Study of nucleon resonances at EBAC@JLab

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(Excited Baryon Analysis Center, Jefferson Lab)

in collaboration with
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Outline

- ✓ Excited Baryon Analysis Center (EBAC) at Jefferson Lab

- ✓ Dynamical origin of P11 nucleon resonances

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)**

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$\Delta(1950)$	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

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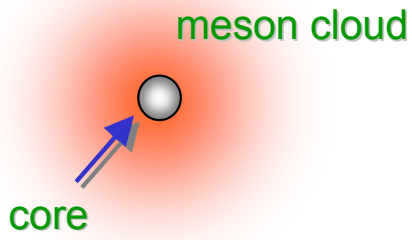
- ✓ **Most of their properties were extracted from**

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

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

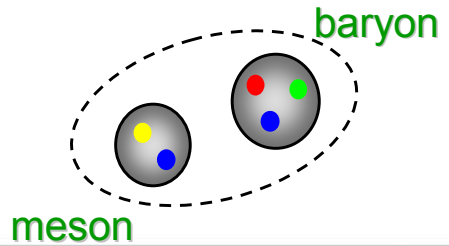
- ✓ **Are they all genuine quark/gluon excitations (with meson cloud) ?**

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



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

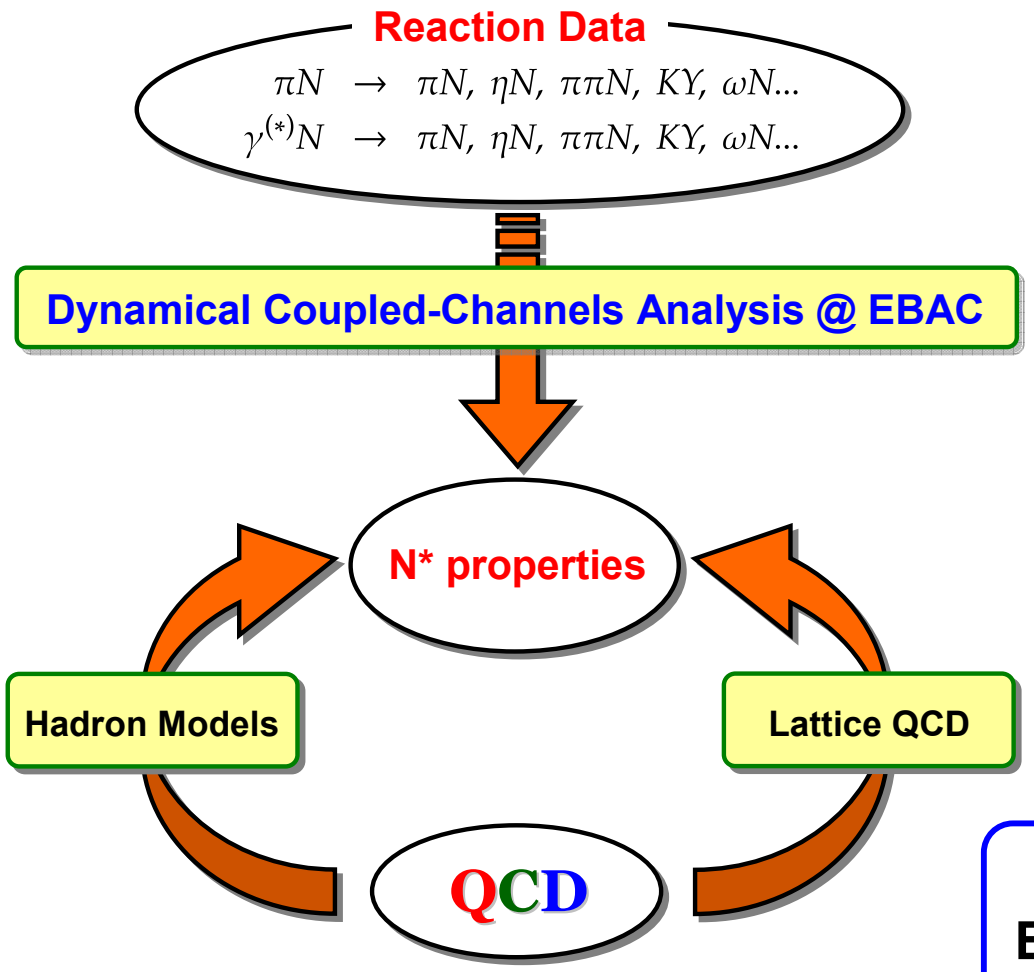
$$|N^*\rangle = |MB\rangle$$



Excited Baryon Analysis Center (EBAC) at 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* e.m. transition form factors**
- ✓ **Provide reaction mechanism information for interpreting the N* properties**

Theory support for Excited Baryon Program by CLAS@JLab (arXiv:0907.1901)

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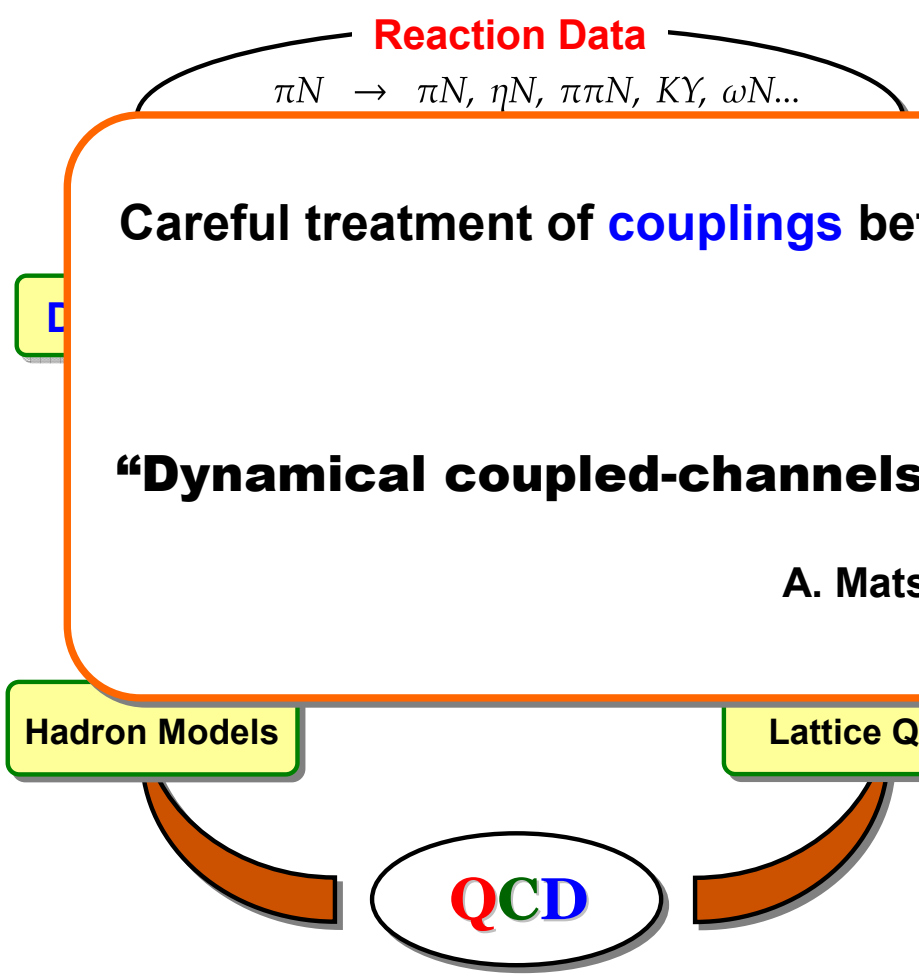


Objectives and goals:

Through the comprehensive analysis

Careful treatment of couplings between *multi*-reaction channels is necessary !!

"Dynamical coupled-channels model of meson production reactions"

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

Theory support for Excited Baryon Program by CLAS@JLab (arXiv:0907.1901)

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:**

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

$\pi\pi N$

- ✓ **Potential:**

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

ground meson-baryon exchange

bare N* state

Current status of the EBAC-DCC analysis

Hadronic part

- ✓ $\pi N \rightarrow \pi N$: model constructed 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)
- ✓ $\pi N \rightarrow \eta N$: model constructed up to W = 2 GeV
  Durand, Julia-Diaz, Lee, Saghai, Sato, PRC78 025204 (2008)

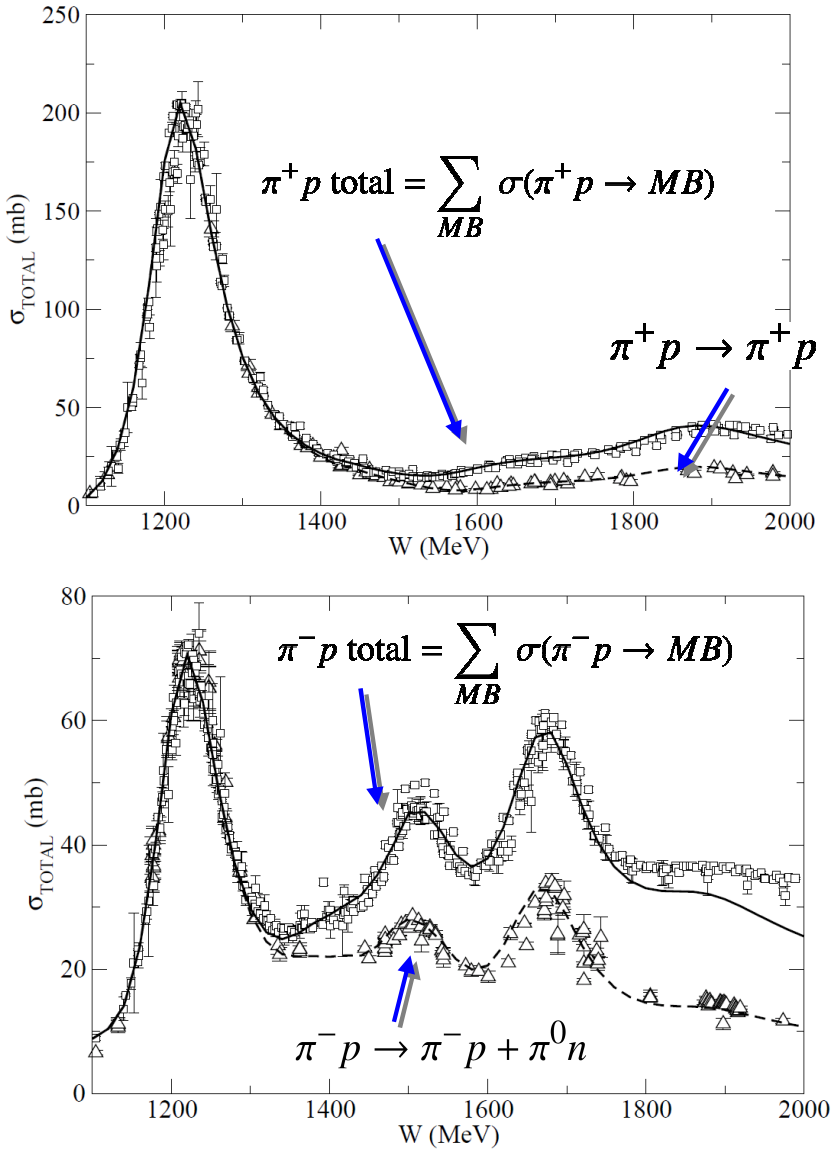
Electromagnetic part

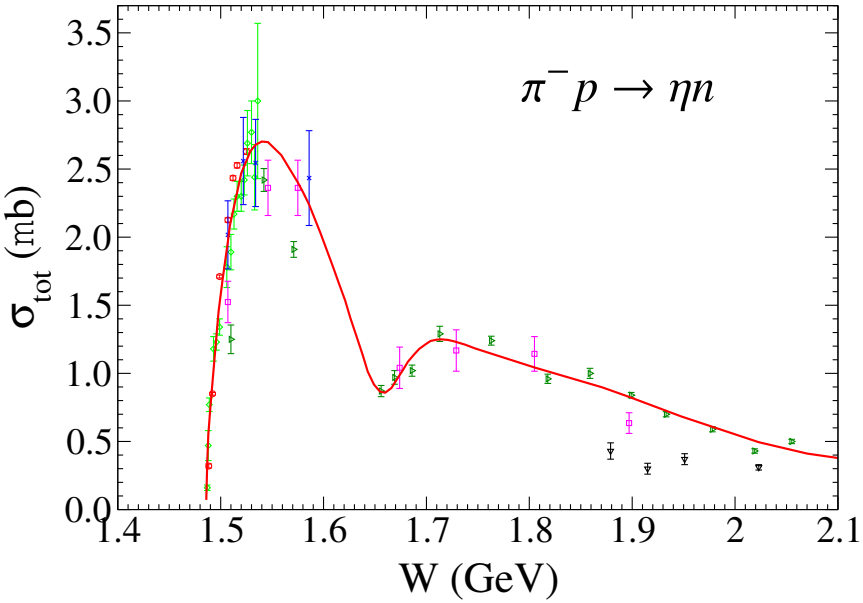
- ✓ $\gamma^{(*)} N \rightarrow \pi N$: model constructed up to W = 1.6 GeV (& up to Q^2 = 1.5 GeV^2)
  (photoproduction) Julia-Diaz, Lee, Matsuyama, Sato, Smith, PRC77 045205 (2008)
  (electroproduction) Julia-Diaz, Kamano, Lee, Matsuyama, Sato, Suzuki, PRC80 025207 (2009)
- ✓ $\gamma N \rightarrow \pi \pi N$: 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*

- ✓ $\gamma N \rightarrow KY, \omega N$: *in progress*

Analysis of pi N → pi N & eta N reactions

Julia-Diaz, Lee, Matsuyama, Sato, PRC76 065201 (2007)
Durand, Julia-Diaz, Lee, Saghai, Sato, PRC78 025204 (2008)





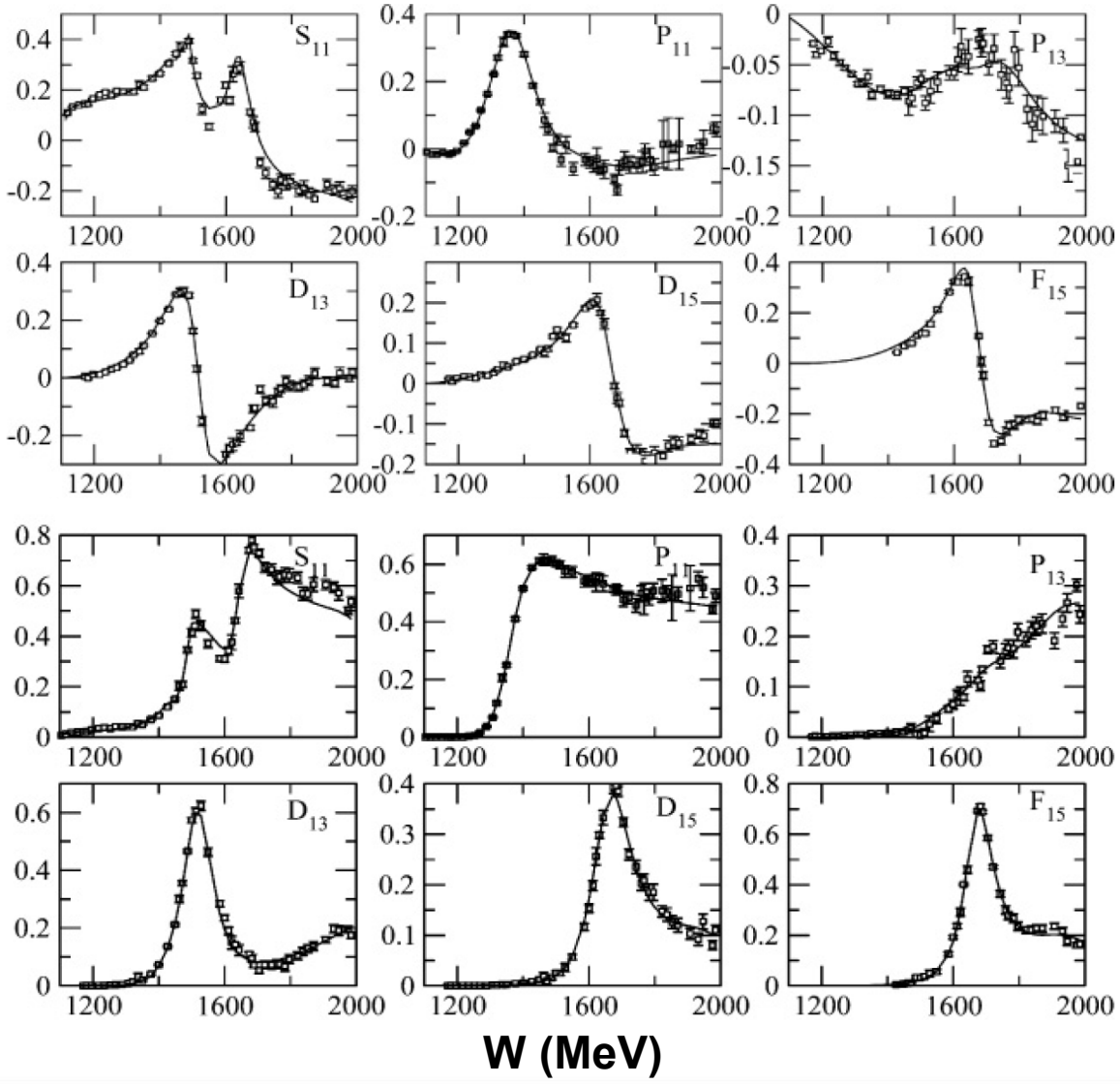
Constructed pi N partial wave amplitudes

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

Isospin = 1/2

Real part

Imaginary part



——— EBAC

SAID06

How can we extract N* information?

PROPER definition of

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

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

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 of the pole**

Need analytic continuation of the amplitudes !!

→ **Suzuki, Sato, Lee, PRC79 025205 (2009); arXiv:0910.1742**

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

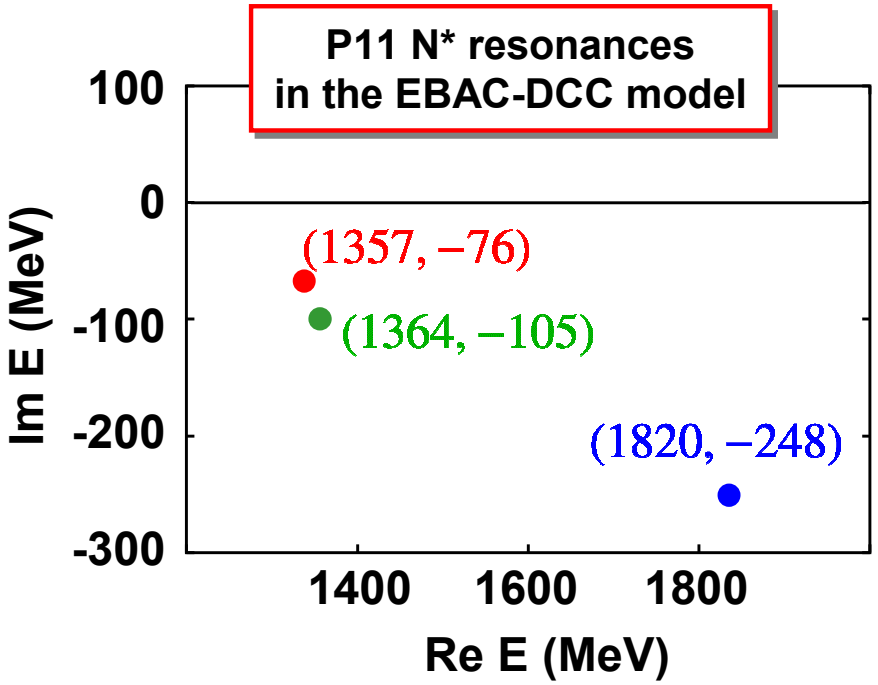
Dynamical origin of P11 nucleon resonances

Suzuki, Julia-Diaz, Kamano, Lee, Matsuyama, Sato arXiv:0909.1356

Findings:

1. ***Two* almost degenerate poles in the Roper resonance region.**
2. **All three poles below 2 GeV evolve from a *same, single* bare state.**

Analysis	P11 poles (MeV)	
EBAC (2009)	(1357, −76)	(1364, −105)
CMB (1990)	(1370, −114)	(1360, −120)
GWU/VPI (2006)	(1359, −82)	(1388, −83)
Jülich (2009)	(1387, −74)	(1387, −71)



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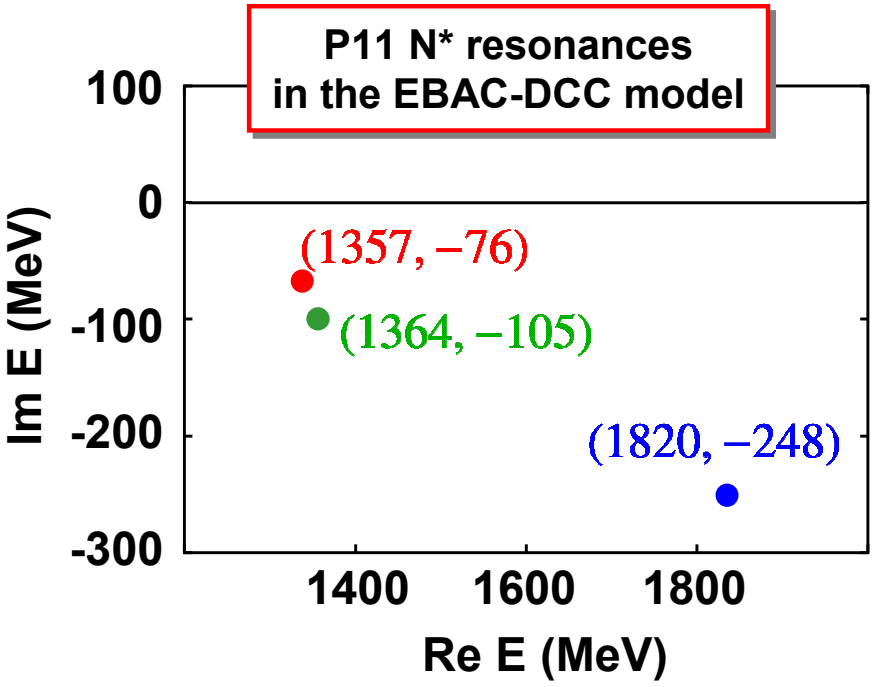
2. All three poles below 2 GeV evolve from a *same, single* bare state.

***Multi*-channels reactions can generate many resonance poles from a single bare state!!**

Eden, Taylor, Phys. Rev. 133 B1575 (1964)

e.g.)
Two poles for $J^{\pi} = 3/2^{+}$ resonance in He^{5}
Hale, Brown, Jarmie, PRL59 763 (1987)

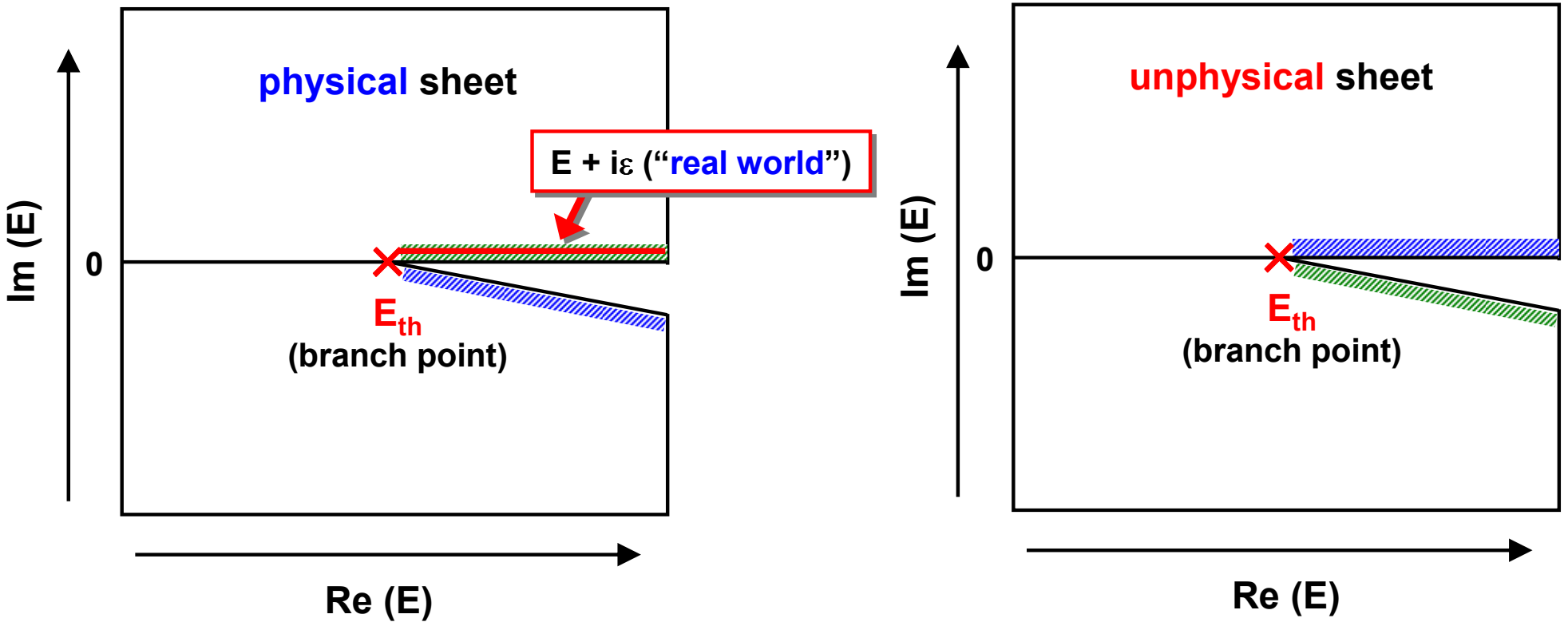


Analytic structure of the scattering amplitudes

e.g.) single-channel meson-baryon scattering

$$T(p,p';E) = V(p,p') + \int q^2 dq V(p,q) G(q;E) T(q,p';E)$$

Scattering amplitude is a double-valued function of E !!



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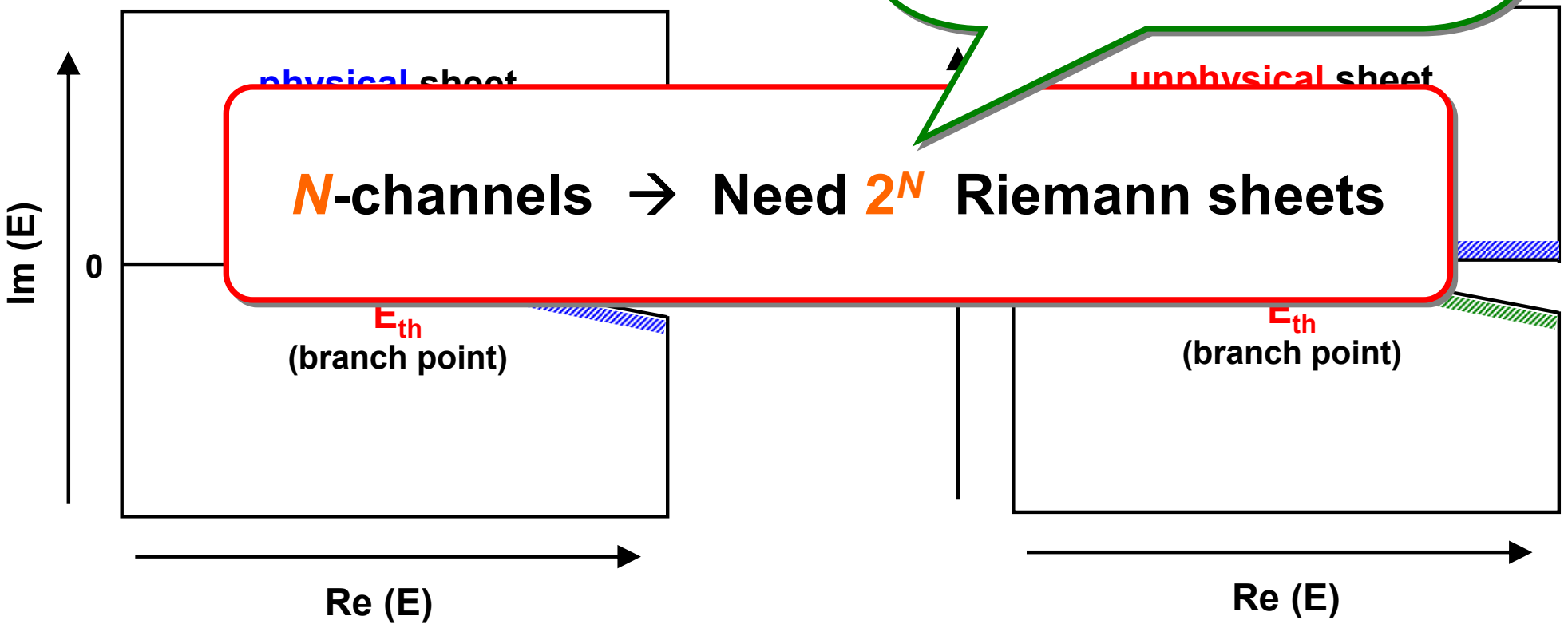
2-channel case (4 sheets):
(channel 1, channel 2) =
(p, p), (u, p) ,(p, u), (u, u)

p = physical sheet
u = unphysical sheet



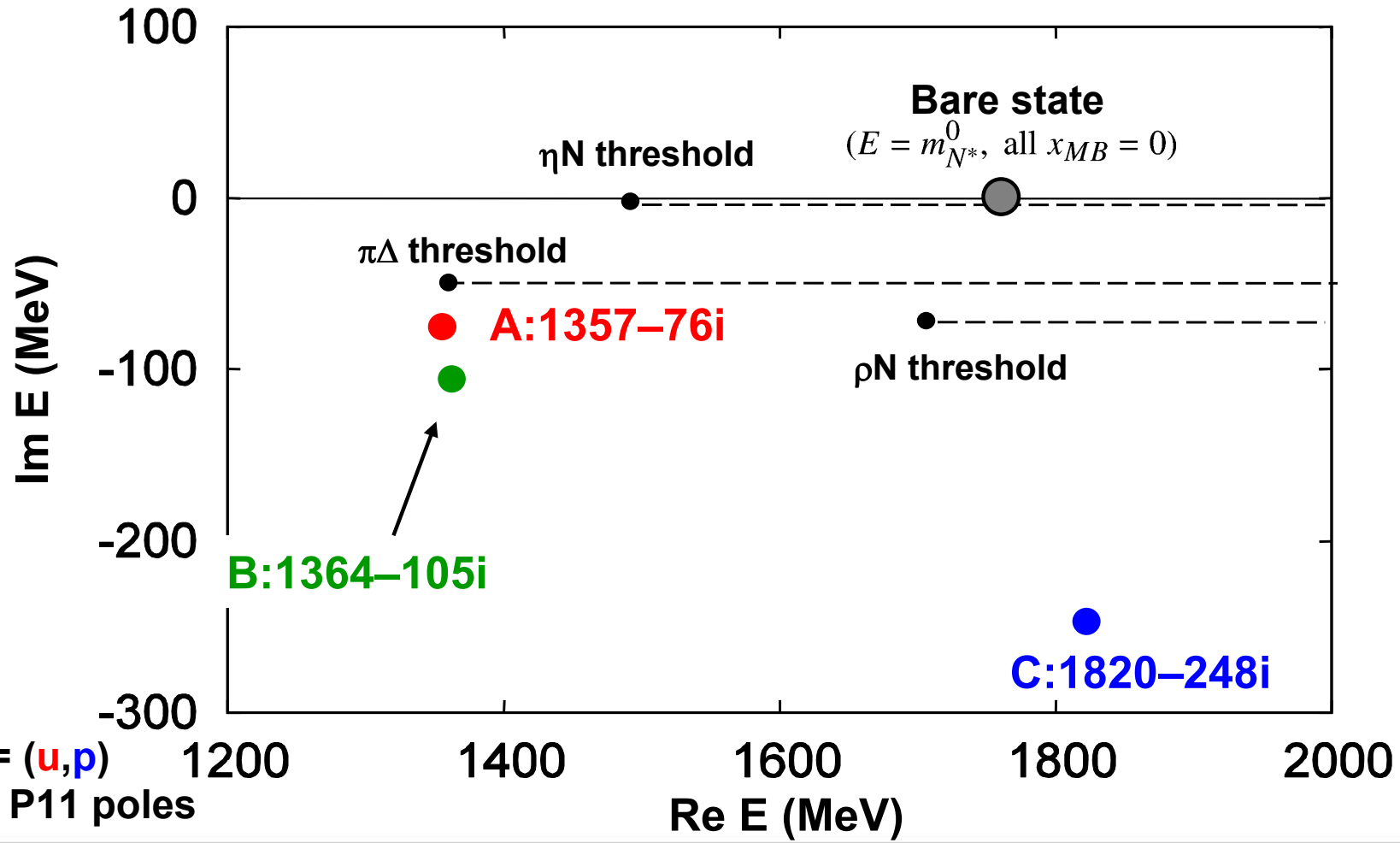
N-channels → Need 2^N Riemann sheets

Dynamical origin of P11 resonances

Suzuki, Julia-Diaz, Kamano, Lee, Matsuyama, Sato, PRL104 042302 (2010)

Pole trajectory of N* propagator

$$\frac{1}{E - m^0_{N^*} - \sigma(E)} \rightarrow \frac{1}{E - m^0_{N^*} - \sum_{MB} x_{MB}\sigma_{MB}(E)} \qquad x_{MB} : 0 \rightarrow 1$$



(πN,σN) = (u,p) for three P11 poles

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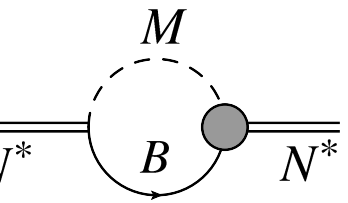
self-energy:

$$\sigma(E) = \sum_{MB} \sigma_{MB}(E) = \sum_{MB}$$



$$[MB = (\pi N,\ \eta N,\ \pi\Delta,\ \sigma N,\ \rho N)]$$

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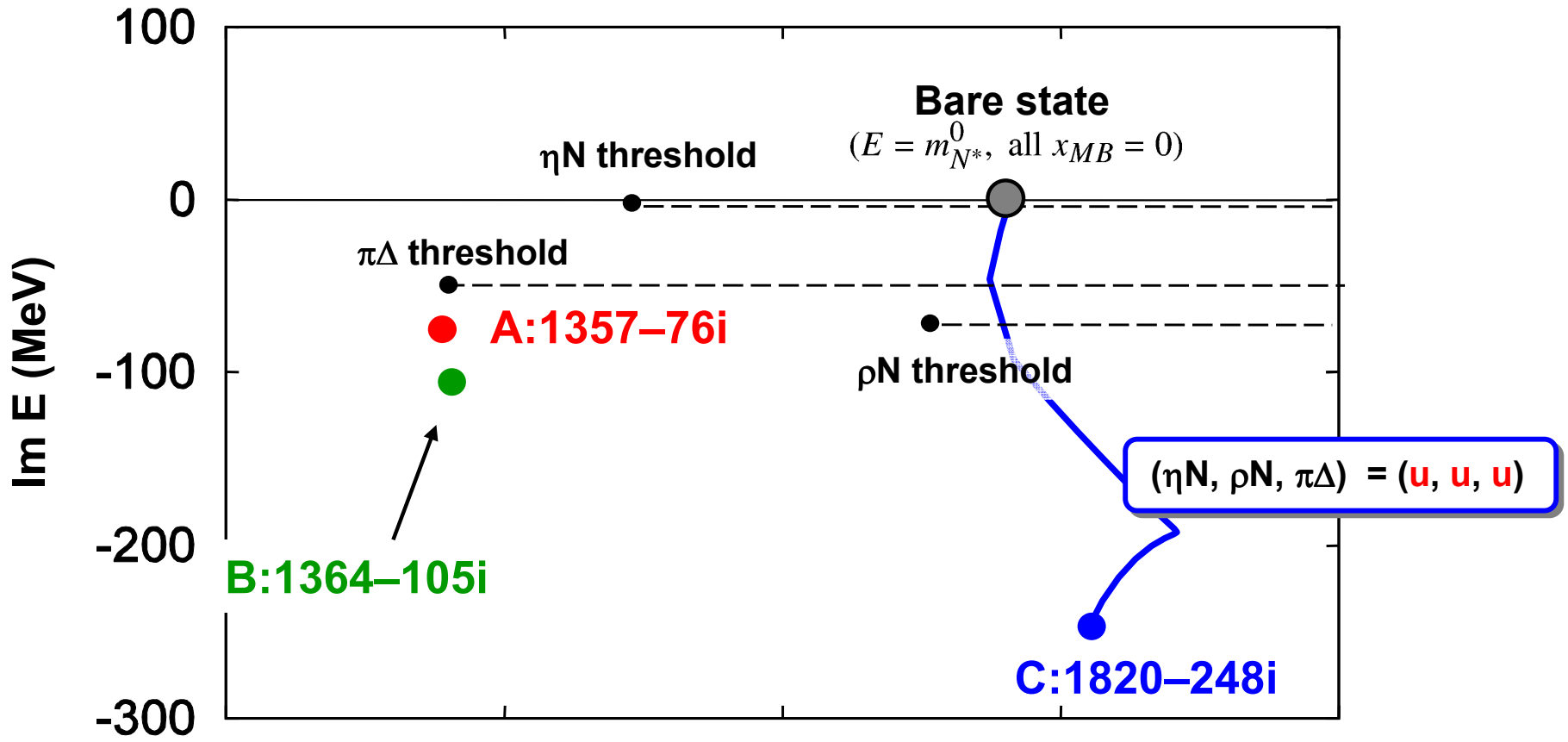

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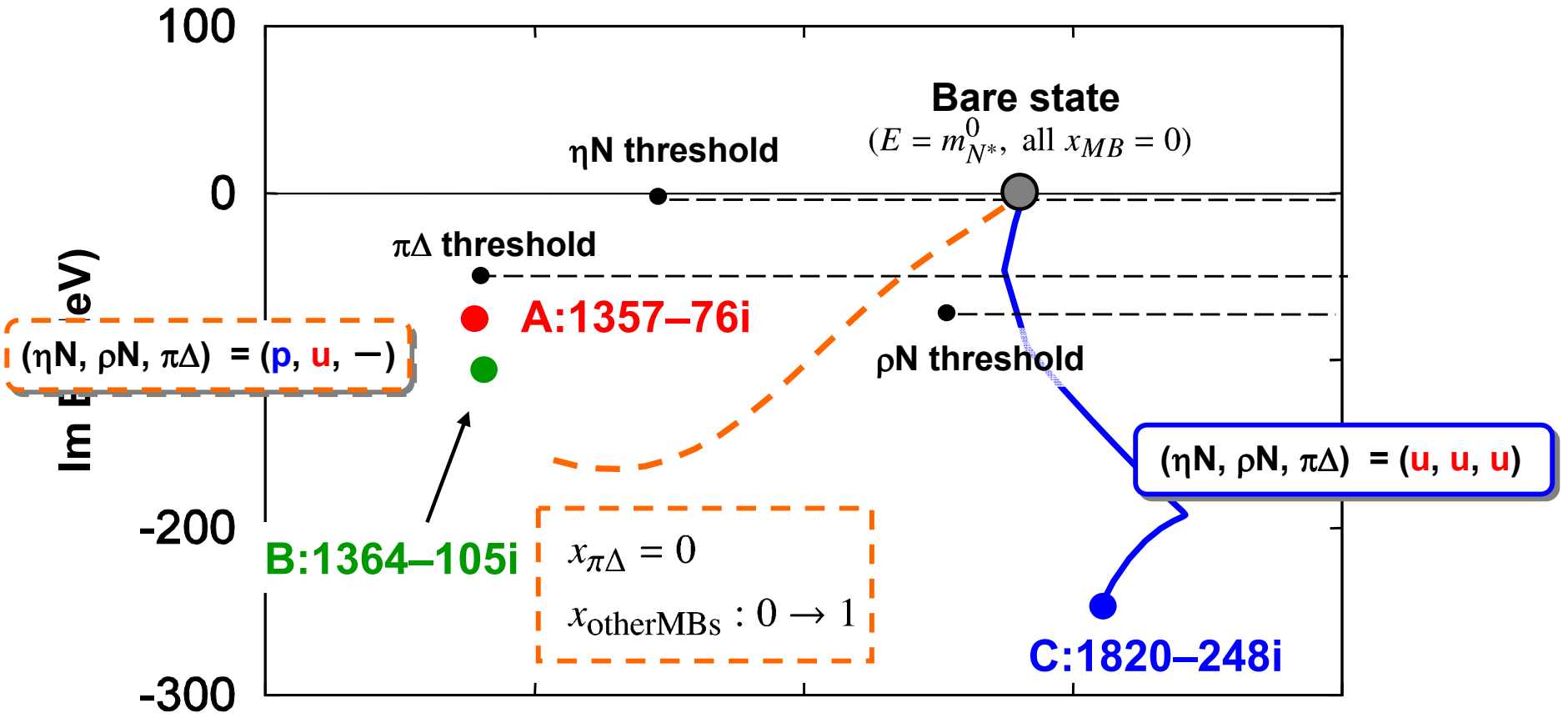

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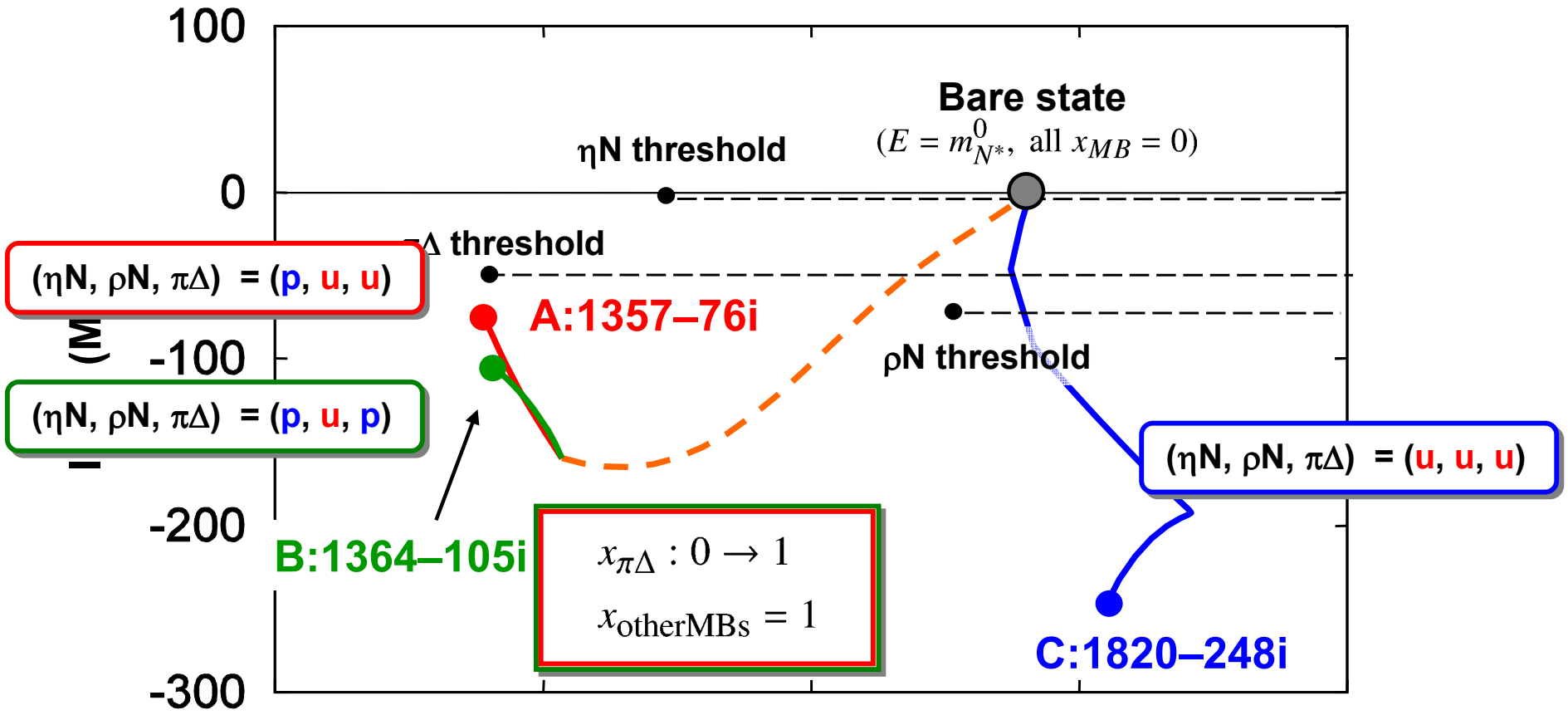

(πN,σN) = (u,p)
for three P11 poles

Summary

- ✓ Continuous effort for exploring the N* states in Excited Baryon Analysis Center (EBAC) at Jefferson Lab.
- ✓ Scattering amplitudes are successfully constructed by dynamical coupled-channels analysis of meson production reactions.
- ✓ Dynamical origin of the P11 nucleon resonances:
  - ➢ *Two* resonance poles are found in the Roper energy region.
  - ➢ (Two) Roper and N*(1710) originate from a same, single bare state.

Treatment of *multi*-reaction channels is key to understanding the N* spectrum !!