Extraction of nucleon resonances from global analysis of meson production reactions at EBAC

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(Excited Baryon Analysis Center, Jefferson Lab)

In collaboration with

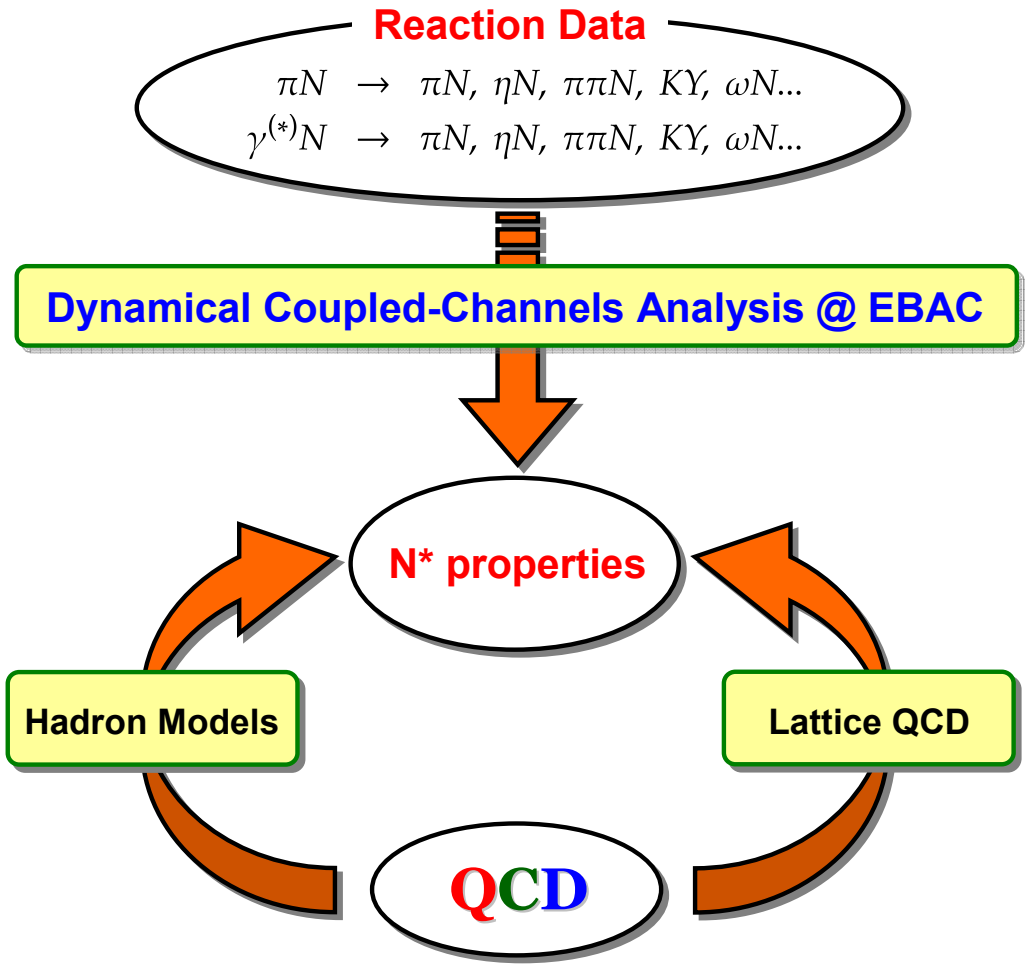
B. Julia-Diaz, T.-S. H. Lee, A. Matsuyama,
S. Nakamura, T. Sato, N. Suzuki

BARYONS'10, December 7th – 11th, Osaka, Japan

Excited Baryon Analysis Center (EBAC) of Jefferson Lab

Founded in January 2006

http://ebac-theory.jlab.org/



Objectives and goals:

Through the comprehensive analysis of world data of πN, γN, N(e,e') reactions,

- ✓ **Determine N* spectrum (pole positions)**
- ✓ **Extract N* form factors**

  (e.g., N-N* e.m. transition form factors)
- ✓ **Provide reaction mechanism information necessary for interpreting N* properties, structures and dynamical origins**

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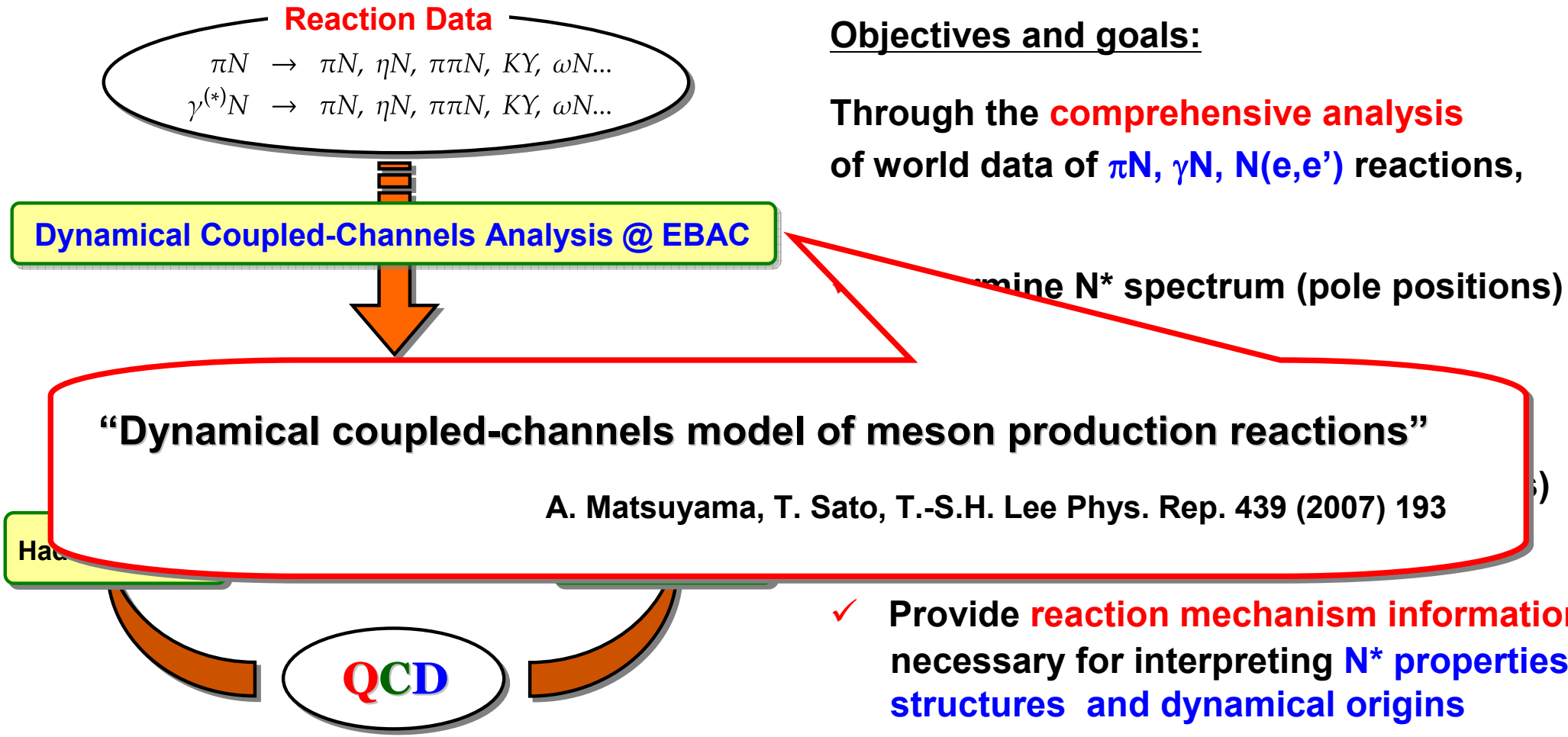

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- ✓ **Provide reaction mechanism information necessary for interpreting N* properties, structures and dynamical origins**

Dynamical coupled-channels model of EBAC (EBAC-DCC model)

For details see Matsuyama, Sato, Lee, Phys. Rep. 439,193 (2007)

✓ **Partial wave (LSJ) amplitude of a → b reaction:**

$$T^{(LSJ)}_{a,b}(p_a, p_b; E) = V^{(LSJ)}_{a,b}(p_a, p_b) + \sum_c \int_0^\infty q^2 dq V^{(LSJ)}_{a,c}(p_a, q) G_c(q; E) T^{(LSJ)}_{c,b}(q, p_b; E)$$

coupled-channels effect

✓ **Reaction channels:**

$$a, b, c = (\gamma^{(*)}N,\ \pi N,\ \eta N,\ \underbrace{\pi\Delta,\ \sigma N,\ \rho N,}_{\pi\pi N}\ K\Lambda,\ K\Sigma\ , \cdots)$$

✓ **Transition potentials:**

$$V_{a,b} = v_{a,b} + \sum_{N^*} \frac{\Gamma^\dagger_{N^*,a}\Gamma_{N^*,b}}{E - M_{N^*}}$$

exchange potentials of ground state mesons and baryons

bare N* states

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7. $\pi(k,i) + N(p) \to \rho(k',j) + N(p')$:

$$\bar{V}(7) = \bar{V}_a^7 + \bar{V}_b^7 + \bar{V}_c^7 + \bar{V}_d^7 + \bar{V}_e^7$$

with

$$\bar{V}_a^7 = i\frac{f_{\pi NN}}{m_\pi} g_{\rho NN} \Gamma_{\rho'} S_N(p+k) \not{k} \gamma_5 \tau^i,$$

$$\bar{V}_b^7 = i\frac{f_{\pi NN}}{m_\pi} g_{\rho NN} \not{k} \gamma_5 \tau^i S_N(p-k') \Gamma_{\rho'},$$

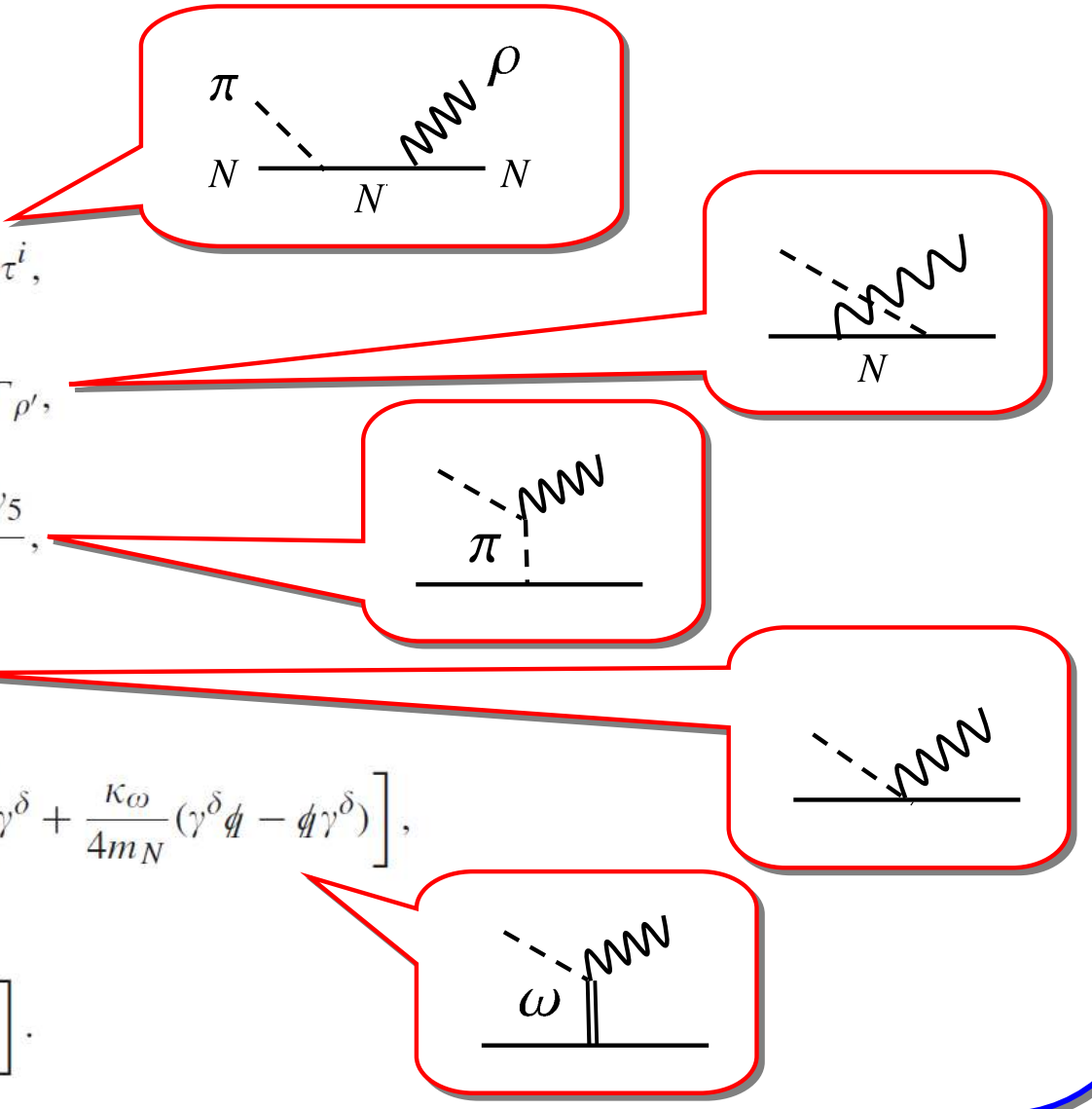
$$\bar{V}_c^7 = \frac{f_{\pi NN}}{m_\pi} g_{\rho\pi\pi} \epsilon_{ijl} \tau^l \frac{(q-k)\cdot \epsilon^*_{\rho'} \not{q} \gamma_5}{q^2 - m_\pi^2},$$

$$\bar{V}_d^7 = -\frac{f_{\pi NN}}{m_\pi} g_{\rho NN} \not{\epsilon}^*_{\rho'} \gamma_5 \epsilon_{jil} \tau^l,$$

$$\bar{V}_e^7 = \frac{g_{\omega NN} g_{\omega\pi\rho}}{m_\omega} \delta_{ij} \frac{\epsilon_{\alpha\beta\gamma\delta} \epsilon^{*\alpha}_{\rho'} k'^\beta k^\gamma}{q^2 - m_\omega^2} \left[\gamma^\delta + \frac{\kappa_\omega}{4m_N}(\gamma^\delta \not{q} - \not{q}\gamma^\delta)\right],$$

where

$$\Gamma_{\rho'} = \frac{\tau^j}{2}\left[\not{\epsilon}^*_{\rho'} + \frac{\kappa_\rho}{4m_N}(\not{\epsilon}^*_{\rho'} \not{k}' - \not{k}' \not{\epsilon}^*_{\rho'})\right].$$



Dynamical coupled-channels model of EBAC (EBAC-DCC model)

For details see Matsuyama, Sato, Lee, Phys. Rep. 439,193 (2007)

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coupled-channels effect

- ✓ **Reaction ch**

$a,$

$$\Gamma_{N^*,a(LS)}(p) = \frac{1}{(2\pi)^{3/2}} \frac{1}{\sqrt{m_N}} \left[\frac{p}{m_\pi}\right]^L C_{N^*,a} \left[\frac{\Lambda_{N^*,a(LS)}{}^2}{\Lambda_{N^*,a(LS)}{}^2 + p^2}\right]^{(2+L)}$$

- ✓ **Transition potentials:**

$$V_{a,b} = v_{a,b} + \sum_{N^*} \frac{\Gamma^\dagger_{N^*,a}\Gamma_{N^*,b}}{E - M_{N^*}}$$

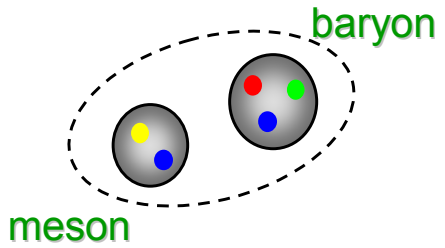
exchange potentials of ground state mesons and baryons

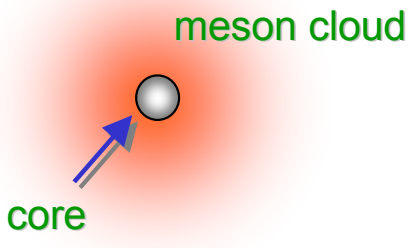
bare N* states

Dynamical coupled-channels model of EBAC (EBAC-DCC model)

For details see Matsuyama, Sato, Lee, Phys. Rep. 439,193 (2007)

Physical N*s will be a "superposition" of the two pictures:





$$|N^*\rangle = |MB\rangle \qquad |N^*\rangle = |qqq\rangle + |\text{m.c.}\rangle$$

Transition potentials:

$$V_{a,b} = v_{a,b} + \sum_{N^*} \frac{\Gamma^{\dagger}_{N^*,a}\Gamma_{N^*,b}}{E - M_{N^*}}$$

exchange potentials of ground state mesons and baryons

bare N* states

Strategy for N* study at EBAC

Stage 1

Construct a reaction model through the comprehensive analysis of meson production reactions

Requires careful analytic continuation of amplitudes to complex energy plane
→ Suzuki, Sato, Lee PRC79 025205; PRC82 045206

Stage 2

Extract resonance information from the constructed reaction model

- N* pole positions; N* → γN, MB transition form factors
- Confirm/reject N* with low-star status; Search for new N*

Stage 3

Make a connection to hadron structure calculations; Explore the structure of the N* states.

- Quark models, DSE, Large Nc, Holographic QCD,…

EBAC-DCC analysis (2006-2009)

πN, ηN, $\pi\pi$N ($\pi\Delta$,ρN,σN) coupled-channels calculations were performed.

Hadronic part

- ✓ π N → π N : **Used for constructing a hadronic model up to W = 2 GeV.**
  Julia-Diaz, Lee, Matsuyama, Sato, PRC76 065201 (2007)
- ✓ π N → η N : **Used for constructing a hadronic model up to W = 2 GeV**
  Durand, Julia-Diaz, Lee, Saghai, Sato, PRC78 025204 (2008)
- ✓ π N → π π N : **First full dynamical coupled-channels calculation up to W = 2 GeV.**
  Kamano, Julia-Diaz, Lee, Matsuyama, Sato, PRC79 025206 (2009)

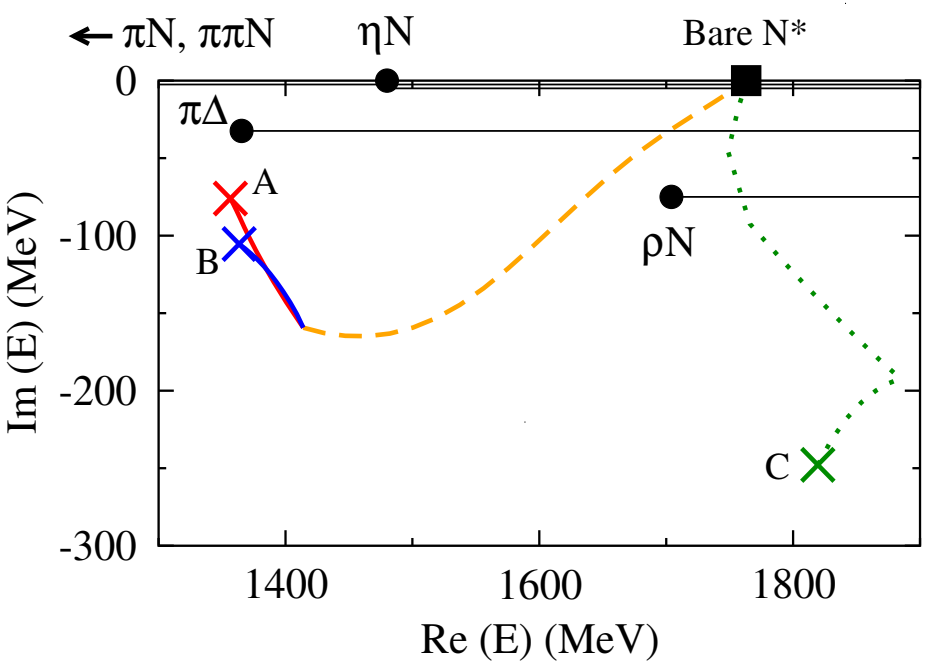
Electromagnetic part

- ✓ $\gamma^{(*)}$ N → π N : **Used for constructing a E.M. model up to W = 1.6 GeV and Q^2 = 1.5 GeV^2**
  (photoproduction) Julia-Diaz, Lee, Matsuyama, Sato, Smith, PRC77 045205 (2008)
  (electroproduction) Julia-Diaz, Kamano, Lee, Matsuyama, Sato, Suzuki, PRC80 025207 (2009)
- ✓ γ N → π π N : **First full dynamical coupled-channels calculation up to W = 1.5 GeV.**
  Kamano, Julia-Diaz, Lee, Matsuyama, Sato, PRC80 065203 (2009)

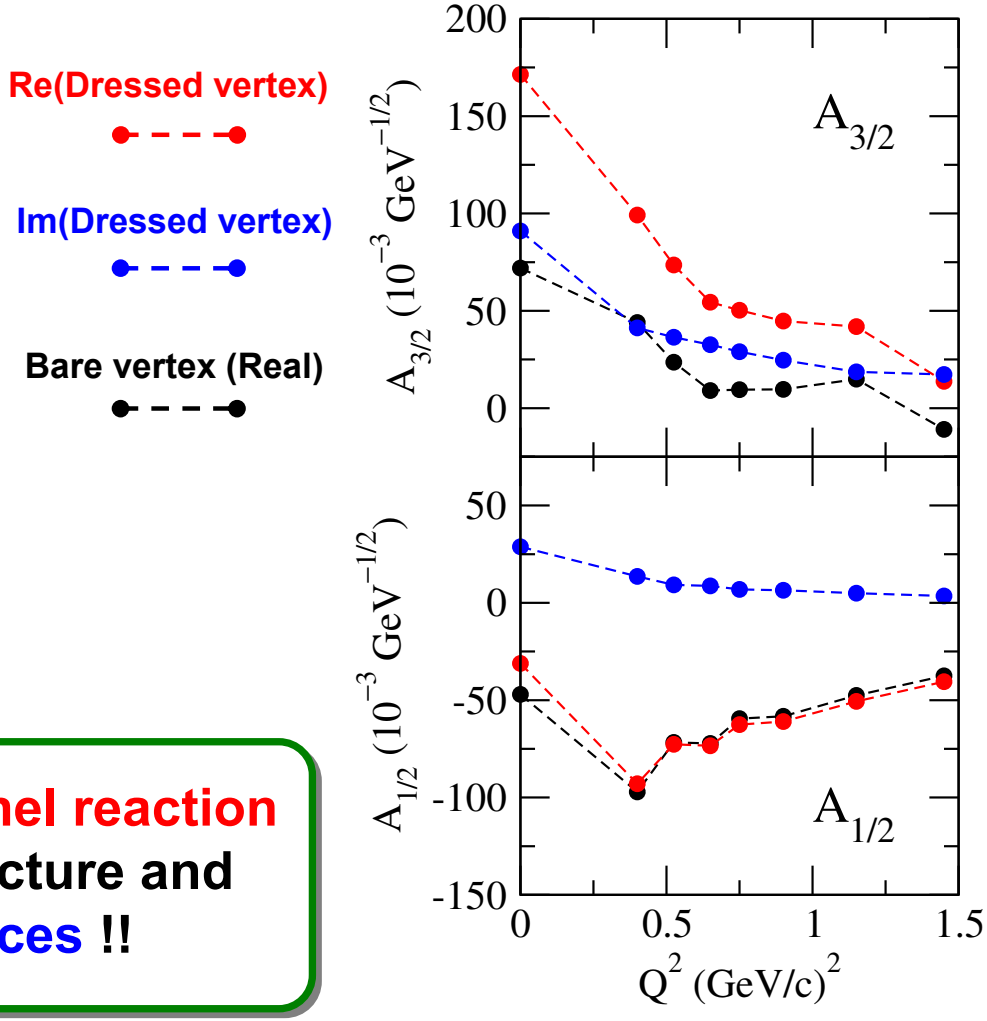
Dynamical coupled-channels effect on N* poles and form factors

Suzuki, Julia-Diaz, Kamano, Lee, Matsuyama, Sato, PRL104 065203 (2010)
Suzuki, Sato, Lee, PRC82 045206 (2010)

Dynamical origin of P11 resonances



N-1st D13 e.m. transition form factor



Critical role of non-trivial multi-channel reaction mechanisms for interpreting the structure and dynamical origin of nucleon resonances !!

EBAC-DCC analysis: 2010 ~

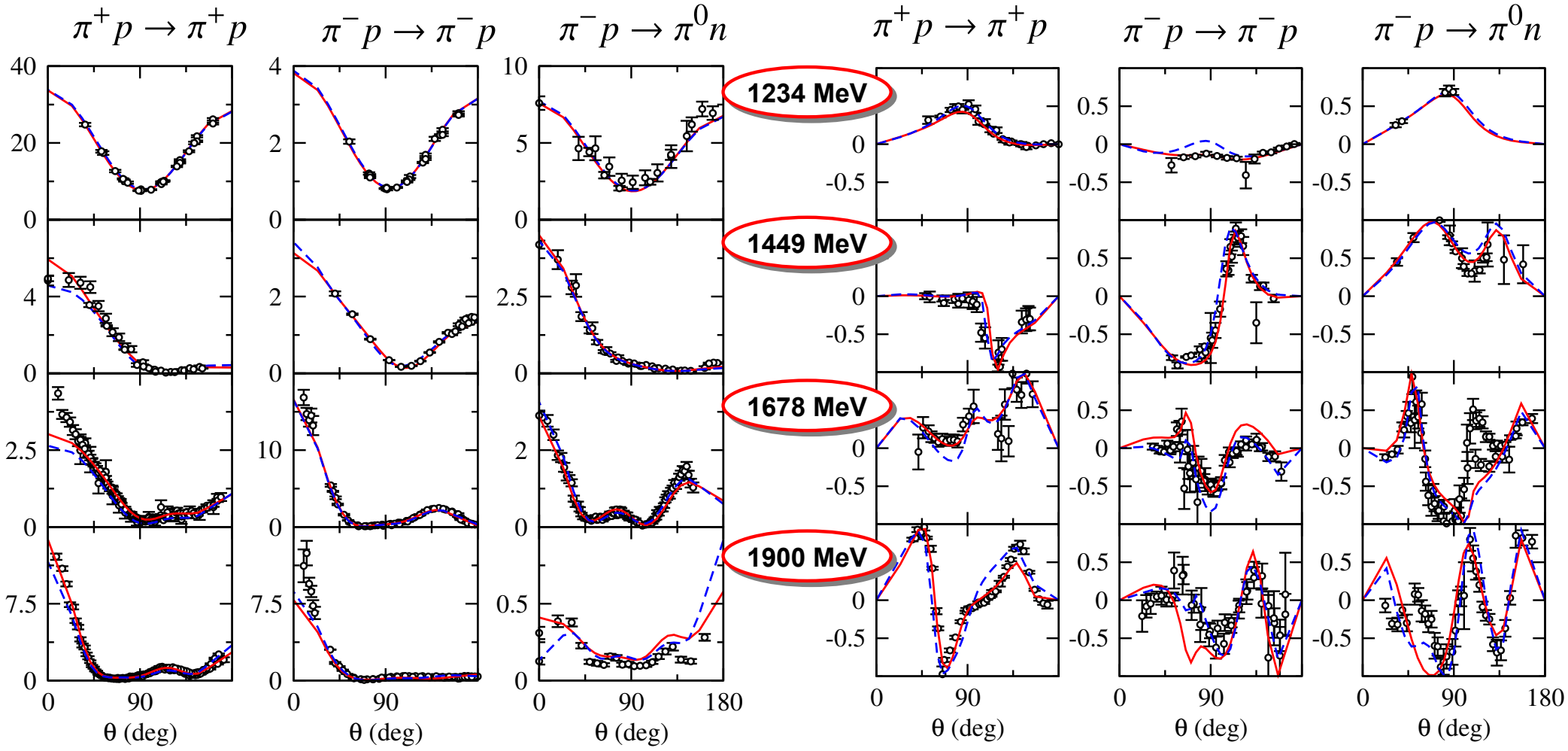
Full-combined **analysis of γN , $\pi N \rightarrow \pi N$, ηN , KY reactions !!**

	2006 ~ 2009	2010 ~
✓ # of coupled channels	5 channels ($\pi N, \eta N, \pi\Delta, \rho N, \sigma N$)	7 channels ($\pi N, \eta N, \pi\Delta, \rho N, \sigma N, K\Lambda, K\Sigma$)
✓ $\pi N \rightarrow \pi N$	< 2 GeV	< 2 GeV
✓ $\gamma N \rightarrow \pi N$	< 1.6 GeV	< 2 GeV
✓ $\pi N \rightarrow \eta N$	< 2 GeV	< 2 GeV
✓ $\gamma N \rightarrow \eta N$	—	< 2GeV
✓ $\pi N \rightarrow KY$	—	< 2.1 GeV
✓ $\gamma N \rightarrow K\Lambda$	—	< 2.1 GeV

Pion-nucleon elastic scattering

Angular distribution $d\sigma/d\Omega$ (mb/sr)

Target polarization



Current model
(**full combined** analysis, ***PRELIMINARY***)

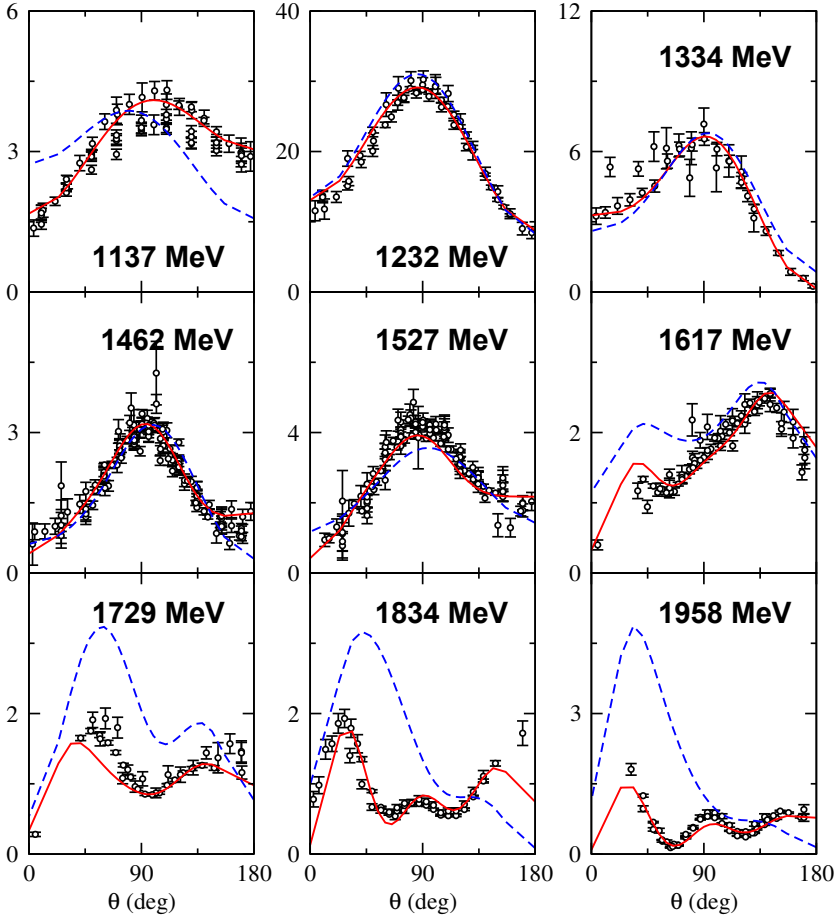
Previous model (fitted to πN → πN data only)
[PRC76 065201 (2007)]

Single pion photoproduction

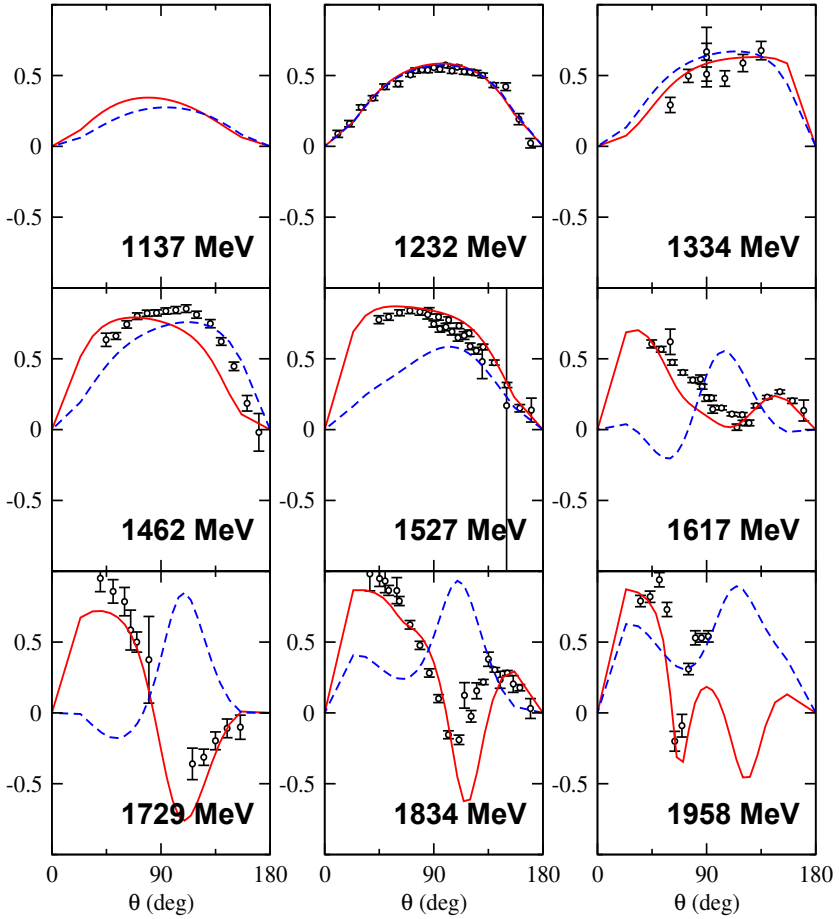
$\gamma p \rightarrow \pi^0 p$

Preliminary!!

Angular distribution $d\sigma/d\Omega$ (μb/sr)



Photon asymmetry Σ



Current model (full combined analysis, *preliminary*)

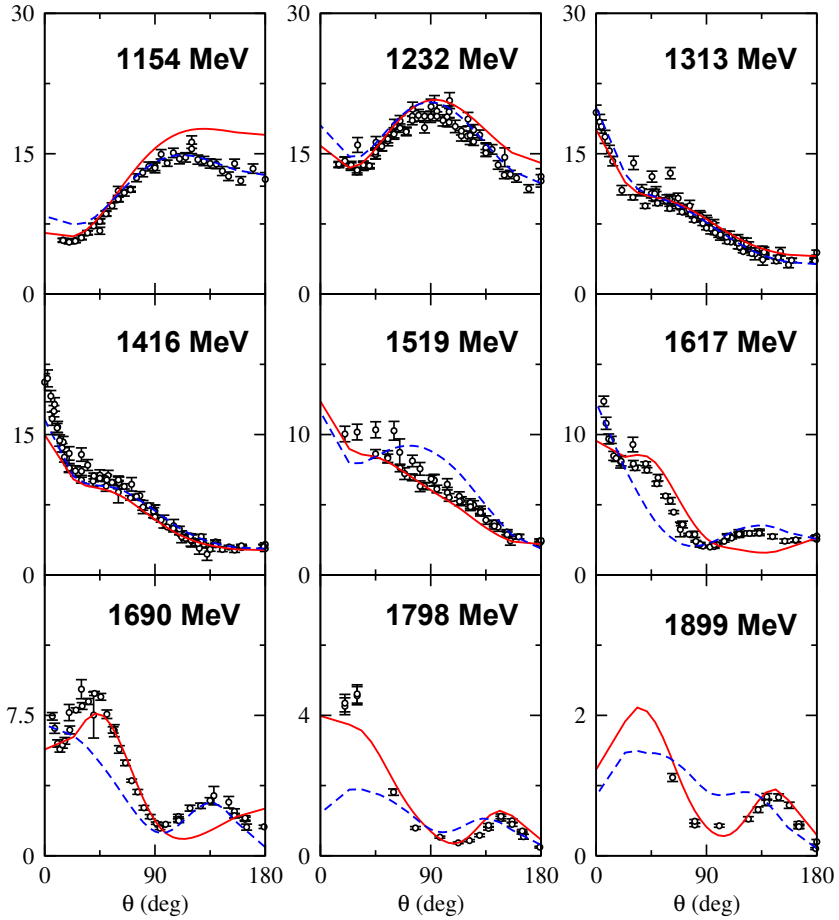
Previous model (fitted to γN → πN data *up to 1.6 GeV*) [PRC77 045205 (2008)]

Single pion photoproduction

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

Preliminary!!

Angular distribution $d\sigma/d\Omega$ (μb/sr)



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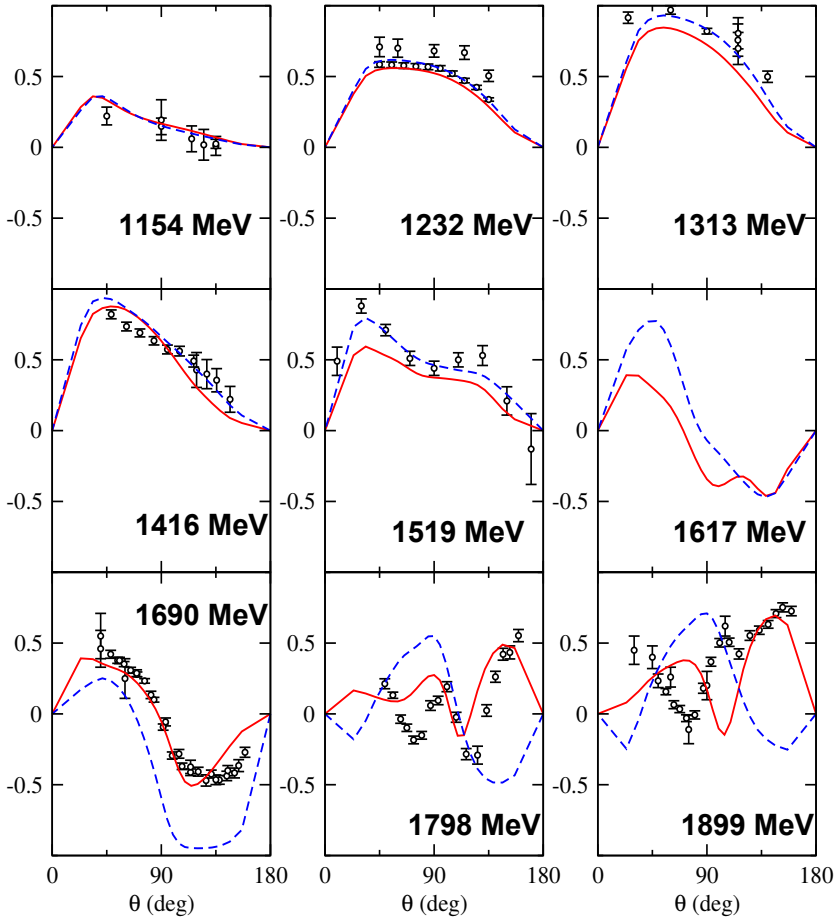


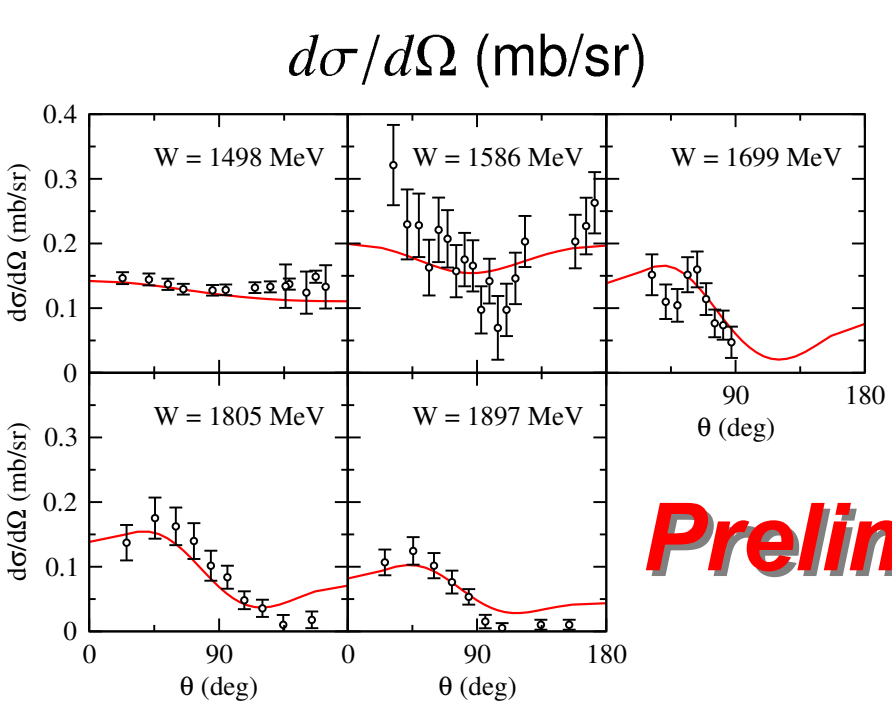
Current model (full combined analysis, *preliminary*)

Previous model (fitted to γN → πN data *up to 1.6 GeV*) [PRC77 045205 (2008)]

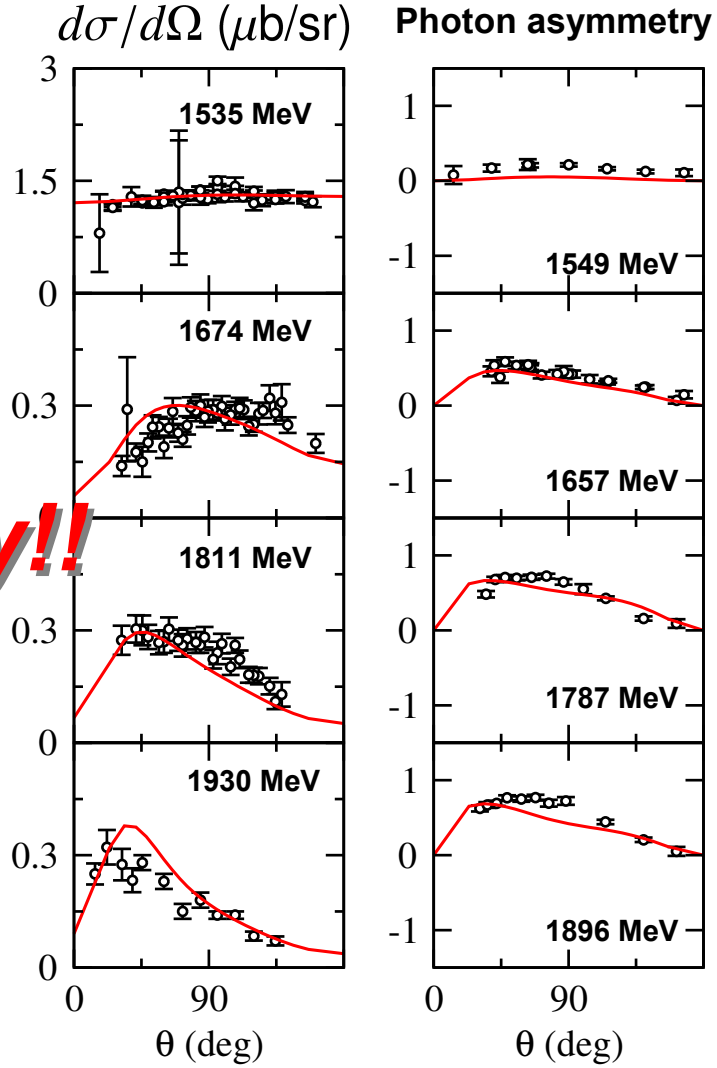
Eta production reactions

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

$\gamma p \rightarrow \eta p$



Preliminary!!

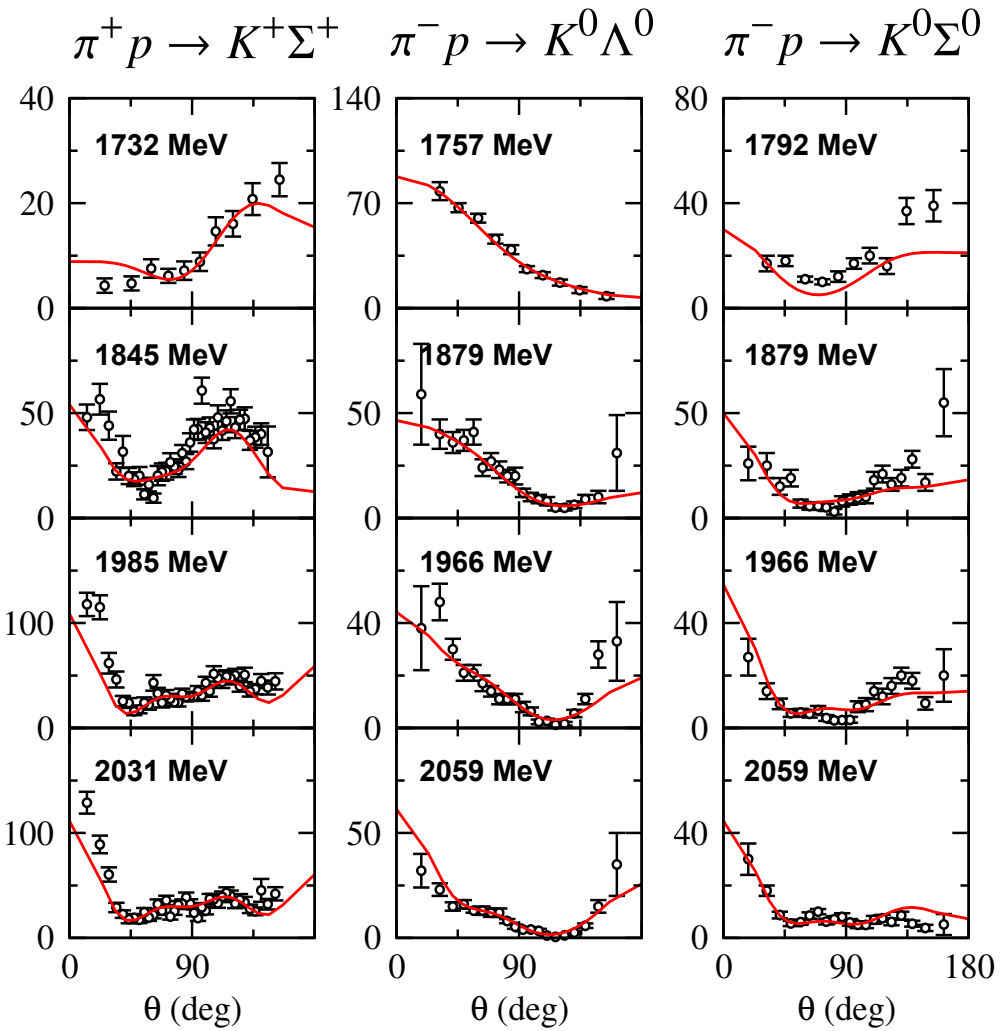


- ✓ **Analyzed data up to W = 2 GeV.**
- ✓ **π^- p → η n data are selected following Durand et al. PRC78 025204.**

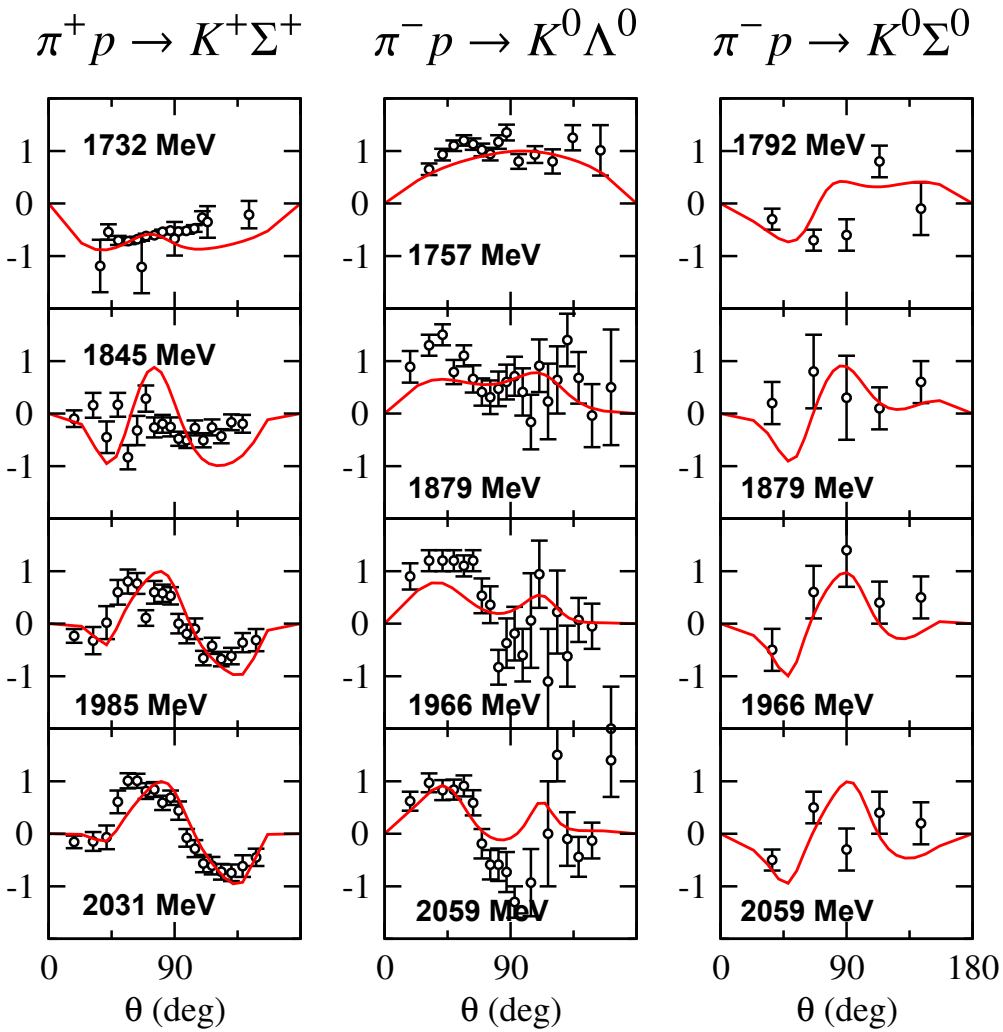
pi N → KY reactions

Preliminary!!

Angular distribution $d\sigma/d\Omega$ (μb/sr)



Recoil polarization



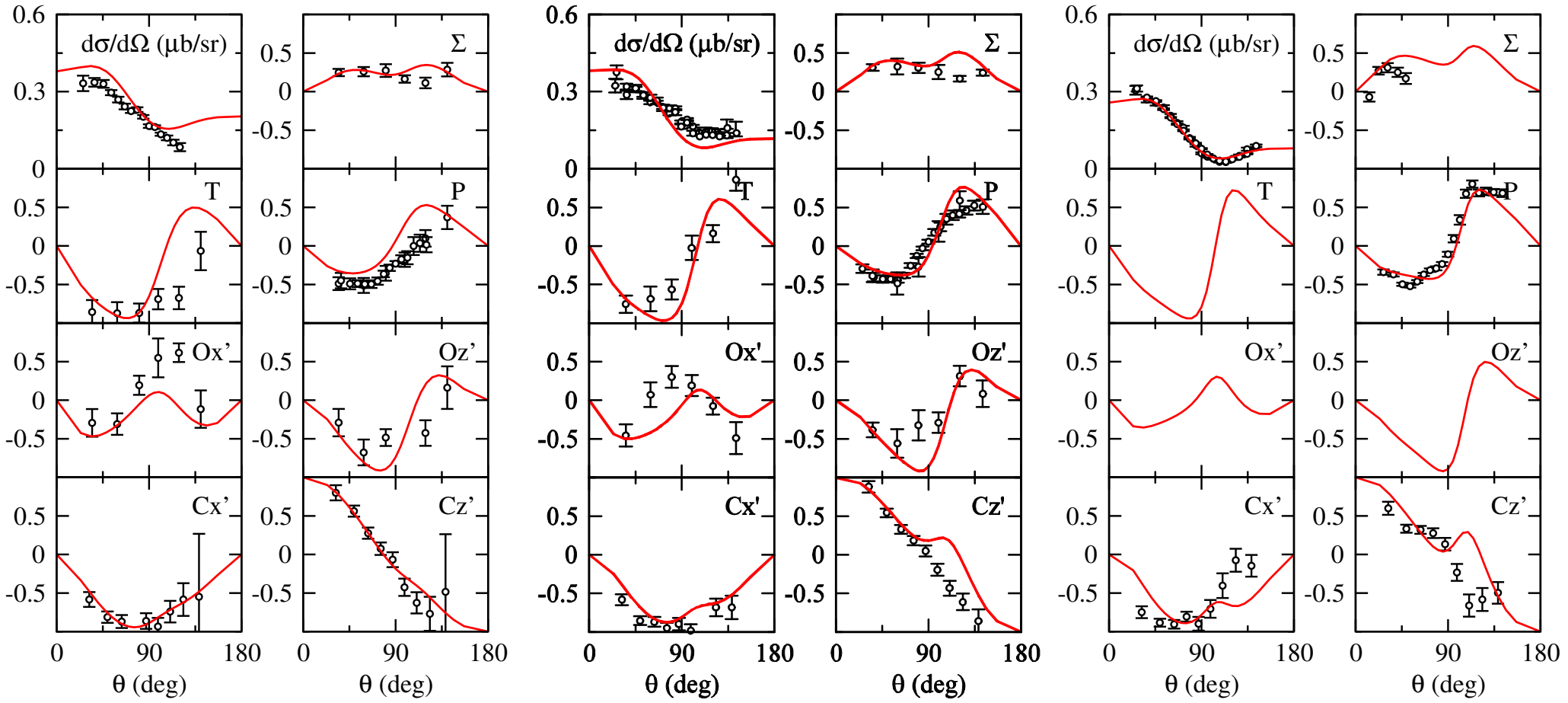
gamma p → K+ Lambda

Preliminary!!

Formulae for calculating polarization observables

→ **Sandorfi, Hoblit, Kamano, Lee arXiv:1010.0455**

1781 MeV **1883 MeV** **2041 MeV**



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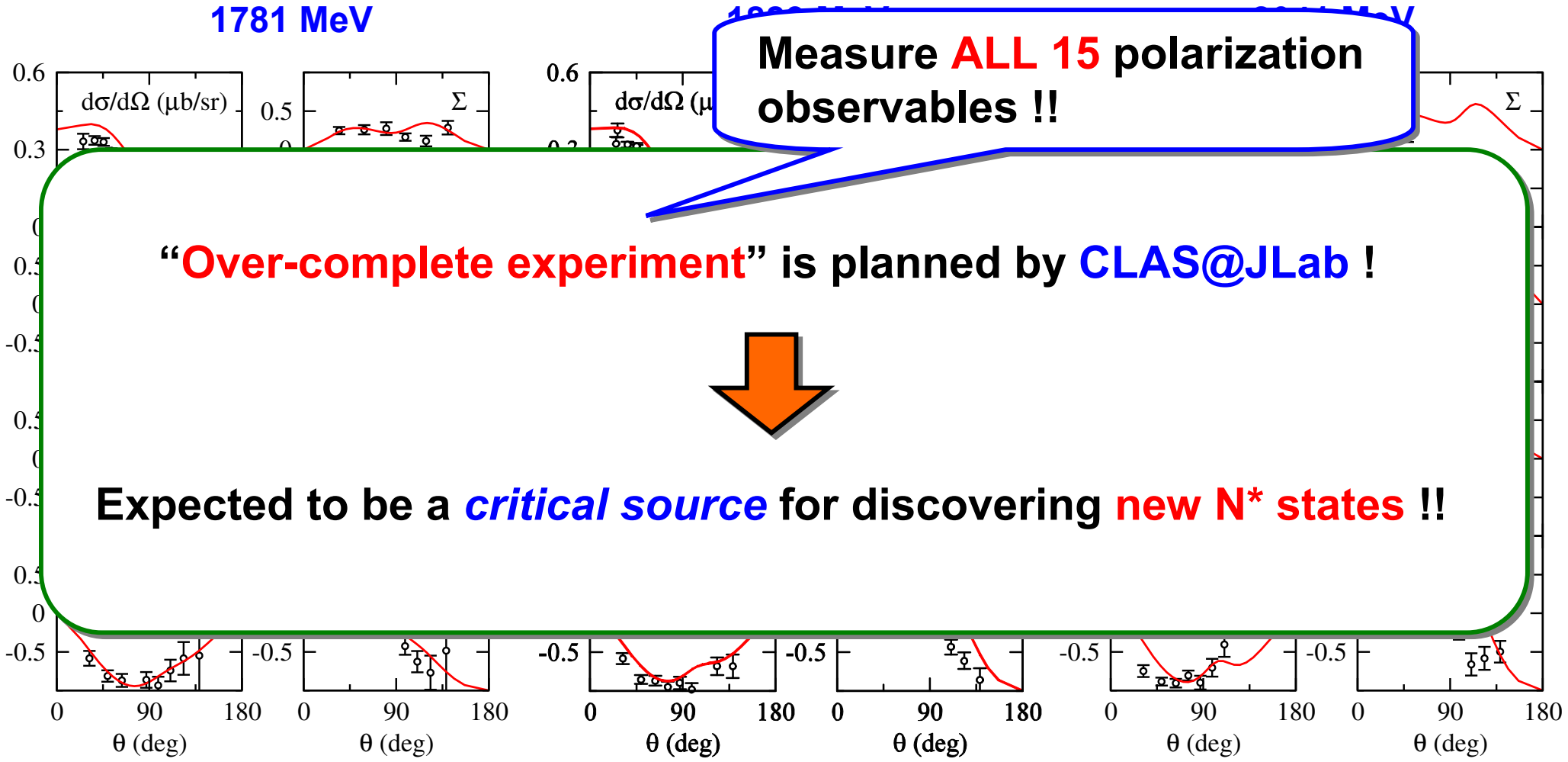


Measure ALL 15 polarization observables !!

"Over-complete experiment" is planned by CLAS@JLab !

Expected to be a *critical source* for discovering new N* states !!

Summary and outlook

✓ **Full-combined analysis of πN, $\gamma N \rightarrow \pi N$, ηN, KY reactions is underway.**

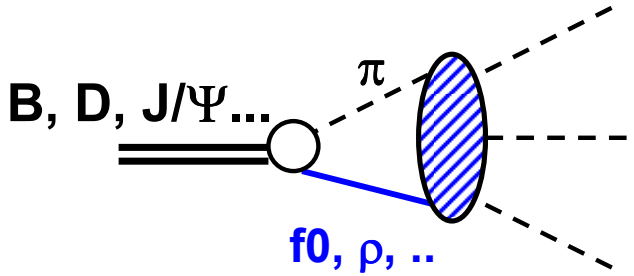
- Re-examine resonance poles

Previous model: $Q^2 < 1.5\ GeV^2$

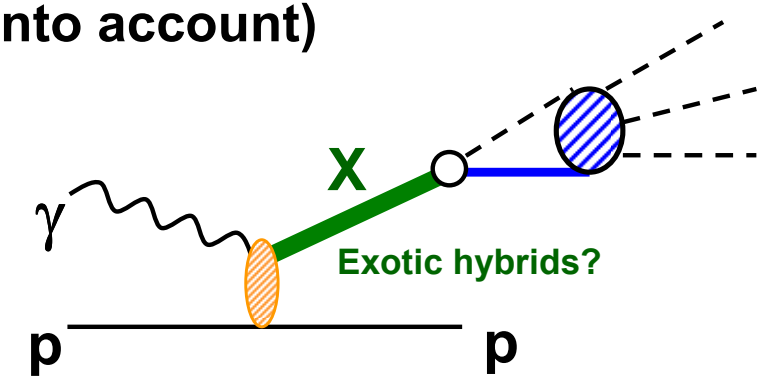
- Analyze CLAS $ep \rightarrow e\pi N$ data with $Q^2 < 6\ GeV^2$; extract N-N* e.m. transition f.f.s
- Include πN, $\gamma N \rightarrow \pi\pi N$, ωN, … reactions to the combined analysis.

New direction (Presented by S. Nakamura at SP01 session)

✓ **Application of the EBAC-DCC approach to meson physics:**
(3-body unitarity effects are fully taken into account)



Heavy meson decays



GlueX experiment @ Hall D of JLab

Back up

N* states and PDG *s

Particle	$L_{2I,2J}$	status	$N\pi$	$N\eta$				
$N(939)$	P_{11}	****						
$N(1440)$	P_{11}	****	****	*				
$N(1520)$	D_{13}	****	****	***				
$N(1535)$	S_{11}	****	****	****				
$N(1650)$	S_{11}	****	****	*	***	**		
$N(1675)$	D_{15}	****	****	*	*		****	
$N(1680)$	F_{15}	****	****	*			**	****
$N(1700)$	D_{13}	***	***	*	**	*	**	
$N(1710)$	P_{11}	***	***	**	**	*	**	
$N(1720)$	P_{13}	****	****	*	**	*	*	
$N(1900)$	P_{13}	**	**					
$N(1990)$	F_{17}	**	**	*	*	*		
$\Delta(1232)$	P_{33}	****	****	F				
$\Delta(1600)$	P_{33}	***	***	o			***	
$\Delta(1620)$	S_{31}	****	****	r			****	
$\Delta(1700)$	D_{33}	****	****	b		*	***	
$\Delta(1750)$	P_{31}	*	*					
$\Delta(1900)$	S_{31}	**	**	d		*	*	
$\Delta(1905)$	F_{35}	****	****	d		*	**	
$\Delta(1910)$	P_{31}	****	****	e		*	*	
$\Delta(1920)$	P_{33}	***	***	n		*	**	
$\Delta(1930)$	D_{35}	***	***			*		
$\Delta(1940)$	D_{33}	*	*	F				
$\Delta(1950)$	F_{37}	****	****	o		*	****	

All of these studies essentially agree on the existence and (most) properties of the 4-star states. For the 3-star and lower states, however, even a statement of existence is problematic.

— **Arndt, Briscoe, Strakovsky, Workman PRC 74 045205 (2006)**

Most of the N*s were extracted from

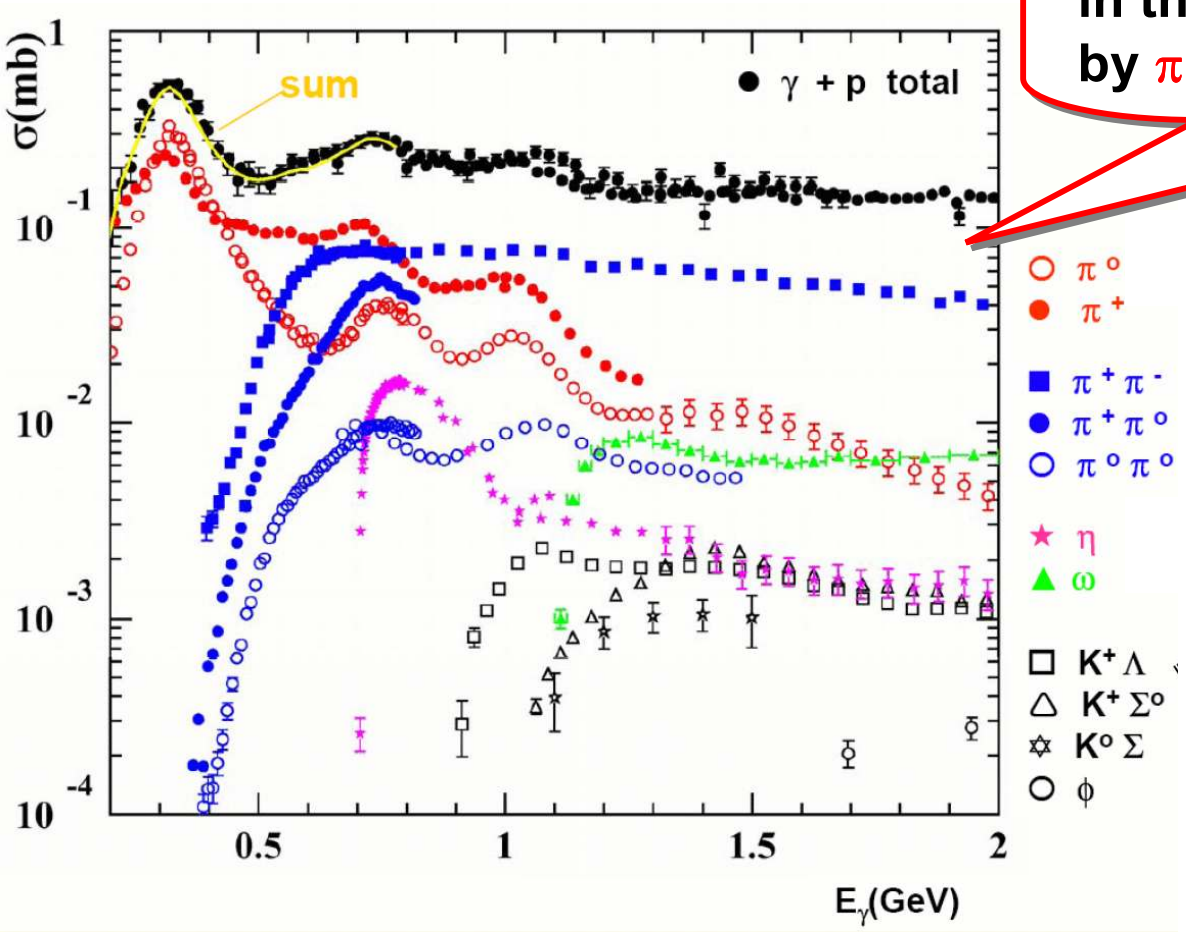
$$\pi N \to \pi N\ ,\quad \gamma N \to \pi N$$

Need *comprehensive analysis* of

$$\pi N,\ \eta N,\ \pi\pi N,\ KY,\ \omega N, \ldots$$

channels !!

“Priority” of coupled-channels effect



γN (also πN) reaction cross sections in the resonance region are dominated by πN and ππN final states.

At least, the couplings of πN and ππN channels should be taken into account in the analyses of any γN (πN) → MB reactions.

Figure: E. Pasyuk’s talk at Hall-B/EBAC meeting

"Complete Experiment" of pseudoscalar meson photoproduction reactions

"Complete Experiment" = Measure ALL polarization observables needed to determine amplitudes up to overall phase

unpolarized diff. crs. sec.

$\rightarrow \quad d\sigma/d\Omega$

single spin

$\rightarrow \quad P, \ \Sigma, \ T$

beam-target

$\rightarrow \quad E, \ F, \ G, \ H$

beam-recoil

$\rightarrow \quad C_{x'}, \ C_{z'}, \ O_{x'}, \ O_{z'}$

target-recoil

$\rightarrow \quad T_{x'}, \ T_{z'}, \ L_{x'}, \ L_{z'}$

8 /16 observables needed!
Chiang, Tabakin PRC55 2054 (1997)

- ✓ **Measurement of γN → KY pol. obs. is very active.**
- ✓ **OVER-complete experiments planned by CLAS for γ p → K⁺ Λ, γ n → KY.**

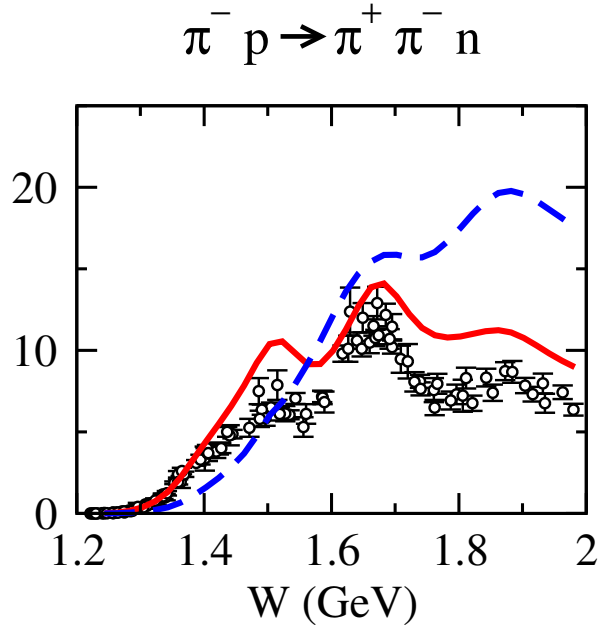
Provides critical information on N* → KY decays !!
Much room for new N* state searches

pi N → pi pi N reaction

Kamano, Julia-Diaz, Lee, Matsuyama, Sato, PRC79 025206 (2009)

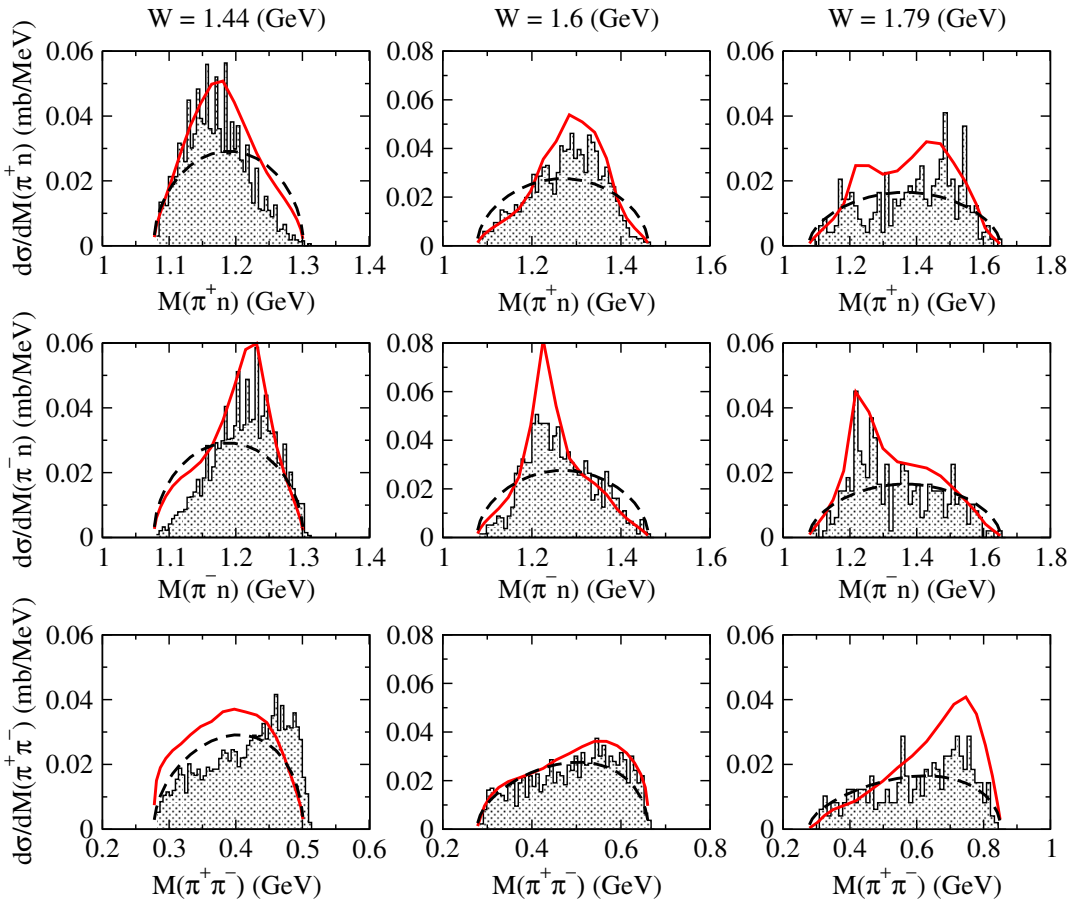
Parameters used in the calculation are from πN → πN analysis.

$$\pi^- p \longrightarrow \pi^+ \pi^- n$$



Full result

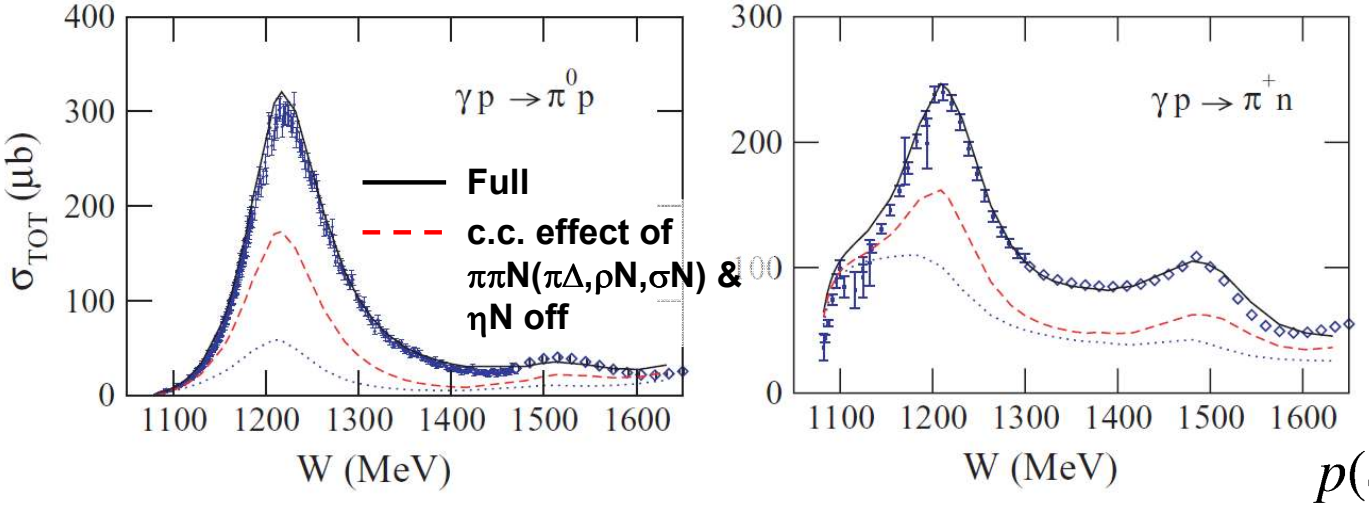
C.C. effect off



Full result **Phase space**

Data handled with the help of R. Arndt

EBAC-DCC analysis (2006-2009)



Coupled-channels effect in various reactions