Dynamical coupled-channels analysis of meson production reactions at EBAC@JLab

Hiroyuki Kamano
(Excited Baryon Analysis Center, Jefferson Lab)

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

PDG *s and N*'s origin

Particle	$L_{2I\cdot 2J}$	status	$N\pi$	$N\eta$	ΛK				
$N(939)$	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)**

PDG *s and N*'s origin

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$N(1680)$	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					****
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$\Delta(1920)$	P_{33}	***	***	n		*	**		*
$\Delta(1930)$	D_{35}	***	***			*			**
$\Delta(1940)$	D_{33}	*	*	F					
$\Delta(1950)$	F_{37}	****	****	o		*	****	*	****

- ✓ **Most of their properties were extracted from**

$$\pi N \to \pi N$$

$$\gamma N \to \pi N$$

Need consistent analysis of πN and $\pi\pi N$ channels

PDG *s and N*'s origin

Particle	$L_{2I\cdot 2J}$	status	$N\pi$	$N\eta$	ΛK	ΣK	$\Delta\pi$	$N\rho$	$N\gamma$
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$\Delta(1920)$	P_{33}	***	***	n		*	**		*
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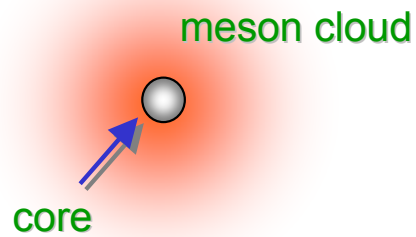
- ✓ **Most of their properties were extracted from**

$$\pi N \to \pi N$$

$$\gamma N \to \pi N$$

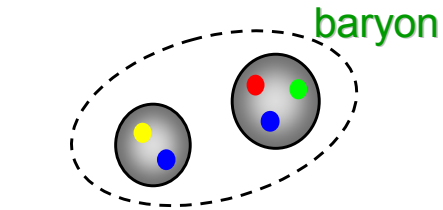
- ✓ **Are they all genuine quark/gluon excitations (with meson cloud) ?**

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



- ✓ **Is their origin dynamical ?**
  - → **some could be understood as arising from meson-baryon dynamics**

$$|N^*\rangle = |MB\rangle$$



Data change N* structure study

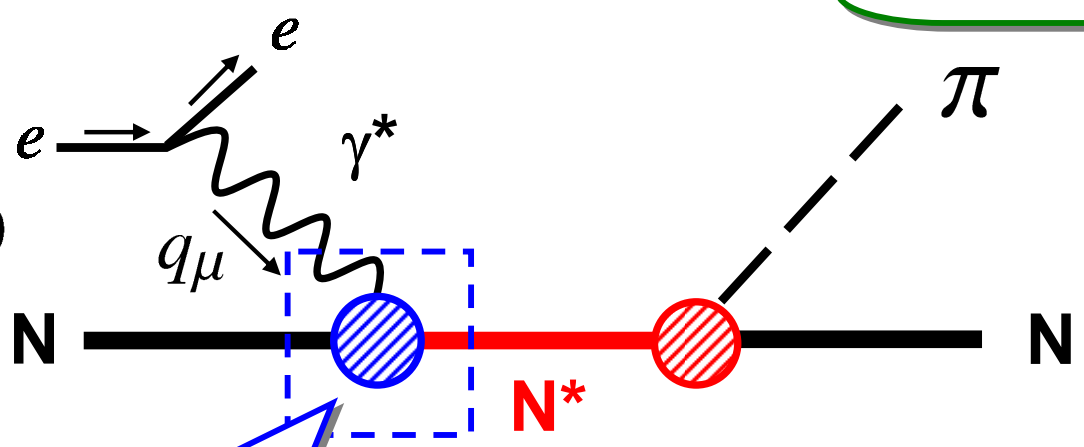
Recent high precision data of meson photo- and electro-production reactions open a great opportunity of making *quantitative* study of the N* structure.

JLab, Bonn, GRAAL, Mainz, SPring-8, …

e.g.) single pion electroproduction reactions

$$Q^2 \equiv -q^2 > 0$$

Corresponds to beam resolution

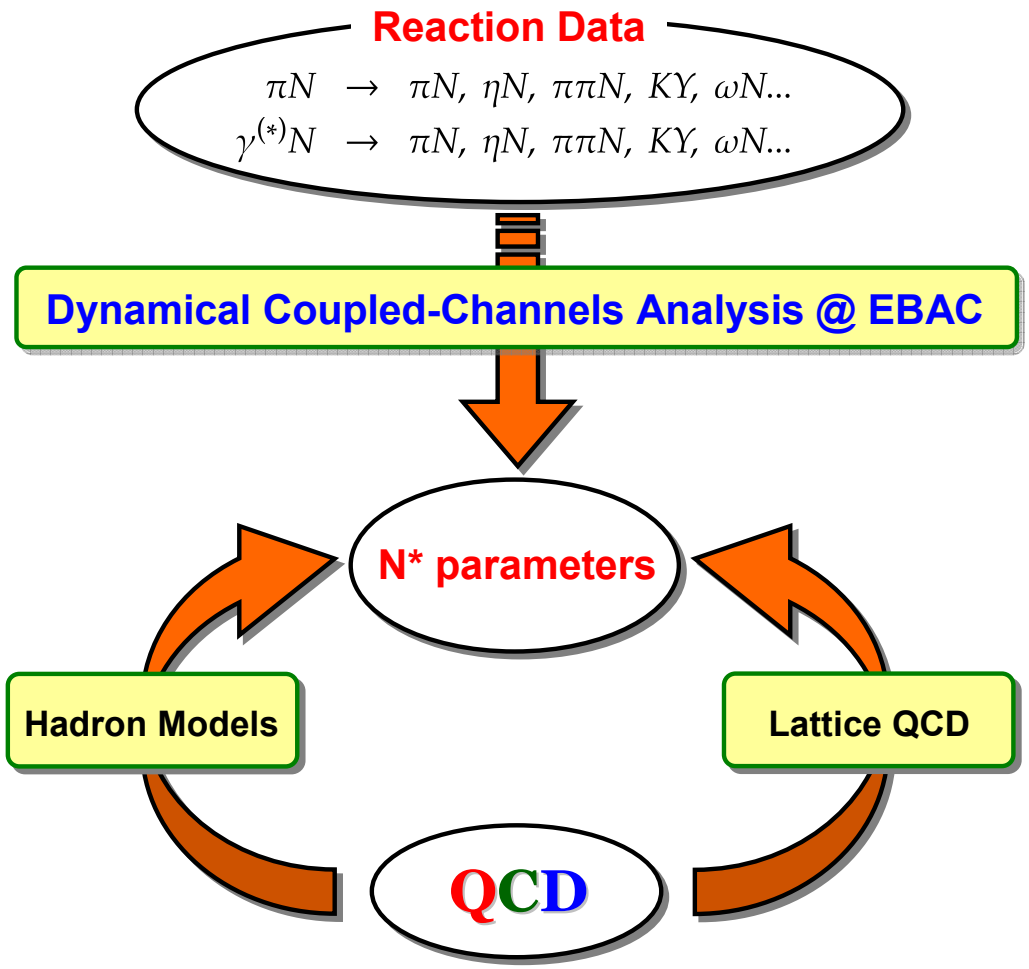


N-N* e.m. transition form factors

Excited Baryon Analysis Center @ Jefferson Lab

Founded in January 2006

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



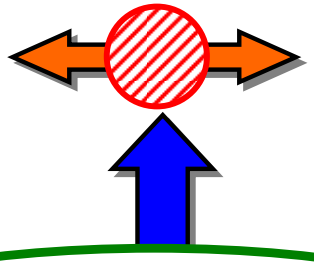
Objectives and goals:

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

- ✓ Determine N* spectrum (masses, widths)
- ✓ Extract N* form factors, in particular the N-N* electromagnetic transition form factors
- ✓ Develop a method to connect with hadron structure calculations and deduce the structure of N* states

Dynamical coupled-channels model @ EBAC

N* spectrum, structure, …



Meson production data

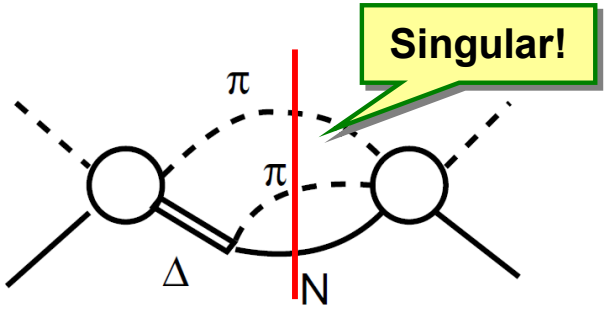
Reaction mechanism

Dynamical coupled-channels model of meson production reactions

A. Matsuyama, T. Sato, T.-S.H. Lee Phys. Rep. 439 (2007) 193

✓ Maintain coupled-channels unitarity of $\pi N,\ \eta N,\ \pi\pi N\ (\ni \pi\Delta,\ \sigma N,\ \rho N)$

✓ Can treat $\pi\pi N$ 3-body unitary cut



Dynamical coupled-channels model @ EBAC

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

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

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

- ✓ **Reaction channels:**

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

- ✓ **Potential:**

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

meson exchange

bare N* state

Impose minimal number of bare N* state: at present 16 of 18 (= # of 3* and 4* N*s below 2 GeV)

Dynamical coupled-channels model @ EBAC

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

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

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

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

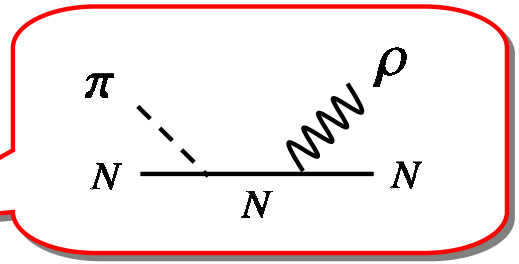
$$\bar{V}_c^7 = \frac{f_{\pi NN}}{m_\pi} g_{\rho\pi\pi} \epsilon_{ijl} \tau^l \frac{(q-k)\cdot \epsilon^*_{\rho'} \not{q} \gamma_5}{q^2 - m_\pi^2},$$

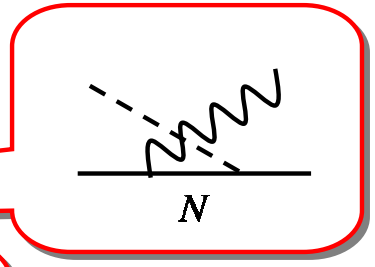
$$\bar{V}_d^7 = -\frac{f_{\pi NN}}{m_\pi} g_{\rho NN} \not{\epsilon}^*_{\rho'} \gamma_5 \epsilon_{jil} \tau^l,$$

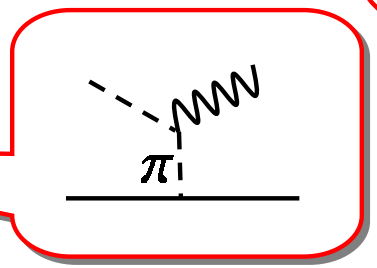
$$\bar{V}_e^7 = \frac{g_{\omega NN} g_{\omega\pi\rho}}{m_\omega} \delta_{ij} \frac{\epsilon_{\alpha\beta\gamma\delta} \epsilon^{*\alpha}_{\rho'} k'^\beta k^\gamma}{q^2 - m_\omega^2} \left[\gamma^\delta + \frac{\kappa_\omega}{4m_N} (\gamma^\delta \not{q} - \not{q} \gamma^\delta) \right],$$

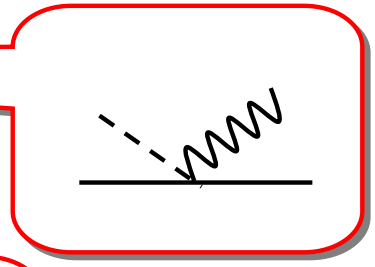
where

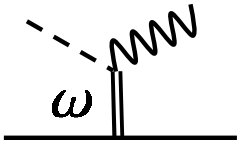
$$\Gamma_{\rho'} = \frac{\tau^j}{2} \left[\not{\epsilon}^*_{\rho'} + \frac{\kappa_\rho}{4m_N} (\not{\epsilon}^*_{\rho'} \not{k}' - \not{k}' \not{\epsilon}^*_{\rho'}) \right].$$



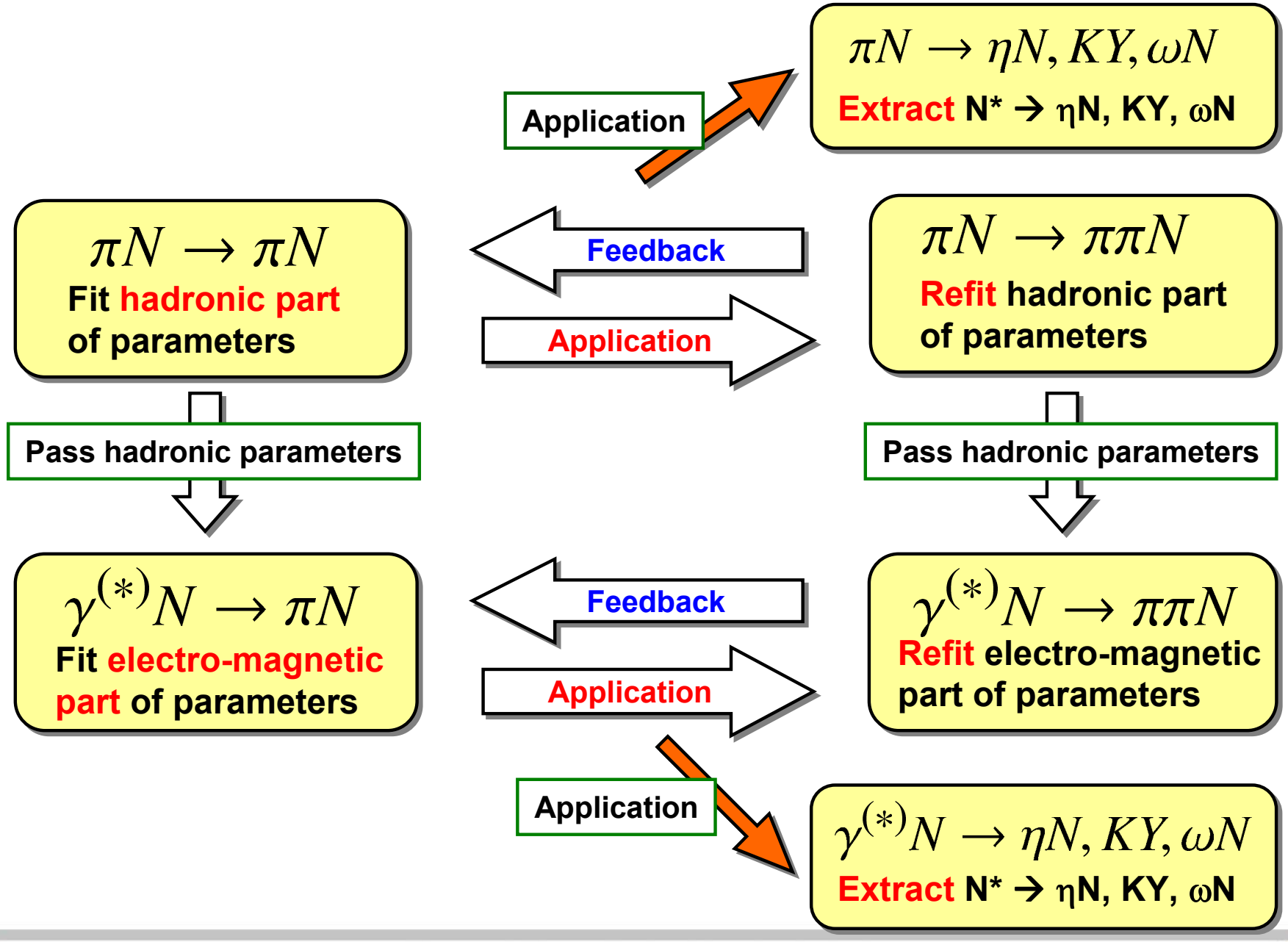








Strategy for N* study @ EBAC



Strategy for N* study @ EBAC

Extraction of N* poles and N* → MB decay vertices

$\pi N \rightarrow \pi N$
Fit hadronic part of parameters

$\pi N \rightarrow \pi\pi N$
Refit hadronic part of parameters

$\gamma^{(*)} N \rightarrow \pi N$
Fit electro-magnetic part of parameters

$\gamma^{(*)} N \rightarrow \pi\pi N$
Refit electro-magnetic part of parameters

Extraction of N-N* ele.-mag. transition form factors

Strategy for N* study @ EBAC

Extraction of N* poles and N* → MB decay vertices

$\pi N \to \pi N$
Fit hadronic part of parameters

$\pi N \to \pi\pi N$
Refit hadronic part of parameters

Develop a method to connect our f.f.s with hadron structure calculations

$\gamma^{(*)} N \to \pi N$
Fit electro-magnetic part of parameters

$\gamma^{(*)} N \to \pi\pi N$
Refit electro-magnetic part of parameters

Extraction of N-N* ele.-mag. transition form factors

Current status of the EBAC-DCC analysis

Hadronic part

- ✓ $\pi N \rightarrow \pi N$: fitted to the SAID PWA up to W = 2 GeV.
  Julia-Diaz, Lee, Matsuyama, Sato, PRC76 065201 (2007)
- ✓ $\pi N \rightarrow \pi \pi N$: cross sections calculated with the πN model; fit is ongoing.
  Kamano, Julia-Diaz, Lee, Matsuyama, Sato, PRC79 025206 (2009)
- ✓ $\pi N \rightarrow \eta N$: fitted to the data up to W = 2 GeV
  Durand, Julia-Diaz, Lee, Saghai, Sato, PRC78 025204 (2008)

Electromagnetic part

- ✓ $\gamma^{(*)} N \rightarrow \pi N$: fitted to the data up to W = 1.6 GeV (and up to 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)
- ✓ $\gamma N \rightarrow \pi \pi N$: cross sections calculated with the γN & πN model; fit is ongoing.
  Kamano, Julia-Diaz, Lee, Matsuyama, Sato, arXiv:0909.1129 [nucl-th]
- ✓ $\gamma^{(*)} N \rightarrow \eta N$: *in progress*
- ✓ $\gamma N \rightarrow K \Lambda$: *in progress*

Current status of the EBAC-DCC analysis

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  (electroproduction) Julia-Diaz, Kamano, Lee, Matsuyama, Sato, Suzuki, PRC80 025207 (2009)
- ✓ $\gamma N \rightarrow \pi \pi N$: cross section
  Kaman
- ✓ $\gamma^{(*)} N \rightarrow \eta N$: *in progress*
- ✓ $\gamma N \rightarrow K \Lambda$: *in progress*

"Complete Experiment" is planned by CLAS.
→ Collaborated project on $\gamma p \rightarrow K^+\Lambda$ with A. Sandorfi (CLAS) and S. Hoblit (BNL) is in progress.

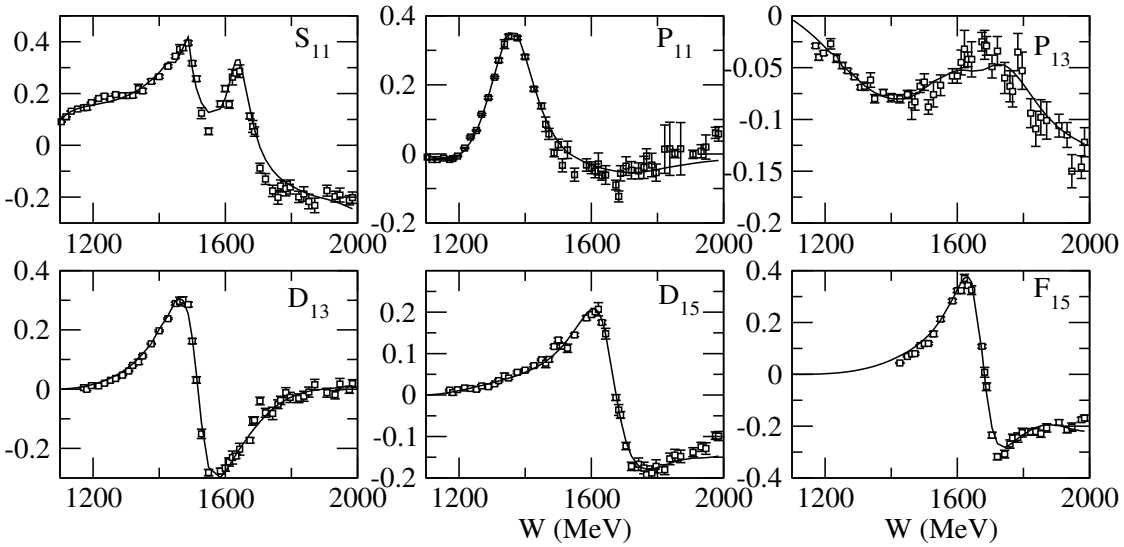
Pion-induced hadronic reactions

1. $\pi N \rightarrow \pi N$ **scattering**
2. $\pi N \rightarrow \pi\pi N$ **reaction**
3. $\pi N \rightarrow \eta N$ **reaction**

1. Pion-nucleon elastic scattering

Julia-Diaz, Lee, Matsuyama, Sato, PRC76 065201 (2007)

- ✓ $MB = \pi N,\ \eta N,\ \pi\pi N\ (\ni \pi\Delta,\ \sigma N,\ \rho N)$ **coupled-channels is considered.**
- ✓ **Fitted to the SAID πN partial wave amplitudes up to 2 GeV.**
- ✓ **MINUIT library is employed for the numerical minimization.**



Re(T) with I = 1/2

1. Pion-nucleon elastic scattering

Julia-Diaz, Lee, Matsuyama, Sato, PRC76 065201 (2007)

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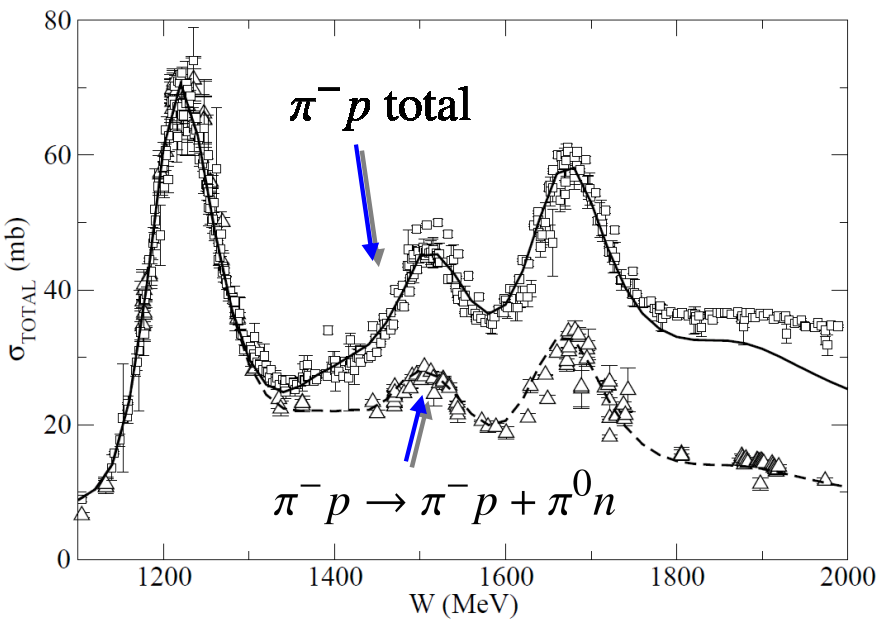
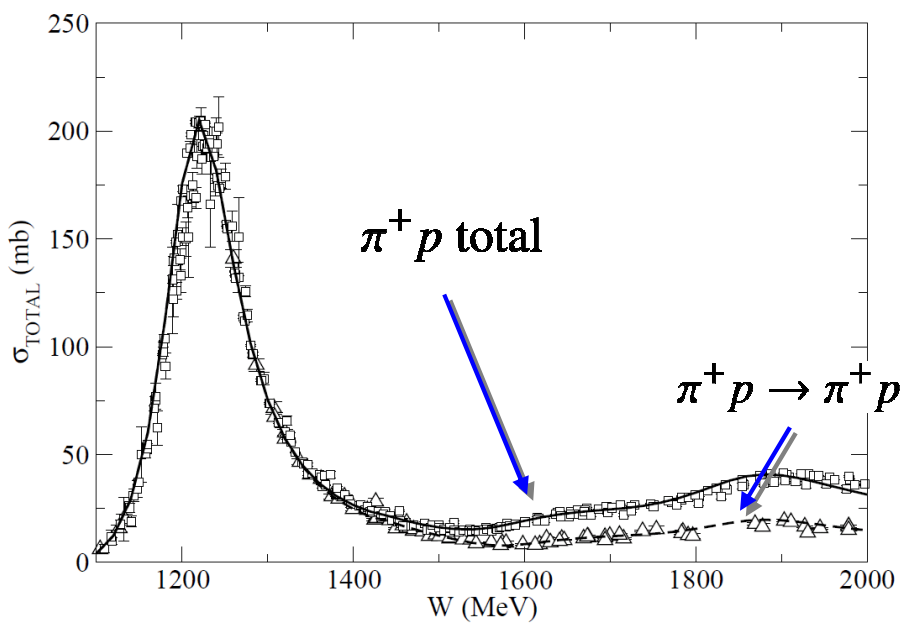
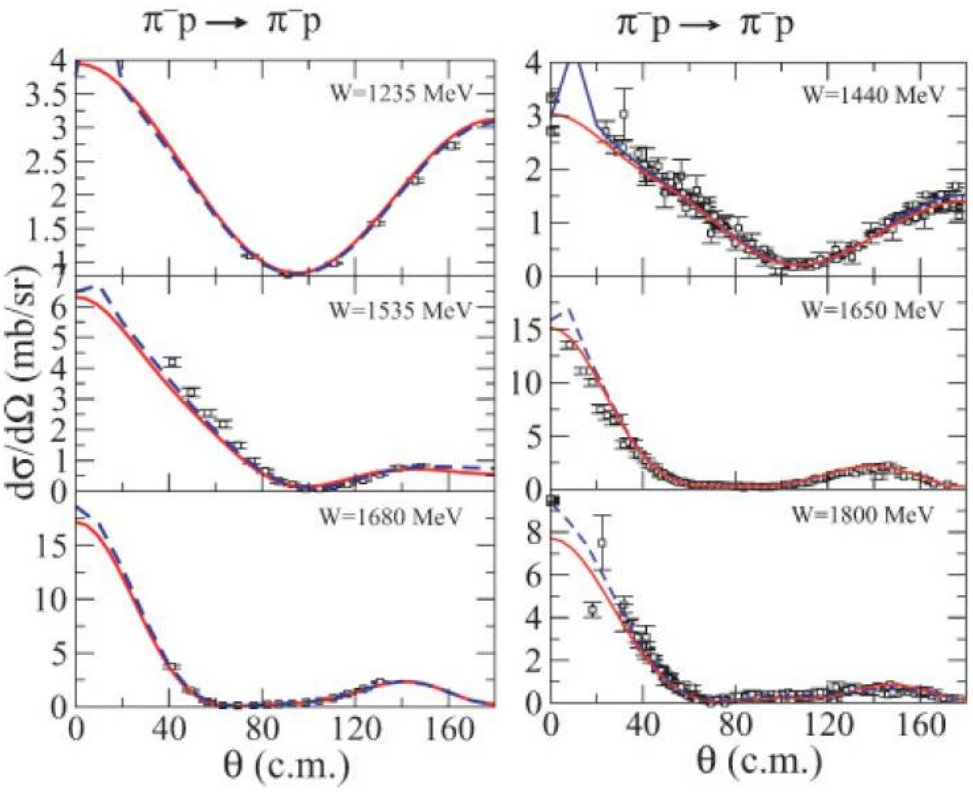




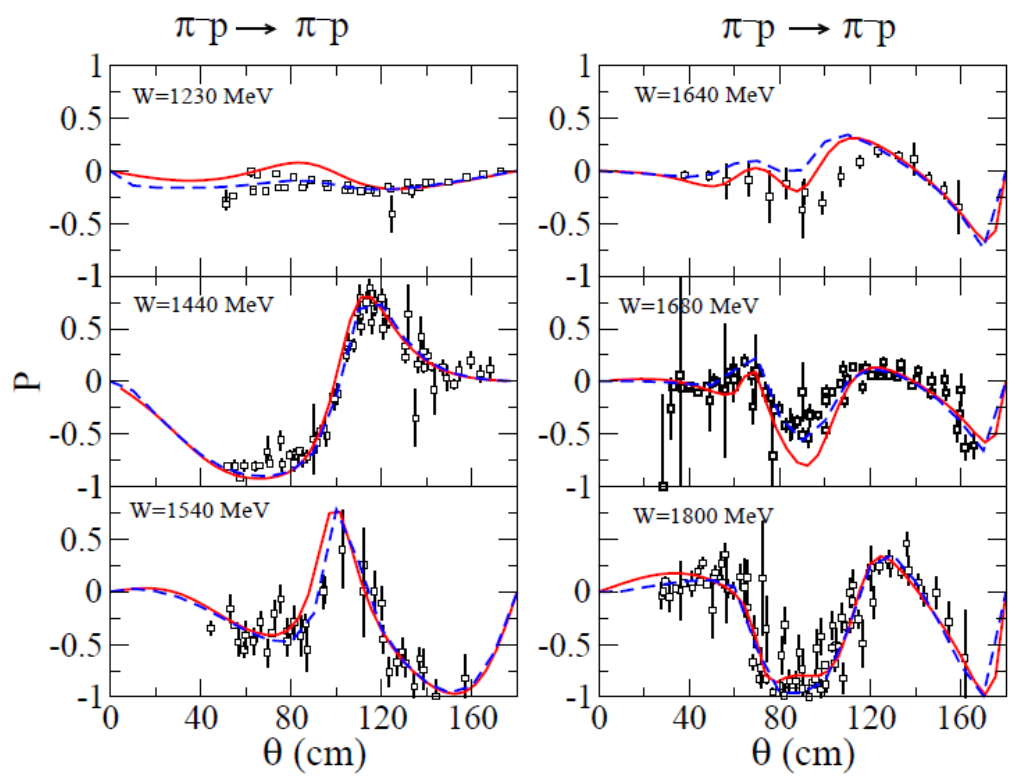
1. Pion-nucleon elastic scattering

Julia-Diaz, Lee, Matsuyama, Sato, PRC76 065201 (2007)

Angular distribution



Target polarization



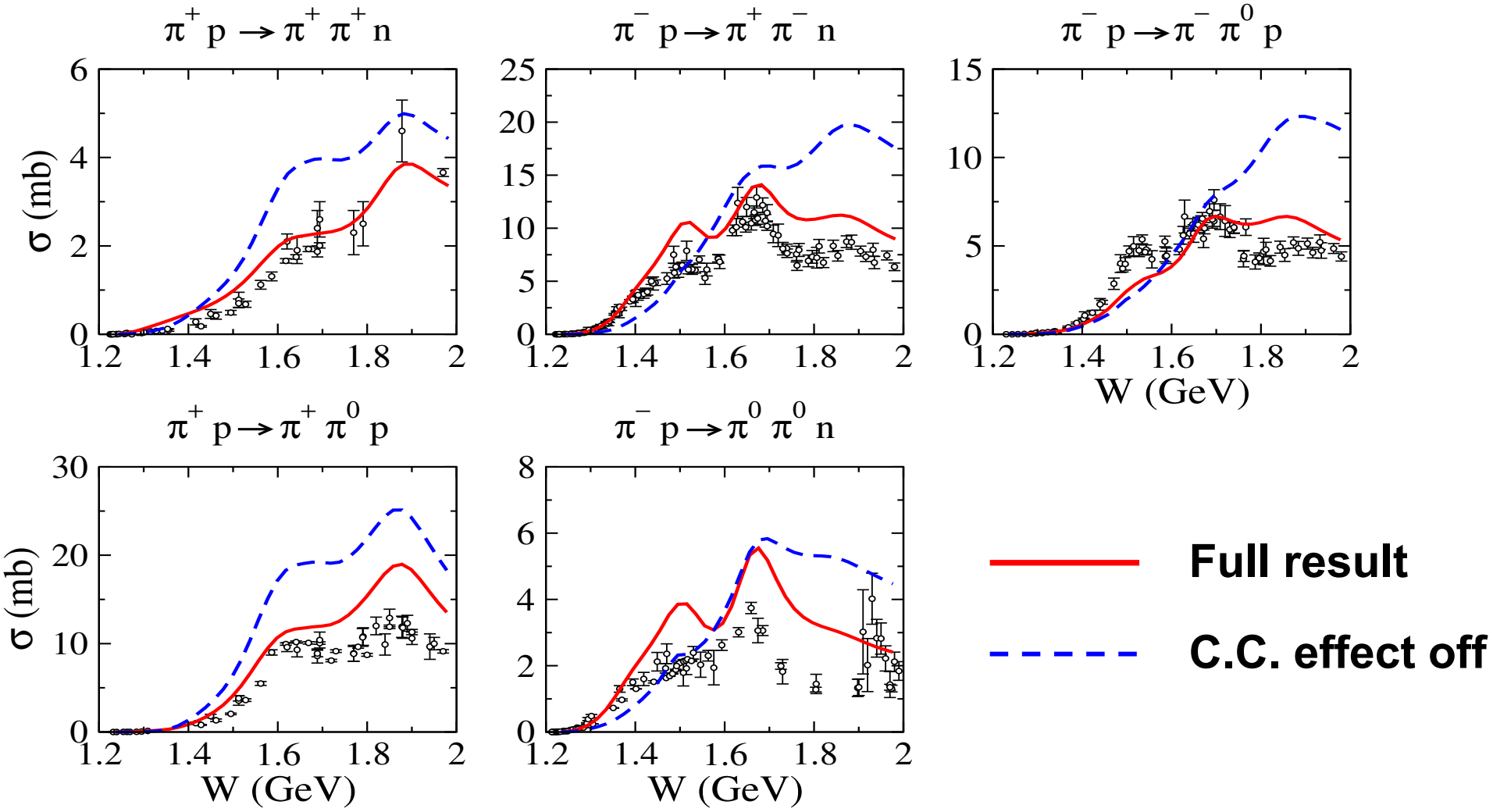
EBAC

SAID06

2. 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.



2. pi N → pi pi N reaction

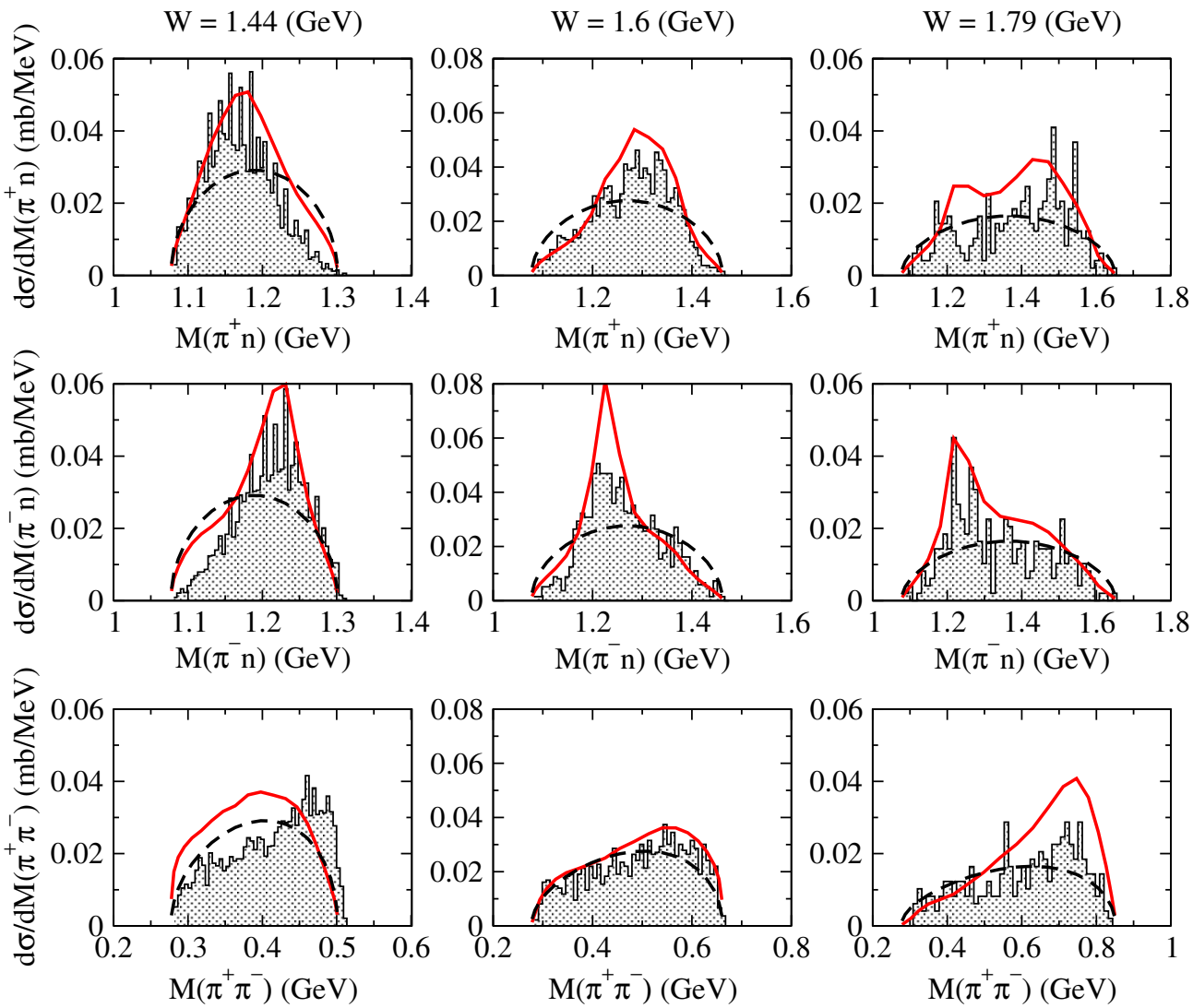
$$\pi^- p \rightarrow \pi^+ \pi^- n$$

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

Invariant mass distributions

Full result

Phase space



Data handled with the help of R. Arndt

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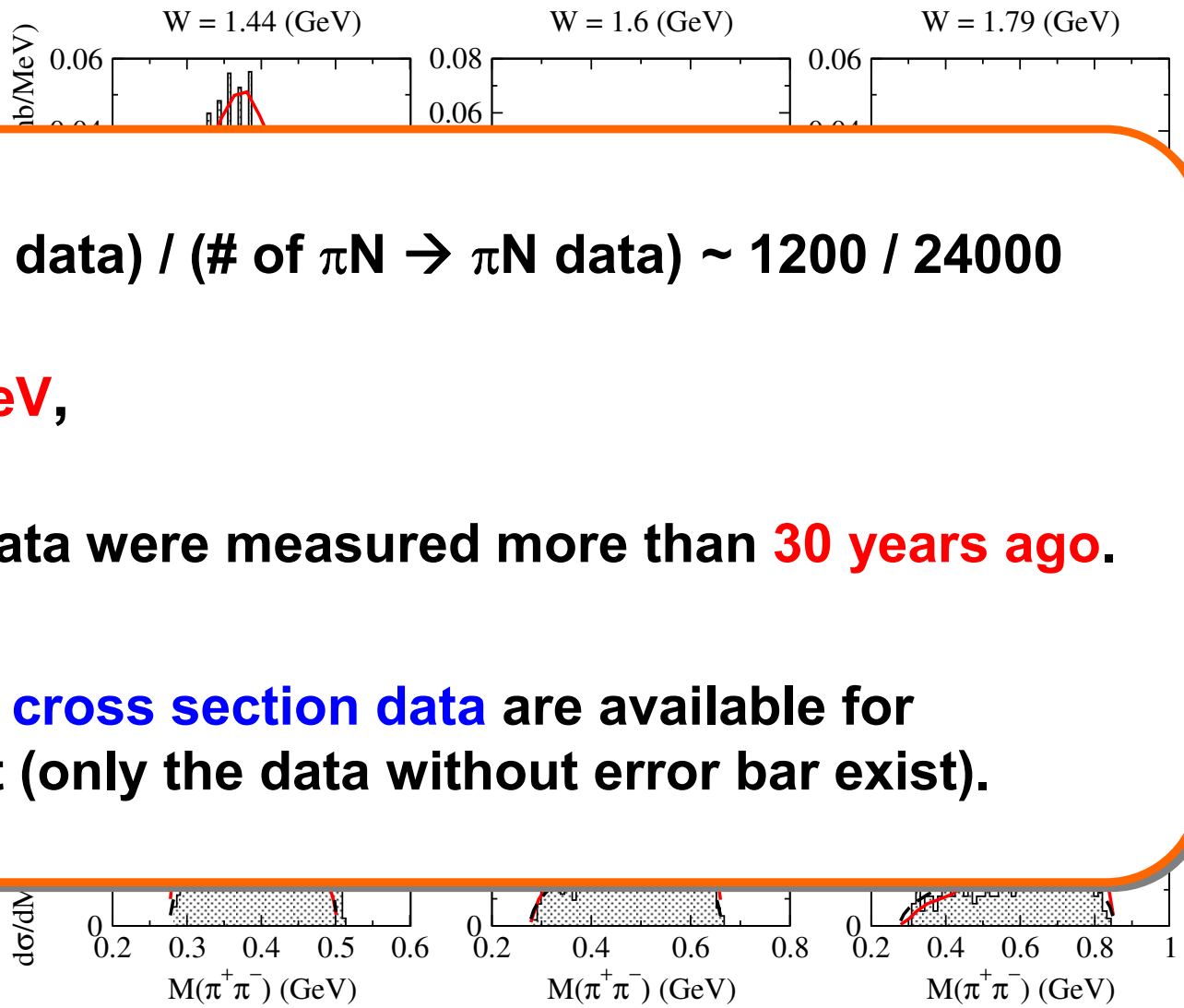
Kamano, Julia-Diaz, Lee, Matsuyama, Sato, PRC79 025206 (2009)



Invariant mass

(# of πN → ππN data) / (# of πN → πN data) ~ 1200 / 24000

Above **W = 1.5 GeV**,

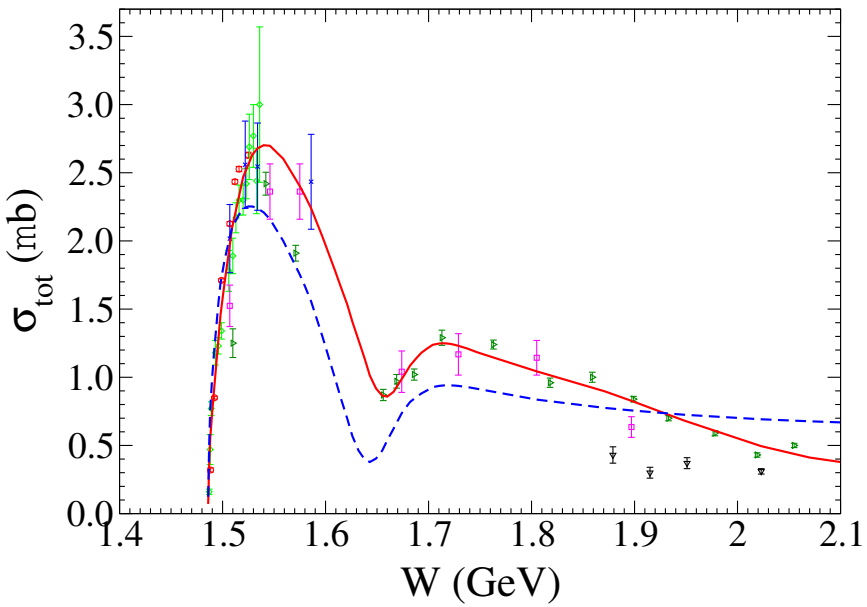
- ✓ All available data were measured more than **30 years ago**.
- ✓ **No differential cross section data** are available for quantitative fit (only the data without error bar exist).

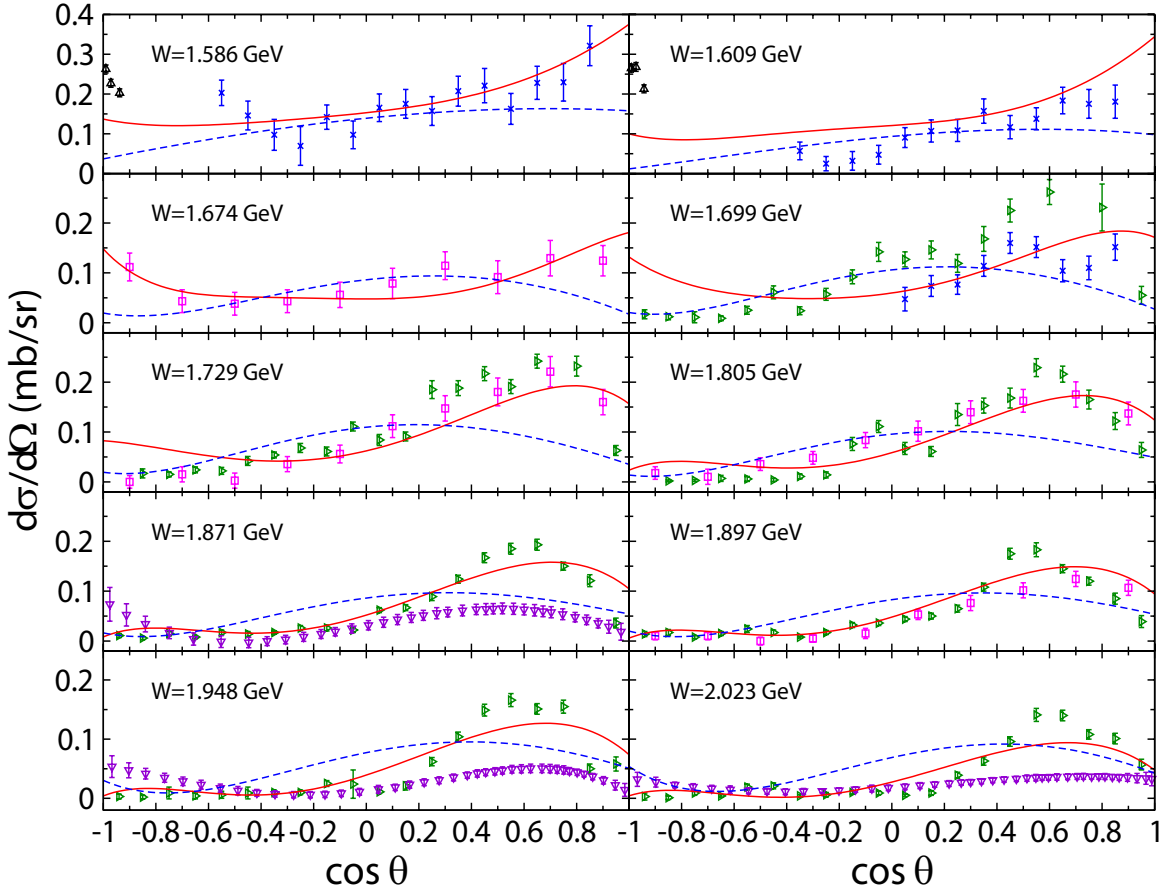
Data handled with the help of R. Arndt

3. pi N → eta N reaction

Durand, Julia-Diaz, Lee, Saghai, Sato, PRC78 025204 (2008)

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





N* → ηN varied

Model constructed from πN → πN analysis only

Photon- and electron-induced reactions

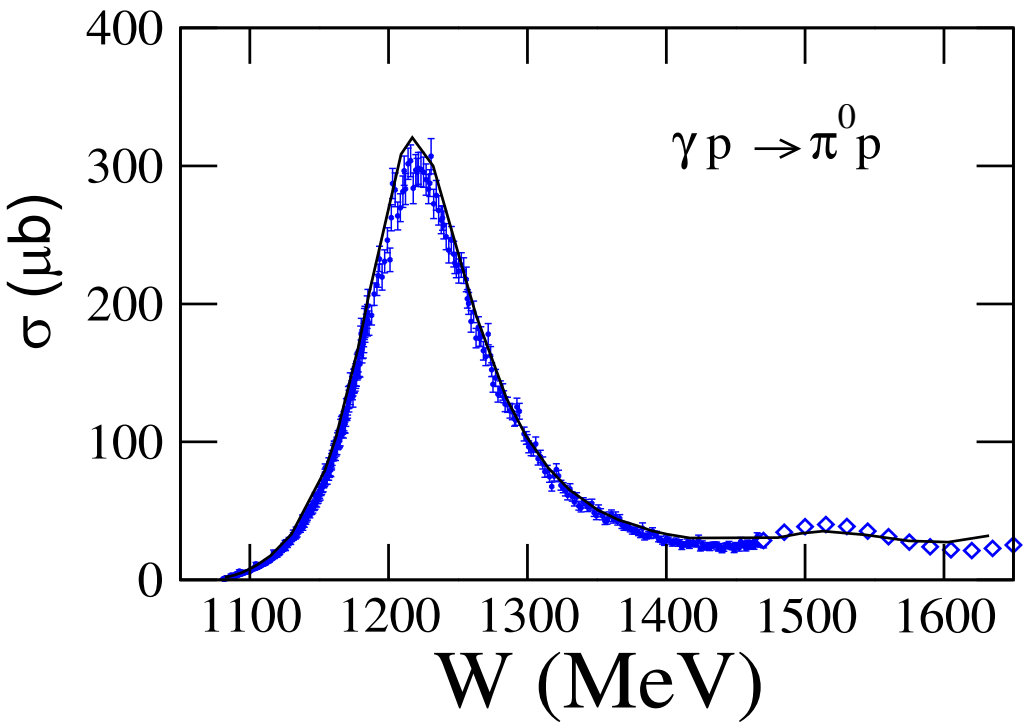
1. $\gamma N \rightarrow \pi N$ reaction
2. $eN \rightarrow e'\pi N$ reaction
3. $\gamma N \rightarrow \pi\pi N$ reaction

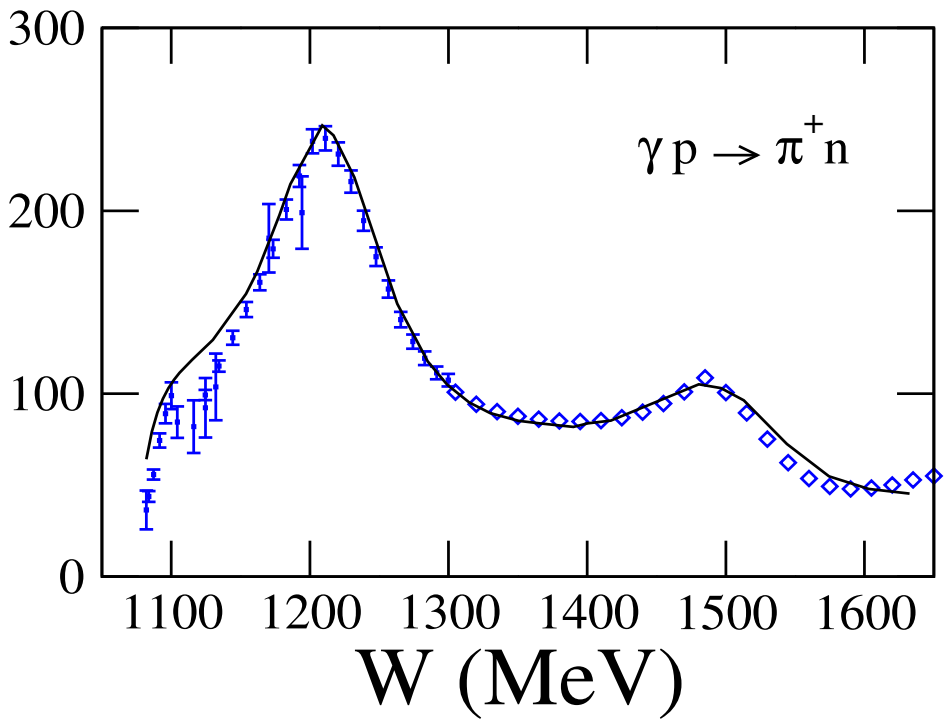
1. Single pion photoproduction ($Q^2 = 0$)

Julia-Diaz, Lee, Matsuyama, Sato, Smith, PRC77 045205 (2008)

- ✓ Fitted up to W = 1.6 GeV.
- ✓ Only $\Gamma^{\text{bare}}_{\gamma N \to N^*}$ is varied.

- Comparison to data
  - Total cross section





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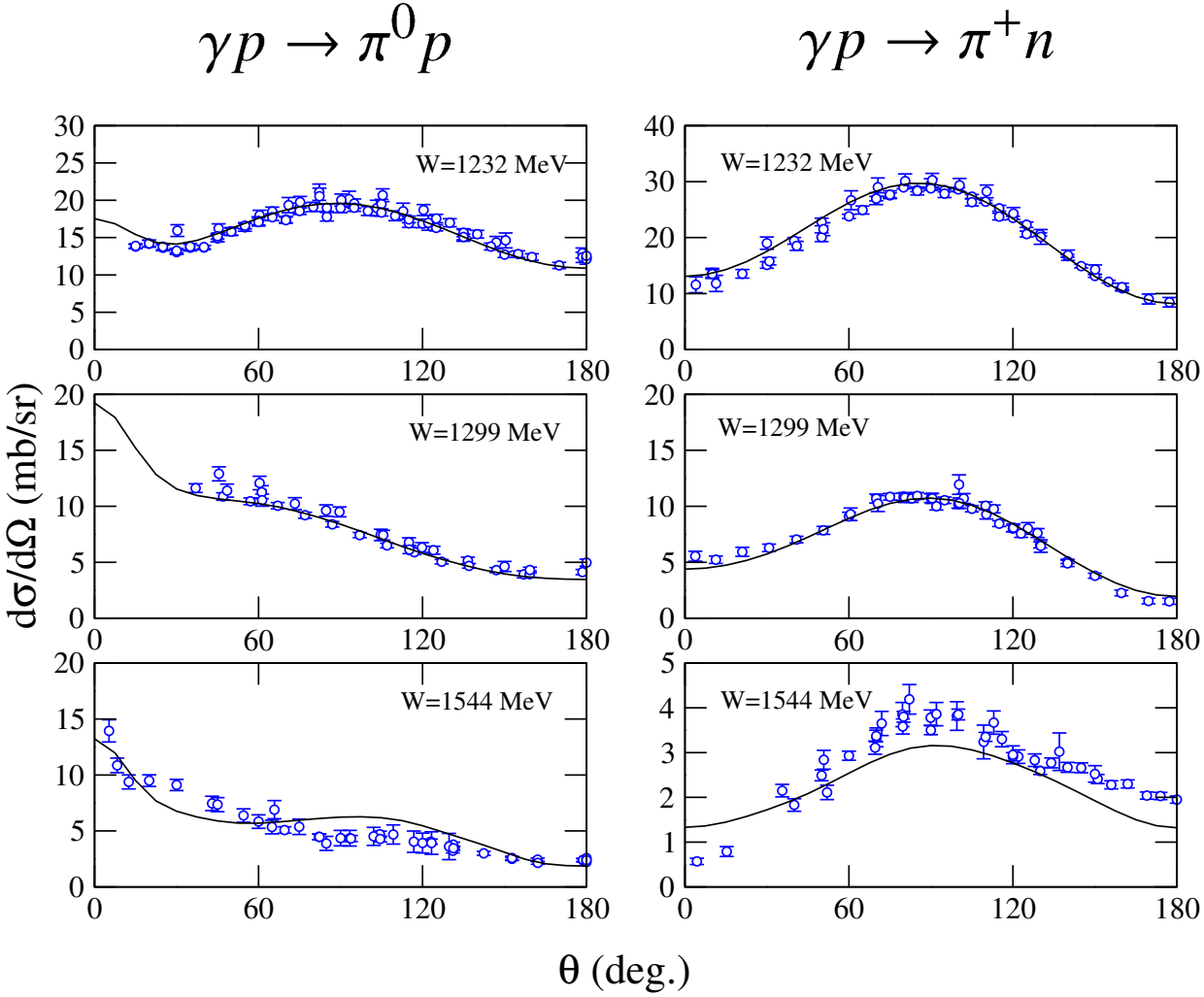
- Comparison to data
  - Total cross section
  - Differential cross section



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- ✓ Fitted up to W = 1.6 GeV.
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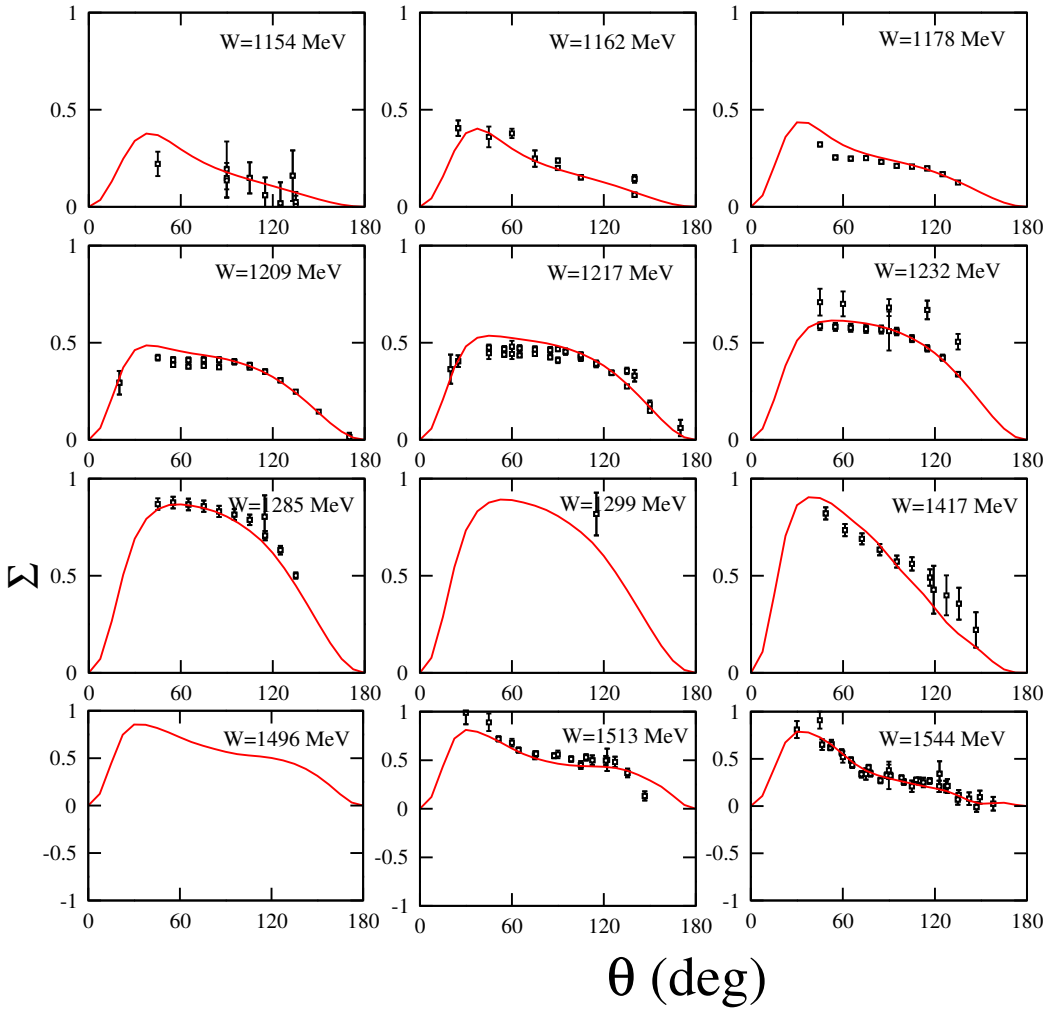
- Comparison to data
  - Total cross section
  - Differential cross section
  - Photon asymmetry

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



2. Single pion electroproduction ($Q^2 > 0$)

Julia-Diaz, Kamano, Lee, Matsuyama, Sato, Suzuki, PRC80 025207 (2009)

Fit to the structure function data from CLAS

$$\sigma_\alpha = \sigma_\alpha(W, Q^2, \cos\theta_\pi^*)$$

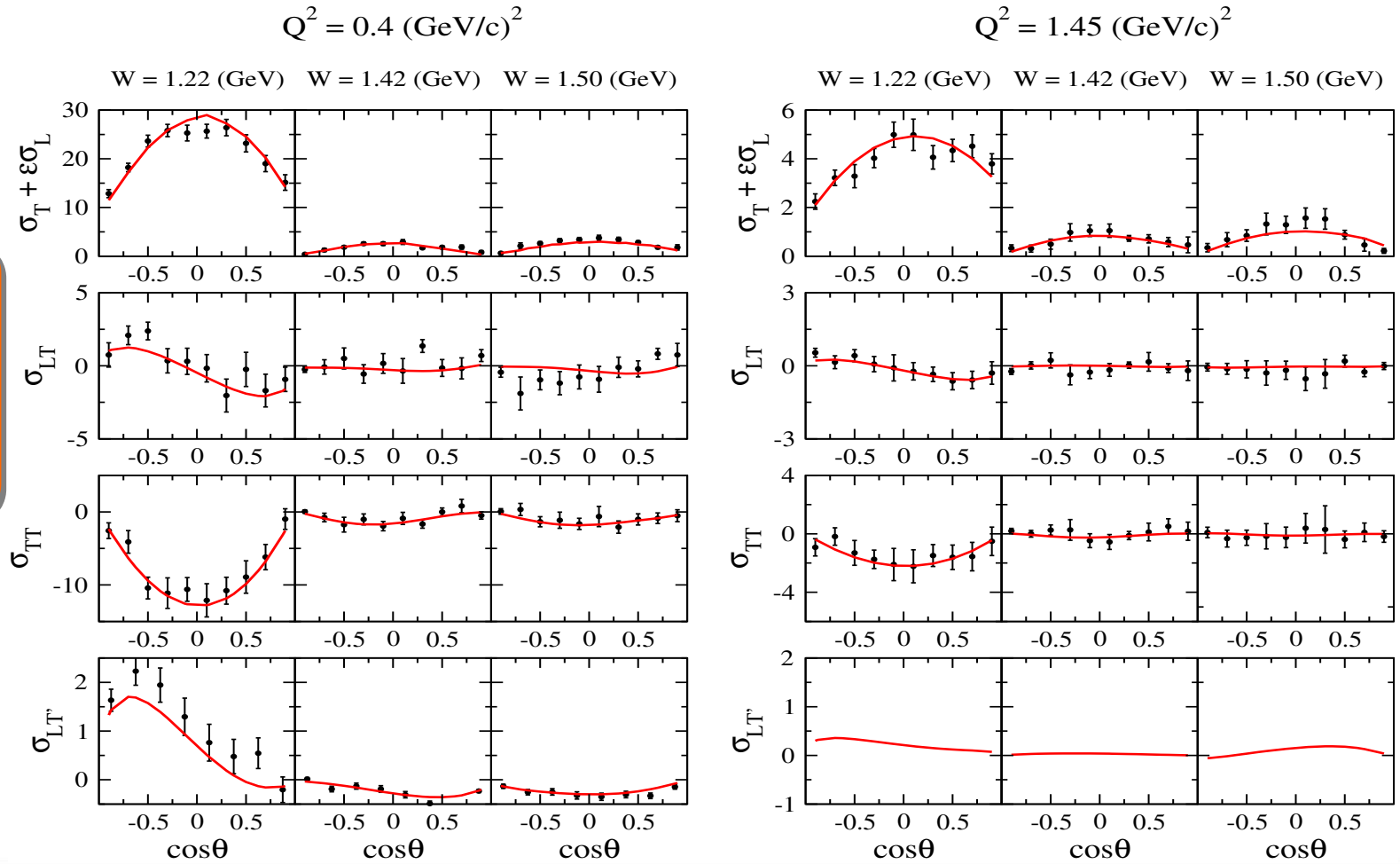
$$\frac{d\sigma^5}{dE_{e'}d\Omega_{e'}d\Omega_\pi^*} = \Gamma_\gamma\left[\sigma_T + \epsilon\sigma_L + \sqrt{2\epsilon(1+\epsilon)}\sigma_{LT}\cos\phi_\pi^* + \epsilon\sigma_{TT}\cos 2\phi_\pi^* + h_e\sqrt{2\epsilon(1-\epsilon)}\sigma_{LT'}\sin\phi_\pi^*\right].$$

p (e,e' π^0) p

W < 1.6 GeV

Q^2 < 1.5 (GeV/c)^2

$\Gamma^{\rm bare}_{\gamma N\to N^*}$ is determined at each Q^2.

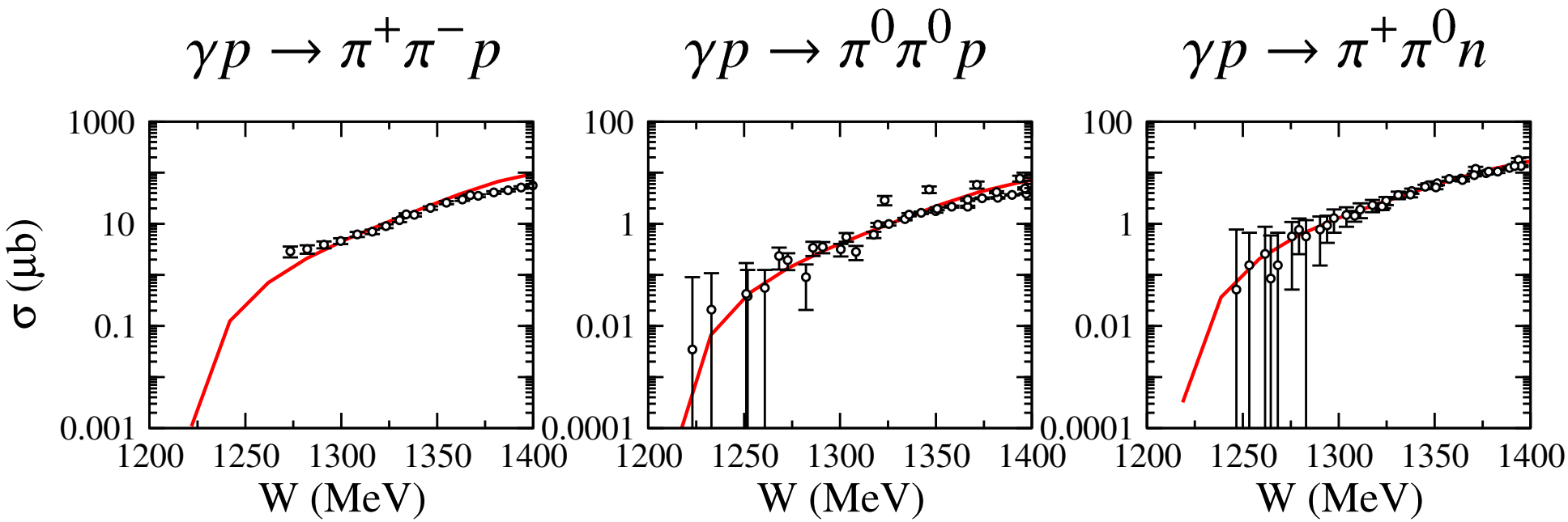


3. Double pion photoproduction

Kamano, Julia-Diaz, Lee, Matsuyama, Sato, arXiv:0909.1129 [nucl-th]

Parameters used in the calculation are from $\pi N \rightarrow \pi N$ & $\gamma N \rightarrow \pi N$ analyses.

Total cross sections at low energies W < 1.4 GeV



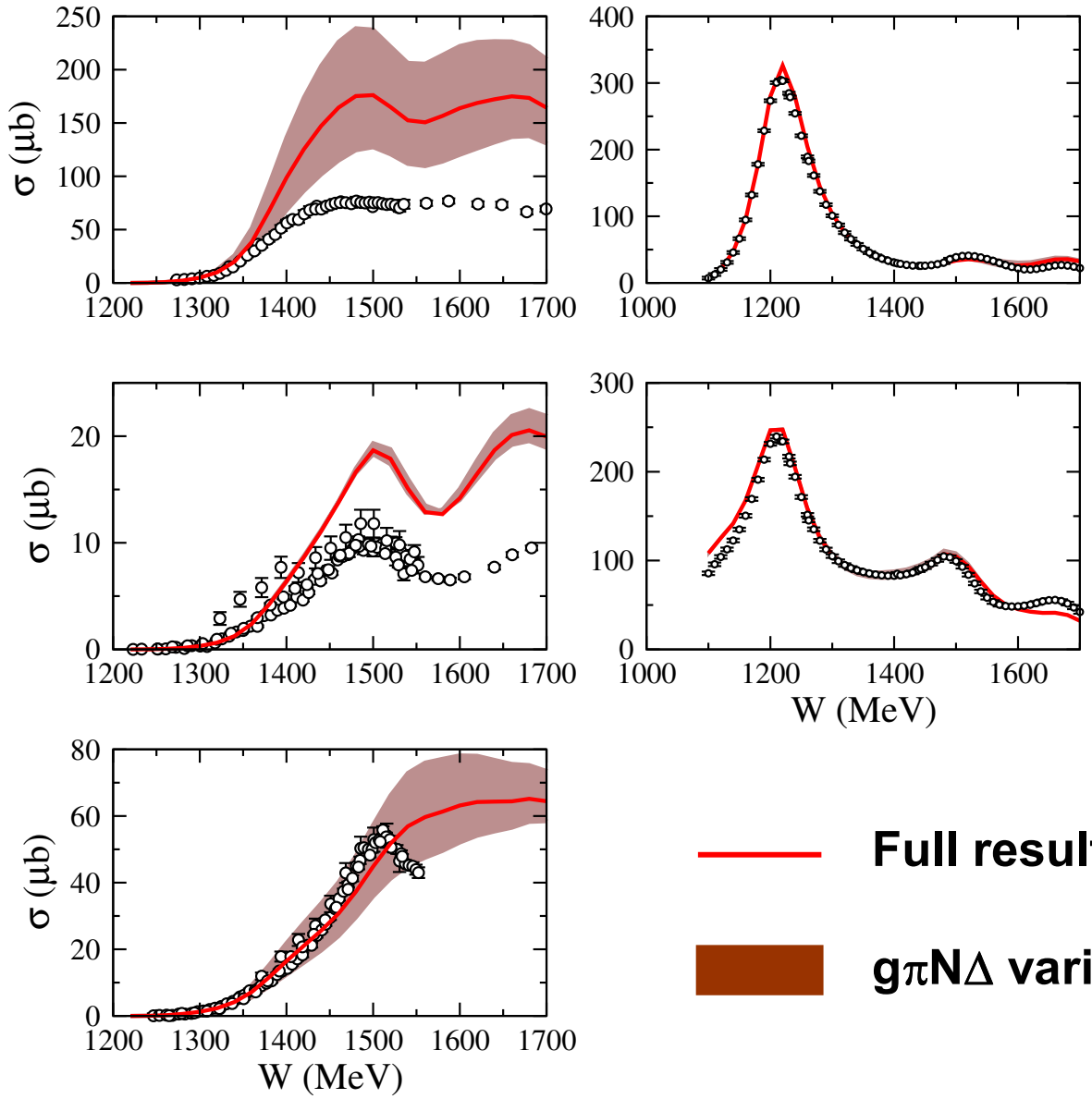
3. Double pion photoproduction

Kamano, Julia-Diaz, Lee, Matsuyama, Sato, arXiv:0909.1129 [nucl-th]

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

$\gamma p \to \pi^0\pi^0 p$

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



Summary and future plans

Summary

- ✓ The EBAC-DCC analysis has successfully constructed a reaction model describing $\pi N \rightarrow \pi N$, ηN up to W = 2 GeV and $\gamma^{(*)}N \rightarrow \pi N$ up to W = 1.6 GeV and Q^2 = 1.5 $(GeV/c)^2$.
- ✓ The model has been applied to $\pi N \rightarrow \pi\pi N$ and $\gamma N \rightarrow \pi\pi N$.

Future plans for EBAC-DCC analysis

- ✓ Refining model parameters by simultaneous, combined analysis of πN, $\gamma N \rightarrow \pi N$, $\pi\pi N$, ηN.
- ✓ Search for new N* states via the analysis of πN, $\gamma N \rightarrow KY$, ωN.

Problem:
Lack of hadronic data in $\pi\pi N$, KY, ωN,…