Non-strange baryons

1. The CLAS N* program
2. Photoproduction off the proton
3. Photoproduction off the neutron

Steffen Strauch for the CLAS Collaboration
University of South Carolina

Supported in parts by the U.S. National Science Foundation: NSF PHY-1812382

NSTAR2019, The 12th International Workshop on the Physics of Excited Nucleons,
Bonn University, June 10th to 14th, 2019

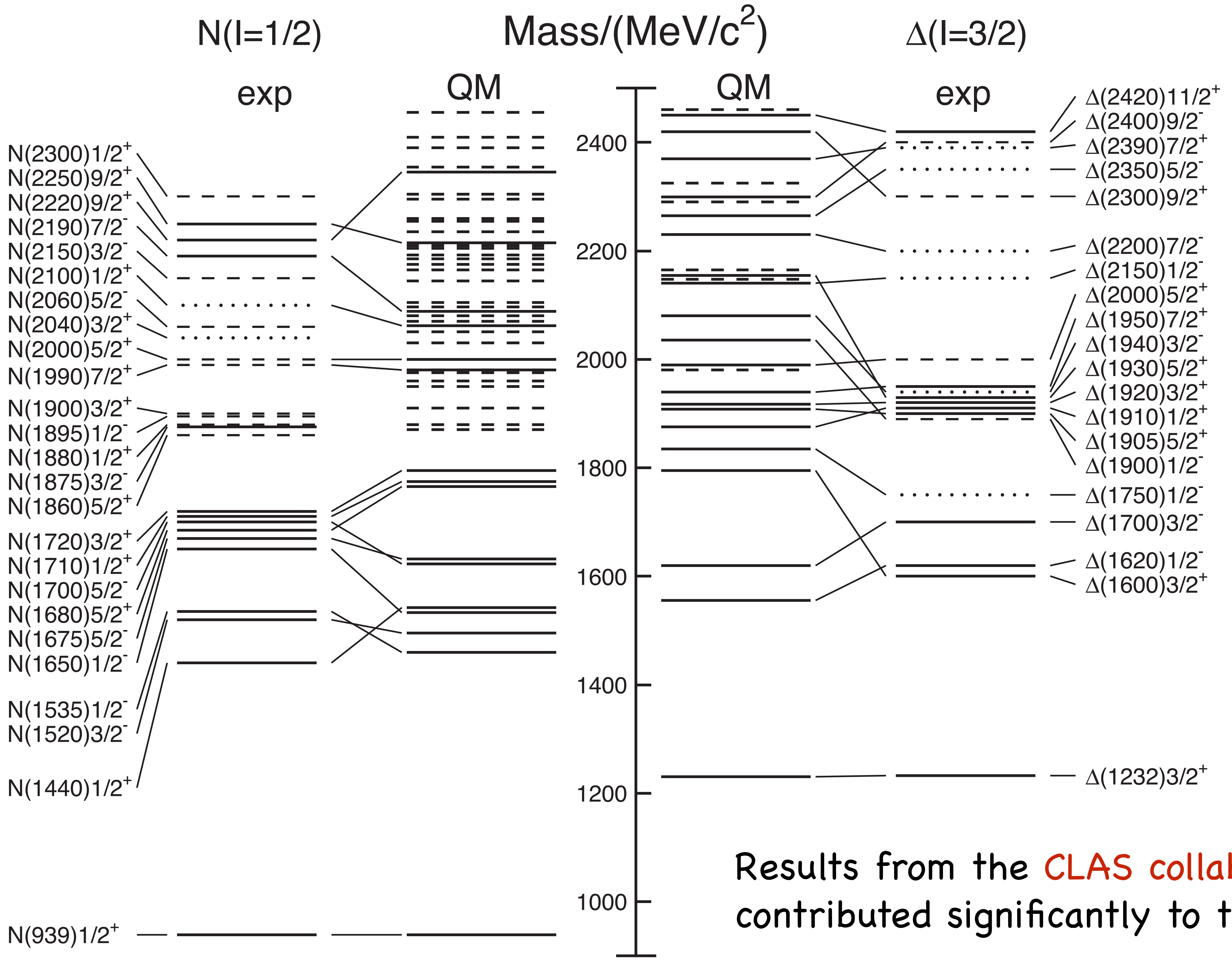
The status of the nucleon resonances (PDG 2018)

Improvements since 2016:

N(2060)5/2-
N(2100)1/2+
N(2060)5/2-

N(1900)3/2+
N(1895)1/2-
N(1990)1/2+

now 21 3☆, 4☆ N



Improvements since 2016:

Δ(2200)7/2-

Δ(1900)1/2-

Δ(1600)3/2+

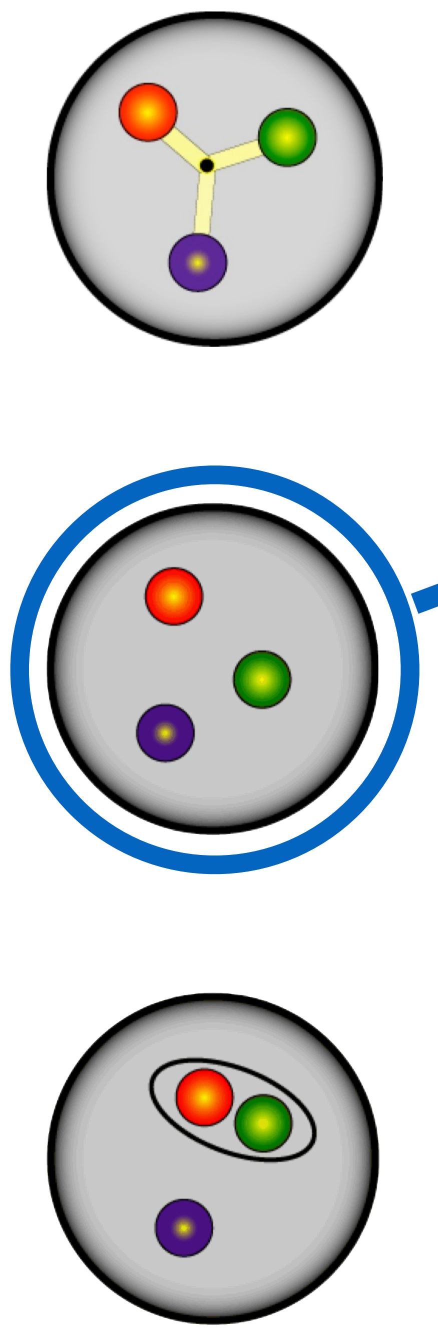
now 12 3☆, 4☆ Δ

Results from the CLAS collaboration contributed significantly to that progress.

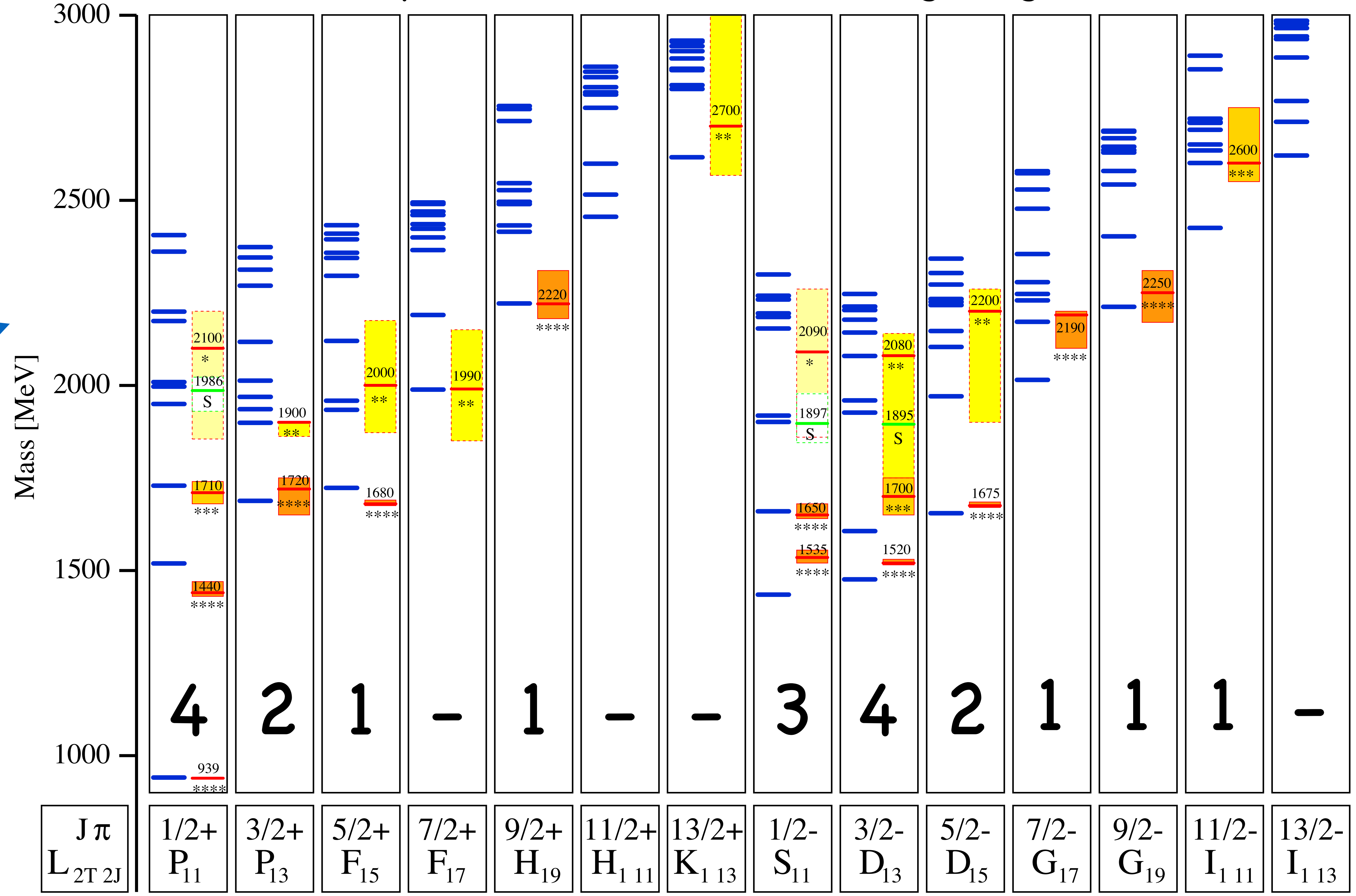
M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018)

Missing-resonance problem and relevant degrees of freedom

Degrees of freedom



N Resonance Spectrum — the low-energy signature of QCD



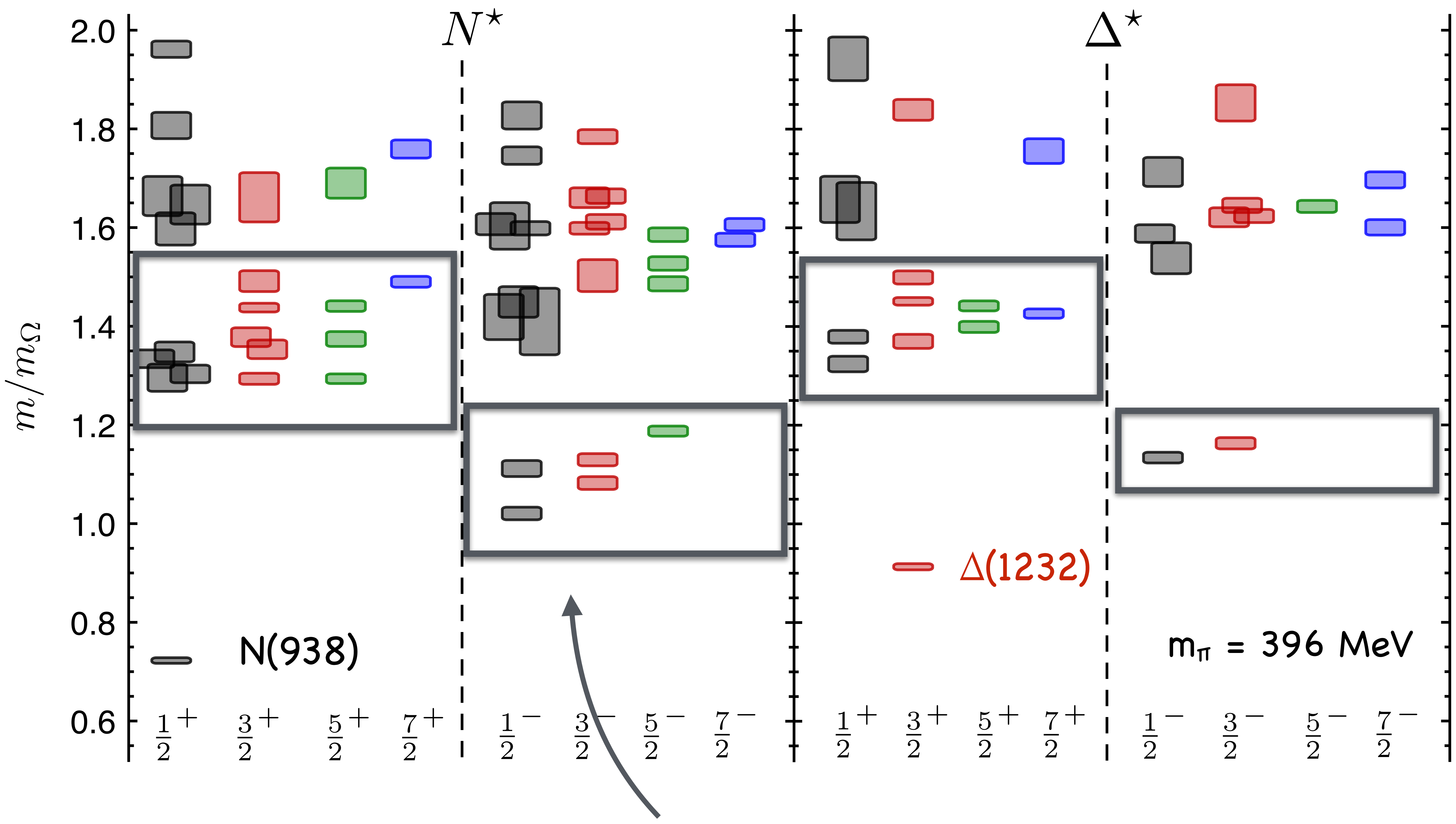
experimentally observed 3☆ or 4☆ states (2018)

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.
- Adding additional gluonic degrees of freedom increases number of bound states (hybrids).

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

Lattice QCD solutions consistent with CQM expectation of an extensive N* spectrum



numbers of low-lying states for each J^P are similar to the numbers obtained in the nonrelativistic quark model

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.

No signs of parity doubling of states.

Hadron spectrum collaboration

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

Two components of the experimental N* program

$Q^2 = 0$: Spectroscopy

search for new states and accounting for the complete excitation spectrum

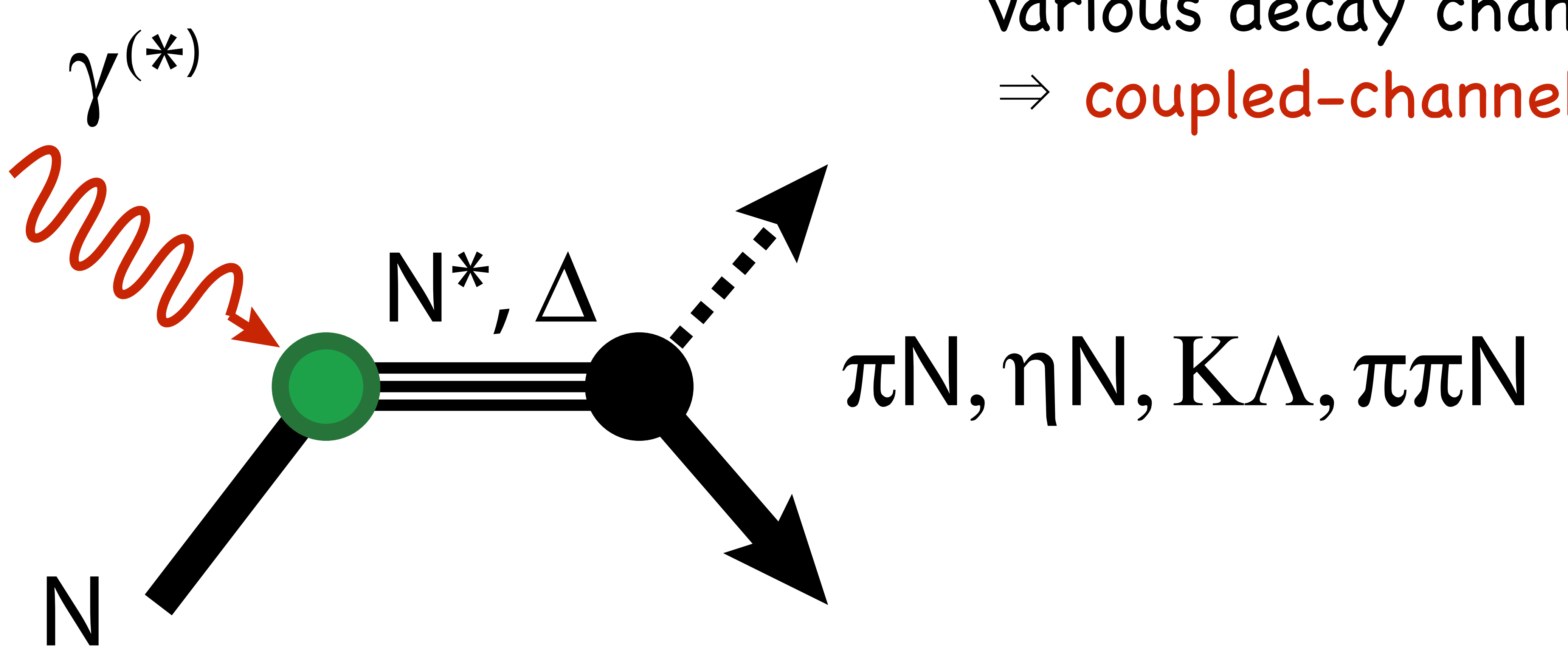
$Q^2 > 0$: Electroproduction

study of the internal structure of a resonance with transition form factors

Electromagnetic Excitation of N*'s

Photon probes the dressed vertex
⇒ reaction models to separate reaction mechanisms from nucleon structure

⇒ $A_{1/2}(Q^2)$, $A_{3/2}(Q^2)$, $S_{1/2}(Q^2)$
helicity amplitudes



various decay channels
⇒ coupled-channel analysis

(Proton and neutron data needed to deduce isospin I=1/2 amplitudes)

Studied decay channels

Proton target

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

present examples

$$\gamma p \to \eta p, \eta' p$$

$$\gamma p \to \omega p, \rho p, \phi p$$

$$\gamma p \to K^+\Lambda, K^+\Sigma^0, K^0\Sigma^+$$

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

$\ldots$ e.g. CLAS frozen spin target (FROST)

Neutron target

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

$$\gamma n \to K^0\Sigma^0, K^0\Lambda$$

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

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

Cross section and polarization observables

Unpolarized, circularly polarized, linearly polarized beam

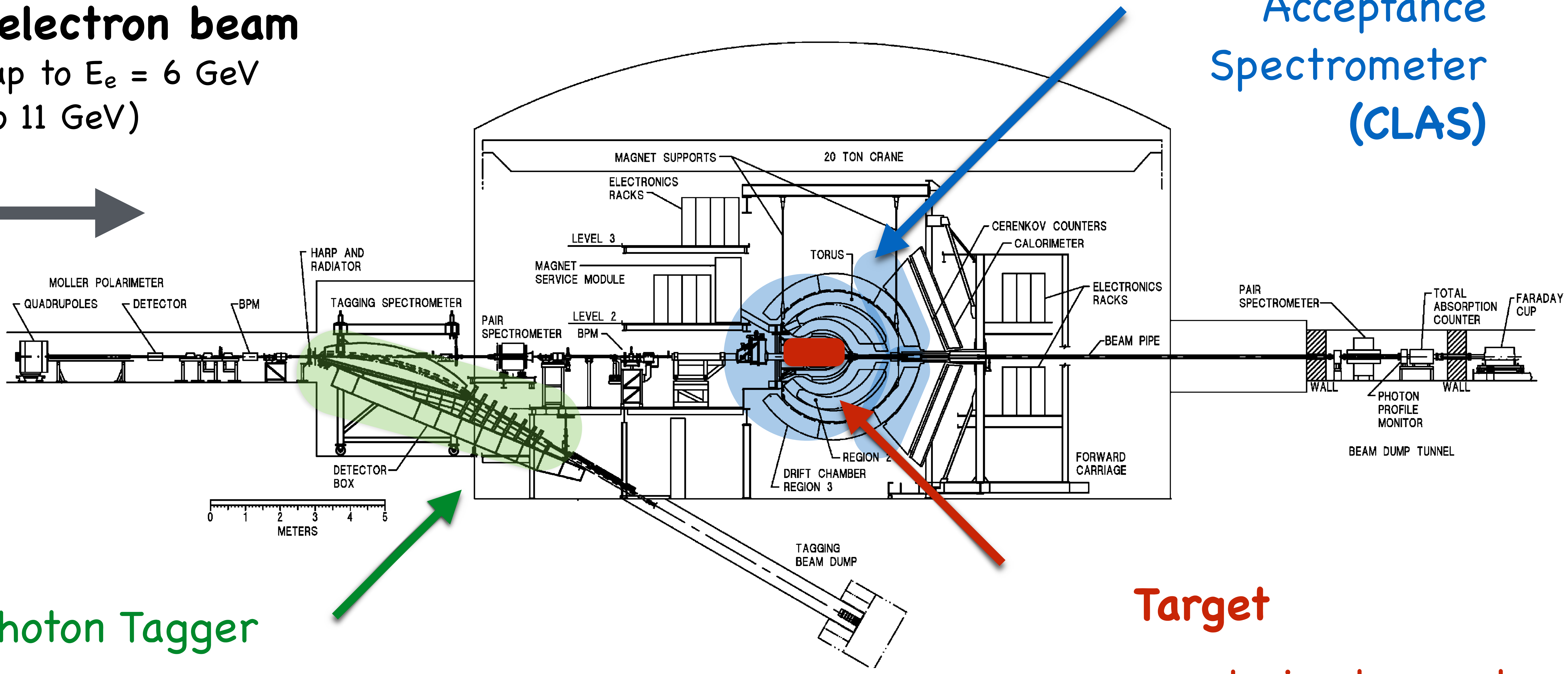
Unpolarized, longitudinally polarized, transversally polarized target

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

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

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

CEBAF Large Acceptance Spectrometer **(CLAS)**



Photon Tagger

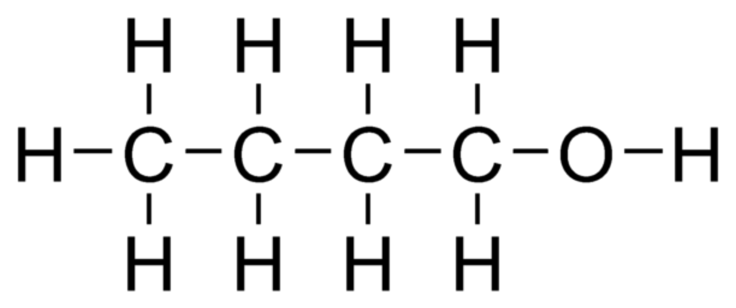
$$E_\gamma = E_e - E_{e'}$$

Target

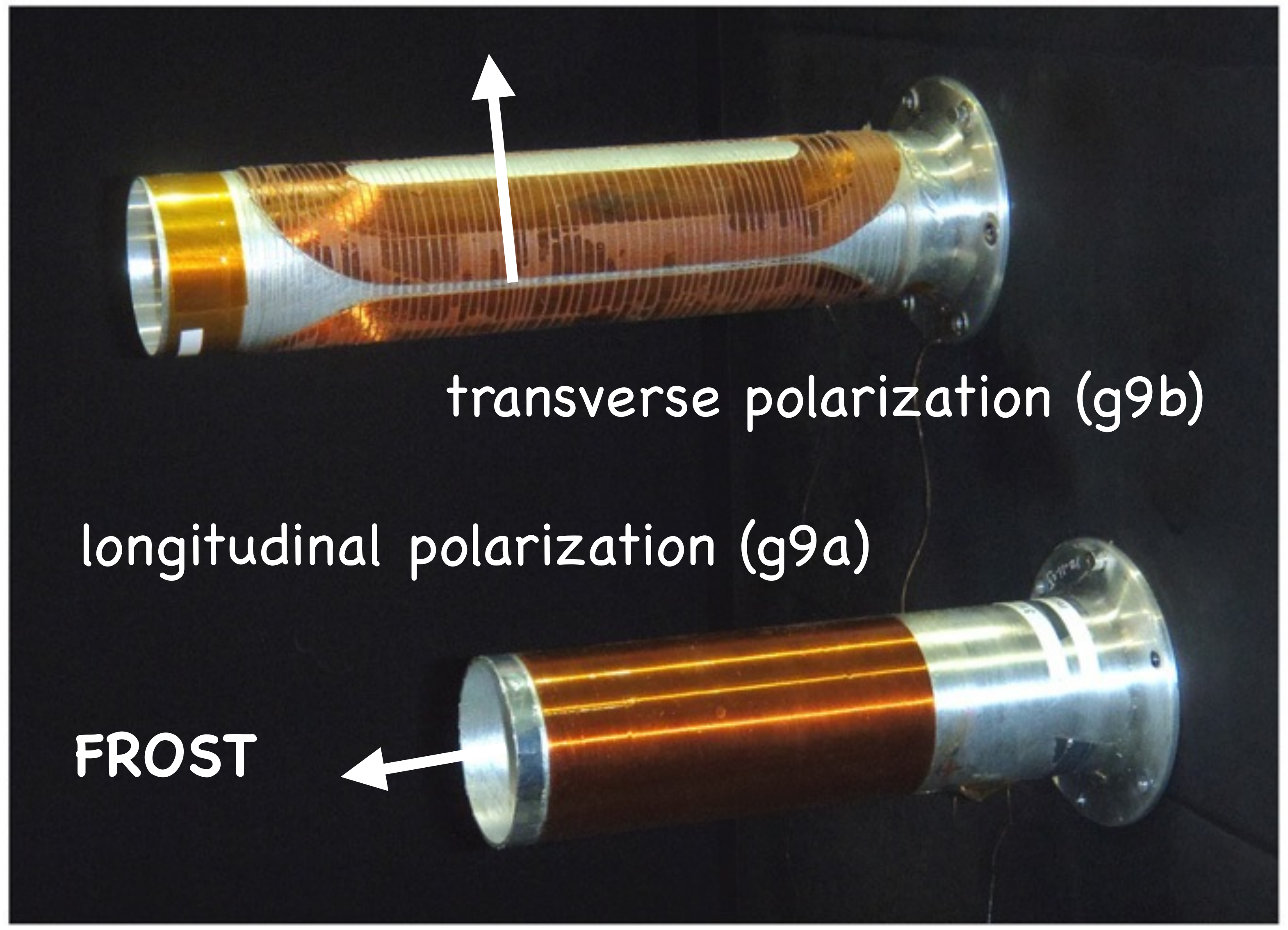
unpolarized p or d,
polarized FROST,
HDice

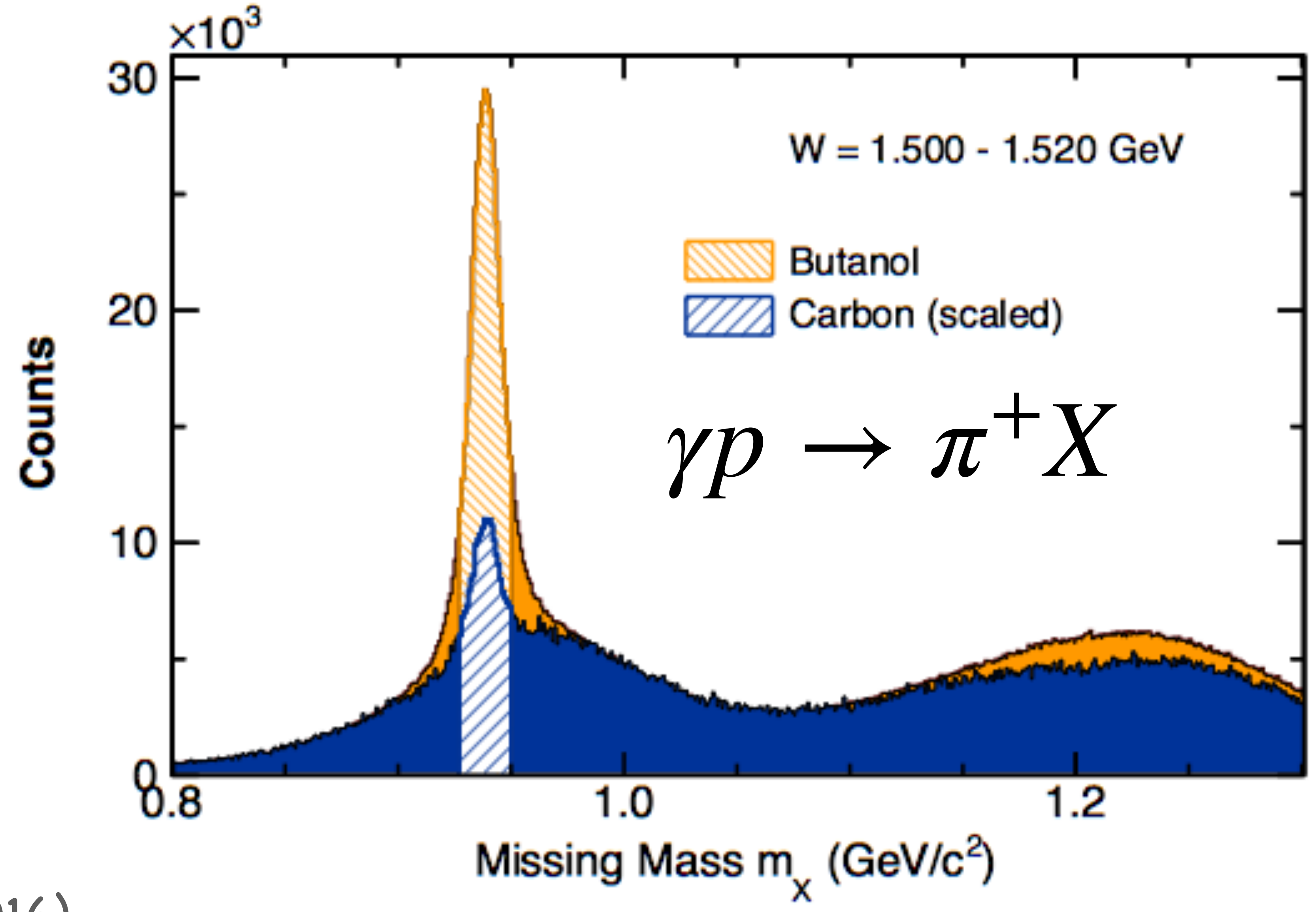
B.A. Mecking et al., Nucl. Instr. and Meth. A **503**, 513 (2003).

Polarized targets for CLAS

Target	FROST	HD-ice
		H—D
Geometry	50 mm x 15 mm ⌀	50 mm x 15 mm ⌀
Polarization	P(p) = 82%; avg. g9a	P(D) = 25%; avg. g14
Spin relaxation	typ. 2800 h with beam	years
Repolarization	once per week	
Dilution	10/74 (in analysis > 0.5)	1/1 for n, 1/2 for p

superconducting holding coils (0.5 T)





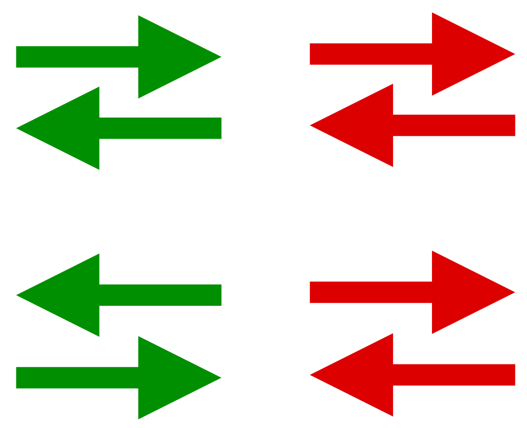
FROST: C.D. Keith et al., NIM **A684**, 27 (2012), HDice: NIM **A737**, 107 (2014), NIM **A815**, 31 (2016)

Double Polarization Observable E

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

$W = 1240 - 2260$ MeV

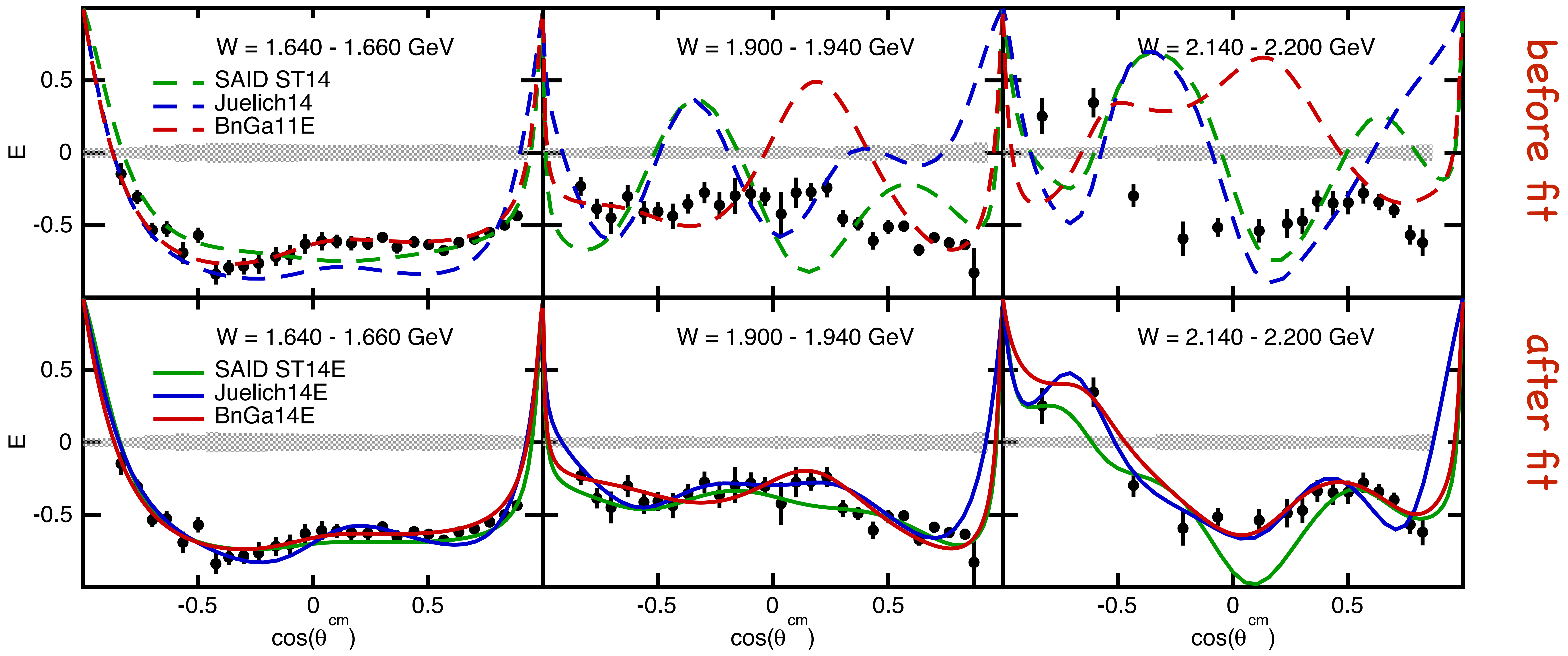
$-0.9 \le \cos(\theta_\pi^{cm}) \le +0.9$



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

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

903 data points



Partial Wave Analyses Good overall description after fit, however, not with identical results.

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

New evidence for a Δ(2200)7/2- resonance

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

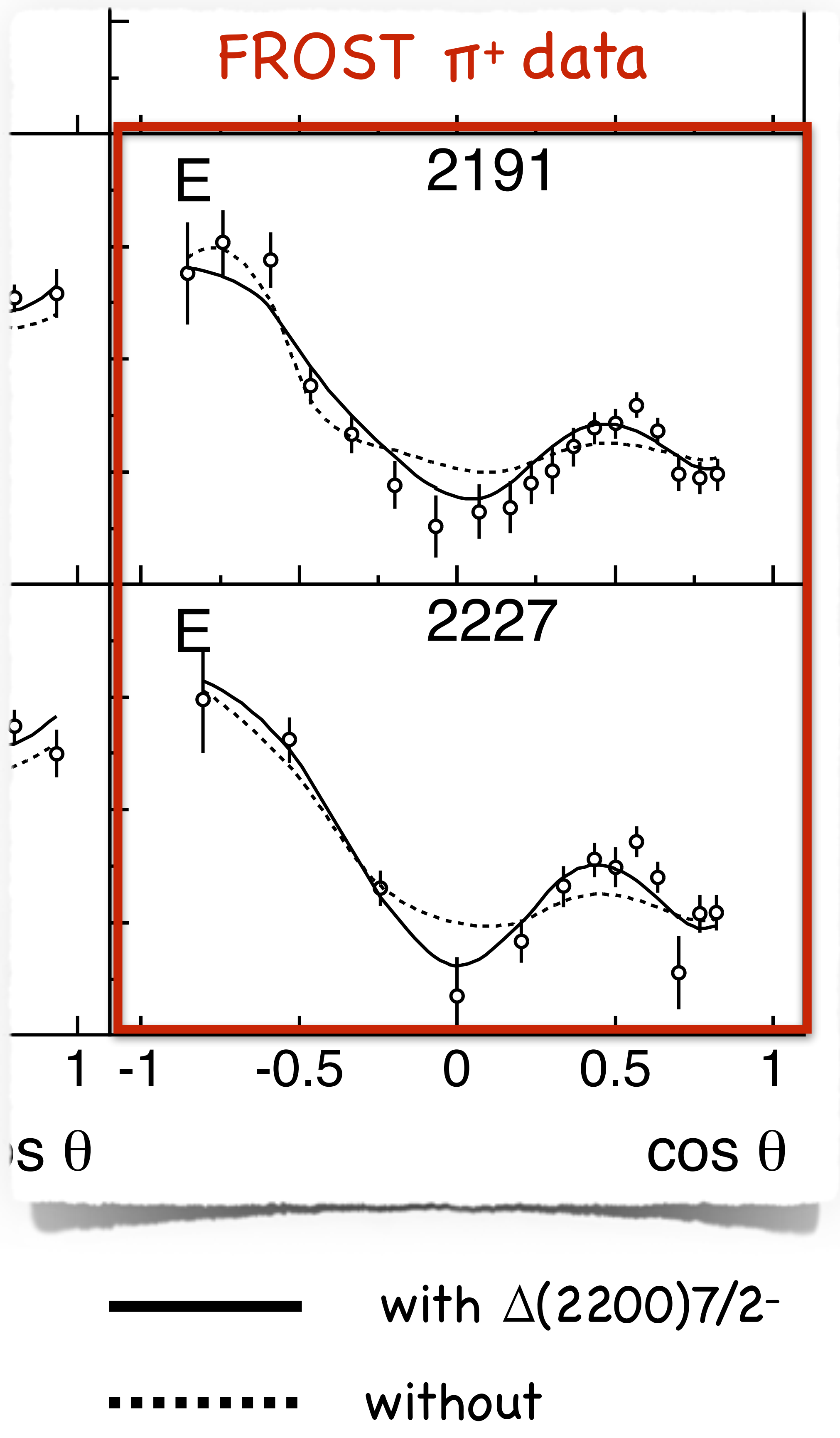
Δ(1950)7/2+ ☆☆☆☆
Δ(2200)7/2- ☆ (now: ☆☆☆)

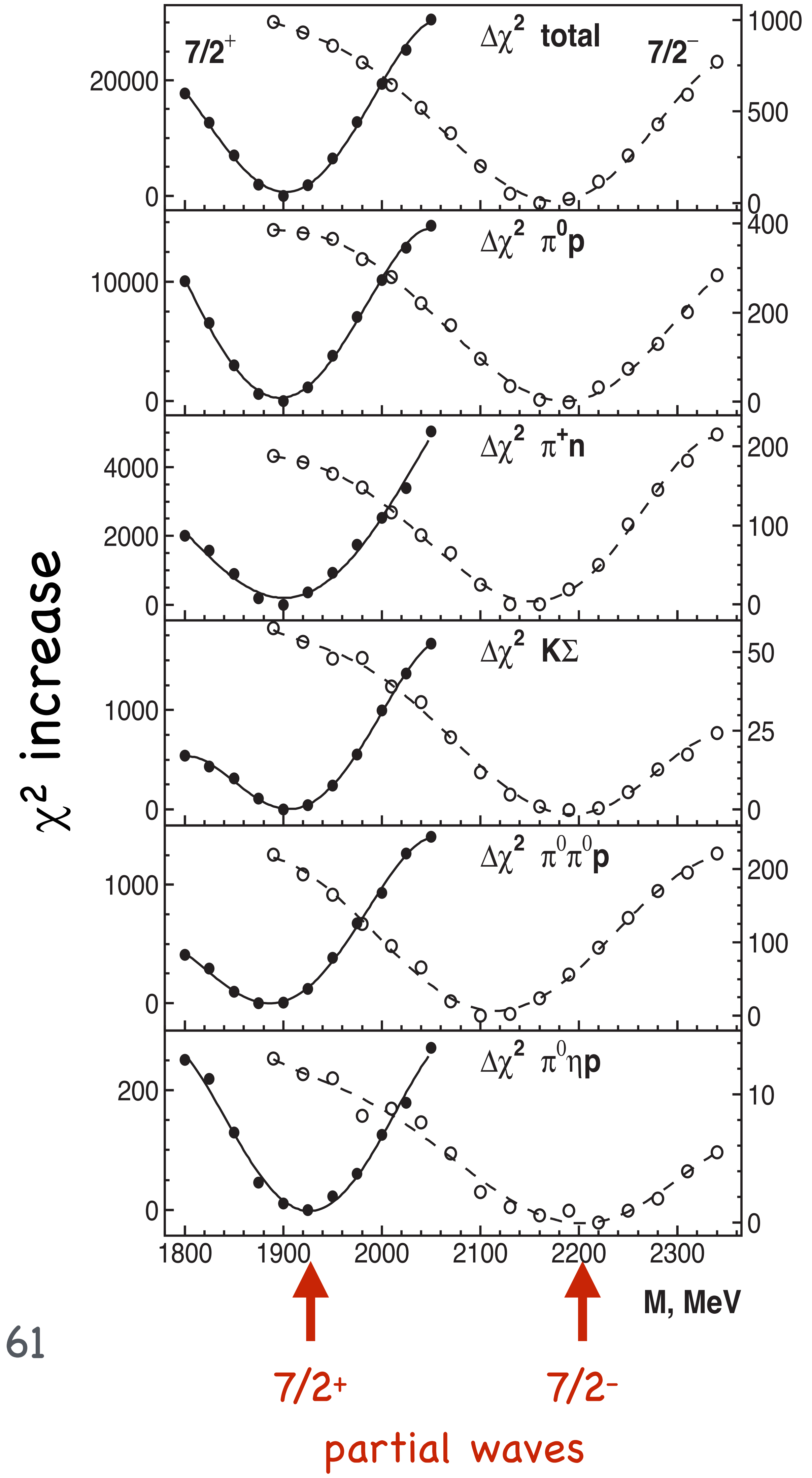
Evidence found for Δ(2200)7/2-
in an analysis of the
Bonn/Gatchina group.

M(Δ7/2-) ≈ 2180 MeV

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

BnGa analysis incl. recent CLAS and CBELSA/TAPS data





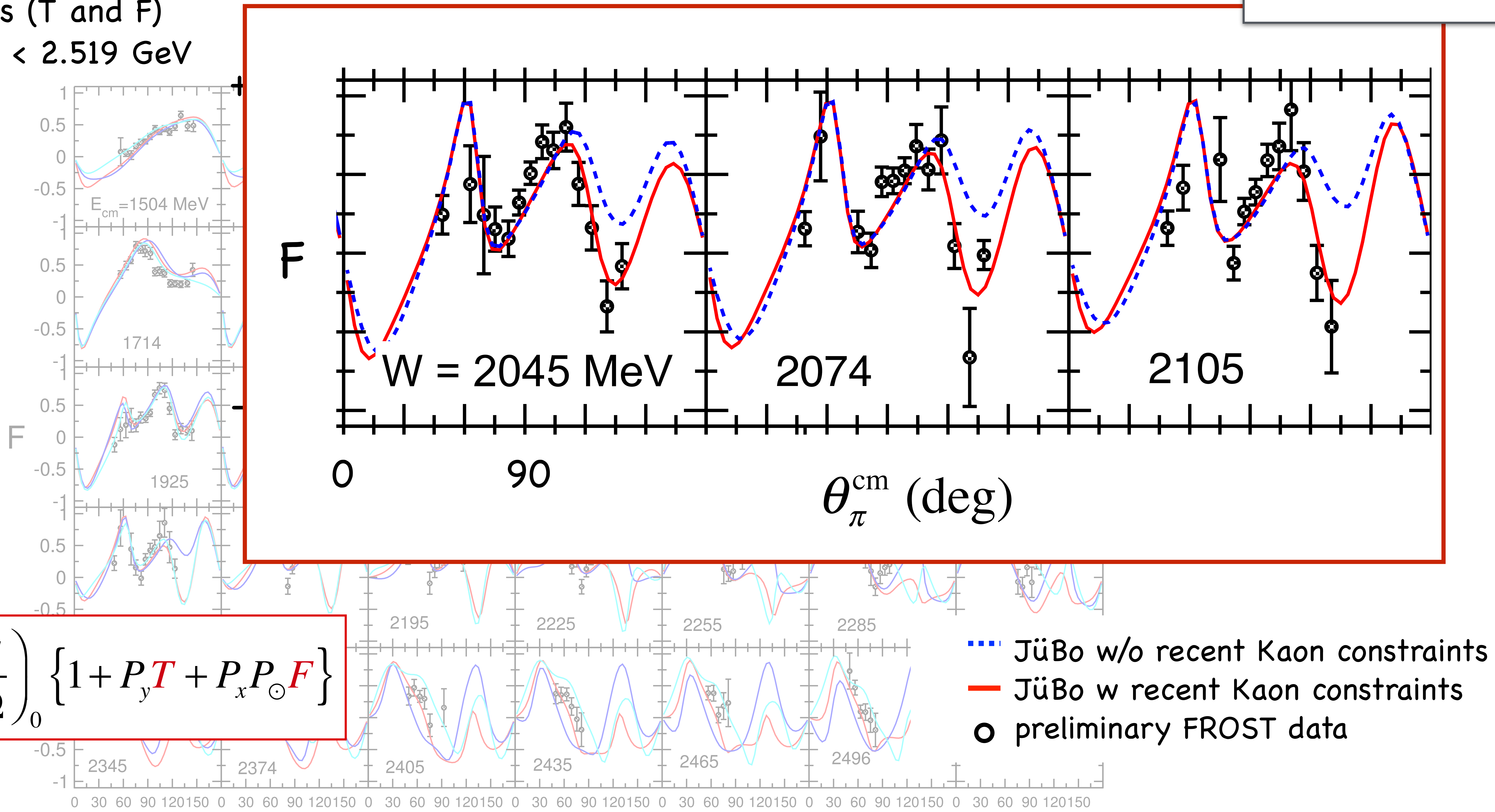
A.V. Anisovich et al., Phys. Lett. B766 (2017) 357-361

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

$\gamma p \rightarrow \pi^0 p$

488 data points (T and F)
1.455 GeV < W < 2.519 GeV

Examples: 3 out of 37 W-bins



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

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

Tight constraints from new FROST data: Double-polarization Observable G

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_0 \left\{1 + P_\gamma \Sigma \cos(2\alpha) + P_\gamma P_z G \sin(2\alpha)\right\}$$

W = 1.4 - 2.3 GeV

PWA predictions of preliminary data:

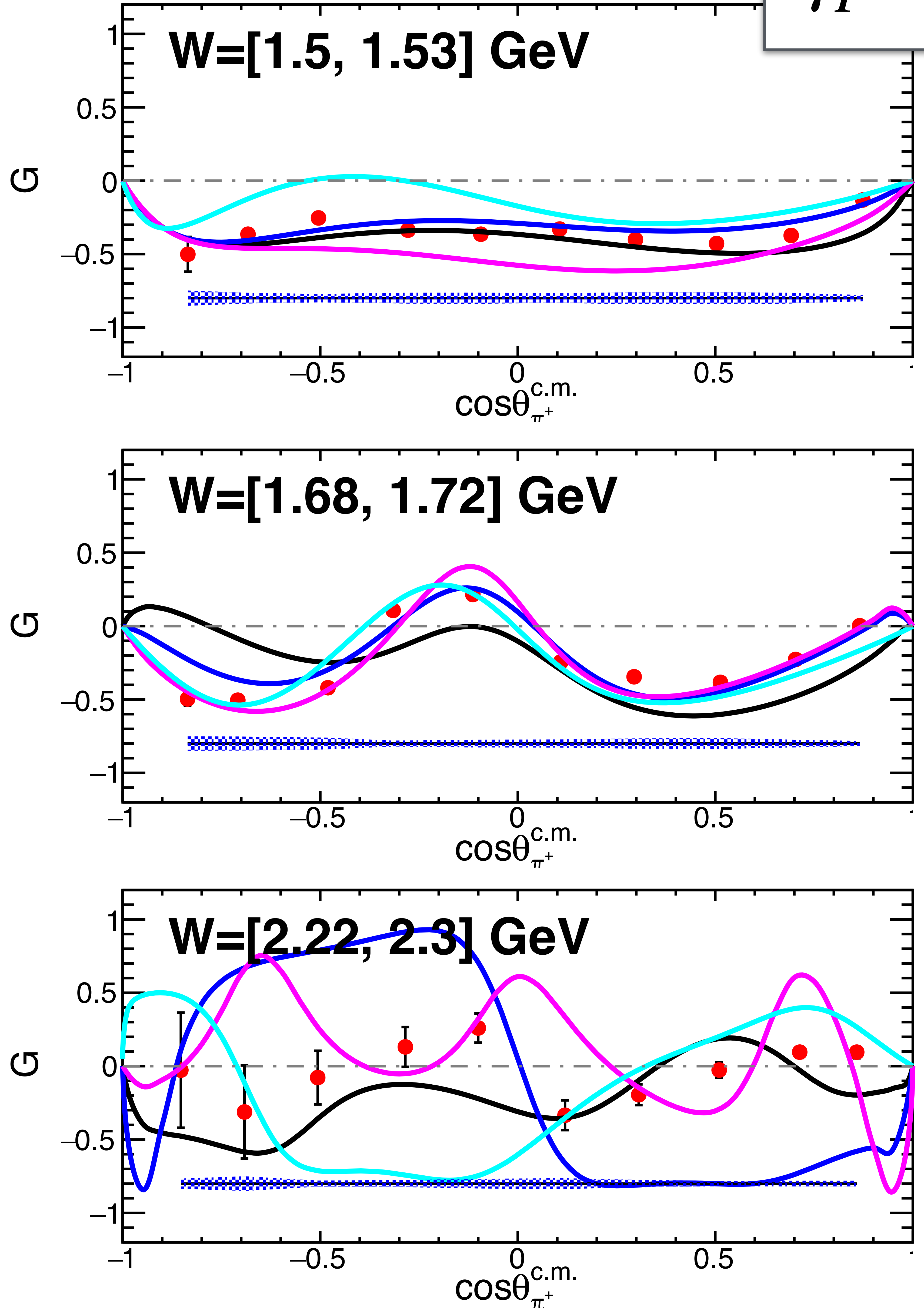
- SAID MA19
- MAID
- GW-Jülich, EPJA 54, 110 (2018)
- Bonn-Gatchina, EPJA 51, 95 (2015), EPJA 52, 284 (2016)

Fair description at low energies.
Poor description at higher energies.

g9 analysis by N. Zachariou (2019, University of York)
- under collaboration review

Examples: 3 out of 23 W-bins

$\gamma p \to \pi^+ n$



Helicity asymmetry E in eta photoproduction on the proton

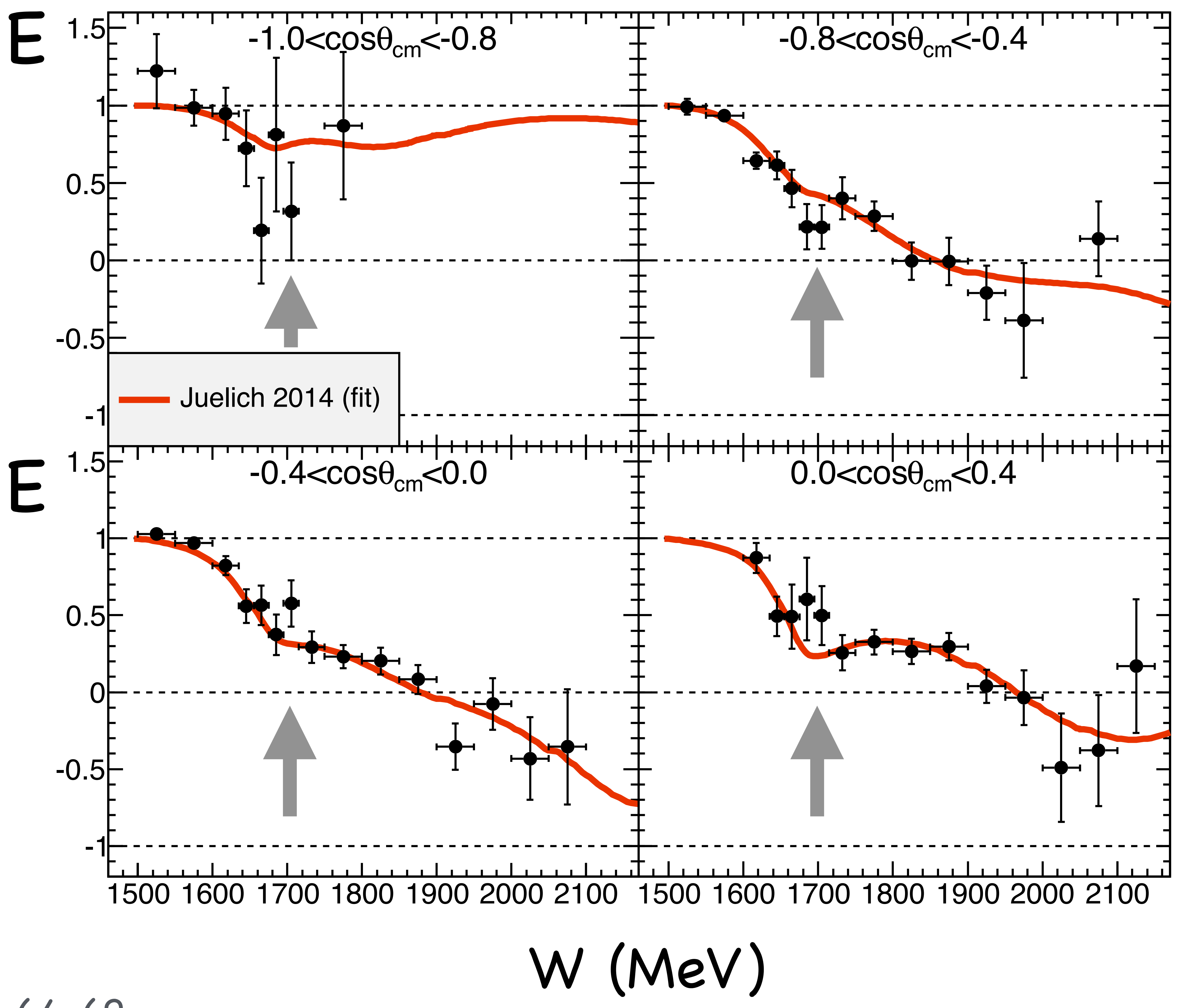
$\gamma p \to \eta p$

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)]

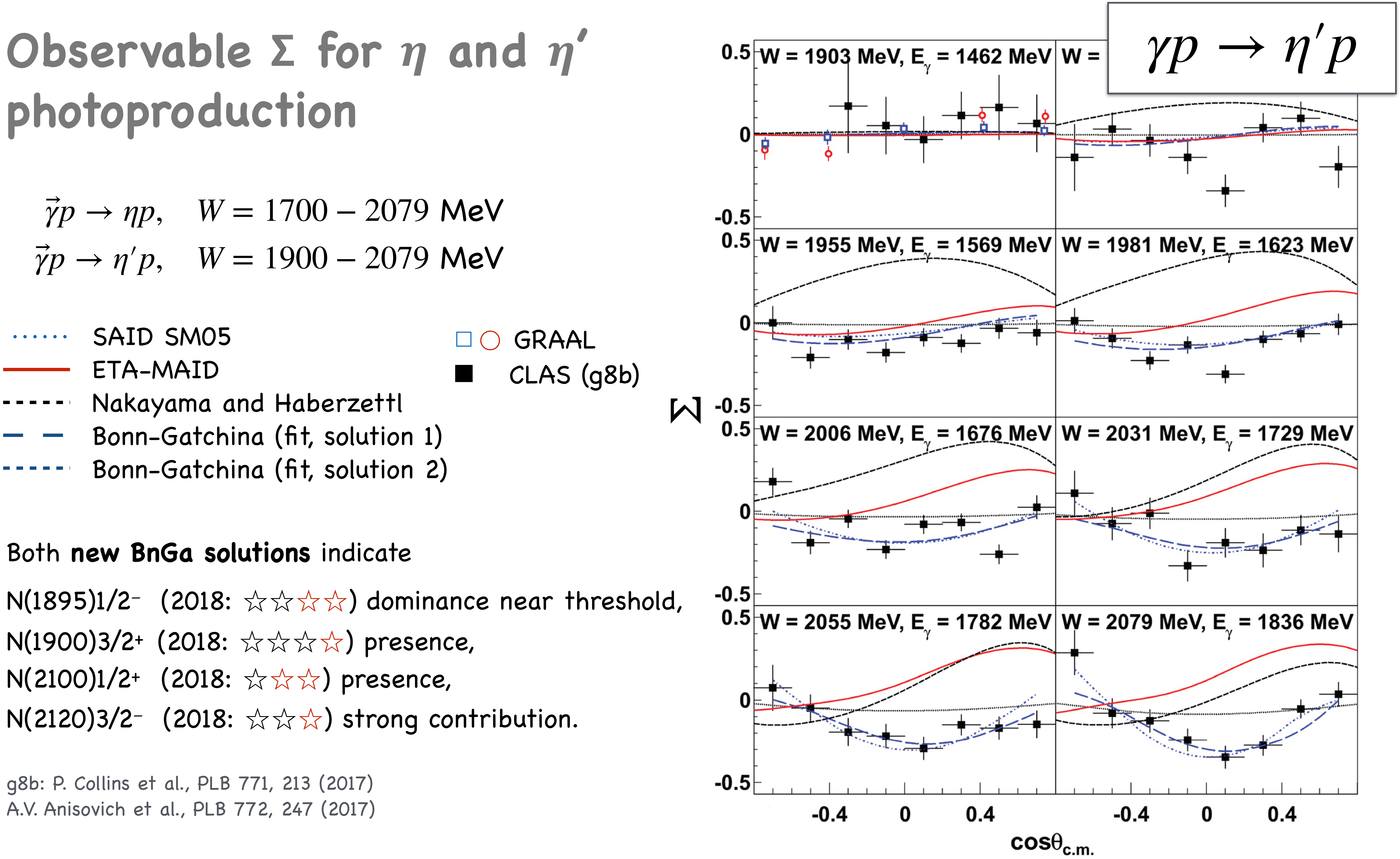
Present CLAS E data do not demand the presence of a narrow resonance with a width of 40 MeV or less at about 1.7 GeV.



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

Observable Σ for η and η' photoproduction

$$\vec{\gamma}p \to \eta p, \quad W = 1700 - 2079 \text{ MeV}$$
$$\vec{\gamma}p \to \eta' p, \quad W = 1900 - 2079 \text{ MeV}$$



Both **new BnGa solutions** indicate

N(1895)1/2⁻ (2018: ☆☆☆☆) dominance near threshold,

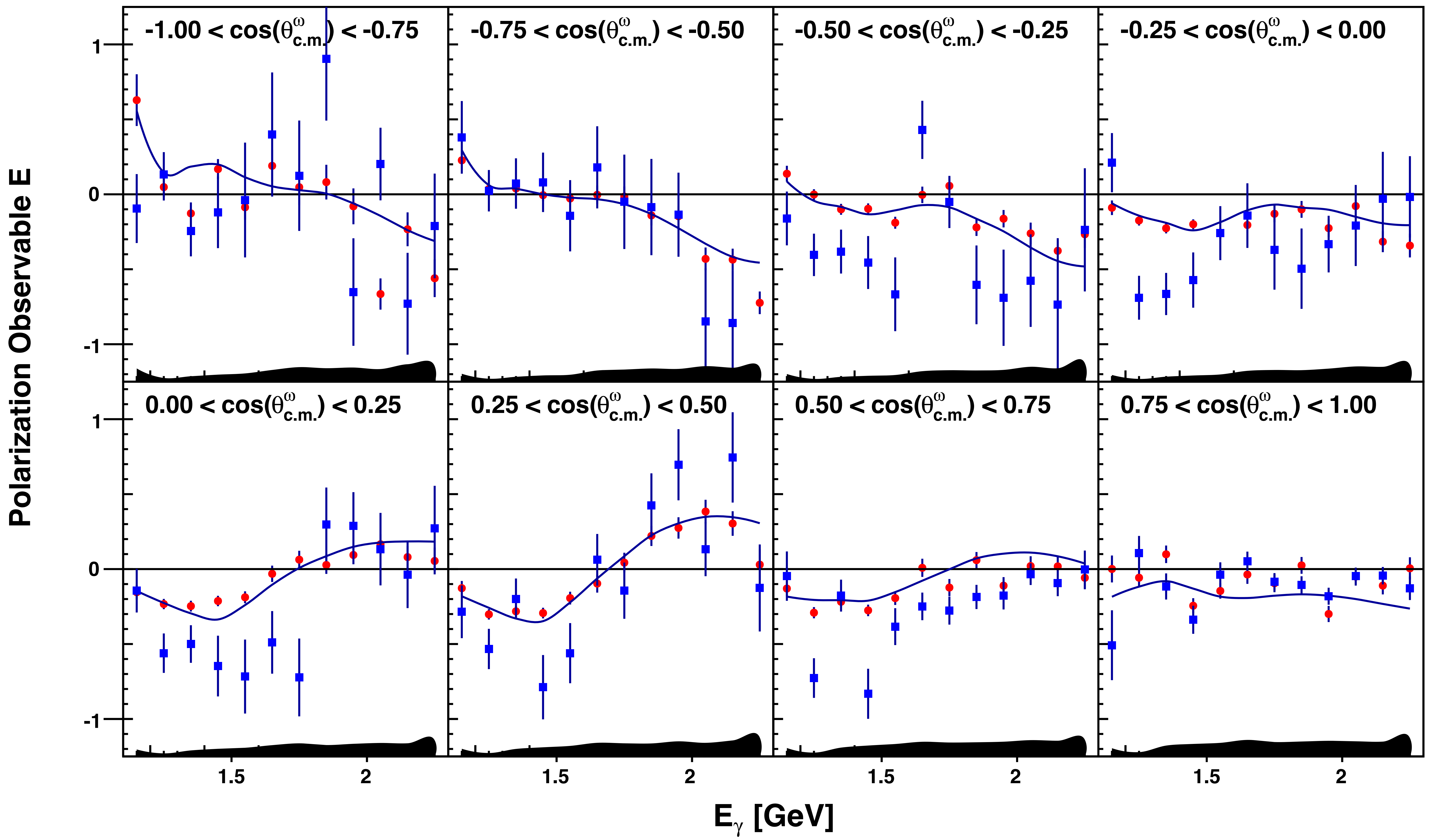
N(1900)3/2⁺ (2018: ☆☆☆☆) presence,

N(2100)1/2⁺ (2018: ☆☆☆) presence,

N(2120)3/2⁻ (2018: ☆☆☆) strong contribution.

g8b: P. Collins et al., PLB 771, 213 (2017)
A.V. Anisovich et al., PLB 772, 247 (2017)

Double-polarization observables E in ω photoproduction



$$\gamma p \rightarrow \omega p$$

- CLAS FROST, $\omega \rightarrow \pi^+\pi^-(\pi^0)$
- CBELSA/TAPS, $\omega \rightarrow \pi^0\gamma$
- BnGa PWA

W = 1700 - 2300 MeV

Z. Akbar et al., Phys. Rev. C **96**, 065209 (2017)

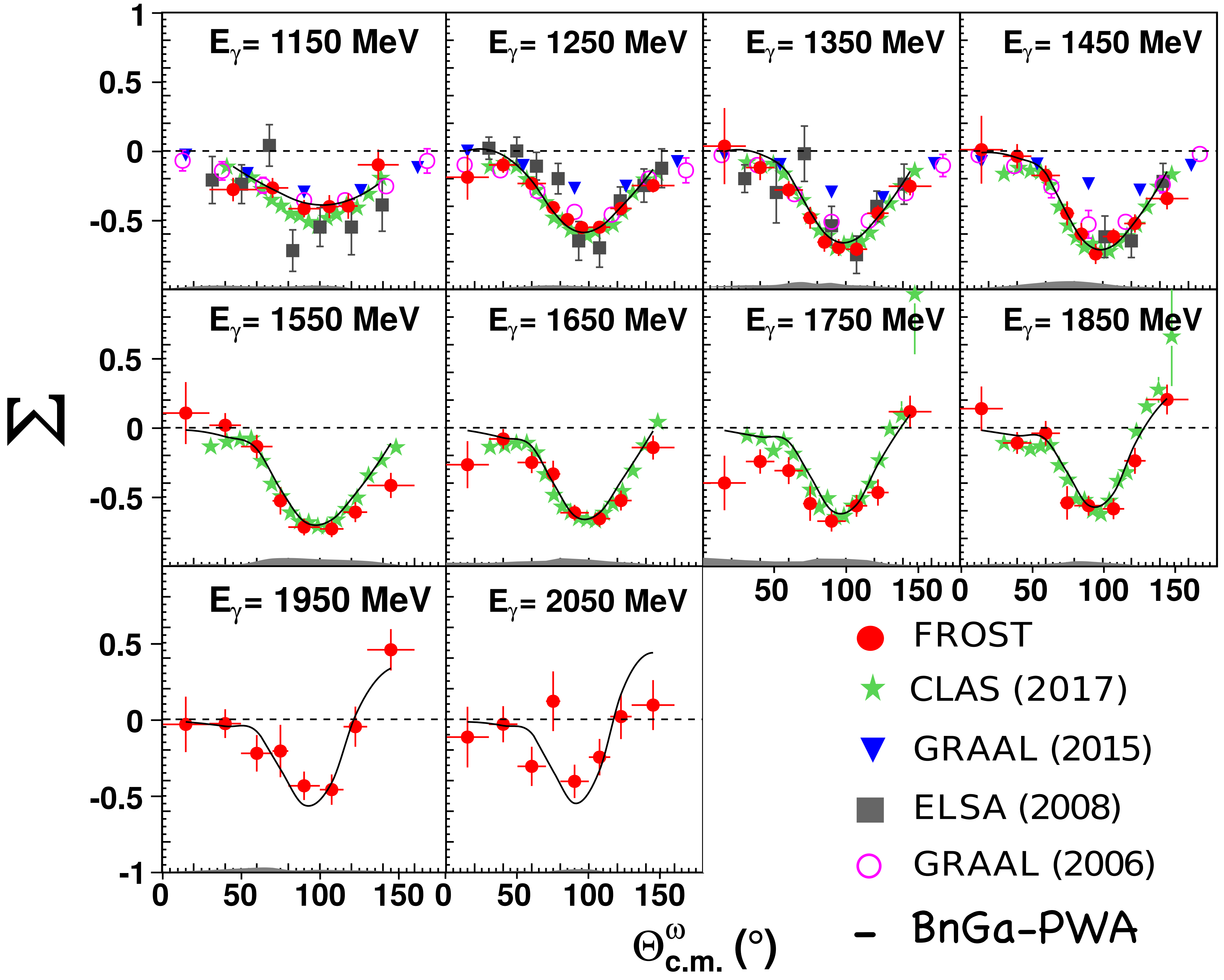
A partial-wave analysis within the Bonn-Gatchina framework found **dominant contributions from the 3/2+ partial wave near threshold**, which is identified with the subthreshold N(1720)3/2+ nucleon resonance.

Observables Σ and T in ω photoproduction

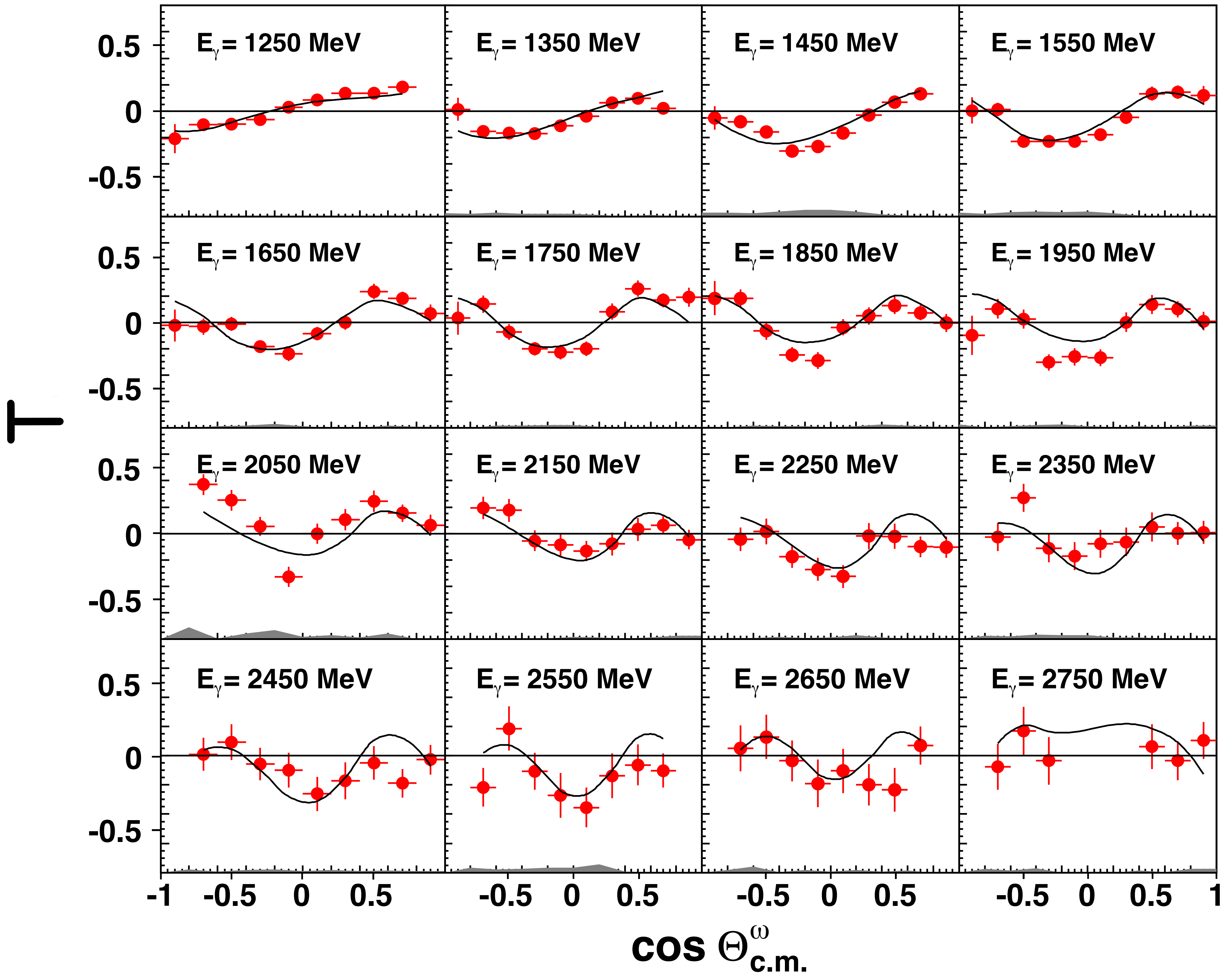
$\gamma p \to \omega p$

★ g8b: P. Collins et al. (CLAS Collaboration), PLB 773, 112 (2017)
● FROST: P. Roy et al. (CLAS Collaboration), PRC 97, 055202 (2018)

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



first time measurement of T

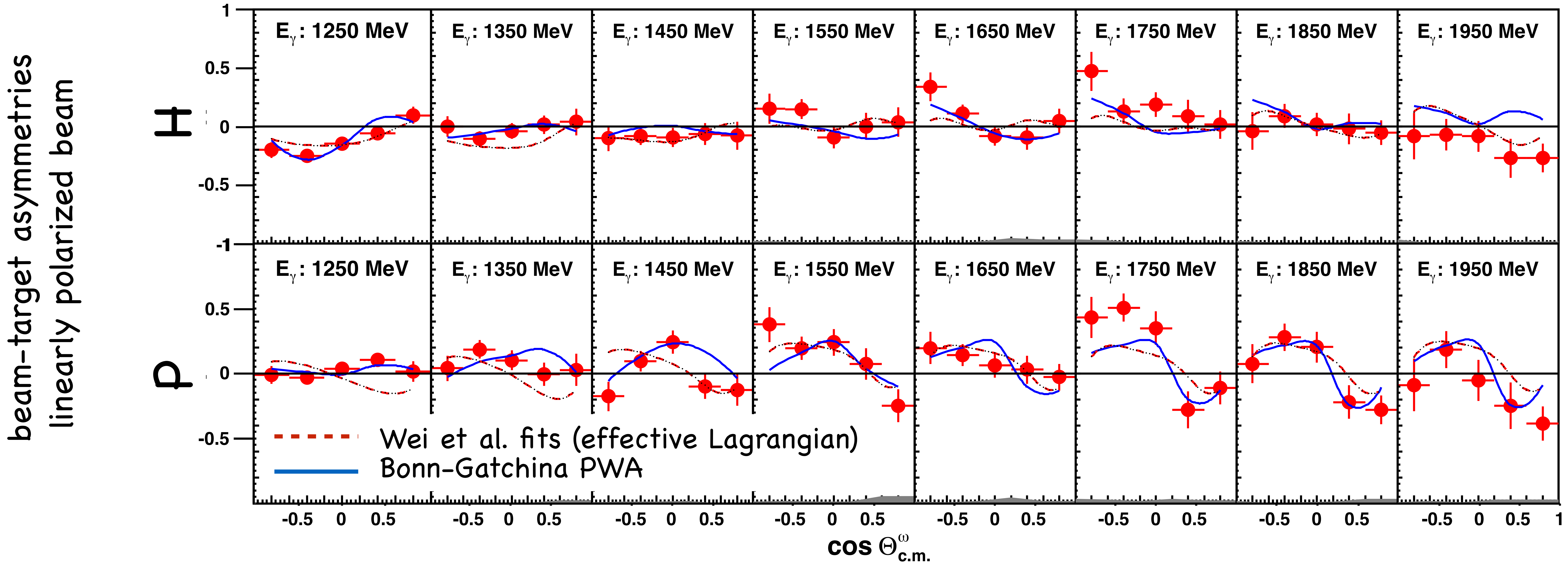


s-channel resonance production and t-channel exchange processes contribute to the reaction.
Data help to fix the magnitudes of the **interference terms** in the BnGa PWA.

Double-polarization observables F, P, and H in ω photoproduction

$\gamma p \to \omega p$

first-time measurements



The results reveal **significant contributions from several nucleon (N*) resonances.**

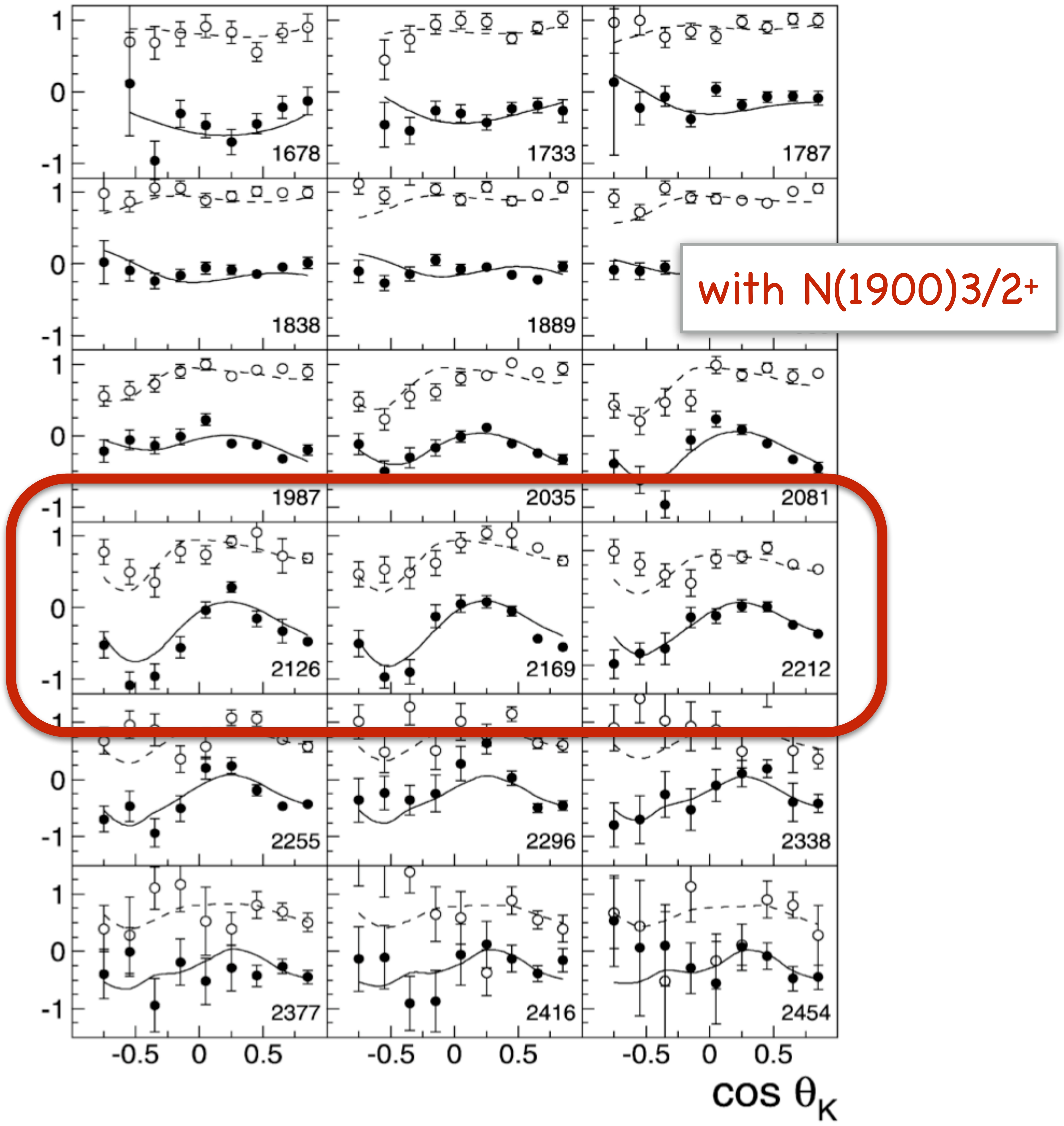
Evidence was found for the poorly known states N(1880)1/2$^+$ ☆☆☆, N(2000)5/2$^+$ ☆☆, N(1895)1/2$^-$ ☆☆☆☆, and N(2120)3/2$^-$ ☆☆☆.

P. Roy et al., Phys. Rev. Lett. 122, 162301 (2019),
consistent with single-channel PWA: M. Williams et. al, Phys. Rev. C80, 065208 (2009) and M. Williams et. al, Phys. Rev. C80, 065209 (2009)

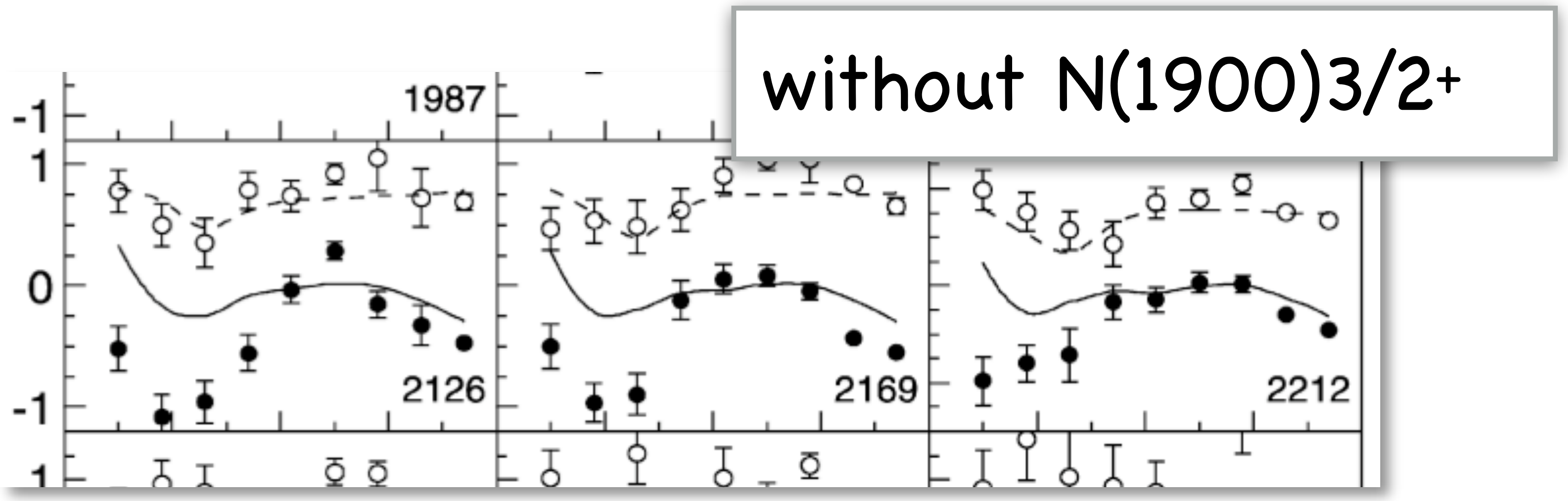
Polarization Transfer Observables C_x, C_z

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

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



Bonn-Gatchina coupled-channel isobar model: N(1900)3/2+ needed in PWA of Nikonov et al.

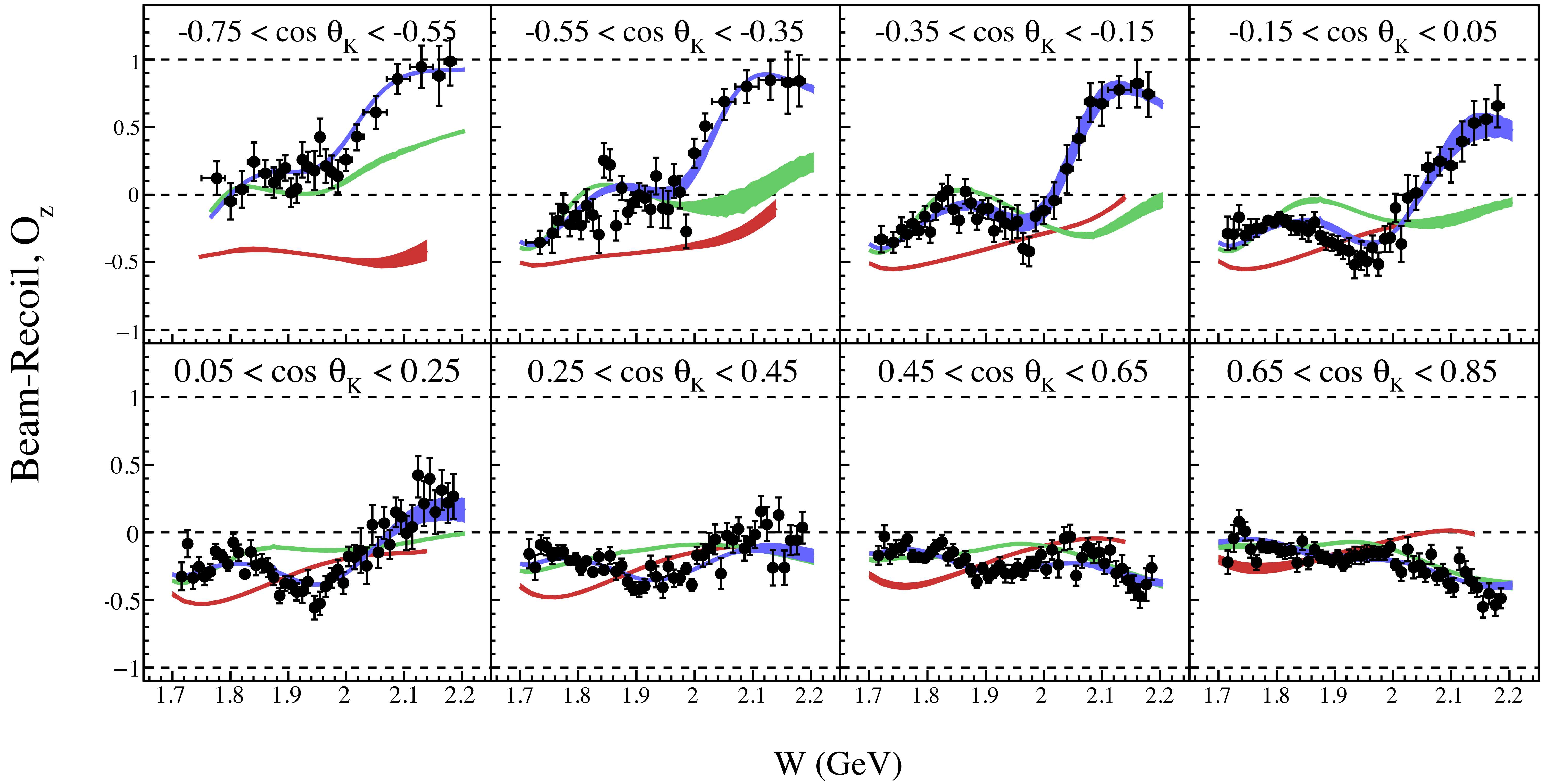


State confirmed in more recent analyses and is now a ☆☆☆☆ resonance.

N(1900)3/2+ 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)

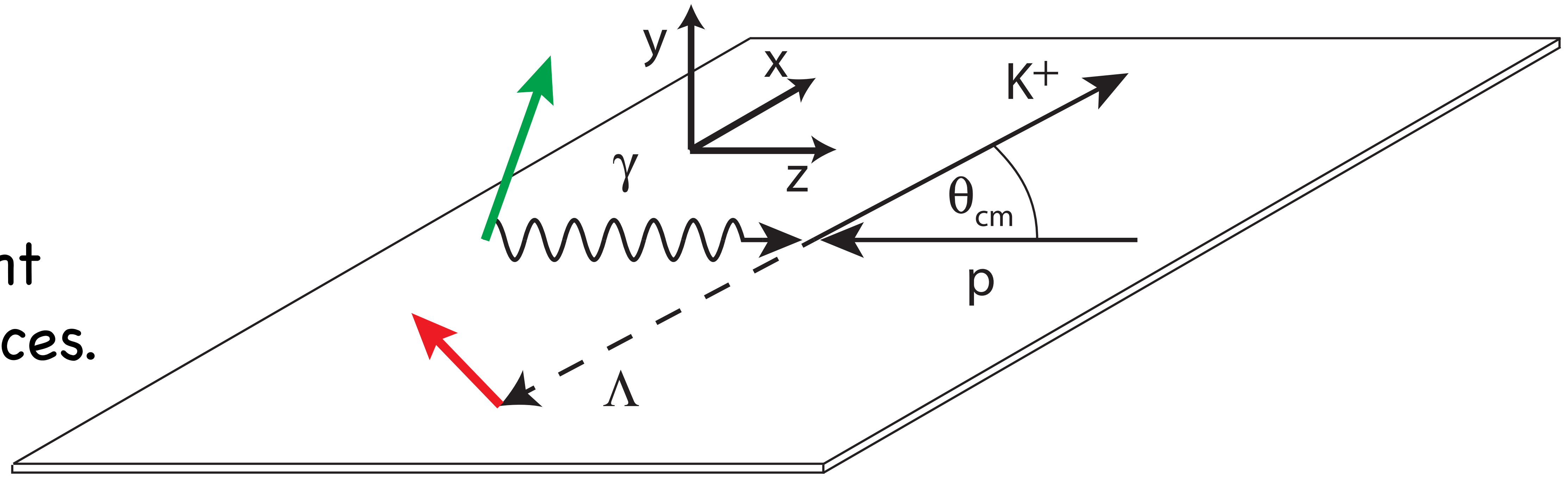
Strengthened evidence for set of 3/2+, 5/2+ resonances



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

CLAS g8 data for observables Σ, T, O_x, O_z

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.



g8: C.A. Paterson et al. (CLAS Collaboration), PRC **93**, 065201 (2016)

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

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

Nππ is a dominant decay channel of highly excited nucleons.

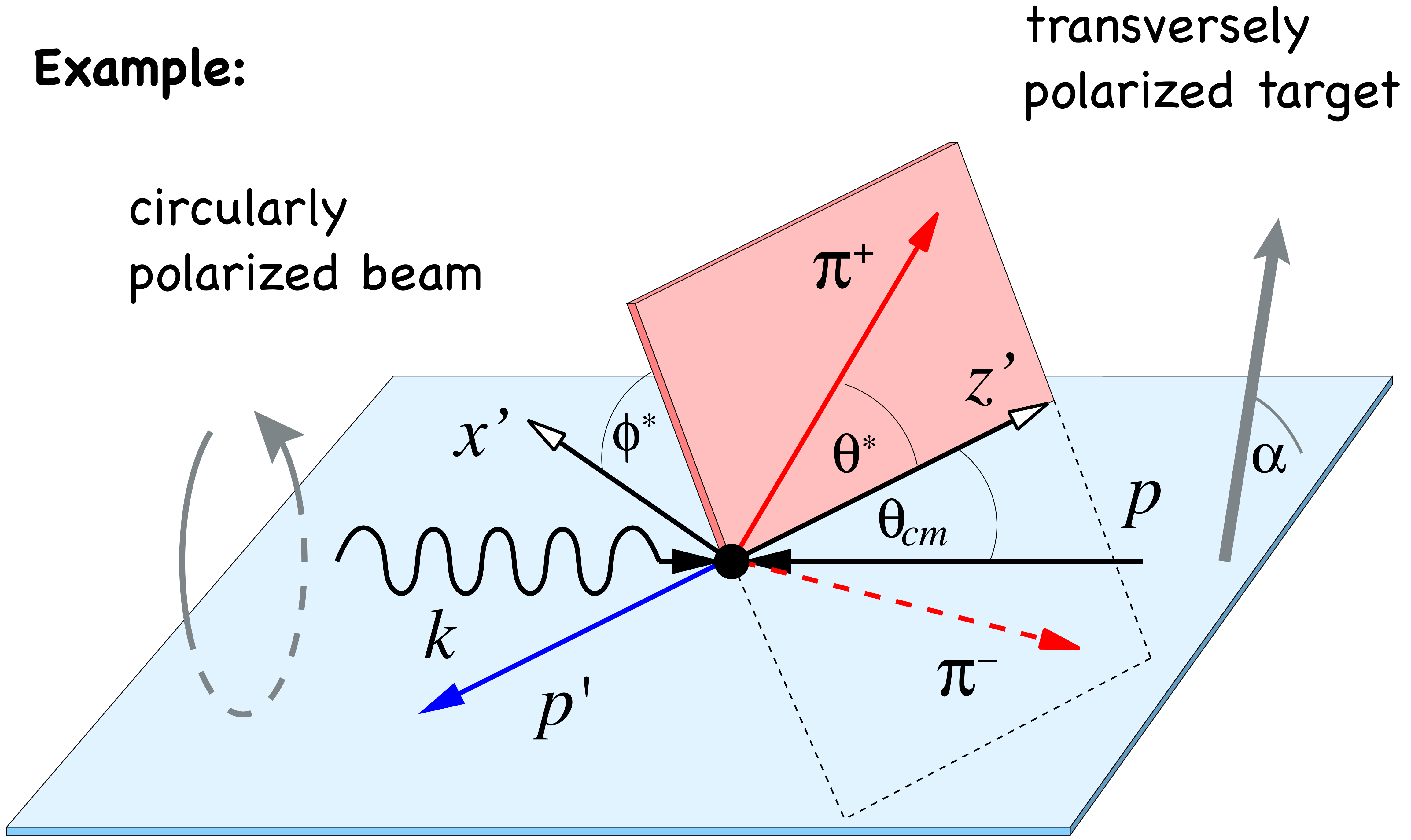
Essential part in coupled-channel calculations.

Allows for the study of sequential decays, e.g.,

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

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

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)

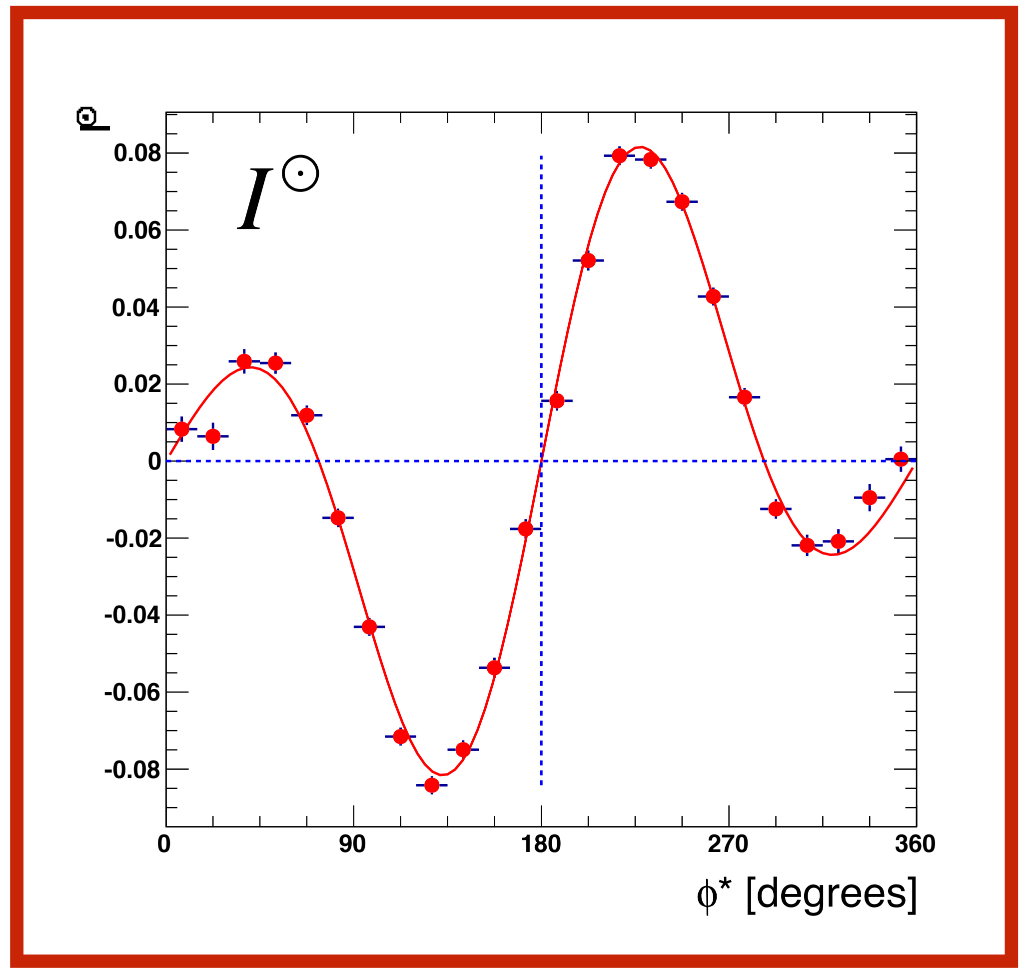
Parity conservation yields to symmetry properties of observables

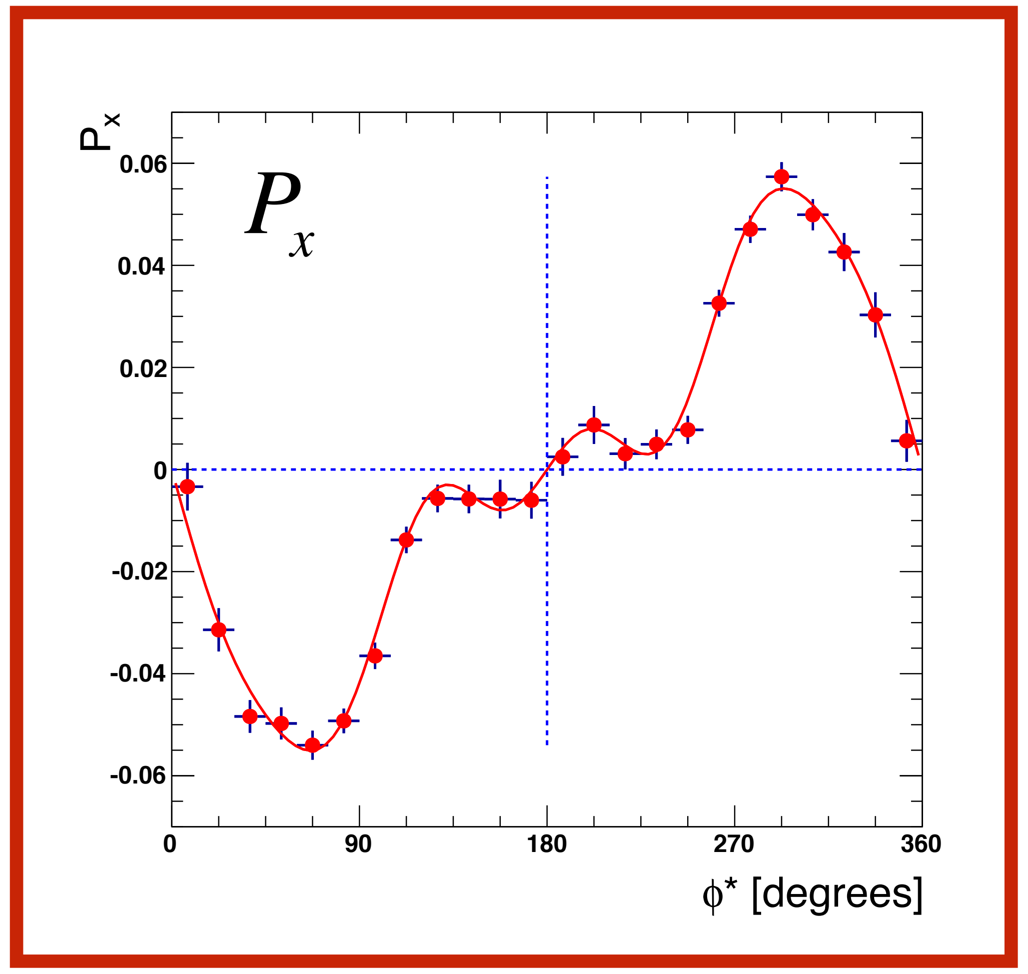
$$\gamma p \rightarrow \pi^{+}\pi^{-} p$$

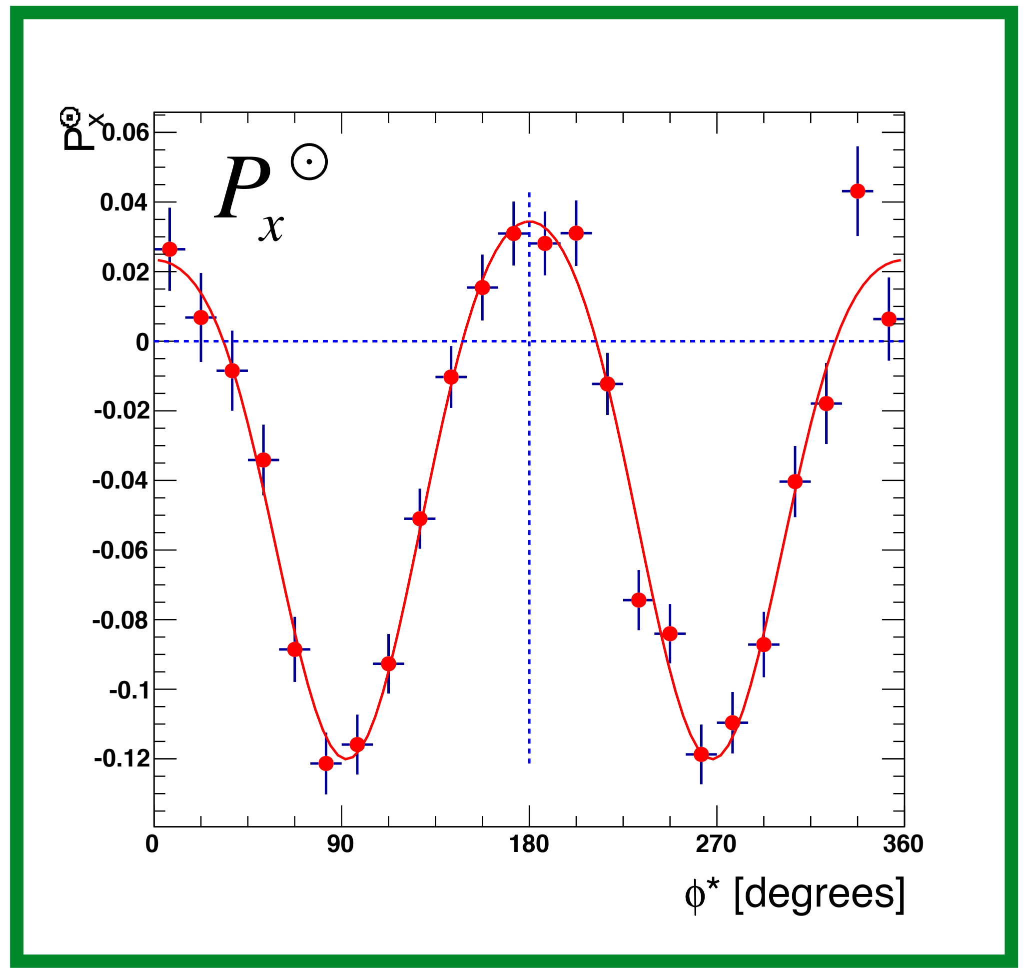
$$M^{-\lambda_\gamma}_{-\lambda_N-\lambda'_N}(\theta,\theta_1,\phi_1) = (-1)^{\lambda_\gamma-\lambda_N+\lambda'_N}\, M^{\lambda_\gamma}_{\lambda_N\lambda'_N}(\theta,\theta_1,2\pi-\phi_1)$$

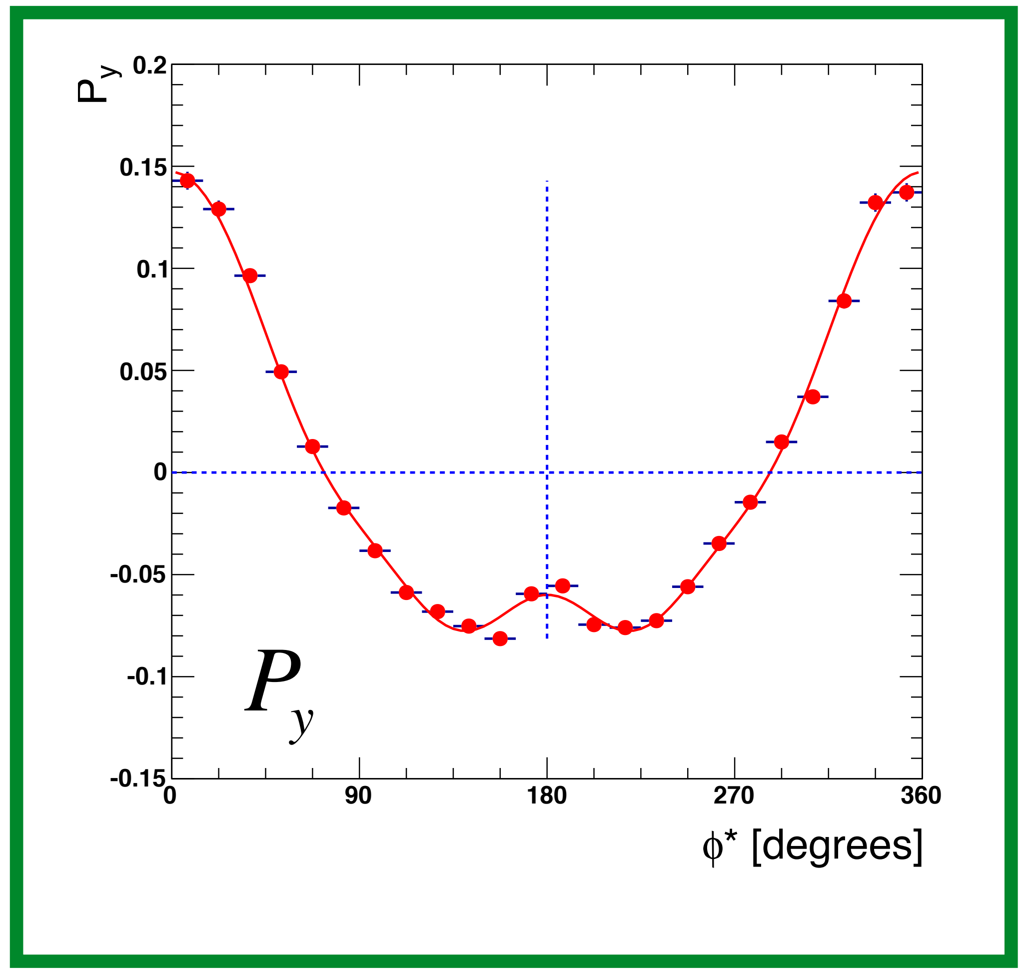
Example:

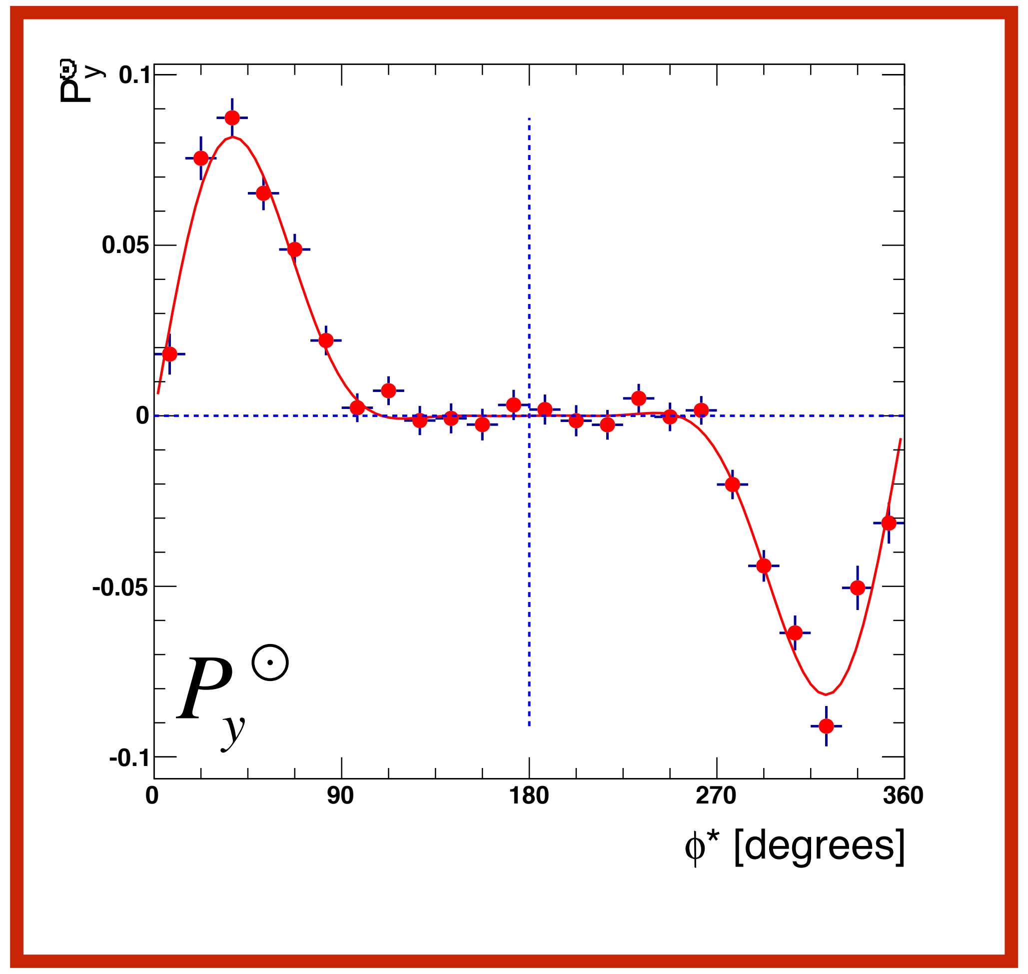
circularly polarized photons – transversely polarized target











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

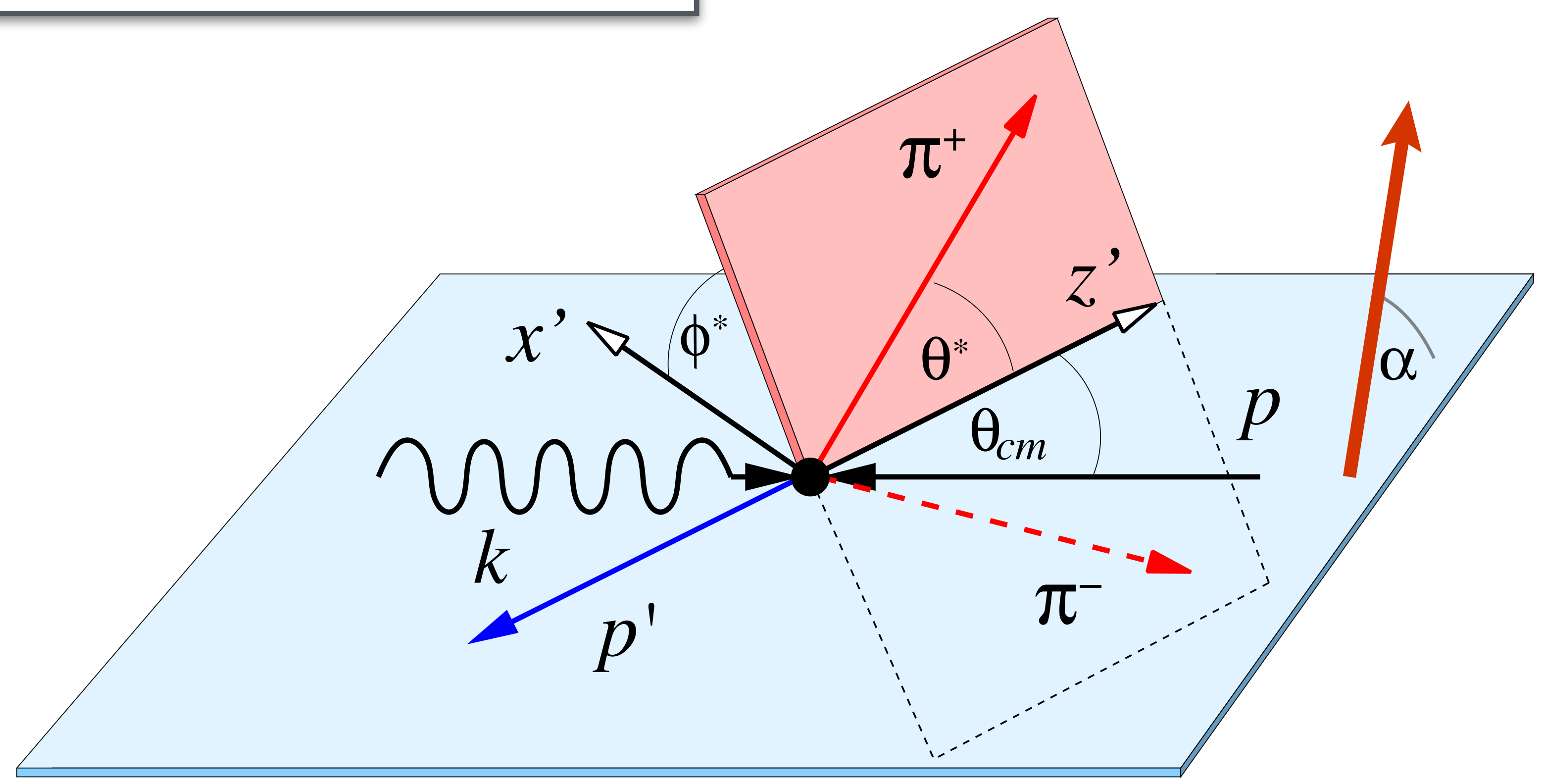
even observables: P_y and $P_x^{\odot}$ correspond to T and F, respectively.

g9 analysis: Aneta Net (USC)

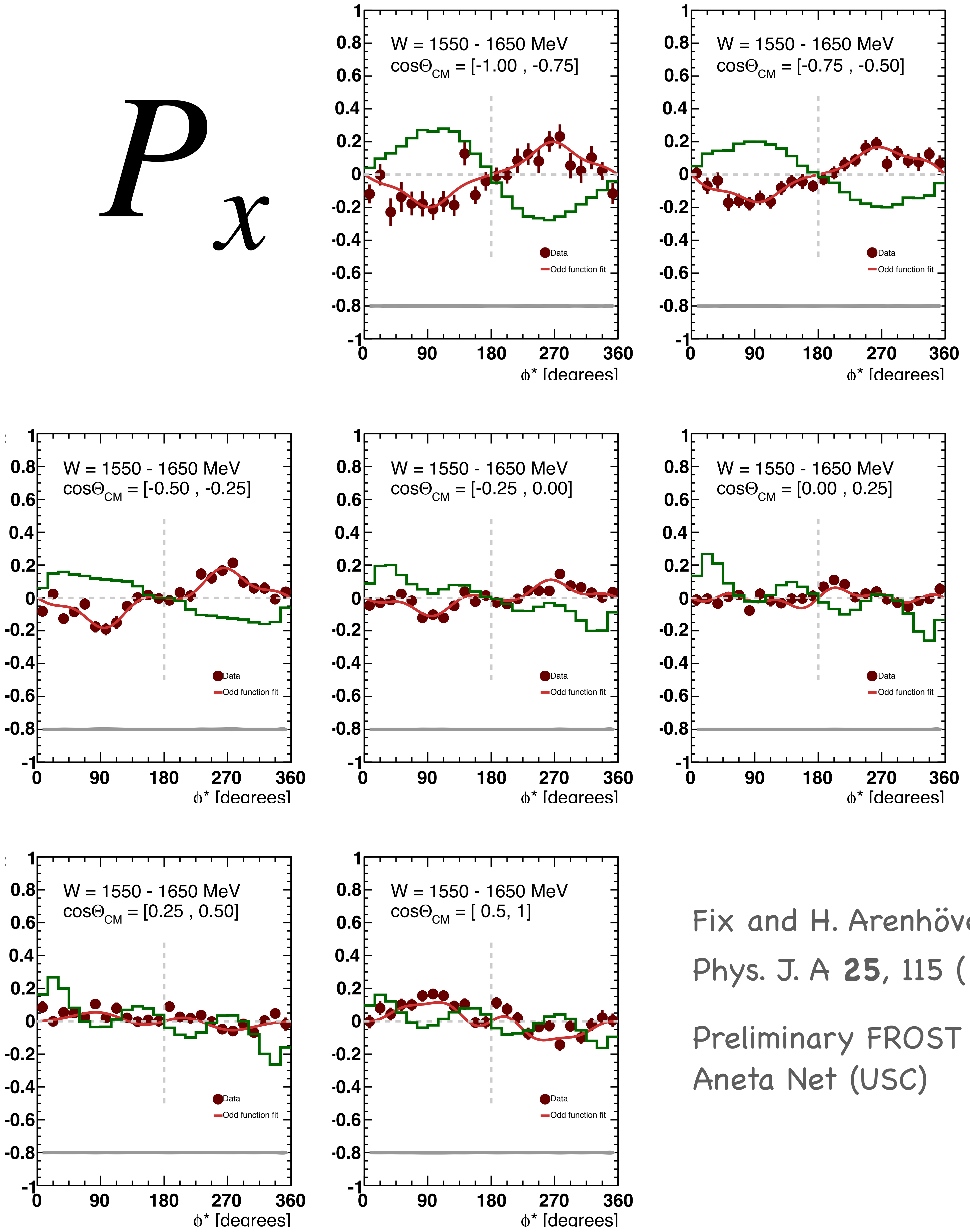
W = 1600 MeV data binned in $\cos\theta_{cm}$,

Preliminary results (g9b)

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

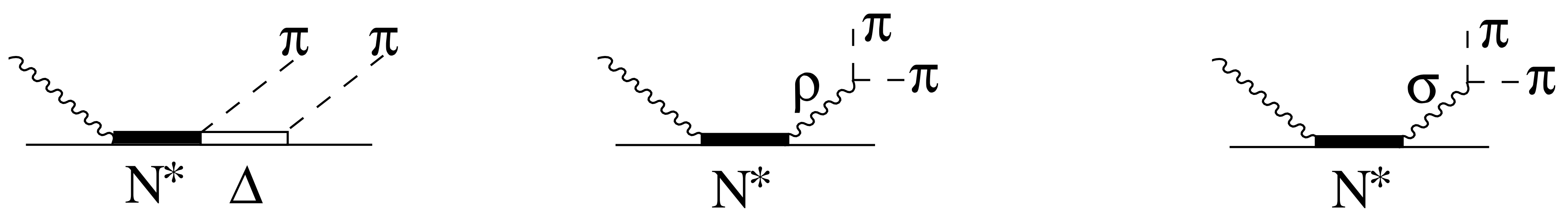


P_x



Effective Lagrangian Model (A. Fix)

Exchange mesons, π,ρ,σ, and resonances, Δ(1232), N*(1440), N*(1520), N*(1535), Δ(1620), N*(1675), N*(1680), Δ(1700), N*(1720), Nucleon and Delta Born terms; Resonance terms:



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

Preliminary FROST g9b data: Aneta Net (USC)

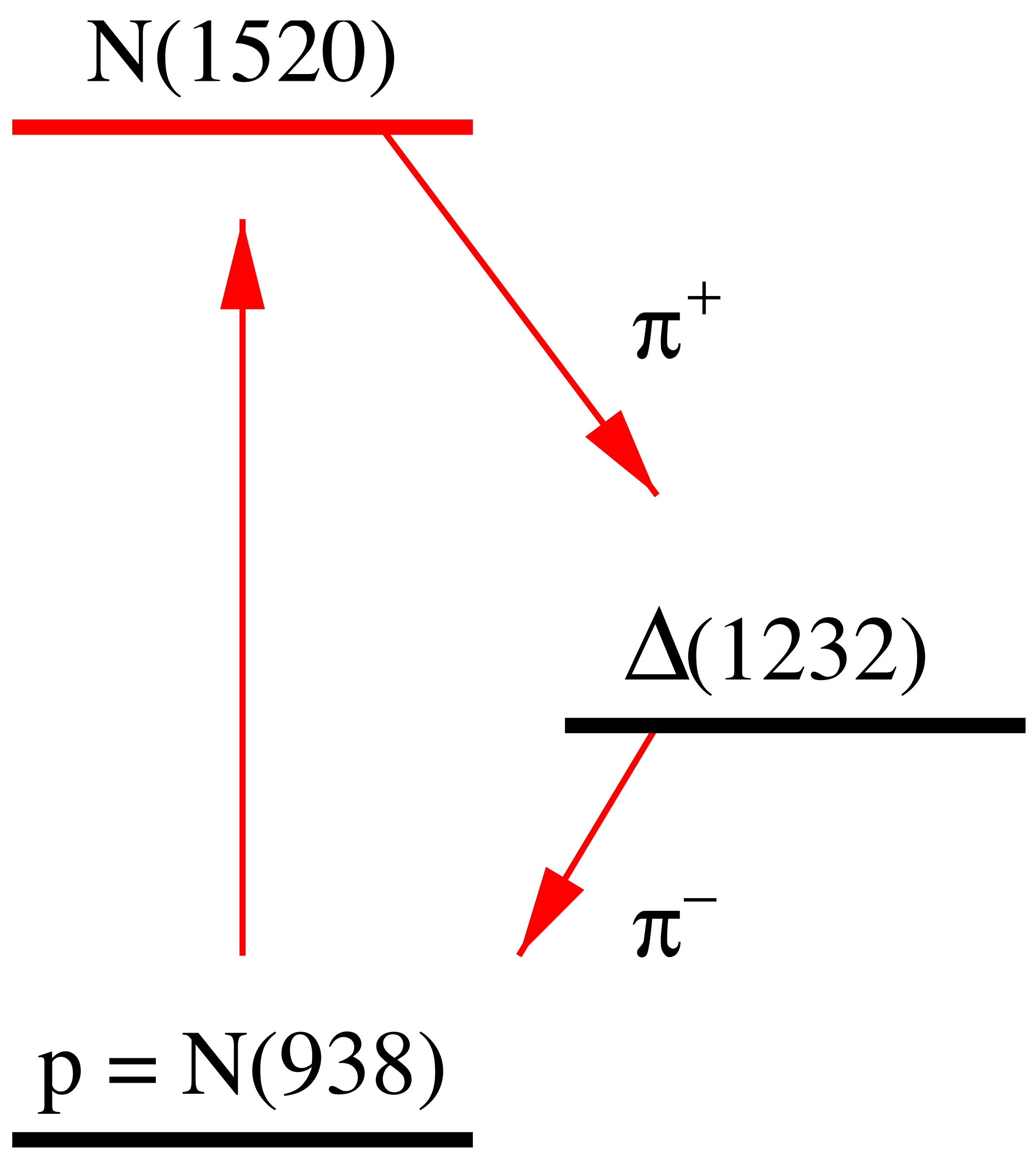
Intermediate Δ(1232) Resonance

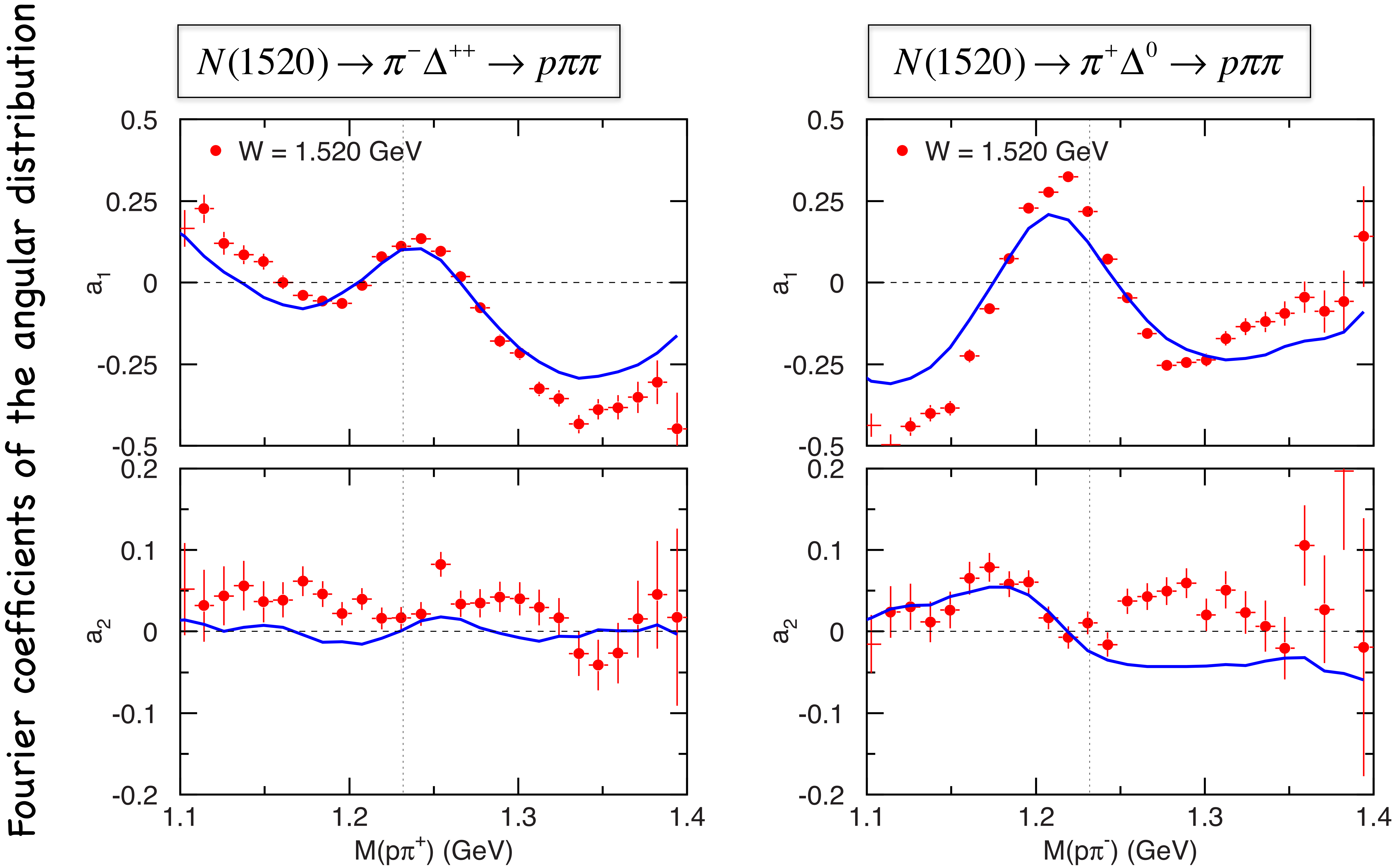
$$\gamma p \rightarrow \pi^+ \pi^- p$$

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

Example of
sequential decays

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





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)

First determination of excited neutron multipoles for $\gamma d \to \pi^- p(p)$

N(1440)1/2+, N(1535)1/2−, N(1650)1/2−, N(1720)3/2+ resonances

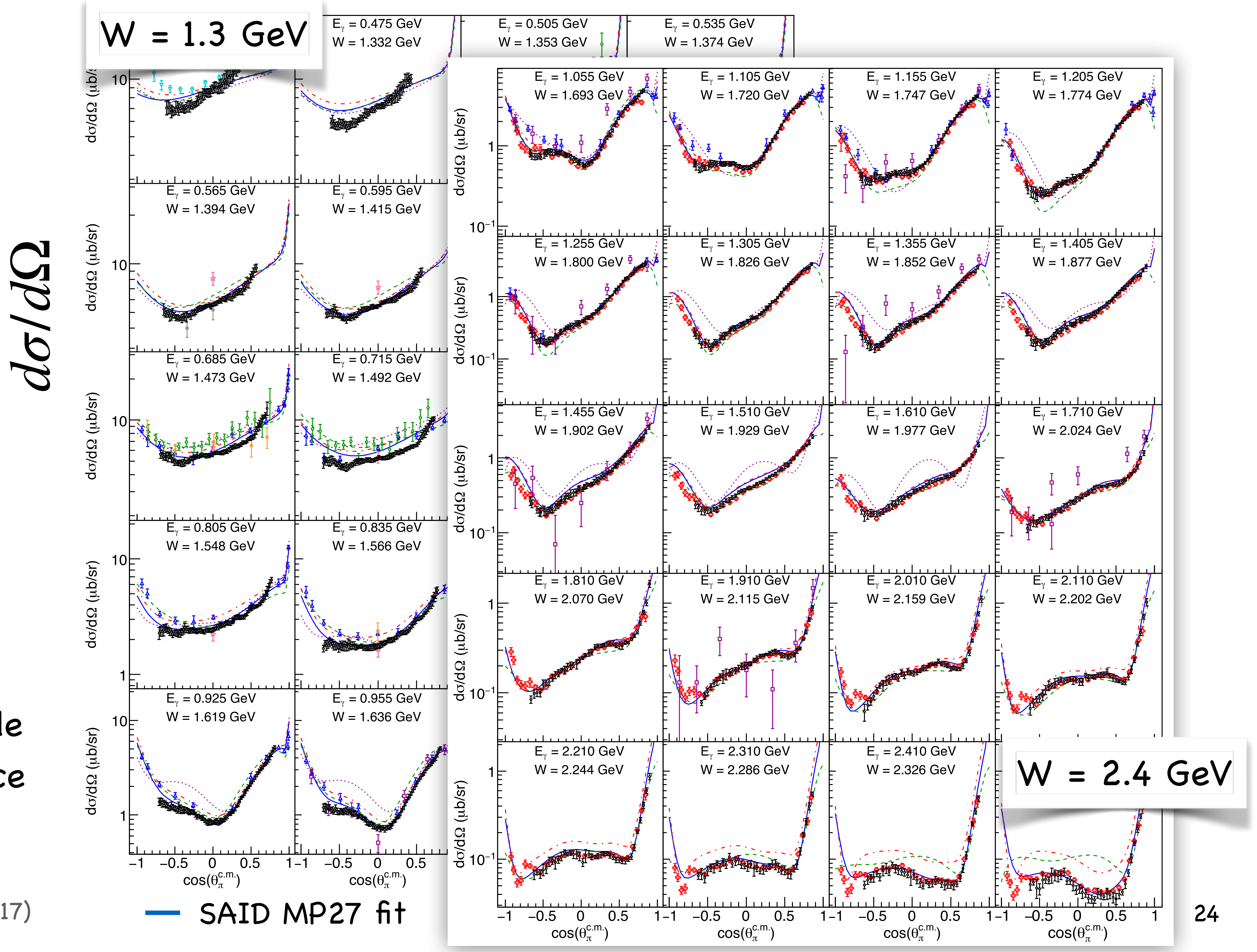
Extensive data set with over 8400 data points

$$W \in [1.31,\ 2.37]\ \text{GeV}$$
$$\cos\theta_\pi^{cm} \in [-0.72, 0.92]$$

The data made possible

- the extraction of $N^* \to \gamma n$ photodecay amplitudes (SAID),
- the first determination of the excited neutron multipoles for the N(1440)1/2+, N(1535)1/2−, N(1650)1/2−, and N(1720)3/2+ resonances.

These new precision $\gamma n \to \pi^- p$ data will provide important and necessary constraints to advance coupled-channel analysis fits.



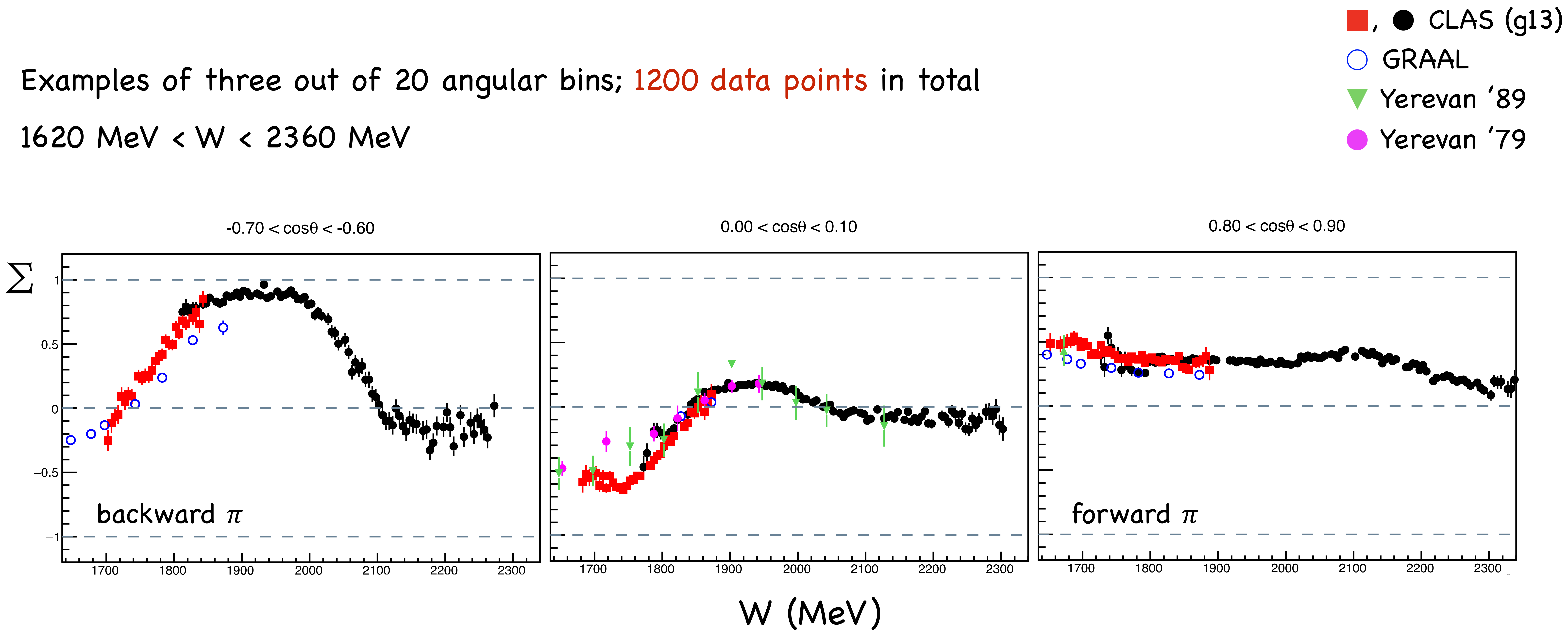
g13: P.T. Mattione et al. (CLAS Collaboration), PRC **96**, 035204 (2017)

Measurement of Σ in π^- photoproduction on the neutron from the g13b dataset

$\gamma d \rightarrow \pi^- p(p)$

Examples of three out of 20 angular bins; 1200 data points in total

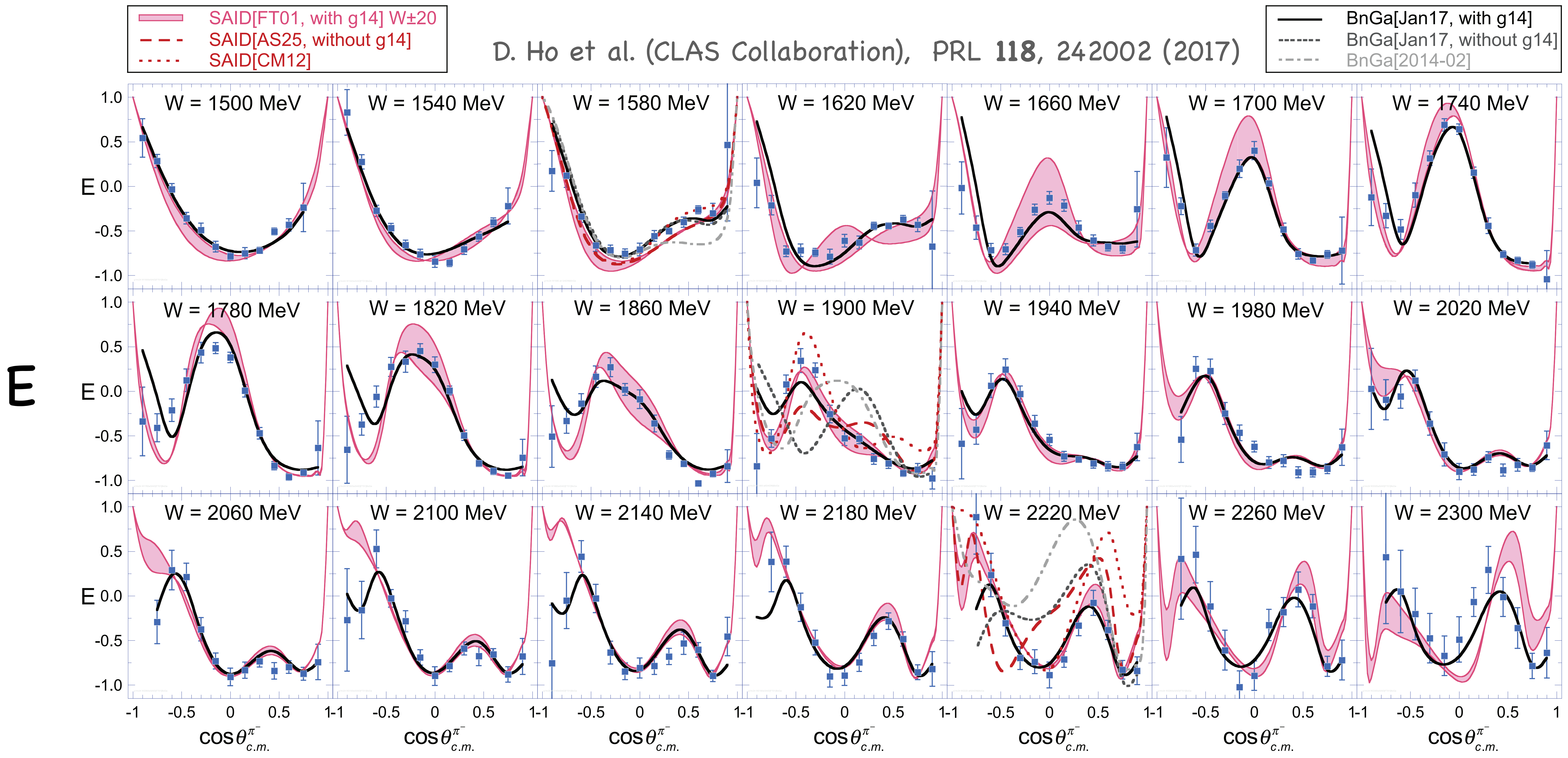
1620 MeV < W < 2360 MeV



g13: Daria Sokhan (University of Glasgow) - finalized analysis

Significant revisions for several γnN* resonance photocouplings

$\gamma d \rightarrow \pi^- p(p)$



HD-ice target

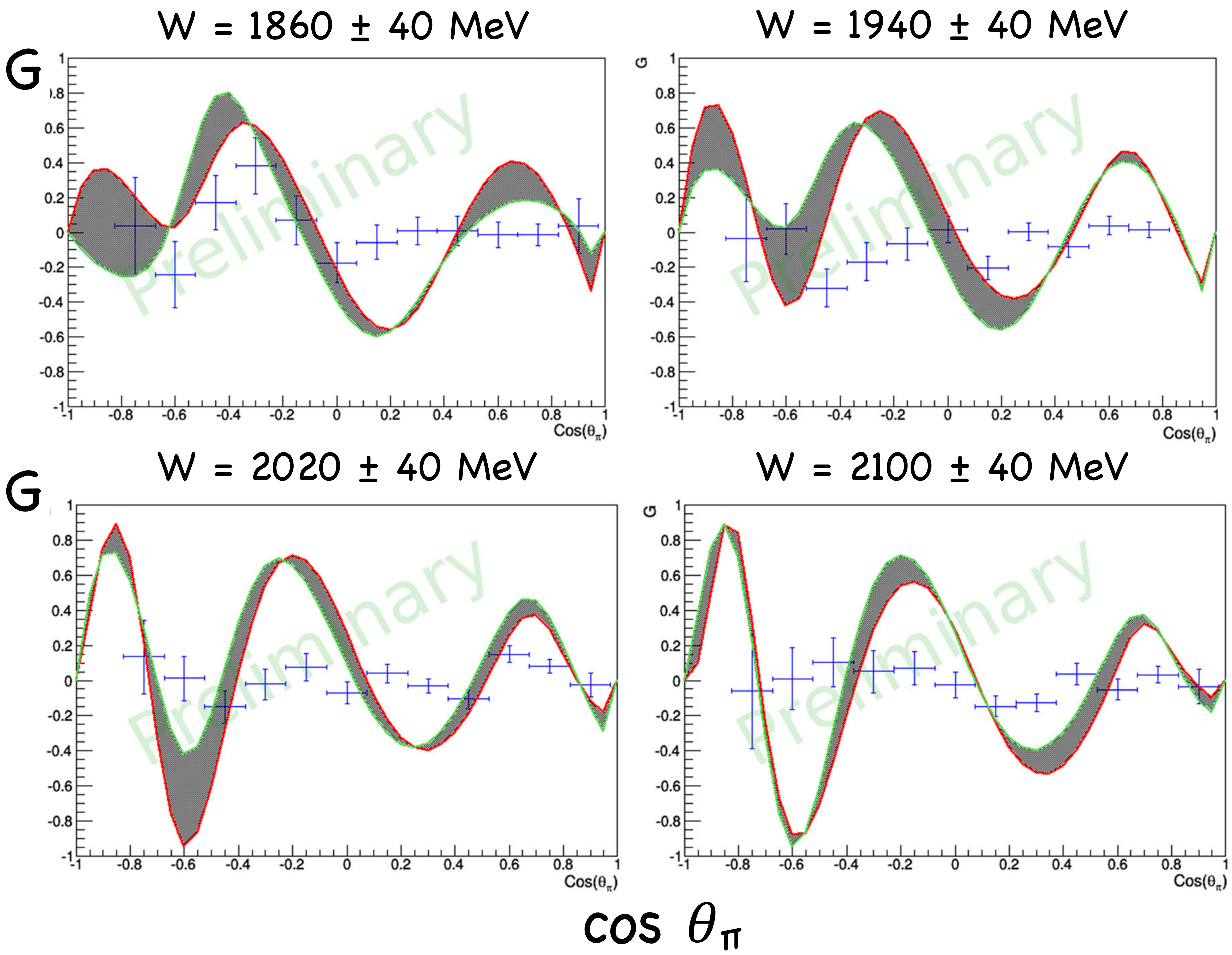
- Inclusion of these results in new PWA calculations has resulted in **revised γnN* couplings** and, in the case of the N(2190)7/2⁻, convergence among different PWA groups.
- Couplings are sensitive to the dynamical process of N* excitation; provide important guides to nucleon structure models.

Asymmetries with Linearly Polarized Beams and Longitudinally Polarized Targets

$\gamma d \rightarrow \pi^- p(p)$

+ Preliminary CLAS (HD-ice)
  W = 1820 - 2140 MeV

▬ SAID (not yet fitted to the data)



- Σ results (not shown) are in quite good agreement with the model prediction.
- G results are generally very much smaller than the PWA values.

g14: H Haiyun Lu, CLAS Collaboration, Few-Body Syst 80, 18 (2018).

Constraints for models describing nucleon resonances that couple strongly to the KY decay channels

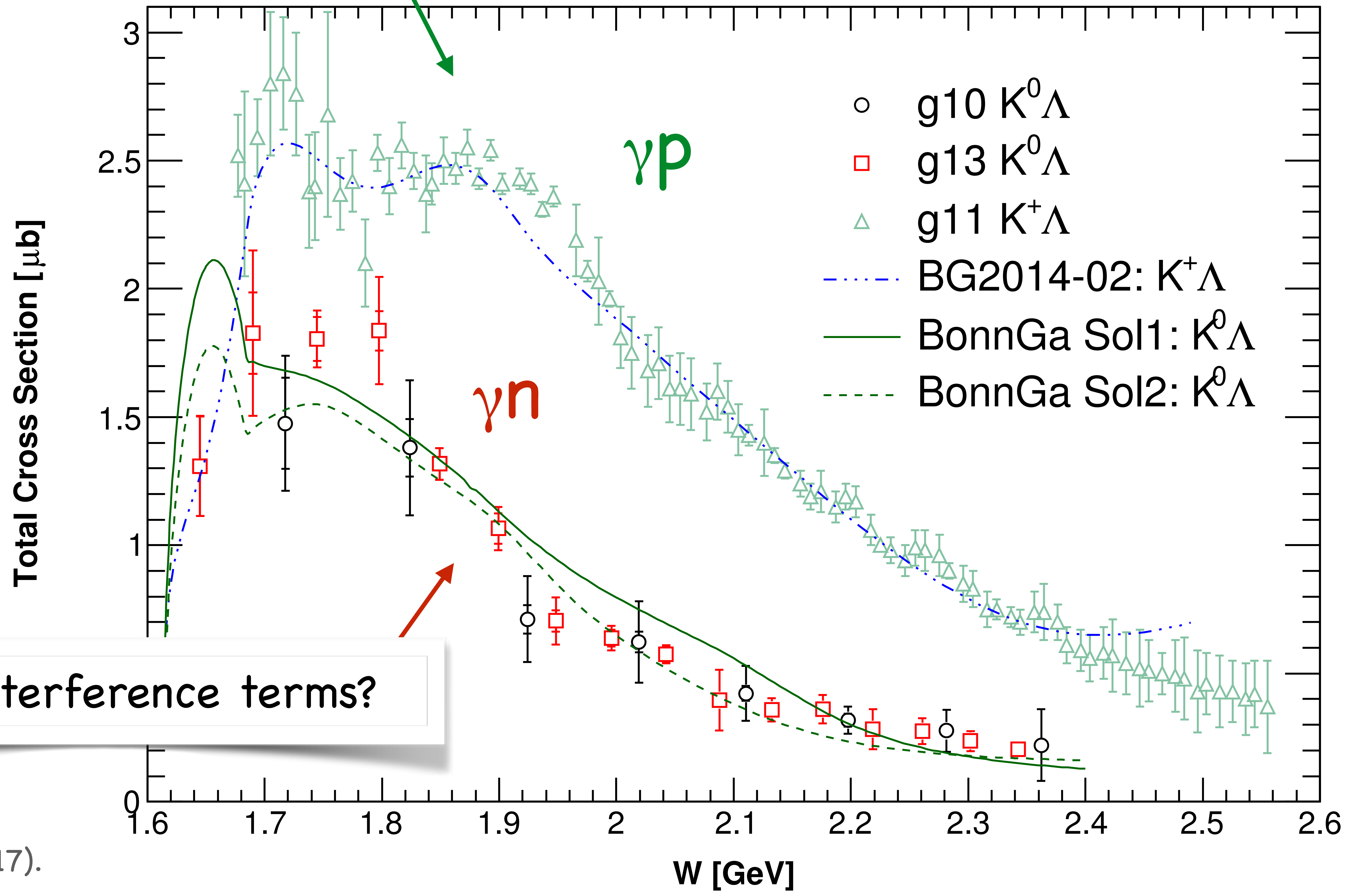
$$\gamma d \rightarrow K^0\Lambda(p)$$

Interference of N(1900)3/2+ and t-channel background processes

The first differential and total cross-section measurements (○, □) of the reaction $\gamma d \rightarrow K^0\Lambda(p)$ where the proton is a spectator.

N(1900)3/2+ couples strongly to KY decay channels.

$\gamma d \rightarrow K^0\Lambda(p)$ has suppression of t-channel terms.

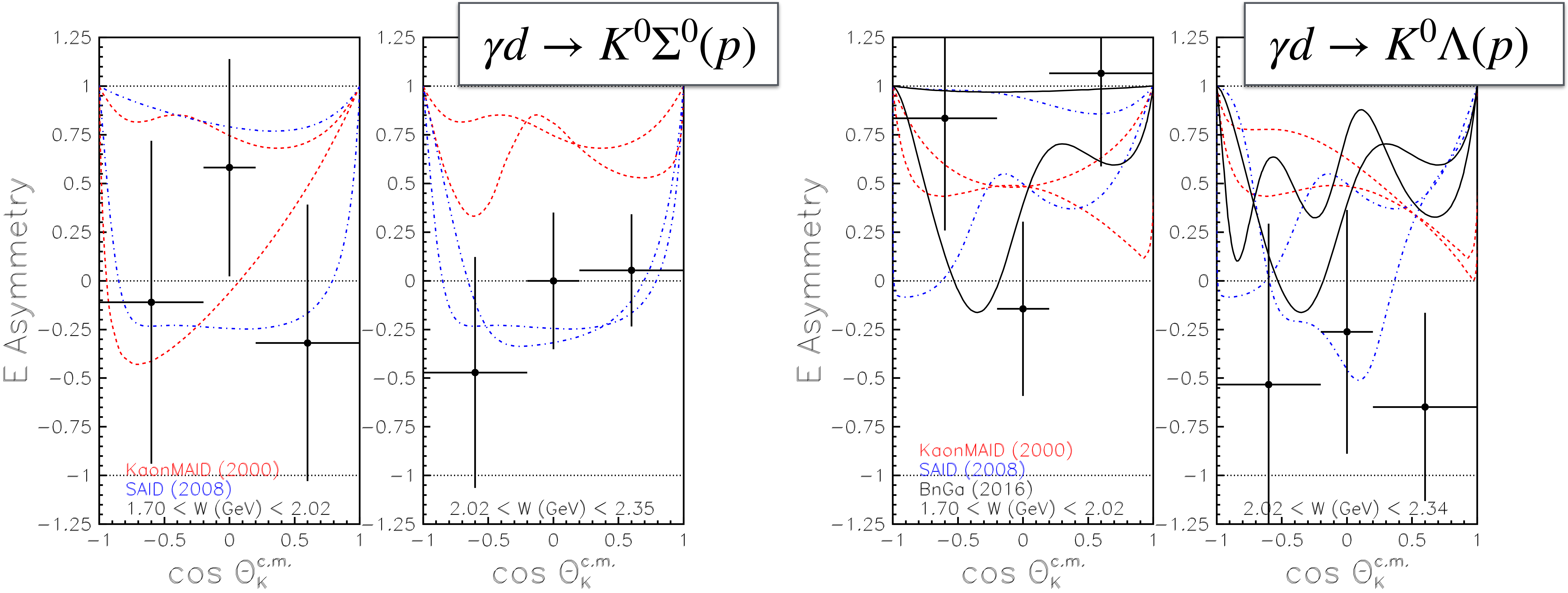


Missing interference terms?

g10+g13 (deuterium): N. Compton et al. (CLAS Collaboration), PRC **96**, 065201 (2017).
g11 (proton): M. E. McCracken et al. (CLAS Collaboration), PRC 81, 025201 (2010).

Beam-target helicity asymmetry E in hyperon photoproduction on the neutron, 1.70 GeV < W < 2.34 GeV

Analysis of clean $p\pi^+\pi^-\pi^-$ sample with intermediate hyperons; limited by small cross section.

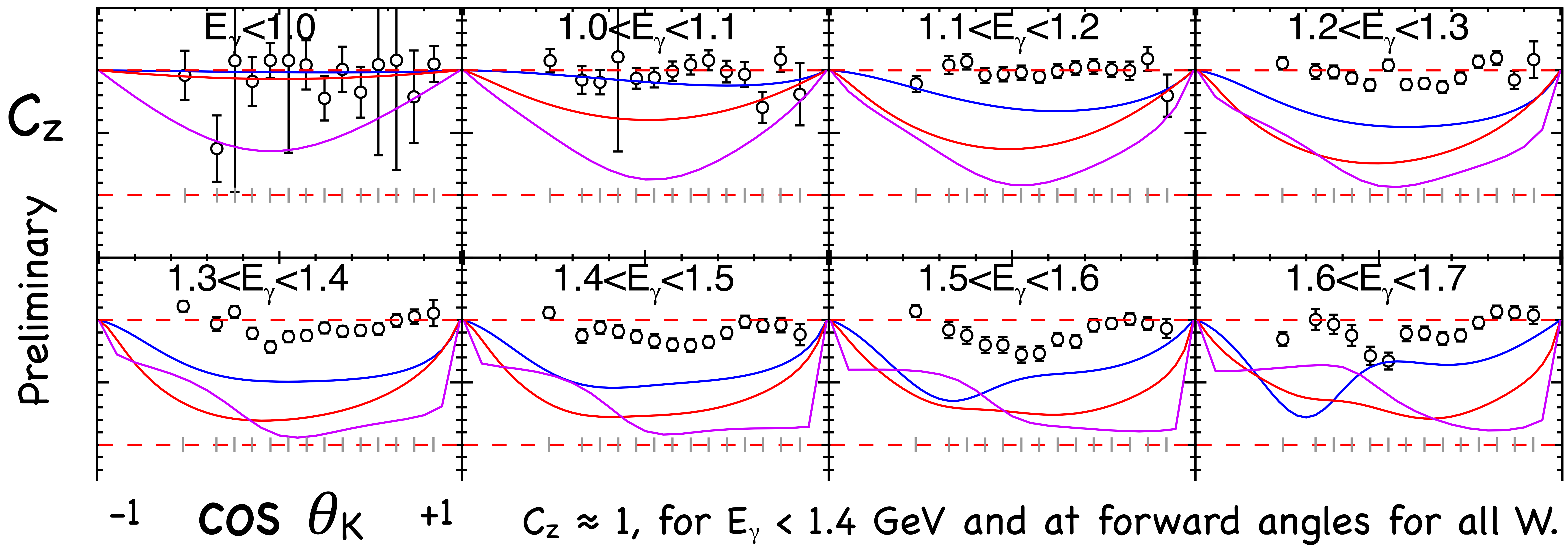


D. Ho et al. (CLAS Collaboration), PRC **98**, 242002 (2017)

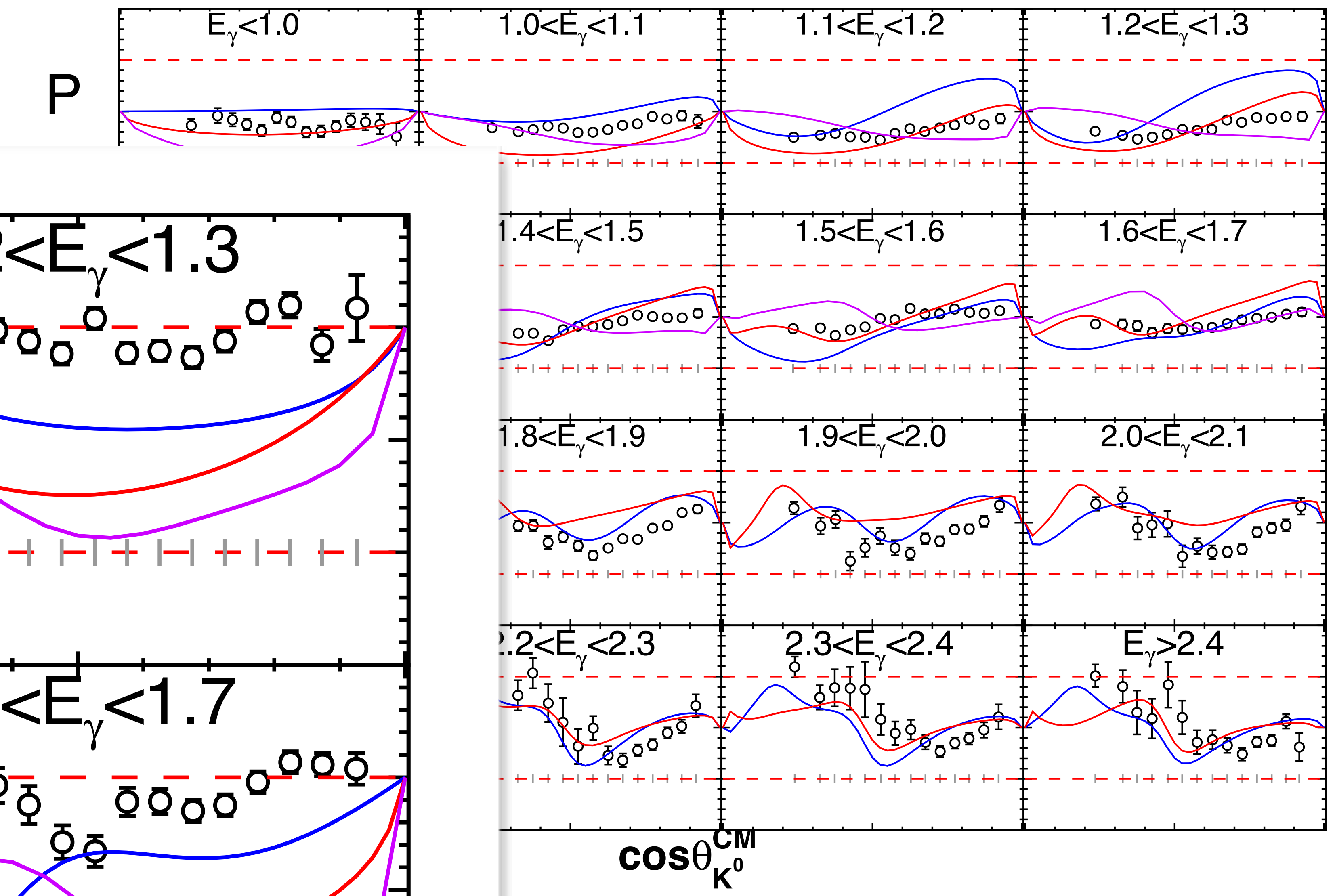
First induced polarization, P, and polarization-transfer, C_x and C_z, data in $K^0\Lambda$ photoproduction

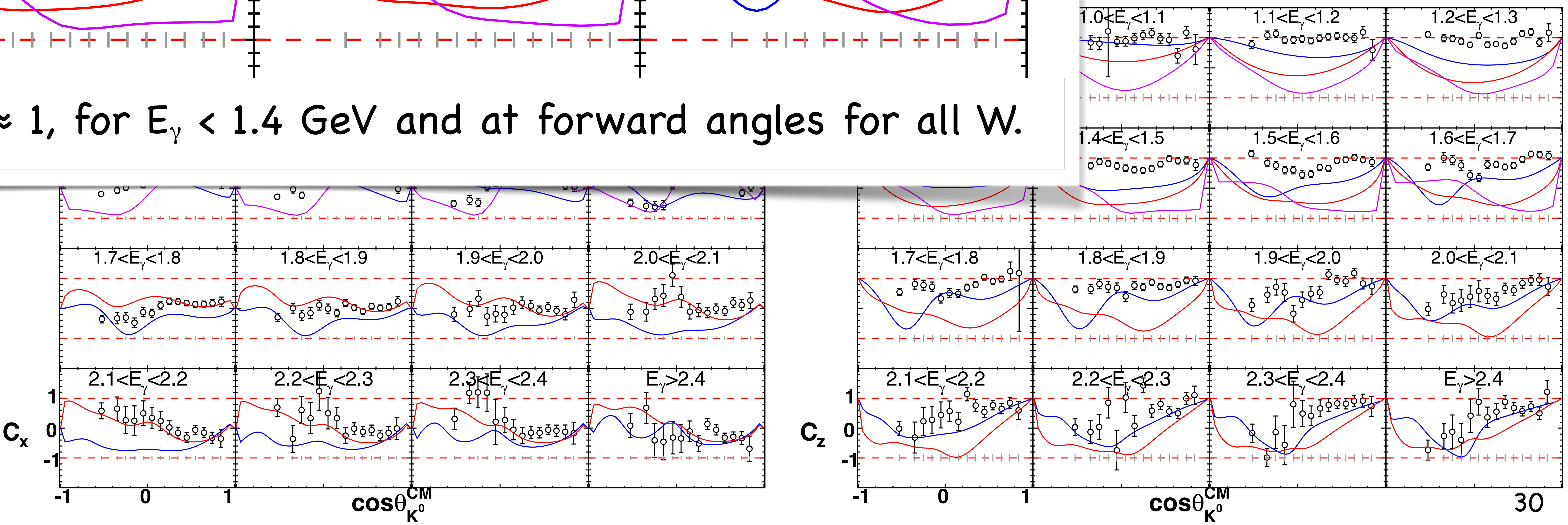
$$\gamma d \rightarrow K^0 \Lambda(p)$$

1.6 GeV < W < 2.4 GeV



$C_z \approx 1$, for E_γ < 1.4 GeV and at forward angles for all W.





- ANL Osaka
- Bonn-Gatchina
- Bonn-Gatchina

g13: C. Gleason, Y. Ilieva, CLAS Collaboration, Few-Body Syst 59, 129 (2018).

Summary and outlook

CLAS polarized photoproduction data off

polarized and unpolarized,
proton and neutron targets

continue to contribute to complete or nearly complete experiments and help establishing new nucleon resonances.

Recent analyses of the data

- strengthened evidence of previously poorly known resonances,
- provided improved values for γpN^* and γnN^* couplings,
- clarified background and interference terms.

Large impact expected as data analyses are being finalized.