Baryon Spectroscopy with Polarized Photoproduction Observables from CLAS

1. CLAS meson photoproduction
2. Single-pion photoproduction (FROST)
3. Double-pion photoproduction (FROST)

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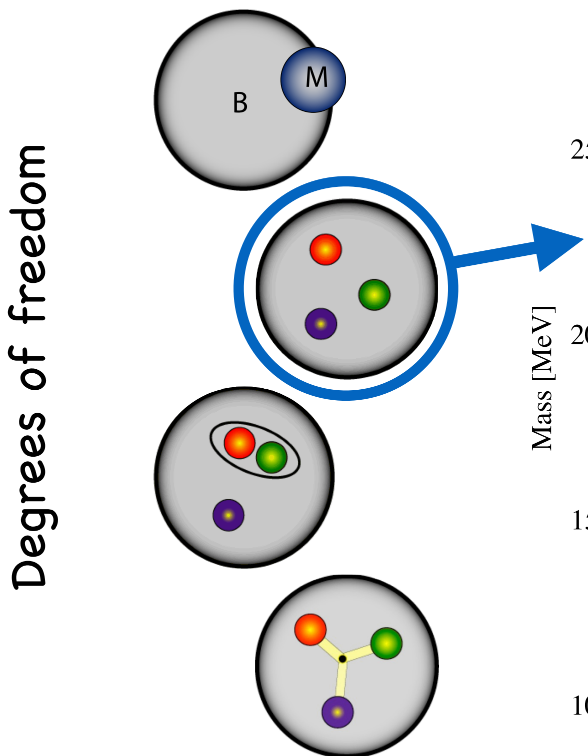
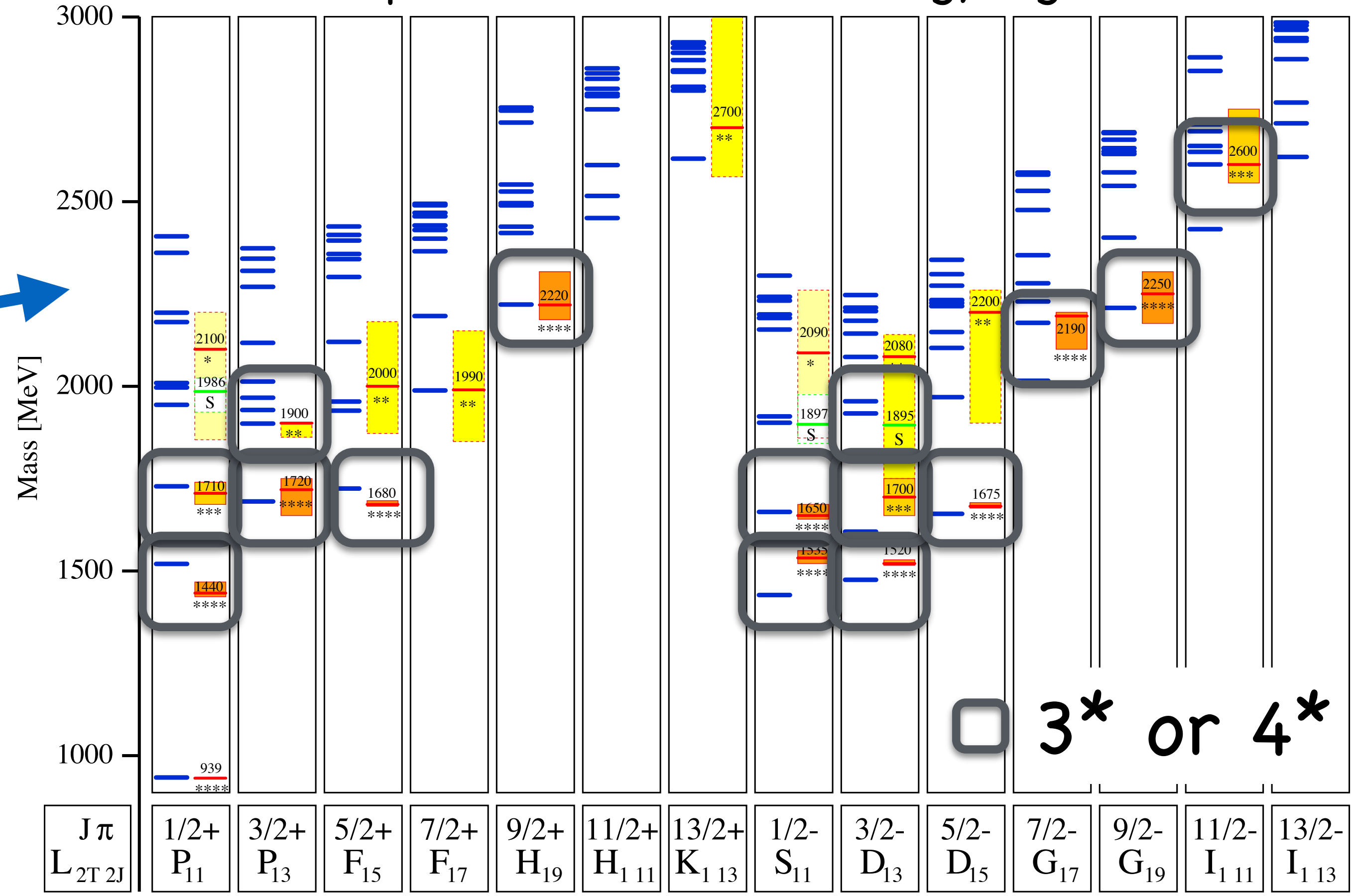
22nd International Spin Symposium
University of Illinois, Champaign, IL, September 25 - 30, 2016

Relevant degrees of freedom and missing resonance problem



N Resonance Spectrum — the low-energy signature of QCD



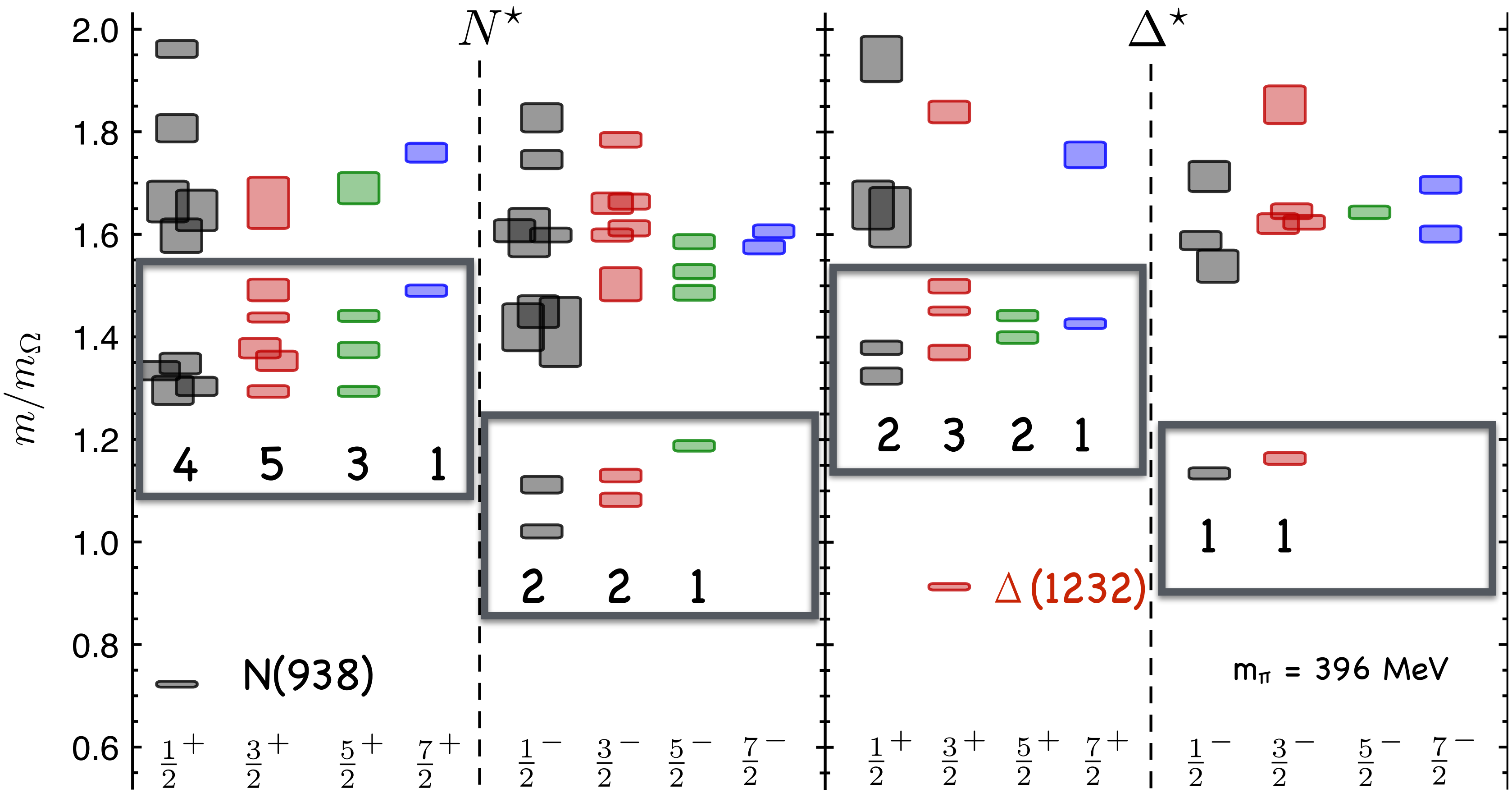
Quark Models

- 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

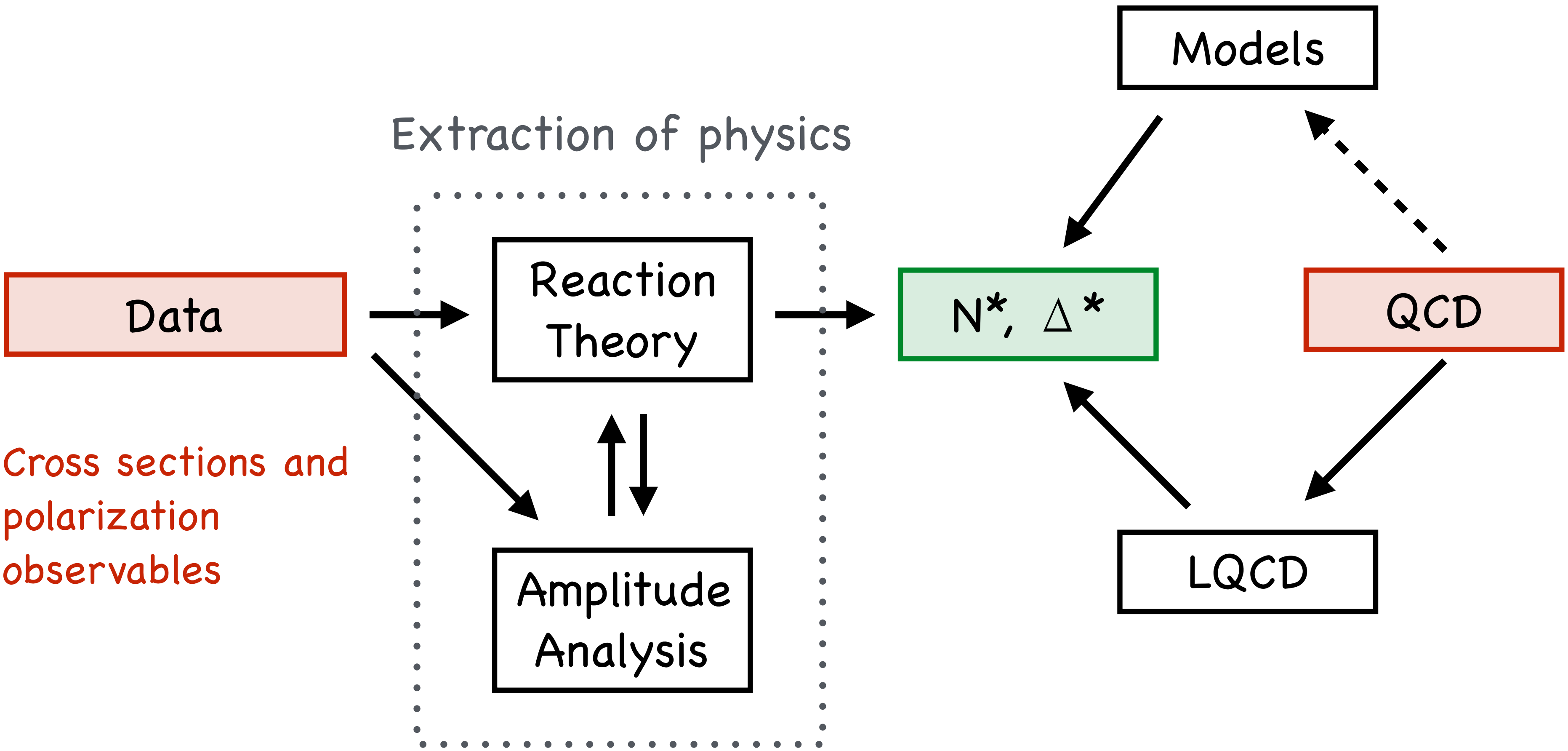
Hadron spectrum collaboration



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



Cross sections and polarization observables

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)

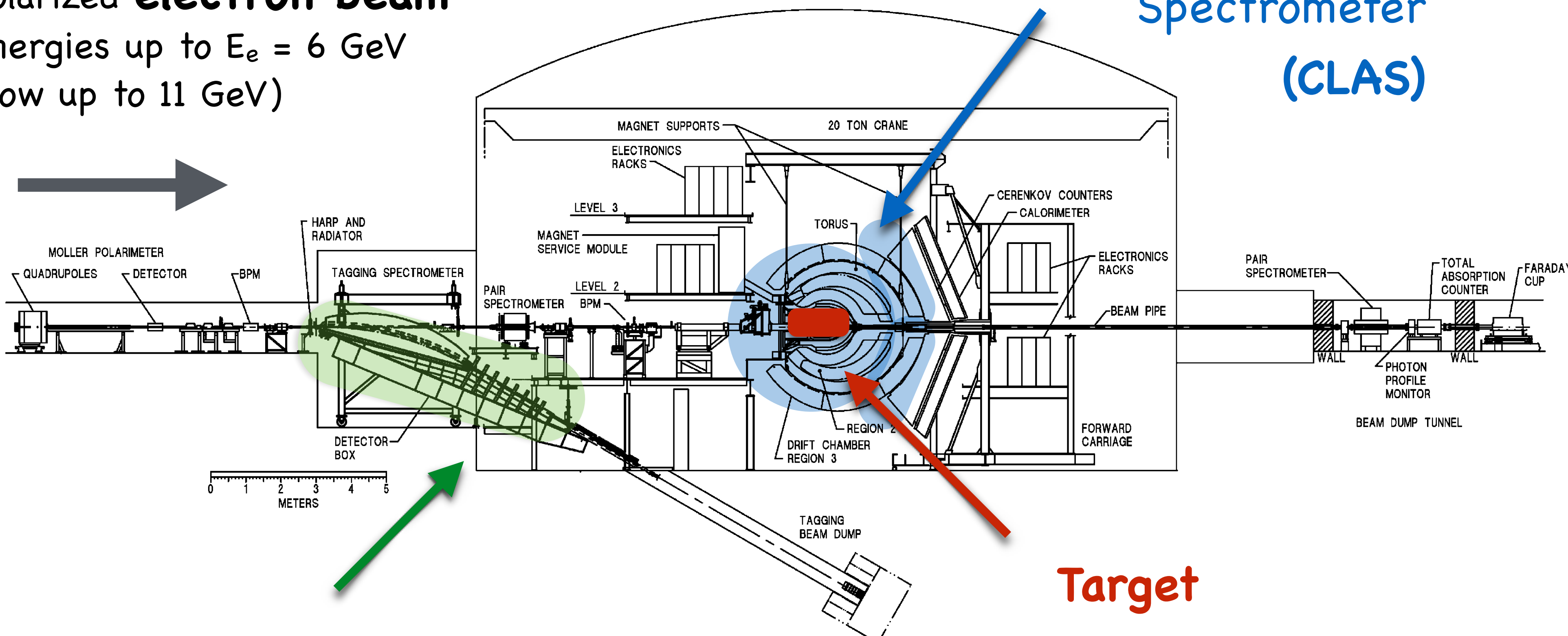
CEBAF Large Acceptance Spectrometer in Hall B (1997 - 2012)

Polarized **electron beam**

Energies up to E_e = 6 GeV

(now up to 11 GeV)

CEBAF Large Acceptance Spectrometer **(CLAS)**



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

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

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

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

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

...

e.g. CLAS frozen spin target (FROST)

Neutron target

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

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

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

...

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

➔ Tsuneo Kageya's talk

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 $\pi^+ n$

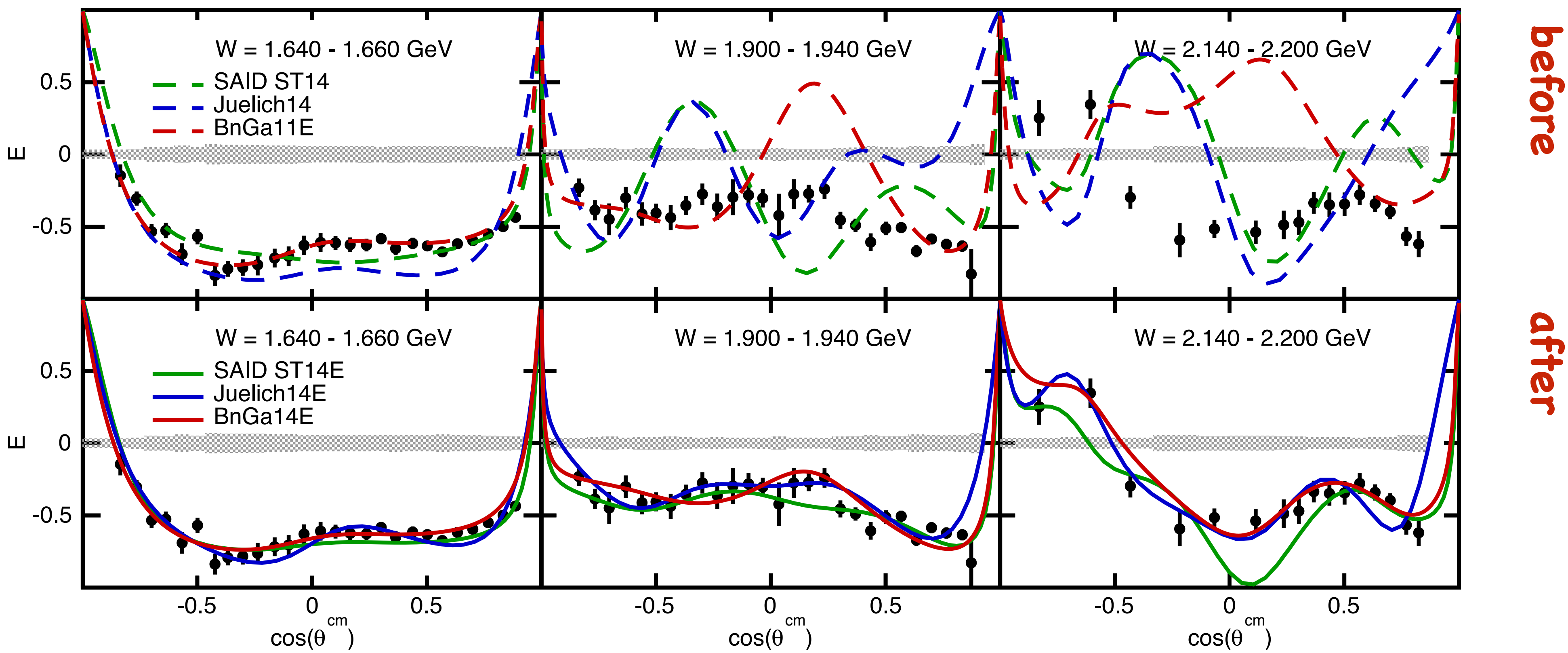
$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_0 \left(1 - P_z P_\odot E\right)$$

$W = 1240 - 2260$ MeV

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

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

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

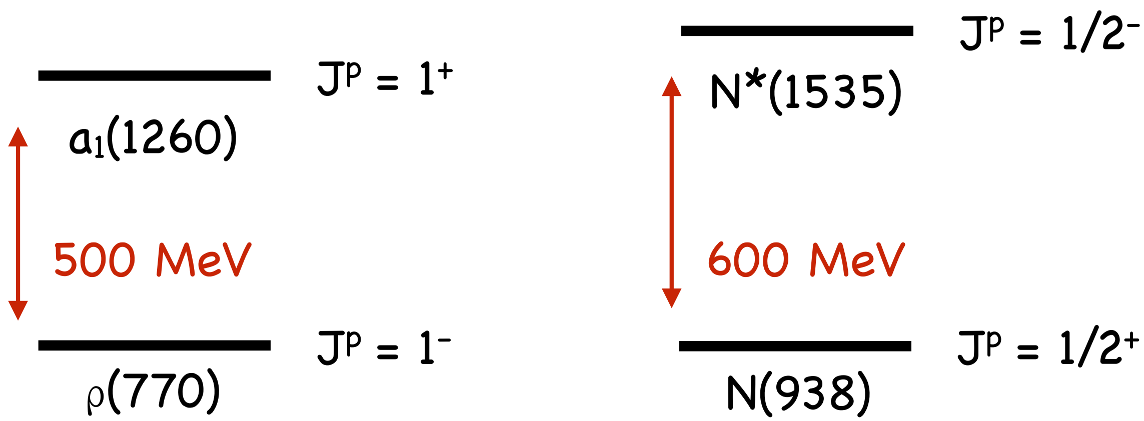


Partial Wave Analyses Good overall description after fit, however, not with identical results.

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

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

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

A.V. Anisovich et al., arXiv:1503.05774 [nucl-ex]

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.

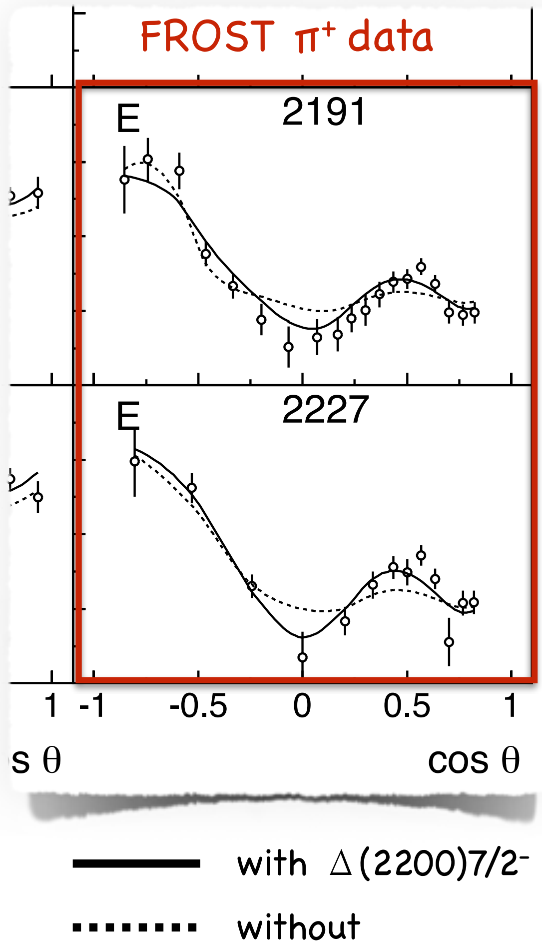
Δ(1950)7/2+ ****

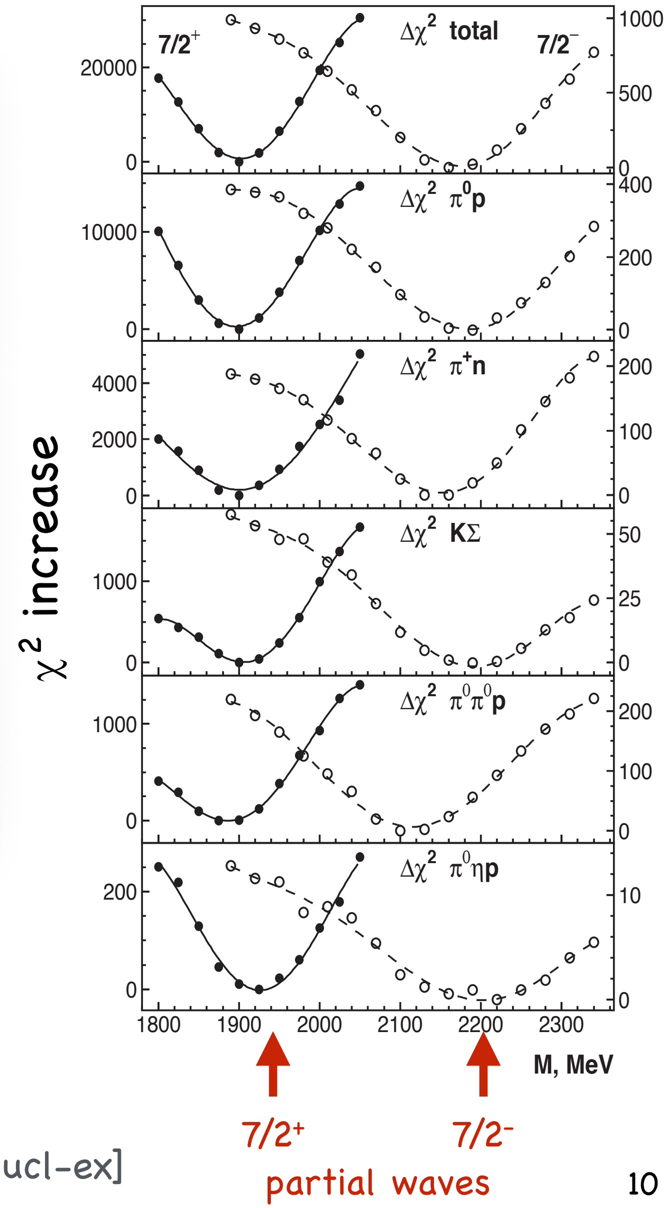
Δ(2200)7/2⁻ *

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.





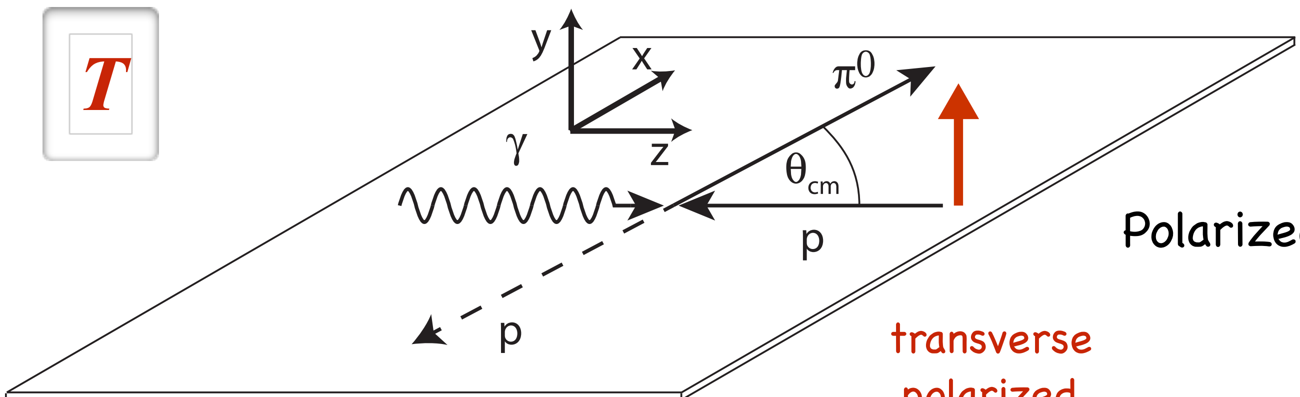
A.V. Anisovich et al., arXiv:1503.05774 [nucl-ex]

All isospin channels are important to constrain coupled-channel analyses: example of $\pi^0 p$

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

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

T



Polarized target (left/right)

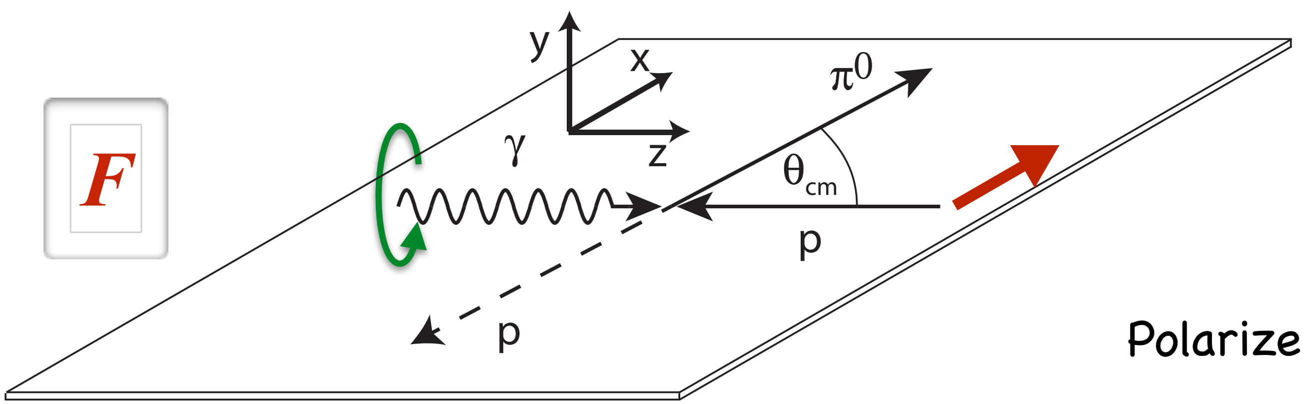
transverse polarized target

FROST data

W = 1.5 - 2.5 GeV

dW = 30 MeV

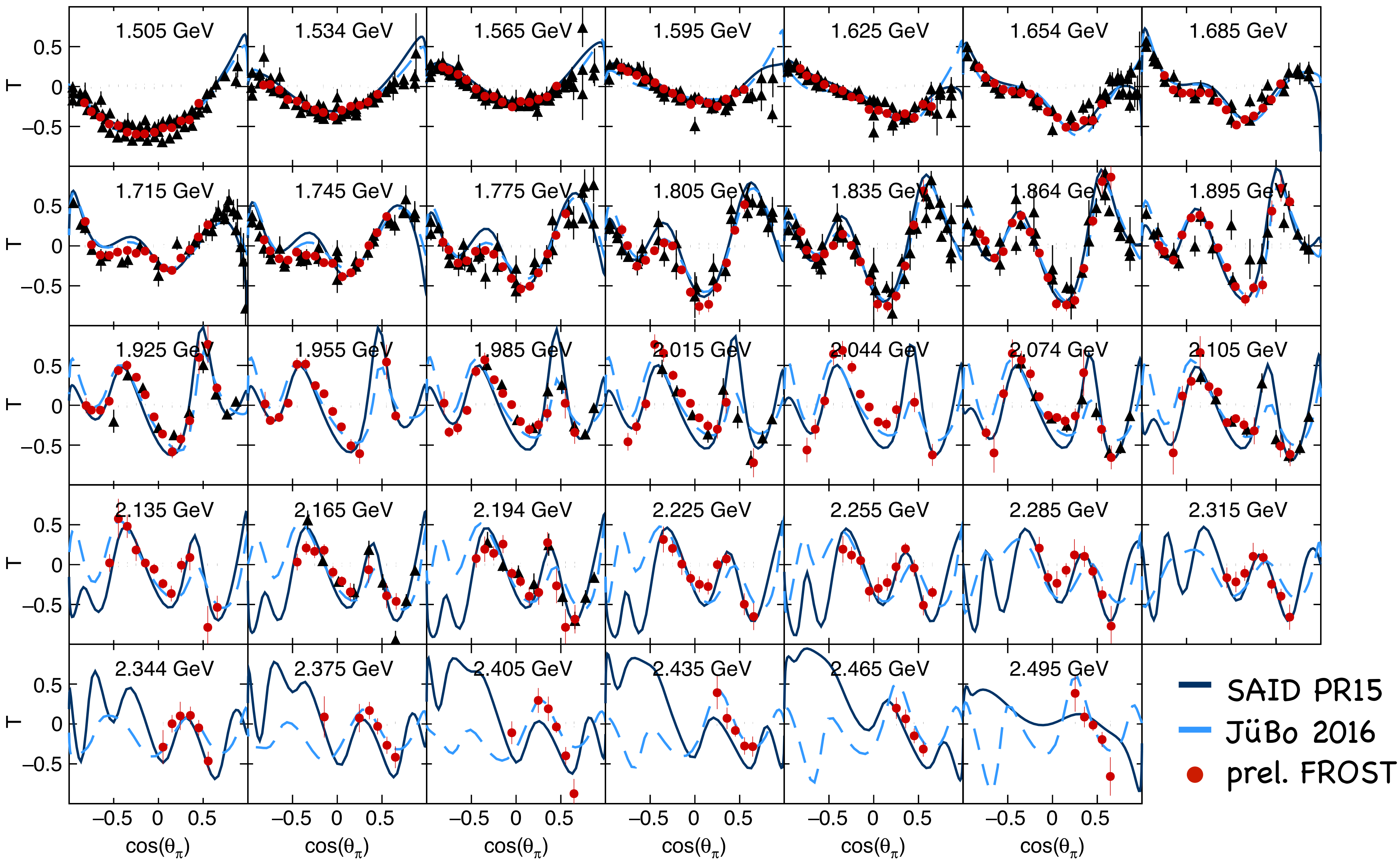
F



Polarized beam and target (up/down)

Single-polarization observable T

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

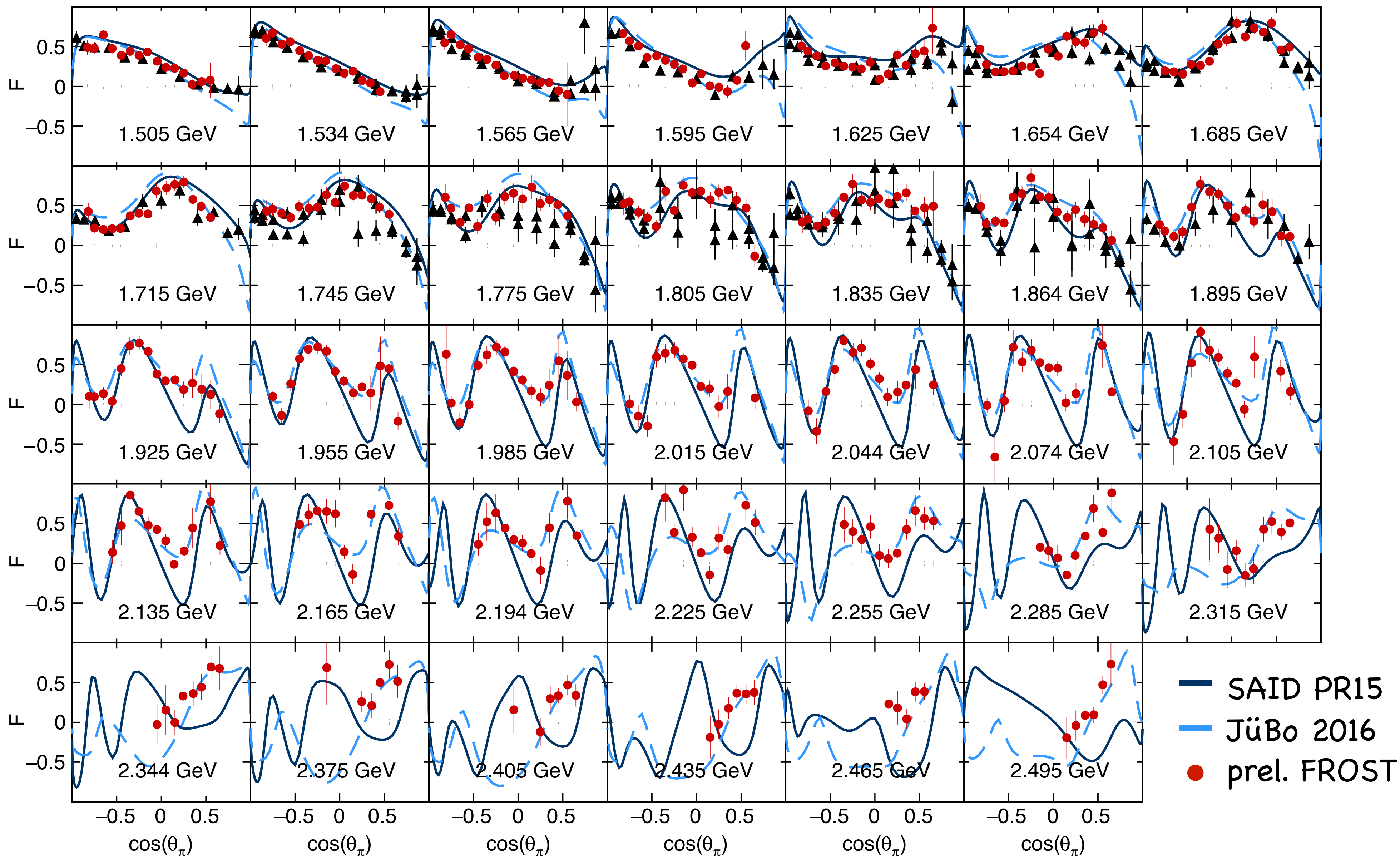


g9 analysis: Hao Jiang (USC)

no fit yet to new CLAS data

Double-polarization observable F

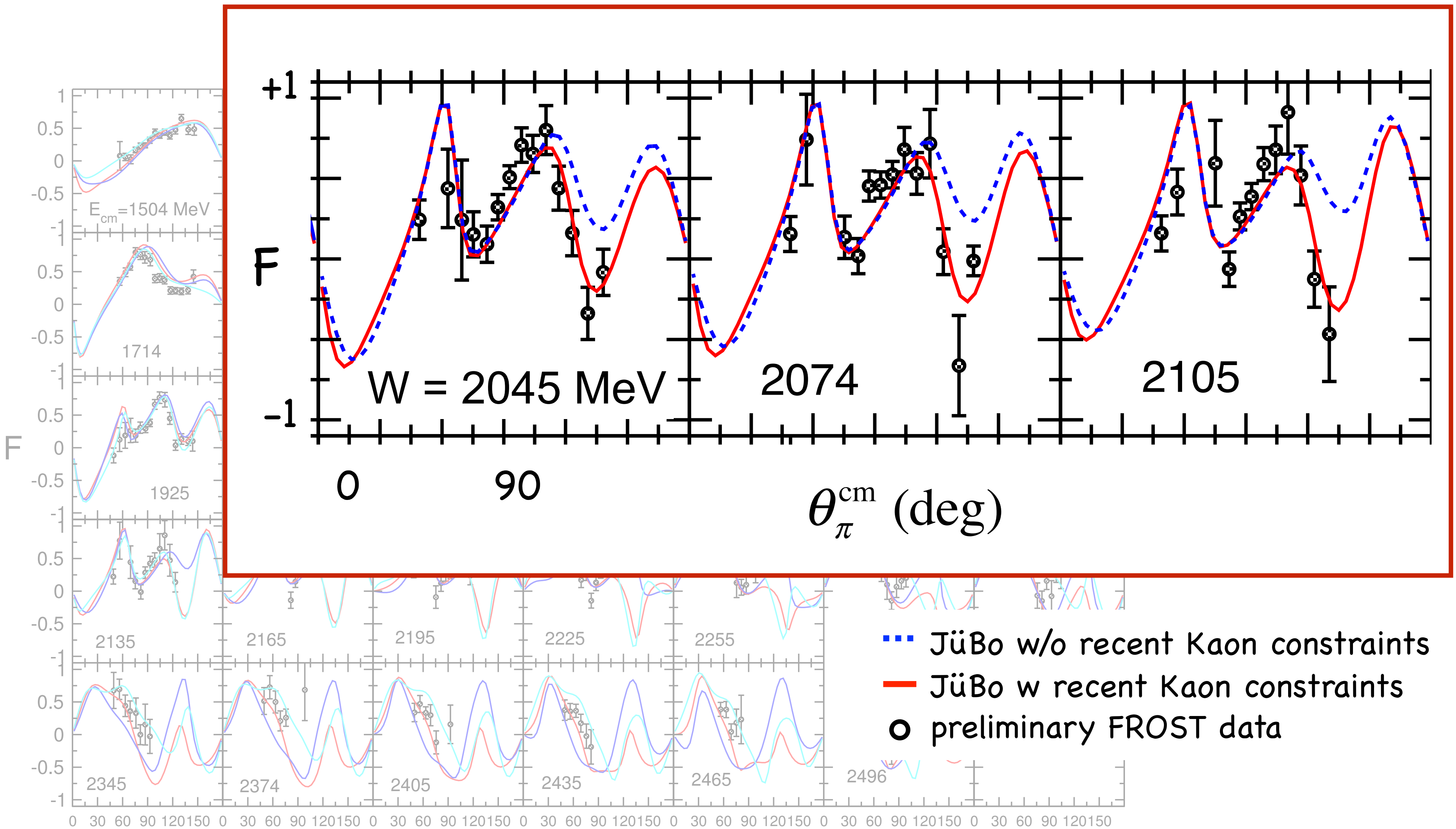
$\vec{\gamma}\vec{p} \to \pi^0 p$



g9 analysis: Hao Jiang (USC)

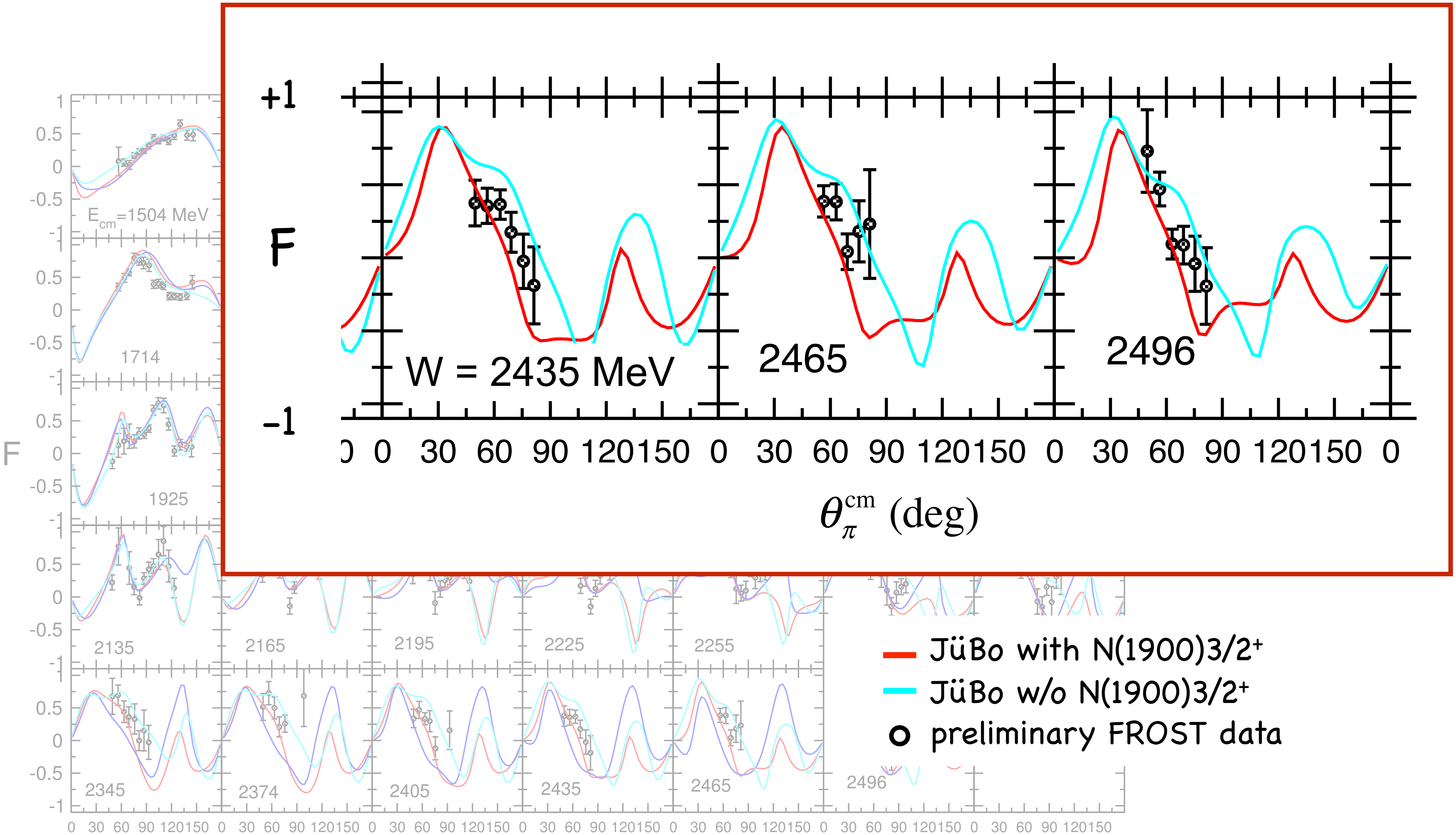
no fit yet to new CLAS data

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



Deborah Rönchen (Bonn), private communication (2016)

New FROST data will improve constraints of partial-wave analyses



Deborah Rönchen (Bonn), private communication (2016)

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

Nππ is a dominant decay channel of highly excited nucleons.

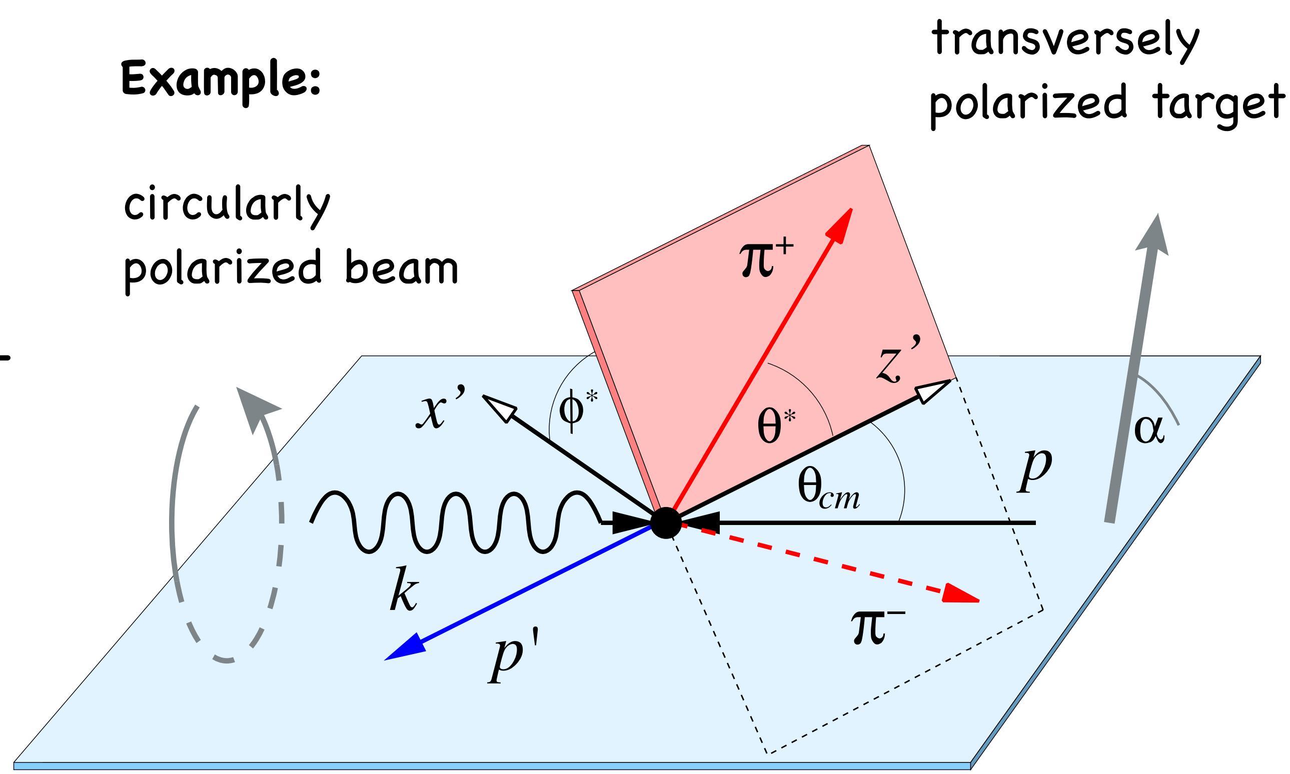
Essential part in coupled-channel calculations.

Allows for the study of sequential decays.

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

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

Example:



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

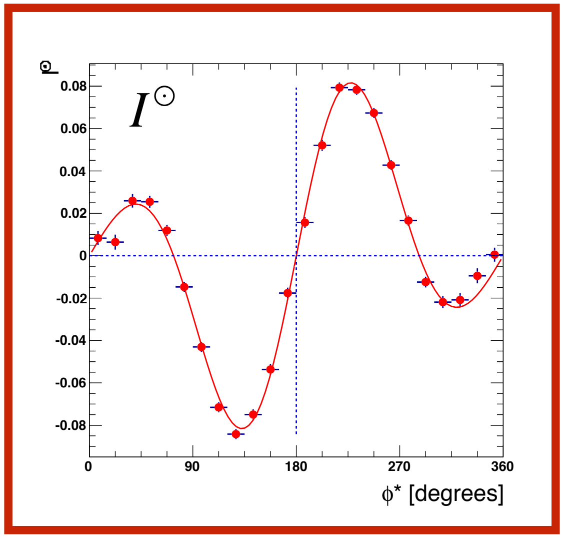
W. Roberts and T. Oed, Phys. Rev. C **71**, 055201 (2005)

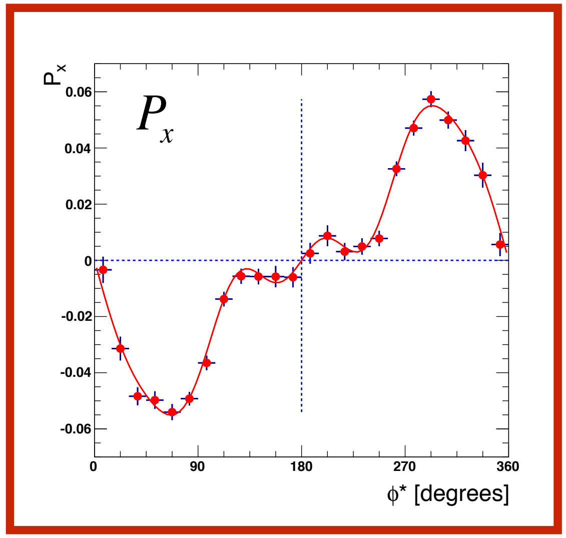
Parity conservation yields to symmetry properties of observables

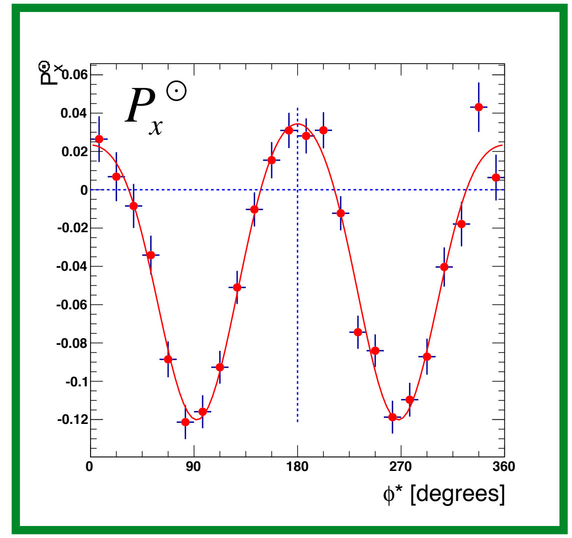
$\gamma p \rightarrow \pi^+ \pi^- p$

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

circularly polarized photons - transversely polarized target

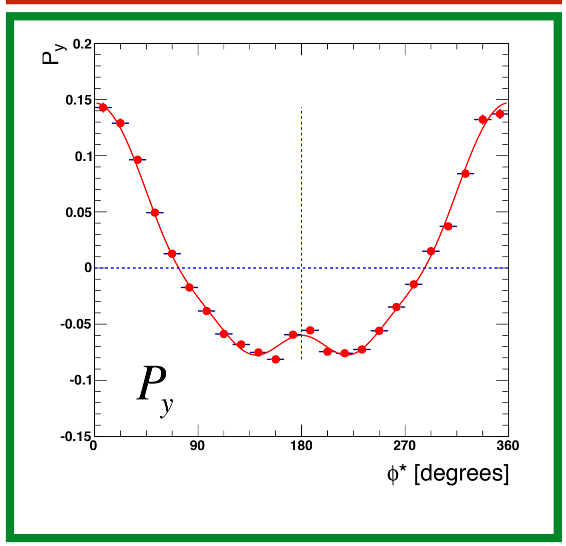


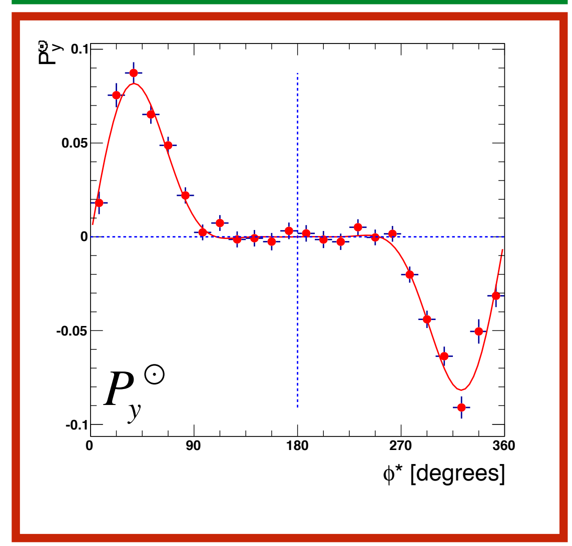




odd observables:
do <u>not</u> exist in single meson final states.

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



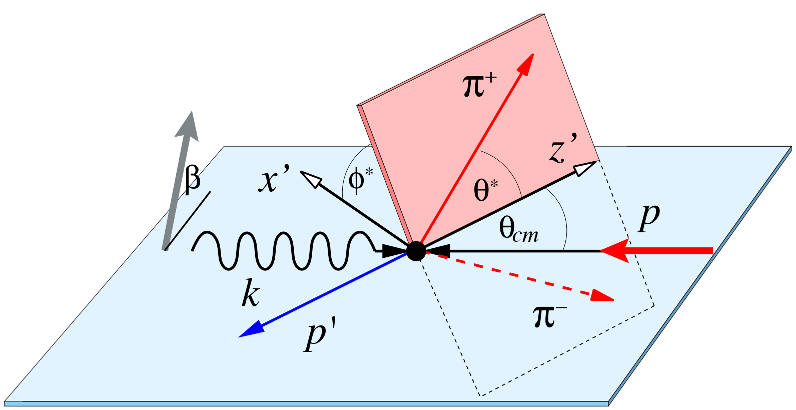


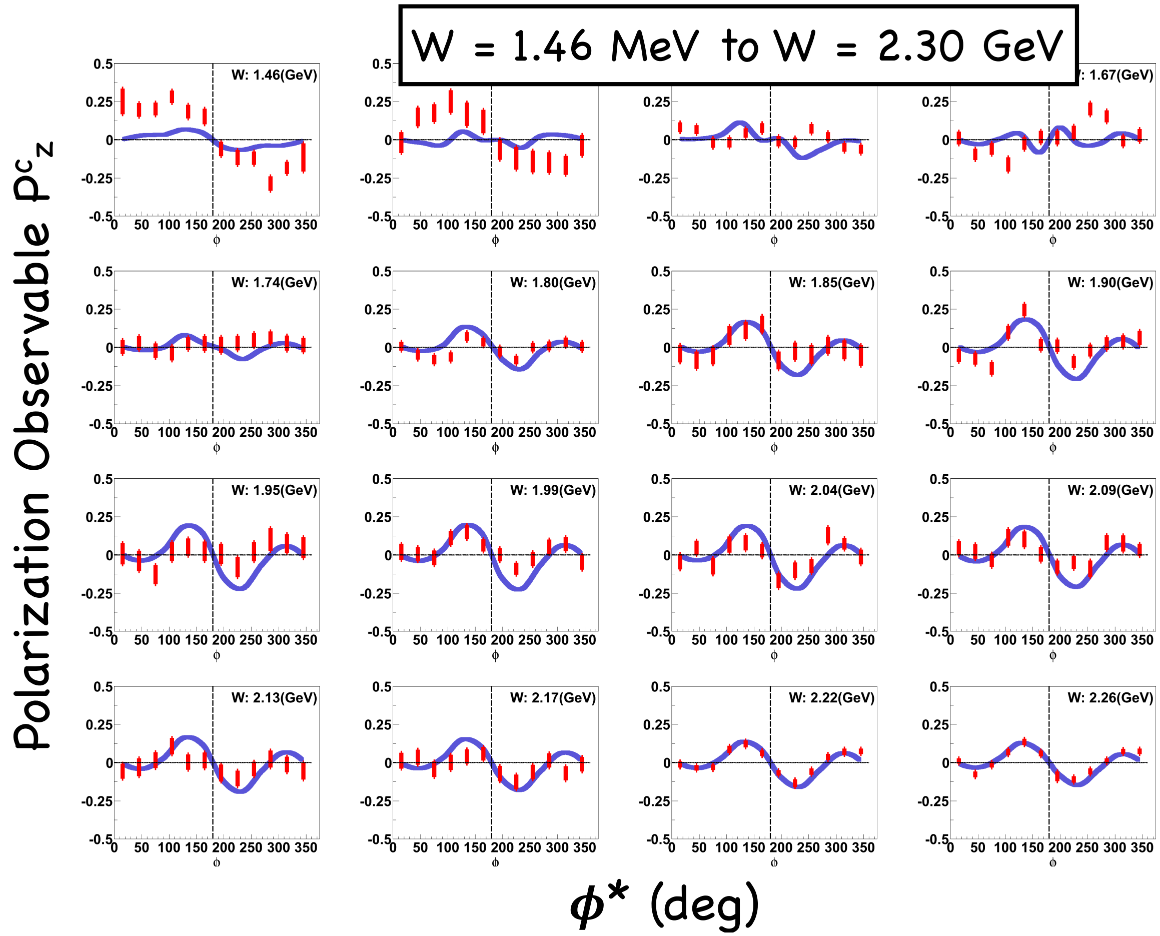
g9 analysis: Aneta Net (USC)

Preliminary results (g9a) for P^c_z

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

$$I = I_0 \{ 1 + \Lambda_z P_z + \delta_\ell \sin 2\beta (I^s + \Lambda_z P^s_z) + \delta_\ell \cos 2\beta (I^c + \Lambda_z P^c_z) \}$$

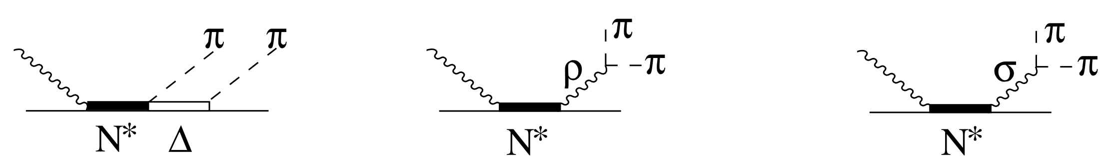




Effective Lagrangian Model (A. Fix)

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:

Yuqing Mao (USC)

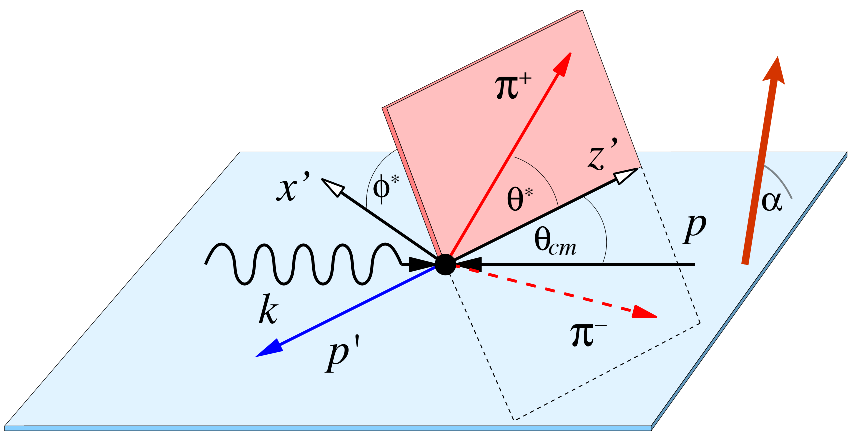


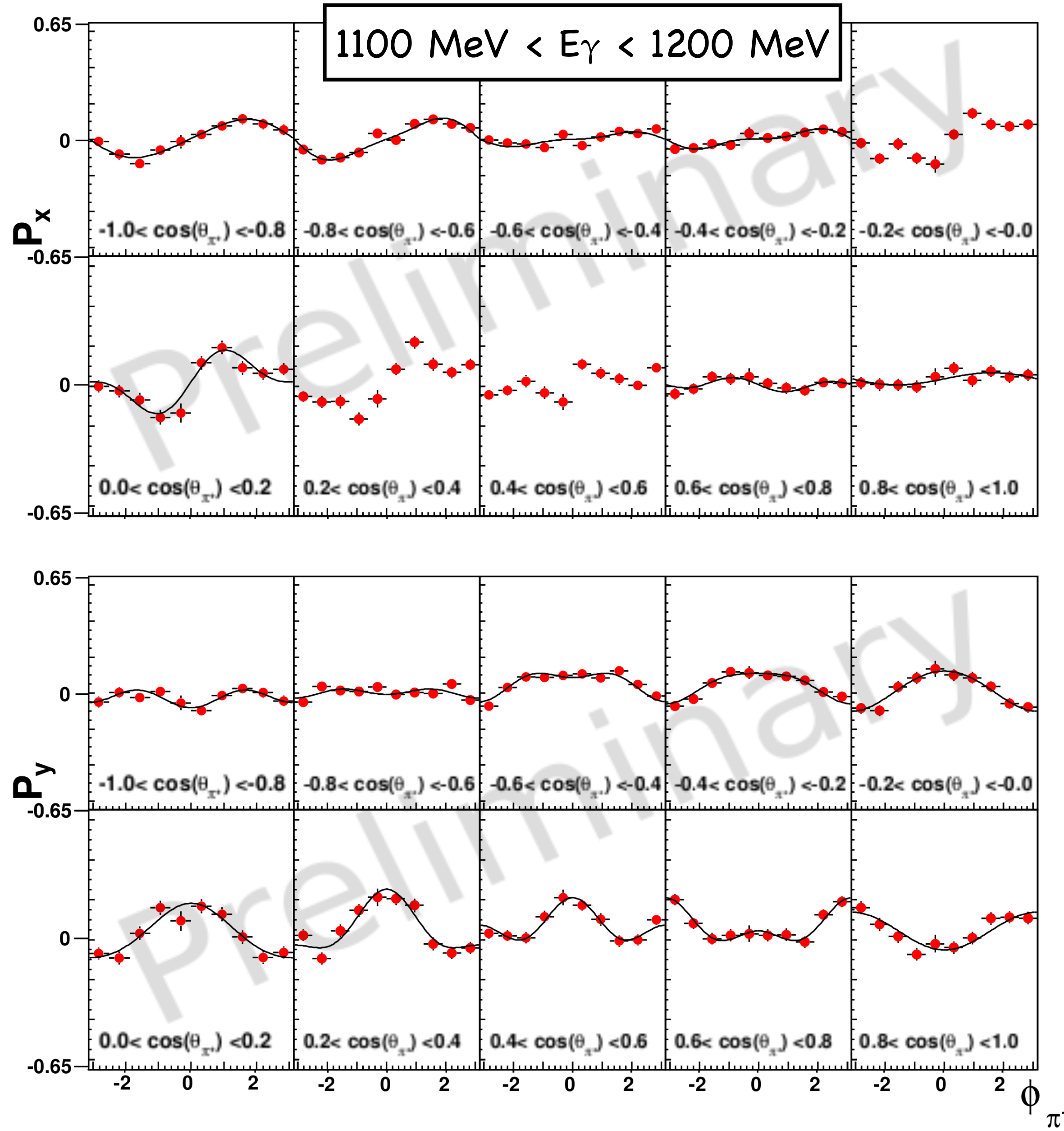
A. Fix and H. Arenhövel, Eur. Phys. J. A **25**, 115 (2005); Preliminary data: Yuqing Mao (USC)

Preliminary results (g9b) for P_x and P_y

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

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





Data binned in E_γ, Φ^*, and cos θ^*,

fit with Fourier series.

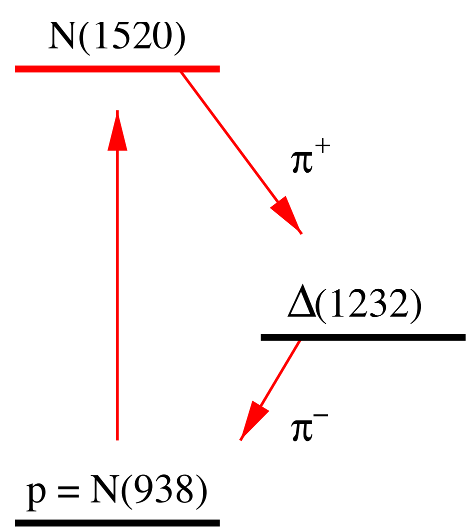
g9 analysis:
Priyashree Roy (FSU)

Intermediate Δ(1232) Resonance

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

Example of
sequential decays

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

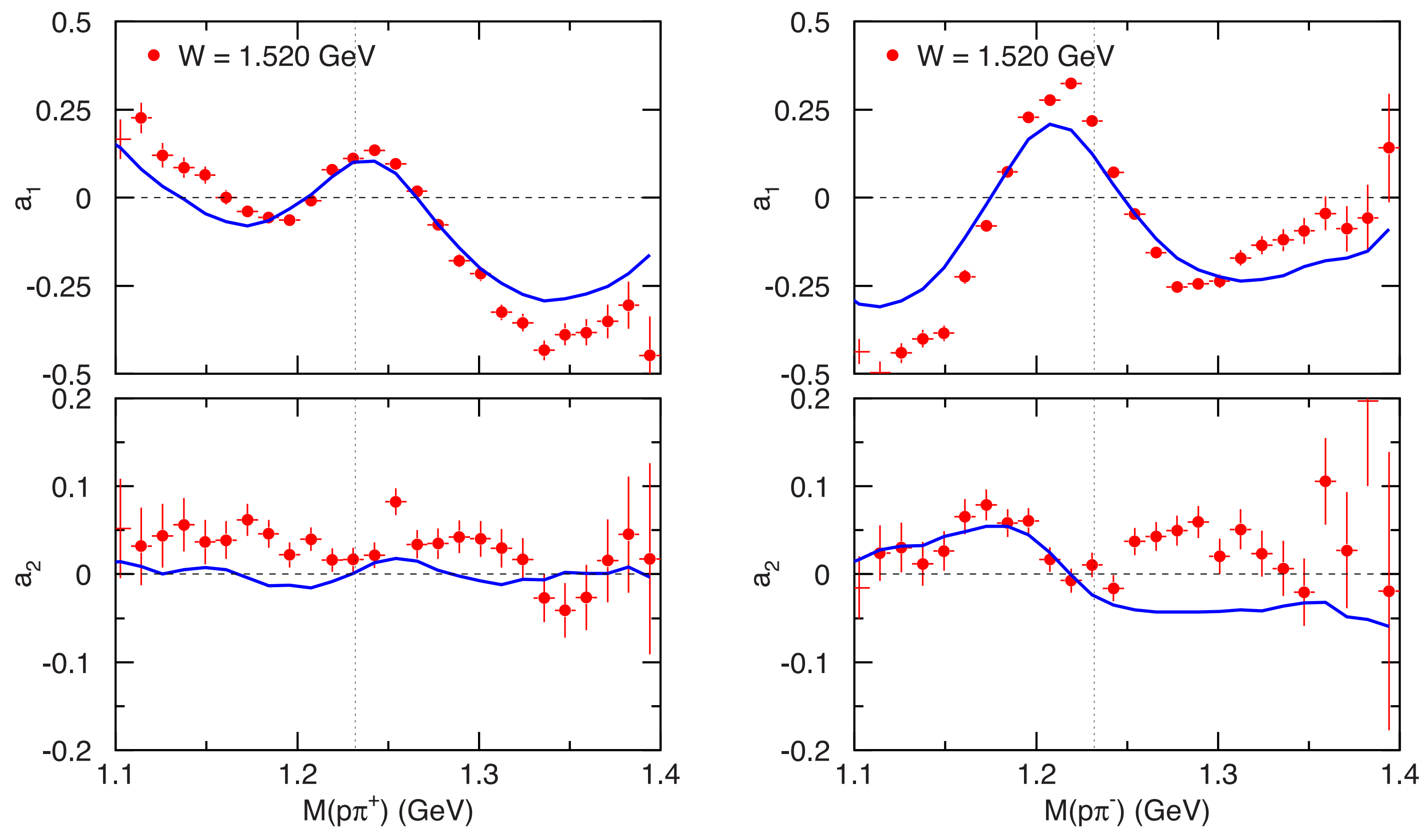


Fourier coefficients of the angular distribution

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

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

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



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. Δ(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