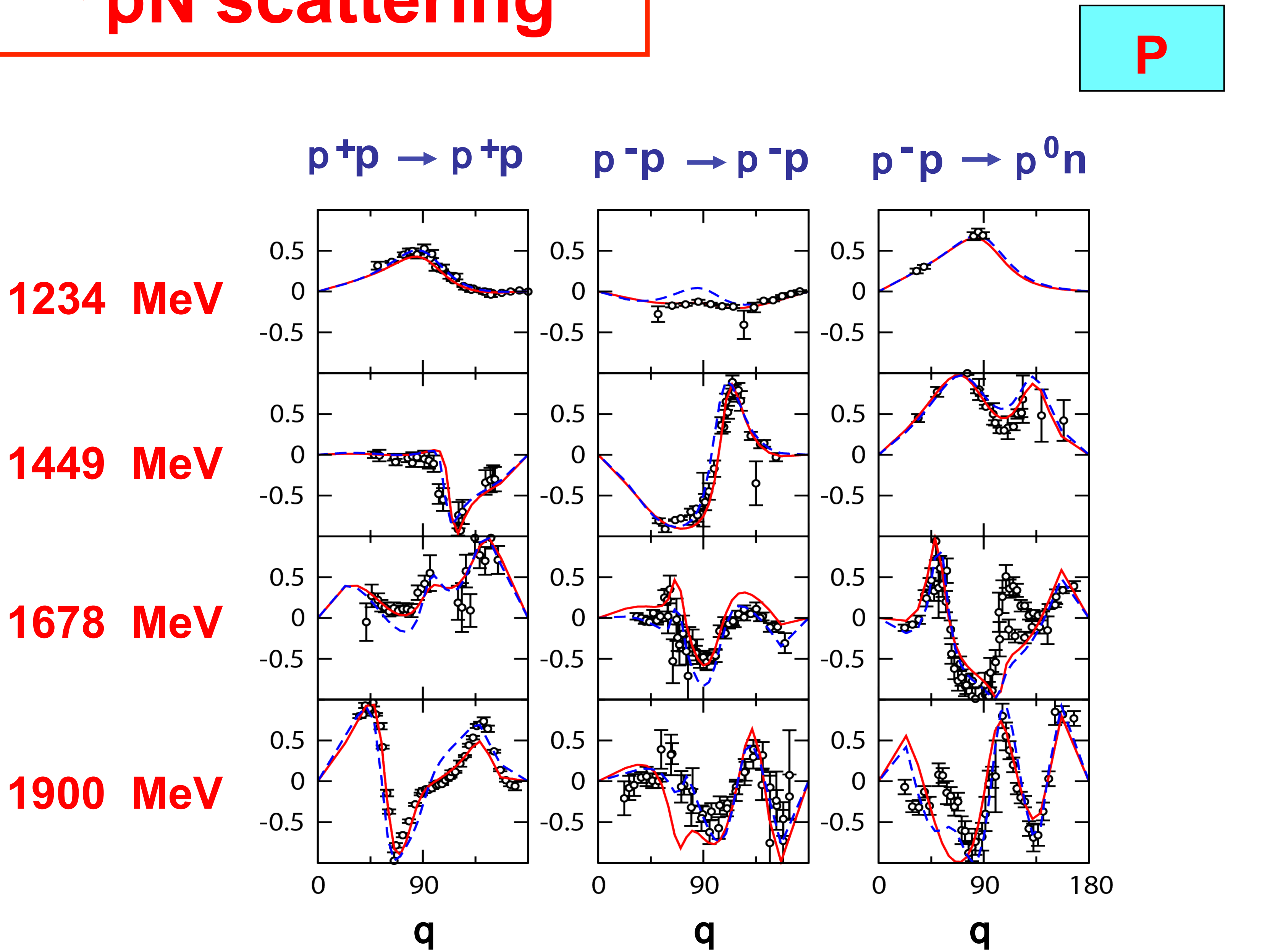
search all channels: not just pN



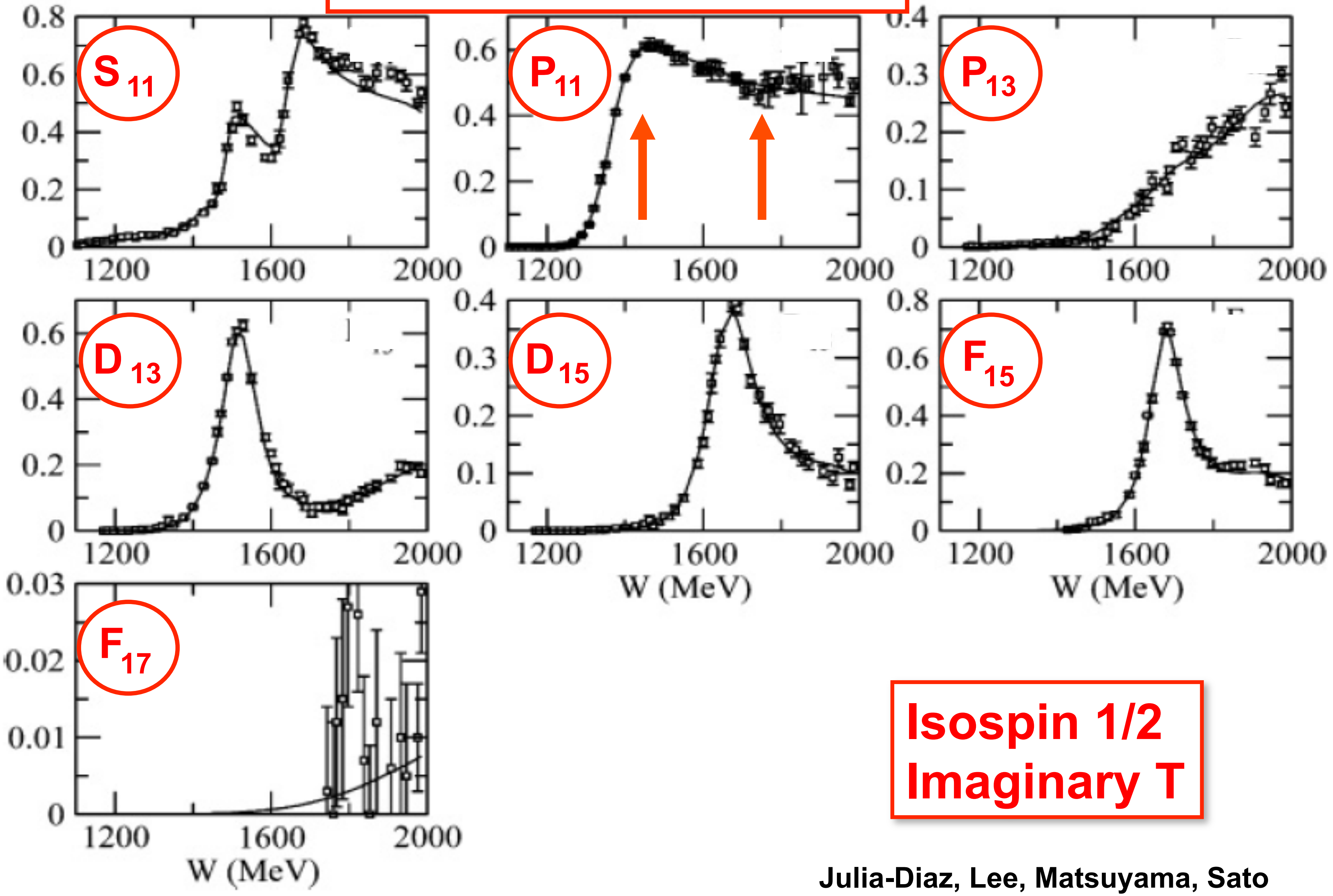
pN → pN scattering



pN → pN scattering



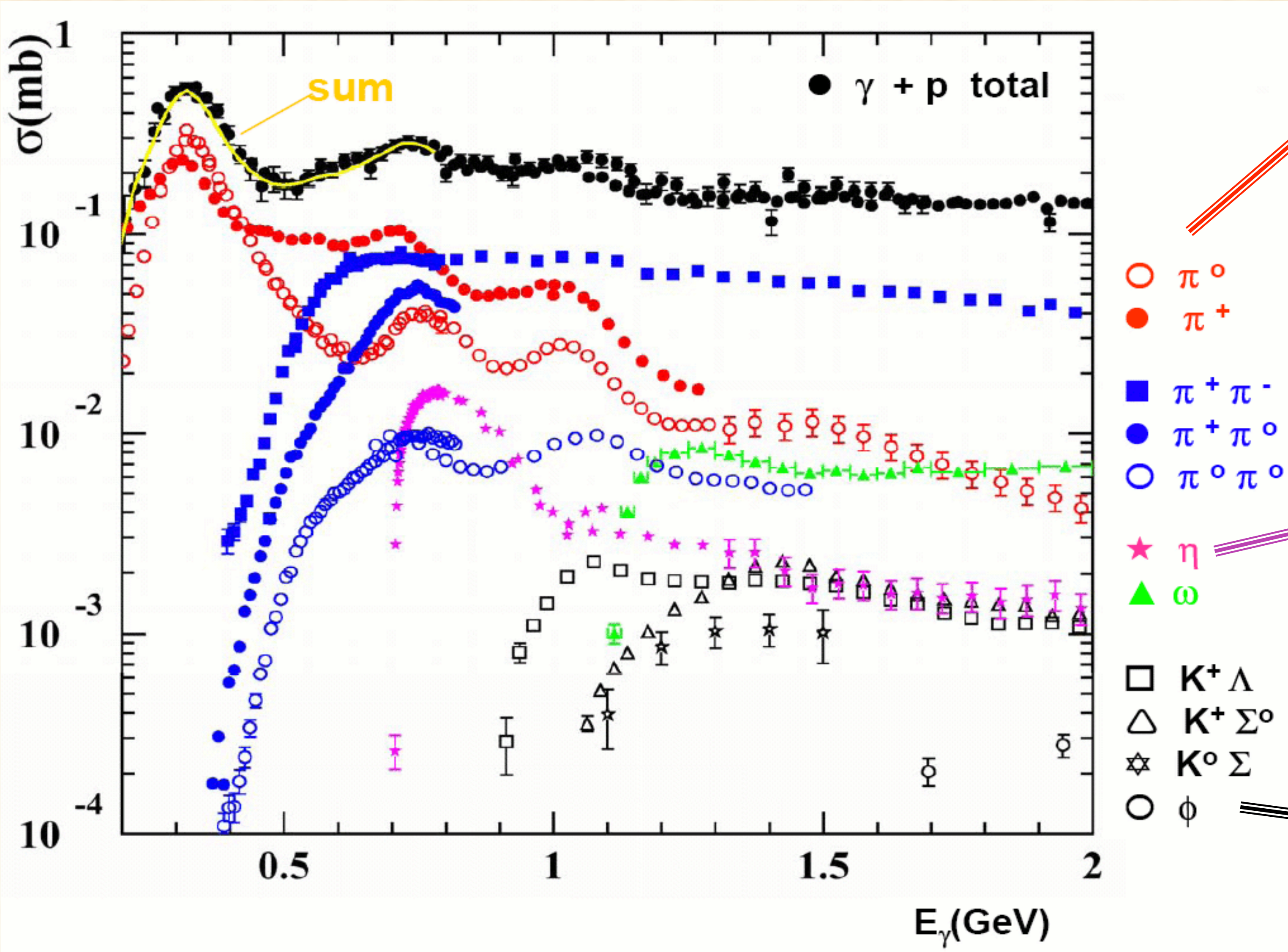
pN amplitudes

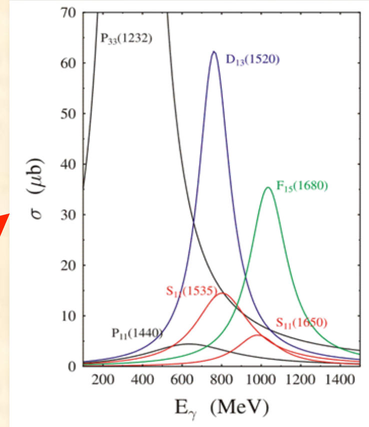


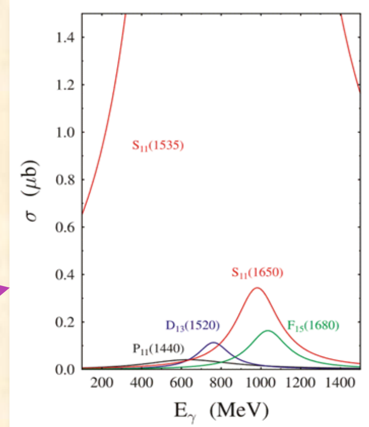
Isospin 1/2
Imaginary T

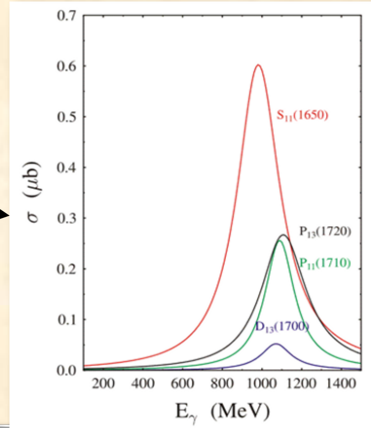
Julia-Diaz, Lee, Matsuyama, Sato

Photonuclear cross sections



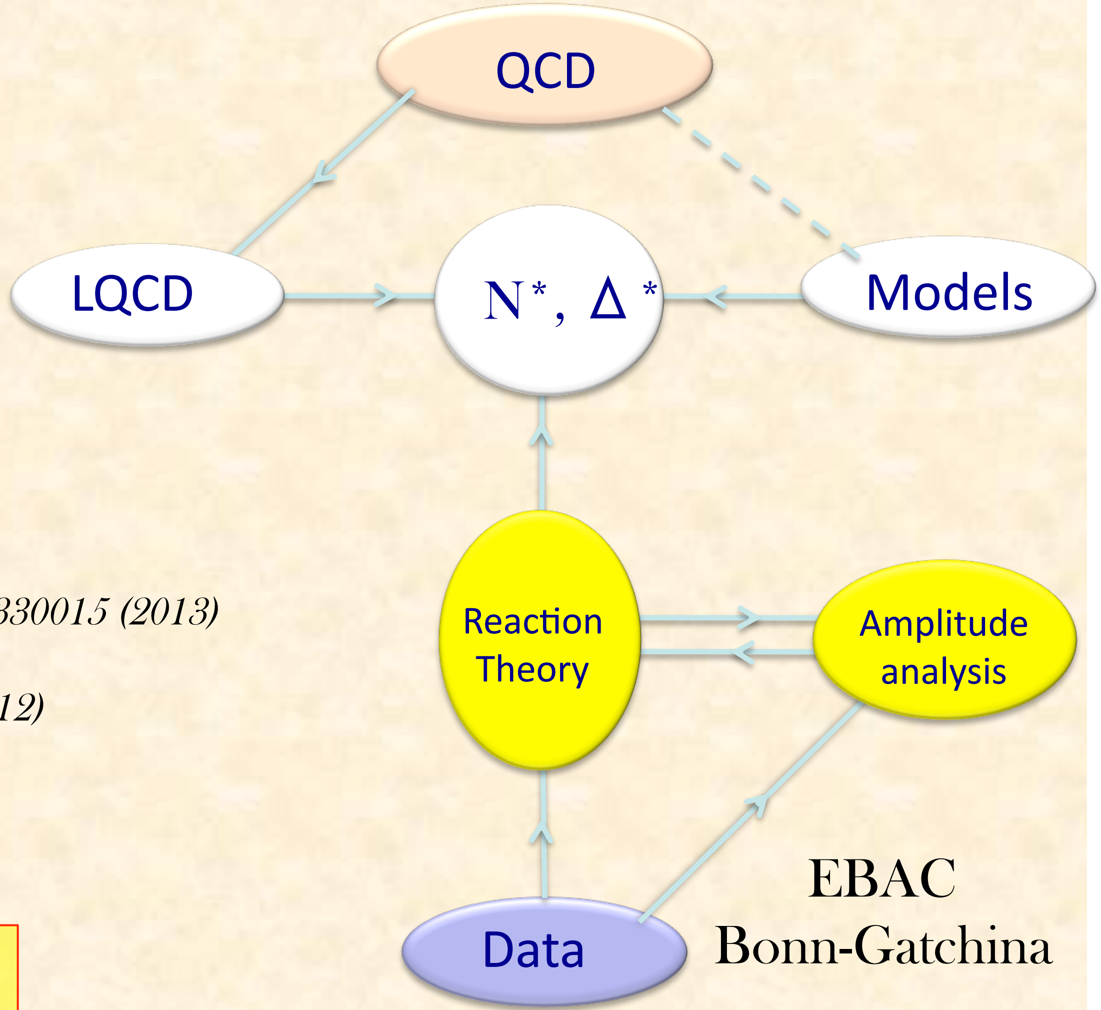






Search for new N* and Δ* states

- Precision measurements of photo-induced processes in wide kinematics, e.g. γp→πN, ηp, KY, .., γn→πN, K^0Y^0, ..
- Polarization observables are essential
- More complex reactions, e.g. γp → ωp, pϕ, ππp, ηπN, K*Y, .. may be sensitive to high mass states through direct transition to ground state or through cascade decays



Hadronic production

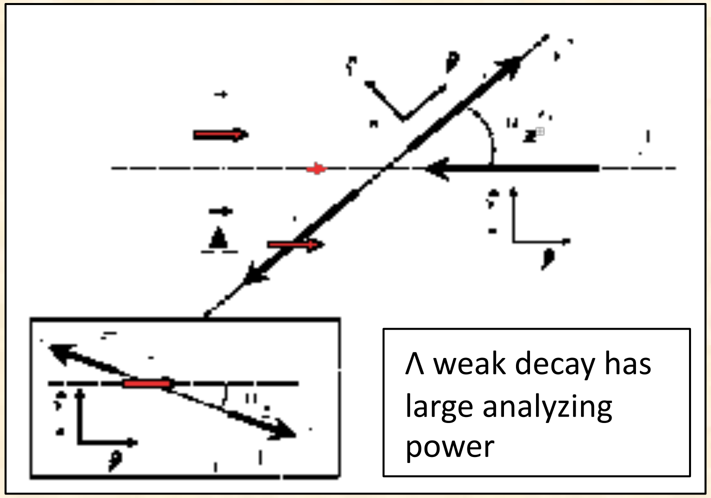
Electromagnetic production

- *I.G. Aznauryan, et al. (White Paper), Int. J. Mod. Phys. E, 22, 1330015 (2013)*
- *V. Crede, W. Roberts, arXiv:1302.7299 (2013)*
- *I.G. Aznauryan, V. D. Burkert, Prog. Part. Nucl. Phys. 67, 1 (2012)*
- *L. Tiator, D. Drechsel, S. Kamalov, M. Vanderhaeghen, Eur. Phys. J. ST198 (2011)*
- *E. Klempt, J.M. Richard, Rev. Mod. Phys. 82, 1095 (2010)*

Engagement of groups to extract physics in theoretically sound analyses is essential.

By Volker Burkert

(Over)complete experiments



The holy grail of baryon resonance analysis

- Process described by 4 complex, parity conserving amplitudes
- 8 well-chosen measurements are needed to determine amplitude.
- Up to **16** observables measured directly
- 3 inferred from double polarization observables
- **13** inferred from triple polarization observables

Beam (P^γ)		Target (P^T)			Recoil (P^R)			Target (P^T) + Recoil (P^R)								
					x'	y'	z'	x'	x'	x'	y'	y'	y'	z'	z'	z'
		x	y	z				x	y	z	x	y	z	x	y	z
unpolarized	$d\sigma_0$		$\hat{T}$			$\hat{P}$		$\hat{T}_{x'}$		$\hat{L}_{x'}$		$\hat{\Sigma}$		$\hat{T}_{z'}$		$\hat{L}_{z'}$
$P_L^\gamma \sin(2\phi_\gamma)$		$\hat{H}$		$\hat{G}$	$\hat{O}_{x'}$		$\hat{O}_{z'}$		$\hat{C}_{z'}$		$\hat{E}$		$\hat{F}$		$-\hat{C}_{x'}$	
$P_L^\gamma \cos(2\phi_\gamma)$	$-\hat{\Sigma}$		$-\hat{P}$			$-\hat{T}$		$-\hat{L}_{z'}$		$\hat{T}_{z'}$		$-d\sigma_0$		$\hat{L}_{x'}$		$-\hat{T}_{x'}$
circular P_c^γ		$\hat{F}$		$-\hat{E}$	$\hat{C}_{x'}$		$\hat{C}_{z'}$		$-\hat{O}_{z'}$		$\hat{G}$		$-\hat{H}$		$\hat{O}_{x'}$	

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

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_{γ} = (500 - 1500)MeV

CLAS in Hall-B

E_{γ} = (500 - 6000)MeV

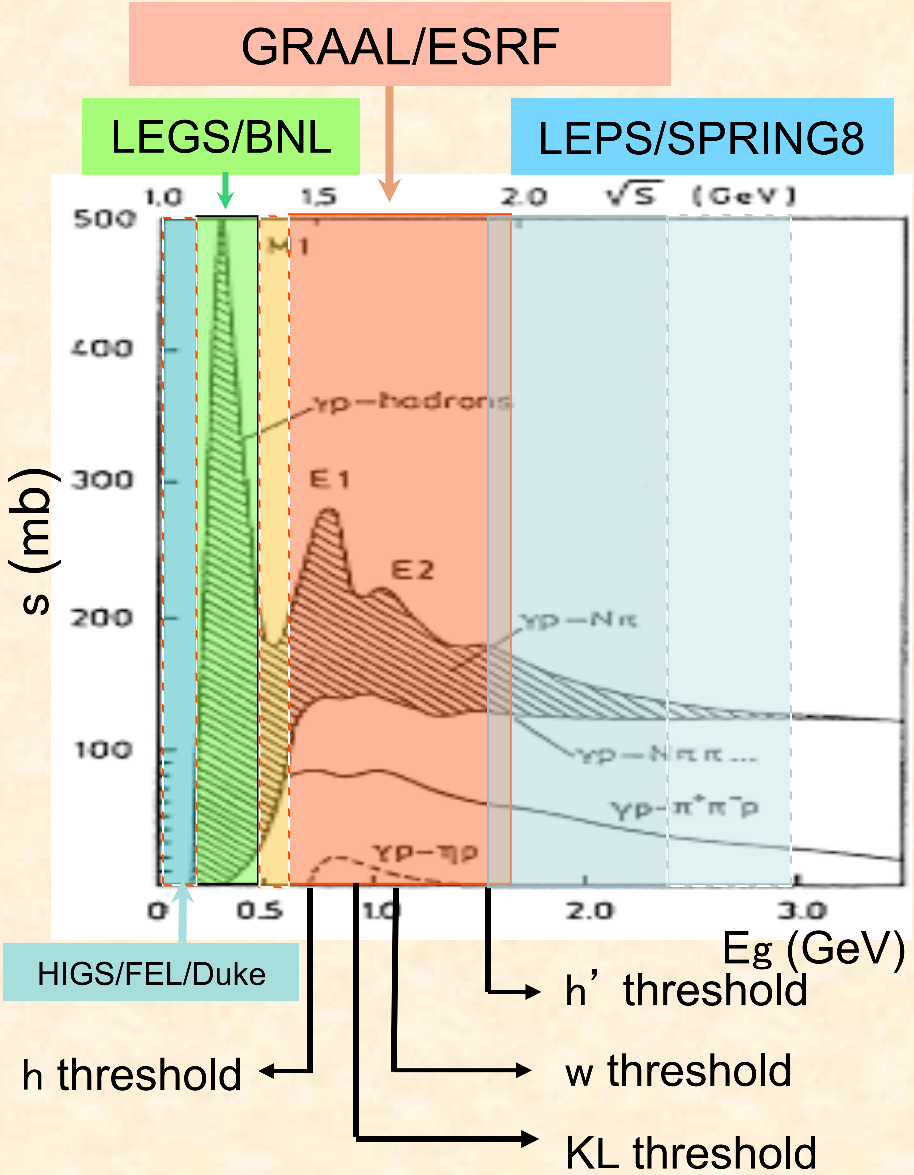
BGO-OD&Crystal Barrel@BONN

E_{γ} = (500 - 3000)MeV

Crystal Ball@MAINZ

E_{γ} = (100 - 1500) MeV

Polarized photon beams: Compton Backscattering



•Hi□s □ below □ threshold

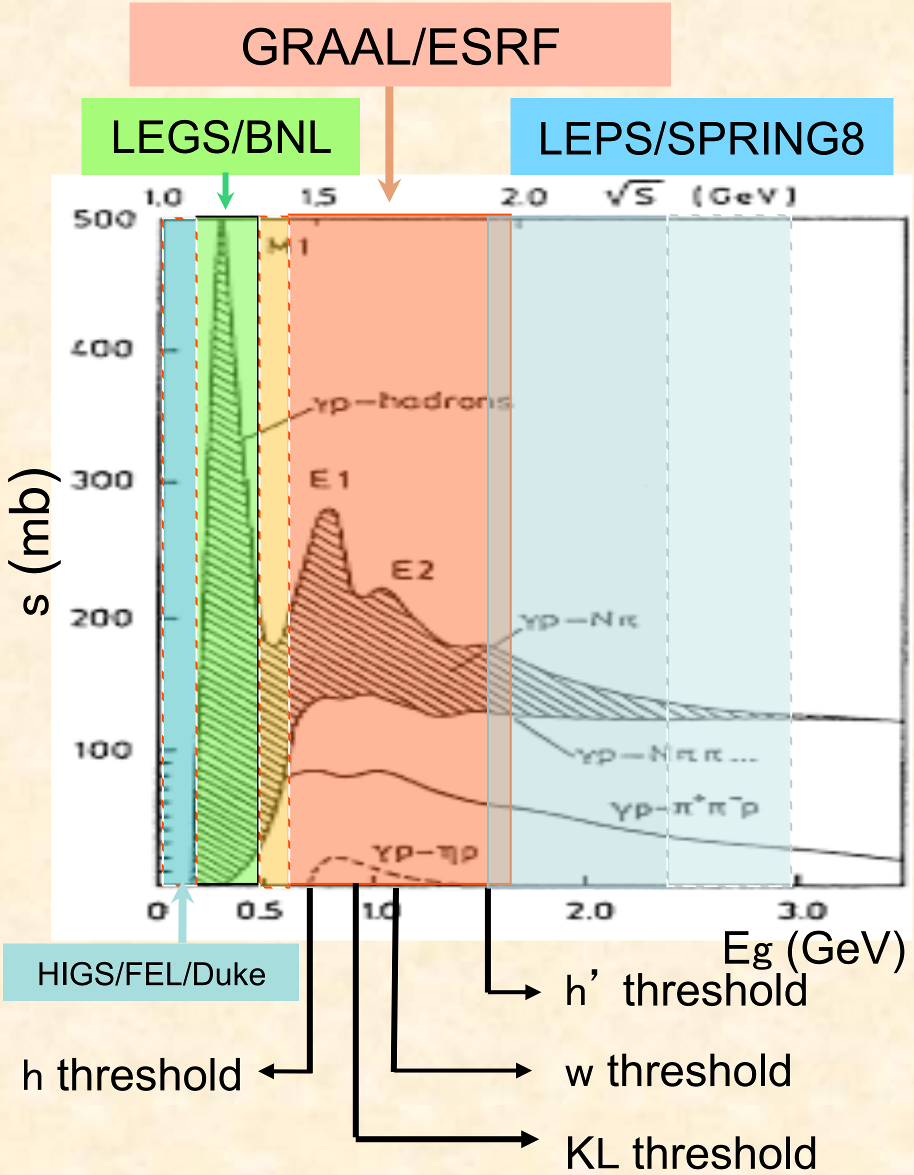
•Legs □ □$_{33}$(1232) resonance region

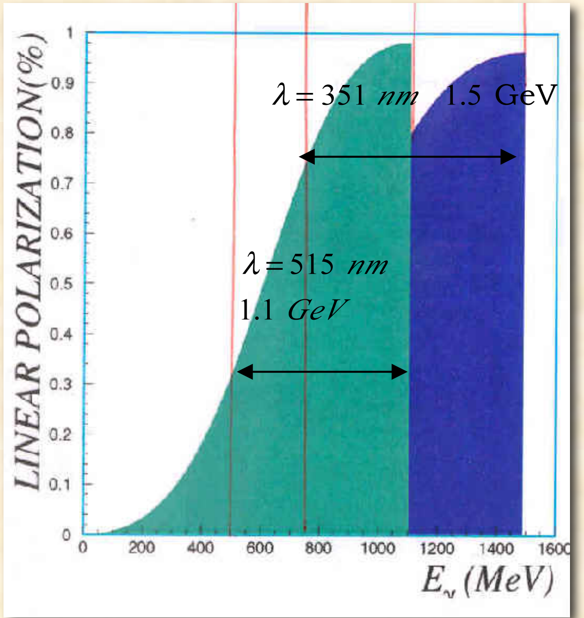
•Graal □ E_g = .6-1.5 GeV / W=1.4-1.9 GeV
Region of the second and third
baryon resonances **η**, K, **ω**, thresholds

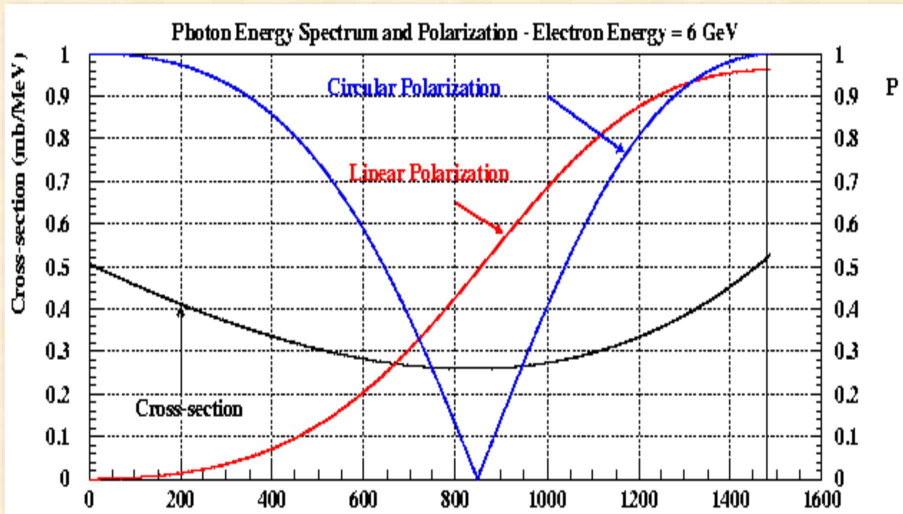
•Leps □ E_g = 1.5-2.5 GeV

η’ □ thresholds

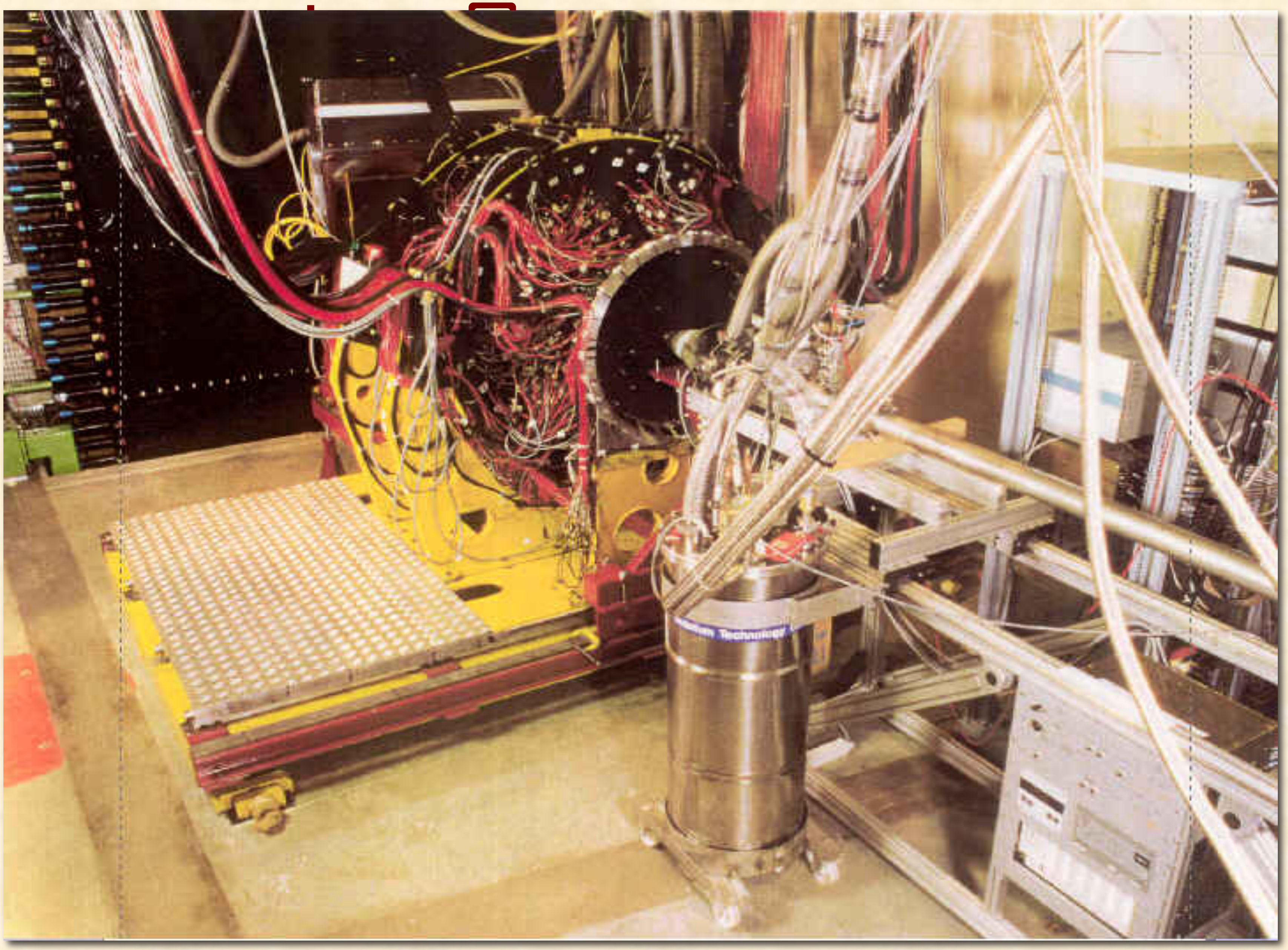
Polarized photon beams: Compton Backscattering



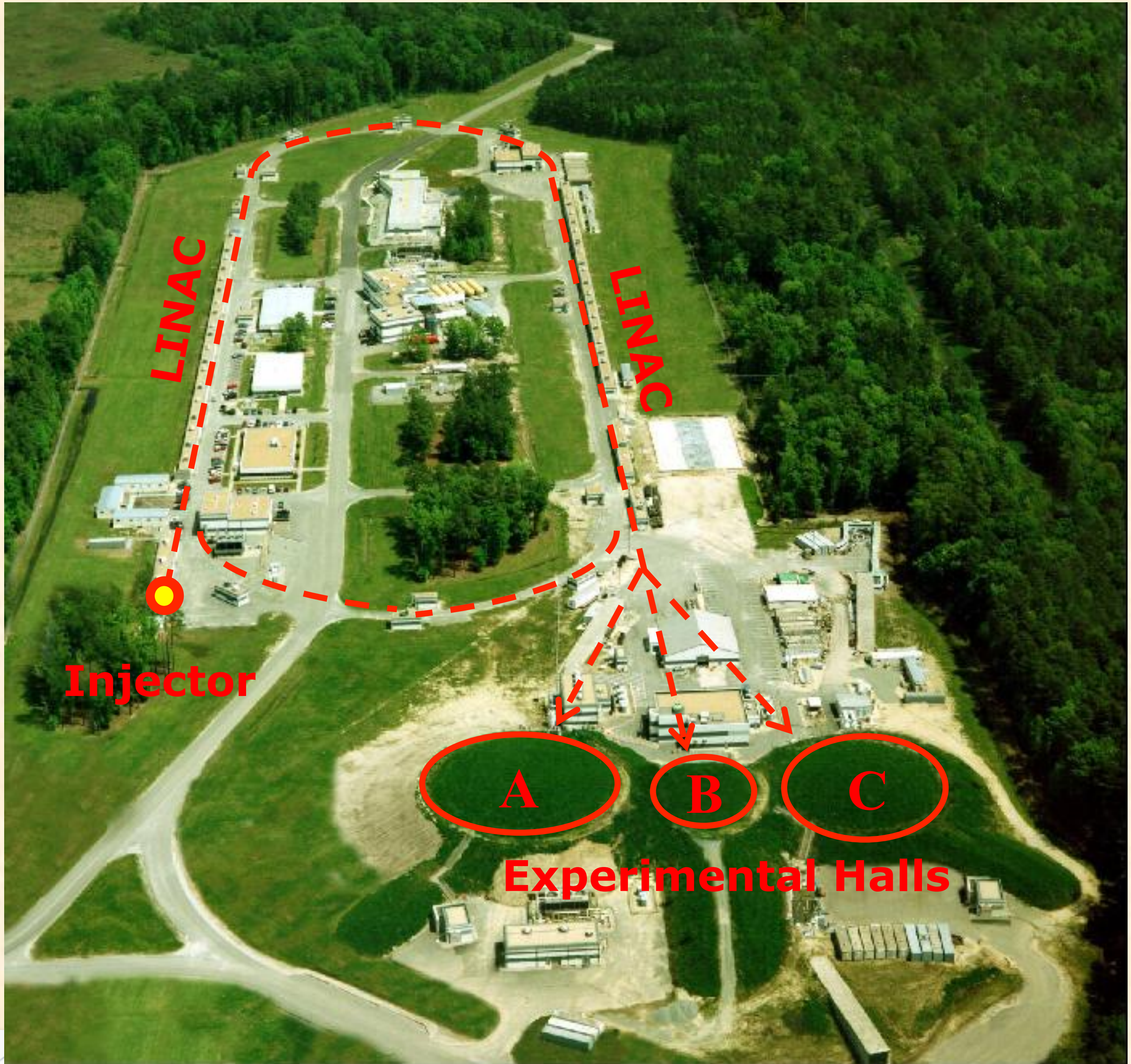




The Graal detector:



Large **A**cceptance **Gr**aal **A**pparatus for **N**uclear **E**xperiments



CEBAF

Continuous
Electron
Beam
Accelerator
Facility

- E: 0.75 –6 GeV
- I_{max}: 200mA
- Duty Cycle: 100%
- (E)/E: 2.5×10^{-5}
- Polarization: ≥85%
- Simultaneous distribution to 3 experimental Halls

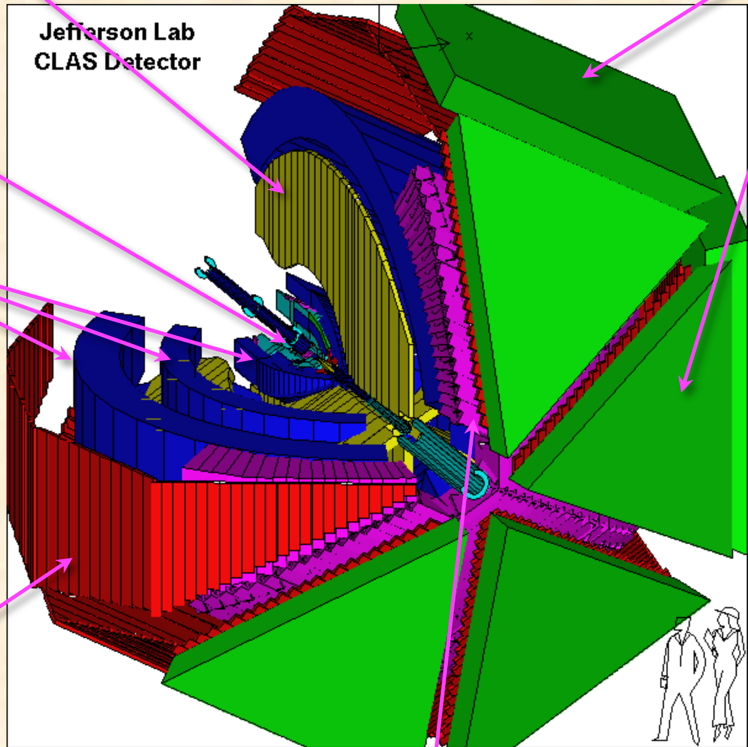
CEBAF Large Acceptance Spectrometer

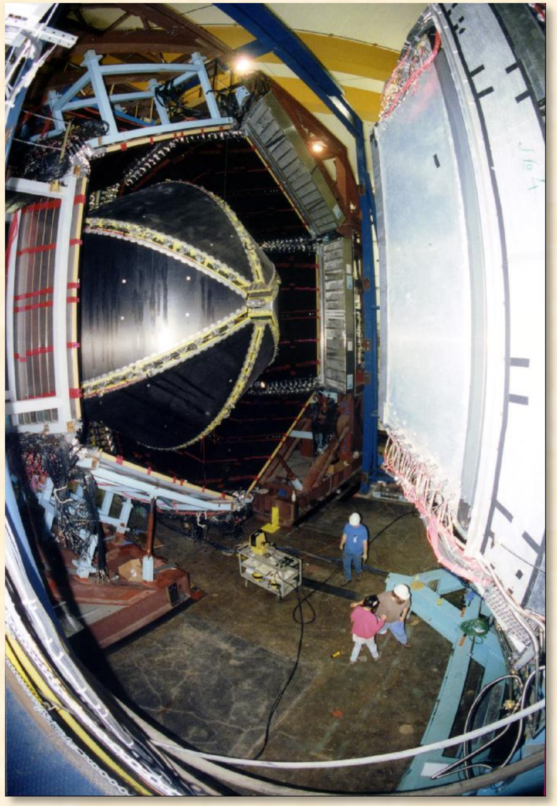
Torus magnet
6 superconducting coils

Electromagnetic calorimeters
Lead/scintillator, 1296 photomultipliers

target + start counter

Drift chambers
35,000 cells

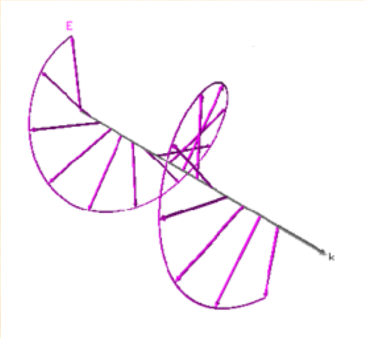




Time-of-flight counters
plastic scintillators, 684 photomultipliers

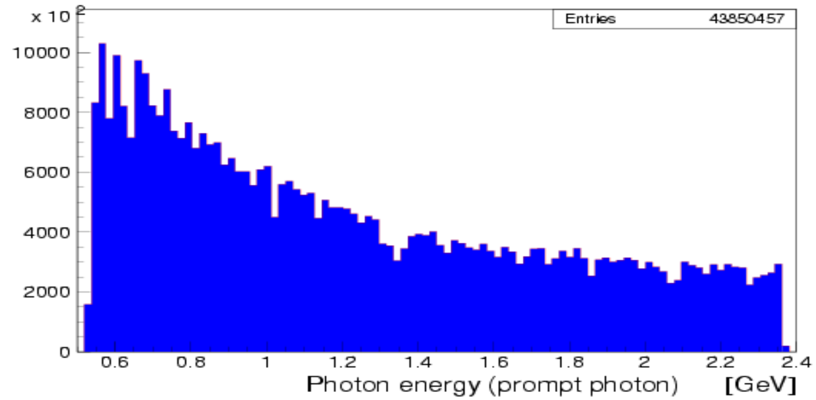
Gas Cherenkov counters
e/   separation, 256 PMTs

Circularly polarized photons

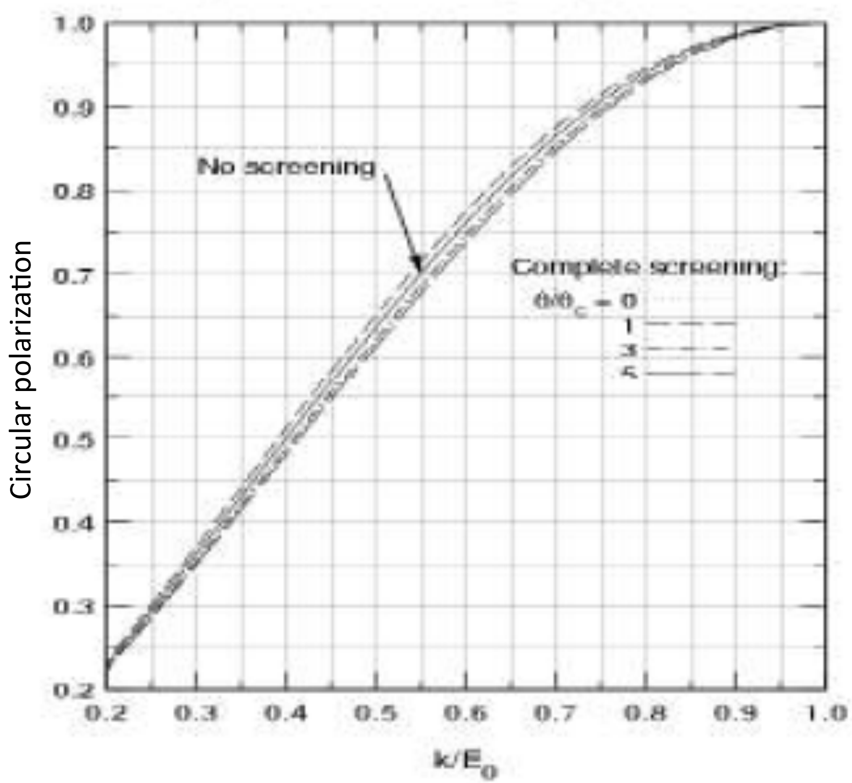


- Circularly polarized beam produced by longitudinally polarized electrons
- CEBAF electron beam polarization >85%
- tagged flux ~ 50 - 100MHz for k>0.5 E_0

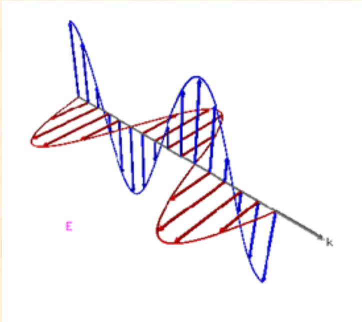
$$P_\gamma = P_e \cdot \frac{4k - k^2}{4 - 4k + 3k^2}$$



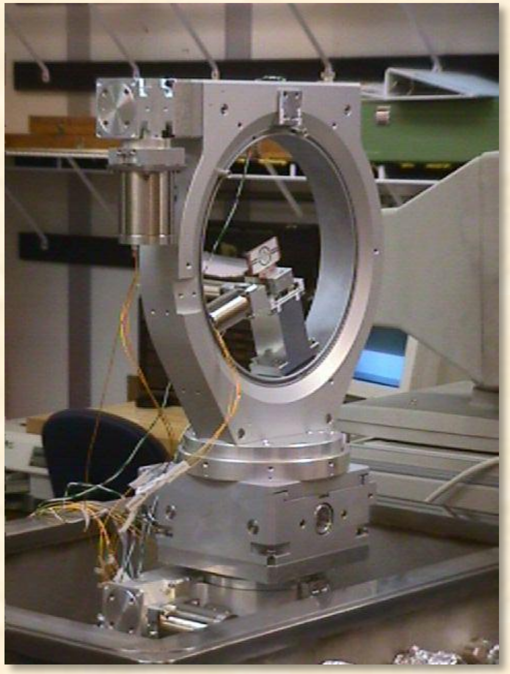
Circular polarization from 100% polarized electron beam

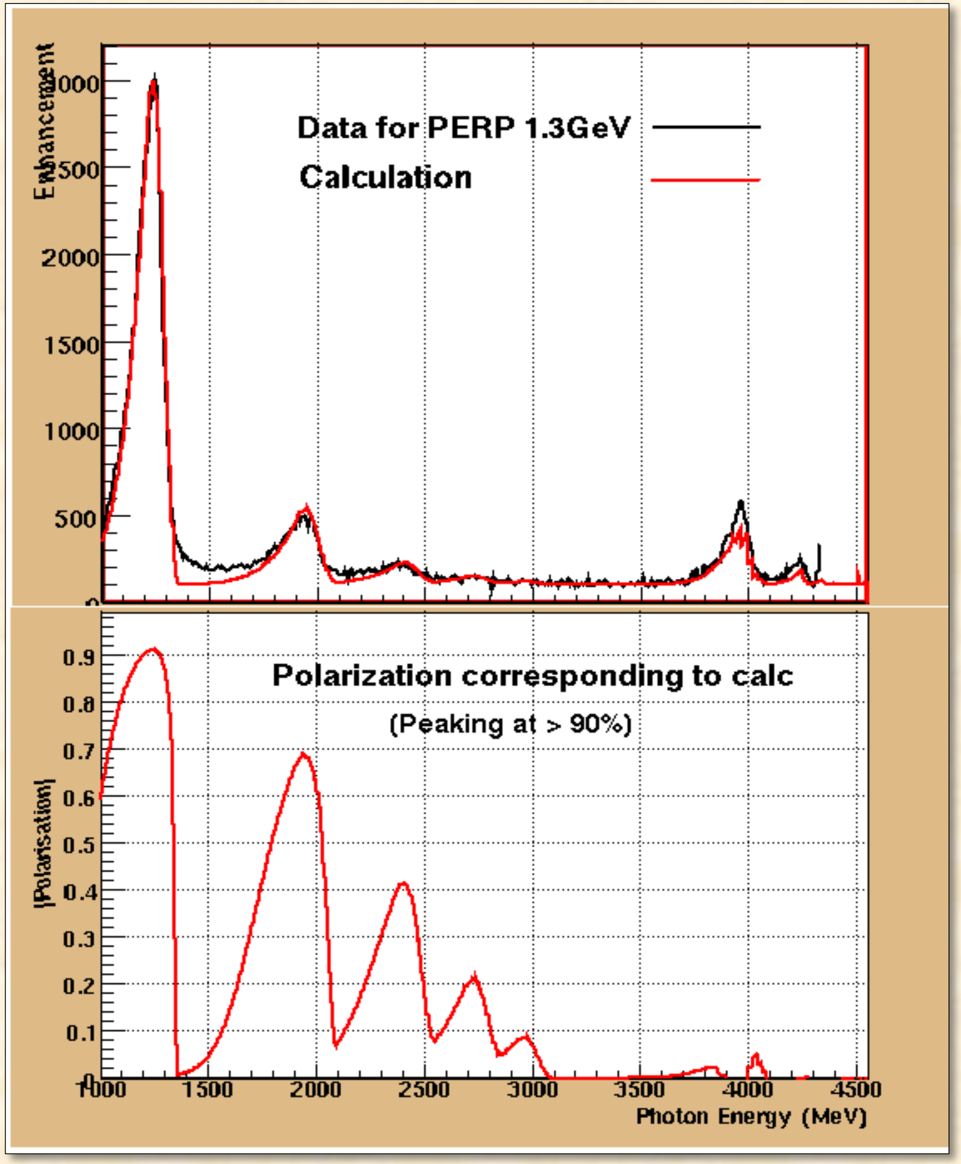


Linearly polarized photons

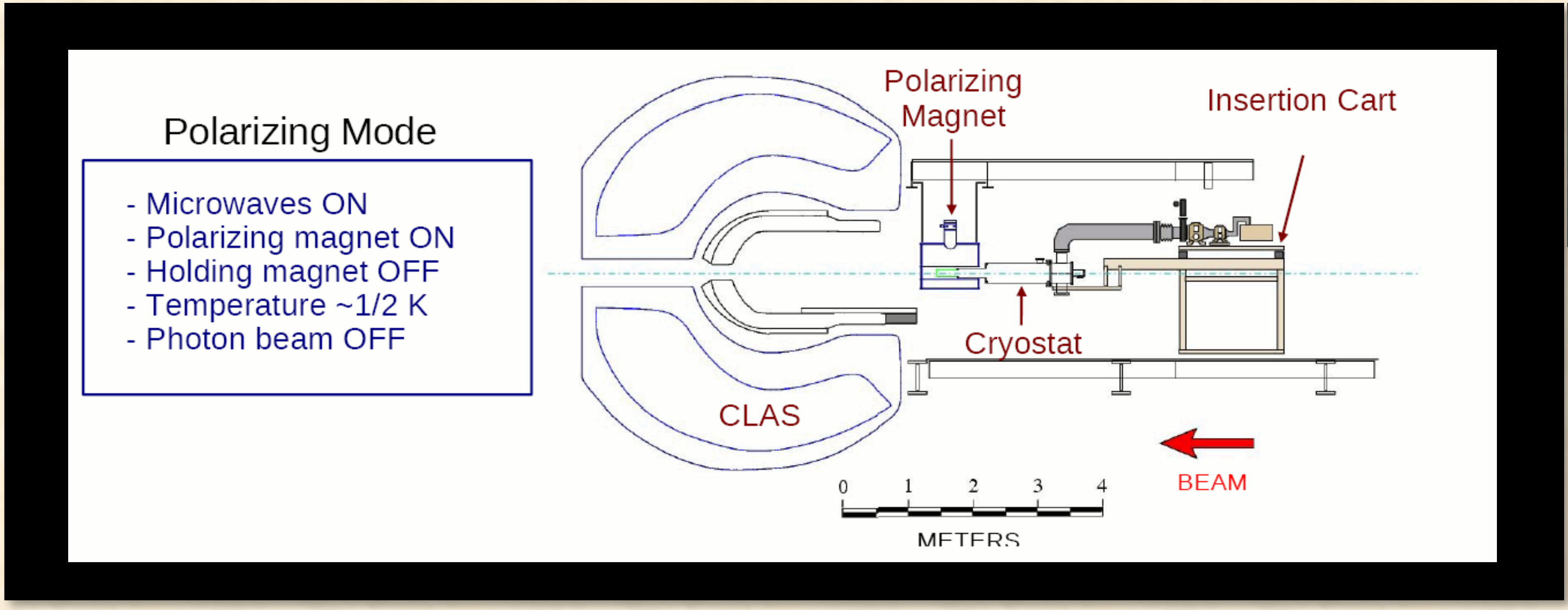


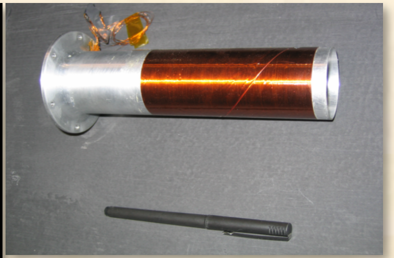
Linearly polarized photons: coherent bremsstrahlung on oriented diamond crystal

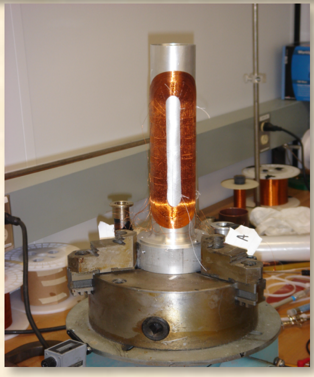


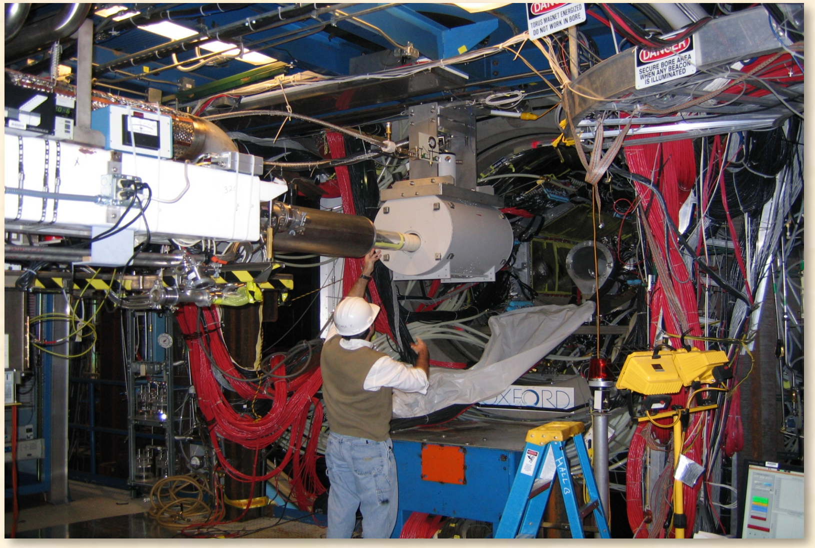


Polarized targets: frozen spin butanol FROST at CLAS









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

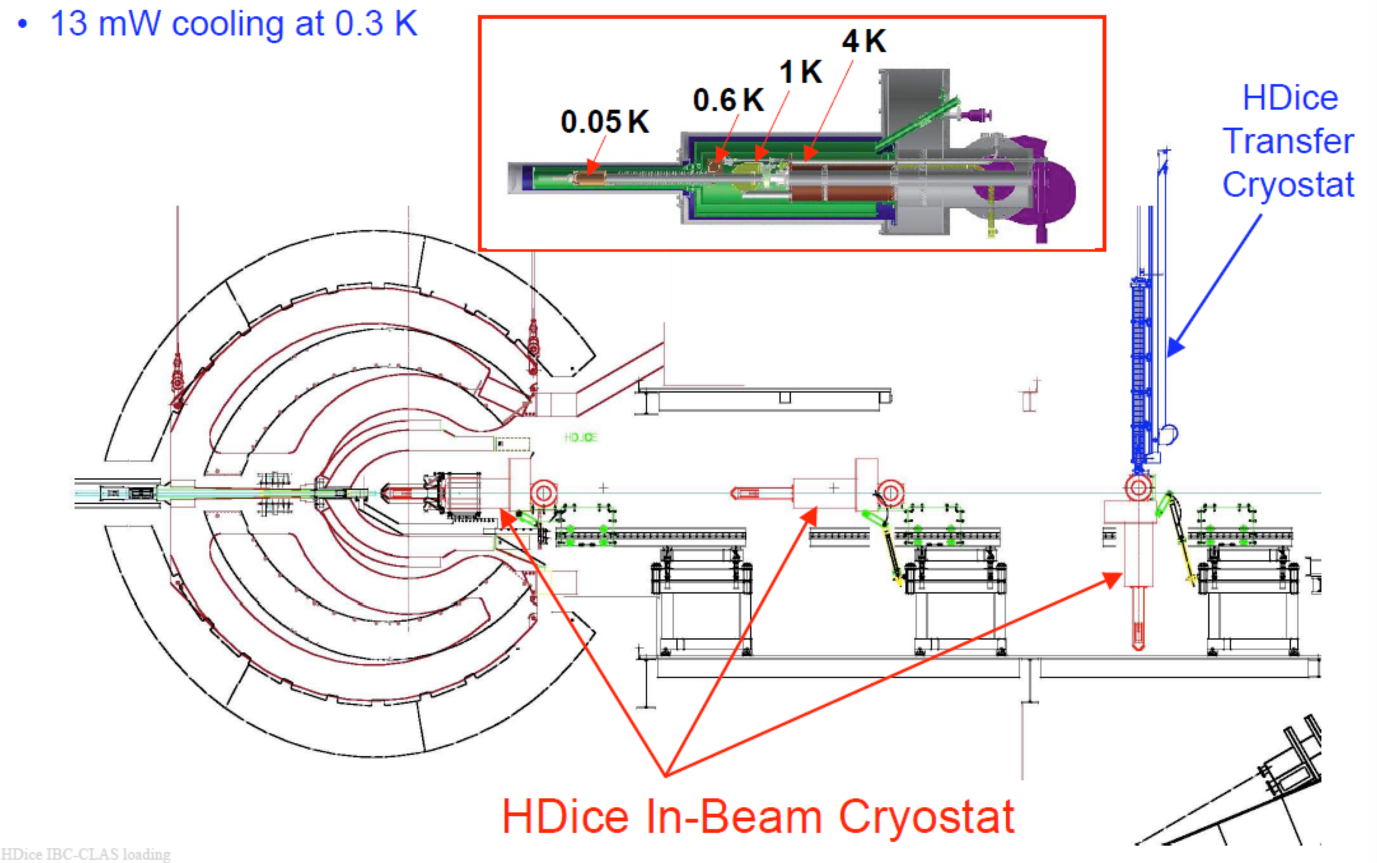
Very reliable.

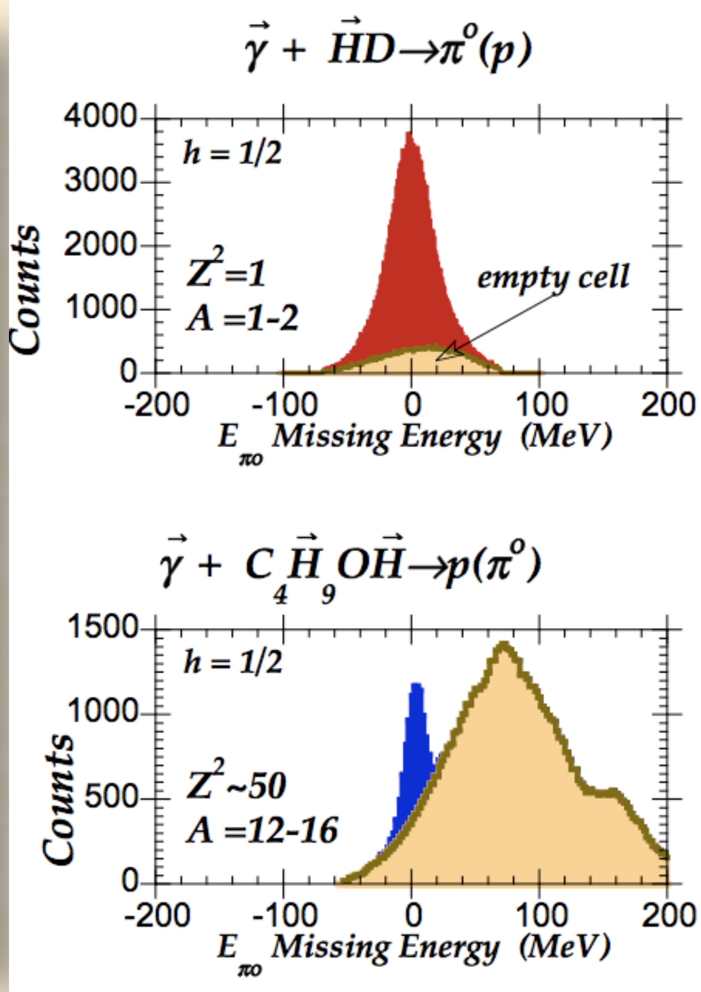
HDIce polarized target

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

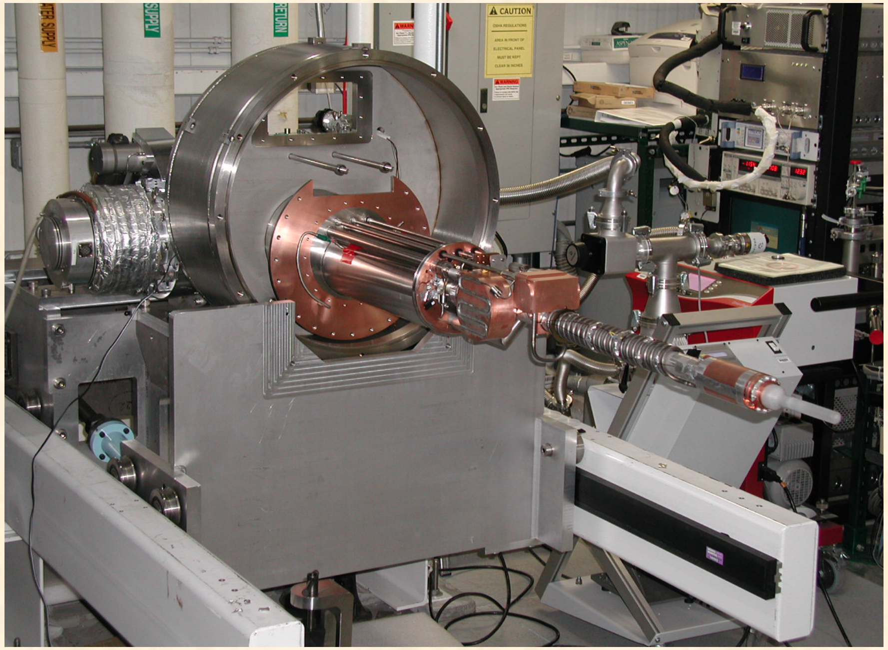
- Spin can be moved between H and D with RF transitions
- All material can be polarized with almost no background

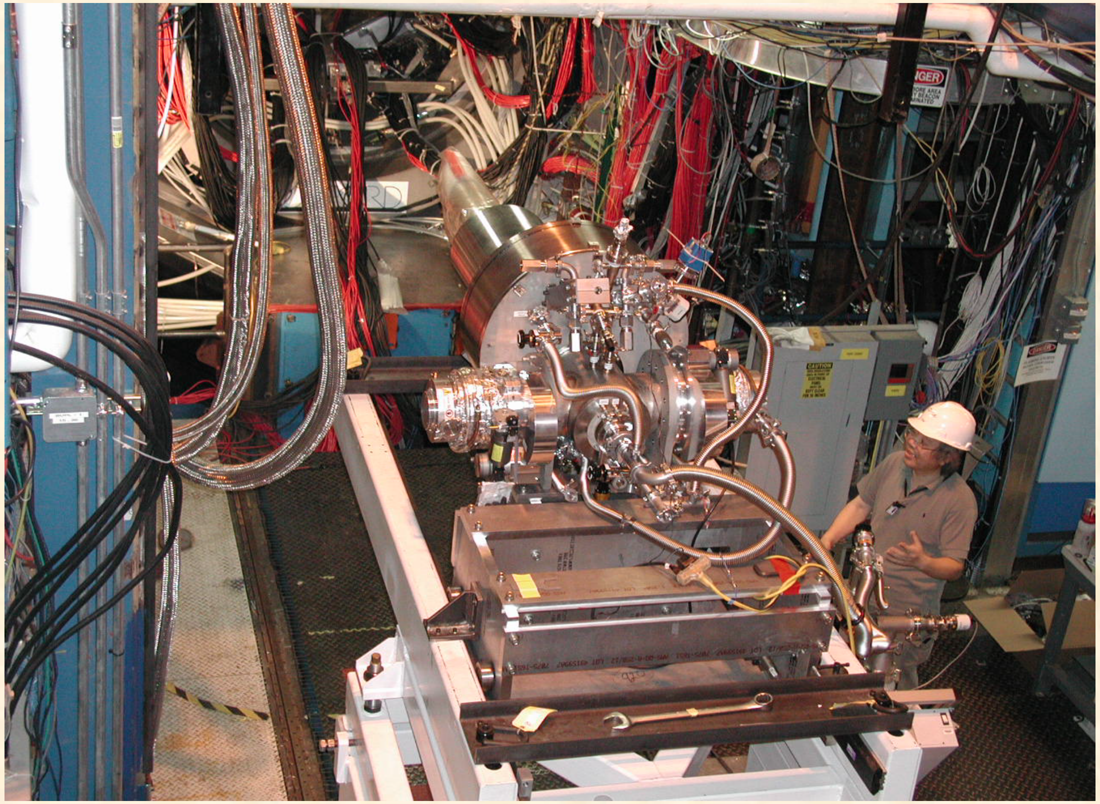
- designed for both γ (w Start Counter) and e⁻ (w mini-Torus) running
- 13 mW cooling at 0.3 K





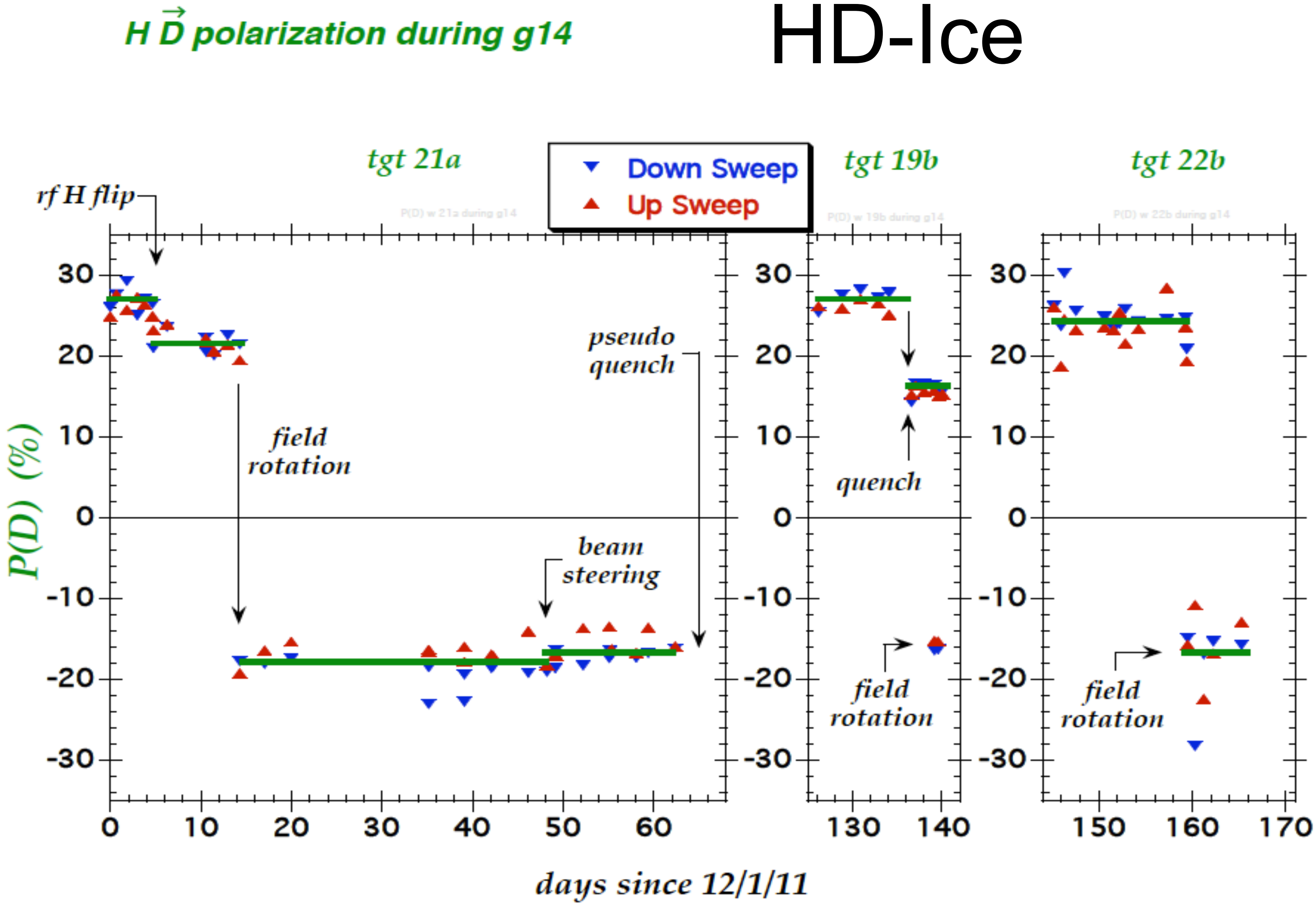
HD-Ice





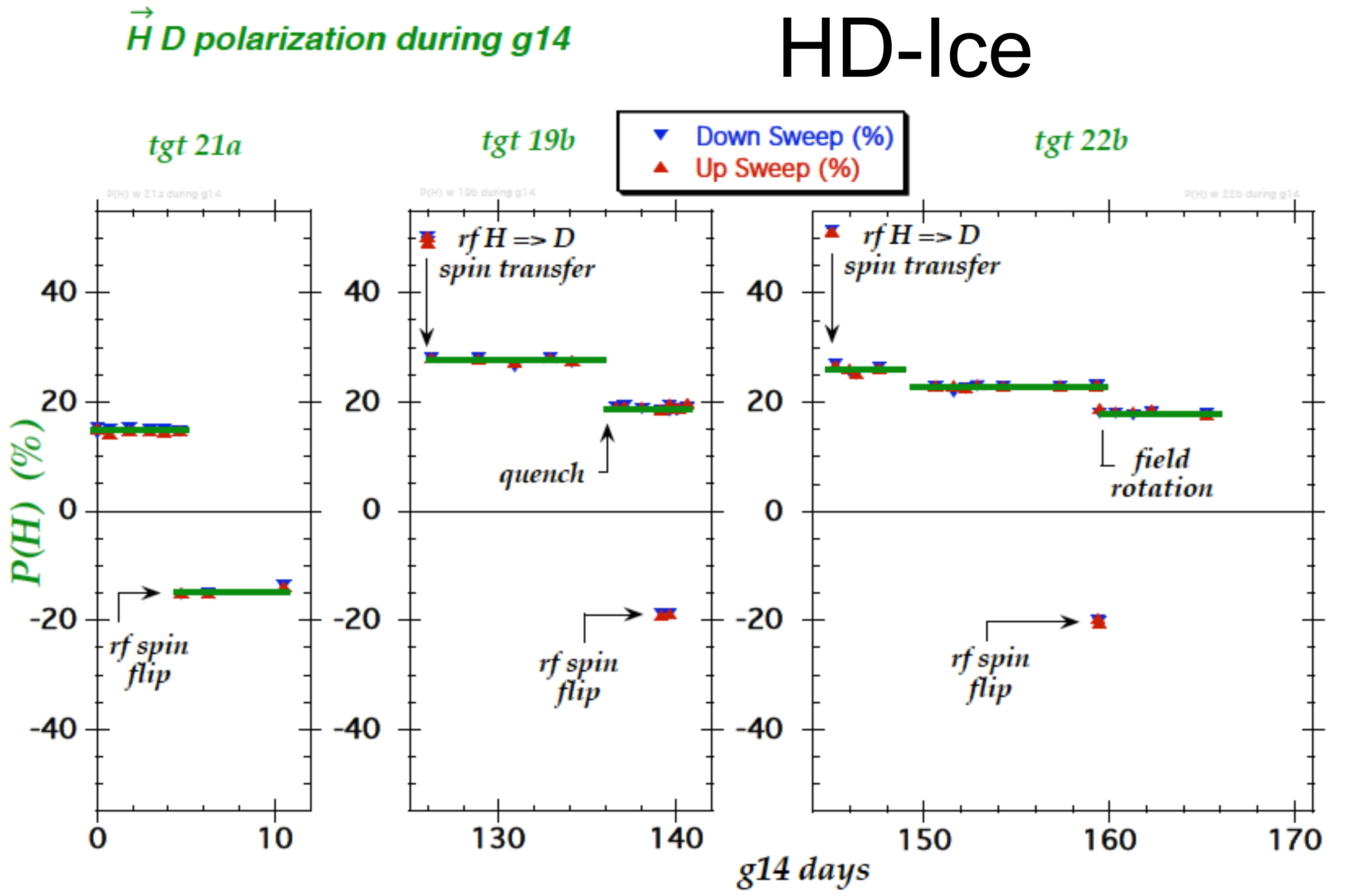
Longitudinal and Transverse Polarizations: > 60%
Relaxation time: > 1 year
Polarization procedure [illegible] 3 months
Data taking: [illegible] months
Very complicated target transfer technology.

HD-Ice



H D⃗ 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) (%)
g14 days
40
20
0
-20
-40
0
10
130
140
150
160
170

Measured Reaction Channels

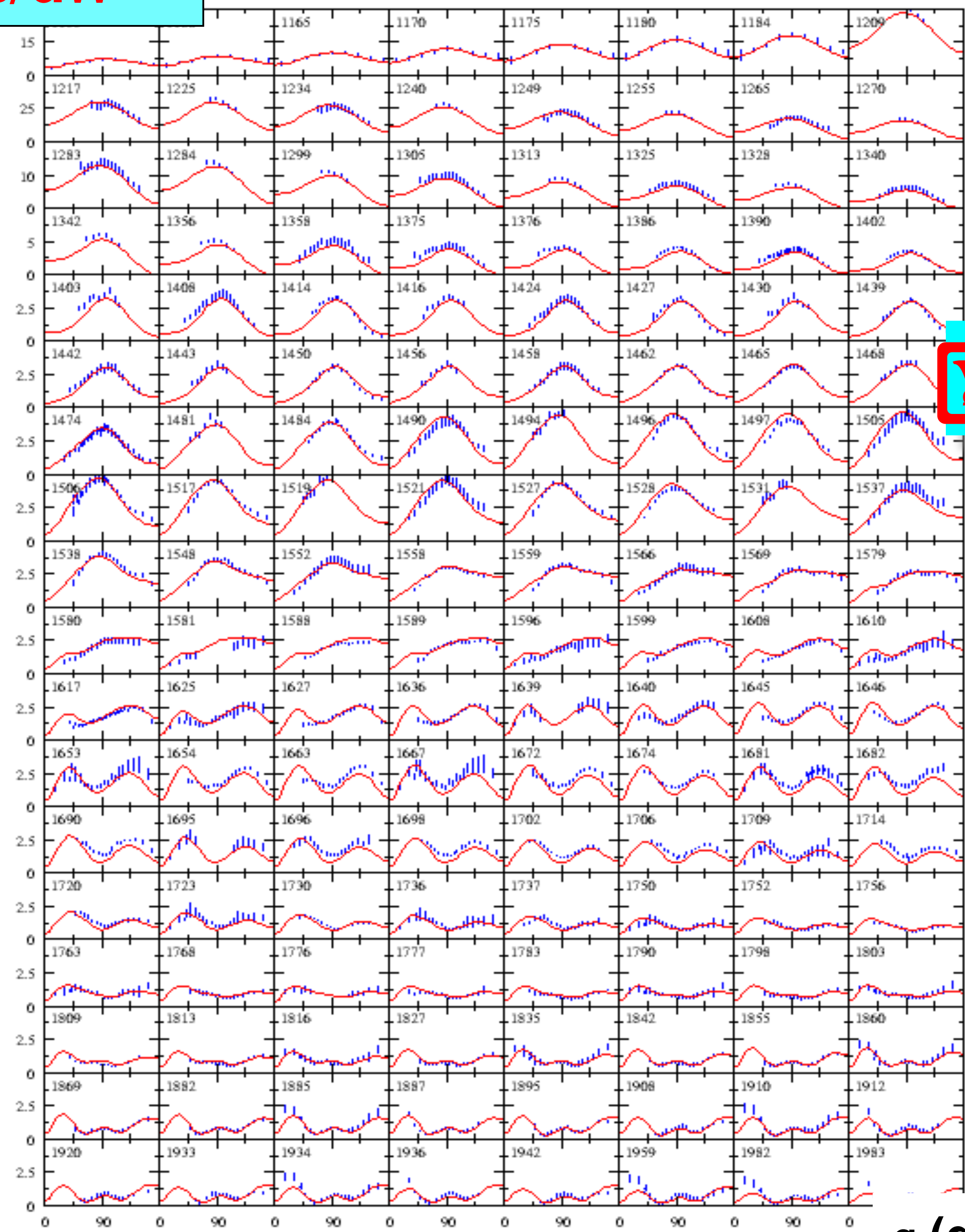
- $\gamma p \to \pi^0 p,\ \pi^+ n$
- $\gamma p \to \eta p$
- $\gamma p \to \eta' p$
- $\gamma p \to KY\ (K^+\Lambda,\ K^+\Sigma^0,\ K^0\Sigma^+)$
- $\gamma p \to \pi^+\pi^- p\ \omega p,\ \rho p,\ \phi p$

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

EBAC

ds/dW

Kamano
Nakamura
Lee &
Sato, 2012



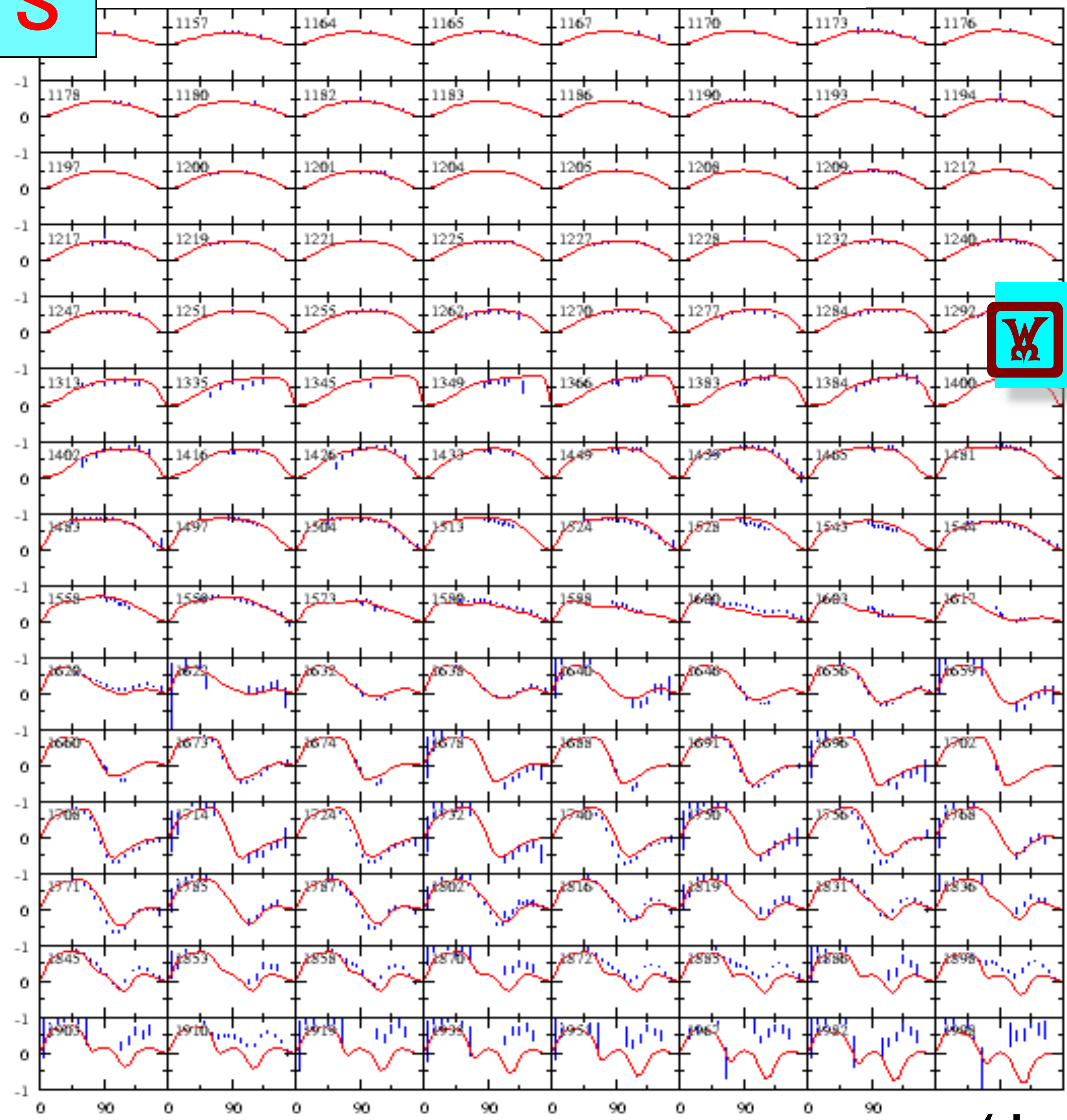
p → 0p

q (deg.)

EBAC

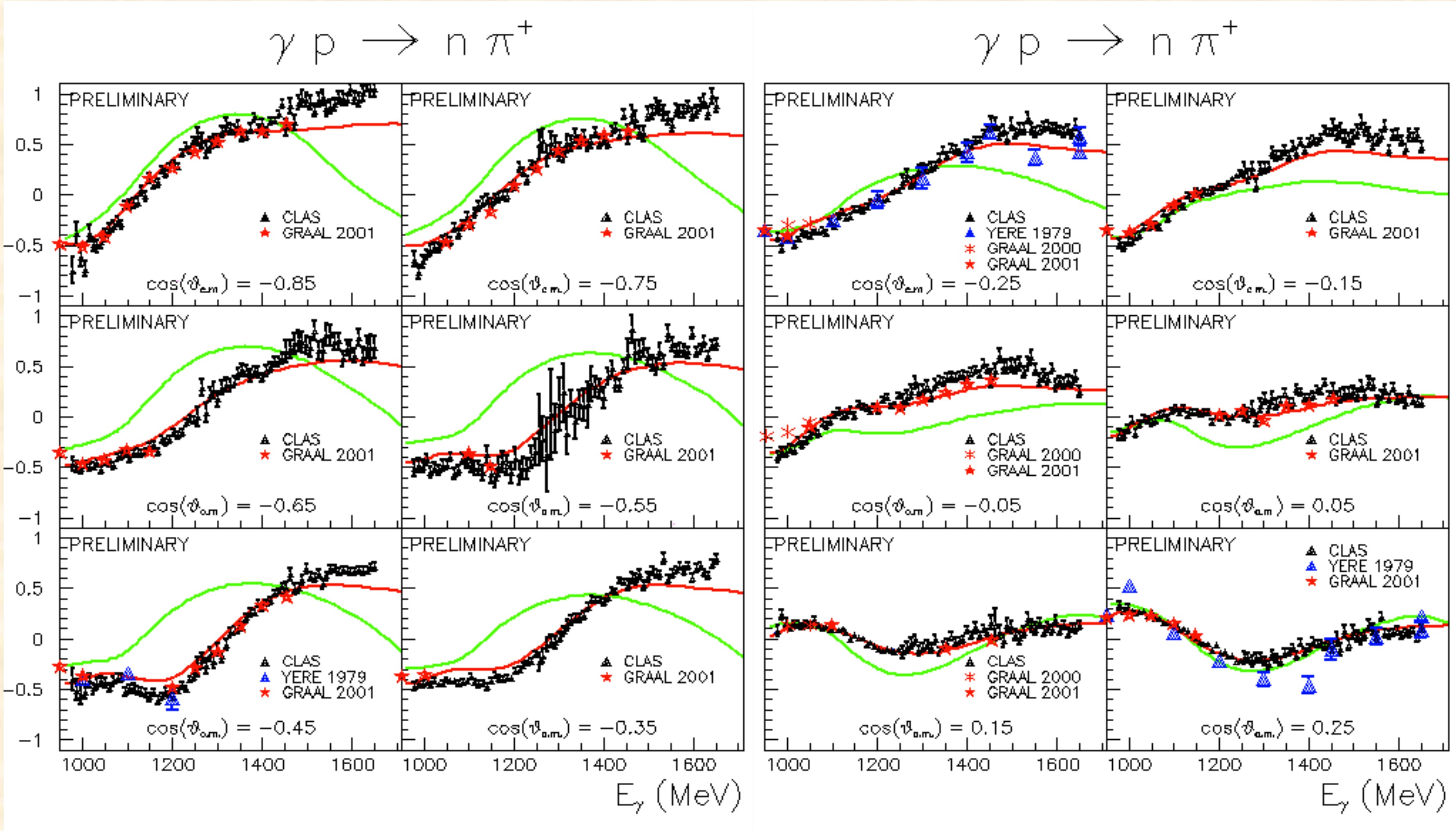
S

Kamano
Nakamura
Lee &
Sato, 2012



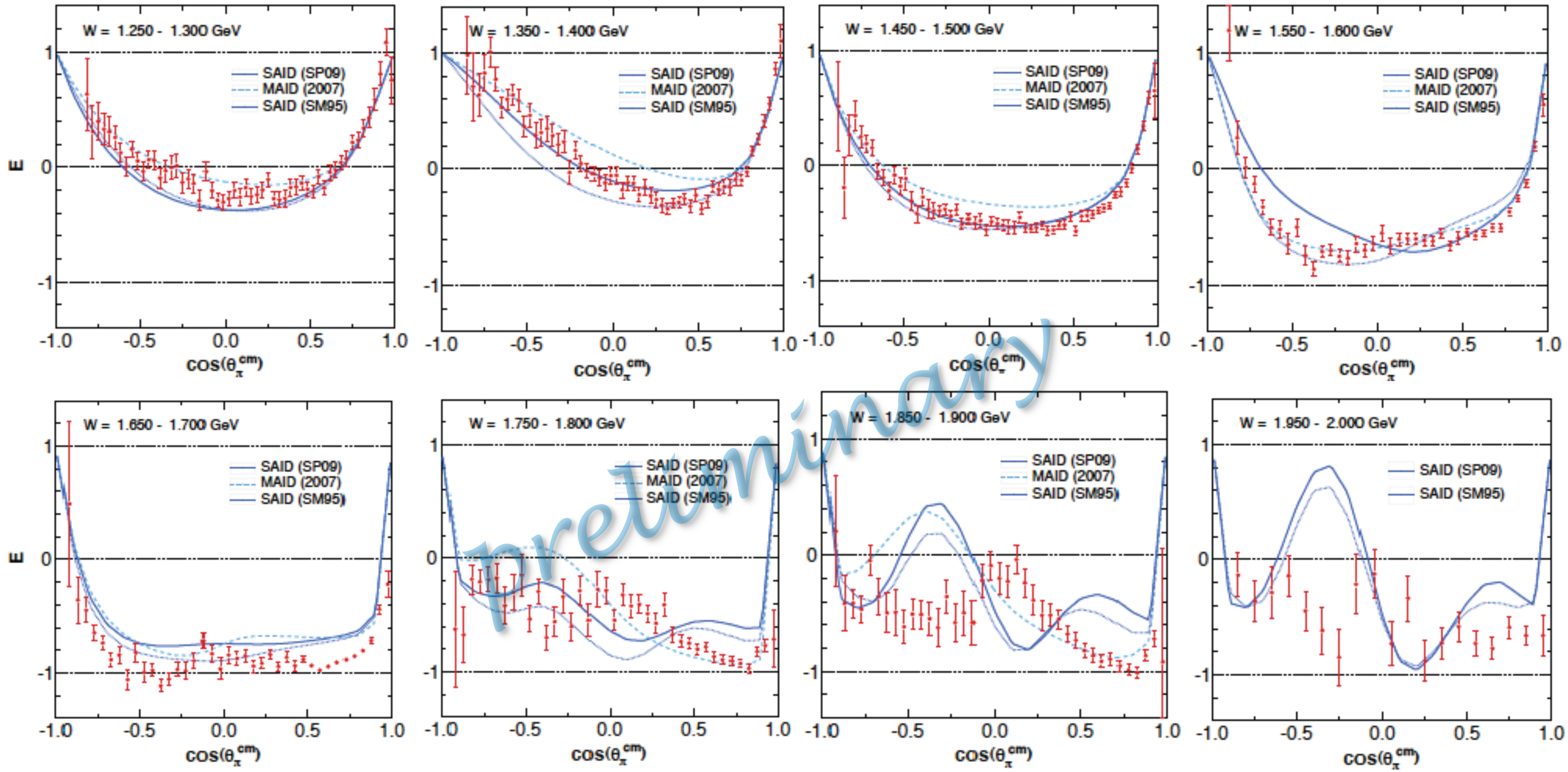
[illegible]p → [illegible]^{0}p

gp p+n Photon asymmetry S



gp p^{+}n Helicity asymmetry E

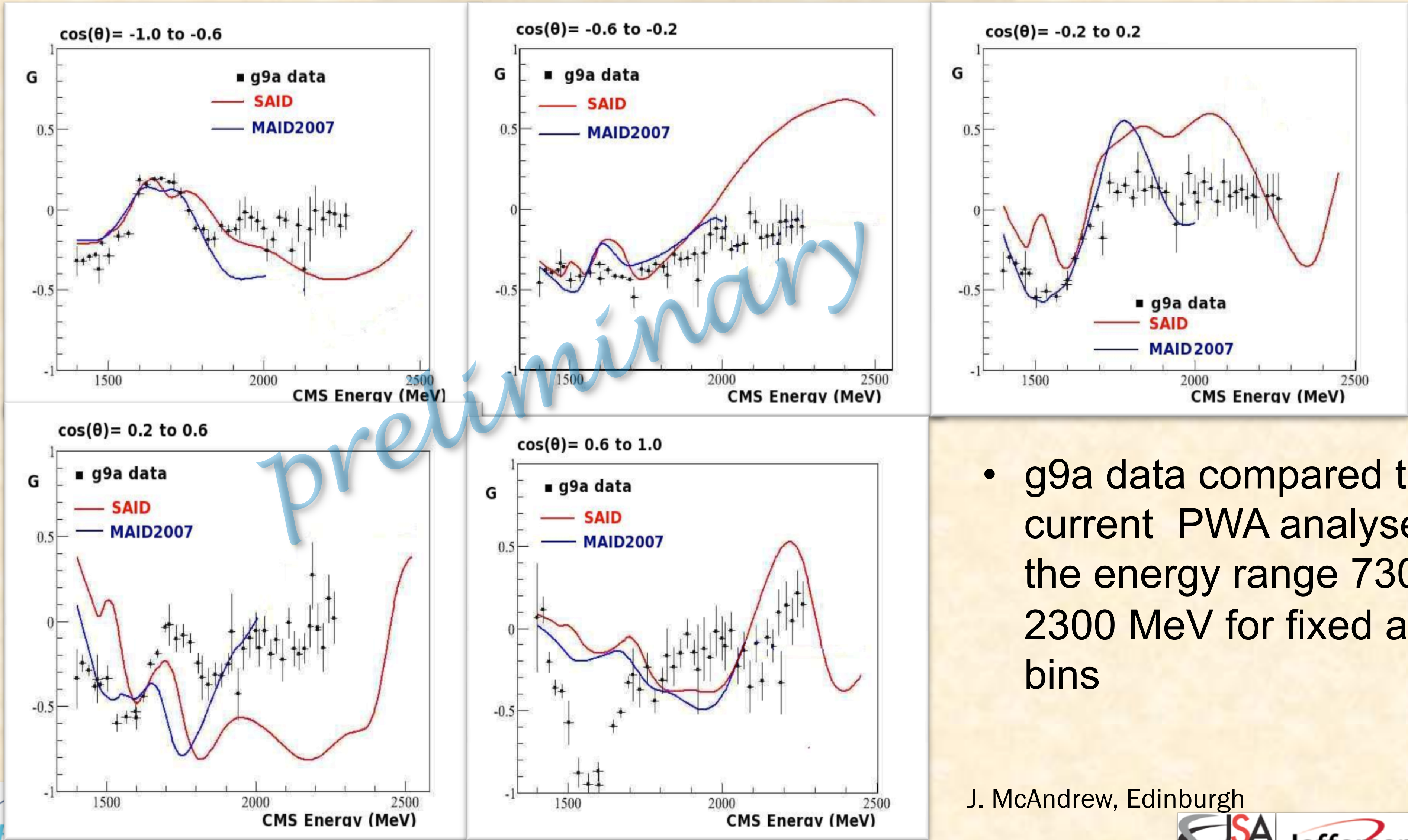
circularly polarized beam – longitudinally polarized target (g9a-FROST)



S. Strauch

gp p⁺n Helicity asymmetry G

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

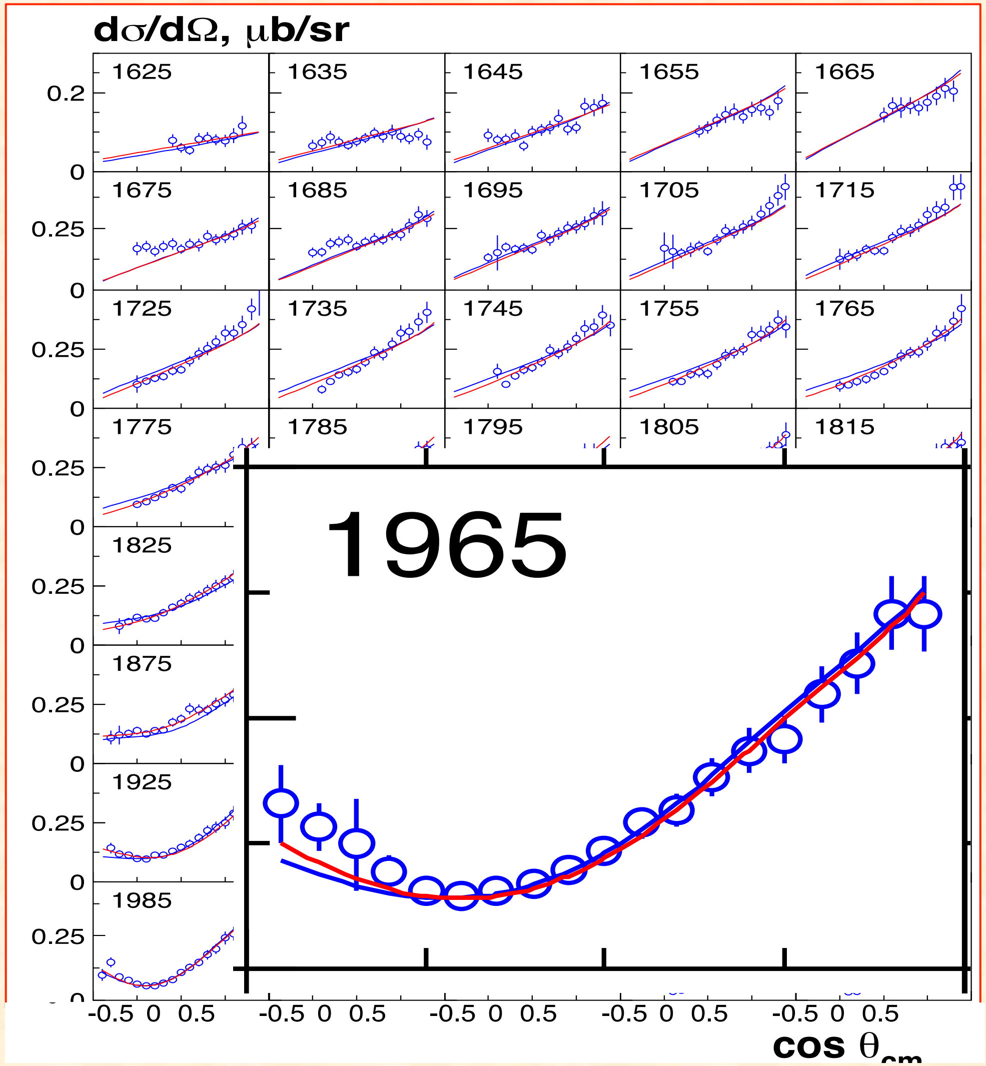


- g9a data compared to current PWA analyses in the energy range 730 – 2300 MeV for fixed angular bins

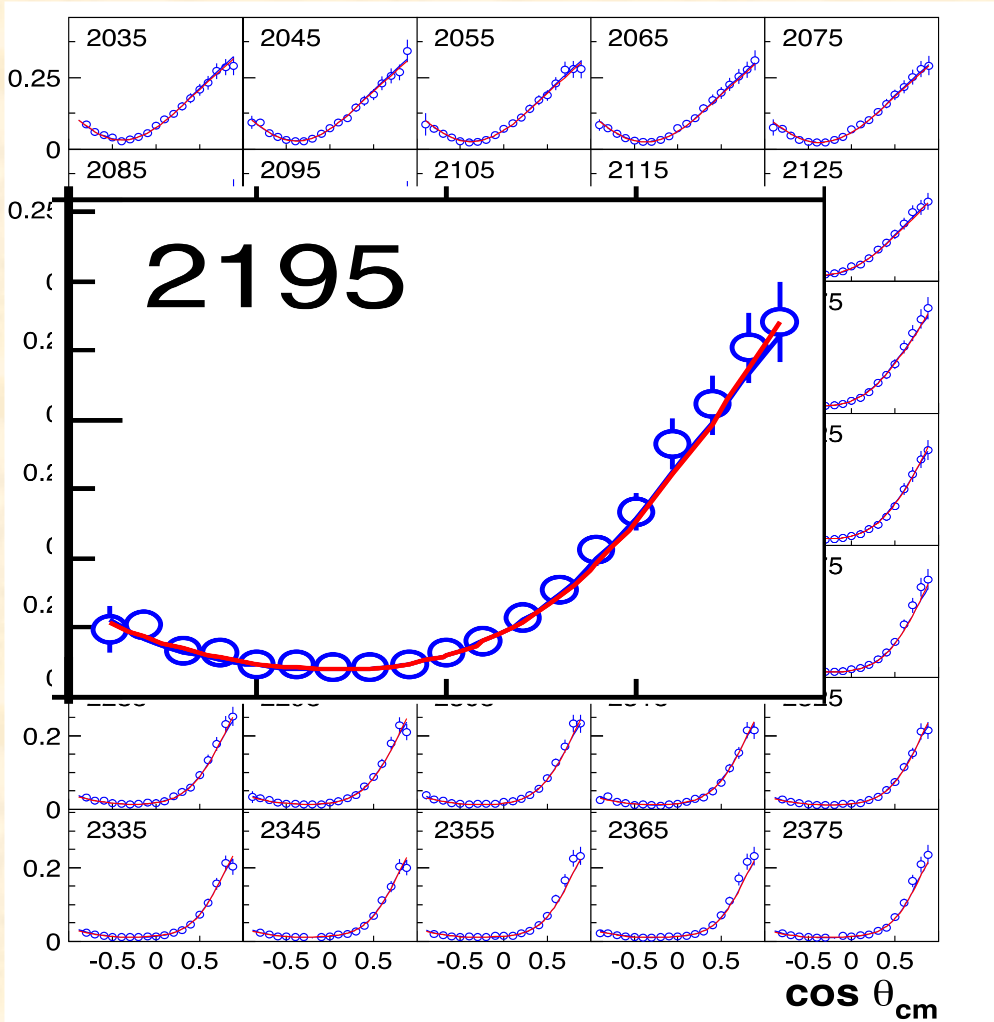
J. McAndrew, Edinburgh

Strangeness production $\gamma p \rightarrow K^+\Lambda \rightarrow K^+ p \pi^-$

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

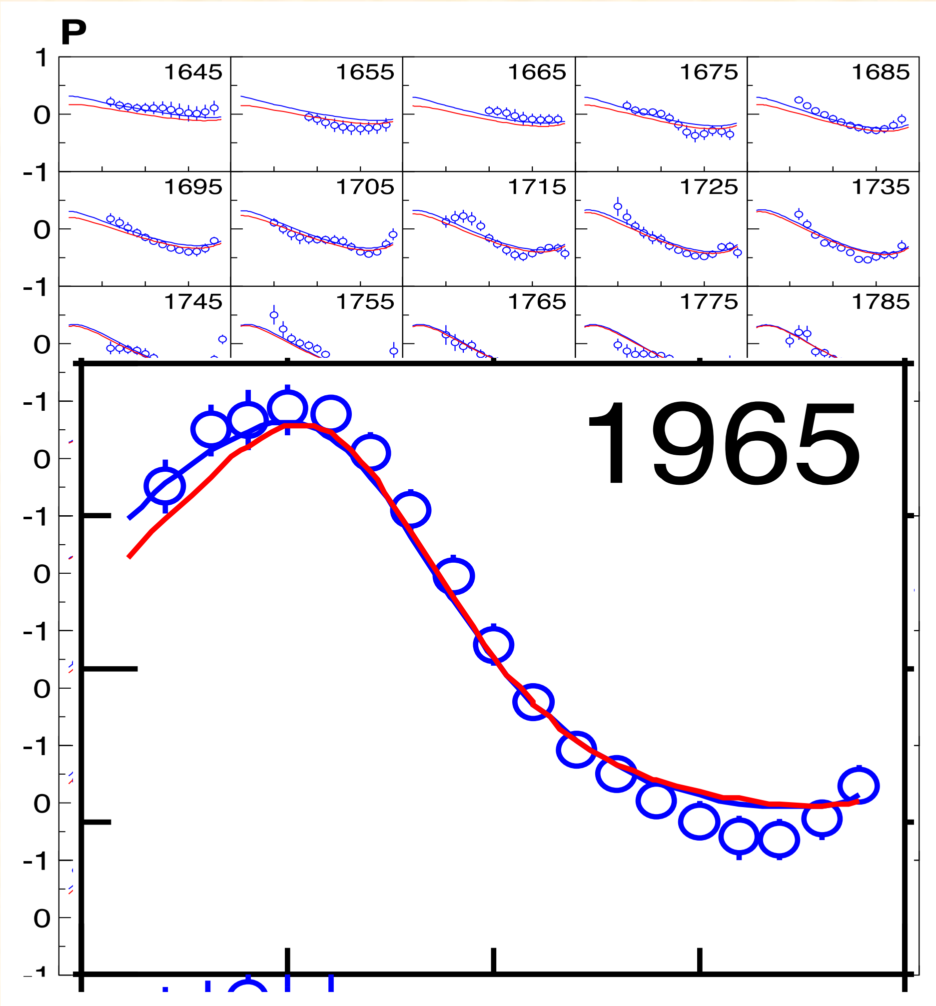


A.V. Anisovich et al, EPJ A48, 15 (2012)



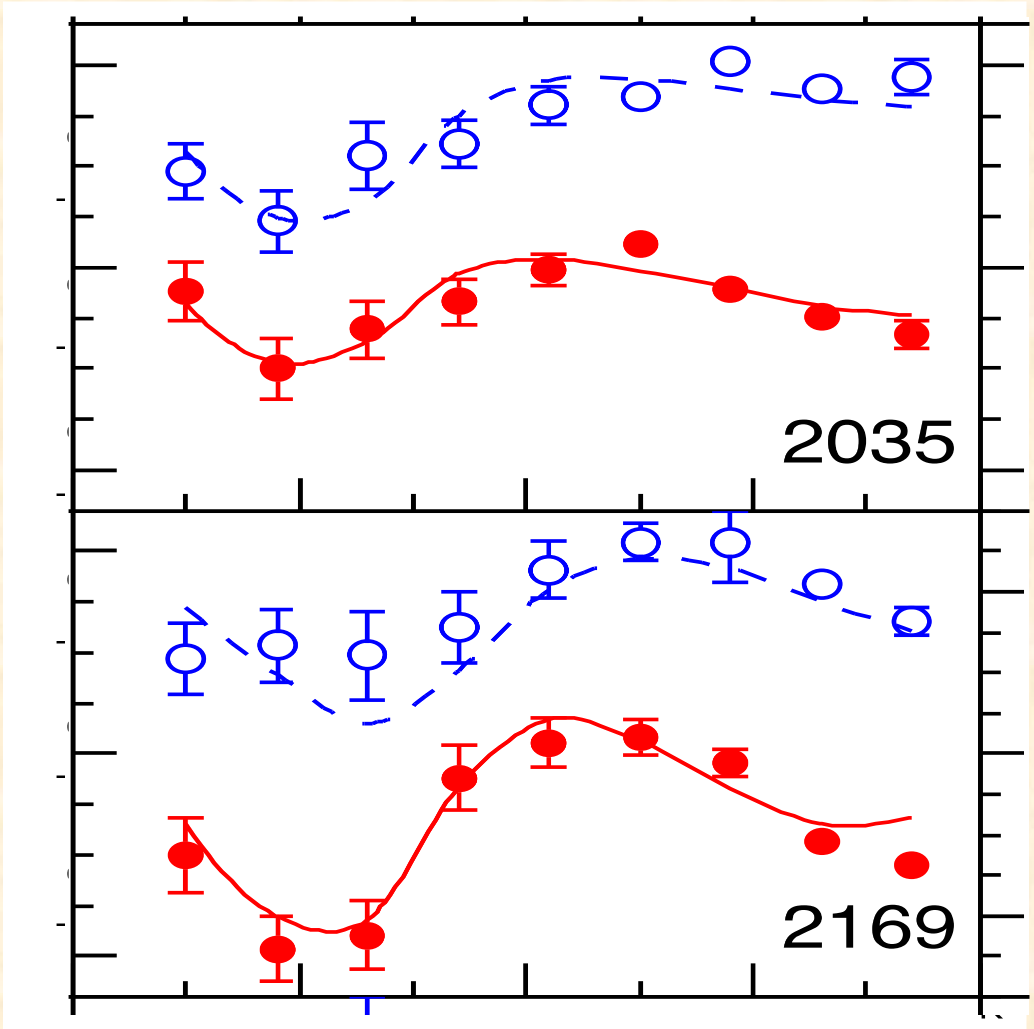
Strangeness production $\vec{\gamma}p \rightarrow K^+\vec{\Lambda} \rightarrow K^+p\pi^-$

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



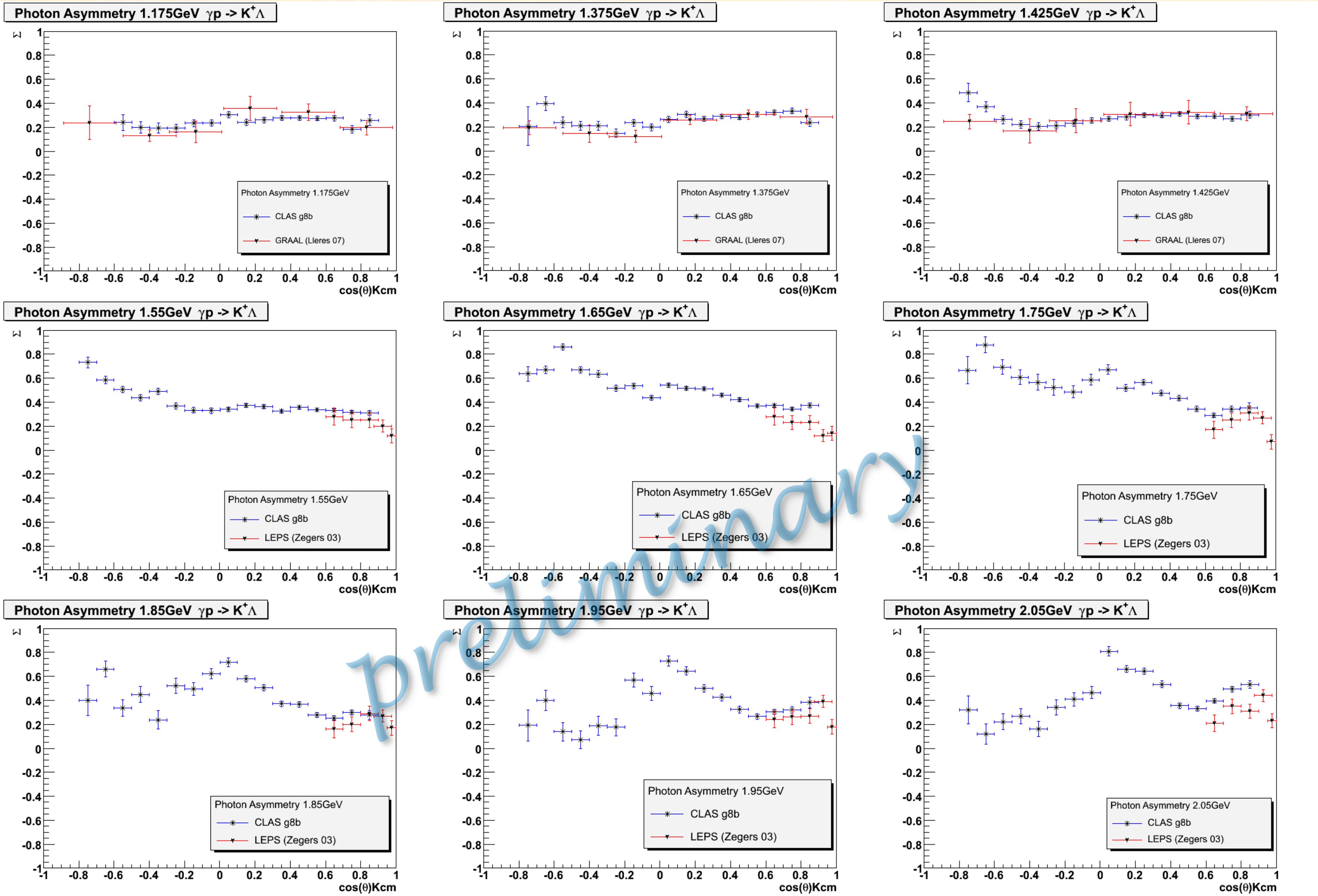
M. Mc Cracken et al. (CLAS), Phys. Rev. C 81, 025201, 2010

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



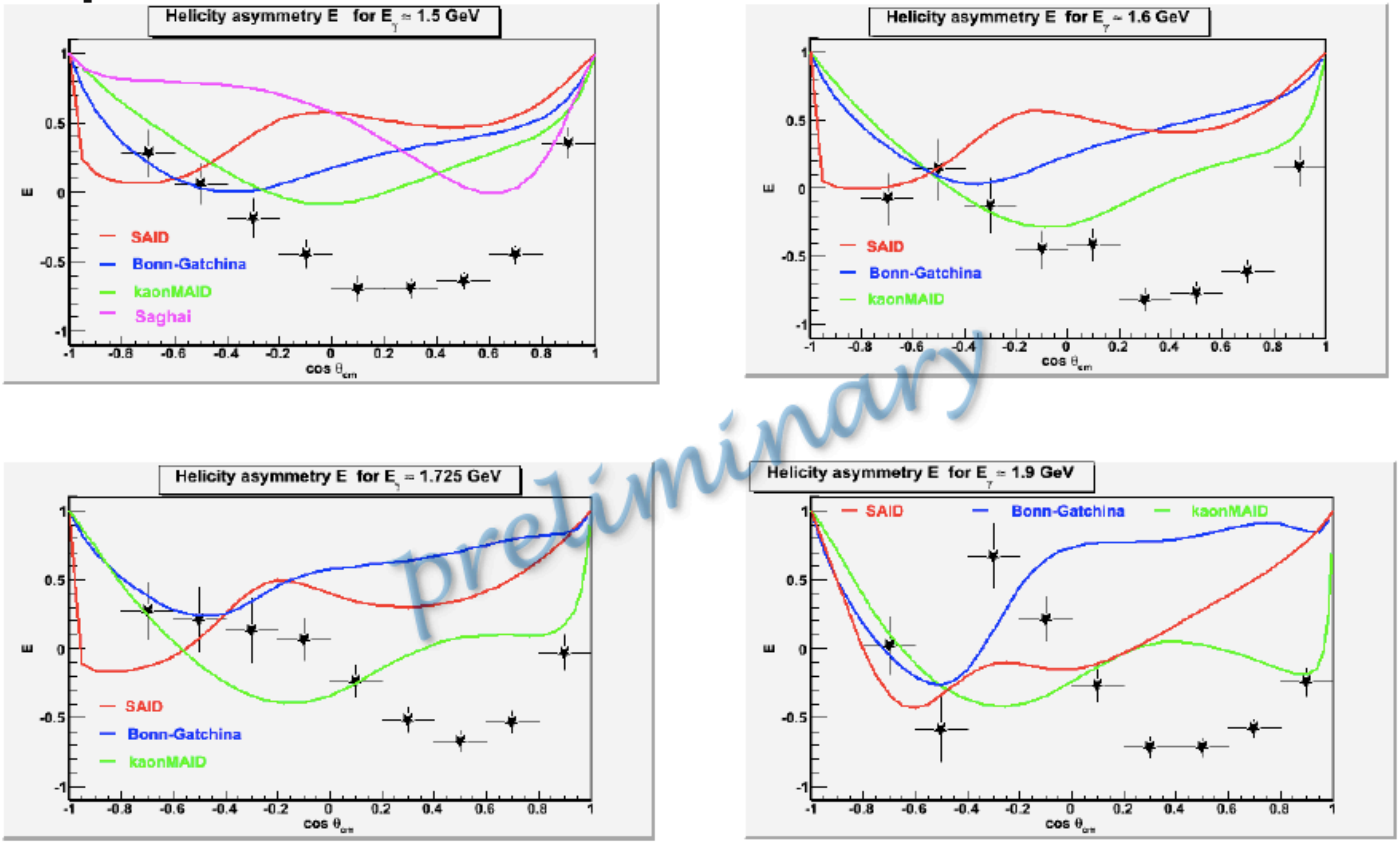
D. Bradford et al. (CLAS), Phys.Rev. C75, 035205, 2007

γp→K⁺Λ Photon Asymmetry S



C. Patterson

$K^+\Lambda$ Helicity Asymmetry E



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

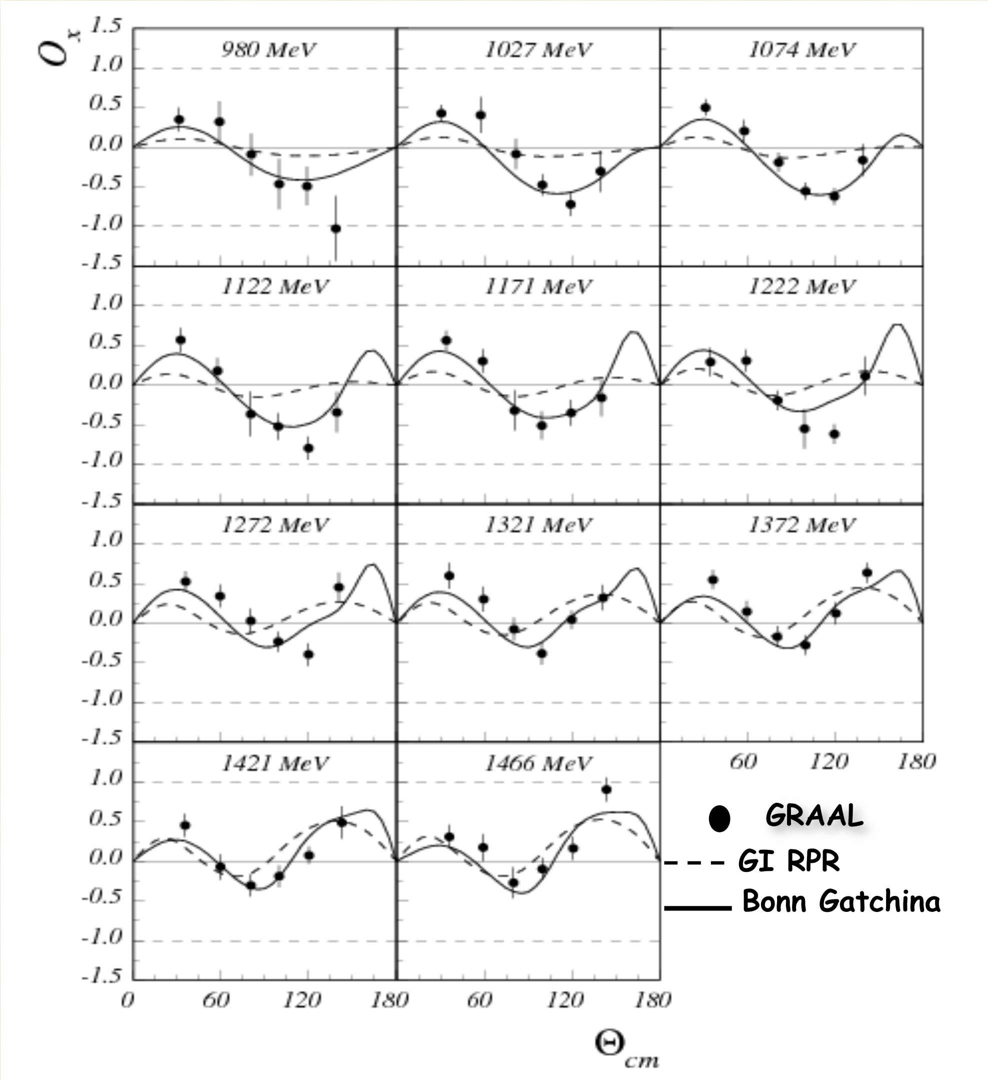
L. Casey, Catholic U.

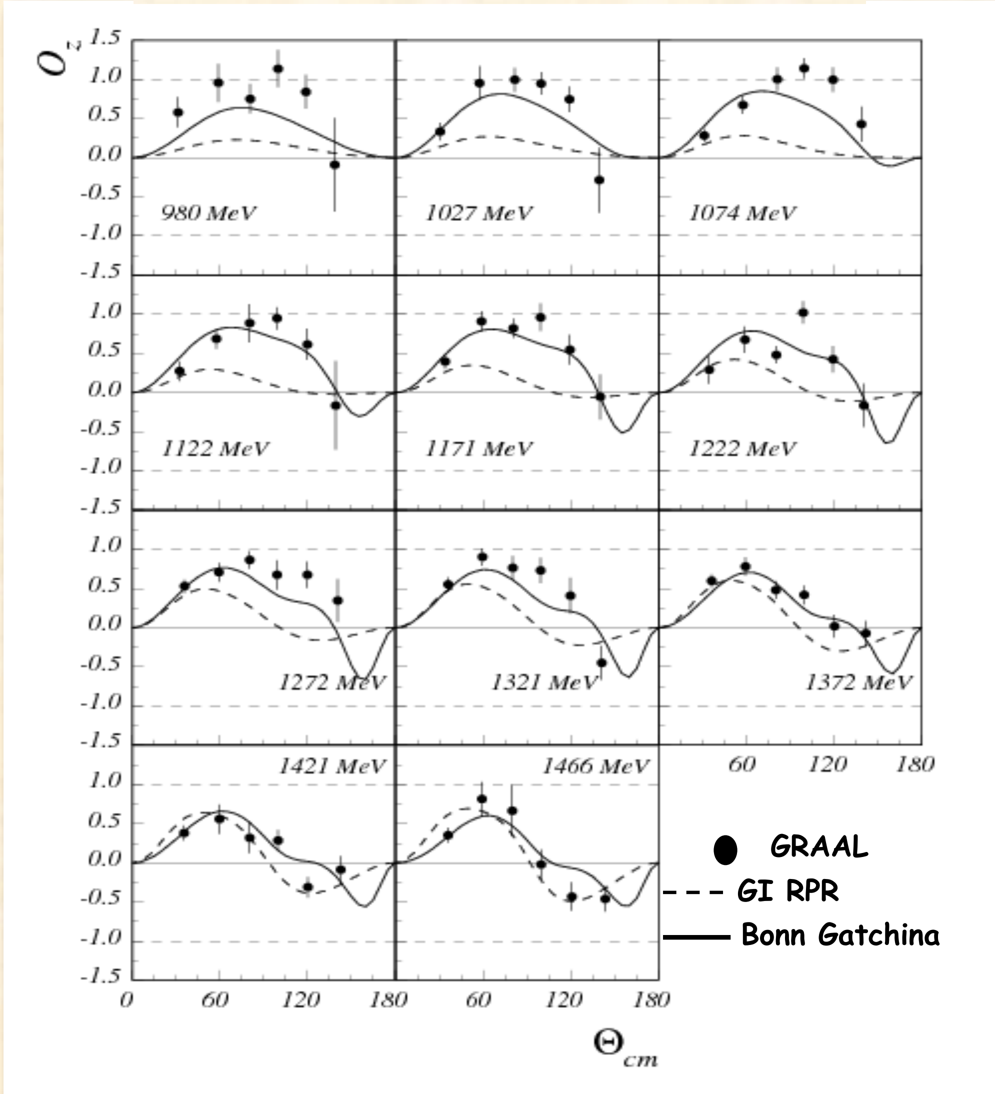
Double Polarization Observables in K+Λ Photoproduction

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

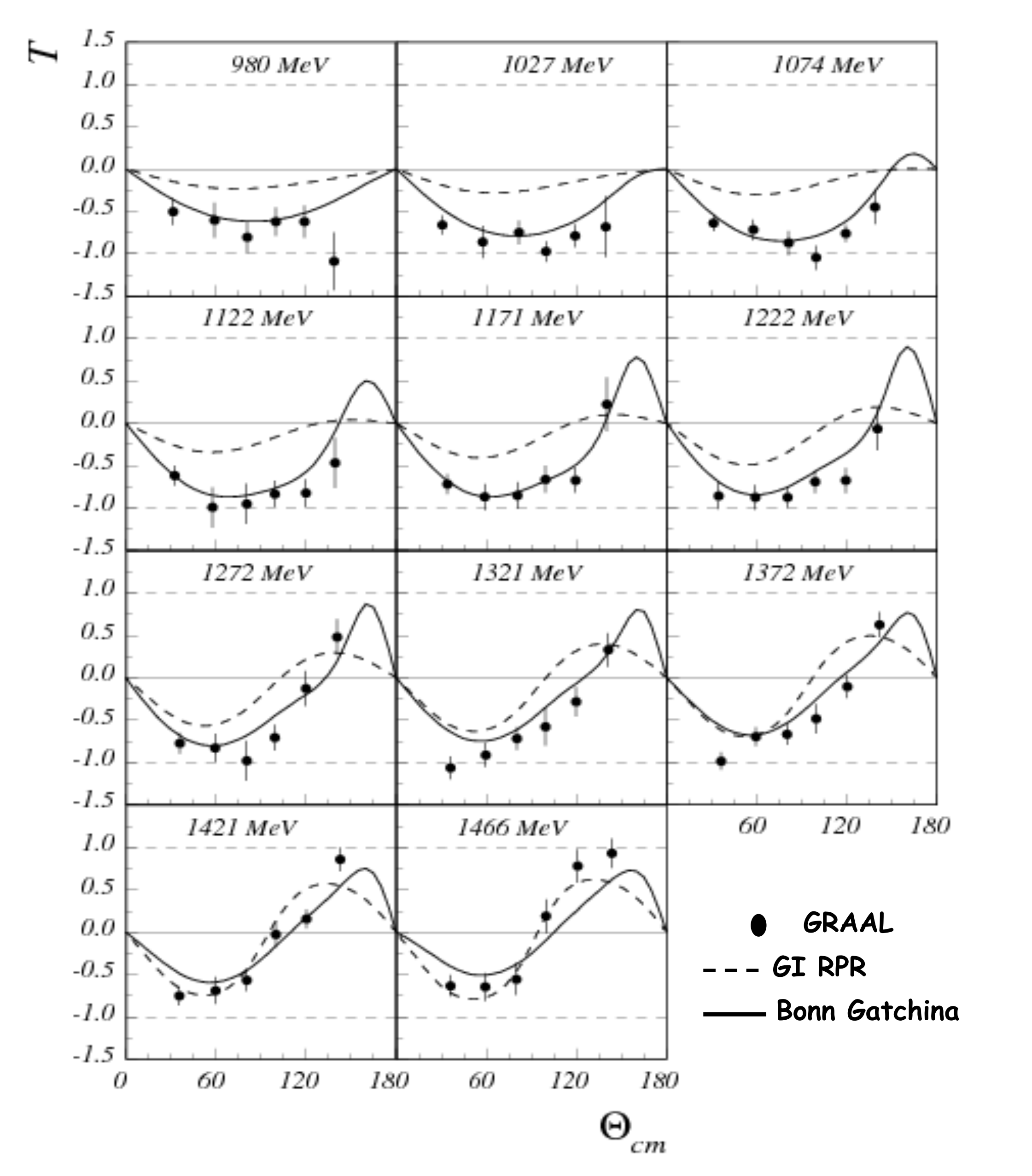
$$\frac{2N_{+}^{x'}}{N_{+}^{x'}+N_{-}^{x'}}=\left(1+\alpha\frac{2P_{\gamma}O_{x}}{\pi}\cos\theta_{p}^{x'}\right)$$

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





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:

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

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

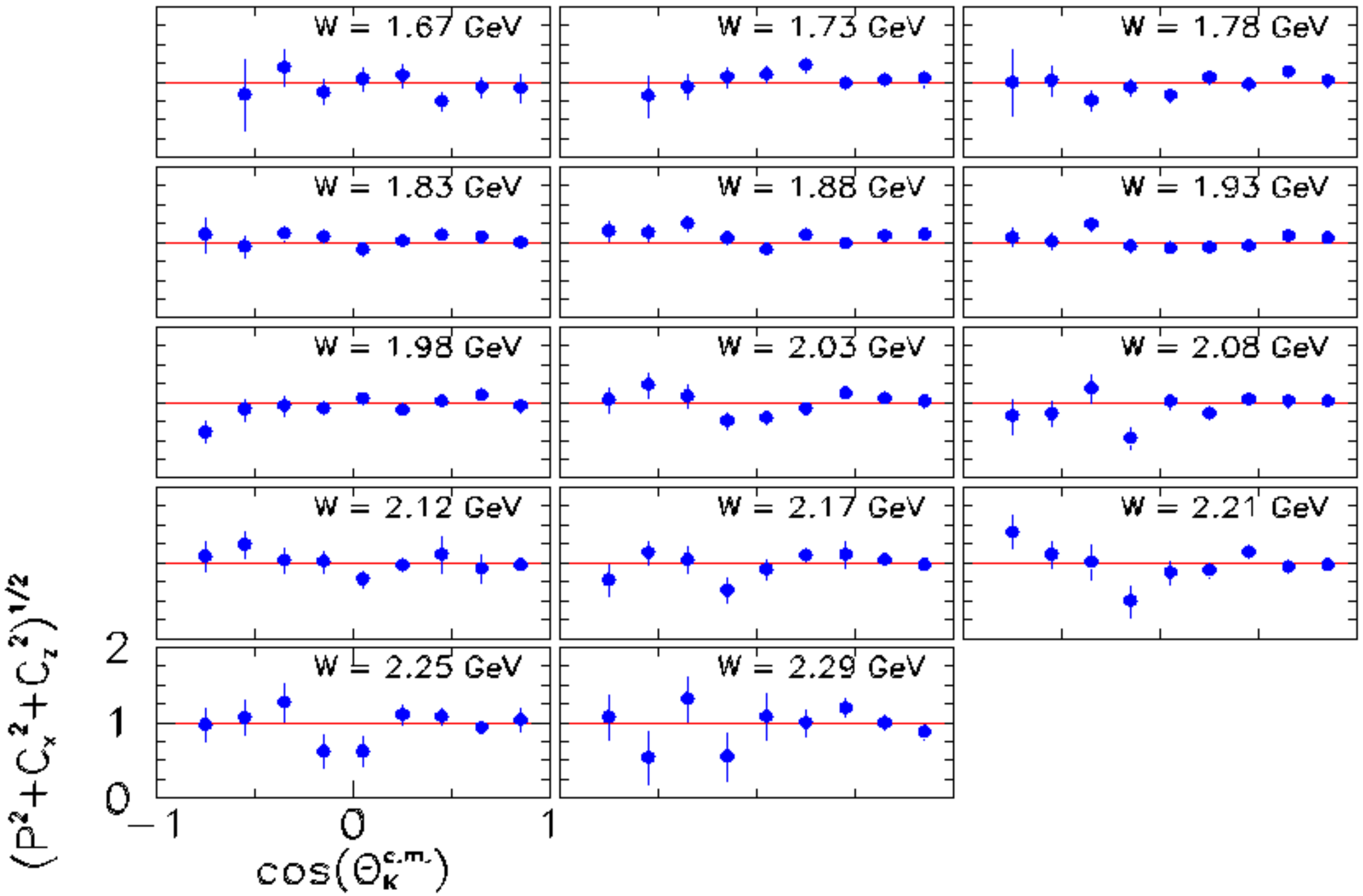
- Bonn Gatchina Model:

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

$P_{13}(1900)$

R Values for the

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



The [illegible] appears 100% polarized when created with a fully polarized beam.

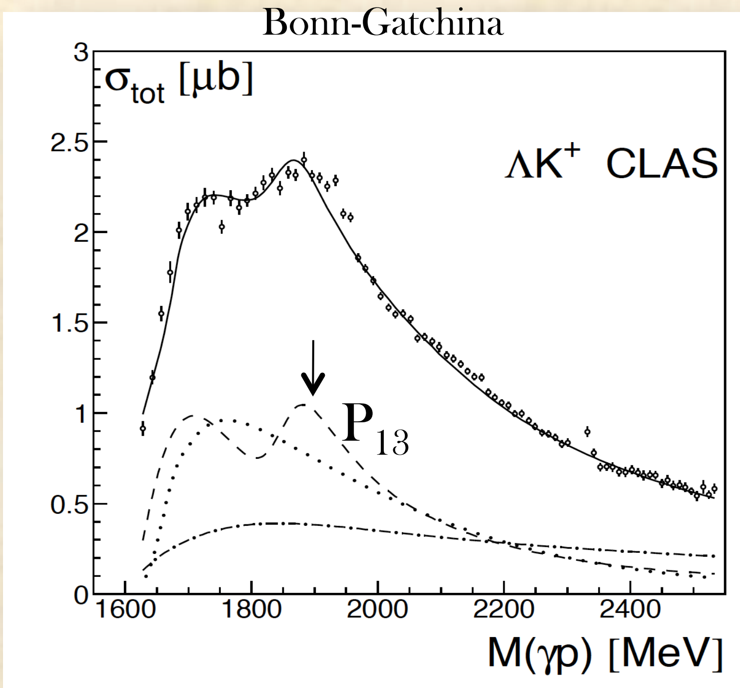
The N(1900)3/2$^+$ State

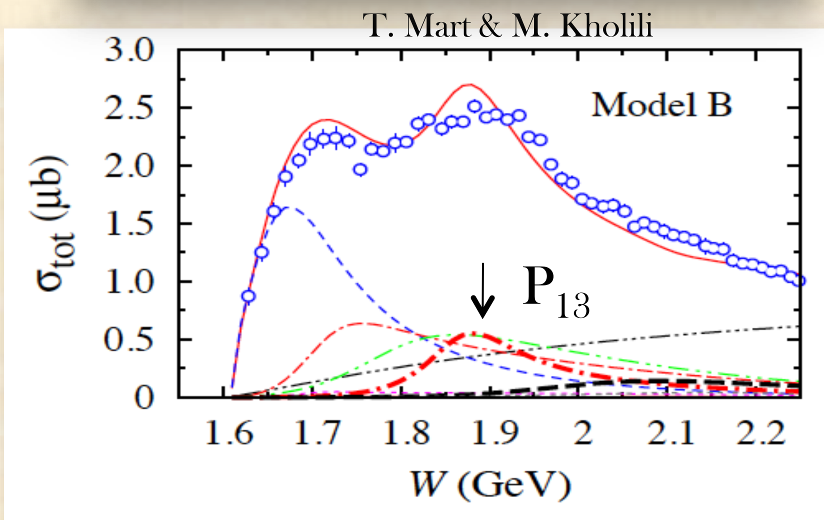
- State solidly established in coupled-channel analysis making use of very precise $K\Lambda$ data, resulting in *** assignment in PDG2012.

- State was confirmed in covariant isobar model analysis (*T. Mart & M. J. Kholili arXiv:1208.2780*) of single channel analysis $\gamma p \rightarrow K^+\Lambda$.

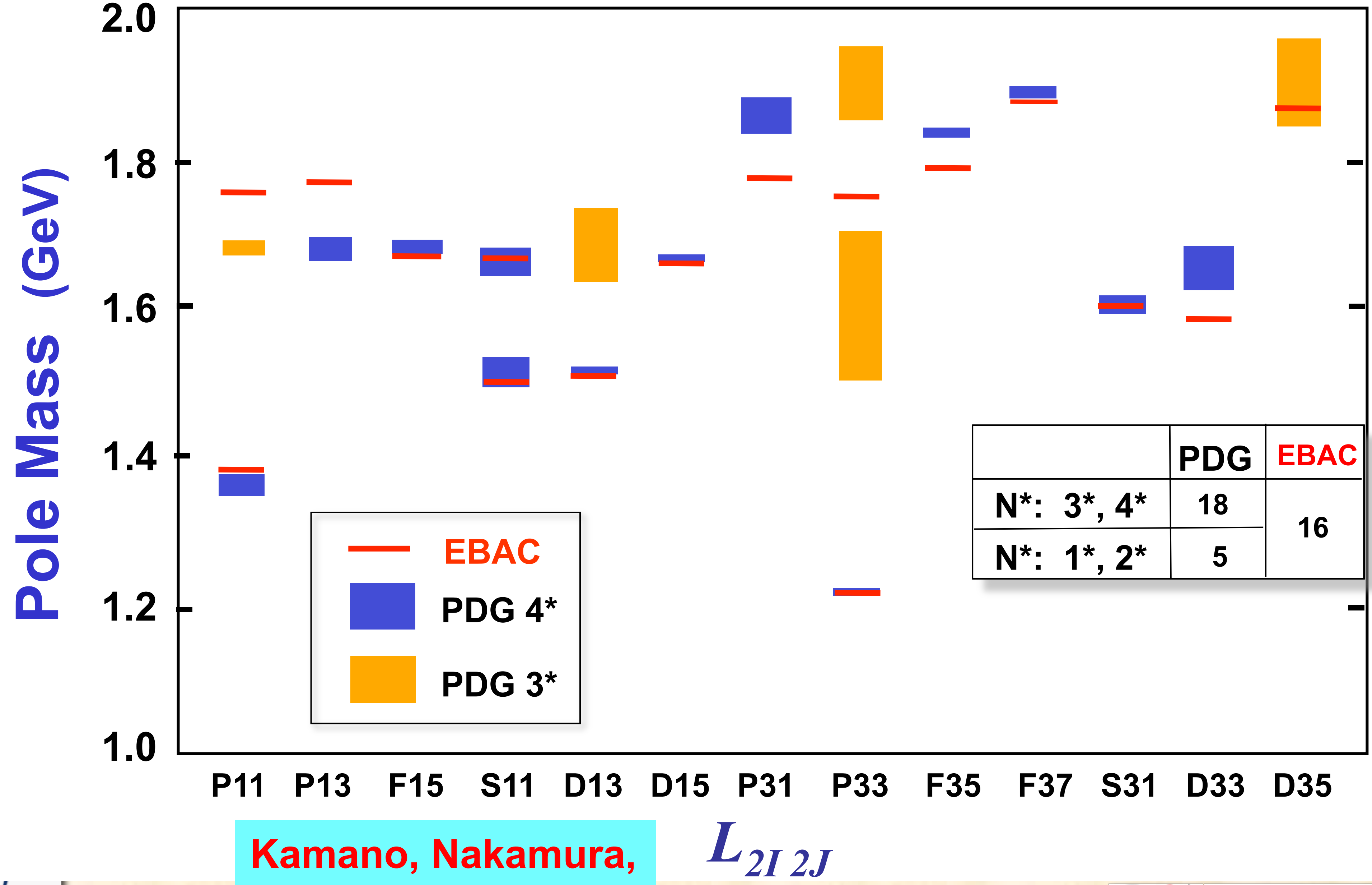
- Confirmed in an effective Langrangian resonance model analysis (*O. V. Maxwell, PRC85,034611, 2012*) of photo- and electroproduction of single channel $K^+\Lambda$ data.

- **State may be ready for promotion to **** assignment and to become the first baryon resonance observed and confirmed in electromagnetic meson production.**





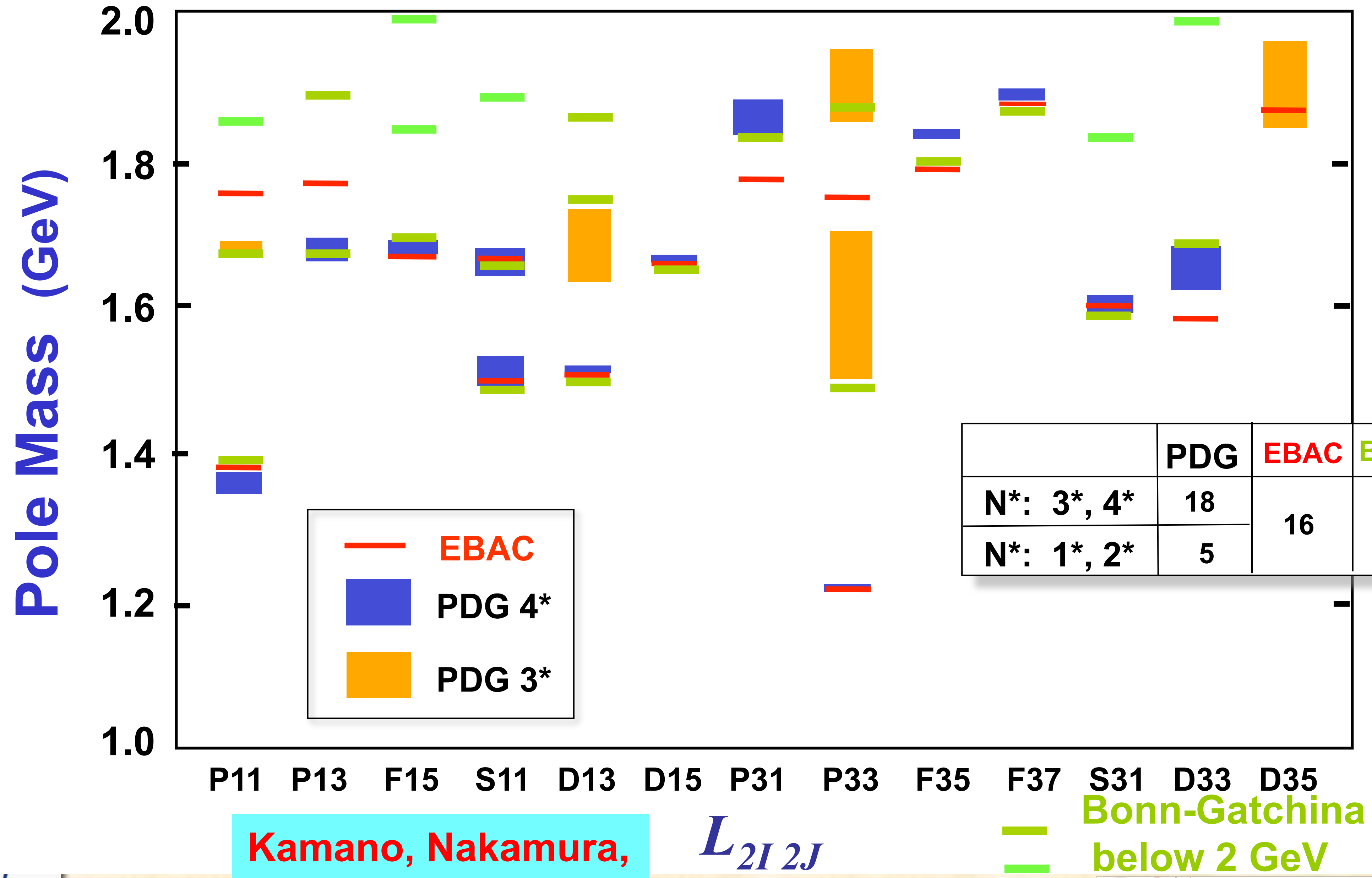
N*, D* spectrum from EBAC



	PDG	EBAC
N*: 3*, 4*	18	16
N*: 1*, 2*	5	

Kamano, Nakamura, Lee, Sato 2012

N*, D* spectrum from EBAC & Bonn-Ga



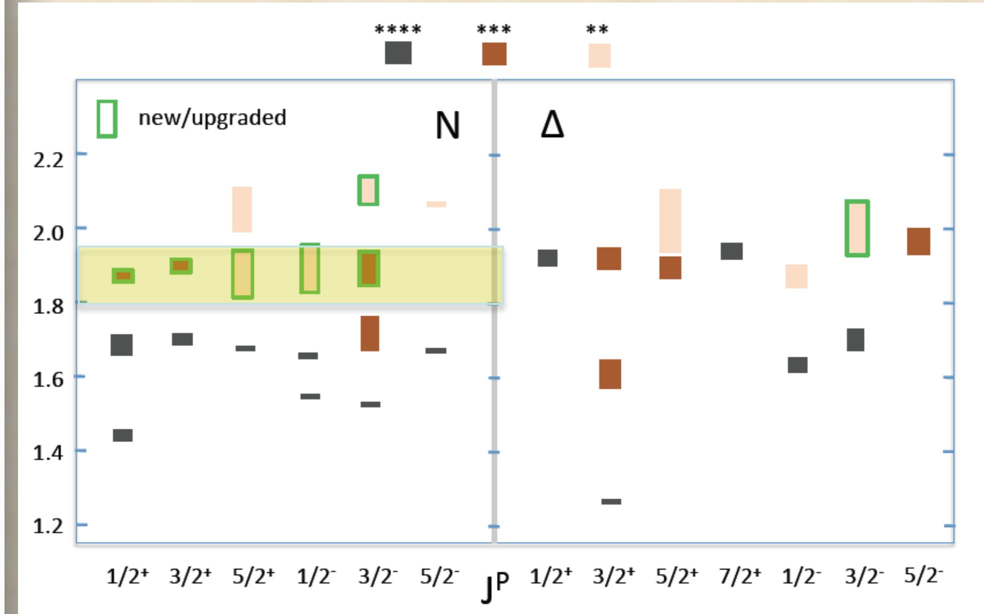
	PDG	EBAC	BoGa
N*: 3*, 4*	18	16	24
N*: 1*, 2*	5		

Kamano, Nakamura, Lee, Sato 2012

N/Δ spectrum in RPP 2012

N^*	J^P ($L_{2I,2J}$)	2010	2012	Δ	J^P ($L_{2I,2J}$)	2010	2012
p	$1/2^+$ (P_{11})	****	****	$\Delta(1232)$	$3/2^+$ (P_{33})	****	****
n	$1/2^+$ (P_{11})	****	****	$\Delta(1600)$	$3/2^+$ (P_{33})	***	***
$N(1440)$	$1/2^+$ (P_{11})	****	****	$\Delta(1620)$	$1/2^-$ (S_{31})	****	****
$N(1520)$	$3/2^-$ (D_{13})	****	****	$\Delta(1700)$	$3/2^-$ (D_{33})	****	****
$N(1535)$	$1/2^-$ (S_{11})	****	****	$\Delta(1750)$	$1/2^+$ (P_{31})	*	*
$N(1650)$	$1/2^-$ (S_{11})	****	****	$\Delta(1900)$	$1/2^-$ (S_{31})	**	**
$N(1675)$	$5/2^-$ (D_{15})	****	****	$\Delta(1905)$	$5/2^+$ (F_{35})	****	****
$N(1680)$	$5/2^+$ (F_{15})	****	****	$\Delta(1910)$	$1/2^+$ (P_{31})	****	****
$N(1685)$			*				
$N(1700)$	$3/2^-$ (D_{13})	***	***	$\Delta(1920)$	$3/2^+$ (P_{33})	***	***
$N(1710)$	$1/2^+$ (P_{11})	***	***	$\Delta(1930)$	$5/2^-$ (D_{35})	***	***
$N(1720)$	$3/2^+$ (P_{13})	****	****	$\Delta(1940)$	$3/2^-$ (D_{33})	*	**
$N(1860)$	$5/2^+$		**				
$N(1875)$	$3/2^-$		***				
$N(1880)$	$1/2^+$		**				
$N(1895)$	$1/2^-$		**				
$N(1900)$	$3/2^+$ (P_{13})	**	***	$\Delta(1950)$	$7/2^+$ (F_{37})	****	****
$N(1990)$	$7/2^+$ (F_{17})	**	**	$\Delta(2000)$	$5/2^+$ (F_{35})	**	**
$N(2000)$	$5/2^+$ (F_{15})	**	**	$\Delta(2150)$	$1/2^-$ (S_{31})	*	*
~~$N(2080)$~~	D_{13}	**		$\Delta(2200)$	$7/2^-$ (G_{37})	*	*
~~$N(2090)$~~	S_{11}	*		$\Delta(2300)$	$9/2^+$ (H_{39})	**	**
$N(2040)$	$3/2^+$		*				
$N(2060)$	$5/2^-$		**				
$N(2100)$	$1/2^+$ (P_{11})	*	*	$\Delta(2350)$	$5/2^-$ (D_{35})	*	*
$N(2120)$	$3/2^-$		**				
$N(2190)$	$7/2^-$ (G_{17})	****	****	$\Delta(2390)$	$7/2^+$ (F_{37})	*	*
~~$N(2200)$~~	D_{15}	**		$\Delta(2400)$	$9/2^-$ (G_{39})	**	**
$N(2220)$	$9/2^+$ (H_{19})	****	****	$\Delta(2420)$	$11/2^+$ ($H_{3,11}$)	****	****
$N(2250)$	$9/2^-$ (G_{19})	****	****	$\Delta(2750)$	$13/2^-$ ($I_{3,13}$)	**	**
$N(2600)$	$11/2^-$ ($I_{1,11}$)	***	***	$\Delta(2950)$	$15/2^+$ ($K_{3,15}$)	**	**
$N(2700)$	$13/2^+$ ($K_{1,13}$)	**	**				

Photoproduction data from JLAB, ELSA, GRAAL, LEPS



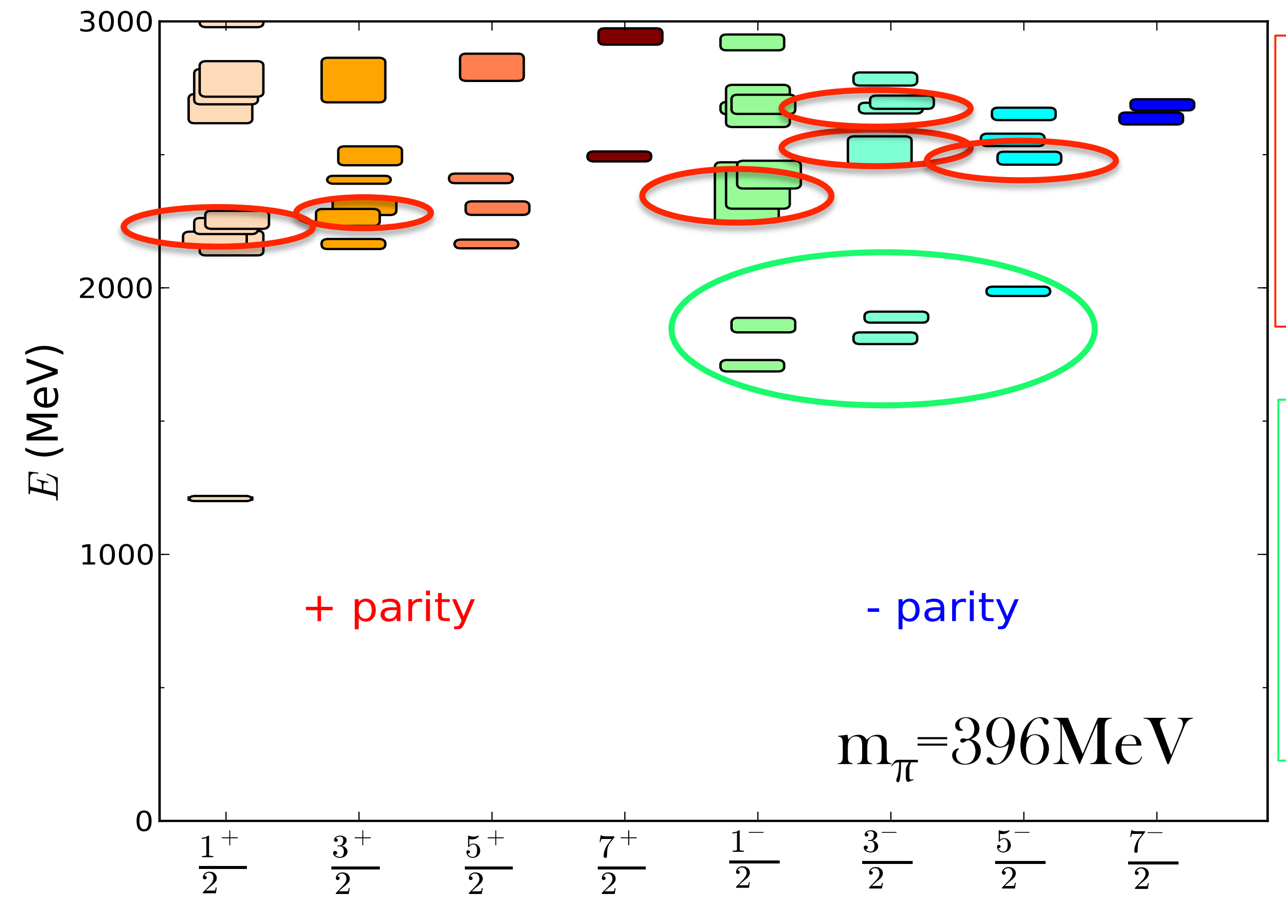
From Bonn-Gatchina coupled-channel analysis with precision photo-production of KΛ, KΣ and polarization observables.

V. Crede & W. Roberts, arXiv:1302.7299

N* spectrum in LQCD

Projected new states constrained largely from meson photoproduction

N(1900)$3/2^+$
N(1880)$1/2^+$



N(2060)$5/2^-$
N(2120)$3/2^-$
N(1875)$3/2^-$
N(1895)$1/2^-$

N(1675)$5/2^-$
N(1700)$3/2^-$
N(1520)$3/2^-$
N(1650)$1/2^-$
N(1535)$1/2^-$

New candidate states may be accommodated in LQCD projections

	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)														

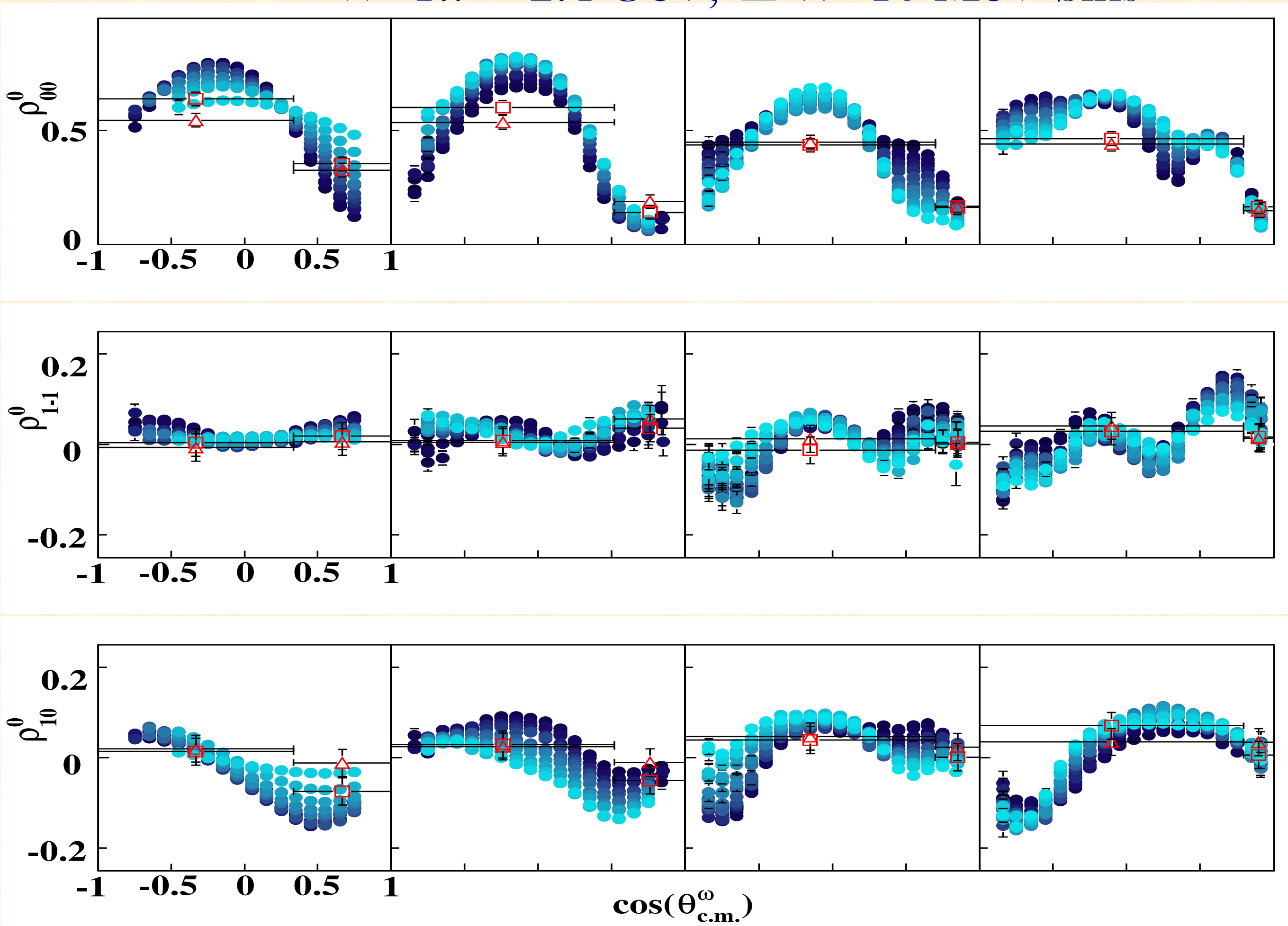
✔ (red) - published, ✔ (green) - acquired, ✔ (blue) - planned

N* states in $\gamma p \to p\omega \to p\pi^+\pi^-(\pi^0)$

M. Williams, et al. (CLAS) Phys. Rev. C80:065209, 2009

- Spin density matrix elements ρ^0_{00}, ρ^0_{1-1}, ρ^0_{10} in blue - blue shades. Previous world data in red.

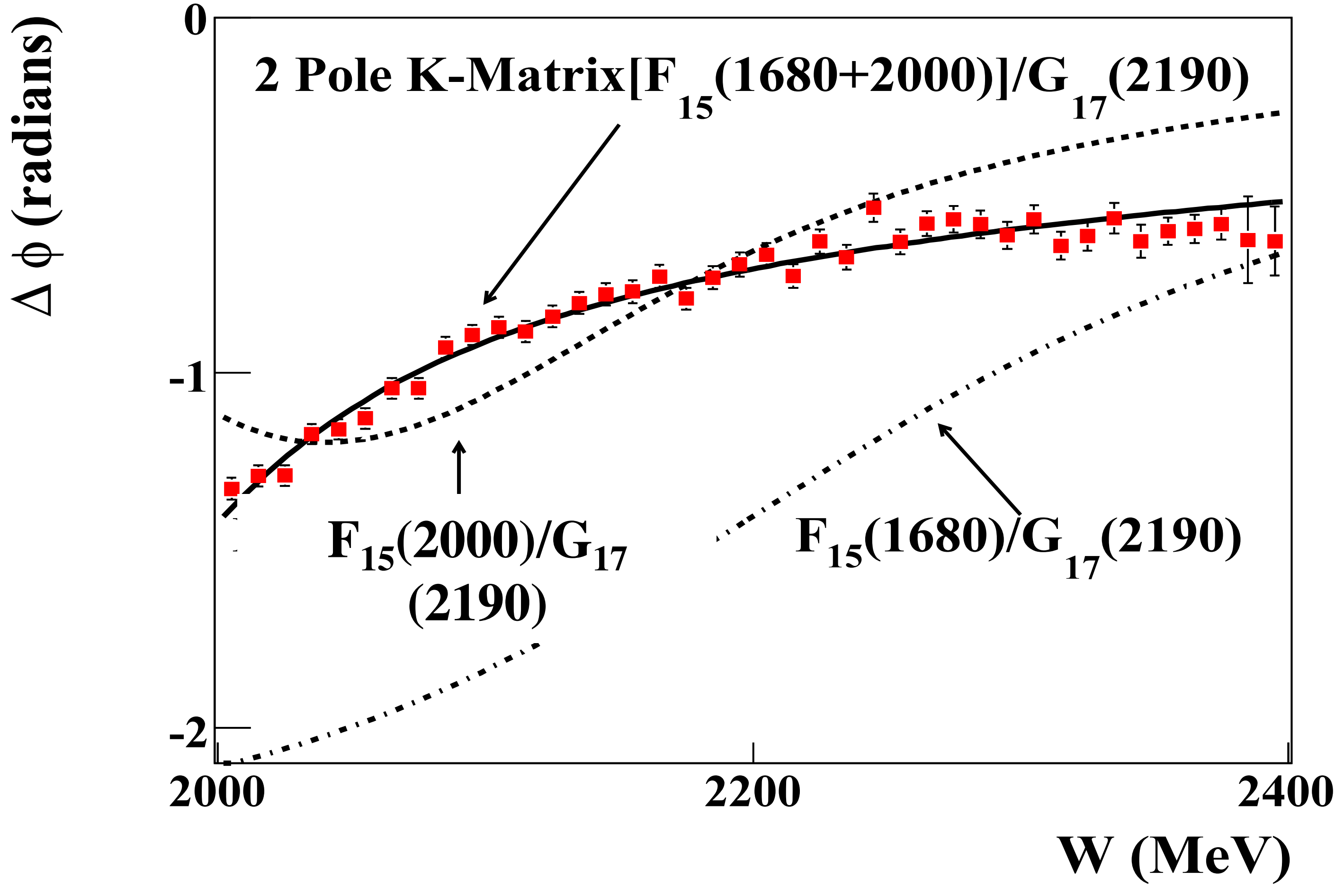
W=1.7 – 2.4 GeV, ΔW=10 MeV bins



SDMEs with **linearly and circularly polarized beams** are being finalized. Together with ρ^0_{00}, ρ^0_{1-1}, ρ^0_{10} they represent precise data sets for coupled-channel analyses.

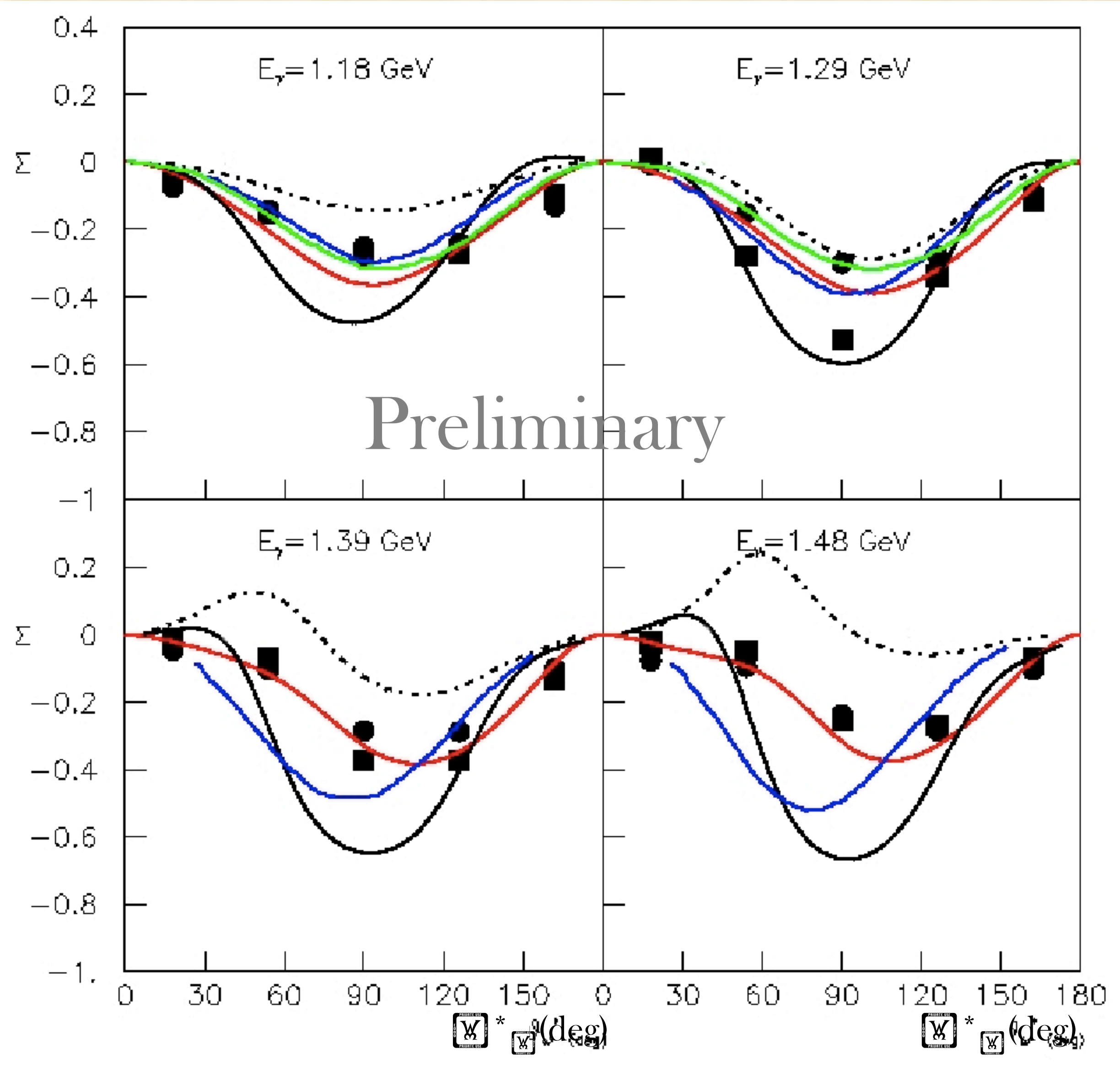
N* states in $\gamma p \to p\omega \to p\pi^+\pi^-(\pi^0)$

M. Williams, et al. (CLAS) , Phys.Rev.C80:065209,2009



- The data are used as input to a single channel event-based, energy independent partial wave analysis (the first ever for baryons).
- **ω** photoproduction is dominated by the well known **F_{15}(1680) and G_{17}(2190)**, and the “missing” ** **F_{15}(2000)**.

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

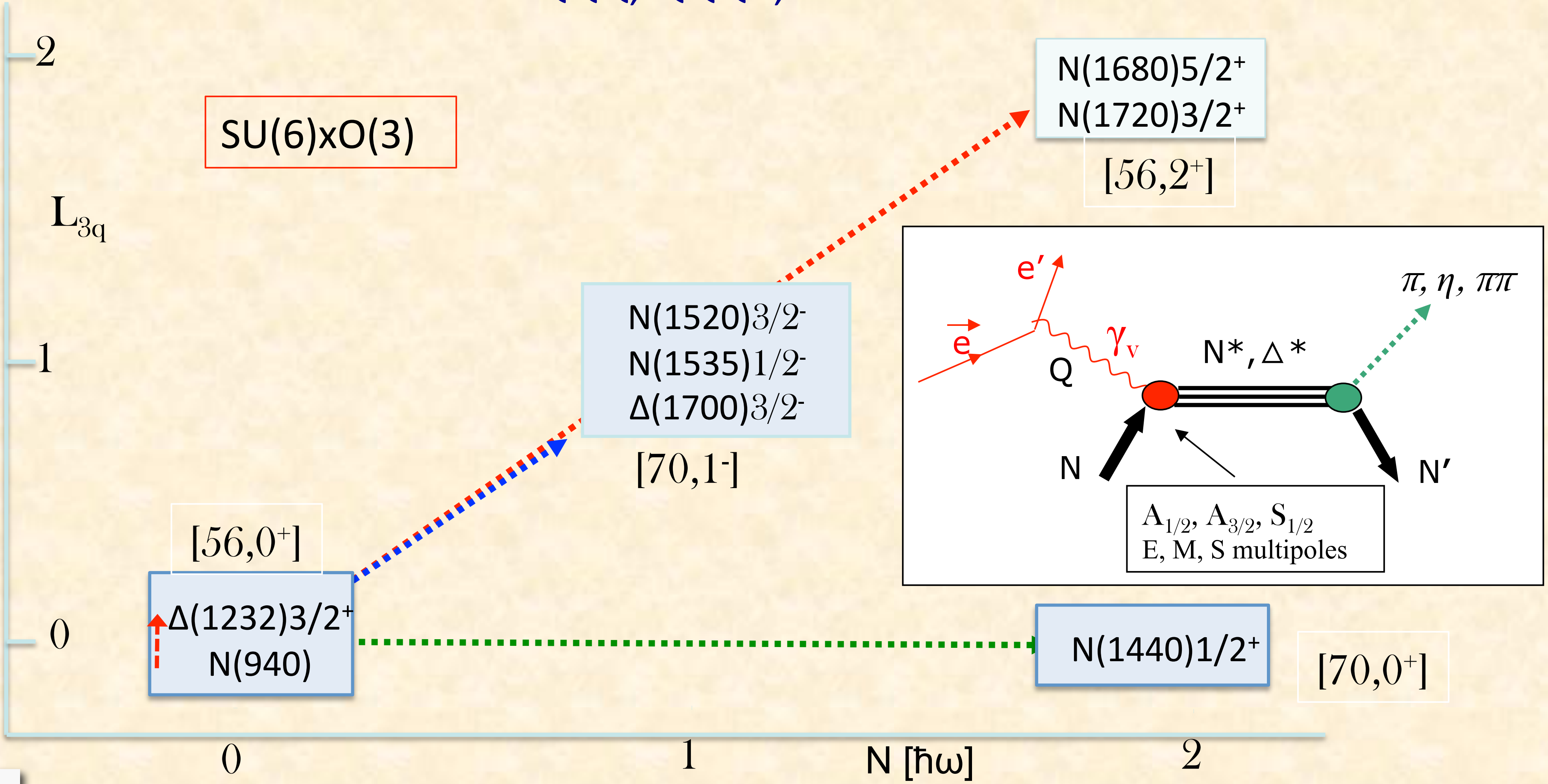
M. Paris
PRC79 (2009) 025208

● $\omega \to \pi^0\gamma$

■ $\omega \to \pi^+\pi^-\pi^0$

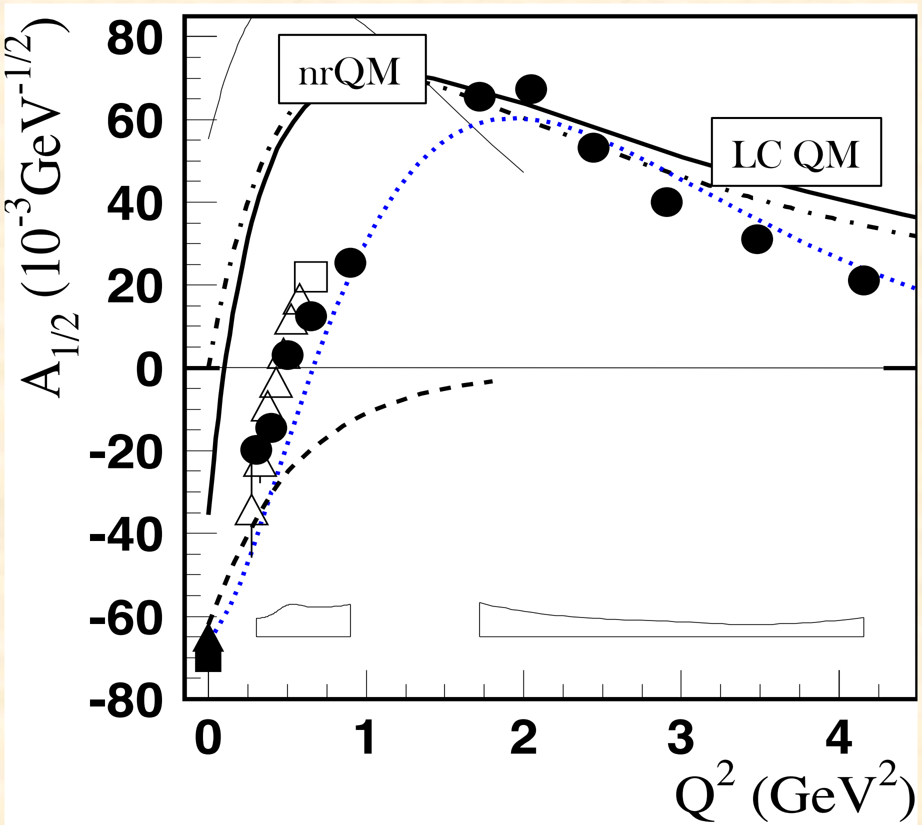
Electroexcitation of N/Δ resonances

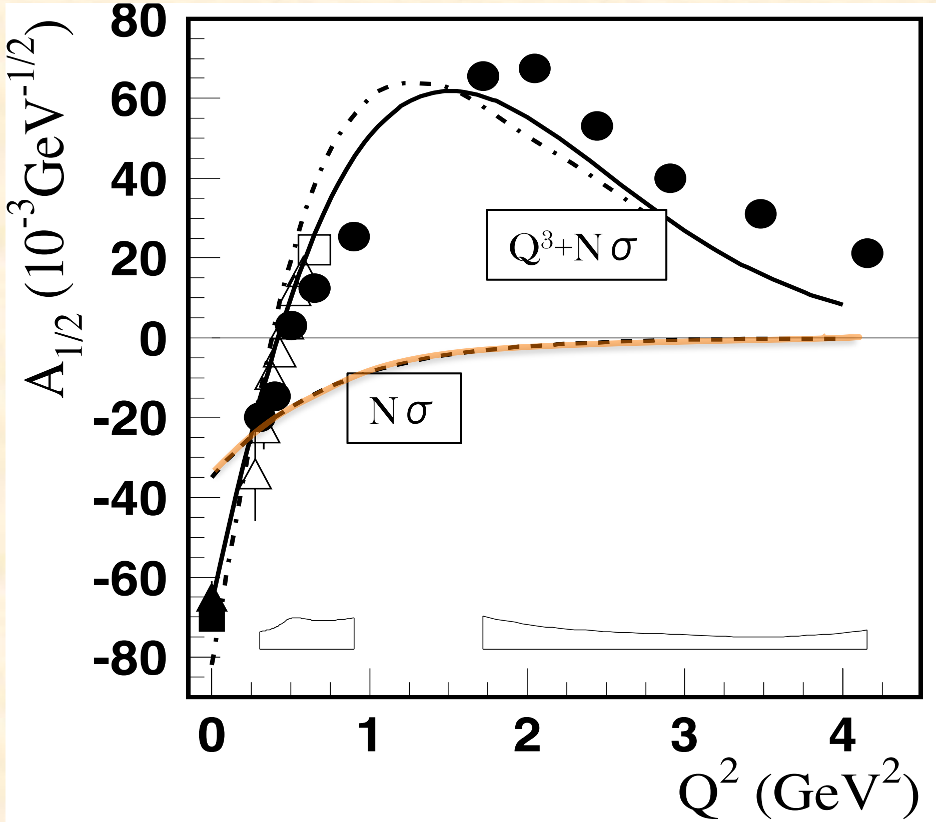
- Probe resonance strength vs photon virtuality Q
- How do effective dof change with distance scale?
- Nature of excited states: QQQ, QQQG, MB



Electrocouplings of 'Roper' N(1440)1/2+

I. Aznauryan et al. (CLAS), PRC80, 055203 (2009), V. Mokeev et al. (CLAS), PRC86, 035203 (2012)

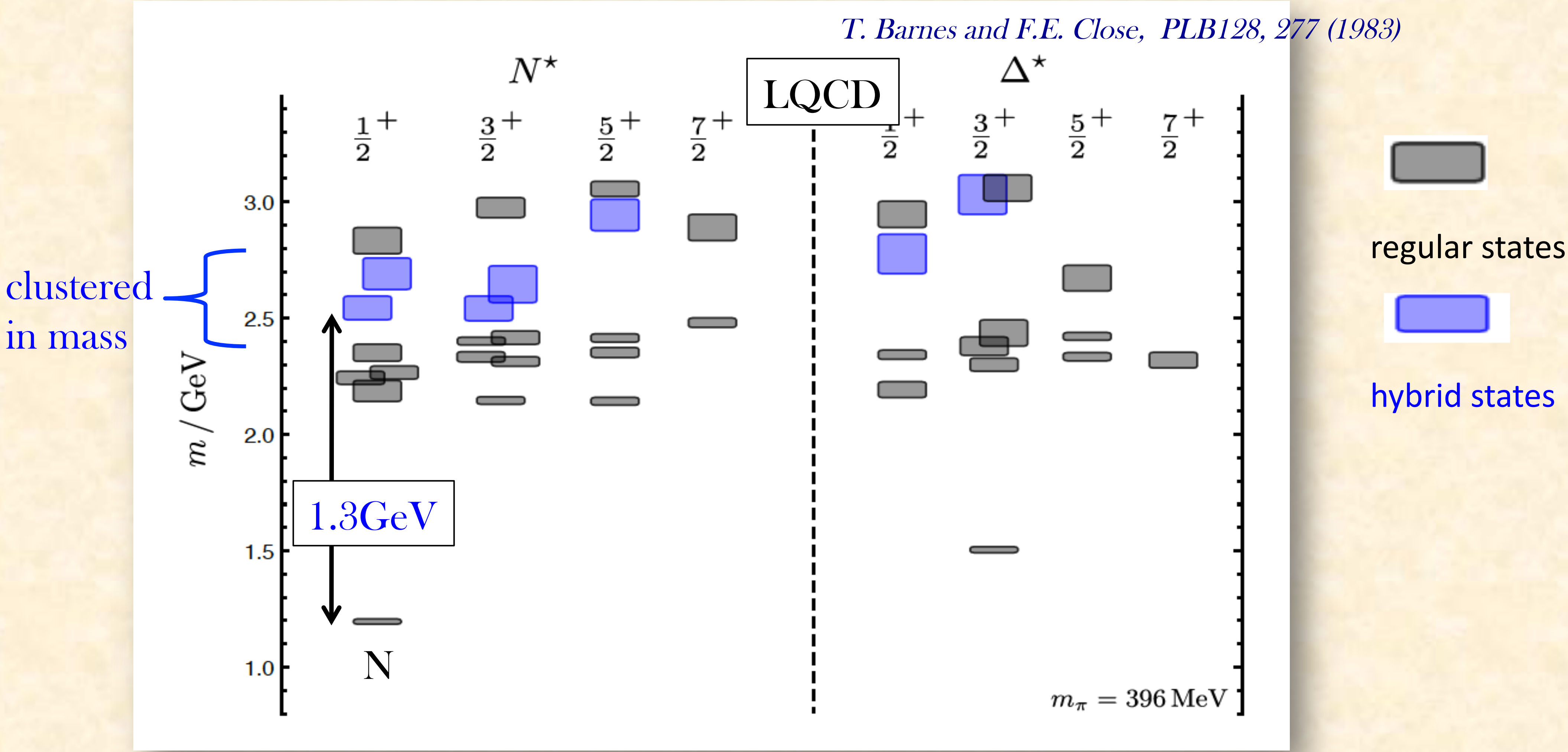




- $A_{1/2}$ dominant amplitude at high Q^2 indicates radial QQQ excitation
- Significant meson-baryon coupling at small Q^2

Hybrid Baryons in LQCD

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



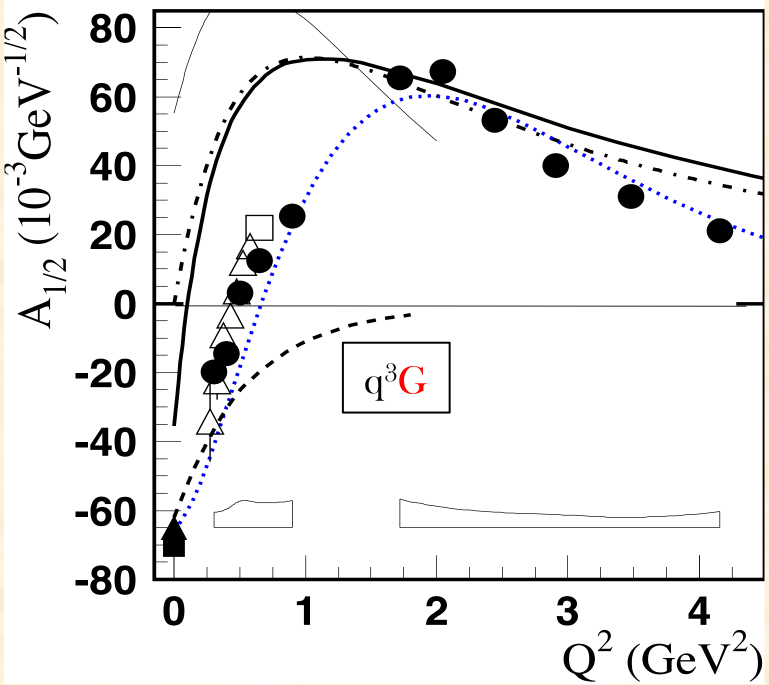
Hybrid states have same J^P values as Q^3 baryons. How to identify them?

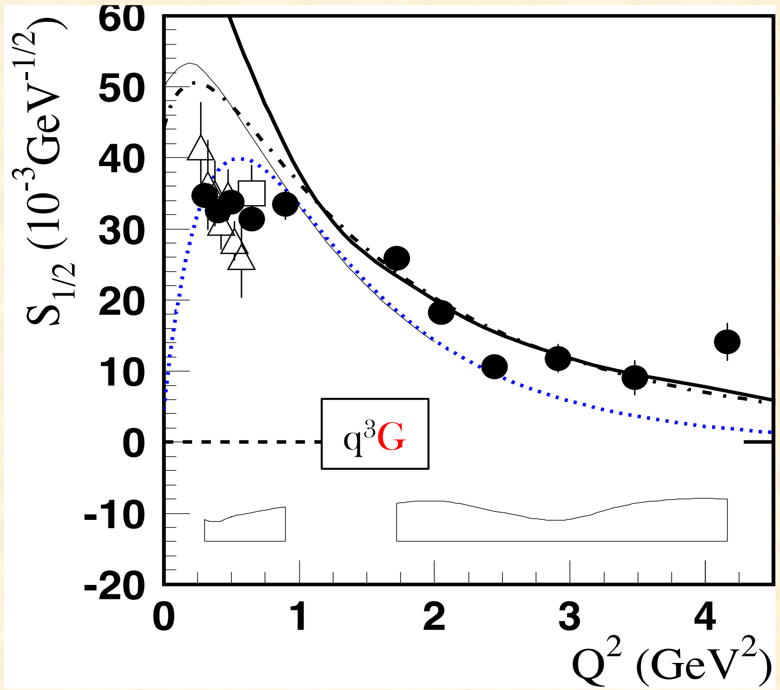
- Overpopulation of $N1/2^+$ and $N3/2^+$ states compared to QM projections?
- Transition form factors in electroproduction have different Q^2 dependence

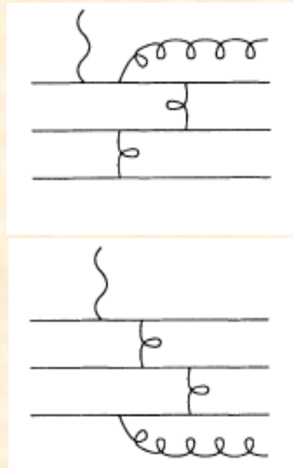
Separating Q^3G from Q^3 states?

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

Lowest mass QQQG state N1/2$^+$







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

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

Conclusions

- Precise new data including double polarization data available or soon to be available, some data sets are "complete".
- EBAC and Bo-Ga have produced their own baryon spectrum.
- 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.
- Community achieved important milestone in the search for new baryon states from photoproduction – 6 new candidates, 2 almost certain in RPP 2012. Two further confirmations for $N(1900)3/2^+$.
- Precise ω (and ϕ) photoproduction data available, can constrain the PWA in the search for high mass states. Should be included in coupled-channel PWA.
- The Q^2 dependence of resonance transition form factors may be employed to separate hybrid baryons from ordinary baryons.

I would like to thank the CLAS collaboration for letting me present preliminary data and Volker Burkert for providing my with slides.