Neutrino induced pion production reaction 3

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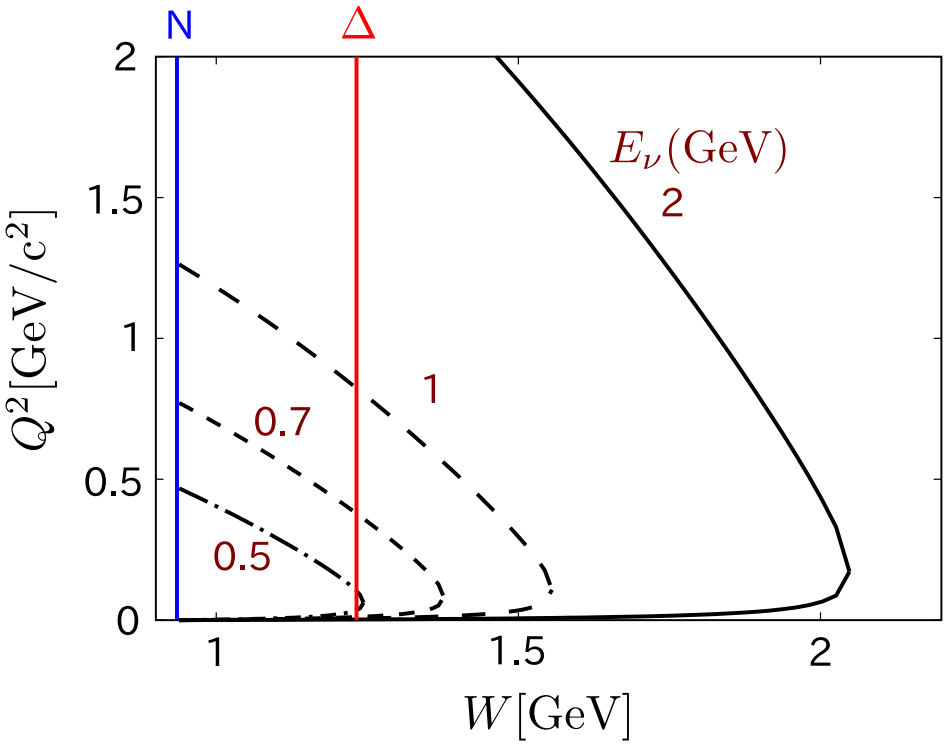
plan of lecture

- Neutrino induced meson production reaction beyond $\Delta(1232)$.
- Delta propagation in nuclei and coherent pion production

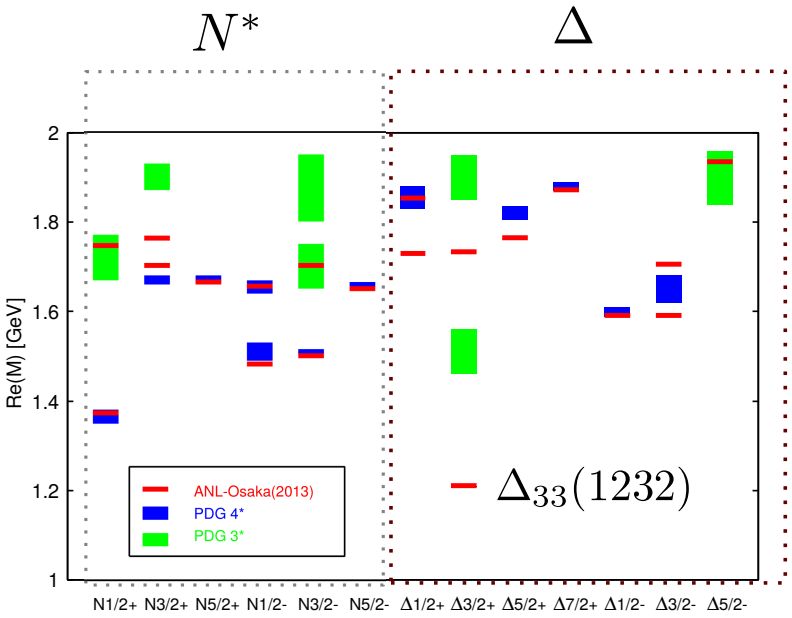
electroweak meson production reaction beyond Delta

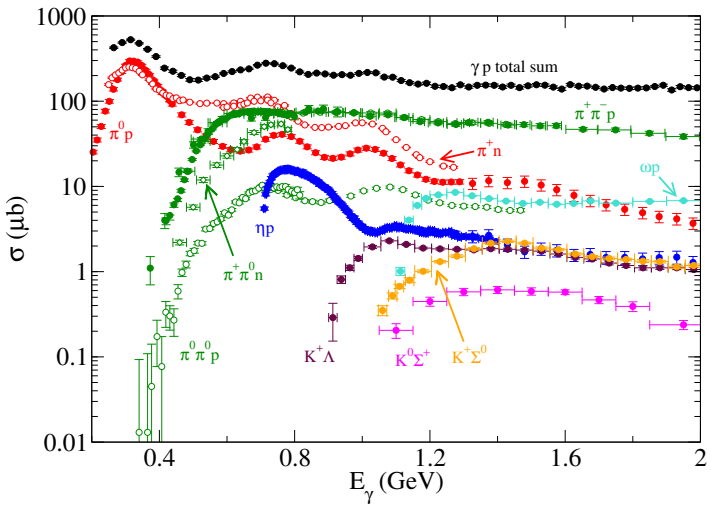
- explore higher mass resonances (original motivation to develop a reaction model)
- smooth transition from resonance to DIS



new feature

- many N^* and Δ resonances $M_R < 2GeV$





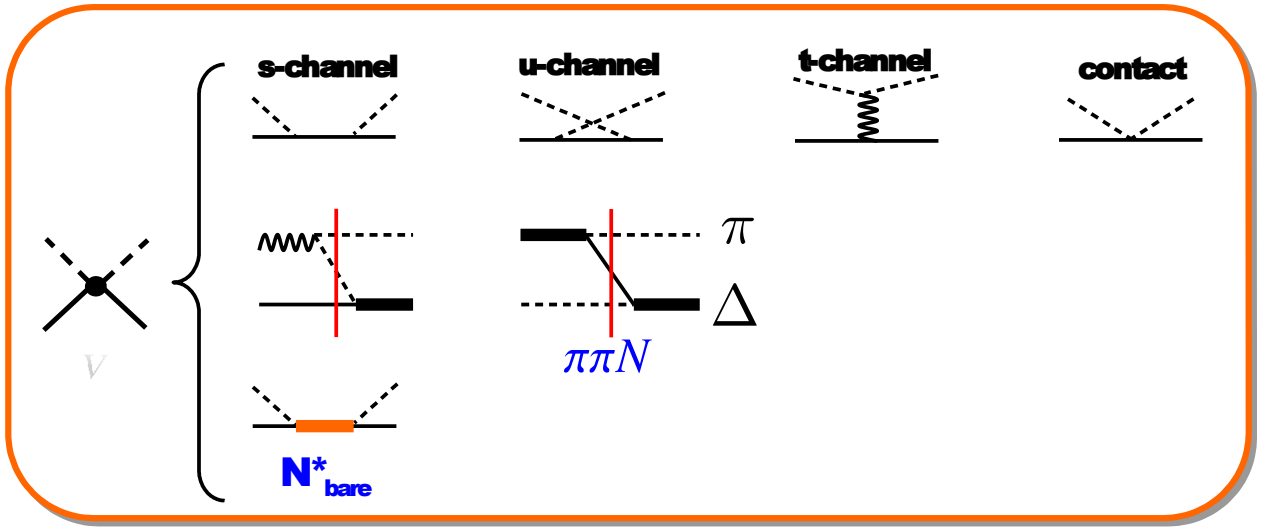
- opening of $\eta N, \pi\pi N, K\Lambda, K\Sigma, , ,$ channels

  $\rightarrow$ needs multi-channel unitarity including three-body($\pi\pi N$).

Extension of coupled channel model

Extend coupled channel model (ANL-Osaka model):

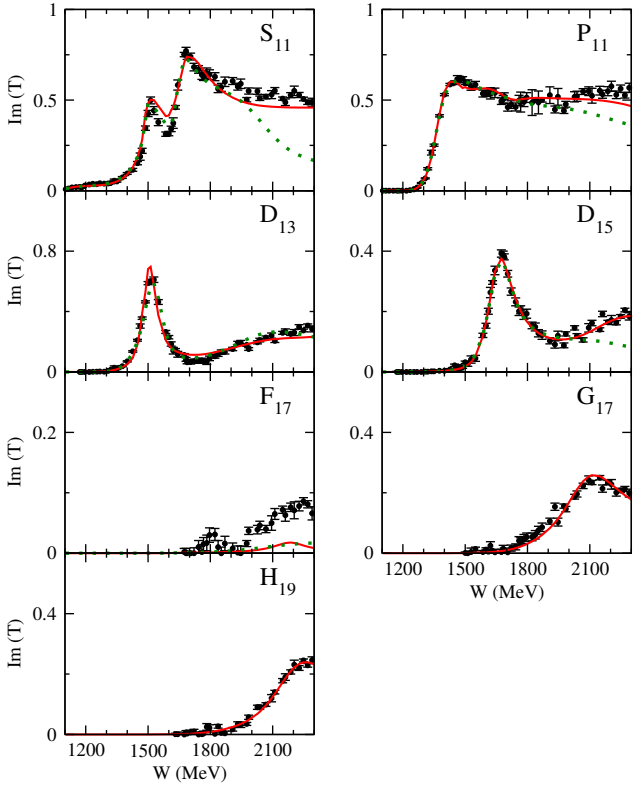
- include N^*, Δ resonances
- coupled channel model $\pi N, \eta N, \pi\pi N(\sigma N, \rho N, \pi\Delta), K\Lambda, K\Sigma$
- Satisfy three body($\pi\pi N$) unitarity

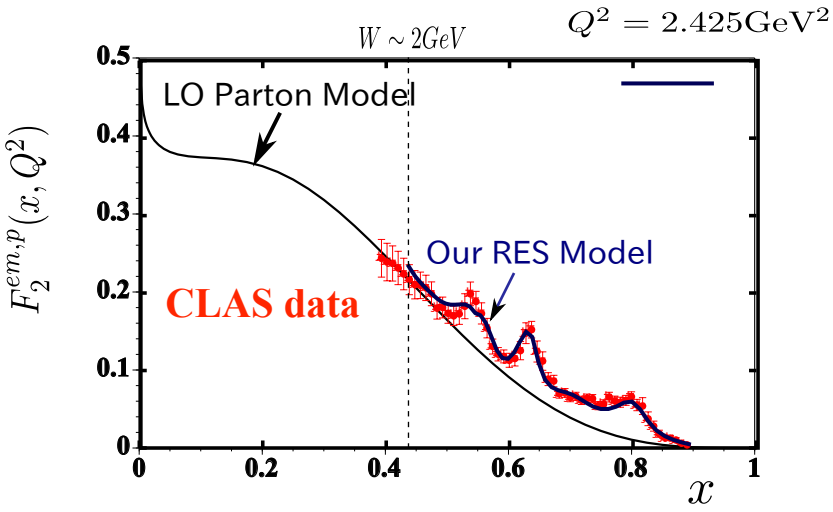


Step 1:
Analysis of πN reactions. $(W < 2.3GeV)$ [fix strong interaction part of model]

Step 2
Analysis of γ, γ^* induced meson production reactions on proton and neutron. $(\sigma/d\Omega, P, \Sigma, ..)$. [fix model of Vector current]

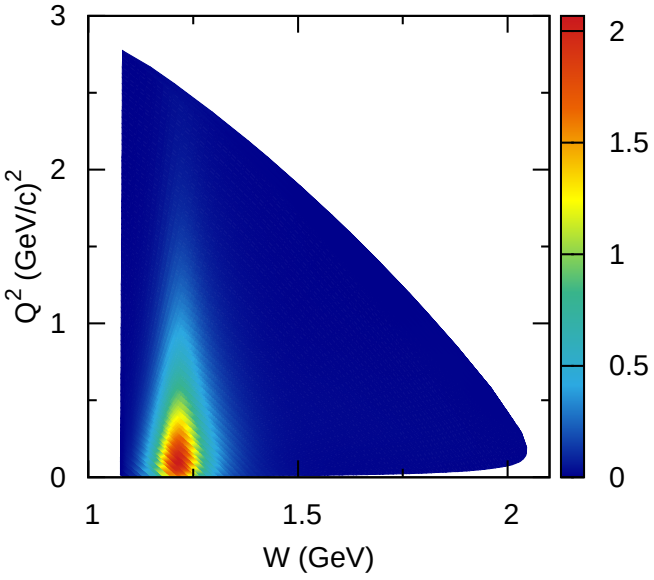
Step 3
Axial vector coupling of N to N^*, Δ: use PCAC. Q^2 dependence: assume dipole



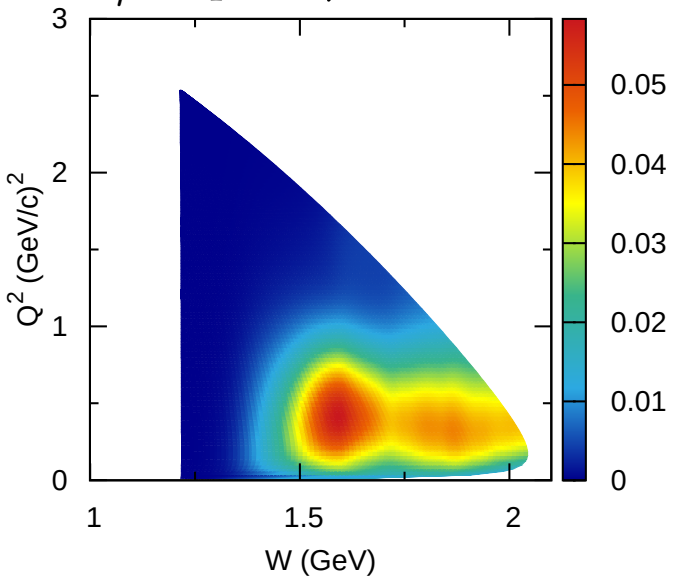


Overview of neutrino induced reaction (ANL-Osaka Model) $d\sigma/dW/dQ^2$ at $E_\nu = 2GeV$

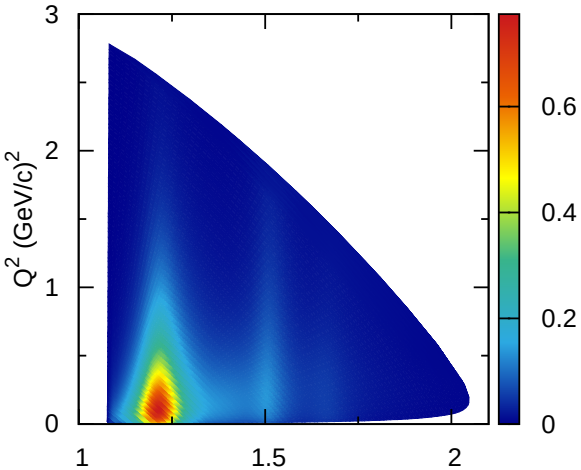
$\nu_\mu + p \to \mu^- + \pi^+ + p$



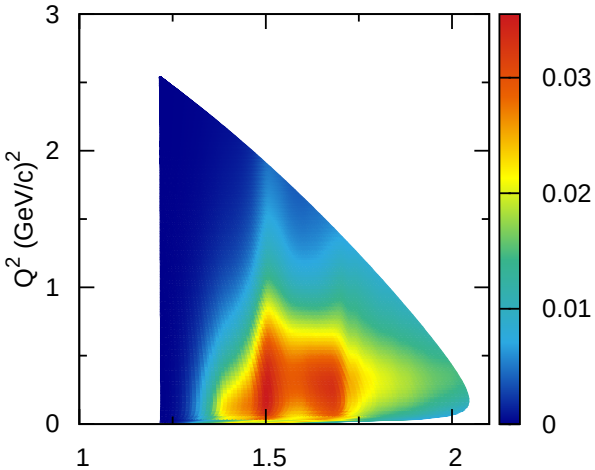
$\nu_\mu + p \to \mu^- + \pi^+ + \pi^0 + p$



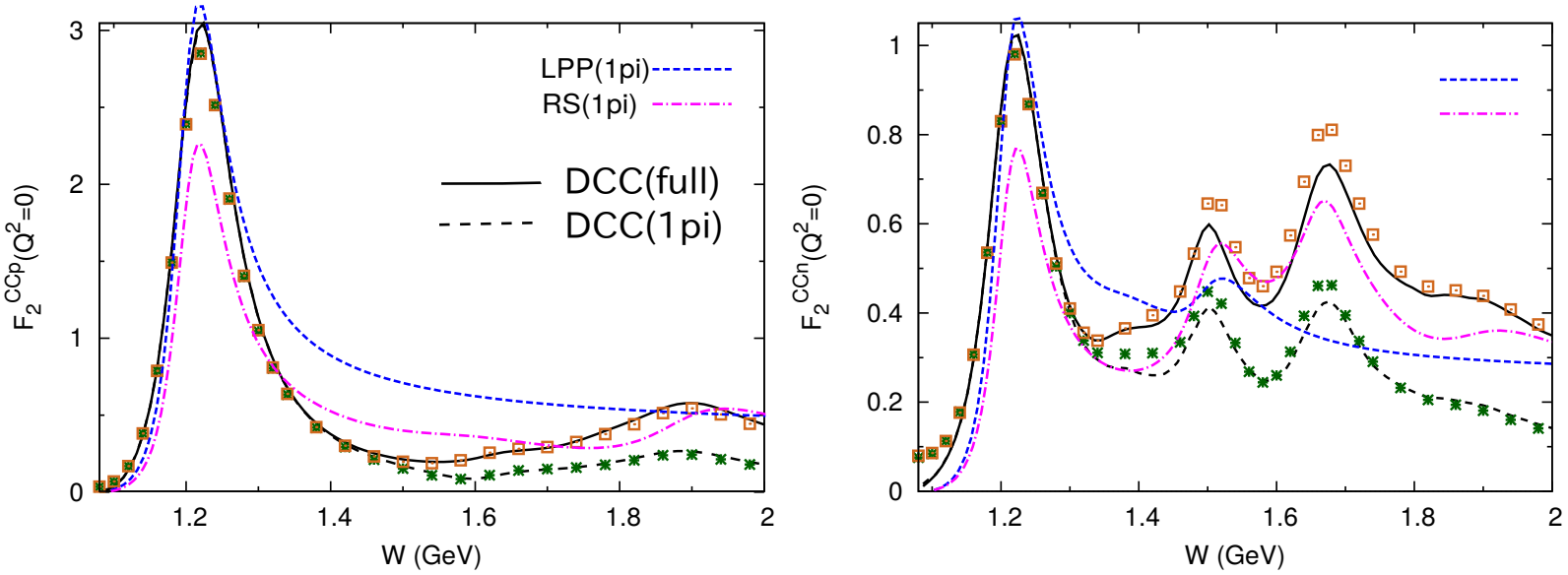
$\nu_\mu + n \to \mu^- + \pi + N$



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

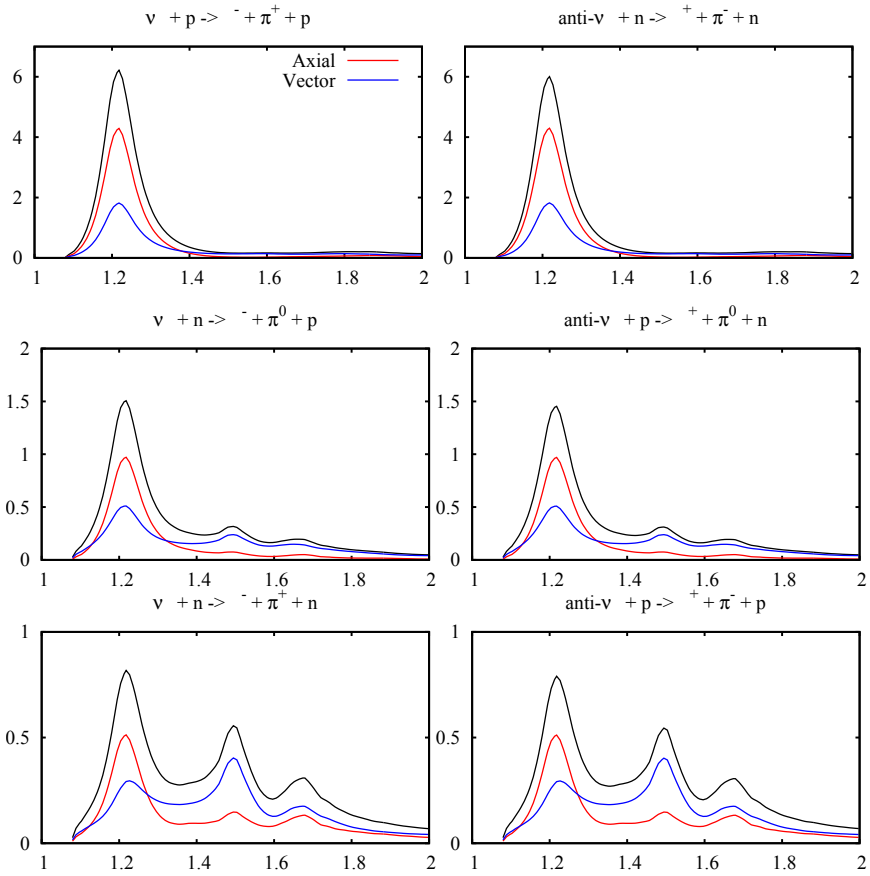


F_2^{CC} at $Q^2 = 0$: test of axial vector current

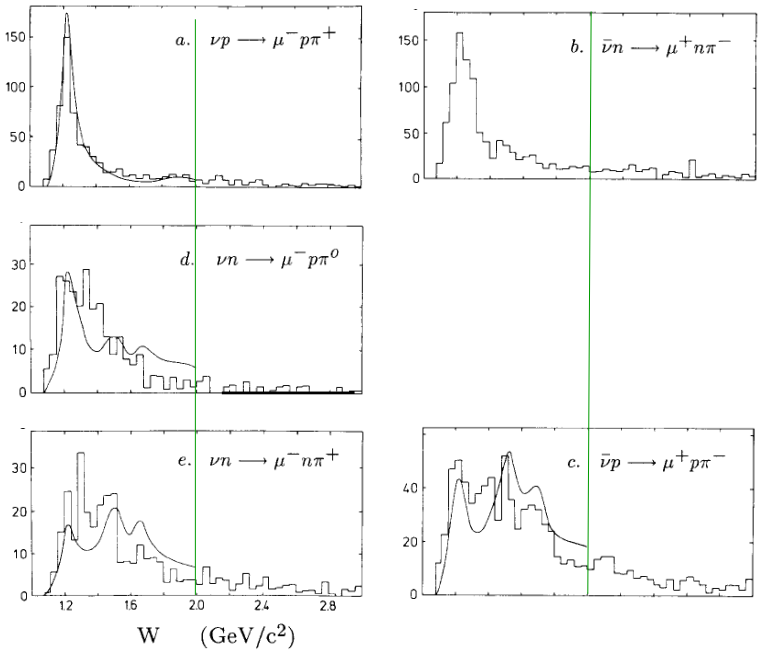


W dependence

$d\sigma/dW$ for single pion production $E_\nu = 40GeV$



Neutrino anti-neutrino

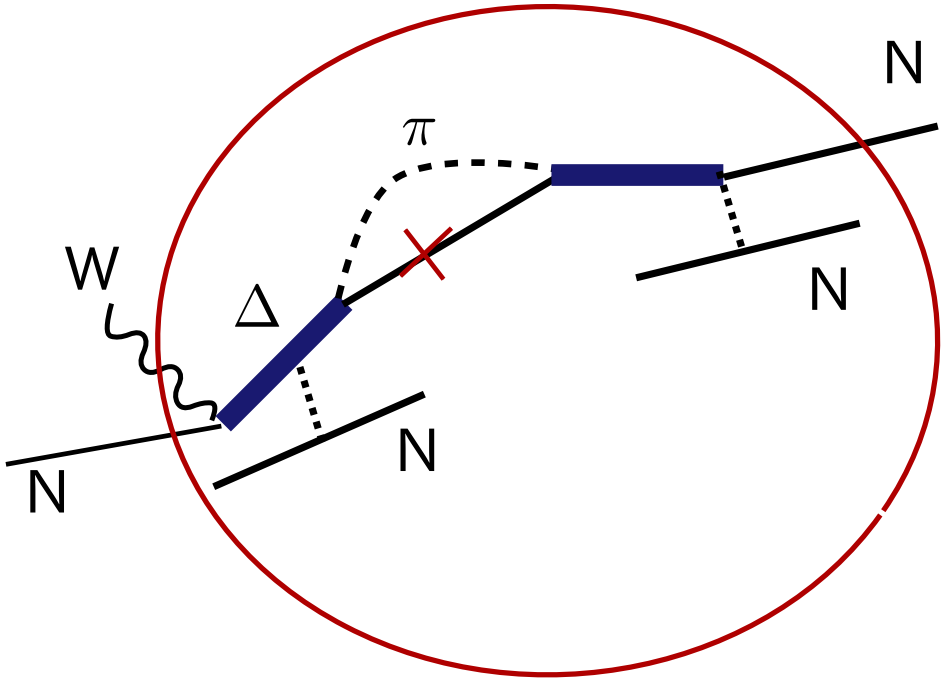


BEBC NP343,285(1990)

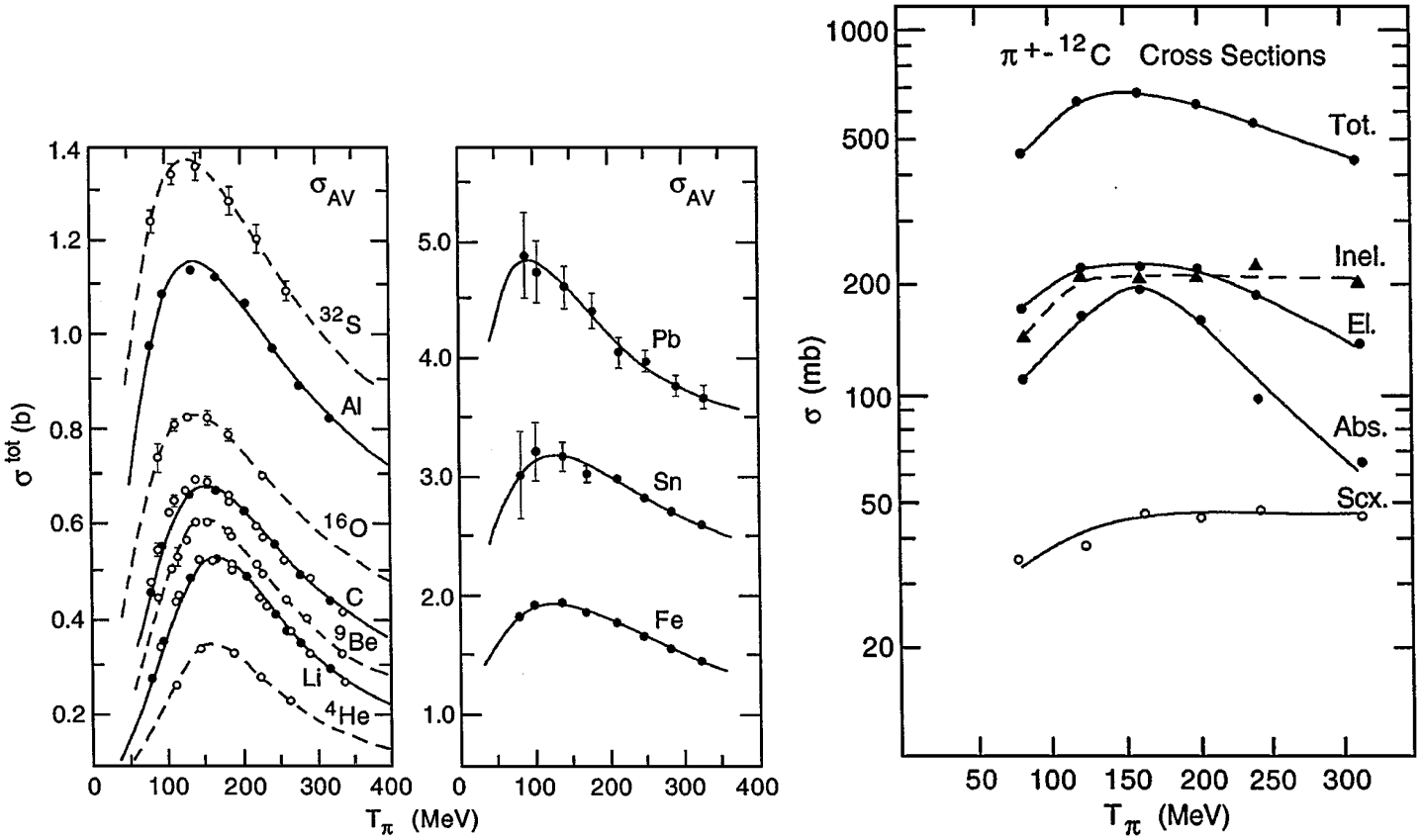
neutrino nucleus reaction in Delta region

- pion-nucleus reaction
- Delta hole model
- Coherent pion production

Delta propagation in nuclei



pion-nucleus reaction

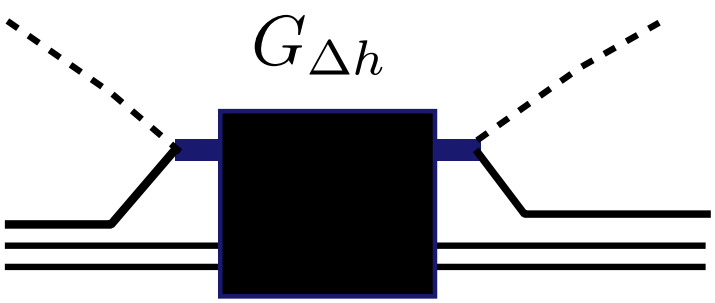


T. -S. H. Lee and R. P. Redwine, Annu. Rev. Nucl. Part. Sci. 52 (2002) 23

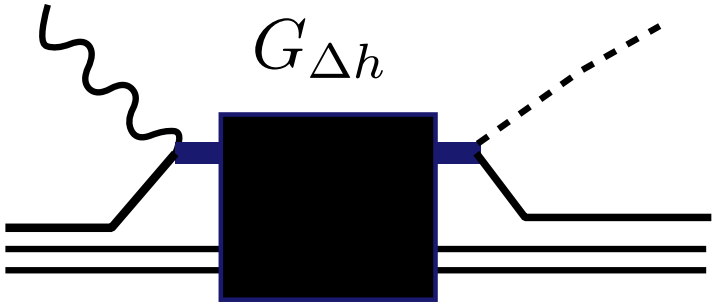
- Δ peak becomes wider
- Important channels of π nucleus reaction:elastic,inelastic,pion absorption

pion-nucleus reaction

- Assumption : Δ-hole doorway state
- Medium effects on pion and delta are in Δ-hole Green function



pi-A elastic



Coherent pion production

Delta-hole Green function

Delta-hole Green's function

$$G_{\Delta h}^{-1} = E - H_\Delta - M_0 - \Sigma_\Delta(E - H_\Delta) - \Sigma_{Pauli} - W_{el} - W_{SP}$$

with $H_\Delta = T_\Delta + V_\Delta + H_{A-1}$

T-matrix for pion elastic scattering.

$$T_{P,P} = PH_{\pi N\Delta} G_{\Delta h}(E) H_{\pi N\Delta} P$$

- Introduce Fock Space projection operator
  $P \to \pi +$ Gr. $\quad D \to \Delta h \quad Q \to$ No$\pi, ...$
- $PHQ = 0$ (doorway state assumption).
- Projecting out P and Q and they re-appear as effective interaction in D space.

Delta-hole Green function

Delta-hole Green's function

$$\boxed{G_{\Delta h}^{-1} = E - H_\Delta - M_0 - \Sigma_\Delta(E - H_\Delta) - \Sigma_{Pauli} - W_{el} - W_{SP}}$$

with $H_\Delta = T_\Delta + V_\Delta + H_{A-1}$

- Non-local Green's function due to T_Δ
- Σ_Δ: πN self energy of free delta. ($G_\Delta^0 = \dfrac{1}{\omega - M_0 - \Sigma_\Delta(\omega)}$)
- Σ_{Pauli}: correction due to forbidden state
- $W_{el} = DH_{\pi N\Delta}\dfrac{P}{E - T_\pi - H_A + i\epsilon}H_{\pi N\Delta}D$: pion-nucleus elastic scattering.
- $W_{SP} = DH_{\pi N\Delta}\dfrac{Q}{E - H_Q + i\epsilon}H_{\pi N\Delta}D$: spreading potential(pion absorption..).

Imaginary part of Δh state ($\pi^{16}O$)

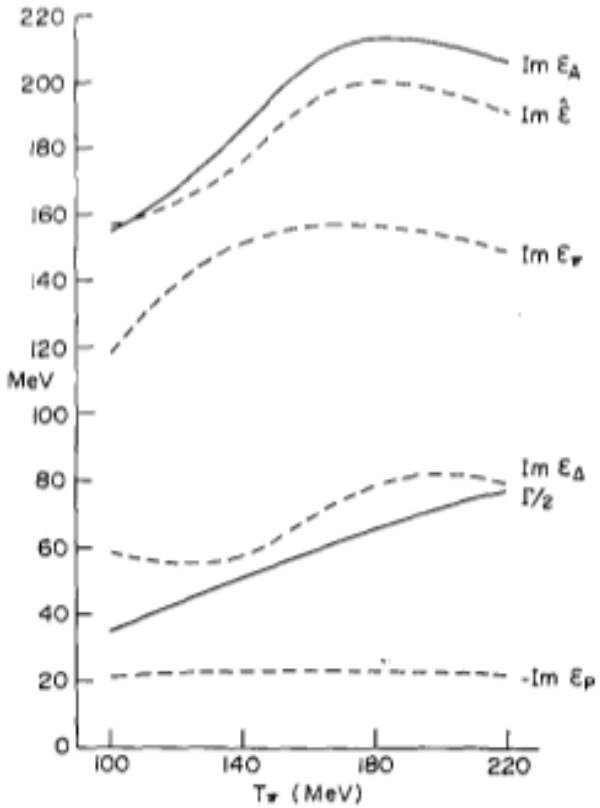


Fig. 1. Decomposition of Im $\epsilon_A = \Gamma/2 + \langle A_1|\mathcal{H}|A_1\rangle$ for 0^- partial wave into contributions from pion term, Im ϵ_π, Pauli blocking, Im ϵ_P, and isobar binding and background potential, Im ϵ_Δ. Im $\hat{\epsilon} = \Gamma/2 + \langle\hat{D}|\mathcal{H}|\hat{D}\rangle$, where $|\hat{D}\rangle$ is the dominant 0^- doorway state and $\Gamma/2$ is the free half width of the isobar.

$$
\begin{aligned}
Im(\epsilon_\pi) &= Im(W_{el}) \\
Im(\epsilon_\Delta) &= Im(W_{sp}) \\
-Im(\epsilon_F) &= Im(\Sigma_{Pauli})
\end{aligned}
$$

M. Hirata,J.H.Koch,F.Lenz,E.J.Moniz PL 70B(1977)281.

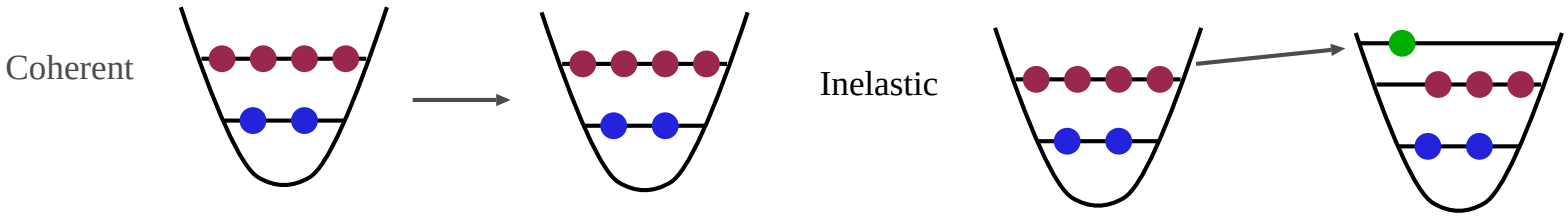
Neutrino induced Coherent pion production

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

Coherent pion production is 'elastic' scattering

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

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



- Selects particular operator of pion production mechanism: quantum number transferred from (a, b) to nuclei is 0^+0. no spin, angular momentum , isospin transfer to nuclei
- momentum transfer to nucleus is limited by nuclear size. $|\vec{p}_\nu - \vec{p}_\mu - \vec{p}_\pi|^2 < 1/R_A^2$

Neutrino induced coherent pion production and PCAC

'parallel kinematic' plus massless lepton

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

$\rightarrow$

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

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

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

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

Extrapolation:

- Non-zero Q^2 region
- Finite lepton mass correction
- (Use empirical $\pi - A$ elastic cross section)
  Ch. Berger and L. H. Sehgal, PRD 79 (2009) 053003

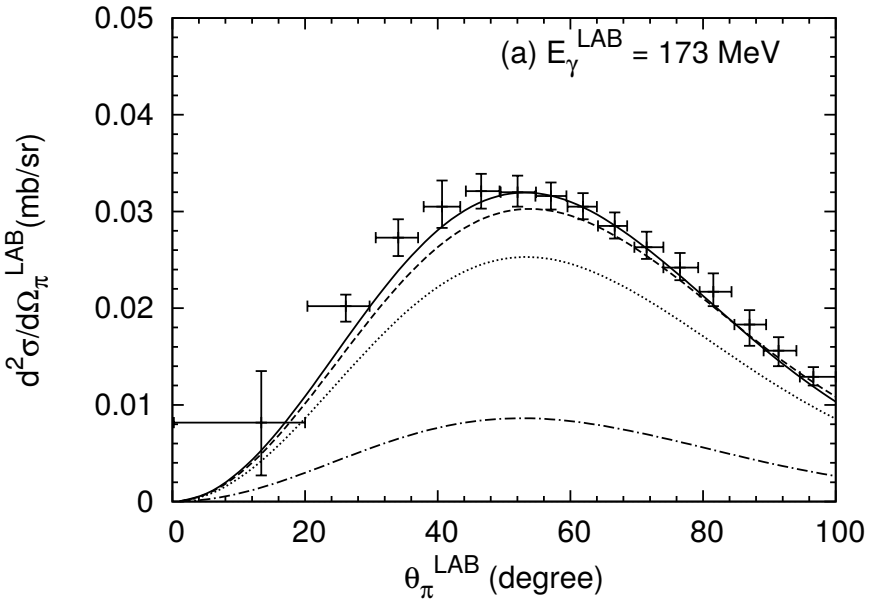
Apply Delta-hole model

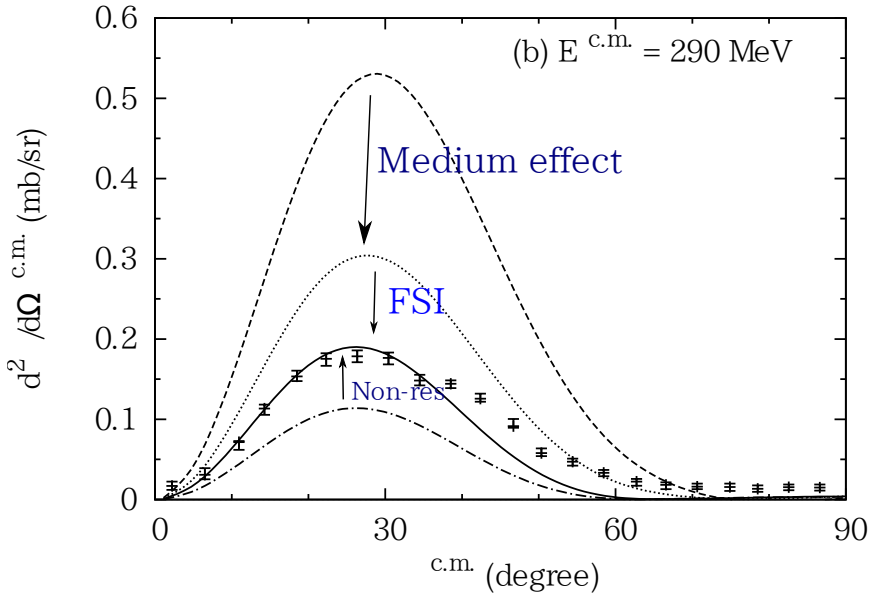
- use reaction model of weak pion production on nucleon for non-resonant and resonant mechanism.(lecture 2)
- interaction of pion with nuclei and propagation of delta inside nuclei are taken into account by using delta-hole model.
- No parameters left to tune for coherent pion production, results are prediction.

Note

- Use local density approximation of Delta-hole model.
  B. Karaoglu, E. J. Moniz, PRC33 (1986)794.
- non-resonant mechanism: DWBA
- Determine spreading potential from the analysis of pion nucleus elastic, total and absorption cross section.
- coherent pion photoproduction as a test of reaction model.

coherent pion photoproduction on 12C

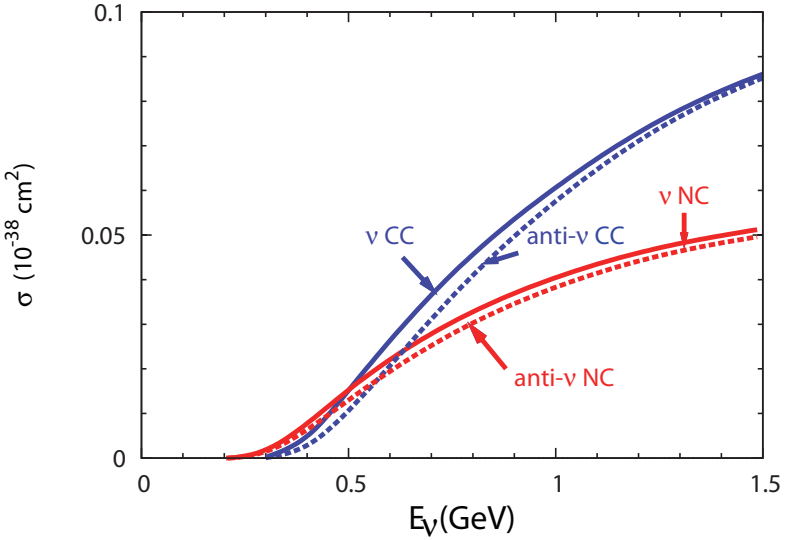




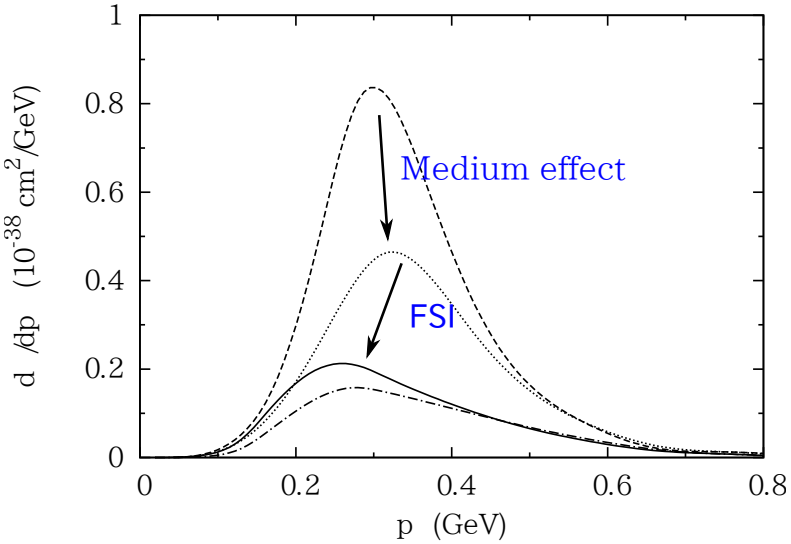
solid (full), dash (without FSI,medium effect in $G^{\Delta h}$), dot(with medium effect), dash-dot(delta only) $E_{\gamma L} = 173,\ 290$MeV

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

CC coherent pion production(^{12}C)



Pion momentum distribution



solid (full), dash (without FSI,medium effect in $G^{\Delta h}$), dot(with medium effect), dash-dot(delta only), $E_\nu = 1GeV$

Channel (EXP.)	CCπ^+(K2K)	CCπ^+(T2K)	NCπ^0(MiniBooNE)
Data	< 7.7	$3.3 \pm 0.8^{+1.3}_{-1.2}$ $3.9 \pm 1.0^{+1.5}_{-1.4}$	$7.7 \pm 1.6 \pm 3.6$
Alvarez-Ruso et al.	8.3 (4.4)	[5.3]	3.9 (2.0)
Berger et al.	0.62×12	–	–
Nakamura et al.	6.3	3.1	2.8
Hernández et al.	6.1 ± 1.3	–	2.6 ± 0.5

- CC and NC coherent pion production cross sections from several theoretical calculations in comparison with data. The unit is $10^{-40}\mathrm{cm}^2$.
- In the second, third, and fourth columns, theoretical cross sections have been convoluted with the neutrino fluxes used in K2K, T2K, and MiniBooNE experiments, respectively.
- The two results of the T2K are from different analyses in which different coherent pion production models were used.
- references are given in S. X. Nakamura et al. Rep. Prog. Phys 80(2017)056301

summary

- meson production reaction beyond Delta
  - Reaction model($W < 2GeV$) for neutirno induced meson production including $\pi N, \eta N, KY, \pi\pi$ N are developed.
  - Model is constrained by currently available meson production data.
  - N^*, Δ, Non-resonant mechanism, interference among amplitudes are important.
  - Only simple dipole form is examined for N to resonance axial transition form factors.
- coherent pion production
  - Medium effects to the propagation of Delta is very important. (pion rescattering, absorption).
  - Microscopic theoretical models give rather stable predictions for coherent reaction cross section and consistent with $CC\pi^+$ data.
  - Inelastic reactions to the low energy excited nuclear states are not fully explored yet.