New understanding of nucleon resonances:
Results from the Excited Baryon Analysis Center

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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

Argonne Physics Division Seminar, March 15, 2010

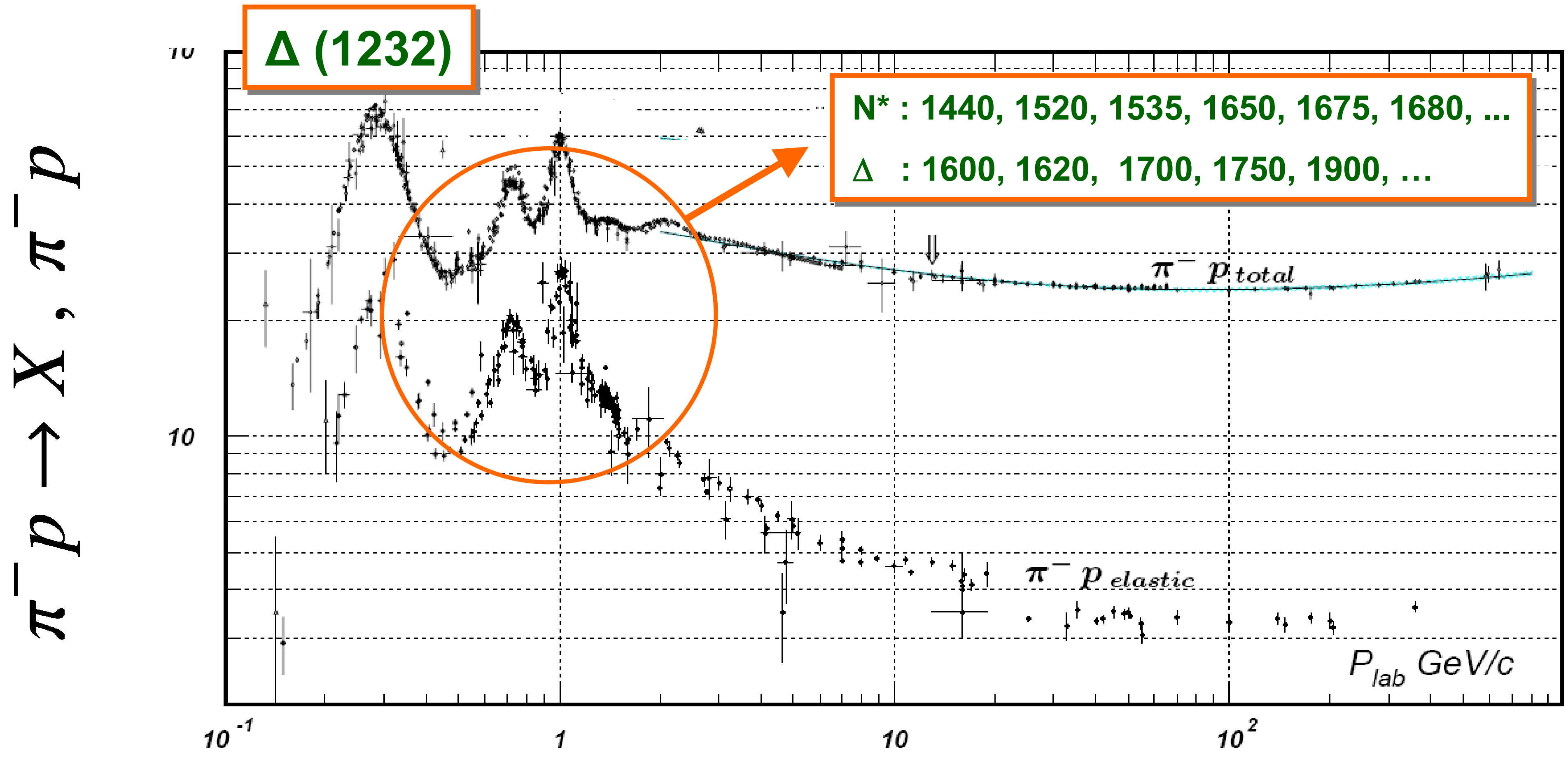
Outline

1. Motivation and research program for the N* study at EBAC

2. Extraction of resonances and their dynamical origins

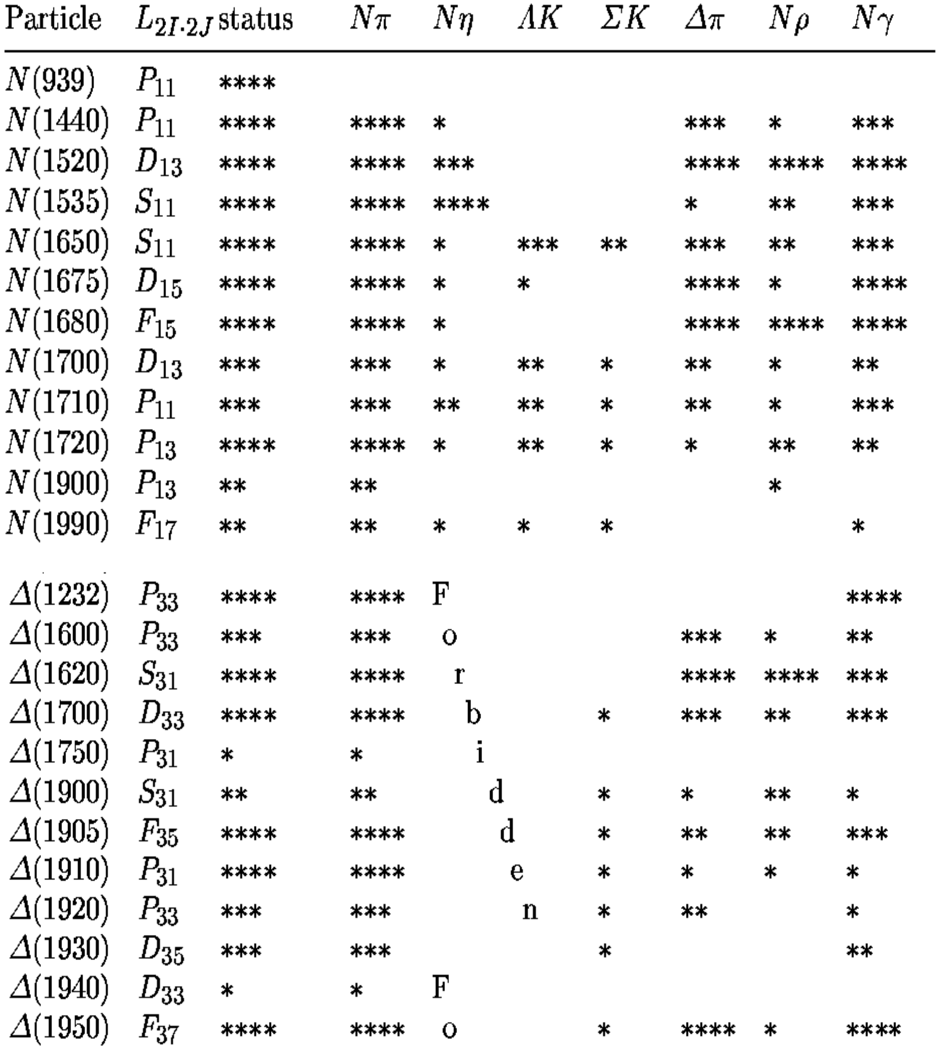
Motivation and research program for the N* study at EBAC
(1 of 2)

N* states - Δ(1232) and others -

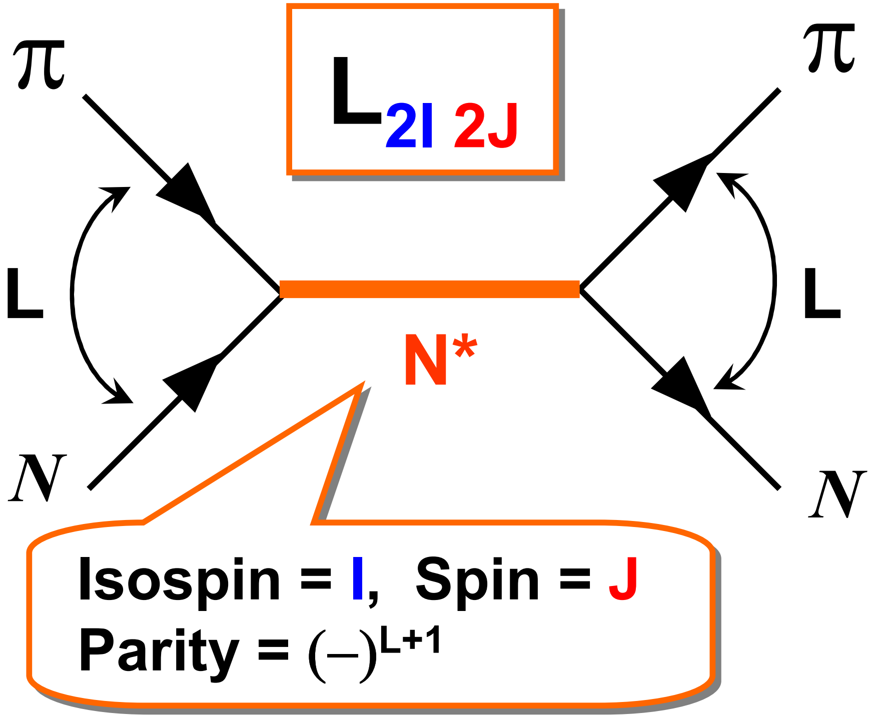


- ✓ The **Delta (1232)** resonance stands as a **clear peak.**
- ✓ The region $s^{1/2}$ = 1.4 – 2 GeV hosts ~ **20** resonances.

N* states and PDG *s



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



$L_{2I\ 2J}$

Isospin = I, Spin = J
Parity = $(-)^{L+1}$

N* states and PDG *s

> 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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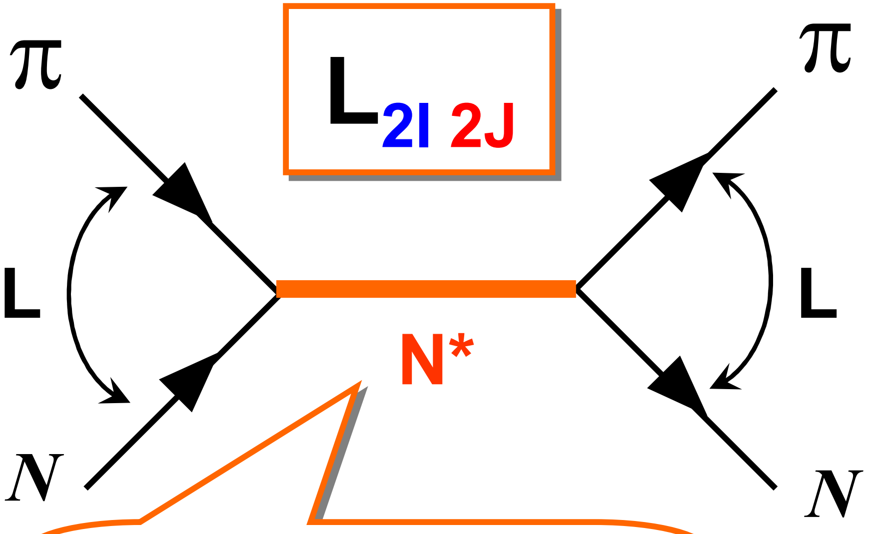

$L_{2I\ 2J}$

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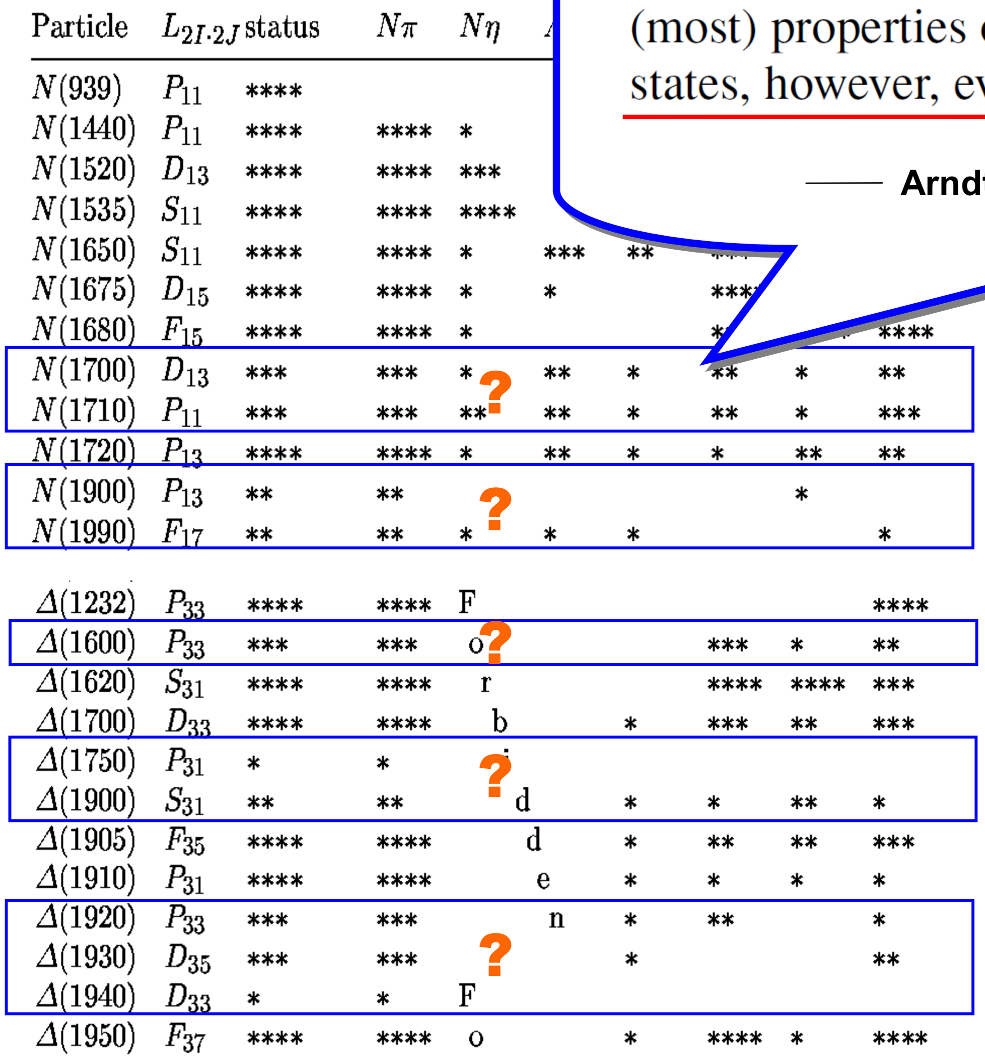
N* states and PDG *s



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$N(1720)$	P_{13}	****	****	*	**	*	*	**	**
$N(1900)$	P_{13}	**	**	?				*	
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> 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

$$\pi N \rightarrow \pi N \;, \quad \gamma N \rightarrow \pi N$$

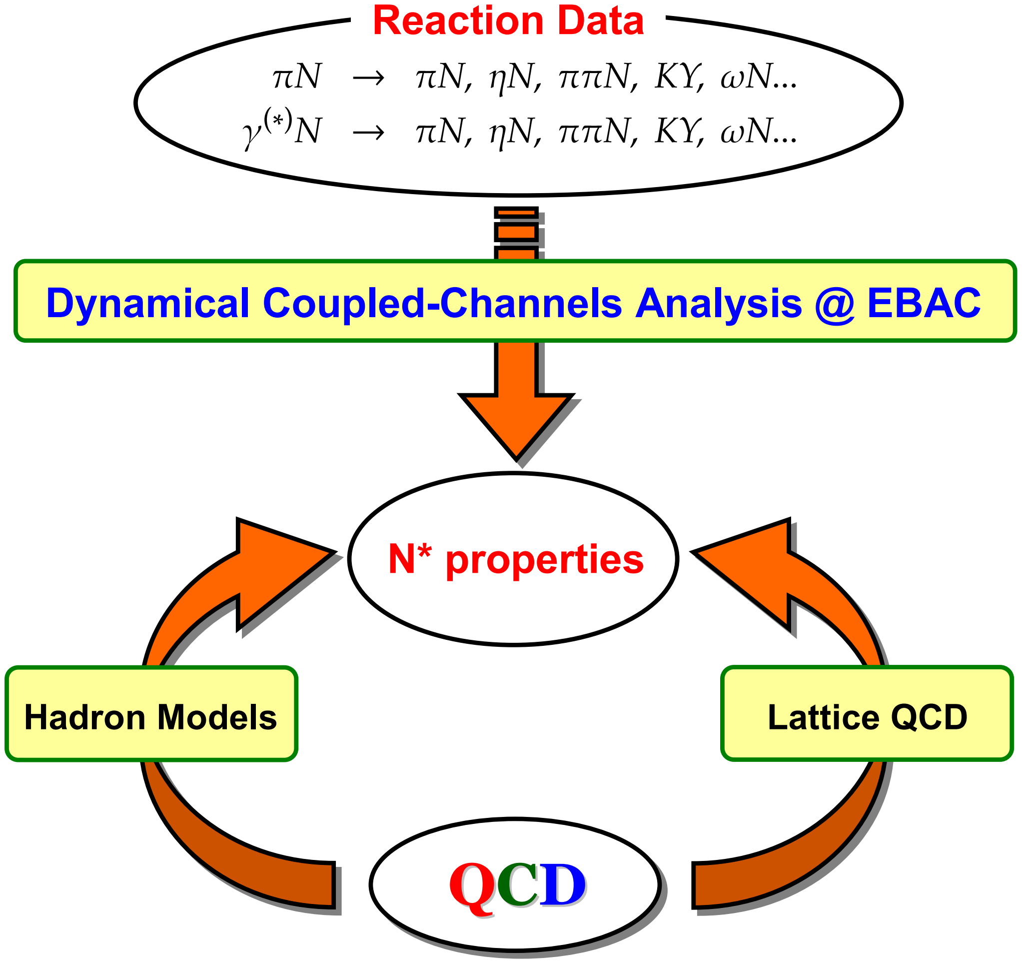
Need *combined analysis* of

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

Excited Baryon Analysis Center (EBAC) of Jefferson Lab

Founded in January 2006

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



Reaction Data

$$\pi N \rightarrow \pi N,\ \eta N,\ \pi\pi N,\ KY,\ \omega N...$$

$$\gamma^{(*)}N \rightarrow \pi N,\ \eta N,\ \pi\pi N,\ KY,\ \omega N...$$

Dynamical Coupled-Channels Analysis @ EBAC

N* properties

Hadron Models

Lattice QCD

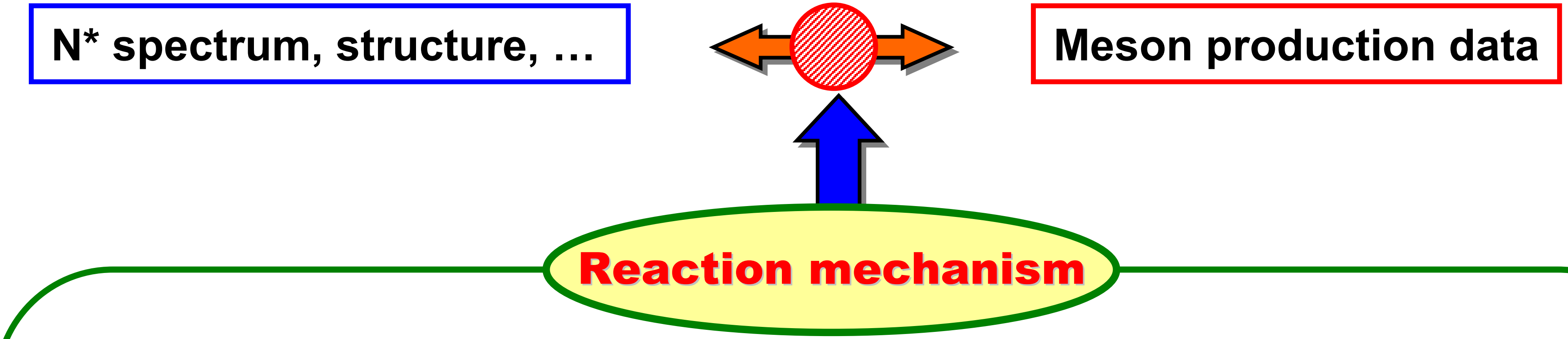
QCD

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**
- ✓ **Provide information about reaction mechanism necessary to interpret the N* properties**

Basic reaction model



N* spectrum, structure, …

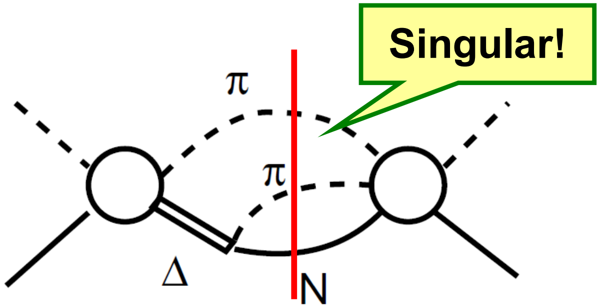
Meson production data

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 $\pi N,\ \eta N,\ \pi\pi N, K\Lambda, K\Sigma, \omega N$...
- ✓ Can treat 3-body $\pi\pi N$ 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:**

$$V_{a,b} = \underbrace{v_{a,b}}_{\text{exchange potential of ground state mesons and baryons}} + \underbrace{\sum_{N^*} \frac{\Gamma^\dagger_{N^*,a}\Gamma_{N^*,b}}{E - M_{N^*}}}_{\text{bare N* state}}$$

Dynamical coupled-channels model @ EBAC

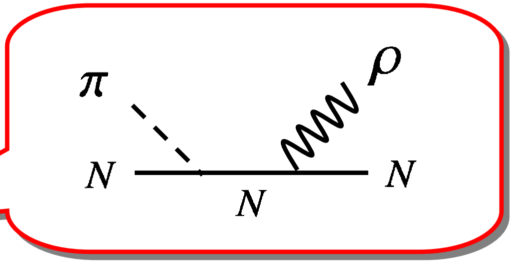
For details see Matsuyama, Sato, Lee, Phys. Rep. 439,193 (2007)

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

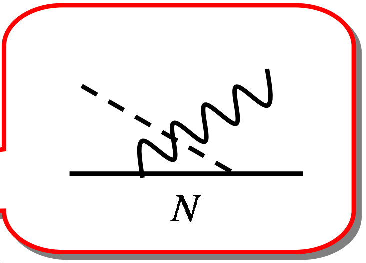
$$\bar{V}(7) = \bar{V}_a^7 + \bar{V}_b^7 + \bar{V}_c^7 + \bar{V}_d^7 + \bar{V}_e^7$$

with

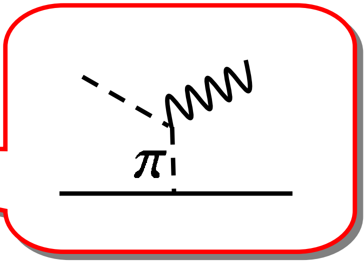
$$\bar{V}_a^7 = i\frac{f_{\pi NN}}{m_\pi} g_{\rho NN} \Gamma_{\rho'} S_N(p+k) \not{k} \gamma_5 \tau^i,$$



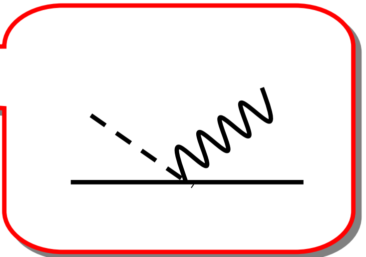
$$\bar{V}_b^7 = i\frac{f_{\pi NN}}{m_\pi} g_{\rho NN} \not{k} \gamma_5 \tau^i S_N(p-k') \Gamma_{\rho'},$$



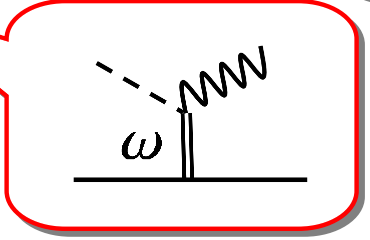
$$\bar{V}_c^7 = \frac{f_{\pi NN}}{m_\pi} g_{\rho\pi\pi} \epsilon_{ijl} \tau^l \frac{(q-k)\cdot\epsilon^*_{\rho'} \not{q} \gamma_5}{q^2 - m_\pi^2},$$



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



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



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 @ EBAC

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

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

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

- ✓ **Reacti**

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

- ✓ **Potential:**

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

exchange potential of ground state mesons and baryons

bare N* state

Strategy for the N* study @ EBAC

Stage 1

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

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.

- CQM, DSE, Large Nc, Soliton models,…
- Connection to the Lattice QCD data

Current status of the EBAC-DCC analysis

Hadronic part

- ✓ $\pi N \rightarrow \pi N$: fitted to the data 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

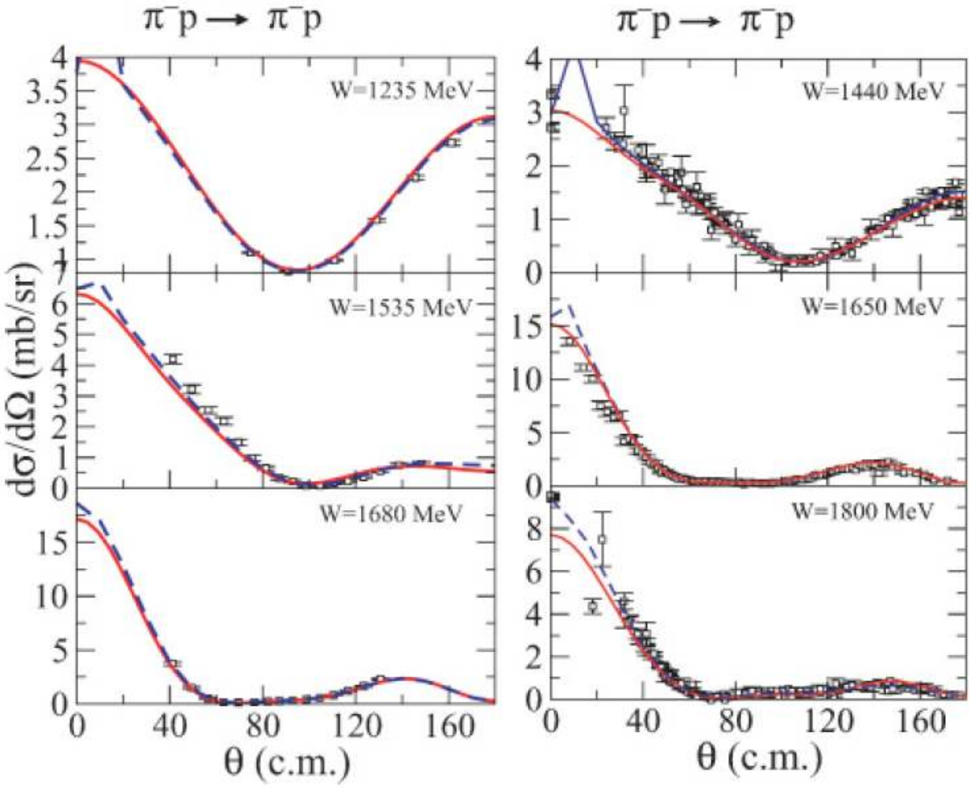
- ✓ $\gamma^{(*)} N \rightarrow \pi N$: fitted to the data up to W = 1.6 GeV (and up to Q^2 = 1.5 GeV^2)
  (photoproduction) Julia-Diaz, Lee, Matsuyama, Sato, Smith, PRC77 045205 (2008)
  (electroproduction) Julia-Diaz, Kamano, Lee, Matsuyama, Sato, Suzuki, PRC80 025207 (2009)
- ✓ $\gamma N \rightarrow \pi \pi N$: cross sections calculated with the γN & πN model; fit is ongoing.
  Kamano, Julia-Diaz, Lee, Matsuyama, Sato, PRC80 065203 (2009)
- ✓ $\gamma^{(*)} N \rightarrow \eta N$: *in progress*
- ✓ $\gamma N \rightarrow K \Lambda$: *in progress* (Sandorfi, Hoblit, Kamano, Lee, arXiv:0912.3505)

Pion-nucleon elastic scattering

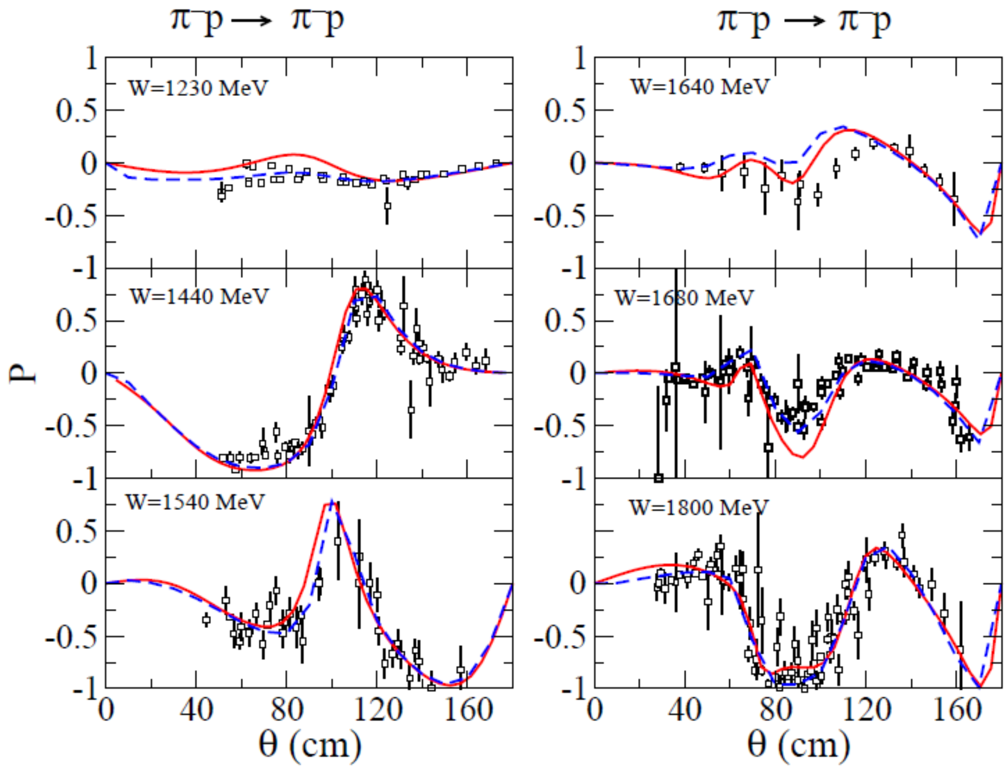
Julia-Diaz, Lee, Matsuyama, Sato, PRC76 065201 (2007)

$MB = \pi N,\ \eta N,\ \pi\pi N\ (\ni \pi\Delta,\ \sigma N,\ \rho N)$ **coupled channels are considered.**

Angular distribution



Target polarization



— **EBAC**

- - - - - **SAID (SP06)**

Pion-nucleon elastic scattering

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

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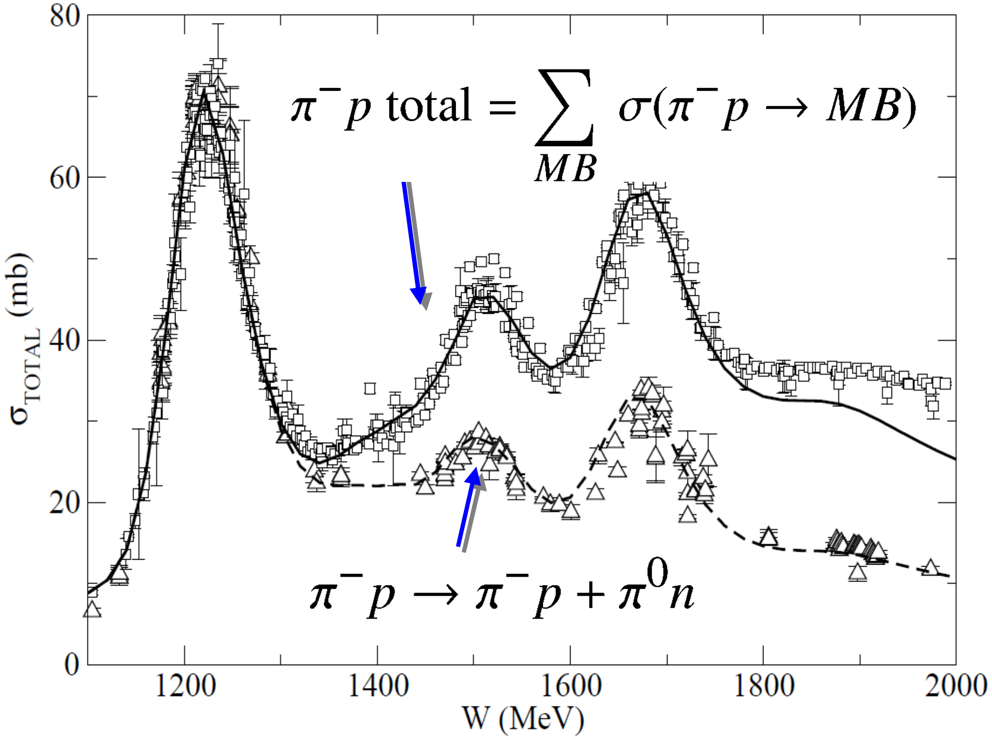
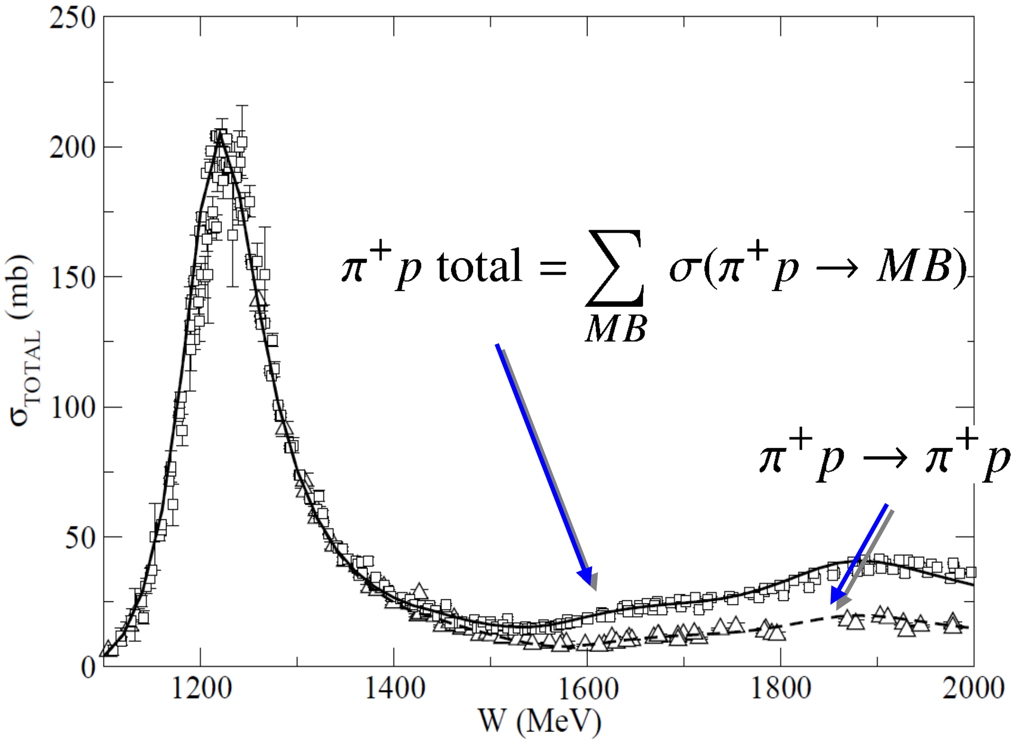


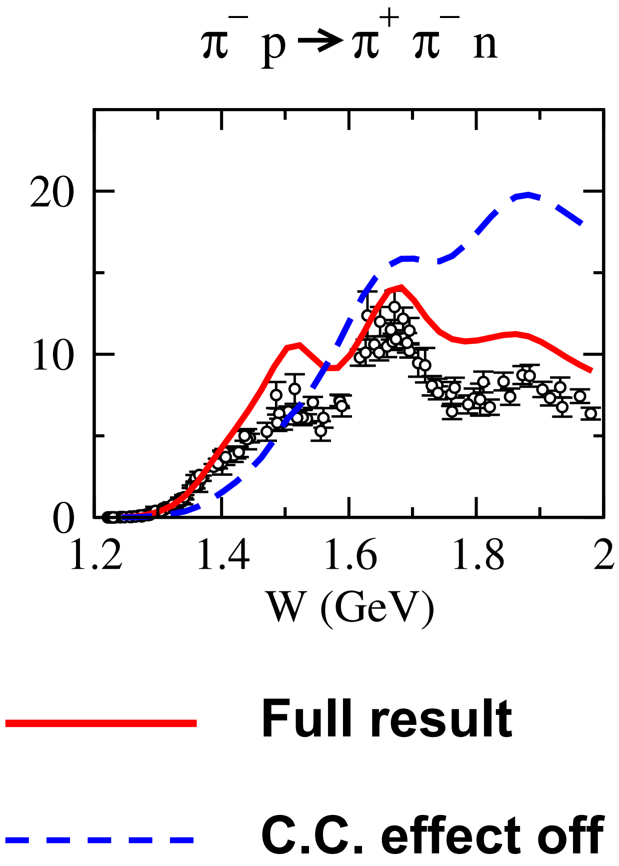


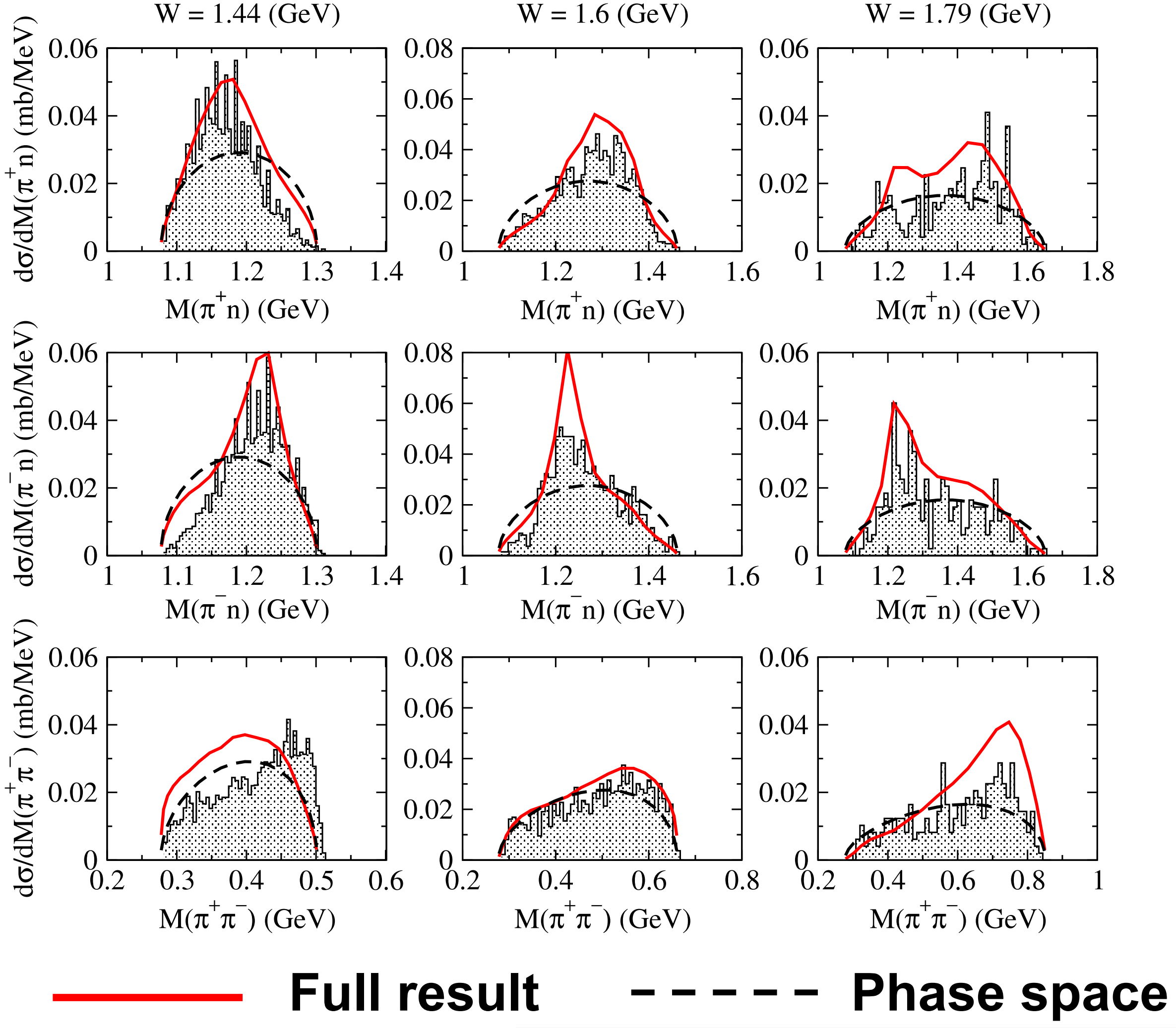
pi N → pi pi N reaction

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

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

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



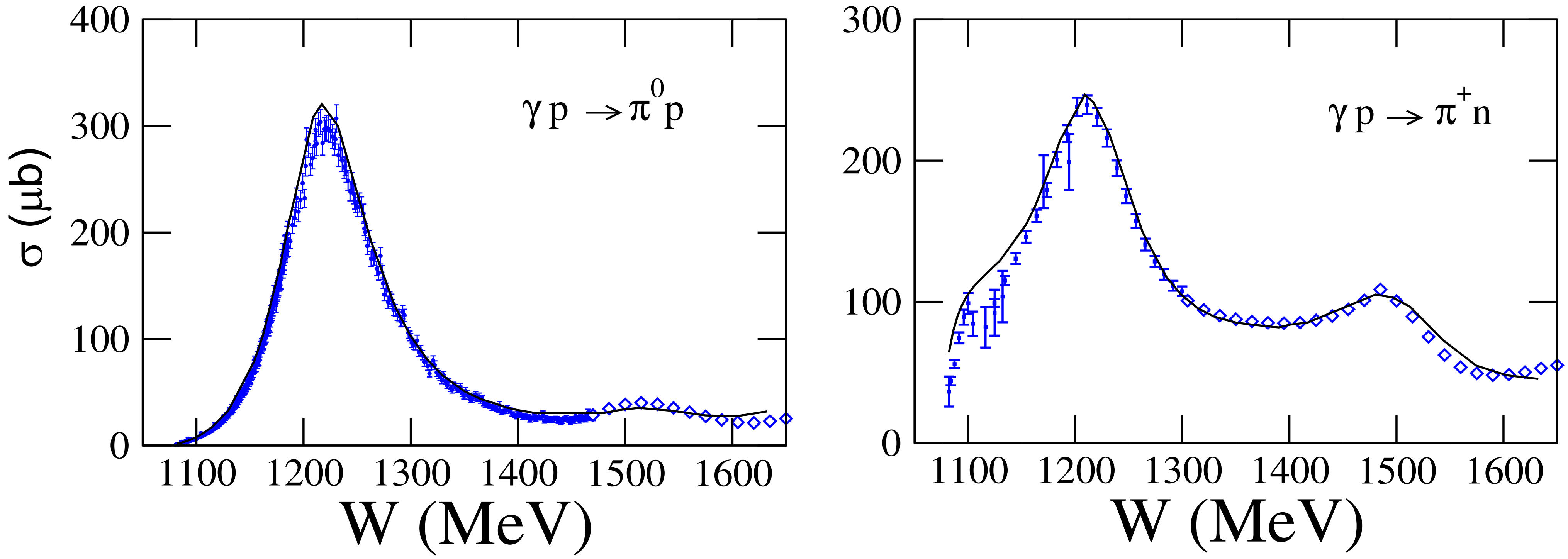


Single pion photoproduction

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**



Single pion photoproduction

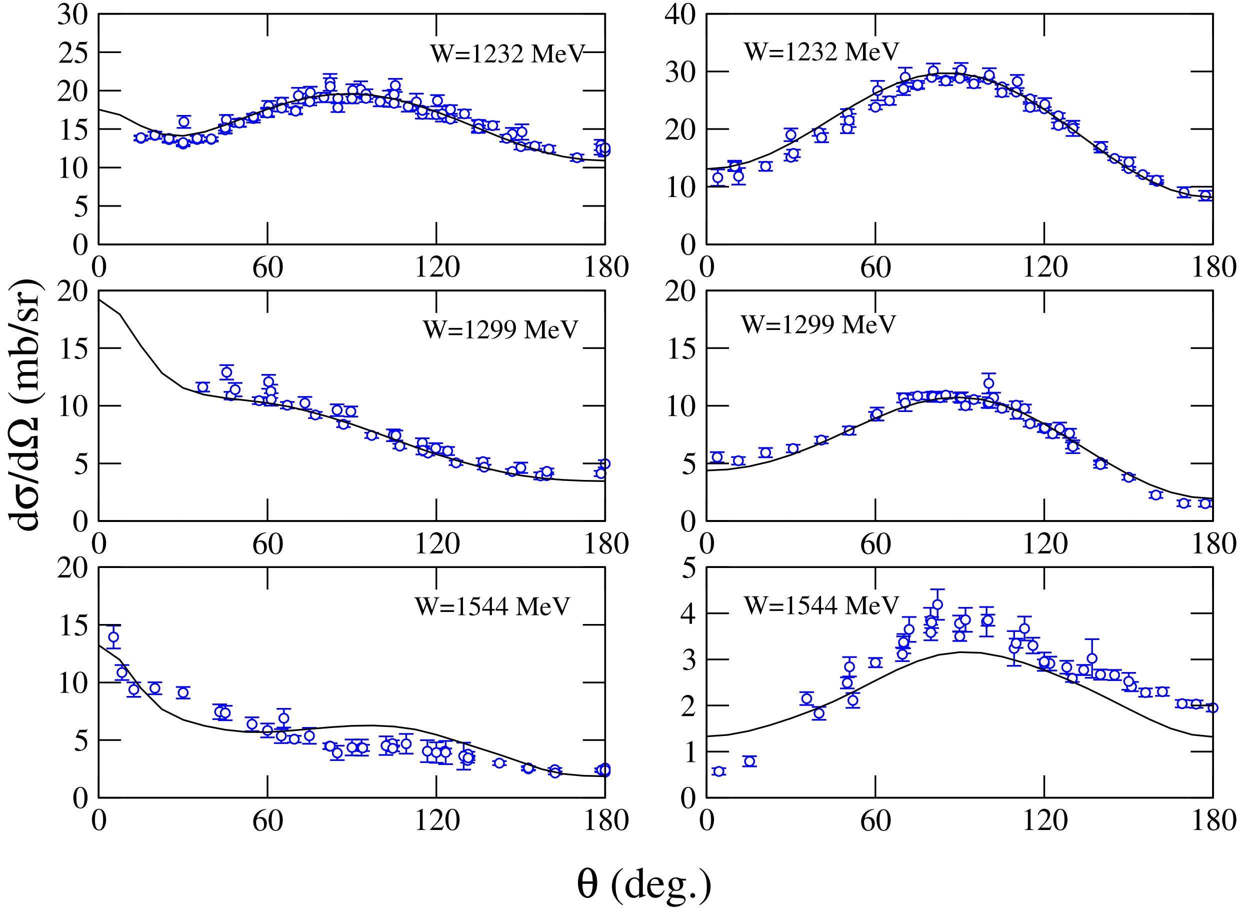
- ✓ **Fitted up to W = 1.6 GeV.**
- ✓ **Only** $\Gamma^{\text{bare}}_{\gamma N\to N^*}$ **is varied.**

☐ **Comparison to data**

- **Total cross section**
- **Differential cross section**

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

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



Single pion photoproduction

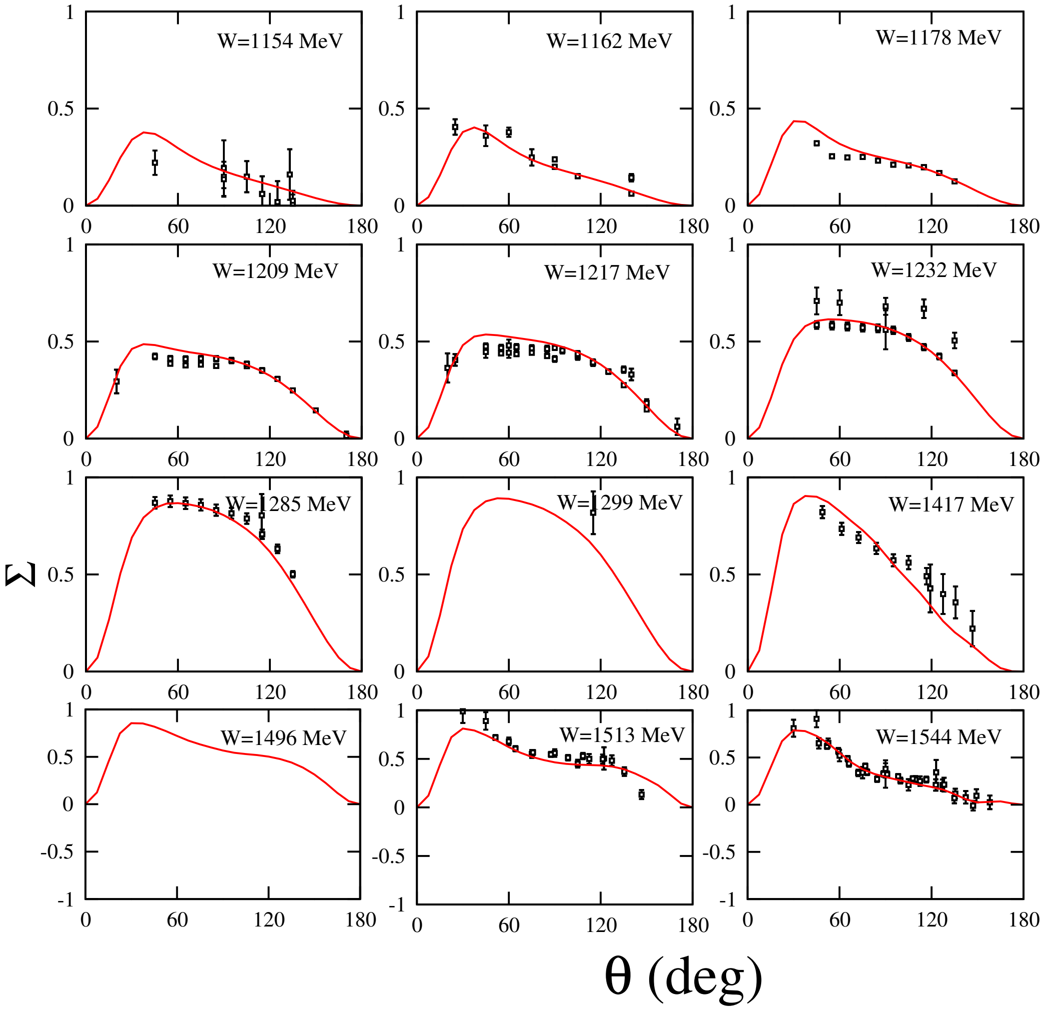
Julia-Diaz, Lee, Matsuyama, Sato, Smith, PRC77 045205 (2008)

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

☐ **Comparison to data**

- – **Total cross section**
- – **Differential cross section**
- – **Photon asymmetry**

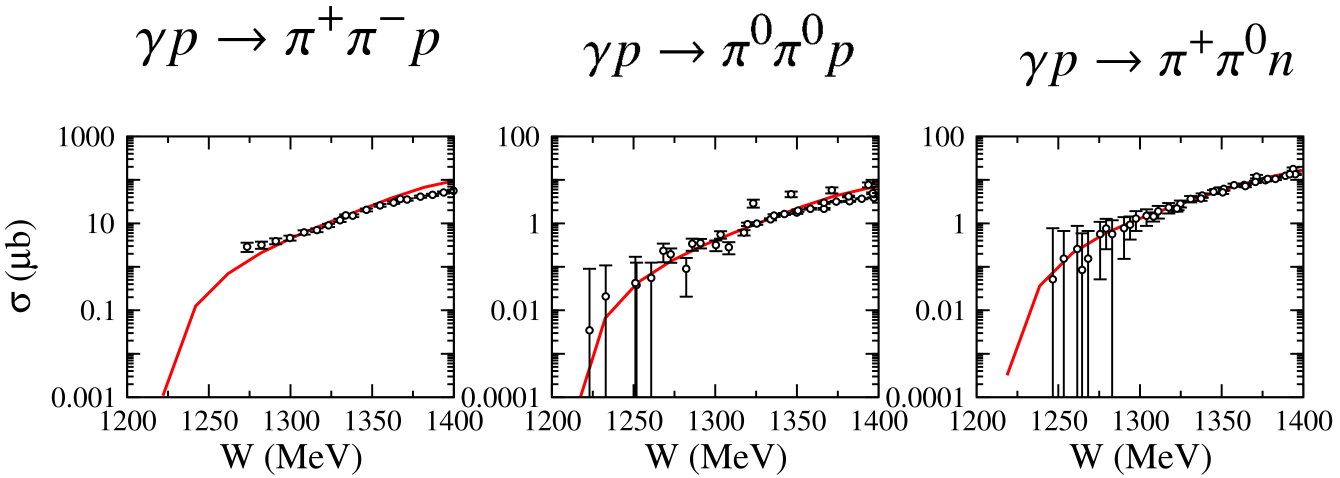
$$\gamma p \to \pi^+ n$$



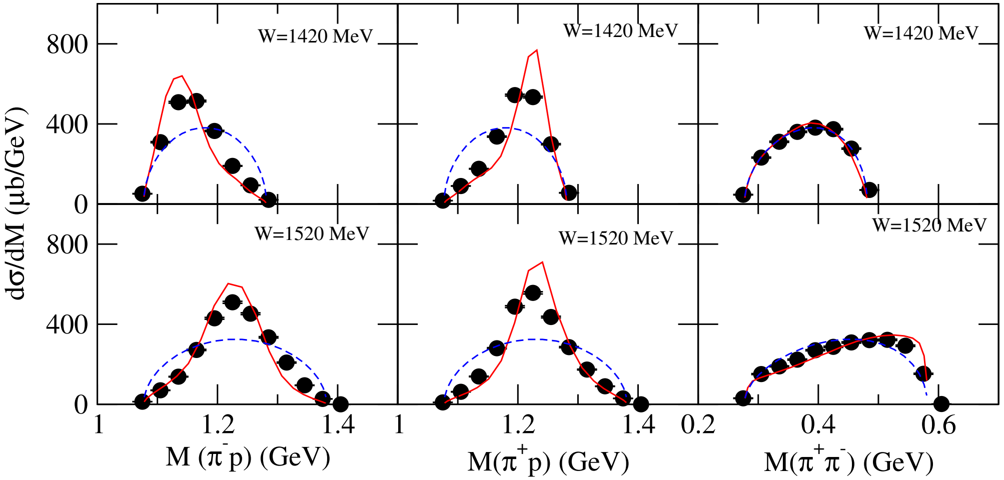
Double pion photoproduction

Kamano, Julia-Diaz, Lee, Matsuyama, Sato, PRC80 065203 (2009)

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



- ✓ **Good description near threshold**
- ✓ **Reasonable shape of invariant mass distributions**
- ✓ **Above 1.5 GeV, the total cross sections of $p\pi^0\pi^0$ and $p\pi^+\pi^-$ overestimate the data.**



Plan for EBAC-DCC analysis in 2010

EBAC second generation model

Full combined analysis (global fit) of:

~ End of 2010	$\pi N \rightarrow \pi N$	(W < 2 GeV)
	$\pi N \rightarrow \eta N$	(W < 2 GeV)
	$\gamma N \rightarrow \pi N$	(W < 1.6 GeV → 2 GeV)
	$\gamma N \rightarrow \eta N$	(W < 2 GeV)
	$\gamma N \rightarrow KY$	(W < 2 GeV)
2010 ~ 2011	$\pi N \rightarrow \pi\pi N$	(W < 2 GeV)
	$\gamma N \rightarrow \pi\pi N$	(W < 1.5 GeV → 2 GeV)

New N* states may be found !!

Extraction of resonances and their dynamical origins

(2 of 2)

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**

N* → b
decay vertex

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

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 !!

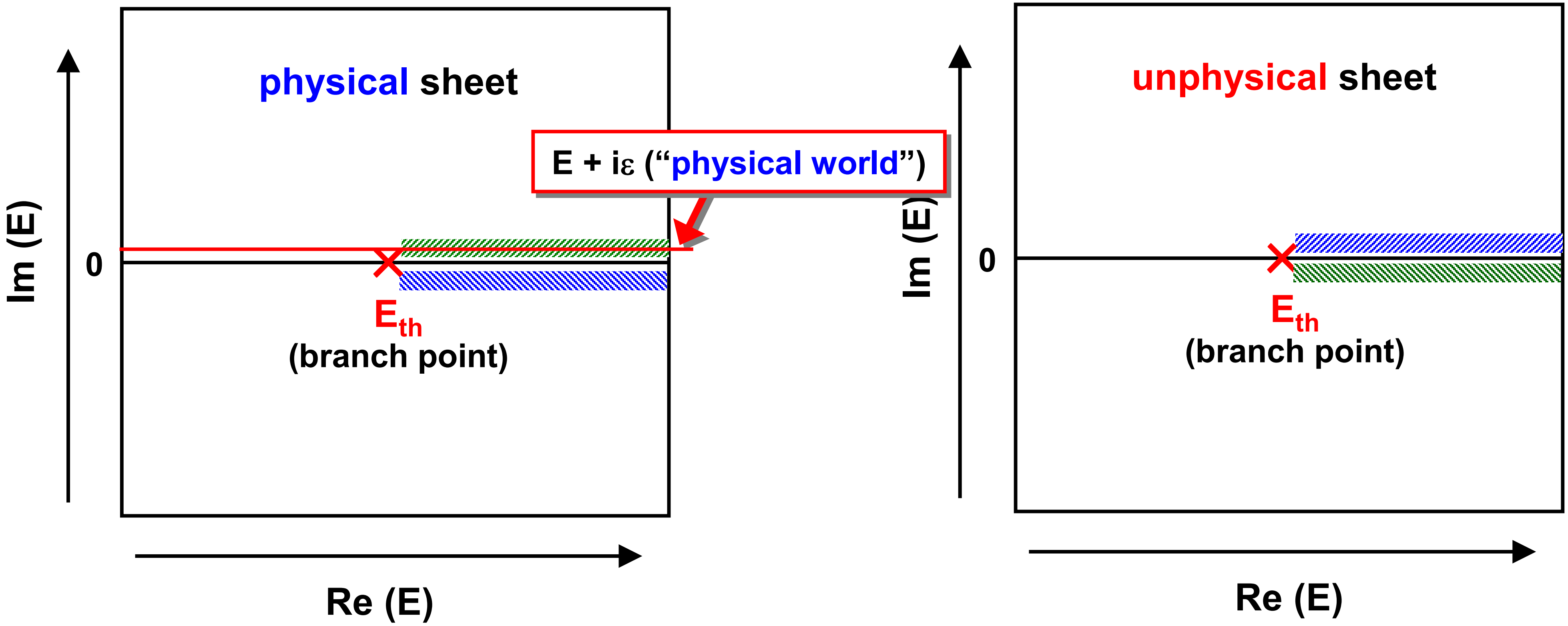
→ Suzuki, Sato, Lee, PRC79 025205 (2009); arXiv:0910.1742

Multi-layered 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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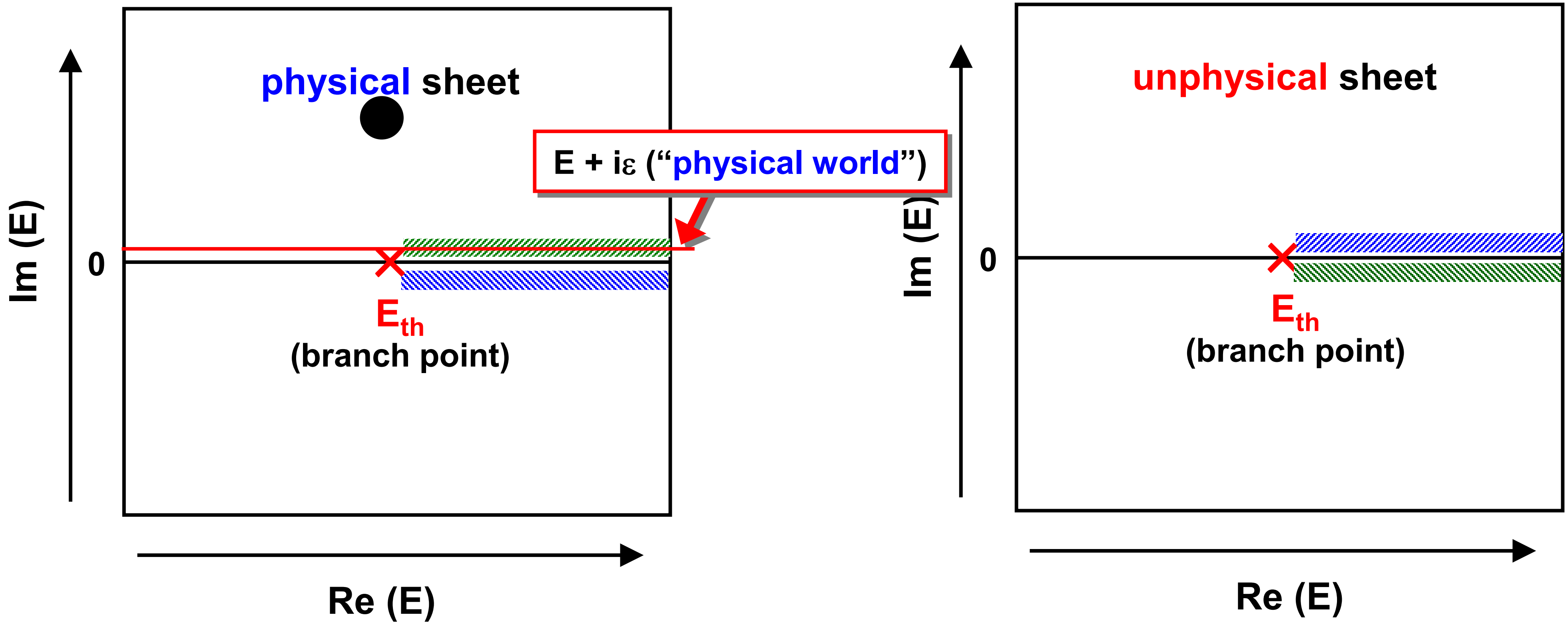

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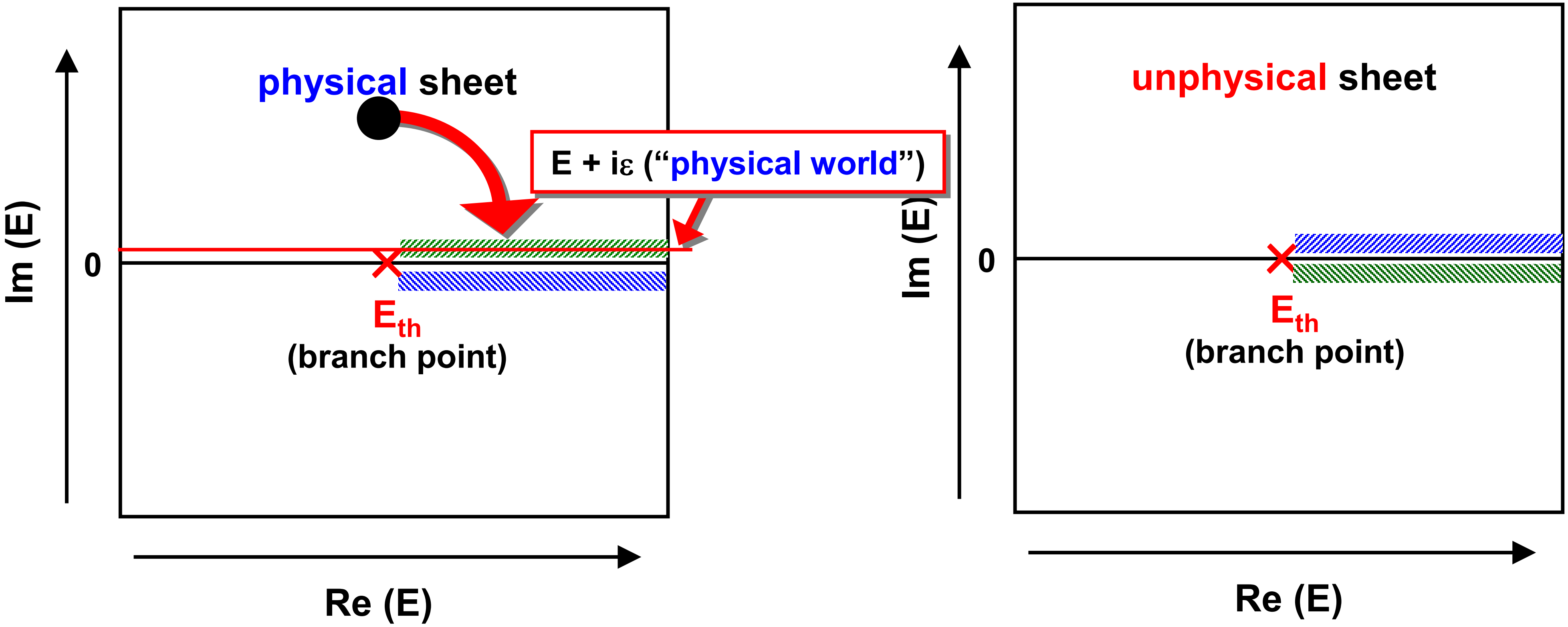

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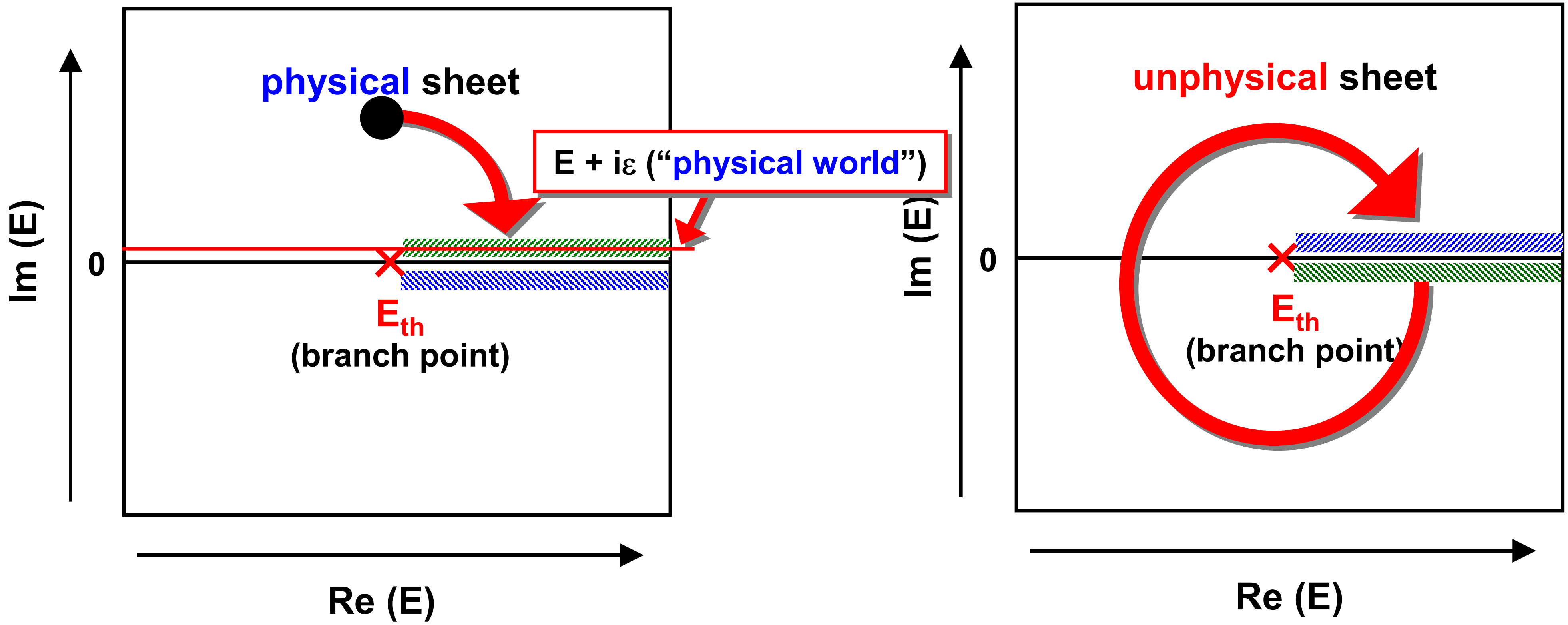

physical sheet

E + iε (“physical world”)

E_{th} (branch point)

unphysical sheet

E_{th} (branch point)

Multi-layered structure of the scattering amplitudes

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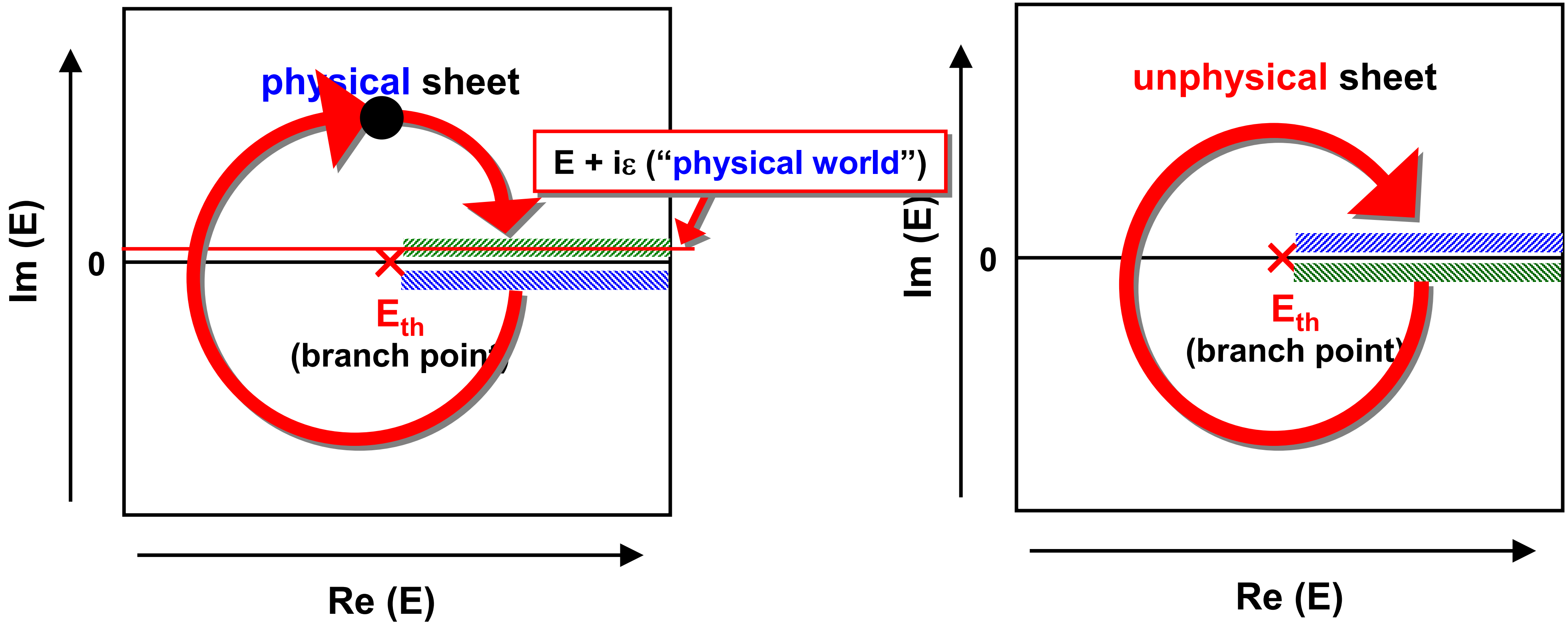


Multi-layer structure of the scattering amplitudes

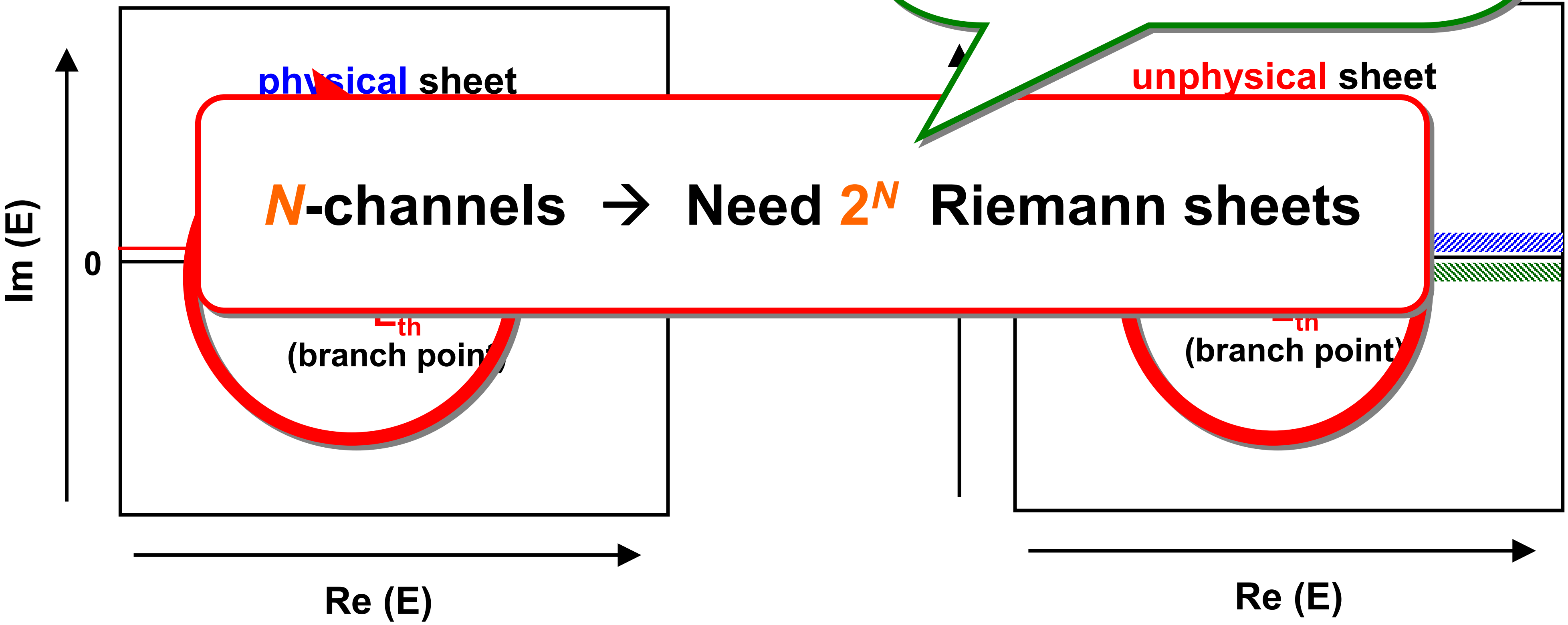
e.g.) single-channel meson-baryon scattering

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

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

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

How to choose Riemann sheet of complex E-plane

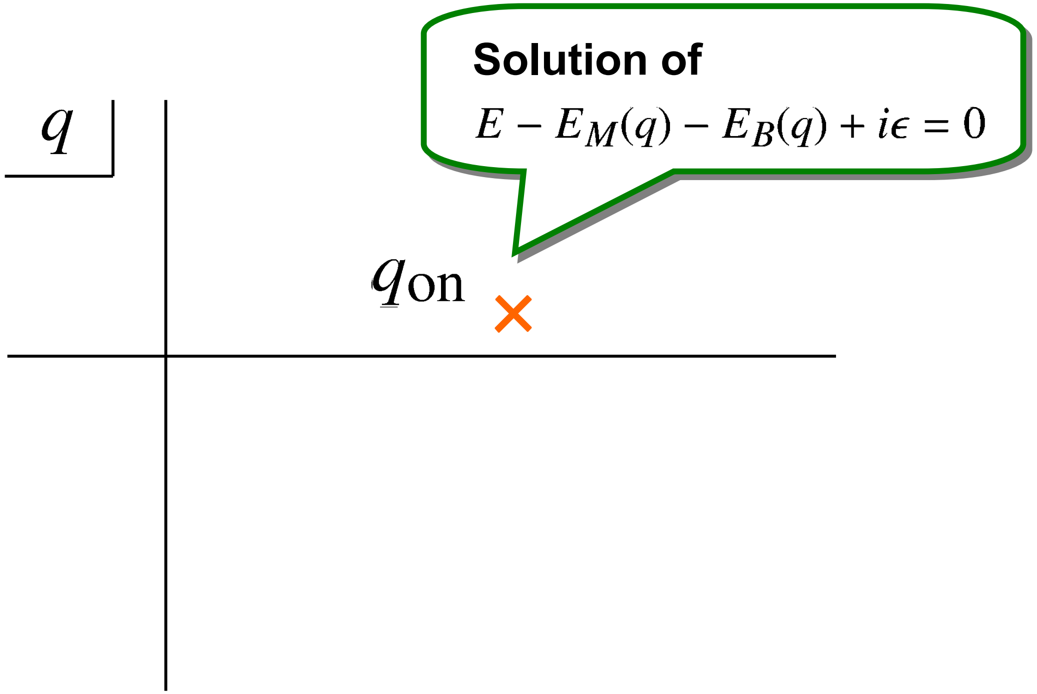
Suzuki, Sato, Lee, PRC79 025205 (2009); arXiv:0910.1742

$$T(p,p';E) = V(p,p') + \int_{\underline{C}} q^2 dq V(p,q) G_{MB}(q;E) T(q,p';E)$$

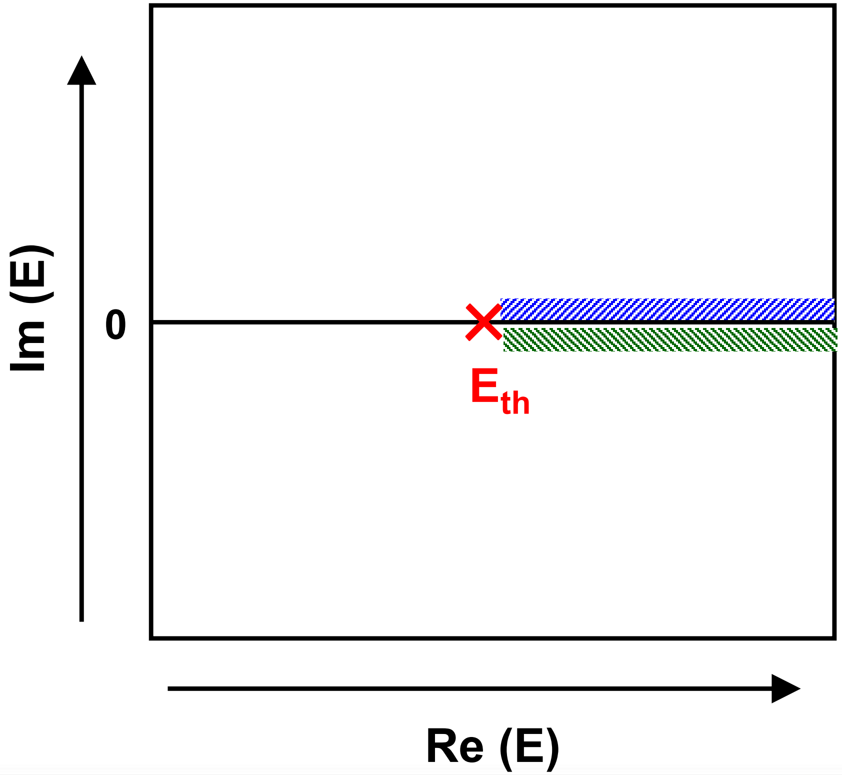
Meson-Baryon Green function $G_{MB}(q,E) = \dfrac{1}{E - E_M(q) - E_B(q) + i\epsilon}$

$$E_M(q) = \sqrt{m_M^2 + q^2}, \quad E_B(q) = \sqrt{m_B^2 + q^2}$$

For real E



Solution of
$E - E_M(q) - E_B(q) + i\epsilon = 0$



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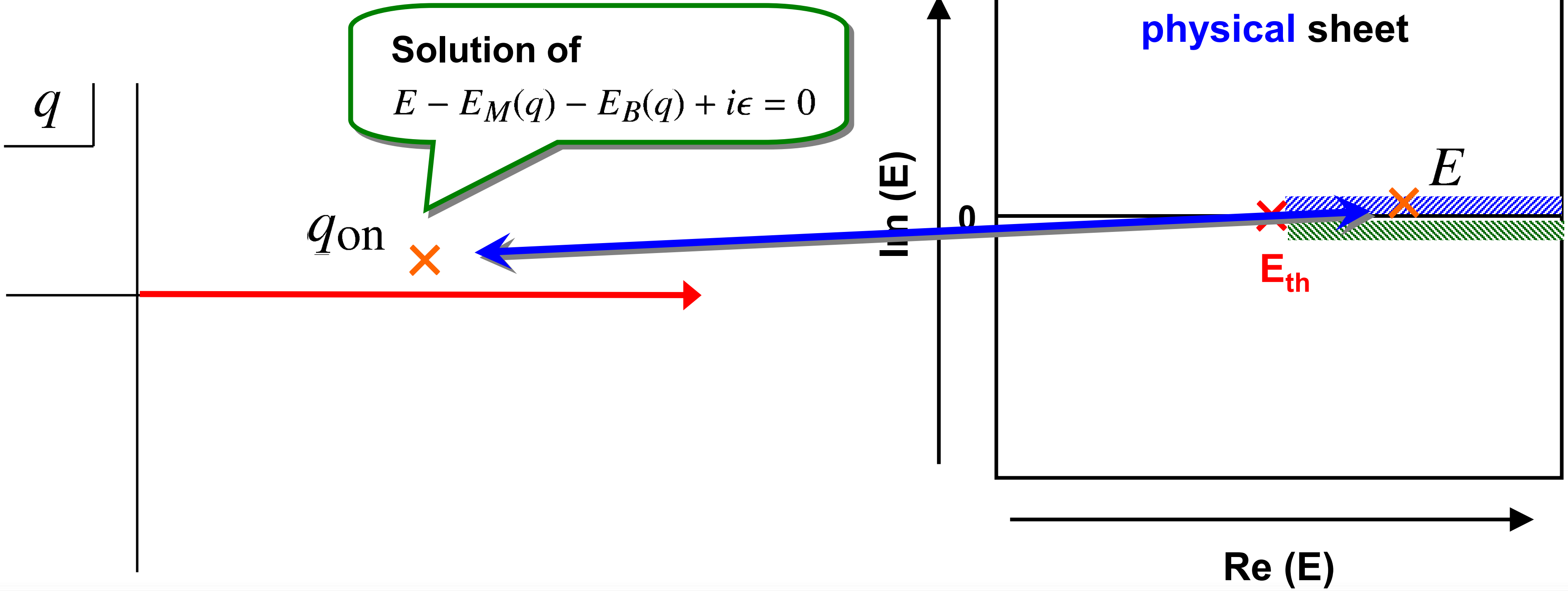

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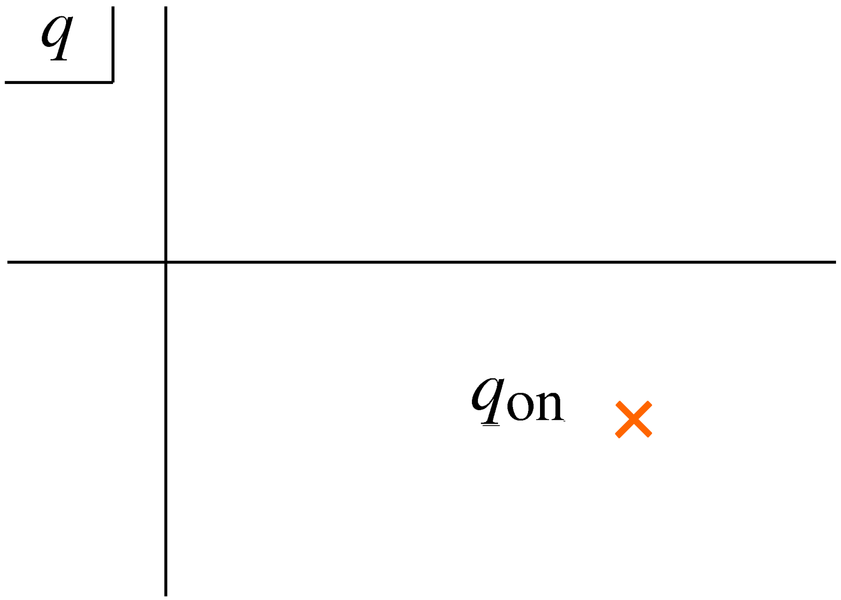
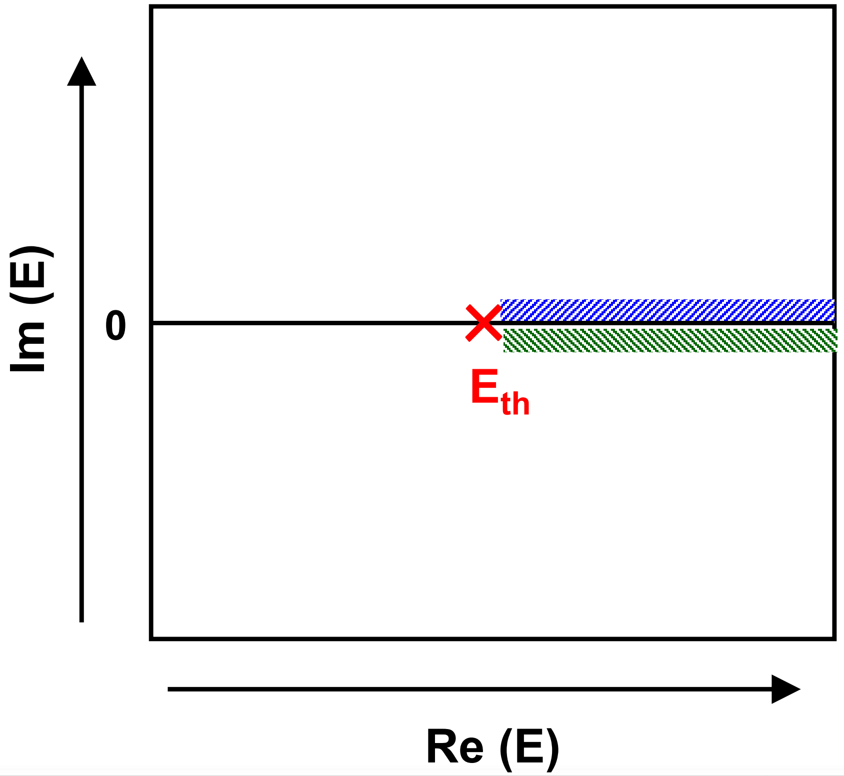
For complex E (Im E < 0)





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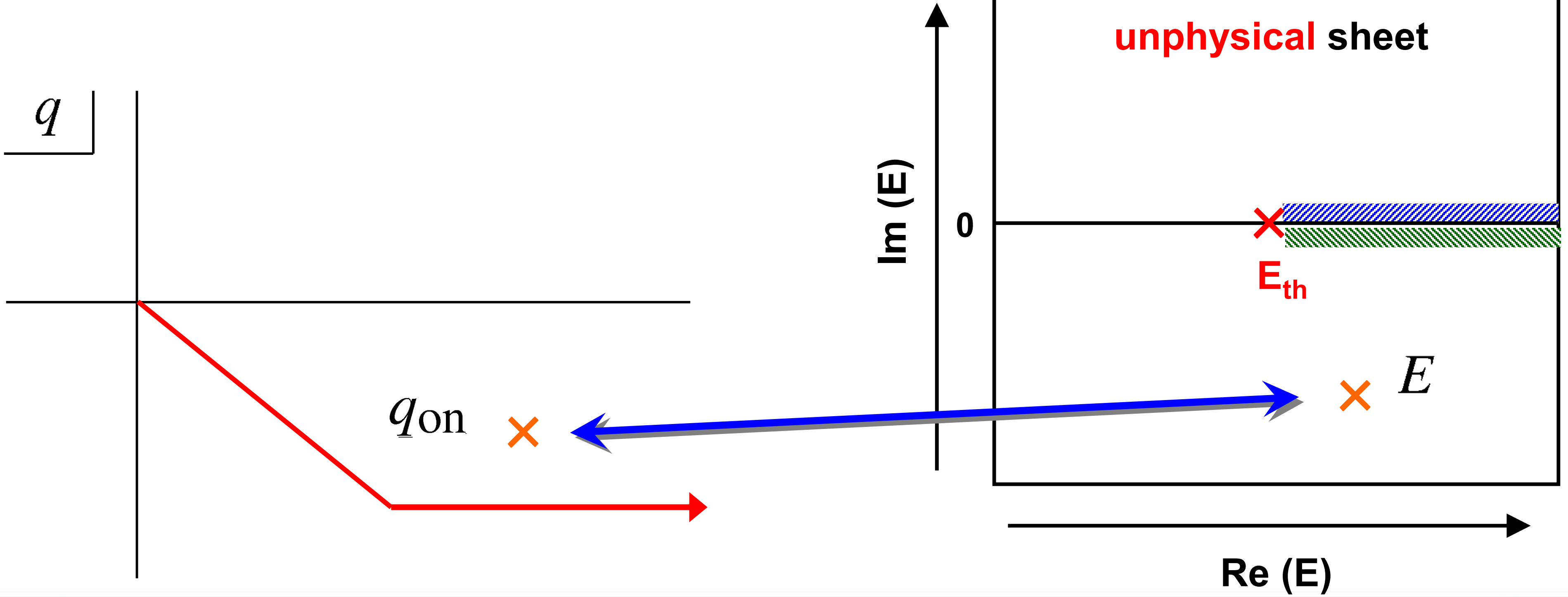

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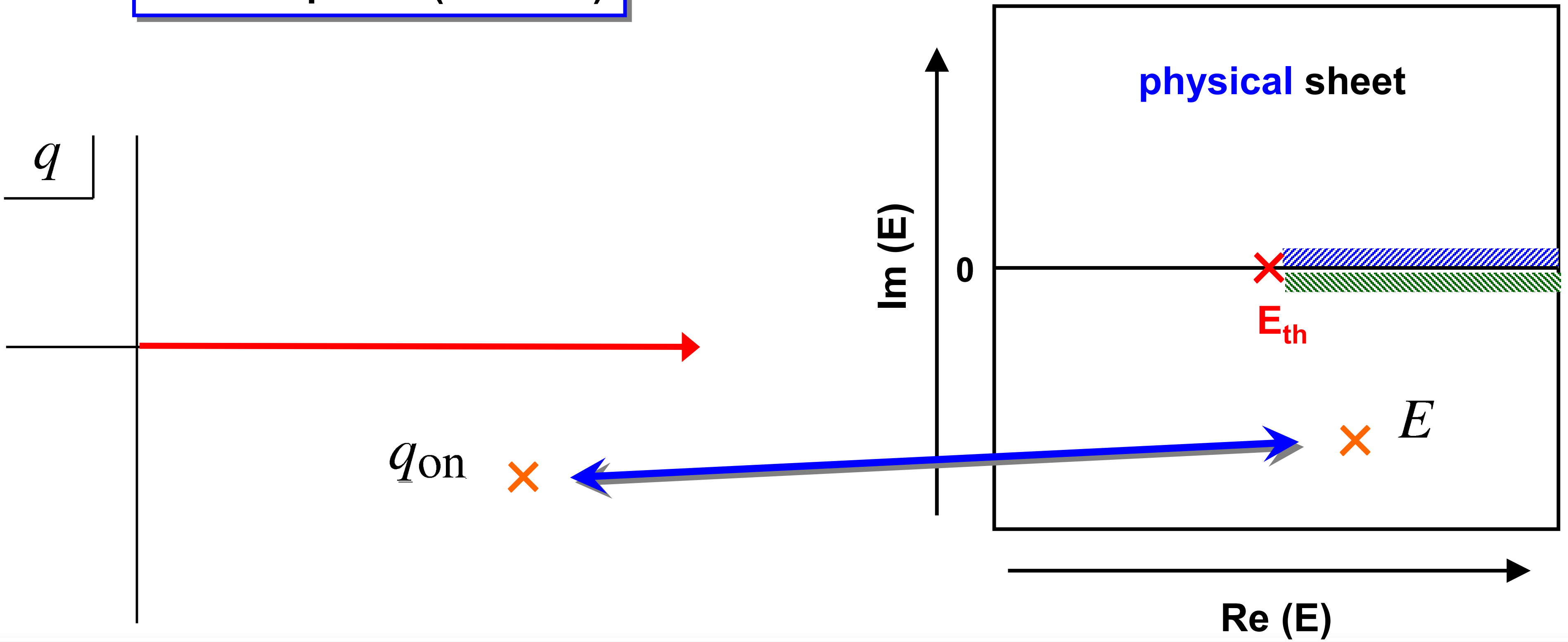


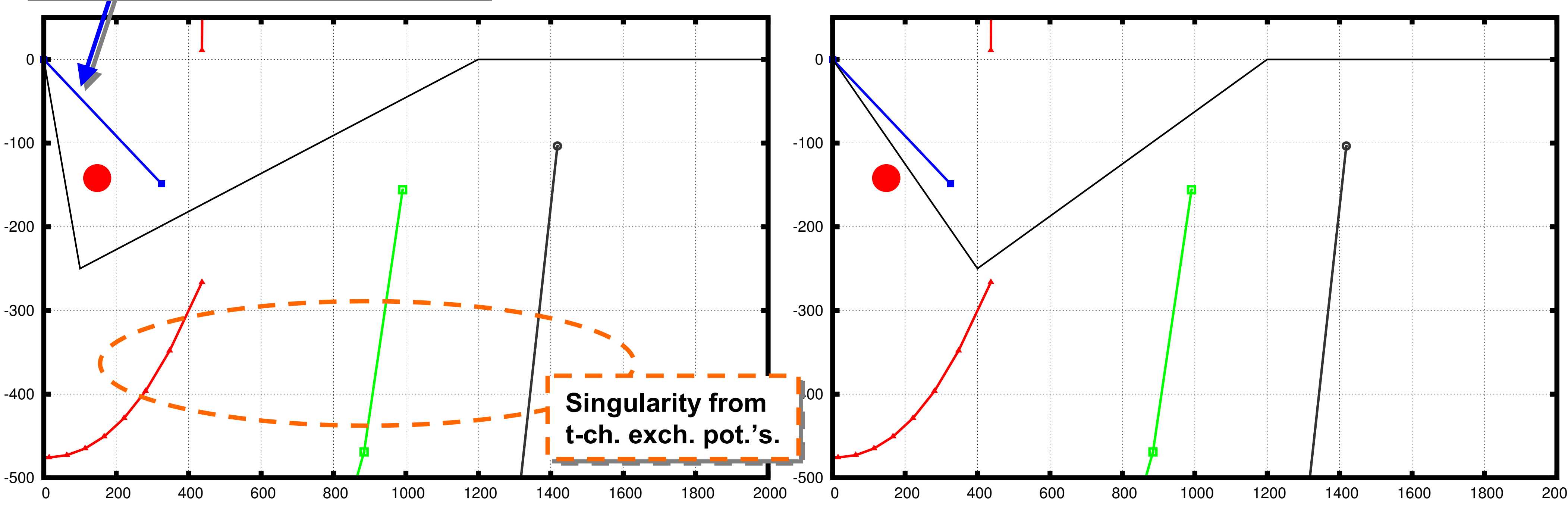
Momentum-integral path to avoid singularities

Suzuki, Sato, Lee, arXiv:0910.1742

In addition, momentum-integral path must be taken not to cross any other singularities.

Discontinuity in $\pi\Delta$, ρN, σN Green functions (coming from $\pi\pi N$ cut)

Momentum plane



Singularity from t-ch. exch. pot.'s.

➔ **Path to look at unphysical sheet of complex energy plane.**

➔ **Path to look at physical sheet of complex energy plane.**

N* poles from EBAC-DCC analysis

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

$L_{2I\,2J}$	EBAC (MeV)	PDG (MeV)
S_{11}	$1540 - 191i$	$(1490 \sim 1530) - (45 \sim 125)i$
	$1642 - 41i$	$(1640 \sim 1670) - (75 \sim 90)i$
S_{31}	$1563 - 95i$	$(1590 \sim 1610) - (57 \sim 60)i$
P_{11}	$1356 - 76i$ $1364 - 105i$	$(1350 \sim 1380) - (80 \sim 110)i$
	$1820 - 248i$	$(1670 \sim 1770) - (40 \sim 190)i$
P_{13}	Not found	$(1660 \sim 1690) - (57 \sim 138)i$
P_{31}	Not found	$(1830 \sim 1880) - (100 \sim 250)i$
P_{33}	$1211 - 50i$	$(1209 \sim 1211) - (49 \sim 51)i$
D_{13}	$1521 - 58i$	$(1505 \sim 1515) - (52 \sim 60)i$
D_{15}	$1654 - 77i$	$(1655 \sim 1665) - (62 \sim 75)i$
D_{33}	$1604 - 106i$	$(1620 \sim 1680) - (80 \sim 120)i$
F_{35}	$1738 - 110i$	$(1825 \sim 1835) - (132 \sim 150)i$
F_{37}	$1858 - 100i$	$(1870 \sim 1890) - (110 \sim 130)i$

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Two **resonance poles in the Roper resonance region !!**

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

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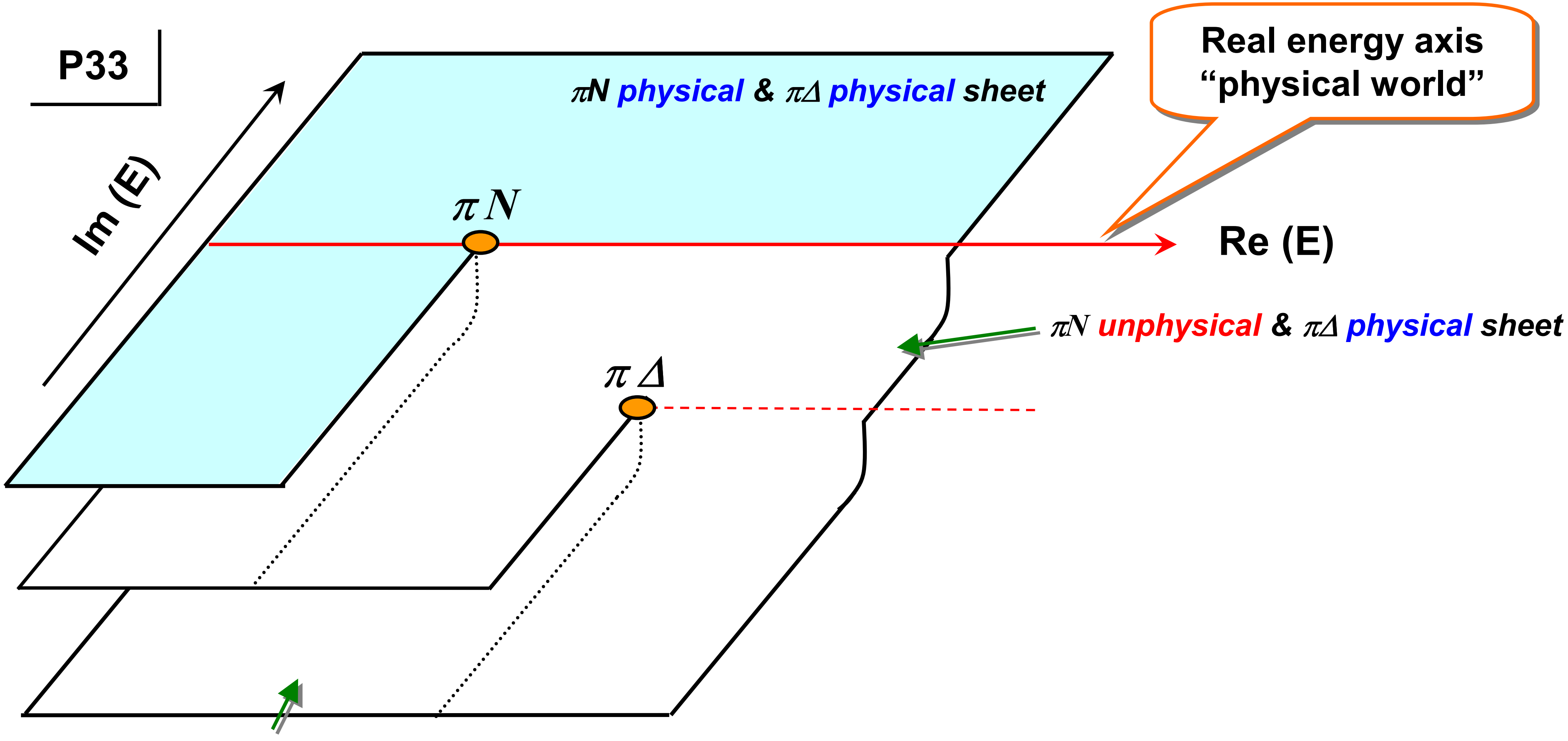
Two **resonance poles in the Roper resonance region !!**

Analysis	P11 poles (MeV)	
CMB (1990)	$1370 - 114i$	$1360 - 120i$
GWU(2006)	$1359 - 82i$	$1388 - 83i$
Jülich (2009)	$1387 - 74i$	$1387 - 71i$

Delta(1232) : The 1st P33 resonance

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

Complex E-plane



πN physical & $\pi\Delta$ physical sheet

Real energy axis
“physical world”

πN unphysical & $\pi\Delta$ physical sheet

πN unphysical & $\pi\Delta$ unphysical sheet

Riemann-sheet for other channels: (ηN,ρN,σN) = (-, p, -)

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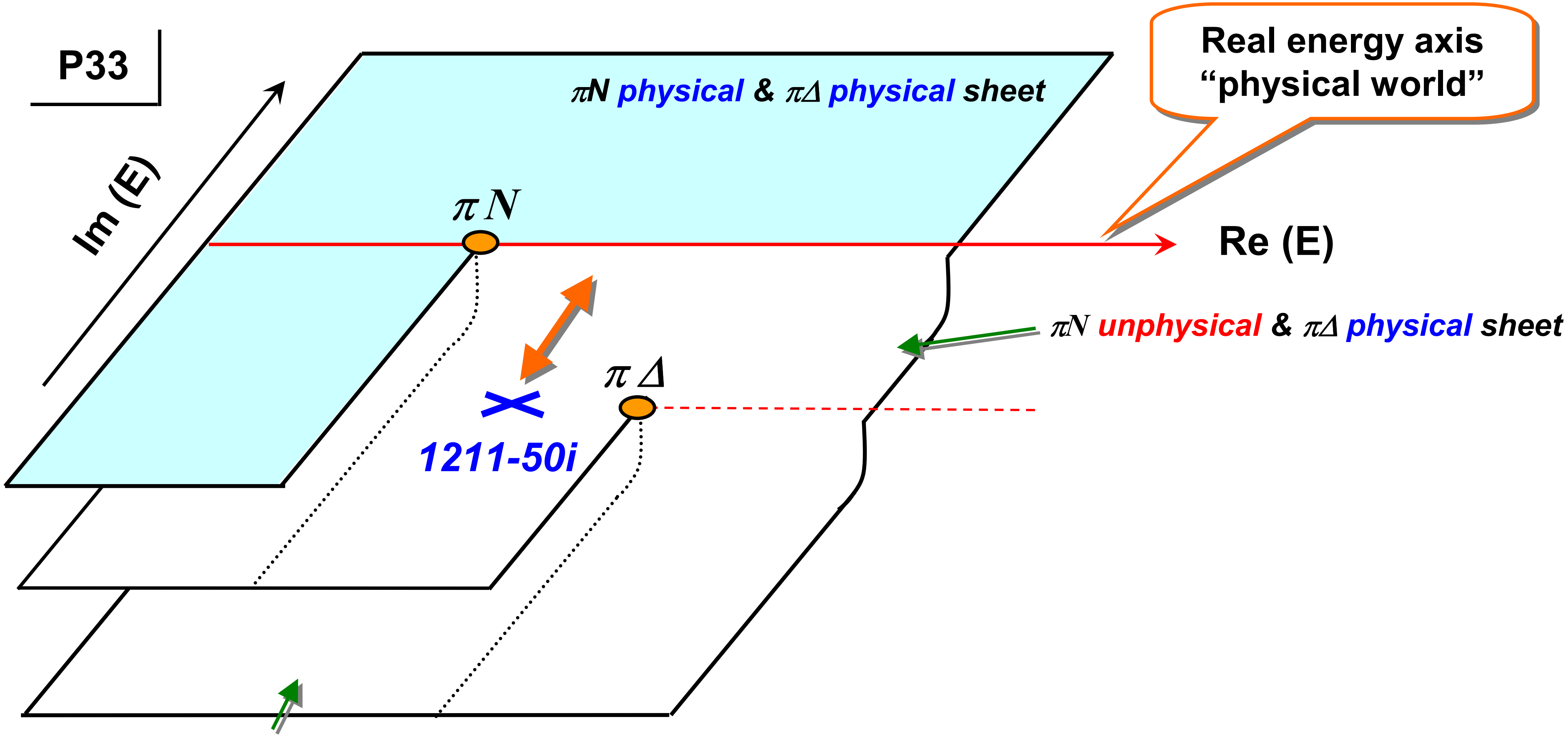

πN physical & $\pi\Delta$ physical sheet

Real energy axis “physical world”

πN unphysical & $\pi\Delta$ physical sheet

1211-50i

πN unphysical & $\pi\Delta$ unphysical sheet

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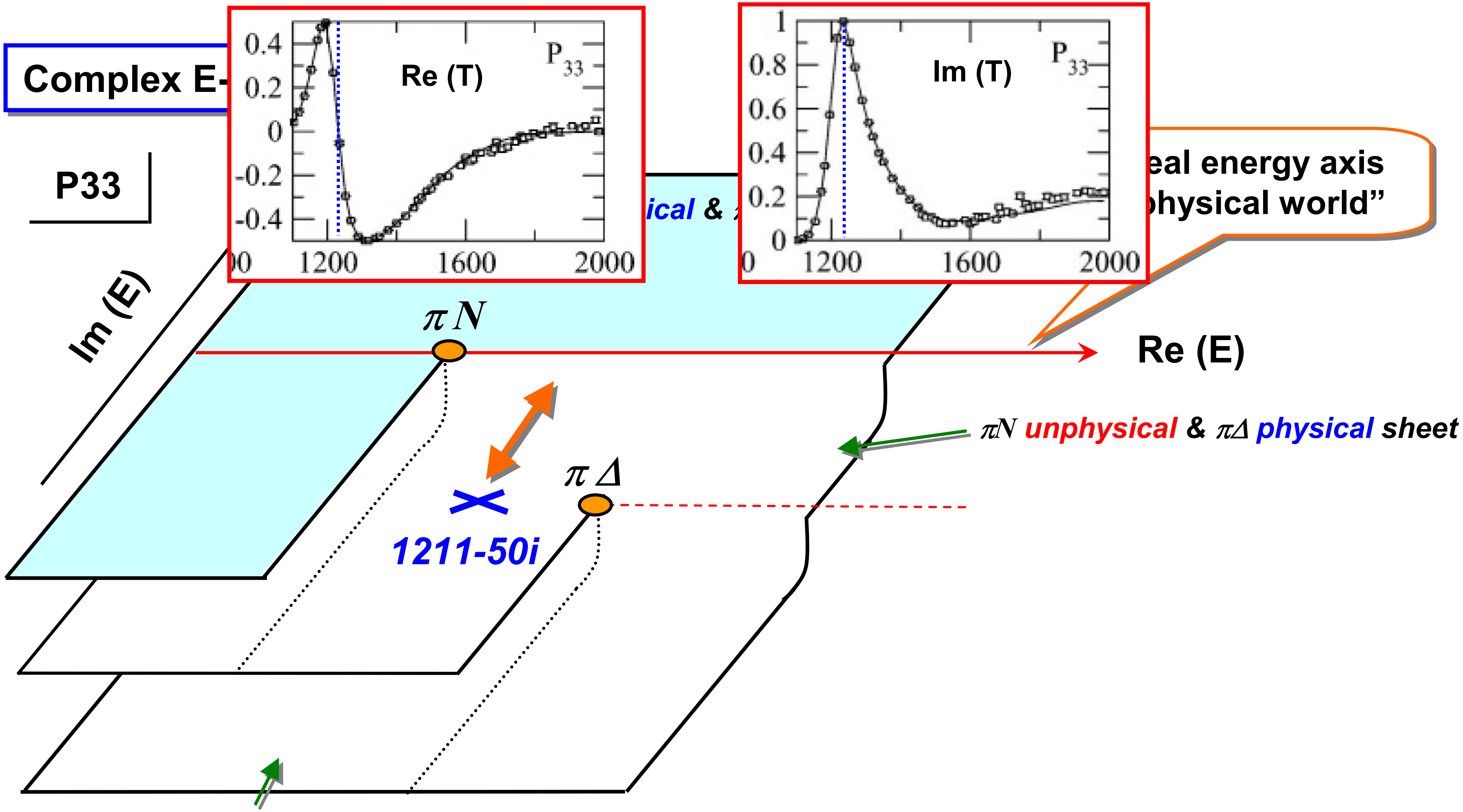


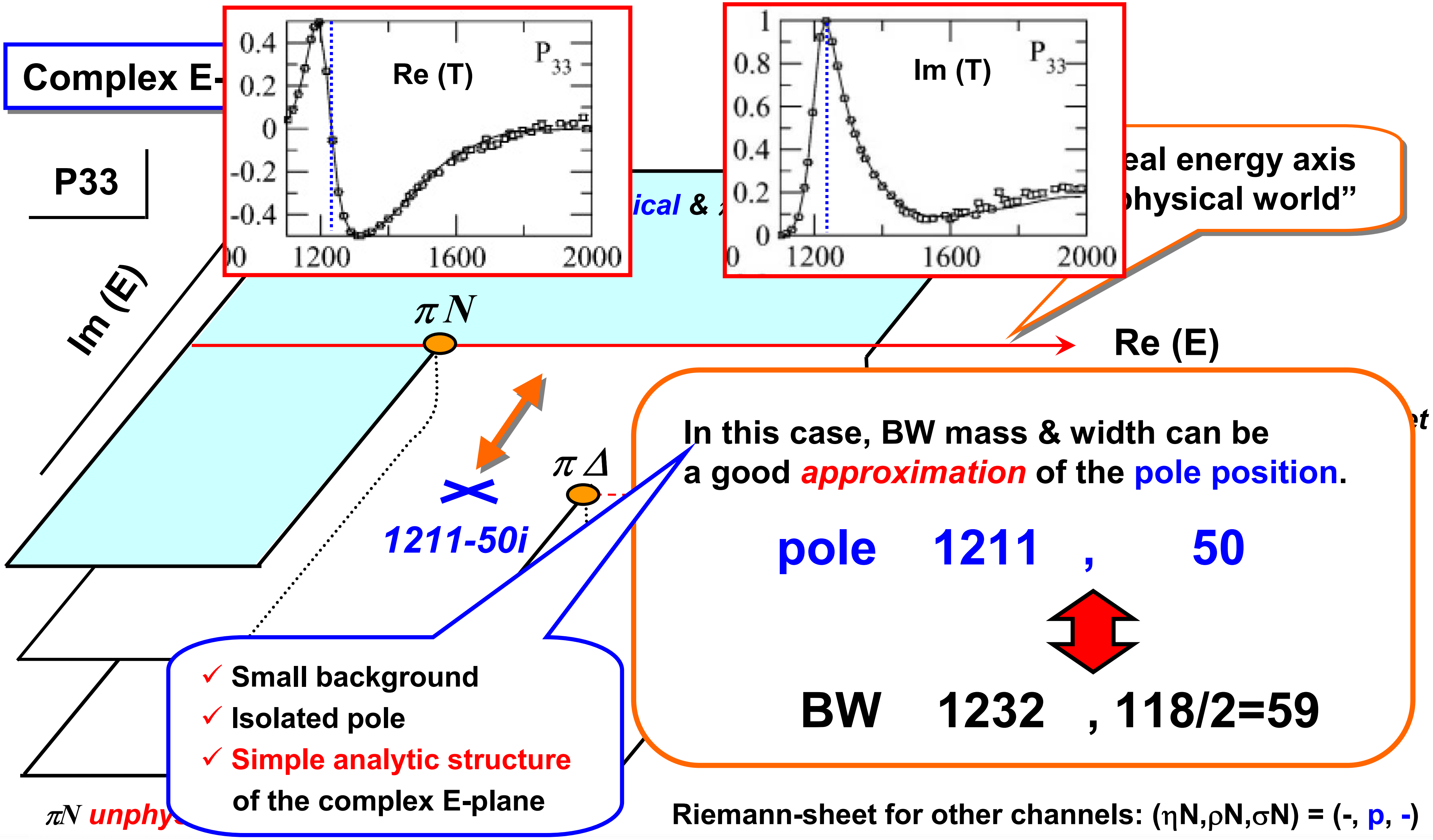
πN *unphysical* & πΔ *physical* sheet

πN *unphysical* & πΔ *unphysical* sheet

Riemann-sheet for other channels: (ηN,ρN,σN) = (-, p, -)

Delta(1232) : The 1st P33 resonance

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



In this case, BW mass & width can be a good *approximation* of the pole position.

pole 1211 , 50

BW 1232 , 118/2=59

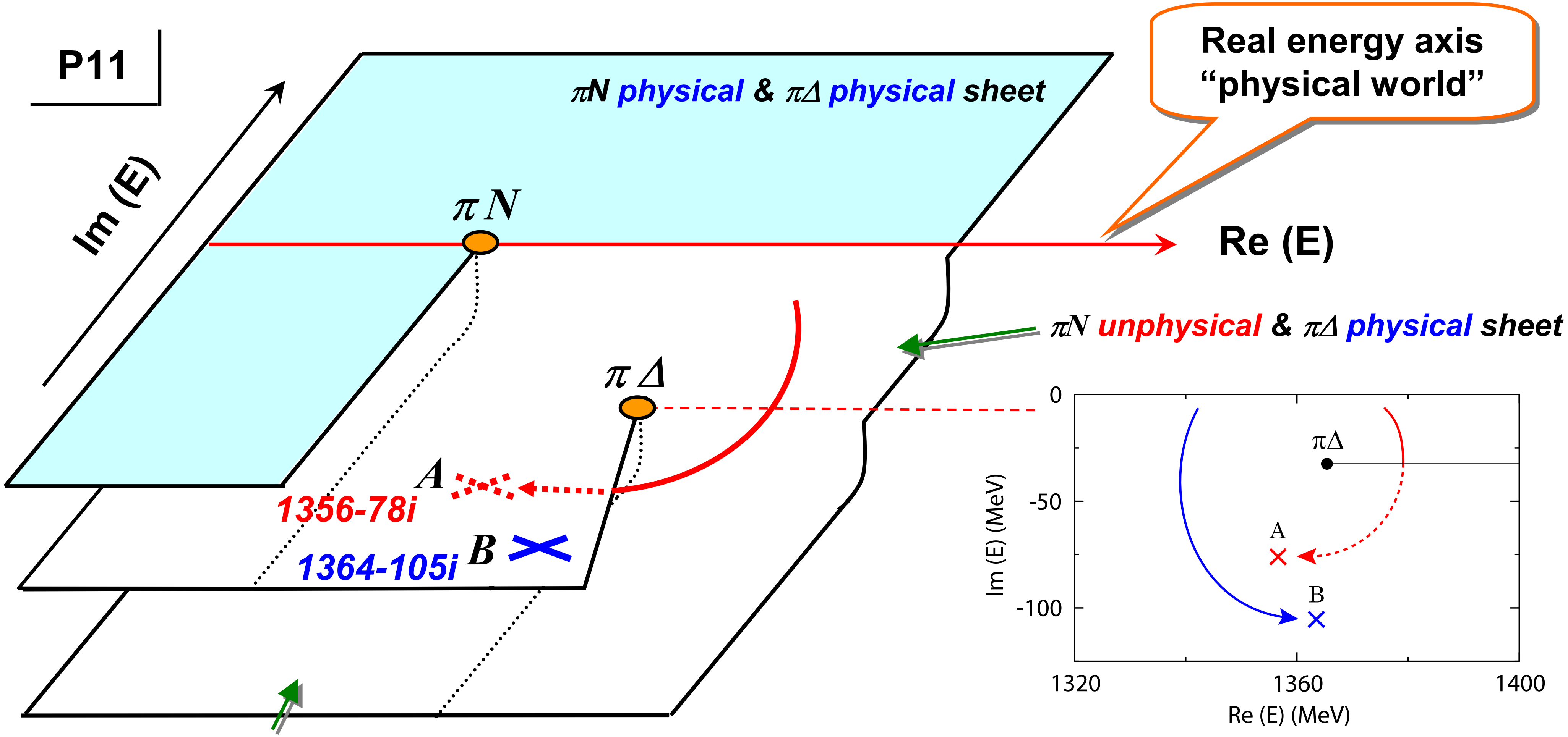
- ✓ Small background
- ✓ Isolated pole
- ✓ Simple analytic structure of the complex E-plane

Riemann-sheet for other channels: ($\eta N,\rho N,\sigma N$) = (-, p, -)

Two-pole structure of the Roper P11(1440)

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

Complex E-plane



Riemann-sheet for other channels: (ηN,ρN,σN) = (p,p,p)

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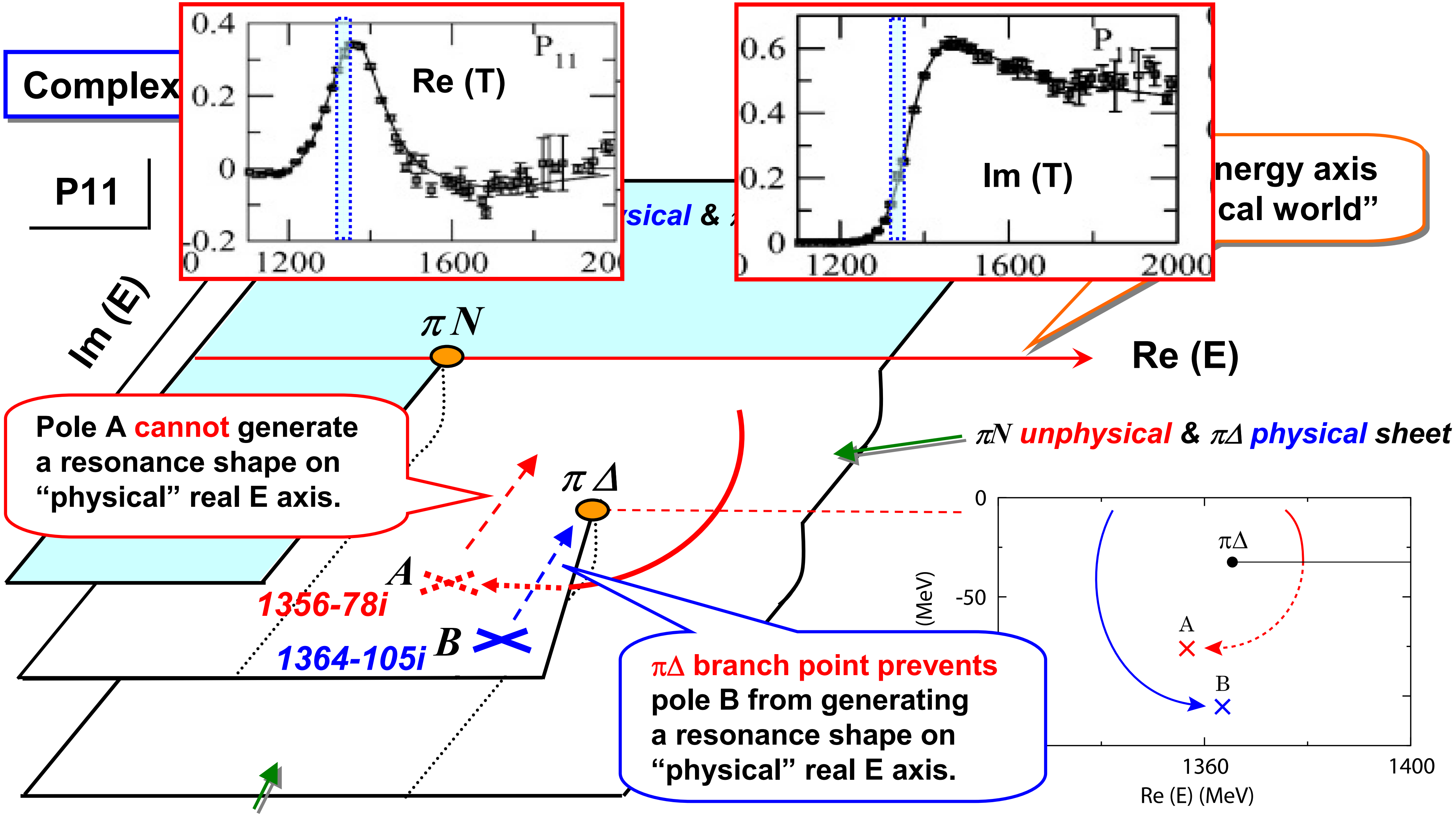


Pole A *cannot* generate a resonance shape on “physical” real E axis.

πN unphysical & πΔ physical sheet

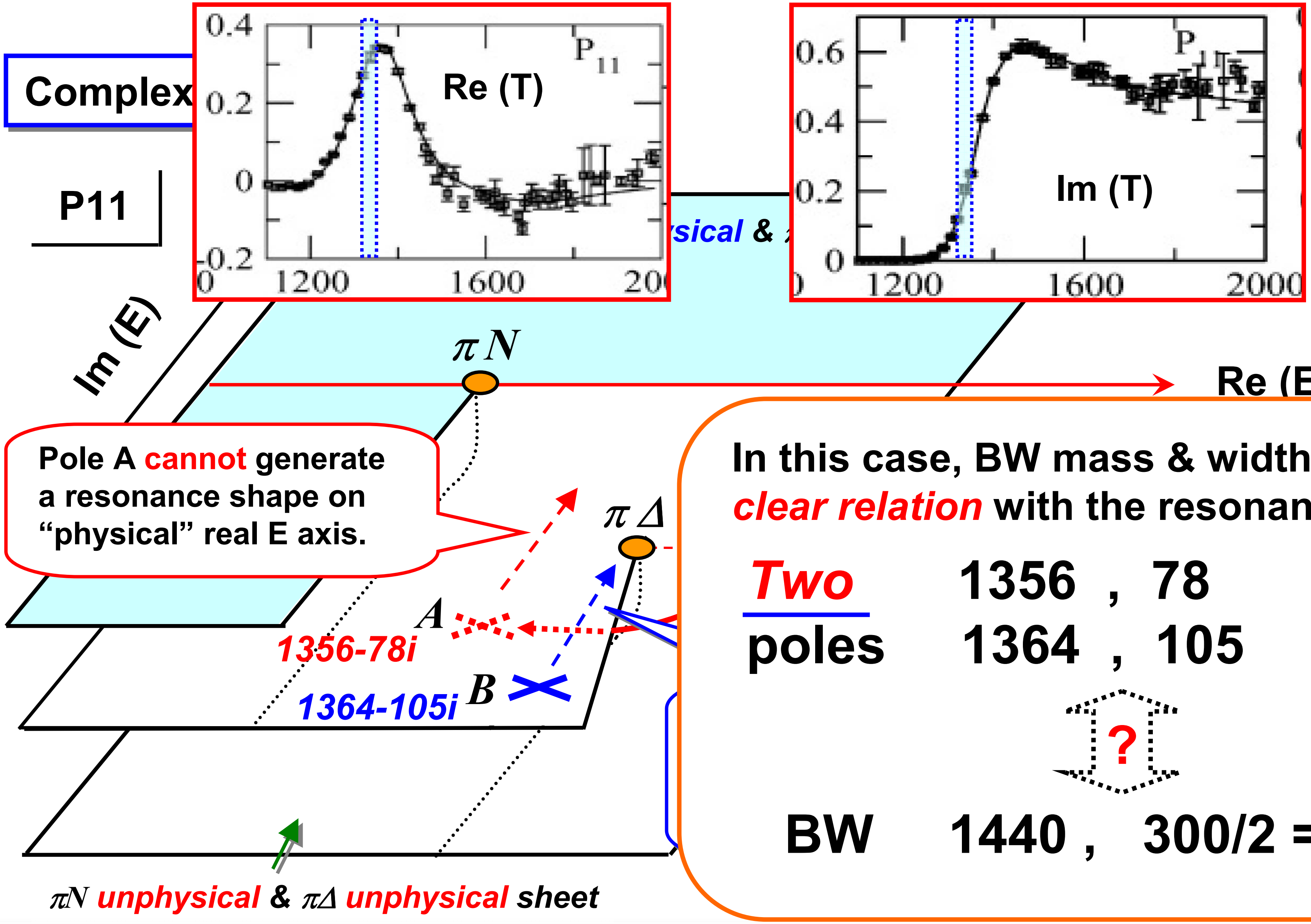
πΔ branch point prevents pole B from generating a resonance shape on “physical” real E axis.

πN unphysical & πΔ unphysical sheet

Riemann-sheet for other channels: (ηN,ρN,σN) = (p,p,p)

Two-pole structure of the Roper P11(1440)

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



Pole A **cannot** generate a resonance shape on "physical" real E axis.

In this case, BW mass & width has ***NO clear relation*** with the resonance poles:

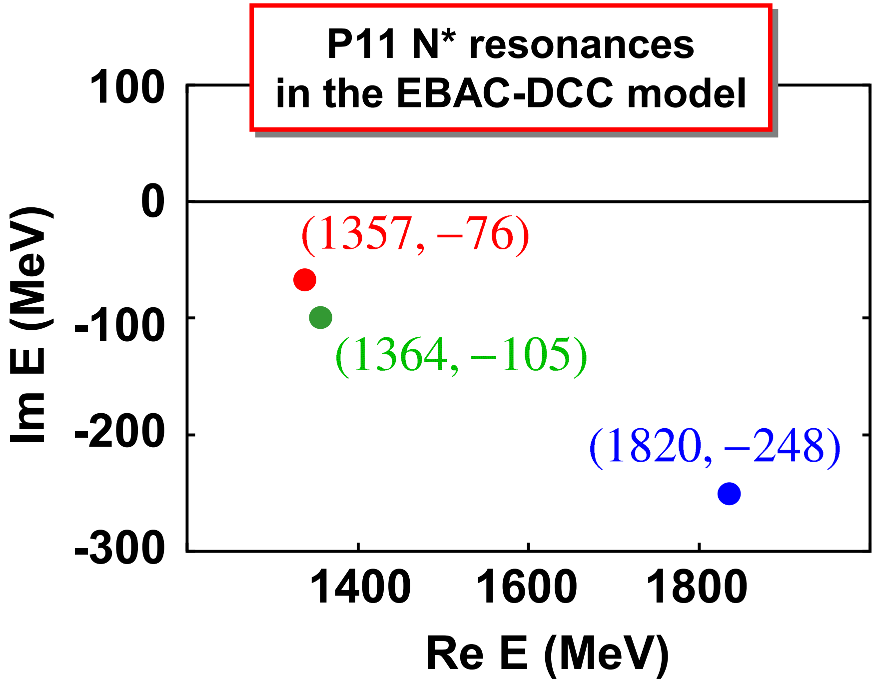
Two poles
1356 , 78
1364 , 105

BW 1440 , 300/2 = 150

Dynamical origin of P11 resonances

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

All three P11 poles below 2 GeV are generated from a *same, single* bare state!



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

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

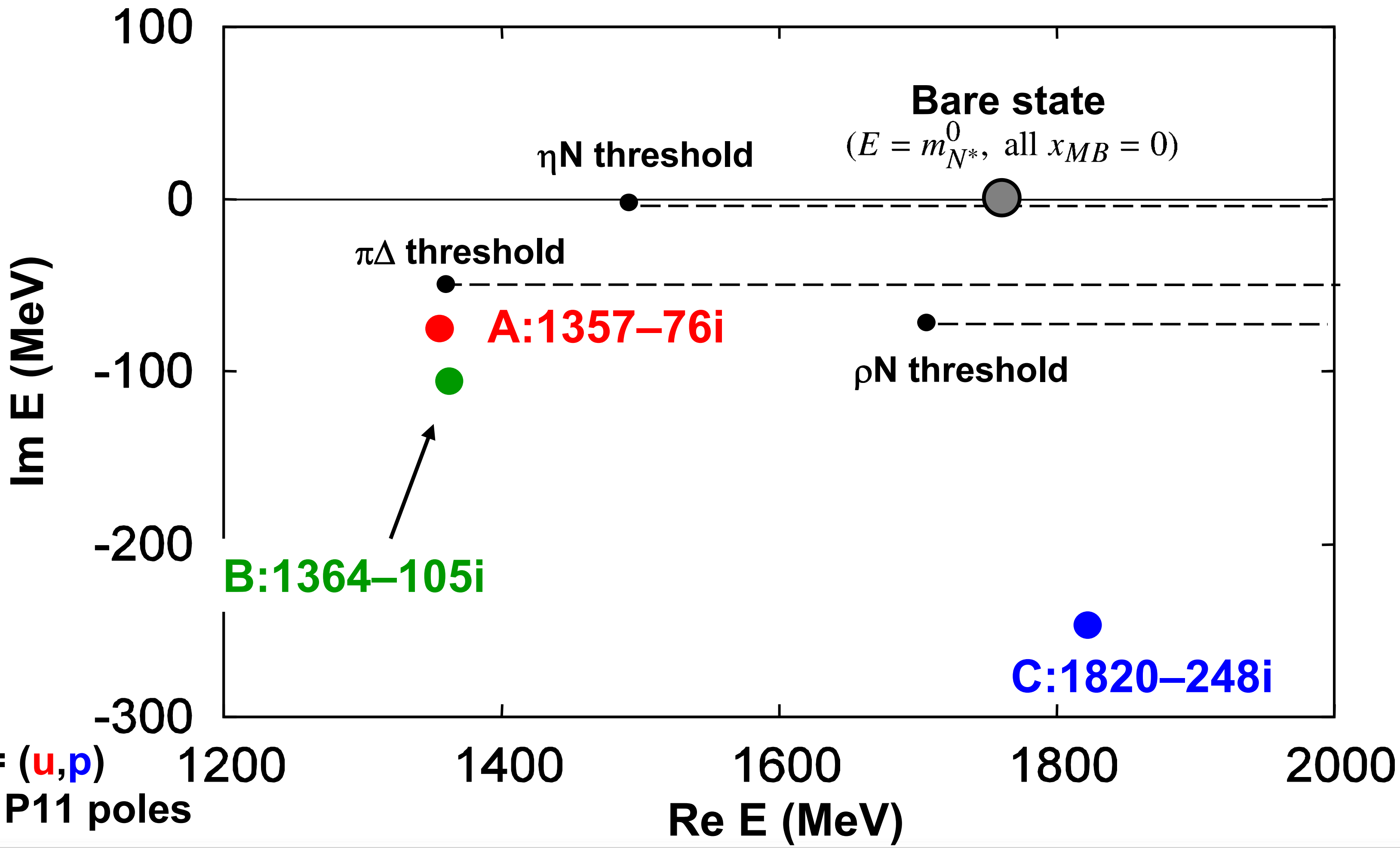
e.g.)
Two poles for $J^\pi = 3/2^+$ resonance in He^5
Hale, Brown, Jarmie, PRL59 763 (1987)

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

Dynamical origin of P11 resonances

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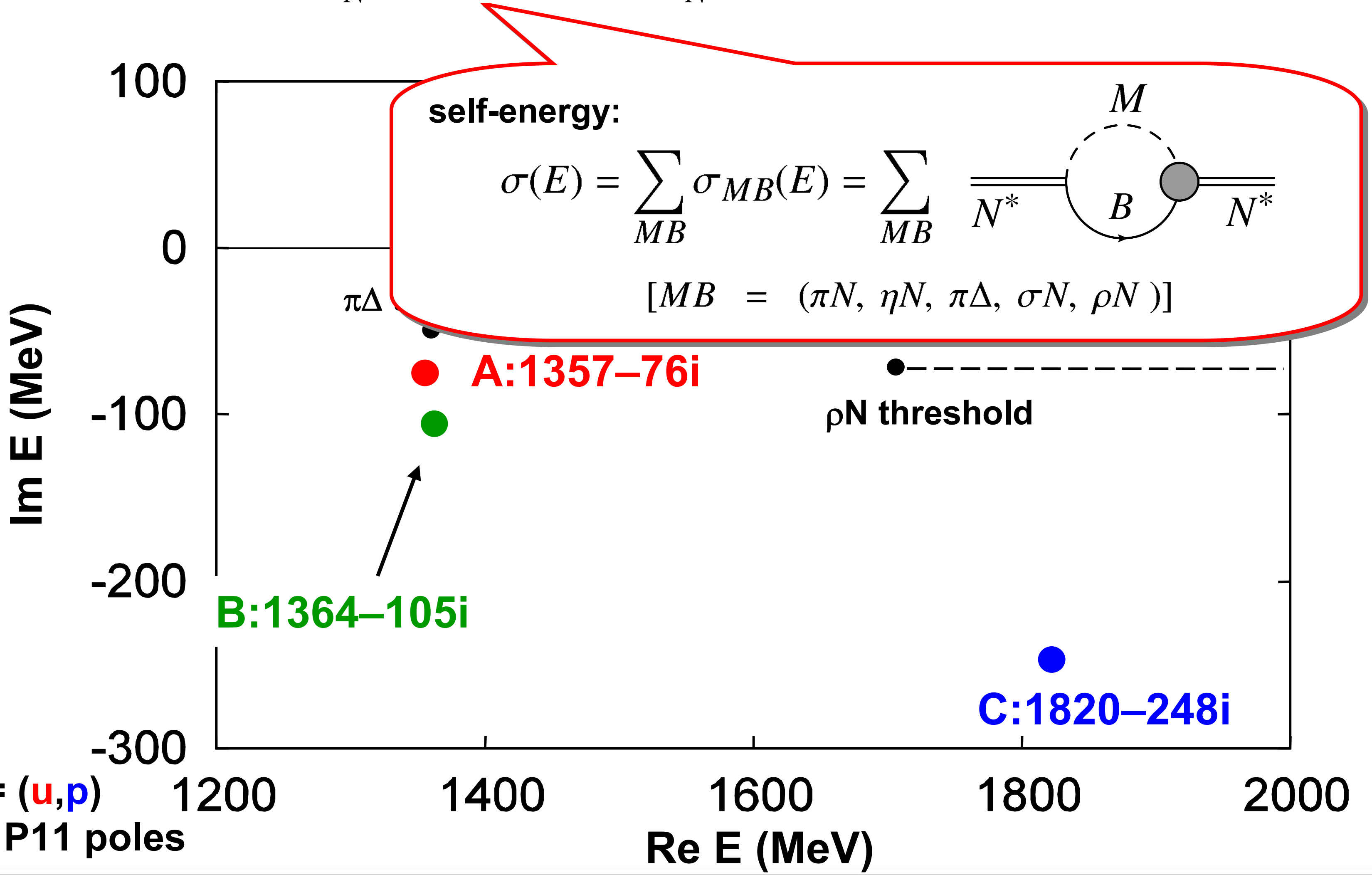

self-energy:

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

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

(πN,σN) = (u,p)
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Dynamical origin of P11 resonances

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

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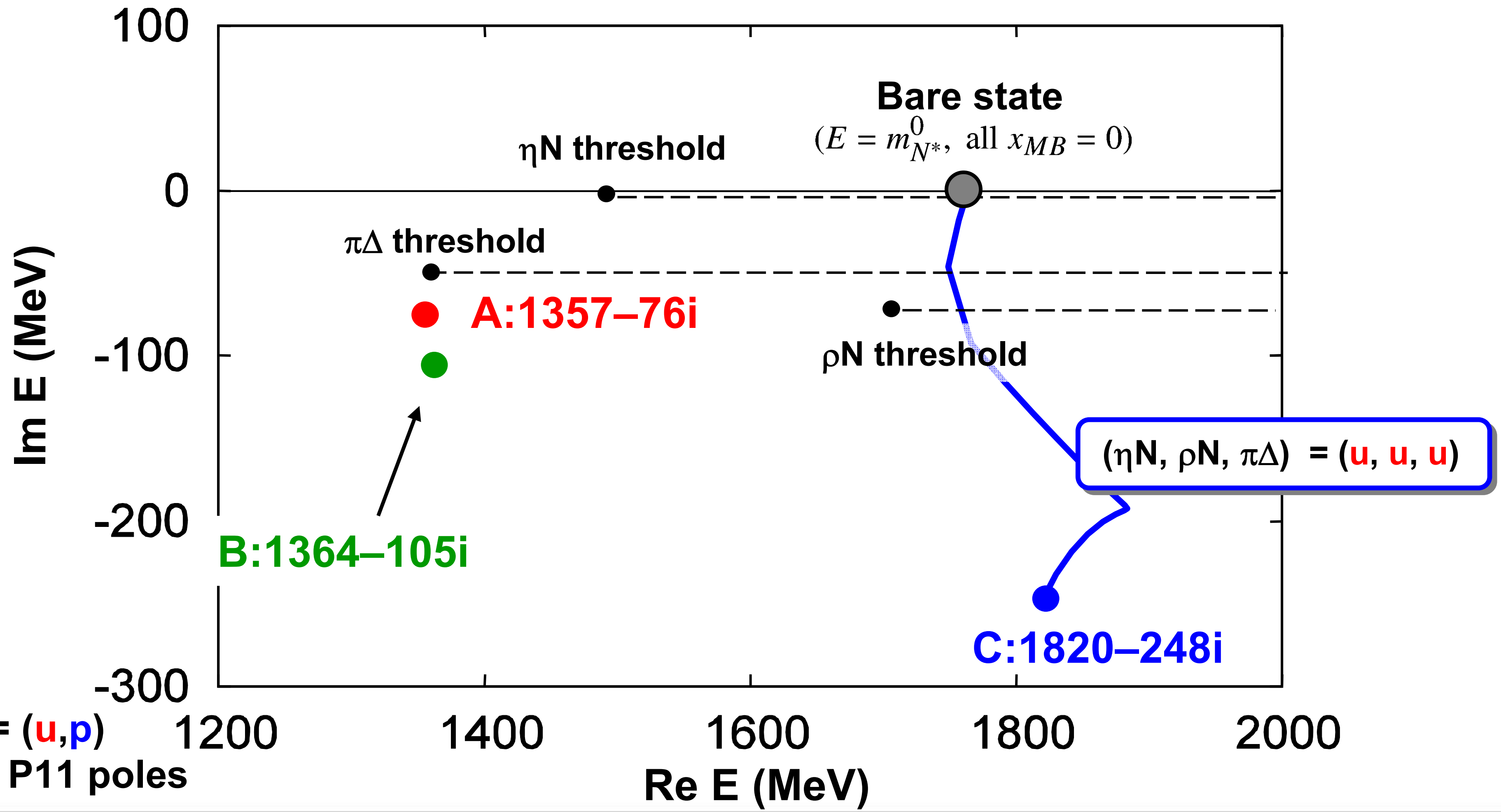

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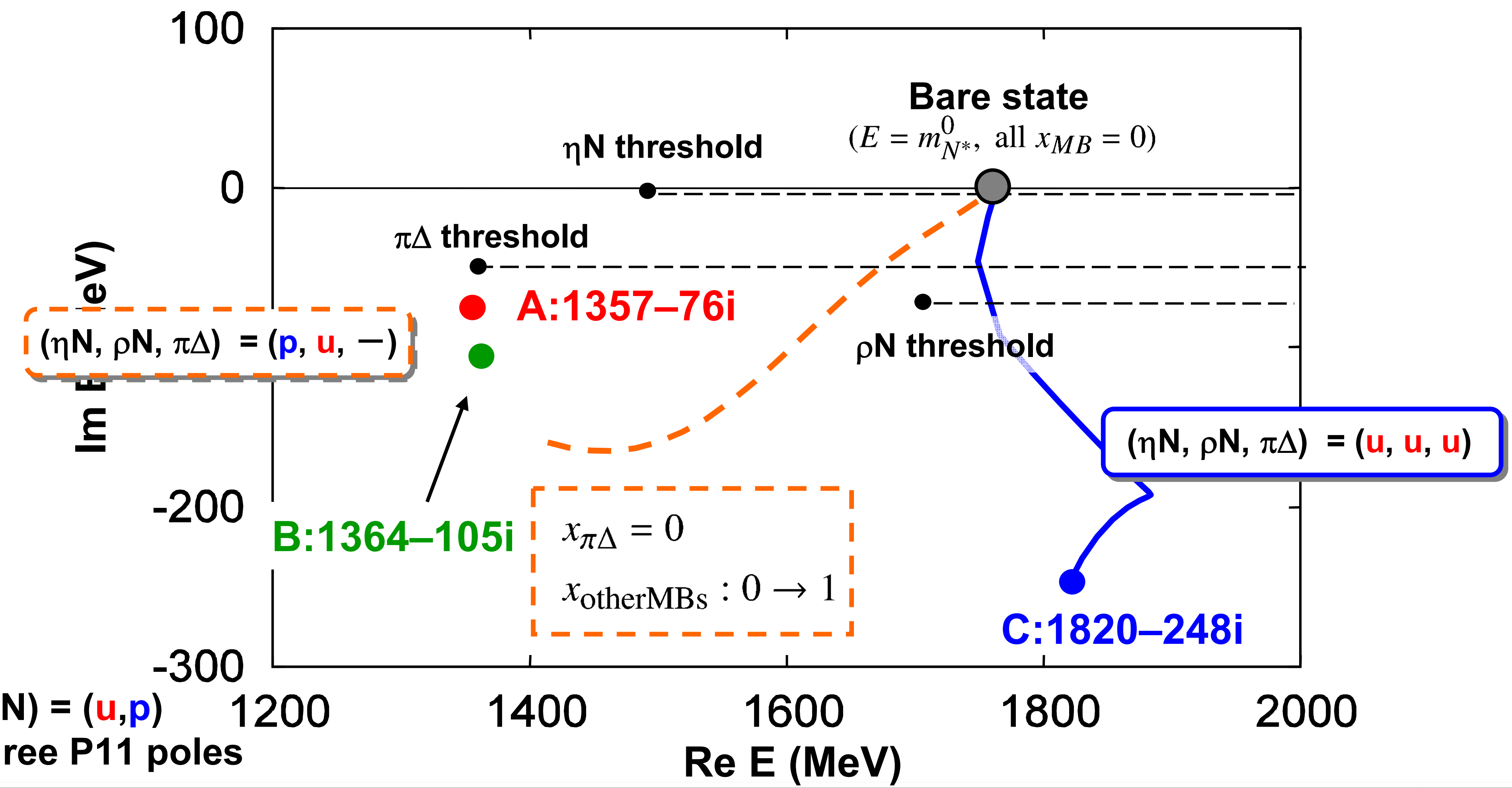

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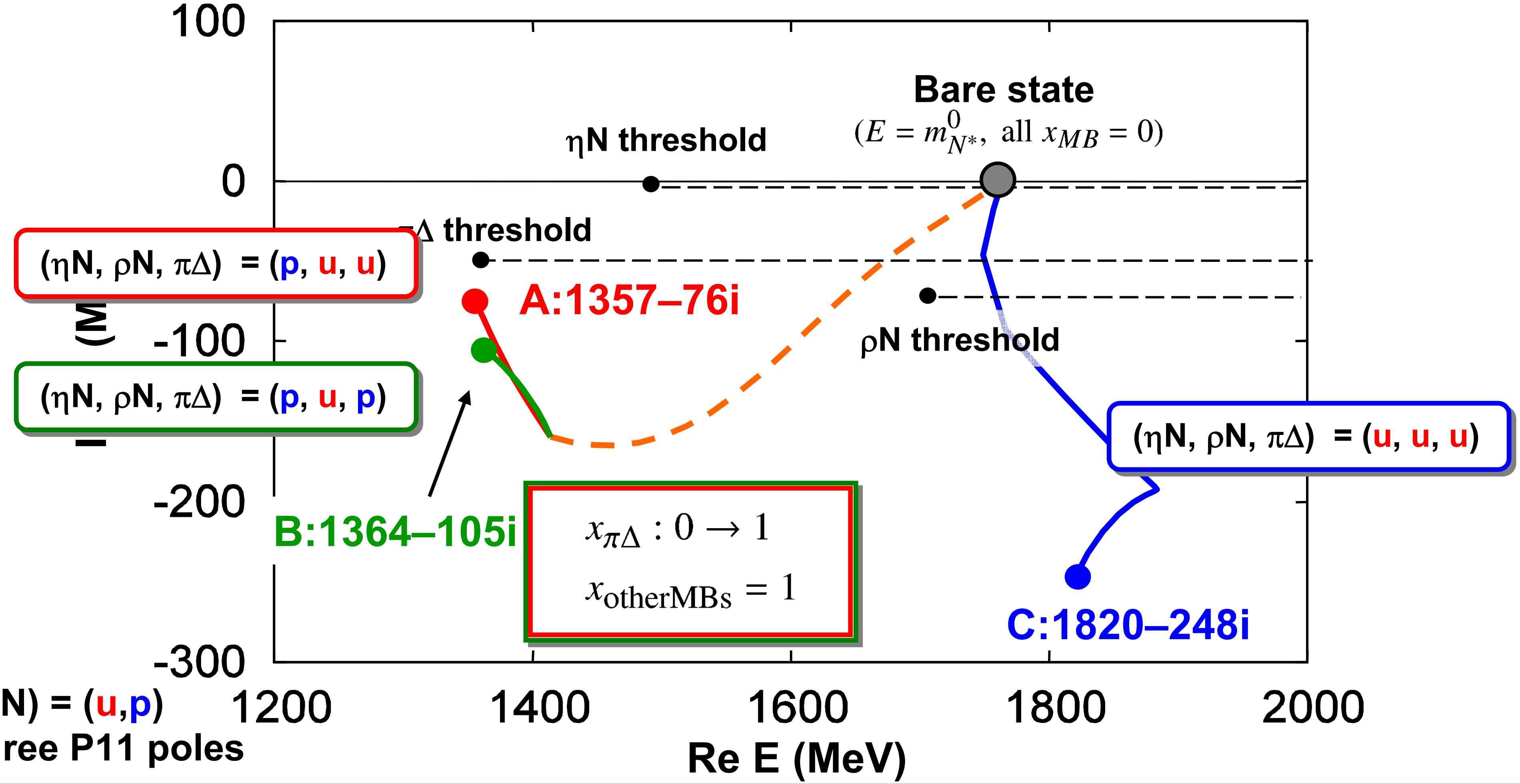

$x_{\pi\Delta} : 0 \rightarrow 1$

$x_{\text{otherMBs}} = 1$

(πN,σN) = (u,p)
for three P11 poles

Summary

- ✓ Continuous effort for exploring the N* states is being made at EBAC of Jefferson Lab.
- ✓ Resonance poles have been successfully extracted from the EBAC-DCC analysis.
- ✓ Dynamical origin of the P11 nucleon resonances:
  - ➢ The Roper resonance is associated with *two* resonance poles.
  - ➢ (Two) Roper and N(1710) originate from a same, single bare state.

N* → γN transition form factors have also been extracted.

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