Electroweak Meson Production Reaction in the Nucleon Resonance Region

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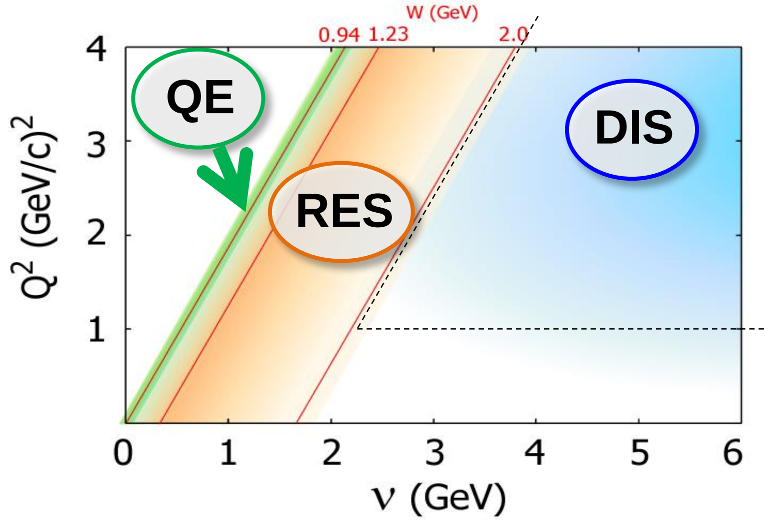
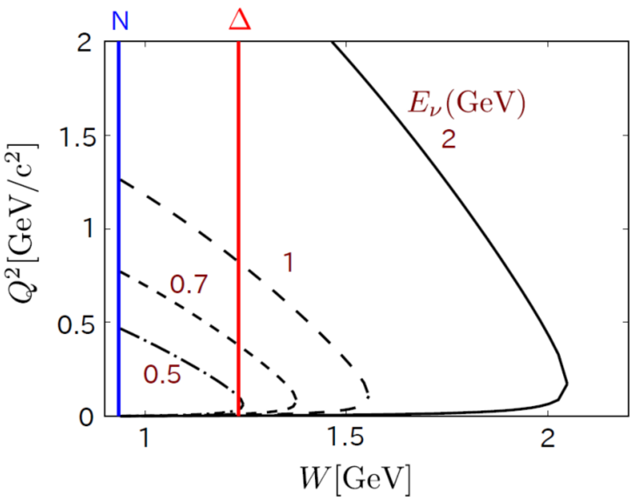
Nov. 2016 EILH-2016, Aligarh

Toward a precise description of neutrino-nucleon reaction in the resonance region





Resonance region:
W< 2GeV

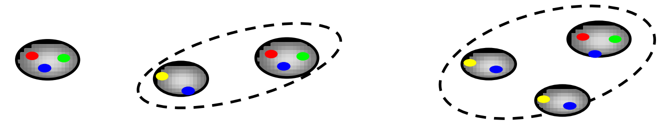
$$\pi N, \eta N, K\Lambda, K\Sigma, \pi\pi N, \omega N$$

Physics of excited baryon:

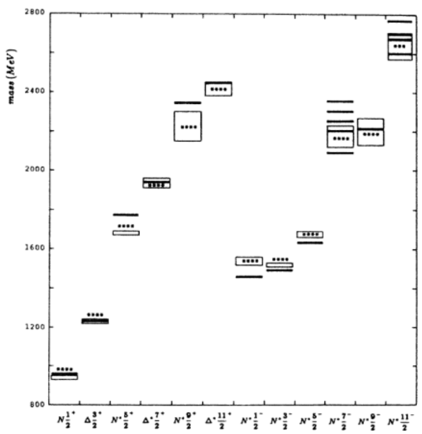
baryon spectrum studies with pion, photon, electron induced reaction

Baryon excited states

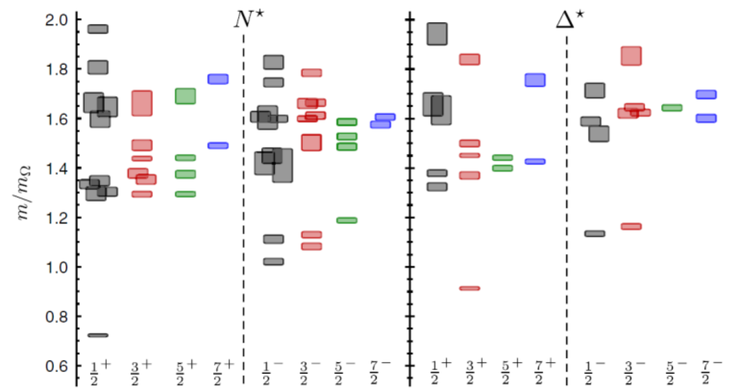
How quark-gluon dynamics or meson-baryon dynamics build hadron excited states



excited baryons are predicted from quark model,… LQCD



S. Capstic, N. Isgur PRD84(1984)



R. Edwards, et al. PRD84(2011)

‘stable’ particles, in reality resonance in continuum

Objective of reaction study:

extract resonance information by analyzing meson production reaction

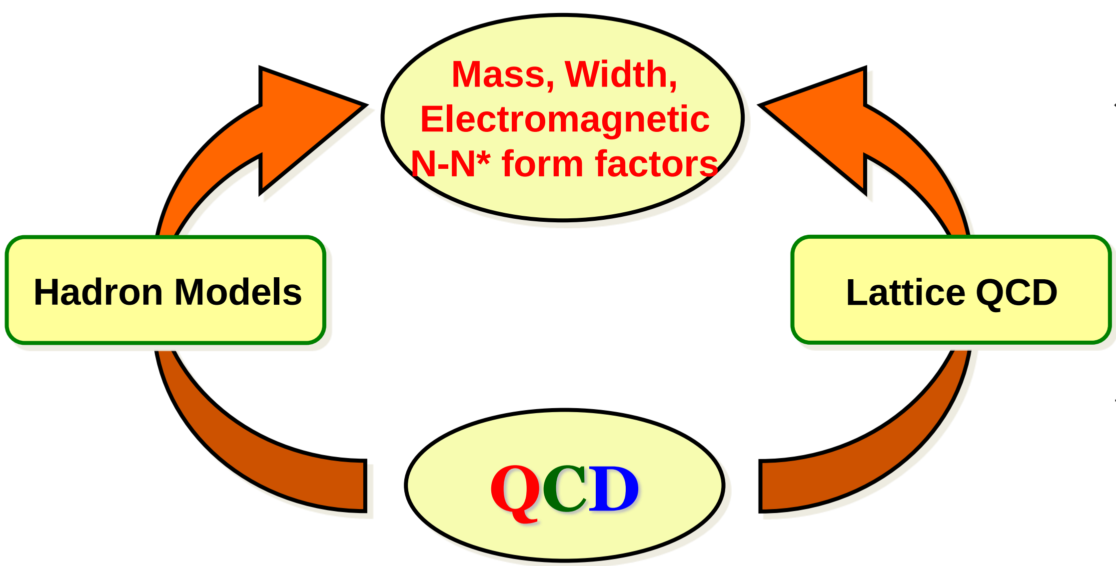
entanglement of reaction dynamics and structure of excited hadrons

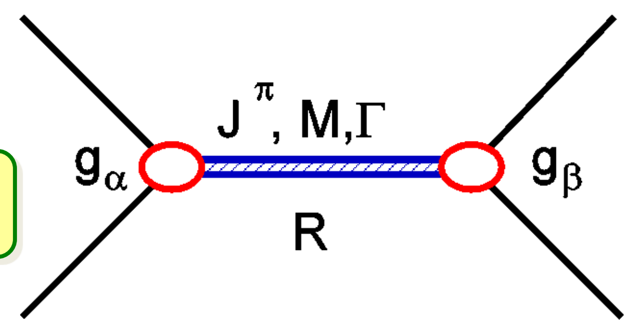
Reaction Data

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

past decade,
high precision data from
Jlab,MAMI, ELSA,
GRALL, LEPS

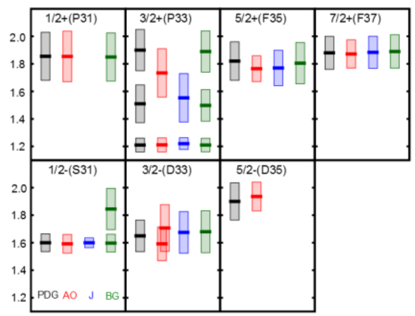
- Analysis of meson production reaction with Dynamical Coupled-Channels approach
- Extraction of resonance spectrum(Mass, width and transition form factor)
- Role of reaction dynamics on the properties of excited states

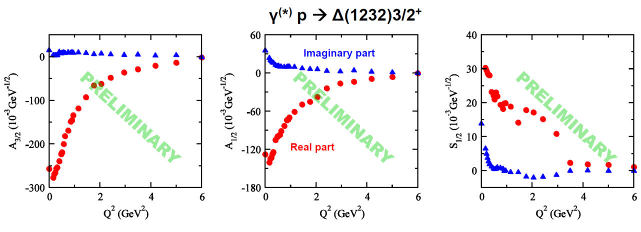




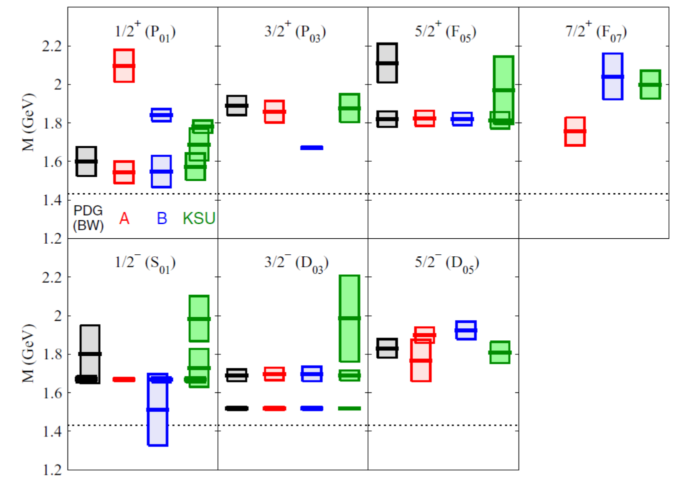
Application of dynamical coupled-channel reaction model

Spectrum and form factor of N* Delta



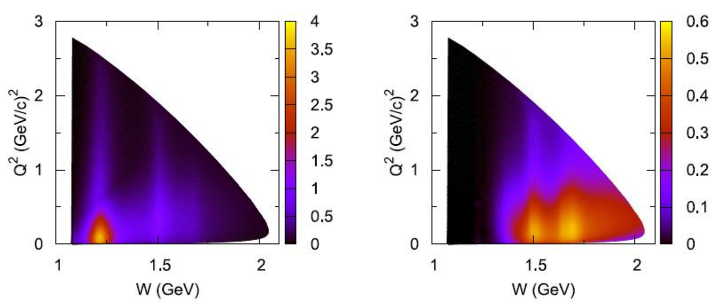


Spectrum of Y* Sigma*

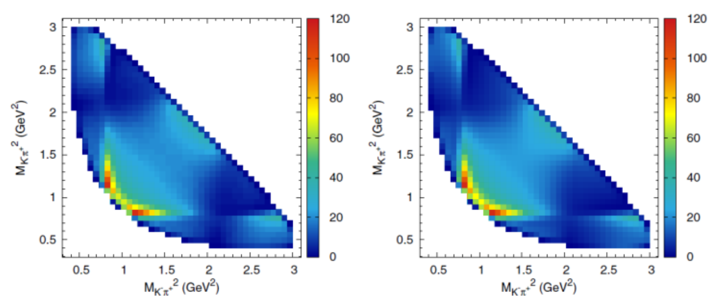


Neutrino induced meson production reaction

$\nu_\mu N \to \mu^- \pi N$ $\nu_\mu N \to \mu^- \pi \pi N$



meson decay and production



Reaction model for electroweak meson production

- Electromagnetic Delta(1232) excitation
- Higher resonance region
- N* spectrum

N-Delta transition form factor and dynamical model of pion production

Nucleon(P11,940) → Delta(P33,1232)

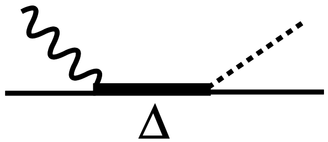
Delta(1232): isolated resonance, decay almost 100% to piN :

$< \Delta | J^{\mu}_{em} | N >$: M1 (spin-isospin flip) C2, E2 (possible deformation)

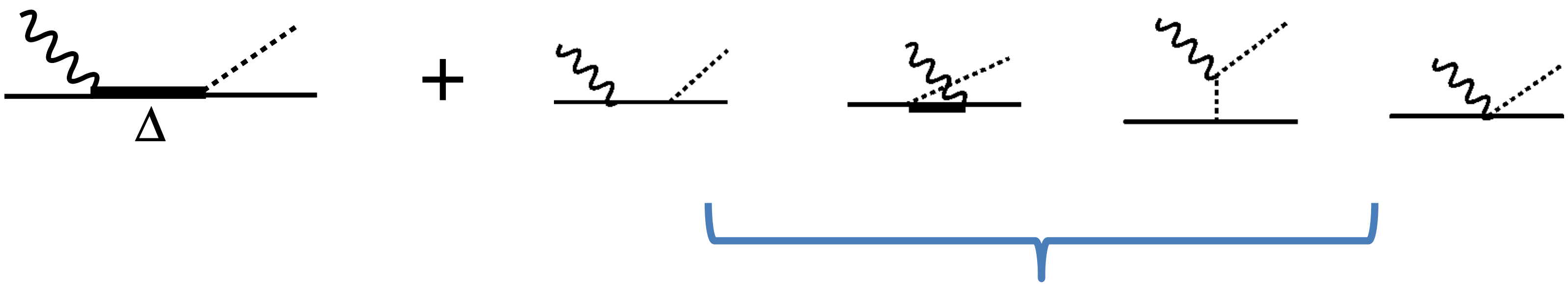
$< \Delta | V^{\mu} - A^{\mu} | N >$: Axial vector coupling (PCAC and ChiPT, LQCD) for N-Delta

Reaction model for pion photo/electro production and pion-nucleon scattering

Resonance dominance : Breit-Wigner form



add non-resonant mechanisms: Isobar Model



Born diagrams (based on chiral Lagrangian)

Unitarity: below 2pion production $T^{\alpha}_{\gamma\pi} = |T^{\alpha}_{\gamma\pi}| e^{i\delta^{\alpha}_{\pi N}}$

Pion photo and electroproduction

K-matrix approach:

Bonn-Gatchina, VPI, Jlab-Yerevan,MAID, Kent state, Giessen,

Dynamical model (solve Lippman-Schwinger equation):

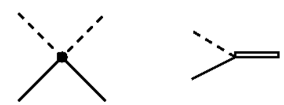
Our approach(ANL-Osaka), Julich-George Washington, Dubna-Mainz-Taipei,…

Olssen's method: L. Alvarez et al.

Dynamical model of pion electromagnetic production

(Sato-Lee 1996(gamma-pi),2001(e,e'), 2003(neutrino))

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



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

$v_{\pi N,MB}$ Non-resonant interaction from t,u,s-channel meson and baryon exchange mechanism

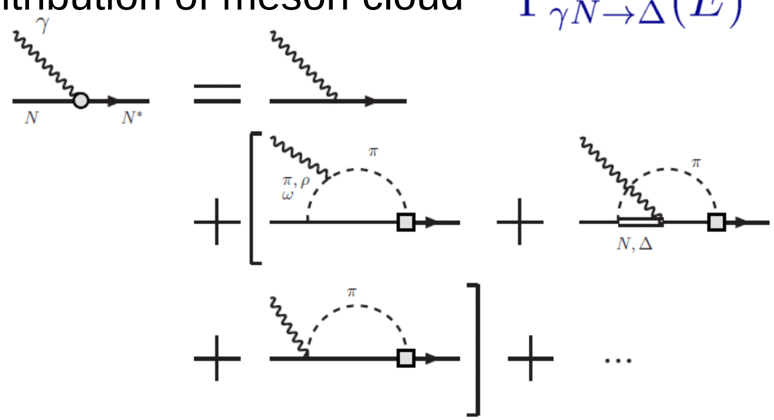
Solve Lippmann-Schwinger equation

$$T_{\gamma\pi}(E) = t_{\gamma\pi}(E) + \frac{\bar{\Gamma}_{\Delta\to\pi N}(E)\bar{\Gamma}_{\gamma N\to\Delta}(E)}{E - m^0_\Delta - \Sigma_\Delta(E)}$$

$$\to \frac{g_\pi g_\gamma}{E - M + i\Gamma/2}$$ at Pole

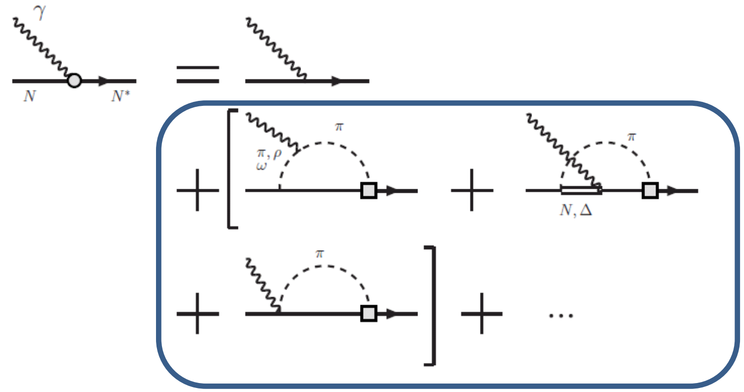
Non-trivial contribution of meson cloud

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

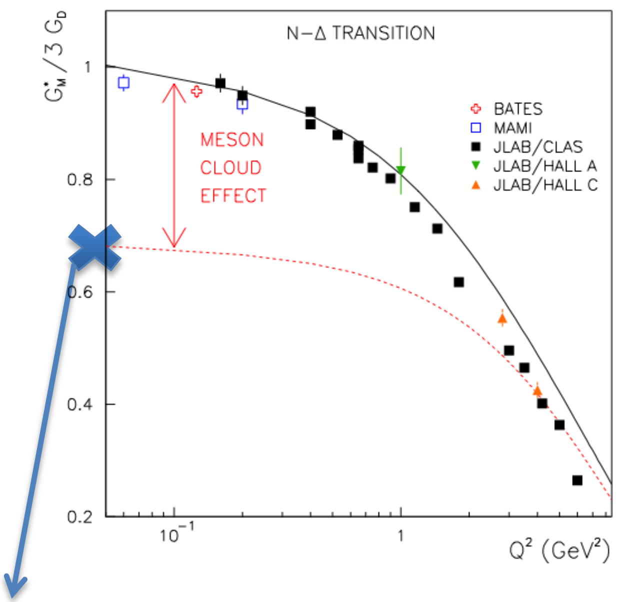


Core + Meson Cloud

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

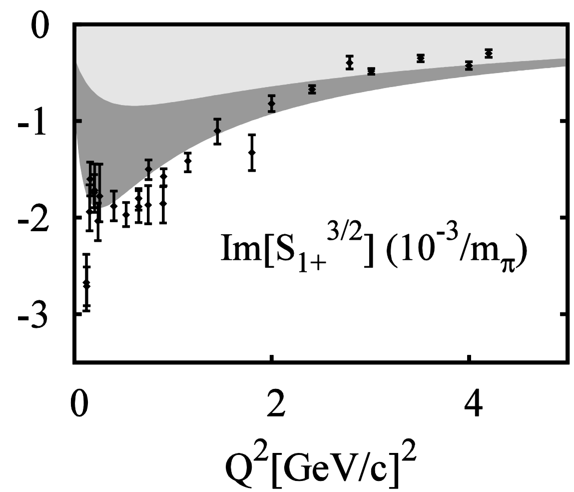


M1: Magnetic dipole



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

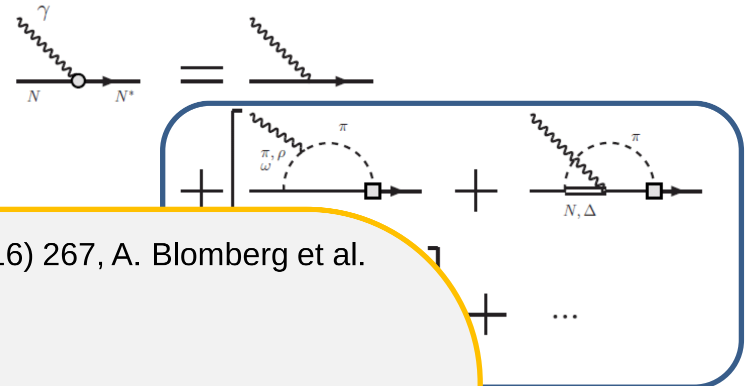
C2: Coulomb quadrupole



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

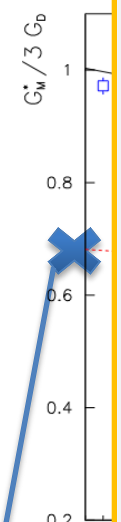
Sato, Lee 96,01

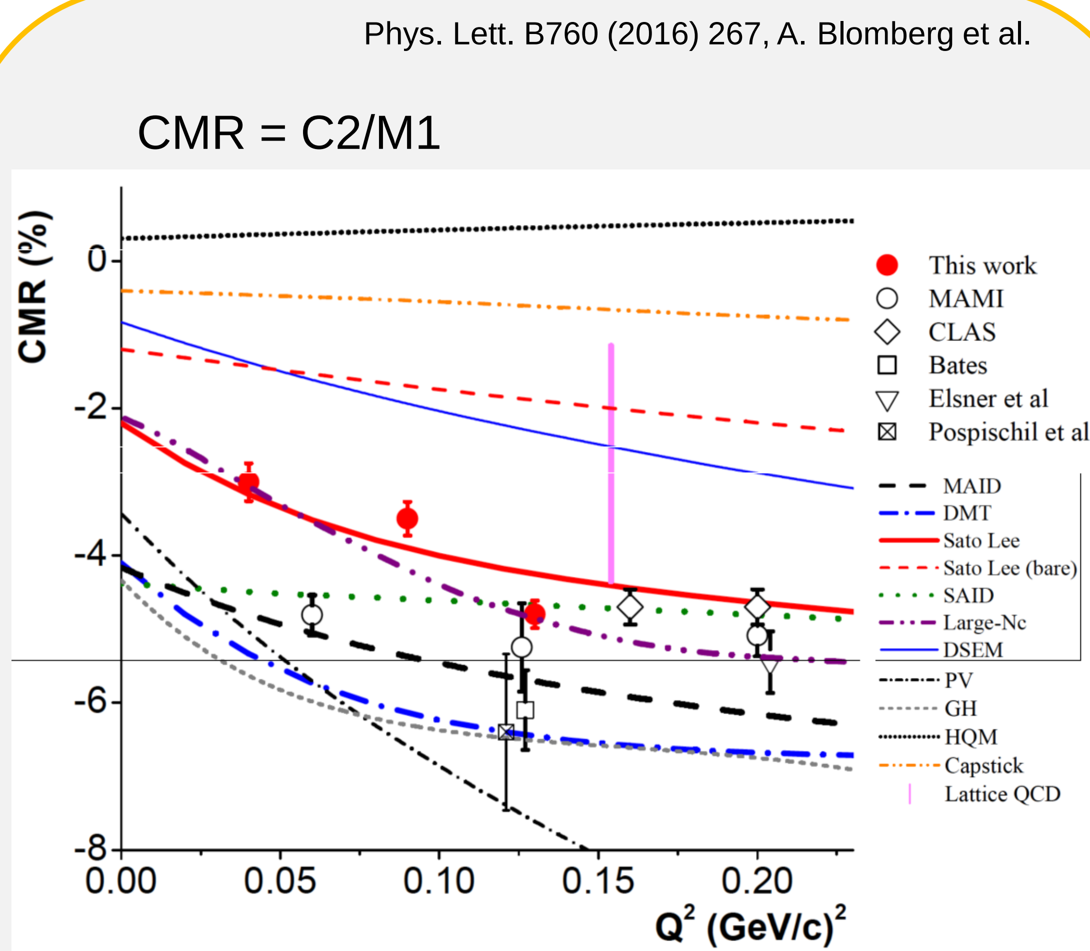
γ N → Δ (1232)
(role of reaction dynamics)

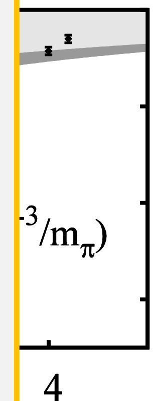


M1:

drupole







Note:
Most of t
hadron m
close to "B

rom pion
eV^2

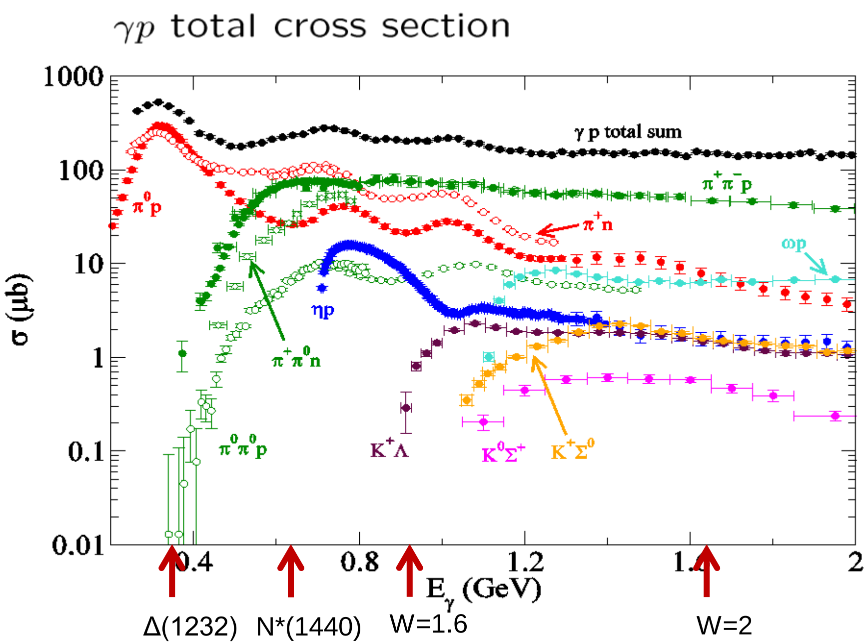
Sato, Lee 96,01

Higher mass resonances N*,Delta

Overlapping resonances, large width

Many meson-baryon channels open

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



→ Coupled channel approach with 2+3(pipiN) unitarity

extended formalism, heavy numerical task to describe data

Number of data points of hadronic processes in addition to pi-N amplitude

	$d\sigma/d\Omega$	P	β	Sum
$\pi^- p \to \eta p$	294	–	–	294
$\pi^- p \to K^0\Lambda$	544	262	43	849
$\pi^- p \to K^0\Sigma^0$	160	70	–	230
$\pi^+ p \to K^+\Sigma^+$	552	312	7	871
Sum	1550	644	50	2244

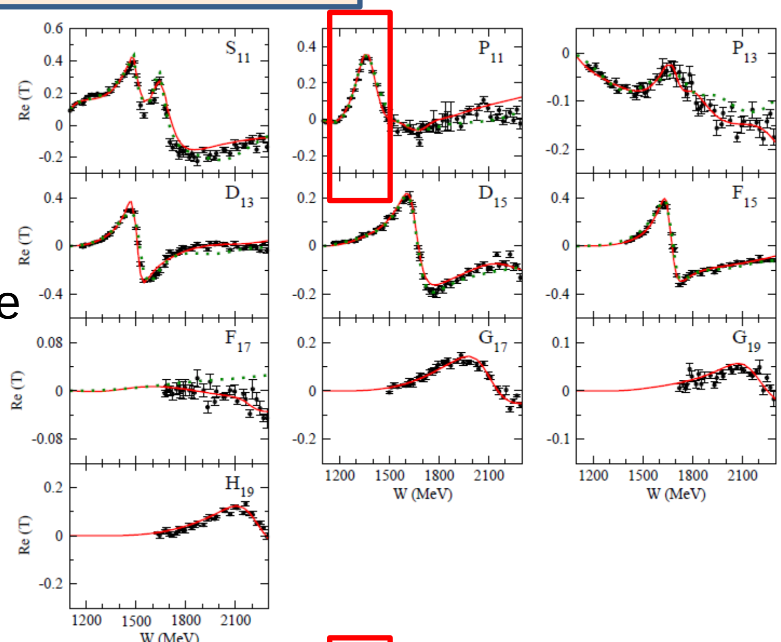
Number of data points of photoproduction processes

	$d\sigma/d\Omega$	Σ	T	P	$\hat{E}$	G	H	$O_{x'}$	$O_{z'}$	C_x	C_z	Sum
$\gamma p \to \pi^0 p$	4381	1128	380	589	140	125	49	7	7	–	–	6806
$\gamma p \to \pi^+ n$	2315	747	678	222	231	86	128	–	–	–	–	4407
$\gamma p \to \eta p$	3221	235	50	–	–	–	–	–	–	–	–	3506
$\gamma p \to K^+\Lambda$	800	86	66	865	–	–	–	66	66	79	79	2107
$\gamma p \to K^+\Sigma^0$	758	62	–	169	–	–	–	–	–	40	40	1069
$\gamma p \to K^0\Sigma^+$	220	15	–	36	–	–	–	–	–	–	–	271
Sum	11695	2273	1174	1881	371	211	177	73	73	119	119	18166

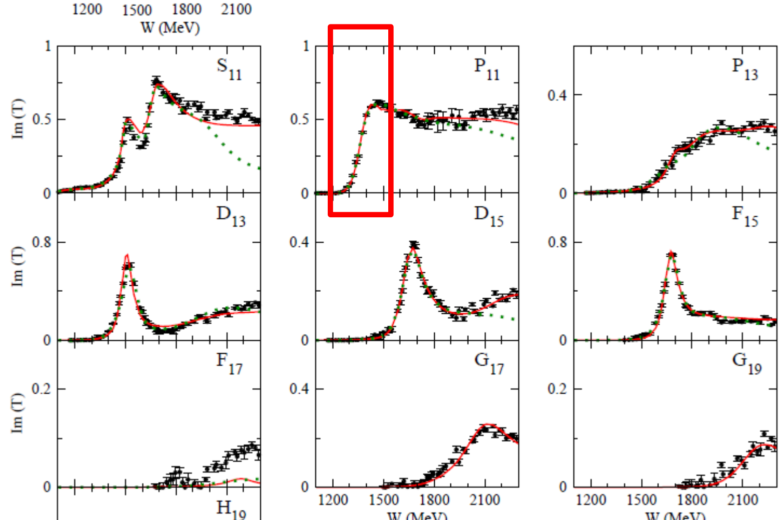
πN amplitude

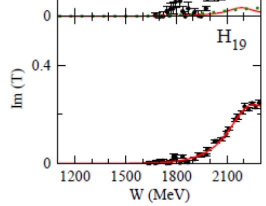
I=1/2

Re

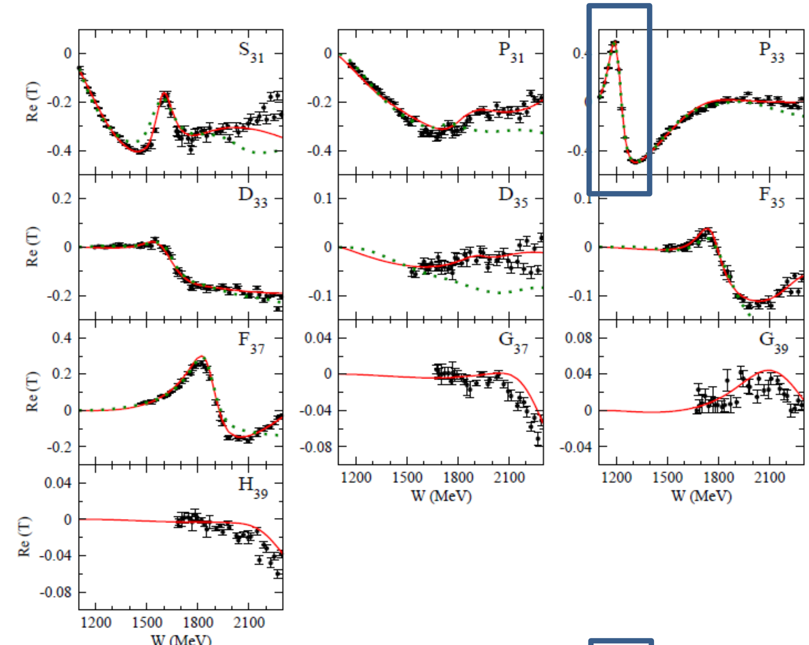


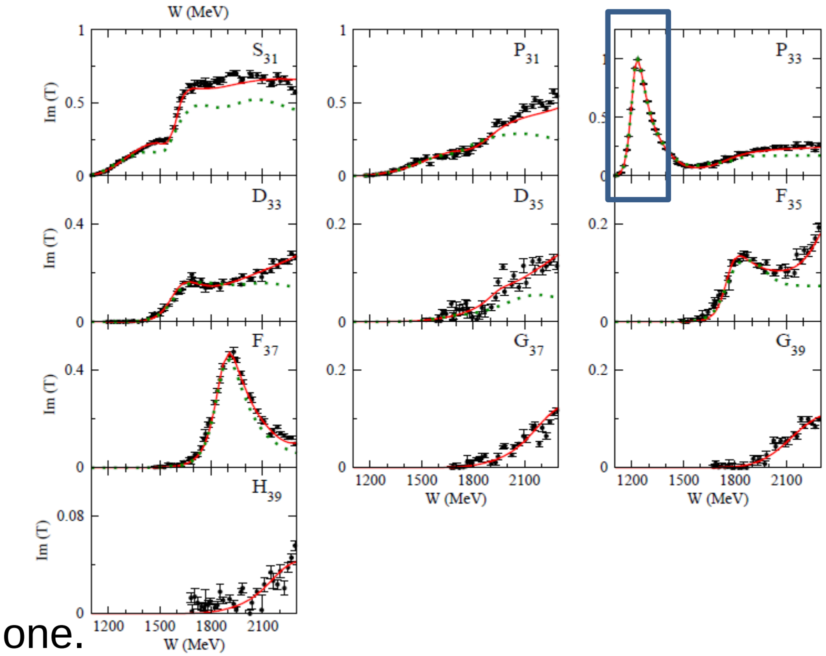
Im





I=3/2

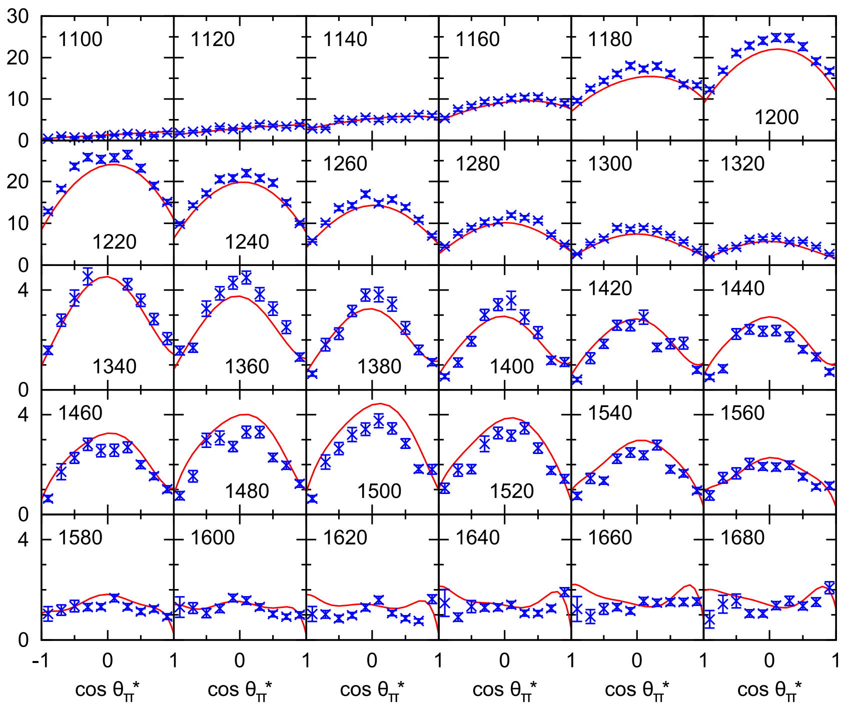


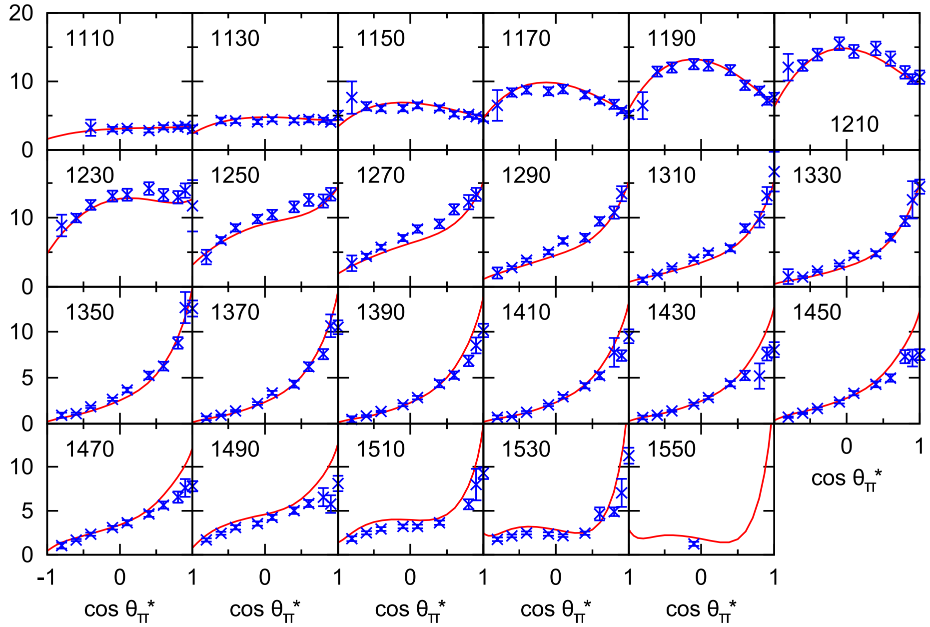


- Improvement for S31,P31,D35
- Direct comparison with obs. was done.

W-dependence of pion angular distributions at Q^2=0.4GeV^2

$$p(e,e'\pi^0)p \qquad \frac{d\sigma_T}{d\Omega}+\epsilon\frac{d\sigma_L}{d\Omega} \qquad p(e,e'\pi^+)n$$



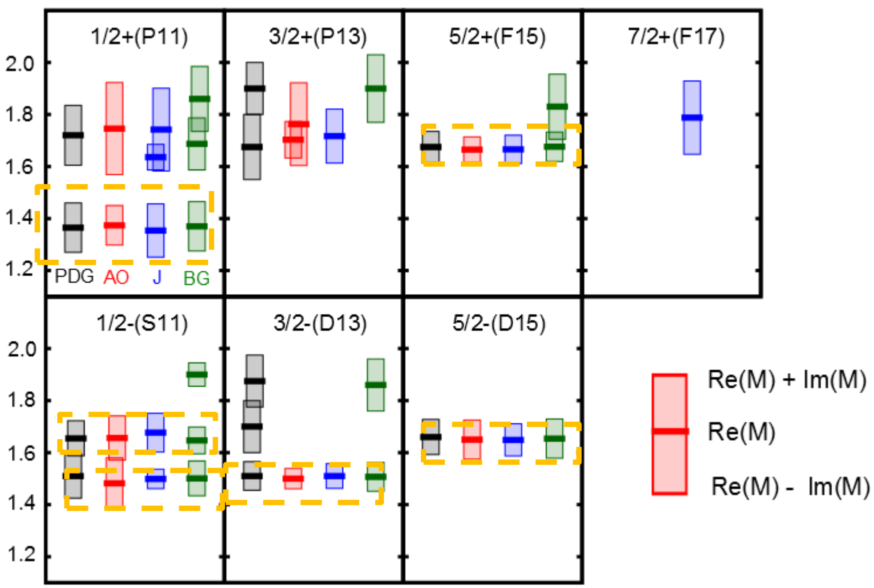


Comparison with CLAS data

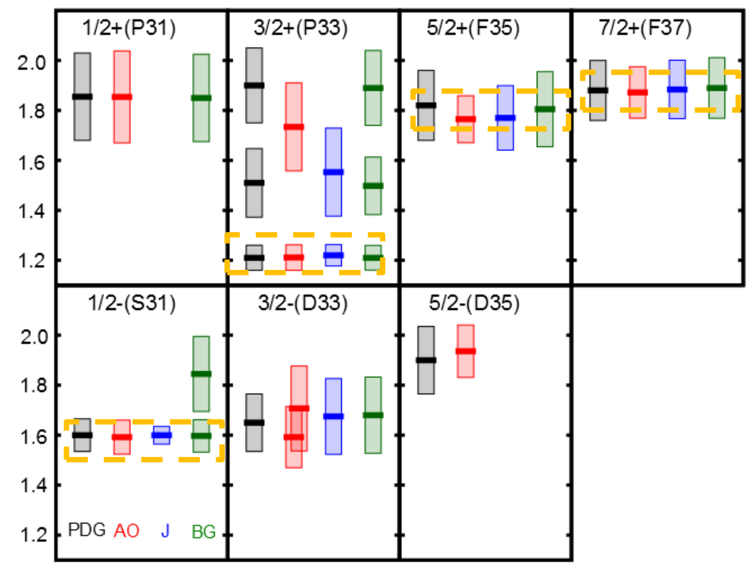
Spectrum of nucleon resonances: pole of amplitude

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

N^* I=1/2



△ I=3/2



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*

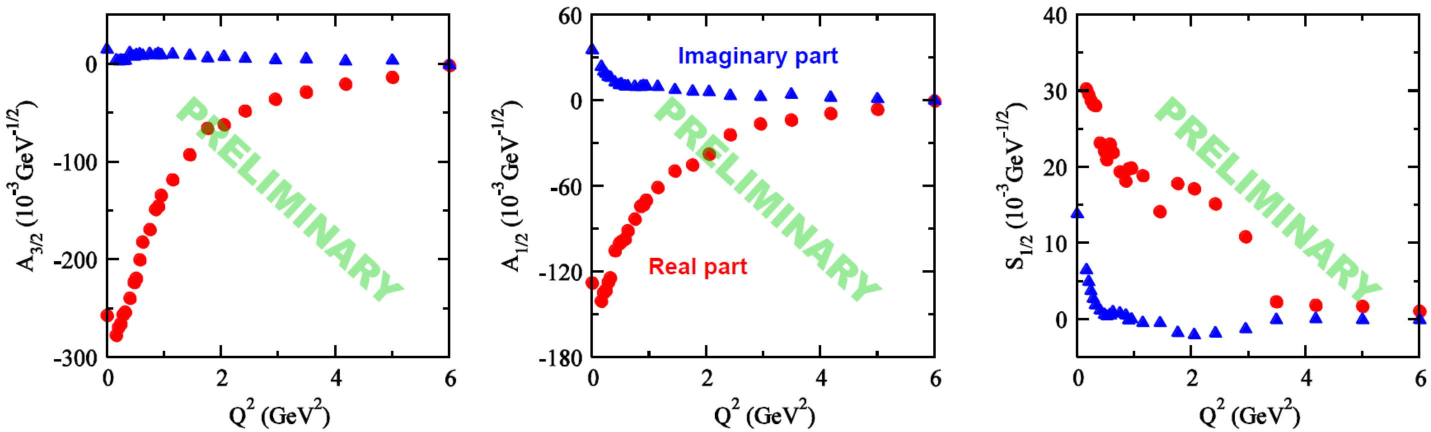
Transition form factor of N* and Delta

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

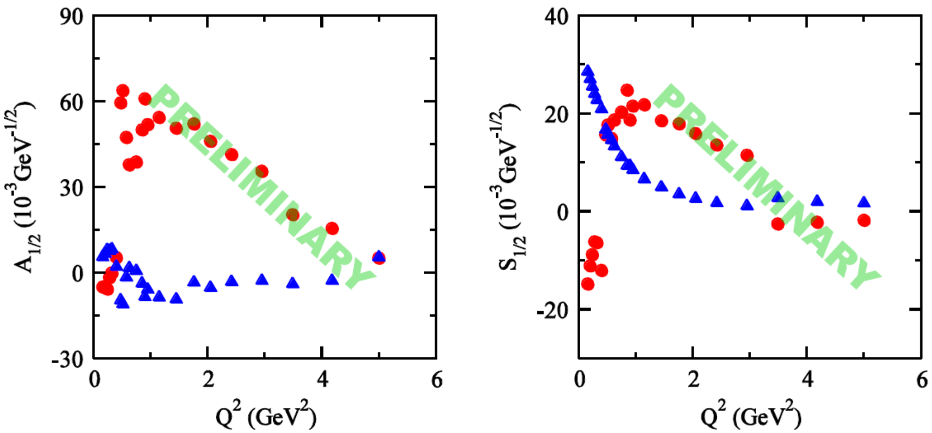
Residue of helicity amplitude at resonance pole: complex number

form factors are determined at Q^2 of the data

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



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

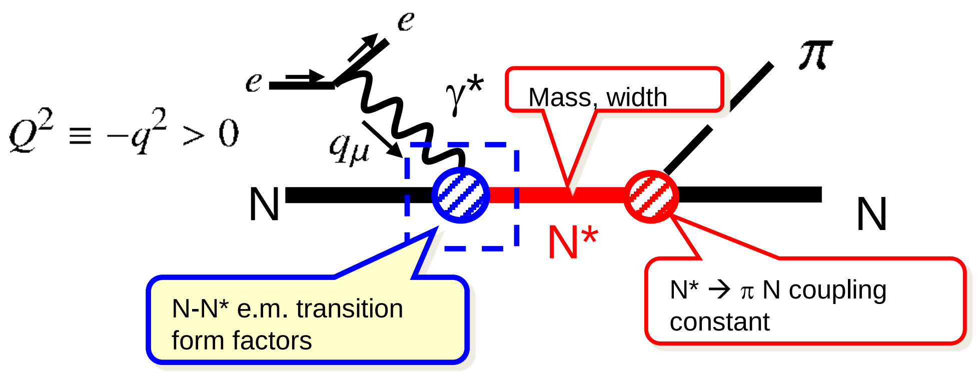


Neutrino induced meson production reaction

Dynamical model for Neutrino-nucleon interaction in the resonance region

construct DCC model from Delta up to W < 2GeV (DIS: W>2GeV, $Q^2 > 1\sim 2GeV^2$)

- nu-Nucleus reaction of GeV neutrino
- axial vector response of nucleon(NN* transition axial vector coupling.)

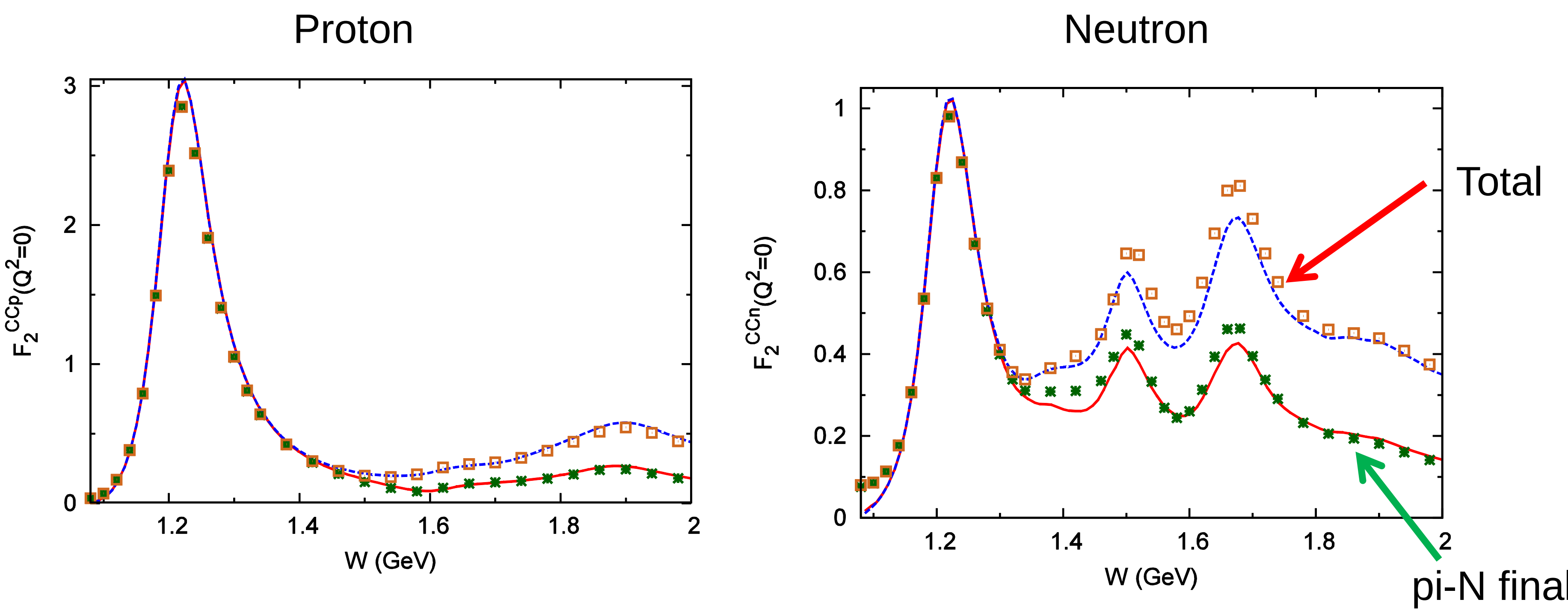


Extension for neutrino reaction

- Vector current: isospin-decomposition for CC,NC (neutron PRC94 015201(16))
  finite Q2 (electron scattering data)
- Axial vector current : PCAC $g_{\pi NN^*} \to g_{ANN^*}$,
  assume dipole form factor for Q^2 dependence

inclusive cross section structure function CC F_2 at $Q^2=0$

only Axial vector contributes, using PCAC $F_2 = \frac{2f_\pi^2}{\pi}\sigma(\text{virtual}\pi + N)$

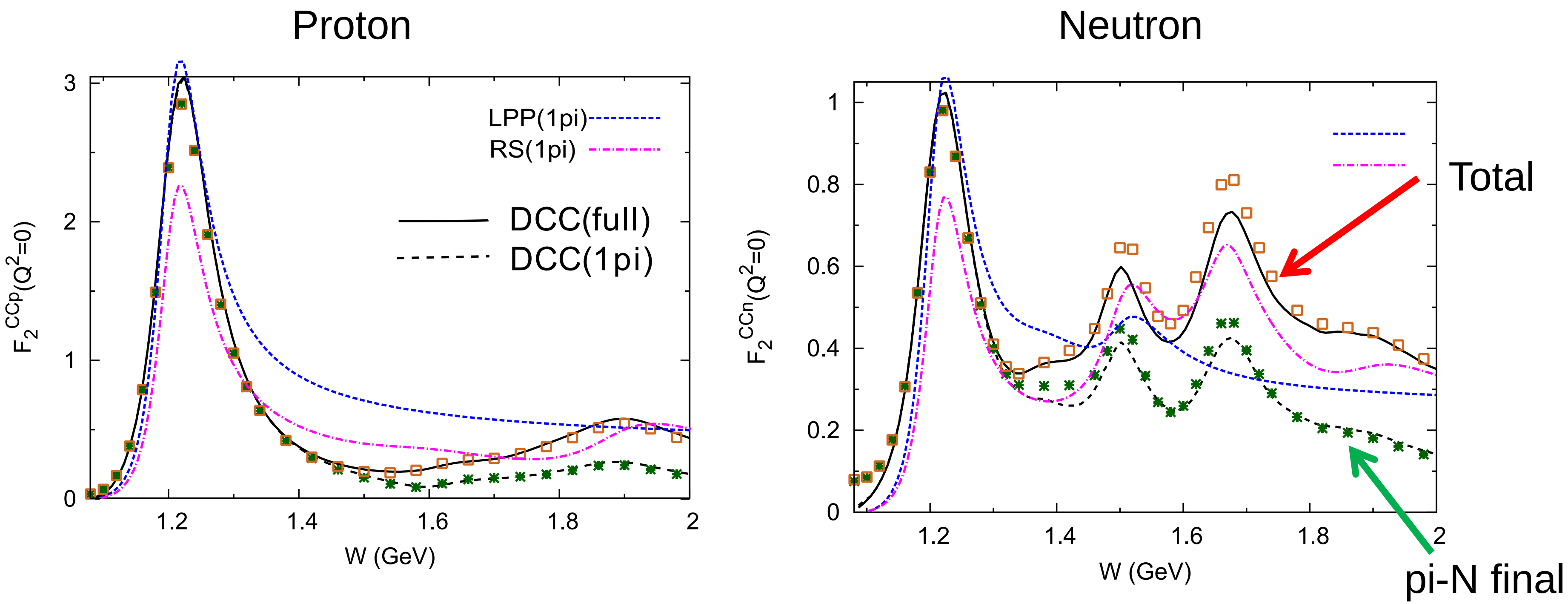


Charge current neutrino reaction
proton : Δ_{33} dominance
neutron : W>1.3GeV non-resonant and other resonance start to
contribute, appreciable contribution of two pion production.

inclusive cross section

structure function CC F_2 at $Q^2=0$

only Axial vector contributes, using PCAC $$F_2 = \frac{2f_\pi^2}{\pi}\sigma(\text{virtual}\pi + N)$$



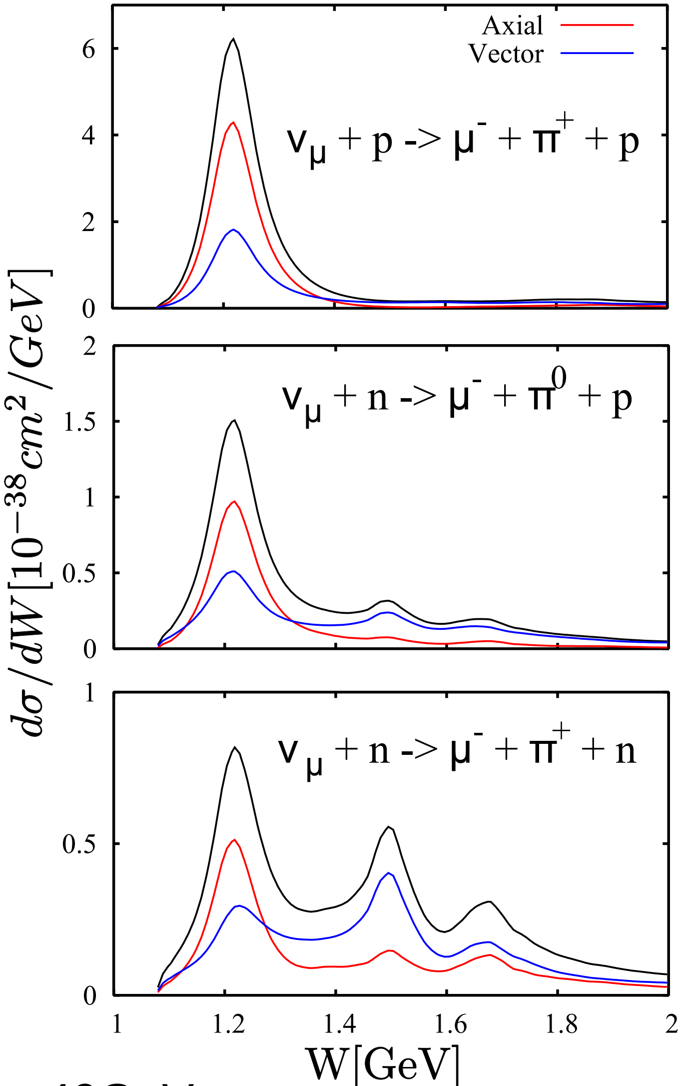
Charge current neutrino reaction

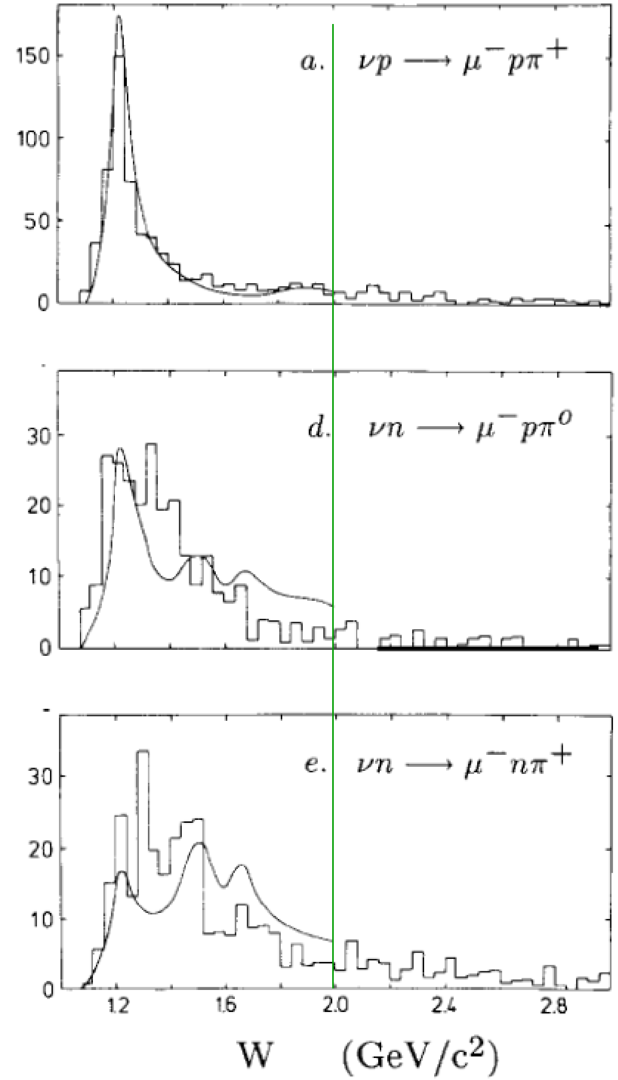
proton : Δ_{33} dominance

neutron : W>1.3GeV non-resonant and other resonance start to contribute, appreciable contribution of two pion production.

Compare DCC with Rein-Sehgal and Lalakulich Paschos, Piranishvili models ‘excitation function’ can be tested by ds/dW

single pion production data : ds/dW

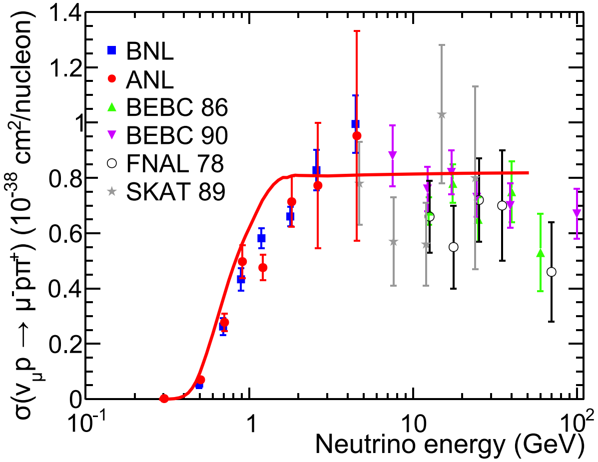




E_nu=40GeV

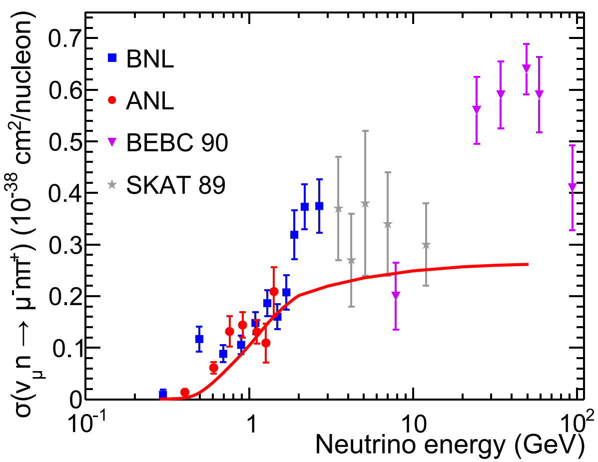
BEBC NP343, 285(1990)

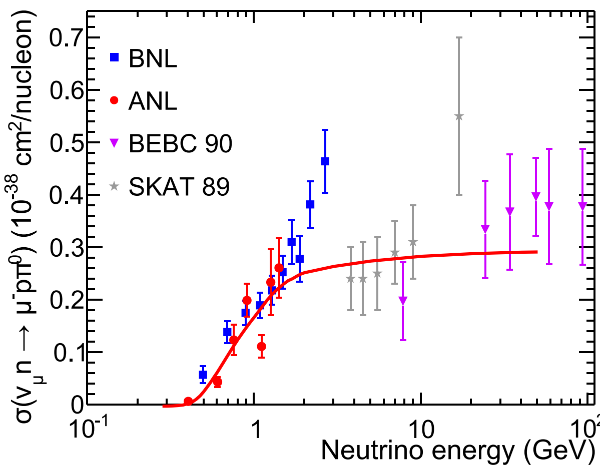
single pion production



Axial vector coupling of Delta(1232), non-resonant mechanism can be studied from 'data'
E_nu < 2GeV and W cut ~1.4GeV

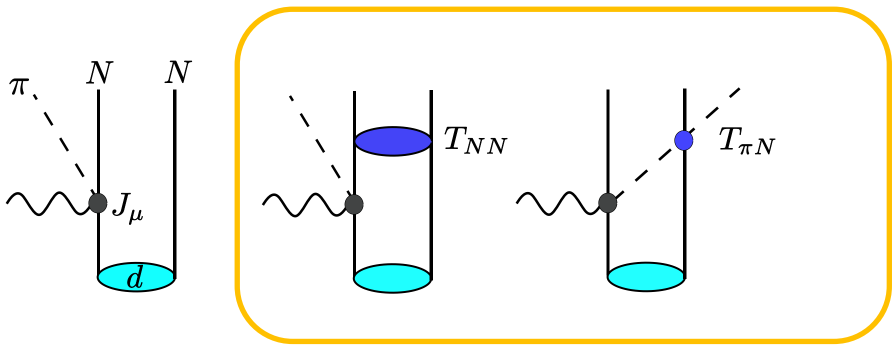
DCC model





data Figs. from P. Rodrigues et al, arXiv:1601.01888

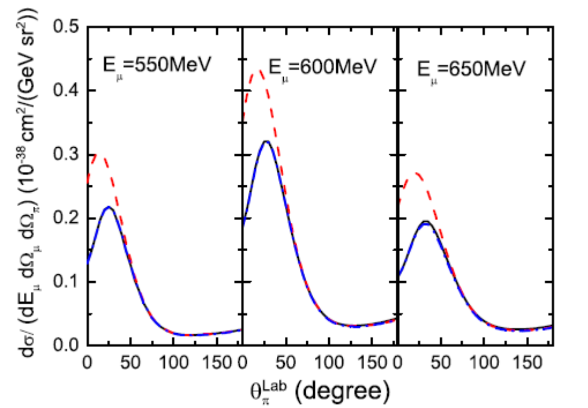
Caution: cross sections are extracted from nu-d data



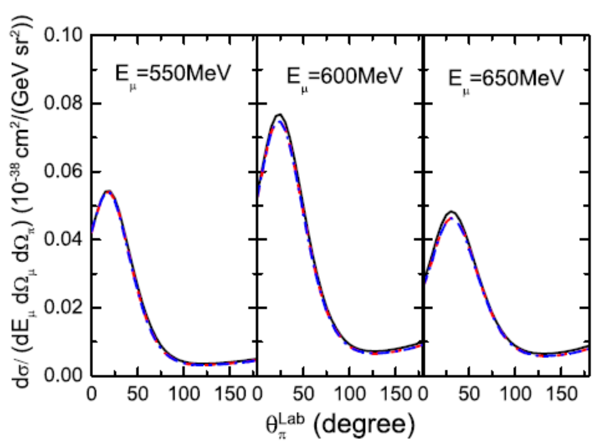
IA | +NN-resc | +piN-resc

Nu-d (E_nu=1GeV, theta_mu=25deg)

$$\nu_\mu d \to \mu^- \pi^+ pn$$



$$\nu_\mu d \to \mu^- \pi^0 pp$$

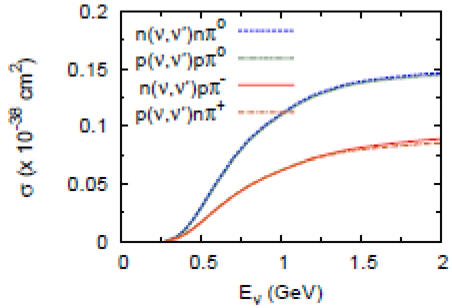


Nuclear effects might be important even for deuteron reaction.

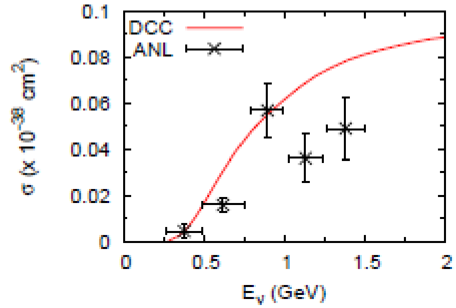
Large NN-rescattering for low energy NN pair

Comparison with the available data (other than CC 1pi)

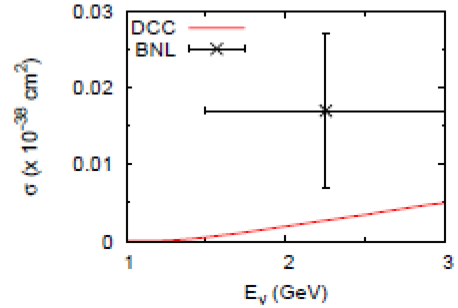
NC(single pion)



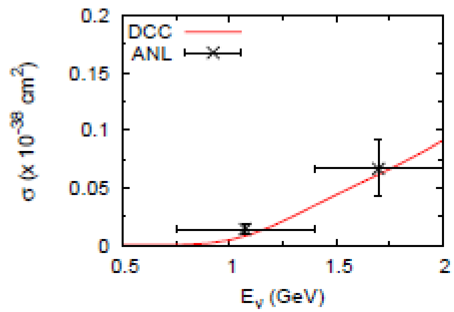
$\nu n \rightarrow \nu p \pi^-$



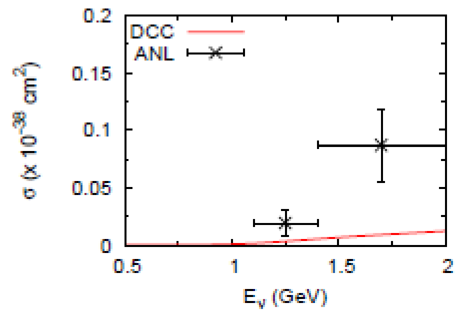
$\nu_\mu n \rightarrow \mu^- K^+ \Lambda$



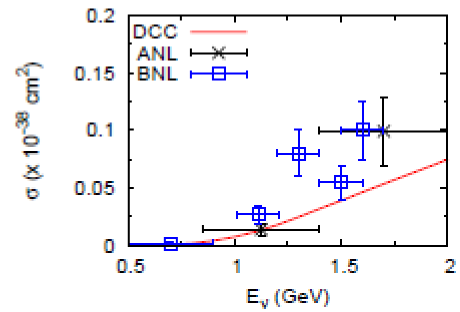
$\nu_\mu p \rightarrow \mu^- \pi^+ \pi^- p$



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

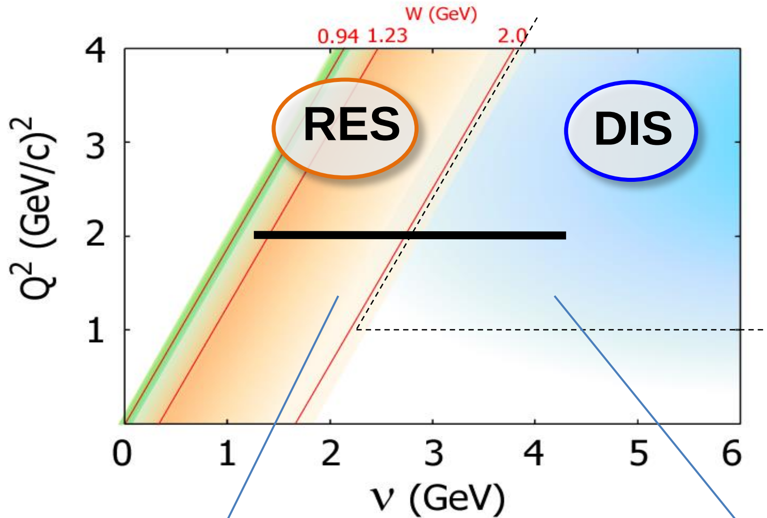


$\nu_\mu n \rightarrow \mu^- \pi^+ \pi^- n$

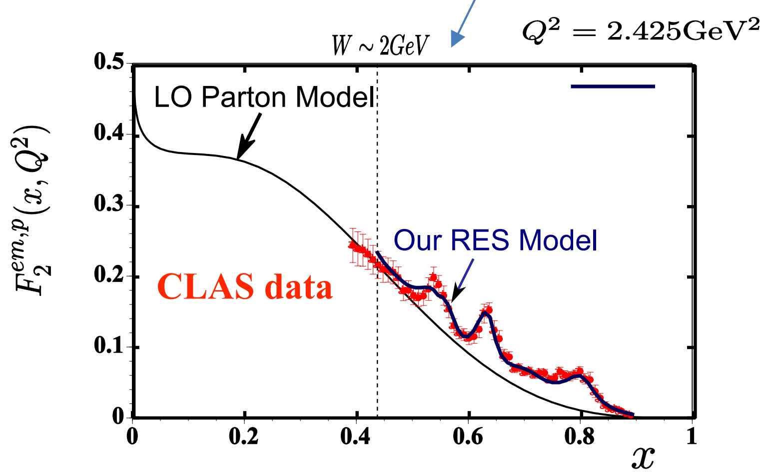


Matching with parton picture

Energy transfer vs momentum transfer



Vector current



Axial vector current

?

Working now

Summary

Model of weak meson production reactions including two-pion production channel for W<2GeV, $Q^2<3\ GeV^2$ is developed

- vector current is obtained from the analysis of electron and photon induced reactions.
- axial vector current is constructed using PCAC (Dipole form factor is assumed)
- The model smoothly connects DIS and RES (em case) regions

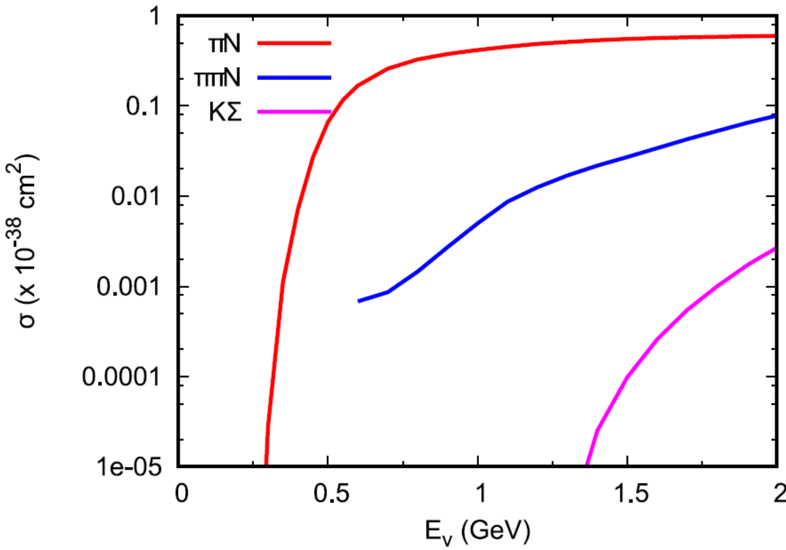
Models for neutrino induced meson production reaction has to be tested against all available data of pion and electromagnetic probes.

For precise tests of theoretical approaches (reaction models, chiral perturbation theory for axial vector coupling constant, ..), more data is needed. At the same time, theoretical tools to analyze deuteron reaction should be prepared.

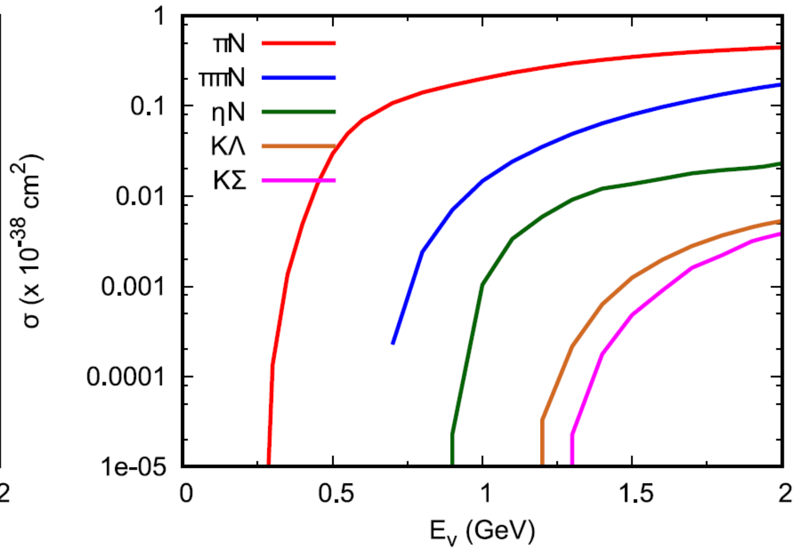
Back up

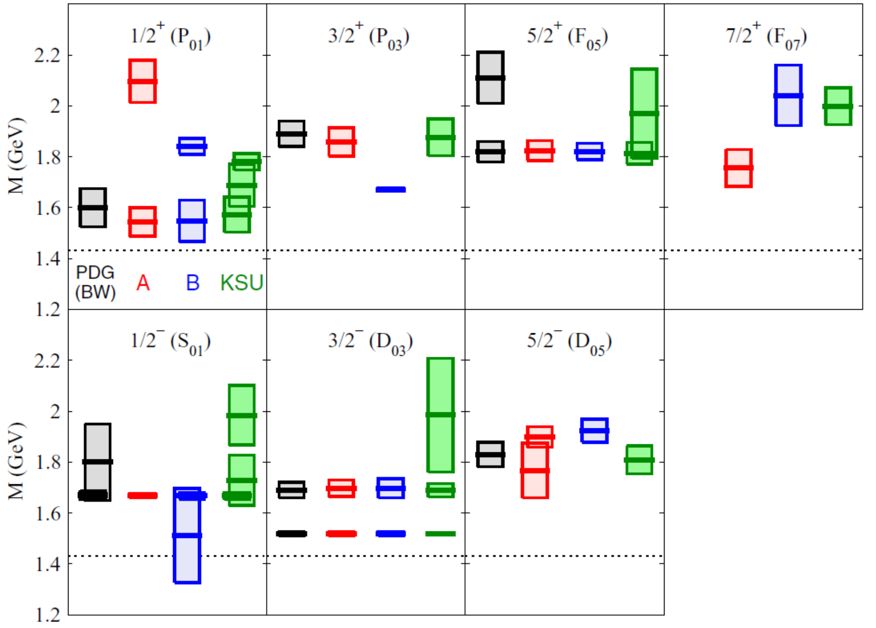
Production of $\pi, \pi\pi, \eta, K$(Total cross section)

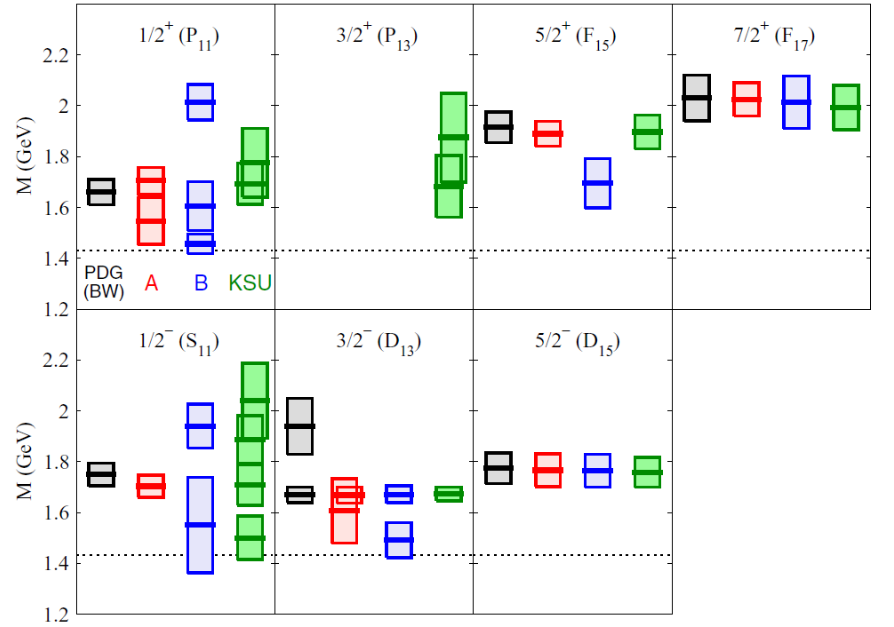
$\nu_\mu + p$



$\nu_\mu + n$




1/2+ (P01)
3/2+ (P03)
5/2+ (F05)
7/2+ (F07)
1/2− (S01)
3/2− (D03)
5/2− (D05)
M (GeV)
PDG (BW)
A
B
KSU


1/2+ (P11)
3/2+ (P13)
5/2+ (F15)
7/2+ (F17)
1/2− (S11)
3/2− (D13)
5/2− (D15)
M (GeV)
PDG (BW)
A
B
KSU

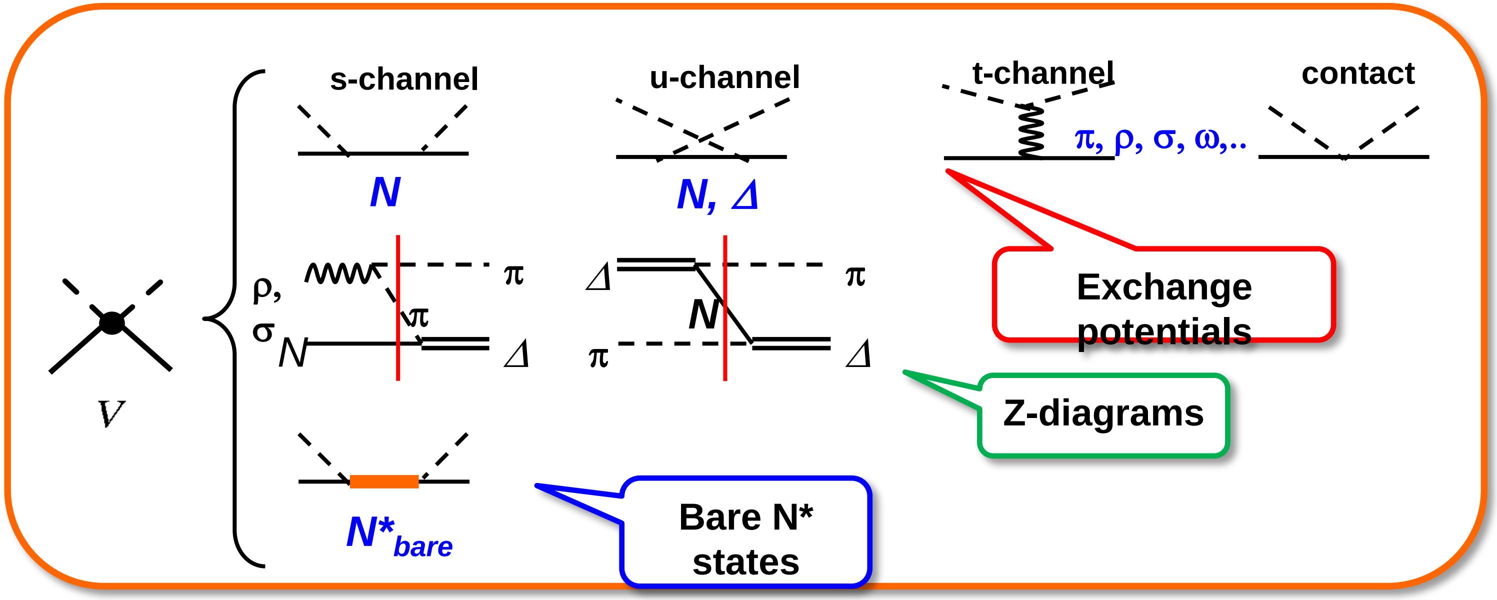
Brief description of DCC model

Fock Space

$$a, b, c \;=\; (\,\gamma^{(*)}N,\ \pi N,\ \eta N,\ \pi\Delta,\ \sigma N,\ \rho N,\ K\Lambda,\ K\Sigma, \cdots)$$

$\pi\pi N$

Interaction



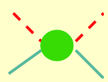
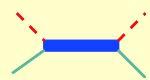
Solve LS equation, three-body unitarity is respected.

$$T^{(LSJ)}_{a,b}(p_a, p_b; E) \;=\; V^{(LSJ)}_{a,b}(p_a, p_b; E) + \sum_c \int_0^\infty q^2 dq V^{(LSJ)}_{a,c}(p_a, q; E) G_c(q; E) T^{(LSJ)}_{c,b}(q, p_b; E)$$

coupled-channels effect

Brief summary of Reaction models

$$T = V + VG_0T$$

	V		G_0
	Non-res	'res'	
Bonn-Gatchina Zagreb DMT Julich-Georgia EBAC	'const' Meson Exc 		$< G_0 >= i\rho$ $Re(\Phi(s)) = \frac{s-s_0}{\pi}\int_{s_t}^{\infty}\frac{Im(\Phi(s'))ds'}{(s'-s)(s-s_0)}$

explicit analytic form introduced

MAID

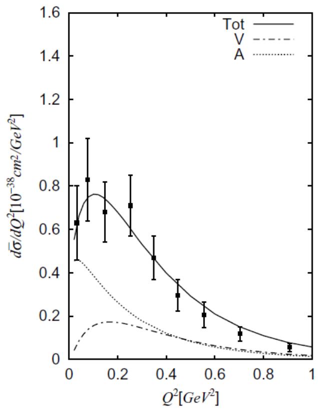
$$t^{\alpha}_{\gamma,\pi} = (Born+\omega+\rho+c.t.)(1 + it^{\alpha}_{\pi N})+\sum_i t^{\alpha}_{BW}(i)e^{i\phi^{\alpha}_i}$$

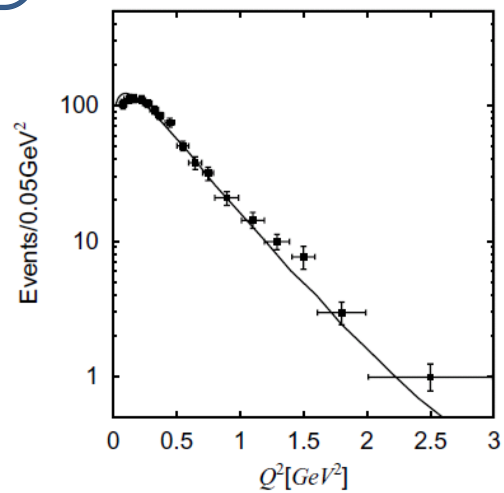
CLAS

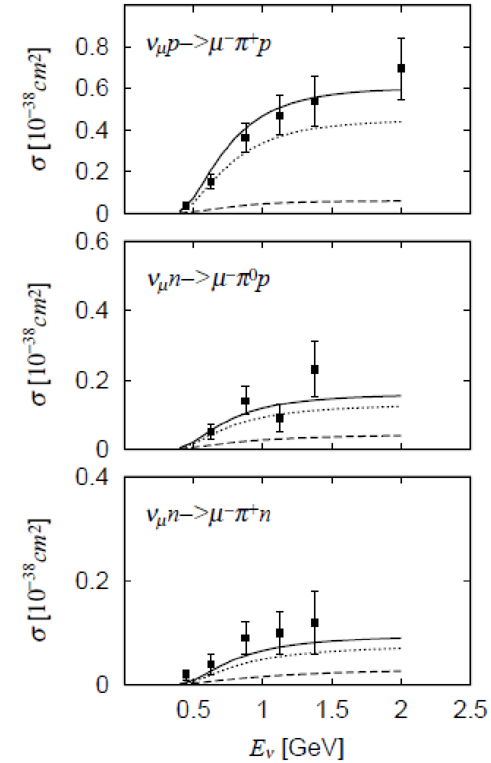
Unitary isobar model (+Regge) , Dispersion relation for single pion production

Isobar model + unitarization for $\gamma + p \rightarrow \pi^+\pi^- p$

$$p(\nu_\mu, \mu^- \pi^+)p$$







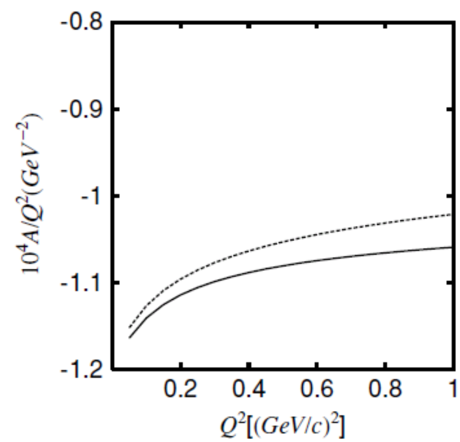
$0.5 < E_\nu < 6GeV$

Barish et al.(79) ANL

Kitagaki et al. (90) BNL

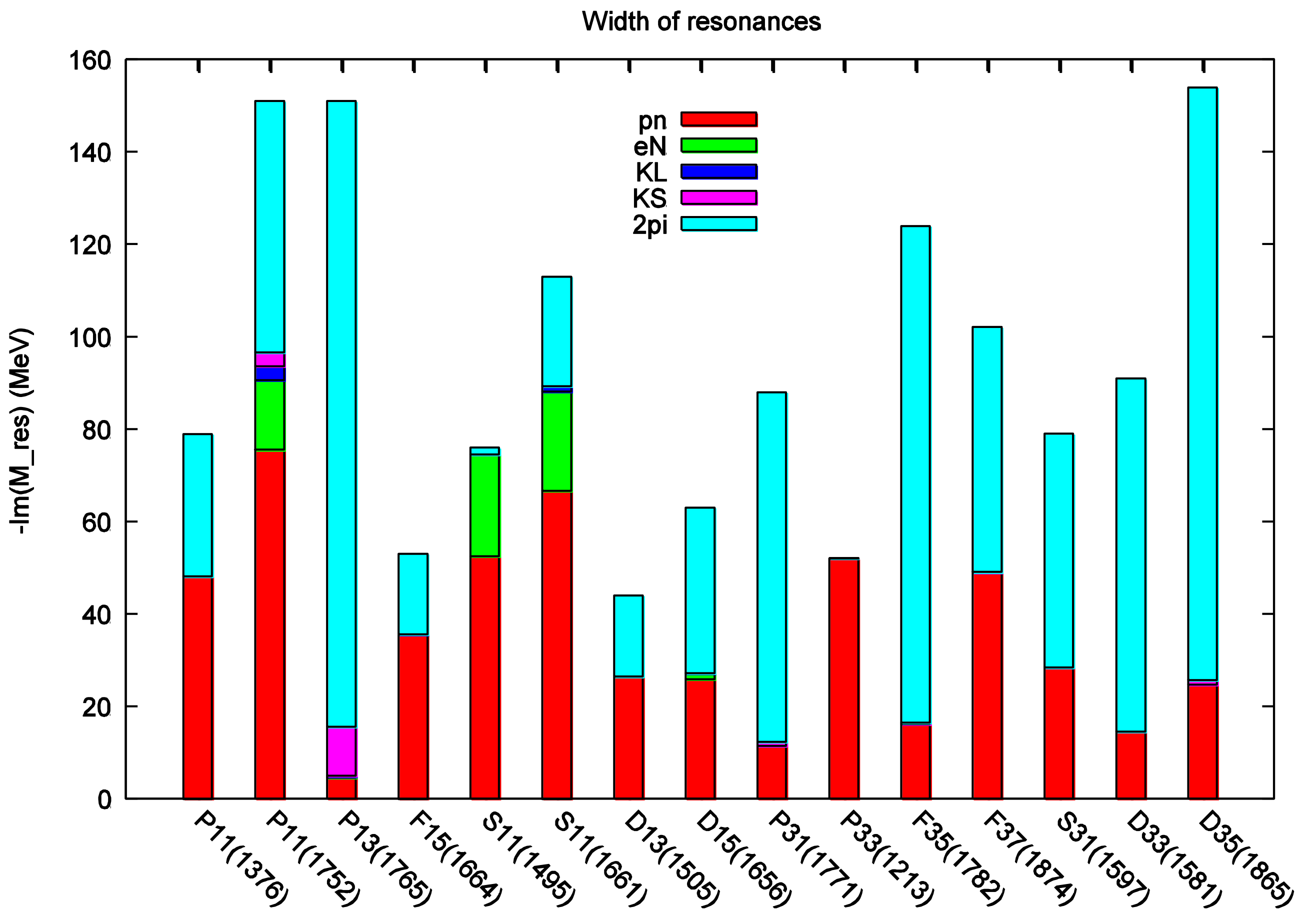
Parity violating asymmetry.

$$A = \frac{d\sigma(h_e = +1) - d\sigma(h_e = -1)}{d\sigma(h_e = +1) + d\sigma(h_e = -1)}$$
$$= -\frac{Q^2 G_F}{\sqrt{2}(4\pi\alpha)} \frac{N}{D},$$



W=1.232, theta=110 deg

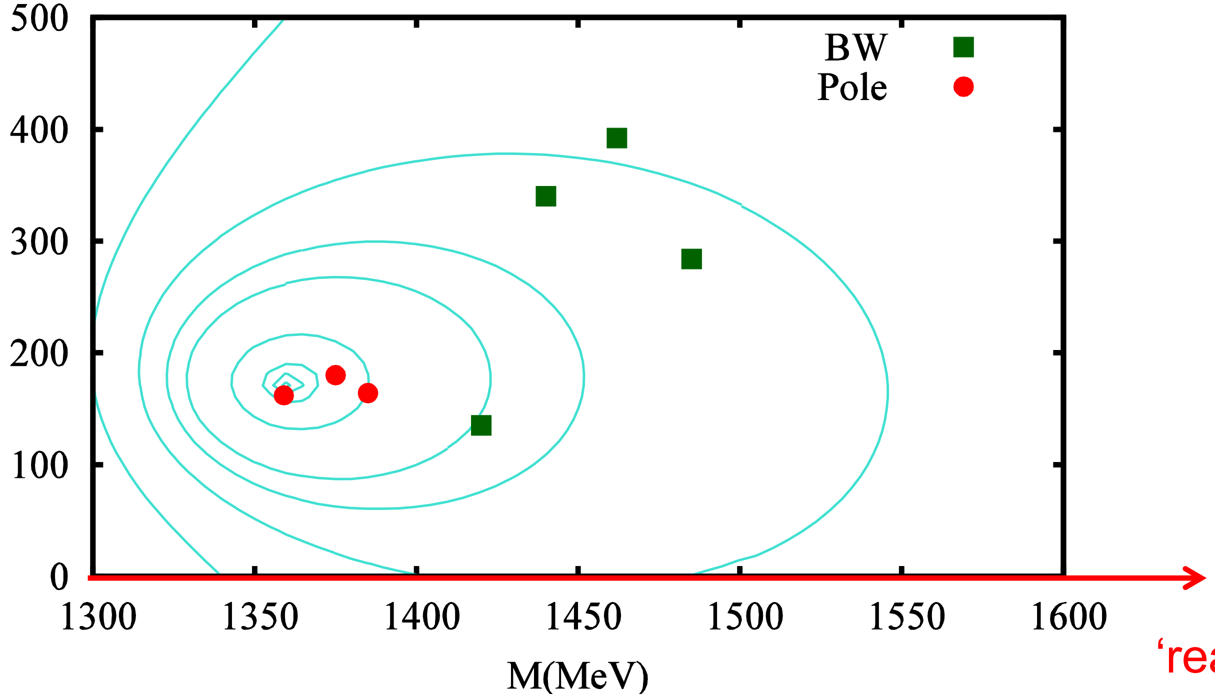
Half width $\Gamma/2 = -Im(E_{res})$



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 .

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

- Im (W)



'real' piN scattering

Re (W)