Structure of Roper Resonance:
Recent Results from EBAC-CC Analysis

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and

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This talk :

- Introduction
- Theoretical Formulation
- Development of EBAC-CC analysis
- Recent Results : focus on Roper Resonance
- Outlook

Introduction

Objectives of EBAC (established in spring of 2006)

- Establish the baryon spectra
- Extract information from data for investigating the structure of baryons

$\longrightarrow$

Understand non-perturbative QCD

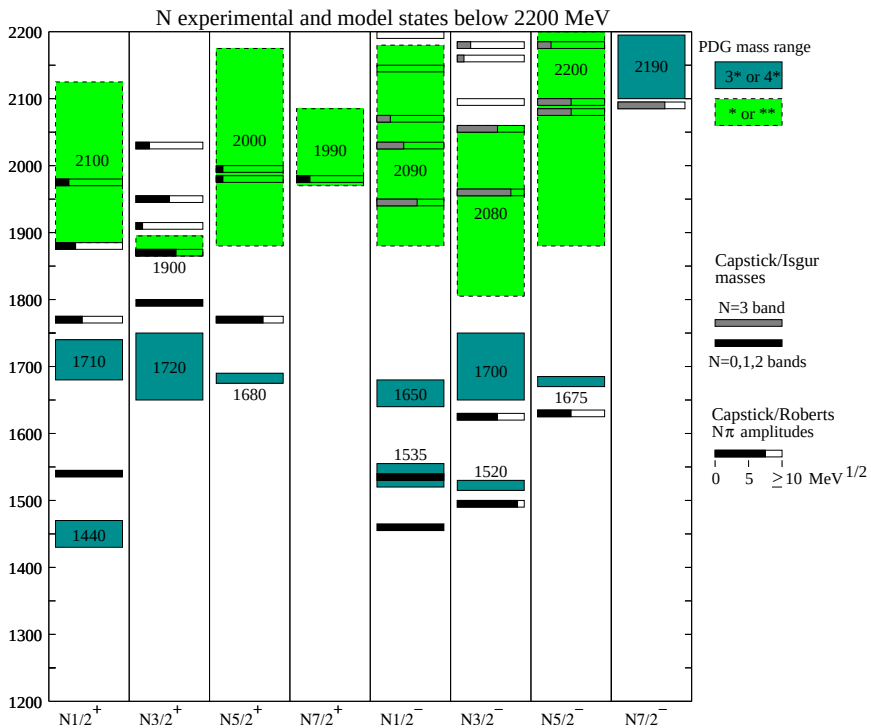
- confinement mechanisms
- Meson cloud associated with the spontaneously and dynamically broken chiral symmetry of QCD
- . . ..

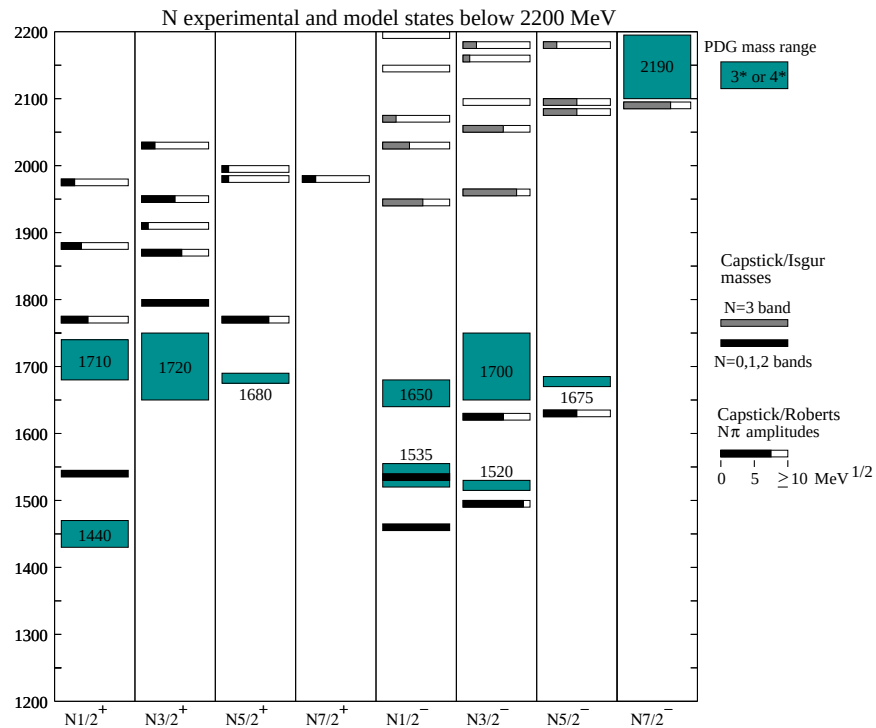
Status of N^* and Δ^* states

2007 PDG : All 2-star and 1-star states are doubtful

Some 3 or 4 stars states are not confirmed in recent analysis

—————— old ——————->>>>>——————current ——————-





Current world-wide efforts :

1. Complete measurements of all polarization observables of γN and $N(e, e')$

   are being pursued at JLab, Bonn, and Mainz

   JLab: 16 polarization obsevables for $\gamma p \to K^+\Lambda$ will be measured before 12 GeV upgrade.

2. perform a coupled-channel analysis of ALL available data of $\pi N, \gamma^* N \to \pi N, \pi\pi N, \eta N, KY, \omega N$

   Being pursued at EBAC , Bonn, and Giessen

Theoretical Formulation

General Considerations :

N^* is unstable

$\longrightarrow$

Structure is coupled to reaction channels to form resonances

$\longrightarrow$

Reaction cross sections are due to

- Excitation of quark-gluon sub-structure of baryons
- reaction mechanisms

$\longrightarrow$

Task :

Separate the contributions from structure and reaction mechanisms

$\longrightarrow$

Analysis must account for :

- Coupled-Channel Unitarity Condition

  $\longrightarrow$

  crucial in extracting the spectrum and structure of N^*

- Reaction mechanisms in the short range region where we want to map out the structure of N^*.

  $\longrightarrow$

  crucial in interpreting the N^* structure

What are the nucleon resonances (N^*) ?

Hamiltonian formulation (Feshbach's textbook):

- A resonance R_c is formed in a process that the incident projectile completely lose its identity, amalgamating with the target system to form a compound state.

  $\pi N \rightarrow (N^*)_c \rightarrow \pi N, \pi\Delta, KY, \cdot\cdot$

- An unstable system R_m is formed during the collision by an attractive force between the interacting particles which do not lose their identities .

  $\pi N \rightarrow (N^*)_{MB} \rightarrow \pi N, \pi\Delta \cdot\cdot$

Question :

How can $(N^*)_c$ and $(N^*)_{MB}$ be defined theoretically and related to the data ?

EBAC-CC Analysis

- Define a Hamiltonian H which can accomodate both mechanisms
- Solve reaction problems to determine the parameters by analyzing the world data of πN and γN, and $N(e, e'\pi)$ data in $W \leq$2 GeV.

- Develop analytical continuation methods for evaluating the resonance parameters at resonance poles of the reaction amplitudes on complex energy plane.

  Findings by Suzuki, Sato, Lee (Phys. Rev. **C79**, 025205 (2009)) :

  Conventional Speed-Plot method (Hohler) and Time-Delayed method (Wigner) are not reliable for multi-channels problems.

EBAC-CC analysis solves a set of dynamical coupled-channel equations :

$$T_{\alpha,\beta}(p_0,p_0;E) = V_{\alpha,\beta}(p_0,p_0) + \sum_\gamma \int_0^\infty dp' V_{\alpha,\gamma}(p_0,p') G_\gamma(p',E) T_{\gamma,\beta}(p',p_0,E)$$

$$V_{\alpha,\beta} = v_{\alpha,\beta} + \sum_{N^*} \frac{\Gamma^\dagger_{N^*,\alpha}\Gamma_{N^*,\beta}}{E-M^*}$$

- $\alpha,\beta,\gamma = \gamma N, \pi N, \eta N, \omega N, KY, \pi\pi N$ ($\pi\Delta, \rho N, \sigma N$)
- $v_{\alpha,\beta}$: Meson-exchange mechanisms
  - Derived from phenomenologcal Lagrangians of earlier works
- $\Gamma_{N^*,\beta}$, M^* : Baryon structure
  - Hadron models with effective degrees of freedom
  - Lattice QCD

Development at EBAC

First step :

Determine the Hadronic parts of the Hamiltonian by analyzing the world data of πN scattering

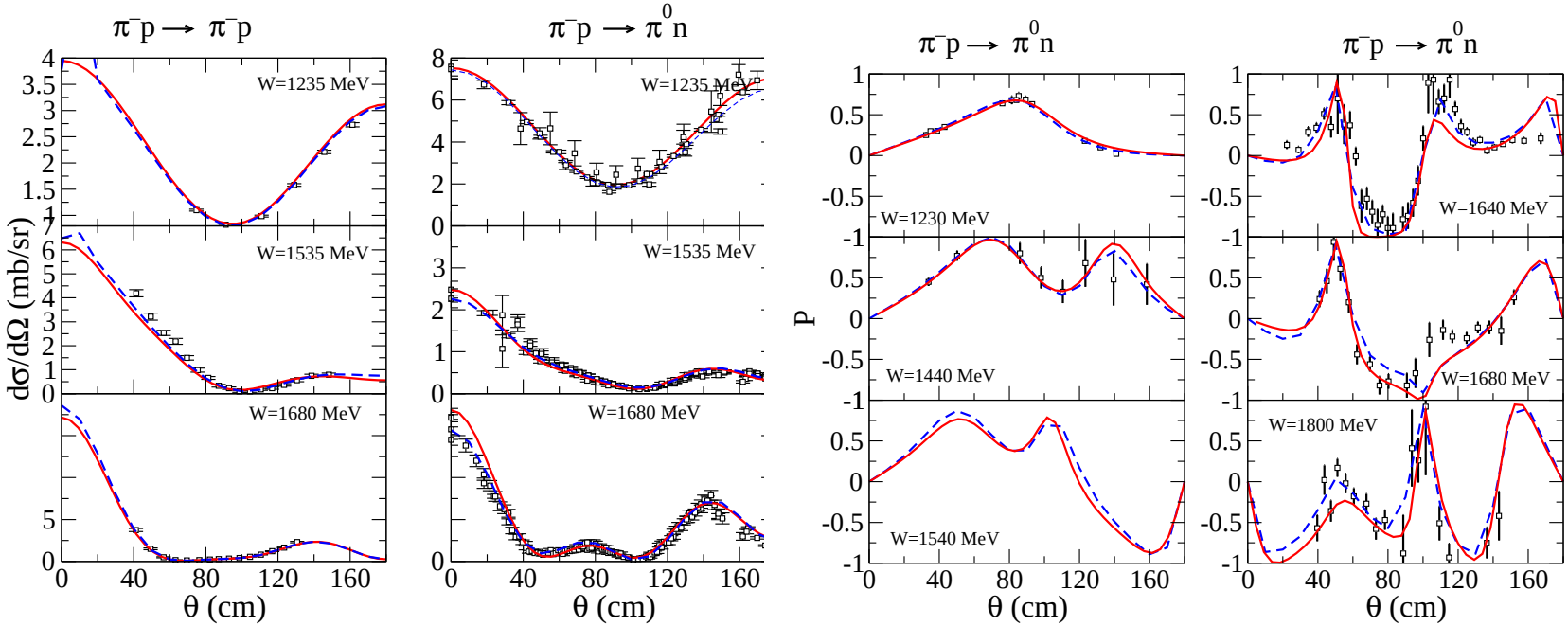
B. Julia-Diaz, T.-S. H. Lee, A. Matsuyama, T. Sato,
Phys. Rev. C76, 065201 (2007)

Procedures:

1. About 15 parameters of meson-exchange interactions are not known well.
2. Introduce the ”minimal” number of bare N^* states.

   Guided by the partial-wave ampludes of GWU/VPI.
3. Refine the parameters by fitting the πN data directly .

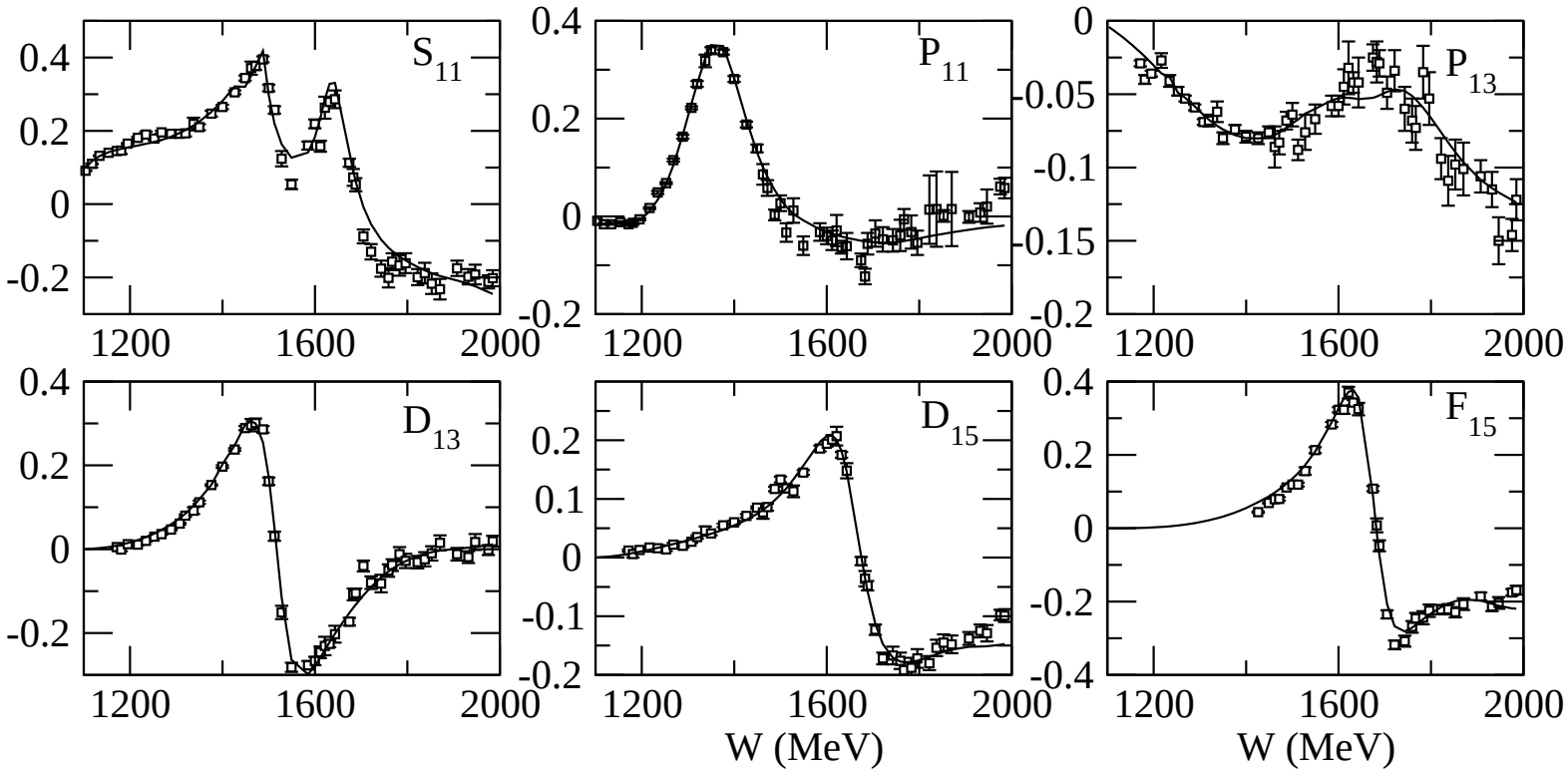
Results for πN scattering /endcenter



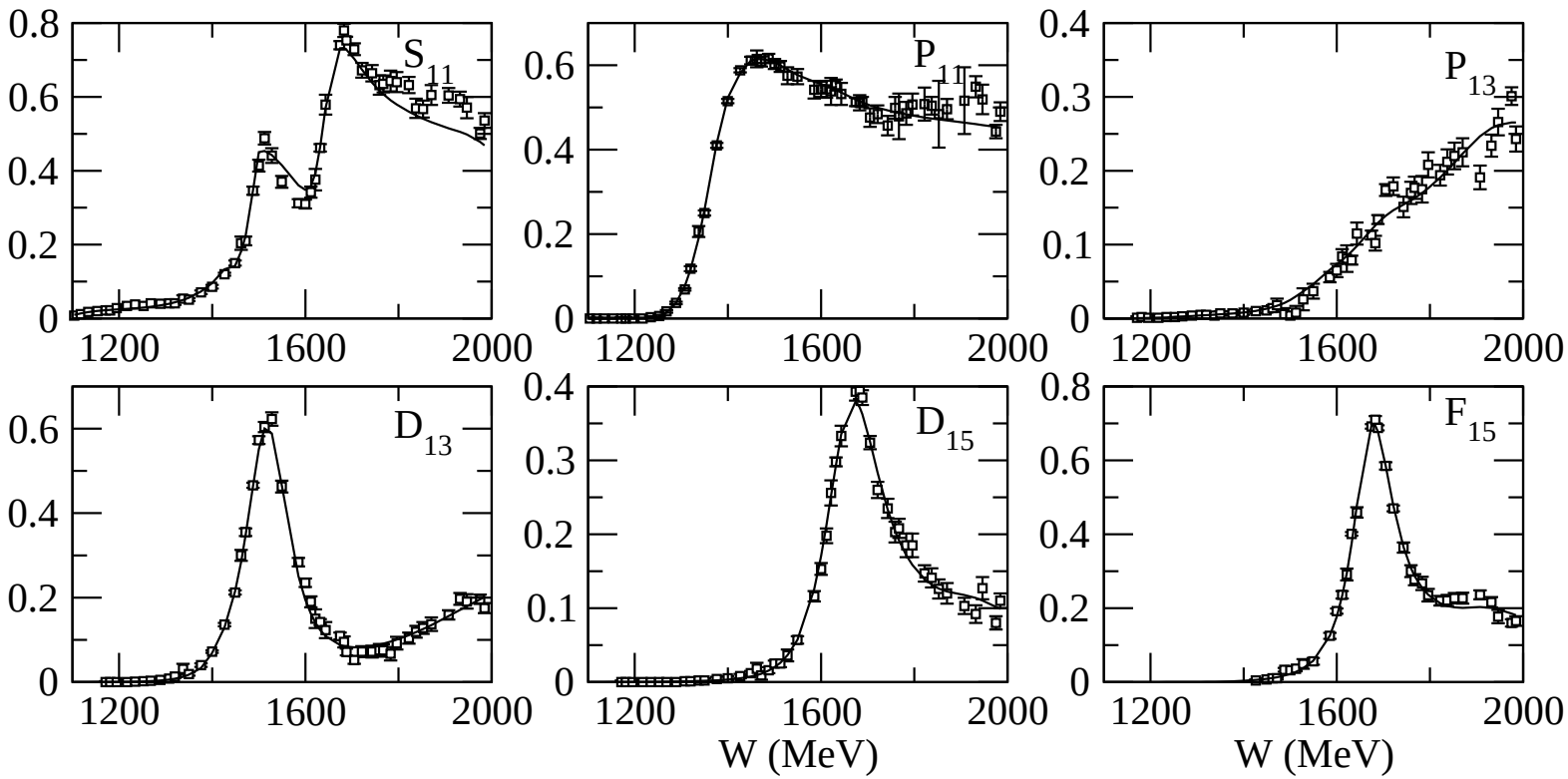
Sample results of $\pi^- p \to \pi^- p, \pi^0 n$:

Left: Differential cross section ($d\sigma/d\Omega$)

Right: Polarization (P)



Compare with the $I = \frac{1}{2}\, Re(T_{\pi N, \pi N})$ of SAID



Compare with the $I = \frac{1}{2}\, Im(T_{\pi N,\pi N})$ of SAID

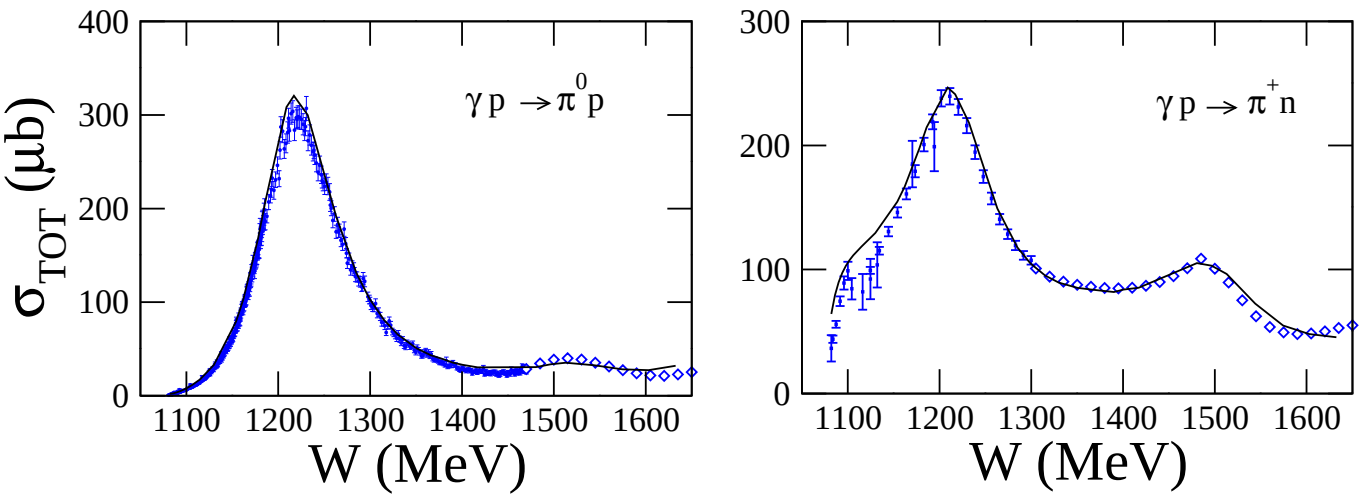
Analysis of $\gamma N \to \pi N$ reactions

B. Julia-Diaz, T.-S. H. Lee, A. Matsuyama, T. Sato, L.C. Smith

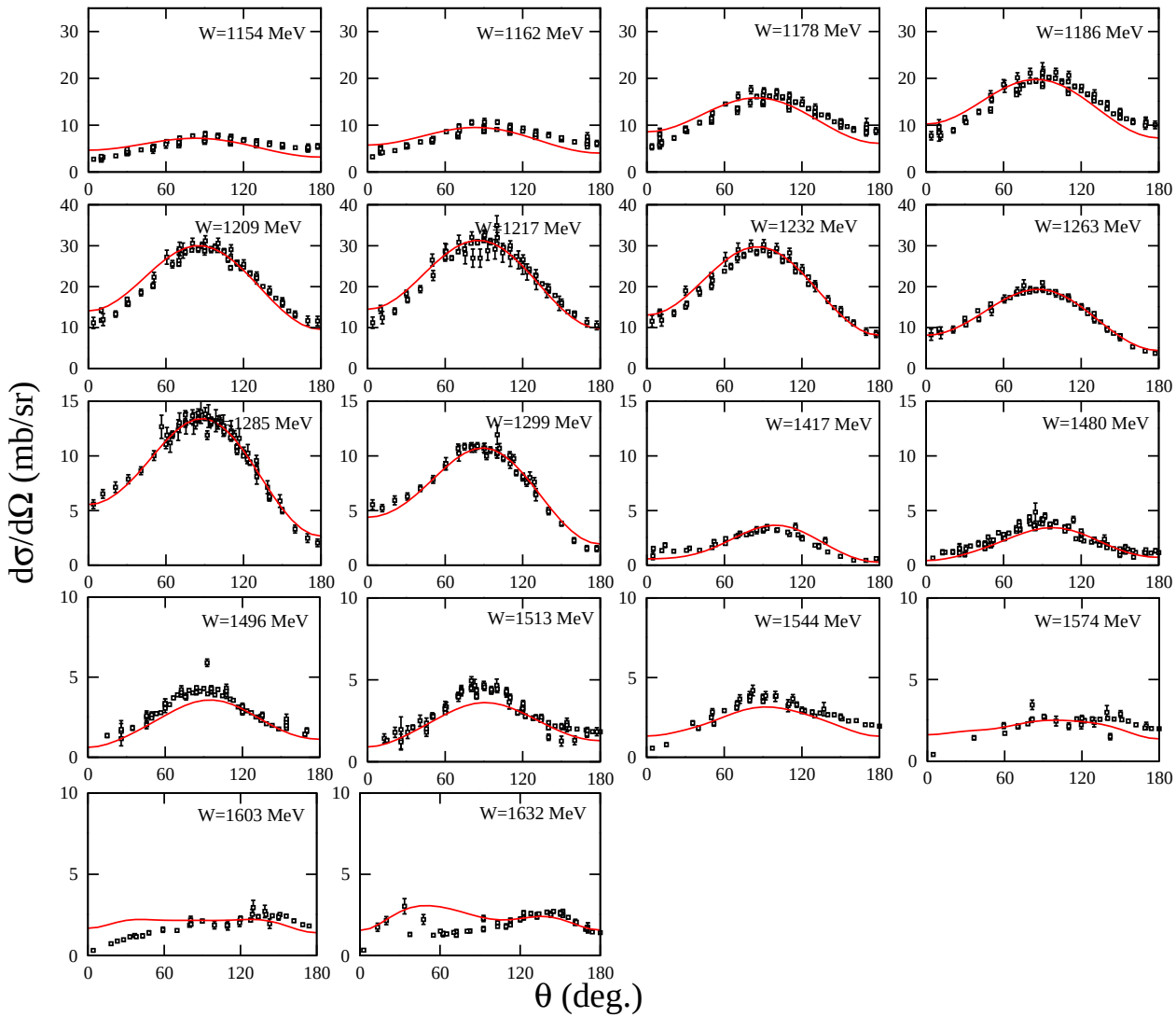
Phys. Rev. C77, 045205 (2008)

$\longrightarrow$

Extract the $\gamma N \to N^*$ helicity amplitudes



$\gamma p \to \pi^0 p, \pi^+ n$ total cross sections



Fit to the $d\sigma/d\Omega$ of $\gamma p \to \pi^0 p$

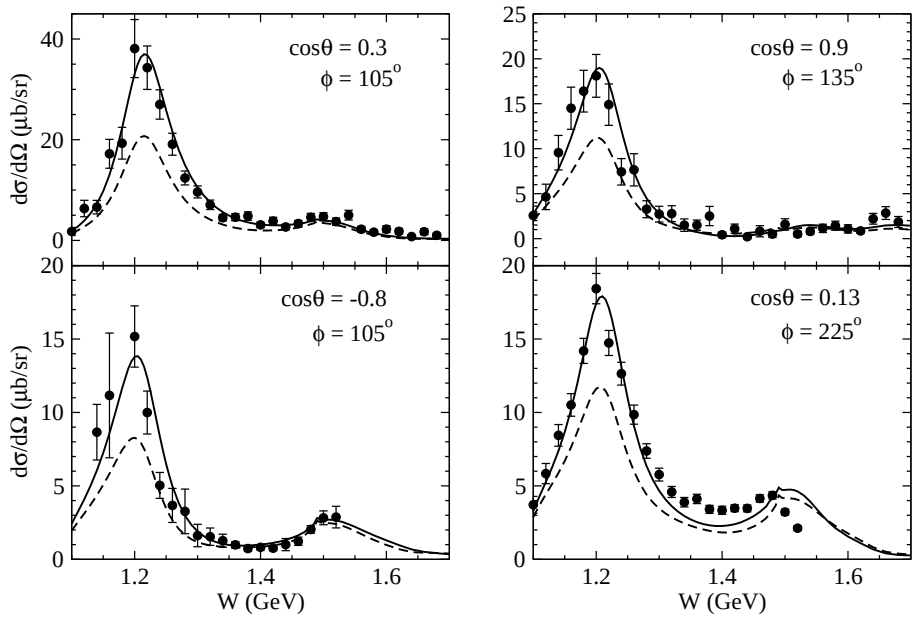
Analysis of $p(e, e'\pi)N$ reactions

B. Julia-Diaz, H. Kamano, T.-S. H. Lee, A. Matsuyama, T. Sato, N. Suzuki,

Submitted to Phys. Rev. C (2009) arXiv:0904.1918

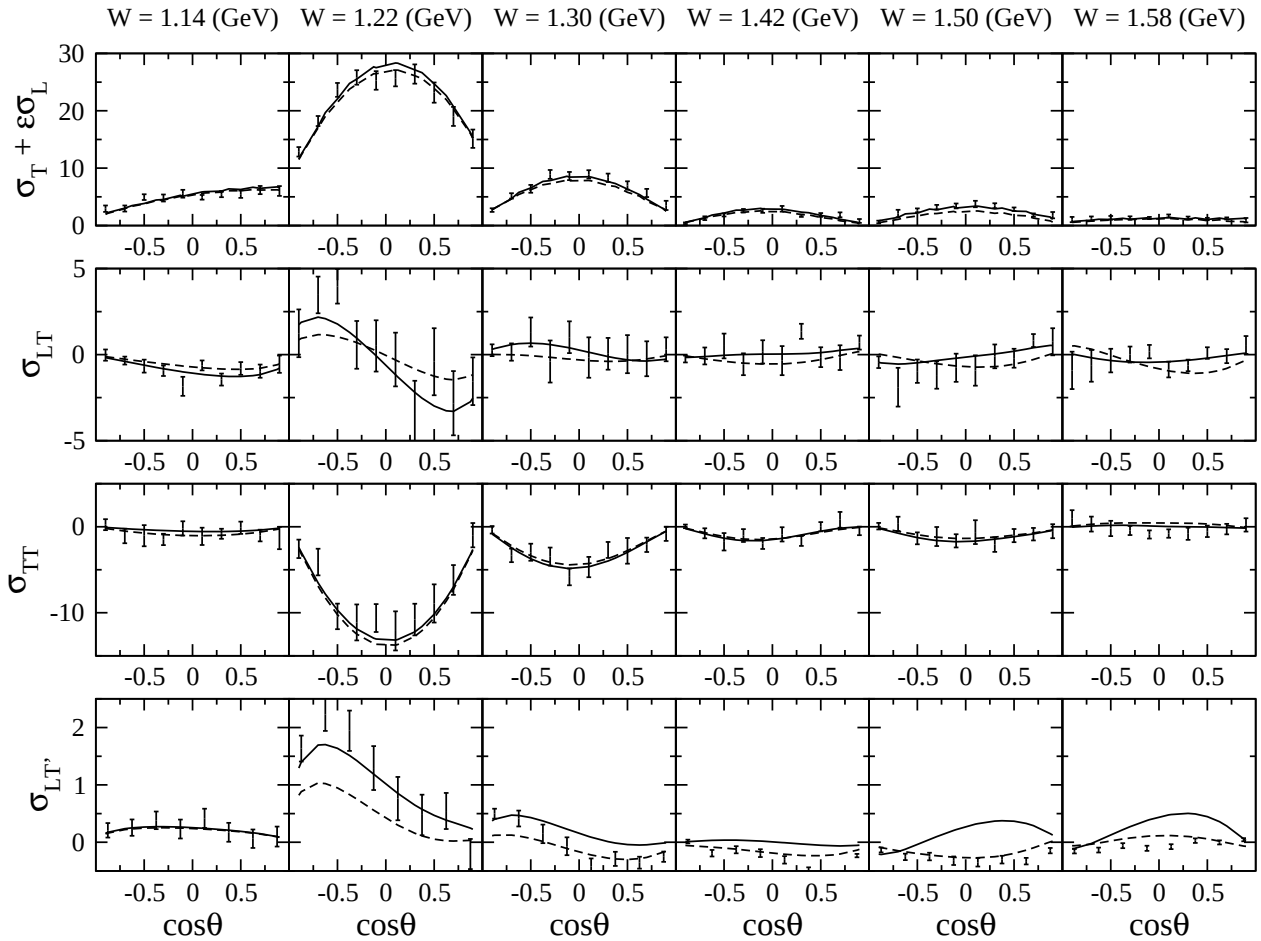
$\longrightarrow$

extract $\gamma N \longrightarrow N^*$ form factors



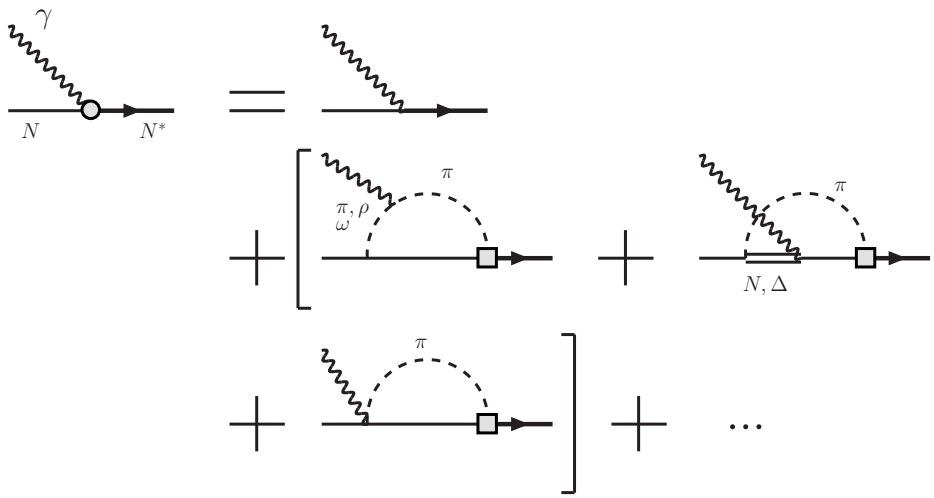
$[d\sigma^5/(dE_{e'}d\Omega_{e'}d\Omega^*_\pi)]$ of $p(e, e'\pi^0)p$ at $Q^2 = 0.4$ (GeV/c)^2.

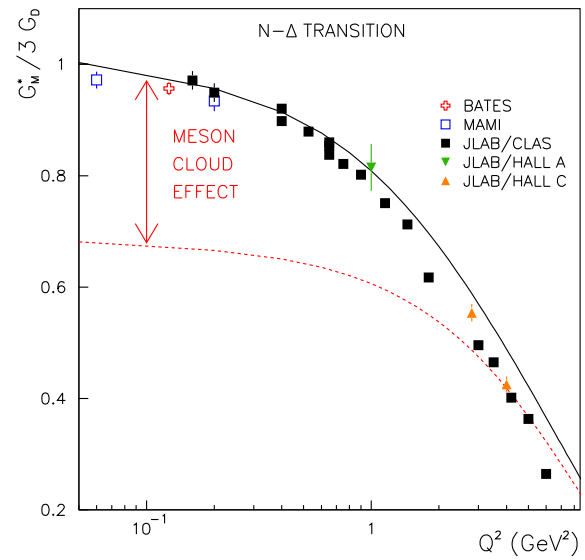
Dashed curves: No coupled-channel effects



$p(e, e'\pi^0)p$ structure functions at $Q^2 = 0.4$ (GeV/c)^2

Determinations of $\gamma^* N \to N^*$ form factors





Left: mechanisms of meson cloud effects on $\gamma N \to N^*$

Right: The magnetic M1 form factor of the $\gamma N \to \Delta$ (1232) transition.

Dynamical Origins and Structure of Nucleon Resonances

N. Suzuki, B. Juliz-Diaz, H. Kamano, T.-S. H. Lee, A. Matsuyama, T. Sato

Submitted to PRL, June (2009)

$$T_{\alpha,\beta}(p_0,p_0;E) = V_{\alpha,\beta}(p_0,p_0) + \sum_\gamma \int_{C_\gamma} dp' V_{\alpha,\gamma}(p_0,p') G_\gamma(p',E) T_{\gamma,\beta}(p',p_0,E)$$

$$V_{\alpha,\beta} = v_{\alpha,\beta} + \sum_{N^*} \frac{\Gamma^\dagger_{N^*,\alpha}\Gamma_{N^*,\beta}}{E-M^*}$$

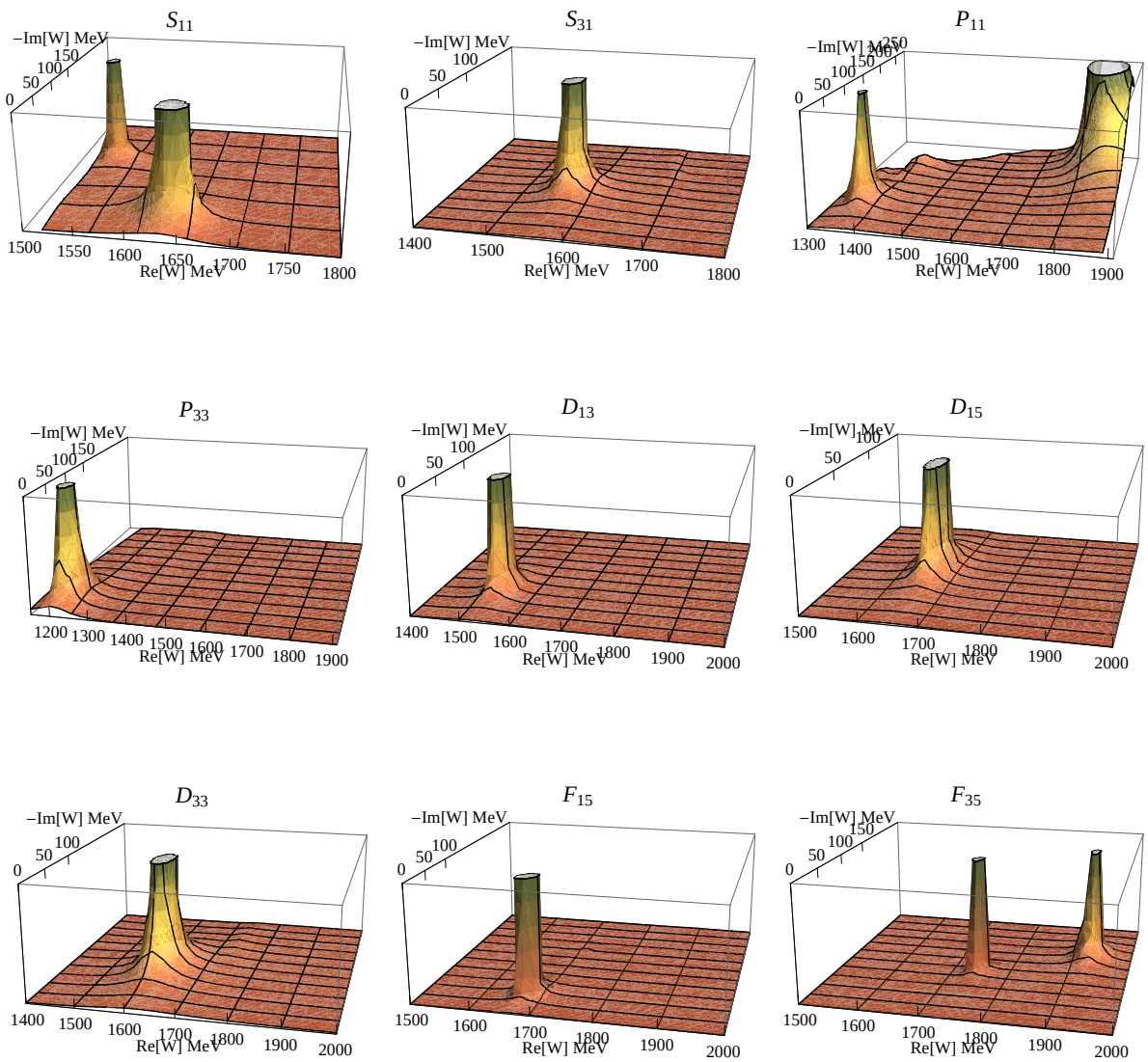
- Search $E = E_{pole}$ on 2^5 sheets of Riemann surface

  Physical (p): $Im(p_{pole,\gamma}) > 0$

  Unphysical (u) : $Im(p_{pole,\gamma}) < 0$

- Contour C_γ should be chosen carefully to perform correct analytic continuation (deveoped by SSL in Phys. Rev. **C79**, 025205 (2009))

	$M^0_{N^*}$ (MeV)	M_R (MeV)	Location	PDG (MeV)
S_{11}	1800	(1540, 191)	$(uuuupp)$	(1490 - 1530, 45 - 125)
	1880	(1642, 41)	$(uuuupp)$	(1640 - 1670, 75 - 90)
P_{11}	1763	(1357, 76)	$(upuupp)$	(1350 - 1380, 80 - 110)
	1763	(1364, 105)	$(upuppp)$	
	1763	(1820, 248)	$(uuuuup)$	(1670 - 1770, 40 - 190)
P_{13}	1711	—		(1660 - 1690, 57 - 138)
D_{13}	1899	(1521, 58)	$(uuuupp)$	(1505 - 1515, 52 - 60)
D_{15}	1898	(1654, 77)	$(uuuupp)$	(1655 - 1665, 62 - 75)
F_{15}	2187	(1674, 53)	$(uuuupp)$	(1665 - 1680, 55 - 68)
S_{31}	1850	(1563, 95)	$(u-uup-)$	(1590 - 1610, 57 - 60)
P_{31}	1900	—		(1830 - 1880, 100 - 250)
P_{33}	1391	(1211, 50)	$(u-ppp-)$	(1209 - 1211, 49 - 51)
D_{33}	1976	(1604, 106)	$(u-uup-)$	(1620 - 1680, 80 - 120)
F_{35}	2162	(1734, 107)	$(u-uuu-)$	(1825 - 1835, 132 - 150)

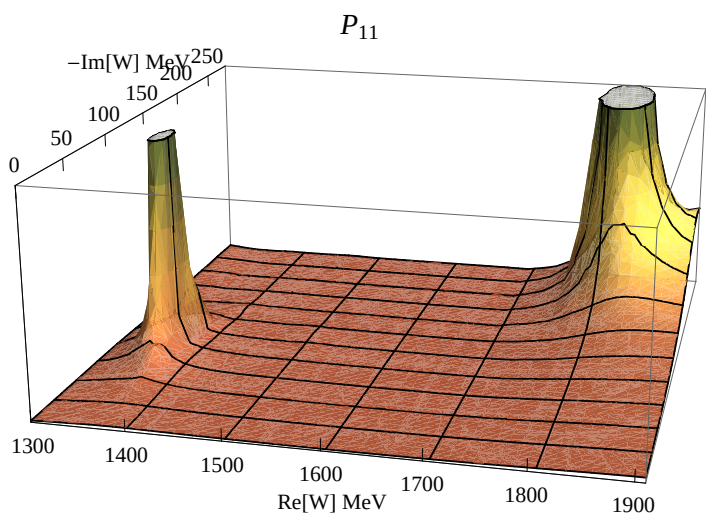


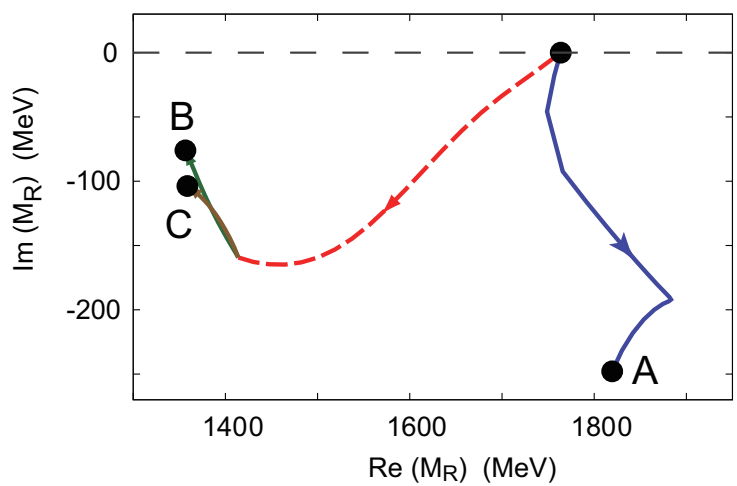
The 3-dimensional depiction of $|T_{\pi N,\pi N}|^2$ on complex E-plane.

Analysis of Roper Resonance (PDG: $N^*(1440)$)

Analysis	P11 poles (MeV)	
This work	(1357, 76)	(1364, 105)
GWU/VPI	(1359, 82)	(1388, 83)
Jülich model (2009)	(1387, 74)	(1387, 71)

Examine $F(E, x) = E - M^0_{N^*} - x\Sigma_{N^*}(E)$, $x = 0 \to 1$.





Left: P_{11} resonances on complex energy plane.

Right:Trajectories of the evolution of the extracted P_{11} resonance poles.

$\longrightarrow$

Roper resonance is made of a bare core and meson cloud ,

not a molecular-type meson-baryon resonance

2009 results of EBAC-CC analysis:

- All extracted nucleon resonances are made of a bare core and meson cloud .
- Disagree with PDG in P_{13} and P_{31} partial-wave.

Outlook

- A combined analysis of $\pi N, \gamma^* N \to \pi N, \eta N, \pi\pi N$ data must be performed to finalize the extracted resonance parameters.

  Status :

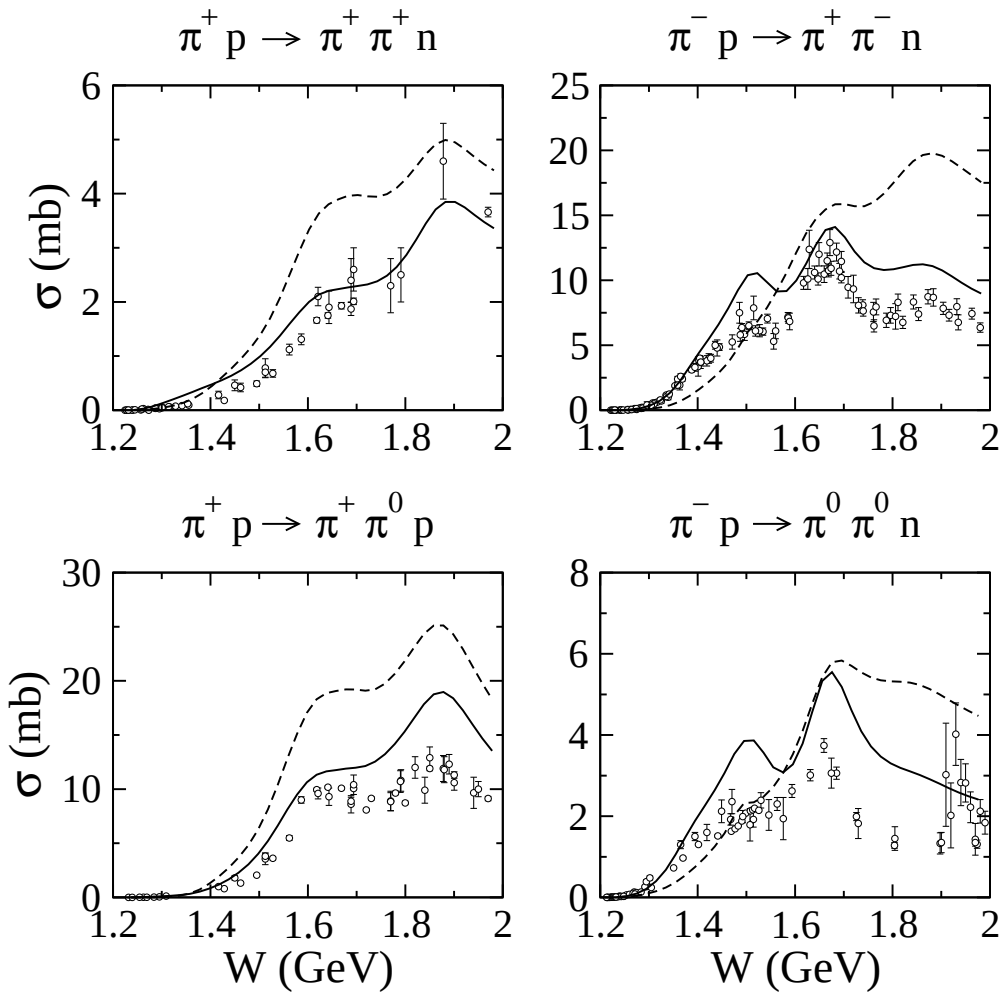
  – The computation code for combined analysis has been well developed and tested.

  – Focus on analysis of $\pi\pi N$ production data : understood qualitatively.

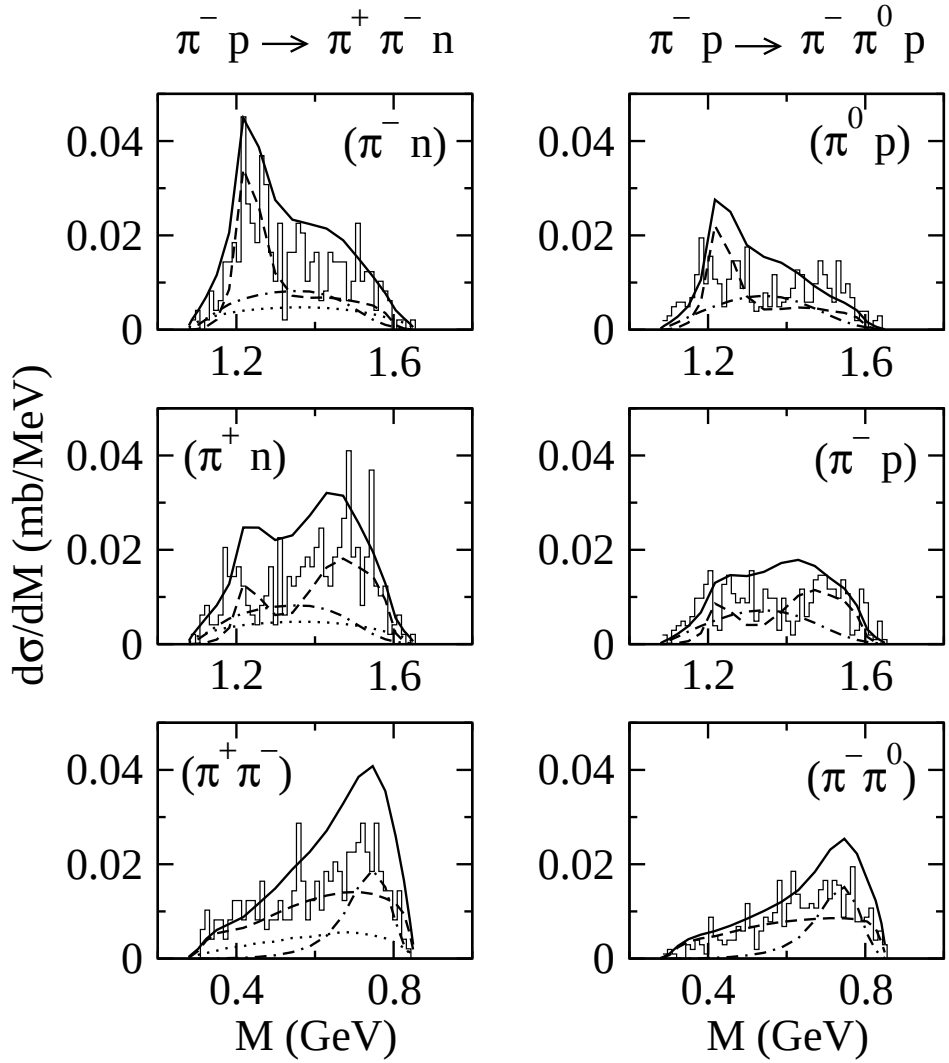
Predicted $\pi N \to \pi\pi N$ cross sections

H. kamno, B. Julia-Diaz,T.-S. H. Lee, A. Matsuyama, T. Sato

Phys. Rev. **C79**,025206 (2009)



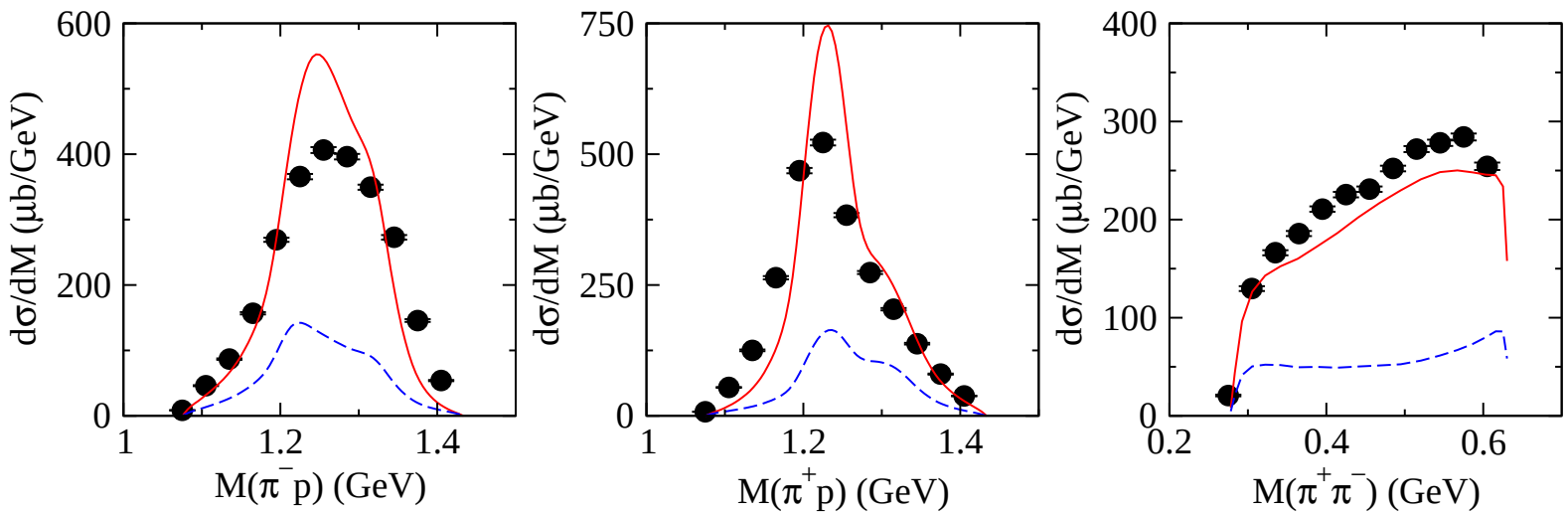
Dotted curves: No coupled-channel effects



Invariant mass distributions of $\pi^- p \to \pi\pi N$ at $W = 1.79$ GeV.

dashed :$\pi\Delta$, dotted: σN , dot-dashed: ρN

Predicted $\gamma p \to \pi^+\pi^- p$ cross sections



Dash curves: No coupled-channel effects

Main difficulties :

Lack of sufficient hadronic production data

$\longrightarrow$

Need to develop collaborations with JPARC

- Challenge :

  How to make contact with hadron structure calculations such as DSE models, LQCD , $\cdots$?

Backup slides

$$T_{a,b}(E) = t_{a,b}(E) + t^R_{a,b}(E)$$

$a, b = \gamma N, \pi N, \eta N, \pi\Delta, \rho N, \sigma N$

Non-resonant term :

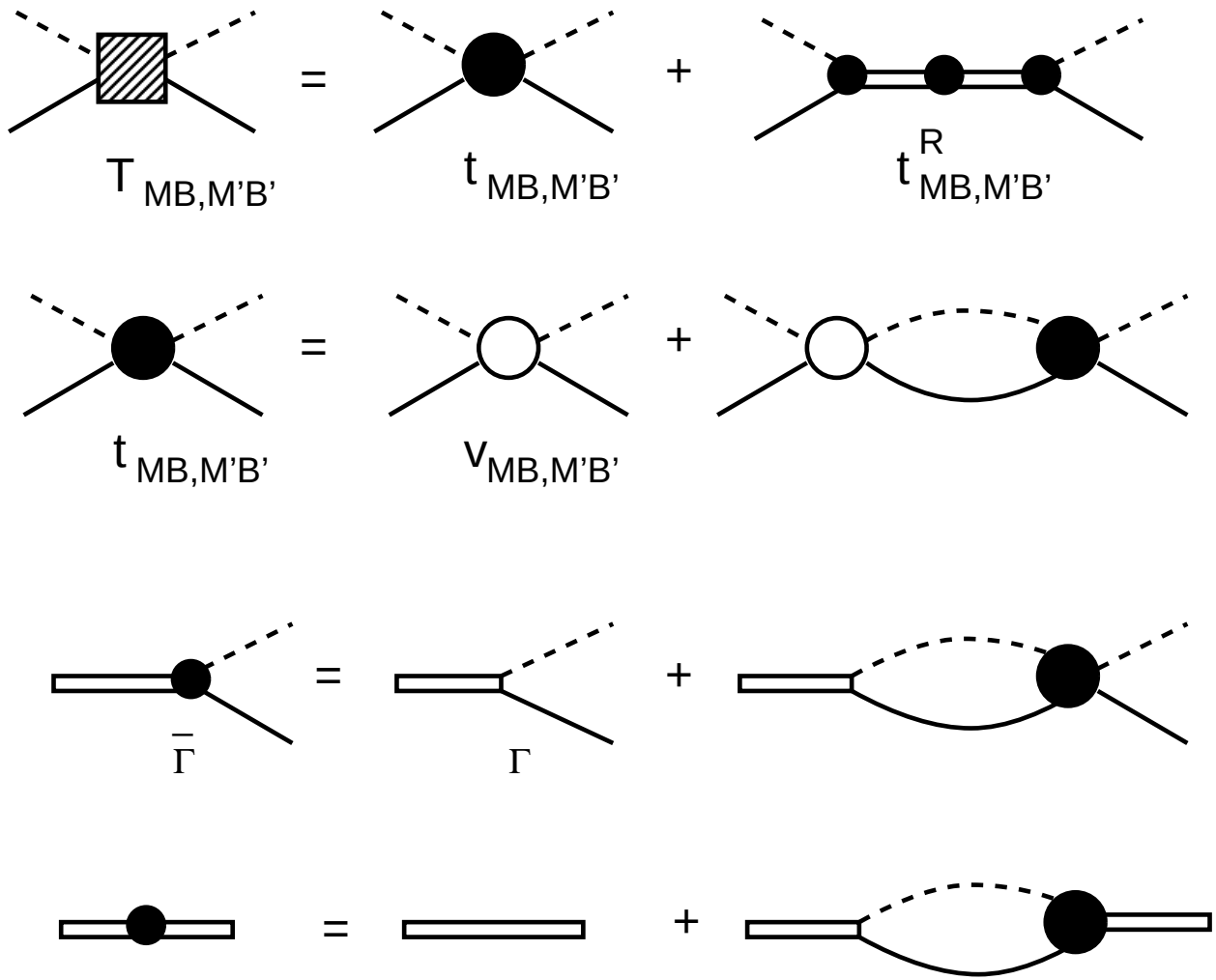
$$t_{a,b}(E) = v_{a,b} + \sum_c v_{a,c} G_c(E) t_{c,b}(E)\,,$$

Resonant term:

$$t^R_{a,b}(E) = \sum_{N^*_i, N^*_j} \bar{\Gamma}^\dagger_{N^*_i,a}(E) [G^*(E)]_{i,j} \bar{\Gamma}_{N^*_j,b}(E)\,.$$

Dressed vertex:

$$\bar{\Gamma}_{N^*,a}(E) = \Gamma_{N^*,a} + \sum_b \Gamma_{N^*,b} G_b(E) t_{b,a}(E)\,,$$

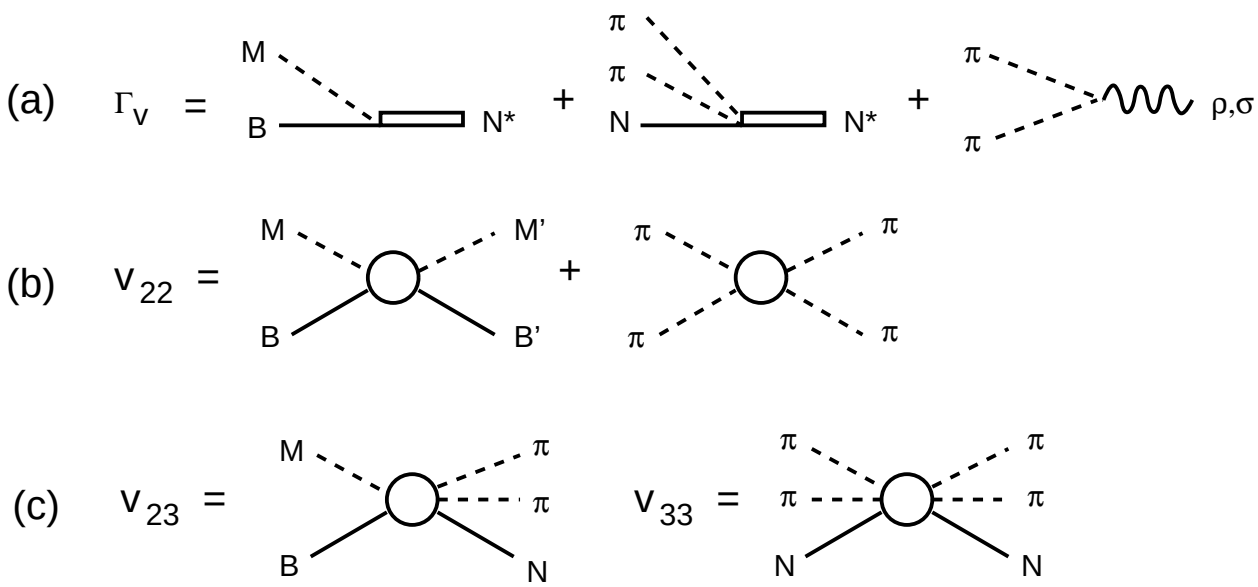

T MB,M'B'
=
t MB,M'B'
+
t R MB,M'B'
t MB,M'B'
=
v MB,M'B'
+
Γ̄
=
Γ
+
=
+

MSL approach :

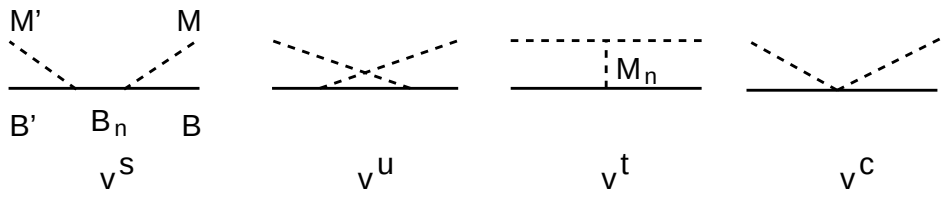
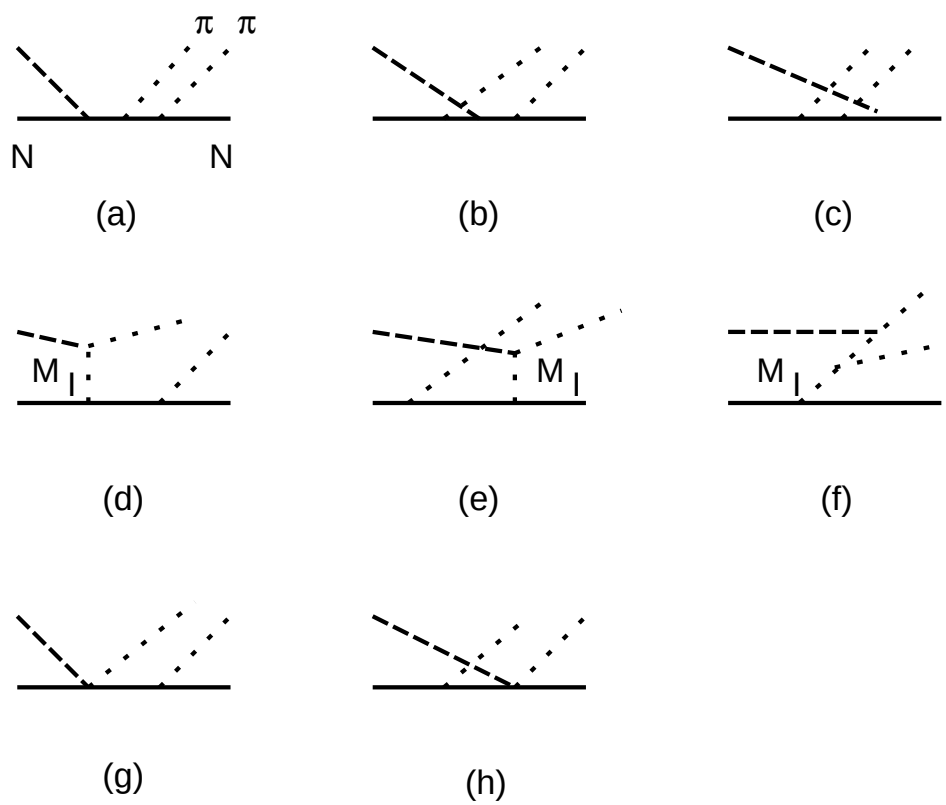
Derive H from Lagrangians by appling the unitary transformation

$\longrightarrow$

$$H_I \quad = \quad \Gamma_V + v_{22} + v_{23} + v_{33}$$



- $2 \to 2$ interaction v_{22} :



- $2 \to 3$ interaction v_{23} :