How parameters of light-flavor baryon resonances are extracted from experimental data?

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Outline

1. "Hadron" and "Hadron Spectroscopy"

2. Reaction analysis for light-flavor baryon (N* and Δ*) spectroscopy

3. Multichannel reaction dynamics in N* and Δ* spectroscopy

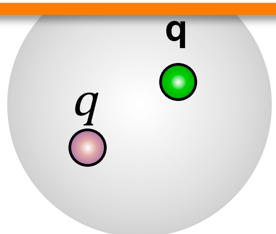
“Hadron” and “Hadron Spectroscopy”
(1 of 3)

What's a hadron ??

Hadron = Composite particle made from
quarks, anti-quarks, and gluons

Besides nucleons and pions, there exist *MANY* hadrons due to excitations of internal degrees of freedom of hadrons and variety of quark "flavors" !!

Specify six types of quarks:
up(u), down(d), strange(s),
charm(c), bottom(b), top(t)



Meson

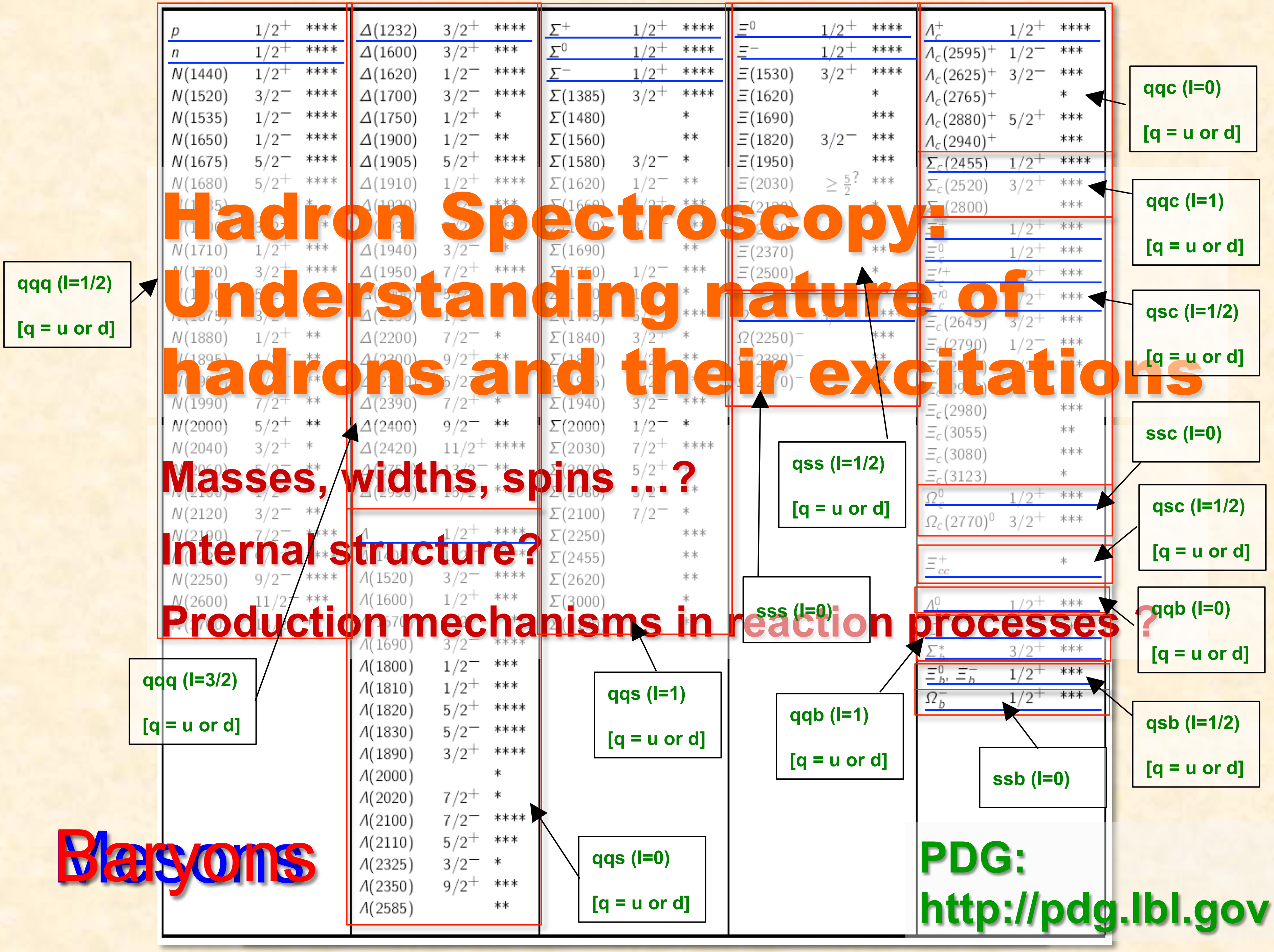
➔ pion

Hadron Spectroscopy: Understanding nature of hadrons and their excitations

Masses, widths, spins …?

Internal structure?

Production mechanisms in reaction processes ?



Baryons

PDG: http://pdg.lbl.gov

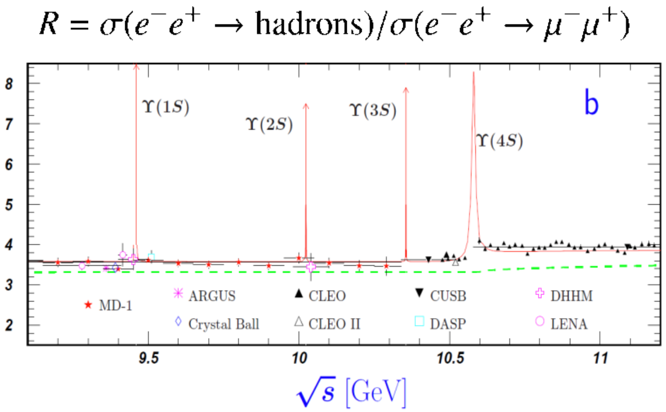
Light-flavor hadron spectroscopy: Physics of broad & overlapping resonances

	Quarks	Masses (scale dep.)
Extremely heavy	top	~ 170 GeV
Heavy	bottom	~ 4 GeV
	charm	~ 1.3 GeV
Light	strange	~ 0.13 GeV
	down	~ 0.006 GeV
	up	~ 0.003 GeV

Bottomonium mesons (b b)

Width:
~ 10 keV to
~ 10 MeV

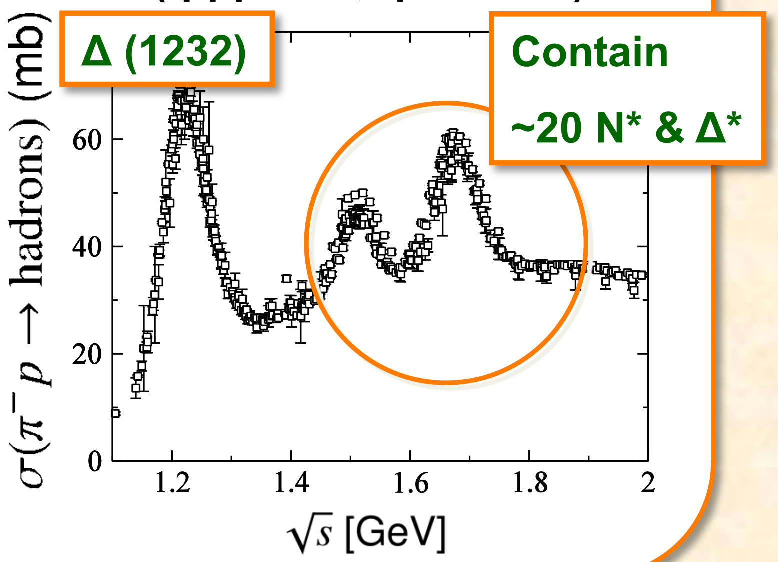
(width/mass)
~ 10^{-4}



N* and Δ* baryons
(qqq state, q = u or d)

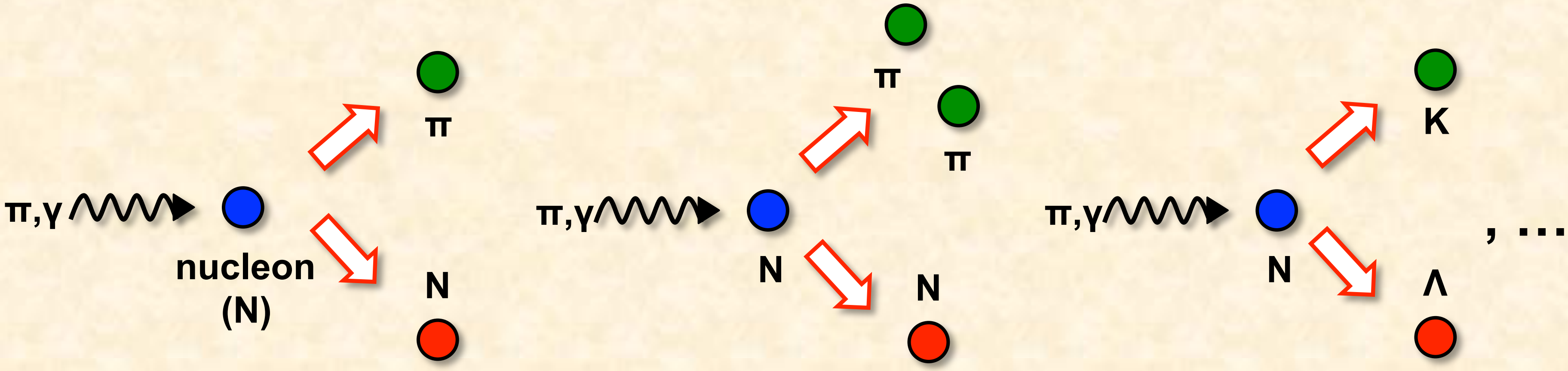
Width:
~ 200 MeV

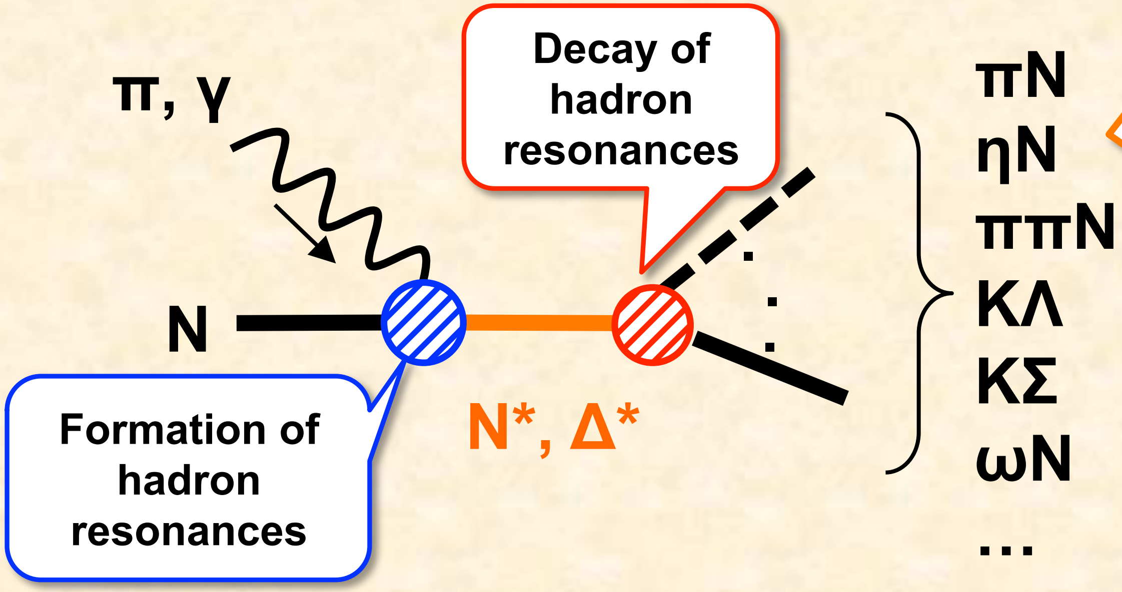
(width/mass)
~ 0.1



Reaction analysis for light-flavor baryon (N^* and Δ^*) spectroscopy (2 of 3)

Pion- and photon-induced meson production reactions off nucleon





Comprehensive partial wave analysis of ***ALL*** **the meson production reactions** in the resonance energy region is required !!

⬇

Analysis based on **multichannel** scattering theory is necessary !!

Approaches for reaction analysis for light-flavor baryon spectroscopy

✓ **Multichannel unitary condition:**

$$T_{ab}(E) - T^{\dagger}_{ab}(E) = -2\pi i \sum_c T^{\dagger}_{ac}\delta(E - E_c)T_{cb}(E)$$

- Ensures conservation of probabilities in multichannel reaction processes.
- Ensures proper analytic structure of amplitudes (branch points etc) in complex energy plane.

✓ **Heitler equation:**

K(E) should be hermitian.

$$T_{ab}(E) = K_{ab}(E) + \sum_c K_{ac}(E)\left[-i\pi\delta(E - E_c)\right]T_{cb}(E)$$

- **K-matrix (on-shell) approach:**

$$K_{ab}(E) \equiv (\text{Polynomials of } E)$$

Bonn-Gatchina, Carnegie Mellon-Berkely,
George Washington U, Giessen, Karlsruhe-Helsinki

✓ Numerical cost: cheap
✓ Cannot address dynamical contents (structure, production mechanism) of resonances

- **Dynamical approach:**

$$K_{ab}(E) \equiv K_{ab}(\vec{p}_a, \vec{p}_b; E) = V_{ab}(\vec{p}_a, \vec{p}_b; E) + \sum_c \mathcal{P}\int d\vec{q}\, V_{ac}(\vec{p}_a, \vec{q}; E)\frac{1}{E - H^0_c + i\varepsilon}K_{cb}(\vec{q}, \vec{p}_b; E)$$

✓ Numerical cost: expensive
✓ Suitable for studying dynamical contents of resonances

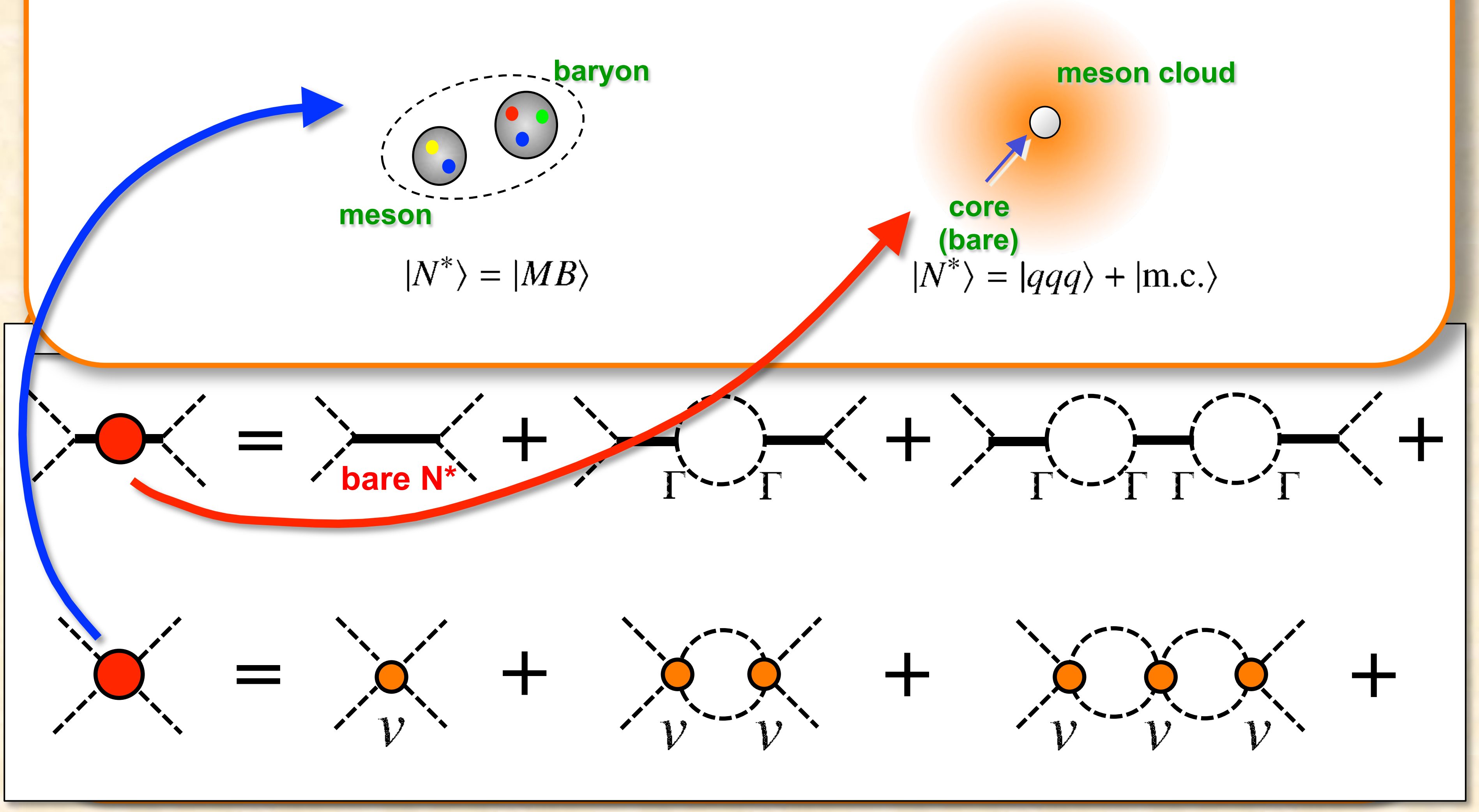
ANL-Osaka/EBAC-JLab, Dubna-Mainz-Taipei, Juelich

Our approach !!

For historical summary for N* and Δ* baryon spectroscopy, see:
http://pdg.lbl.gov/2012/reviews/rpp2012-rev-n-delta-resonances.pdf

ANL-Osaka dynamical coupled-channels analysis of meson production reactions

Physical N*s will be a “mixture” of the two pictures:



Strategy for the N* spectroscopy

Step 1

Couplings, cutoffs, bare N* masses etc.

Determine model parameters by making χ^2-fit of the world data of meson production reactions. (more than 20,000 data points to fit)

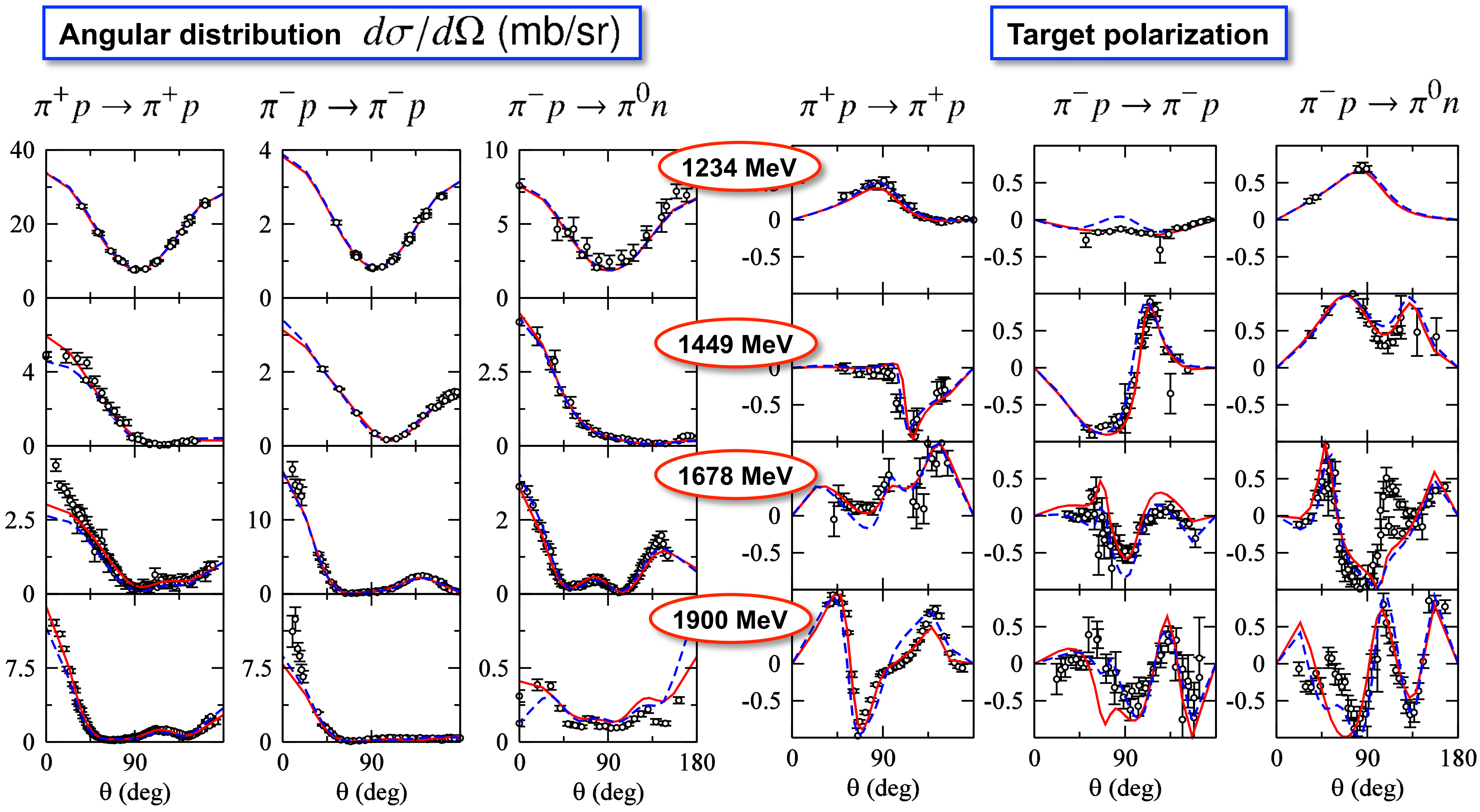
Step 2

Extract resonance properties (pole masses, form factors etc.) from the constructed model by performing the analytic continuation of the amplitudes to the complex energy plane.

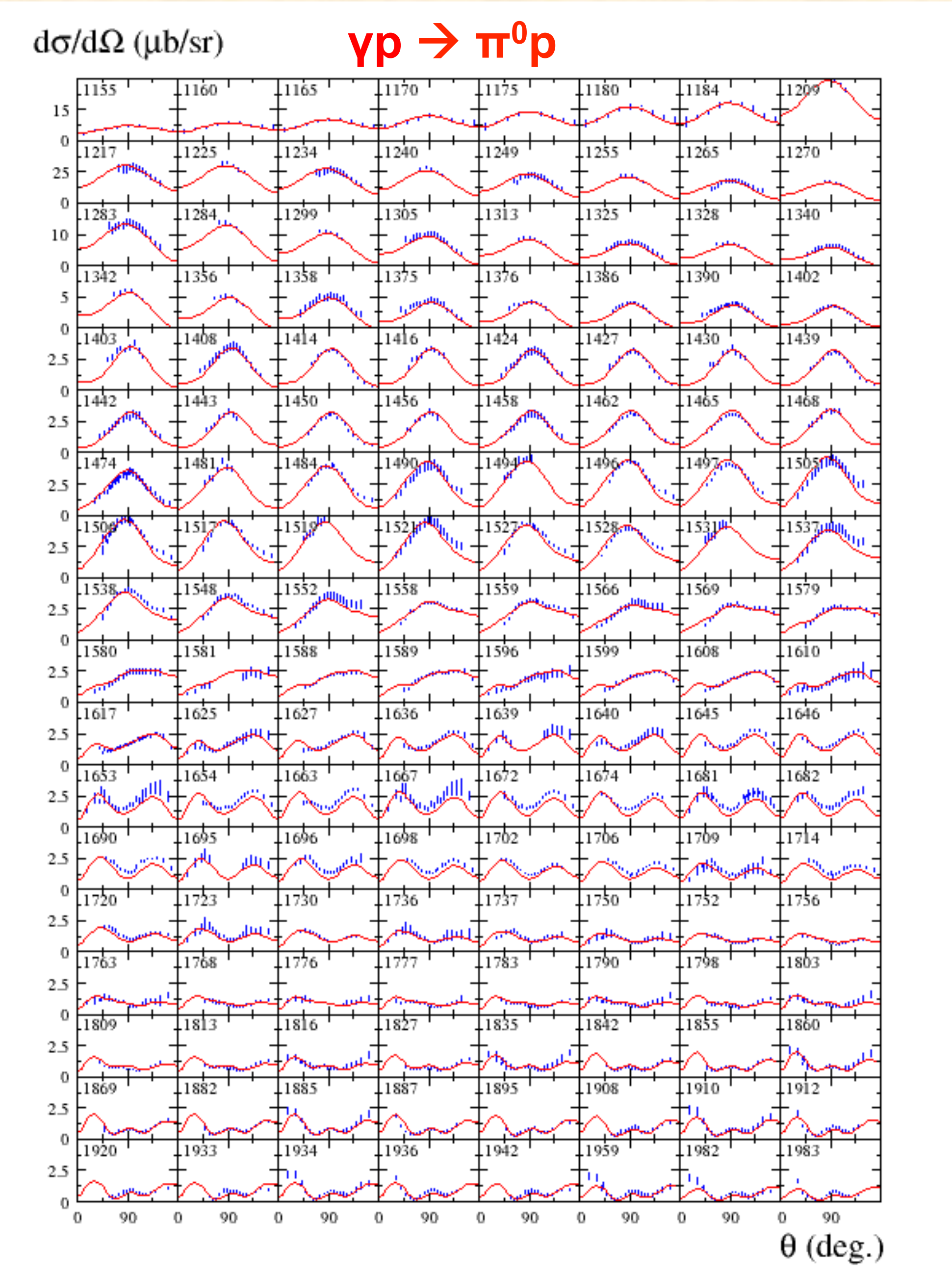
Step 3

Examine role of multichannel reaction dynamics in understanding the spectrum, internal structure and production mechanisms of the N* resonances.

Pion-nucleon elastic scattering



γp → πN reactions



Multichannel reaction dynamics in N* and Δ* spectroscopy (3 of 3)

How can we extract N* information?

PROPER definition of

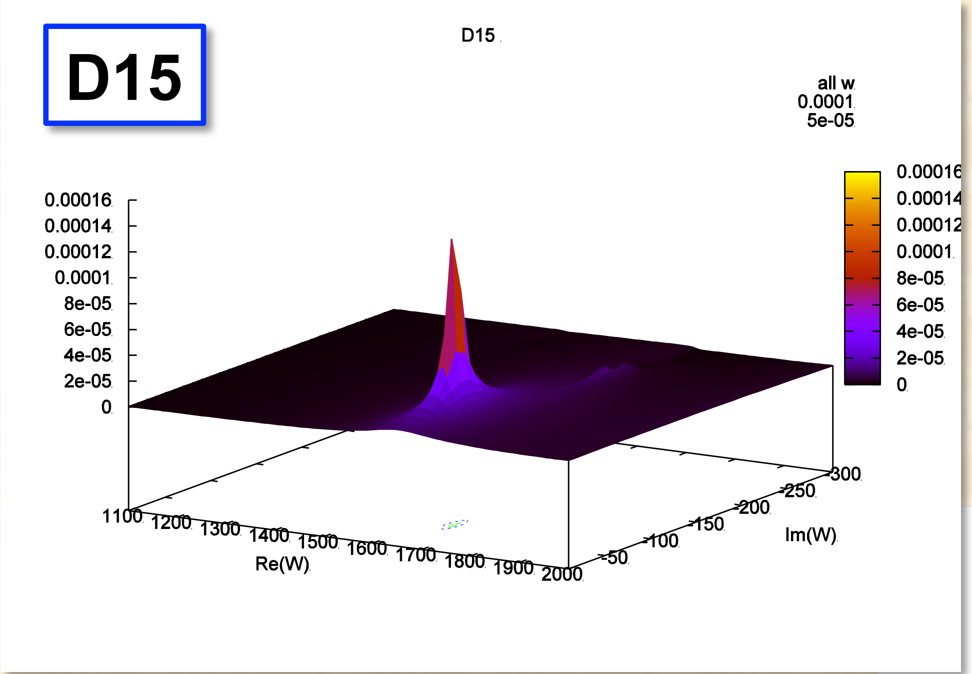
- ✓ N* mass and width ➔ Pole position of the amplitudes
- ✓ N* → MB, gN decay vertices ➔ Residue of the pole

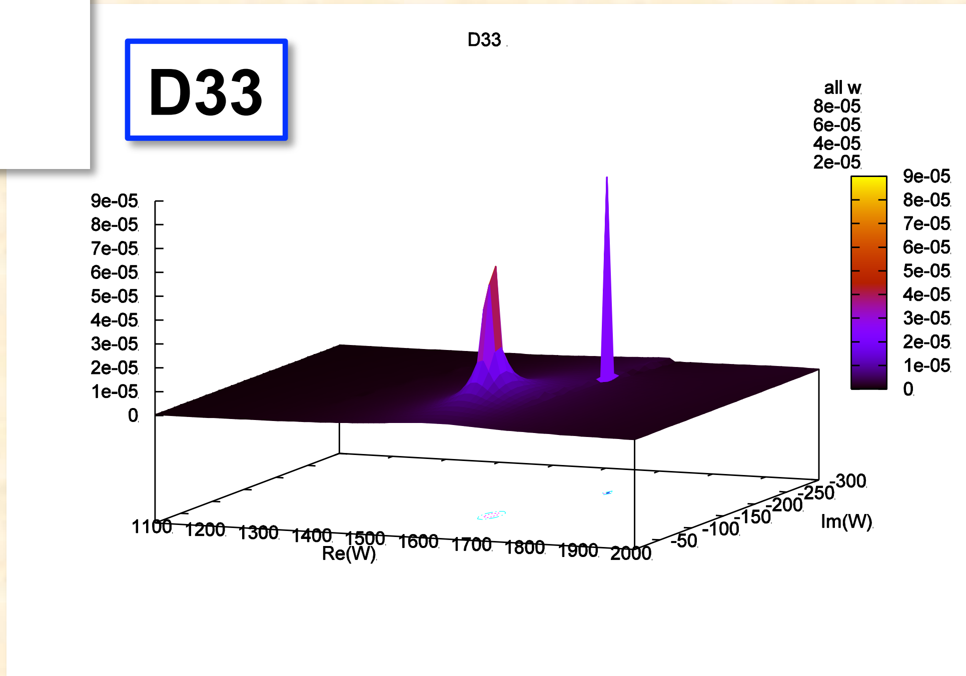
Need analytic continuation of the amplitudes !!

→ Suzuki, Sato, Lee, PRC79 025205 (2009); PRC82 045206 (2010).

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

Resonance poles of πN partial wave amplitude in complex energy plane





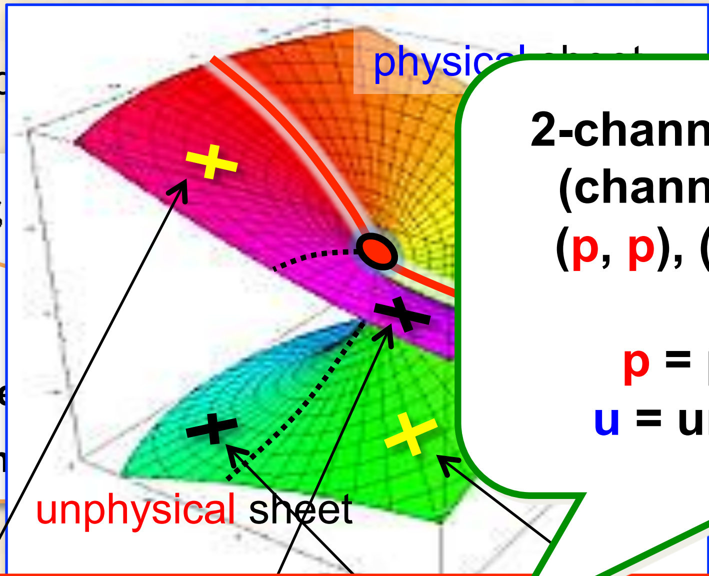
Multi-layer structure of the scattering amplitudes

e.g.) single-channel two-bod

$T(p, p';$

Scattering amplitude

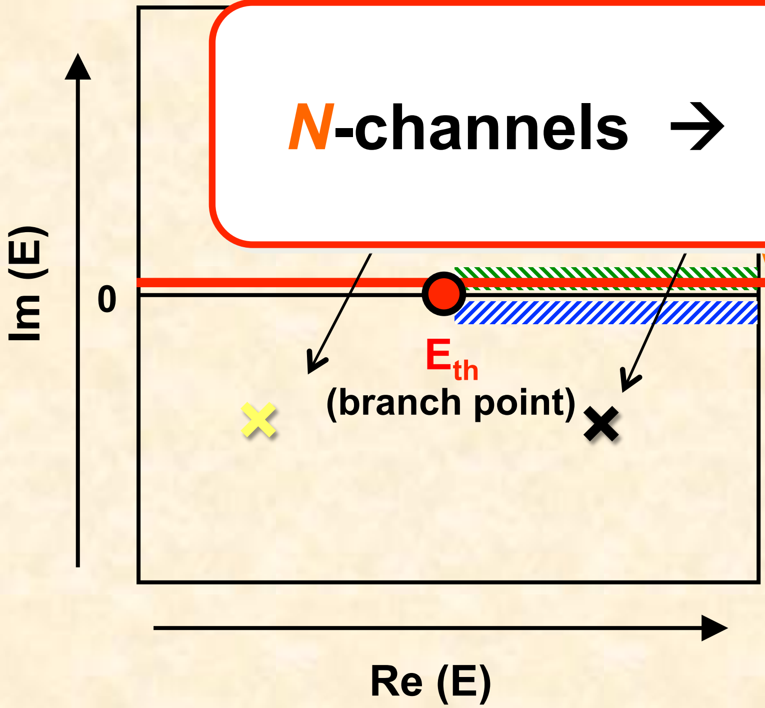
Essentially, same an

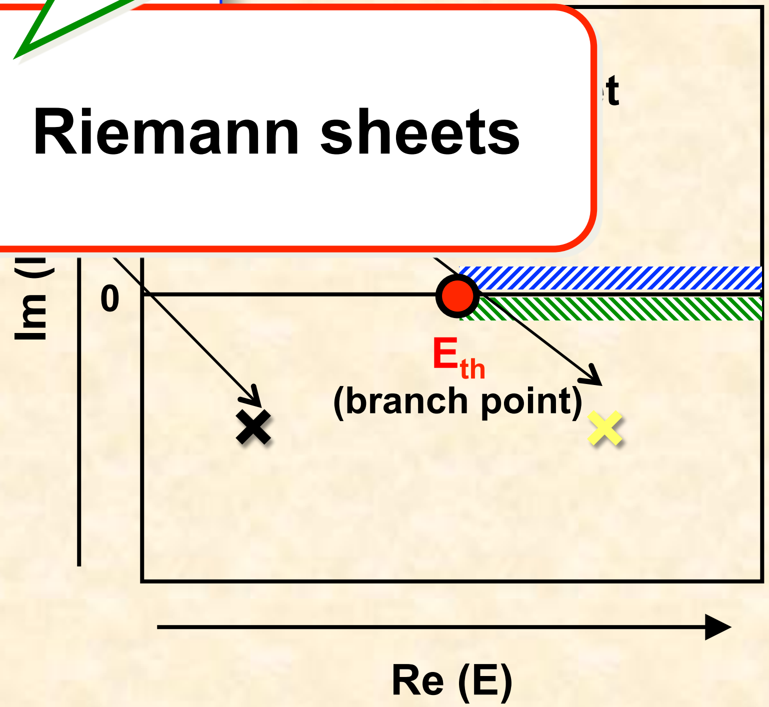


2-channel case (4 sheets):
(channel 1, channel 2) =
(p, p), (u, p) ,(p, u), (u, u)

p = physical sheet
u = unphysical sheet

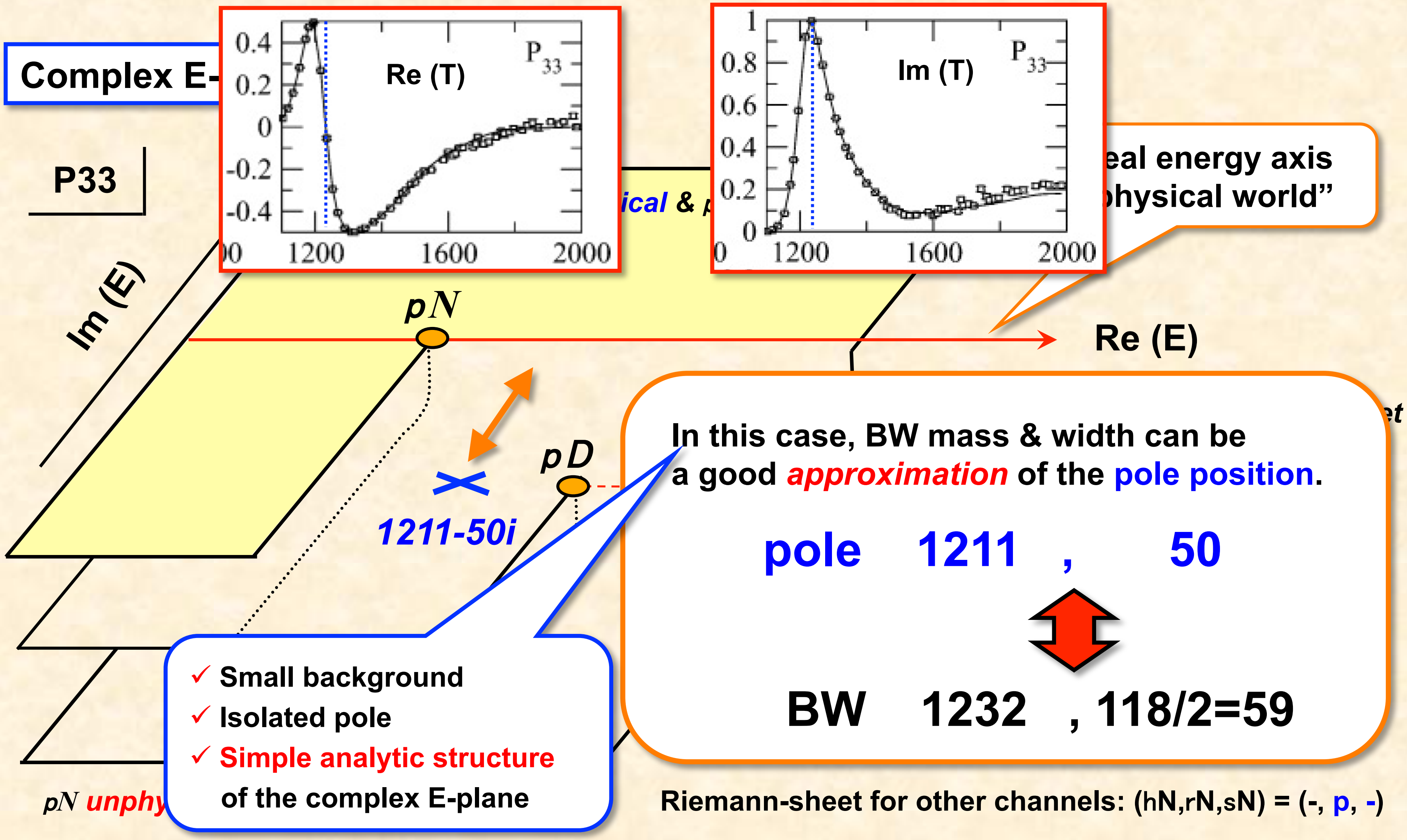
N-channels → Need 2^N Riemann sheets





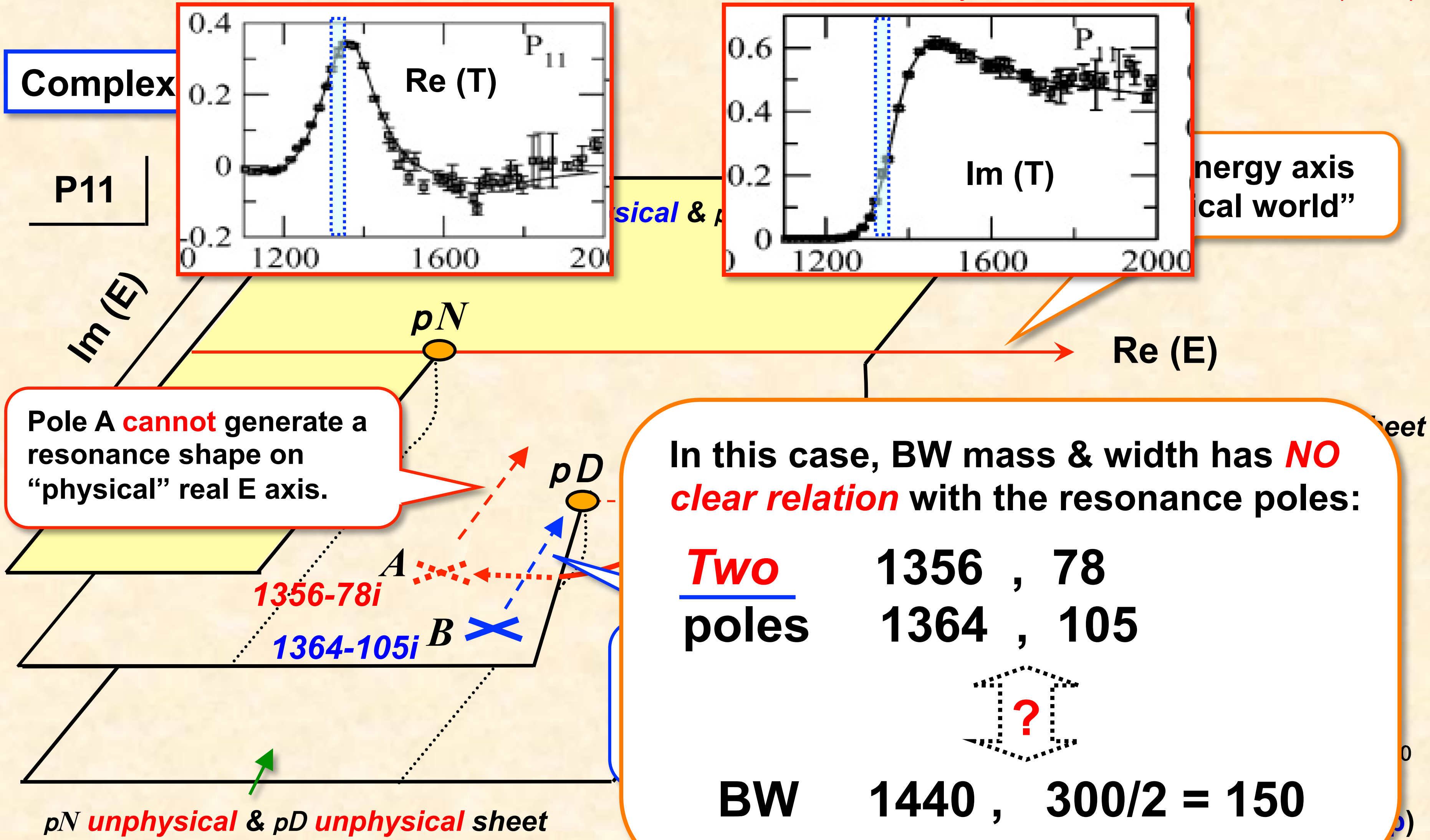
Delta(1232) : The 1st P33 resonance

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



Two-pole structure of the Roper P11(1440)

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



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

Two	1356 ,	78
poles	1364 ,	105

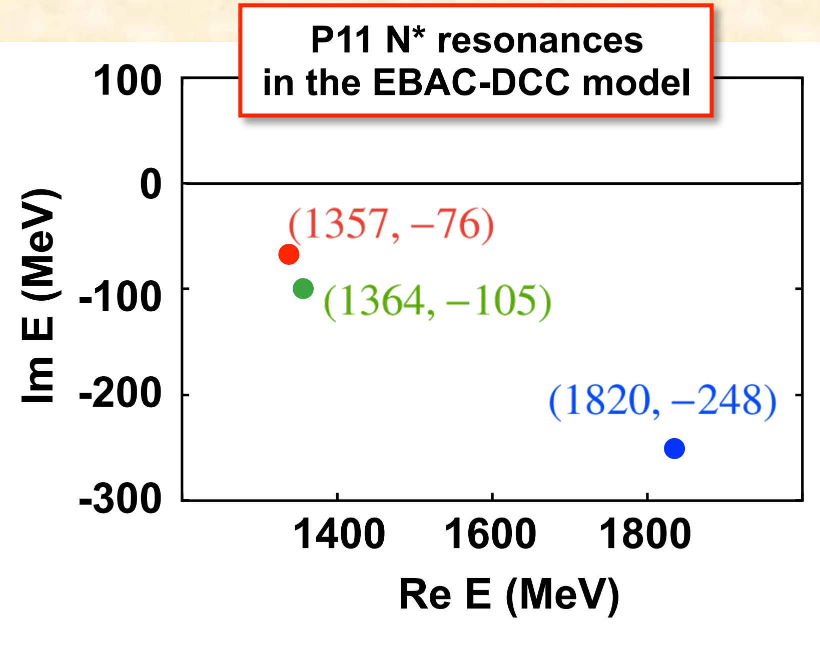
?

BW	1440 ,	300/2 = 150

Dynamical origin of P11 resonances

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

Three P11 N* poles 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)

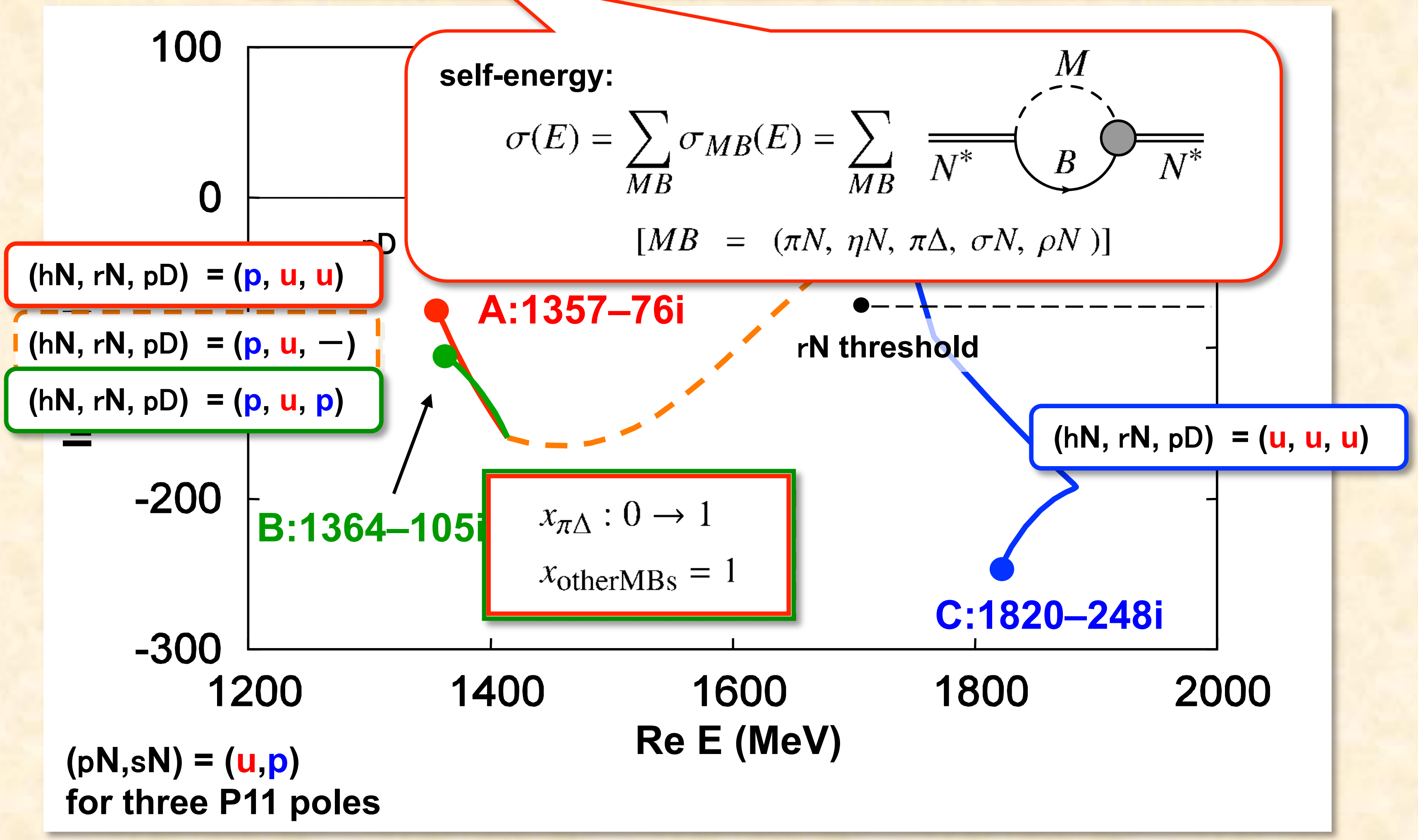
Evidences in hadron and nuclear physics are summarized e.g., in Morgan and Pennington, PRL59 2818 (1987)

Dynamical origin of P11 resonances

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

Pole trajectory of N* propagator

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



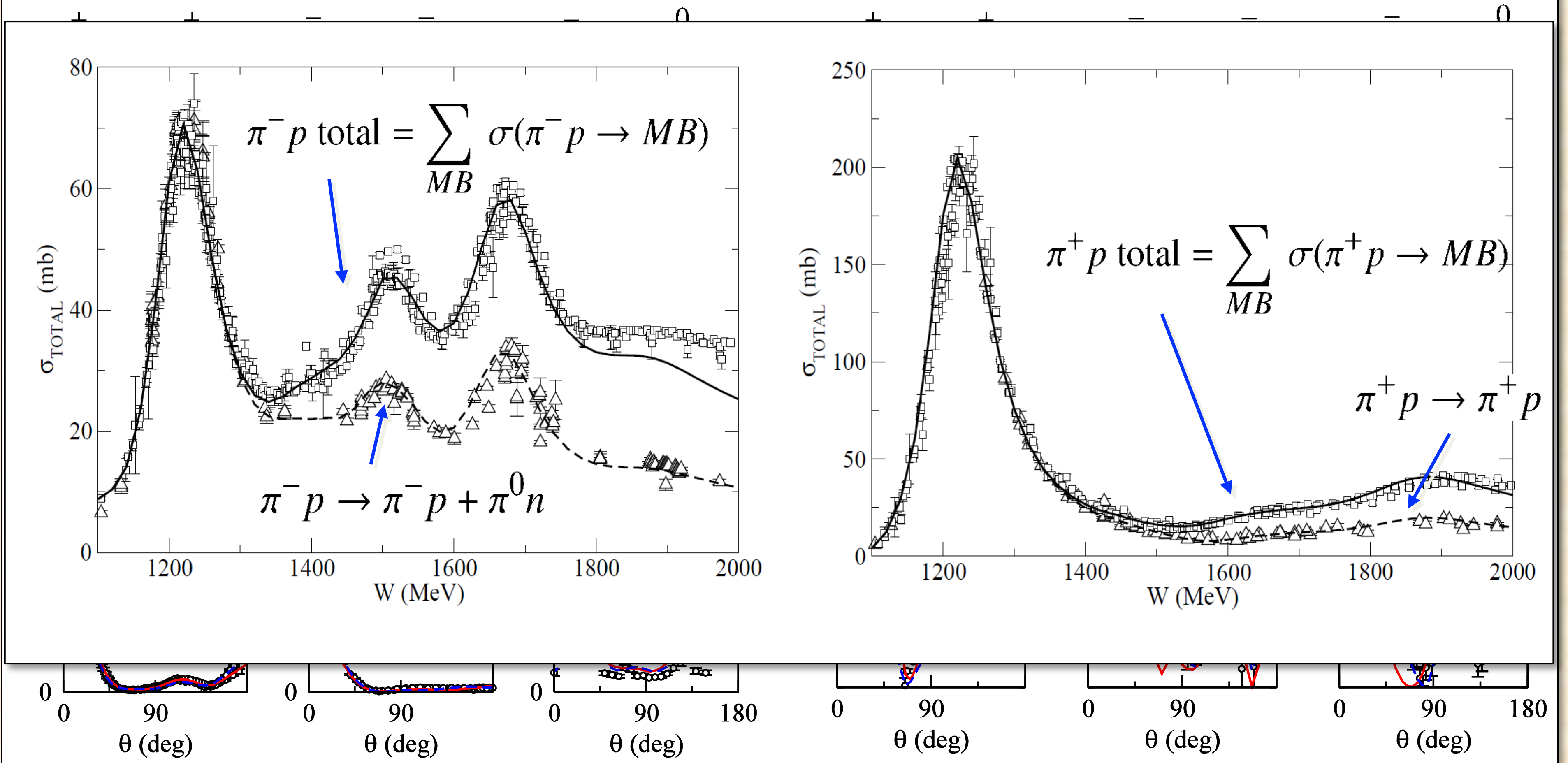
Thank you for your attention!

back up

Pion-nucleon elastic scattering

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

Target polarization



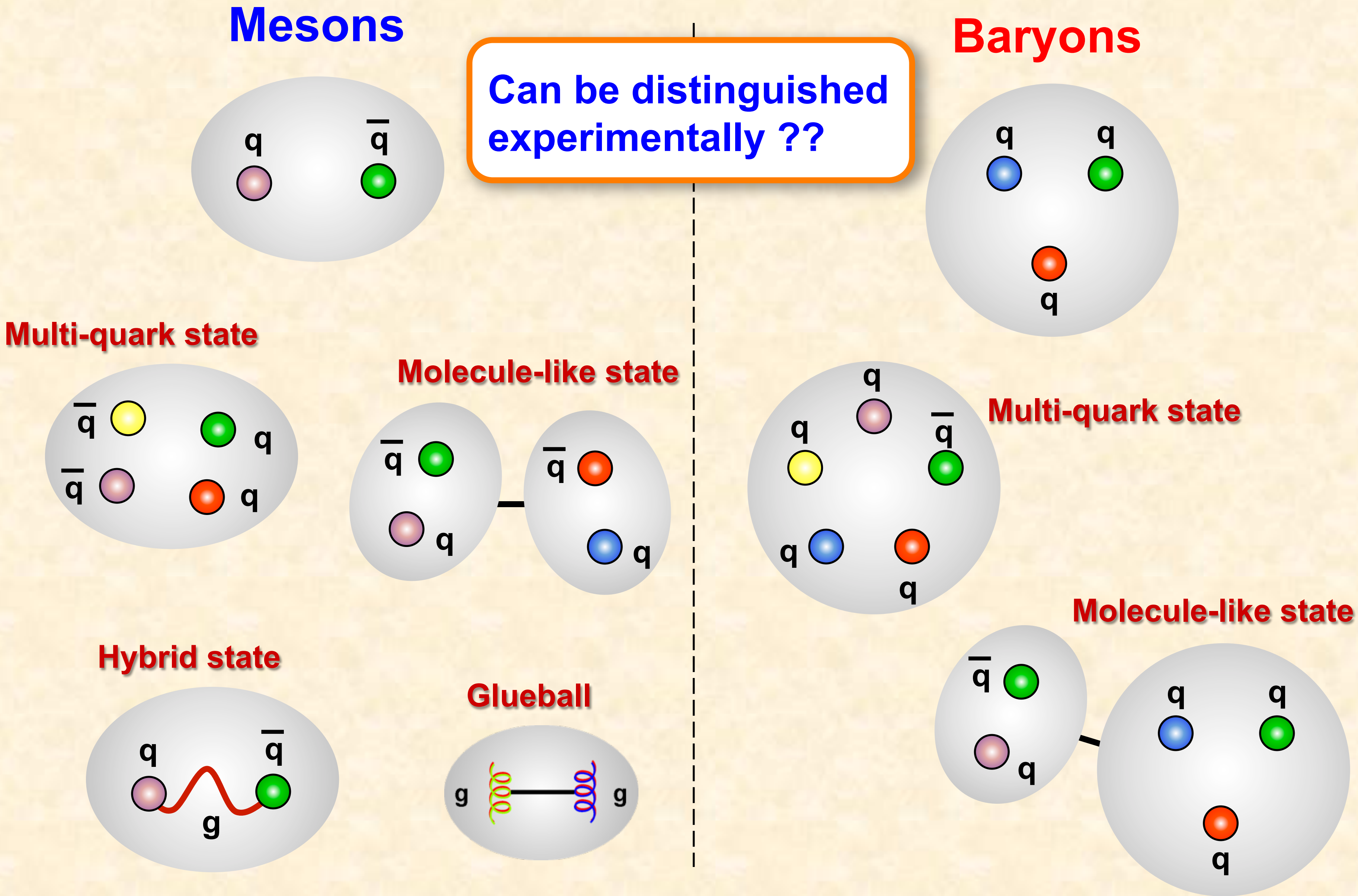
Kamano, Nakamura, Lee, Sato

Accelerators for hadron physics around the world

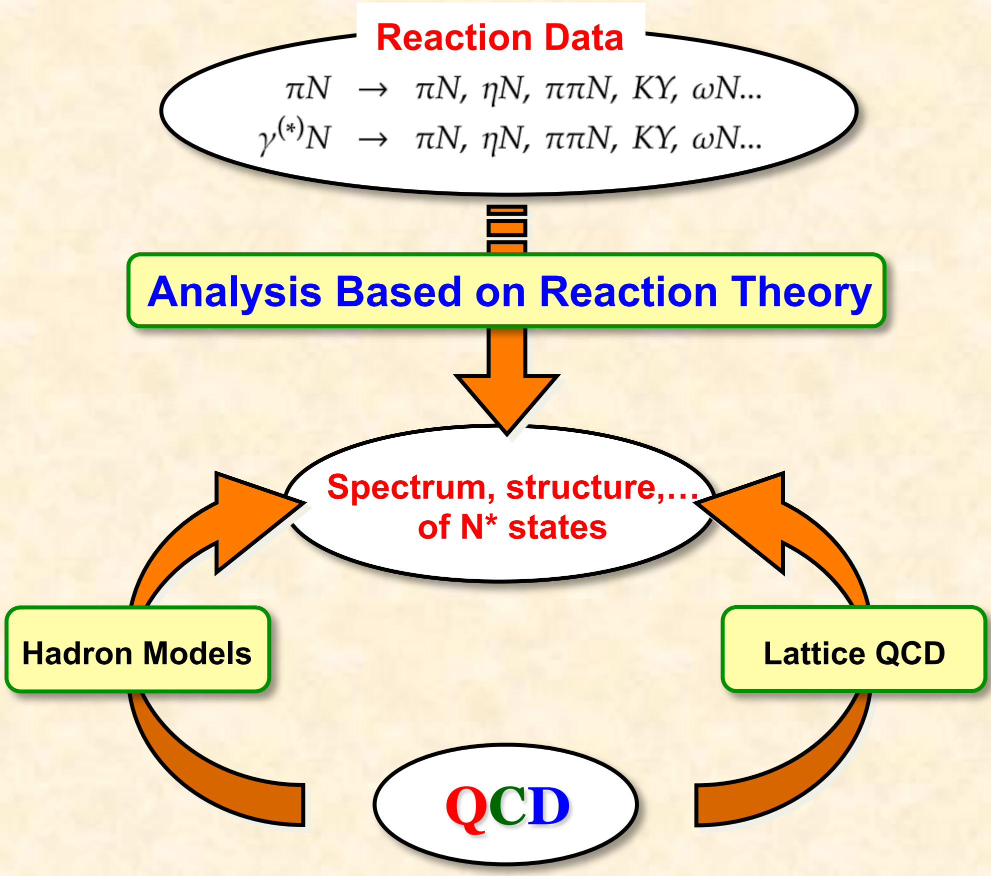
... and more !!

Figures are from M. Pennington's talk

Hadrons


Mesons
q
$\bar{q}$
Can be distinguished experimentally ??
Baryons
q
q
q
Multi-quark state
$\bar{q}$
q
$\bar{q}$
q
Molecule-like state
$\bar{q}$
q
$\bar{q}$
q
Multi-quark state
q
q
$\bar{q}$
q
q
Hybrid state
q
$\bar{q}$
g
Glueball
g
g
Molecule-like state
$\bar{q}$
q
q
q
q

Dynamical coupled-channels analysis of meson production reactions



<u>Objectives and goals:</u>

Through the comprehensive analysis of world data of pN, gN, N(e,e') reactions,

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

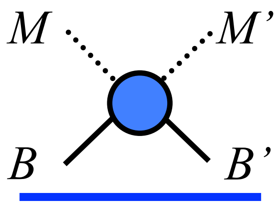
  (e.g., N-N* e.m. transition form factors)
- ✓ Provide reaction mechanism information necessary for interpreting N* spectrum, structures and dynamical origins

Hadronic amplitudes in the DCC model

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

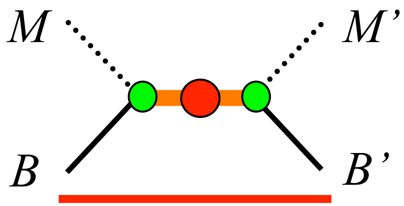
Amplitudes of two-body meson-baryon reactions

$T_{MB \to M'B'} =$



Non-resonant amp.

+



Rsonant amp.

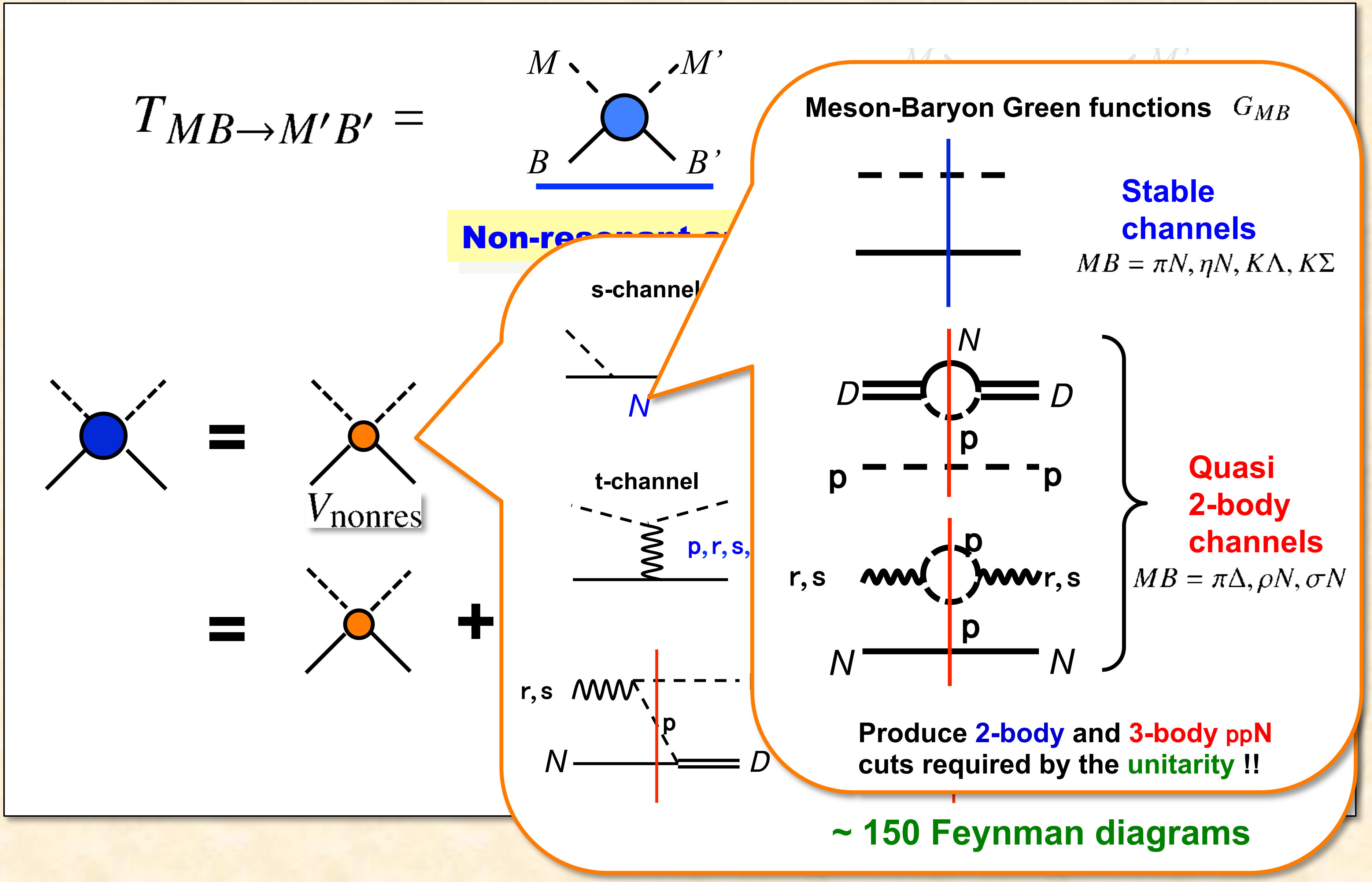
Reaction channels:

$$(M, B), (M', B') \;=\; (\pi N,\ \eta N,\ \pi\Delta,\ \sigma N,\ \rho N,\ K\Lambda,\ K\Sigma,\ \omega N, \cdots)$$

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

Hadronic amplitudes in the DCC model

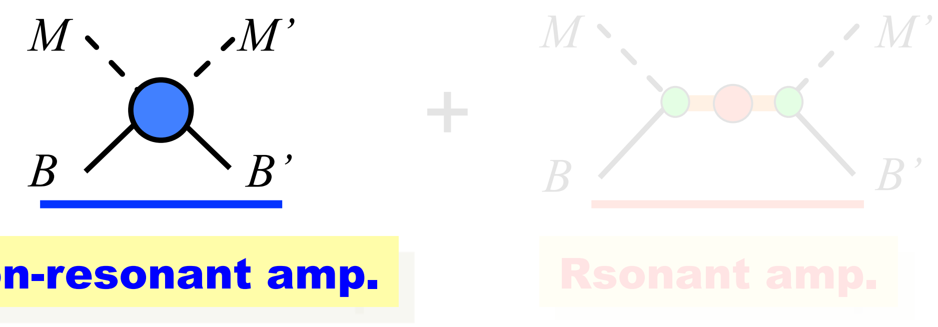
For details see Matsuyama, Sato, Lee, Phys. Rep. 439,193 (2007)

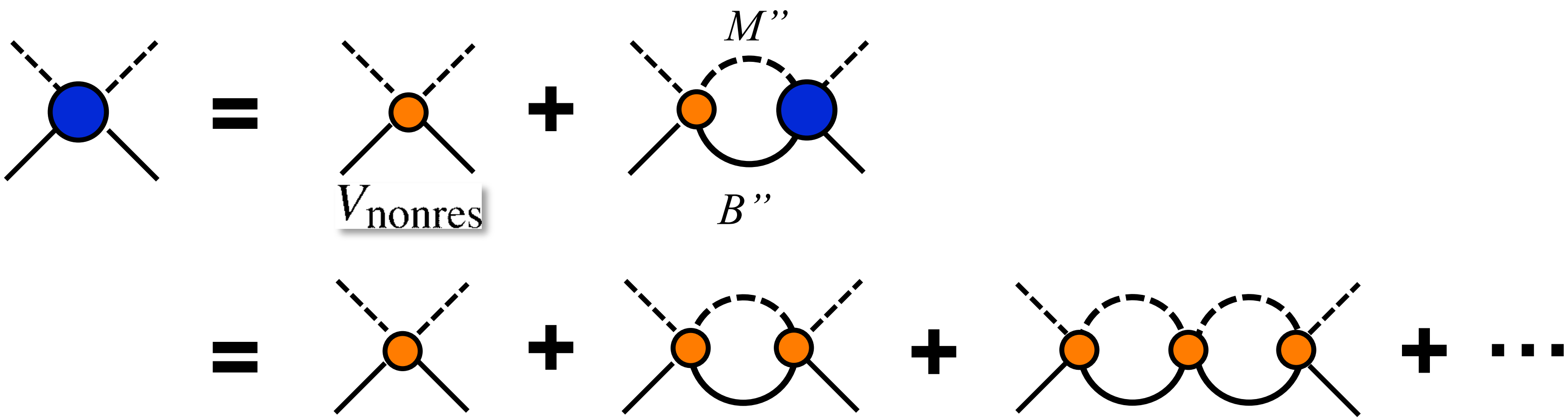


Hadronic amplitudes in the DCC model

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

$$T_{MB\rightarrow M'B'} =$$

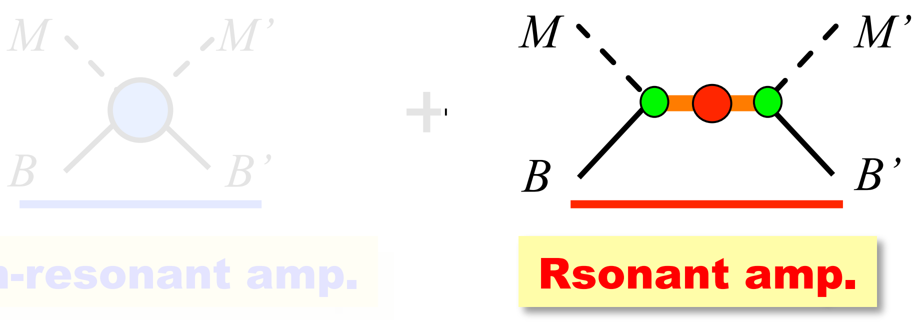




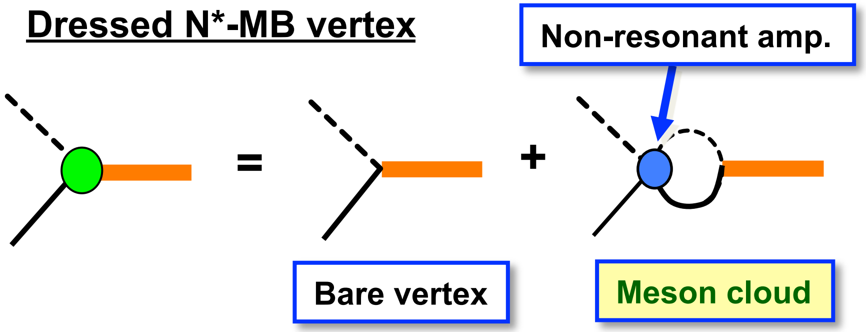
Hadronic amplitudes in the DCC model

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

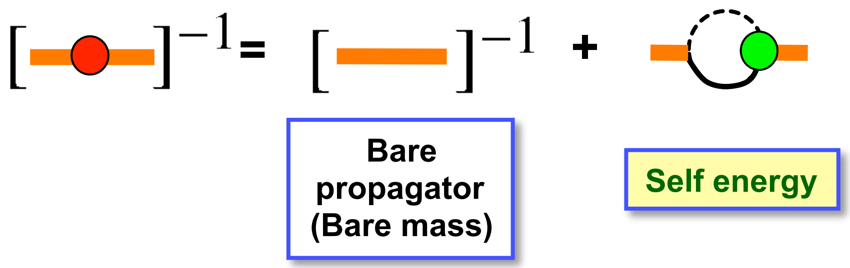
$$T_{MB\to M'B'} =$$



Dressed N*-MB vertex



Dressed N* propagator



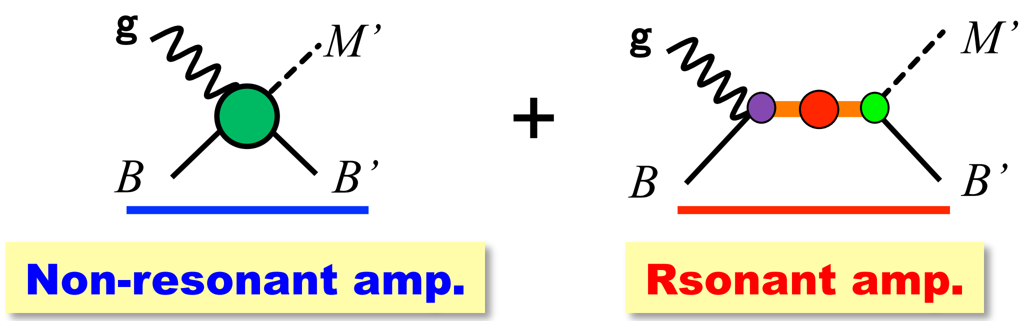
Effects of rescattering processes (reaction dynamics) are included consistently with the unitarity of S-matrix.

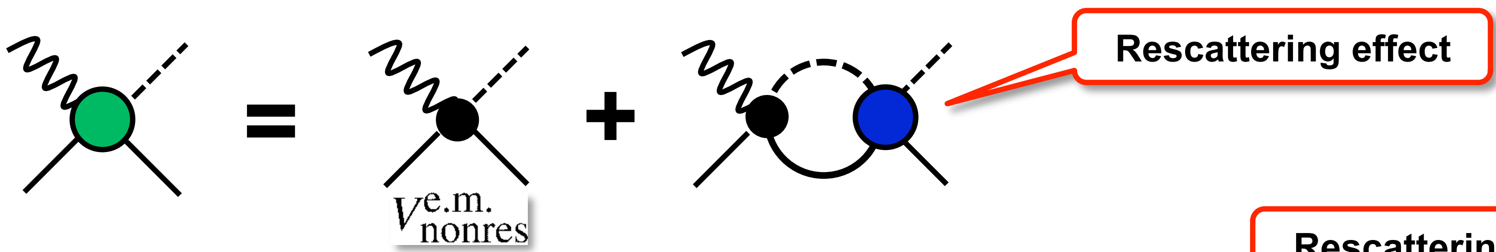
Electromagnetic amplitudes in the DCC model

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

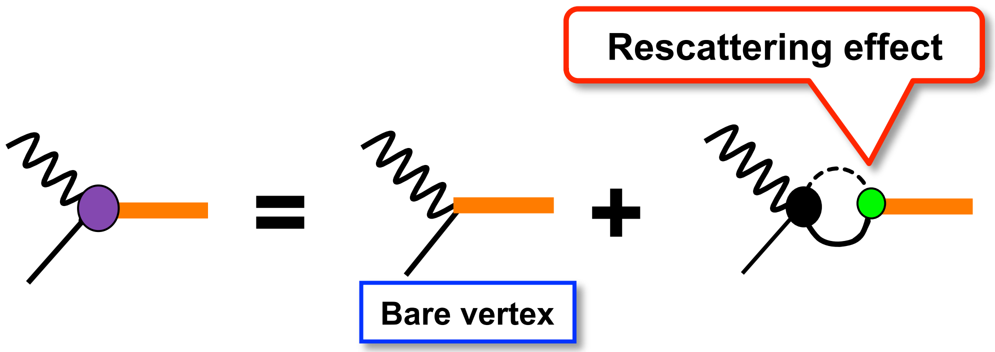
E.M. current interactions are treated perturbatively.

$$T_{\gamma B \to M'B'} =$$





Dressed gN → N* vertex



Analysis database and procedure

Pion-induced reactions (purely strong interactions)

	Waves	# of data	Waves	# of data
$\pi N \to \pi N$ PWA	S_{11}	56×2	D_{13}	52×2
	S_{31}	56×2	D_{15}	52×2
	P_{11}	56×2	D_{33}	50×2
	P_{13}	52×2	D_{35}	31×2
	P_{31}	52×2	F_{15}	39×2
	P_{33}	56×2	F_{17}	23×2
			F_{35}	34×2
			F_{37}	35×2
			Sum	1288

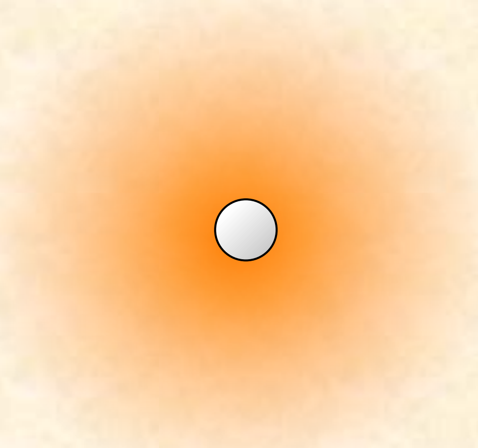
	$d\sigma/d\Omega$	P	R	a	Sum
$\pi^- p \to \eta p$	294	-	-	-	294
$\pi^- p \to K^0 \Lambda$	544	262	-	-	806
$\pi^- p \to K^0 \Sigma^0$	215	70	-	-	285
$\pi^+ p \to K^+ \Sigma^+$	552	312	-	-	864
Sum	1605	644	-	-	2249

More than 20,000 data points to fit

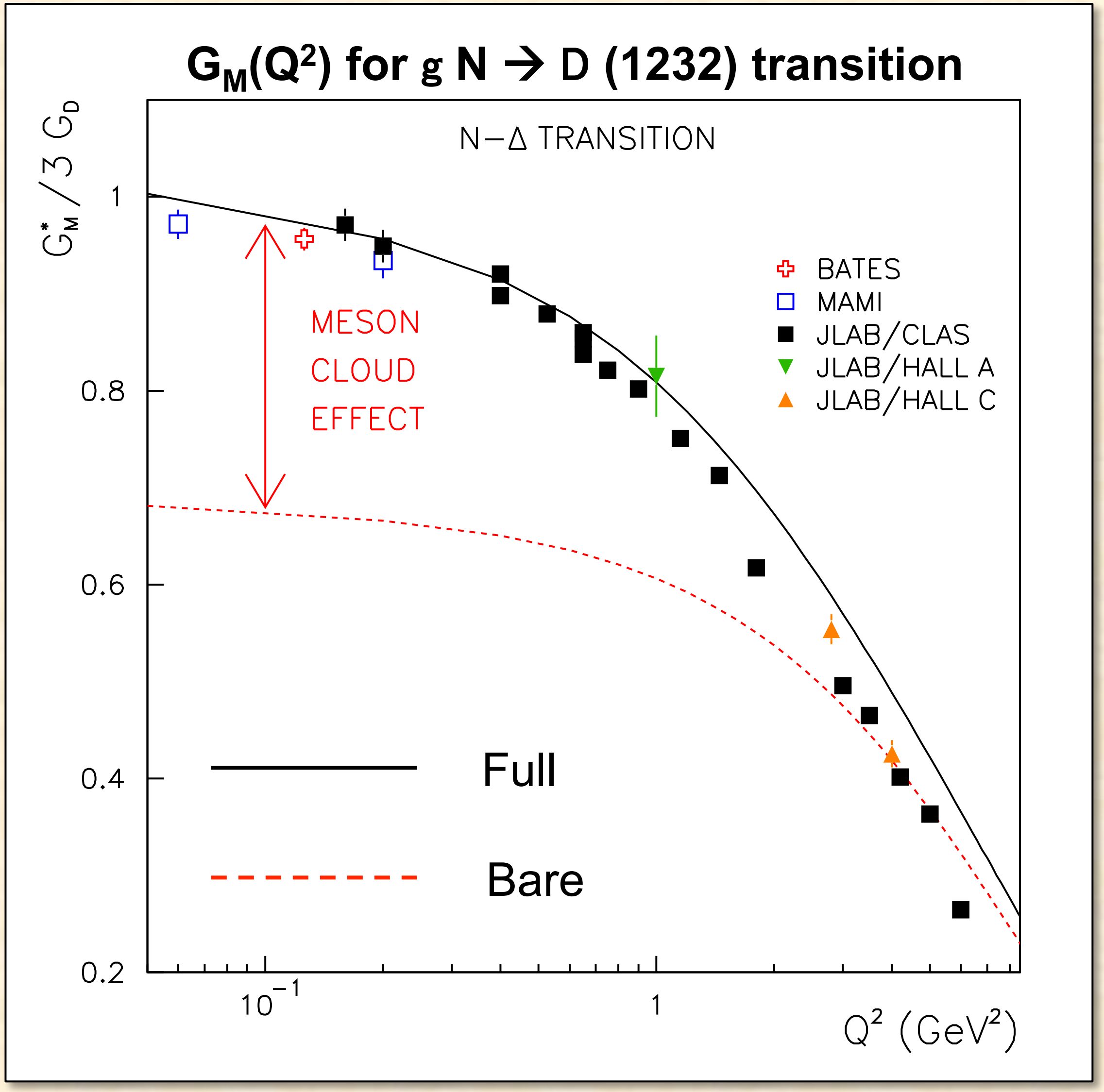
Photo-production reactions

	$d\sigma/d\Omega$	Σ	T	P	G	H	E	F	$O_{x'}$	$O_{z'}$	$C_{x'}$	$C_{z'}$	$T_{x'}$	$T_{z'}$	$L_{x'}$	$L_{z'}$	sum
$\gamma p \to \pi^0 p$	8290	1680	353	557	28	24	-	-	-	-	-	-	-	-	-	-	10860
$\gamma p \to \pi^+ n$	5384	1014	661	221	75	123	-	-	-	-	-	-	-	-	-	-	7478
$\gamma p \to \eta p$	1076	197	50	-	-	-	-	-	-	-	-	-	-	-	-	-	1323
$\gamma p \to K^+ \Lambda$	611	118	69	410	-	-	-	-	66	66	89	89	-	-	-	-	1518
$\gamma p \to K^+ \Sigma^0$	2949	116	-	320	-	-	-	-	-	-	52	52	-	-	-	-	3489
Sum	18310	3043	1133	1508	103	147	-	-	66	66	141	141	-	-	-	-	24668

Meson cloud effect in gamma N → N* form factors



N, N*



Note:
Most of the available static hadron models give $G_M(Q^2)$ close to "Bare" form factor.

N-N* transition form factors at resonance poles

Extracted from analyzing the p(e,e'p)N data (~ 20,000) from CLAS@JLab

Nucleon - 1st N*(3/2-) e.m. transition form factors

200

virt

1.5

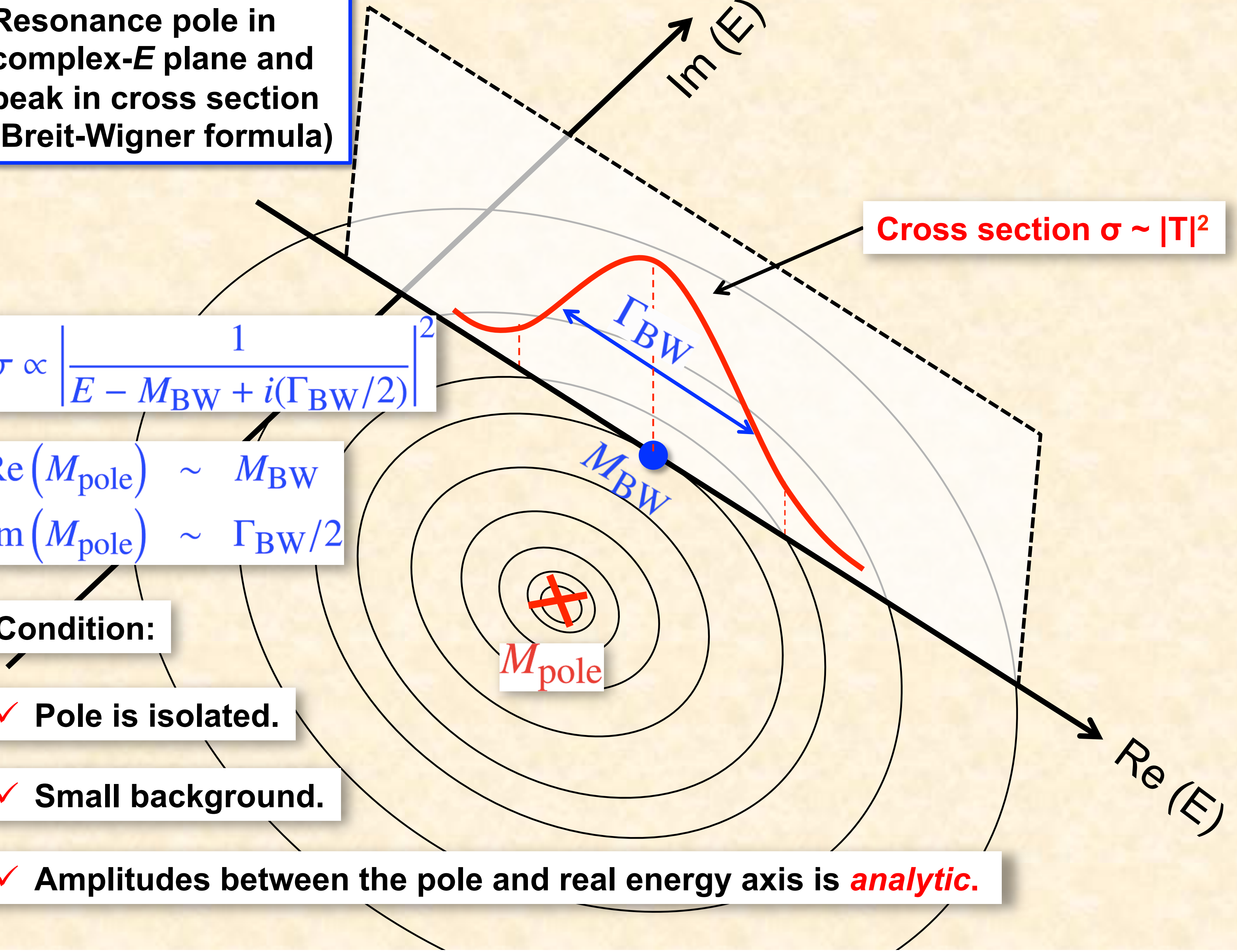
Coupling to meson-baryon continuum states makes N* form factors *complex* !!

Fundamental nature of resonant particles (decaying states)

How can we interpret this complex form factor ??

Julia-Diaz, Kamano, Lee, Matsuyama, Sato, Suzuki PRC80 025207 (2009)
Suzuki, Sato, Lee, PRC82 045206 (2010)

Resonance pole in complex-*E* plane and peak in cross section (Breit-Wigner formula)



$$\sigma \propto \left| \frac{1}{E - M_{BW} + i(\Gamma_{BW}/2)} \right|^2$$

$$\mathrm{Re}\left(M_{pole}\right) \sim M_{BW}$$
$$\mathrm{Im}\left(M_{pole}\right) \sim \Gamma_{BW}/2$$

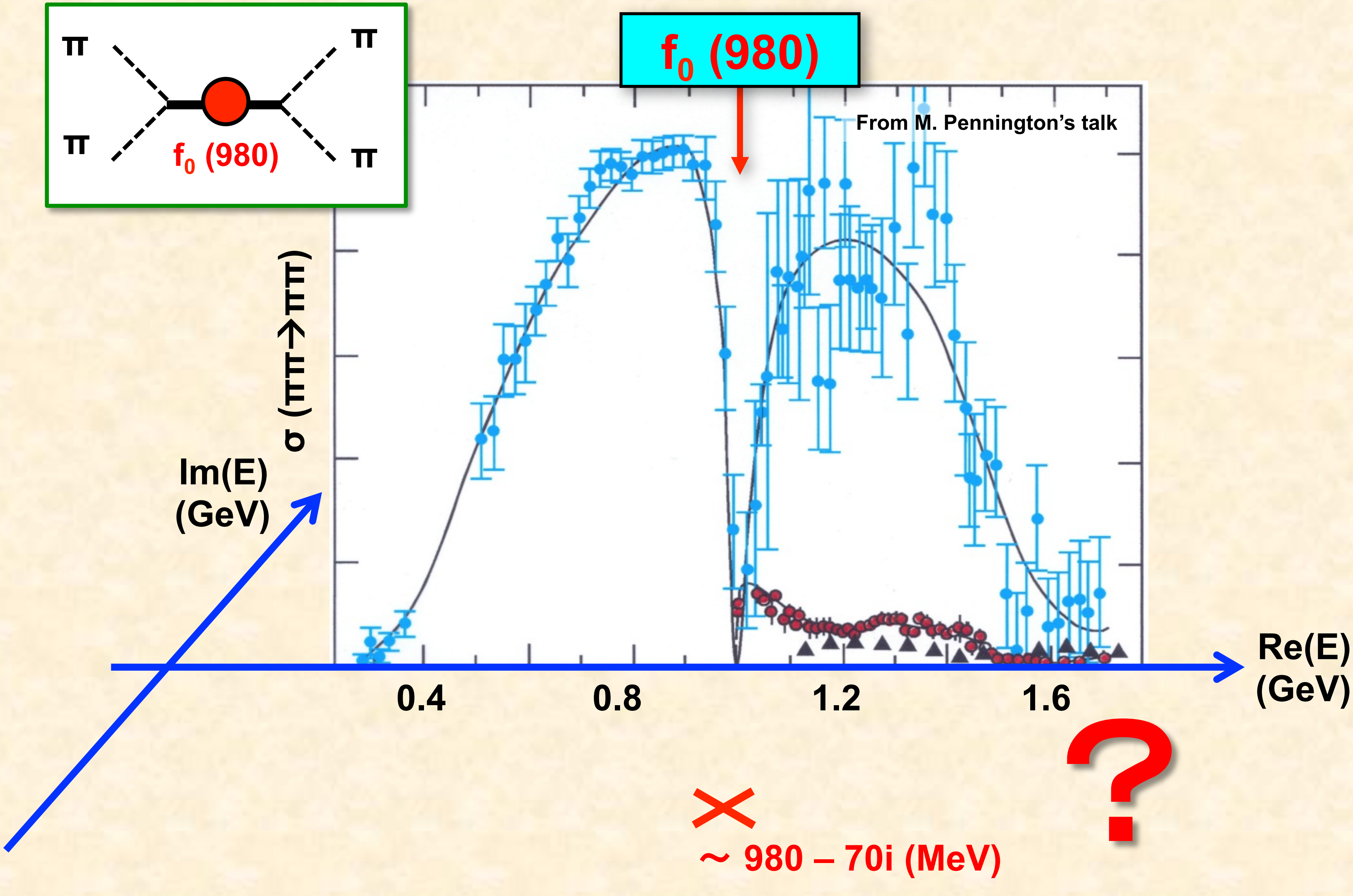
Condition:

✓ **Pole is isolated.**

✓ **Small background.**

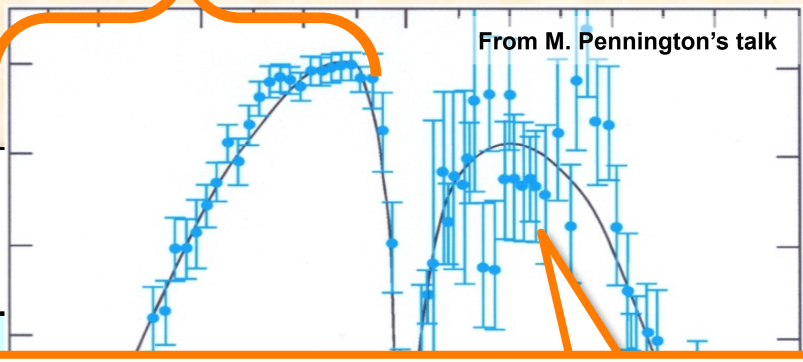
✓ **Amplitudes between the pole and real energy axis is *analytic*.**

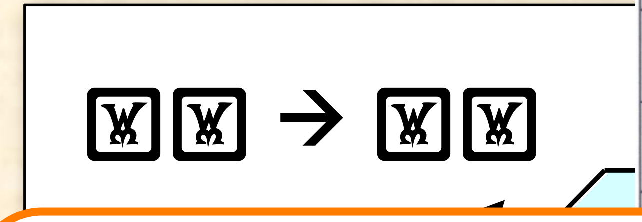
$f_0(980)$ in pi-pi scattering



f_0(980) in pi-pi scattering, Cont'd

f_0(980) is barely contributed





Not only the resonance poles, but also the analytic structure of the scattering amplitudes in the complex E-plane plays a crucial role for the shape of cross sections on the real energy axis (= real world) !!