

# Dynamical Model Approach to Coherent Pion Production

Satoshi Nakamura (U. São Paulo)

## Collaborators

T. Sato (Osaka U.)

T. S.-H. Lee (ANL)

B. Szczerbinska (Dakota State U.)

K. Kubodera (U. South Carolina)

## Introduction

### Recent interest in coherent $\pi$ production in $\nu$ -nucleus interaction

- \* New neutrino oscillation experiments (T2K, MiniBooNE, ...)
- \* Puzzling experimental results (K2K, SciBooNE, MiniBooNE)

$$\sigma_{CC} \sim 2 \sigma_{NC} ?$$

- \* Two theoretical approaches

PCAC-based model, Dynamical model

## Dynamical model approach to coherent $\pi$ production

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

\* Medium effects

Final state interaction ( $\pi$ -nucleus scattering)

$\Delta$ -properties in nucleus (mass, width, non-locality)

## Dynamical model approach to coherent $\pi$ production

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

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

\* Medium effects

Final state interaction ( $\pi$ -nucleus scattering)

$\Delta$ -properties in nucleus (mass, width, **non-locality**)

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

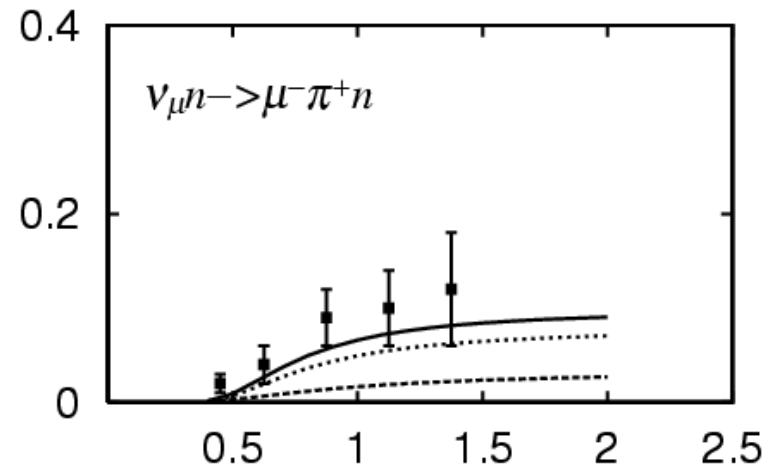
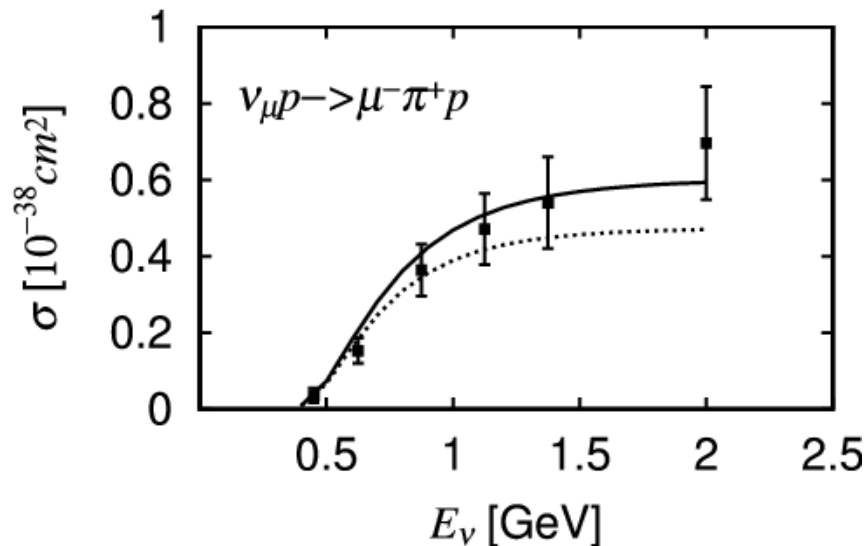
### **This work**

*Combine SL and  $\Delta$ -hole model and study coherent  $\pi$  production !*

## SL model

[Sato and Lee, PRC **54**, 2660 (1996); **67**, 065201 (2003)]

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



## Optical potential for $\pi$ - $A$ (nucleus) scattering

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

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

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

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

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

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

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

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

$$a_{\lambda N \rightarrow \pi N}^{SL} = a_{\Delta} + a_{non-R} \quad \Rightarrow \quad A_{\lambda A \rightarrow \pi A} = A_{\Delta} + A_{non-R}$$

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

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

$$\Rightarrow \quad A_{\lambda A \rightarrow \pi A}^{DW} = \int d\vec{k}' \psi_{\pi A}(\vec{k}') A_{\lambda A \rightarrow \pi A}(\vec{k}', \vec{q}_{\lambda})$$

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

All parameters fixed by  $\pi$ -nucleus scattering data

$\Rightarrow$  parameter-free prediction for  $\lambda A \rightarrow \pi A$

# Results

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

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

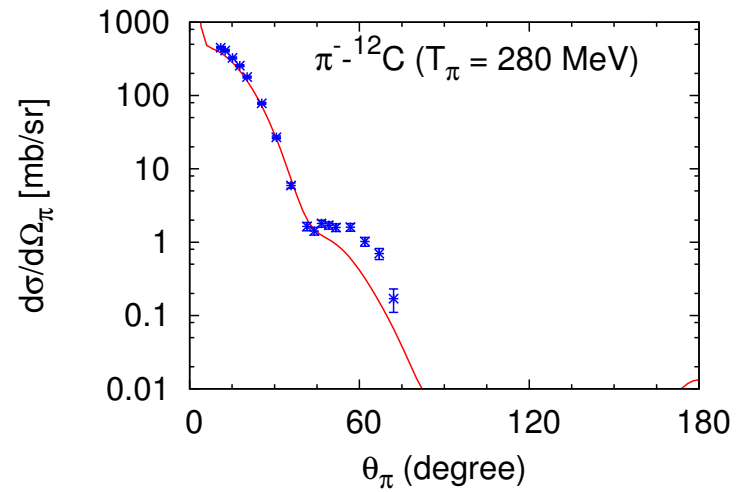
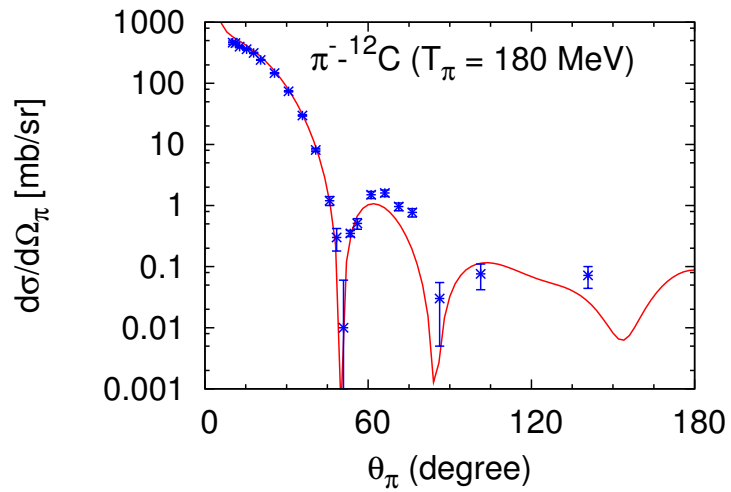
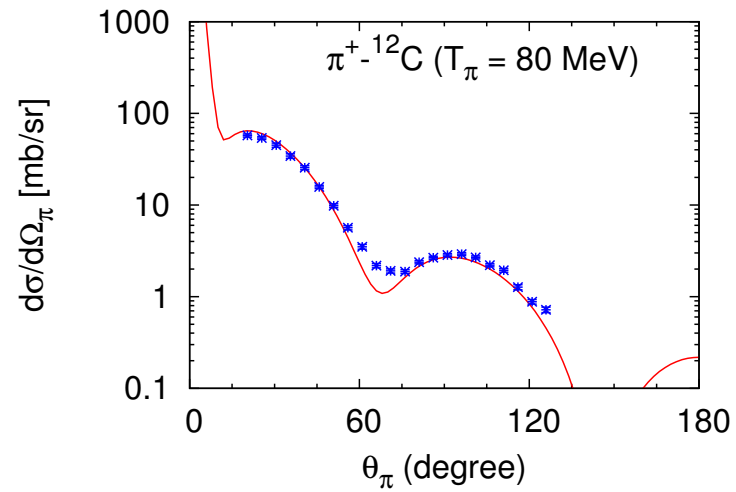
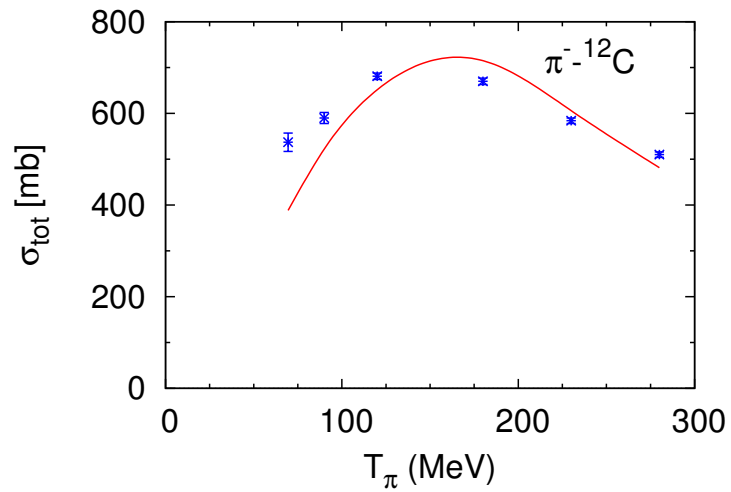
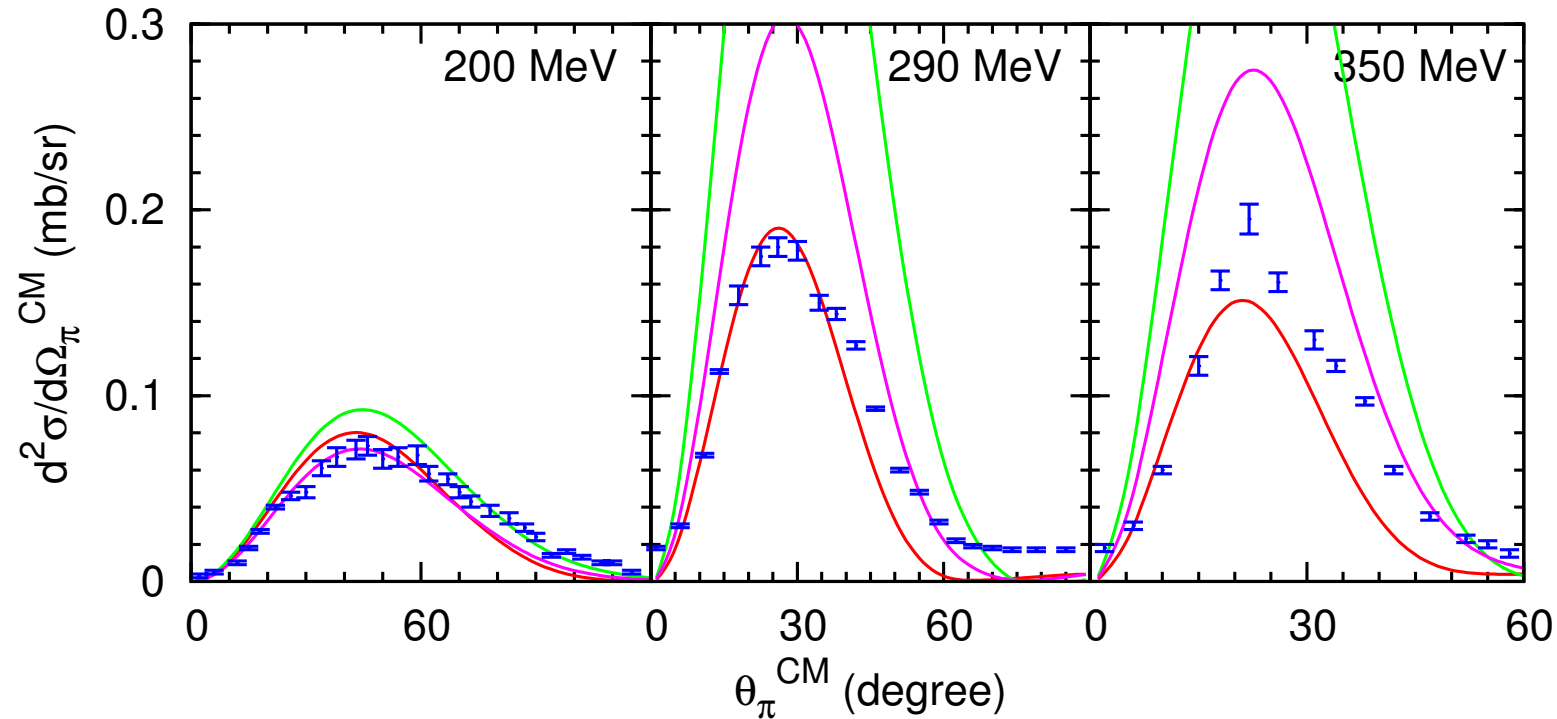




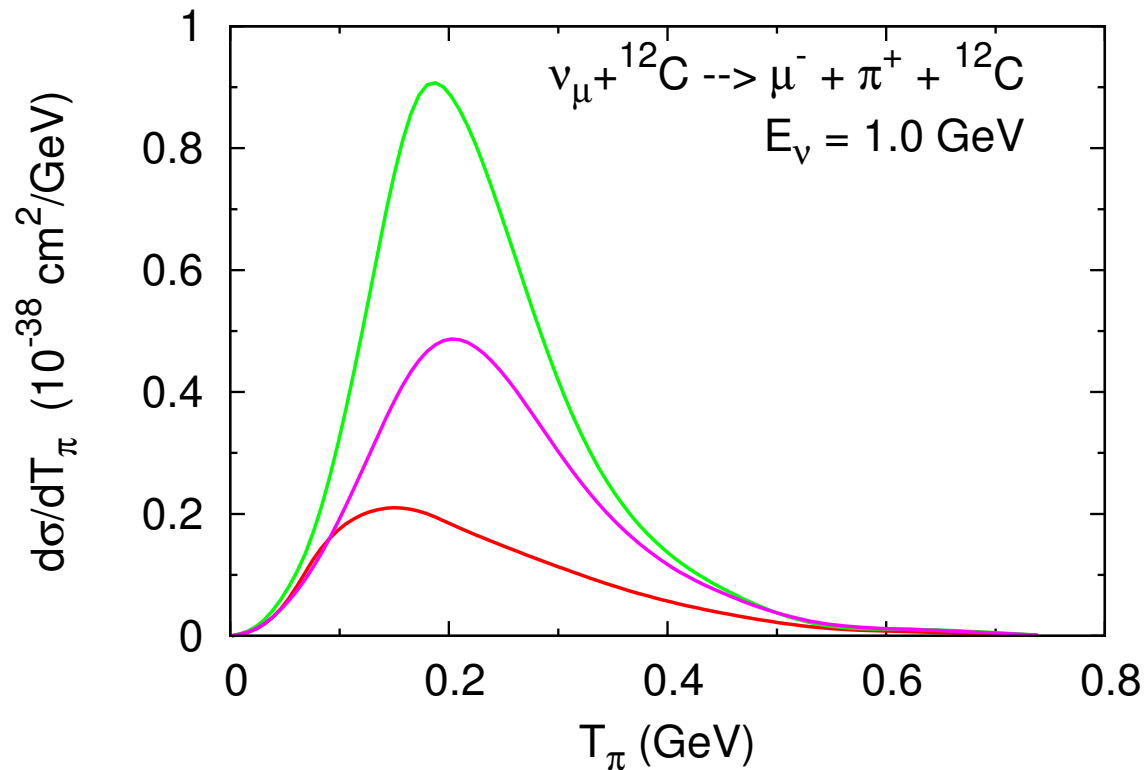
Photo coherent  $\pi$  production ( $\gamma + {}^{12}\text{C} \rightarrow \pi^0 + {}^{12}\text{C}_{g.s.}$ )



[Data: Krusche et al., PLB **526**, 287 (2002)]

- Parameter-free prediction
- Important medium effects

# Neutrino-induced coherent $\pi$ production on $^{12}\text{C}$



## CC

$$\sigma_{\text{ave}} = 6.5 \times 10^{-40} \text{ cm}^2$$

(no  $p_{\mu} < 450 \text{ MeV}$  cut applied)

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

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

## NC

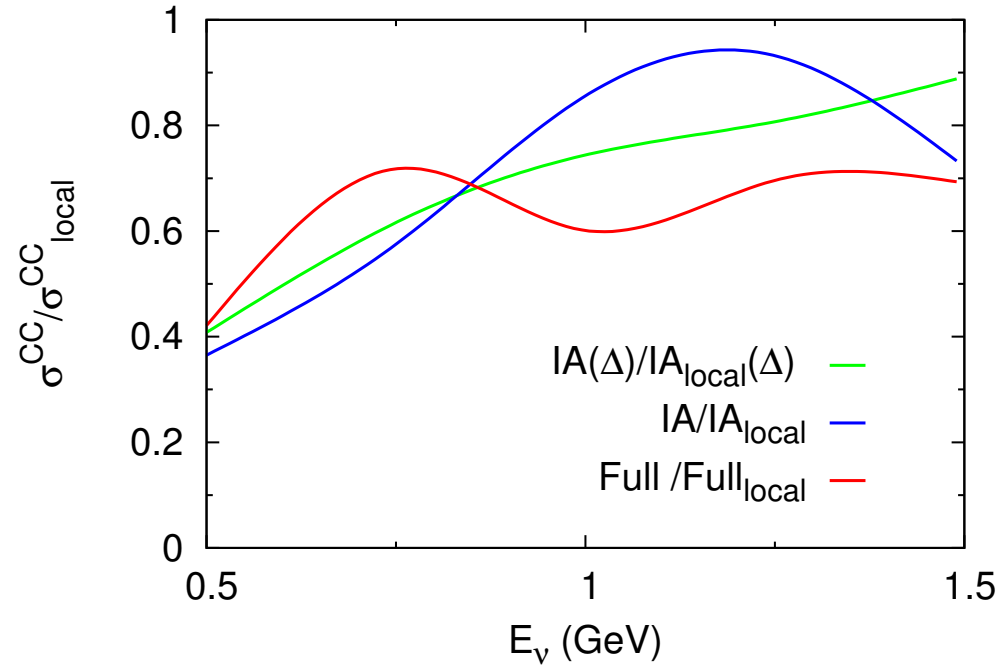
$$\sigma_{\text{ave}} = 3.9 \times 10^{-40} \text{ cm}^2$$

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

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

# Non-locality of $\Delta$ -propagation

(Leitner, et al., arXiv:0901.2837)



- 60, 30, 10 % reduction for  $E_\nu = 0.5, 1, 1.5$  GeV for  $\Delta$  without DW
- DW enhances non-local effect for higher  $E_\nu$

## Summary

### Development of theoretical model for coherent $\pi$ production

*SL model +  $\Delta$ -hole model* which enables a **unified** description of:

$$\pi A \rightarrow \pi A \quad \gamma A \rightarrow \pi^0 A \quad \nu A \rightarrow \ell^- \pi^+ A \quad \nu A \rightarrow \nu \pi^0 A$$

- Reproduce  $\pi - A$  and  $\gamma A \rightarrow \pi^0 A$  data fairly well
- Consistent with K2K data for CC coherent  $\pi$  production
- Non-locality of  $\Delta$  is important