N* Properties and Coupled Channel Analysis of Meson Production Reactions

T. Sato (Osaka U.)

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1 Analysis of meson production reaction
2 Extraction of resonance parameters
3 Future plan

JPARC Dec. 2011

The Δ (1232) and others

Total Cross Sections of Positive Pions in Hydrogen*

H. L. ANDERSON, E. FERMI, E. A. LONG,† AND D. E. NAGLE
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois

(Received January 21, 1952)

N* physics started 60 years ago

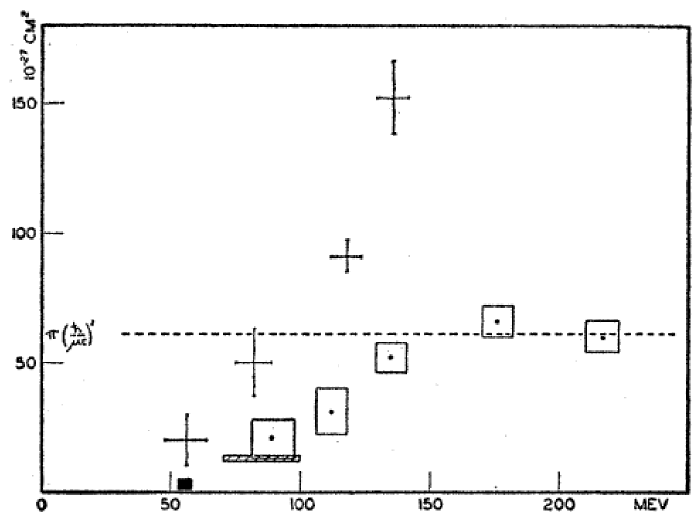
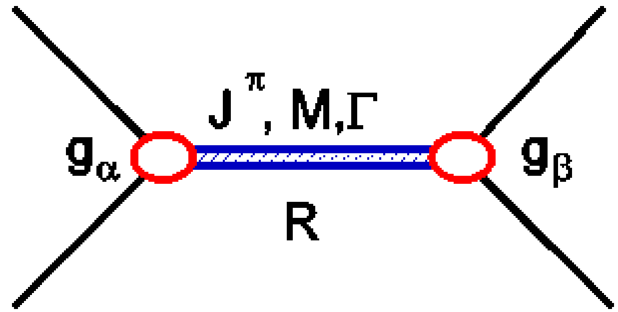


FIG. 1. Total cross sections of negative pions in hydrogen (sides of the rectangle represent the error) and positive pions in hydrogen (arms of the cross represent the error). The cross-hatched rectangle is the Columbia result. The black square is the Brookhaven result and does not include the charge exchange contribution.

Spectrum of hadron excited states and their decay scheme

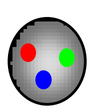
mass, width,
form factor



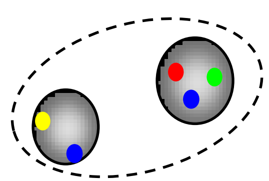
Recent 10 years

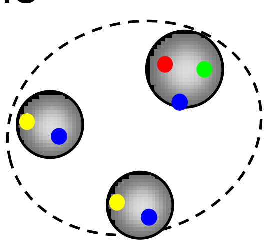
high precision data from electromagnetic probe
Jlab, Mainz, Bonn, GRAAL, Spring-8,MIT-bates

constituent quarks



hadron molecule





LQCD

model of hadron

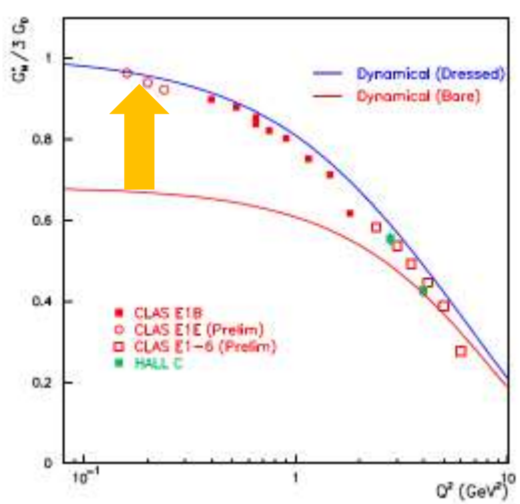
Note: excited baryons are not stable particles
strong coupling with meson-baryon channels

→ affects spectrum, structure of resonances.

→ analyze meson production reaction with dynamical
coupled channel reaction model

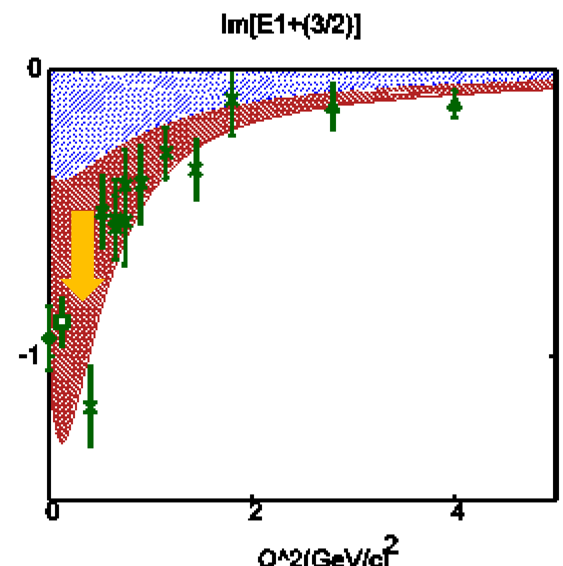
Electromagnetic N(1/2+)-Delta_33(3/2+) transition form factor

pion cloud



M1: Magnetic dipole

[spin flip]



E2: Electric quadrupole

[deformation]

Sato, Lee 96,01

Objective:

I. coupled channel analysis of meson production reaction

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

II Extract resonance information from partial wave amplitude

Establish spectrum of excited nucleons

Extract N* coupling constants, form factors ⟺ **Hadron Models**

interpret N* parameters ⟺ **Lattice QCD**

Dynamical Coupled Channel Approach

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

Start from effective, Hermite Hamiltonian of meson-baryon

$$H = \begin{pmatrix} H_r & V_{r,MB} \\ V_{r,MB} & H_{MB} \end{pmatrix}$$

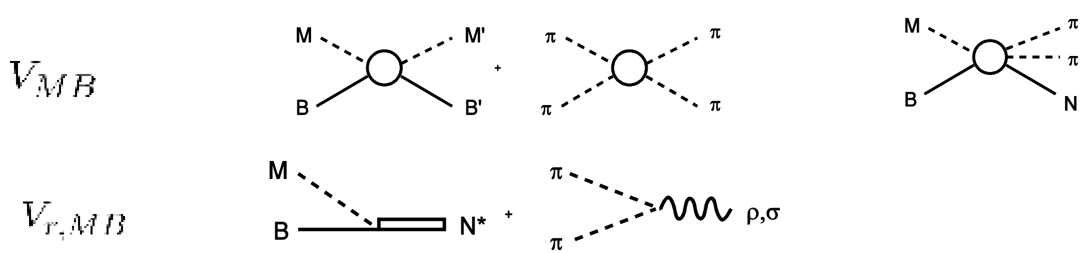
r: 'short range' $N^*, \Delta, \rho, \sigma$

MB: 'long range'

$\gamma N \oplus \pi N \oplus \eta N \oplus KY(\Lambda, \Sigma)$

$\pi\pi N(\sigma N, \rho N, \pi\Delta)$

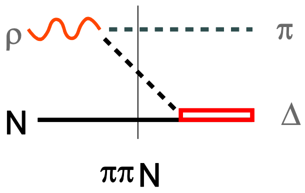
- meson/baryon exchange interactions using effective Lagrangian of meson and baryon

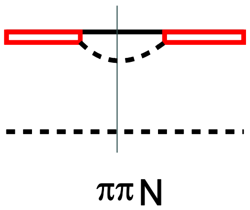


Scattering amplitude of pion and photon induced meson production amplitudes: solving coupled channel LS equation (3-dim reduction) in momentum space

$$T_{\beta,\alpha}(k',k,W) = V_{\beta,\alpha}(k',k) + \sum_{\gamma}\int_0^{\infty} dq q^2 V_{\beta,\gamma}(k',q) G^0_{\gamma}(q,W) T_{\gamma,\alpha}(q,k,W)$$

Scattering amplitudes satisfy two-body and three-body unitarity

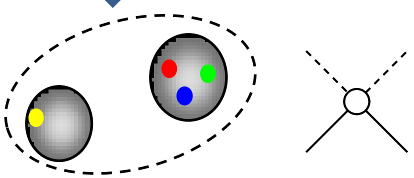


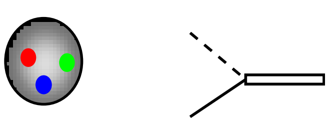


2-2 amplitudes

$$T_{\alpha,\beta}(W) \;=\; t^{nr}_{\alpha,\beta}(W) + \sum_{i,j} \bar{\Gamma}_{\alpha,i}(W)\left[\frac{1}{W - m_0 - \Sigma(W)}\right]_{ij} \bar{\Gamma}_{\beta,j}(W)$$

α, β Meson-Baryon channel $\quad i, j$ Resonances





Analysis of meson production reaction:

(2006-2009)

πN, ηN, $\pi\pi N$ ($\pi\Delta$,ρN,σN) coupled-channels calculations

Hadronic part

- ✓ $\pi N \rightarrow \pi N$: Used for constructing a hadronic model up to W = 2 GeV. (JLMS)
  Julia-Diaz, Lee, Matsuyama, Sato, PRC76 065201 (2007)
- ✓ $\pi N \rightarrow \eta N$: Used for constructing a hadronic model up to W = 2 GeV
  Durand, Julia-Diaz, Lee, Saghai, Sato, PRC78 025204 (2008)
- ✓ $\pi N \rightarrow \pi \pi N$: First full dynamical coupled-channels calculation up to W = 2 GeV.
  Kamano, Julia-Diaz, Lee, Matsuyama, Sato, PRC79 025206 (2009)

Electromagnetic part

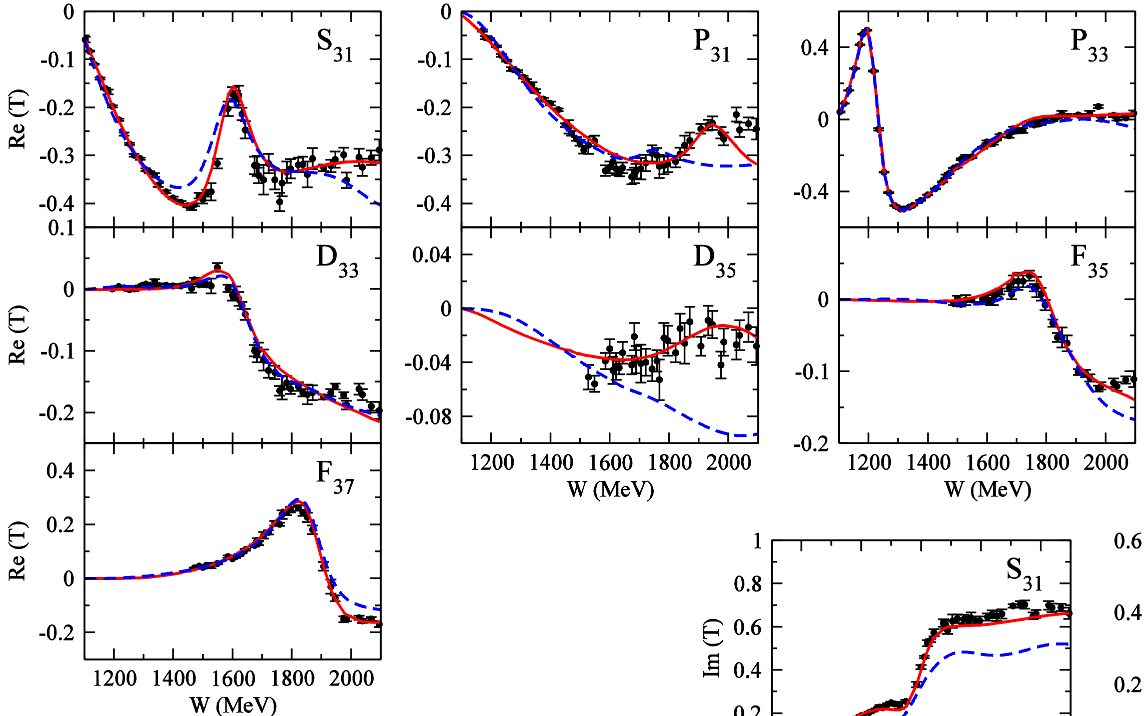
- ✓ $\gamma^{(*)} N \rightarrow \pi N$: Used for constructing a E.M. model up to W = 1.6 GeV and Q^2 = 1.5 GeV^2
  (photoproduction) Julia-Diaz, Lee, Matsuyama, Sato, Smith, PRC77 045205 (2008)
  (electroproduction) Julia-Diaz, Kamano, Lee, Matsuyama, Sato, Suzuki, PRC80 025207 (2009)
- ✓ $\gamma N \rightarrow \pi \pi N$: First full dynamical coupled-channels calculation up to W = 1.5 GeV.
  Kamano, Julia-Diaz, Lee, Matsuyama, Sato, PRC80 065203 (2009)

Recently : piN -> KY, gamma N -> KY in preparation

of data points

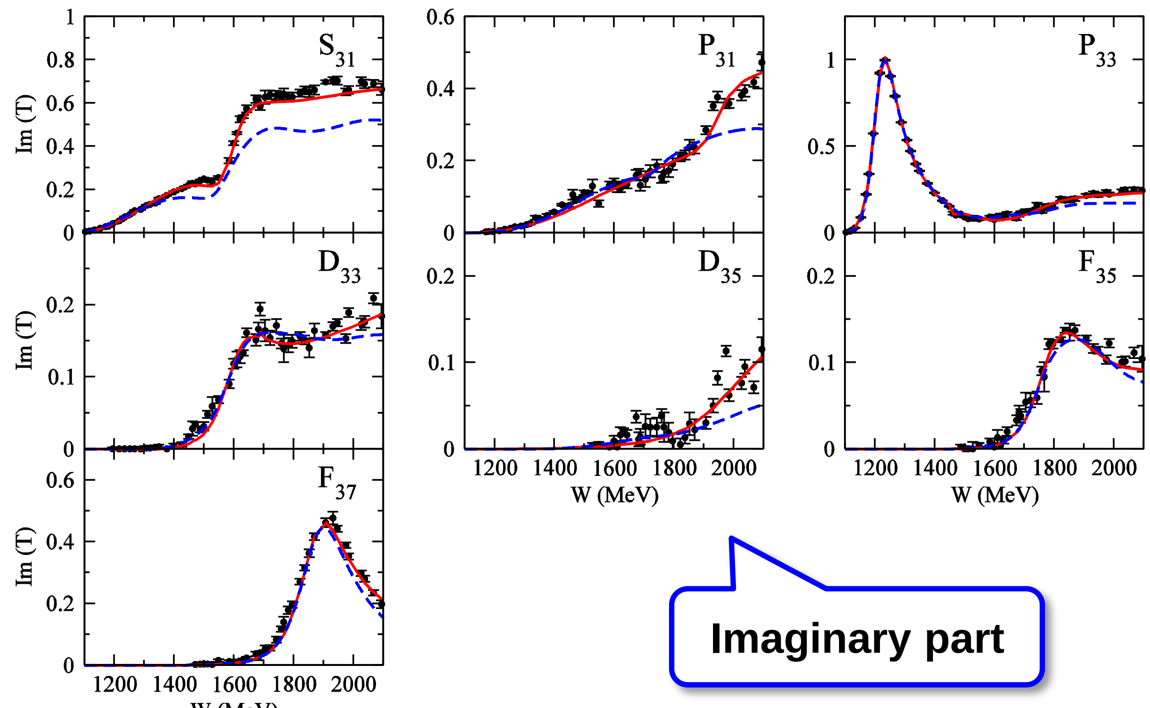
pi N -> pi N	~	23000
-> eta N	~	300
-> KY	~	2000
-> pipiN	~	350

gamma N -> pi N	~	18000
-> eta N	~	1700
-> KY	~	3300



Real part

$$I = \frac{3}{2}$$



Imaginary part

Current model
(fully combined analysis,
PRELIMINALY)

Previous model
(fitted to πN → πN data only)
[PRC76 065201 (2007)]

By H. Kamano

By H. Kamano

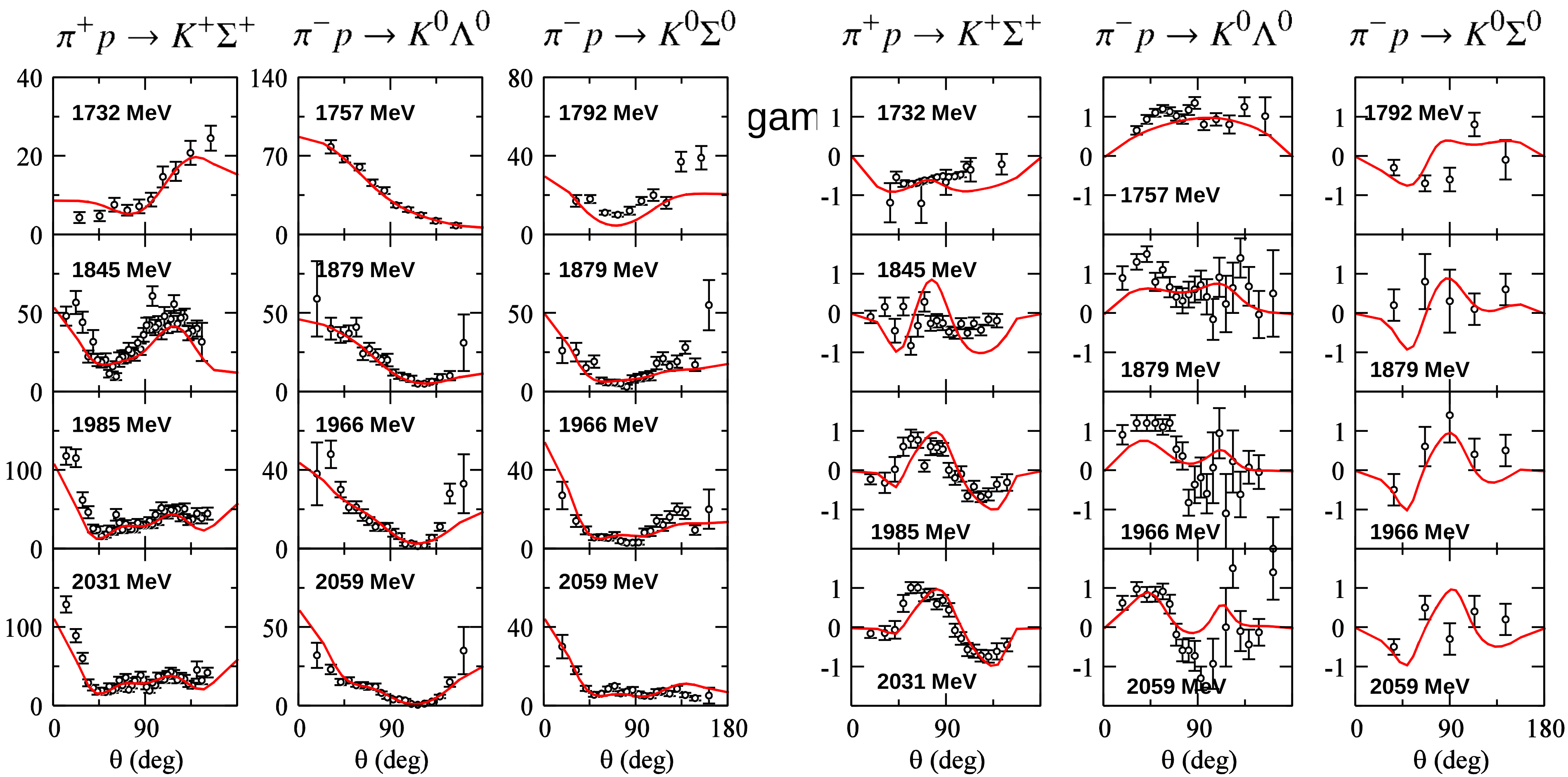
pi N → KY reactions

Kamano, Nakamura, Lee, Sato in preparation

Preliminary!!

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

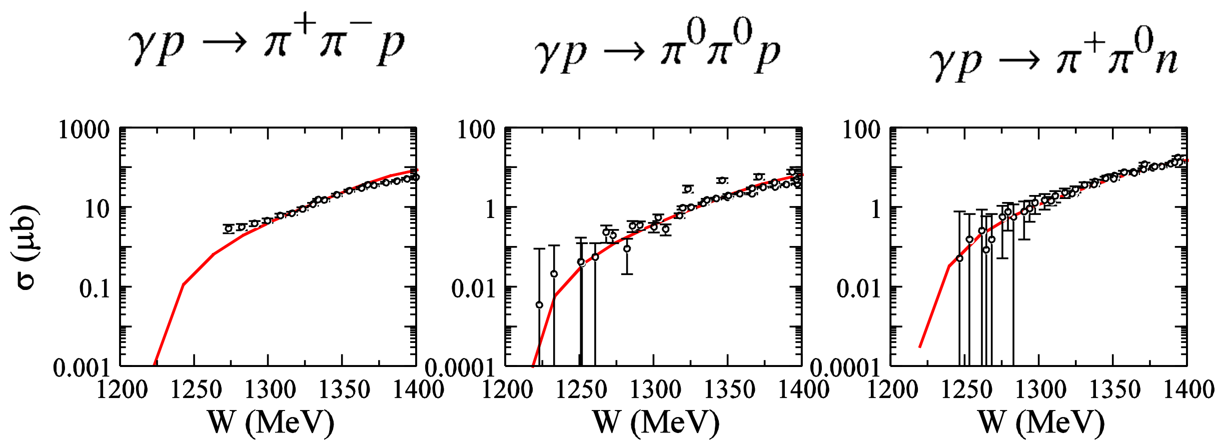
Recoil polarization



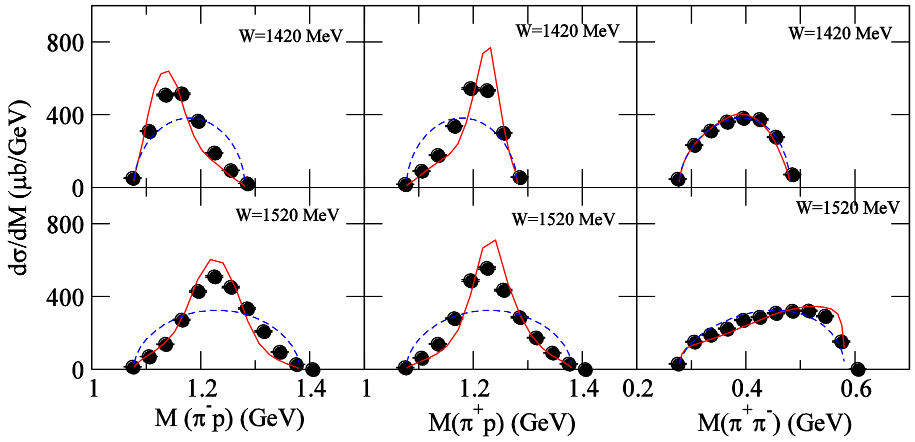
Double pion photoproduction

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.**



By H. Kamano

By H. Kamano

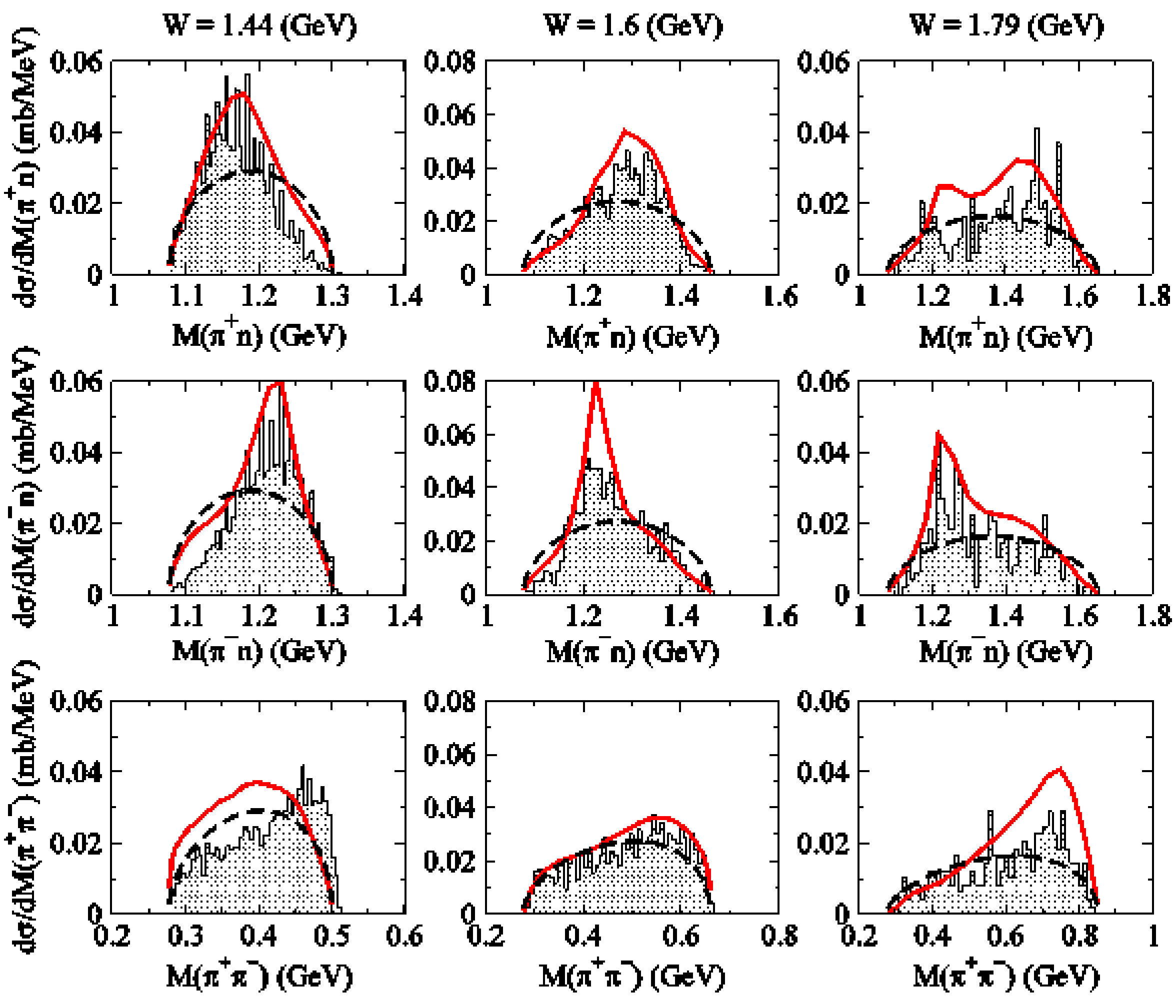
$\pi^- p \rightarrow \pi^+ \pi^- n$

Invariant mass distributions

Full result

Phase space

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



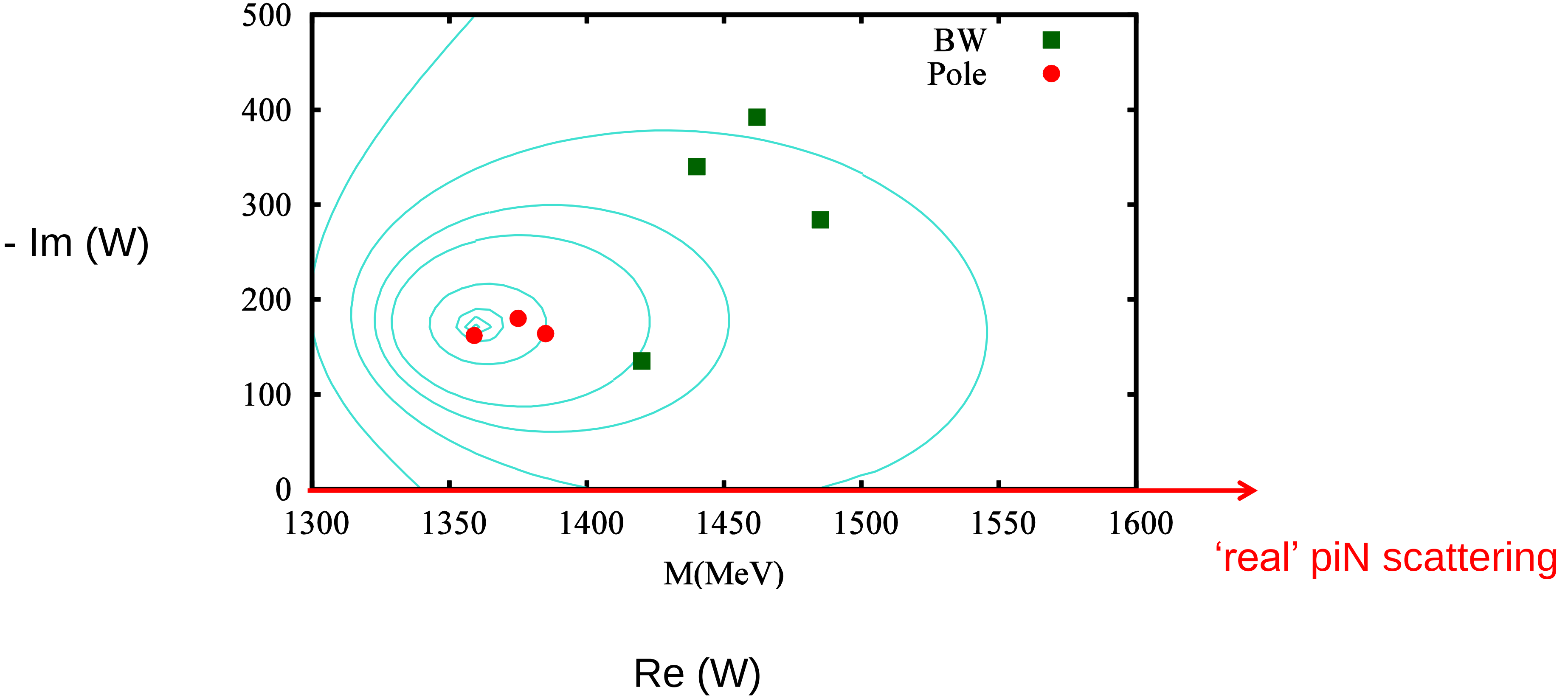
Data handled with the help of R. Arndt

By H. Kamano

Extraction of resonance parameters

N. Suzuki, Sato, Lee ,PRC82 (2010)045296
PRC79 (2009)025295

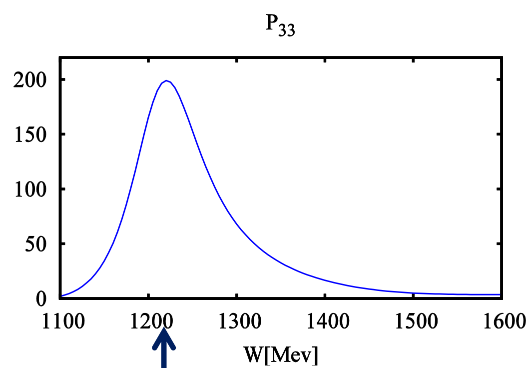
Resonance energy of P11 (BW, pole)
+ coutour plot of piN scattering amplitude |F|



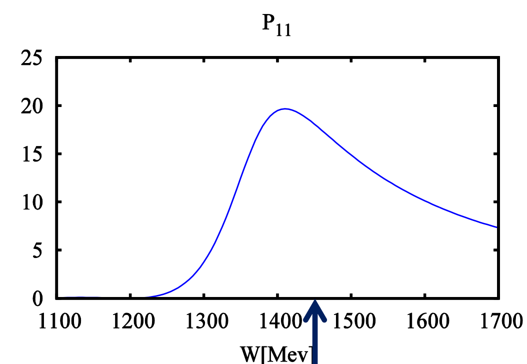
Extraction of resonance parameters

Breit-Wigner parametrization of partial wave amplitudes

$$T(E) = \frac{e^{2i\delta_b(E)} R_{BW}(E)}{M_{BW} - E - i\Gamma_{BW}(E)/2} + B(E)$$

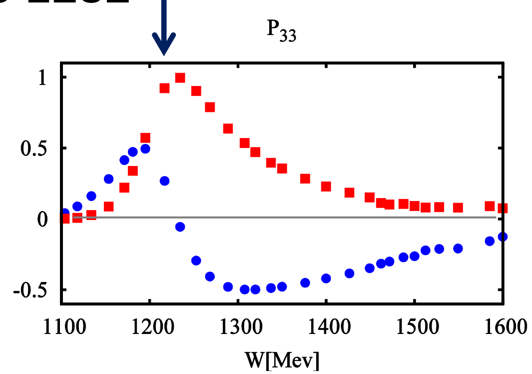


piN elastic scattering partial wave cross section



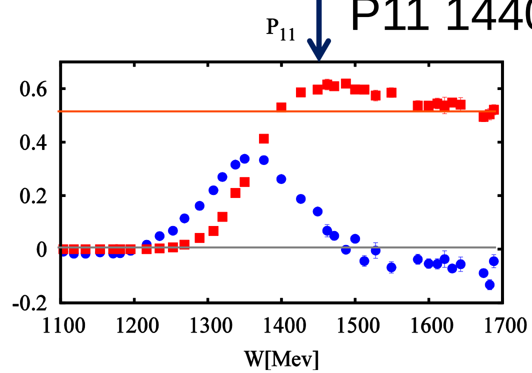
P33 1232

P11 1440



piN elastic scattering amplitude

$$F = \frac{S-1}{2i}$$



Im(F),

Re(F)

Resonance parameters from pole of amplitude on un-physical sheet

$$T(E) = \frac{R}{M - E - i\Gamma/2} + B(E)$$

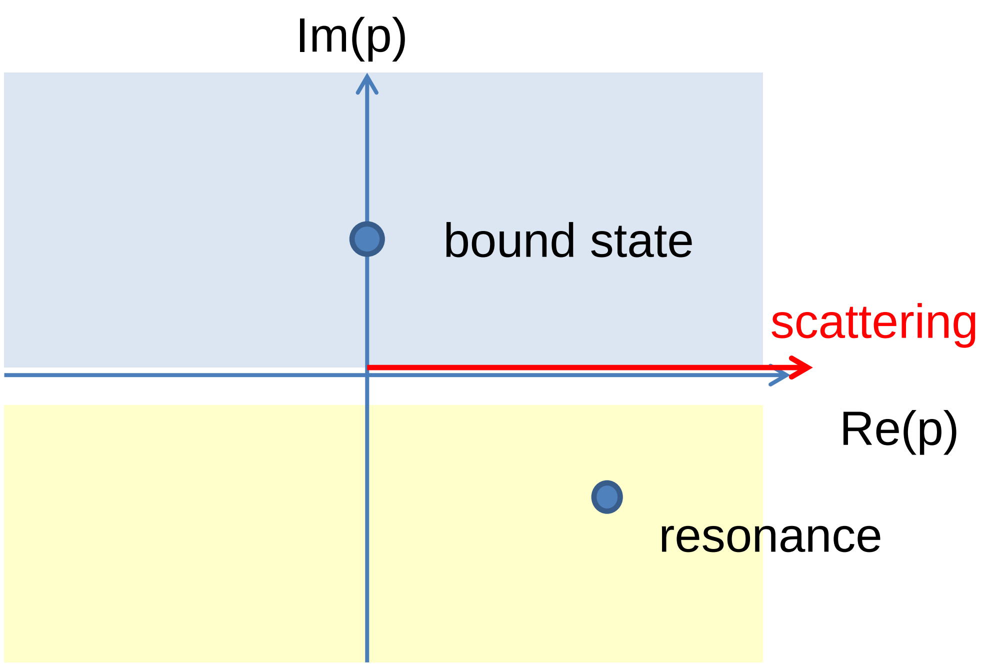
✓ pole energy → resonance mass and width M Γ

✓residue of amplitude → coupling constant of resonance with meson-baryon

physical (E) sheet

$$E = \frac{p^2}{2m}$$

un-physical



Resonance as eigen state of Hamiltonian with outgoing boundary condition(non-hermit)

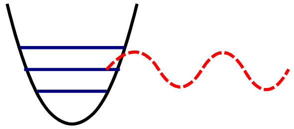
Siegert(39), R. H. Dalitz, R. G. Moorhouse(70)

$$H\psi_{res} = E_{res}\psi_{res} \qquad \partial\psi_{res}/\partial r - iq_{res}\psi_{res} = 0$$

Coupling constant, form factor : residue of the amplitude at pole

$$\gamma_{em} = < \psi_{res}|j_{em}|\psi_N >$$

Coupling constants need not be real



$$\psi_{res} = \psi('bound') + \psi('scattering')$$

Well defined resonance parameters can be a starting point to contact with hadron models

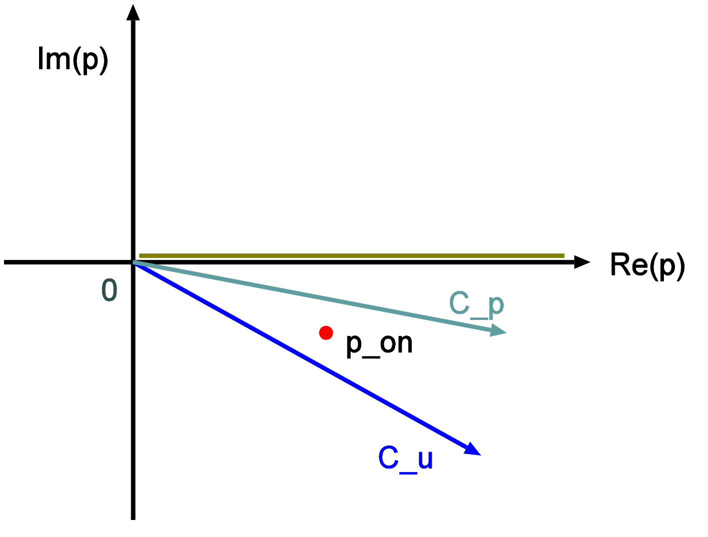
How to obtain T-matrix on un-physical/physical sheet for complex W

- Scattering amplitudes are obtained by solving LS equation in momentum space

$$T_{\beta,\alpha}(k',k,W) = V_{\beta,\alpha}(k',k)+\sum_{\gamma}\int_C dqq^2 V_{\beta,\gamma}(k',q)G^0_{\gamma}(q,W)T_{\gamma,\alpha}(q,k,W)$$

analytic continuation within the model by using contour deformation of momentum of momentum integral.

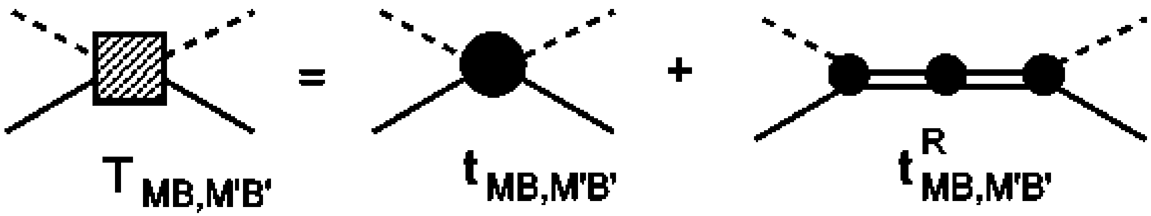
by choosing appropriate contour on each channel, we can obtain p- or u-sheet T-matrix.



How to evaluate poles and residue

$$T_{\alpha,\beta}(W) = t^{nr}_{\alpha,\beta}(W) + \sum_{i,j} \bar{\Gamma}_{\alpha,i}(W)[\frac{1}{W - m_0 - \Sigma(W)}]_{ij}\bar{\Gamma}_{\beta,j}(W)$$

α, β Meson-Baryon channel i, j Resonances



- Determinant of N* green function gives resonance position

$$Det[(W - m_0 - \Sigma(W))_{ij}]$$

- Resonance form factors from residue of amplitude MB

$$\bar{\Gamma} \sim < \tilde{N}^*|j|N > = < N^*|j|N > + < N^*|\Gamma G_0 t_j|N >$$

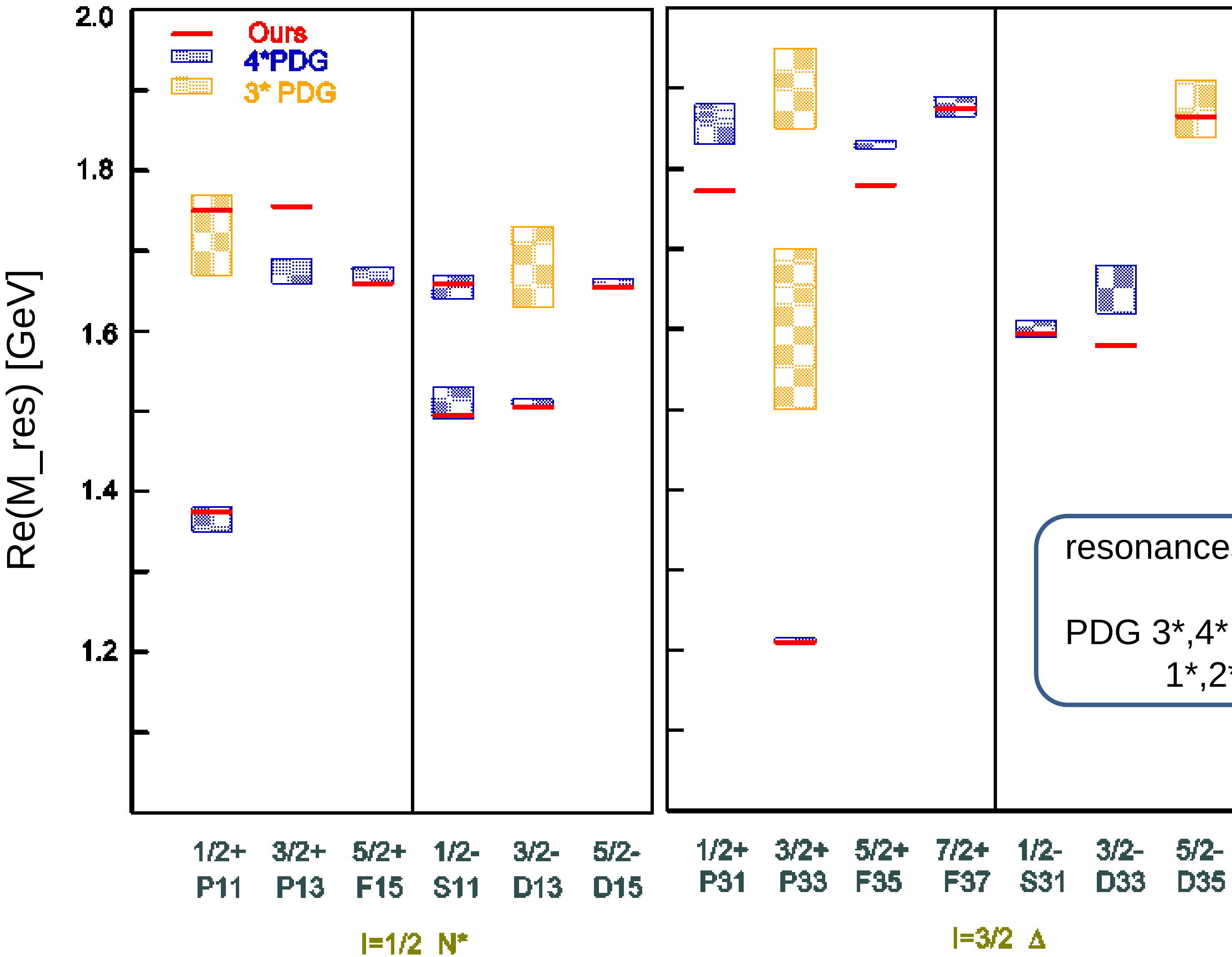
poles on sheet near physical cut are searched.
(u-sheet for open channel, p-sheet for closed channel)
energy around threshold, both p- and u- sheets are searched.

Results using reaction model from global fit of meson production reaction

- Spectrum (Re(M_res))
- Width(Im(M_res))
- P11

Spectrum of excited nucleons Re(M_res) below 2GeV

current model

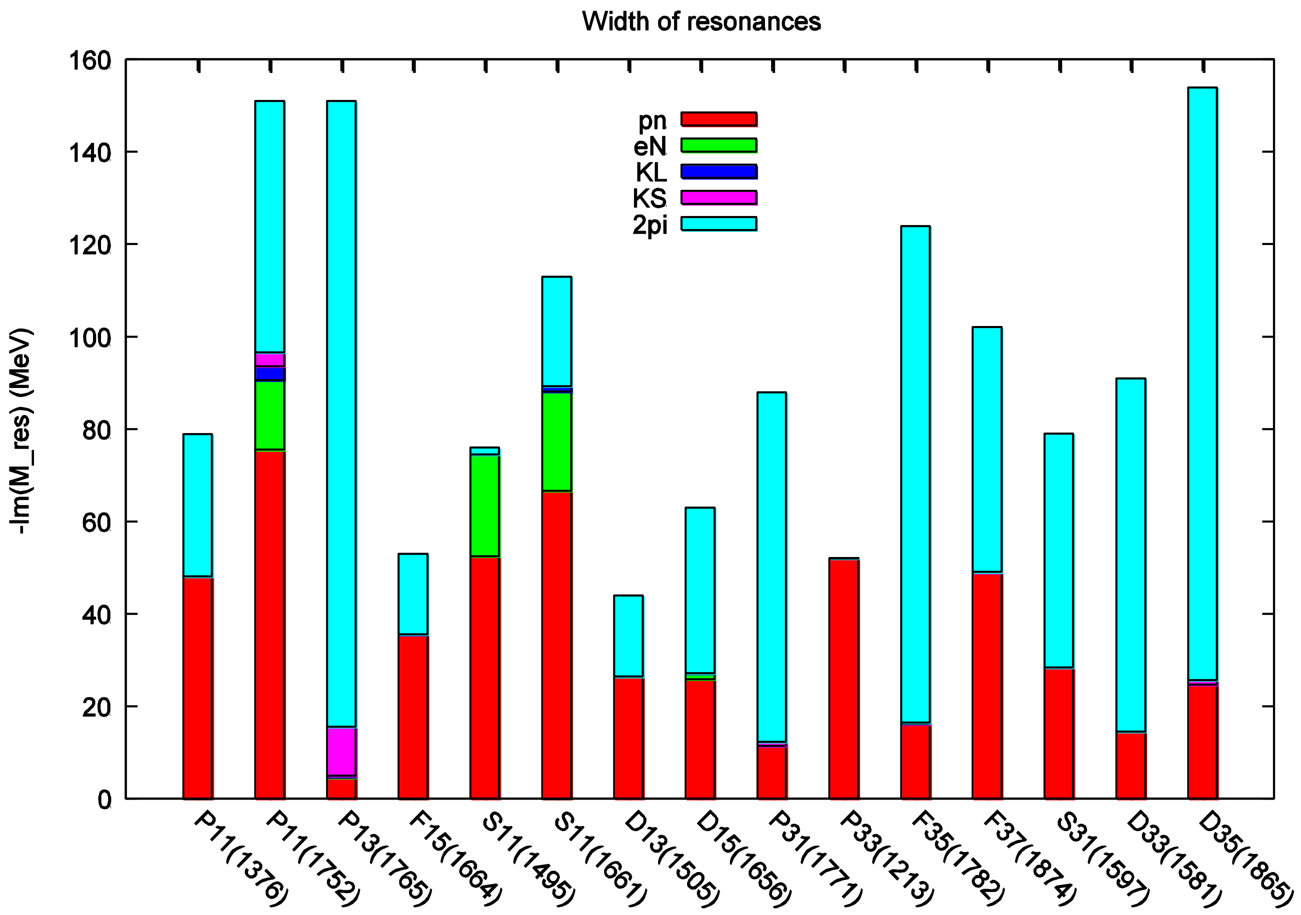


resonances below 2GeV

PDG 3*,4* 18<-> Ours 15
1*,2* 5<-> 0

Half width $\Gamma/2 = -Im(E_{res})$

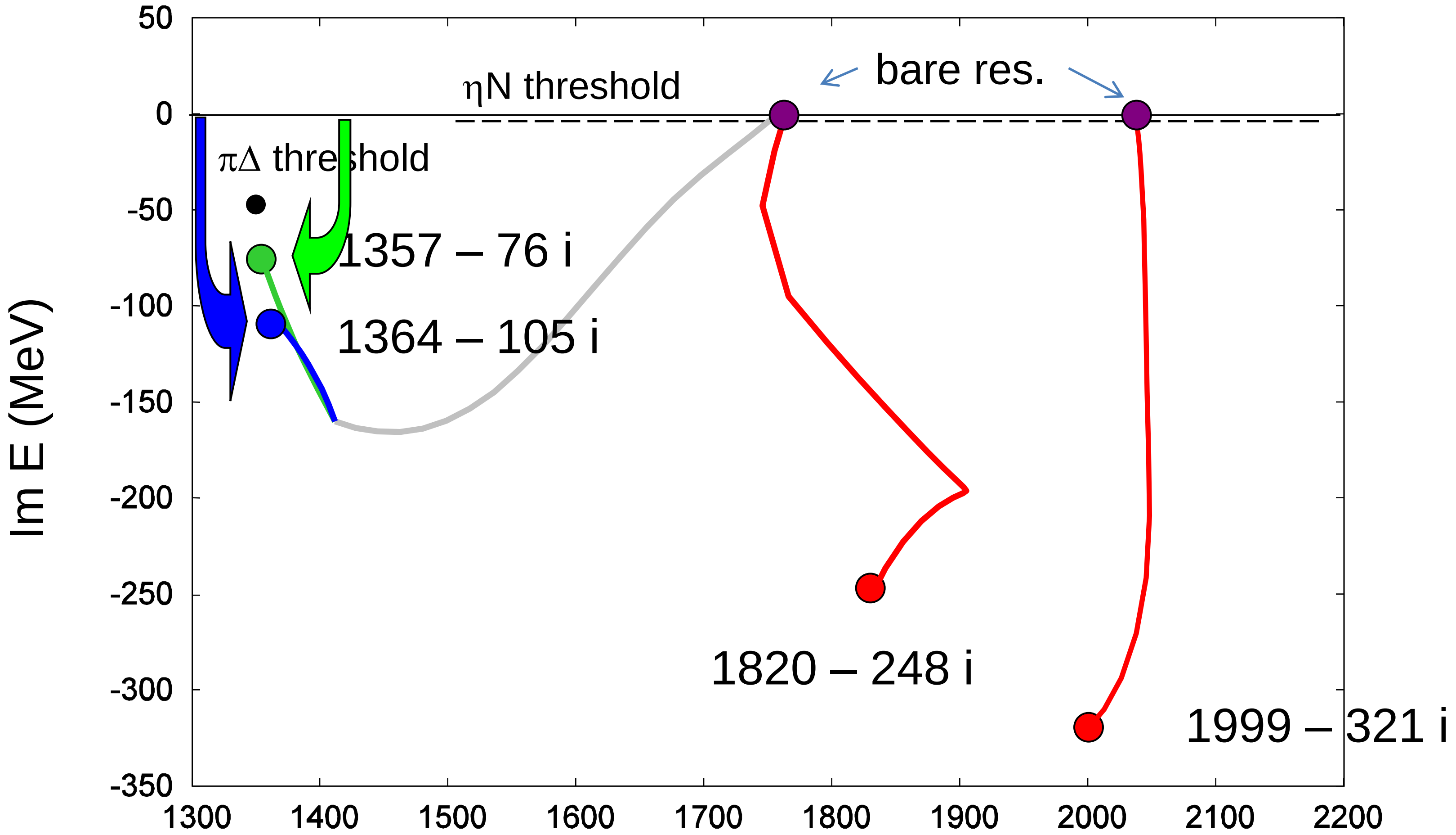
current model



Some freedom exists on the definition of partial width from the residue of the amplitude. The numbers should be taken as a one estimation of the MB-res coupling strength .

Trajectory of P11 poles from 'bare' to 'dressed'

$$det[(W - M_i)\delta_{ij} - x\Sigma_{ij}(W)] = 0 \quad 0 \leq x \leq 1$$



N. Suzuki

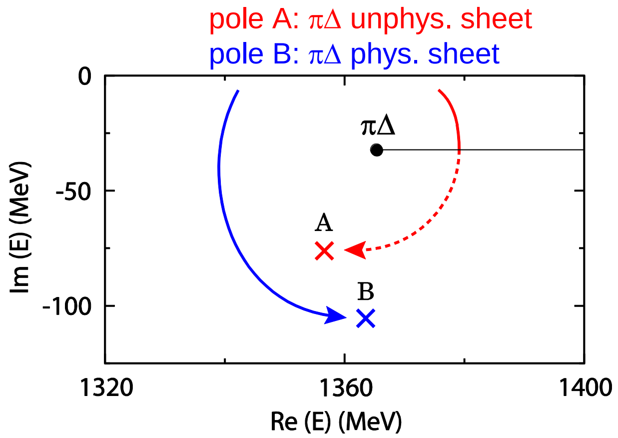
* two poles near branching points

examples :

$$f_0(\pi\pi - K\bar{K})$$

$$^5He(n-\alpha, d-t)$$

P11 pole



* input: 2 bare ‘stable’ resonances --> output: three resonance poles

Resonance in coupled channel problem

* phys and un-phys sheets for each channel
* poles of t-matrix on more than one sheet
  (the above example, the resonance has two poles uu and up/pu)
* usually one of the poles close to the real energy (scattering takes place) affects 'cross section', which is used to characterize resonance.
* exceptional case: both poles can be near physical sheet.

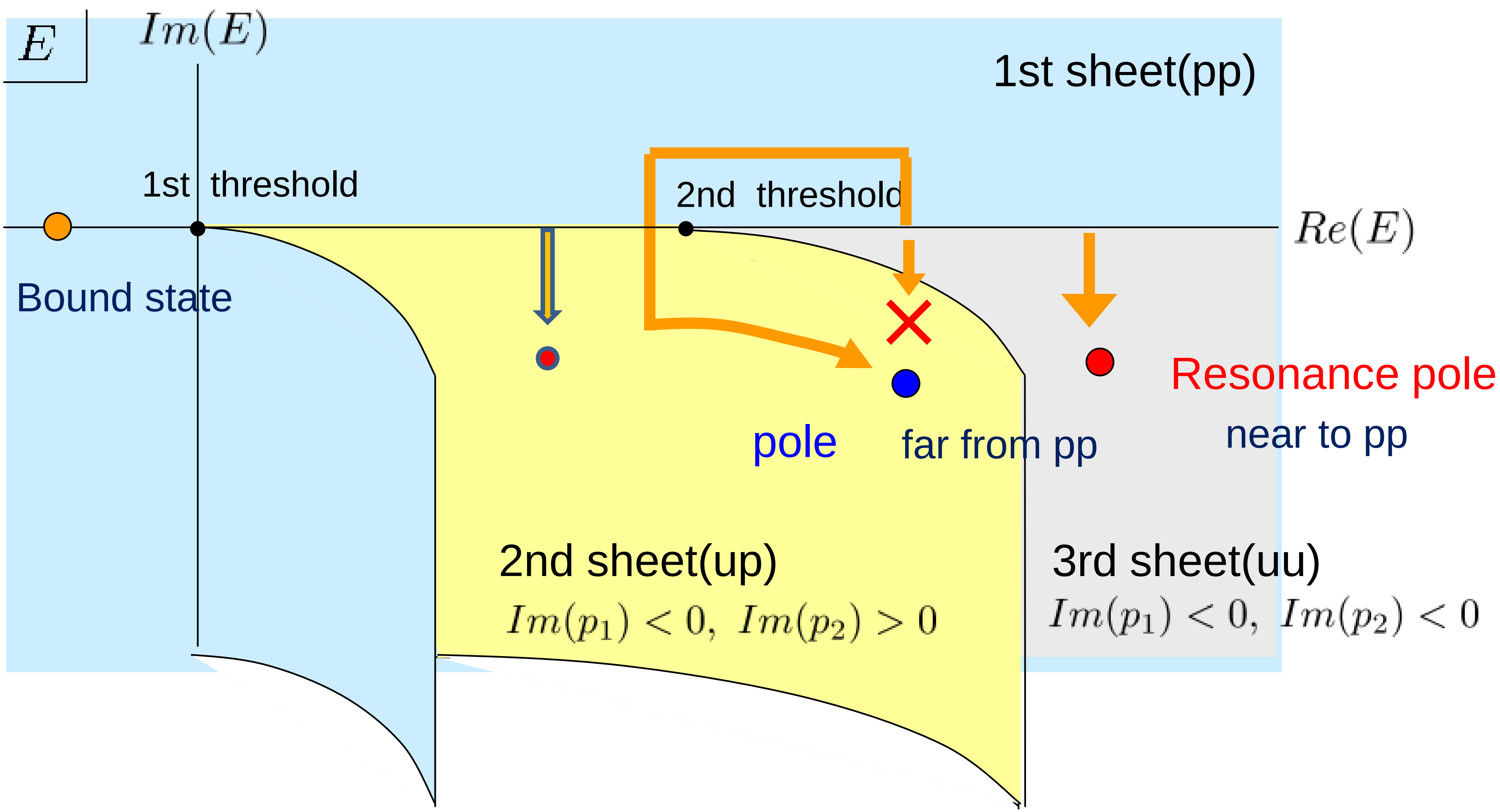
Simple example of two-channel Breit-Wigner formula

$$T_{11}(E) = \frac{-\gamma_1 p_1}{E - M + i\gamma_1 p_1 + i\gamma_2 p_2}$$

$$p_i = \sqrt{2\mu_i(E - m_{ia} - m_{ib})}$$

pole position : $E - M + i\gamma_1 p_1 + i\gamma_2 p_2 = 0$

Pole of scattering amplitude on complex energy plane

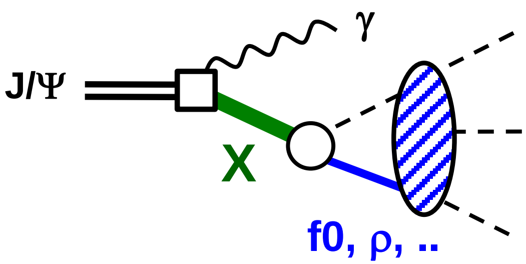


N. Suzuki

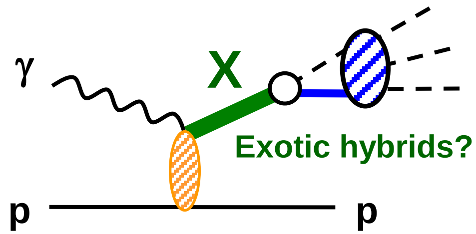
- reaction dynamics strongly affects resonance properties !
- more analysis necessary to understand the mechanism why those phenomena happened.
- understanding of hadron's reaction dynamics is important before we are able to compare extracted resonance parameters with model of hadron.

Future plan

Study of meson spectroscopy , Exotic meson, CP phase



Heavy meson decays



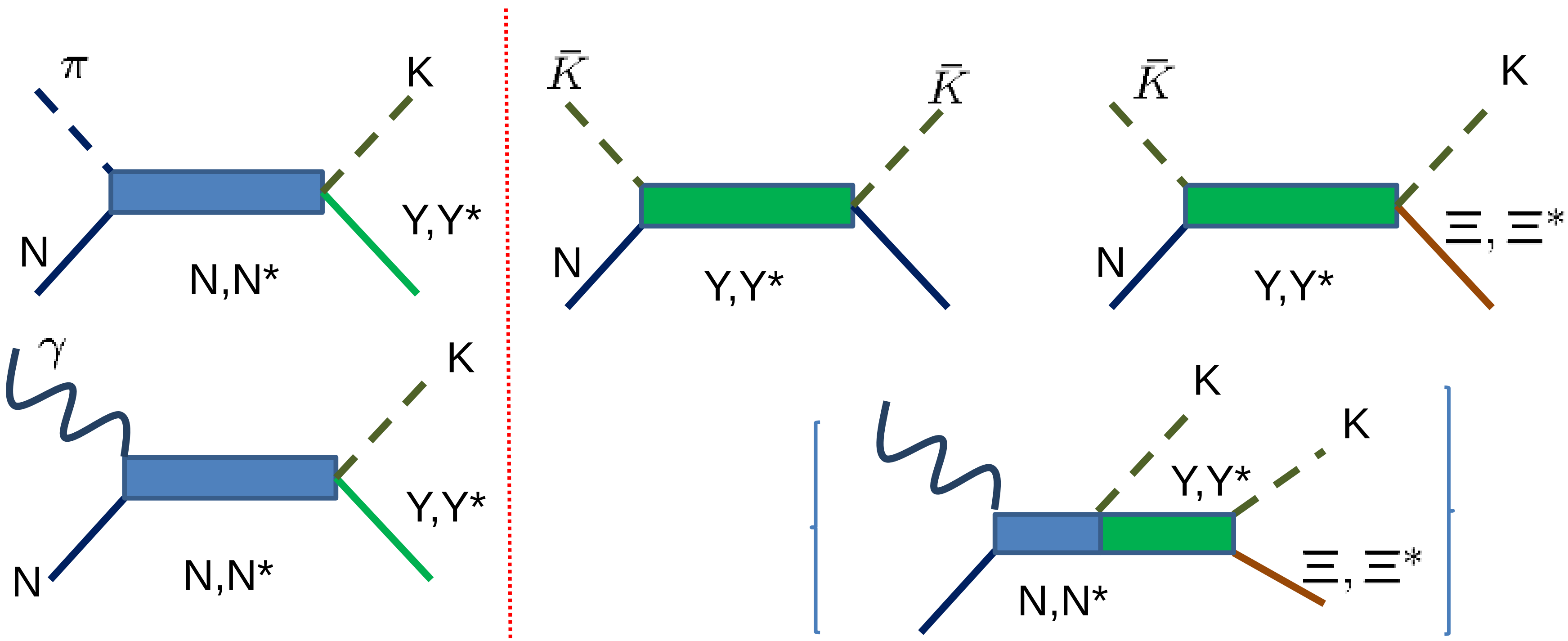
GlueX experiment at HallD@JLab

Kamano, Nakamura, Lee, Sato, arXiv:1106.4523 to appear in PRD

Theory Projects for Strangeness production Reactions on the Nucleon and Nuclei

H. Kamano (RCNP, Osaka U.) T.-S. H. Lee (ANL) Y. Oh (Kyungpook U.)
T. Sato(Osaka U.) Dec. 4-10 2011 @ Kyungpook Univ.

use developed tools, code of coupled channel reaction for N* to investigate strange baryon Y* → cascade*
→ [reaction on a few nucleon system (BB interaction)]



Summary

Meson production reactions for W<2GeV are analyzed with dynamical coupled channel reaction theory and partial wave amplitudes are extracted with improved description of meson production reaction.

Resonance parameters defined as the pole of the scattering amplitude are extracted from analytic continuation of PWA.

Reaction dynamics of meson and baryon plays significant role on resonance properties.

Combined analysis of the ‘reaction theory’ + ‘ structure of hadron’ is necessary ways to understand excited states of nucleon.

---> extended works using developed tools

* strange (hyperon, cascade) baryons
* meson resonances in heavy meson decay
  and pion and photon induced meson resonance production
* reactions on electroweak probe
* contact with LQCD, scattering in finite box