Neutrino induced pion production reaction 3

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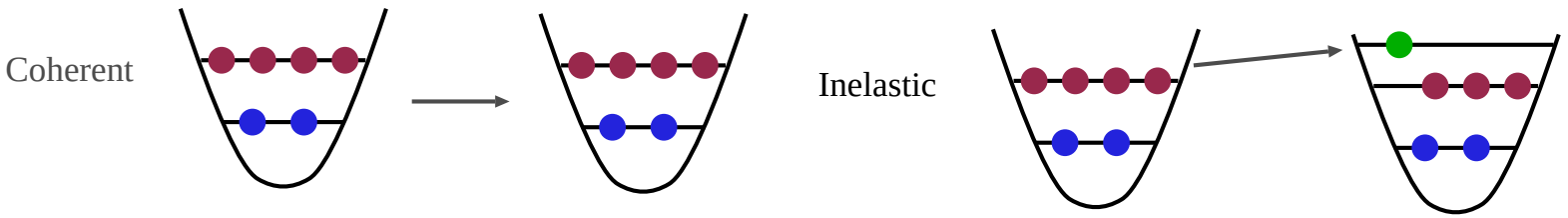
1. Coherent pion production
   - Coherent reactions
   - Neutrino induced coherent pion production at $Q^2 = 0$
   - Coherent reactions (Delta resonance region)
2. electroweak meson production reaction in resonance region
   - neutrino reaction at $Q^2 = 0$
   - π, γ^* induced meson production reaction
   - neutrino reaction

Coherent reaction

'elastic' scattering

$$a + |Ground> \to b + |Ground>, \quad \mathcal{F} = <Ground|f|Ground>$$

$$\sigma_{coh} = |f_1 + f_2 + ...f_A|^2 \propto A^2 \qquad \sigma_{inel} = \sum_h |f_h|^2 \propto A$$



even-even $N = Z$ nucleus, ground state is 0^+0.
quantum number transferred from (a, b) to nuclei is 0^+0. no spin, angular momentum , isospin transfer to nuclei

Momentum transfer $p_a - p_b$ and form factor

$$\sum_h < h|e^{i\vec{q}\cdot\vec{r}}|h > \sim A(1 - \frac{< r^2 > q^2}{6} + ..)$$

$$
\begin{aligned}
\gamma + A &\rightarrow \pi^0 + A \quad \text{O} \\
\gamma + A &\rightarrow \pi^+ + B \quad \text{x} \\
\nu + A &\rightarrow l^- + \pi^+ + A \quad \text{O} \quad CC\pi^+ \\
\nu + A &\rightarrow l^- + \pi^0 + B \quad \text{x} \\
\nu + A &\rightarrow \nu + \pi^0 + A \quad \text{O} \quad NC\pi^0
\end{aligned}
$$

Neutrino induced coherent pion production at $Q^2 = 0$

'parallel kinematic' plus massless lepton

$$p_\nu^2 = p_l^2 = 0, \vec{p}_l \propto \vec{p}_\nu$$

leads

$$Q^2 = 0, p_l^\mu \propto p_\nu^\mu \propto q^\mu$$

Then

$$Tr(l^\alpha l^\beta) \propto p_\nu^\alpha p_l^\beta + p_\nu^\beta p_l^\alpha - g^{\mu\nu}(p_\nu \cdot p_l) + i\epsilon^{\alpha\beta\gamma\rho} p_{\nu,\gamma} p_{l,\rho} \propto q^\alpha q^\beta$$

We obtain

$$| < l\beta | H_W | \nu\alpha > |^2 \propto | < \beta | q \cdot A | \alpha > |^2$$

Remember relation between pion absorption/production and matrix element of axial vector current.

$$M_{\beta,\alpha} = \frac{iq_\mu}{f_\pi} N^\mu_{\beta,\alpha}$$

The neutrino reaction of parallel kinematics can be given by soft pion absorption.

$$\sigma(\nu + \alpha \to l + \beta) \propto f_\pi^2 \sigma(\pi(m_\pi^2 = 0)\alpha \to \beta)$$

S. L. Adler, PR 135 B963 (1964)

By choosing, $\alpha = |ground>$ and $\beta = |\pi + ground>$

$$\sigma(\nu + ground \to l + \pi + ground) \propto f_\pi^2 \sigma(\pi(m_\pi^2 = 0) + ground \to \pi + ground)$$

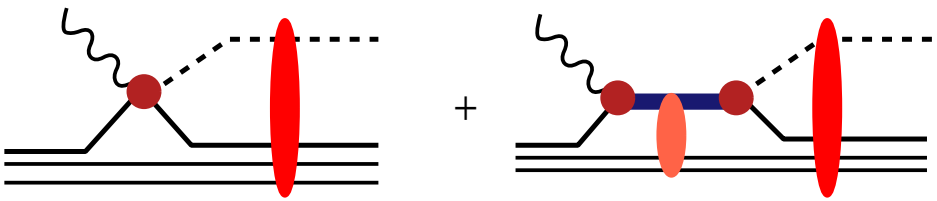
LHS: Cross section of coherent pion production by neutrino
RHS: pion-nucleon elastic scattering cross section

- $m_\pi = 0 \to 140 MeV$ for FSI of finite size objects?
- non-forward cross section?

D. Rein, L. M. Sehgal, NPB223, 29(1983)
D. Rein, L. M. Sehgal, PLB657, 207(2007)
E. Hernandez,J. Nieves, M. J. Vicente Vacas, PRD80, 013003 (2009)

Coherent reactions (Delta resonance region, microscopic model)

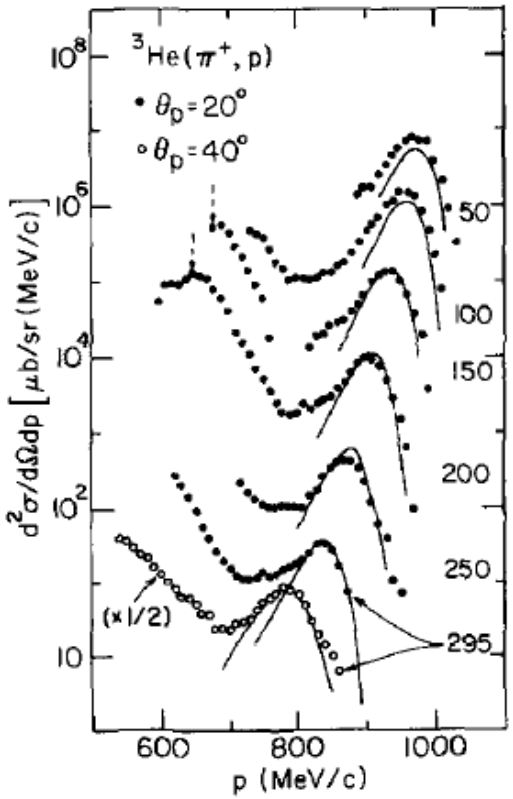
- apply model of weak pion production of nucleon.
- interaction of pion with nuclei and propagation of delta inside nuclei are taken into account by using delta-hole model
- Test reaction model for coherent pion photoproduction and predict neutrino reaction.



Note

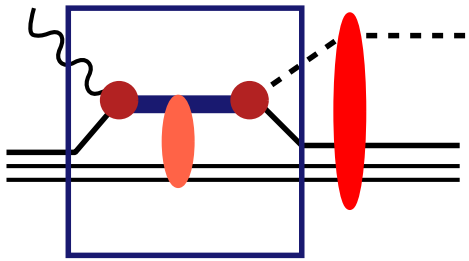
- final state interaction of pion is taken into account by optical potential.
  No intial state interaction of W, Z with nuclei.
- non-resonant mechanism: DWBA
- resonant mechanism:finite range propagation of delta

Delta-hole model and pion absorption $^3He(\pi^+, p)$



K. Ohta, M. Thies, T.-S. H. Lee, Ann. of Phys. 163, 420 (1985)

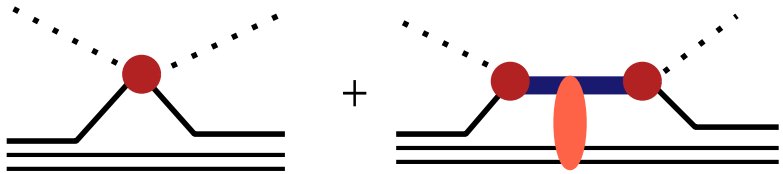
Delta-hole Green's function



$$< \pi \quad gr.|H_{\pi N\Delta}|\Delta h > G_{\Delta h} < \Delta h|H_{J_W N\Delta}|gr. >$$

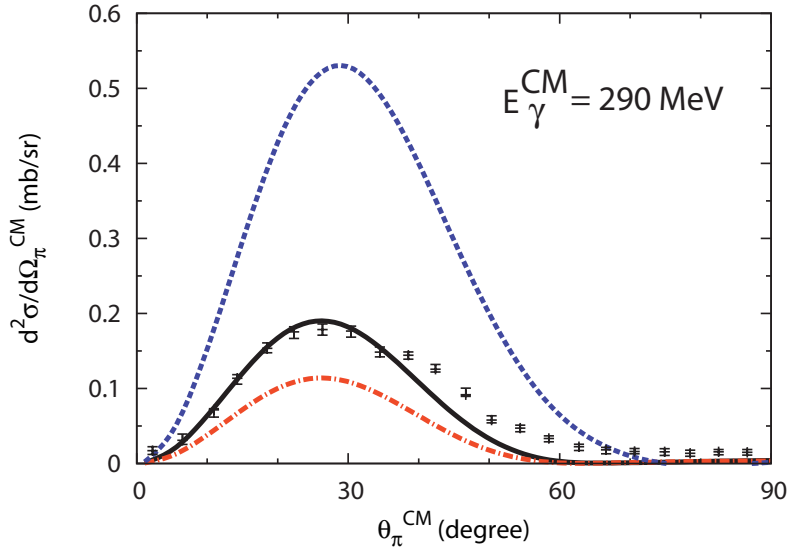
$$G^{-1}_{\Delta h} = W - (-e_h + \frac{p^2_\Delta}{2m_\Delta} + \Sigma(W) + \Sigma_{Pauli}(W) + V_\Delta + V_{sp})$$

Pion-Nucleus Optical potential



- Determine spreading potential from the analysis of pion nucleus elastic, total and absorption cross section.
- coherent pion photoproduction. Test of reaction model.

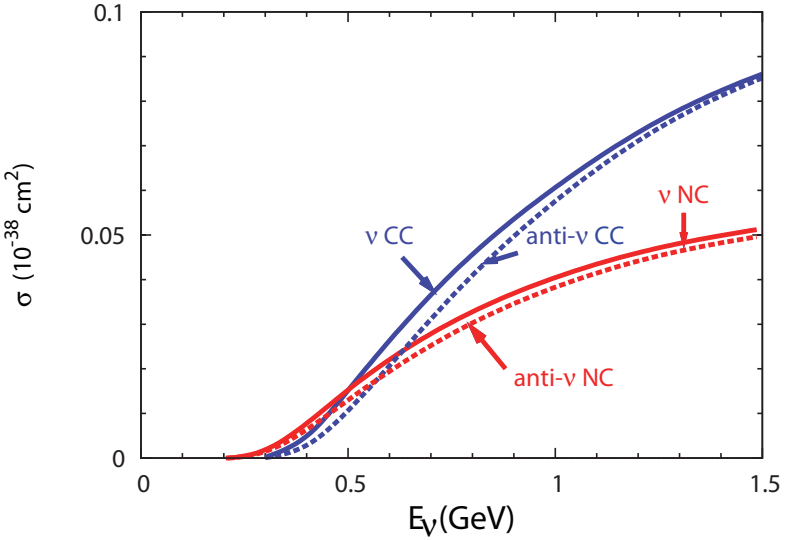
coherent pion photoproduction on 12C



solid (full), dot (without FSI,medium effect), dash-dot(delta)

S. Nakamura,T. Sato, T. -S. H. Lee, B. Szczerbinska, K. Kubodera, PRC81 035502 (2010)

Neutrino induced coherent pion production



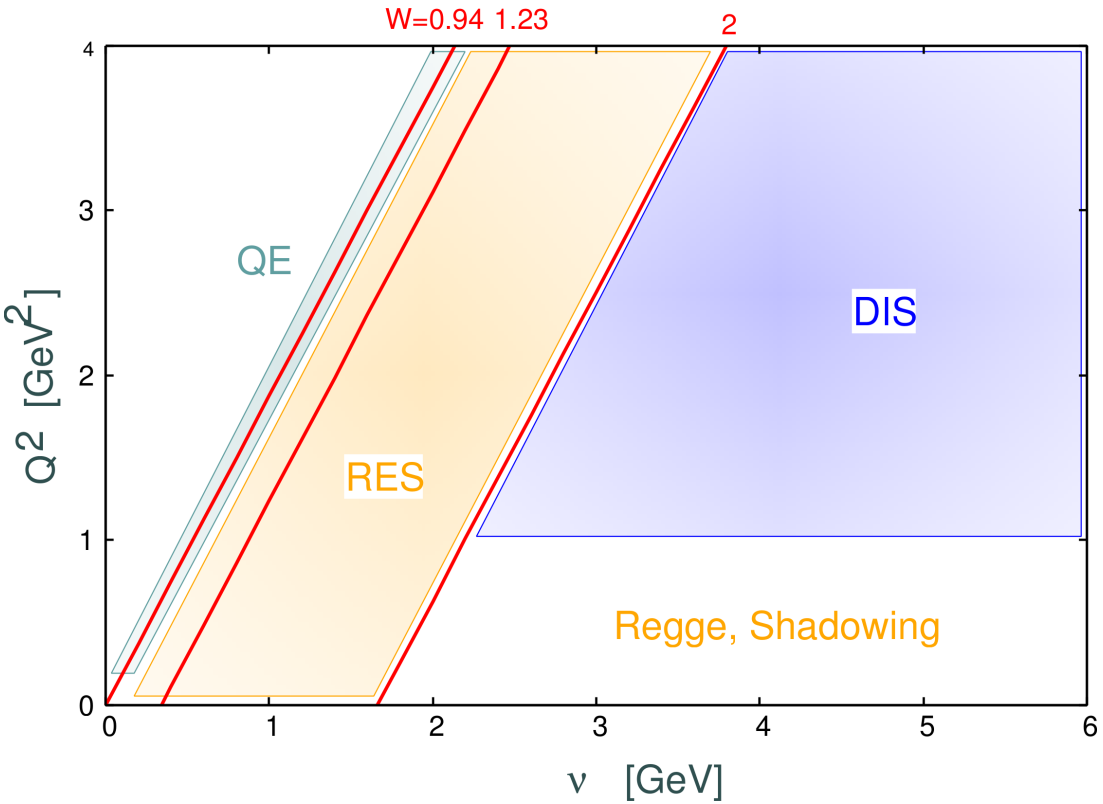
CCpi+ $\sigma_{ave}^{CC} = 6.3 \times 10^{-40} cm^2$ $\sigma_{K2K} < 7.7 \times 10^{-40} cm^2$

NCpi0 $\sigma_{ave}^{NC} = 2.8 \times 10^{-40} cm^2$

$\sigma_{MiniBooNE} = 7.7 \pm 1.6 \pm 3.6 \times 10^{-40} cm^2$

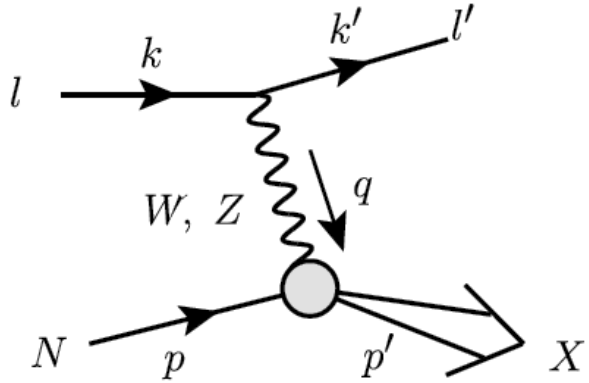
	Alvarez-Ruso et al.(07)	Hernandez et. al(10)	Nakamura et al.(10)	Berger Sehgal (09)
CCpi+(K2K)	10.8/5.7	6.1+/-1.3	6.3	0.62x12
NCpi0(MiniBooNE)	5.0/2.6	2.6+/-0.5	2.8	

electroweak meson production reaction in resonance region



Focus reaction above Delta, below DIS

Neutrino reaction beyond Delta



- Isobar model

  D. Rein, L.M. Sehgal Ann. Phys. 133, 79 (1981), D. Rein, Z. Phys. C 35, 43 (1987)

- Effective Lagrangian approach

  O. Lalakulich, E. A. Paschos, G. Piranishvik, PRD74, 014009 (2006)
  E. Hernandez, J. Nieves, S. K. Singh, M. Valverde, M. J. Vicente Vacas, PRD77, 053009 (2008)
  T. Leitner, O. Buss, L. Alvarez-Ruso, U. Mosel, PRC79, 034601 (2009)

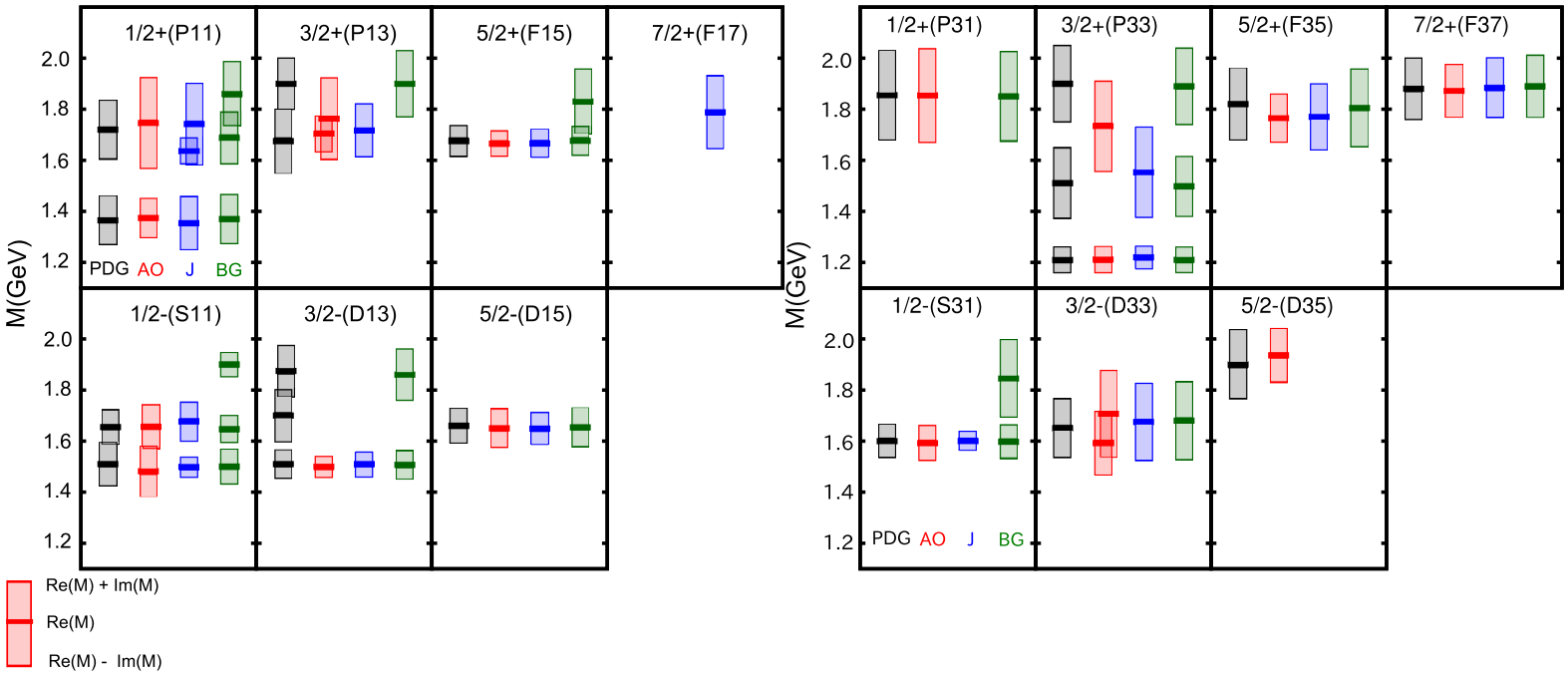
Isobar Model

- resonance + background
- use Breit-Wigner formula, couplings determined form the branching ratio of PDG

$$
\begin{aligned}
F &= \sum_{\alpha=JPI} S_{sign} f_\alpha^{decay} \frac{1}{W - M_\alpha + i\Gamma_\alpha} f_\alpha^{prod} P_\alpha \\
f_\alpha^{decay} &= \sqrt{\frac{\Gamma_\alpha \eta_\pi}{2\pi}} \\
f_\alpha^{prod} &= quark - model
\end{aligned}
$$

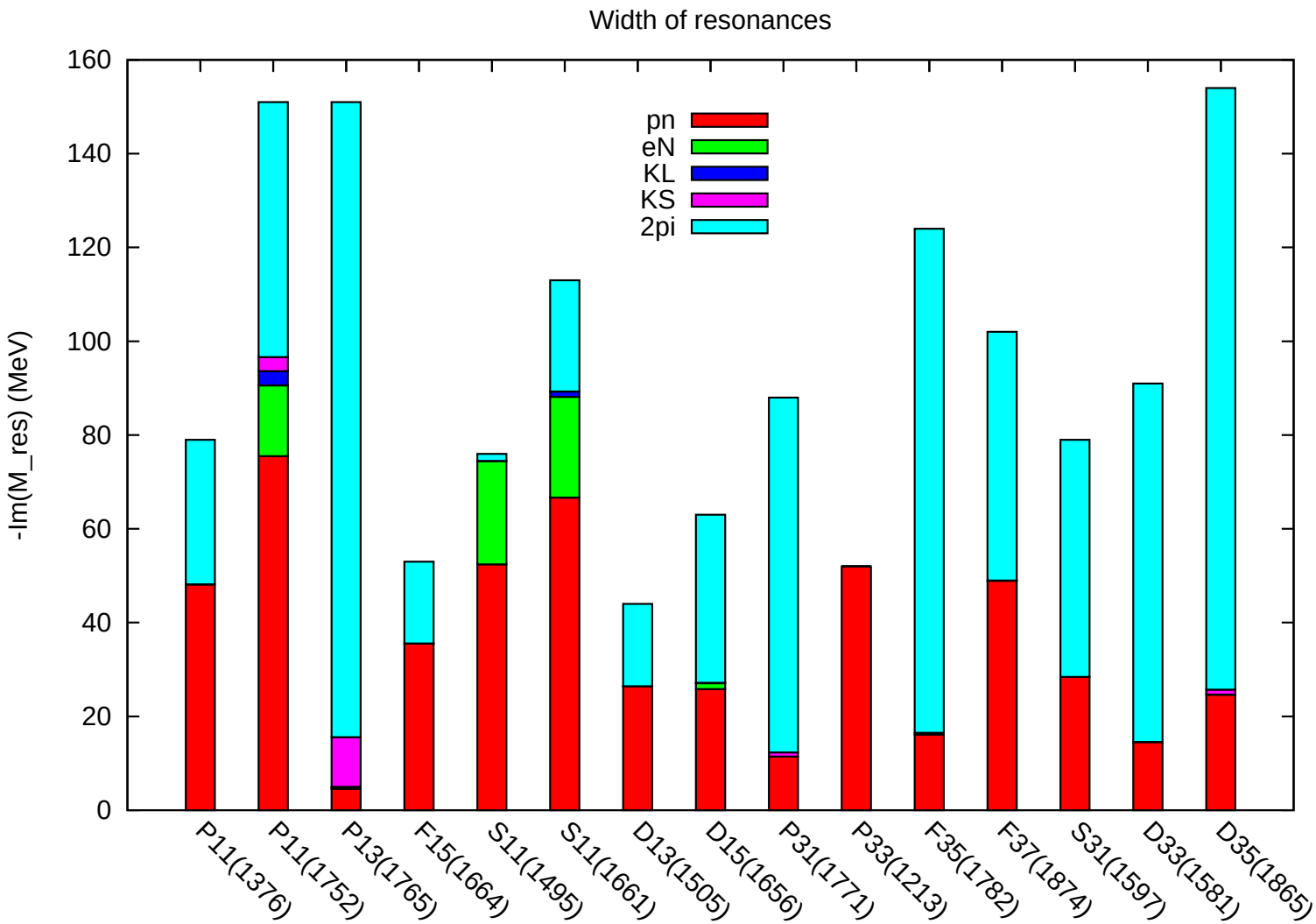
spectrum of nucleon resonance

situation of N^* states at 2013

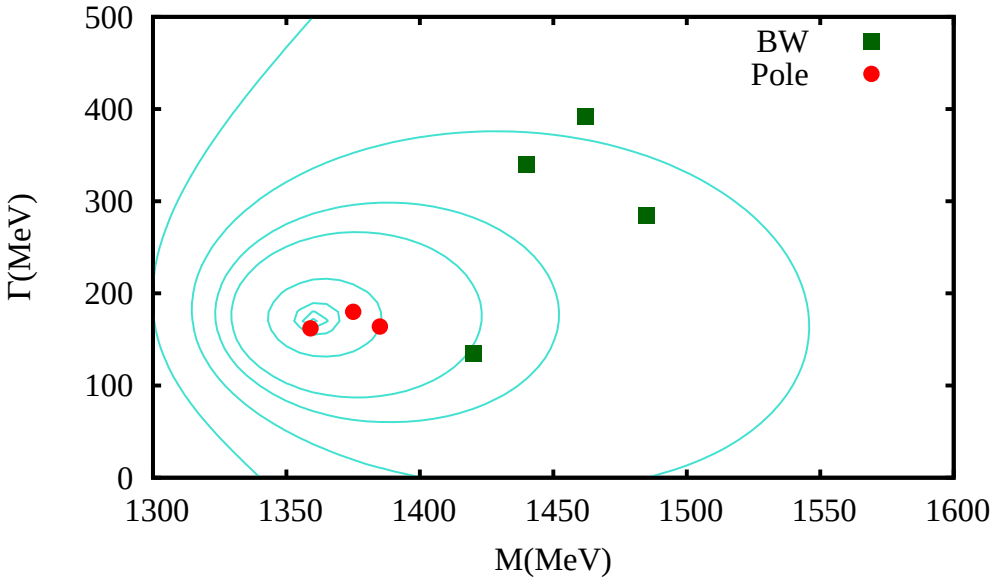


AO: ANL-Osaka, J: Julich, BG:Bonn-Gatchina, PDG(3*,4*)

large branching ratio to $\pi\pi N$ channel

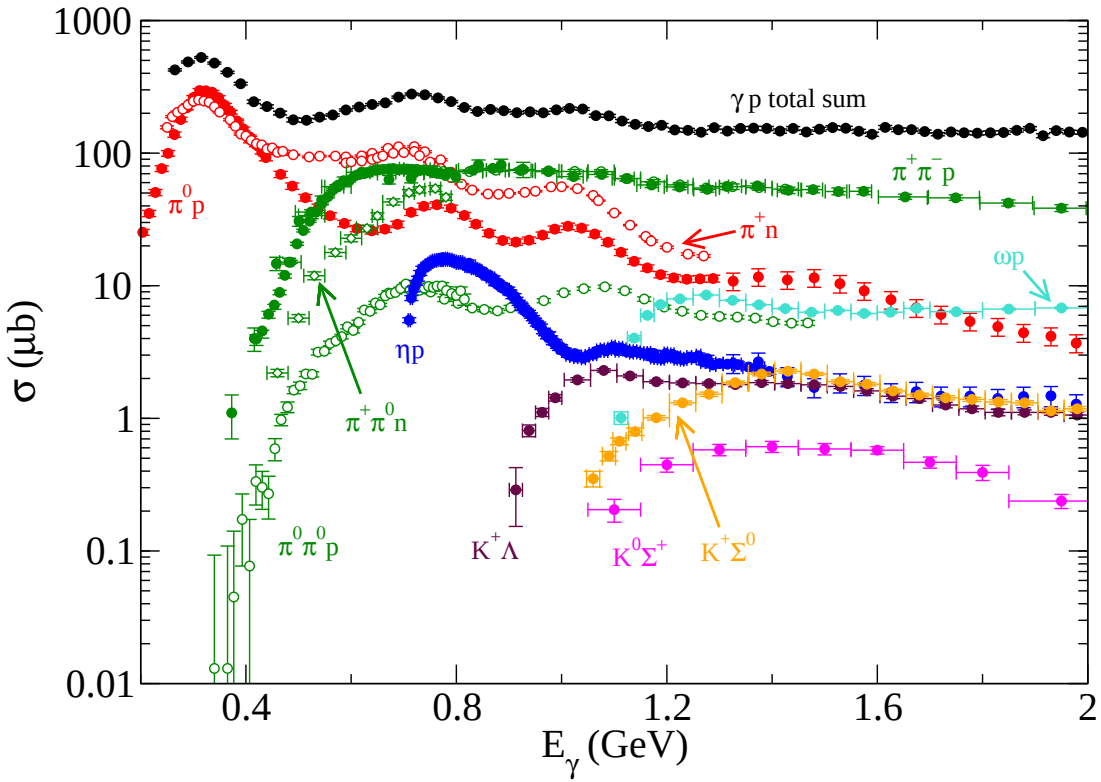


Pole of amplitude and Breit-Wigner formula



- Diff pole and BW: momentum dependence of width in BW + non-resonant amplitude
- BW: large model dependence of res. non-res. separation
- For application to neutrino physics: total amplitude must be right one.

What will happen beyond delta?: multi-pion production and meson-production



- Understand meson production reactions up to $W < 2GeV$
- Available data π and photon induced reactions

Method

- Isobar model
  Bonn-Gachina, VPI-GW, Mainz-Dubna-Taipei
- Coupled channel reaction models
  ANL-Osaka(PRC 2013), Julich

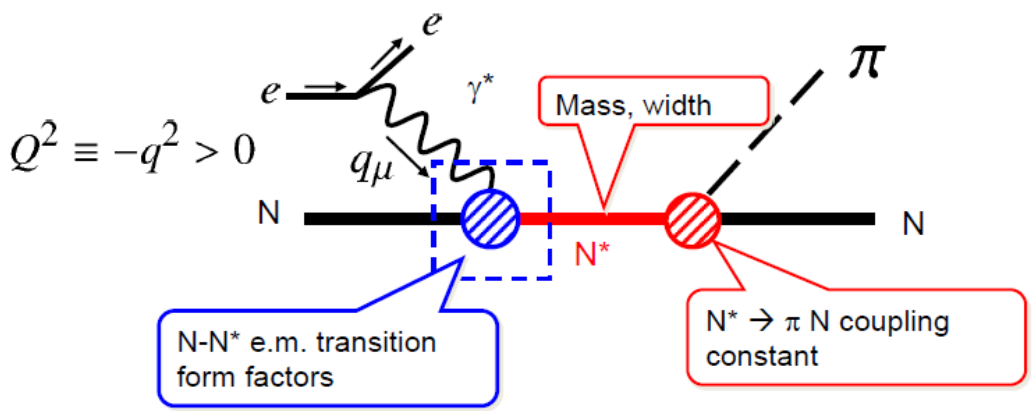
ANL-Osaka Coupled channel model

- start from meson exchange model of non-resonant interaction based on chiral Lagrangian
- $+$ nucleon resonances
- coupled channel model $\pi N, \pi\pi N(\sigma N, \rho N, \pi\Delta), K\Lambda, K\Sigma$
- Satisfy three body unitarity
- Analysis of πN elastic ($W < 2.3GeV$)
- Analysis of π and γ induced meson production reactions. Total 22K data points.

H. Kamano et al. PRC88 035209 (2013)

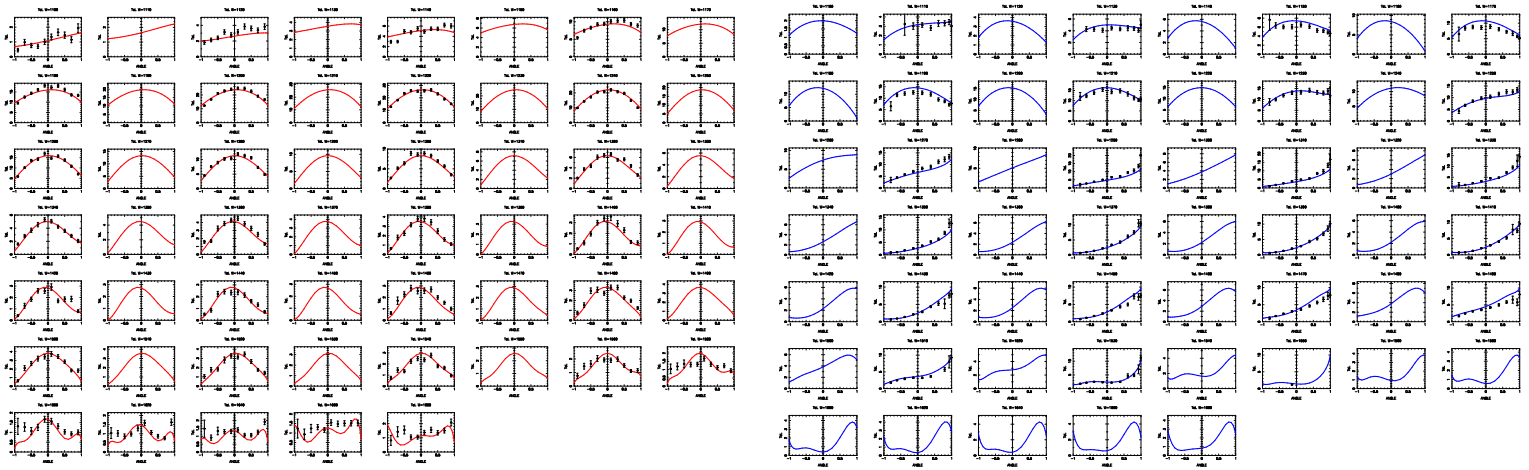
Step for electroweak meson production reaction (preliminary)

Need to determine transition NN^* form factors.



- photo reaction on neutron (need to separate iso-vector and iso-scalar)
- pion electroproduction (Finite Q^2 for vector current)
- NN^* axial form factor
  Use PCAC to relate known $\pi NN*$ coupling to ANN^* coupling
  (independent ANN^* couplings M, E, L, S but one constrain. $\rightarrow$ keep only 'dominant term'
  Still assumption for Q^2 dependence needed)

Preliminary results of π^0, π^+ electroproduction on proton
($\sigma_T + \epsilon\sigma_L$ for $W = 1.1 - 1.68 GeV$ at $Q^2 = 0.4 (GeV/c)^2$

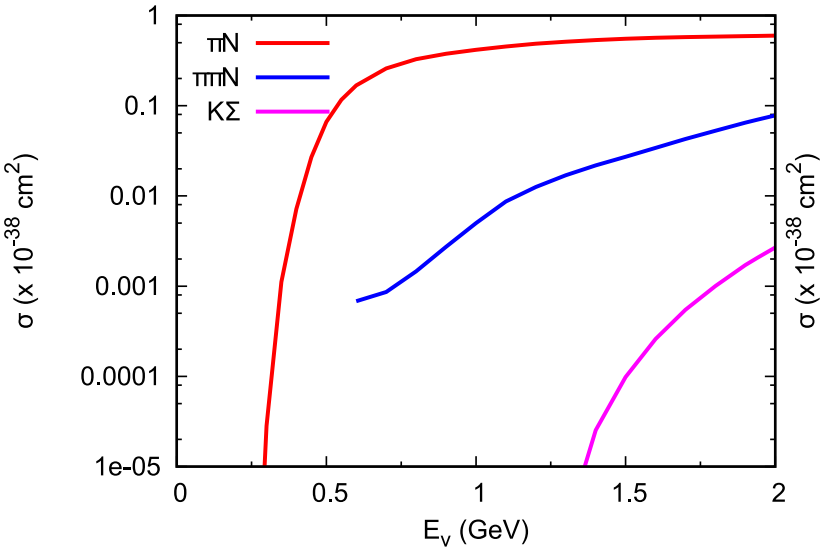


By fitting single pion production, electromagnetic NN^* transition form factors are obtained.

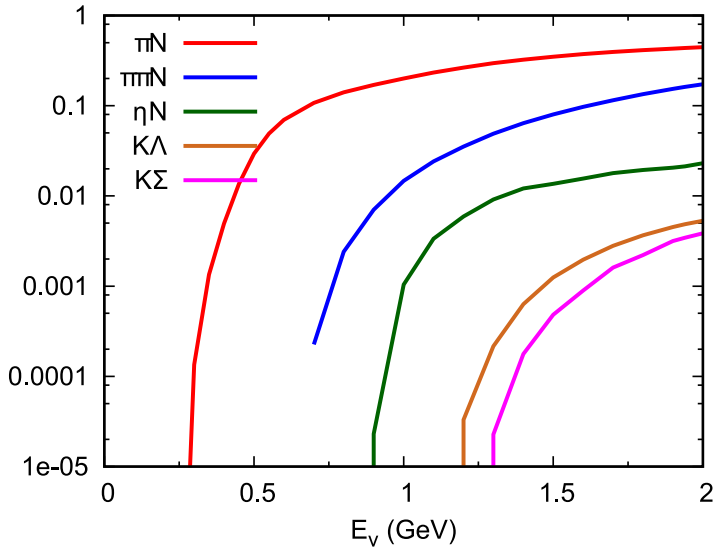
neutrino induced meson production reaction

How many two pion and kaon will be produced?

$\nu_\mu p \to \mu^- X$

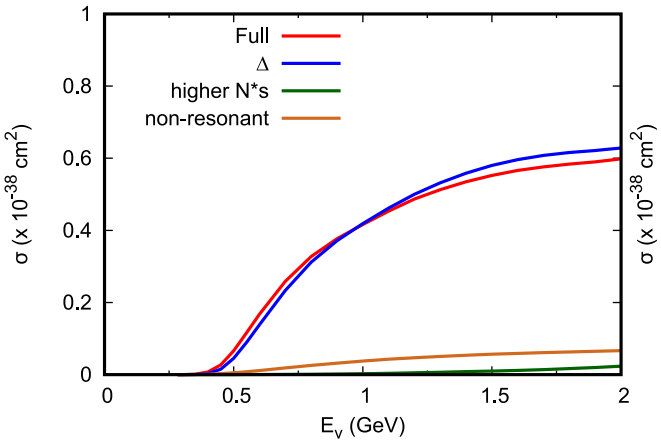


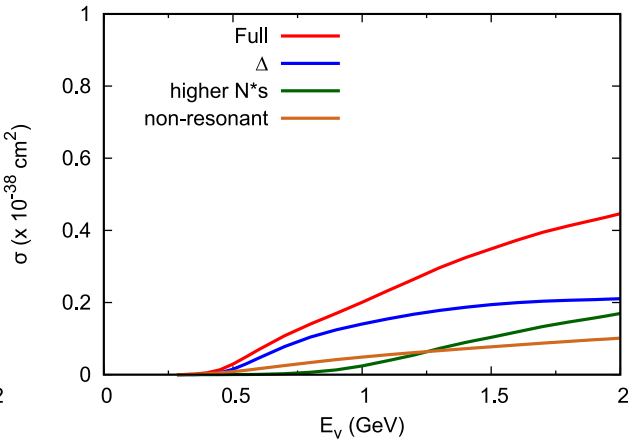
$\nu_\mu n \to \mu^- X$

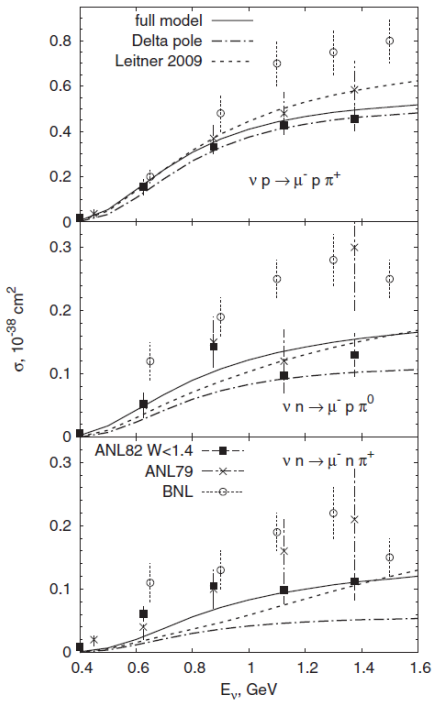


Mechanism of single pion production

$\nu_\mu p \to \mu^- \pi^+ p$ $\nu_\mu n \to \mu^- \pi N$

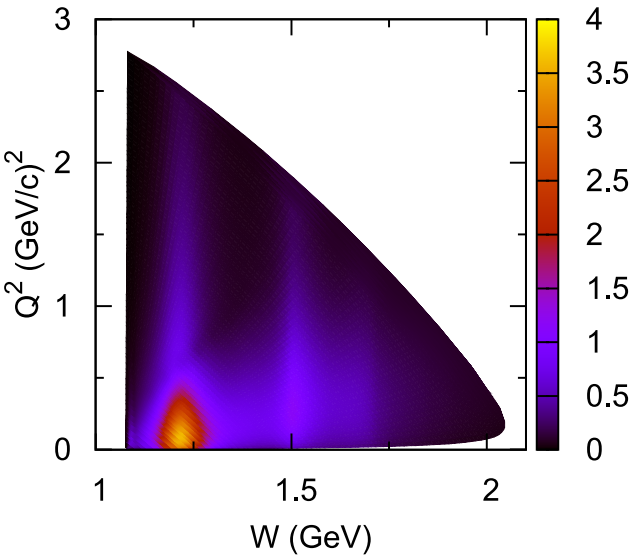




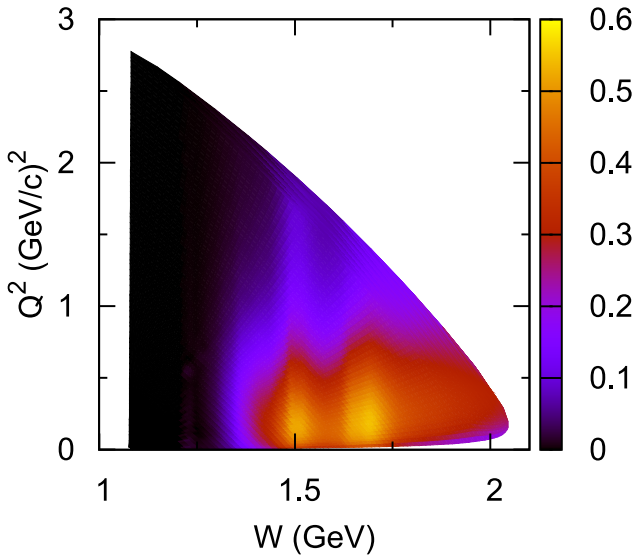


$d\sigma/dWdQ^2$ for single and double pion production $E_\nu = 2GeV$

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



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



summary

- coherent pion production
  - PCAC and microscopic reaction model are explained.
  - Reaction models should include large medium effects (pion rescattering, absorption, delta propagation).
  - Theoretical models gives rather stable predictions for coherent reaction cross section. ('elastic scattering', where nuclear state is ground, bound state.)
  - Inelastic reactions to the low energy excited states are not fully explored yet.
- meson production reaction beyond Delta
  - πN and $\pi\pi$ N are main channels in a few GeV neutrino induced meson production reaction.
  - N^*, Δ, Non-resonant mechanisms are all important.
    The interference pattern among them is crucial.
    The dynamical model fix it by analyzing π and photon induced meson production reactions.
  - Needs 'assumption' on the axial vector transition form factor.