Neutrino-induced pion productions off the deuteron and final state interactions

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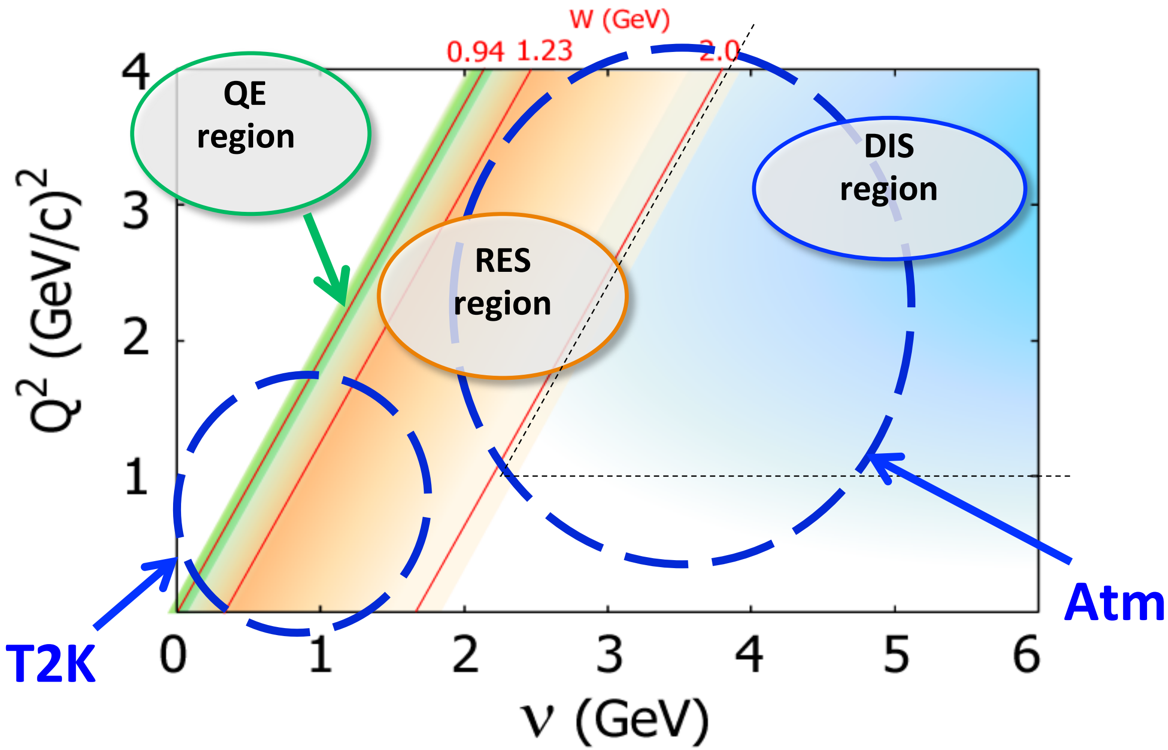
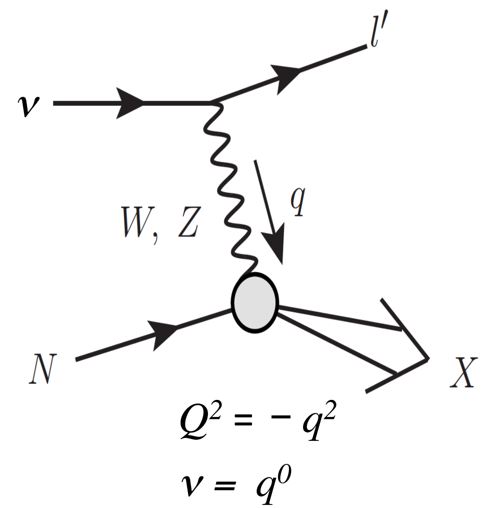
Introduction

Neutrino-nucleus scattering for ν-oscillation experiments

Wide kinematical region with different characteristic ➔ Different expertise need integrated





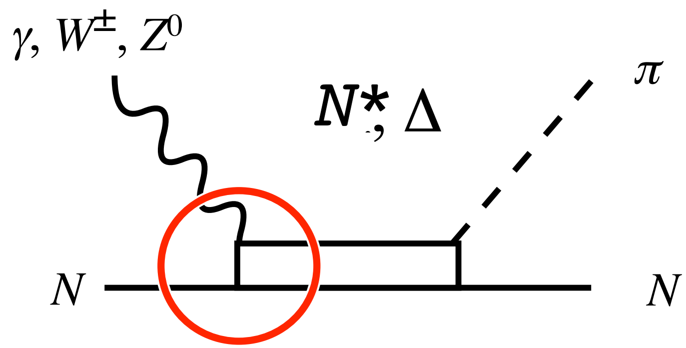
Collaboration at J-PARC Branch of KEK Theory Center

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

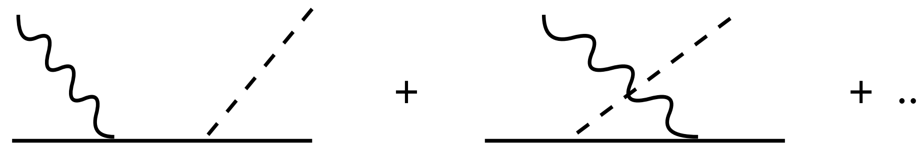
“Towards a Unified Model of Neutrino-Nucleus Reactions for Neutrino Oscillation Experiments”

Theoretical description of elementary process in resonance region

Resonance excitations



Non-resonant mechanisms



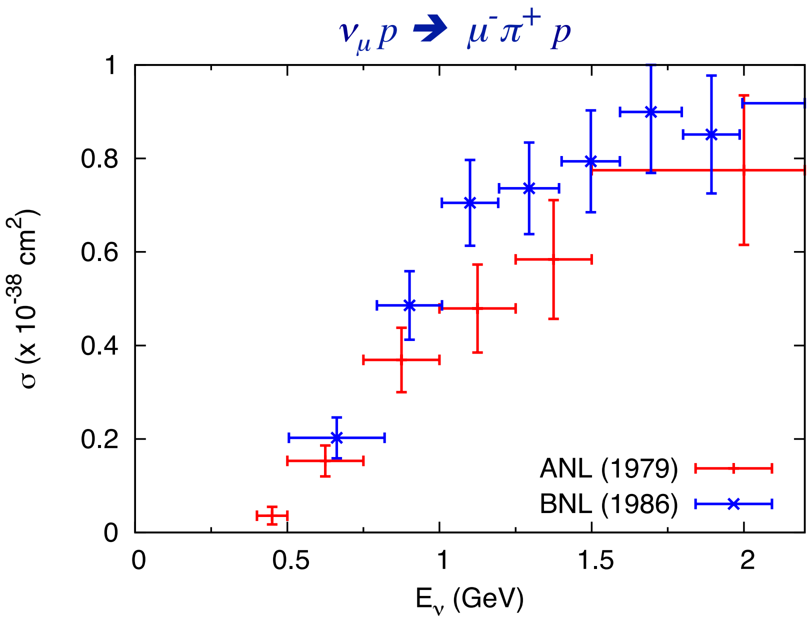
$\Delta(1232)$-excitation is particularly important in ν-induced 1π productions

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

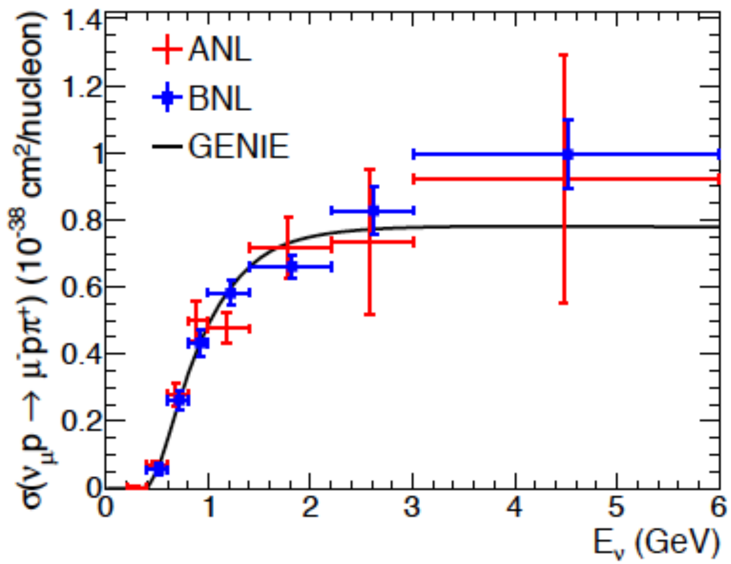
Vector current : photon- and electron-nucleon 1π production data

Axial current : neutrino-nucleon 1π production data

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



Wilkinson et al. PRD 90 (2014)



- Data to fix $g_{AN\Delta}$
- Discrepancy between BNL & ANL data

  → theoretical uncertainty in neutrino-nucleus cross sections

Reanalysis of original data

→ discrepancy resolved (probably)

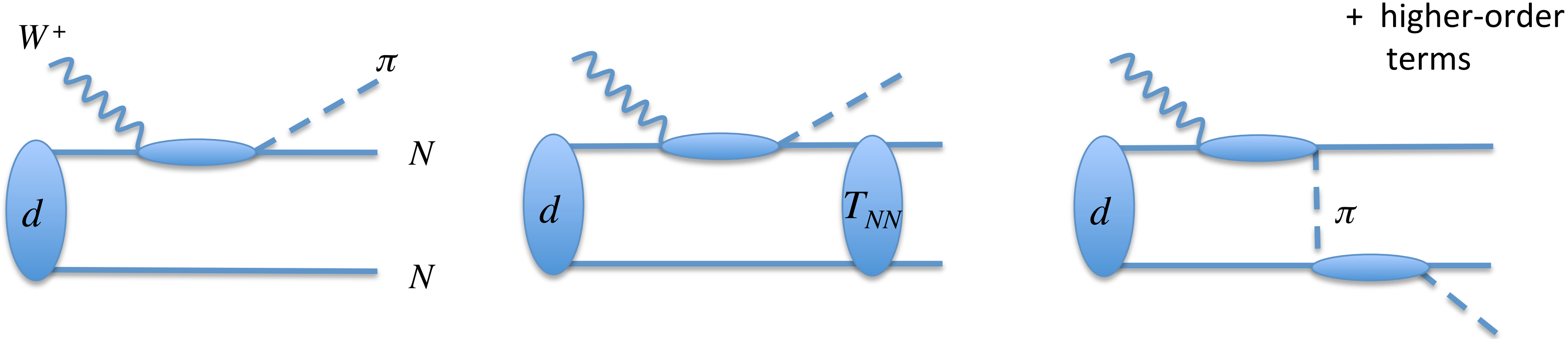
$$\frac{\sigma(\mathrm{CC}1\pi;\mathrm{data})}{\sigma(\mathrm{CC}0\pi;\mathrm{data})} \times \sigma(\mathrm{CCQE};\mathrm{model})$$

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



Nuclear effect managements

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

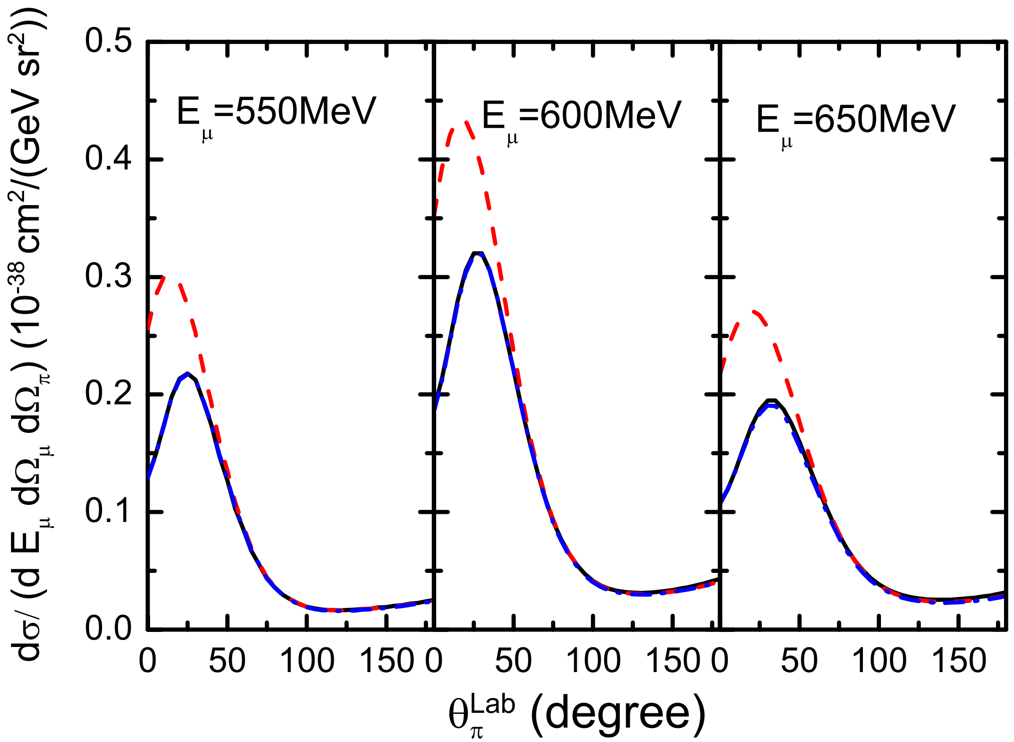
Theory Fermi motion considered in fixing $g_{AN\Delta}$ Hernandez et al. (2010), Alam et al. (2016)

Q : Final state interactions (FSI) effects can be removed with simple kinematical cuts ?

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)



$E_\nu = 1$ 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

Limitation of Wu et al.'s work : Tiny fraction of the whole phase-space was covered

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

(7 dim. non-trivial numerical integral)

Computationally challenging problem *will be managed in this work*

This work

- Total (σ) and single differential ($d\sigma/dX$) cross sections for $\nu_\mu d \rightarrow \mu^- \pi^+ p\, n\,,\, \mu^- \pi^0 pp$ with FSI are calculated

  --- $\nu\, d$ reaction model based on dynamical coupled-channels model for $\nu_\mu N \rightarrow \mu^- \pi\, N$ elementary amplitudes

  --- 7-dim. numerical integral is managed with Monte-Carlo method

- FSI effects on σ and $d\sigma/dX$ are examined

- How FSI could distort $\nu_\mu p \rightarrow \mu^- \pi^+ p$ and $\nu_\mu n \rightarrow \mu^- \pi^+ n\,,\, \mu^- \pi^0 p$ cross sections extracted from $\nu_\mu d \rightarrow \mu^- \pi^+ p\, n\,,\, \mu^- \pi^0 pp$ cross sections ?

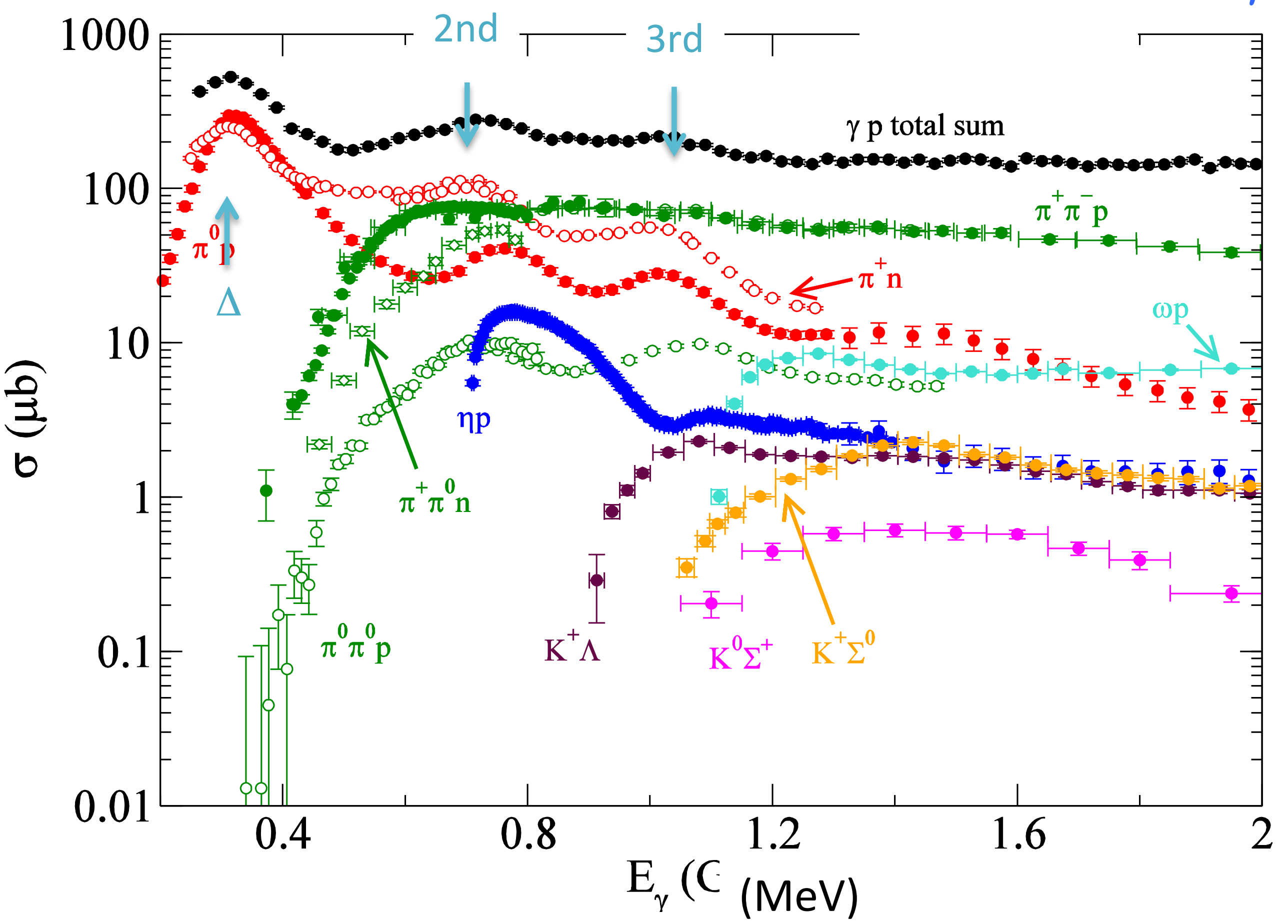
Dynamical Coupled-Channels model for electroweak meson productions on single nucleon

Kamano, SXN, Lee, Sato, PRC 88, 035209 (2013)

SXN, Kamano, Lee, Sato, PRD 92, 074024 (2015)

Meson productions on single nucleon in resonance region

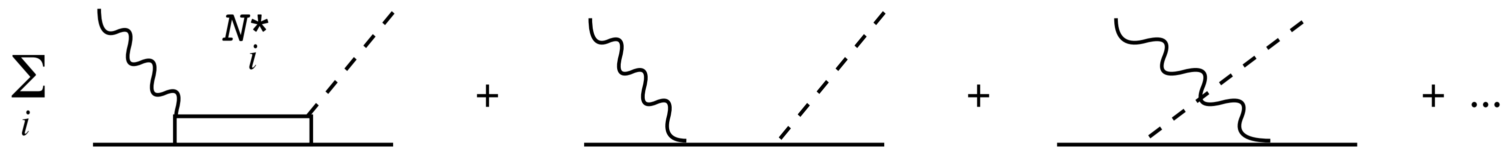
$\gamma N \rightarrow X$



- Several resonances form characteristic peaks
- 2π production is comparable to 1π
- η, K productions (multi-channel couplings are important physics)

νN-reaction model in resonance region

Main mechanisms (considered in most previous models)



Theoretically sound model should also account for:

(Most νN-reaction models do not)

- Channel-couplings required by unitarity
- Important 2 π production
- Relative phases among different ANN^* under control

Dynamical Coupled-Channels (DCC) model accounts for these features through:

★ Develop DCC model for $\gamma^{(*)}N$, $\pi N \rightarrow \pi N, \pi\pi N, \eta N, K\Lambda, K\Sigma$

★ Extension to $\nu N \rightarrow l^- X$ ($X = \pi N, \pi\pi N, \eta N, K\Lambda, K\Sigma$)

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

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

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

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

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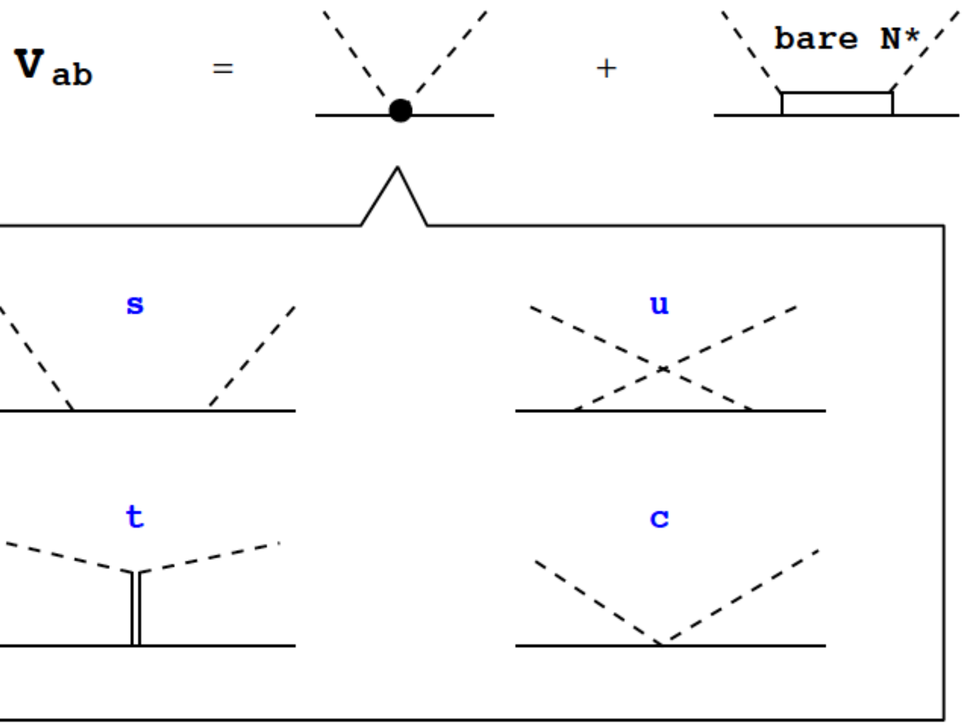

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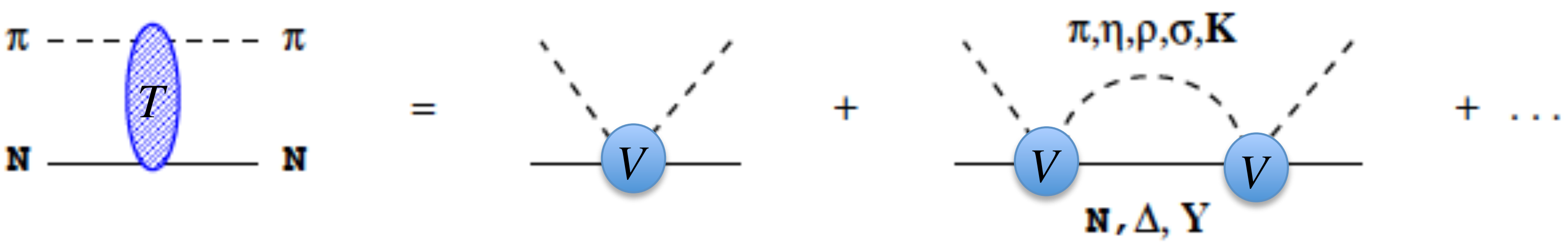
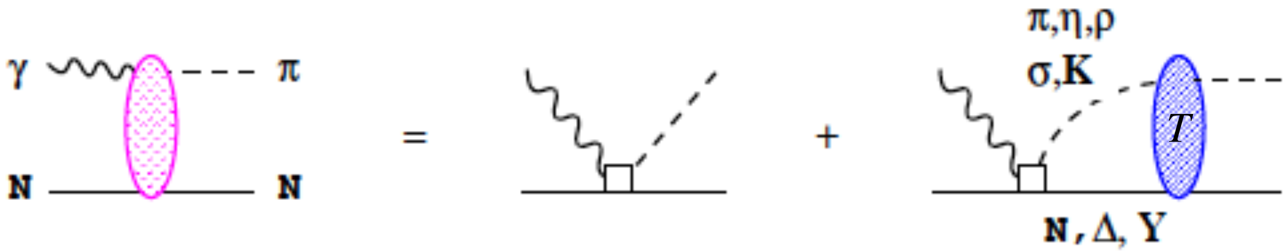
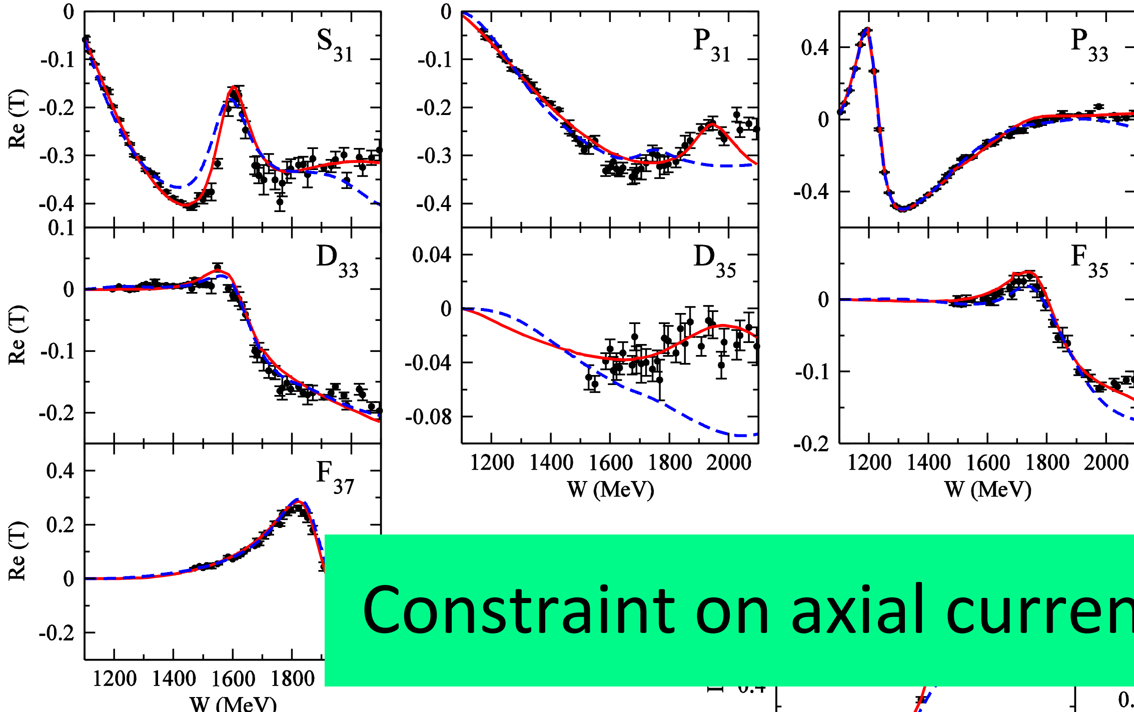


In addition, γN, $W^{\pm}N$, ZN channels are included perturbatively



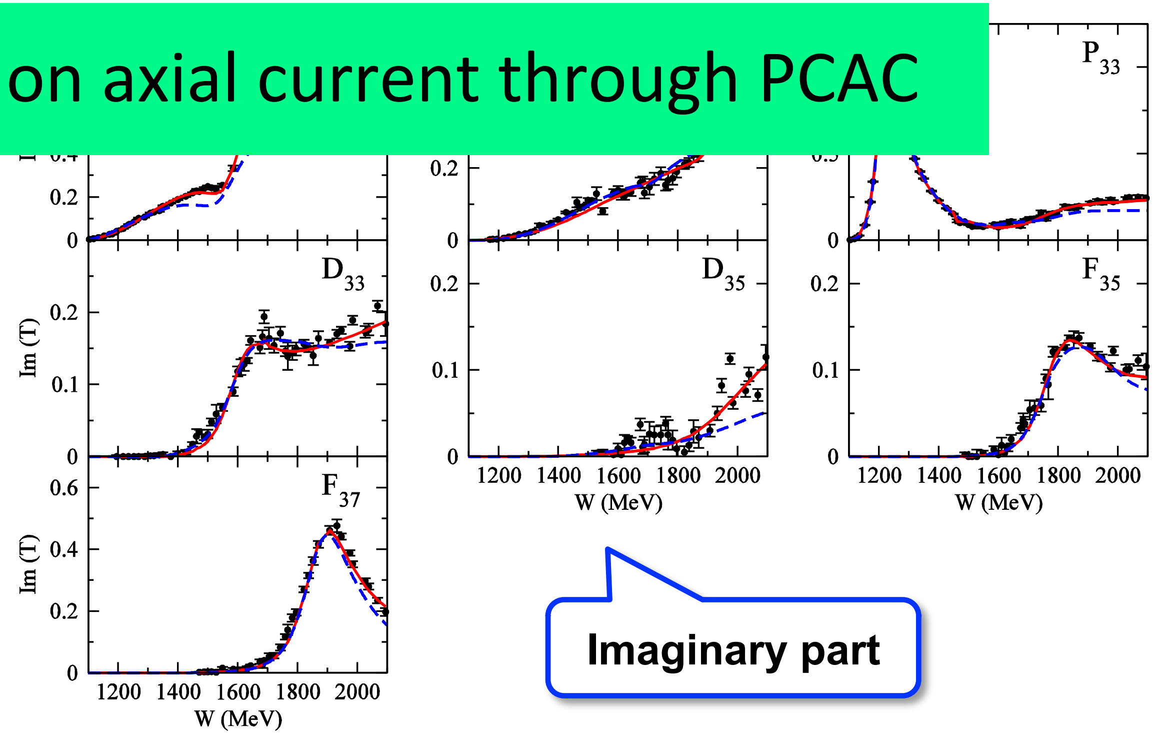
Partial wave amplitudes of π N scattering



Real part

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

Constraint on axial current through PCAC



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

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

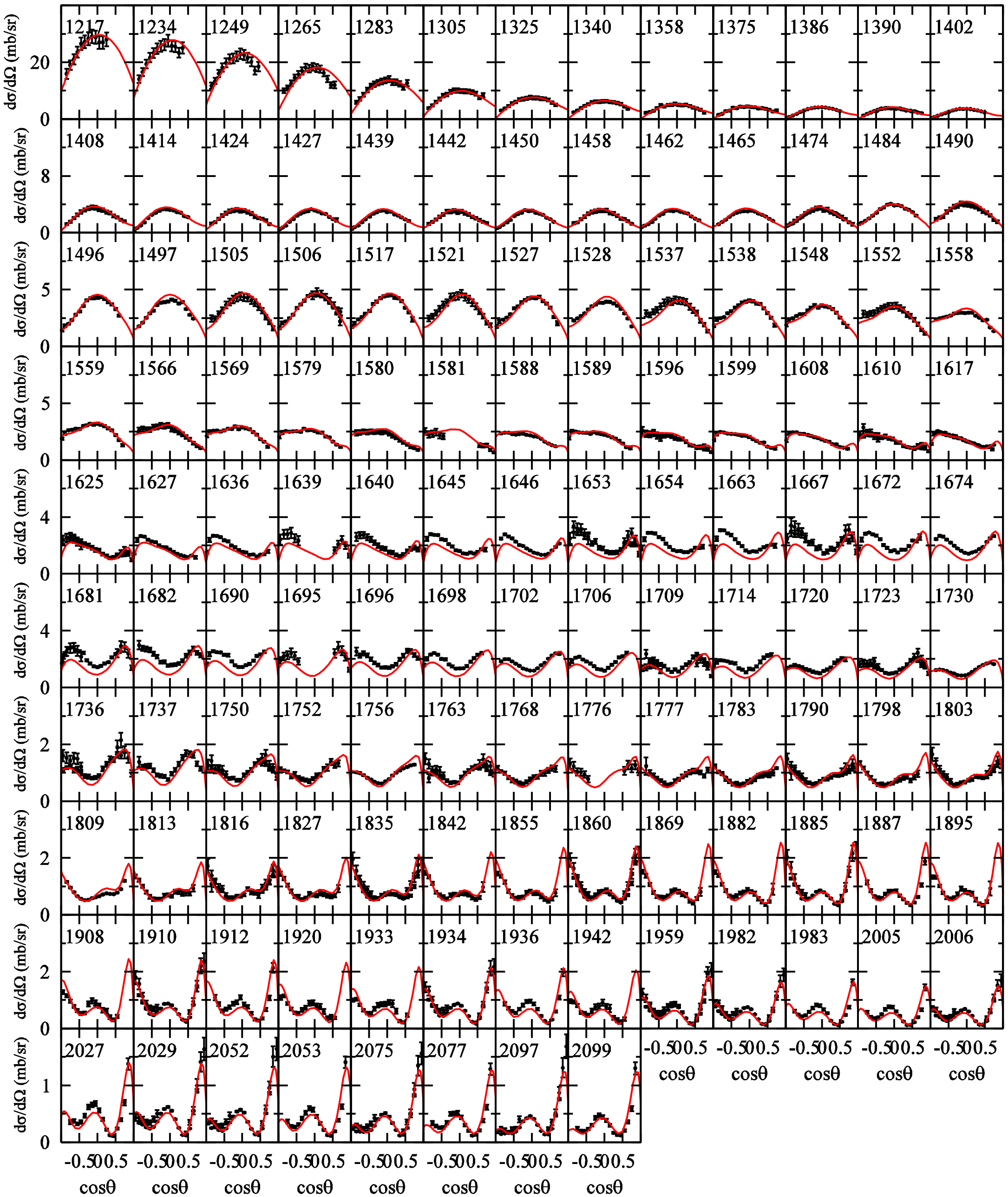
Imaginary part

Data: SAID πN amplitude

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

$d\sigma/d\Omega$ 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

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. $\gamma^{(*)} + p \rightarrow p$)

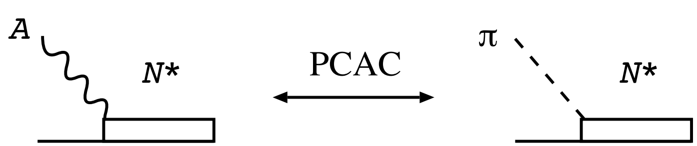
$$L^{em} = e\ J^{em}_\lambda A^\lambda_{em} \qquad J^{em}_\lambda = V_\lambda + V^{IS}_\lambda$$

V and V^{IS} can be separated by analyzing (virtual) photon data on proton and neutron

Axial current

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

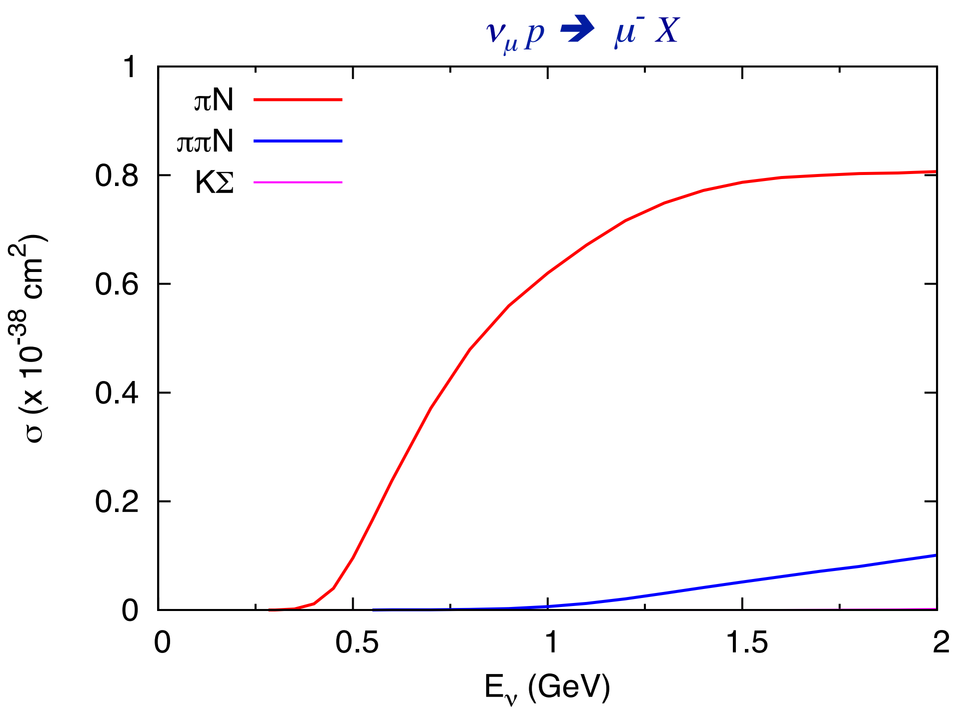
PCAC relation

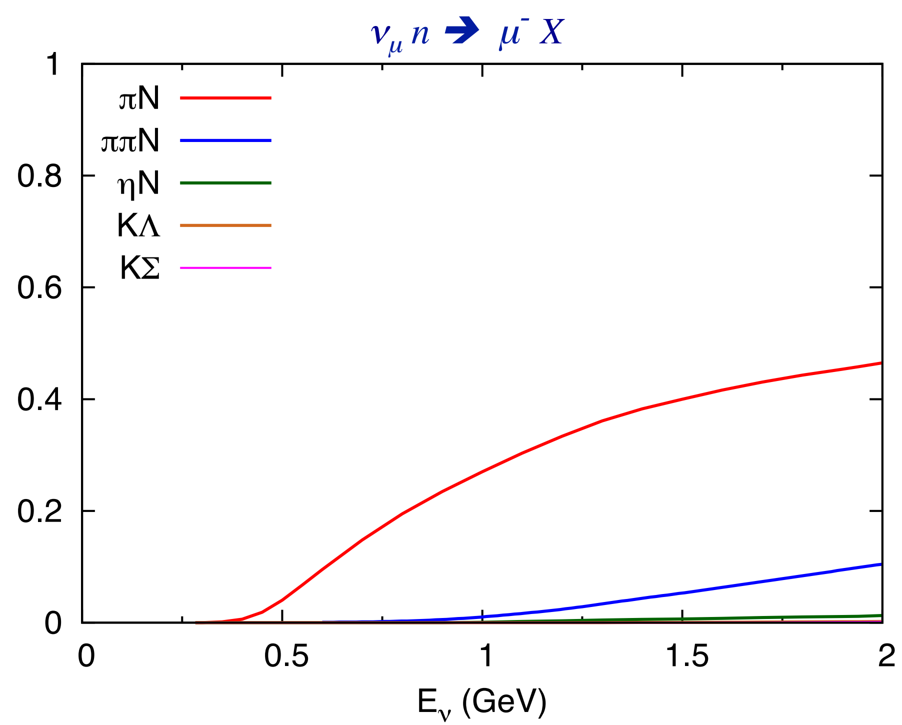


(Q^2-dependence is assumed)

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

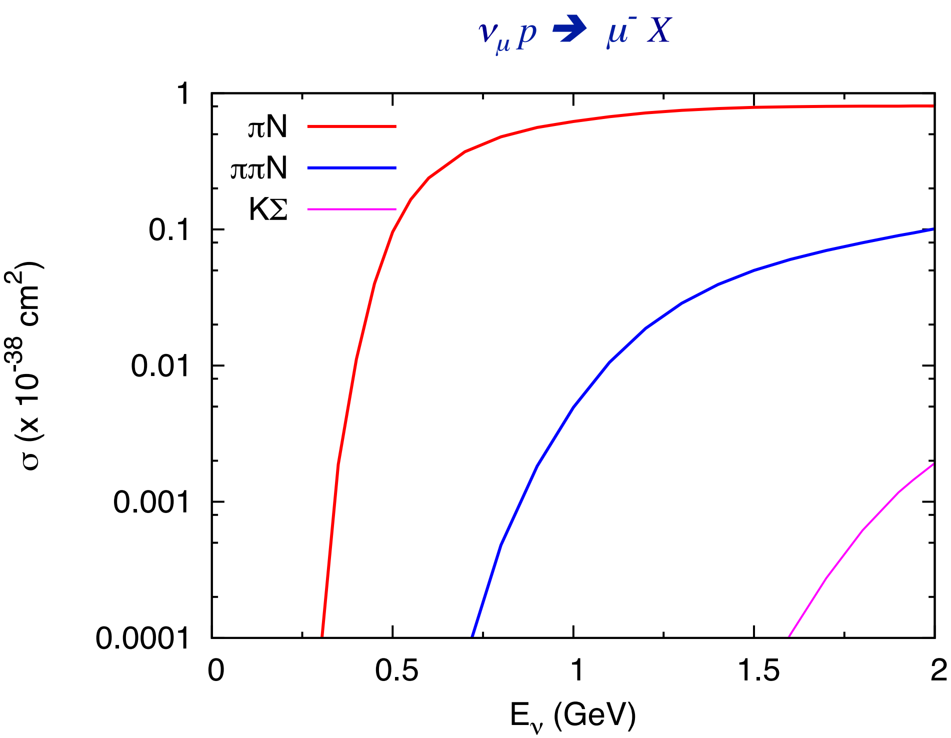
DCC predictions for $\nu_\mu N \rightarrow \mu^- X$ cross sections

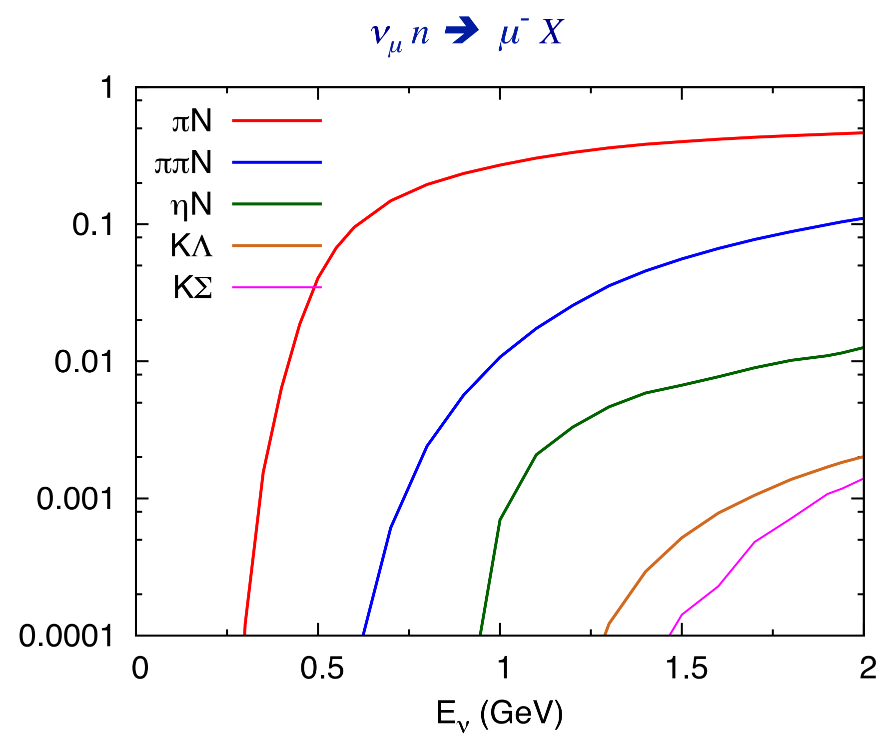




- πN & $\pi\pi N$ are main channels in few-GeV region
- DCC model gives predictions for all final states
- ηN, KY cross sections are $10^{-1} - 10^{-2}$ smaller

DCC predictions for $\nu_\mu N \rightarrow \mu^- X$ cross sections





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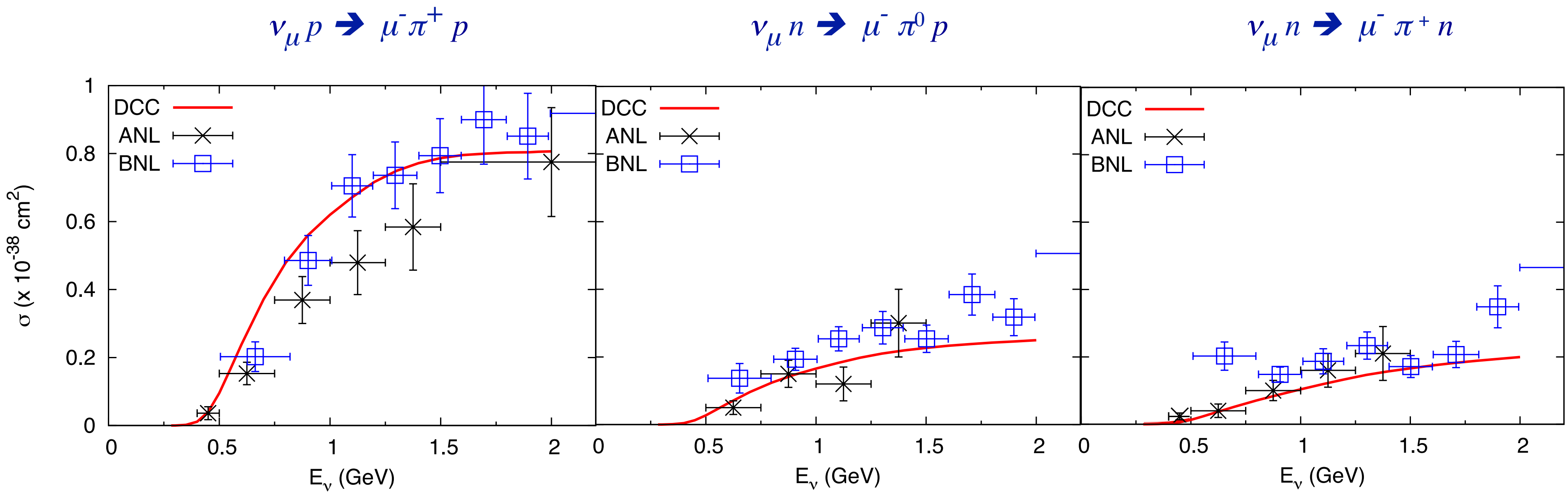
Comparison of DCC model with single pion data



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 is clarified

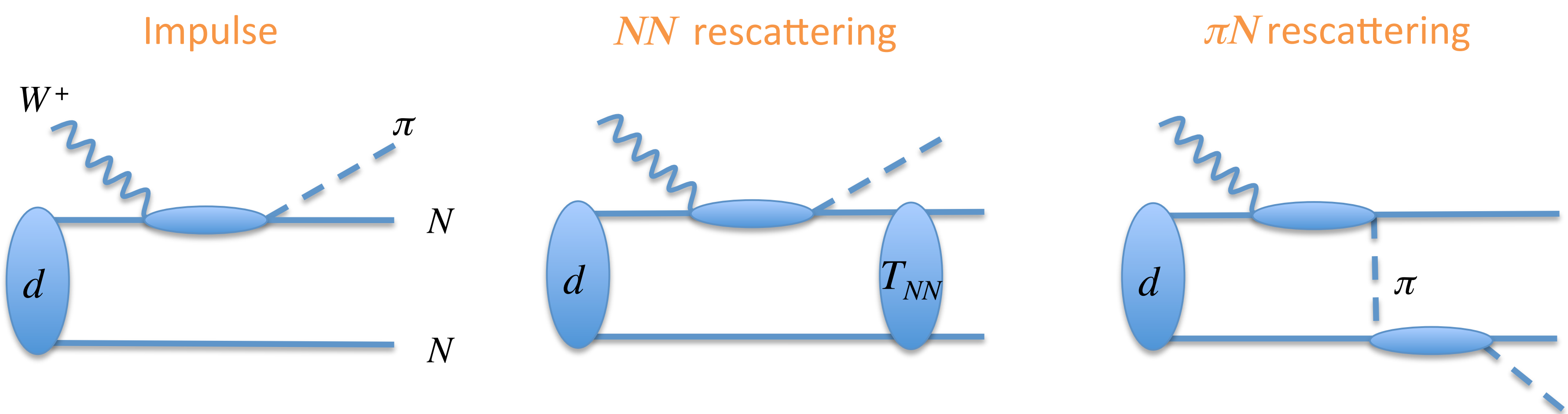
$\nu_\mu d \rightarrow \mu^- \pi^+ p\, n,\ \mu^- \pi^0 p\, p$ model

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



Elementary amplitudes

$W^{\pm}N \rightarrow \pi N$, $\pi N \rightarrow \pi N$ 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

The model has been validated in photo-induced pion productions

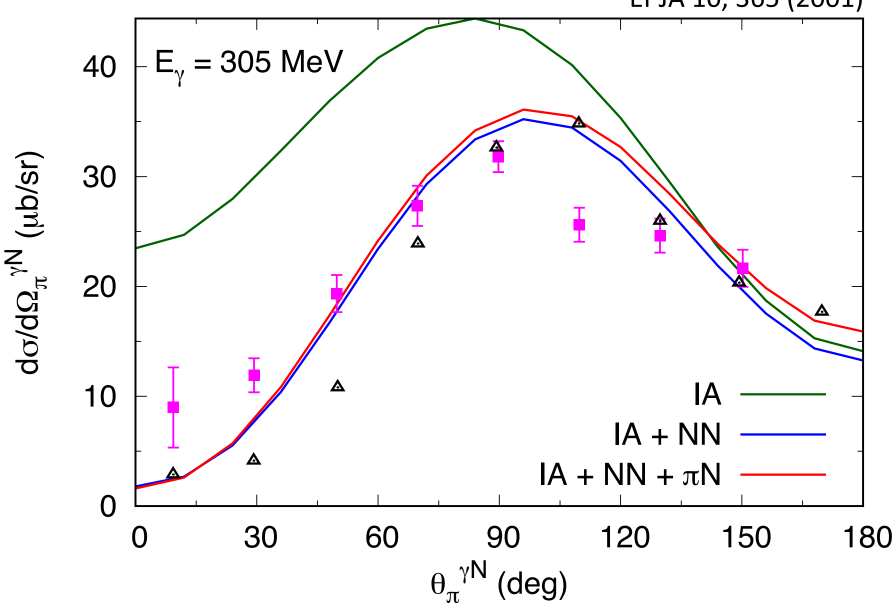
Results

$\gamma d \to \pi N N$

Purpose : test the soundness of the model

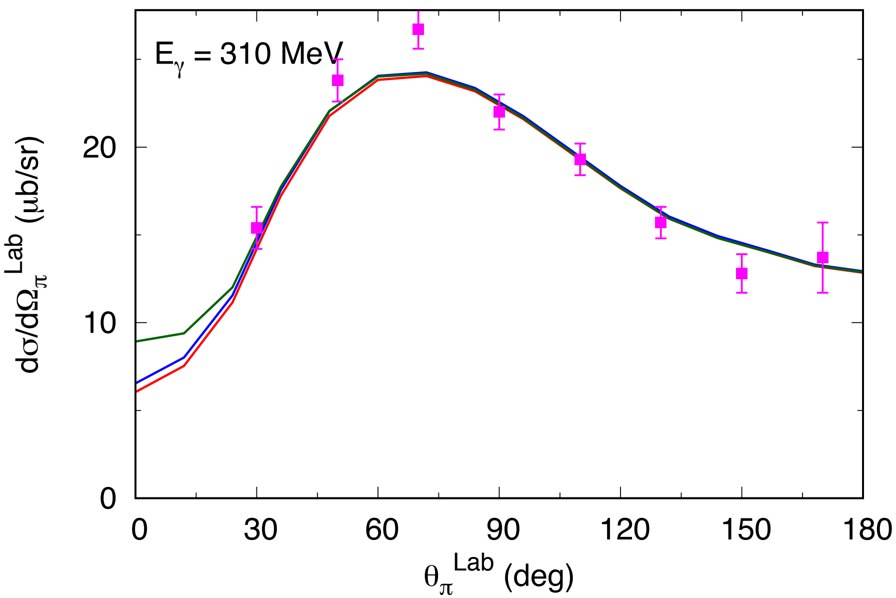
$\gamma d \to \pi^0 pn$

Data: EPJA 6, 309 (1999)
EPJA 10, 365 (2001)



$\gamma d \to \pi^- pp$

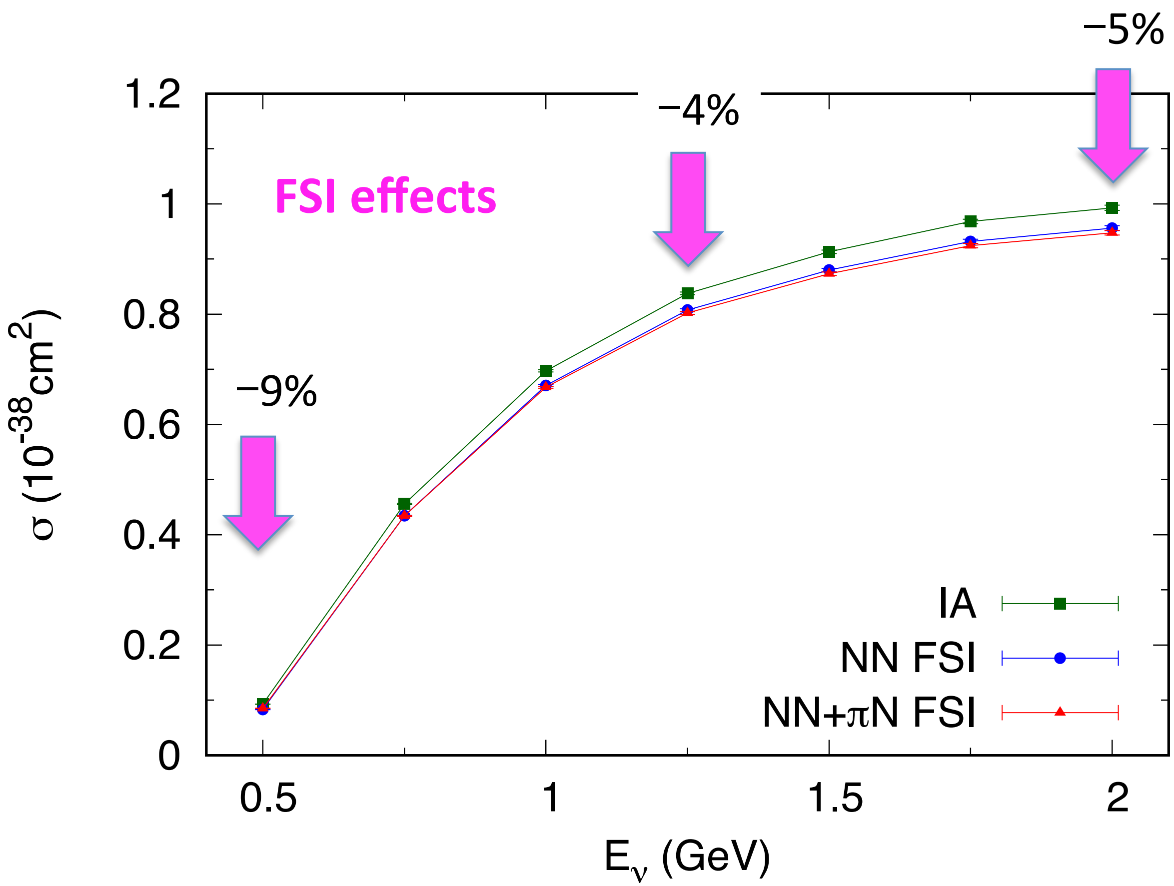
Data: NPB 65, 158 (1973)



- Model prediction is reasonably consistent with data
- Large *NN* (small πN) rescattering effect for π^0 production

  orthogonality between deuteron and *pn* scattering wave functions
- Small rescattering effect for π^- production

$\nu_\mu\, d \rightarrow \mu^- \pi^+ p\, n$ total cross sections

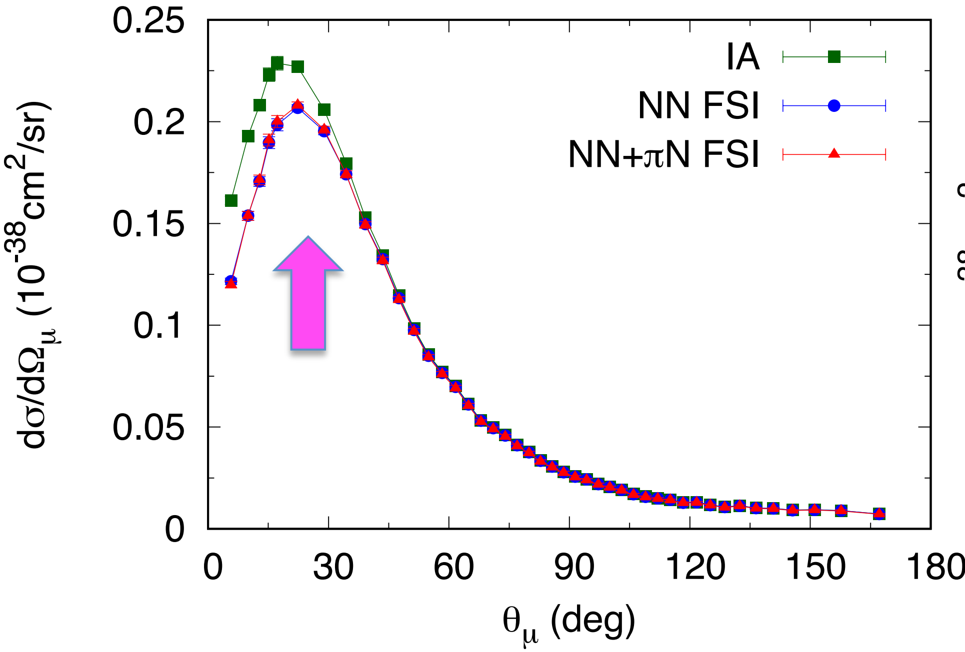


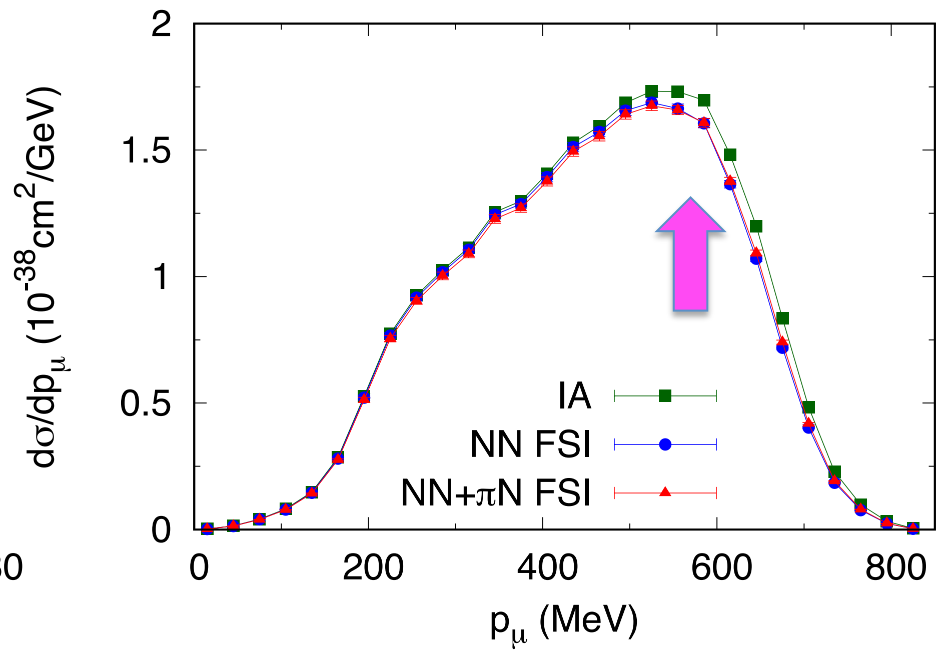
Caveat: calculations have been done only at several E_ν for a large computational cost; lines are just for guiding your eyes

- (Mostly NN) FSI reduces σ by 9%, 4%, 5% at E_ν = 0.5, 1.25, 2 GeV
- πN FSI hardly changes $\sigma(\nu_\mu\, d \rightarrow \mu^- \pi^+ p\, n)$
- Much smaller FSI effects than what you might have expected from Wu et al.'s result ?

$d\sigma/d\Omega_\mu$ and $d\sigma/dp_\mu$ for $\nu_\mu\, d \rightarrow \mu^- \pi^+ p\, n$

E_ν = 1 GeV





- Significant FSI effects are seen in narrow kinematical windows

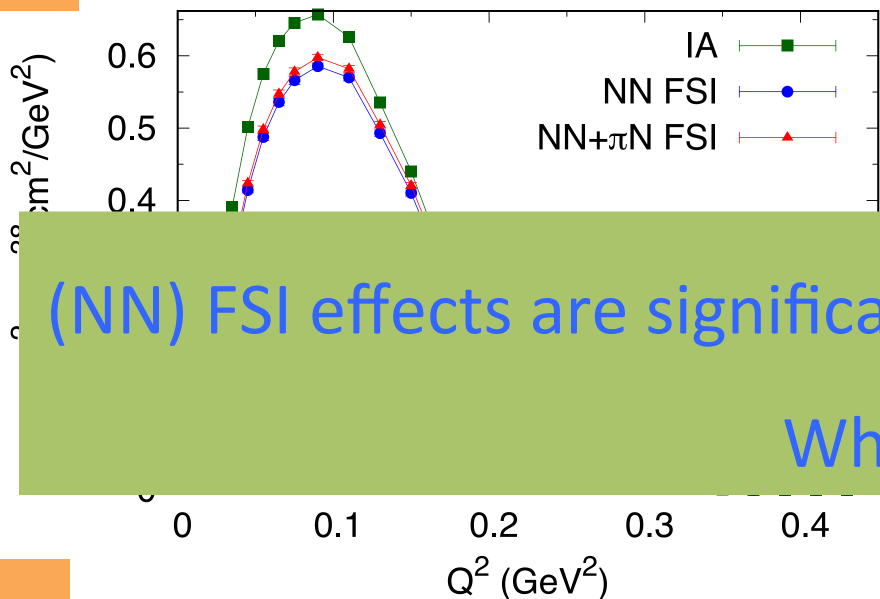
  → moderate reduction of total cross sections

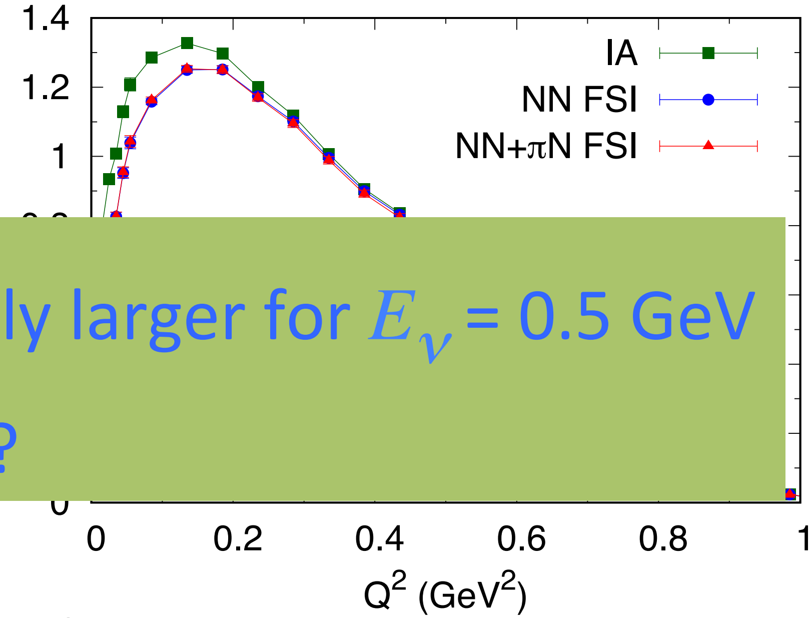
- Wu et al.'s calculation was done at $\theta_\mu = 25°$ and $E_\mu = 550, 600, 650$ MeV

  (region where quasi-free kinematics is important)

$E_\nu = 0.5$ GeV vs $E_\nu = 1$ GeV

Q^2

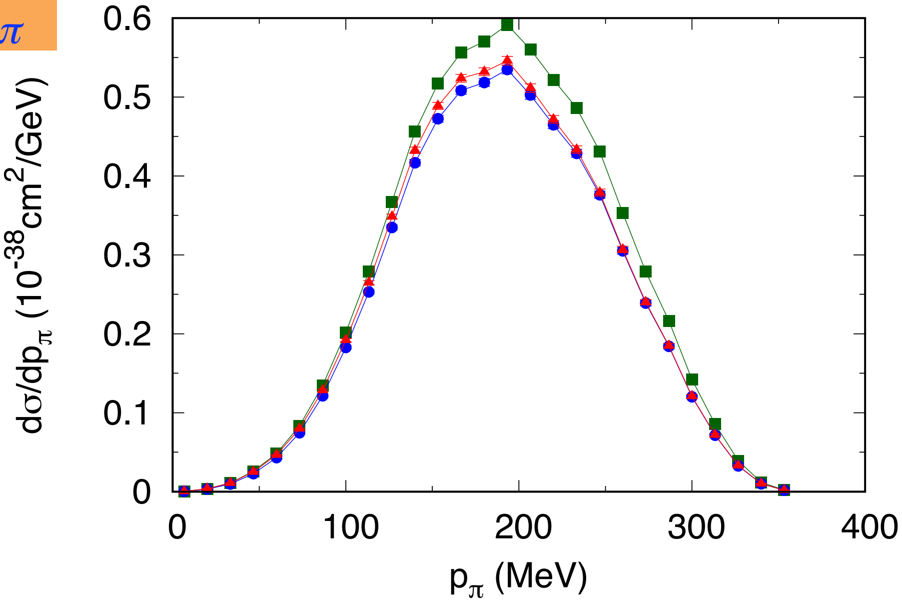


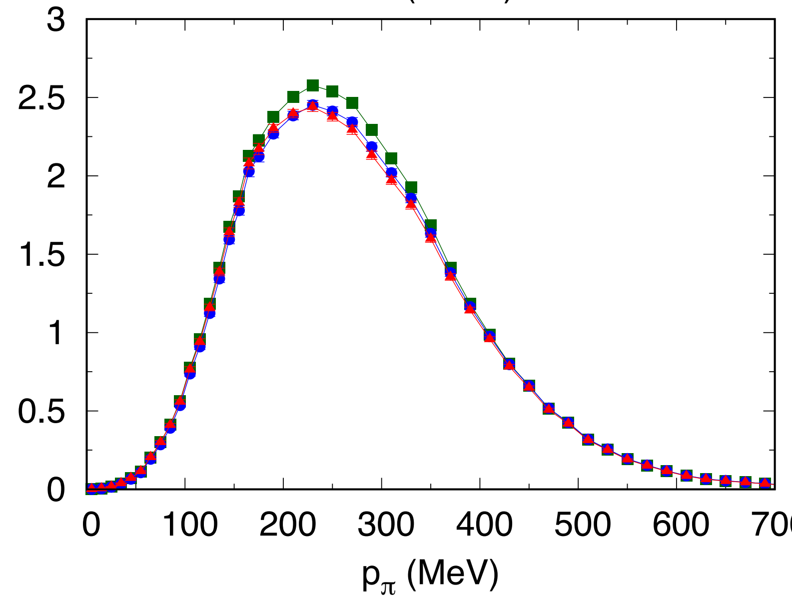


(NN) FSI effects are significantly larger for $E_\nu = 0.5$ GeV

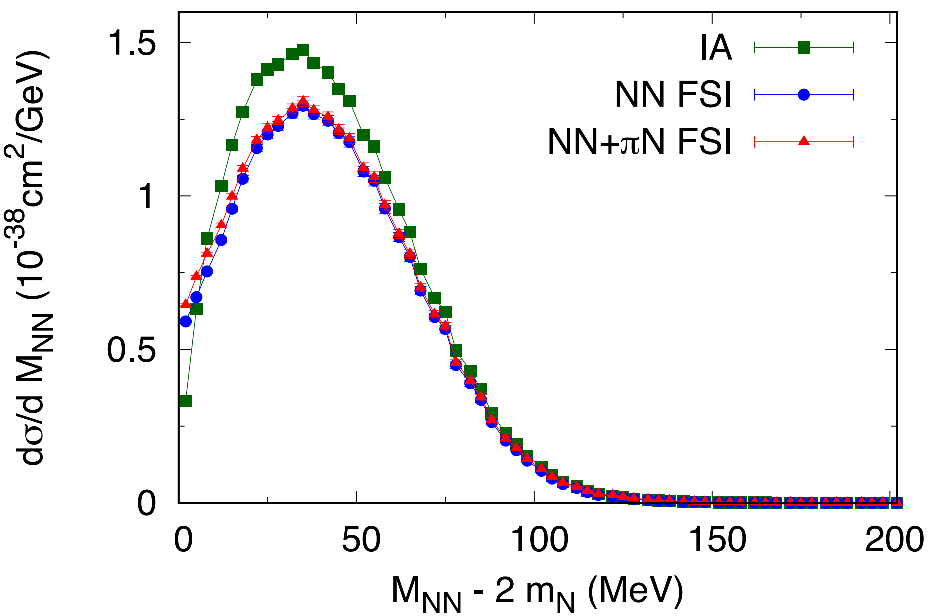
Why ?

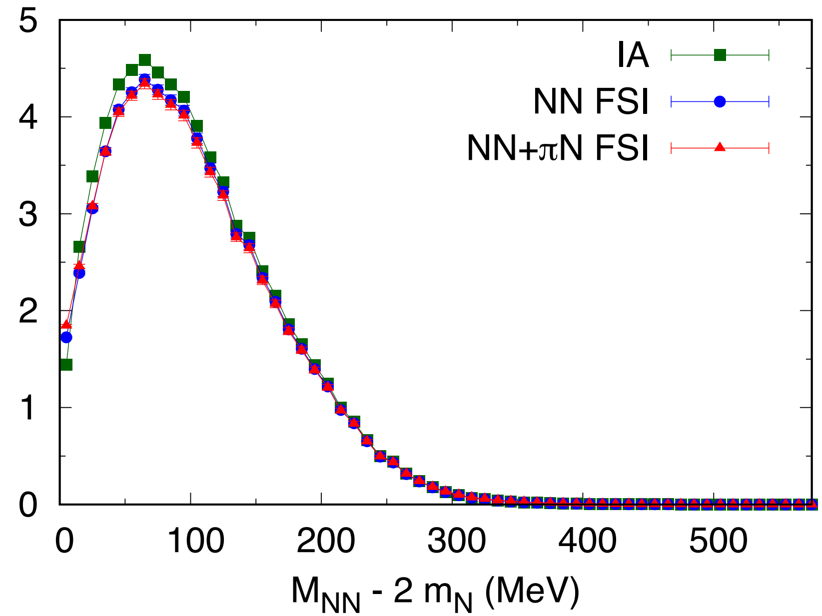
p_π





E_ν = 0.5 GeV vs E_ν = 1 GeV

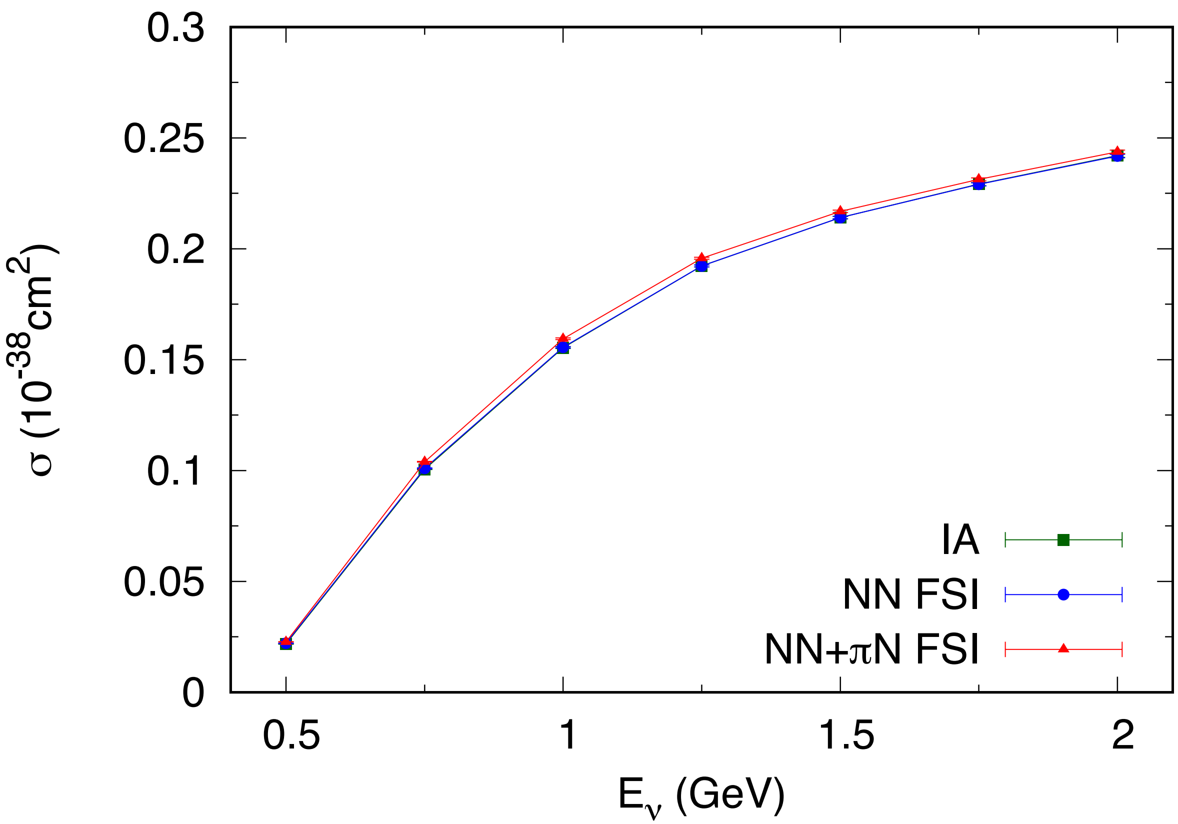


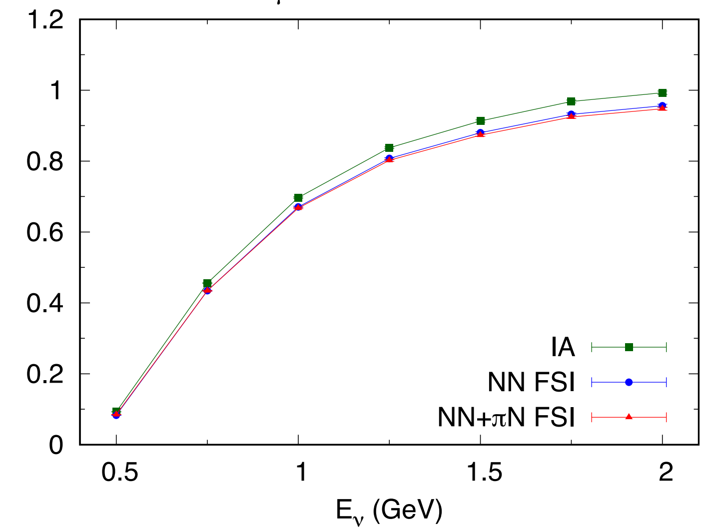


- NN FSI effect is large at low NN energy region ($\lesssim$ 50 MeV) where orthogonality between pn scattering states and deuteron is most effective
- Low NN energy region occupies a relatively larger portion of phase-space for low E_ν

→ Larger NN FSI effect for lower E_ν

$\nu_\mu\, d \rightarrow \mu^-\pi^0\, p\, p$ total cross sections





- FSI effects are much smaller than those for $\nu_\mu\, d \rightarrow \mu^-\pi^+\, p\, n$
- NN FSI is negligible (no orthogonality with deuteron wave function)
- πN FSI slightly enhances $\sigma(\nu_\mu\, d \rightarrow \mu^-\pi^0\, p\, p)$

How could FSI distort elementary ν-p and ν-n cross sections extracted from ν-d cross sections ?

Q : How to extract $\sigma(\nu_\mu p \to \mu^- \pi^+ p)$ and $\sigma(\nu_\mu n \to \mu^- \pi^+ n)$ from $\sigma(\nu_\mu d \to \mu^- \pi^+ pn)$

and $\sigma(\nu_\mu n \to \mu^- \pi^0 p)$ from $\sigma(\nu_\mu d \to \mu^- \pi^0 pp)$?

- An ideal procedure

Develop a deuteron reaction model with FSI, and analyze $\sigma(\nu_\mu d \to \mu^- \pi NN)$ data

$\to$ (correct) $\nu_\mu p \to \mu^- \pi^+ p$ and $\nu_\mu n \to \mu^- \pi^+ n,\ \mu^- \pi^0 p$ elementary amplitudes

☹ Not very practical because calculating $\sigma(\nu_\mu d \to \mu^- \pi NN)$ takes too much time

☹ $\sigma(\nu_\mu d \to \mu^- \pi NN)$ data without kinematical cuts do not exist at present

ANL & BNL analyses used kinematical cuts (and etc.) to isolate each of elementary $\nu_\mu p \to \mu^- \pi^+ p$, $\nu_\mu n \to \mu^- \pi^+ n$, $\nu_\mu n \to \mu^- \pi^0 p$ contributions to $\sigma(\nu_\mu d \to \mu^- \pi NN)$

Note : ANL & BNL analyses did not extract $\sigma(\nu_\mu N \to \mu^- \pi N)$

$\to$ corrections are needed to account for Fermi motion and FSI

How could FSI distort elementary ν-p and ν-n cross sections extracted from ν-d cross sections ?

Q : How to extract $\sigma(\nu_\mu p \rightarrow \mu^- \pi^+ p)$ and $\sigma(\nu_\mu n \rightarrow \mu^- \pi^+ n)$ from $\sigma(\nu_\mu d \rightarrow \mu^- \pi^+ pn)$

and $\sigma(\nu_\mu n \rightarrow \mu^- \pi^0 p)$ from $\sigma(\nu_\mu d \rightarrow \mu^- \pi^0 pp)$?

- Another ideal procedure

→ Follow ANL and BNL analyses

Apply their cuts (and etc.) to calculated $\sigma(\nu\, d)$ → comparison with ANL & BNL data

☹ Calculating $\sigma(\nu_\mu d \rightarrow \mu^- \pi NN)$ takes too much time

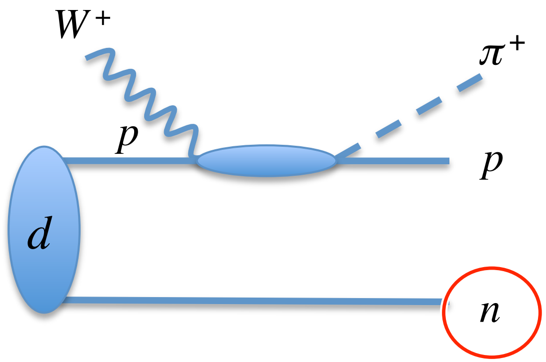
☹ Details of ANL and BNL analyses (cuts etc.) have been lost in history

- We propose a practical method for extracting $\sigma(\nu_\mu N)$ from $\sigma(\nu_\mu d)$

Useful for (i) interpretation of ANL and BNL data; (ii) future experiments

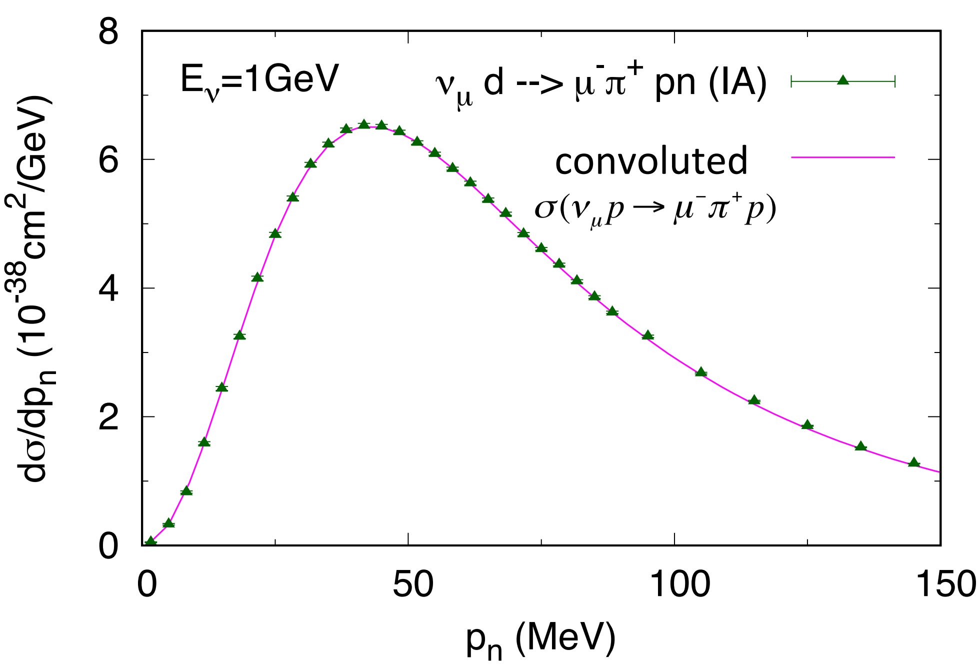
Extract $\sigma(\nu_\mu p \rightarrow \mu^- \pi^+ p)$ from $\sigma(\nu_\mu d \rightarrow \mu^- \pi^+ pn)$ IA case

How ?



Use spectator momentum (p_n) distribution from observations below (cf. ANL & BNL analyses)

- $\nu_\mu p \rightarrow \mu^- \pi^+ p$ contribution dominates in low-p_n well separated from $\nu_\mu n \rightarrow \mu^- \pi^+ n$ in high-p_n
- Quasi-free (QF) peak → good statistics exp.
- FSI would enhance high-p_n contribution



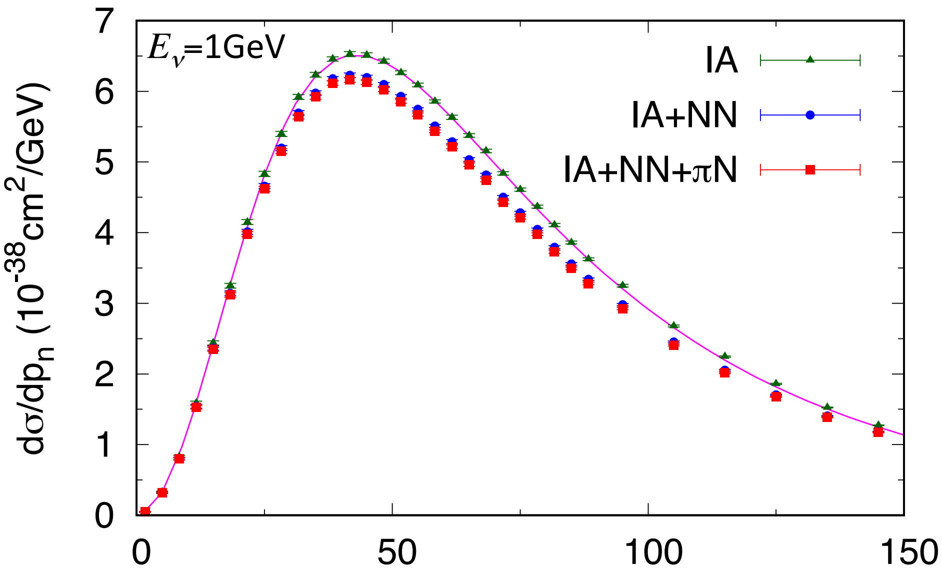
Def. for convoluted $\sigma(\nu_\mu p \rightarrow \mu^- \pi^+ p)$

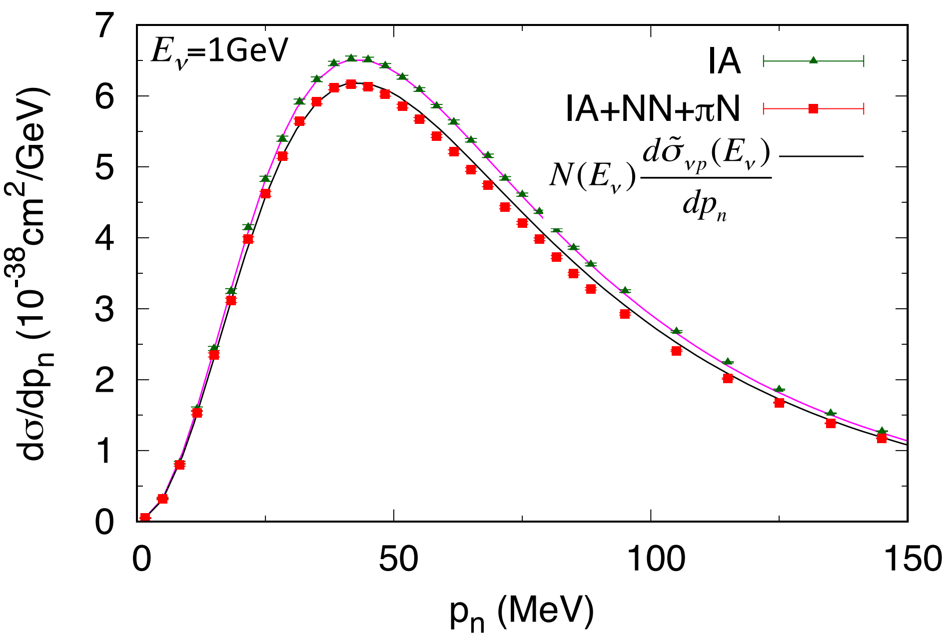
$$\frac{d\tilde{\sigma}_{\nu p}(E_\nu)}{dp_n} = p_n^2 \int d\Omega_{p_n} \sigma_{\nu_\mu p \rightarrow \mu^- \pi^+ p}(\tilde{E}_\nu) \left| \Psi_d(\vec{p}_n) \right|^2$$

If FSI were absent, we fit $\boxed{\dfrac{d\sigma_{\nu d}(E_\nu)}{dp_n}}$ data with $\boxed{\dfrac{d\tilde{\sigma}_{\nu p}(E_\nu)}{dp_n}}$ in QF region

→ $\sigma(\nu_\mu p \rightarrow \mu^- \pi^+ p)$ is obtained (de-convolution)

Extract $\sigma(\nu_\mu p \rightarrow \mu^- \pi^+ p)$ from $\sigma(\nu_\mu d \rightarrow \mu^- \pi^+ pn)$ IA+FSI case





Previous naïve expectation

- ~~FSI would enhance high p_n contribution~~

NN FSI reduces $\frac{d\sigma_{\nu d}(E_\nu)}{dp_n}$ in QF peak region

Introduce FSI correction factor : $N(E_\nu)$

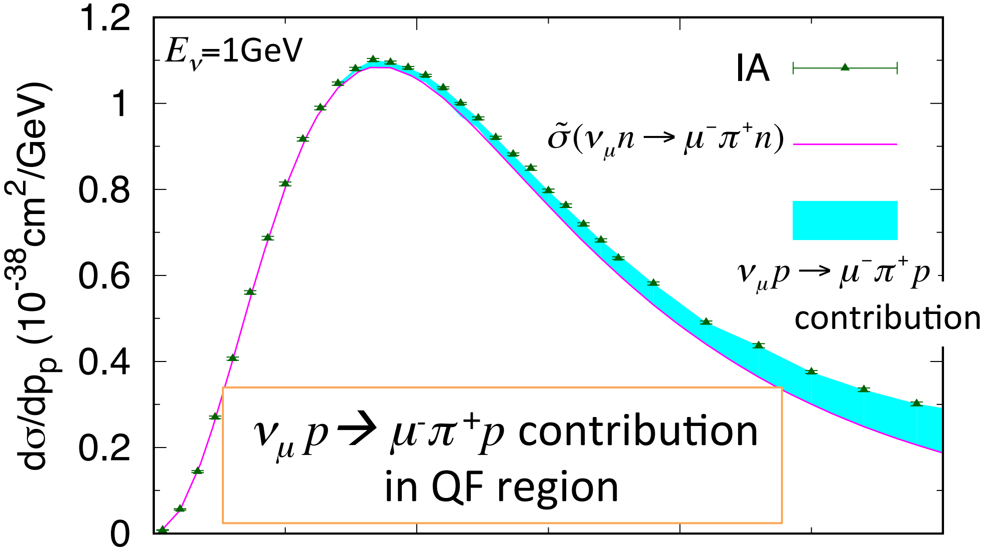
$$\frac{d\sigma_{\nu d}(E_\nu)}{dp_n} \approx N(E_\nu)\frac{d\tilde{\sigma}_{\nu p}(E_\nu)}{dp_n}$$

for $p_n < p_n^{\max} \approx 50$ MeV where FSI does not significantly change the spectrum shape

Once $N(E_\nu)$ is given, you can fit your $\nu_\mu p \rightarrow \mu^- \pi^+ p$ model to $d\sigma_{\nu d}(E_\nu)/dp_n$ data without calculating FSI corrections !

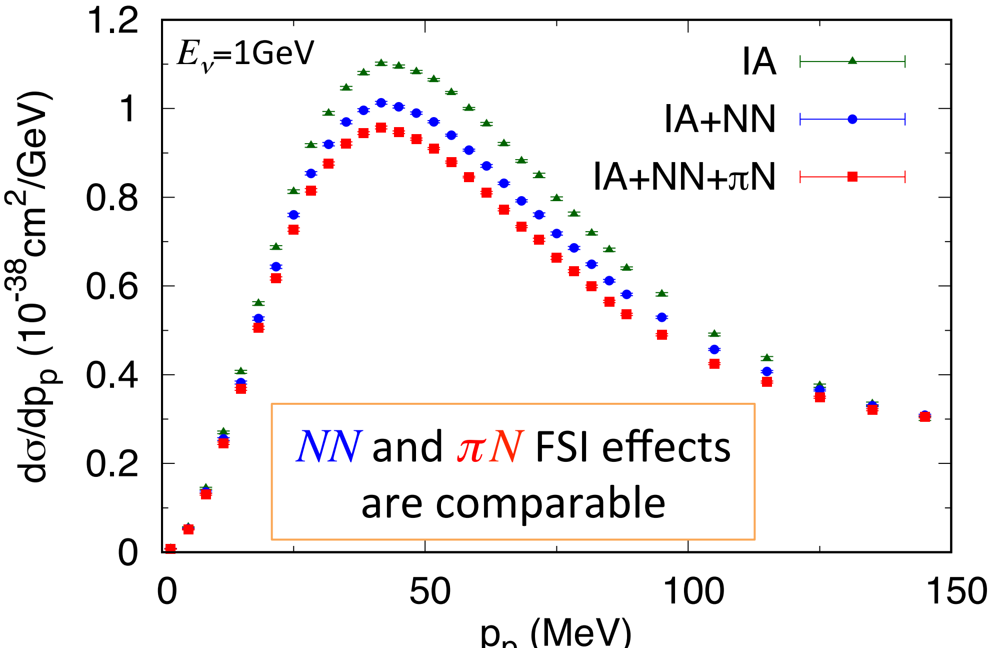
We provide $N(E_\nu)$

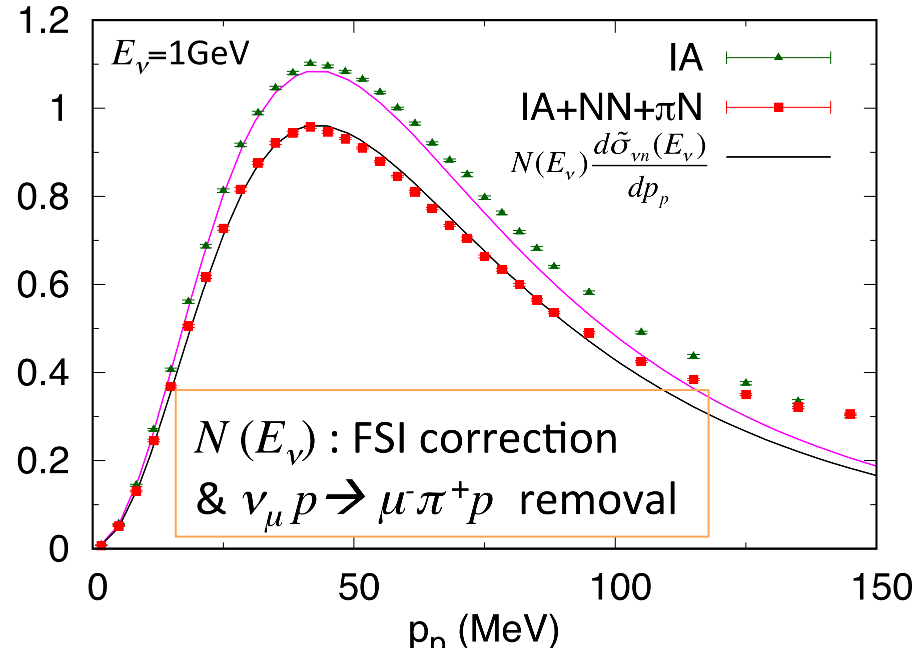
Extract $\sigma(\nu_\mu n \rightarrow \mu^- \pi^+ n)$ from $\sigma(\nu_\mu d \rightarrow \mu^- \pi^+ pn)$



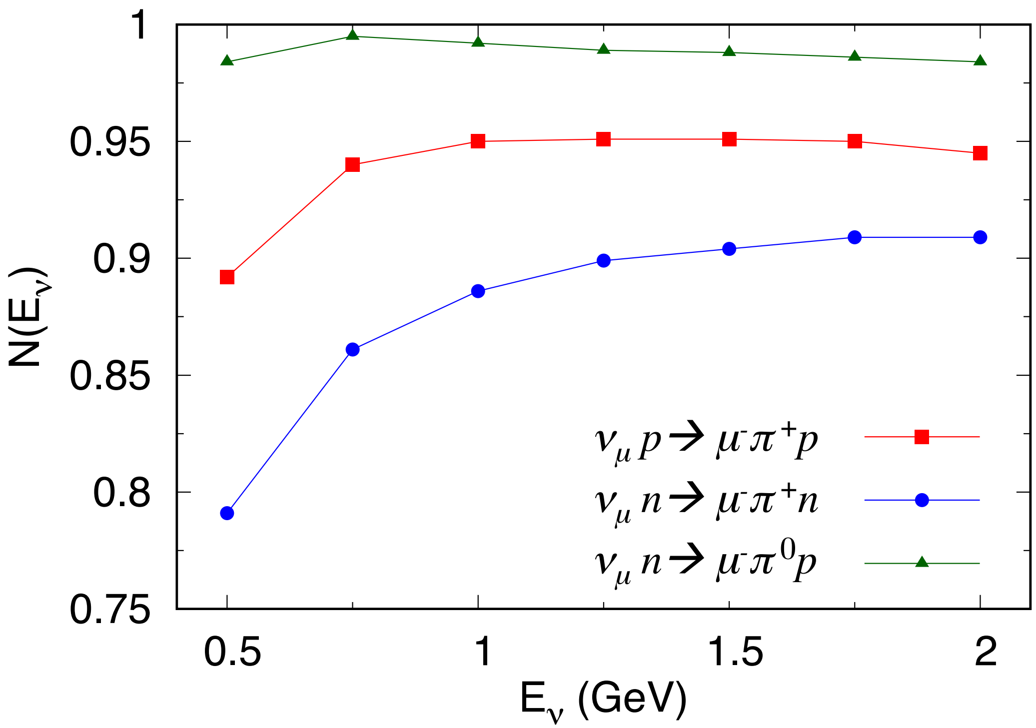
Method similar to extracting $\sigma(\nu_\mu p \rightarrow \mu^- \pi^+ p)$

Some different features in extracting $\sigma(\nu_\mu n \rightarrow \mu^- \pi^+ n)$ by analyzing $d\sigma(\nu_\mu d \rightarrow \mu^- \pi^+ pn)/dp_p$





$N\,(E_\nu)$: FSI correction factor



$$\frac{d\sigma_{\nu d}(E_\nu)}{dp_s} \approx N(E_\nu)\,\frac{d\tilde{\sigma}_{\nu N}(E_\nu)}{dp_s}$$

for $p_s < p_s^{\max} \approx$ 50 MeV

	$N\,(E_\nu)$
$\nu_\mu\, p \rightarrow \mu^- \pi^+ p$	0.89 - 0.95
$\nu_\mu\, n \rightarrow \mu^- \pi^+ n$	0.79 - 0.91
$\nu_\mu\, n \rightarrow \mu^- \pi^0 p$	0.98 - 0.99

- ANL and BNL analyses did not compensate for the cross section reduction due to FSI in QF region

  $\rightarrow$ $N\,(E_\nu)$ would be a reasonable FSI correction in analyzing ANL & BNL data

- Useful for designing and analyzing a possible future experiment

Conclusion

Conclusions

- Total (σ) and single differential ($d\sigma/dX$) cross sections for $\nu_\mu\, d \rightarrow\ \mu^- \pi^+ p\, n,\ \mu^- \pi^0 p\, p$ with FSI are calculated for the first time

- FSI effects on σ and $d\sigma/dX$ for $\nu_\mu\, d \rightarrow \mu^- \pi^+ p\, n$ are examined;
  (NN) FSI reduces σ by 9%, 4%, and 5% at E_ν = 0.5, 1.25, and 2 GeV

  FSI effect on $\nu_\mu\, d \rightarrow\ \mu^- \pi^0 p\, p$ is very small

- We present the FSI correction factors $N\,(E_\nu)$ that will be useful

  in extracting $\sigma(\nu_\mu N \rightarrow \mu^- \pi N)$ from $\sigma(\nu_\mu d \rightarrow \mu^- \pi\, NN)$ data.

  Convoluted $\sigma(\nu\, N)$ would be fitted to FSI-corrected ANL & BNL data:

+ 5-12%	for	$\nu_\mu p \rightarrow\ \mu^- \pi^+ p$
+10-25%	for	$\nu_\mu n \rightarrow\ \mu^- \pi^+ n$
+ 1-2 %	for	$\nu_\mu n \rightarrow\ \mu^- \pi^0 p$

Thank you very much for your attention

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