Nucleon Structure and Spectrum

1. Baryon spectroscopy
2. CLAS meson photoproduction
3. Selected examples
   - Single-meson photoproduction
   - Double-pion photoproduction

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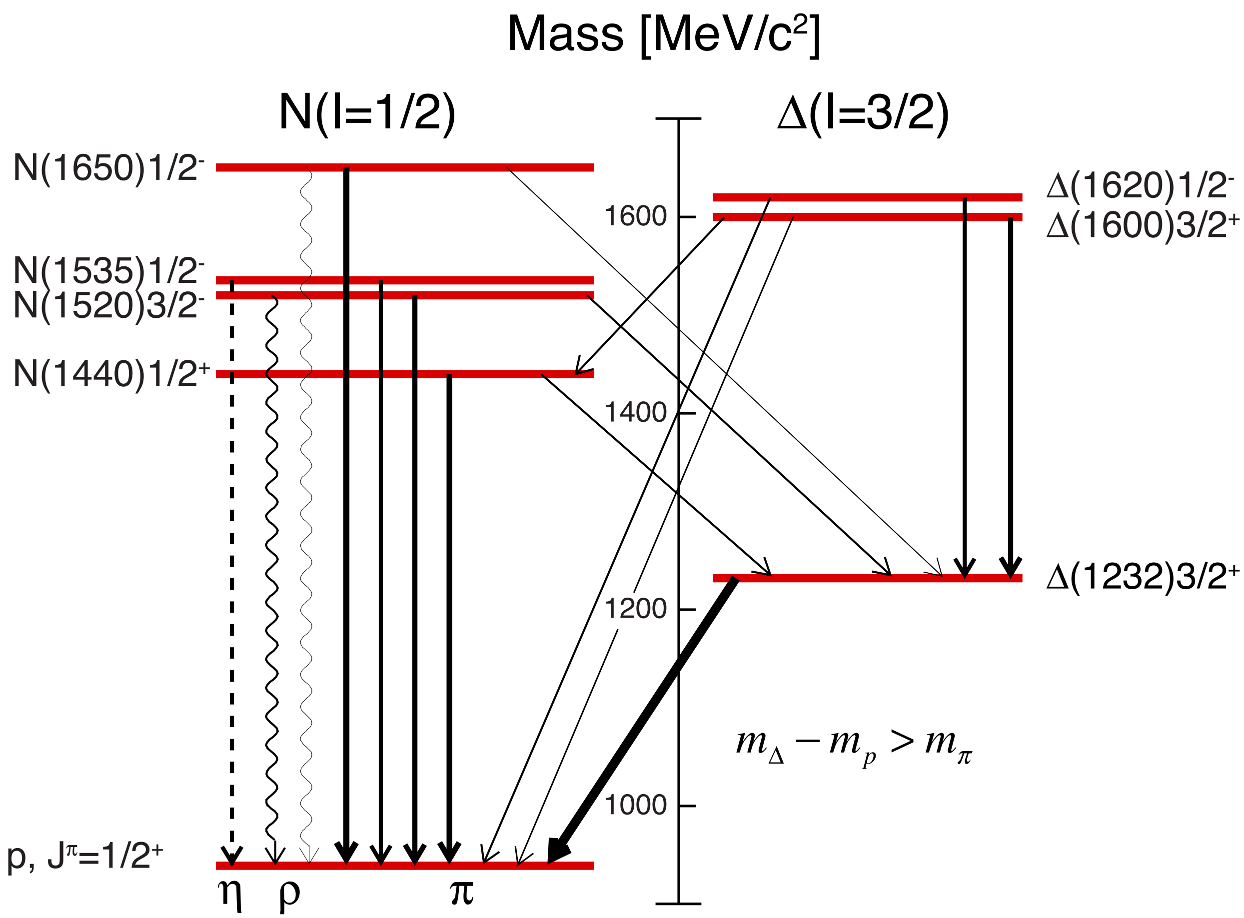
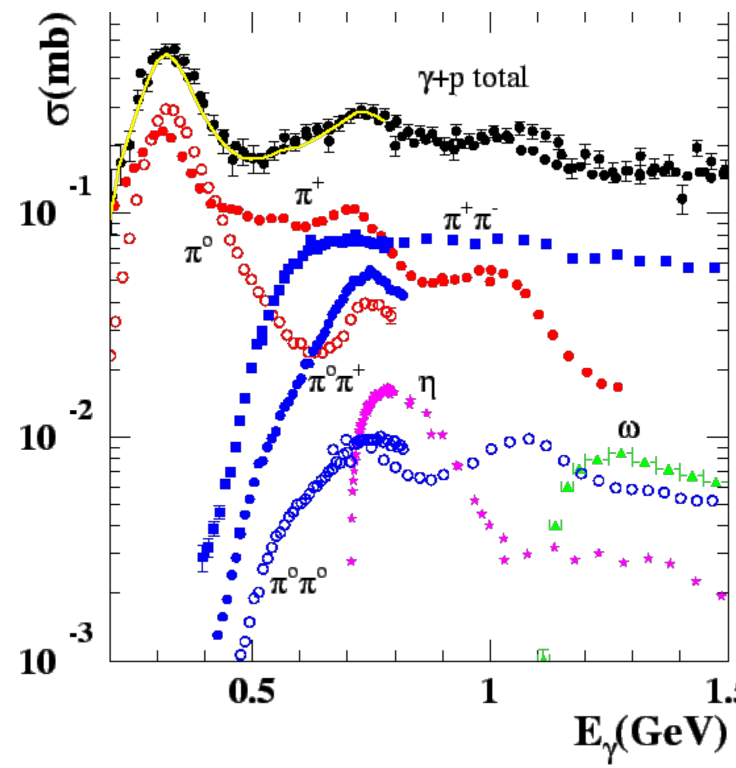
XLVII International Symposium on Multiparticle Dynamics (ISMD2017)
September 11 - 15, 2017, Tlaxcala City, Mexico

Baryon Spectroscopy



Photoproduction cross section

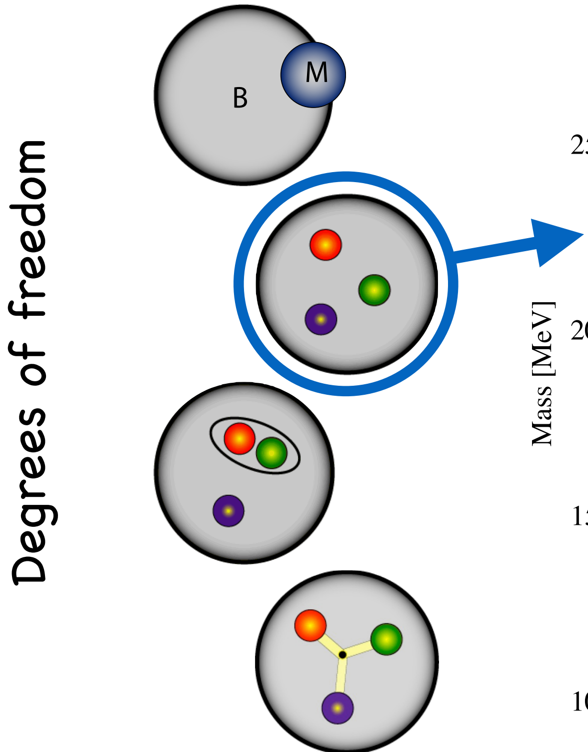


$$\Gamma \propto \frac{\hbar}{\tau} \approx 100 - 400 \text{ MeV}$$

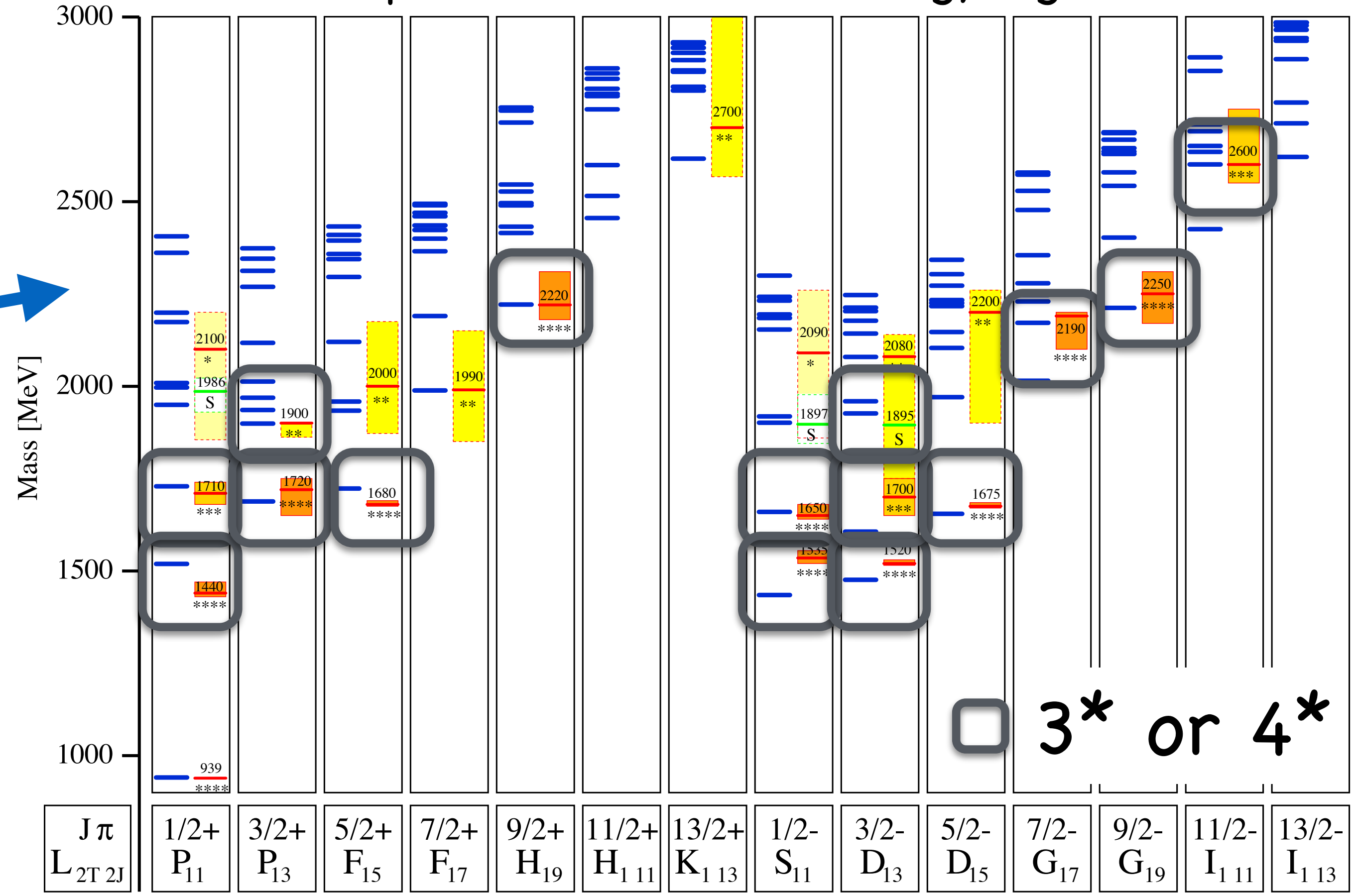
Location and properties of excited states

B. Krusche and S. Schadmand, Prog. Nucl. Phys. 51, 399 (2003)
K. Hagiwara et al. (Particle Data Group), Phys. Rev. D66, 010001 (2002)

Relevant degrees of freedom and missing resonance problem



N Resonance Spectrum — the low-energy signature of QCD



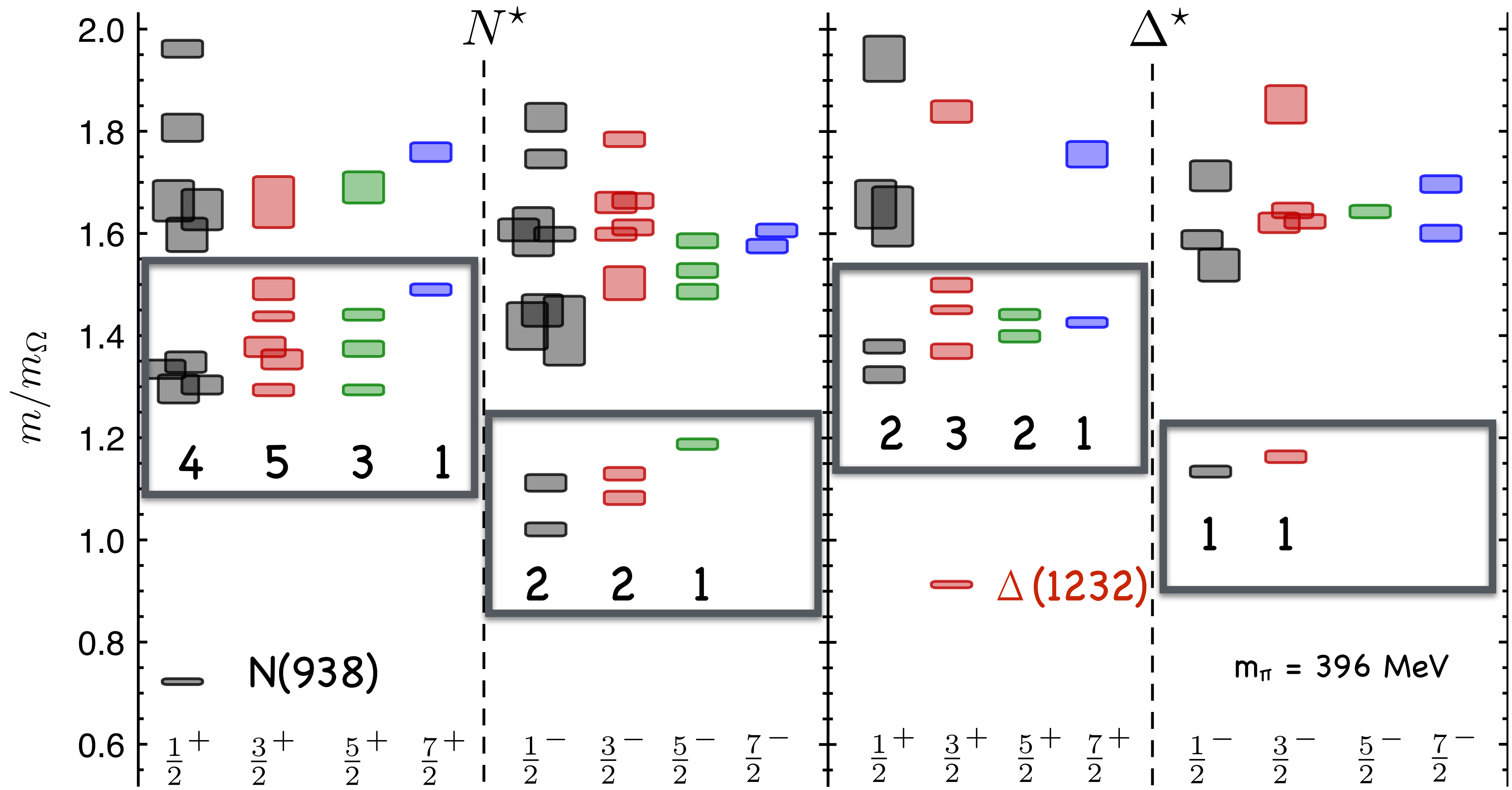
Quark Models

- Constituent Quark Models predict many more of excited states than have been observed; some of the states may only couple weakly to πN.
- Quark-Diquark Models with a tightly bound diquark predict fewer states.
- Quark and Flux-Tube Models predict increased number of states.

CQM: U. Löring, B.C. Metsch, and H.R. Petry, Eur. Phys. J. **A10** 395 (2001)

Resonance spectrum in Lattice QCD

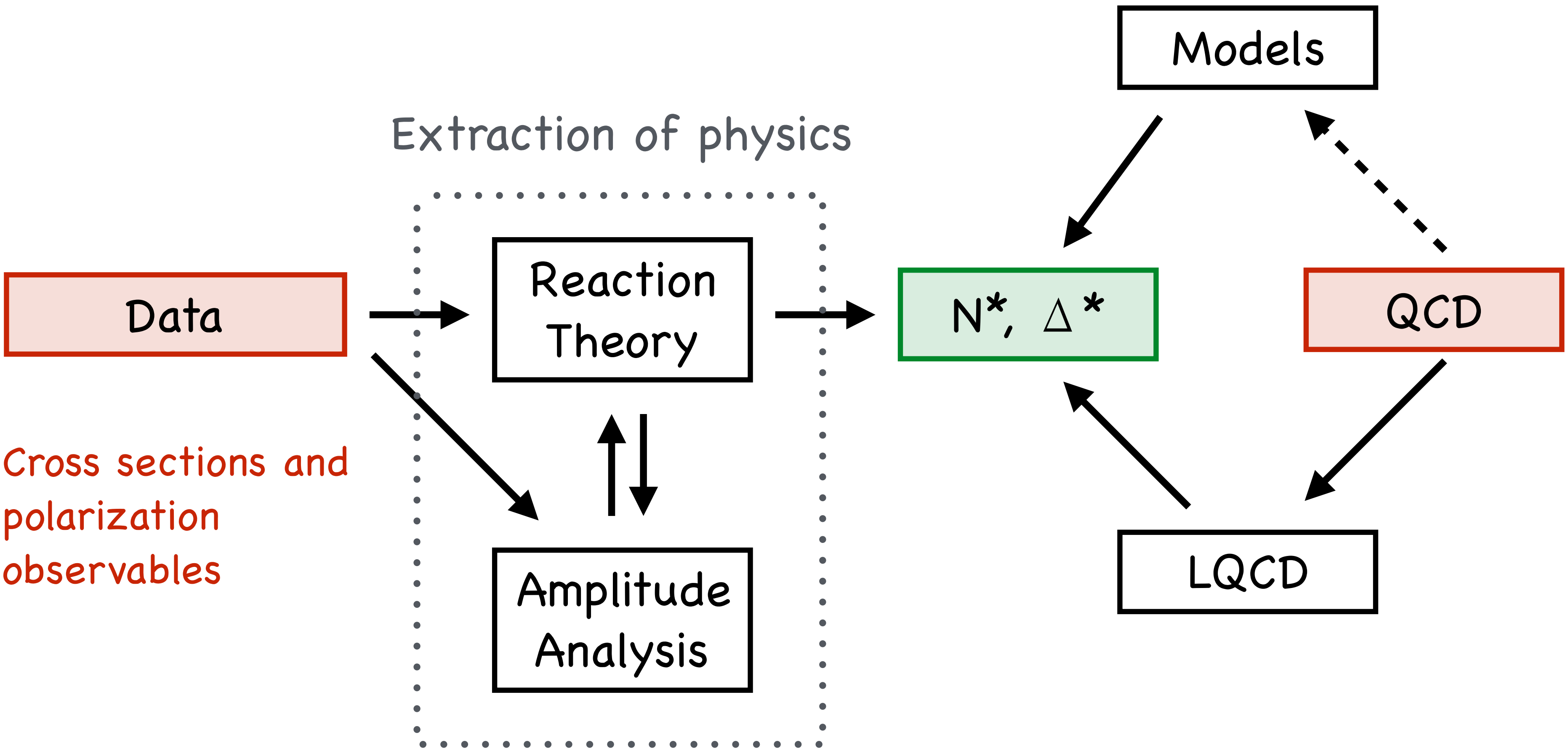
Hadron spectrum collaboration



LQCD predicts states with the same quantum numbers as CQMs with underlying SU(6) x O(3) symmetry; **more states** than have been identified experimentally.

R.G. Edwards, J.J. Dudek, D.G. Richards, and S.J. Wallace, Phys. Rev. D **84**, 074508 (2011)

Extracting nucleon-resonance information from experimental data



Coupled-channel analysis especially important

Nucleon resonance information: mass, spin, parity, coupling constants, decay parameters, ...

Observables in pseudoscalar meson photoproduction

4 complex amplitudes ⇒ 16 possible (not independent) observables

double pion photoproduction fills empty cells in the table

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	$d\sigma_0$		T			P		$T_{x'}$		$L_{x'}$		Σ		$T_{z'}$		$L_{z'}$
$P_L^\gamma \sin(2\varphi_\gamma)$		H		G	$O_{x'}$		$O_{z'}$		$C_{z'}$		E		F		$-C_{x'}$	
$P_L^\gamma \cos(2\varphi_\gamma)$	$-\Sigma$		$-P$			$-T$		$-L_{x'}$		$T_{z'}$		$-d\sigma_0$		$L_{x'}$		$-T_{x'}$
circular P_c^γ		F		$-E$	$C_{x'}$		$C_{z'}$		$-O_{z'}$		G		$-H$		$O_{x'}$	

coherent and incoherent Bremsstrahlung

e.g, FROST and HDice

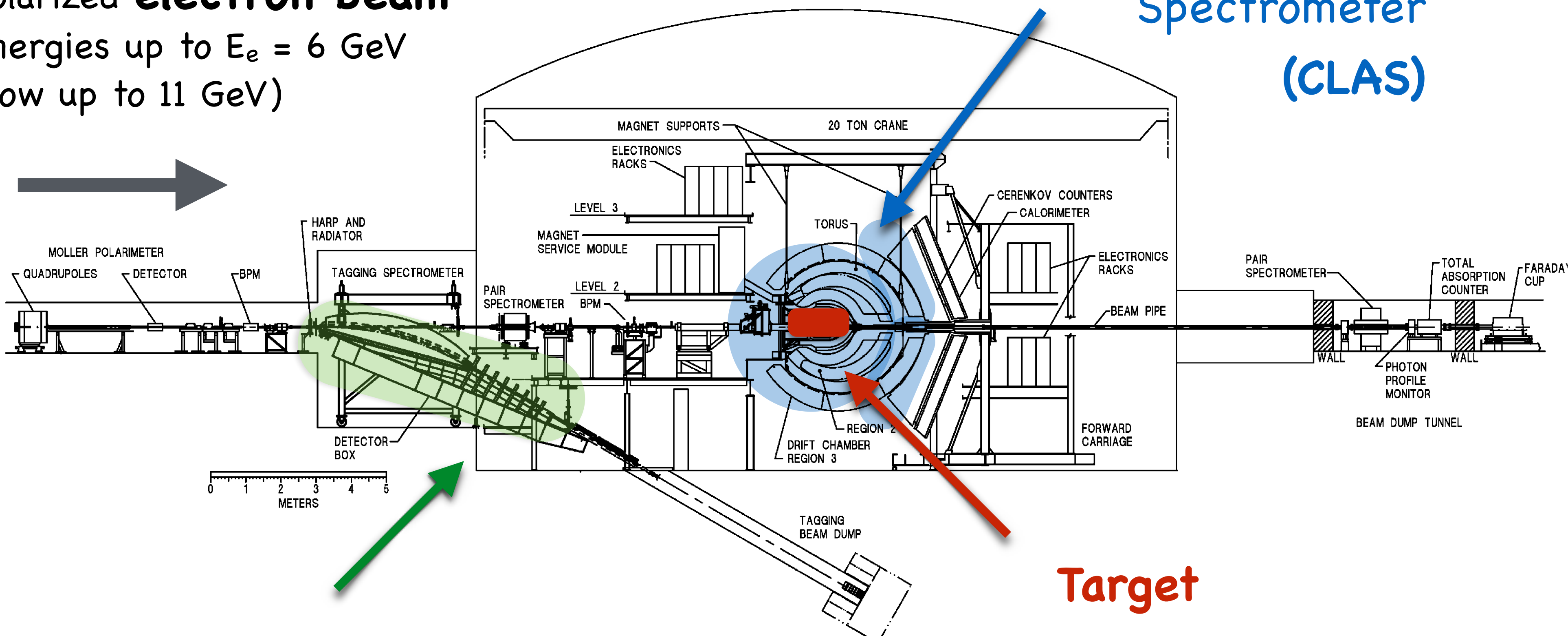
e.g, Hyperon weak decay

A.M. Sandorfi, S. Hoblit, H. Kamano and T.-S.H. Lee, J. Phys. G, Nucl. Part. Phys. **38**, 053001 (2011)

CEBAF Large Acceptance Spectrometer in Hall B (1997 - 2012)

CEBAF Large Acceptance Spectrometer **(CLAS)**

Polarized **electron beam**
Energies up to E_e = 6 GeV
(now up to 11 GeV)



Target

unpolarized p or d,
polarized FROST,
HDice

Photon Tagger

$$E_\gamma = E_e - E_{e'}$$

B.A. Mecking et al., Nucl. Instr. and Meth. A **503**, 513 (2003).

CLAS meson photoproduction analyses

Proton target

$$\gamma p \rightarrow \pi^0 p, \pi^+ n$$

$$\gamma p \rightarrow \eta p, \eta' p$$

$$\gamma p \rightarrow KY \; (K^+\Lambda, K^+\Sigma^0, K^0\Sigma^+)$$

$$\gamma p \rightarrow \pi^+\pi^- p, \omega p, \rho p, \phi p$$

...

present examples

e.g. CLAS frozen spin target (FROST)

Neutron target

$$\gamma n \rightarrow \pi^- p$$

$$\gamma n \rightarrow \pi^+\pi^- n$$

$$\gamma n \rightarrow \Sigma^- K^+, \Lambda K^0$$

...

e.g. unpolarized deuterium target (g13), polarized HD-Ice target (g14)

Cross section and polarization observables

Unpolarized, circularly polarized, linearly polarized beam

Unpolarized, longitudinally polarized, transversally polarized target

Recoil polarization (asymmetry in the weak decay of the hyperon)

Double Polarization Observable E in π^+n

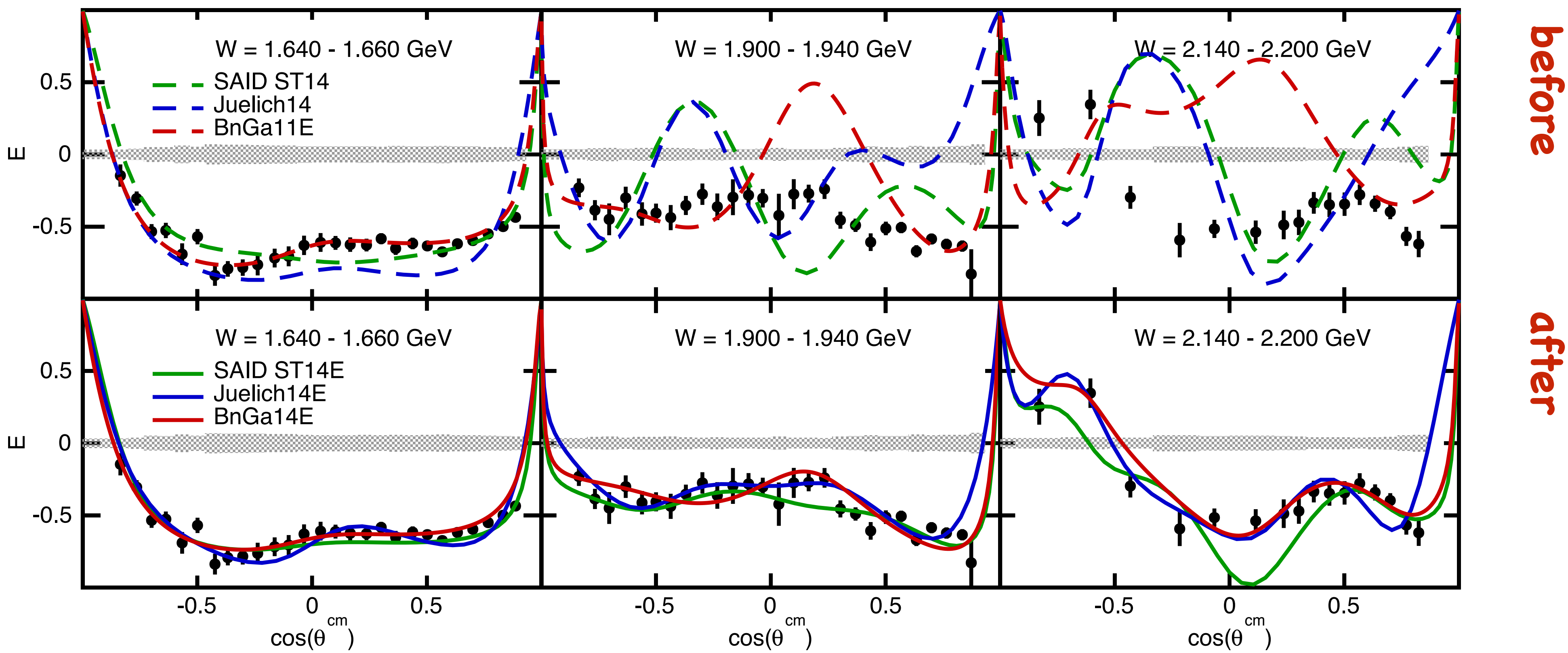
$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_0 \left(1 - P_z P_\odot E\right)$$

$W = 1240 - 2260$ MeV

$-0.9 \le \cos(\theta_\pi^{cm}) \le +0.9$

$$\vec{\gamma}\,\vec{p} \rightarrow \pi^+ n$$

W = 1.650 GeV W = 1.920 GeV W = 2.170 GeV

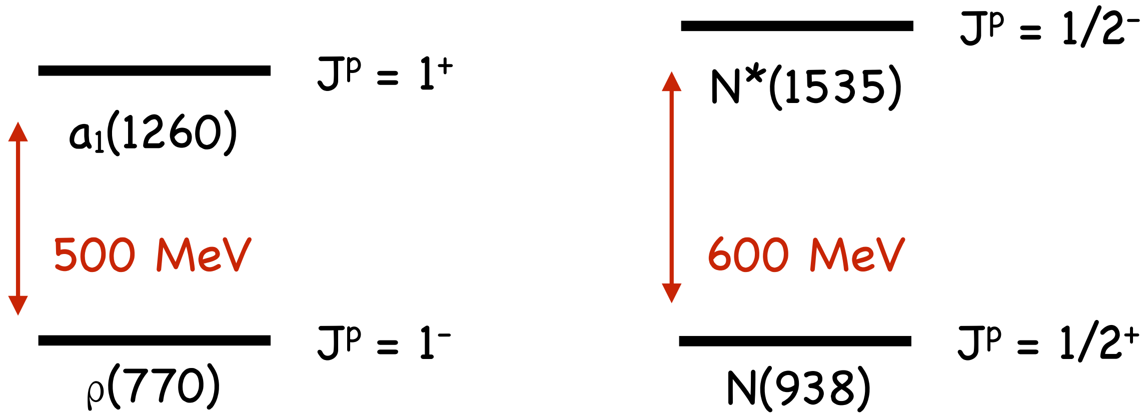


Partial Wave Analyses Good overall description <u>after</u> fit, however, not with identical results.

S.S. et al. (CLAS Collaboration), PLB **750**, 53 (2015)

Is chiral symmetry effectively restored in highly excited mesons and baryons?

An important consequence of the spontaneous breaking of the chiral symmetry is the large mass gap between chiral partners:



Mesons and baryons at higher masses are often observed in parity doublets. Example: four positive-parity and four negative-parity $\Delta*$ resonances at about 1900 MeV

$$\Delta(1910)1/2^+ \quad \Delta(1920)3/2^+ \quad \Delta(1905)5/2^+ \quad \Delta(1950)7/2^+ \ (****)$$

$$\Delta(1900)1/2^- \quad \Delta(1940)3/2^- \quad \Delta(1930)5/2^- \quad \Delta(2200)7/2^- \ (*)$$

A.V. Anisovich et al., Phys.Lett. B766 (2017) 357-361

New evidence for Δ(2200)7/2⁻ resonance

BnGa analysis incl. recent CLAS and CBELSA/TAPS data

Parity partner of Δ(1950)7/2⁺ is poorly known.

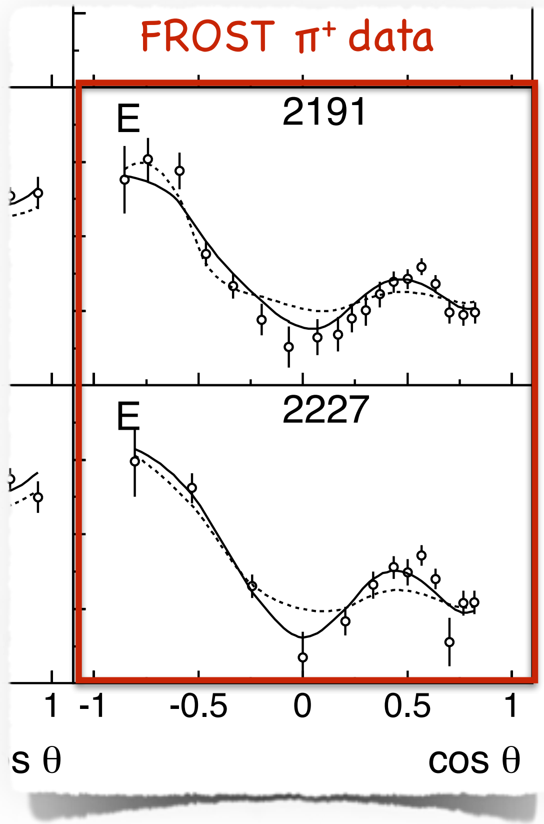
Δ(1950)7/2+ ****

Δ(2200)7/2⁻ *

Evidence found for Δ(2200)7/2⁻ in a preliminary analysis of the Bonn/Gatchina group.

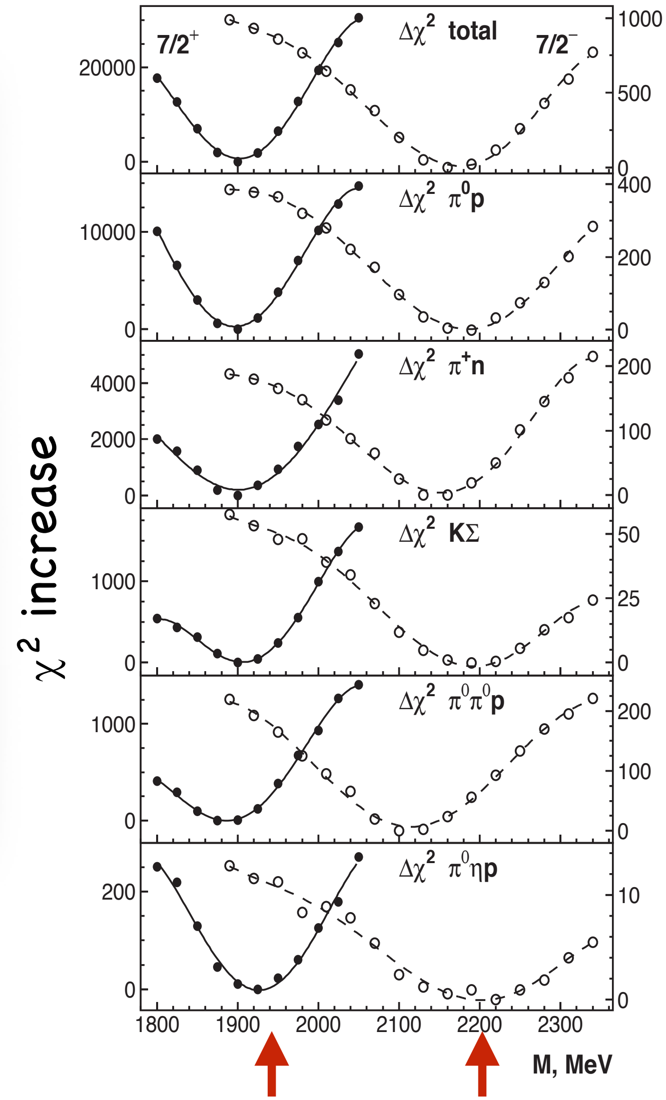
M(Δ 7/2⁻) ≈ 2180 MeV

... and not ≈ 1950 MeV. Chiral symmetry is not restored in high-mass hadrons.



with Δ(2200)7/2⁻

without

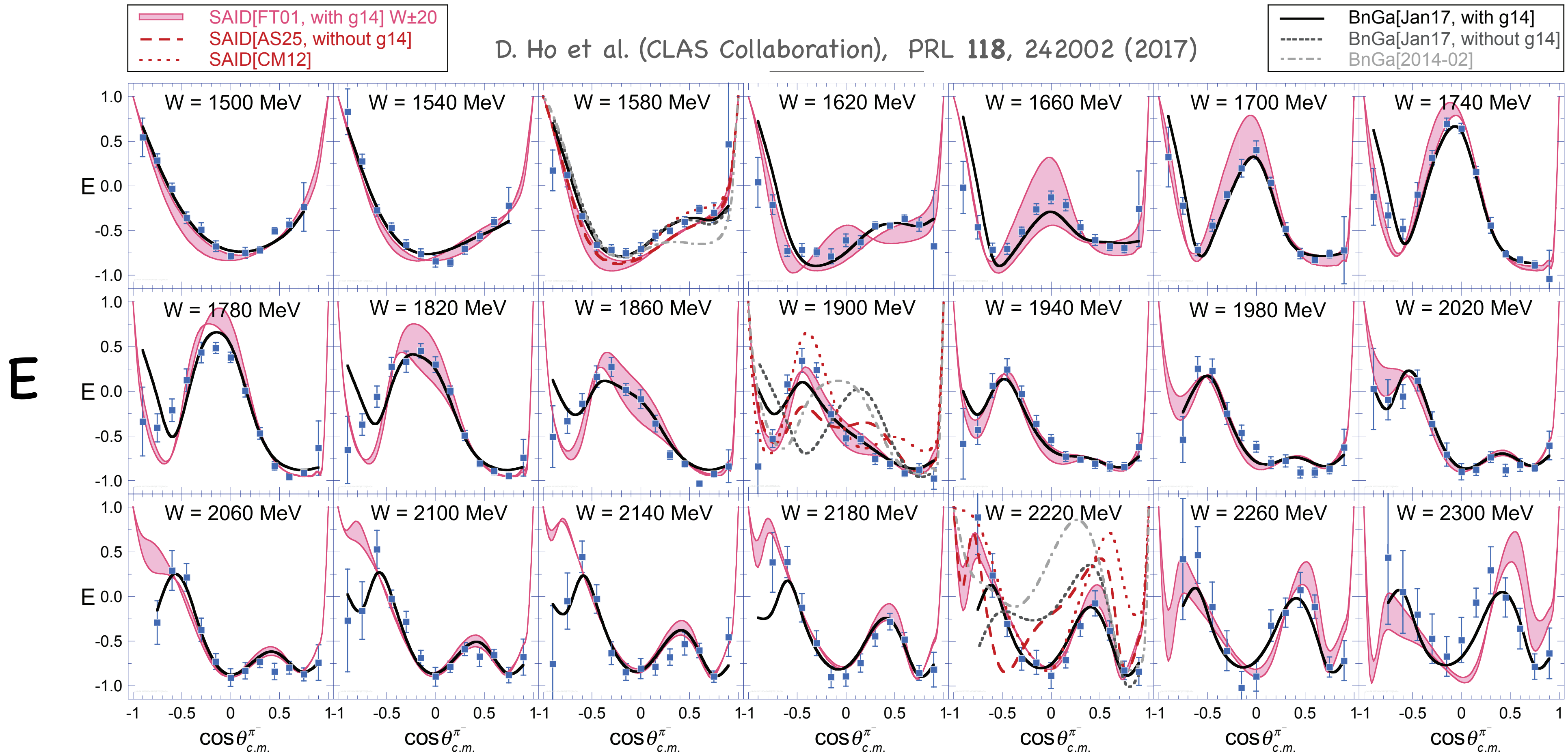


A.V. Anisovich et al., Phys.Lett. B766 (2017) 357-361

Significant revisions for several γnN* resonance photocouplings

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

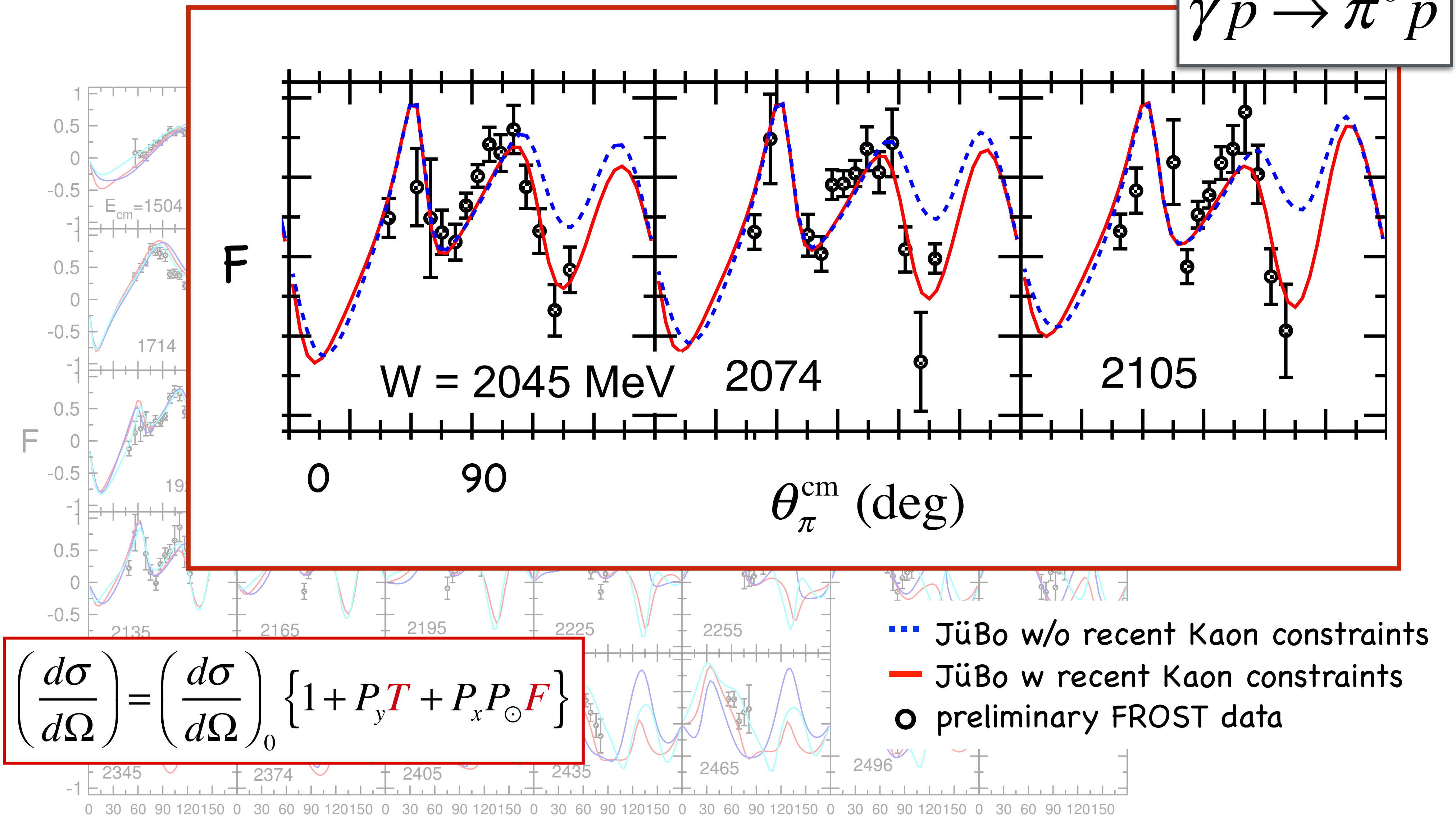
D. Ho et al. (CLAS Collaboration), PRL **118**, 242002 (2017)



- Inclusion of these results in new PWA calculations has resulted in revised γnN* couplings and, in the case of the N(2190)7/2⁻, convergence among different PWA groups.
- Such couplings are sensitive to the dynamical process of N*excitation and provide important guides to nucleon structure models.

Kaon-data-constrained Jülich-Bonn solutions describe new π^0 photoproduction data well

$$\gamma \vec{p} \rightarrow \pi^0 p$$



$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_0 \left\{1 + P_y T + P_x P_\odot F\right\}$$

g9b analysis of Hao Jiang (South Carolina); model: Deborah Rönchen (Bonn), private communication (2016)

Helicity asymmetry E in eta photoproduction on the proton

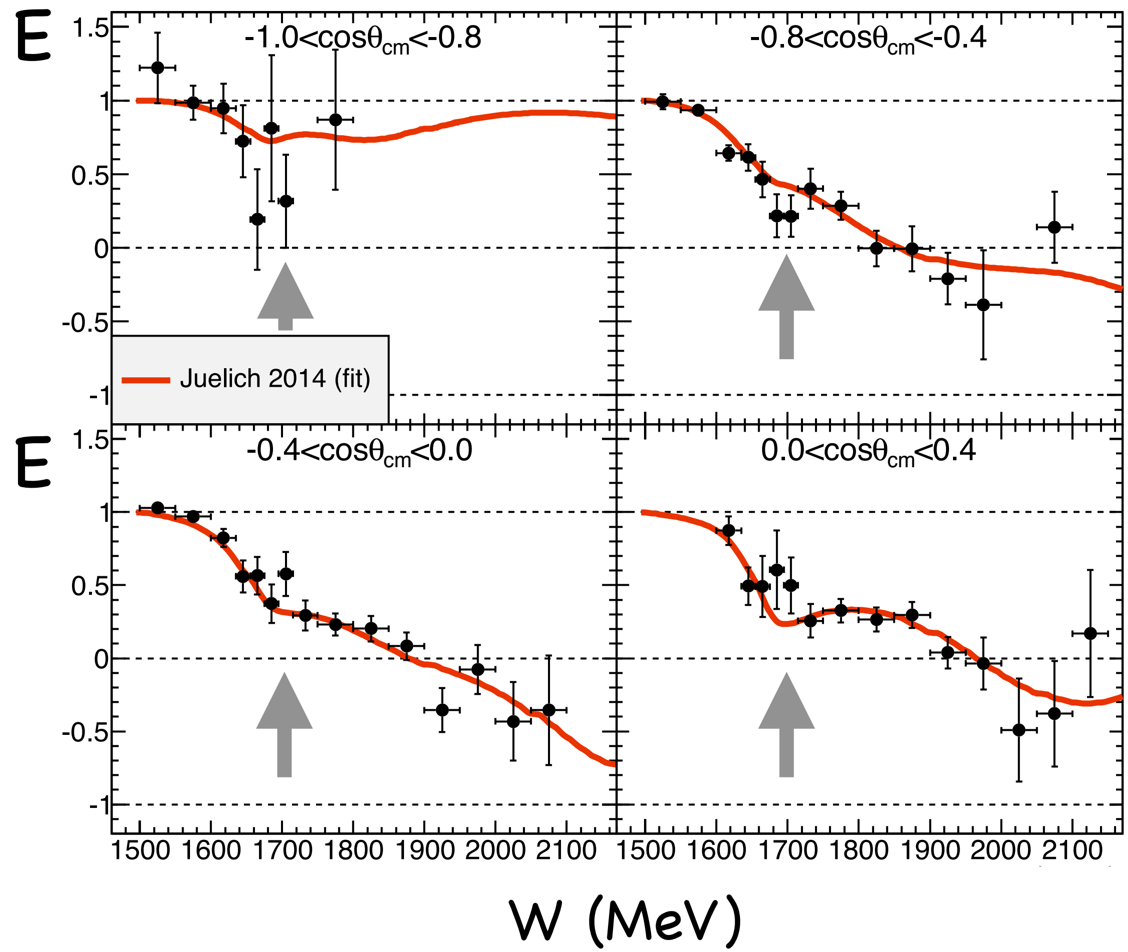
$$\vec{\gamma}\vec{p} \to \eta p$$

η photoproduction isolates N*(I=1/2) states in the resonance spectrum.

Narrow structure seen in MAMI $\gamma p \to \eta p$ cross section data.

[predicted in πN PWA: Phys. Rev. C 69, 035208 (2004)]

Present CLAS E data do not demand the presence of a narrow resonance with a width of 40 MeV or less at about 1.7 GeV.

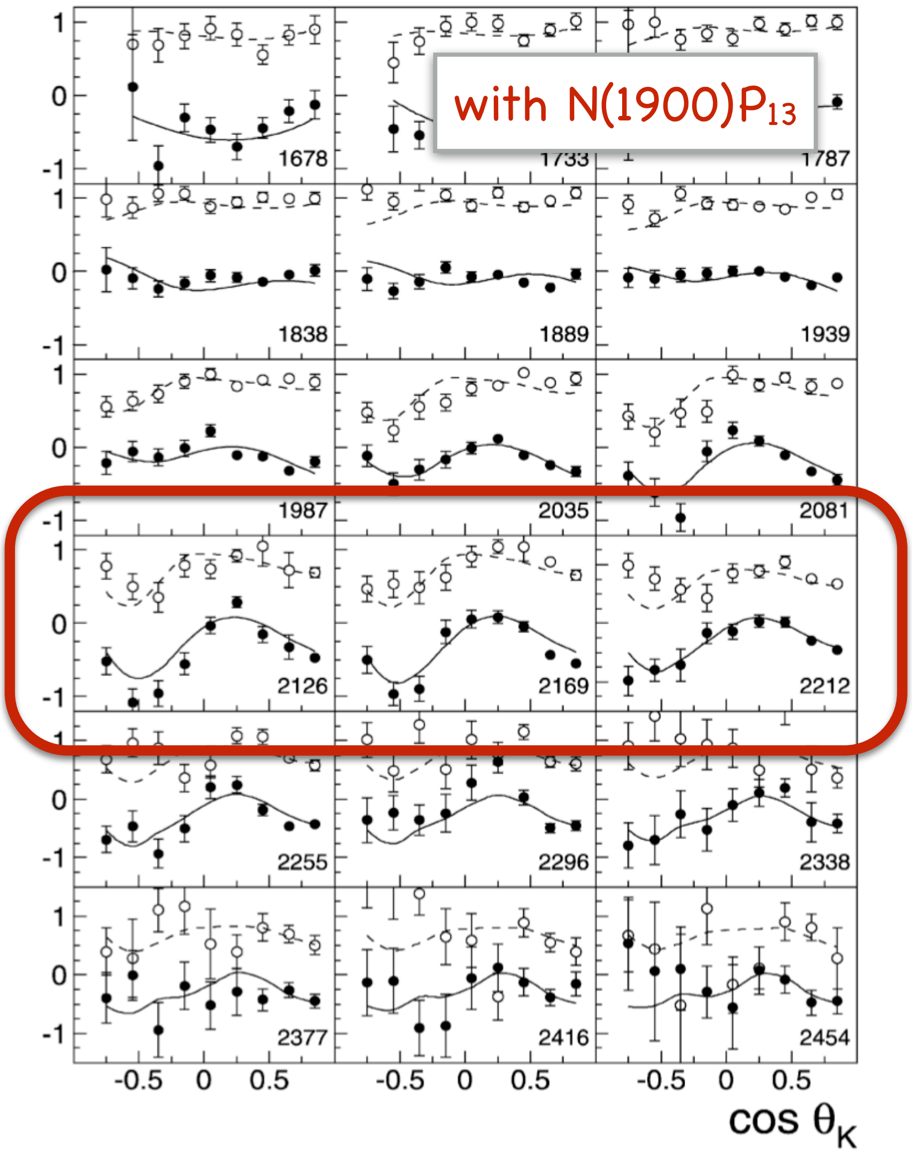


I. Senderovich et al. (CLAS Collaboration), Phys.Lett. B**755** (2016) 64-69

Polarization Transfer Observables C_x, C_z

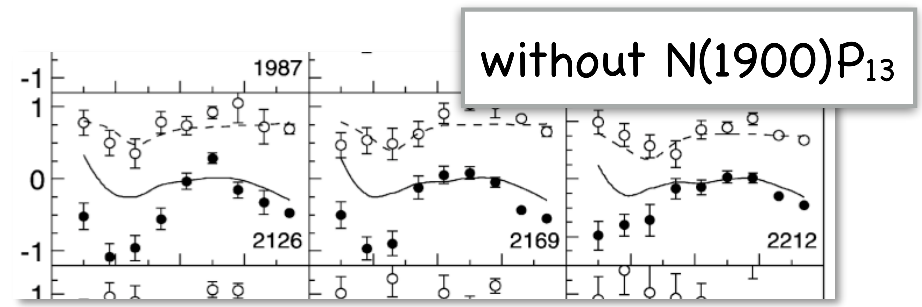
$\vec{\gamma} p \rightarrow K^+ \vec{\Lambda}$

C_x (●), C_z (○) for $K^+\Lambda$ channel



Bonn-Gatchina coupled-channel isobar model: N(1900)P_{13} needed in PWA of Nikonov et al.

Strongest contributions to $\gamma p \rightarrow K\Lambda$: S_{11}-wave, P_{13}(1720), P_{13}(1900), P_{11}(1840)



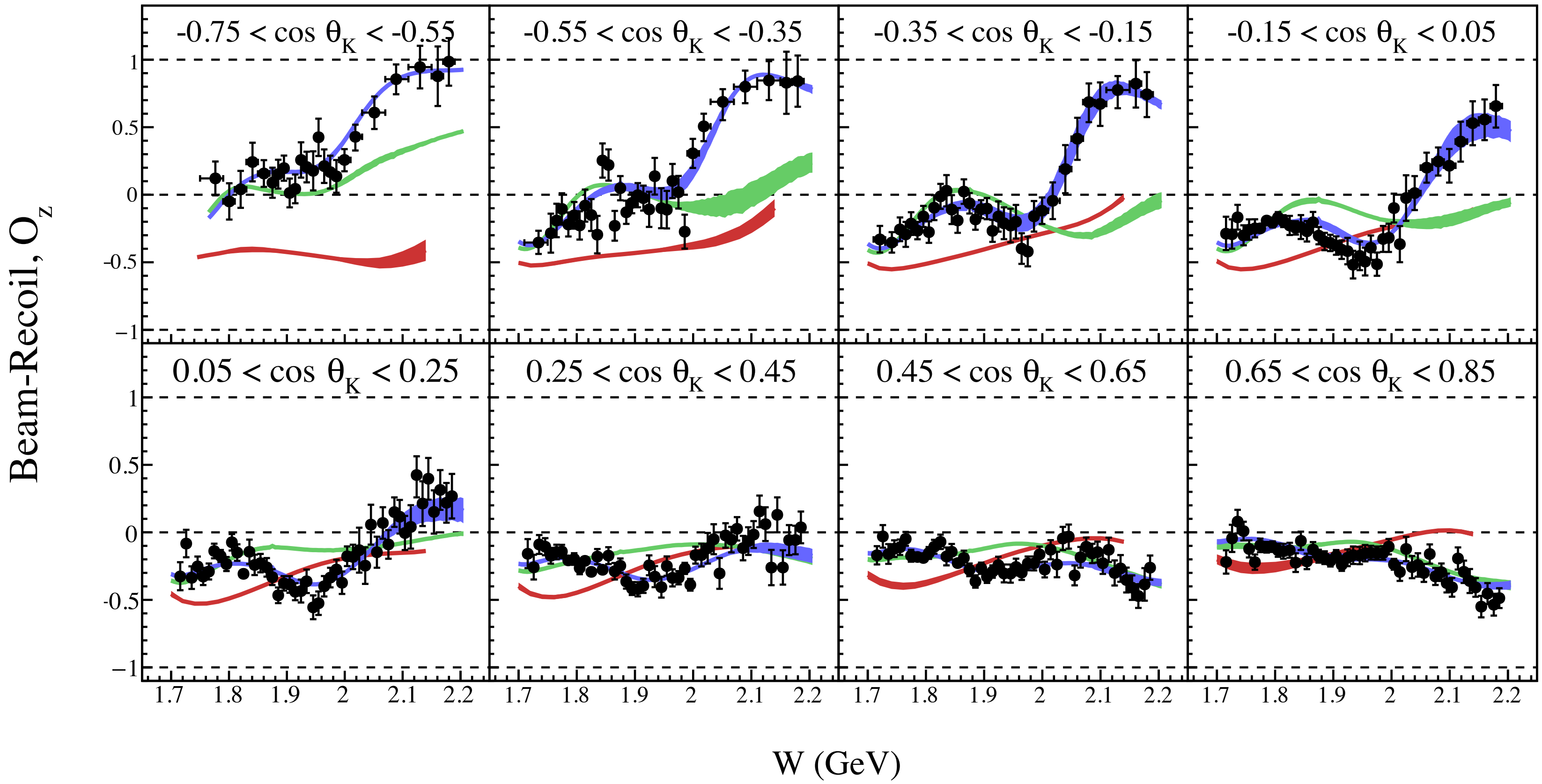
State confirmed in more recent analyses.

N(1900)P_{13} found in qqq models, not expected in some quark-diquark models.

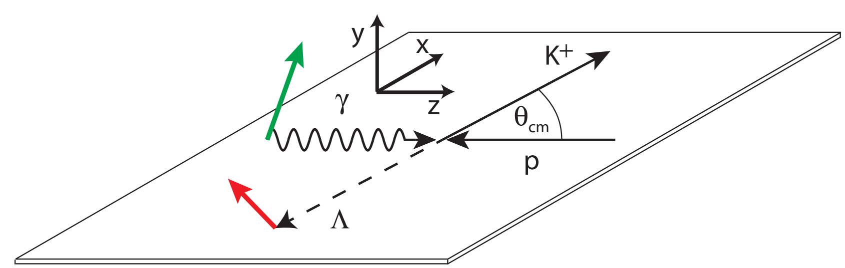
CLAS Data: R. Bradford, et al., Phys. Rev. C 75, 035205 (2007).
Analysis: V.A. Nikonov et al., Phys. Lett. B 662, 245 (2008)

Strengthened evidence for set of resonances in latest BoGa fit

$$\vec{\gamma} p \rightarrow K^+ \Lambda$$



ANL-Osaka coupled-channels calculations,
Bonn-Gatchina partial wave analysis (2014),
Bonn-Gatchina calculations after a refit including the present data, which include additional N*(3/2+) and N*(5/2+) resonances.



C.A. Paterson et al. (CLAS Collaboration), PRC **93**, 065201 (2016)

Double-pion photoproduction as a tool in the study of excited nucleons

$$\gamma p \rightarrow \pi^+ \pi^- p$$

Nππ is a dominant decay channel of highly excited nucleons.

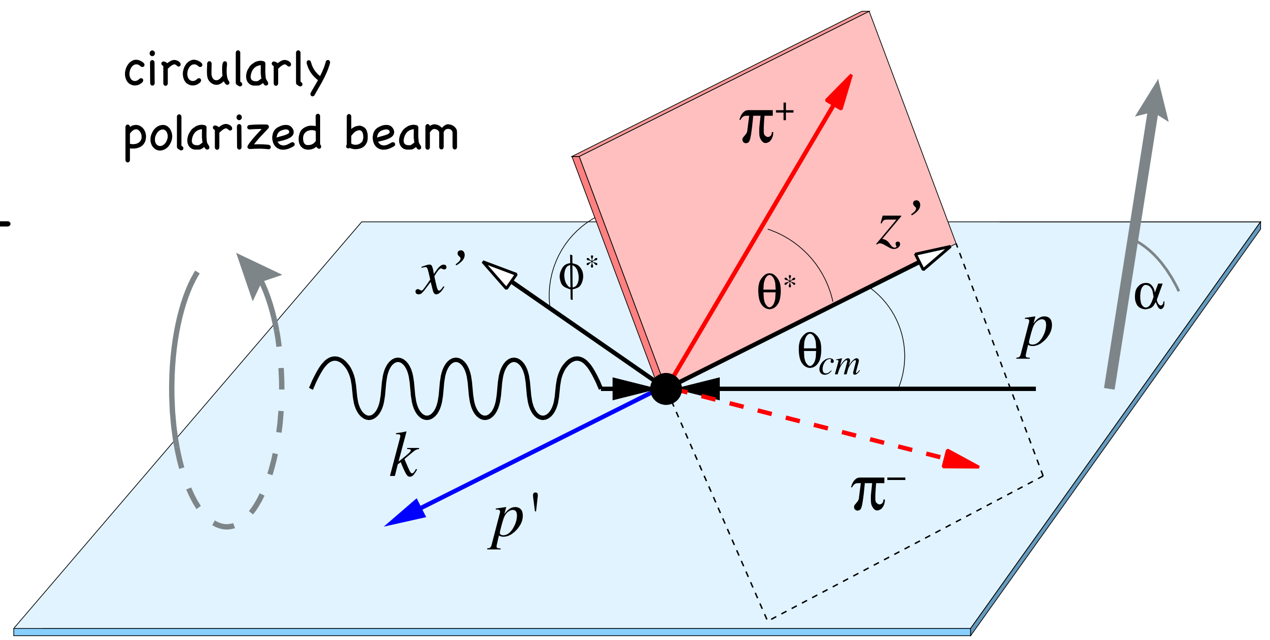
Essential part in coupled-channel calculations.

Allows for the study of sequential decays.

$$\gamma p \rightarrow N^* \rightarrow \pi \Delta$$

$$\gamma p \rightarrow N^* \rightarrow \rho p$$

Example:



$$\frac{d^5\sigma}{dm(\pi^+\pi^-)\, d\Omega^*_{\pi+}\, d\cos\theta}$$

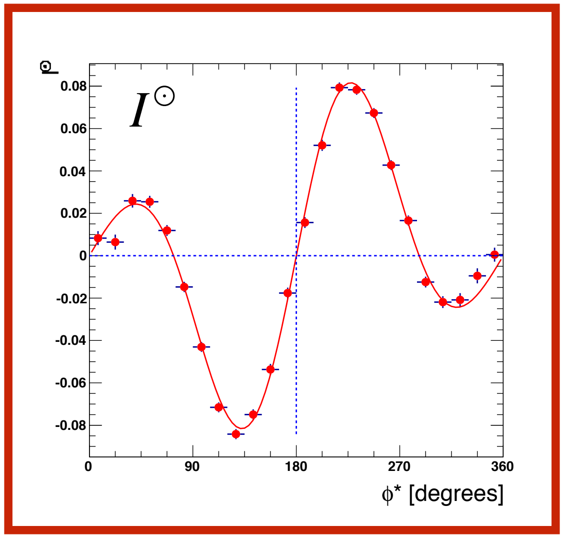
W. Roberts and T. Oed, Phys. Rev. C **71**, 055201 (2005)

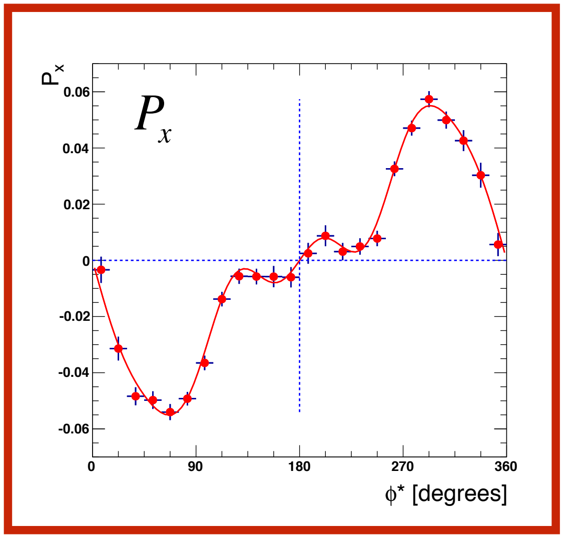
Parity conservation yields to symmetry properties of observables

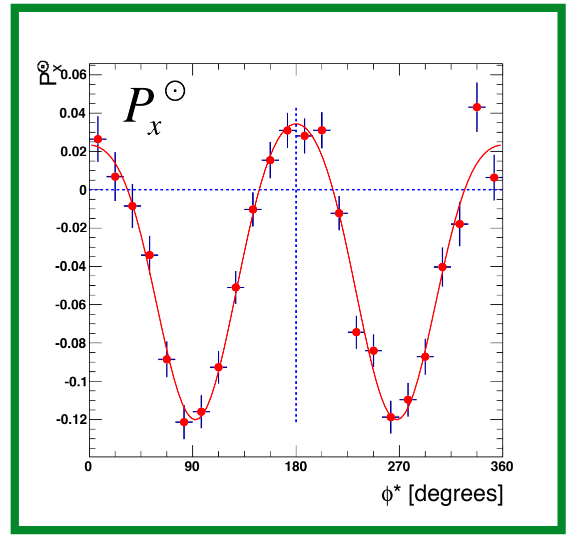
$$\gamma p \rightarrow \pi^+ \pi^- p$$

$$M^{-\lambda_\gamma}_{-\lambda_N -\lambda'_N}(\theta,\theta_1,\phi_1) = (-1)^{\lambda_\gamma - \lambda_N + \lambda'_N} M^{\lambda_\gamma}_{\lambda_N \lambda'_N}(\theta,\theta_1,2\pi-\phi_1)$$

circularly polarized photons - transversely polarized target

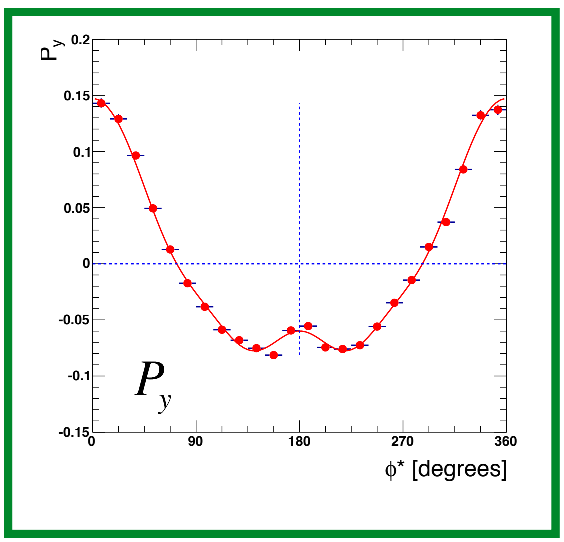


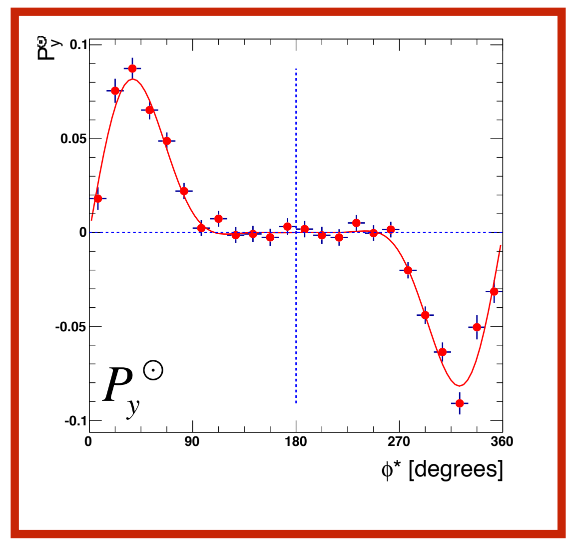




odd observables: do not exist in single meson final states.

even observables: P_y and $P_x^{\odot}$ correspond to T and F, respectively.





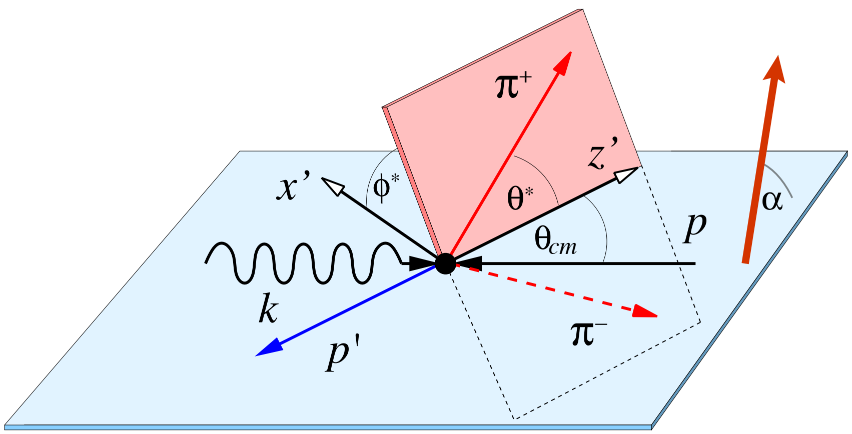
g9 analysis: Aneta Net (USC)

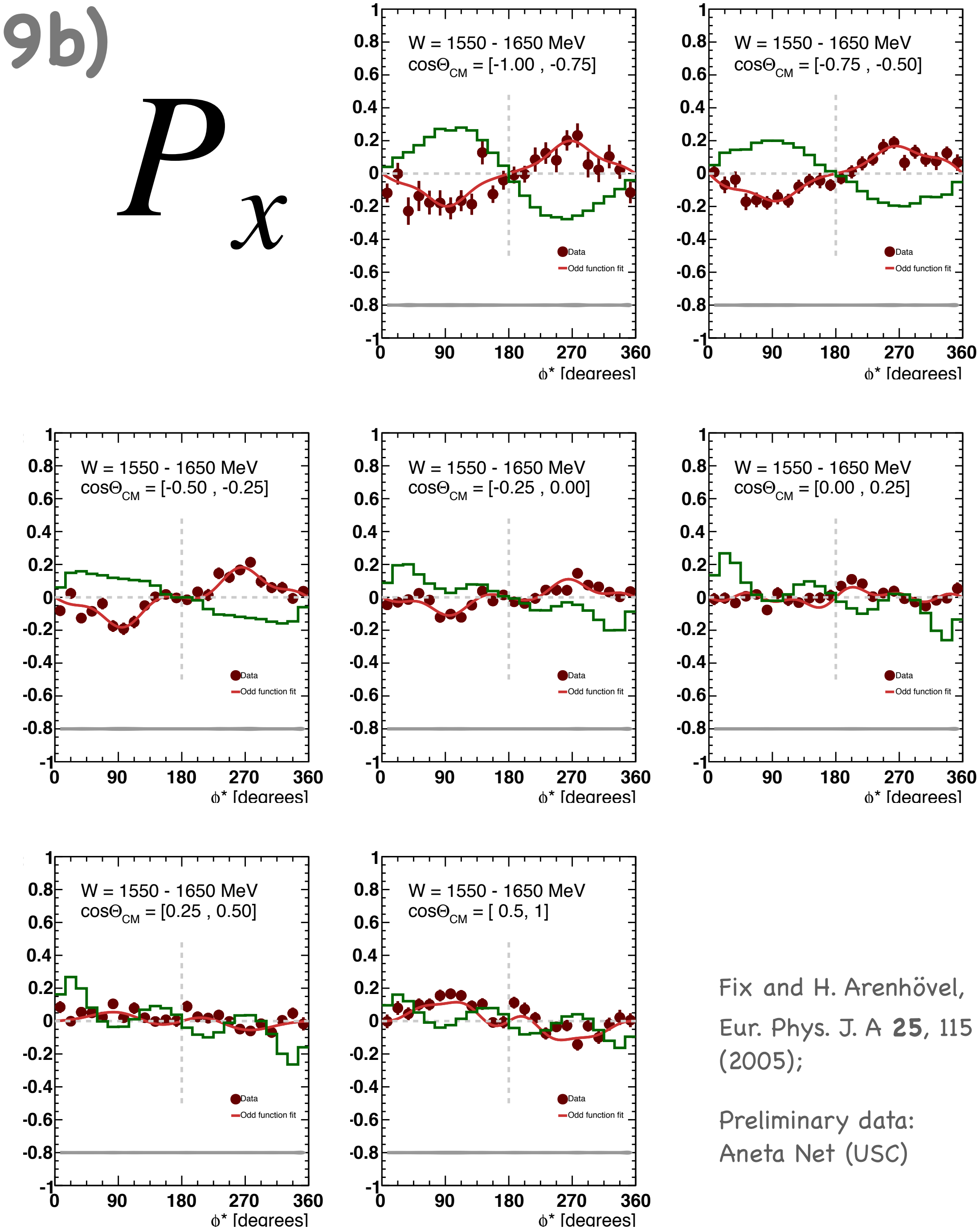
Preliminary results (g9b)

$$\gamma \vec{p} \rightarrow \pi^{+}\pi^{-} p$$

$$P_x$$

$$I = I_0\left(1 + \Lambda\cos(\alpha)P_x + \Lambda\sin(\alpha)P_y\right)$$





W = 1600 MeV data binned in $\cos\theta_{cm}$,

Fourier series fit

Effective Lagrangian model (A. Fix)

Fix and H. Arenhövel, Eur. Phys. J. A **25**, 115 (2005);

Preliminary data: Aneta Net (USC)

Intermediate Δ(1232) Resonance

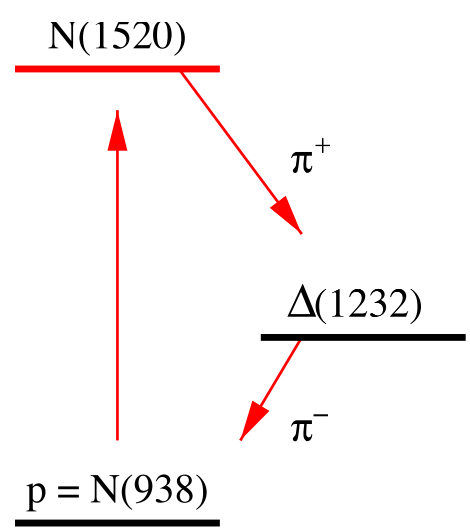
$$\vec{\gamma} p \to \pi^+ \pi^- p$$

Fourier coefficients of the angular distribution

$$I^{\odot} = \sum a_k \sin(k\phi)$$

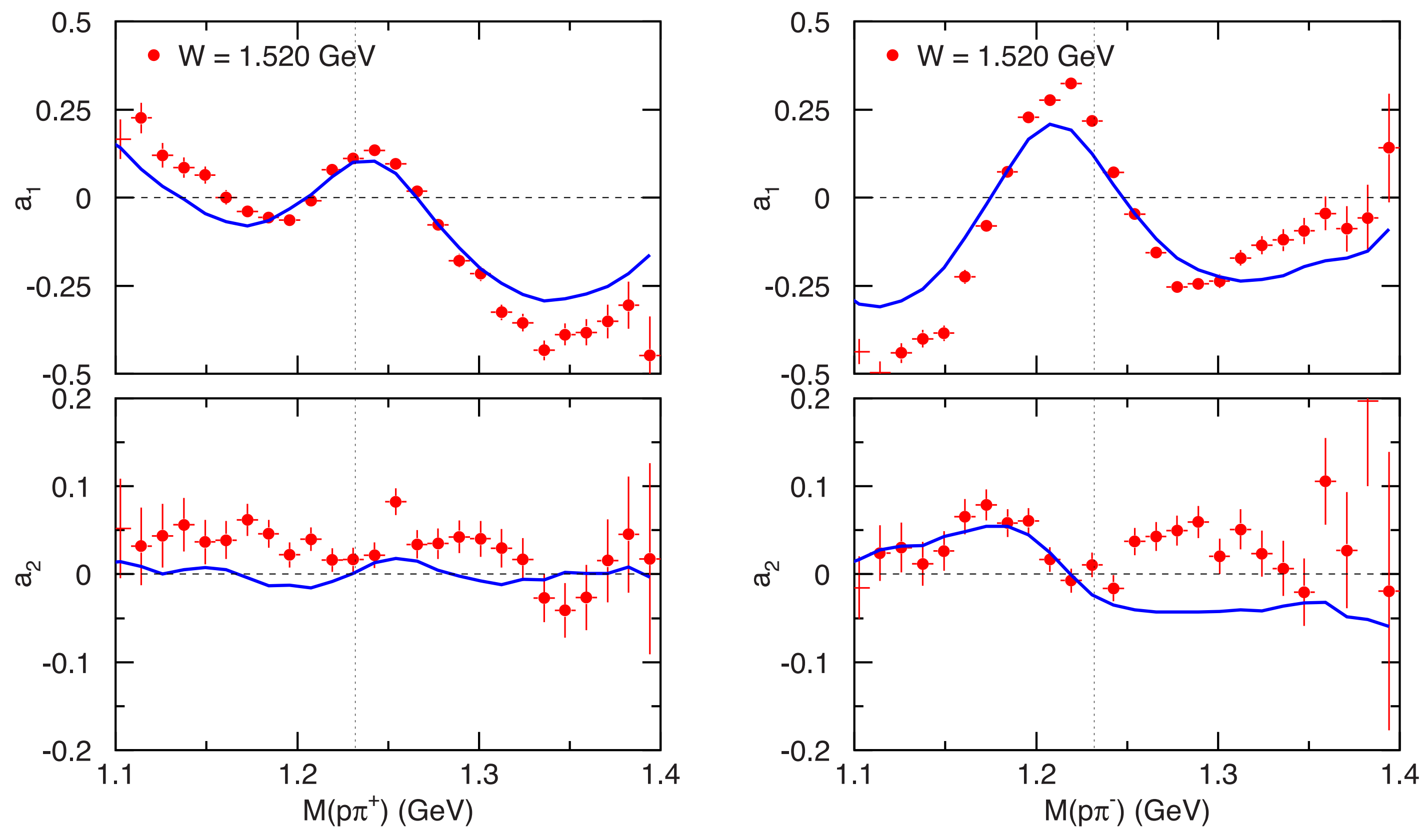
Example of sequential decays

$$\gamma p \to N^* \to \pi\Delta$$



$$N(1520) \to \pi^- \Delta^{++} \to p\pi\pi$$

$$N(1520) \to \pi^+ \Delta^{0} \to p\pi\pi$$



CLAS Data: S.S. et al (CLAS Collaboration), Phys. Rev. Lett 95, 162003 (2005); Model: A. Fix and H. Arenhövel, Eur. Phys. J. A **25**, 115 (2005)

Summary and outlook

New CLAS polarized photoproduction data off

polarized and unpolarized,
proton and neutron targets

contribute to complete or nearly complete experiments.

Evidence of new states found in coupled-channel analyses;
e.g. $\Delta(2200)7/2^{-}$

Large impact expected as data analyses are being finalized.

PDG baryon summary table for N* resonances

N^*	J^P	2010	2012	2016	future
p	$1/2^+$	****	****	****	
n	$1/2^+$	****	****	****	
$N(1440)$	$1/2^+$	****	****	****	
$N(1520)$	$3/2^-$	****	****	****	
$N(1535)$	$1/2^-$	****	****	****	
$N(1650)$	$1/2^-$	****	****	****	
$N(1675)$	$5/2^-$	****	****	****	
$N(1680)$	$5/2^+$	****	****	****	
~~$N(1685)$~~			*		
$N(1700)$	$3/2^-$	***	***	***	
$N(1710)$	$1/2^+$	***	***	****	
$N(1720)$	$3/2^+$	****	****	****	
$N(1860)$	$5/2^+$		**	**	
$N(1875)$	$3/2^-$		***	***	
$N(1880)$	$1/2^+$		**	**	
$N(1895)$	$1/2^-$		**	**	
$N(1900)$	$3/2^+$	**	***	***	
$N(1990)$	$7/2^+$	**	**	**	
$N(2000)$	$5/2^+$	**	**	**	
~~$N(2080)$~~	D_{13}	**			
~~$N(2090)$~~	S_{11}	*			
$N(2040)$	$3/2^+$		*	*	
$N(2060)$	$5/2^-$		**	**	
$N(2100)$	$1/2^+$	*	*	*	
$N(2120)$	$3/2^-$		**	**	
$N(2190)$	$7/2^-$	****	****	****	
~~$N(2200)$~~	D_{15}	**			
$N(2220)$	$9/2^+$	****	****	****	
$N(2250)$	$9/2^-$	****	****	****	
$N(2300)$	$1/2^+$			**	
$N(2570)$	$5/2^-$			**	
$N(2600)$	$11/2^-$	***	***	***	
$N(2700)$	$13/2^+$	**	**	**	

... future updates ...

Table adapted from: V. Crede and W. Roberts, Rep. Prog. Phys. 76 (2013) 076301