Impact of final state interactions on neutrino-nucleon pion production cross sections extracted from neutrino-deuteron reaction data

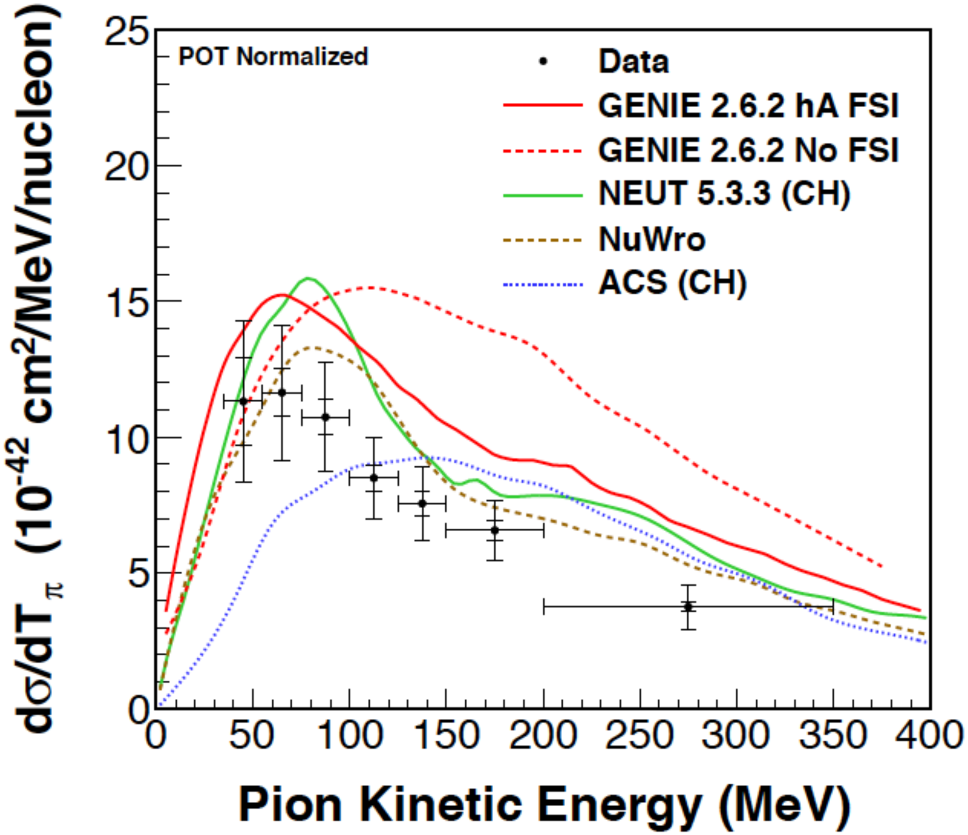
Satoshi Nakamura

Universidade Cruzeiro do Sul, Brazil

Collaborators: H. Kamano (KEK), T. Sato (Osaka U.)

Introduction

Neutrino experiments need neutrino-nucleus pion production model



$\nu_\mu \, \mathrm{CH} \rightarrow \mu^- \pi^\pm X$

$\langle E_\nu \rangle = 4.0 \text{ GeV}, W < 1.4 \text{ GeV}$

MINERvA PRD 92 (2015)

→ Model goes into analysis of oscillation data

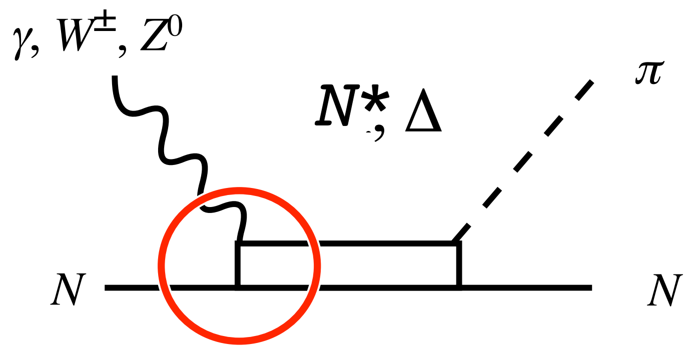
An essential ingredient of neutrino-nucleus model : elementary neutrino-nucleon model

We are still in a process of establishing the elementary neutrino-nucleon pion production model

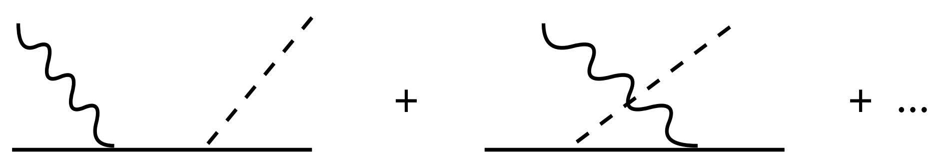
Precision era of neutrino experiments (CP, mass hierarchy) → models of comparable quality

Theoretical description of elementary process in resonance region (single pion productions)

Resonance excitations



Non-resonant mechanisms



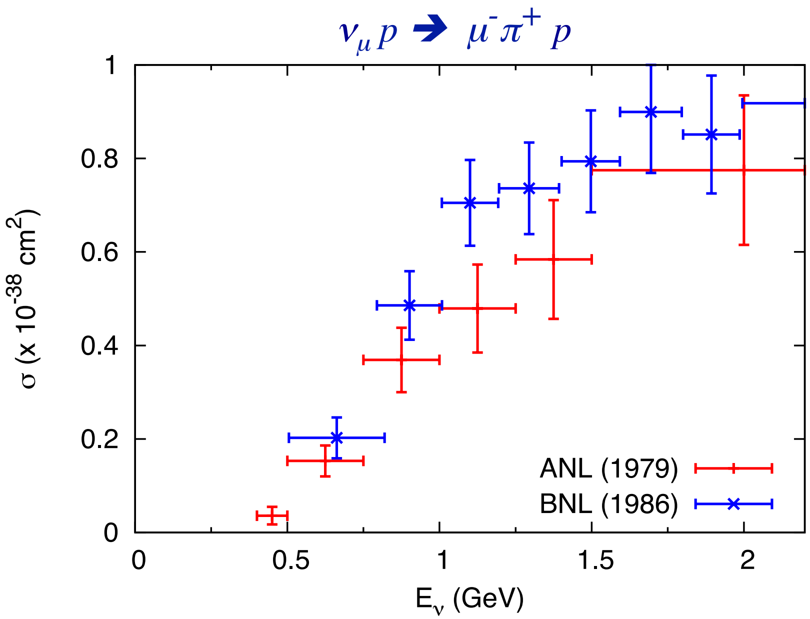
Dominant $\Delta(1232)$-excitation and sub-leading non-resonant mechanisms

- Accurate determination of N-$\Delta(1232)$ transition strength is of vital importance
- Experimental inputs are needed to examine pion production mechanisms

Vector current : photon- and electron-nucleon 1π production data

Axial current : neutrino-nucleon 1π production data

Neutrino interaction data in $\Delta(1232)$ region



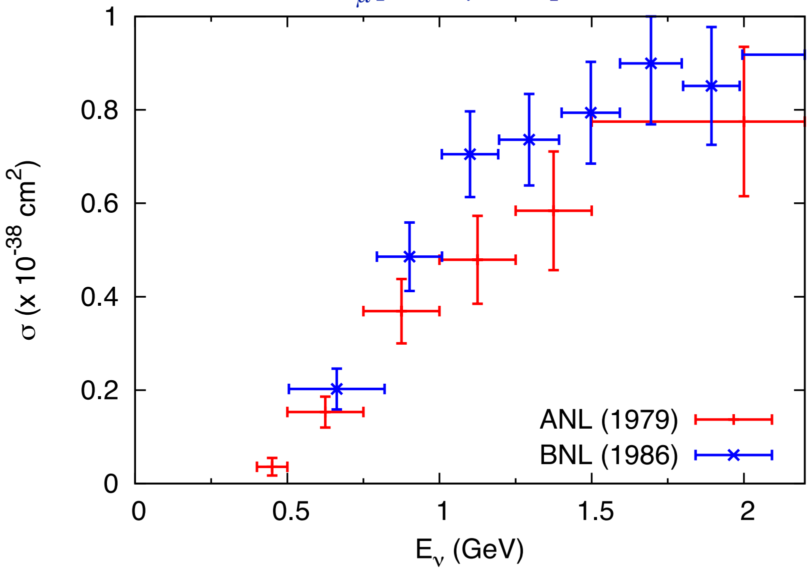
- *ALL* models fit this data by adjusting $g_{AN\Delta}$

  → very important data

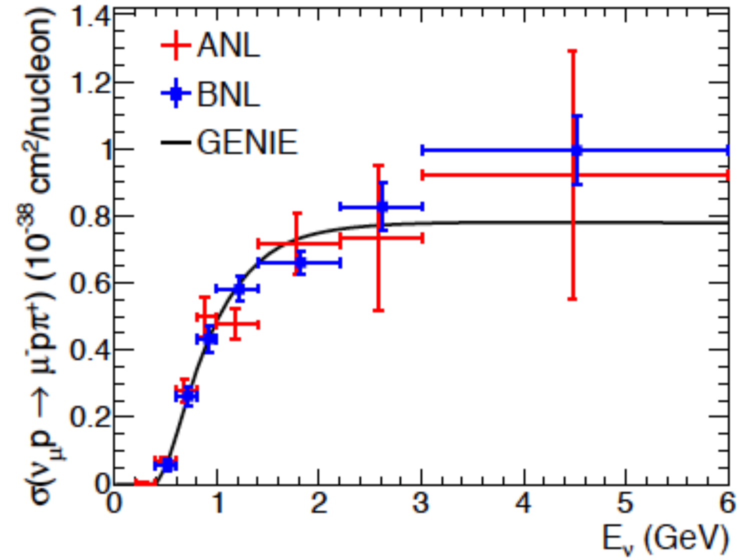
- Discrepancy between BNL & ANL data

  → theoretical uncertainty in neutrino-nucleus cross sections

Neutrino interaction data in $\Delta(1232)$ region



Wilkinson et al. PRD 90 (2014)



- *ALL* models fit this data by adjusting $g_{AN\Delta}$

  → very important data

- Discrepancy between BNL & ANL data

  → theoretical uncertainty in neutrino-nucleus cross sections

Reanalysis of original data

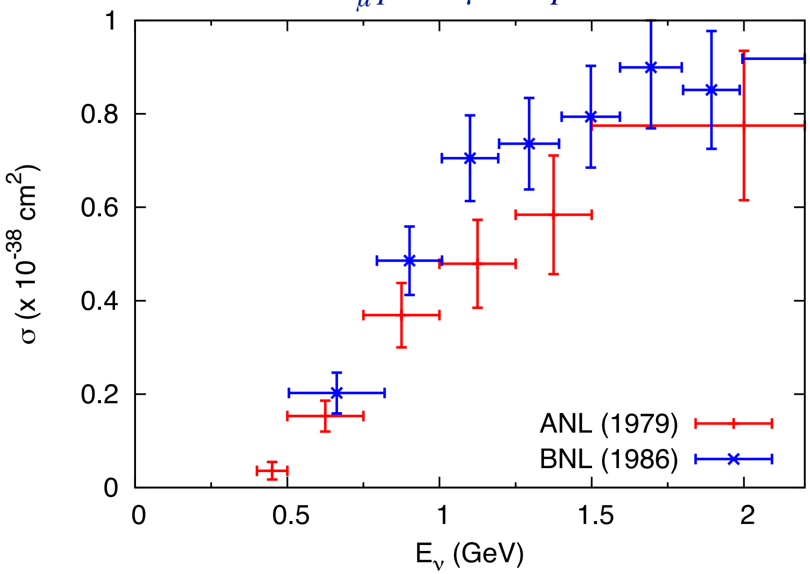
→ discrepancy resolved (probably)

$$\frac{\sigma(\mathrm{CC}1\pi;\mathrm{data})}{\sigma(\mathrm{CC}0\pi;\mathrm{data})} \times \sigma(\mathrm{CCQE};\mathrm{model})$$

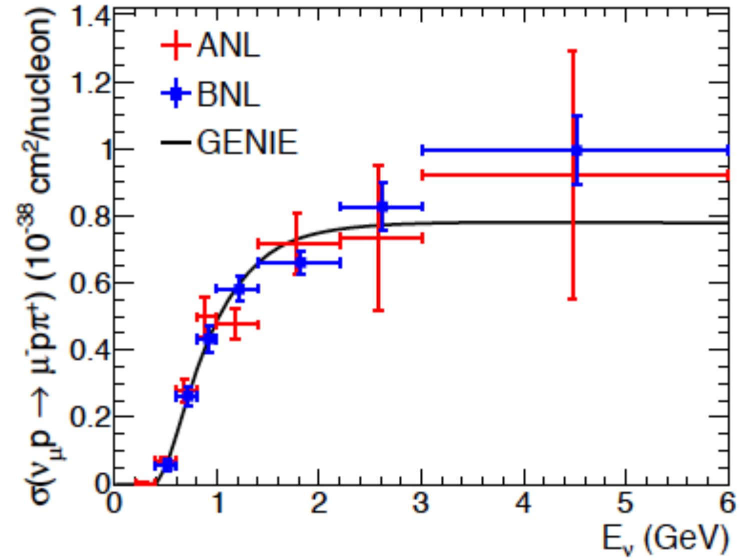
Flux uncertainty is cancelled out

Neutrino interaction data in Δ(1232) region

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



Wilkinson et al. PRD 90 (2014)



- *ALL* models fit this data by adjusting $g_{AN\Delta}$

  → very important data

- Discrepancy between BNL & ANL data

  → theoretical uncertainty in neutrino-nucleus cross sections

Reanalysis of original data

→ discrepancy resolved (probably)

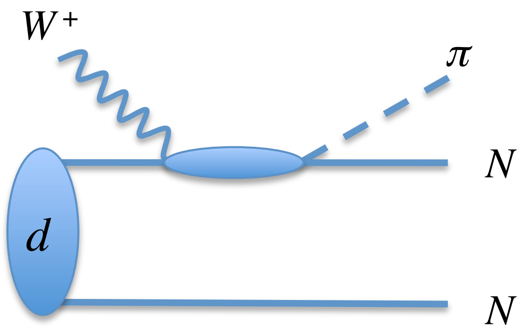
$$\frac{\sigma(\mathrm{CC}1\pi;\mathrm{data})}{\sigma(\mathrm{CC}0\pi;\mathrm{data})} \times \sigma(\mathrm{CCQE};\mathrm{model})$$

Flux uncertainty is cancelled out

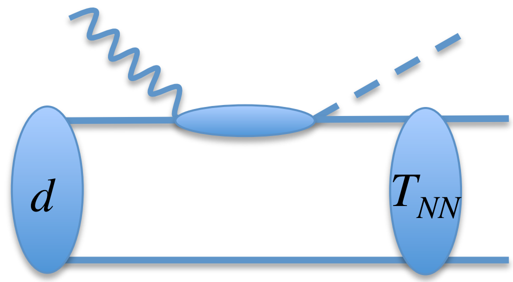
$\nu_\mu p \rightarrow \mu^- \pi^+ p$ data were extracted from $\nu_\mu d \rightarrow \mu^- \pi^+ p\, n$ data   Nuclear effects matter ?

Mechanisms (including nuclear effects) for $\nu_\mu d \rightarrow \mu^- \pi N N$

Impulse

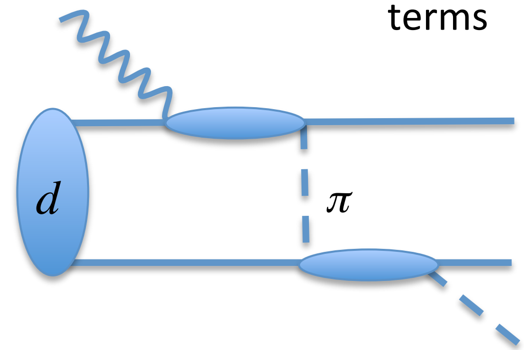


NN rescattering



πN rescattering

+ higher-order terms



Nuclear effect managements

Exp. Quasi-free events were (supposedly) selected in ANL and BNL analyses

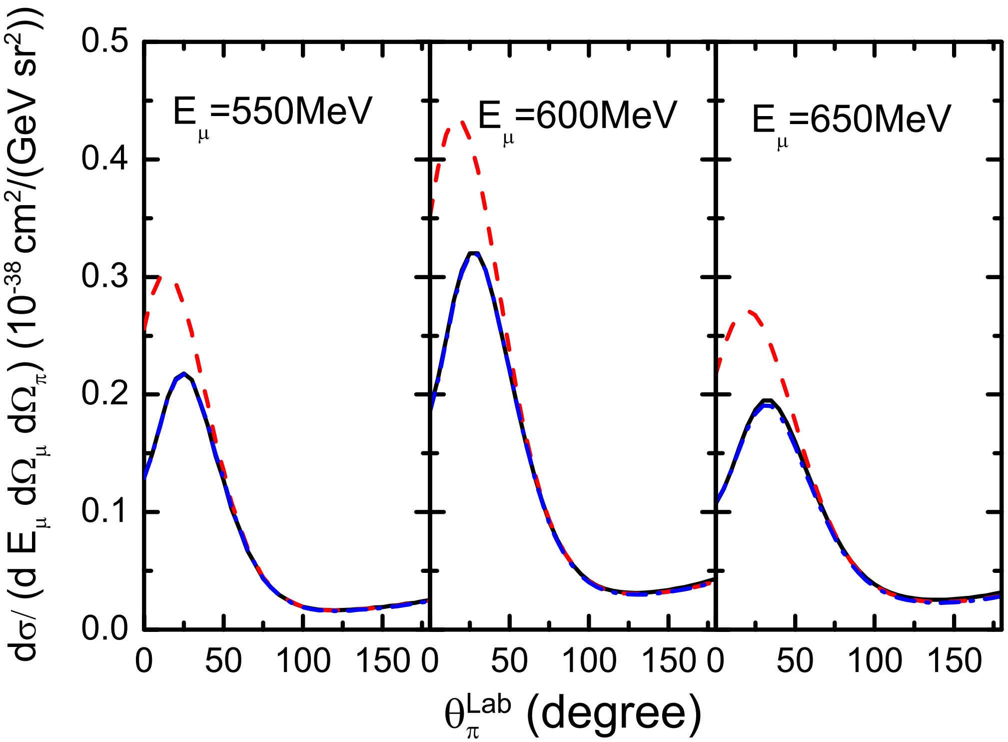
Theory Fermi motion considered in fixing $g_{AN\Delta}$ Hernandez et al. (2010), Alam et al. (2016)

Q : Should we still consider final state interactions (FSI) effects ?

FSI effects on $\nu_\mu d \rightarrow \mu^- \pi N N$ have been explored with a dynamical model Wu et al. (2015)

FSI effects on $\nu_\mu d \rightarrow \mu^- \pi^+ p n$

Wu, Lee, Sato, PRC91, 035203 (2015)



E_ν = 1 GeV,

E_μ = 550, 600, 650 MeV, θ_μ = 25°, ϕ_π= 0°

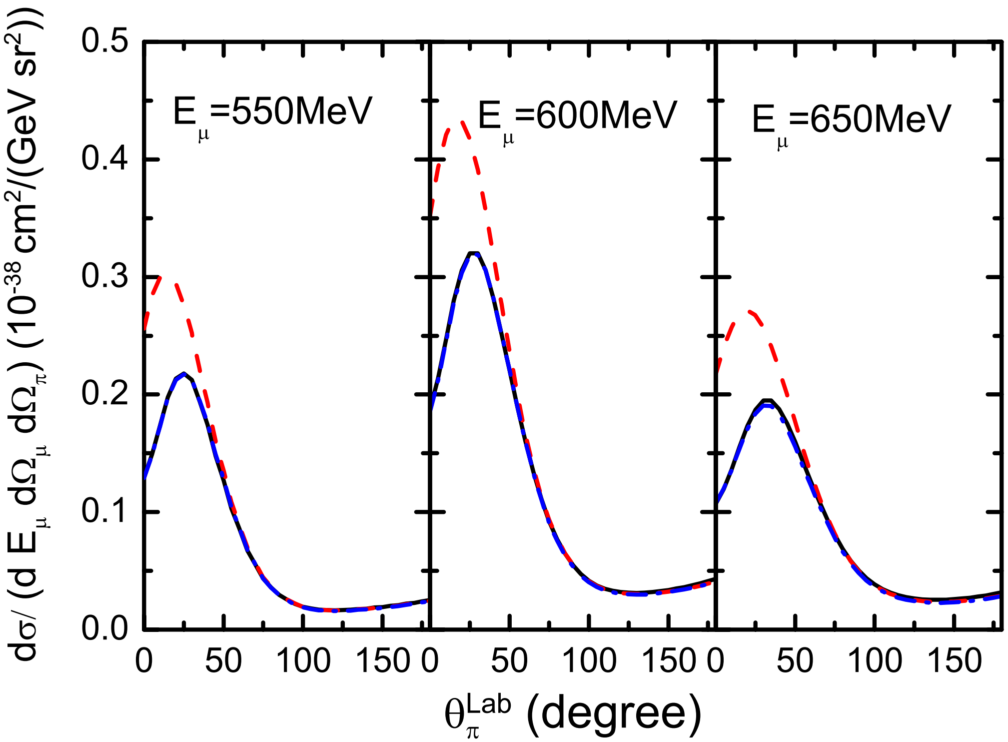
Significant reduction due to NN FSI

↑

Orthogonality of *pn* and *d* wave functions

FSI effects on $\nu_\mu d \rightarrow \mu^- \pi^+ p\, n$

Wu, Lee, Sato, PRC91, 035203 (2015)



$E_\nu = 1$ GeV,

$E_\mu = 550, 600, 650$ MeV, $\theta_\mu = 25°$, $\phi_\pi = 0°$

Impulse approx.

NN FSI

NN + πN FSI

Significant reduction due to NN FSI

↑

Orthogonality of *pn* and *d* wave functions

Wu et al. focused on quasi-free kinematics only

→ whole phase-space need to be examined to understand FSI effects on ANL and BNL data

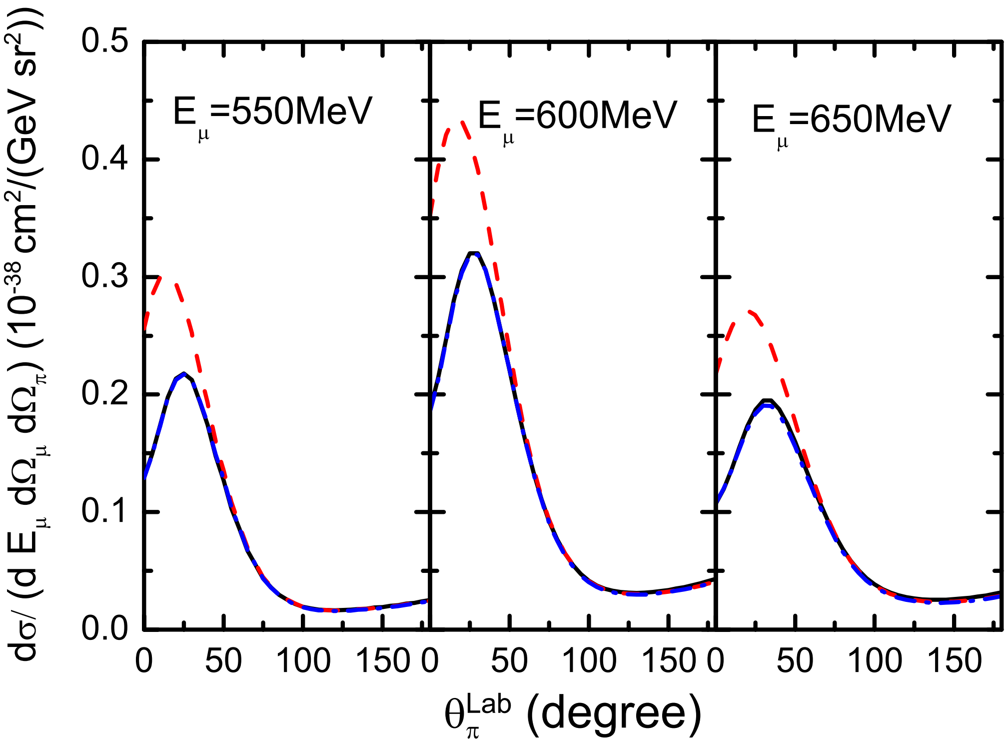
$$\sigma = \int dp_{N_1} dp_{N_2} dp_\mu dp_\pi \delta^{(4)}(P_i - P_f) \,|\, M \,|^2$$

(7 dim. non-trivial numerical integral)

Numerically challenging problem

FSI effects on $\nu_\mu d \rightarrow \mu^- \pi^+ p\, n$

Wu, Lee, Sato, PRC91, 035203 (2015)



$E_\nu = 1$ GeV,

$E_\mu = 550, 600, 650$ MeV, $\theta_\mu = 25°$, $\phi_\pi = 0°$

Impulse approx.

NN FSI

NN + πN FSI

Significant reduction due to NN FSI

↑

Orthogonality of *pn* and *d* wave functions

Wu et al. focused on quasi-free kinematics only

→ whole phase-space need to be examined to understand FSI effects on ANL and BNL data

$$\sigma = \int dp_{N_1} dp_{N_2} dp_\mu dp_\pi \delta^{(4)}(P_i - P_f) | M |^2$$

(7 dim. non-trivial numerical integral)

Numerically challenging problem *will be managed with Monte-Carlo integral*

This work

- $\nu_\mu d \rightarrow \mu^- \pi NN$ cross sections of the whole phase-space are calculated with a dynamical model including FSI ; for the first time

- FSI effect on spectator momentum distribution $d\sigma/dp_s$ is examined

- Find a useful recipe to extract elementary $\nu_\mu N \rightarrow \mu^- \pi N$ cross sections from $\nu_\mu d \rightarrow \mu^- \pi NN$ spectator momentum distribution

- Extract $\nu_\mu N \rightarrow \mu^- \pi N$ total cross sections by correcting (flux-corrected) ANL and BNL data for FSI and Fermi motion

Future impact

→ Significantly improved elementary $\nu_\mu N \rightarrow \mu^- \pi N$ model to be implemented in neutrino-nucleus reaction model for oscillation experiments of the precision era

$\nu_\mu d \rightarrow \mu^- \pi NN$ reaction model

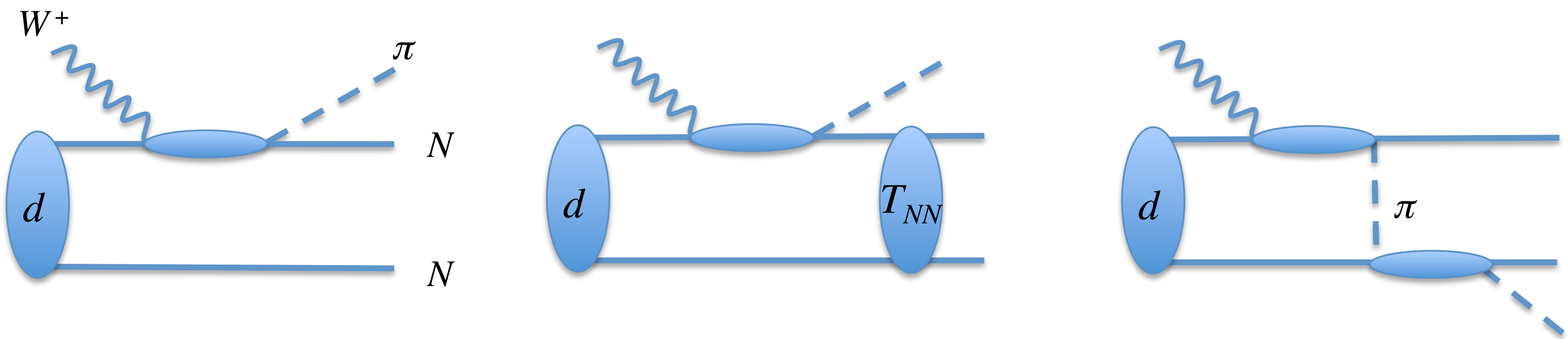
based on

dynamical coupled-channels model

Model for $\nu_\mu\, d \rightarrow \mu^- \pi N N$

Multiple scattering theory truncated at the first-order rescattering

Impulse NN rescattering πN rescattering



Elementary amplitudes

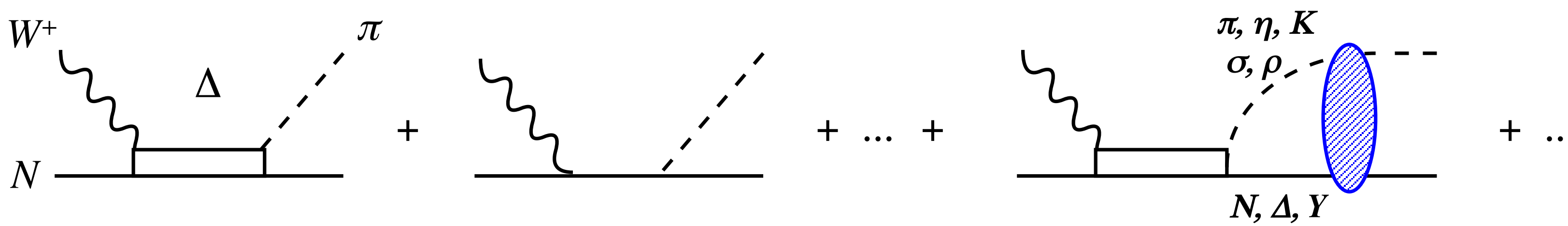
$W^{\pm}N \rightarrow \pi N$, $\pi N \rightarrow \pi N$ (off-shell) amplitude ← DCC model (SXN et al., PRD92 (2015))

T_{NN}, deuteron w.f. ← CD-Bonn potential (Machleidt et al., PRC 63 (2001))

3-dim. loop integral with off-shell amplitudes are numerically evaluated

Dynamical coupled-channels model

Kamano, SXN, Lee, Sato, PRC 88, 035209 (2013)
SXN, Kamano, Lee, Sato, PRD 92, 074024 (2015)



Developed through analyzing $\gamma^{(*)}N, \pi N \rightarrow \pi N, \eta N, K\Lambda, K\Sigma$ data (~27,000 data pts.)

→ Extended to $\nu N \rightarrow l^- X$ $\quad(X= \pi N, \pi\pi N, \eta N, K\Lambda, K\Sigma)$

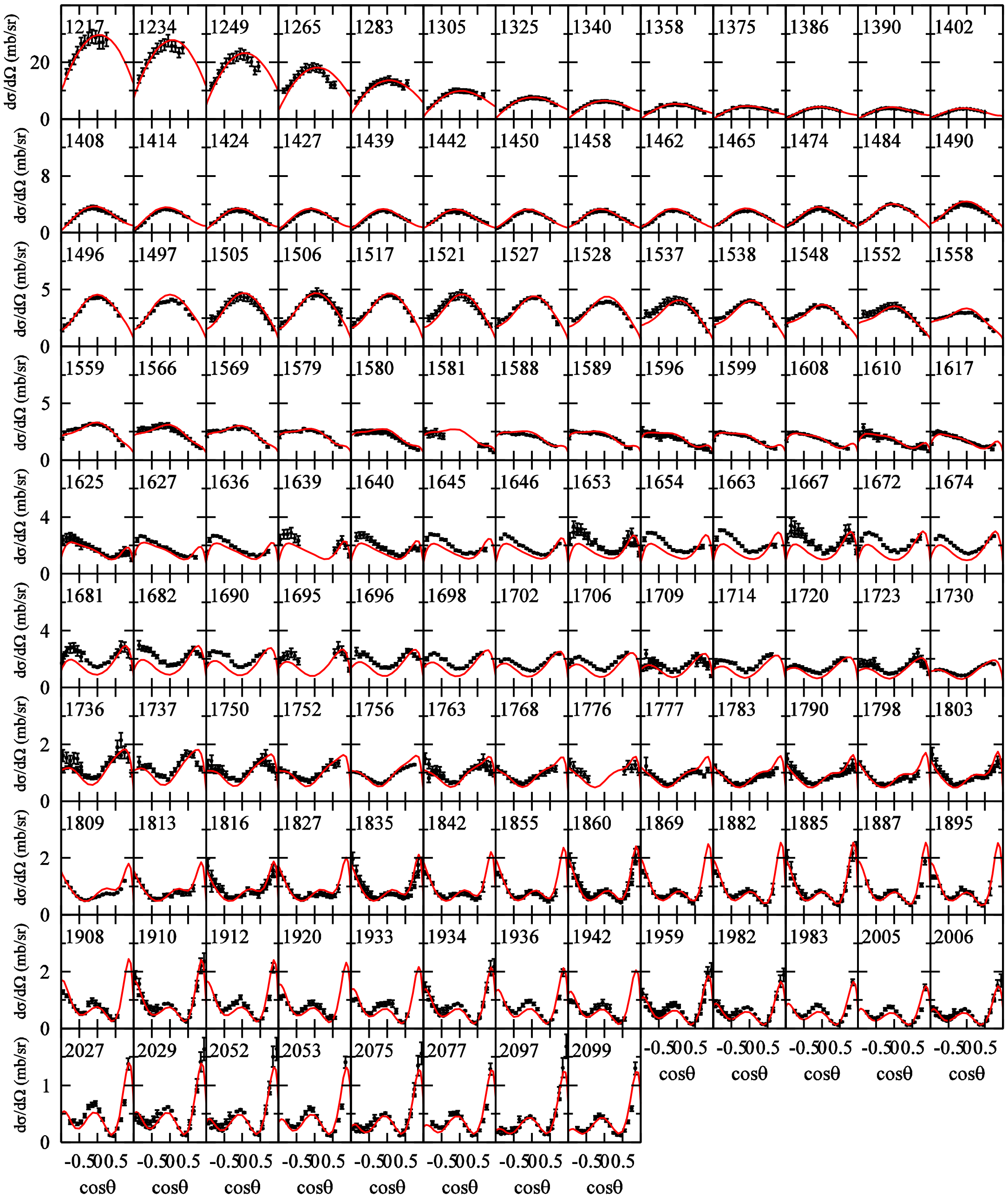
Unique features

- Hadronic rescattering and channel-couplings are taken into account
  ← requirement from the unitarity
- Interference among resonant and non-resonant mechanisms are under control within the model
- One-pion AND two-pion productions for the whole resonance region are described

$\gamma p \rightarrow \pi^0 p$

$d\sigma/d\Omega$ for W < 2.1 GeV

Comparison of DCC model with data

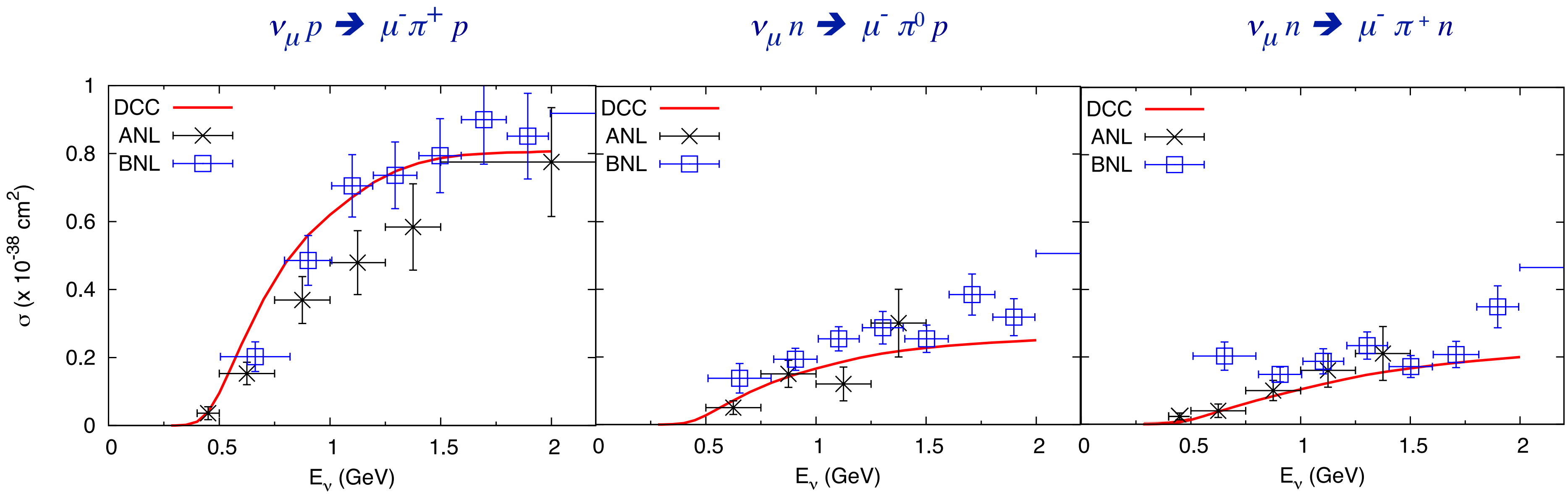


Kamano, Nakamura, Lee, Sato, PRC 88 (2013)

Vector current (Q^2=0) for 1π

Production is well-tested by data

Comparison of DCC model with single pion data



ANL Data : PRD **19**, 2521 (1979)
BNL Data : PRD **34**, 2554 (1986)

DCC model prediction is consistent with BNL data (before flux correction)

DCC model has flexibility to fit ANL data ($ANN^*(Q^2)$)

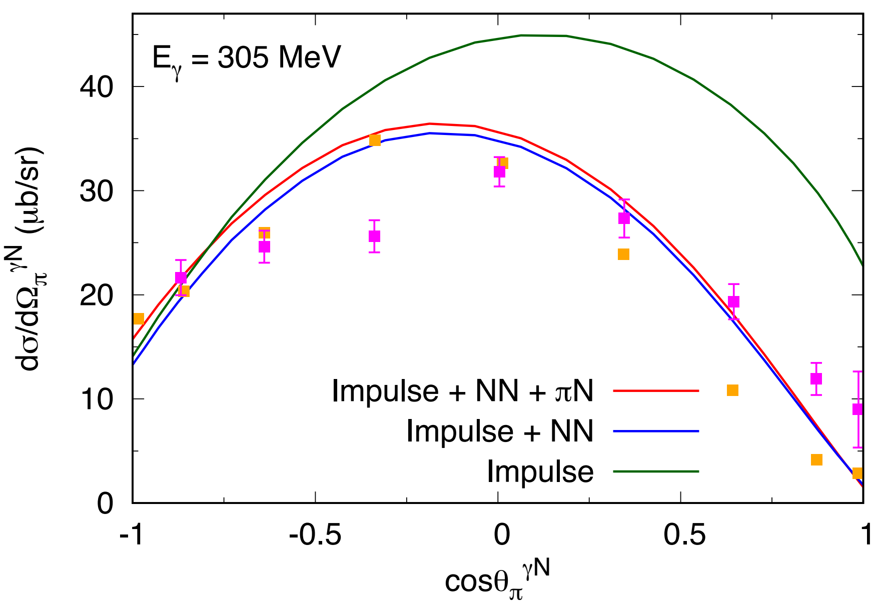
We will fit data after the issue of nuclear effects on the data is clarified

Results

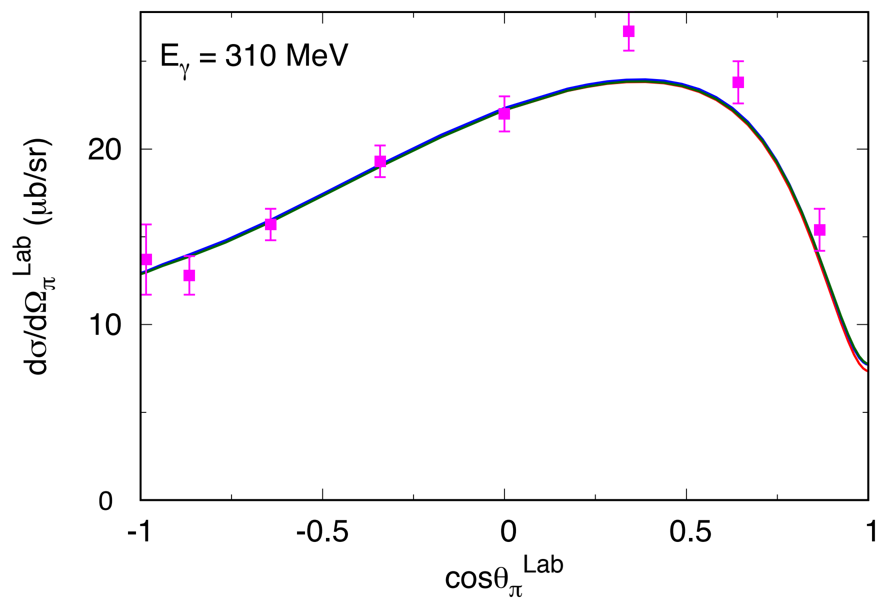
$\gamma\, d \rightarrow \pi\, N\, N$: model predictions and data

Purpose : validate our DCC-based deuteron-reaction model

$\gamma\, d \rightarrow \pi^0\, pn$



$\gamma\, d \rightarrow \pi^-\, pp$



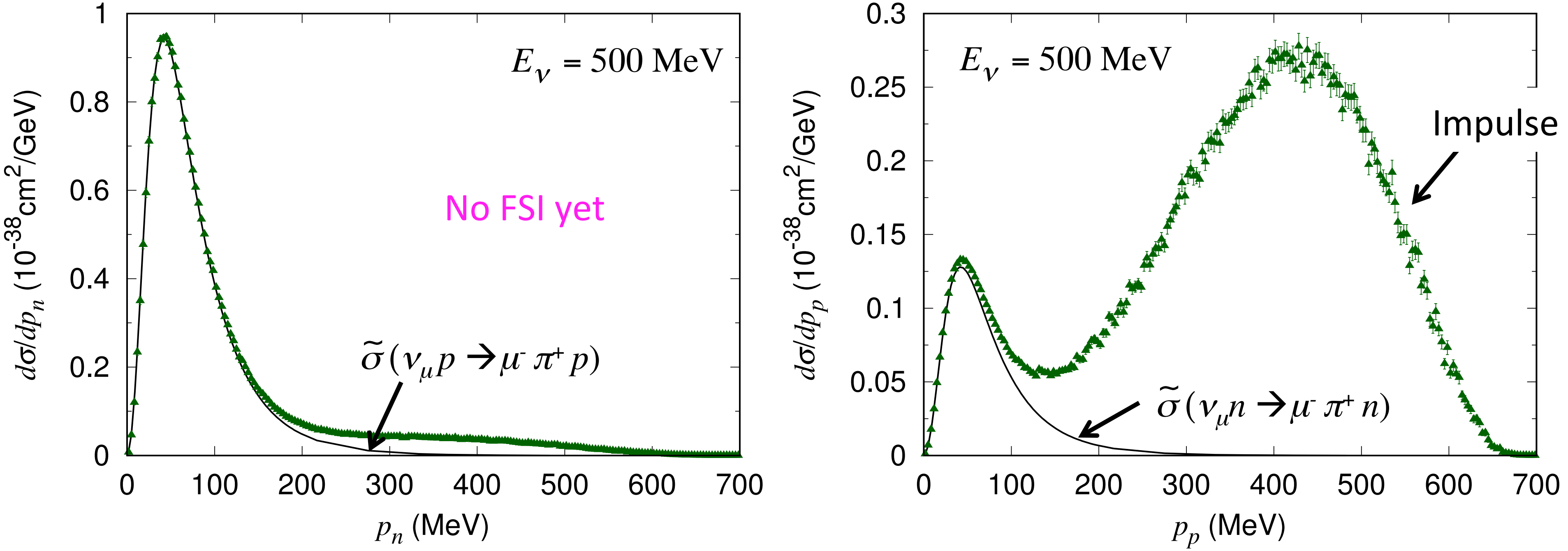
- Large NN FSI effect for π^0 productions ← NN and deuteron wave fn. are orthogonal
- FSI effects are small for π^- productions
- Reasonable agreement with data → reliable estimate of FSI effects on neutrino-deuteron

Data: EPJA 6, 309 (1999); 10, 365 (2001) for $\gamma\, d \rightarrow \pi^0\, pn$, NPB 65, 158 (1973) for $\gamma\, d \rightarrow \pi^-\, pp$

$\nu_\mu\, d \rightarrow \mu^- \pi^+ p\, n$ spectator momentum distribution

Minimal information to extract $\nu_\mu N \rightarrow \mu^- \pi N$ cross sections

Contribution from other nucleon (spectator) is expected to be small in small p_s region



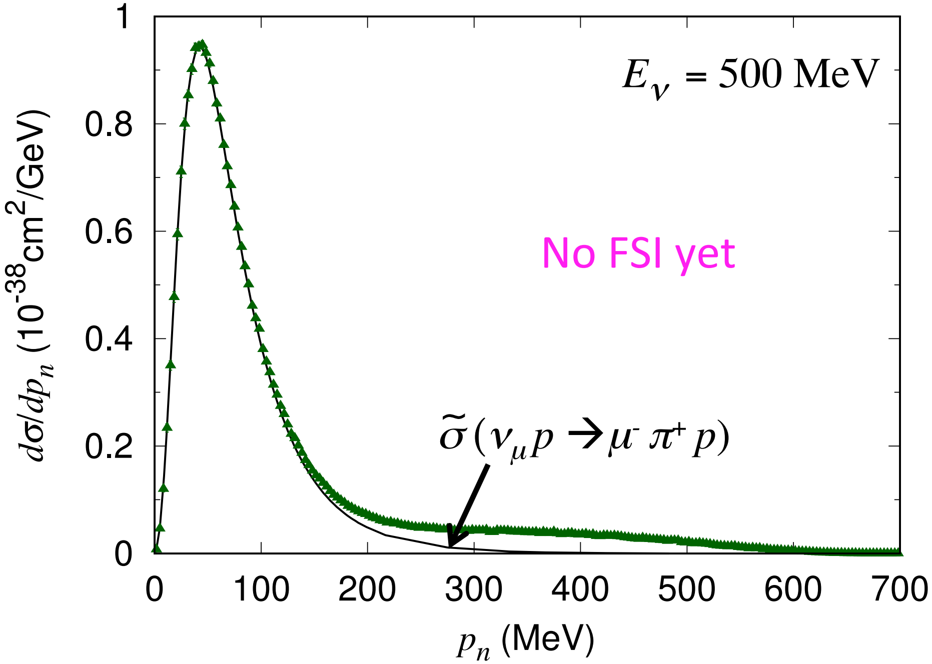
Phase-space integral for $\nu_\mu\, d \rightarrow \mu^- \pi^+ p\, n$ is done with Monte-Carlo method

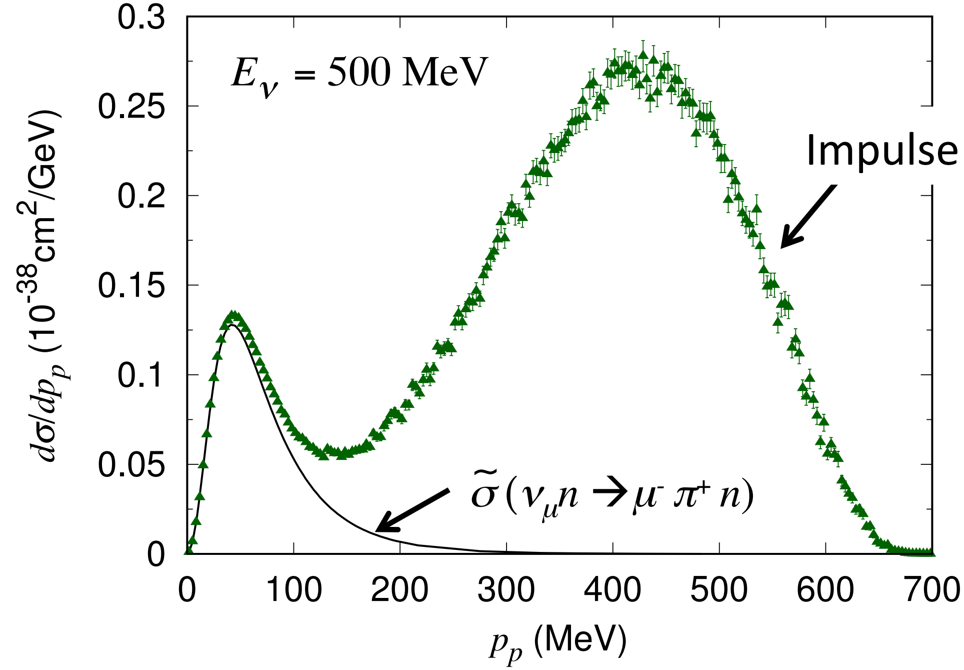
$\rightarrow$ central values with statistical errors

$\nu_\mu d \rightarrow \mu^- \pi^+ p\, n$ spectator momentum distribution

Minimal information to extract $\nu_\mu N \rightarrow \mu^- \pi N$ cross sections

Contribution from other nucleon (spectator) is expected to be small in small p_s region





Convoluted cross section ($\tilde{\sigma}$): $\dfrac{d\tilde{\sigma}_\alpha(E_\nu)}{dp_s} = p_s^2 \int d\Omega_{p_s} \sigma_\alpha(\tilde{E}_\nu) |\Psi_d(\vec{p}_s)|^2$

= Quasi-free contribution

$\alpha = \nu_\mu N \rightarrow \mu^- \pi^+ N$

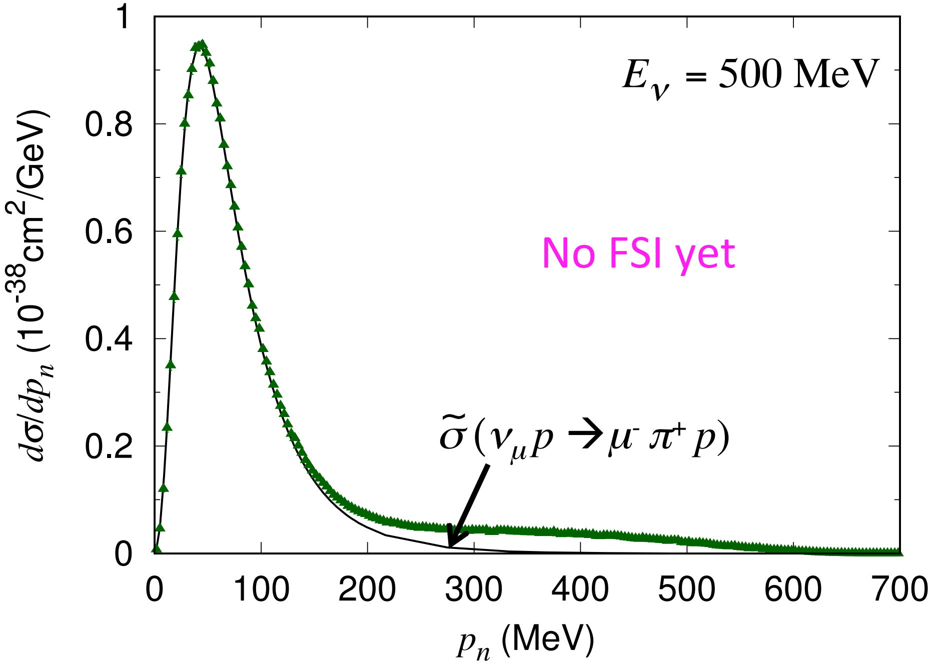
Ψ_d : deuteron w.f.

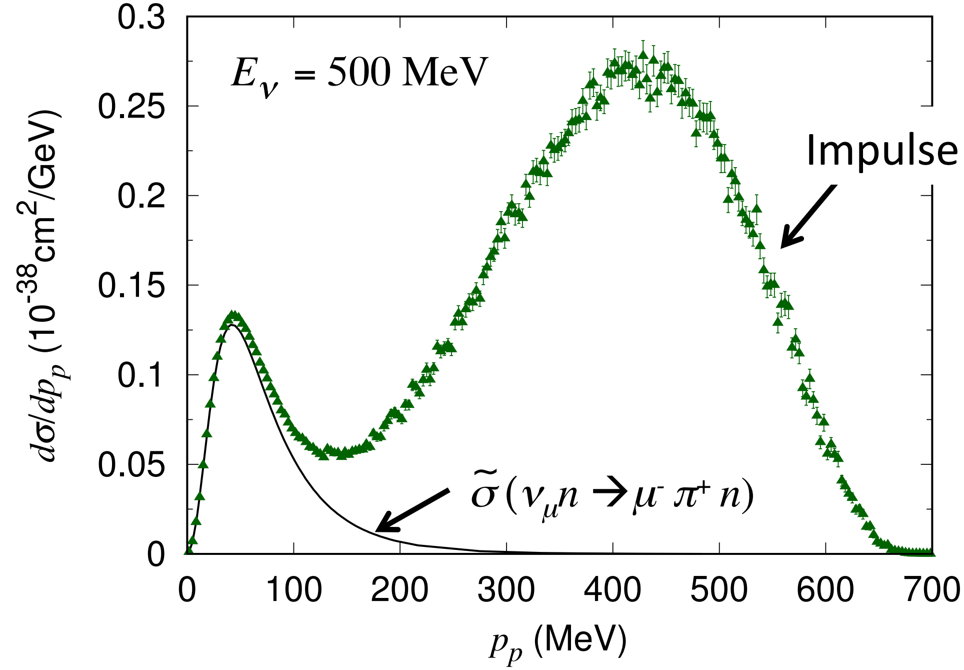
cross section for free nucleon

$\nu_\mu d \rightarrow \mu^- \pi^+ p\, n$ spectator momentum distribution

Minimal information to extract $\nu_\mu N \rightarrow \mu^- \pi N$ cross sections

Contribution from other nucleon (spectator) is expected to be small in small p_s region





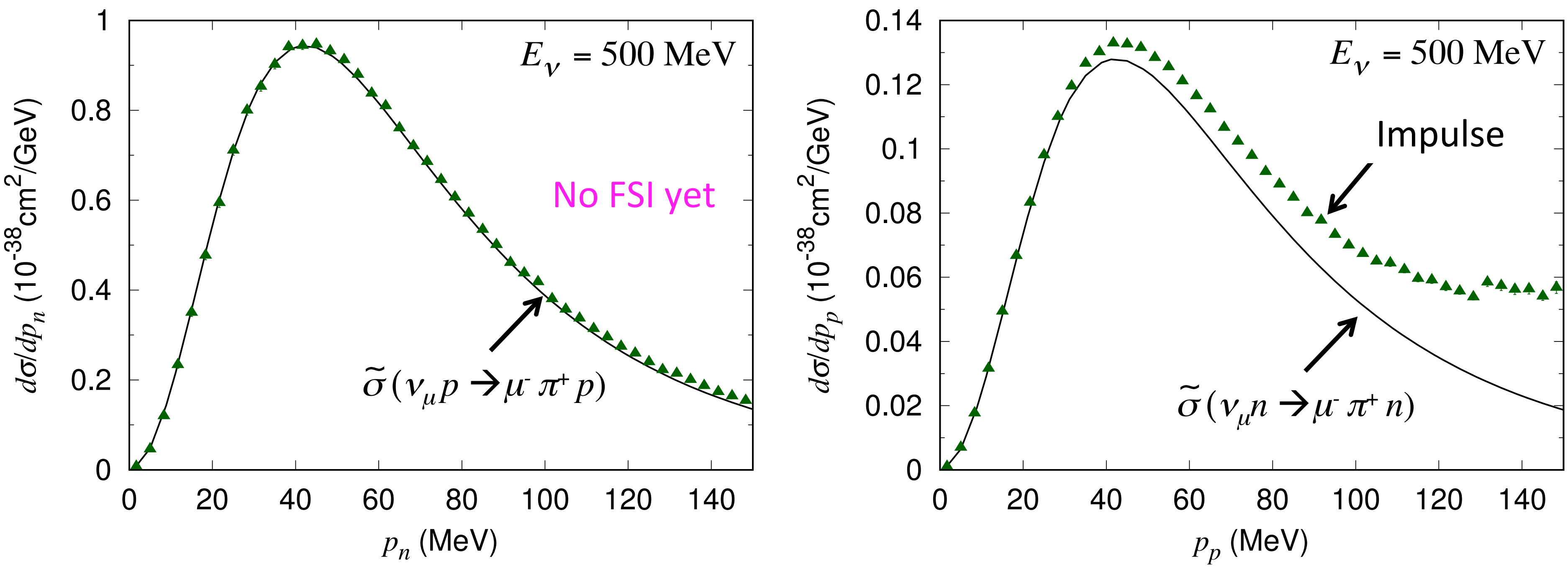
Difference between σ (Impulse) and $\tilde{\sigma}$ → contribution from the other nucleon

$\sigma(\nu_\mu p \rightarrow \mu^- \pi^+ p) \approx$ 9 x $\sigma(\nu_\mu n \rightarrow \mu^- \pi^+ n)$

$\nu_\mu d \rightarrow \mu^- \pi^+ p\, n$ spectator momentum distribution

Minimal information to extract $\nu_\mu N \rightarrow \mu^- \pi N$ cross sections

Contribution from other nucleon (spectator) is expected to be small in small p_s region



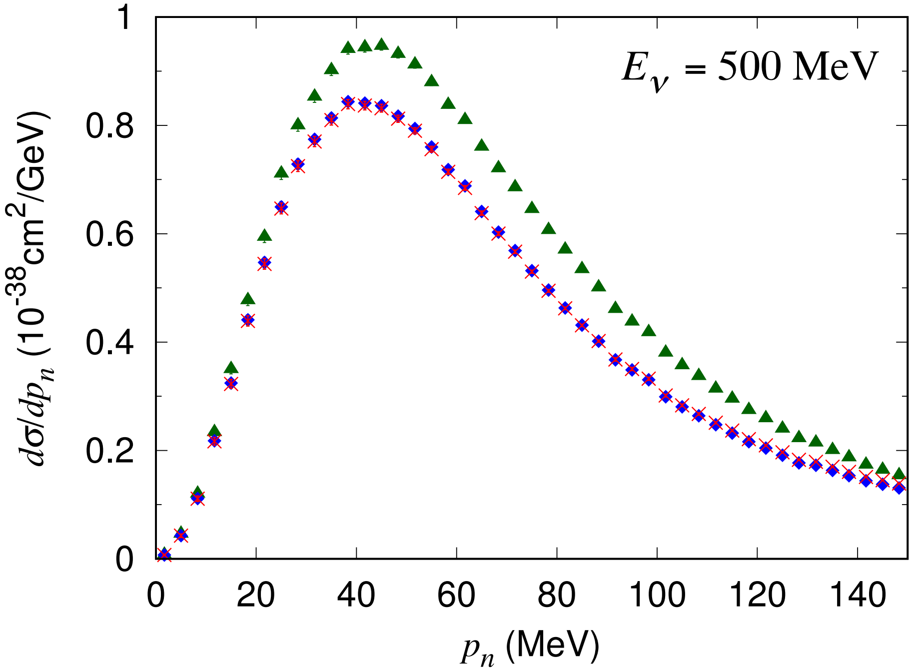
Small p_s region

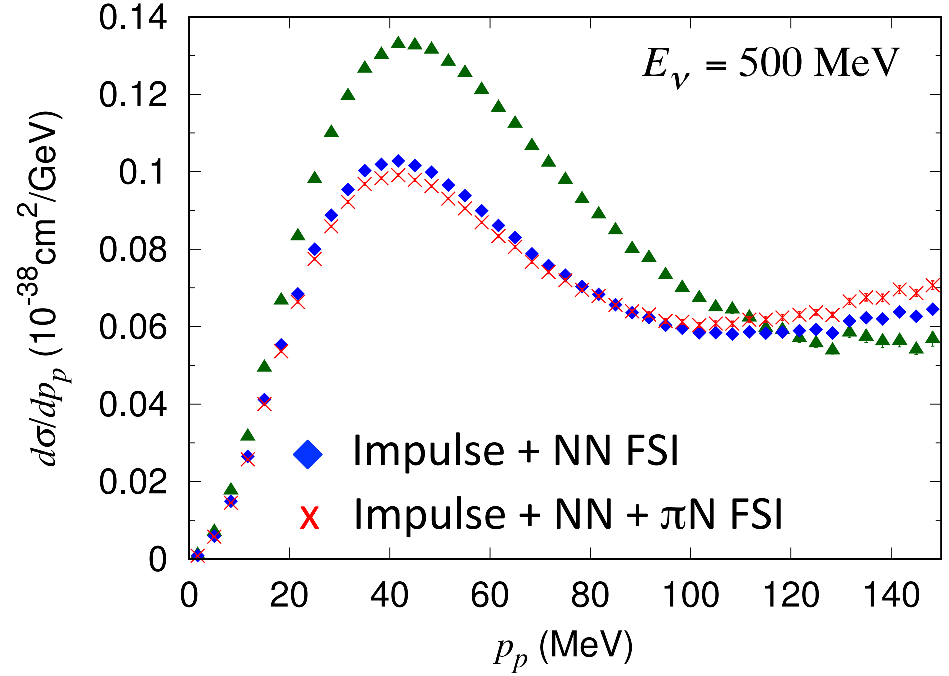
Larger contamination of $\nu_\mu p \rightarrow \mu^- \pi^+ p$ in quasi-free neutron (small p_p) region

← $\sigma(\nu_\mu p \rightarrow \mu^- \pi^+ p) \approx$ 9 x $\sigma(\nu_\mu n \rightarrow \mu^- \pi^+ n)$

$\nu_\mu\, d \rightarrow \mu^- \pi^+ p\, n$ spectator momentum distribution

FSI effect





Naïve expectation : FSI affects high p_s region, leaving small p_s region unchanged

Reality : FSI significantly reduces spectrum in small p_s (quasi-free peak) region

large NN FSI effect ← orthogonality between NN scattering state and deuteron

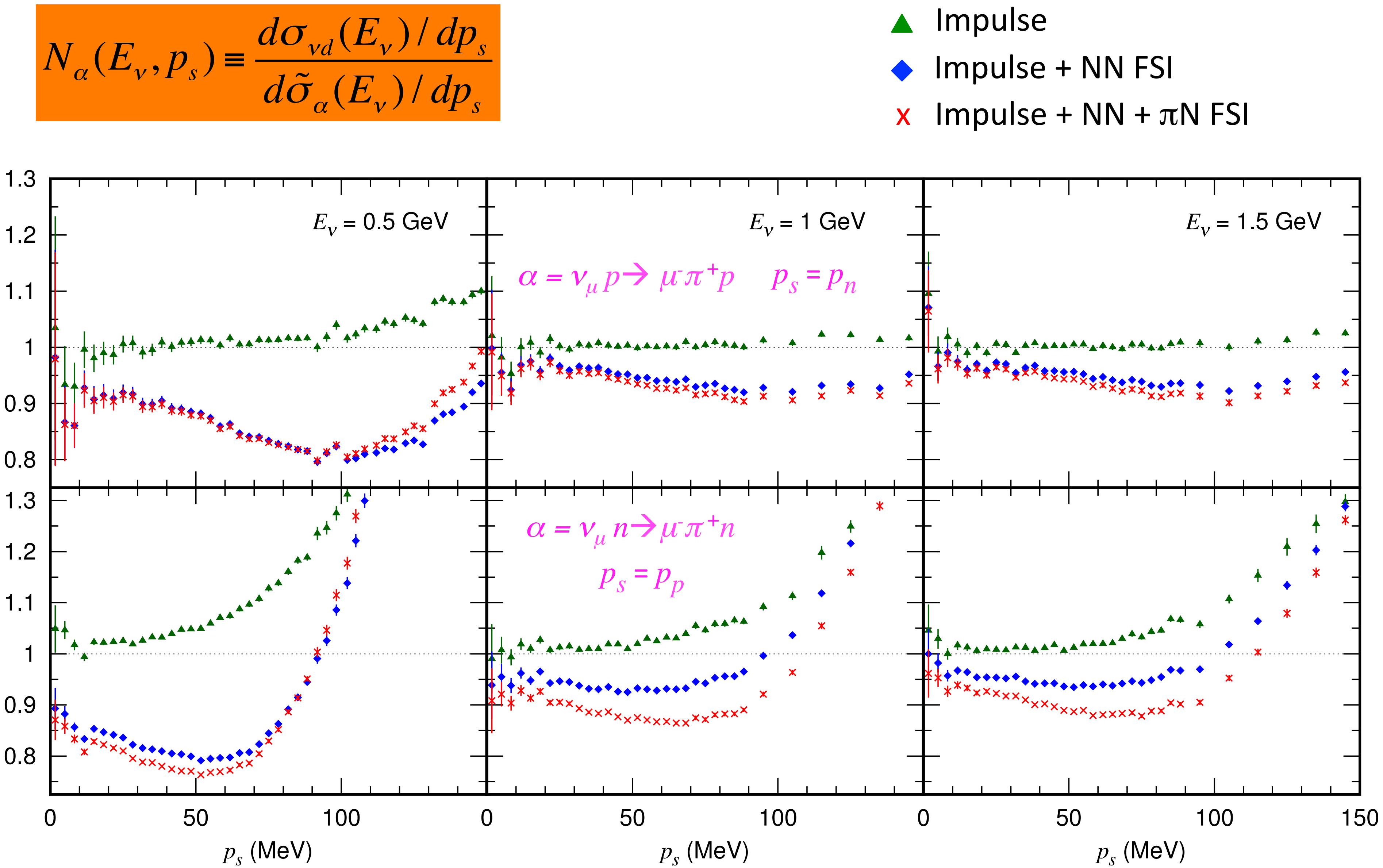
FSI effect is small for $\nu_\mu\, d \rightarrow \mu^- \pi^0 p\, p$ spectator momentum distribution

$$N_{\alpha}(E_{\nu}, p_s) \equiv \frac{d\sigma_{\nu d}(E_{\nu}) / dp_s}{d\tilde{\sigma}_{\alpha}(E_{\nu}) / dp_s}$$

Ratio of spectator momentum distribution and convoluted cross section

Other nucleon's contribution and FSI effects on the spectator momentum distributions can be seen more clearly and quantitatively

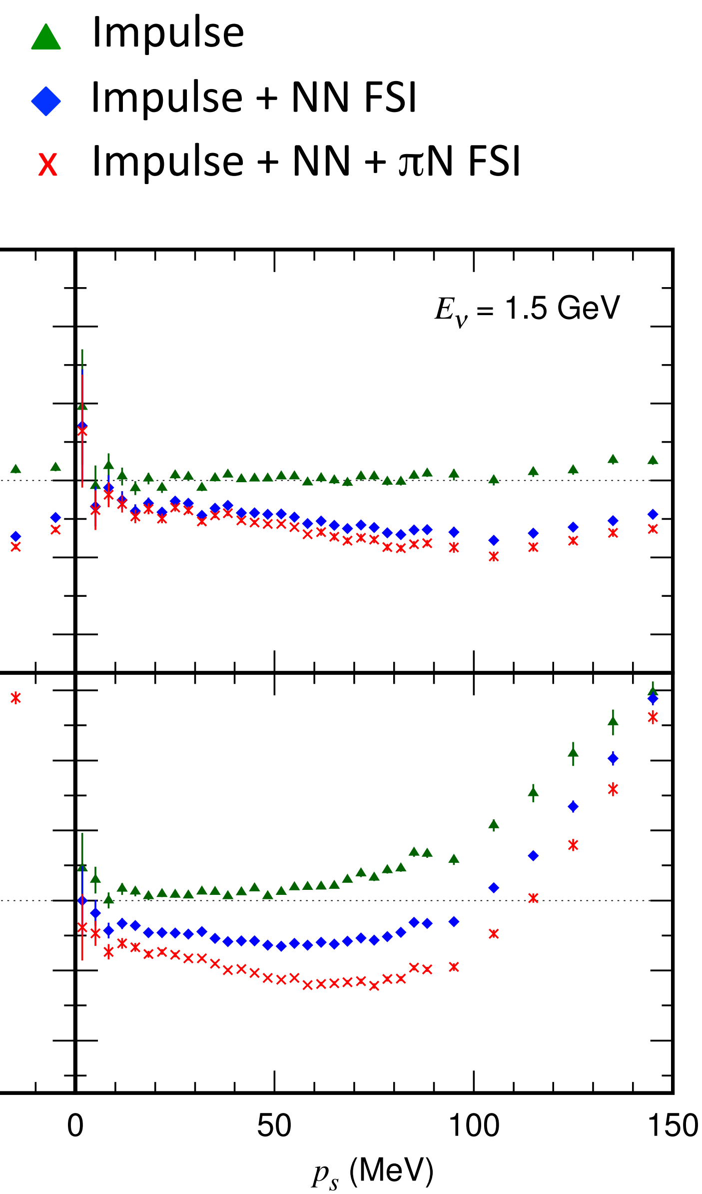
$$N_\alpha(E_\nu, p_s) \equiv \frac{d\sigma_{\nu d}(E_\nu)/dp_s}{d\tilde{\sigma}_\alpha(E_\nu)/dp_s}$$



$N_\alpha(E_\nu, p_s) \approx 1$ → quasi-free process dominates

$\neq 1$ → other nucleon's contribution and/or FSI

$$N_\alpha(E_\nu, p_s) \equiv \frac{d\sigma_{\nu d}(E_\nu)/dp_s}{d\tilde{\sigma}_\alpha(E_\nu)/dp_s}$$



FSI effects

- NN FSI effect is larger for smaller E_ν
- πN FSI is large correction to quasi-free $\nu_\mu n \rightarrow \mu^- \pi^+ n$; $\sigma(\pi^+ p \rightarrow \pi^+ p) \approx 9 \times \sigma(\pi^+ n \rightarrow \pi^+ n)$
- FSI effects depend on spectator momentum

$$N_\alpha(E_\nu, p_s) \equiv \frac{d\sigma_{\nu d}(E_\nu)/dp_s}{d\tilde{\sigma}_\alpha(E_\nu)/dp_s}$$

Phenomenological formula fitted to $N_\alpha(E_\nu, p_s)$ is practically useful

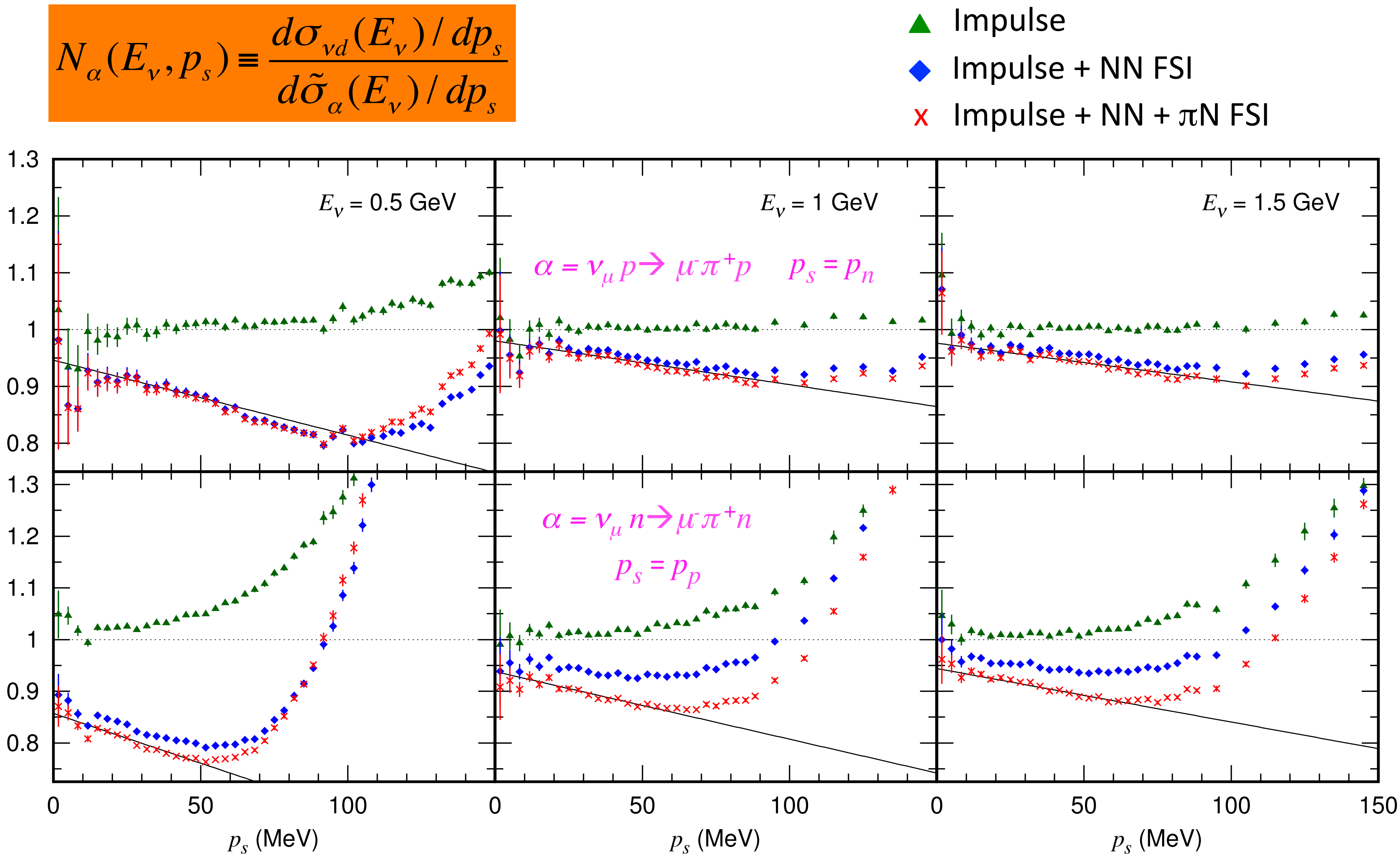
- From $d\sigma_{\nu d}(E_\nu)/dp_s$ data, $d\tilde{\sigma}_\alpha(E_\nu)/dp_s$ can be extracted with FSI taken into account
- Model can be easily tested against $d\tilde{\sigma}_\alpha(E_\nu)/dp_s$
- $d\sigma_{\nu d}(E_\nu)/dp_s$ data may be obtained in future neutrino-deuteron experiment

INT embedded workshop, June 25-29, 2018

- $N_\alpha(E_\nu, p_s)$ is ratio

→ model dependence from using DCC $\nu_\mu N$ ➔ $\mu^- \pi N$ model is expected to be small

$$N_\alpha(E_\nu, p_s) \equiv \frac{d\sigma_{\nu d}(E_\nu)/dp_s}{d\tilde{\sigma}_\alpha(E_\nu)/dp_s}$$



$$N_\alpha^{\text{fit}}(E_\nu, p_s) = A_\alpha(E_\nu) + B_\alpha(E_\nu)p_s \qquad A_\alpha(x) = \frac{a_\alpha x^2 + b_\alpha x + c_\alpha}{x^2 + d_\alpha x + e_\alpha}, \quad B_\alpha(x) = \frac{f_\alpha x + g_\alpha}{x + h_\alpha}$$

Parameters ($a_\alpha - h_\alpha$) are fitted to $N_\alpha(E_\nu, p_s)$ over $p_s < 50$ MeV and $0.4 < E_\nu < 2$ GeV

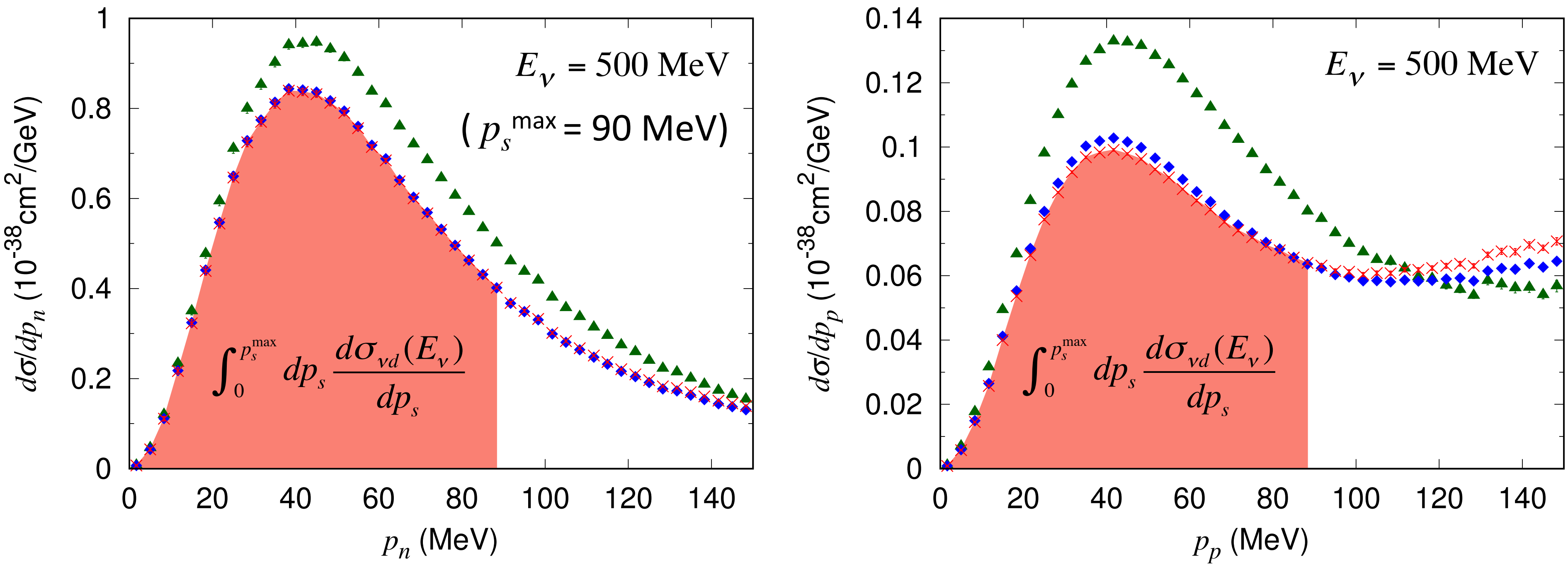
$\nu_\mu N \rightarrow \mu^- \pi N$ cross section data corrected for FSI and Fermi-motion

- Significant FSI effects on spectator momentum distributions of $\nu_\mu d \rightarrow \mu^- \pi^+ p n$ in quasi-free peak region
- (Flux-corrected) ANL and BNL data have not been corrected for FSI but need to be
- We extract $\nu_\mu N \rightarrow \mu^- \pi N$ cross section from flux-corrected ANL and BNL data by further correcting it for FSI and Fermi-motion
- Details of ANL and BNL analyses have been lost
  → A reasonable assumption needs to be made

$\nu_\mu N \rightarrow \mu^- \pi N$ cross section data corrected for FSI and Fermi-motion

Procedure (temporary; still under study)

1. Fit $d\sigma_{\nu d}(E_\nu)/dp_s$ with $\sigma^{\text{fit}}_{\nu N}(E_\nu)$ so that $\int_0^{p_s^{\max}} dp_s \frac{d\sigma_{\nu d}(E_\nu)}{dp_s} \approx \int_0^{p_s^{\max}} d^3 p_s\, \sigma^{\text{fit}}_{\nu N}(E_\nu) \left|\Psi_d(\vec{p}_s)\right|^2$



$\nu_\mu N \rightarrow \mu^- \pi N$ cross section data corrected for FSI and Fermi-motion

Procedure (temporary; still under study)

1. Fit $d\sigma_{\nu d}(E_\nu)/dp_s$ with $\sigma_{\nu N}^{\mathrm{fit}}(E_\nu)$ so that $\int_0^{p_s^{\max}} dp_s \frac{d\sigma_{\nu d}(E_\nu)}{dp_s} \approx \int_0^{p_s^{\max}} d^3p_s\, \sigma_{\nu N}^{\mathrm{fit}}(E_\nu) \left|\Psi_d(\vec{p}_s)\right|^2$

Assumption:

For $p_s < p_s^{\max}$ (small p_s region including quasi-free peak) ,

$d\sigma_{\nu d}(E_\nu)/dp_s$ is from quasi-free $\nu_\mu N \rightarrow \mu^- \pi N$ process (no effect from the other nucleon)

and mostly follows Fermi motion shape, $\left|\Psi_d(\vec{p}_s)\right|^2$

$\nu_\mu N \rightarrow \mu^- \pi N$ cross section data corrected for FSI and Fermi-motion

Procedure (temporary; still under study)

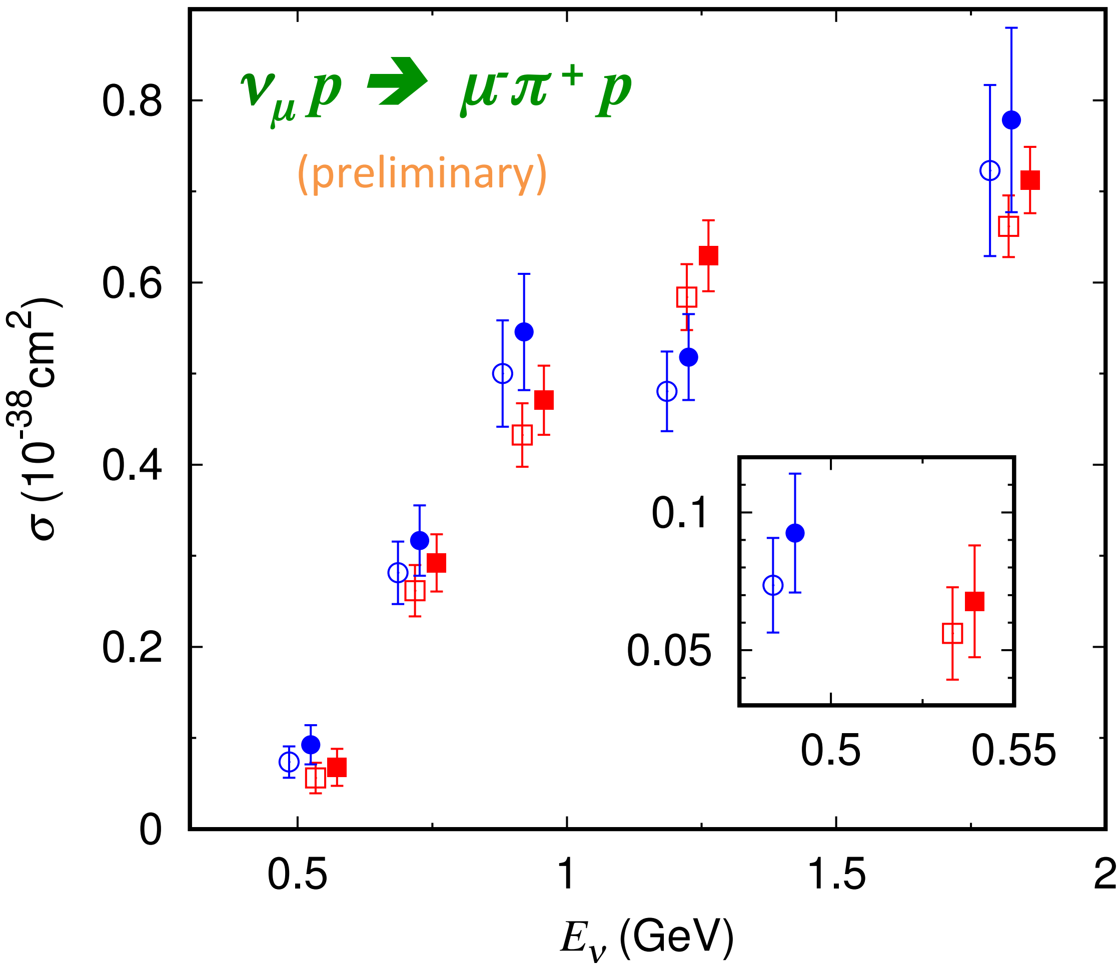
1. Fit $d\sigma_{\nu d}(E_\nu)/dp_s$ with $\sigma^{\rm fit}_{\nu N}(E_\nu)$ so that $\int_0^{p_s^{\max}} dp_s \frac{d\sigma_{\nu d}(E_\nu)}{dp_s} \approx \int_0^{p_s^{\max}} d^3 p_s \, \sigma^{\rm fit}_{\nu N}(E_\nu) \left|\Psi_d(\vec{p}_s)\right|^2$

2. Ratio $\sigma_{\nu N}(E_\nu)/\sigma^{\rm fit}_{\nu N}(E_\nu)$ is the correction factor to be multiplied to

   flux-corrected ANL and BNL data (PRD 90, 112017 (2014), EPJC 76, 474 (2016))

   ($\sigma_{\nu N}(E_\nu)$: DCC $\nu_\mu N \rightarrow \mu^- \pi N$ model)

$\nu_\mu N \rightarrow \mu^- \pi N$ cross section data corrected for FSI and Fermi-motion

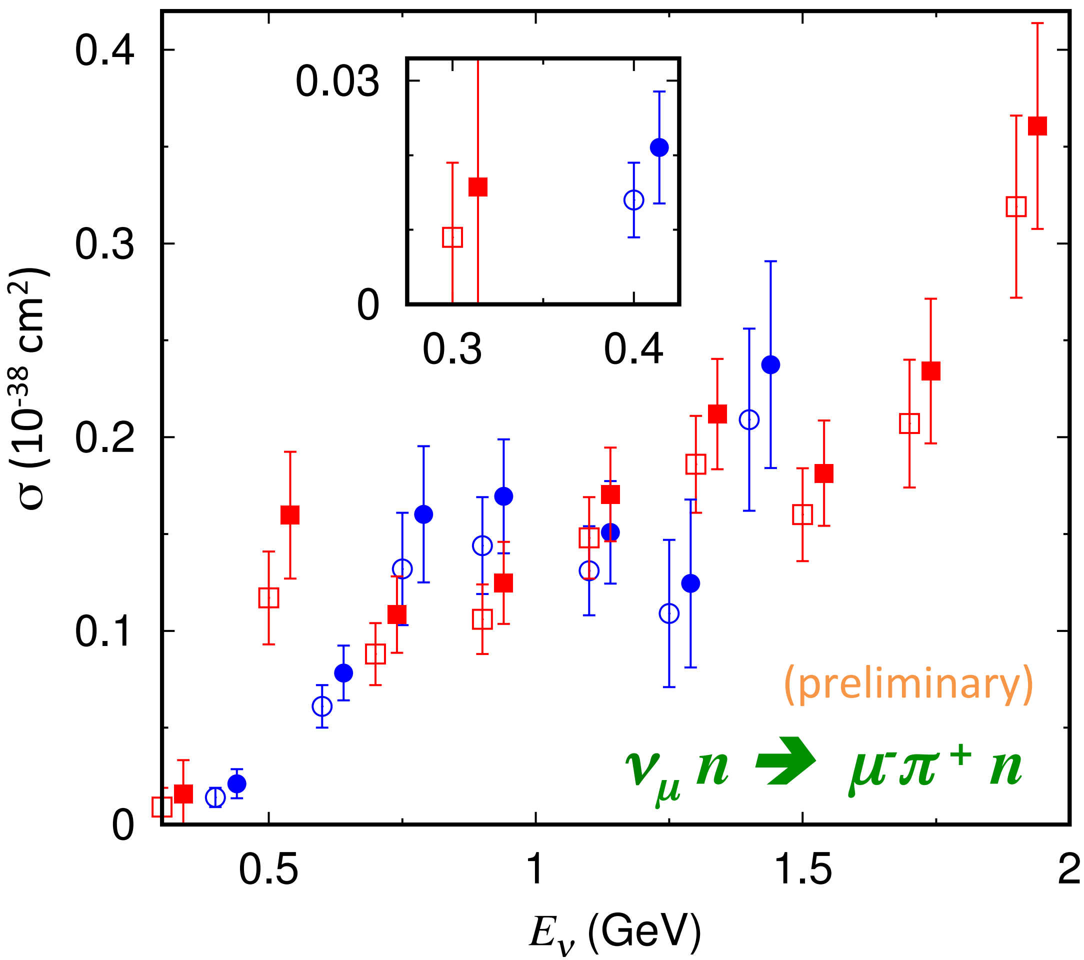


ANL data
- Flux corrected
- FSI, Fermi-motion, Flux corrected

BNL data
- Flux corrected
- FSI, Fermi-motion, Flux corrected

E_ν (GeV)	0.5	1	2
Correction	+24%	+8%	+7%

$\nu_\mu N \rightarrow \mu^- \pi N$ cross section data corrected for FSI and Fermi-motion



ANL data

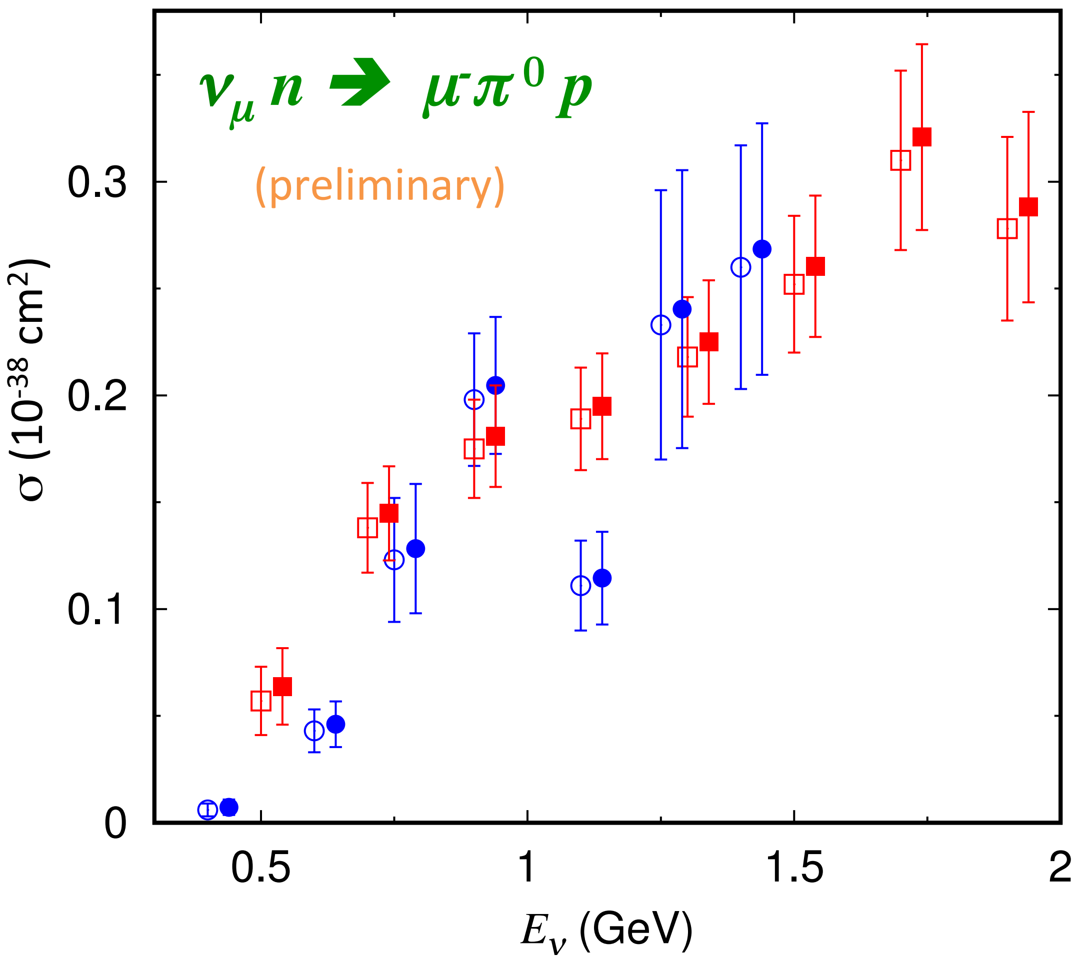
- ○ Flux corrected
- ● FSI, Fermi-motion, Flux corrected

BNL data

- □ Flux corrected
- ■ FSI, Fermi-motion, Flux corrected

E_ν (GeV)	0.5	1	2
Correction	+37%	+16%	+13%

$\nu_\mu N \rightarrow \mu^- \pi\, N$ cross section data corrected for FSI and Fermi-motion



ANL data

- Flux corrected
- FSI, Fermi-motion, Flux corrected

BNL data

- Flux corrected
- FSI, Fermi-motion, Flux corrected

E_ν (GeV)	0.5	1	2
Correction	+12%	+3%	+4%

Summary

Summary

- $\nu_\mu d \rightarrow \mu^- \pi NN$ cross sections of the whole phase-space are calculated with a dynamical model including FSI ; for the first time

- Examined FSI effect on spectator momentum distribution $d\sigma/dp_s$

- Found a useful recipe to extract $\nu_\mu N \rightarrow \mu^- \pi N$ cross sections from $\nu_\mu d \rightarrow \mu^- \pi NN$ spectator momentum distribution (from future exp.)

- Extracted $\nu_\mu N \rightarrow \mu^- \pi N$ total cross sections by correcting (flux-corrected) ANL and BNL data for FSI and Fermi motion (preliminary)

Future impact

→ Significantly improved elementary $\nu_\mu N \rightarrow \mu^- \pi N$ model to be implemented in neutrino-nucleus reaction model for oscillation experiments of the precision era

Thank you very much for your attention

Acknowledgments

- Financial support for this work

  KAKENHI JP25105010

  FAPESP 2016/15618-8

- Computing resource

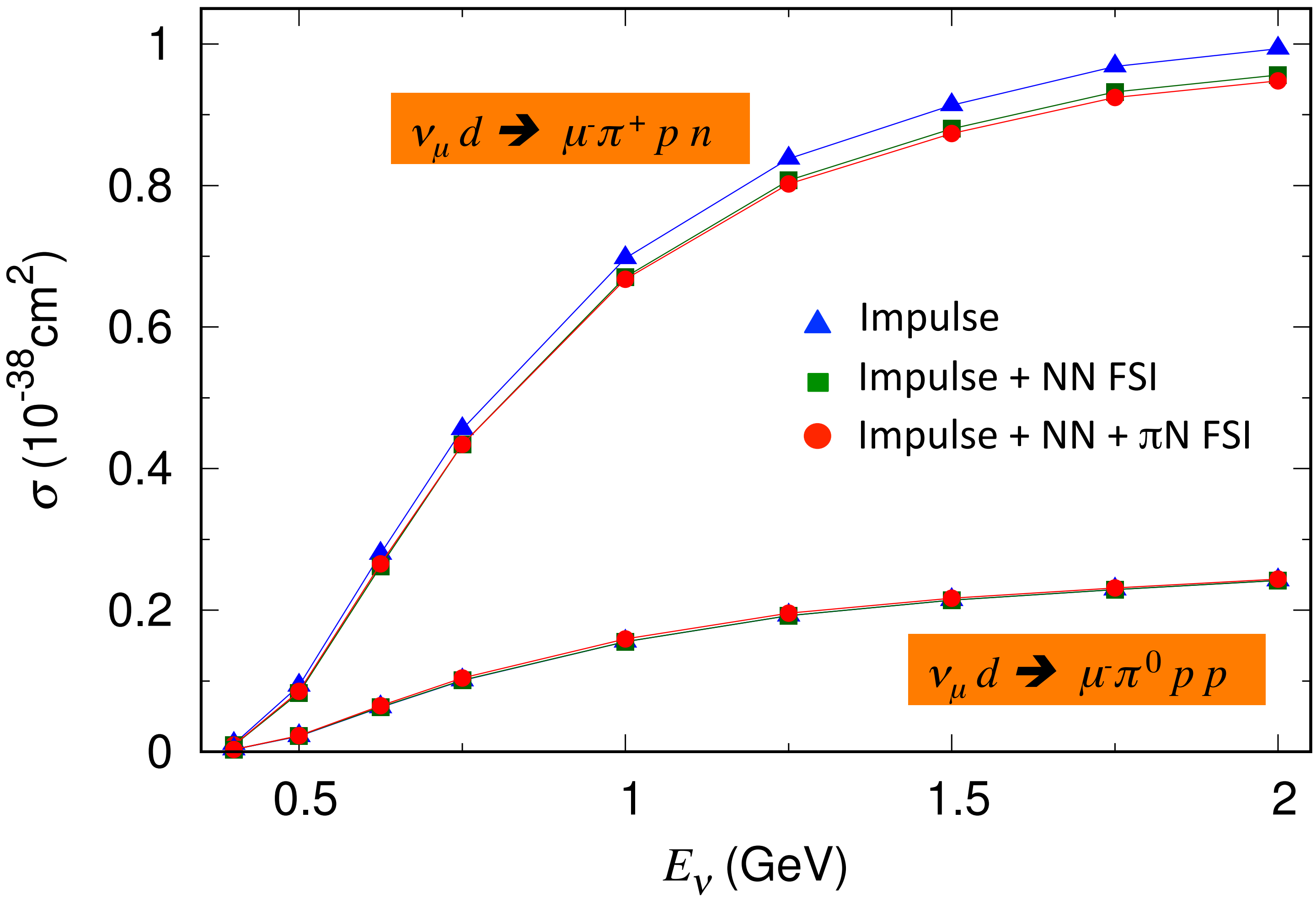
  SR16000 at YITP in Kyoto University

  Bebop at Argonne National Laboratory

  Cori at National Energy Research Scientific Computing Center

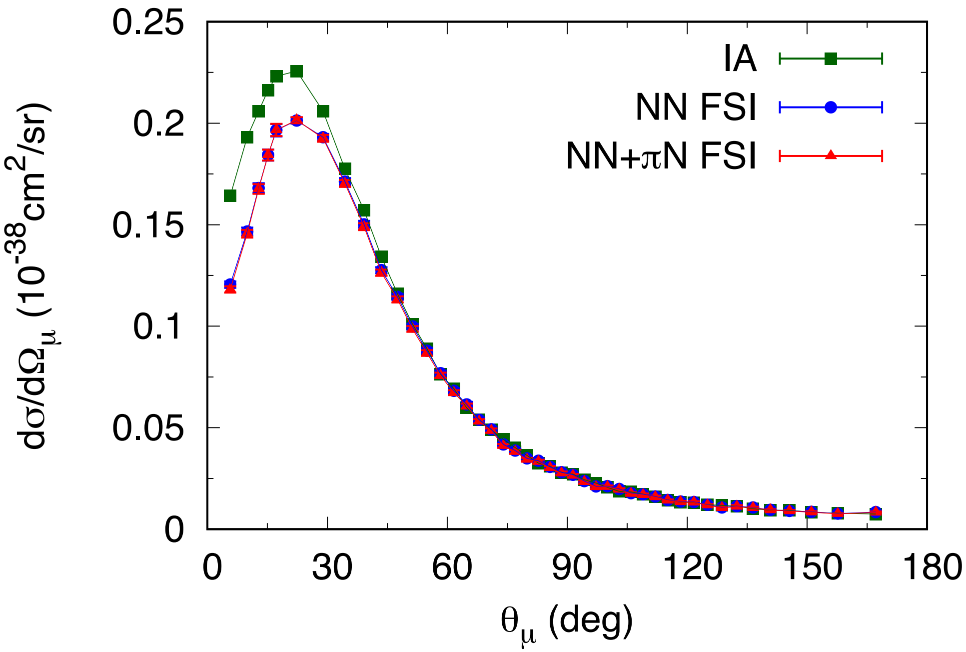
BACKUP

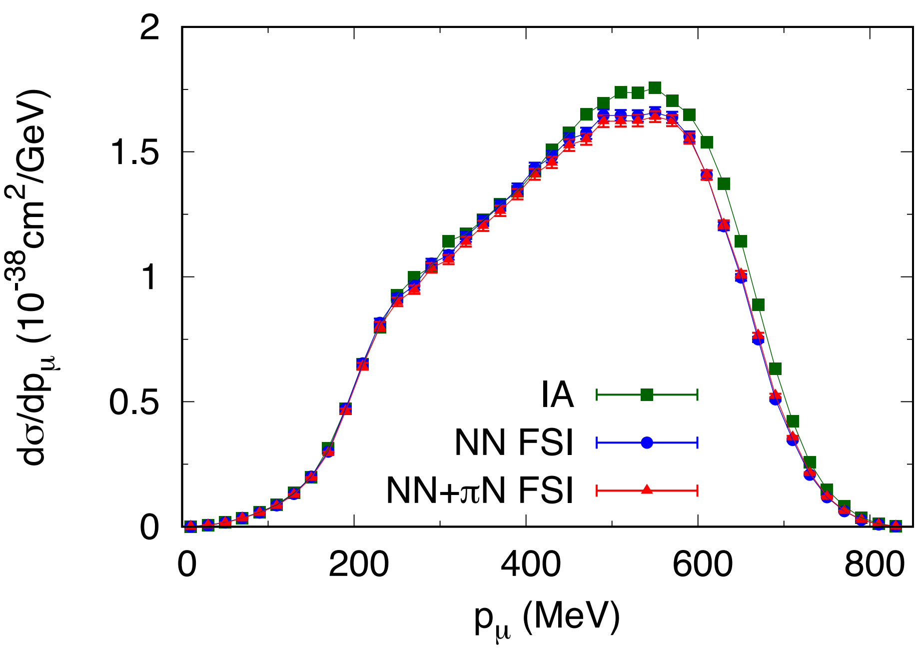
$\nu_\mu d \rightarrow \mu^- \pi NN$ total cross sections



- (Mostly NN) FSI reduces σ by 10%, 6%, 5% at E_ν = 0.5, 1, 1.5 GeV
- πN FSI hardly changes $\sigma(\nu_\mu d \rightarrow \mu^- \pi^+ p n)$
- FSI effects are very small for $\sigma(\nu_\mu d \rightarrow \mu^- \pi^0 p p)$

$d\sigma/d\Omega_\mu$ and $d\sigma/dp_\mu$ for $\nu_\mu d \rightarrow \mu^- \pi^+ p\, n$ at E_ν = 1 GeV





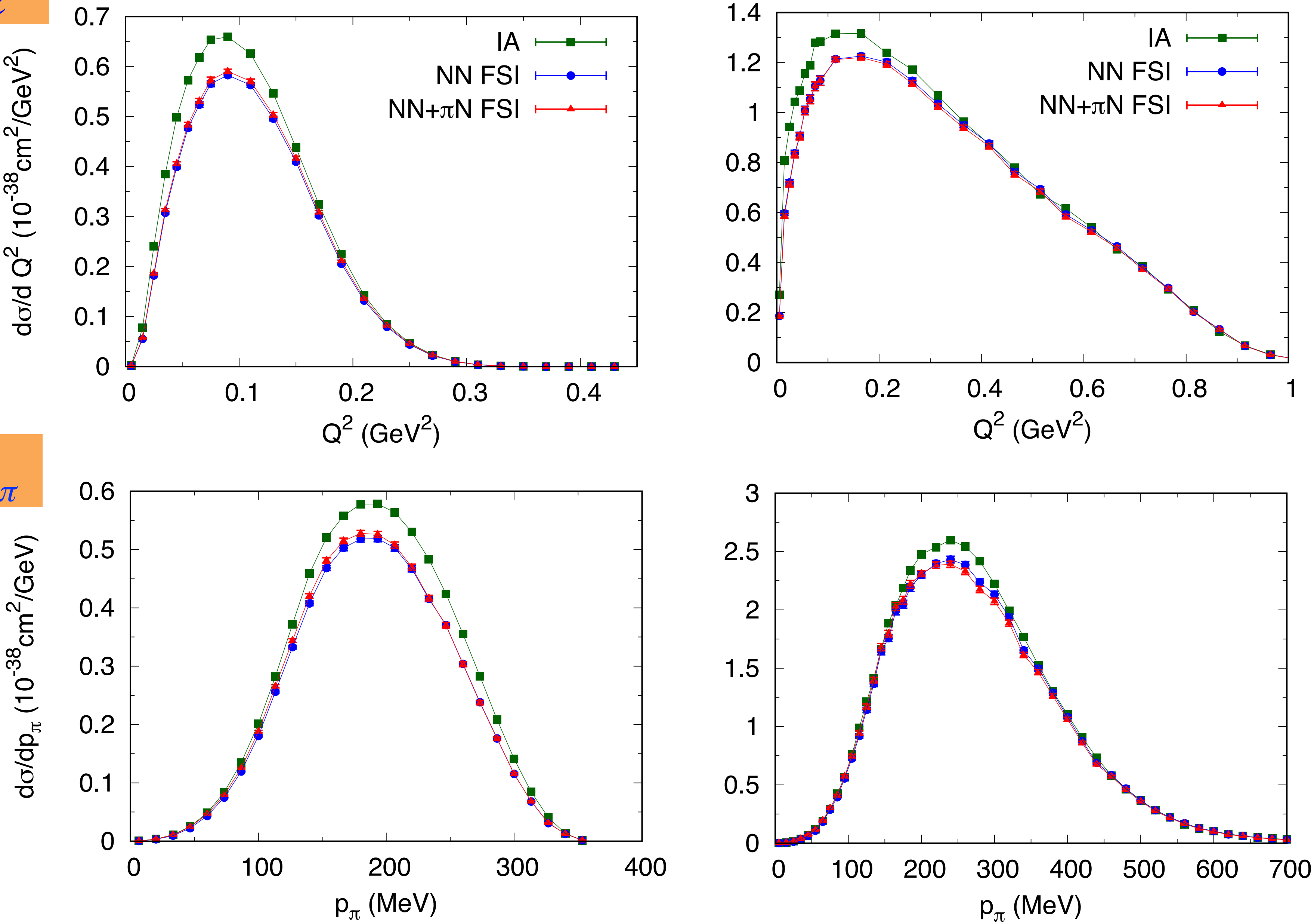
- Significant FSI effects are seen in narrow kinematical windows

  → moderate reduction of total cross sections

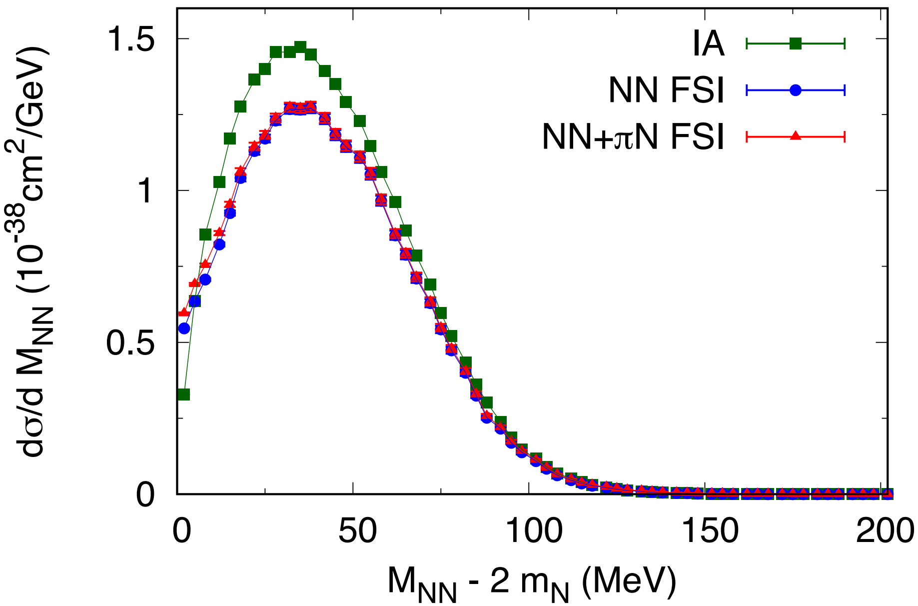
E_ν = 0.5 GeV vs E_ν = 1 GeV

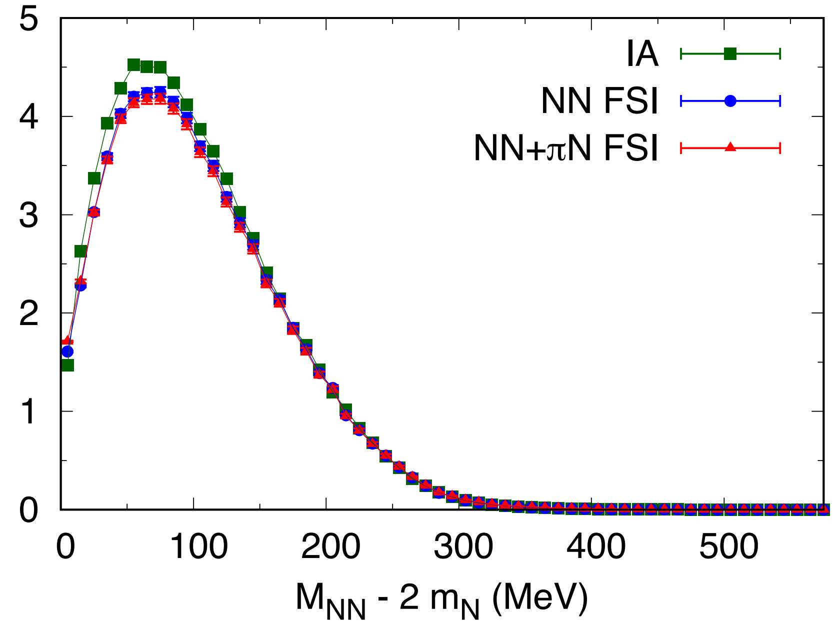
Q^2

p_π



E_ν = 0.5 GeV vs E_ν = 1 GeV



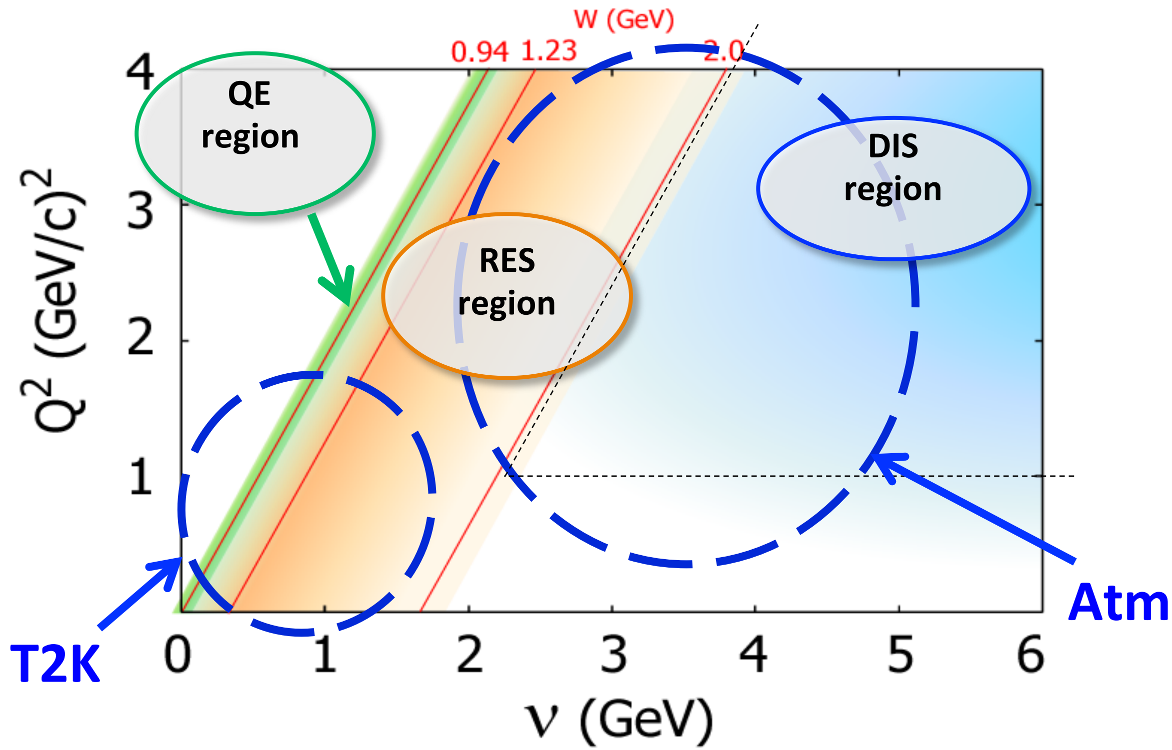


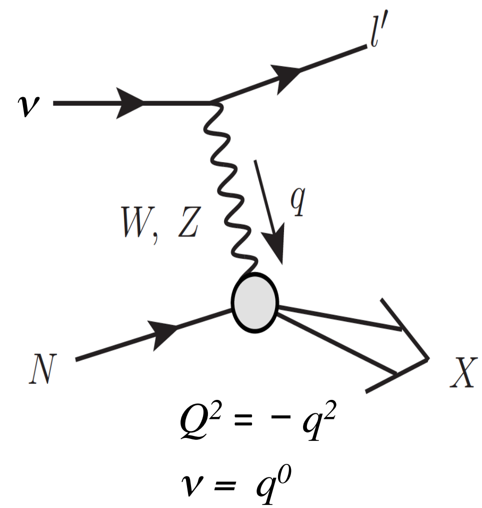
- NN FSI effect is large at low NN energy region ($\lesssim$ 50 MeV) where orthogonality between pn scattering states and deuteron is most effective
- Low NN energy region occupies a relatively larger portion of phase-space for low E_ν

→ Larger NN FSI effect for low E_ν

Neutrino-nucleus scattering for ν-oscillation experiments

Wide kinematical region with different characteristic ➔ Different expertise need integrated





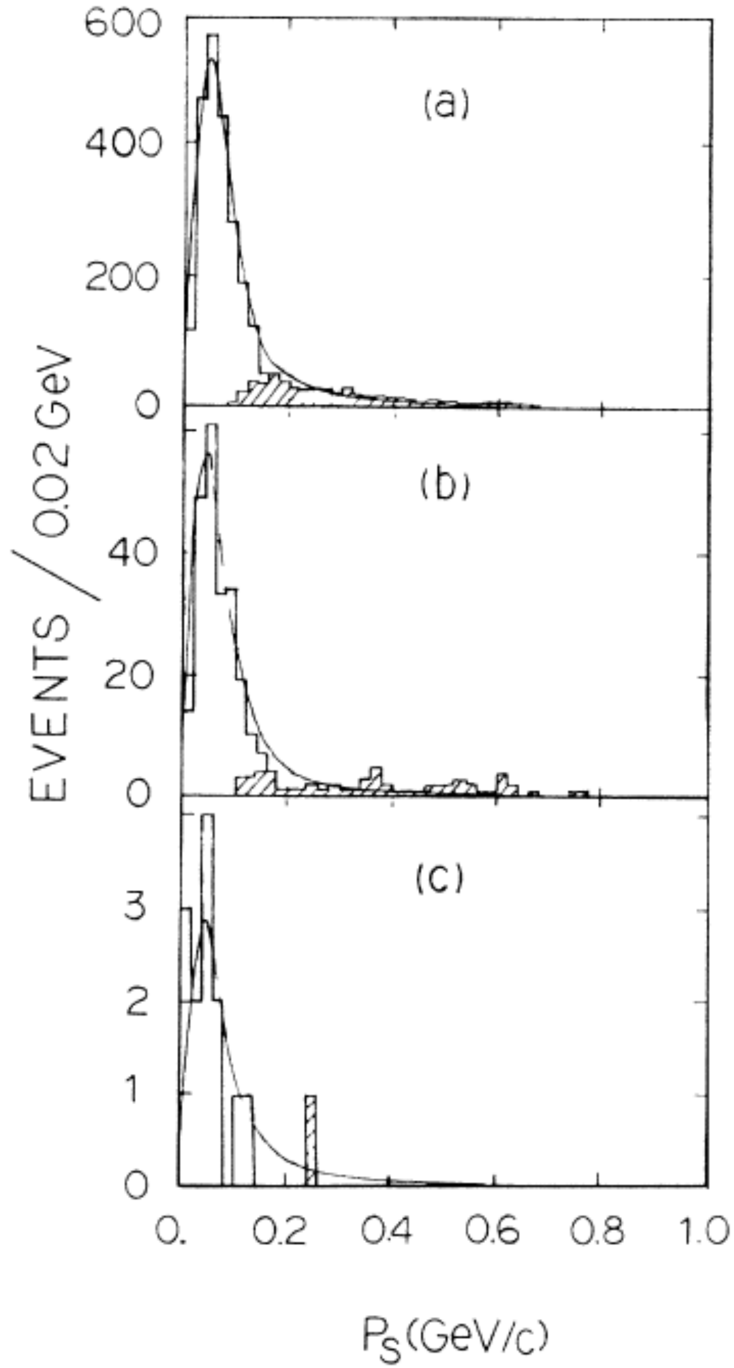
Collaboration at J-PARC Branch of KEK Theory Center

Current status reviewed in *Reports on Progress in Physics* **80** (2017) 056301

"Towards a Unified Model of Neutrino-Nucleus Reactions for Neutrino Oscillation Experiments"

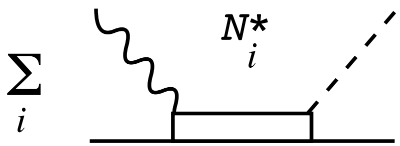
BNL analysis

PRD 34, 2554 (1986)



Previous models for ν–induced 1π production in resonance region

resonant only   Rein et al. (1981), (1987) ; Lalalulich et al. (2005), (2006)

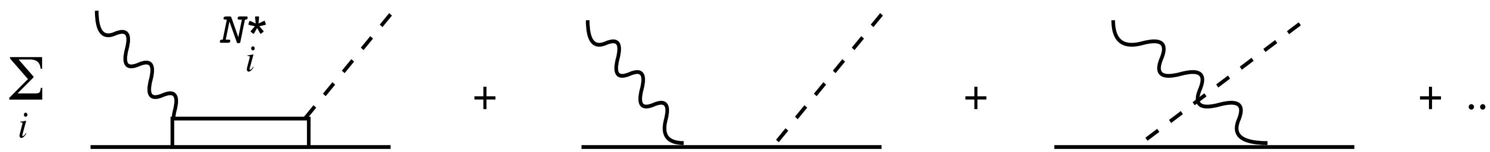


VNN^* : helicity amplitudes listed in PDG

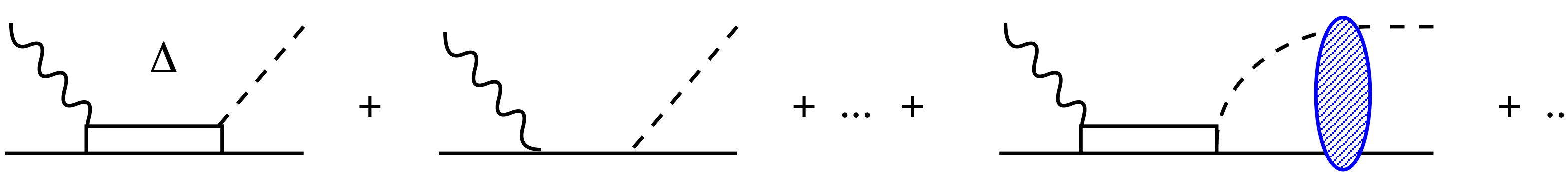
ANN^* : quark model, PCAC relation to $|\pi NN^*|$ (PDG)

relative phases among N^*'s are out of control

+ non-resonant (tree-level non-res)   Hernandez et al. (2007), (2010) ; Lalakulich et al. (2010)



+ rescattering (πN unitarity, $\Delta(1232)$ region)   Sato, Lee (2003), (2005)



DCC (Dynamical Coupled-Channel) model

Matsuyama et al., Phys. Rep. **439**, 193 (2007)

Kamano et al., PRC 88, 035209 (2013)

Coupled-channel Lippmann-Schwinger equation for meson-baryon scattering

$$T_{ab} \quad = \quad V_{ab} + \sum_c V_{ac}\, G_c\, T_{cb}$$

$$\{a,b,c\} \quad = \qquad \pi N,\ \eta N,\ \pi\pi N\ ,\pi\Delta, \sigma N, \rho N\ ,\ K\Lambda,\ K\Sigma$$

By solving the LS equation, coupled-channel unitarity is fully taken into account

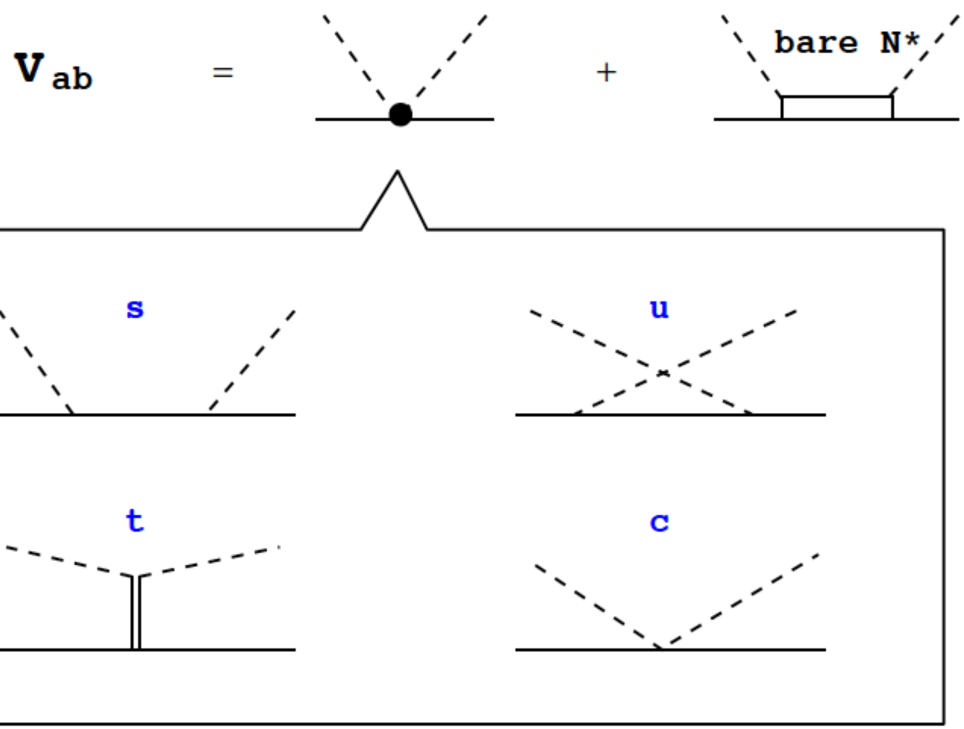
DCC (Dynamical Coupled-Channel) model

Matsuyama et al., Phys. Rep. **439**, 193 (2007)

Kamano et al., PRC 88, 035209 (2013)

Coupled-channel Lippmann-Schwinger equation for meson-baryon scattering

$$T_{ab} = V_{ab} + \sum_{c} V_{ac} \, G_c \, T_{cb}$$



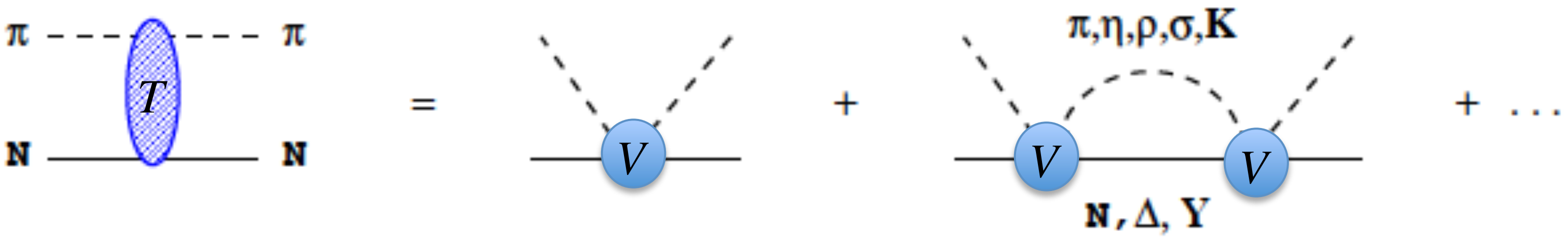
DCC (Dynamical Coupled-Channel) model

Matsuyama et al., Phys. Rep. **439**, 193 (2007)

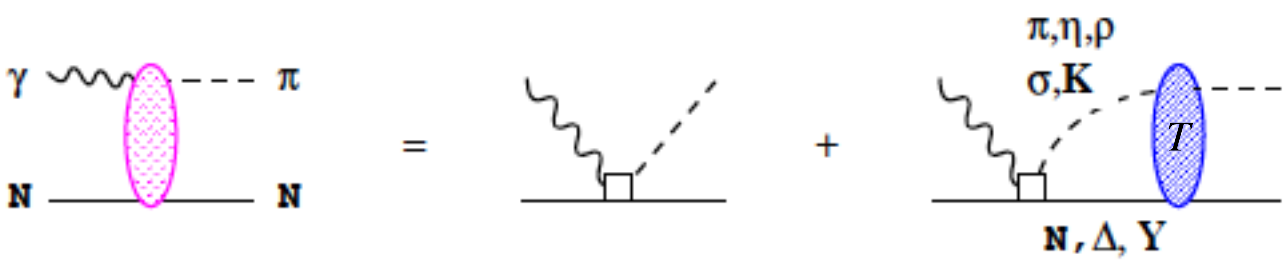
Kamano et al., PRC 88, 035209 (2013)

Coupled-channel Lippmann-Schwinger equation for meson-baryon scattering

$$T_{ab} = V_{ab} + \sum_c V_{ac} G_c T_{cb}$$



In addition, γN, $W^{\pm}N$, ZN channels are included perturbatively



Relation between neutrino and electron (photon) interactions

Charged-current (CC) interaction (e.g. $\nu_\mu + n \rightarrow \mu^- + p$)

$$L^{cc} = \frac{G_F V_{ud}}{\sqrt{2}} [J^{cc}_\lambda \ell^\lambda_{cc} + h.c.] \qquad J^{cc}_\lambda = V_\lambda - A_\lambda \qquad \ell^\lambda_{cc} = \bar{\psi}_\mu \gamma^\lambda (1-\gamma_5)\psi_\nu$$

Electromagnetic interaction (e.g. $\gamma^{(*)} + p \rightarrow p$)

$$L^{em} = e\, J^{em}_\lambda A^\lambda_{em} \qquad J^{em}_\lambda = V_\lambda + V^{IS}_\lambda$$

V and V^{IS} in J^{em} can be separately determined by analyzing photon ($Q^2=0$) and electron reaction ($Q^2 \neq 0$) data on both proton and neutron targets, because:

$$< p | V_\lambda | p > = - < n | V_\lambda | n > \qquad < p | V^{IS}_\lambda | p > = < n | V^{IS}_\lambda | n >$$

Matrix element for the weak vector current is obtained from analyzing electromagnetic processes

$$< p | V_\lambda | n > = \sqrt{2} < p | V_\lambda | p >$$

DCC model for axial current

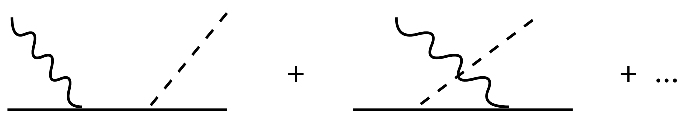
Because neutrino reaction data are scarce, axial current cannot be determined phenomenologically
→ Chiral symmetry and PCAC (partially conserved axial current) are guiding principle

PCAC relation $< X' | q \cdot A | X > \sim i f_\pi < X' | T | \pi X >$

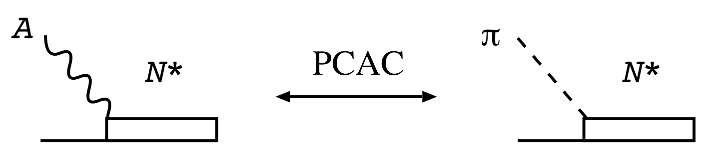
Q^2=0

non-resonant mechanisms

$$\partial_\mu \pi \rightarrow f_\pi A_\mu^{external}$$



resonant mechanisms



Interference among resonances and background can be uniquely fixed within DCC model

DCC model for axial current

$Q^2 \neq 0$ $F_A(Q^2)$: axial form factors

non-resonant mechanisms $F_A(Q^2) = \left(\dfrac{1}{1+Q^2/M_A^2}\right)^2$ M_A=1.02 GeV

resonant mechanisms $F_A(Q^2) = \left(\dfrac{1}{1+Q^2/M_A^2}\right)^2$

More neutrino data are necessary to fix axial form factors for ANN^*

Neutrino cross sections will be predicted with this axial current

DCC analysis of $\gamma N, \pi N \rightarrow \pi N, \eta N, K\Lambda, K\Sigma$

and electron scattering data

DCC analysis of meson production data

Kamano, Nakamura, Lee, Sato, PRC 88 (2013)

Fully combined analysis of $\gamma N, \pi N$ ➔ $\pi N, \eta N, K\Lambda, K\Sigma$ data

$d\sigma / d\Omega$ and polarization observables (W ≤ 2.1 GeV)

~ 23,000 data points are fitted

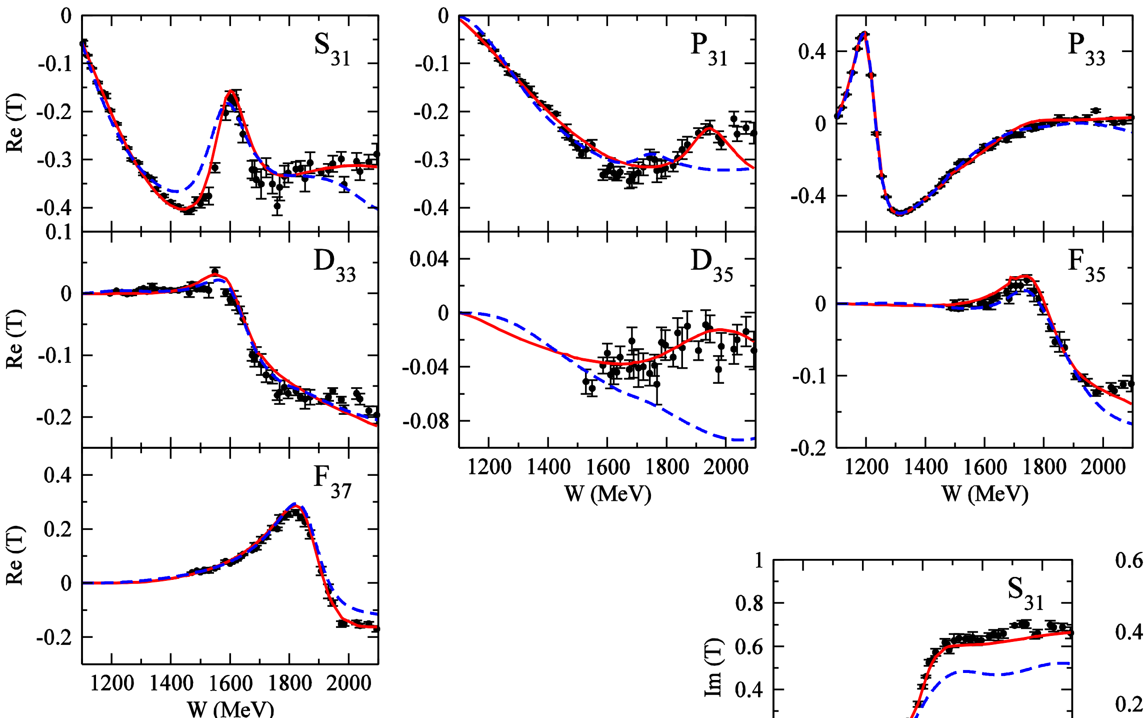
by adjusting parameters (*N** mass, *N** ➔ *MB* couplings, cutoffs)

⬇

Data for electron scattering on proton and neutron are analyzed by adjusting

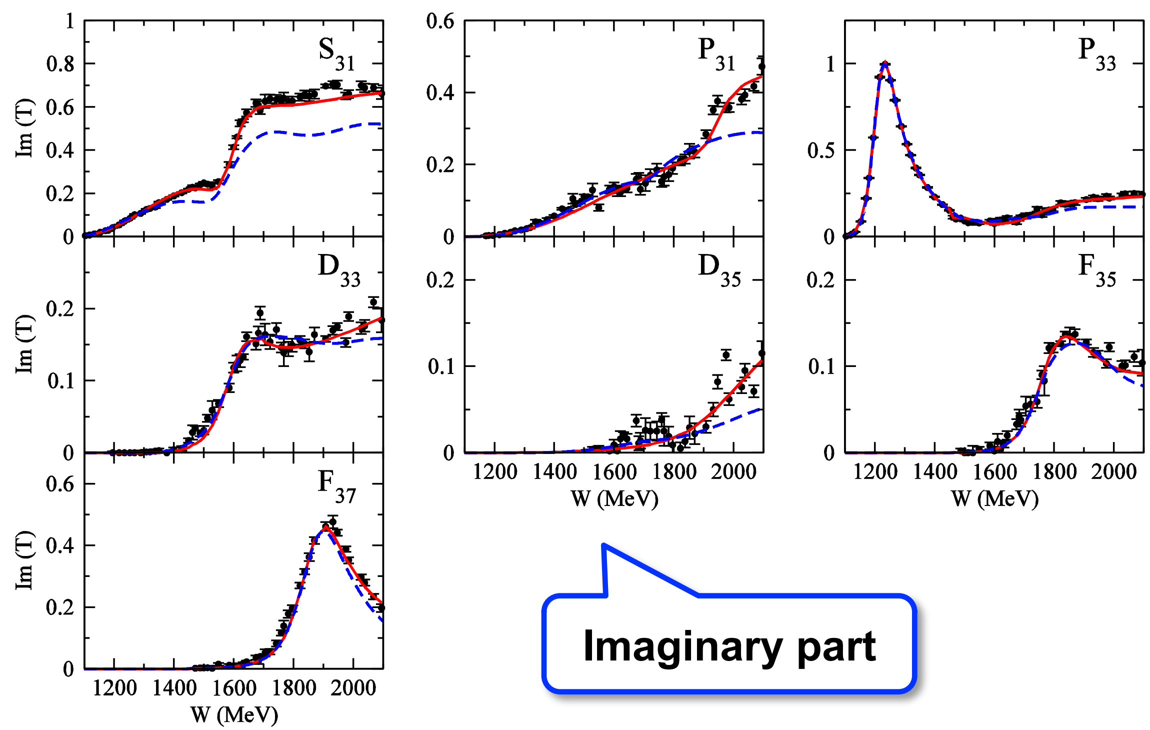
$\gamma^* N$ ➔ N^* coupling strength at different Q^2 values ($Q^2 \leq 3\ (\mathrm{GeV}/c)^2$)

Partial wave amplitudes of π N scattering



Real part

$$I = \frac{3}{2}$$



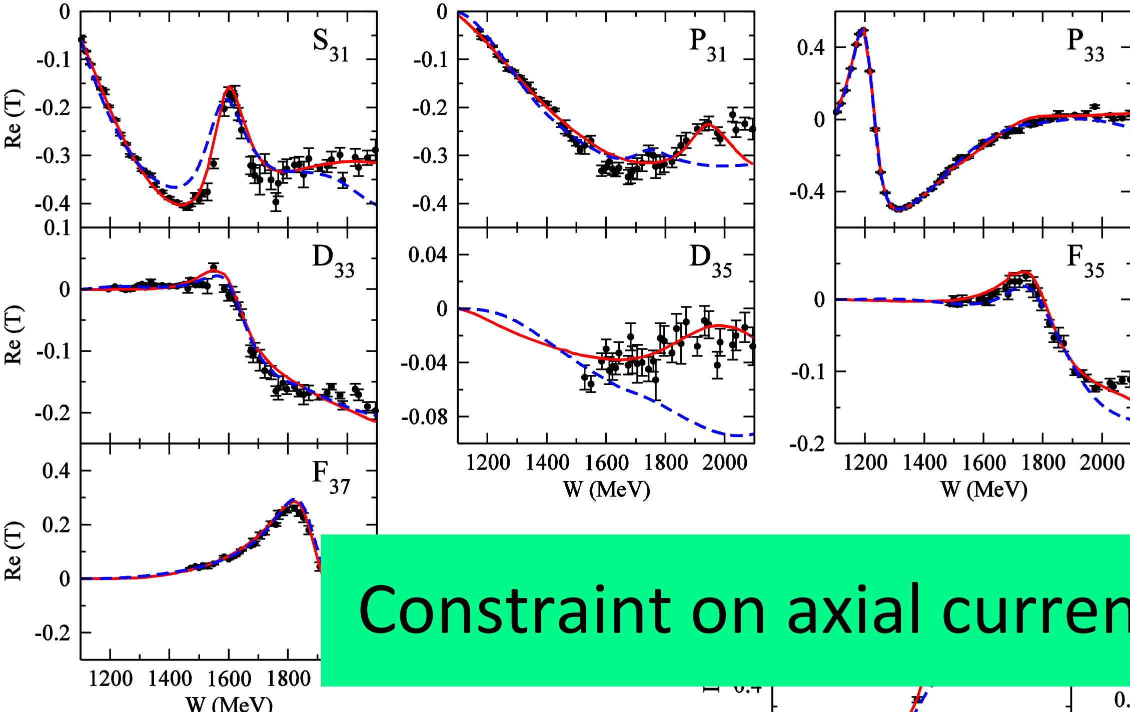
Imaginary part

Kamano, Nakamura, Lee, Sato, PRC 88 (2013)

Previous model (fitted to πN → πN data only) [PRC76 065201 (2007)]

Data: SAID πN amplitude

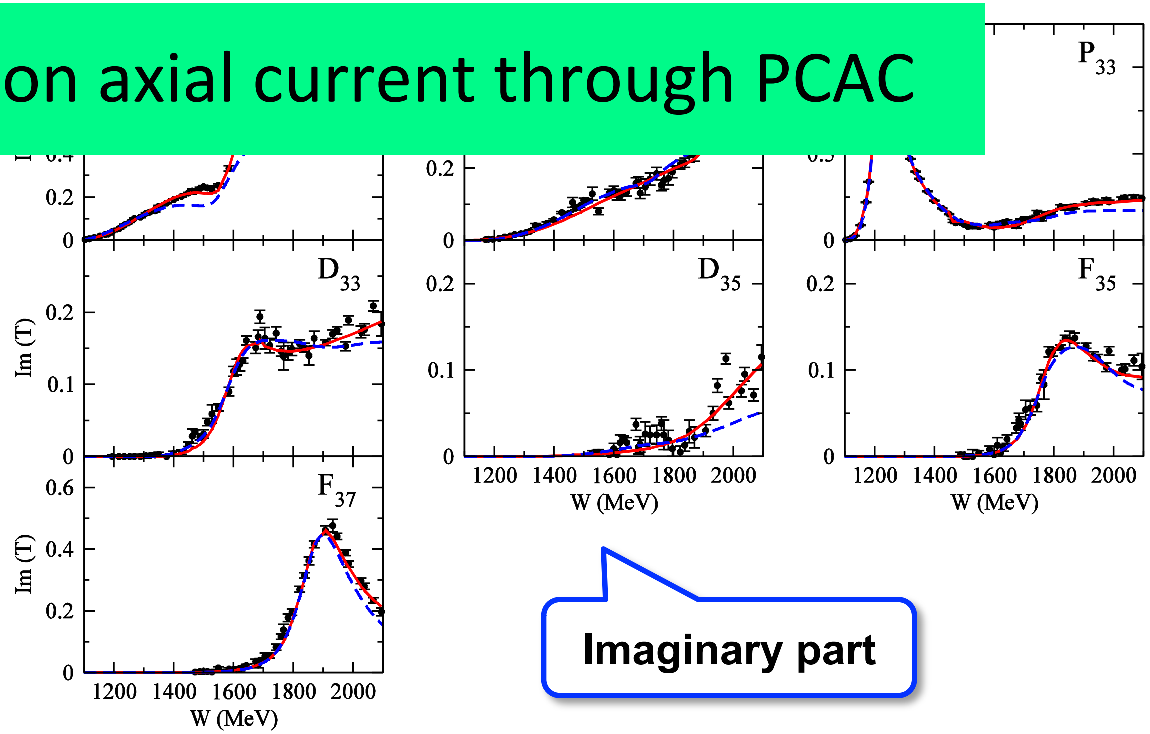
Partial wave amplitudes of π N scattering



Real part

$$I = \frac{3}{2}$$

Constraint on axial current through PCAC



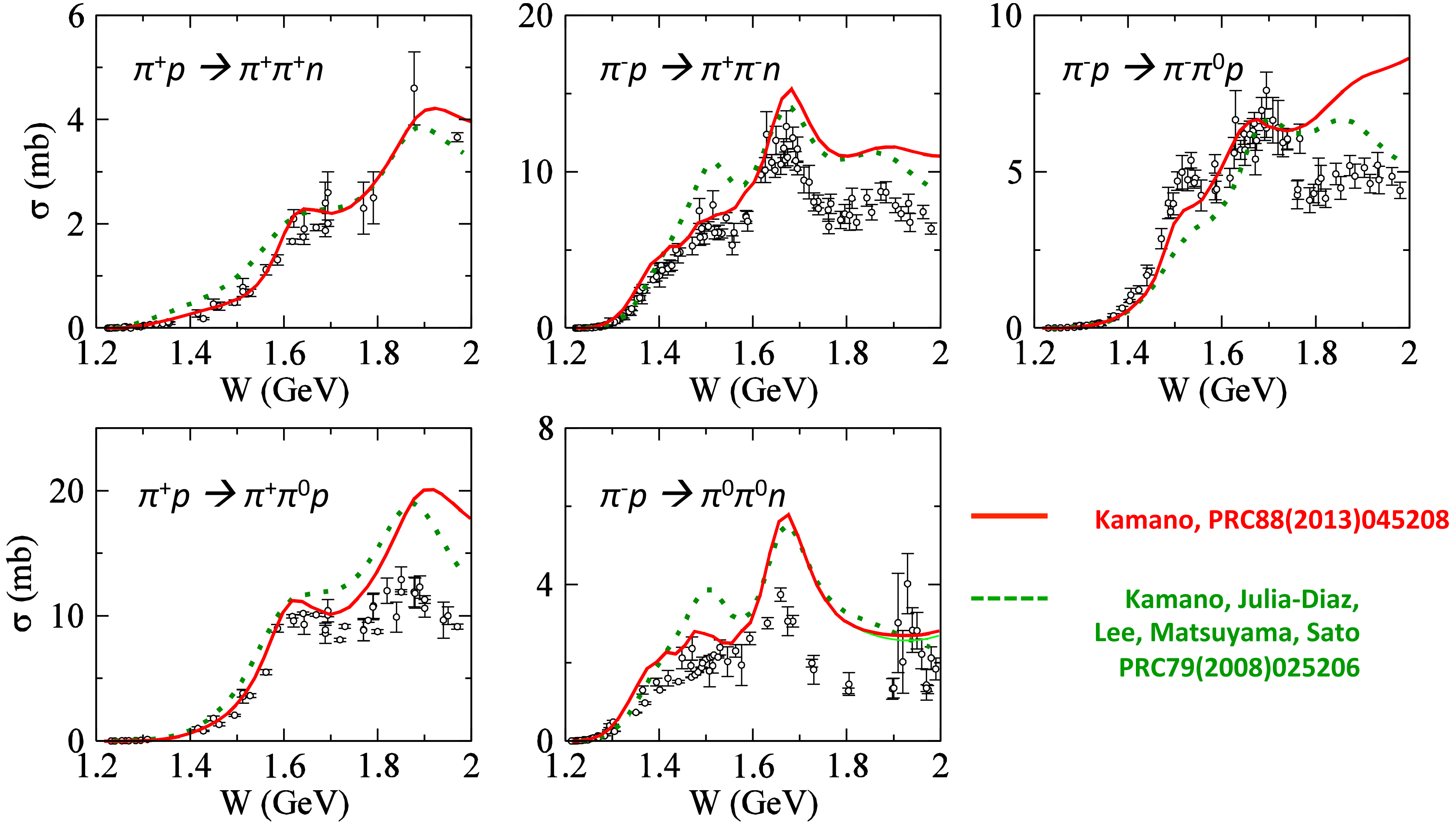
Imaginary part

Kamano, Nakamura, Lee, Sato, PRC 88 (2013) (red solid line)

Previous model (fitted to πN → πN data only) [PRC76 065201 (2007)] (blue dashed line)

Data: SAID πN amplitude

Predicted πN → ππN total cross sections with our DCC model

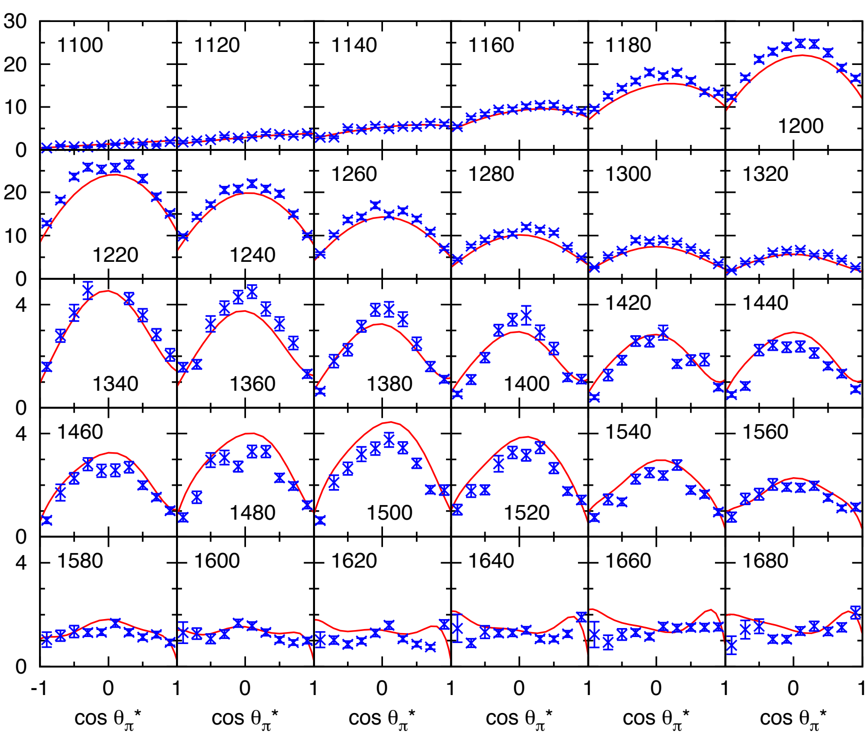


Single π production in electron-proton scattering

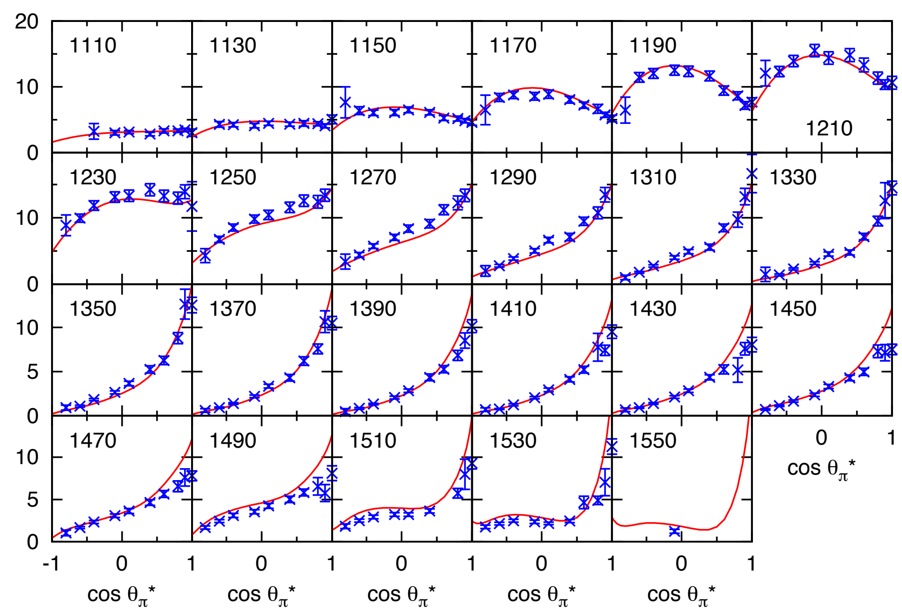
Purpose : Determine Q^2 –dependence of vector coupling of p-N^* : $VpN^*(Q^2)$

$\sigma_T + \varepsilon\, \sigma_L$ for Q^2=0.40 (GeV/c)^2 and W=1.1 – 1.68 GeV

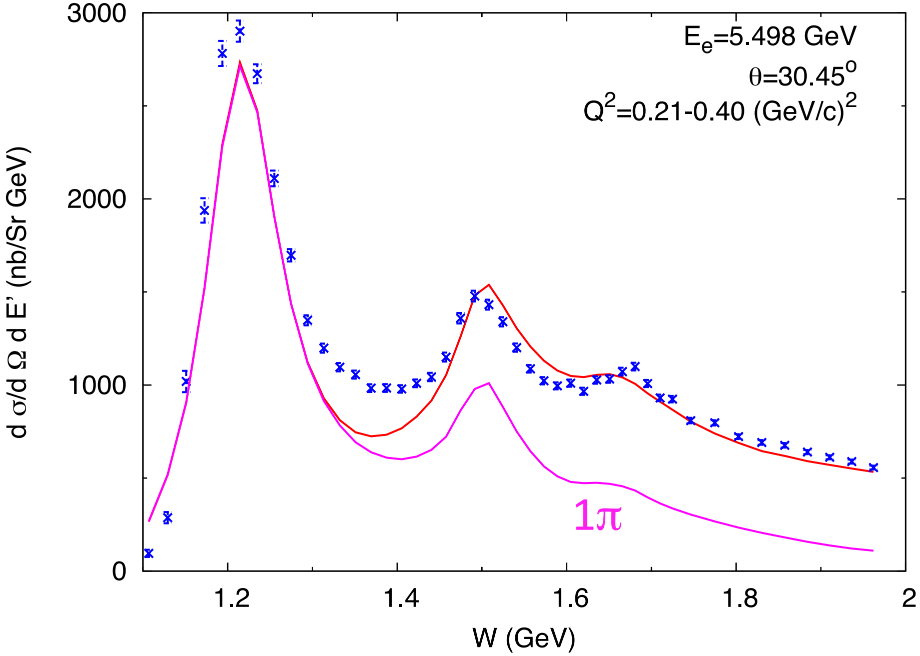
$p(e,e'\pi^0)p$

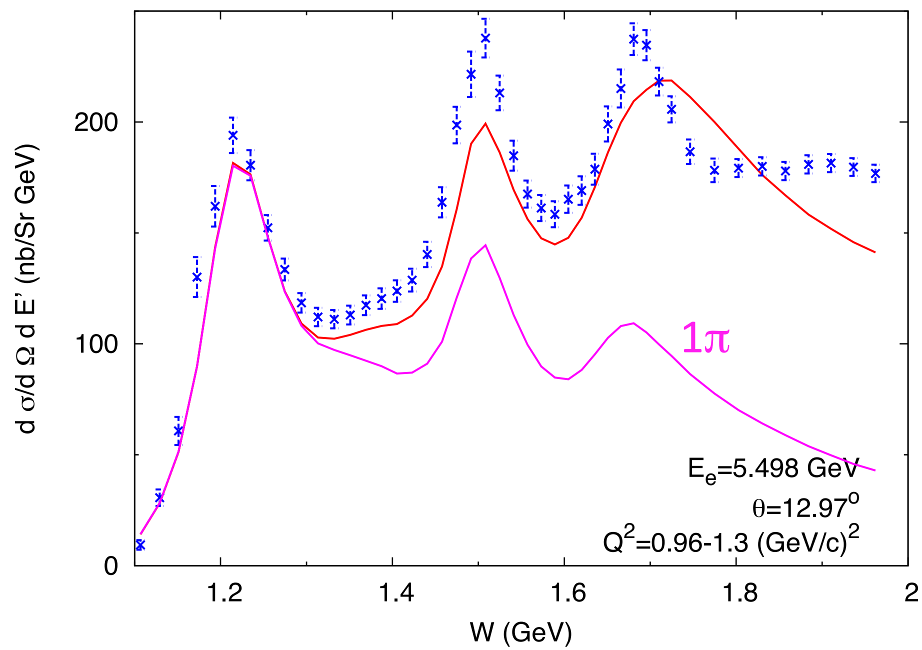


$p(e,e'\pi^+)n$



Inclusive electron-proton scattering





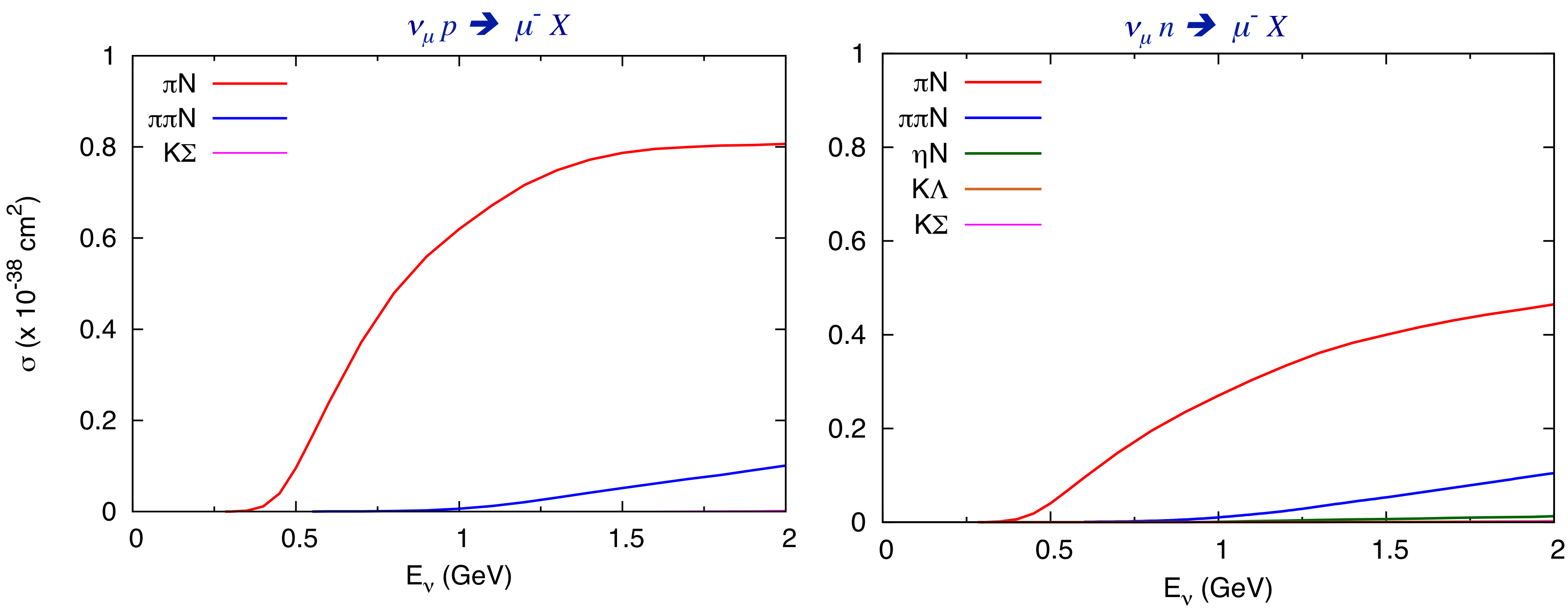
Data: JLab E00-002 (preliminary)

- Reasonable fit to data for application to neutrino interactions
- Important 2π contributions for high W region

Similar analysis of electron-neutron scattering data has also been done

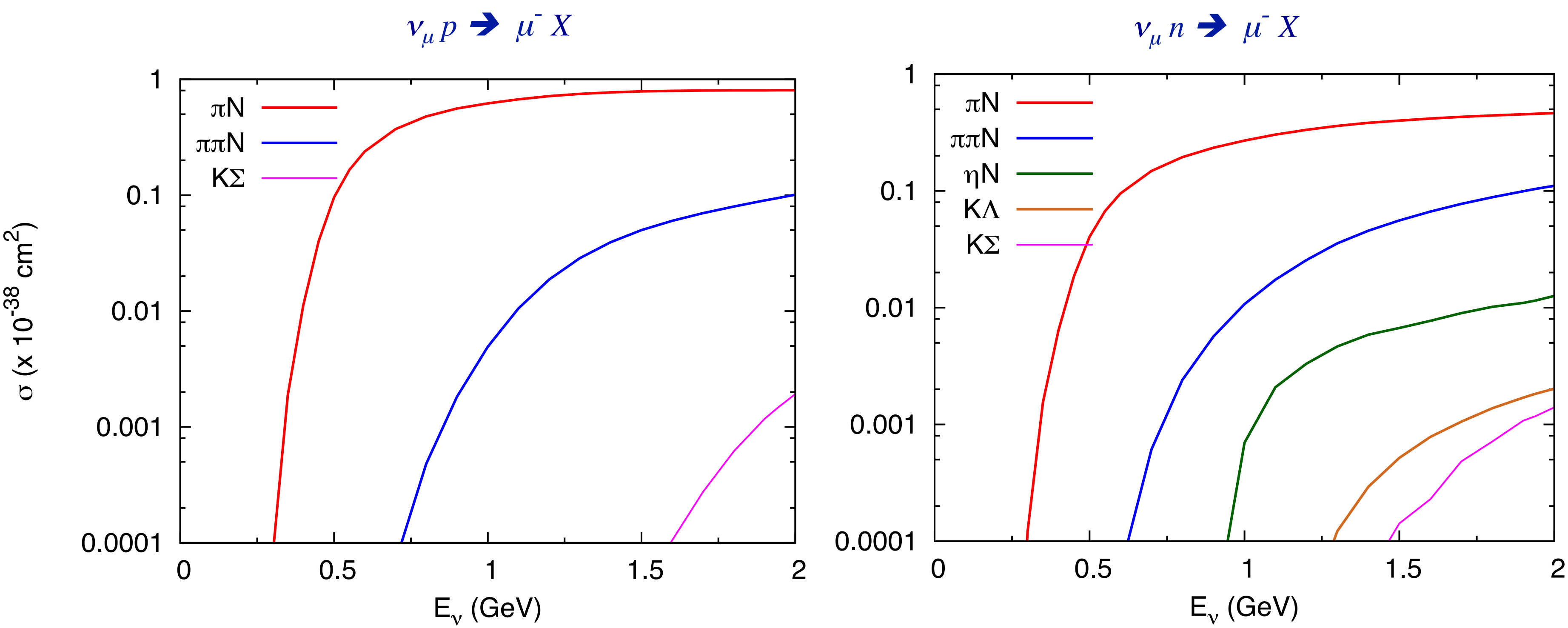
DCC vector currents has been tested by data for whole kinematical region relevant to neutrino interactions of $E_\nu \leq 2$ GeV

Cross section for $\nu_\mu N \rightarrow \mu^- X$



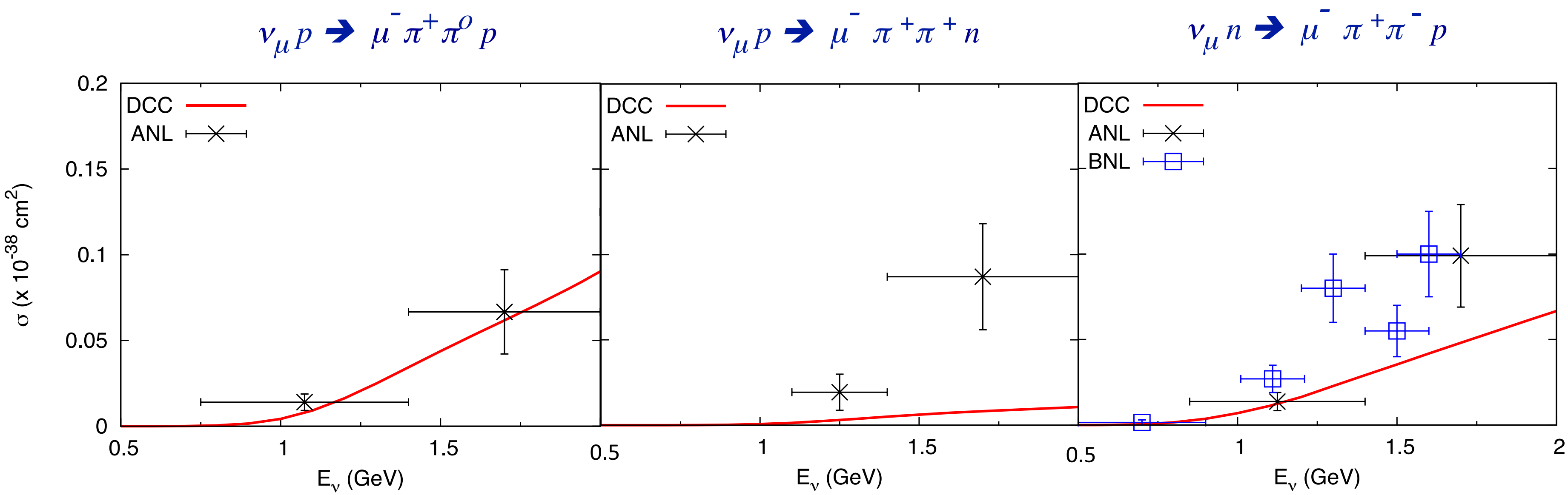
- πN & $\pi\pi N$ are main channels in few-GeV region
- DCC model gives predictions for all final states
- ηN, KY cross sections are $10^{-1} - 10^{-2}$ smaller

Cross section for $\nu_\mu N \rightarrow \mu^- X$



- πN & $\pi\pi N$ are main channels in few-GeV region
- DCC model gives predictions for all final states
- ηN, KY cross sections are $10^{-1} - 10^{-2}$ smaller

Comparison with double pion data

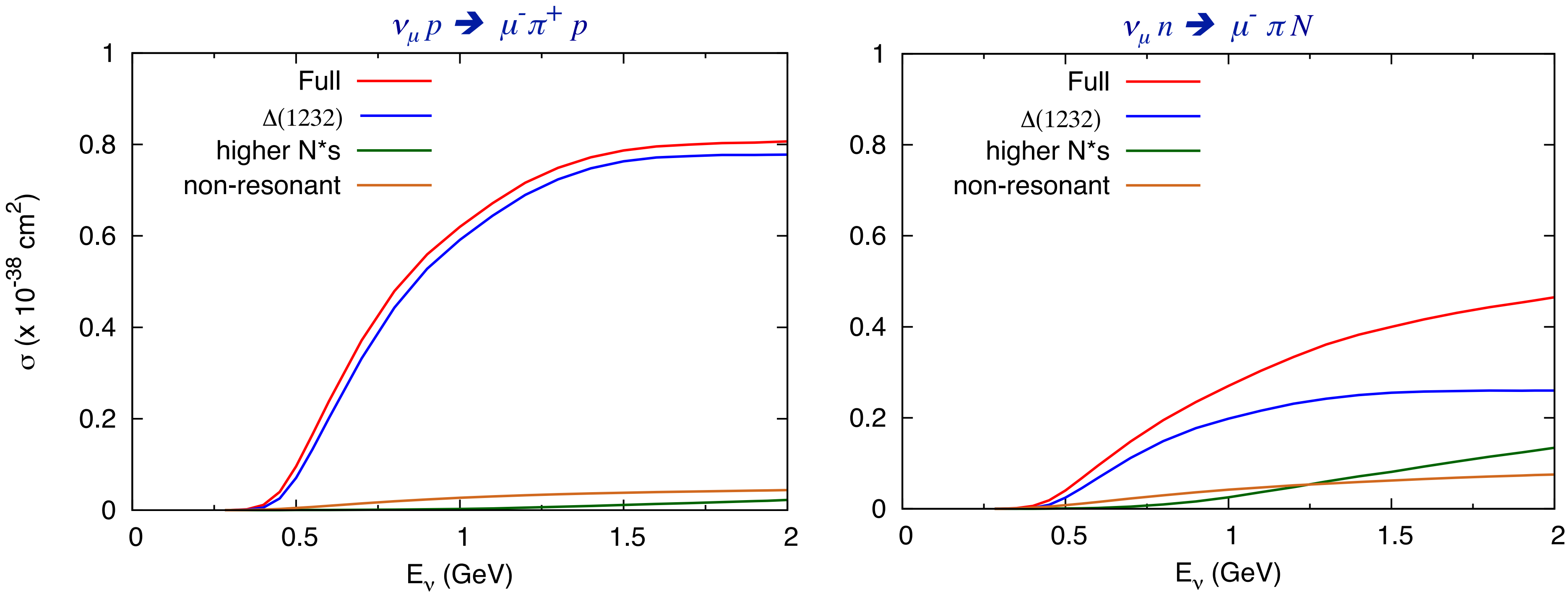


Fairly good DCC predication

ANL Data : PRD **28**, 2714 (1983)
BNL Data : PRD **34**, 2554 (1986)

First dynamical model for 2 π production in resonance region

Mechanisms for $\nu_\mu N \rightarrow \mu^- \pi N$

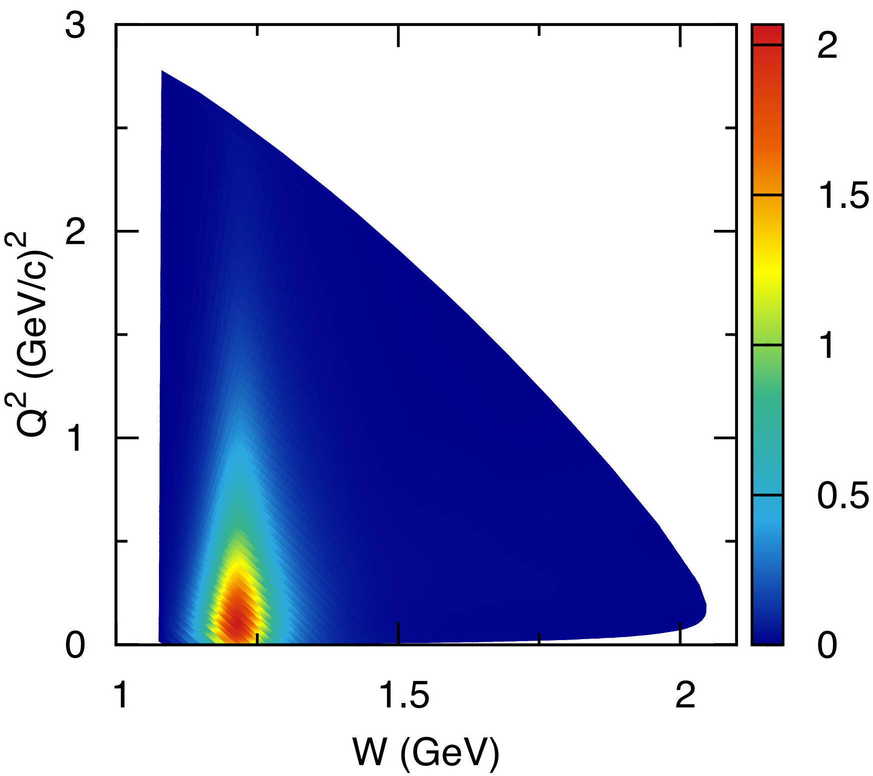


- Δ(1232) dominates for $\nu_\mu p \rightarrow \mu^- \pi^+ p$ $(I=3/2)$ for $E_\nu \leq 2$ GeV
- Non-resonant mechanisms contribute significantly
- Higher N^*s becomes important towards $E_\nu \approx 2$ GeV for $\nu_\mu n \rightarrow \mu^- \pi N$

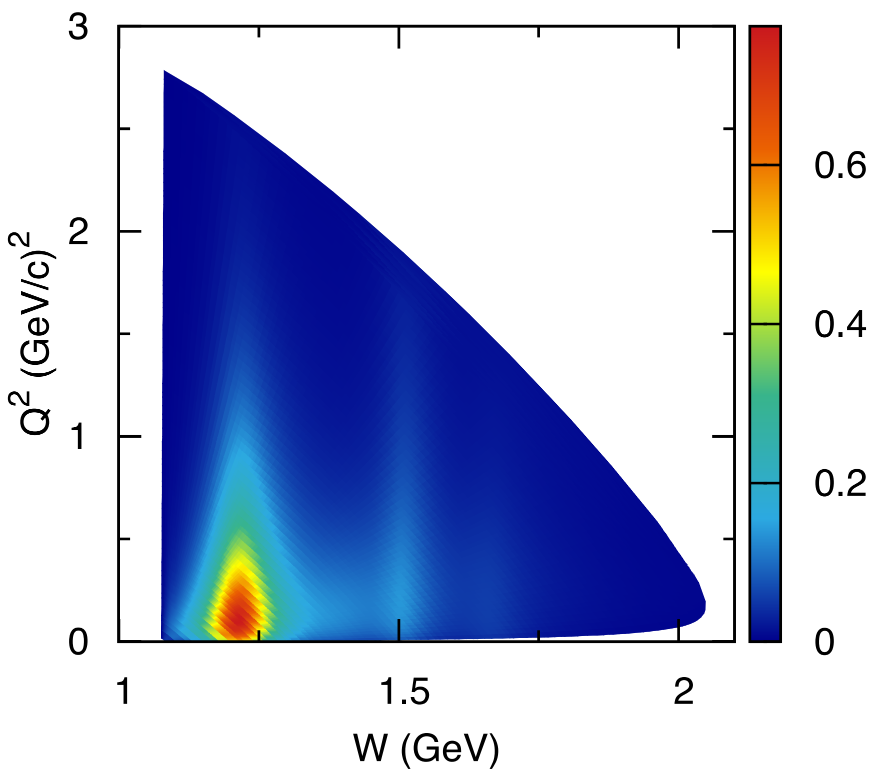
$d\sigma / dW\, dQ^2$ ($\times 10^{-38}$ cm^2 / GeV^2)

E_ν = 2 GeV

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



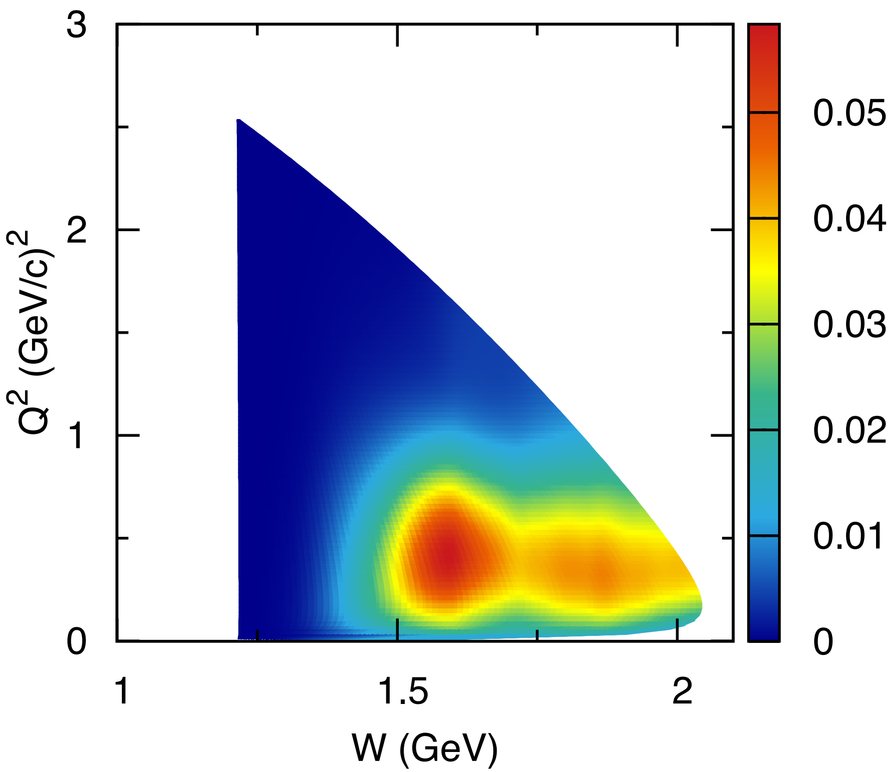
$\nu_\mu n \rightarrow \mu^- \pi N$



$$d\sigma / dW\, dQ^2 \;(\times 10^{-38}\, \text{cm}^2 / \text{GeV}^2)$$

E_ν = 2 GeV

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



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