Baryon Resonance
and
Meson Production Reactions

T. Sato Osaka U./KEK

contents

- Introduction
- Analysis of meson production reaction and dynamical coupled channel model
- N* and Δ resonance
  - ✓ Resonance mass and width
  - ✓ Role of reaction dynamics on resonance properties
    Δ33, N*(1440)
- Summary

Baryon Summary Table PDG2012

p	$1/2^+$	****
n	$1/2^+$	****
$N(1440)$	$1/2^+$	****
$N(1520)$	$3/2^-$	****
$N(1535)$	$1/2^-$	****
$N(1650)$	$1/2^-$	****
$N(1675)$	$5/2^-$	****
$N(1680)$	$5/2^+$	****
$N(1685)$		*
$N(1700)$	$3/2^-$	***
$N(1710)$	$1/2^+$	***
$N(1720)$	$3/2^+$	****
$N(1860)$	$5/2^+$	**
$N(1875)$	$3/2^-$	***
$N(1880)$	$1/2^+$	**
$N(1895)$	$1/2^-$	**
$N(1900)$	$3/2^+$	***
$N(1990)$	$7/2^+$	**
$N(2000)$	$5/2^+$	**
$N(2040)$	$3/2^+$	*
$N(2060)$	$5/2^-$	**
$N(2100)$	$1/2^+$	*
$N(2120)$	$3/2^-$	**
$N(2190)$	$7/2^-$	****
$N(2220)$	$9/2^+$	****
$N(2250)$	$9/2^-$	****
$N(2600)$	$11/2^-$	***
$N(2700)$	$13/2^+$	**

$\Delta(1232)$	$3/2^+$	****
$\Delta(1600)$	$3/2^+$	***
$\Delta(1620)$	$1/2^-$	****
$\Delta(1700)$	$3/2^-$	****
$\Delta(1750)$	$1/2^+$	*
$\Delta(1900)$	$1/2^-$	**
$\Delta(1905)$	$5/2^+$	****
$\Delta(1910)$	$1/2^+$	****
$\Delta(1920)$	$3/2^+$	***
$\Delta(1930)$	$5/2^-$	***
$\Delta(1940)$	$3/2^-$	**
$\Delta(1950)$	$7/2^+$	****
$\Delta(2000)$	$5/2^+$	**
$\Delta(2150)$	$1/2^-$	*
$\Delta(2200)$	$7/2^-$	*
$\Delta(2300)$	$9/2^+$	**
$\Delta(2350)$	$5/2^-$	*
$\Delta(2390)$	$7/2^+$	*
$\Delta(2400)$	$9/2^-$	**
$\Delta(2420)$	$11/2^+$	****
$\Delta(2750)$	$13/2^-$	**
$\Delta(2950)$	$15/2^+$	**
Λ	$1/2^+$	****
$\Lambda(1405)$	$1/2^-$	****
$\Lambda(1520)$	$3/2^-$	****
$\Lambda(1600)$	$1/2^+$	***
$\Lambda(1670)$	$1/2^-$	****
$\Lambda(1690)$	$3/2^-$	****
$\Lambda(1800)$	$1/2^-$	***
$\Lambda(1810)$	$1/2^+$	***
$\Lambda(1820)$	$5/2^+$	****
$\Lambda(1830)$	$5/2^-$	****
$\Lambda(1890)$	$3/2^+$	****
$\Lambda(2000)$		*
$\Lambda(2020)$	$7/2^+$	*
$\Lambda(2100)$	$7/2^-$	****
$\Lambda(2110)$	$5/2^+$	***
$\Lambda(2325)$	$3/2^-$	*
$\Lambda(2350)$	$9/2^+$	***
$\Lambda(2585)$		**

Σ^+	$1/2^+$	****
Σ^0	$1/2^+$	****
Σ^-	$1/2^+$	****
$\Sigma(1385)$	$3/2^+$	****
$\Sigma(1480)$		*
$\Sigma(1560)$		**
$\Sigma(1580)$	$3/2^-$	*
$\Sigma(1620)$	$1/2^-$	**
$\Sigma(1660)$	$1/2^+$	***
$\Sigma(1670)$	$3/2^-$	****
$\Sigma(1690)$		**
$\Sigma(1750)$	$1/2^-$	***
$\Sigma(1770)$	$1/2^+$	*
$\Sigma(1775)$	$5/2^-$	****
$\Sigma(1840)$	$3/2^+$	*
$\Sigma(1880)$	$1/2^+$	**
$\Sigma(1915)$	$5/2^+$	****
$\Sigma(1940)$	$3/2^-$	***
$\Sigma(2000)$	$1/2^-$	*
$\Sigma(2030)$	$7/2^+$	****
$\Sigma(2070)$	$5/2^+$	*
$\Sigma(2080)$	$3/2^+$	**
$\Sigma(2100)$	$7/2^-$	*
$\Sigma(2250)$		***
$\Sigma(2455)$		**
$\Sigma(2620)$		**
$\Sigma(3000)$		*
$\Sigma(3170)$		*

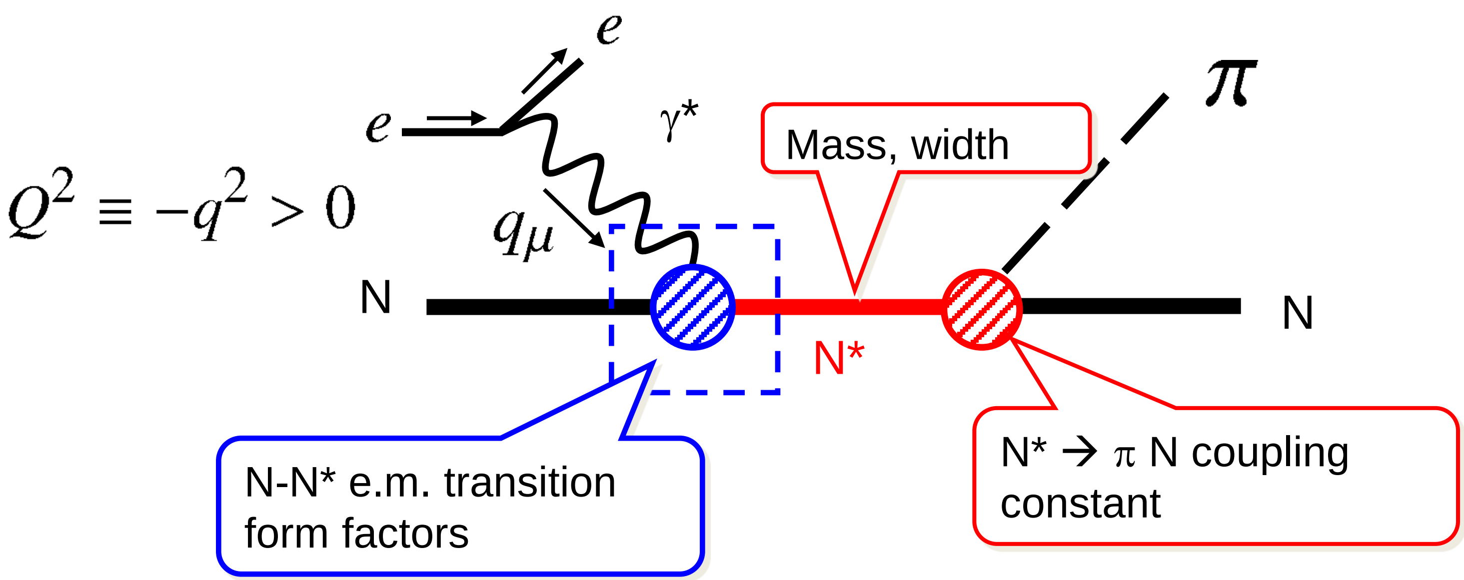
Ξ^0	$1/2^+$	****
Ξ^-	$1/2^+$	****
$\Xi(1530)$	$3/2^+$	****
$\Xi(1620)$		*
$\Xi(1690)$		***
$\Xi(1820)$	$3/2^-$	***
$\Xi(1950)$		***
$\Xi(2030)$	$\geq \frac{5}{2}?$	***
$\Xi(2120)$		*
$\Xi(2250)$		**
$\Xi(2370)$		**
$\Xi(2500)$		*
Ω^-	$3/2^+$	****
$\Omega(2250)^-$		***
$\Omega(2380)^-$		**
$\Omega(2470)^-$		**

Λ_c^+	$1/2^+$	****
$\Lambda_c(2595)^+$	$1/2^-$	***
$\Lambda_c(2625)^+$	$3/2^-$	***
$\Lambda_c(2765)^+$		*
$\Lambda_c(2880)^+$	$5/2^+$	***
$\Lambda_c(2940)^+$		***
$\Sigma_c(2455)$	$1/2^+$	****
$\Sigma_c(2520)$	$3/2^+$	***
$\Sigma_c(2800)$		***
Ξ_c^+	$1/2^+$	***
Ξ_c^0	$1/2^+$	***
$\Xi_c'^+$	$1/2^+$	***
$\Xi_c'^0$	$1/2^+$	***
$\Xi_c(2645)$	$3/2^+$	***
$\Xi_c(2790)$	$1/2^-$	***
$\Xi_c(2815)$	$3/2^-$	***
$\Xi_c(2930)$		*
$\Xi_c(2980)$		***
$\Xi_c(3055)$		**
$\Xi_c(3080)$		***
$\Xi_c(3123)$		*
Ω_c^0	$1/2^+$	***
$\Omega_c(2770)^0$	$3/2^+$	***
Ξ_{cc}^+		*
Λ_b^0	$1/2^+$	***
Σ_b	$1/2^+$	***
Σ_b^*	$3/2^+$	***
Ξ_b^0, Ξ_b^-	$1/2^+$	***
Ω_b^-	$1/2^+$	***

Resonance Below 2GeV

	N*	Δ
****	8	6
***	4	3
**	5	3
*	1	1

Extract resonance properties from meson production reactions



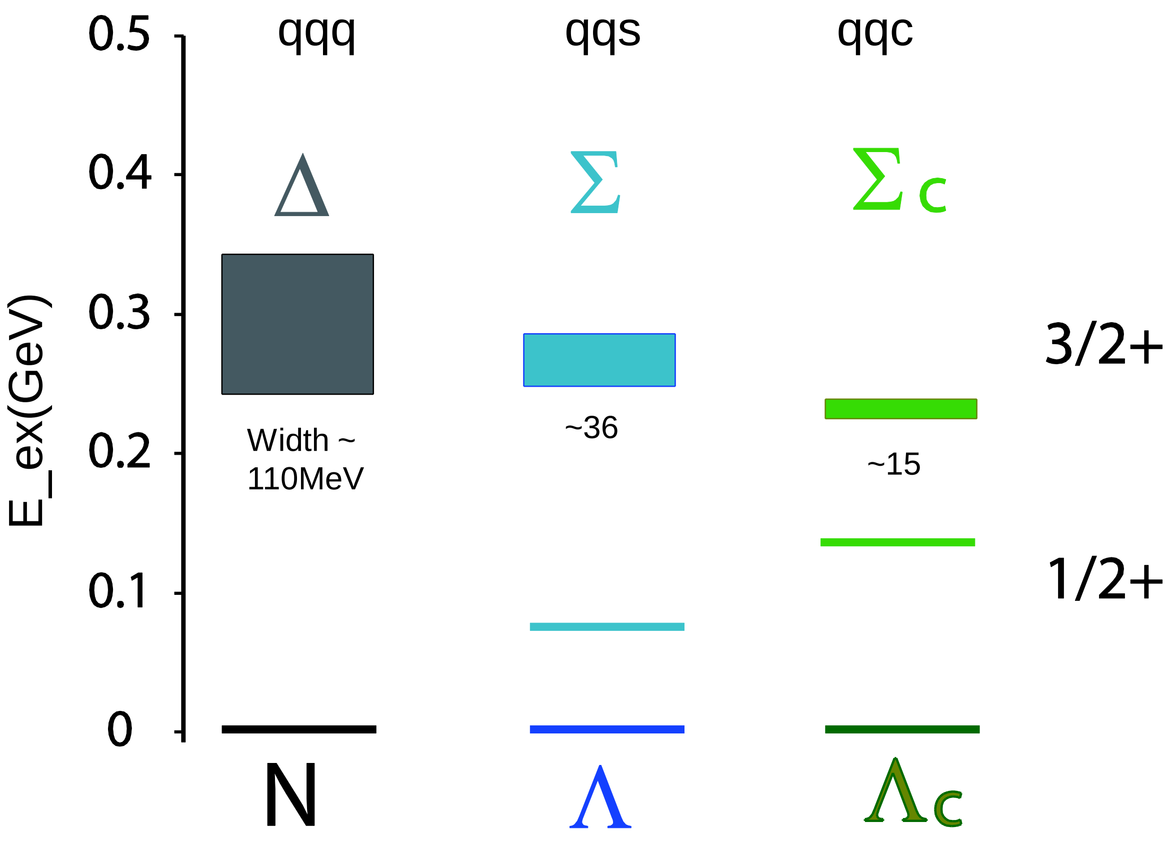
Resonance parameters:

mass, width, coupling constants, transition form factor

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

N*,Δ:

overlapping resonances,   large width (~> 100MeV)



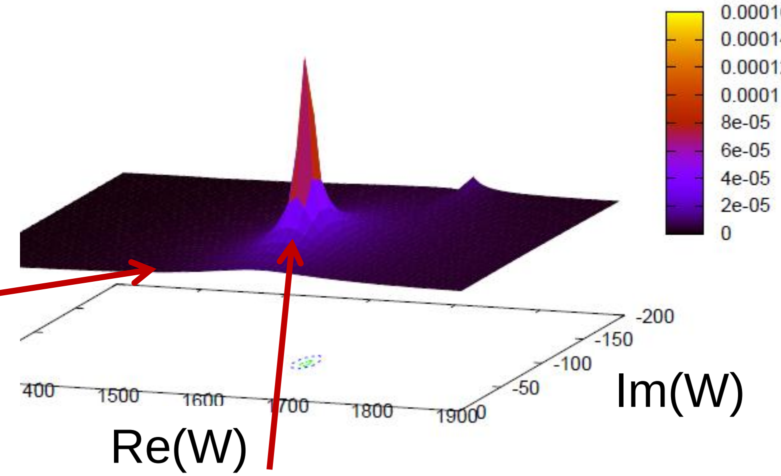
Extraction of resonance parameters

Data

Coupled channel reaction model of meson production reactions

Partial wave amplitude

$$\mathcal{F}(W)$$



Characterize resonance from pole and residue of the amplitude by analytic continuation of amplitude

$$< f|\mathcal{F}(W)|i > \sim \frac{< f|V|\phi_R >< \tilde{\phi}_R|V|i >}{W - M + i\Gamma/2}$$

Resonance parameter

Pole position → mass, width

Residue → Form factors, coupling constants

Examine structure of N* and role of MB dynamics

Analysis of meson production reaction and dynamical coupled-channels (DCC) model

Extraction of resonance parameters

Data

Coupled channel reaction model of meson production reactions

Partial wave amplitude

$$\mathcal{F}(W)$$

Characterize resonance from pole and residue of the amplitude by analytic continuation of amplitude

$$< f|\mathcal{F}(W)|i > \sim \frac{< f|V|\phi_R >< \tilde{\phi}_R|V|i >}{W - M + i\Gamma/2}$$

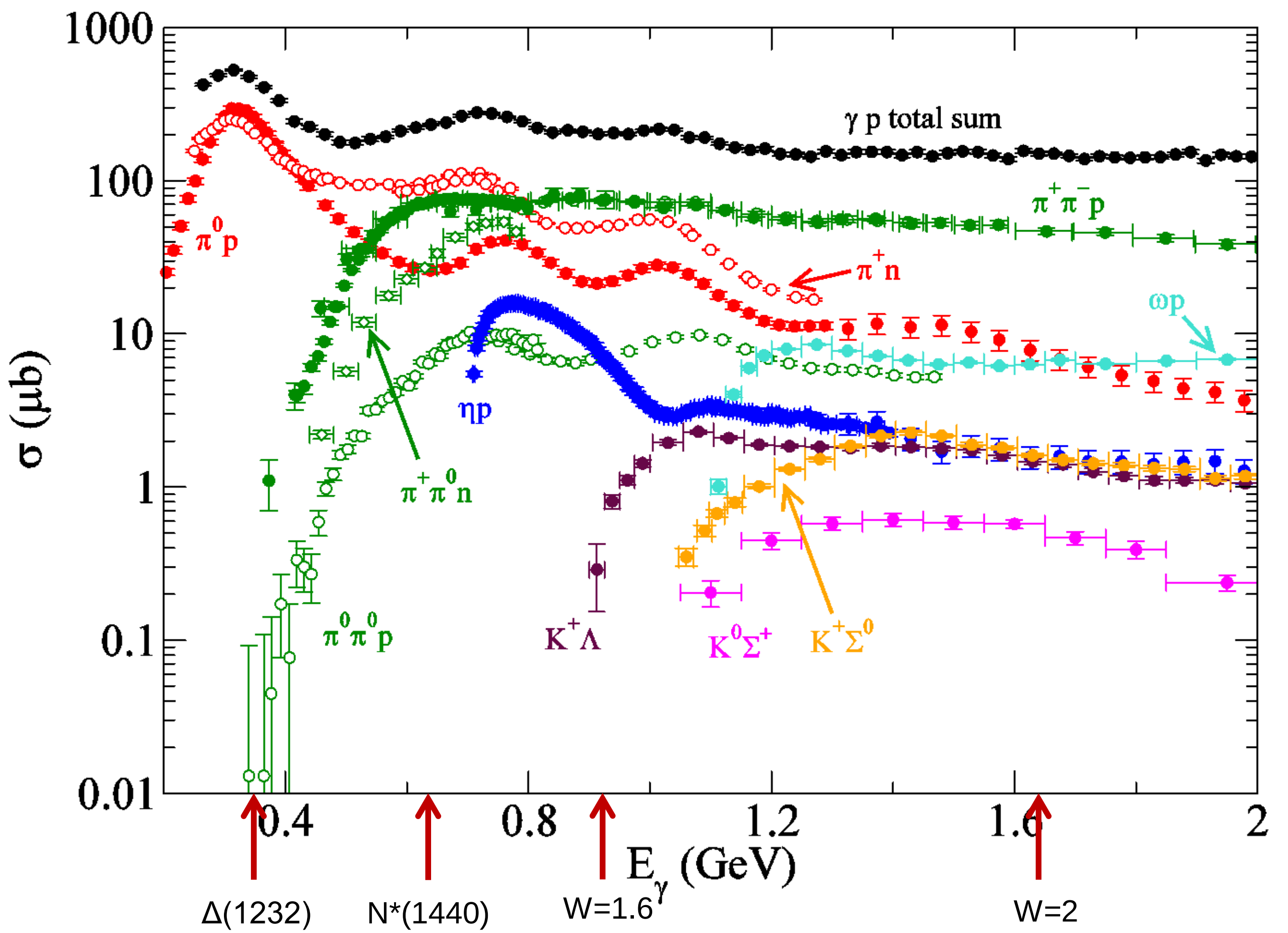
Resonance parameter

Pole position → mass, width

Residue → Form factors, coupling constants

Examine structure of N* and role of MB dynamics

γp total cross section



Below W<2GeV, important channels are $\pi N, \eta N, K\Lambda, K\Sigma, \pi\pi N, \omega N$

ANL-Osaka Dynamical Coupled-Channels analysis

Fully combined **analysis of γN , πN → πN , ηN , KΛ, KΣ reactions !!**

	2006-2009	2010-2012
✓ # of coupled channels	6 channels (γN,πN,ηN,πΔ,ρN,σN)	8 channels (γN,πN,ηN,πΔ,ρN,σN,KΛ,KΣ)
✓ πp → πN	< 2 GeV	< 2.1 GeV
✓ γp → πN	< 1.6 GeV	< 2 GeV
✓ π-p → ηn	< 2 GeV	< 2 GeV
✓ γp → ηp	–	< 2 GeV
✓ πp → KΛ, KΣ	–	< 2.2 GeV
✓ γp → KΛ, KΣ	–	< 2.2 GeV

Kamano, Nakamura, Lee, Sato, 2012

Dynamical coupled-channels (DCC) model for meson production reactions

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

- start from Hamiltonian of meson-baryon system with

Fock space of excited baryon('bare' resonance') and meson baryon continuum

$$|N^* > \qquad |\pi N >, |\eta N >, |K\Lambda >, |K\Sigma >, |\pi\pi N >$$

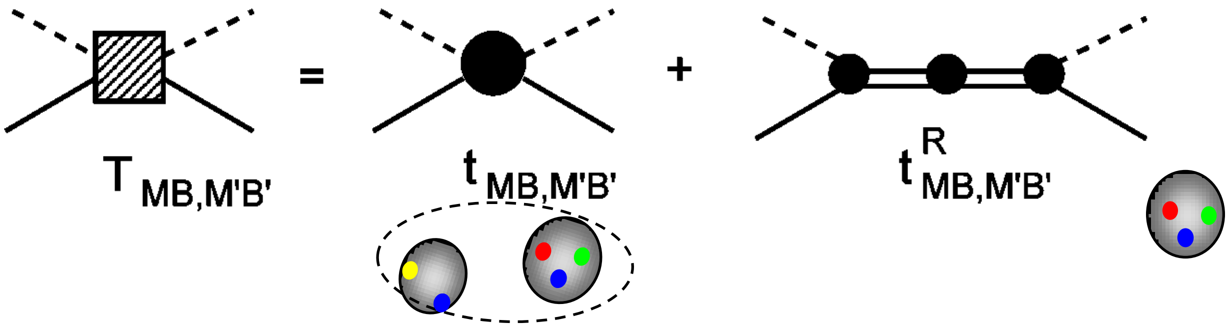
meson-baryon interaction based on chiral effective theory
masses, coupling constants of excited baryon are determined from fitting data

- Scattering amplitude are given by coupled channel reaction equation.

amplitudes satisfy three-body unitarity
solve momentum space equation numerically.

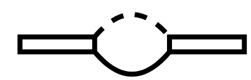
$$T_{\alpha,\beta}(W) \;=\; t^{nr}_{\alpha,\beta}(W) + \sum_{i,j} \bar{\Gamma}_{\alpha,i}(W)\left[\frac{1}{W - m_0 - \Sigma(W)}\right]_{ij} \bar{\Gamma}_{\beta,j}(W)$$

α, β Meson-Baryon channel i, j Resonances



- N*-> MB : width and shift of resonance energy

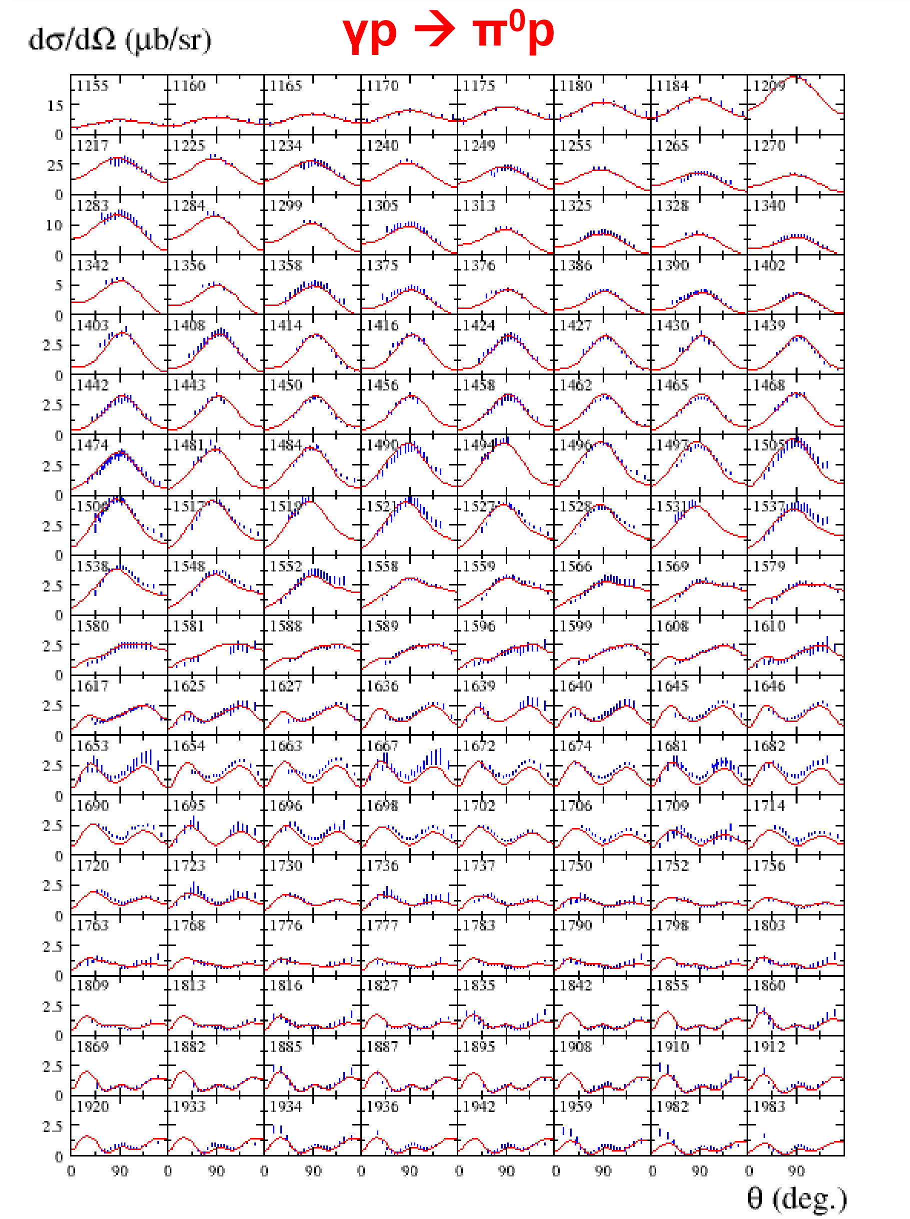
$$m_0 + \Sigma(W)$$

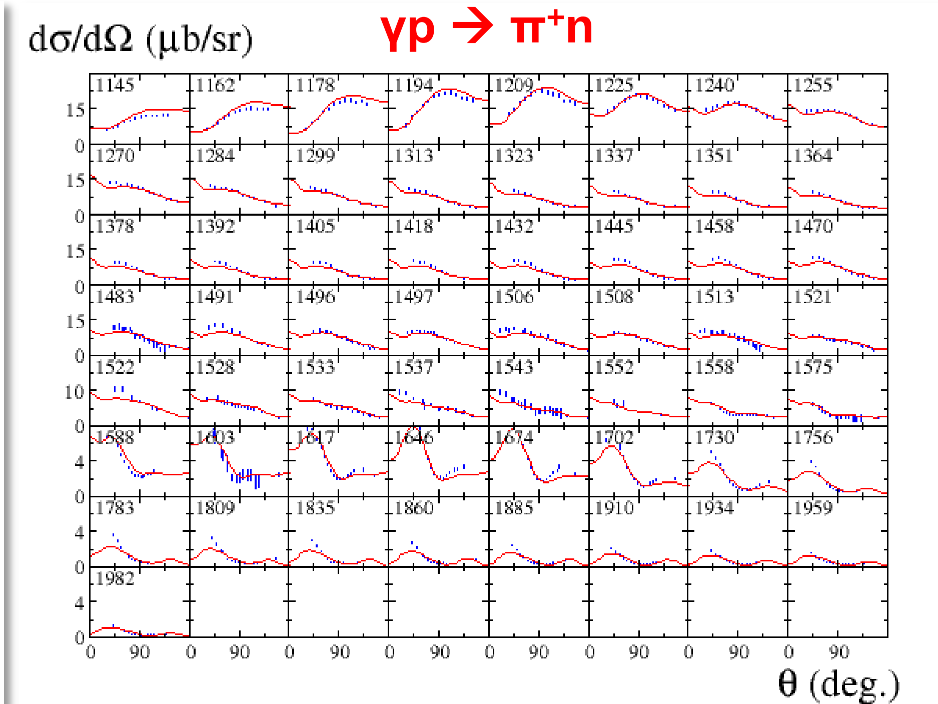


- N* coupling : vertex correction from non-resonant mechanism

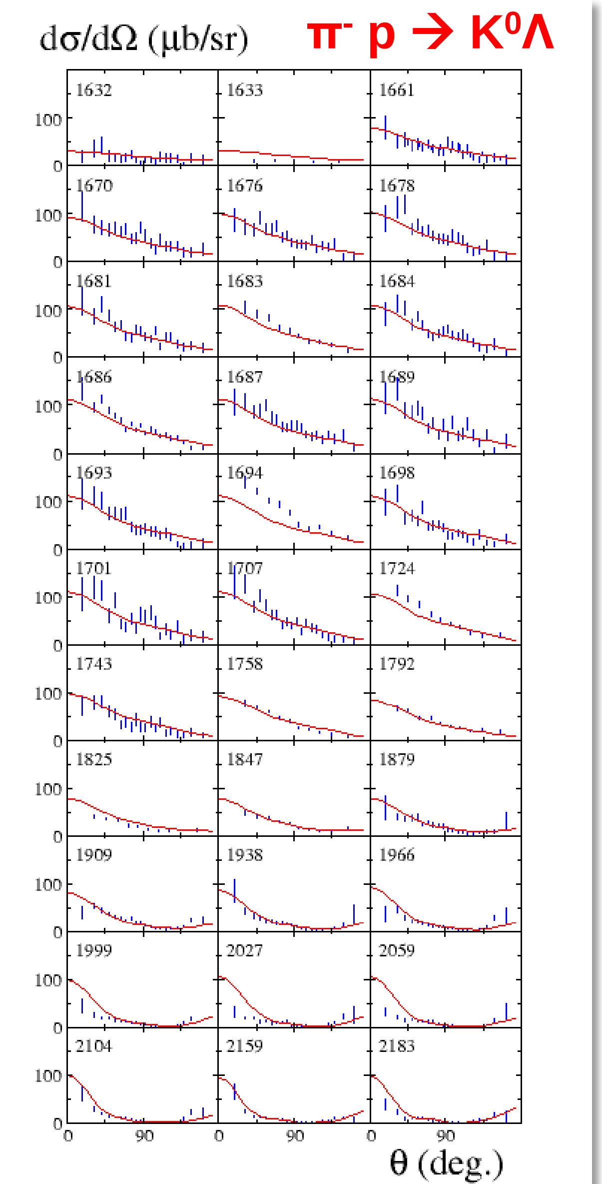
$$\bar{\Gamma} \sim < \tilde{N}^*|j|N > = < N^*|j|N > + < N^*|\Gamma G_0 t_j|N >$$

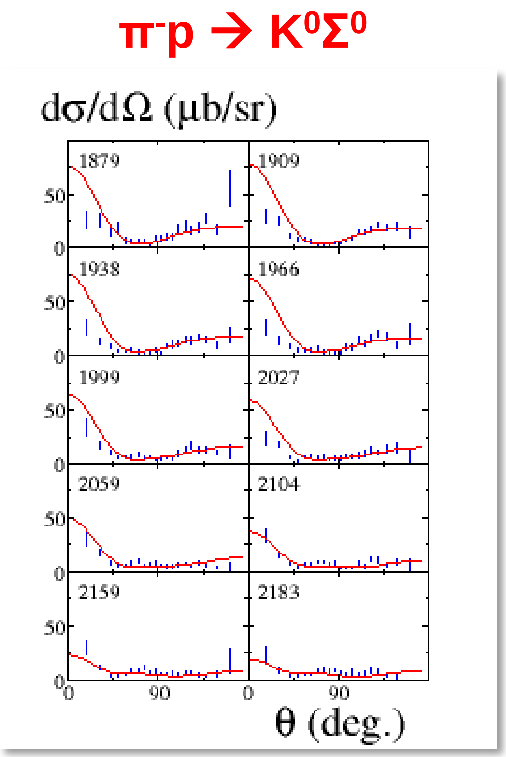
γp → πN reactions(1/2)

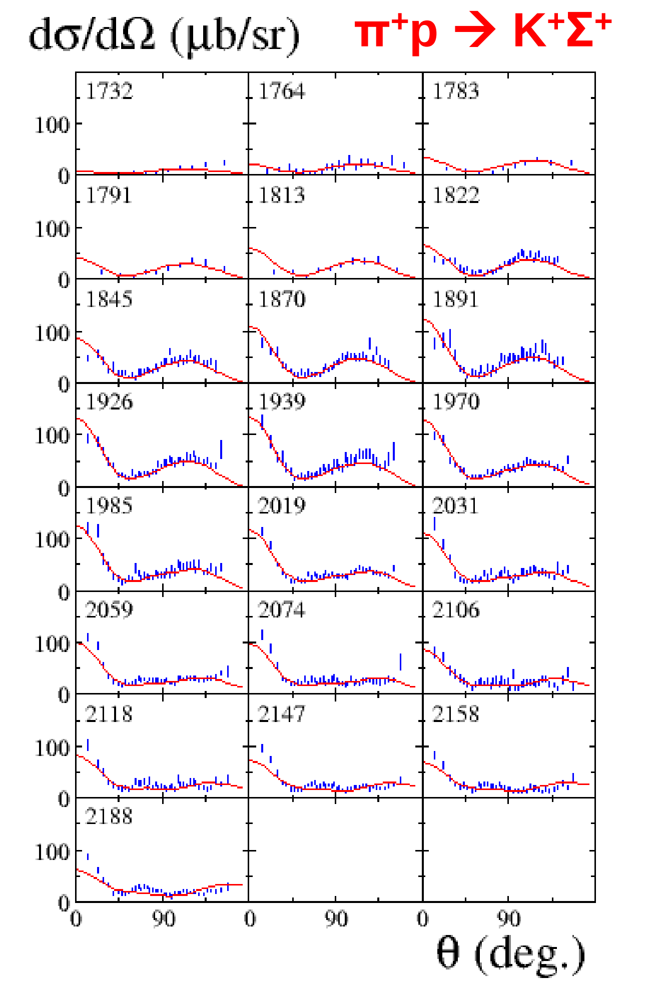




πN → KY reactions (1/2)







Single pion electroproduction ($Q^2 > 0$)

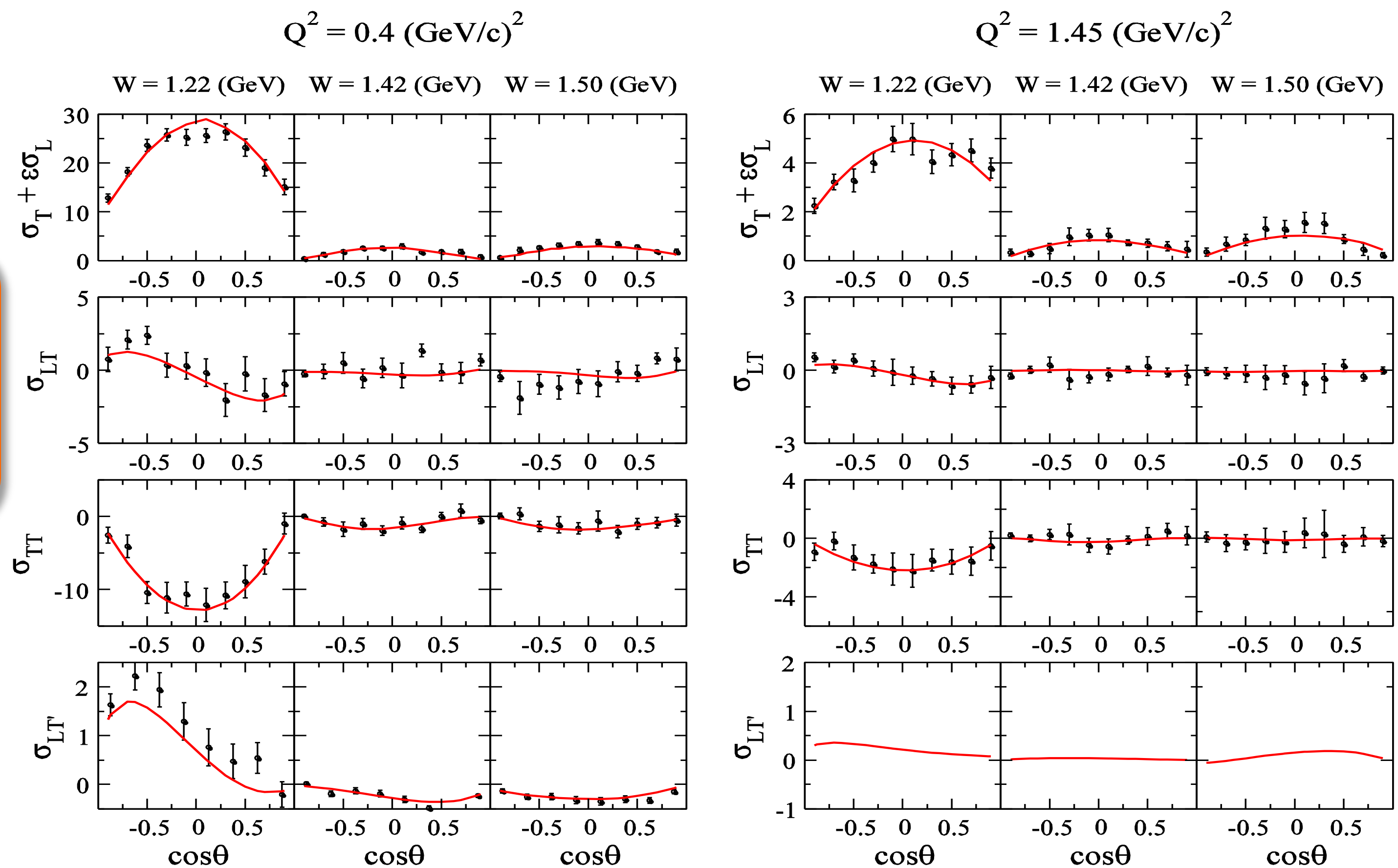
Julia-Diaz, Kamano, Lee, Matsuyama, Sato, Suzuki, PRC80 025207 (2009)

Fit to the structure function data from CLAS

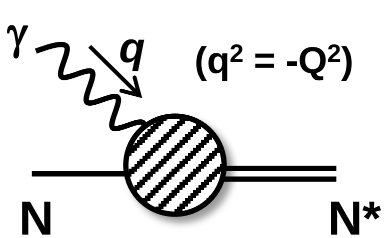
$$\sigma_\alpha = \sigma_\alpha(W, Q^2, \cos\theta_\pi^*)$$

$$\frac{d\sigma^5}{dE_{e'}d\Omega_{e'}d\Omega_\pi^*} = \Gamma_\gamma\left[\sigma_T + \epsilon\sigma_L + \sqrt{2\epsilon(1+\epsilon)}\sigma_{LT}\cos\phi_\pi^* + \epsilon\sigma_{TT}\cos 2\phi_\pi^* + h_e\sqrt{2\epsilon(1-\epsilon)}\sigma_{LT'}\sin\phi_\pi^*\right].$$

p (e,e' π^0) p



W < 1.6 GeV
Q^2 < 1.5 (GeV/c)^2
$\Gamma^{\text{bare}}_{\gamma N \to N^*}$ **is determined at each Q^2.**



N-N* e.m. transition form factor

Remarks on numerical tasks :

1. DCC is not an algebraic approach like analysis based on polynomials or K-matrix

   Solve coupled integral equations with 8 channels by inverting 400 X 400 complex matrix formed by about 150 Feynman diagrams for each partial waves (about 20 partial waves up to L=5)

2. Fits to about 28,000 data points

3. New mechanisms are usually needed to develop theoretically to improve the fits, not just blindly vary the parameters

4. Analytic continuation for extracting resonances requires careful analysis of the analytic structure of driving terms (150 Feynman amplitudes) of the coupled integral equations with 8 channels

Mass, width and form factors of resonances

Extraction of resonance parameters

Data

Coupled channel reaction model of meson production reactions

Partial wave amplitude

$$\mathcal{F}(W)$$

Characterize resonance from pole and residue of the amplitude by analytic continuation of amplitude

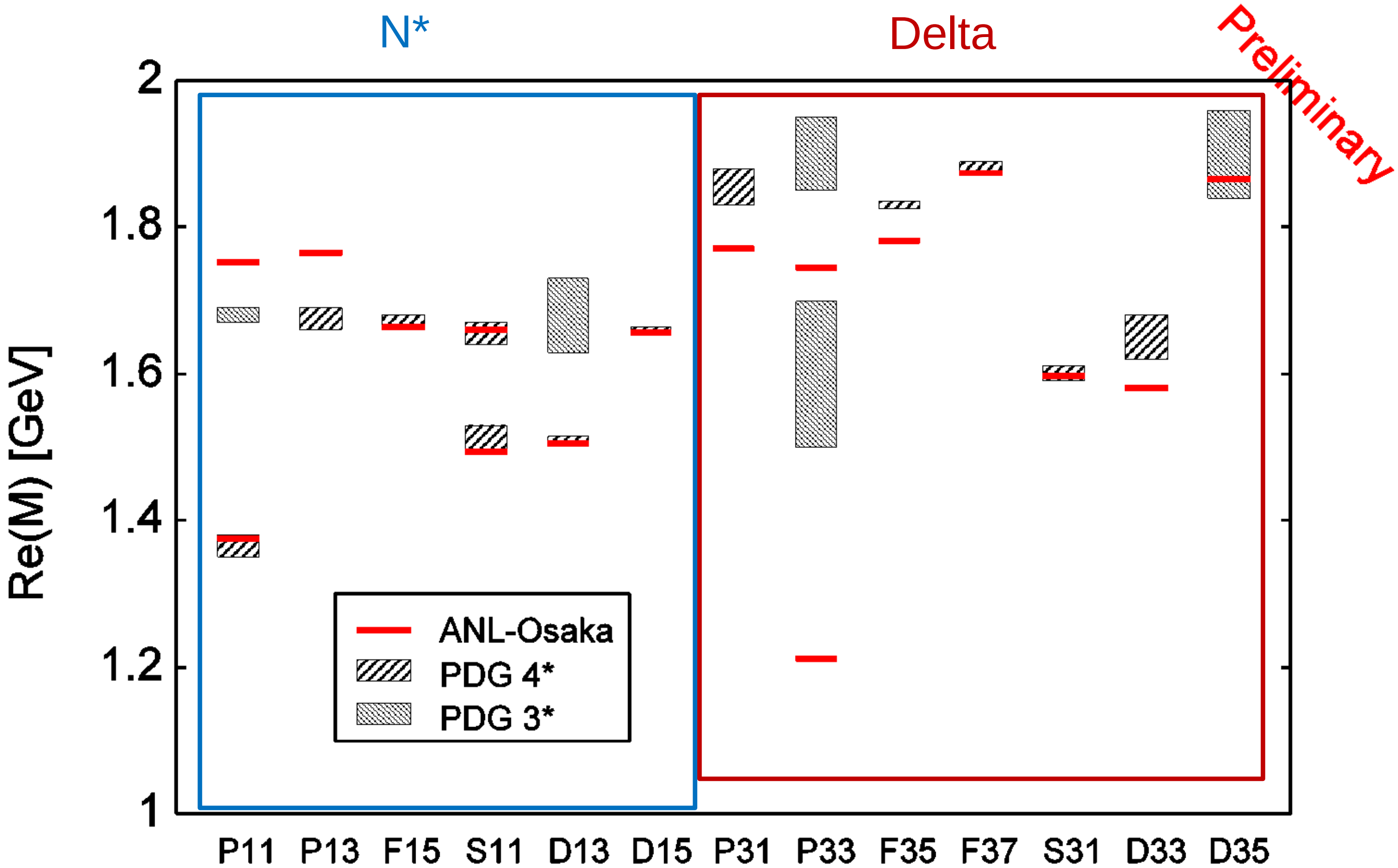
$$< f|\mathcal{F}(W)|i > \sim \frac{< f|V|\phi_R >< \tilde{\phi}_R|V|i >}{W - M + i\Gamma/2}$$

Resonance parameter

Pole position → mass, width

Residue → Form factors, coupling constants

Examine structure of N* and role of MB dynamics



Spectrum of nucleon resonances (N* and Delta)from the ANL-Osaka coupled channel analysis(2012 model) of meson production reactions

Analysis of meson production reaction and nucleon resonances

- K-matrix approach

GWU PRC74, 045205 (2006) R. Arndt et al.
Bonn-Gatchina EPJA 48, 15 (2012), A.V. Anisovich et al.

MAID, Giessen, Kent State

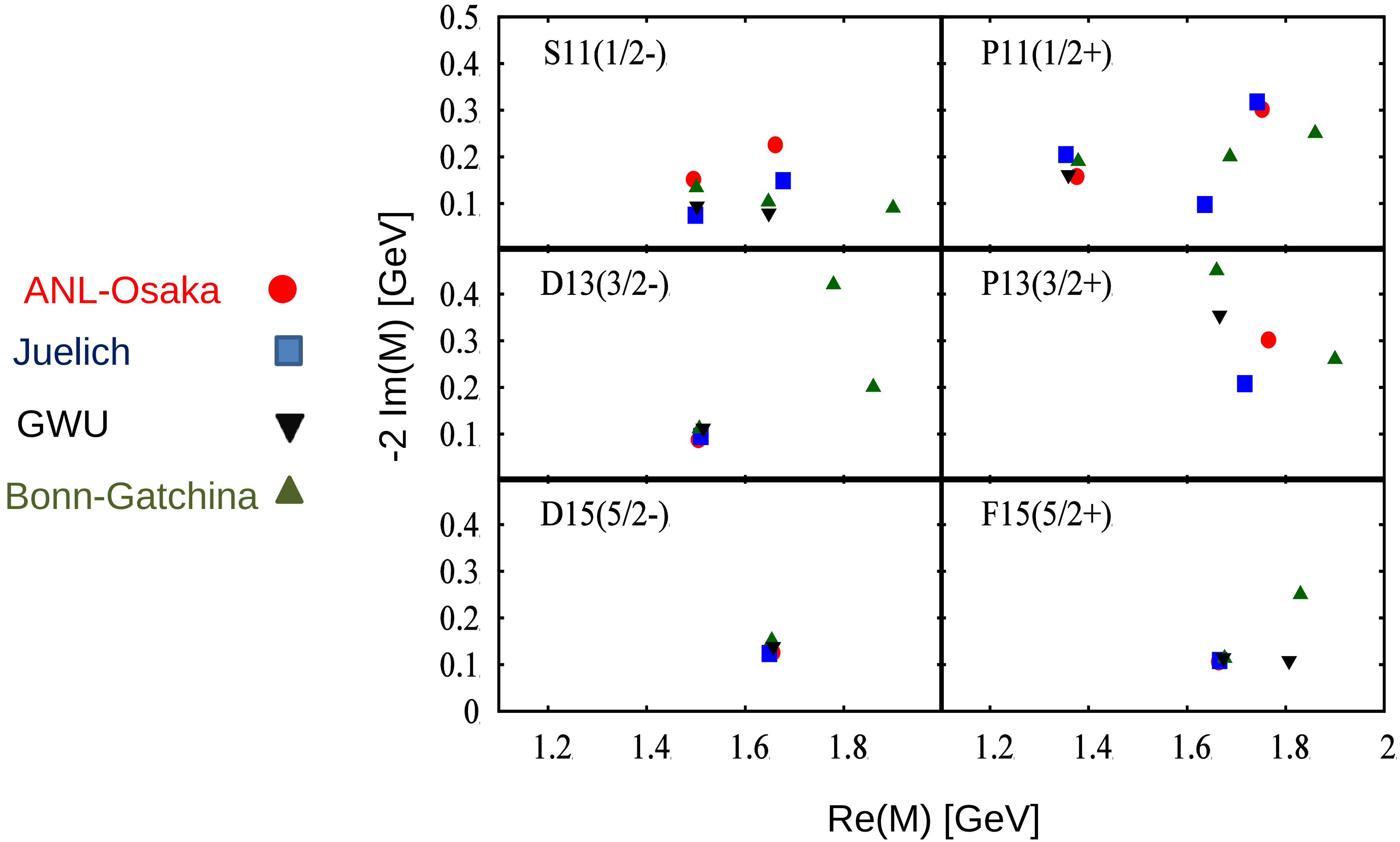
- Dynamical reaction model

Juelich arXiv 1211.6998 D. Ronchen et al.
ANL-Osaka H. Kamano et al. in preparation

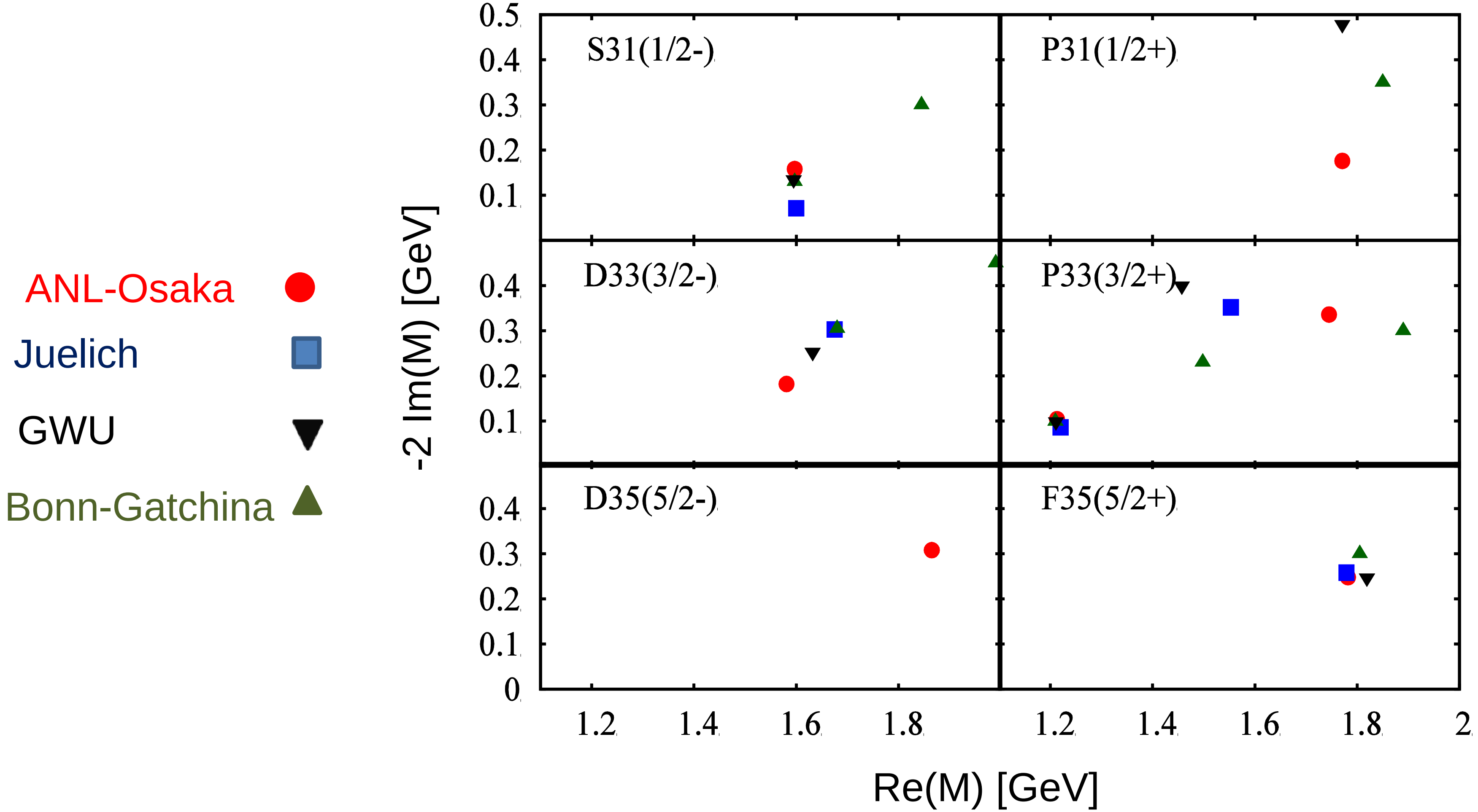
KVI,DMT

$\pi N \to$ $\gamma N \to$	πN	ηN	$K\Lambda, \Sigma$
Bonn-Gatchina	○ ○	○ ○	○ ○
GWU	○	○	
Juelich-Georgia	○	○	○
ANL-Osaka	○ ○	○ ○	○ ○

I=1/2 resonances N*



I=3/2 resonances Δ



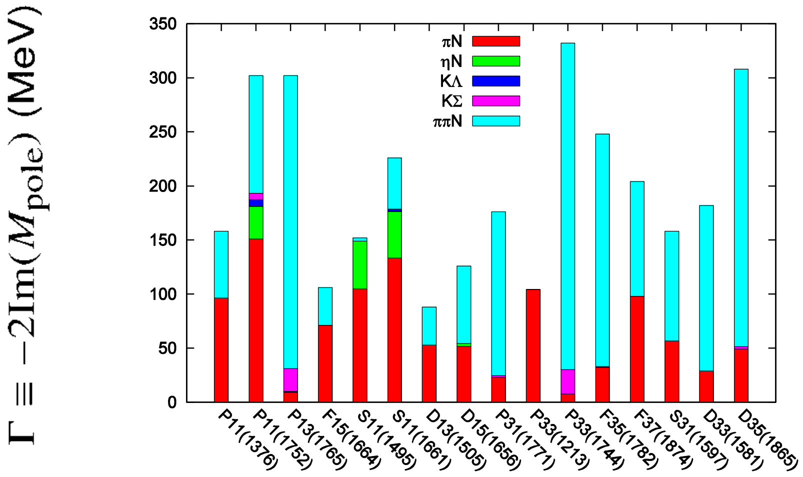
Near future:

- Over complete measurement of observables for $\gamma + p \to K^+ + \Lambda$ (Jlab)

  'New ?' I=1/2 1.6 < W < 2(in our model) resonances

- $\pi + N \to \pi + \pi + N$ (JPARC proposal)

Currently, we have little pion induced two-pion reaction data compared with large amount of photon, electorproduction available data.



"Complete Experiment" of pseudoscalar meson photoproduction reactions

"Complete Experiment" = Measure ALL polarization observables needed to determine amplitudes up to overall phase

8 /16 observables needed!
Chiang, Tabakin PRC55 2054 (1997)

unpolarized diff. crs. sec.

$\rightarrow \quad d\sigma/d\Omega$

single spin

$\rightarrow \quad P, \quad \Sigma, \quad T$

beam-target

$\rightarrow \quad E, \quad F, \quad G, \quad H$

beam-recoil

$\rightarrow \quad C_{x'}, \quad C_{z'}, \quad O_{x'}, \quad O_{z'}$

target-recoil

$\rightarrow \quad T_{x'}, \quad T_{z'}, \quad L_{x'}, \quad L_{z'}$

✓ Measurement of $\gamma N \rightarrow KY$ pol. obs. is very active.

✓ OVER-complete experiments planned by CLAS for $\gamma p \rightarrow K^+ \Lambda$, $\gamma n \rightarrow KY$.

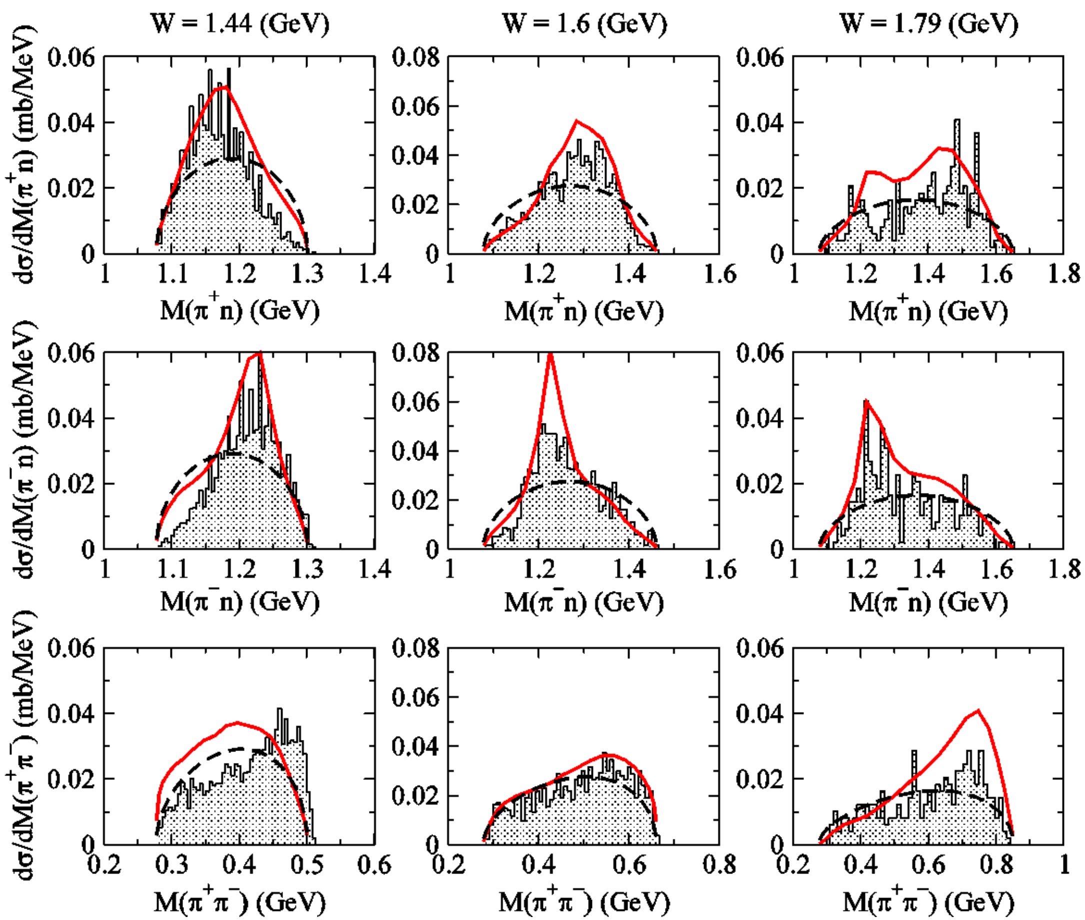
Provides critical information on $N^* \rightarrow KY$ decays !!
Much room for new N* state searches

Need for data on pi-N Double pion production

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

Invariant mass distributions

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



Full result

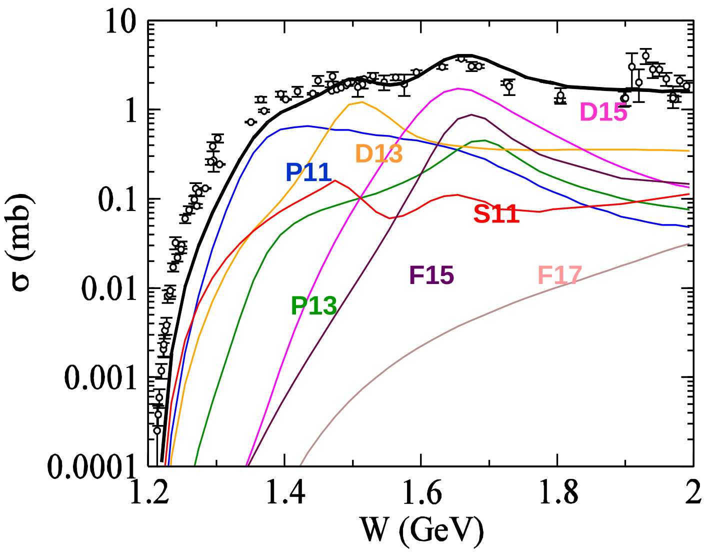
Phase space

Data handled with the help of R. Arndt

By H. Kamano

Contribution of each partial wave

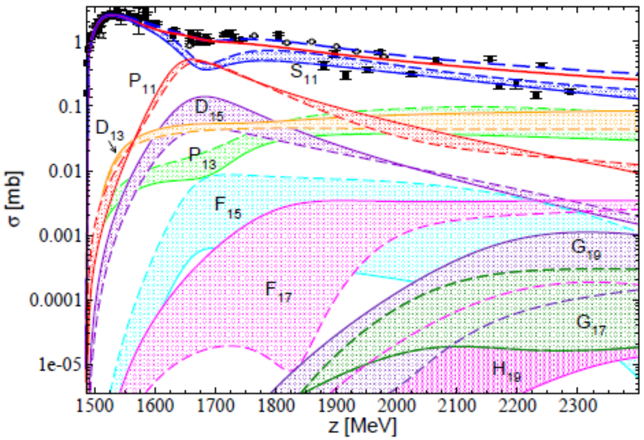
Very preliminary(H. Kamano)



$$\pi^- p \to \pi^0 \pi^0 n$$

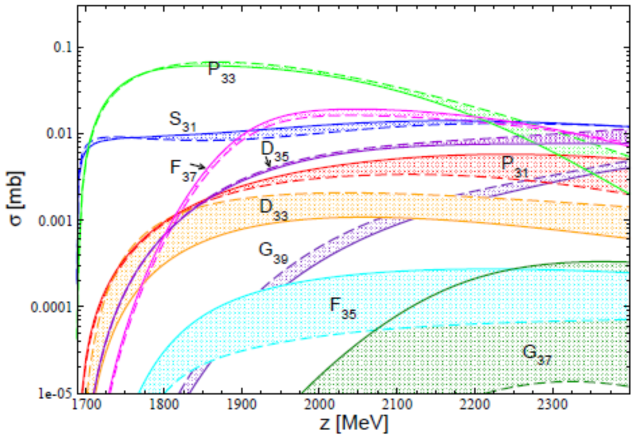
P11,D13,D15
I=3/2 are small

D. Ronchen et al. arXiv:1211.6998(nucl-th)



$$\pi^- p \to \eta n$$

S11,P11

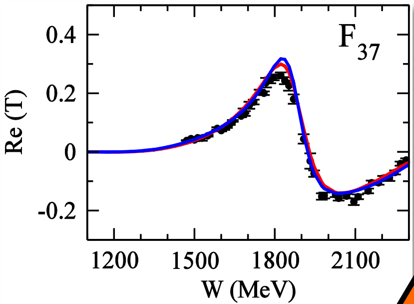


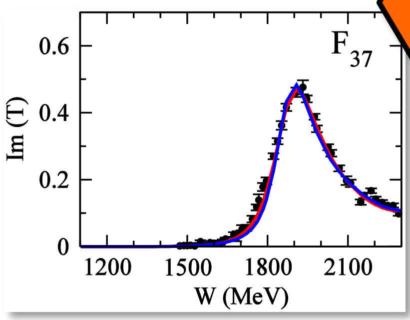
$$\pi^- p \to K^0 \Sigma^0$$

P33

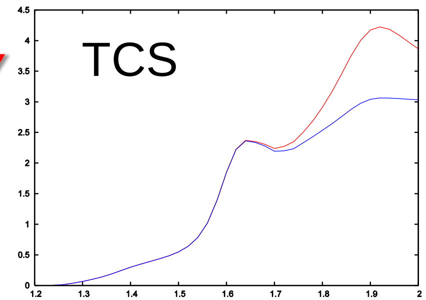
Importance of πN → ππN data

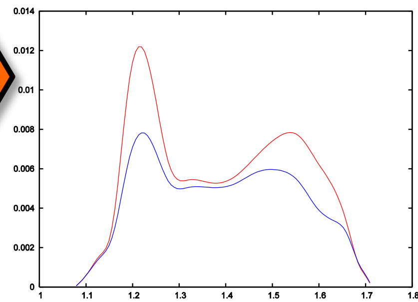
VERY PRELIMINARY



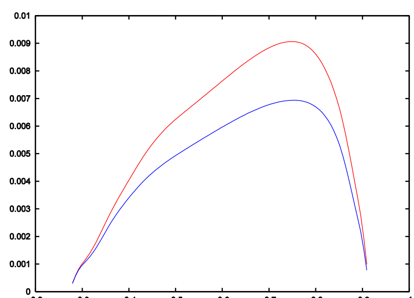


$\pi^+ p \rightarrow \pi^+ \pi^+ n$



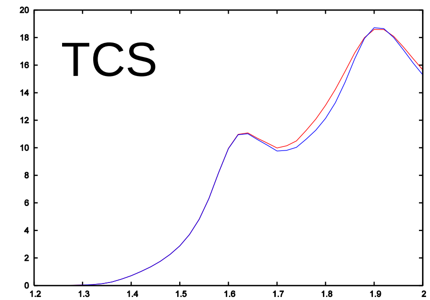


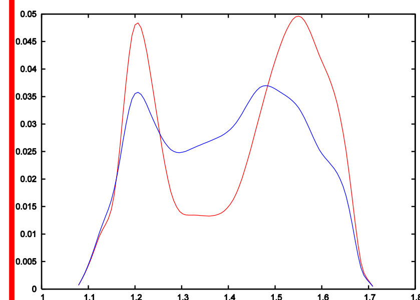
M(π+ n)



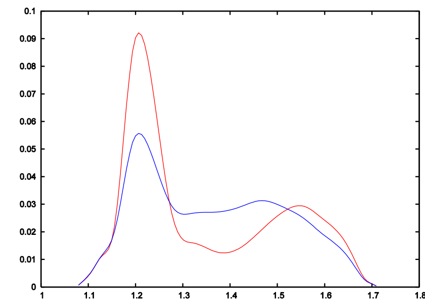
M(π+ π+)

$\pi^+ p \rightarrow \pi^+ \pi^0 p$

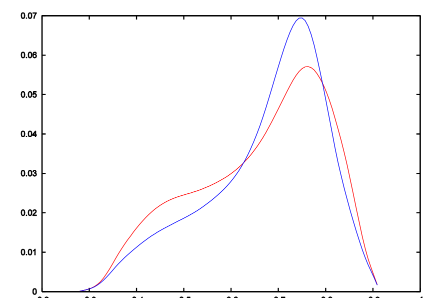




M(π0 p)



M(π+ p)



M(π+ π0)

Current model

Refit F37 PWA keeping N* → πΔ off

By H. Kamano

Role of reaction dynamics on resonance properties

Extraction of resonance parameters

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Coupled channel reaction model of meson production reactions

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$\mathcal{F}(W)$

Characterize resonance from pole and residue of the amplitude by analytic continuation of amplitude

$$< f|\mathcal{F}(W)|i > \sim \frac{< f|V|\phi_R >< \tilde{\phi}_R|V|i >}{W - M + i\Gamma/2}$$

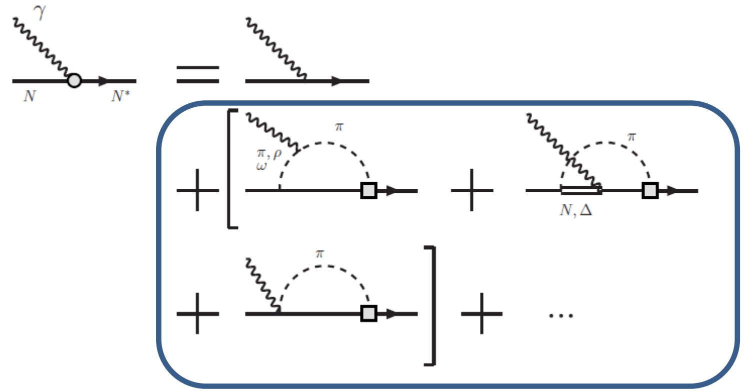
Resonance parameter

Pole position → mass, width

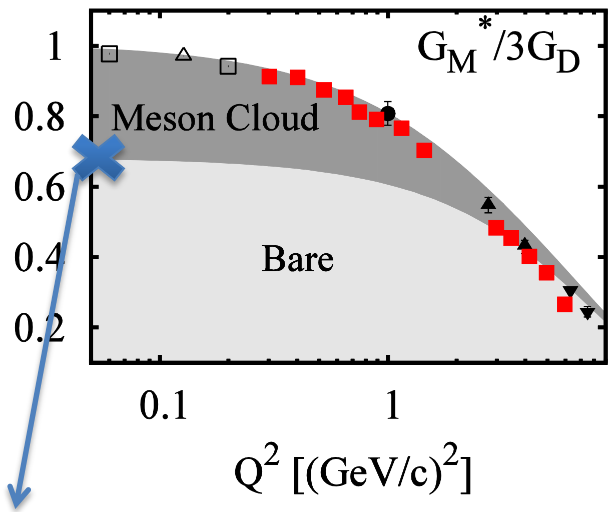
Residue → Form factors, coupling constants

Examine structure of N* and role of MB dynamics

γ N → Δ (1232) transition form factor (role of reaction dynamics)

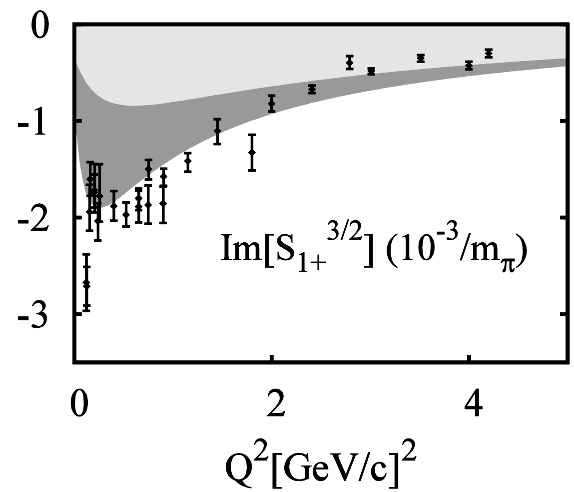


M1: Magnetic dipole



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

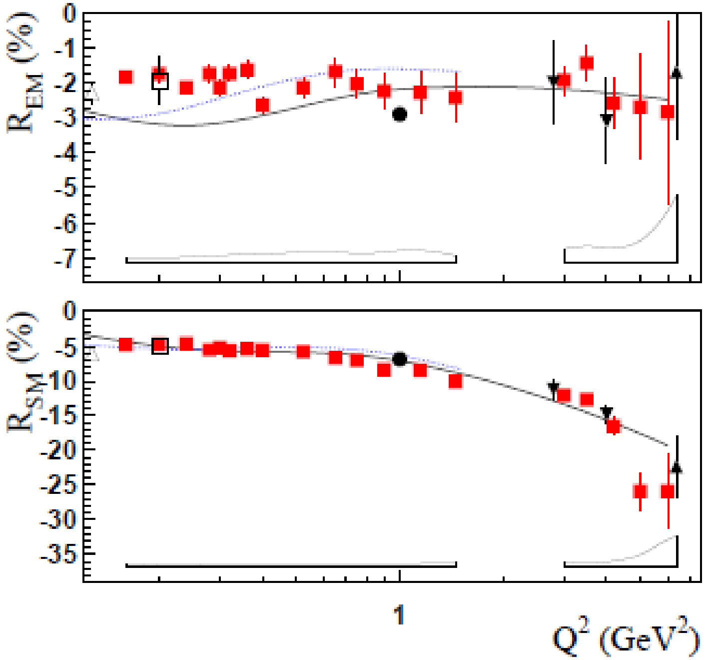
C2: Coulomb quadrupole



deformation from pion cloud for Q^2<1GeV^2

pion cloud effect is essential to understand (long range part of) resonance structure

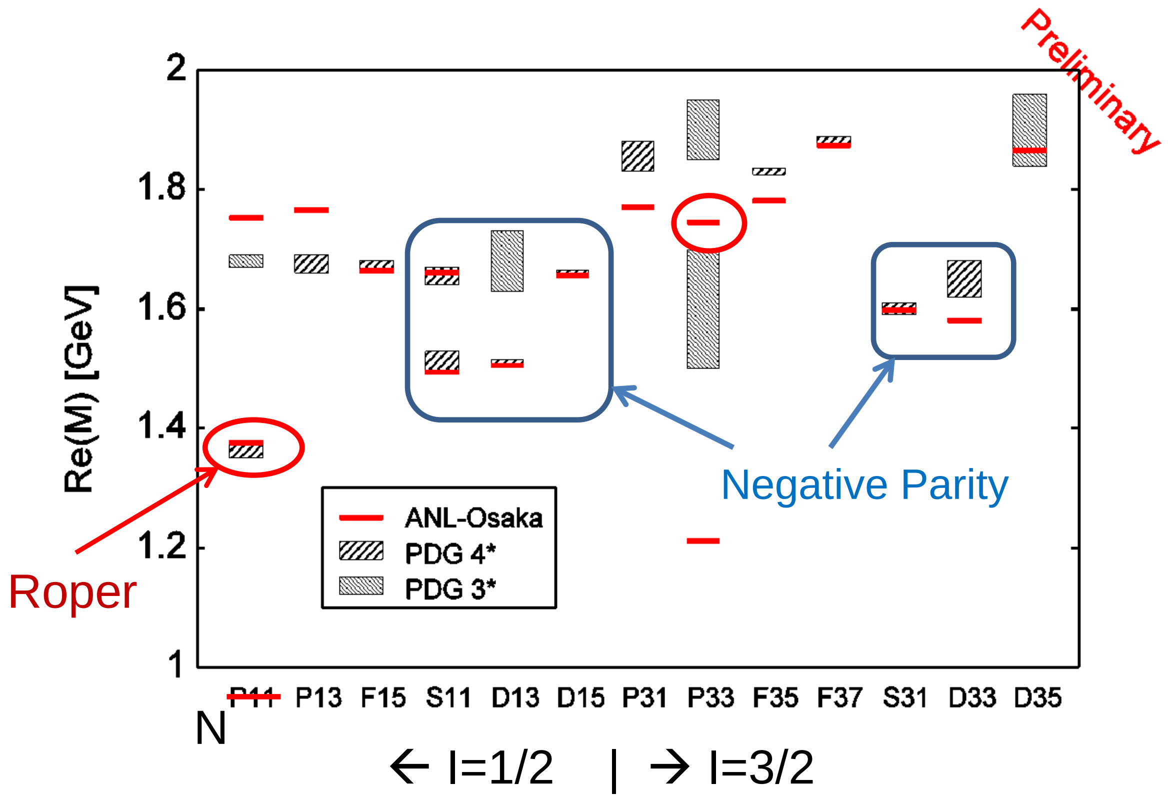
Sato, Lee 96,01

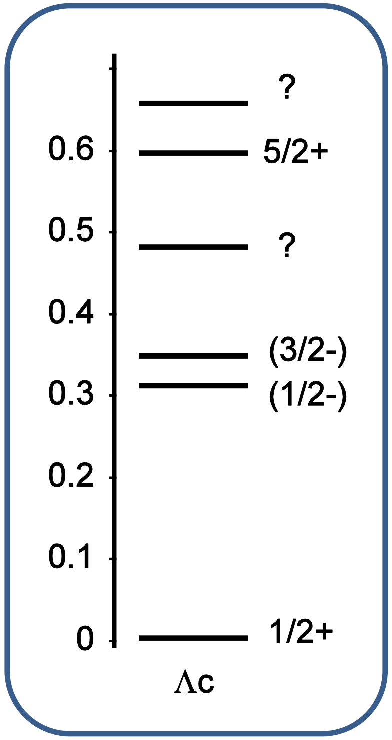


Rem(E1+/M1+) remains
- a few percent Q^2<6GeV^2

($E1/M1 \rightarrow 1$
helicity conservation PQCD)

Properties of Roper resonance P11 (I=1/2, J=1/2, P=+1)





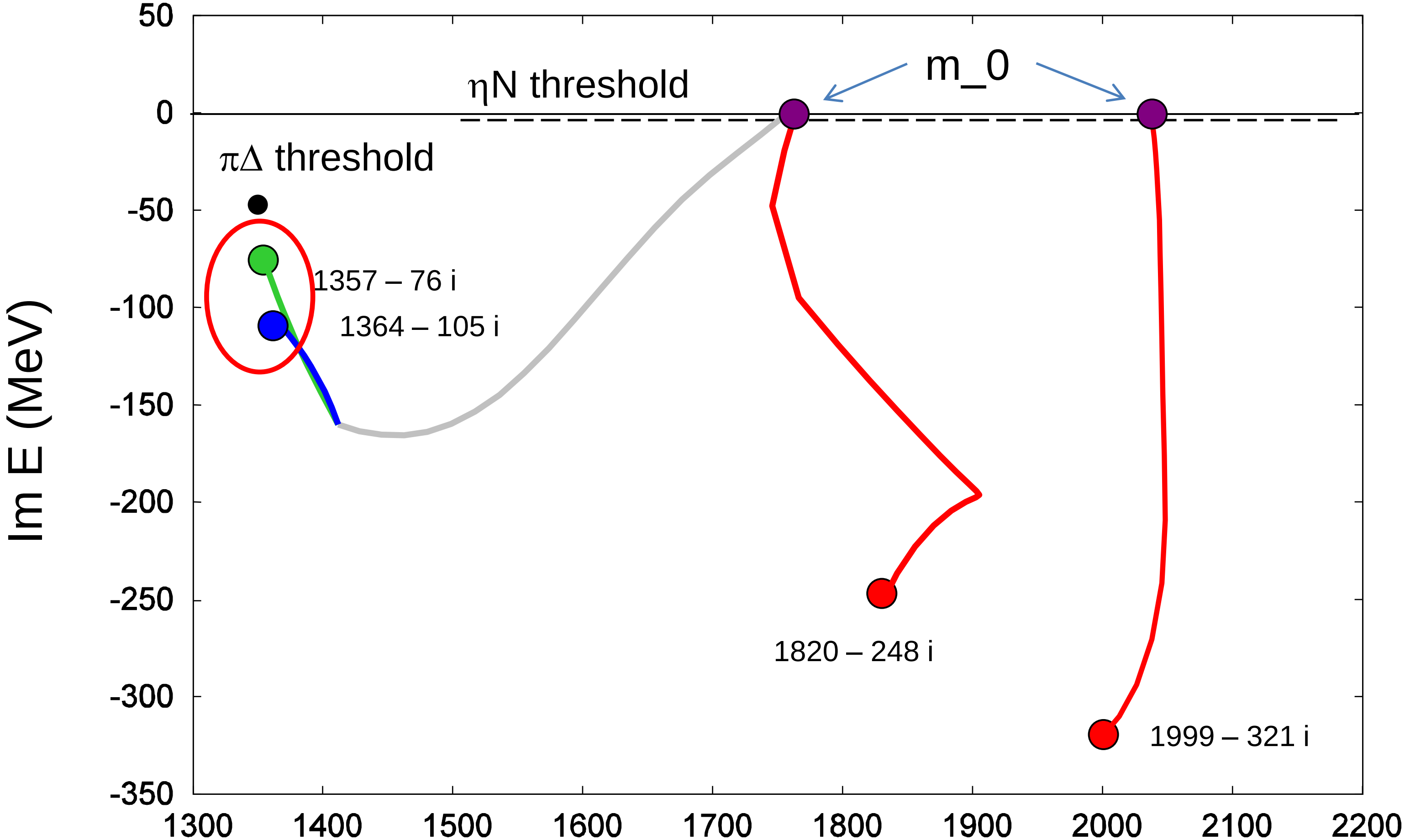
Charmed baryon

Pole positions of P11

Suzuki, Julia-Diaz, Kamano, Lee, Matsuyama, Sato, PRL104 065203 (2010)

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

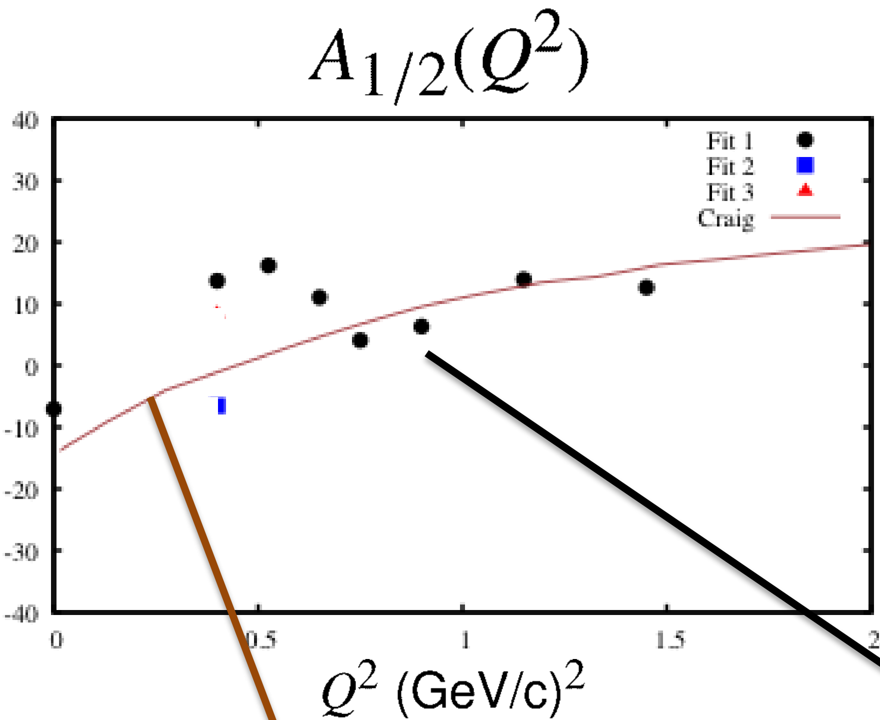
$$0 \leq x \leq 1$$

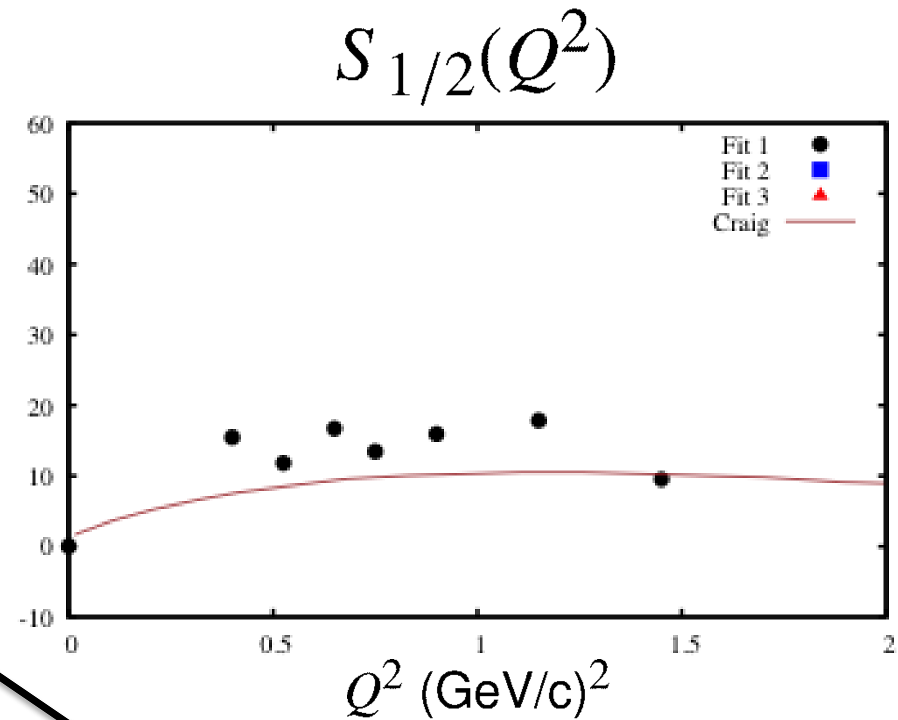


3 resonance pole out of 2 excited(bare) N* (6-channel model)

mass shift of excited states due to coupling with scattering state

γ p → Roper e.m. transition





"Static" form factor from DSE-model calculation. (D. W. Wilson et al, 2012 PRC85 025205)

"Bare" form factor determined from our DCC analysis (2010).

Collaborators

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Next Tasks

1. **Complete the extraction of resonance parameters including N-N* form factors .**

    Analysis on the structure of major resonances(S11,D13)

    understand difference among other analyses

2. **predictions for J-PARC projects on πN -> ππN, KΛ, KN-> KN, …**

3. **Apply heavy meson decay into mesons.**

    H. Kamano, S. X. Nakamura, T.-S. H. Lee, TS PRD84, 114019 (2011)

4. **Neutrino reaction in resonance and DIS region**

➔ **A new collaboration at J-PARC branch of KEK theory Center**

http://j-parc-th.kek.jp/html/English/e-index.html PRD86, 097503 (2012)

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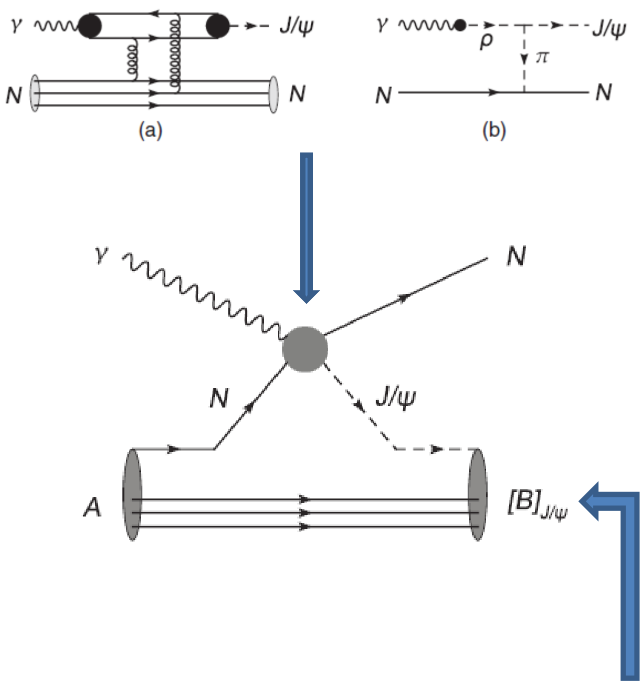
Meson production reactions at higher energy

Photoproduction of bound states with hidden charm
Jia-Jun Wu and T. –S. H. Lee Phys. Rev. C86 065203 (2012)



$$V_{J/\Psi,A}(r) = -\alpha_A \frac{e^{-\mu_A r}}{r}$$