Dynamical Model of Coherent Pion Production in Neutrino-Nucleus Scattering

[Phys. Rev. C **81**, 035502 (2010)]

Satoshi Nakamura (JLab)

Collaborators

T. Sato (Osaka U.)

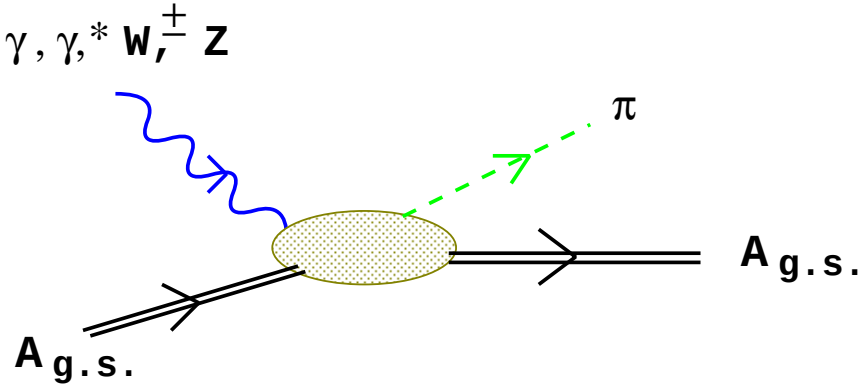
T. S.-H. Lee (ANL)

B. Szczerbinska (Dakota State U.)

K. Kubodera (U. South Carolina)

Introduction

What is coherent pion production ?



* Amplitude is approximately proportional to nuclear form factor

  $\Longrightarrow$ Forward scattering (small momentum transfer) is favored

* Δ-excitation and its propagation in nuclei

  $\Longrightarrow$ Good laboratory to study Δ in nuclei

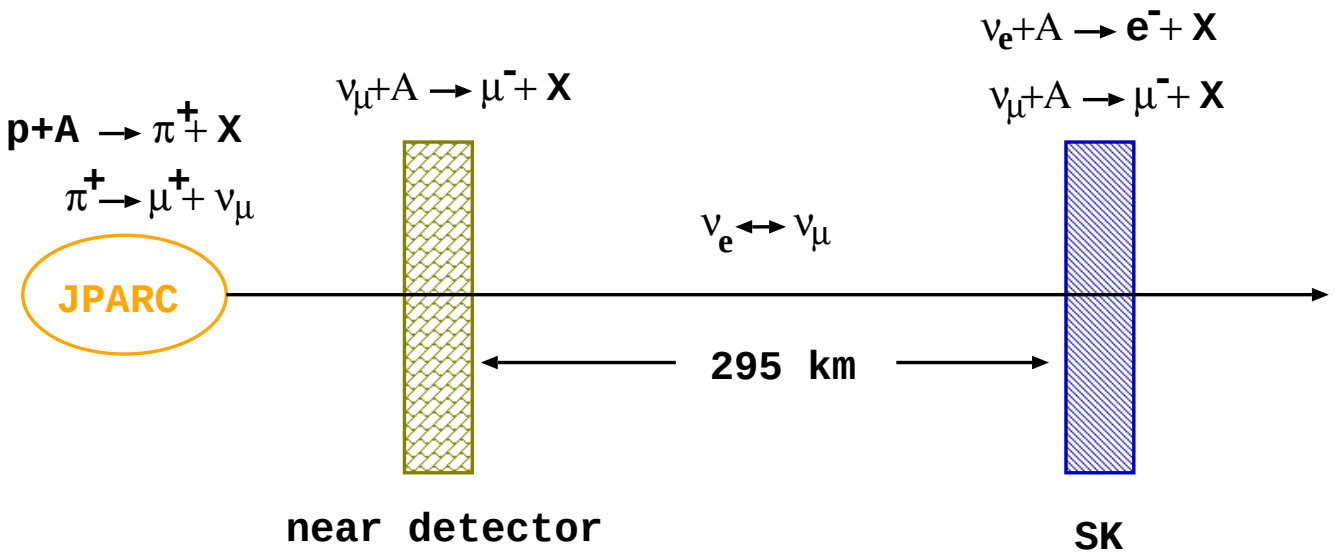
Recent interest in coherent π production in ν-nucleus interaction

Neutrino oscillation experiments (K2K, T2K, MiniBooNE ... etc.)

current trend : accelerator neutrino in sub- few-GeV region

precise determination of neutrino mixing angle and Δm^2_ν

e.g. **T2K**



ν-nucleus scattering in few-GeV region

* dominant

  - Quasi-elastic $\nu_\mu + A \to \mu^- + p + (A-1)$

  - Quasi-free 1π production $\nu_\mu + A \to \mu^- + \Delta^{++} + (A-1)$, $\Delta^{++} \to \pi^+ + p$

* sub-dominant (still need to be understood)

  - Coherent π production $\nu_\mu + A \to \mu^- + \pi^+ + A_{g.s.}$ (CC)

    $\nu + A \to \nu + \pi^0 + A_{g.s.}$ (NC)

    — Improved description of π event in forward direction

    — Excess of Electron-like Events in MiniBooNE ($\nu_\mu \to \nu_e$)

PRL **102**, 101802 (2009)

Recent experiments for ν-induced coherent π production

* No evidence for CC ($\nu_\mu + {}^{12}\mathrm{C} \to \mu^- + \pi^+ + {}^{12}\mathrm{C}_{g.s.}$, $E_\nu \sim 1$ GeV)

  K2K [PRL **95**, 252301 (2005)], SciBooNE [PRD **78**, 112004 (2008)]

* Signature for NC ($\nu_\mu + {}^{12}\mathrm{C} \to \nu_\mu + \pi^0 + {}^{12}\mathrm{C}_{g.s.}$, $E_\nu \sim 1$ GeV)

  MiniBooNE [PLB **664**, 41 (2008)], SciBooNE [PRD **81**, 111102 (2010)]

Puzzling result because ...

- Naive expectation from isospin matrix element : $\sigma_{CC} \sim 2\ \sigma_{NC}$
- Finite μ mass reduces phase space at low-energy

Theoretical approaches to coherent π production

* PCAC (Partially Conserved Axial Current)-based model
  - Rein, Sehgal, NPB **223**, 29 (1983)
  - Paschos, Kartavtsev, Gounaris, PRD **74**, 054007 (2006)
  - Berger, Sehgal, PRD **79**, 053003 (2009)
* Dynamical microscopic model
  - Amaro, Hernandez, Nieves, Valverde, PRD **79**, 013002 (2009)
  - Alvarez-Ruso et al., PRC **75**, 055501 (2007)
  - Martini, Ericson, Chanfray, Marteau, PRC **80**, 065501 (2009)

PCAC-based model

Rein and Sehgal, NPB **223**, 29 (1983)

- For $q^2 \to 0$ (q_μ : momentum transfer from lepton)

$$\mathcal{M}_{coh} \sim q_\mu \left(F_{\pi N\Delta} G_\Delta A^\mu_{\Delta N} + F_{\pi NN} G_N A^\mu_{NN}\right) F_A \; F_{abs}$$

- PCAC relation and Klein-Gordon Equation

$$\begin{aligned} q_\mu A^\mu &= f_\pi m_\pi^2 \, \pi && \text{(PCAC)} \\ (-q^2 + m_\pi^2)\, \pi &= S_\pi && (\text{K} - \text{G eq.}) \end{aligned}$$

$$\Longrightarrow \qquad \mathcal{M}_{coh} \sim f_{\pi N \to \pi N} \; F_A \; F_{abs}$$

Good approximation for

* $E_\nu \gtrsim 2$ GeV
* medium and heavy nuclei

Dynamical model for coherent π production

* Elementary amplitudes ($\nu N \to \mu^- \pi^+ N$, $\nu N \to \nu \pi^0 N$)

* Medium effects

  Final state interaction (π-nucleus scattering)

  Δ-properties in nucleus (mass, width, non-locality)

Dynamical model for coherent π production

* Elementary amplitudes ($\nu N \to \mu^- \pi^+ N$, $\nu N \to \nu \pi^0 N$)

  $\Rightarrow$ SL model [Sato and Lee, PRC **54**, 2660 (1996); **67**, 065201 (2003)]

* Medium effects

  Final state interaction (π-nucleus scattering)

  Δ-properties in nucleus (mass, width, non-locality)

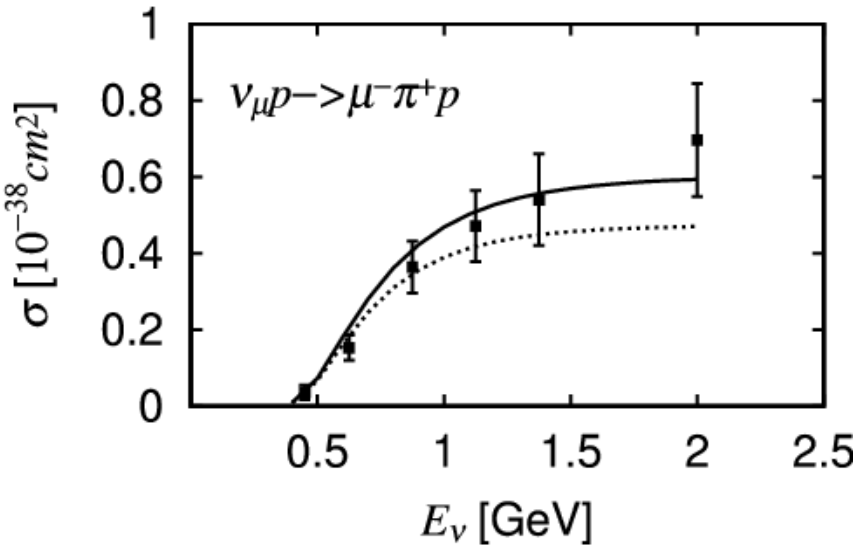
  $\Rightarrow$ Δ-hole model [*e.g.*, Koch and Moniz, PRC **27**, 751 (1983)]

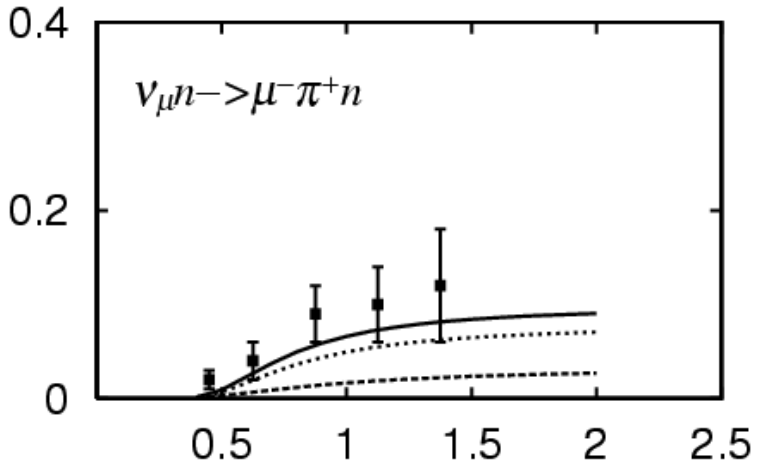
This work

Combine SL and Δ-hole model and study coherent π production !

Model SL model [PRC **54**, 2660 (1996); **67**, 065201 (2003)]

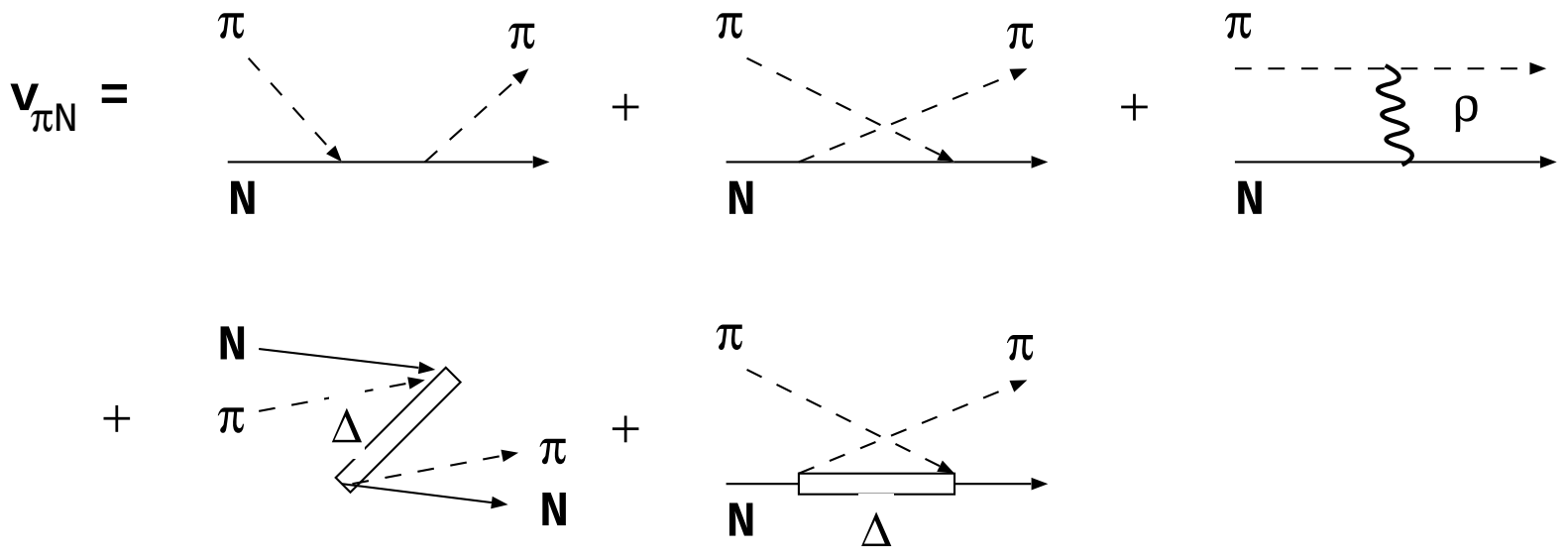
* Model for electroweak π production off nucleon in Δ region
* Non-perturbative resonant and non-resonant amplitudes (π cloud)
* Consistent description of JLab, BNL data for (γ, π^0) and $(e, e'\pi^0)$

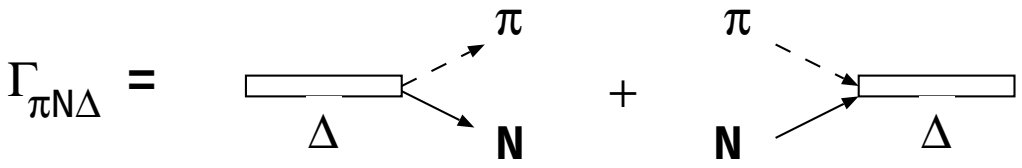




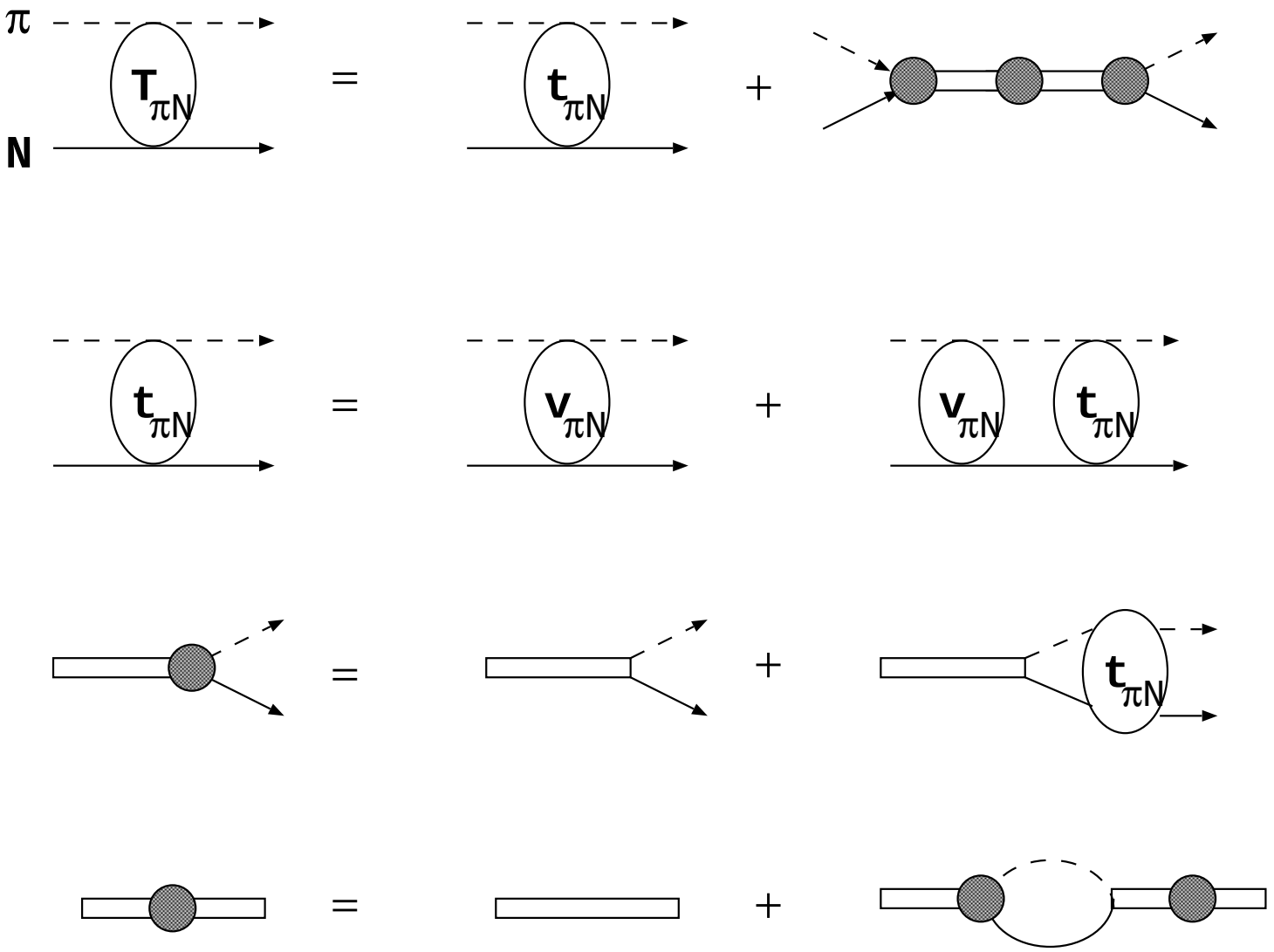
example : πN scattering in SL model

Kernels





T-matrix and Lippman-Schwinger Equation



π-A (nucleus) optical potential from Δ-hole model

[Karaoglu *et al.*, PRC **33**, 974 (1986)]

$$t_{\pi N}^{SL} = t_\Delta + t_{non-R} \qquad \Rightarrow \qquad U_{\pi A} = U_\Delta + U_{non-R} + c\rho^2$$

$$t_\Delta = \frac{F_{\pi N\Delta}(\tilde{k}')F_{\pi N\Delta}(\tilde{k})}{D(W)} \ , \qquad D(W) = W - m_\Delta^0 - \Sigma_{self}(W)$$

$$\Longrightarrow \qquad U_\Delta(k',k) \sim \sum_n^{occupied} \int d\vec{p}_\Delta \ \ \phi_n^* \ \frac{F_{\pi N\Delta}(\tilde{k}')F_{\pi N\Delta}(\tilde{k})}{D(E - H_\Delta) - \Sigma_{Pauli} - \Sigma_{spr}} \ \phi_n$$

$$H_\Delta = T_\Delta + V_\Delta + H_{A-1} \ , \qquad T_\Delta \Rightarrow \text{non-local effect}$$

$$\Sigma_{spr} = V_C \ \rho(r) + V_{LS}(r) \ \vec{L}_\Delta \cdot \vec{S}_\Delta$$

Parameters (complex) : V_C, V_{LS}, c_s, c_p $\quad \rightarrow \quad$ π-nucleus scattering data

Optical potential for π-A scattering (contn'd)

$$U_\Delta(k',k) \sim \sum_n^{occupied} \int d\vec{p}\ \phi_n^*(\vec{p'})\ \frac{F_{\pi N\Delta}(\tilde{k}')F_{\pi N\Delta}(\tilde{k})}{D(E-H_\Delta)-\Sigma_{Pauli}-\Sigma_{spr}}\ \phi_n(\vec{p})$$

$$= \int d\vec{r}d\vec{r'} \int d\vec{p}\ \frac{F_{\pi N\Delta}(\tilde{k}')F_{\pi N\Delta}(\tilde{k})}{D(E-H_\Delta)-\Sigma_{Pauli}-\Sigma_{spr}}\ e^{-i\vec{p'}\cdot\vec{r'}}\,\rho(\vec{r},\vec{r'})\ e^{i\vec{p}\cdot\vec{r}}$$

$*$ Negele's local density approx. [PRC **5**, 1472 (1972)]

$$\rho(\vec{r},\vec{r'}) \sim \rho(R)\ j_1(k_F s)\ \frac{3}{k_F s}\ , \qquad [\ \rho(R) \Leftarrow \text{electron scattering data}\ ]$$

$$R = |\vec{r}+\vec{r'}|/2\ , \quad s=|\vec{r}-\vec{r'}|\ , \quad k_F^3 = 3\pi^2\rho(R)/2$$

$*$ Local approx. (*not* used in this work)

$$T_\Delta = p_\Delta^2/2m_\Delta \to 0 \qquad \Longrightarrow \qquad \rho(\vec{r},\vec{r'}) \to \rho(R)$$

Transition amplitude for $\lambda A \to \pi A$ [λ : (axial-)vector current]

$$a^{SL}_{\lambda N\to\pi N} = a_\Delta + a_{non-R} \qquad \Rightarrow \qquad A_{\lambda A\to\pi A} = A_\Delta + A_{non-R}$$

$$a_\Delta = \frac{N(\tilde{k},\tilde{q}_\lambda)}{D(W)} \ , \qquad D(W) = W - m^0_\Delta - \Sigma_{self}(W)$$

$$\Longrightarrow \qquad A_\Delta(k,q) \sim \sum_n^{occupied} \int d\vec{p}_\Delta \ \ \phi^*_n \ \frac{N(\tilde{k},\tilde{q}_\lambda)}{D(E-H_\Delta) - \Sigma_{Pauli} - \Sigma_{spr}} \ \phi_n$$

$$\Longrightarrow \qquad A^{DW}_{\lambda A\to\pi A} = \int d\vec{k}' \ \psi_{\pi A}(\vec{k}') \ A_{\lambda A\to\pi A}(\vec{k}',\vec{q}_\lambda)$$

$\psi_{\pi A}$: π wave function (final state interaction, $U_{\pi A}$)

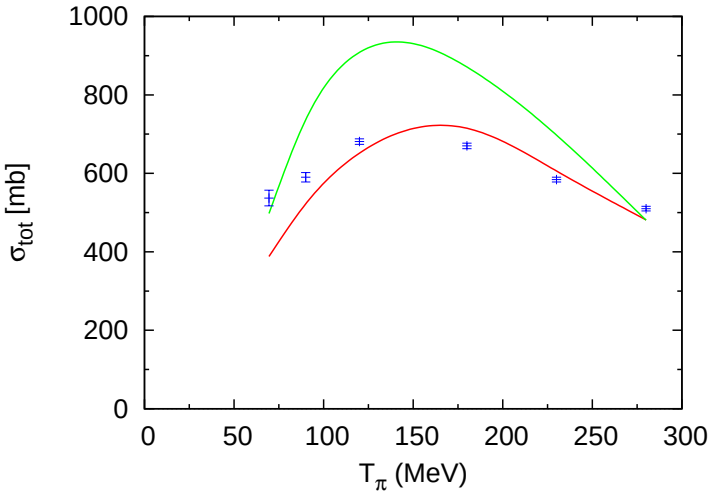
All parameters fixed by π-nucleus scattering data

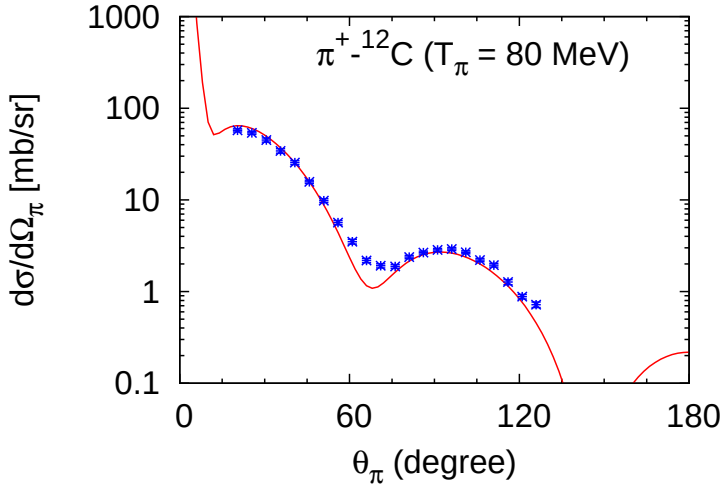
$\Longrightarrow$ parameter-free prediction for $\lambda A \to \pi A$ (consistent model-building)

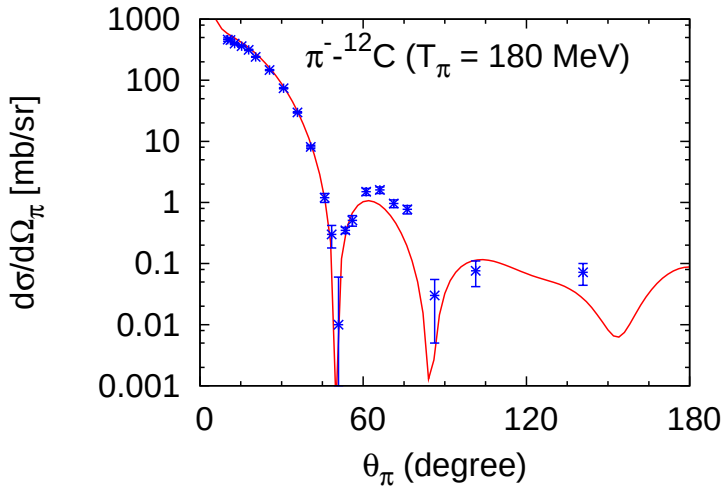
Results

$\pi^{\pm}$ - ^{12}C scattering

[Data : NPB **17**, 168 (1970), PRC **29**, 561 (1984)]







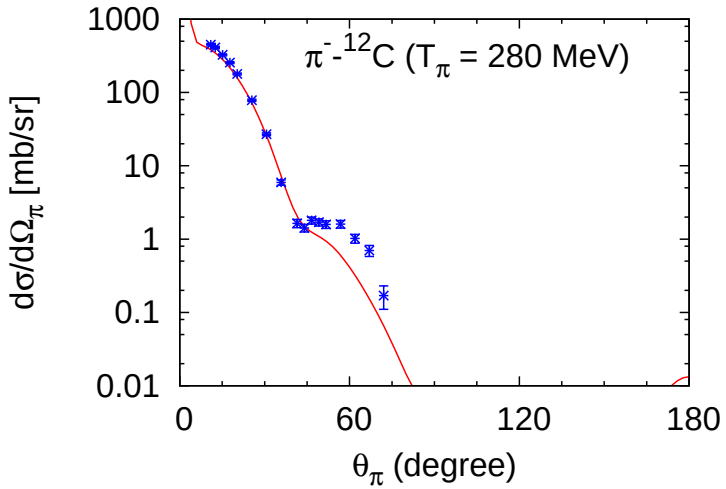
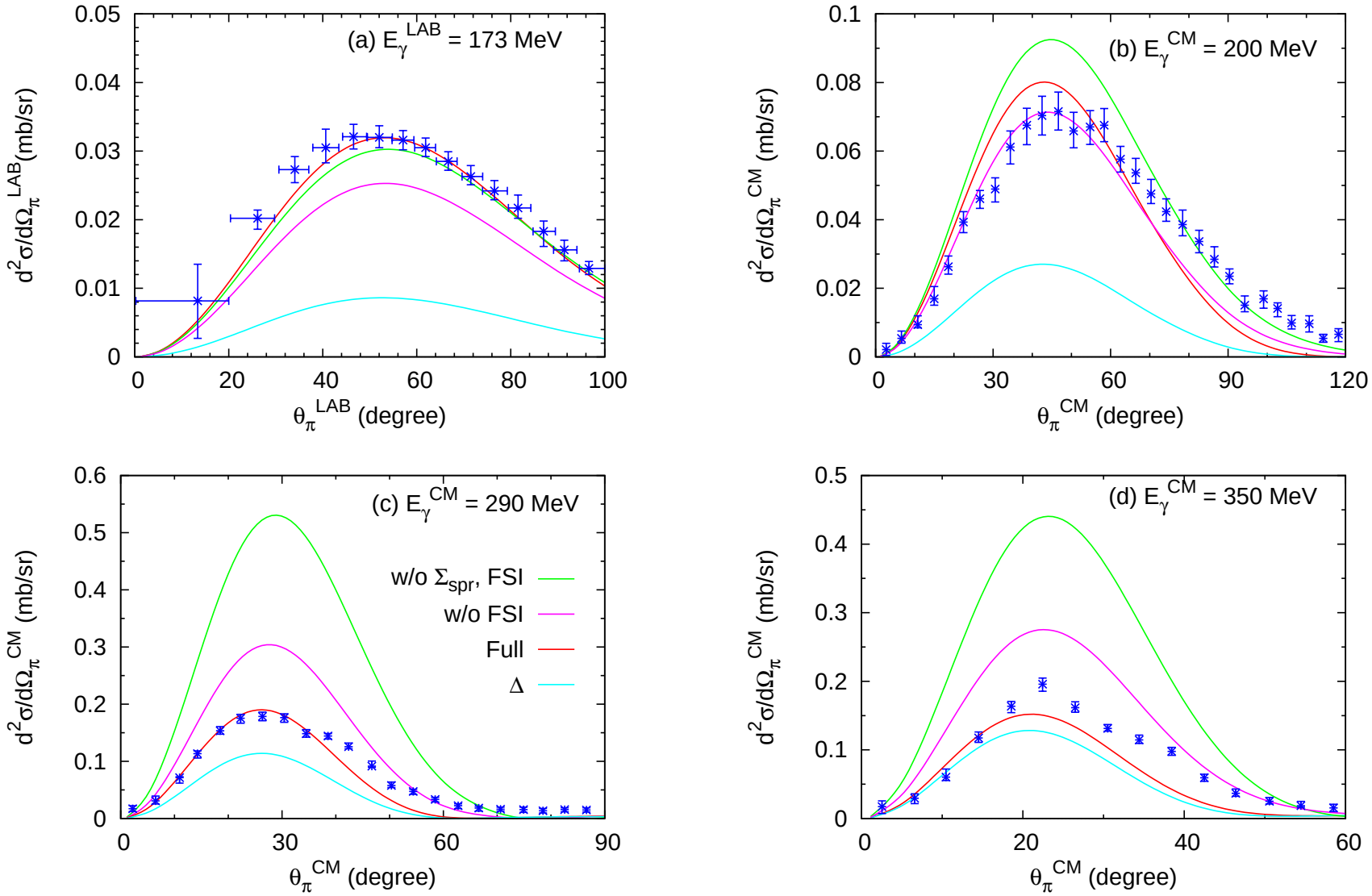


Photo coherent π production $(\gamma + {}^{12}\mathrm{C} \to \pi^0 + {}^{12}\mathrm{C}_{g.s.})$

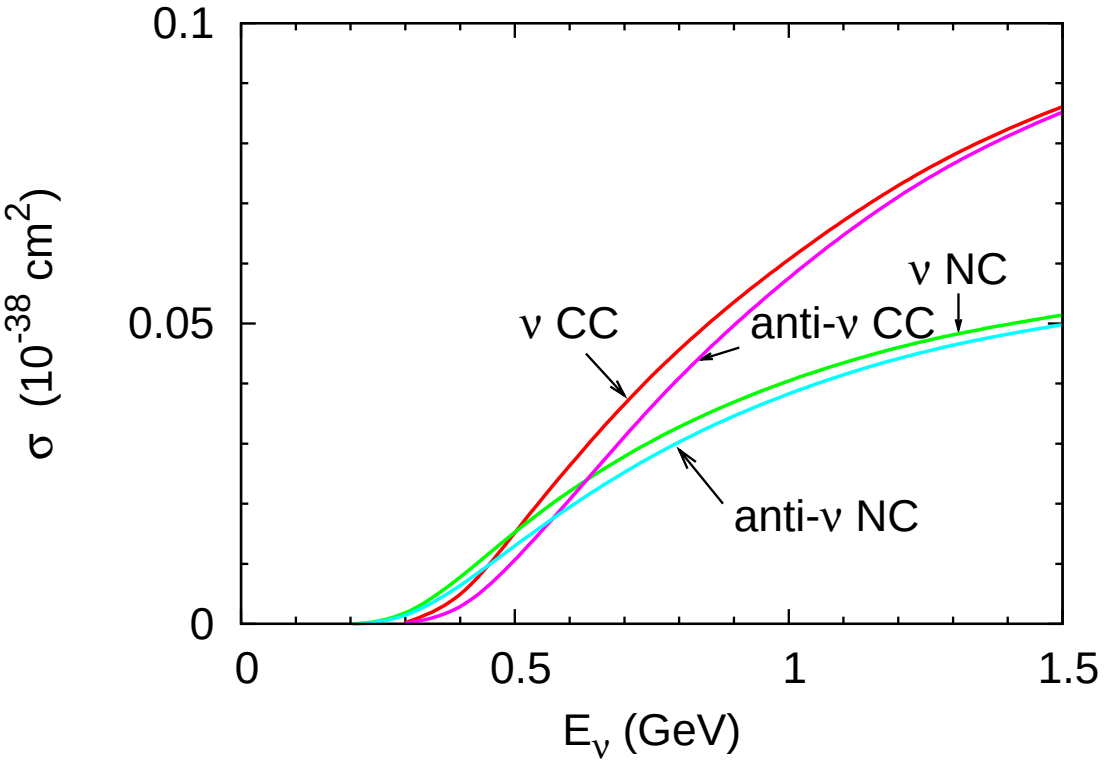


[Data:(a) Gothe et al., PLB**355**,59(1995); (b)-(d) Krusche et al., PLB**526**,287(2002)]

Discussion

- Parameter-free prediction
- Important medium effects
- Important non-resonant mechanism
- Discrepancy in larger angle region
  $\Rightarrow$ contamination from incoherent processes

ν-induced coherent π production on ^{12}C



CC

$\sigma_{\rm ave} = 6.3 \times 10^{-40}{\rm cm}^2$

($p_\mu < 450$ MeV cut applied)

$\sigma_{\rm K2K} < 7.7 \times 10^{-40}{\rm cm}^2$

[ν-flux, $\sigma_{\rm exp}$: PRD **74**, 072003 (2006); PRL **95**, 252301 (2005)]

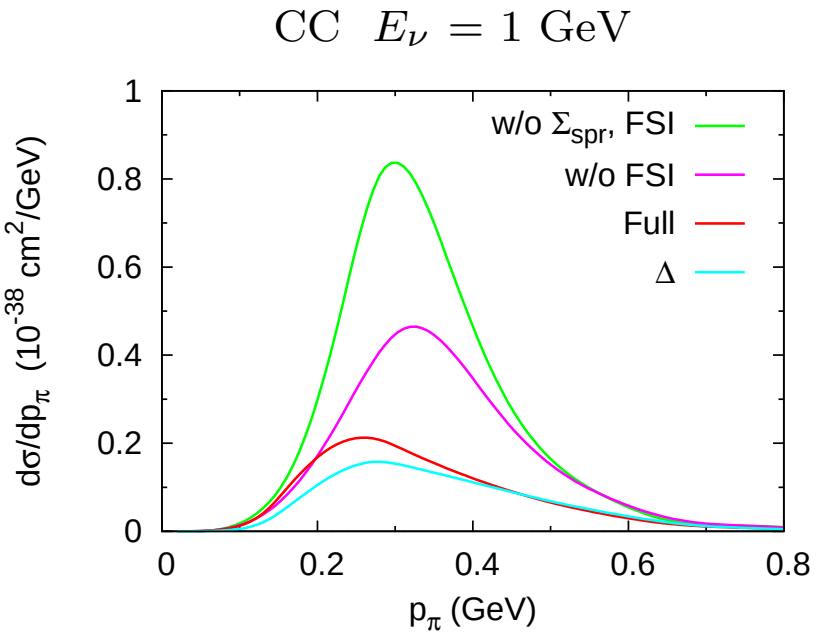
NC

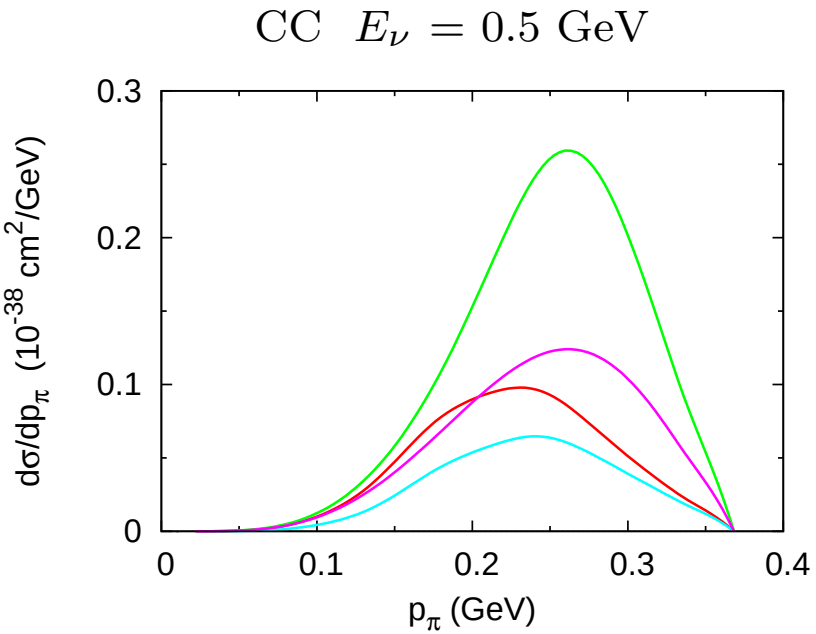
$\sigma_{\rm ave} = 3.9 \times 10^{-40}{\rm cm}^2$

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

[ν-flux, $\sigma_{\rm exp}$: PLB **664**, 41 (2008); Raaf, PhD thesis]

π momentum spectra

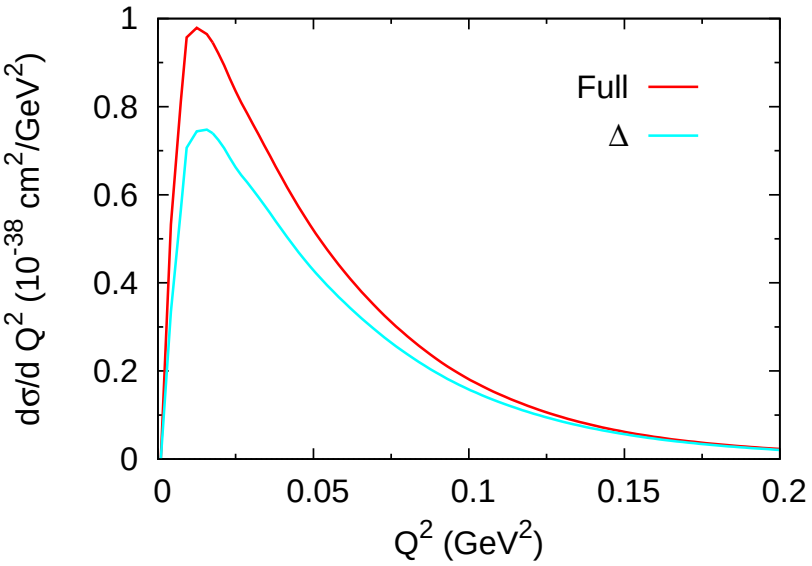




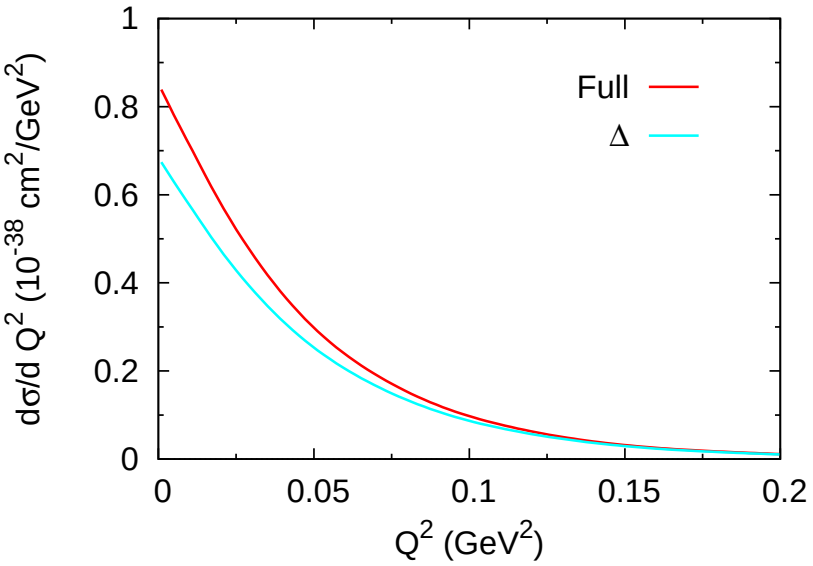
- Large medium effects in Δ region
- Enhancement due to non-resonance (interference with Δ)
  32 (10) % at $E_\nu = 0.5$ (1) GeV
- No contribution from (tree-level) non-resonant mechanism
  in previous calculations

Q^2 distribution

CC $E_\nu = 1$ GeV



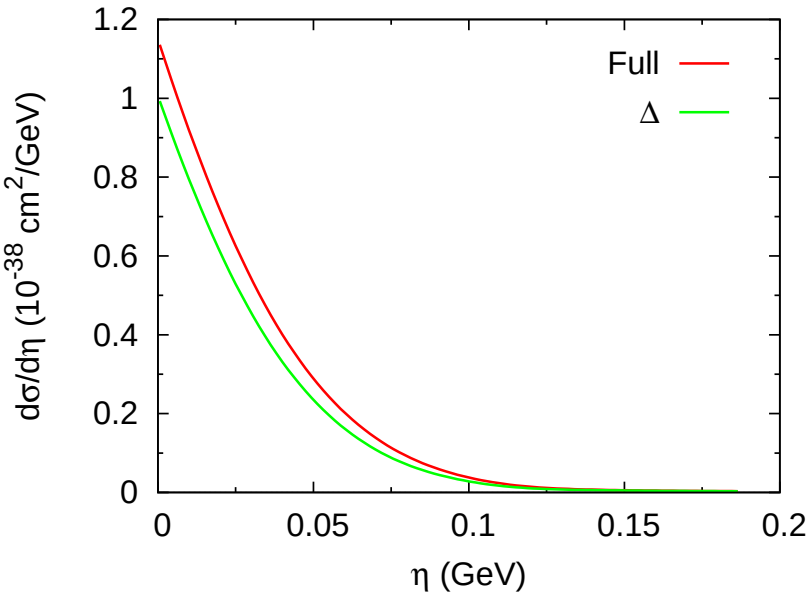
NC $E_\nu = 1$ GeV



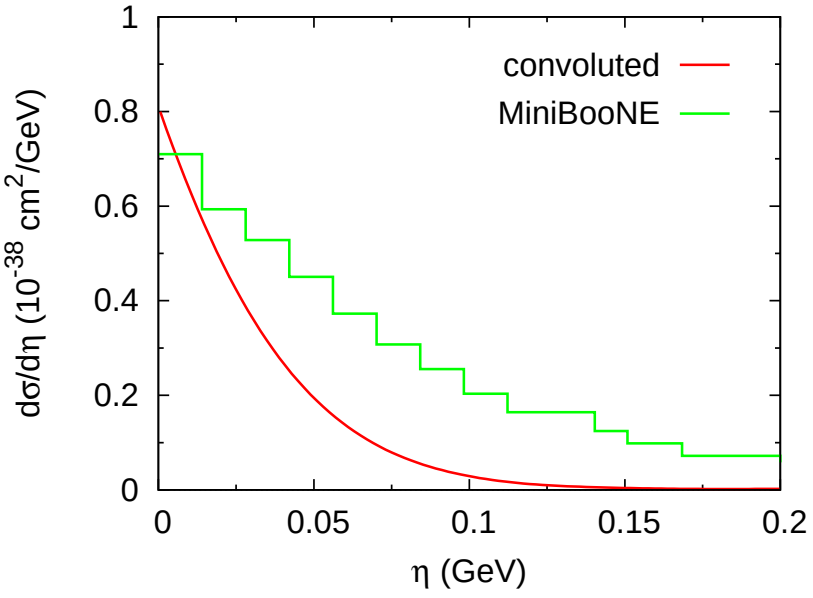
- Sharp peak at $Q^2 \sim 0$ due to strong damping by nuclear form factor
- Non-resonant mechanism sharpens the peak

$\eta \equiv E_\pi(1-\cos\theta_\pi)$ distribution for NC

$E_\nu = 1$ GeV



flux-convoluted

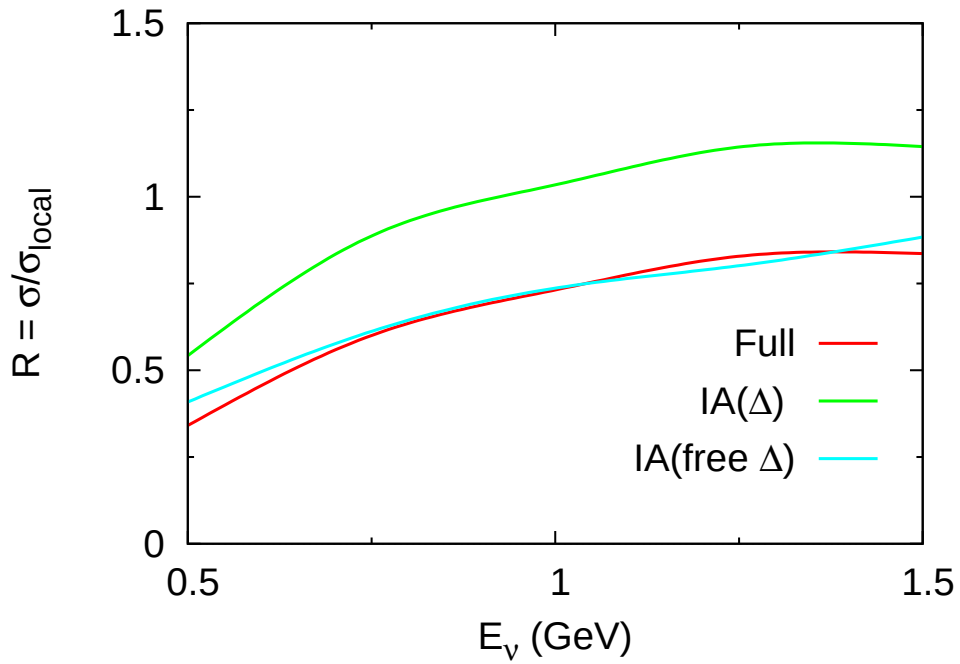


[flux and MC result of MiniBooNE
PLB **664**, 41 (2008)]

- η is useful to break degeneracy of several pion productions in data
- Discrepancy between Monte Carlo (Rein-Sehgal model) and ours
  $\Rightarrow$ possible overestimation of NC cross section

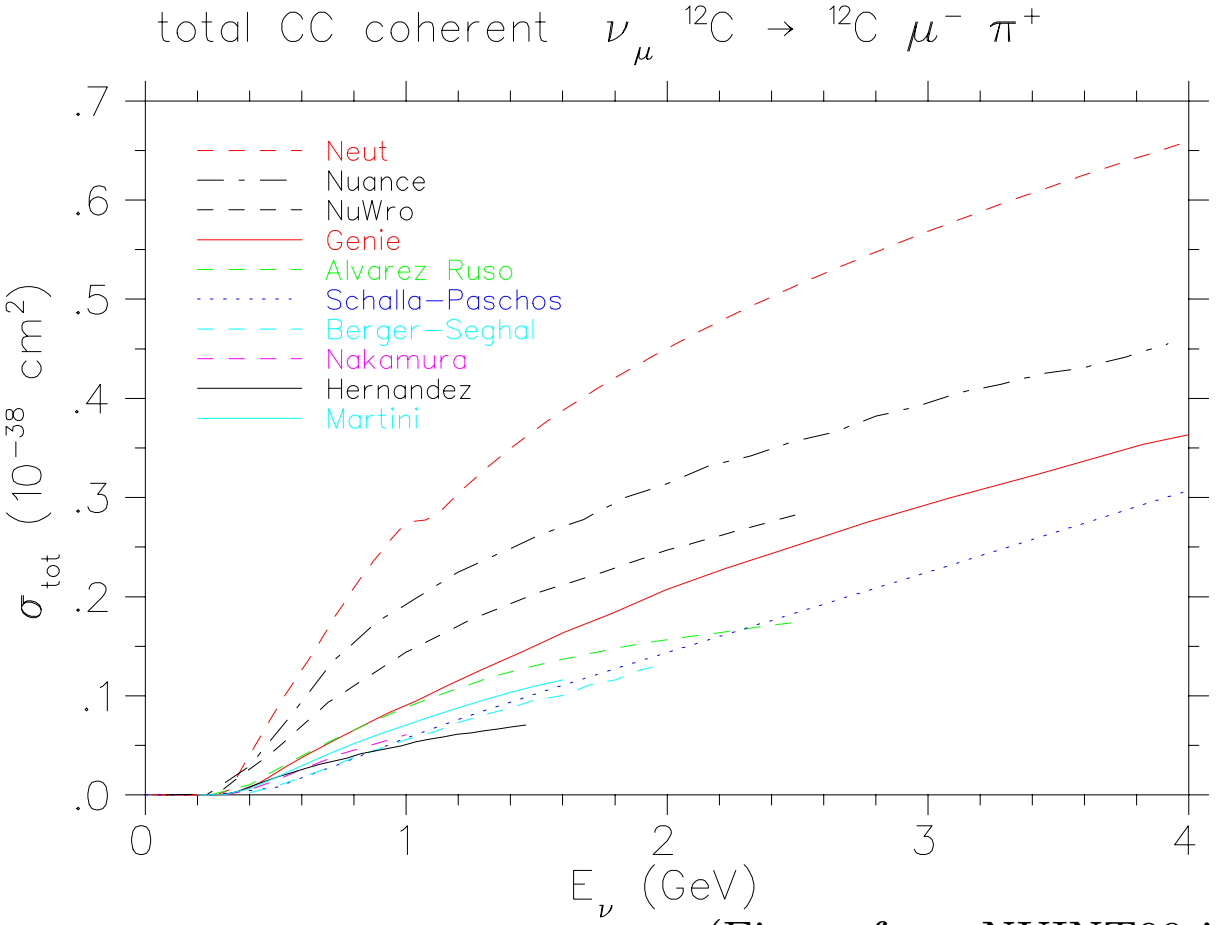
Non-locality of Δ-propagation

(Leitner et al., PRC **79**,057601 (2009))



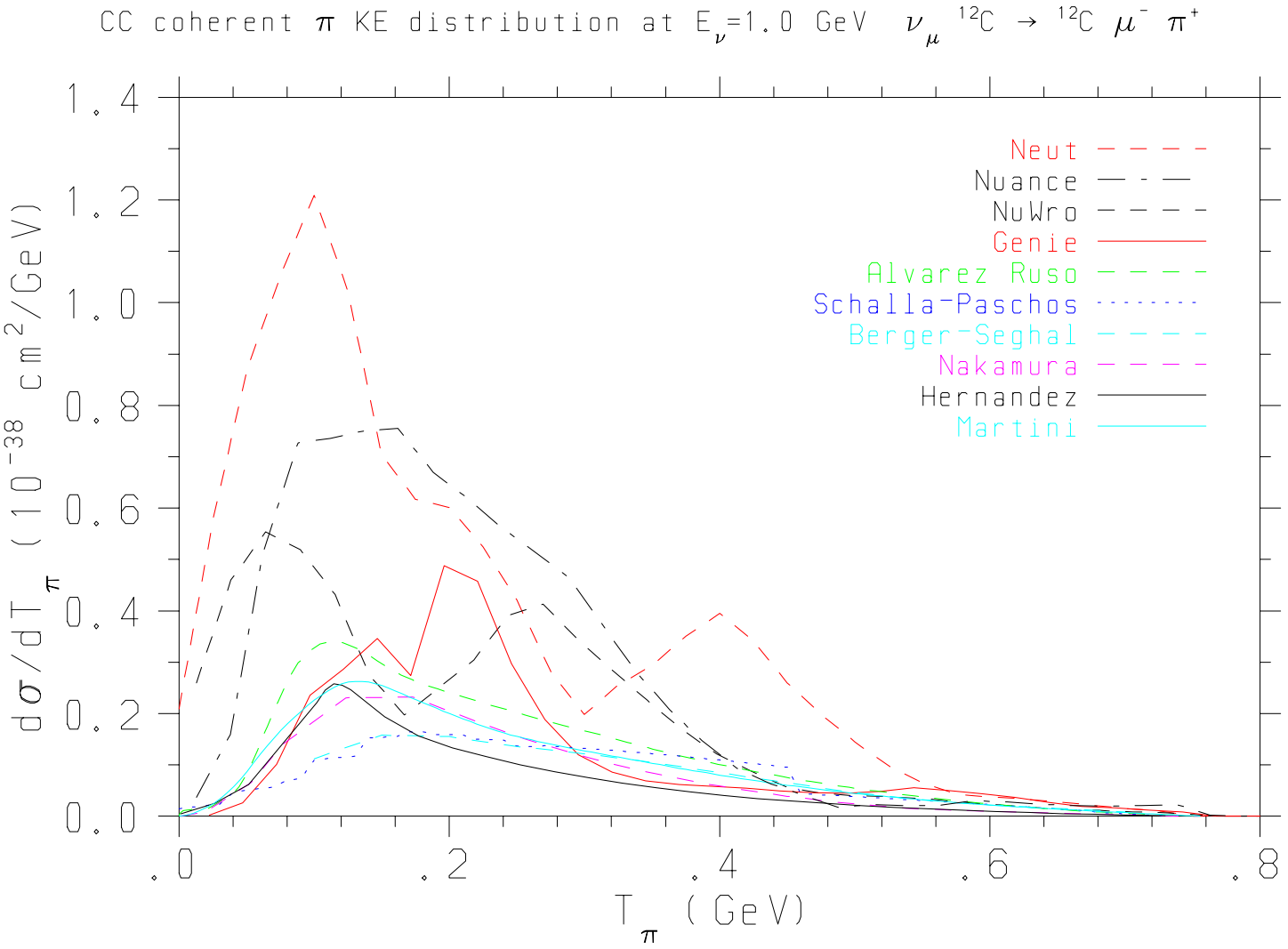
- 60, 30, 20 % reduction for $E_\nu = 0.5$, 1, 1.5 GeV for free Δ and Full
- Non-local effect is still important after including medium effects
- All previous microscopic calculations used local approximation

Comparison of models



(Figure from NUINT09 joint project)

- Large discrepancy between MC code (Rein-Sehgal model) and recent calculations



(Figure from NUINT09 joint project)

Discussion

PCAC-based model

Basic assumptions are questionable for $E_\nu \lesssim 2$ GeV and light nuclei

- $Q^2 = 0$ kinematics
- $p_\pi = q$ kinematics
- local approximation

[critical review : Amaro et al., PRD **79**, 013002 (2009)]

Microscopic model

- Elementary amplitude, tree-level or unitarized, scarce data
- Medium effect, local approximation
- Final state interaction around Δ region
- Comparison with photo-reaction data

Summary

Development of microscopic model for coherent π production

SL model + Δ-hole model which enables a unified description of:

$$\pi A \to \pi A \qquad \gamma A \to \pi^0 A \qquad \nu A \to \ell^- \pi^+ A \qquad \nu A \to \nu \pi^0 A$$

- Reproduce $\pi - A$ and $\gamma A \to \pi^0 A$ data reasonably
- Consistent with K2K data for CC coherent π production
- Numerical results relevant to neutrino experiments presented
- Comparison and review of models made

Future development

* Elementary amplitude with higher resonances beyond Δ

* Implementation of more detailed nuclear structure

QMC wave function significantly improves B(E2) over shell-model

$\Longrightarrow$ Improved description of $\pi - {}^{6,7}\mathrm{Li}$ inelastic scattering

[Lee and Wiringa, PRC **63**,014006 (2000)]

$$\rho_N(\vec{r},\vec{r'}) \;=\; \langle \Psi_{\mathrm{QMC}}| \; \frac{1}{A}\sum_{i=1}^{A} \delta(\vec{r'}-\vec{r_i'})\;\delta(\vec{r}-\vec{r}_i)\frac{1+2t_N\tau_z(i)}{2}\;|\Psi_{\mathrm{QMC}}\rangle$$

Fit to data improves ? Spreading potential changes ?

Future development (contn'd)

Implementation of detailed nuclear structure

$\Longrightarrow$ Fully utilize pion-nucleus processes as laboratory to study

- Δ in nucleus

  Quantitative microscopic evaluation of Δ spreading potential

  ($\Leftrightarrow$ Phenomenological parameterization)

- Role of many-body correlations

  How two-body correlation contributes ?

  More than two-body correlation ?