Electromagnetic form factors of nucleon resonances within dynamical coupled channel model of meson production reactions

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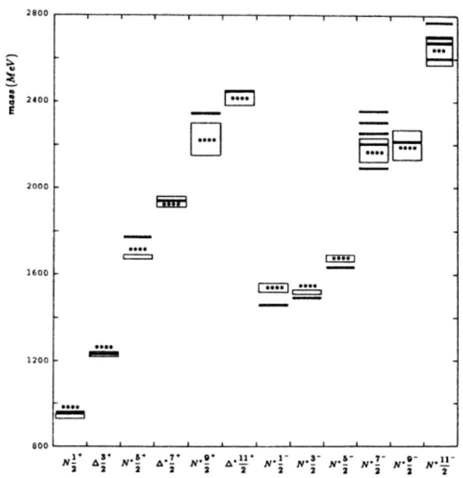
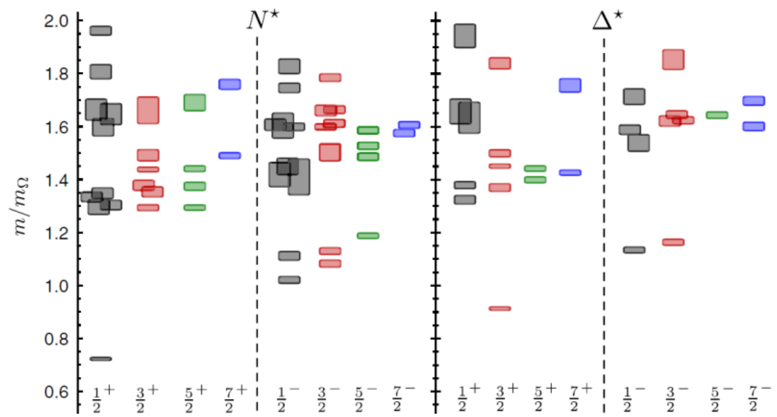
Baryon excited states

Baryon excited states are predicted from quark models, SD,… LQCD

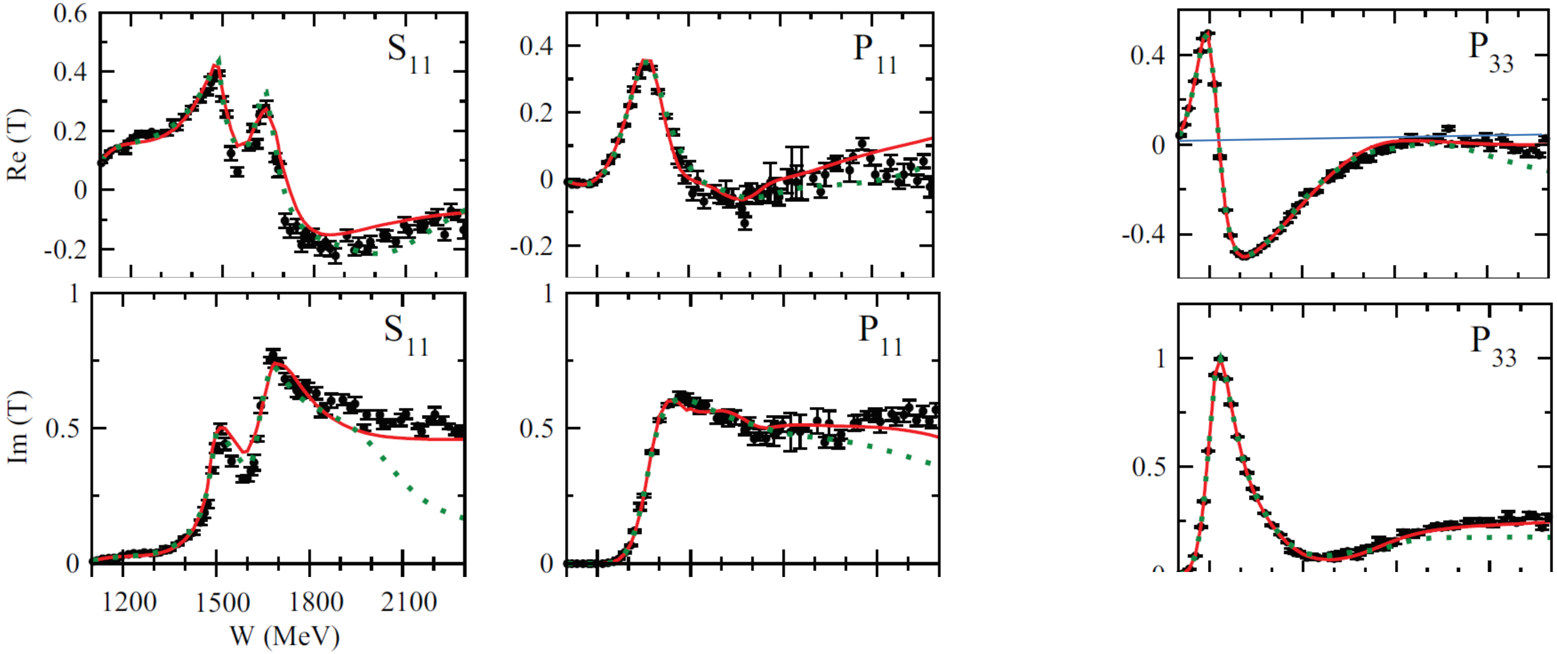


S. Capstic, N. Isgur PRD84(1984)



R. Edwards, et al. PRD84(2011)

Excited states : resonances in meson-baryon scattering state



N*: large width, overlapping, inelastic resonances

- Reaction model (meson-baryon degrees of freedom)
  K-matrix approach, dynamical reaction model,..

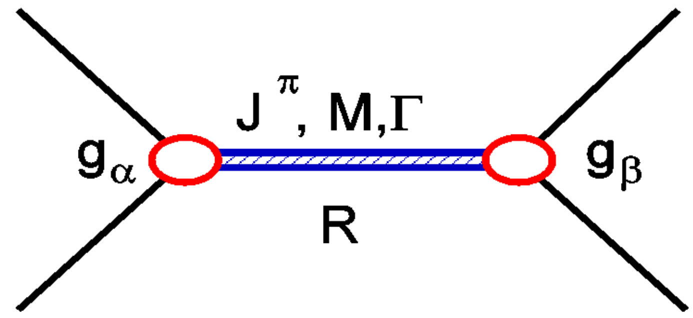
- LQCD: scattering in box, effective potential

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

analysis of meson production reactions with Dynamical Coupled-Channels approach

- **partial wave amplitudes**
- **analytic continuation of amplitudes**

- **resonance spectrum(Mass, width and transition form factor)**
- **Role of reaction dynamics on the properties of excited states**



$$F_{em}(Q^2) =< N^*|J_{em}(Q^2)|N >$$

- Dynamical coupled channel approach(ANL-Osaka model)
- Transition form factor

◆ N-Delta transition Form factor : imaginary part of multipole amplitude

◆ Form factor from the residue at the resonance pole of amplitude

◆ Preliminary results from current DCC model

- Dynamical coupled channel approach(ANL-Osaka model)
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  - Preliminary results from current DCC model

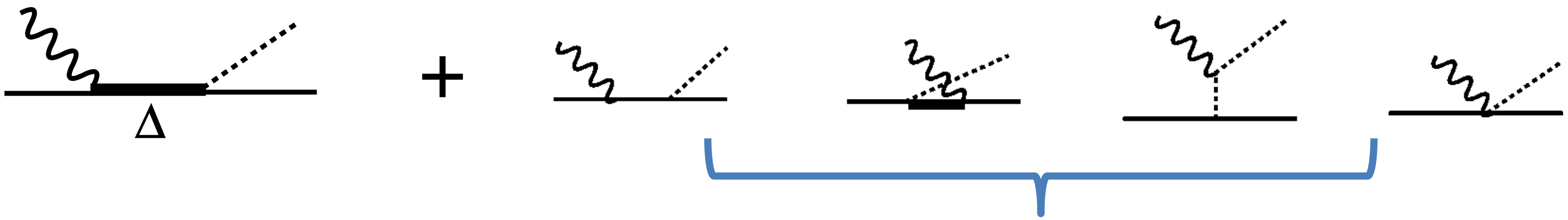
Scattering amplitudes and unitarity

Phase relation among partial wave amplitudes is essential for the description of observables(polarization,..), unitarity plays important role.

Example: below two pion production threshold, phase of pion photoproduction amplitude is given by that of pion-nucleon elastic scattering.(Watoson theorem)

$$T^{\alpha}_{\gamma\pi} = |T^{\alpha}_{\gamma\pi}| e^{i\delta^{\alpha}_{\pi N}}$$

Breit-Wigner resonant amplitude + non-resonant mechanisms does not work



Born diagrams (based on chiral Lagrangian)

Many meson-baryon channels open for W<2GeV

$$\pi N, \eta N, K\Lambda, K\Sigma, \pi\pi N, \omega N$$

Needs coupled channel approach with 2body+3body ($\pi\pi N$) unitarity

$$\frac{T - T^{\dagger}}{i} = T^{\dagger} T$$

Dynamical Coupled Channel Approach

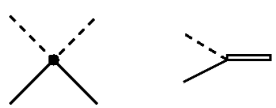
start from Hamiltonian of meson-baryon system

'excited nucleon' $|N^* >$

continuum $|\pi N >, |\eta N >, |K\Lambda >, |K\Sigma >, |\pi\pi N >$

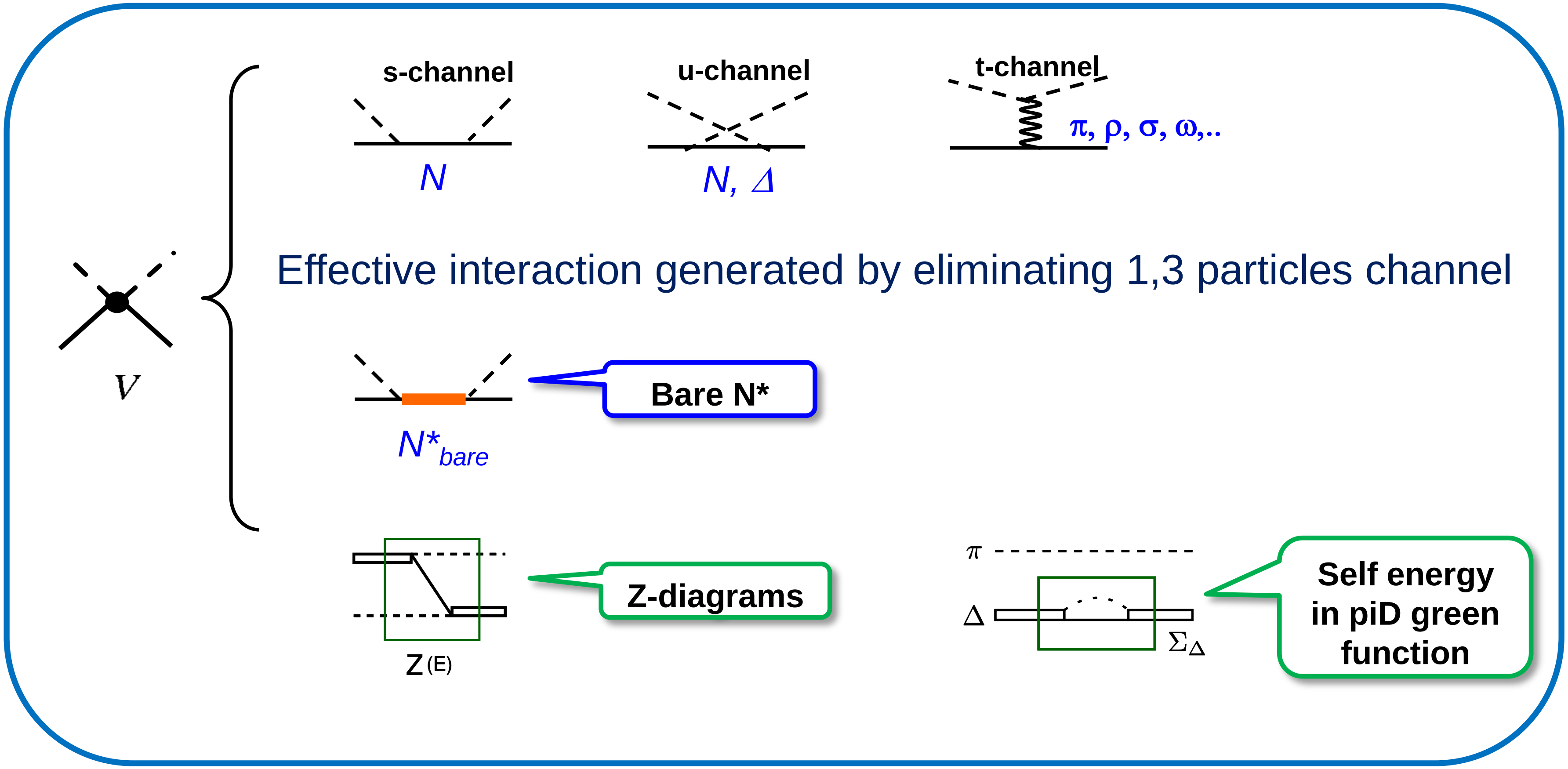
interaction $\Gamma_{N^* \leftrightarrow MB}$ $\quad v_{MB,M'B'}$

Hamiltonian $\pi N \oplus \Delta \oplus \gamma N$



$$H = H_0 + v_{\pi N,\pi N} + v_{\pi N,\gamma N} + \Gamma_{\Delta \leftarrow \pi N} + \Gamma_{\Delta \leftarrow \gamma N} + (h.c.)$$

Building block of our model $(\gamma^{(*)}N,\ \pi N,\ \eta N,\ \pi\Delta,\ \sigma N,\ \rho N,\ K\Lambda,\ K\Sigma,\cdots)$



→ Solve scattering equation that satisfies two+three body unitarity

$$T^{IJP}_{\beta,\alpha}(k',k,W) = V^{IJP}_{\beta,\alpha}(k',k) + \sum_{\gamma} \int dq q^2 V^{IJP}_{\beta,\gamma}(k',q) G^0_{\gamma}(q,W) T^{IJP}_{\gamma,\alpha}(q,k,W)$$

$$\alpha,\beta,\gamma \ = \ (\ \gamma^{(*)}N,\ \pi N,\ \eta N,\ \underbrace{\pi\Delta,\ \sigma N,\ \rho N}_{\pi\pi N},\ K\Lambda,\ K\Sigma,\cdots)$$

each meson-exchange potential V contributes many partial waves

→ partial waves, W-region, MB channels are related

→ simultaneous analysis MB channels constrains model, but time consuming to fit data

Scattering amplitude can be rewritten as

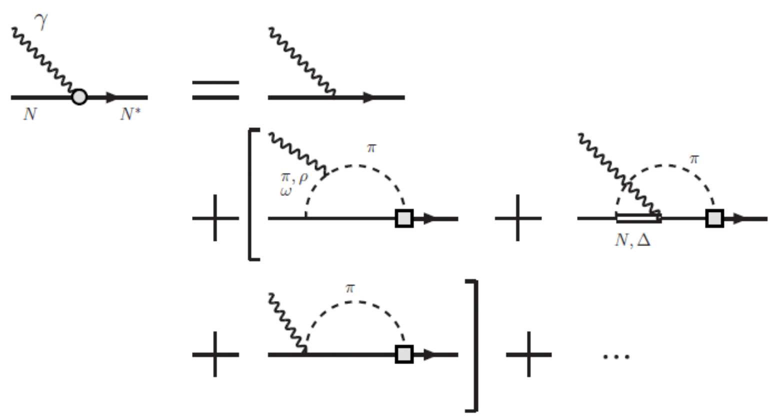
$$T_{\alpha,\beta}(W) = t^{nr}_{\alpha,\beta}(W) + \sum_{i,j} \bar{\Gamma}_{\alpha,i}(W)[\frac{1}{W - m_0 - \Sigma(W)}]_{ij}\bar{\Gamma}_{\beta,j}(W)$$

α, β Meson-Baryon channel i, j Resonances

$$< N_i^{*0}|\Sigma(W)|N_j^{*0} >= \sum_{\alpha} \bar{\Gamma}(W)_{\alpha,i} G^0_{\alpha}(W)\Gamma(W)_{\alpha,j}$$

Non-trivial contribution of meson loop:

$$\bar{\Gamma}_{\gamma N\to\Delta}(E) = \Gamma_{\gamma N\to\Delta} + \int \bar{\Gamma}_{\Delta\to\pi N} G^0_{\pi N}(E) v_{\gamma\pi}$$



Core + Meson Cloud

- Dynamical coupled channel approach(ANL-Osaka model)
- Transition form factor
  - N-Delta transition Form factor : imaginary part of multipole amplitude
  - Form factor from the residue at the resonance pole of amplitude
  - Preliminary results from current DCC model

Delta(1232): isolated, elastic(BR~100% piN) resonance

Sato,Lee PRC54(1996), PRC63(2001)

$\Delta + \pi N$: fix model by analyzing $(\pi N), (\gamma, \pi), (e, e'\pi)$

'Transition form factors' are presented by using the imaginary part of the multipole amplitudes at W=1.232, where piN phase shift of P33 channel goes through 90 degree.

$$G^*_M \sim Im[M^{3/2}_{1+}]$$

transition amplitude

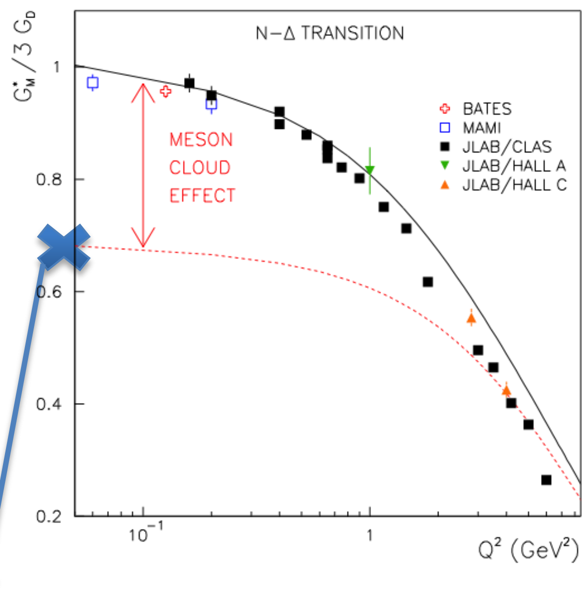
$$T_{\pi,\gamma}(W) = t^{nr}_{\pi,\gamma}(W) + \bar{\Gamma}_{\Delta\pi}(W)[\frac{1}{W - m_0 - \Sigma_\Delta(W)}]\bar{\Gamma}_{\Delta\gamma}(W)$$

$$[\bar{\Gamma}^K_{\Delta,\gamma}]_{M1} = \sqrt{\frac{8\pi m_\Delta k \Gamma_\Delta}{3 m_N q}} \times Im[M^{3/2}_{1+}]$$

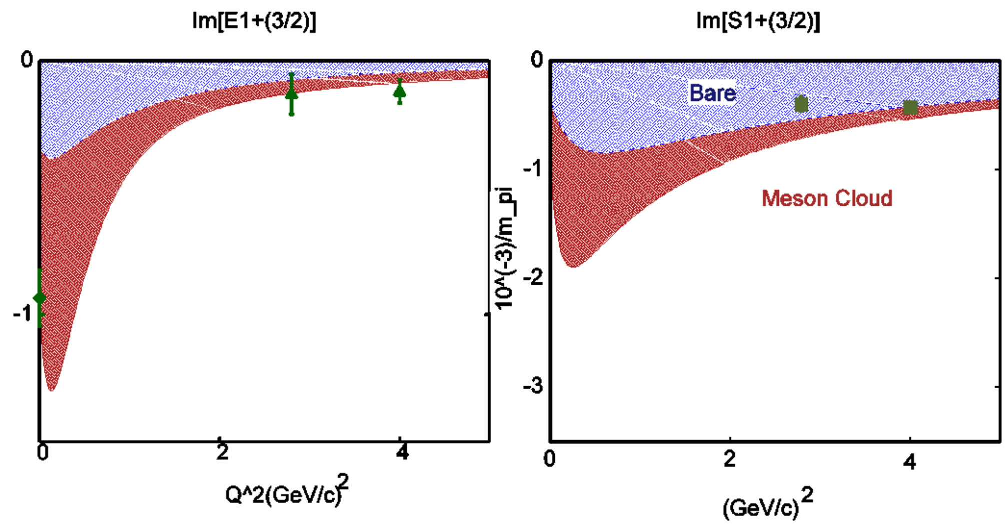
Similar relation : E2, C2 ←→ $E^{3/2}_{1+}, S^{3/2}_{1+}$

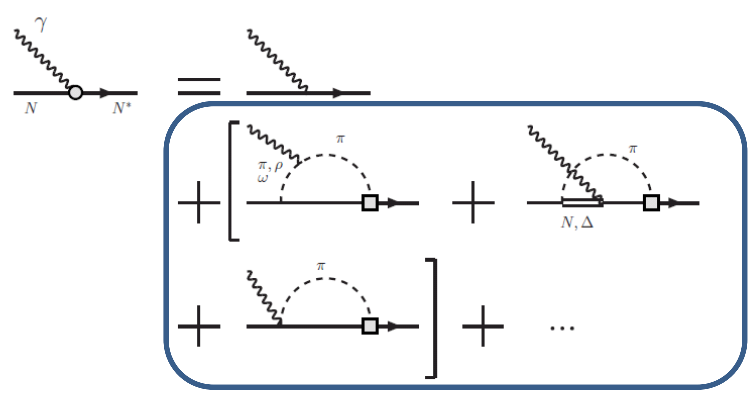
γ N → Δ (1232)
(role of reaction dynamics)

M1: Magnetic dipole



Quadrupole transition E2,C2





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

γ N → Δ (1232)
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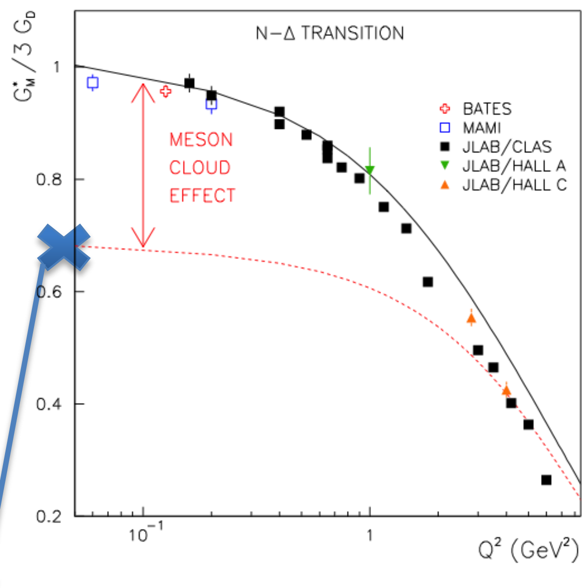
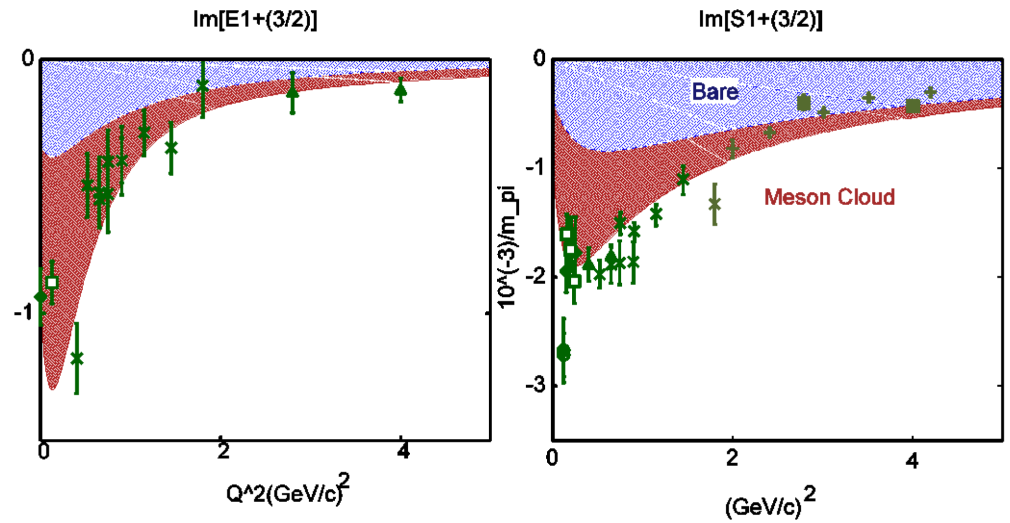
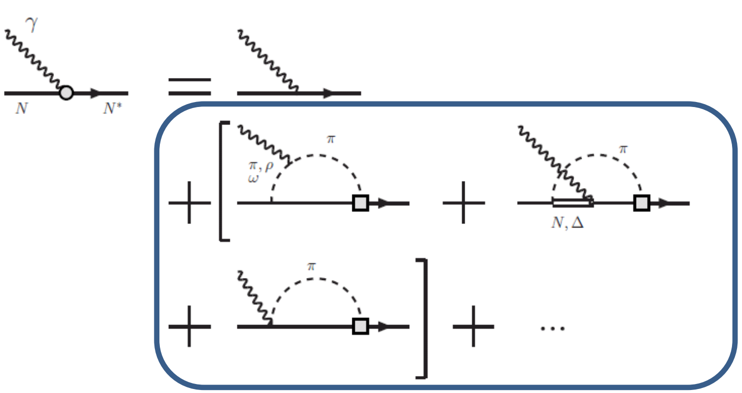


Quadrupole transition E2,C2





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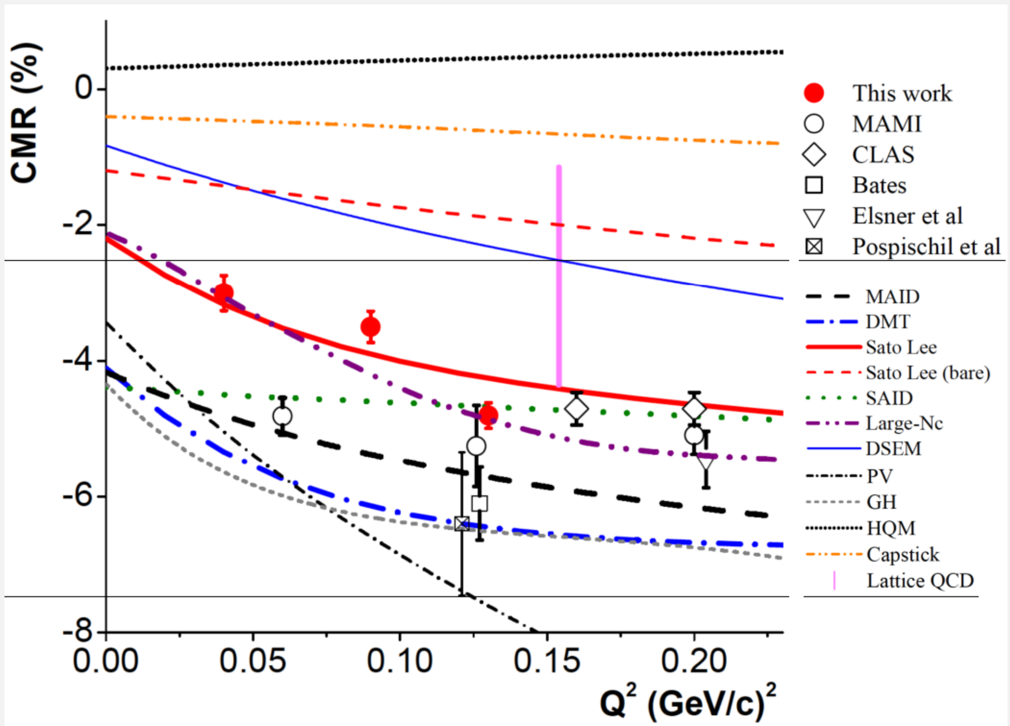
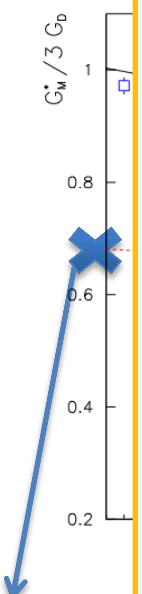
γ N → Δ (1232)
(role of reaction dynamics)

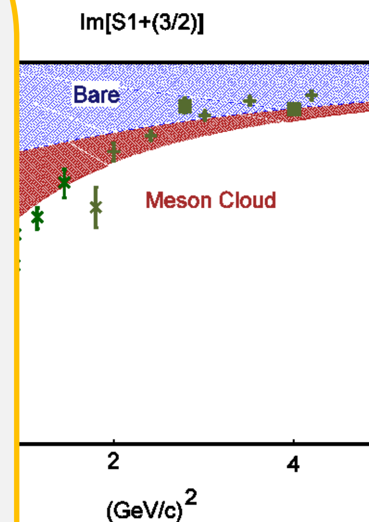
M1: ... n E2,C2

Phys. Lett. B760 (2016) 267, A. Blomberg et al.

CMR = C2/M1







Note:
Most of t... hadron m... close to "B...

- Dynamical coupled channel approach(ANL-Osaka model)
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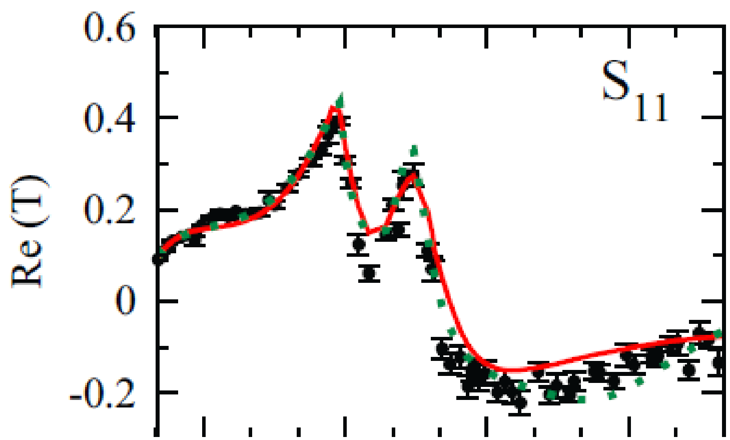
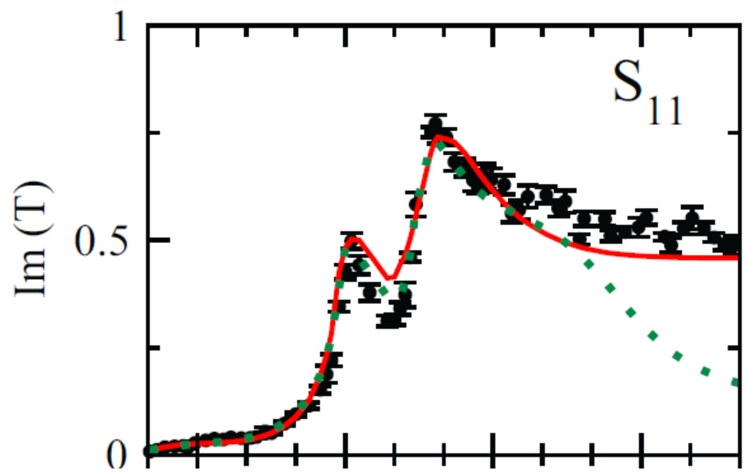
Calculating from factor from the imaginary part of the amplitudes does not work except Delta(1232)





$$T_{\beta,\alpha} = t^{nr}_{\beta,\alpha} + \bar{\Gamma}_{\beta,1}[\frac{1}{W - m_0 - \Sigma}]_{11}\bar{\Gamma}_{\alpha,1} + \bar{\Gamma}_{\beta,1}[\frac{1}{W - m_0 - \Sigma}]_{12}\bar{\Gamma}_{\alpha,2}$$
$$+\bar{\Gamma}_{\beta,2}[\frac{1}{W - m_0 - \Sigma}]_{21}\bar{\Gamma}_{\alpha,1} + \bar{\Gamma}_{\beta,2}[\frac{1}{W - m_0 - \Sigma}]_{22}\bar{\Gamma}_{\alpha,2}$$

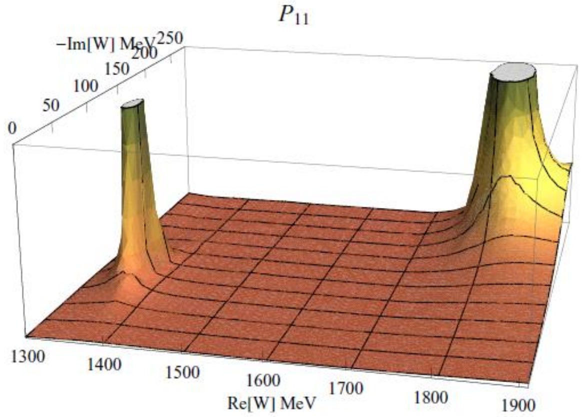
Two resonances mix with each other through Σ

(In our previous report PRC80 (2009), we presented MC by using $\bar{\Gamma}_{\gamma,1}$ at resonance energy)

Extract resonance properties from pole of amplitude

$$T_{\alpha,\beta}(W) = t^{nr}_{\alpha,\beta}(W) + \sum_{i,j} \bar{\Gamma}_{\alpha,i}(W)[\frac{1}{W - m_0 - \Sigma(W)}]_{ij} \bar{\Gamma}_{\beta,j}(W)$$
$$\sim \frac{\gamma_\alpha \gamma_\beta}{W - M + i\Gamma/2}$$

- Analytic continuation of T(W) on unphysical sheet by using contour deformation
- Pole can be found in the second term(non-resonant amplitude may have a pole)



Resonance Mass

(Single resonance case)

$$M - i\Gamma/2 = m_0 + \Sigma(M - i\Gamma/2)$$

Resonance Form Factor (complex number)

$$< N^*|j_{em}|N >= \frac{1}{\sqrt{1 - d\Sigma/dW}}\bar{\Gamma}(M - i\Gamma/2)$$

$$|N^* >= \frac{1}{\sqrt{1-d\Sigma/dW}}[1+G_0^+(1+t^{non-res})\Gamma]|N_0^* >$$

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models for meson production reactions

- JLSM model: B. Julia-Diaz et al. PRC76 (2007) (EBAC)

→ pion photo and electroproduction: B. Julia-Diaz PRC80(2009)

- tools to extract resonance information from the pole of amplitudes:

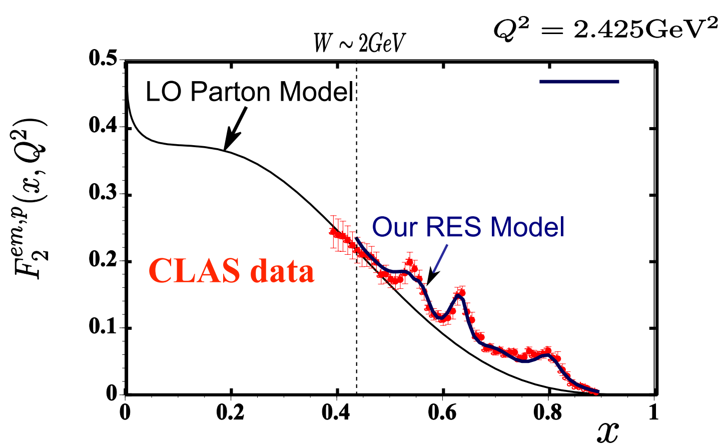
N.Suzuki et al. PRC79(2009),C82(2010)

- Grand fit model (Current): H.Kamano et al. PRC83(2013) (ANL-Osaka)

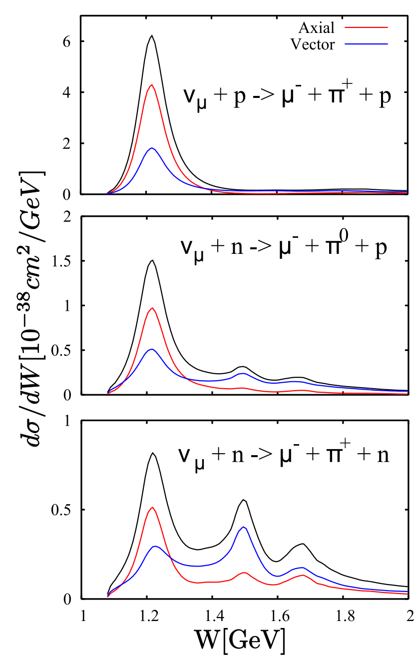
→ neutrino induced meson production reaction: S.Nakamura et al. PRC92 (2015)

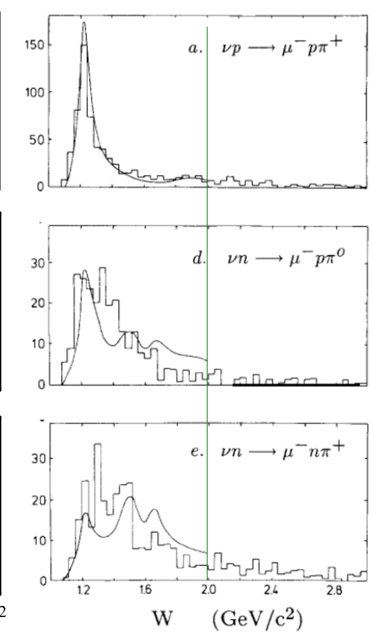
pion photoproduction on neutron: H.Kamano et al. PRC94(2016)

→ electron scattering (preliminary results)

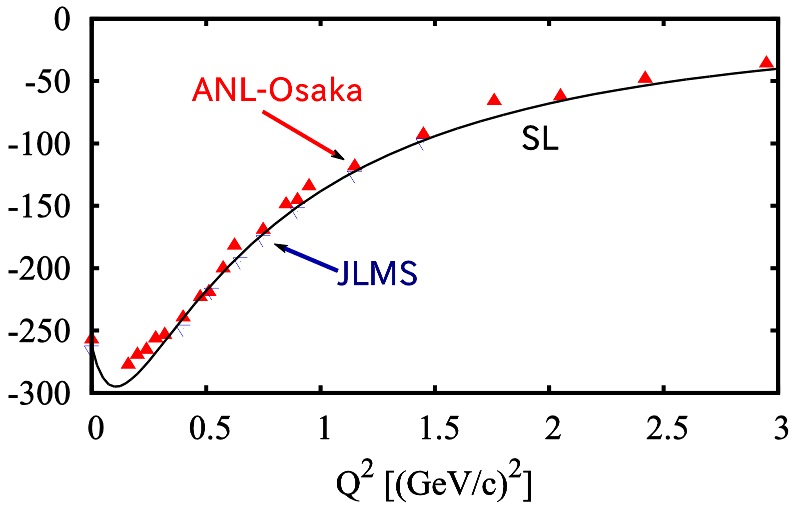


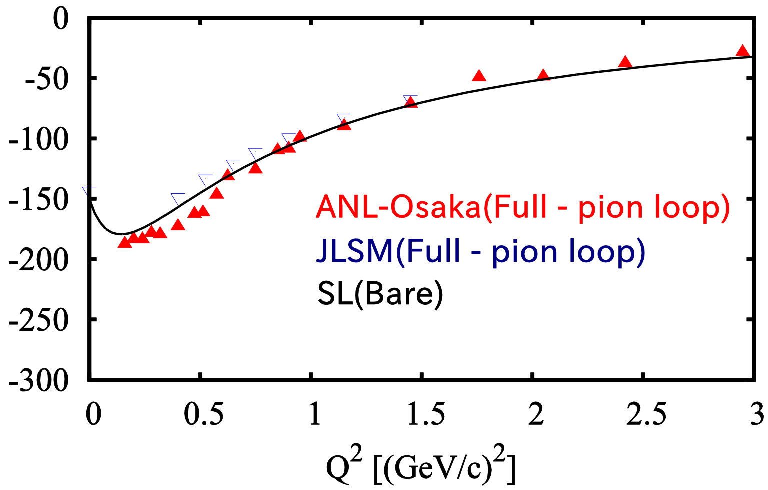
E_nu=40GeV,BEBC NP343, 285(1990)





Stability of extracted form factor of Delta(1232) Re(A_{3/2})

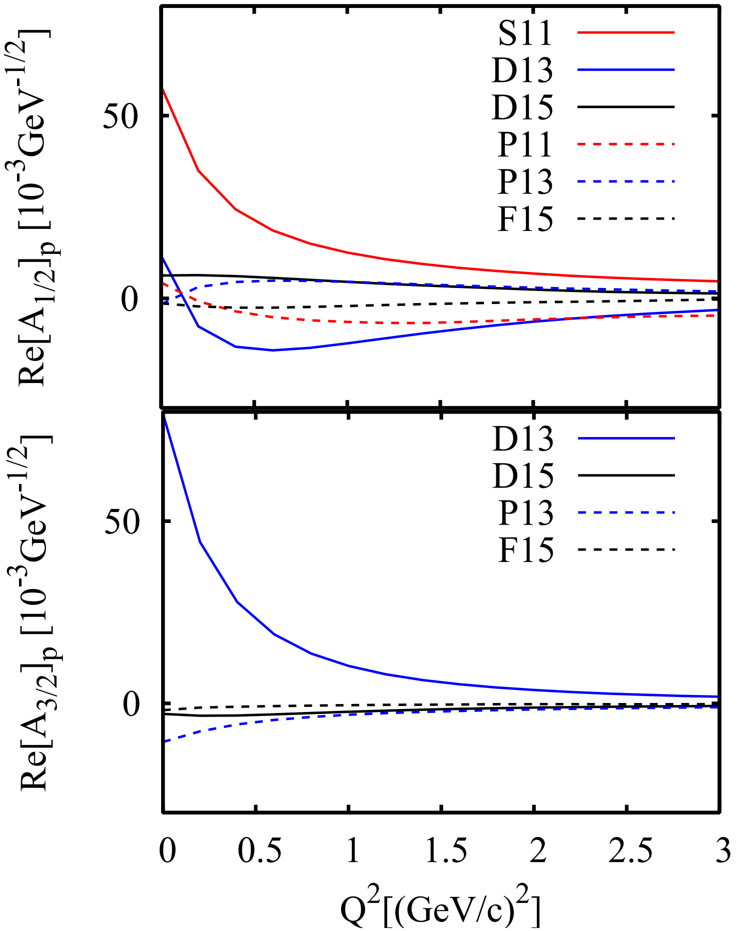




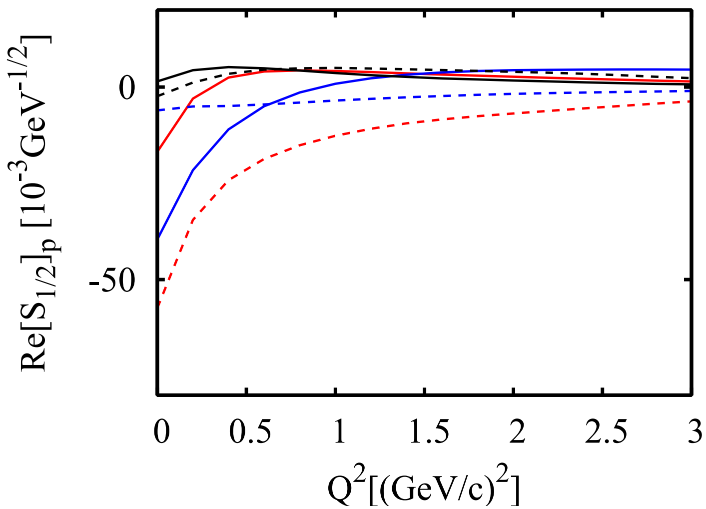
extracted A_{3/2}, pion loop contribution of three reaction models agree well

Multipole dependence of meson loop contribution (Preliminary)

Transverse form factor



Longitudinal form factor



N1520

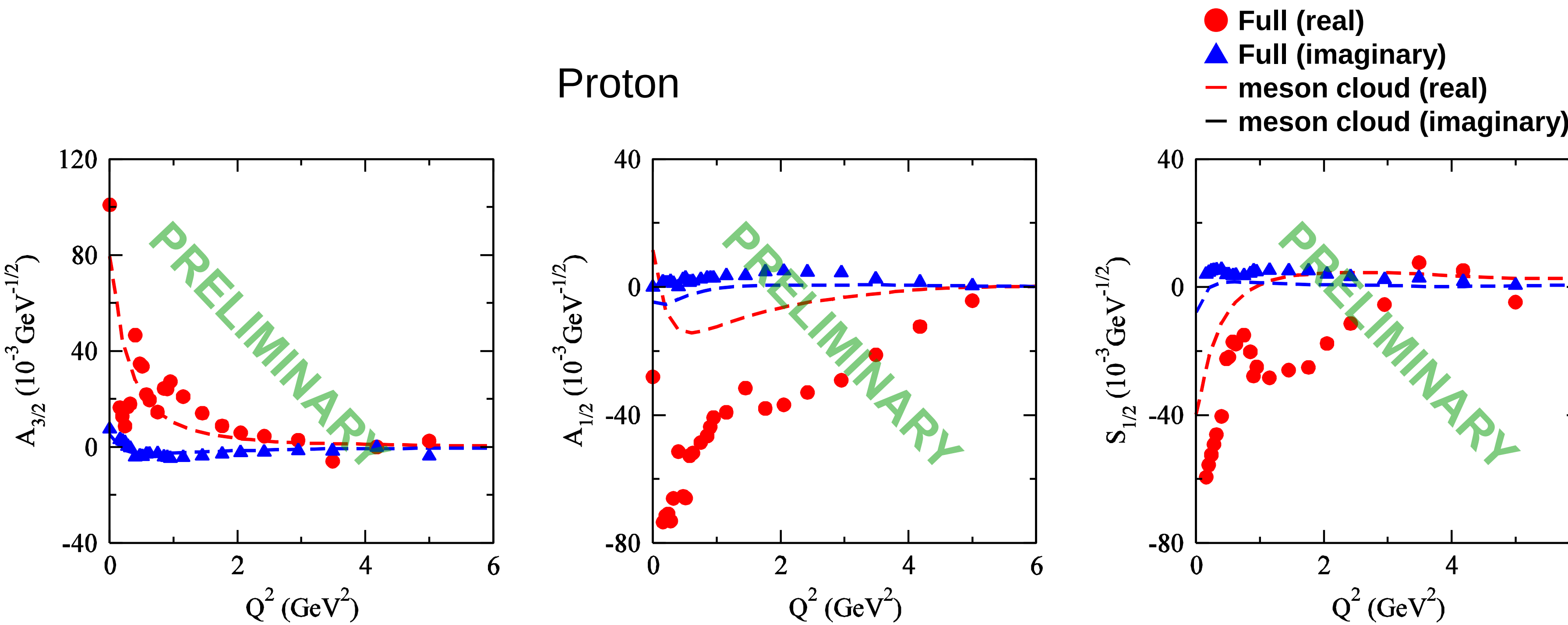
$$A_{3/2} = -\frac{\sqrt{3}}{2}[E_{2-} + M_{2-}]$$

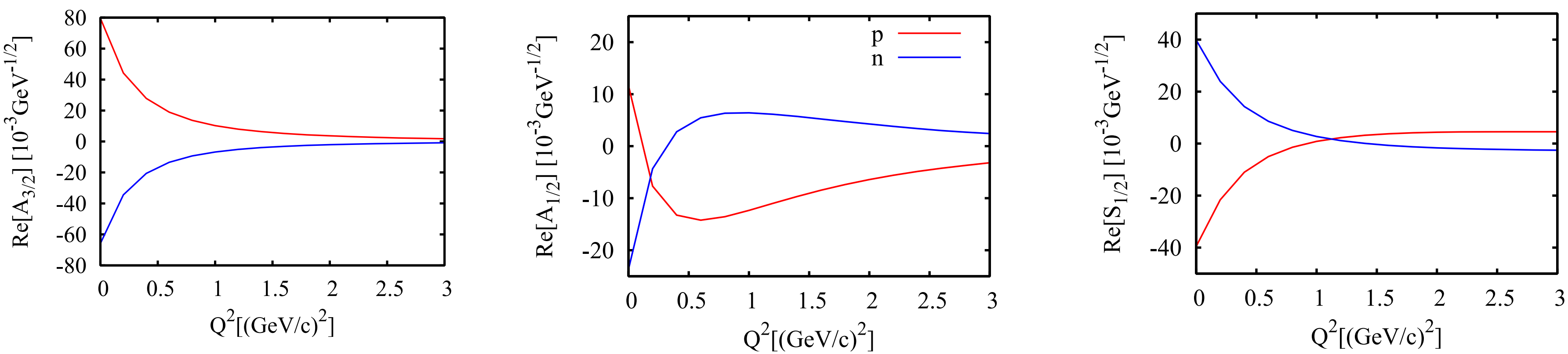
$$A_{1/2} = -\frac{1}{2}[E_{2-} - 3M_{2-}]$$

	T	L
S11(N1535 1/2-)	E1(E0+)	C1(S0+)
D13(N1520 3/2-)	E1(E2-),M2(M2-)	C1(S2-)
D15(N1675 5/2-)	E3(E2+),M2(M2+)	C3(S2+)
P11(N1440 1/2+)	M1(M1-)	C0(S1-)
P13(N1720 3/2+)	M1(M1+) ,E2(E1+)	C2(S1+)
F15(N1680 5/2+)	M3(M3-),E2(E3-)	C2(S3-)

larger meson loop for lower multipole

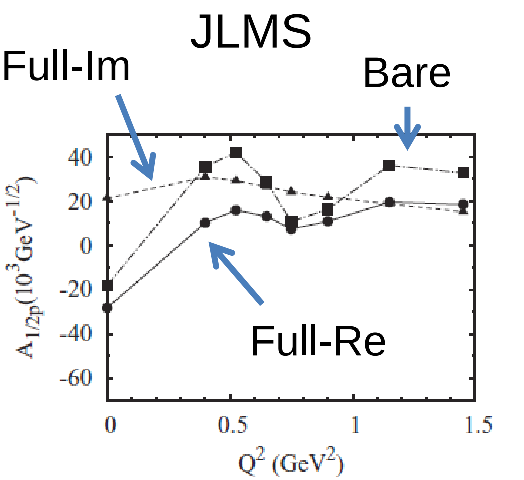
Iso-spin dependence of meson-loop N1520 3/2-





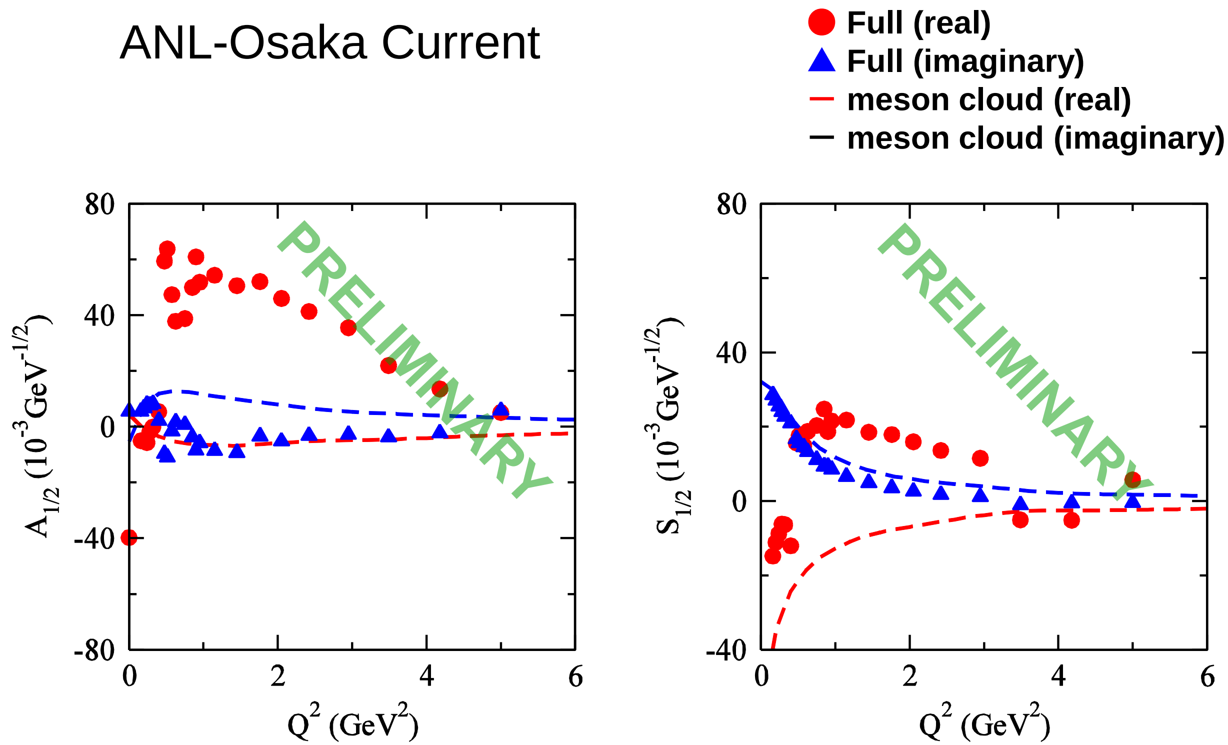
Meson-loop ~ iso-vector, interesting to study transition form factor of neutron

N1440 ½+ (proton)



Suzuki et al.PRC82 (2009)

ANL-Osaka Current



Total Helicity amplitude at Q^2=0

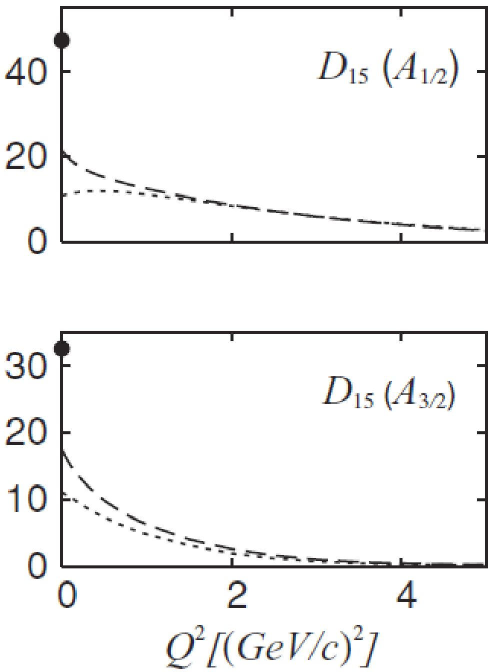
$$A_p^{1/2} = -40e^{-i8^o}(10^{-3}GeV^{-1/2})$$
$$A_n^{1/2} = 95e^{-i15^o}(10^{-3}GeV^{-1/2})$$

N1675 5/2-(proton)

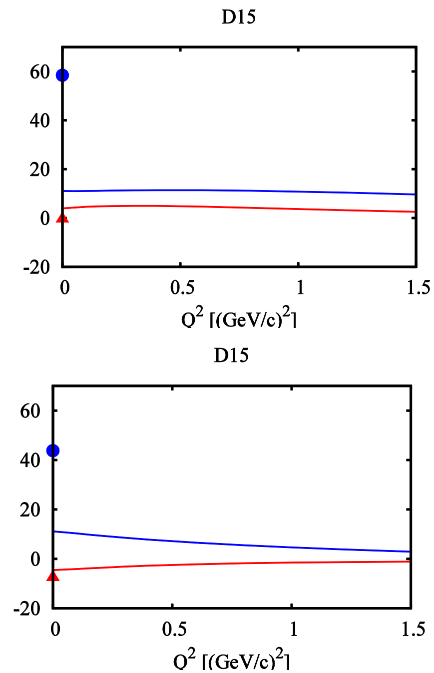
EBAC(JLMS)

ANL-Osaka Current

real W, not pole

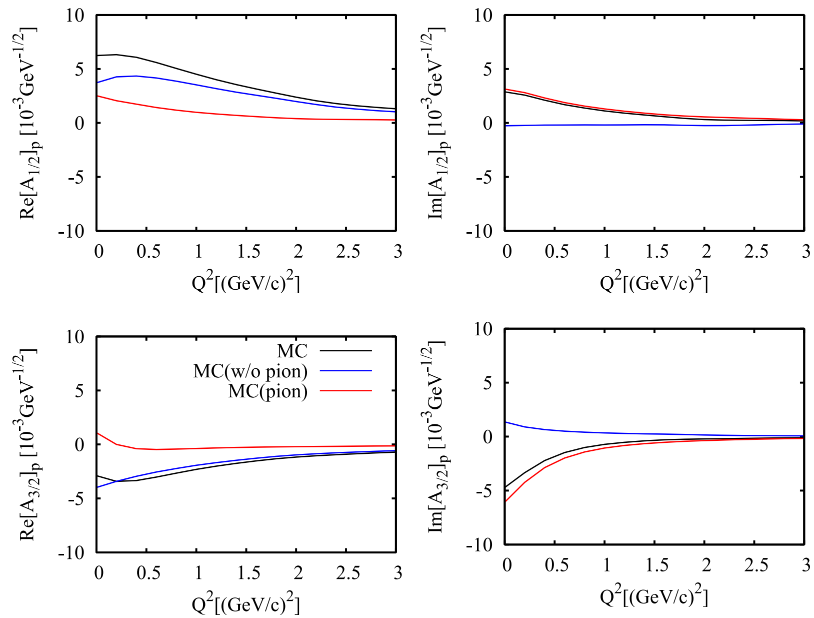


Pole



Re

Im



PRC77 (2008) B. Julia-Diaz et al.

$$A_{1/2p} = 8e^{i19^o} \qquad A_{3/2p} = 49e^{-i12^o}$$

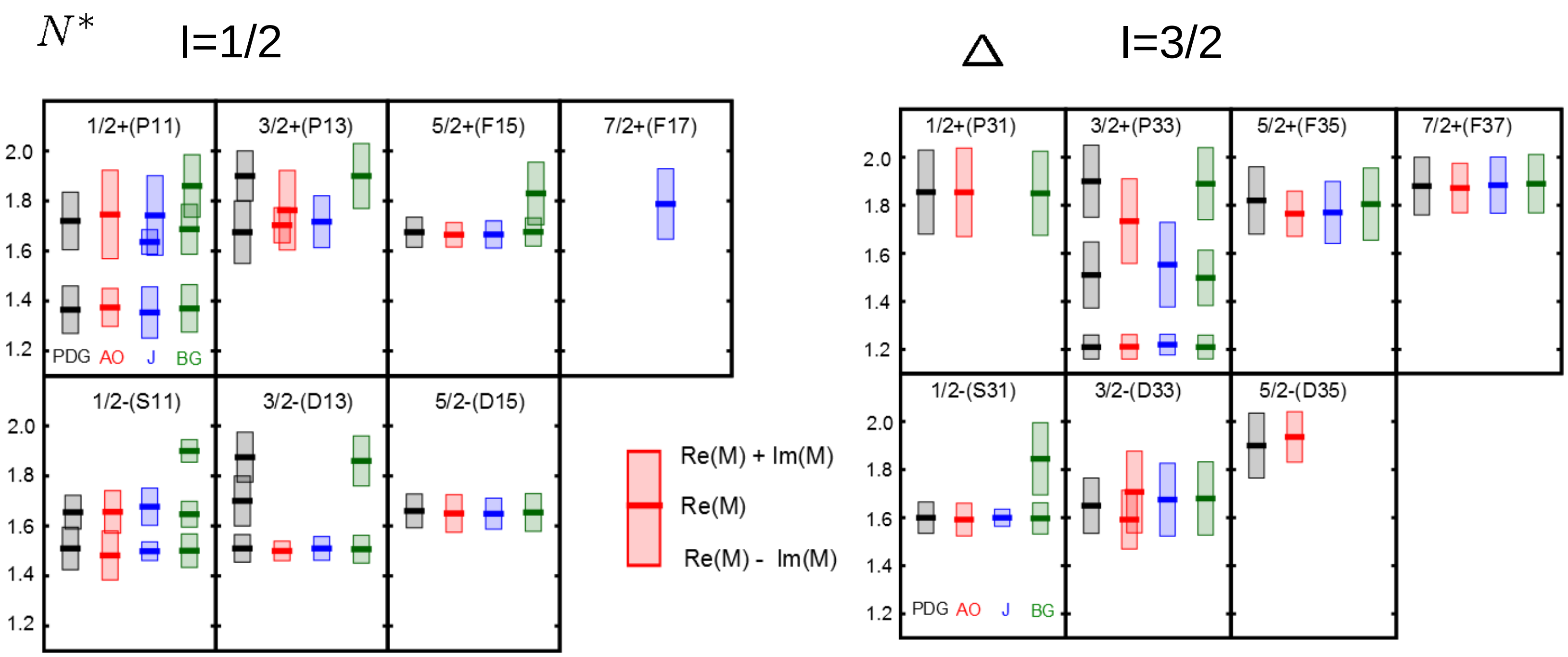
$$A_{1/2n} = -76e^{i3^o} \qquad A_{3/2n} = -38e^{-i4^o}$$

Summary

- We have investigated within a dynamical coupled channel model of pi-N and gamma-N reactions up to 2GeV
- The meson baryon channels included in calculations are
  $\gamma N\ \pi N,\ \eta N,\ K\Lambda,\ K\Sigma\ \ \pi\pi N$ ($\pi\Delta,\ \rho N$ and σN)
- Pole positions and residues(coupling constants of N*) are extracted by analytic continuation of the amplitudes.
- Qualitative feature of Meson loop effects: Q^2 dependence, multipole dep., iso-spin dep.

Spectrum of nucleon resonances: pole of amplitude

Re(M) < 2GeV ,Width < 0.4GeV, (AO only poles on the nearest sheet)



AO: Argonne-Osaka

J: Julich (model A: dynamical reaction model)
EPJA(2013)**49**,44 D. Ronchen et al.

BG: Bonn-Gachina(K-matrix approach)
EPJ A(2012)**48**,15 A.V.Anisovich et al.

PDG: 2012 3*, 4*

- AO agree with PDG for W<2GeV(3*,4*) except
  no 3rd P33,D13, additional 2nd D33, 2nd S31
- Pole positions of AO,Julich,Bonn-Gachina agree well only for the first N*

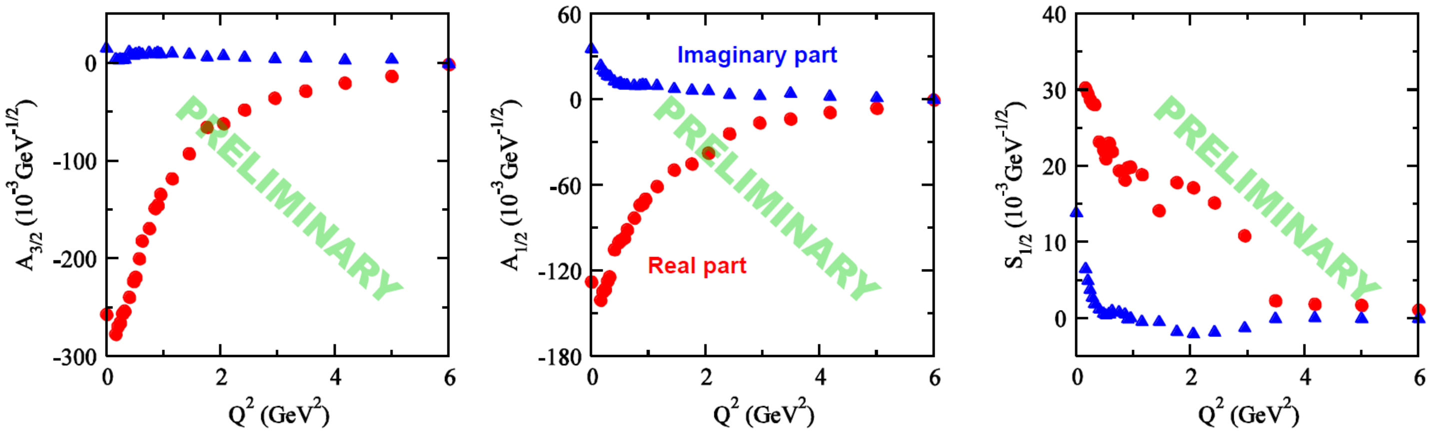
Transition form factor of N* and Delta

$$< \Delta | j_{em}(q) | N >$$

Residue of helicity amplitude at resonance pole: complex number

form factors are determined at each Q^2

$\gamma^{(*)} p \rightarrow \Delta(1232)3/2^+$



$\gamma^{(*)} p \rightarrow N(1440)1/2^+$