Study of Excited Nucleon States at EBAC: Status and Plans

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in collaboration with
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NSTAR 2009, April 19-22, 2009

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}	*	*	i					
$\Delta(1900)$	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

Particle	$L_{2I \cdot 2J}$	status	$N\pi$	$N\eta$	ΛK	ΣK	$\Delta\pi$	$N\rho$	$N\gamma$
$N(939)$	P_{11}	****							
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$N(1535)$	S_{11}	****	****	****			*	**	***
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$N(1680)$	F_{15}	****	****	*			****	****	****
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$N(1710)$	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		*	***	**	***
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$\Delta(1900)$	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		*	****	*	****

✓ **Most of their properties are 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

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$N(1680)$	F_{15}	****	****	*			****	****	****
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$\Delta(1920)$	P_{33}	***	***	n		*	**		*
$\Delta(1930)$	D_{35}	***	***			*			**
$\Delta(1940)$	D_{33}	*	*	F					
$\Delta(1950)$	F_{37}	****	****	o		*	****	*	****

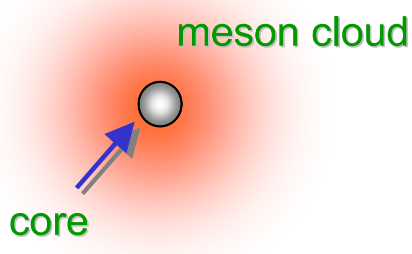
✓ **Most of their properties are extracted from**

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

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

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

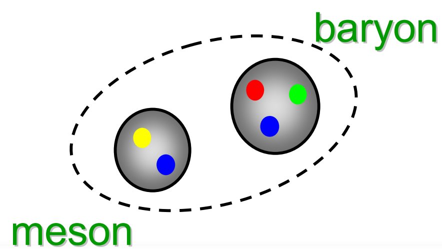
$$|N^*\rangle = |qqq\rangle + |\mathrm{m.c.}\rangle$$



✓ **Is their origin dynamical ?**

→ **some could be understood as arising from meson-baryon dynamics**

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



Data will change N* structure study

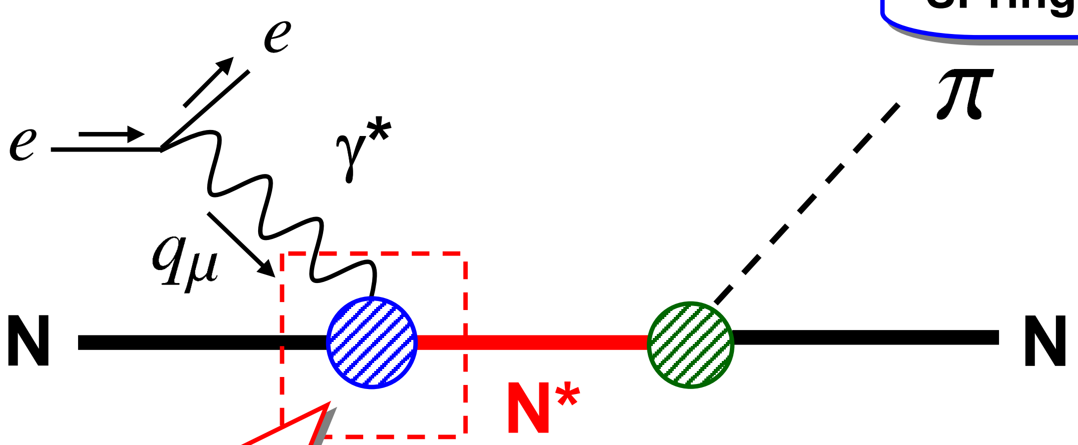
Recent high precision data of meson photo- and electro-production reactions open a great opportunity of making quantitative study of the N* structure.

ELSA, JLab, MAMI, SPring-8 …

e.g.) single pion electroproduction

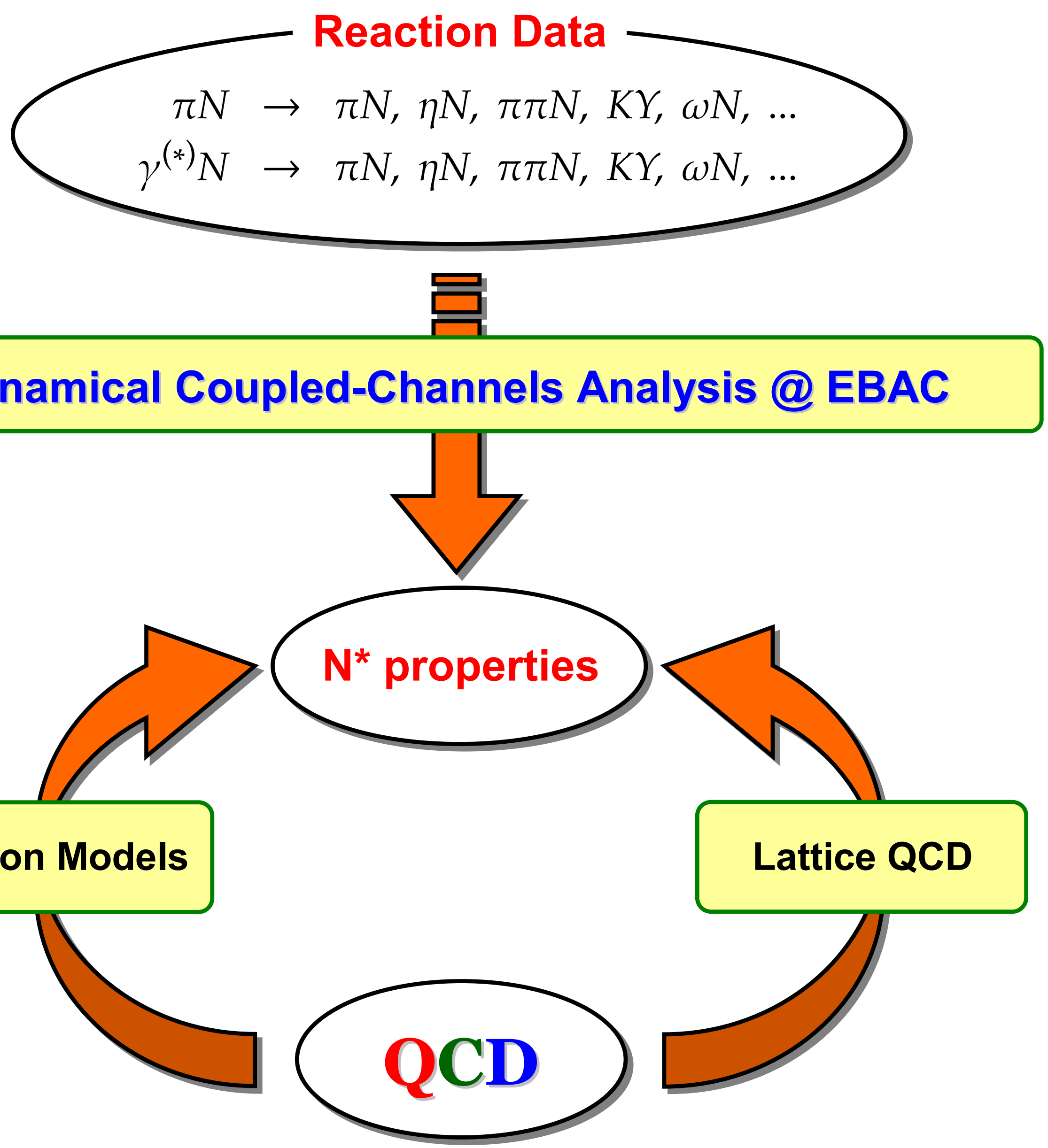
$$Q^2 \equiv -q^2 > 0$$

Corresponds to beam resolution



N-N* e.m. transition form factors

Approaches to extracting N* properties



Dynamical coupled-channels model @ EBAC

N* spectrum, structure, … ⟷ Meson production data

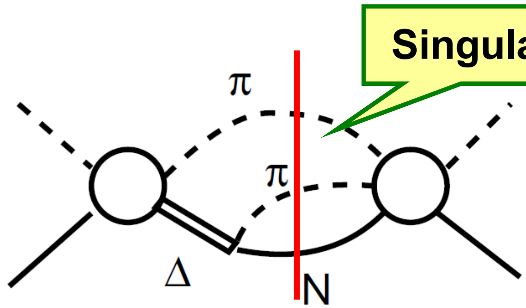
Reaction mechanism

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 3-body $\pi\pi N$ 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:**

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

coupled-channels effect

- ✓ **Reaction channels:**

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

$\pi\Delta, \sigma N, \rho N$: $\pi\pi N$

- ✓ **Potential:**

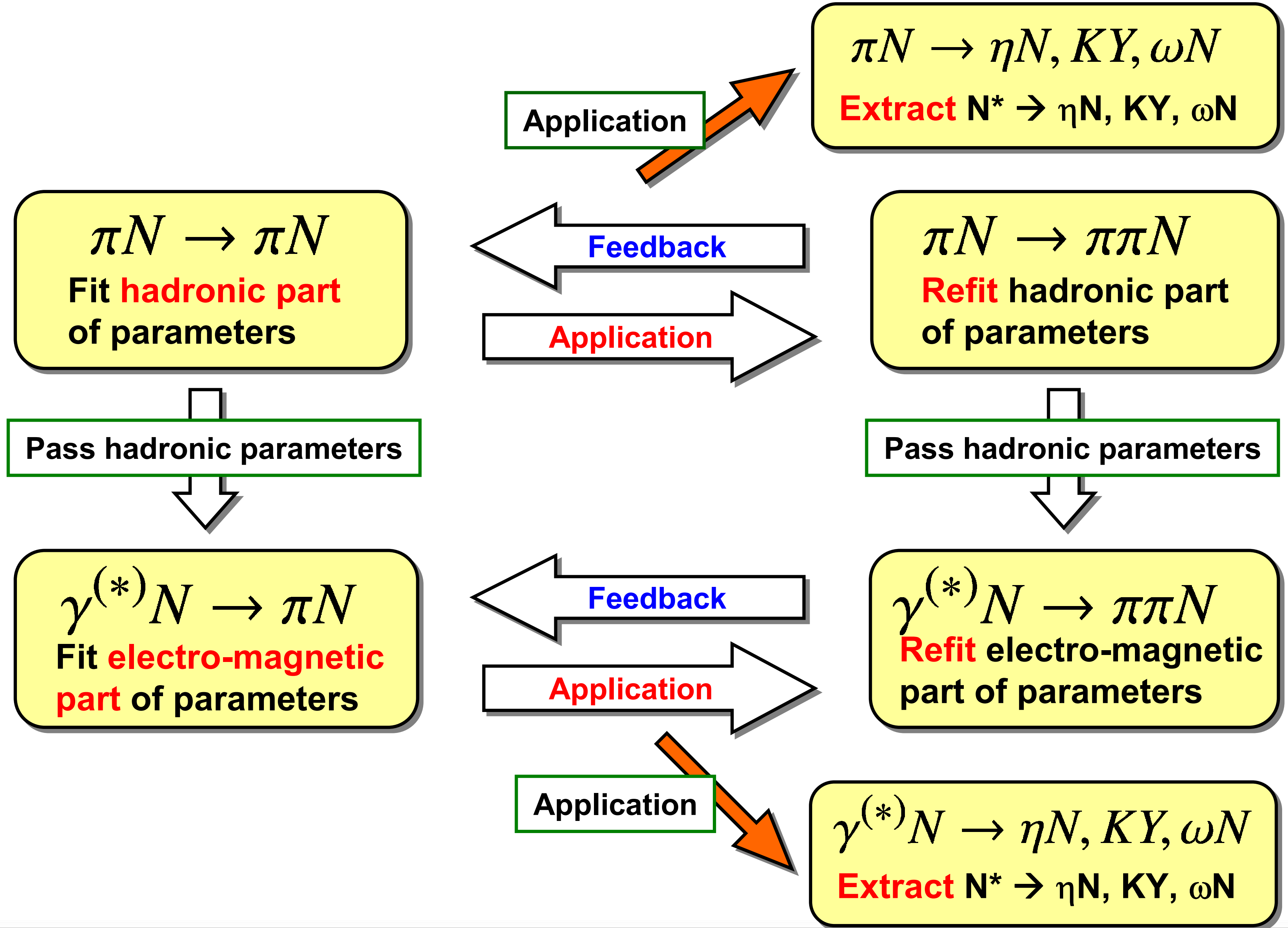
$$V_{a,b} = v_{a,b} + \sum_{N^*} \frac{\Gamma^\dagger_{N^*,a}\Gamma_{N^*,b}}{E - M_{N^*}}$$

meson exchange ($v_{a,b}$)

bare N* state (pole term)

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

Strategy for N* study @ EBAC



Strategy for N* study @ EBAC

Extraction of N* poles and N* → MB decay form factors

$\pi N \rightarrow \pi N$

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 form factors

$\pi N \to \pi N$

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 analysis @ EBAC

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 not finished.

  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)

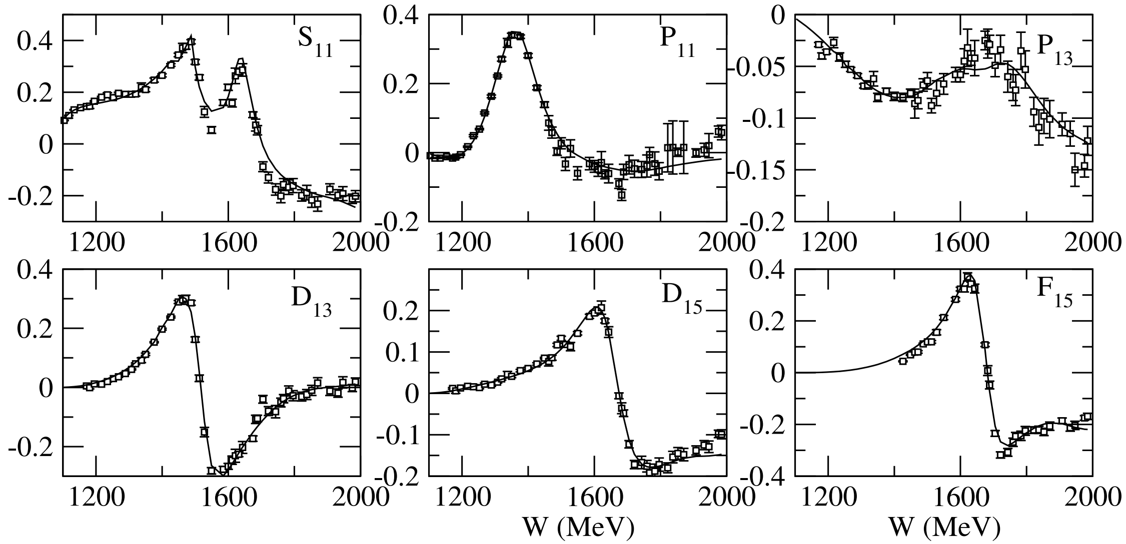
  (electroproduction) Julia-Diaz, Kamano, Lee, Matsuyama, Sato, Suzuki, arXiv:0904.1918

- ✓ $\gamma^{(*)} N \rightarrow \pi \pi N$: *in progress*
- ✓ $\gamma^{(*)} N \rightarrow \eta N$: *in progress*
- ✓ $\gamma N \rightarrow K \Lambda$: *in progress*

Pion-nucleon elastic scattering

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

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



Re(T) with I = 1/2

Pion-nucleon elastic scattering

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

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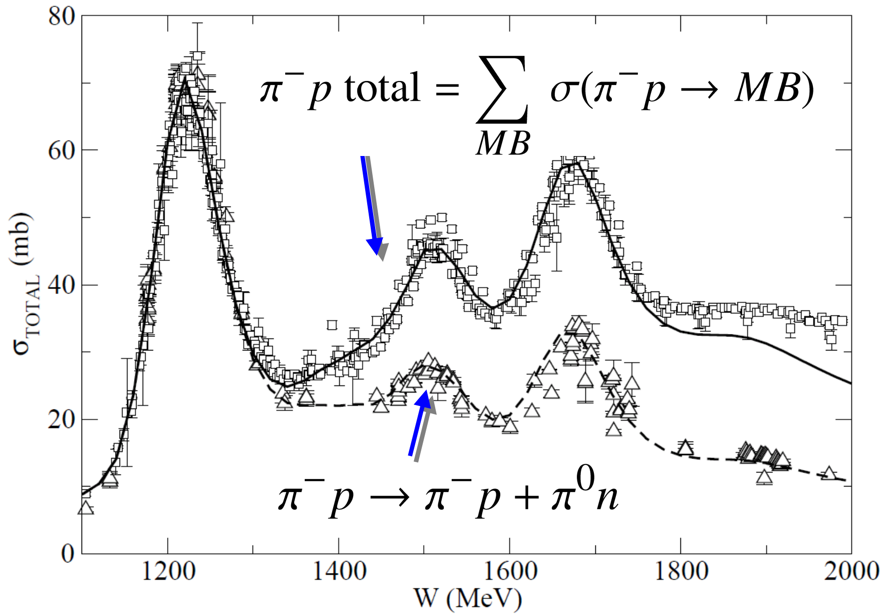

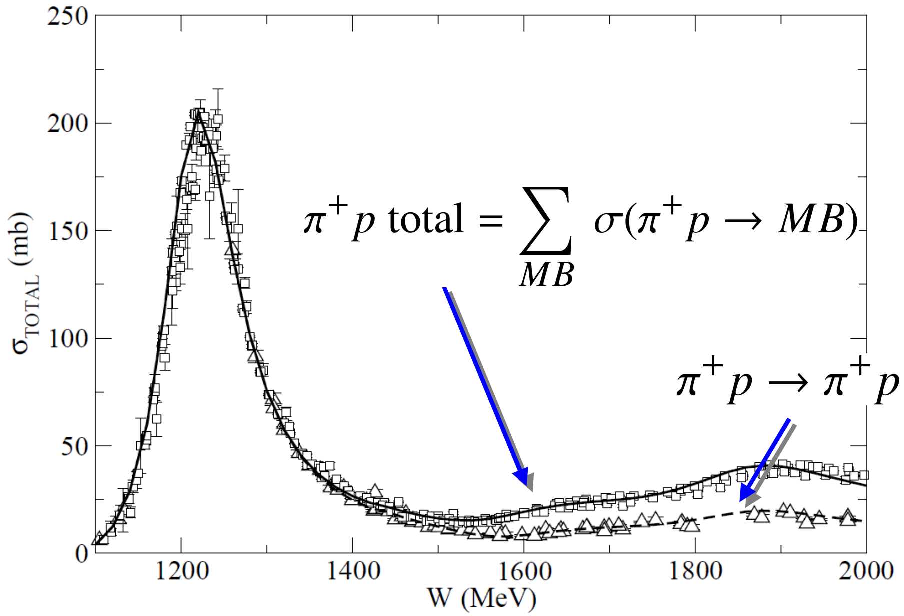

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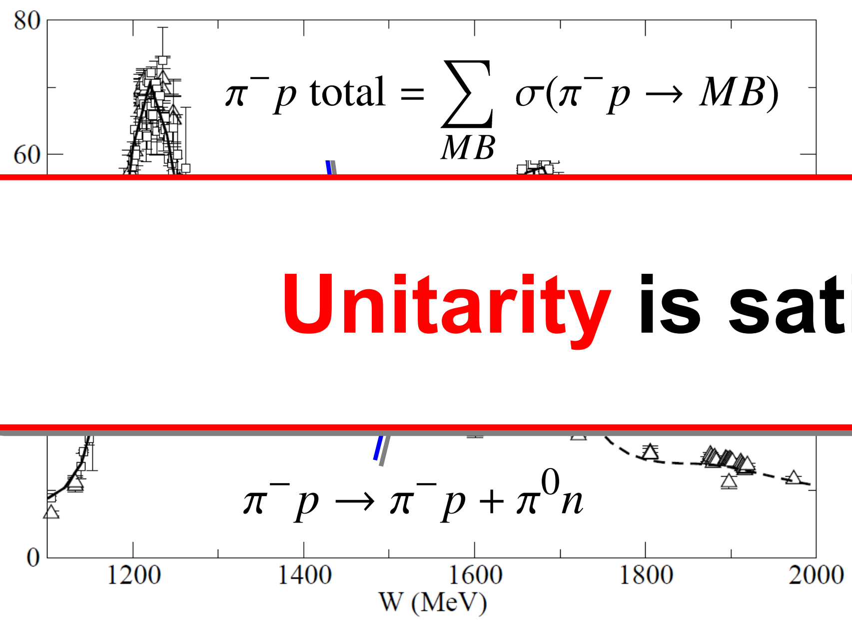
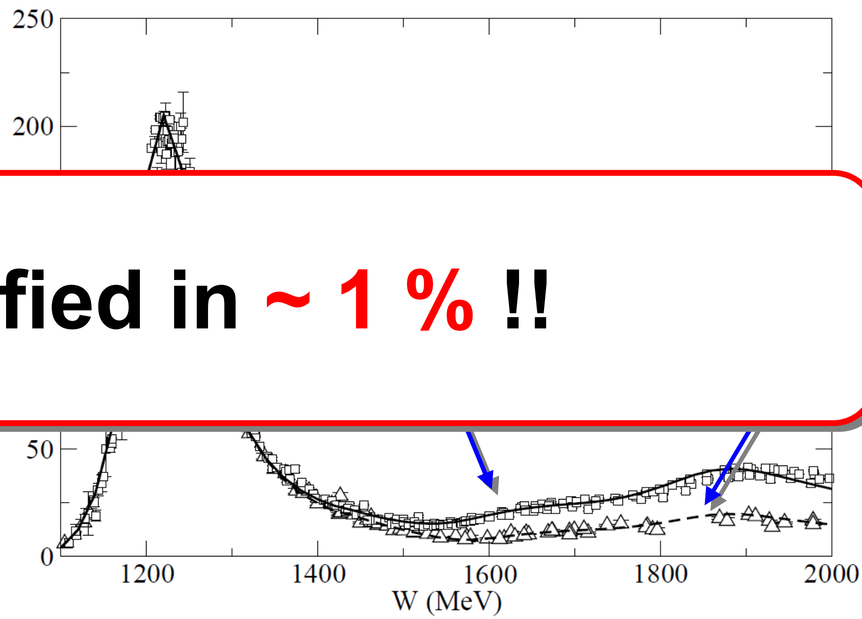




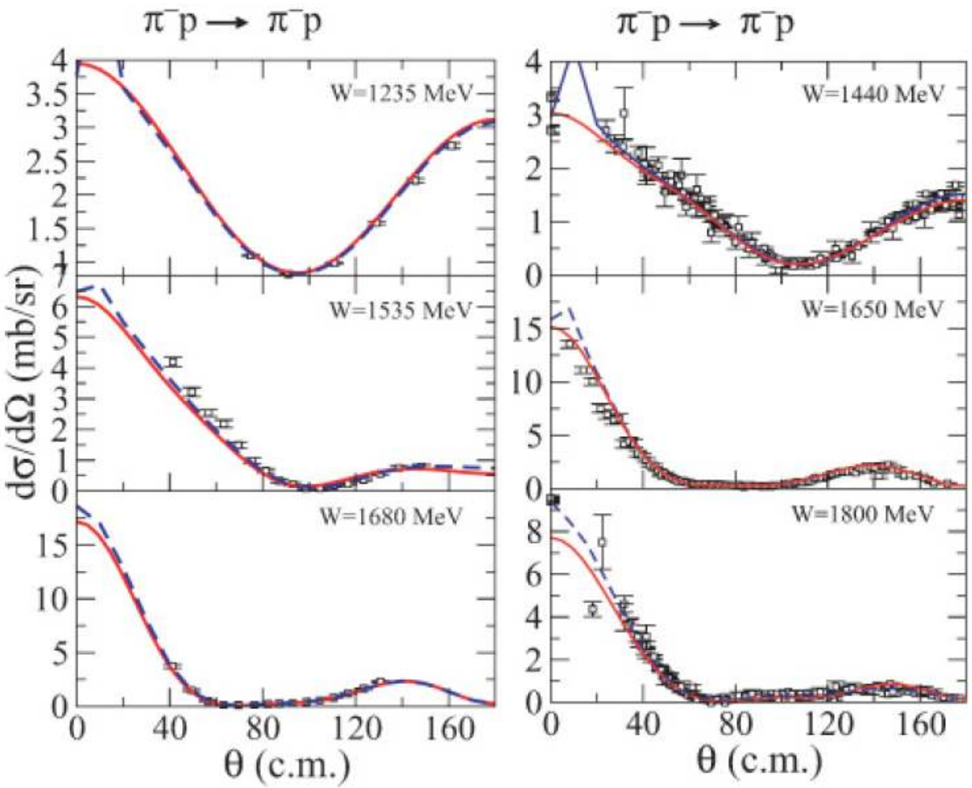
Unitarity is satisfied in ~ 1 % !!

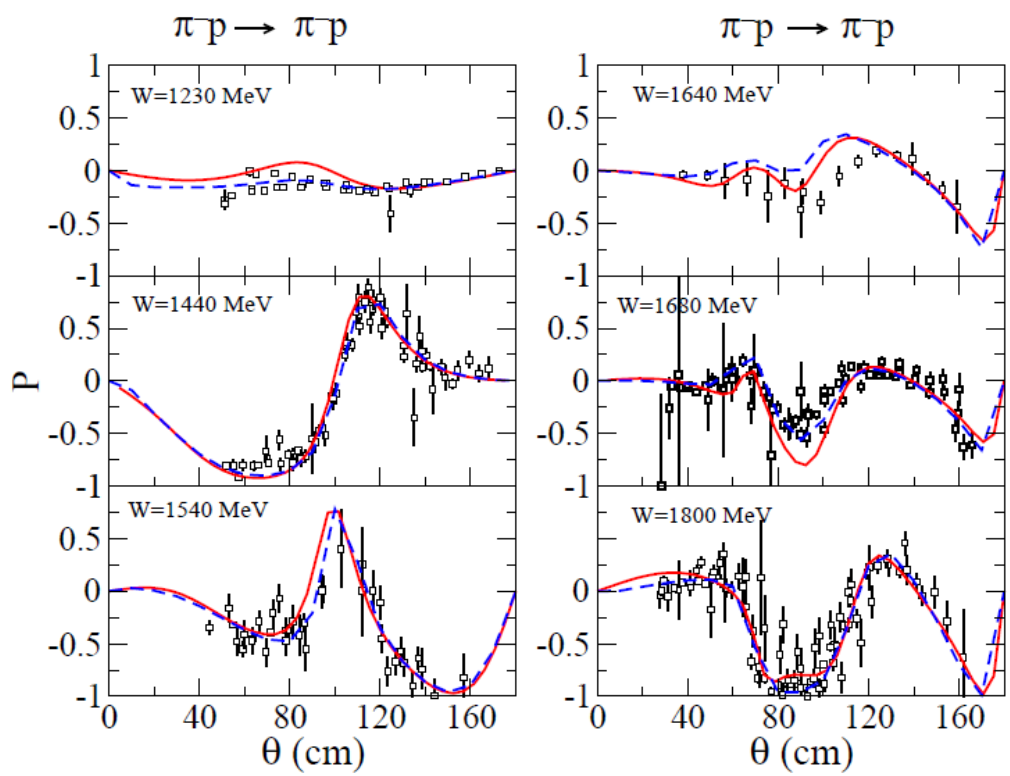
Pion-nucleon elastic scattering

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

Angular distribution

Target polarization





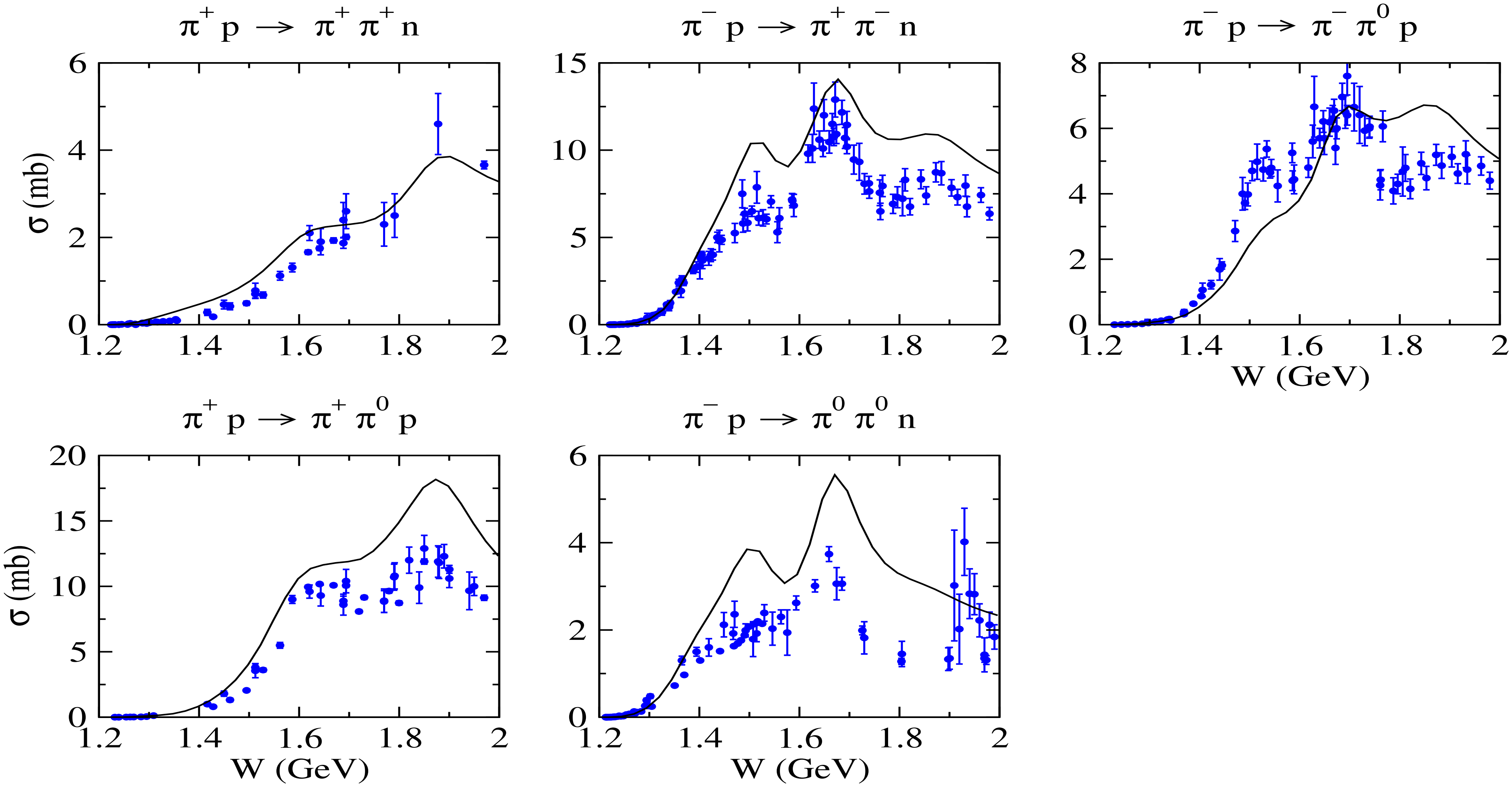
EBAC ———

SAID06 - - - - - -

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.



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

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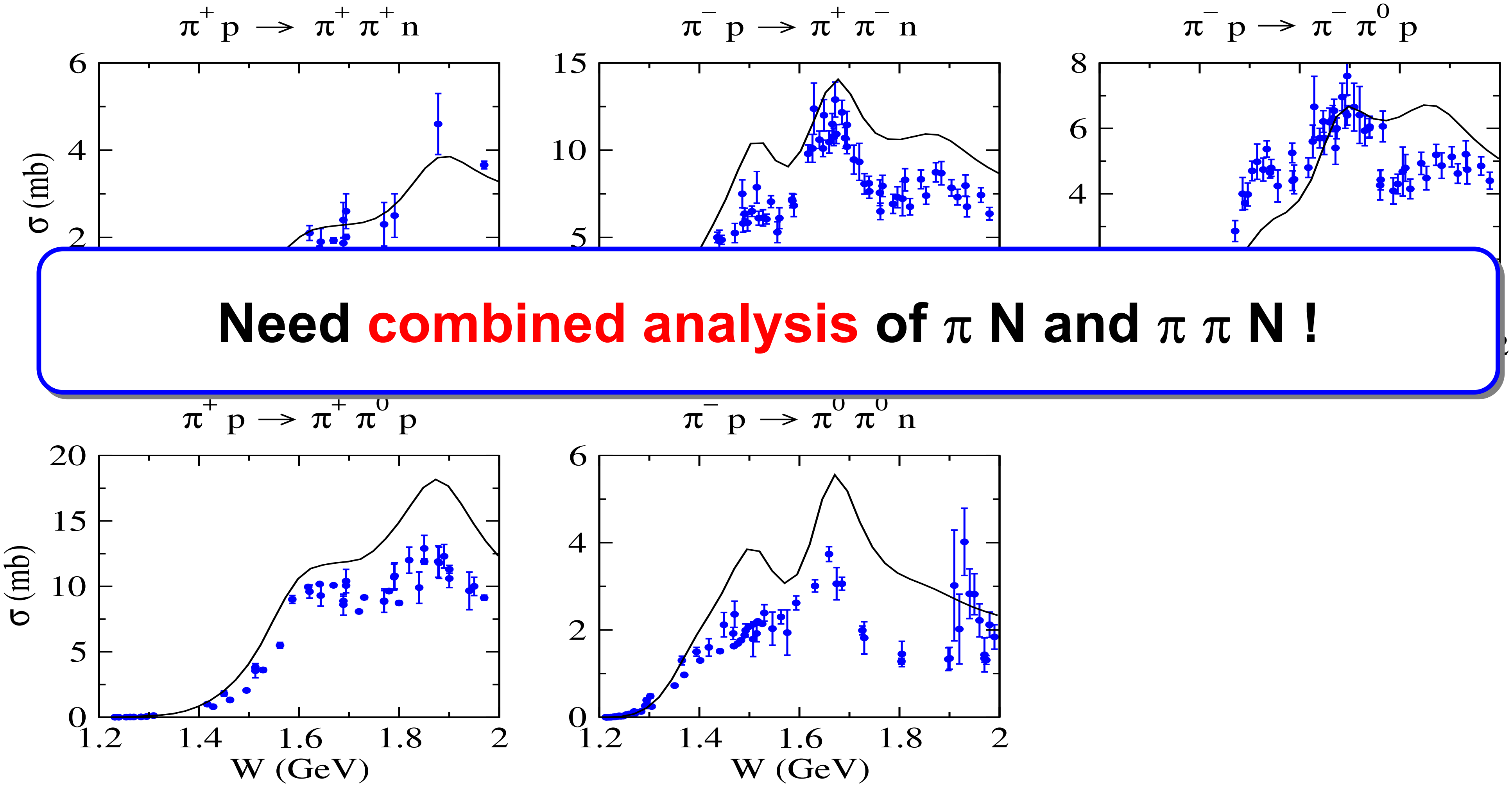


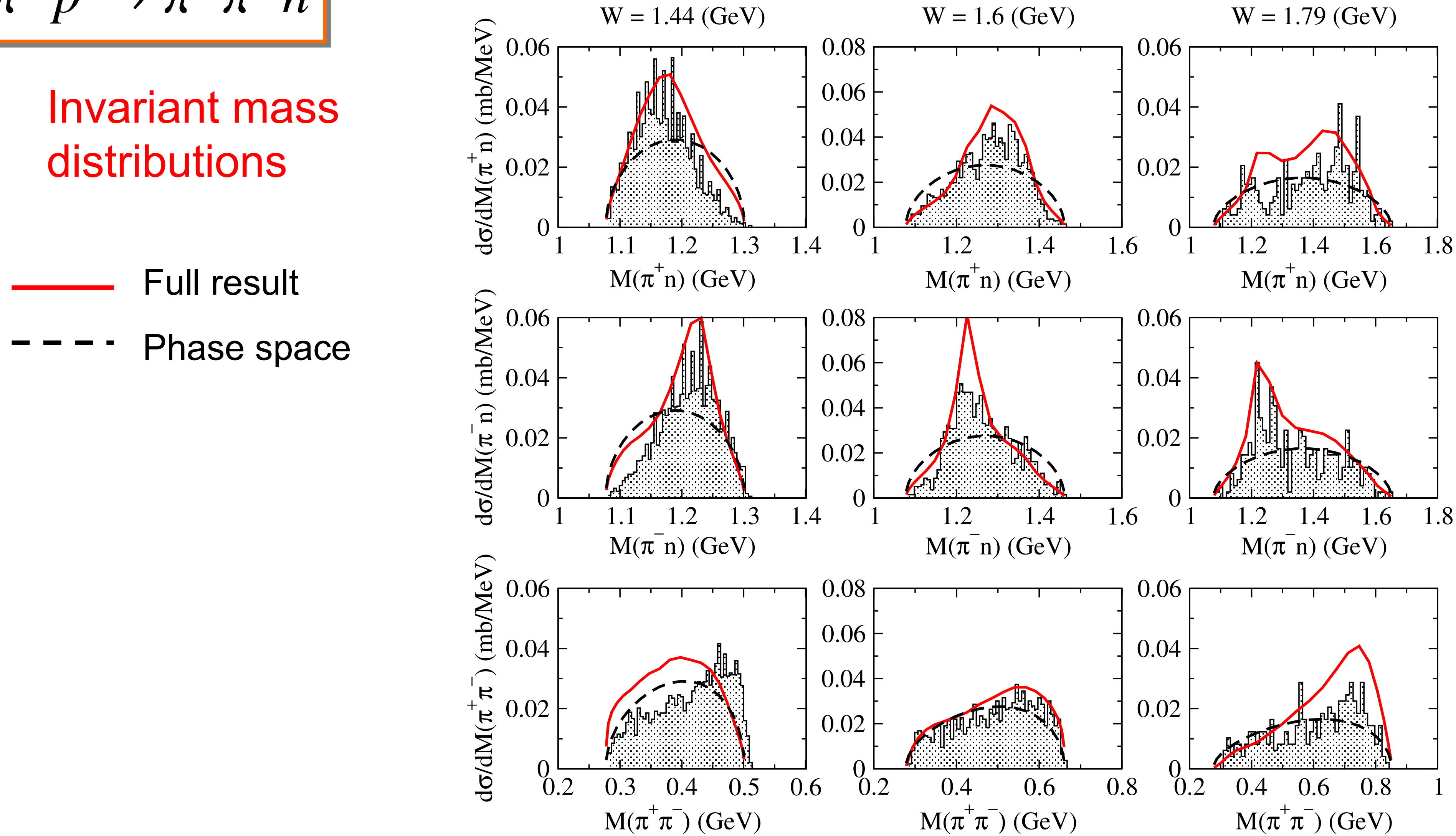
Need combined analysis of π N and π π N !

pi N → pi pi N reaction

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

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

Invariant mass distributions



Data handled with the help of R. Arndt

How can we extract N* information?

PROPER definition of

- ✓ **N* mass and width** → **Pole position of the amplitudes**
- ✓ **N* → MB, γN decay vertices** → **Residue at the pole**

$$\langle p_a|\hat{T}(E)|p_b\rangle\Big|_{E\to E_0} \quad\to\quad \frac{\bar{\Gamma}(E_0,p_a)\bar{\Gamma}(E_0,p_b)}{E-E_0} + (\text{regular terms})$$

N* → b decay vertex

N* pole position (Im(E_0) < 0)

How can we extract N* information?

PROPER definition of

- ✓ N* mass and width ➔ Pole position of the amplitudes
- ✓ N* → MB, γN decay vertices ➔ Residue at the pole

Need analytic continuation of the amplitudes !!

$$\ldots |_{E \to E_0} \qquad \ldots \frac{\ldots}{E - E_0}$$

N* pole position
($\mathrm{Im}(E_0) < 0$)

Comparison with PDG values

PRELIMINARY

Suzuki, Julia-Diaz, Kamano, Lee, Matsuyama, Sato, in preparation

	Analytic Continuation	PDG
S_{11}	(1540,191)	(1490–1530, 45 –125)
	(1642, 41)	(1640–1670, 75 – 90)
S_{31}	(1563, 95)	(1590–1610, 57 – 60)
P_{11}	(1356, 76)	(1350–1380, 80 –110)
	(1364,105)	
	(1820,248)	(1670–1770, 40 –190)
P_{13}	In progress	(1660–1690, 57 –138)
P_{31}	In progress	(1830–1880,100–250)
P_{33}	(1211, 50)	(1209–1211, 49 – 51)
D_{13}	(1521, 58)	(1505–1515, 52 – 60)
D_{15}	(1654, 77)	(1655–1665, 62 – 75)
D_{33}	(1604,106)	(1620–1680, 80 –120)
F_{35}	(1928,165)	(1825–1835,132–150)

All extracted N*s originate from bare N* states.
(At present it is found no pole associated with meson exchanges.)

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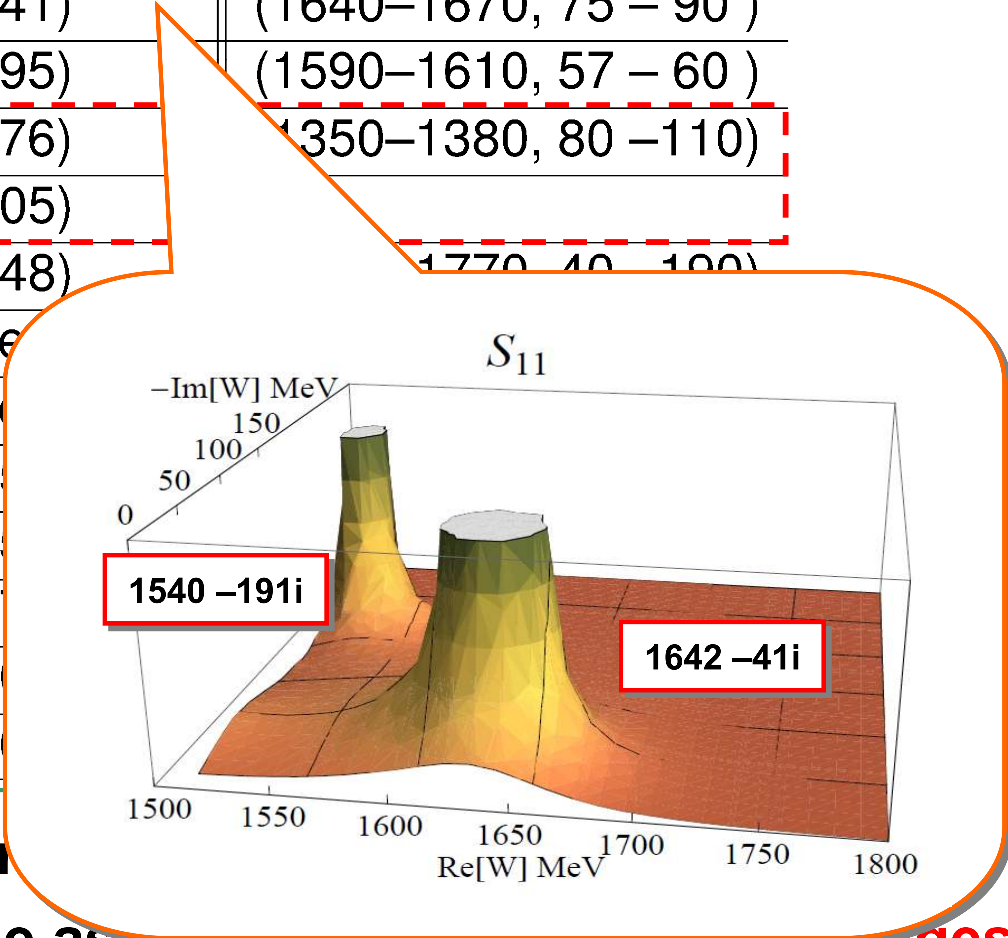
	(1364,105)	
	(1820,248)	[illegible]
P_{13}	In progre[illegible]	[illegible]
P_{31}	In progr[illegible]	[illegible]
P_{33}	(1211, [illegible]	[illegible]
D_{13}	(1521, [illegible]	[illegible]
D_{15}	(1654, [illegible]	[illegible]
D_{33}	(1604,1[illegible]	[illegible]
F_{35}	(1928,1[illegible]	[illegible]



All extracted N*s o[illegible]

(At present it is found no pole as[illegible]ges.)

Future works

N* Study

- ✓ Extracting N* → MB, γN decay form factors from the EBAC model
- ✓ Searching for new N* states via the analysis of γ N → K Y, ω N
- ✓ Developing a method linking our form factors to Hadron models and Lattice QCD calculations

Model Upgrade

- ✓ Refinement of the model parameters with the combined analysis of π N, $\gamma^{(*)}$ N → π N, π π N
- ✓ Full treatment of the direct $\pi\pi$N 3-body unitarity cut.