Analysis of bubble-chamber data on neutrino-induced pion productions off the deuteron

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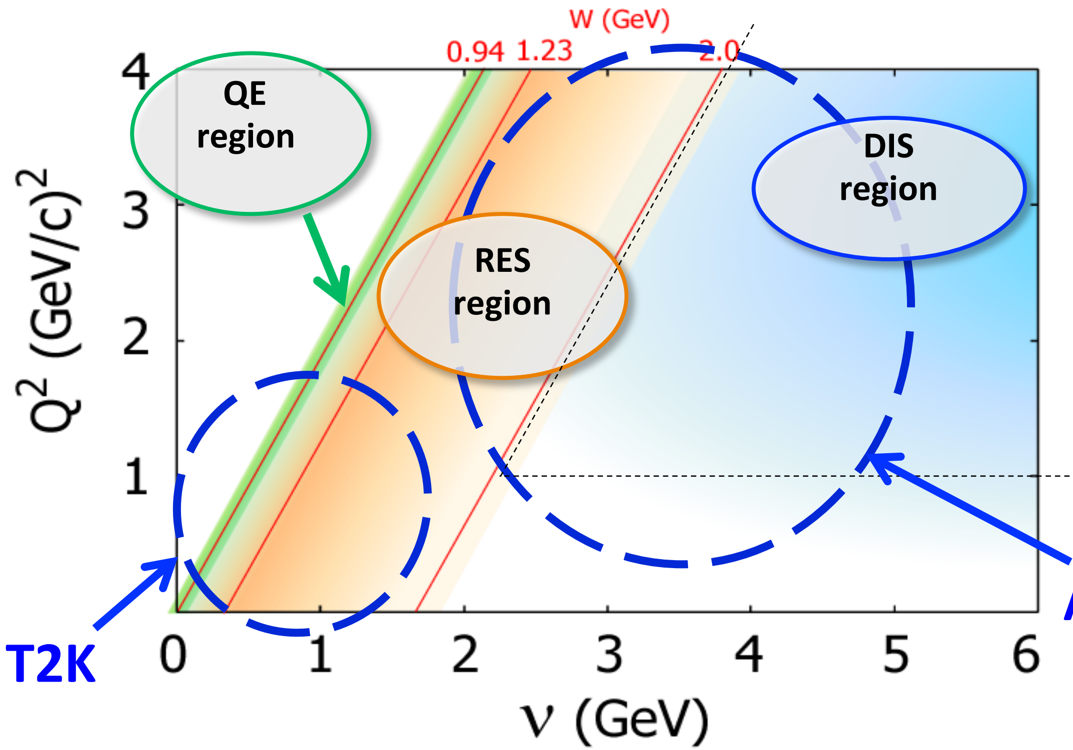
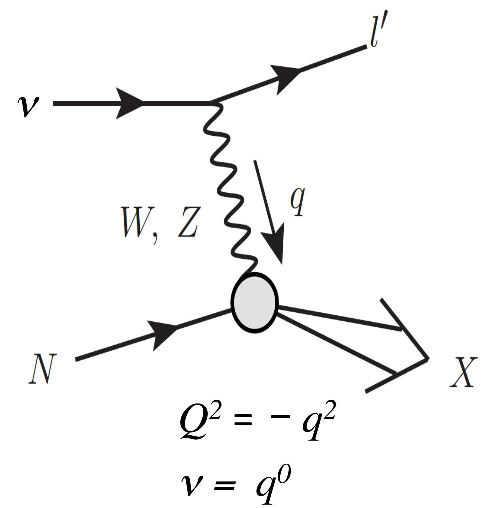
Collaborators: H. Kamano (KEK), T. Sato (Osaka U.)

Introduction

Neutrino-nucleus scattering for ν-oscillation experiments

Wide kinematical region with different characteristic ➔ Different expertise need integrated





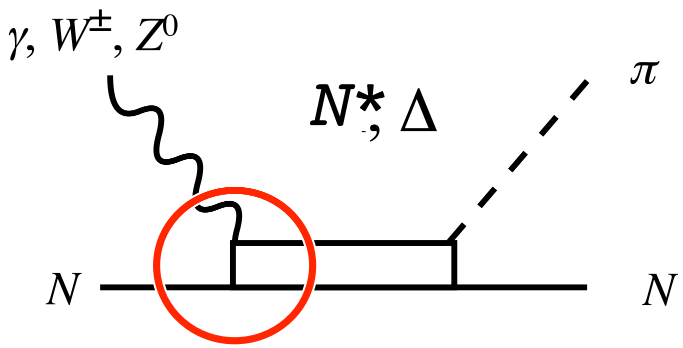
Collaboration at J-PARC Branch of KEK Theory Center

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

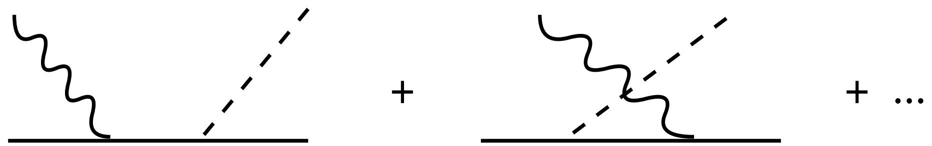
"Towards a Unified Model of Neutrino-Nucleus Reactions for Neutrino Oscillation Experiments"

Theoretical description of elementary process in resonance region

Resonance excitations



Non-resonant mechanisms



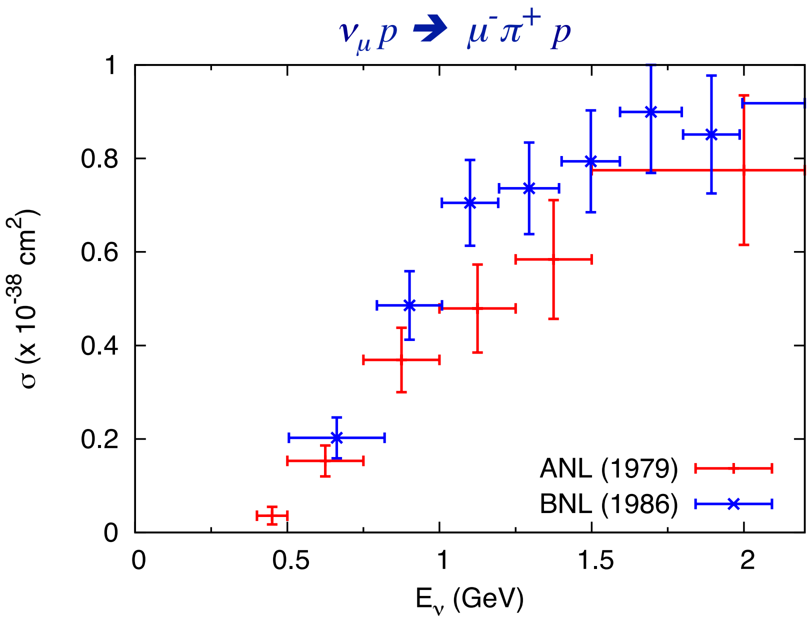
$\Delta(1232)$-excitation is particularly important in ν-induced 1π productions

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

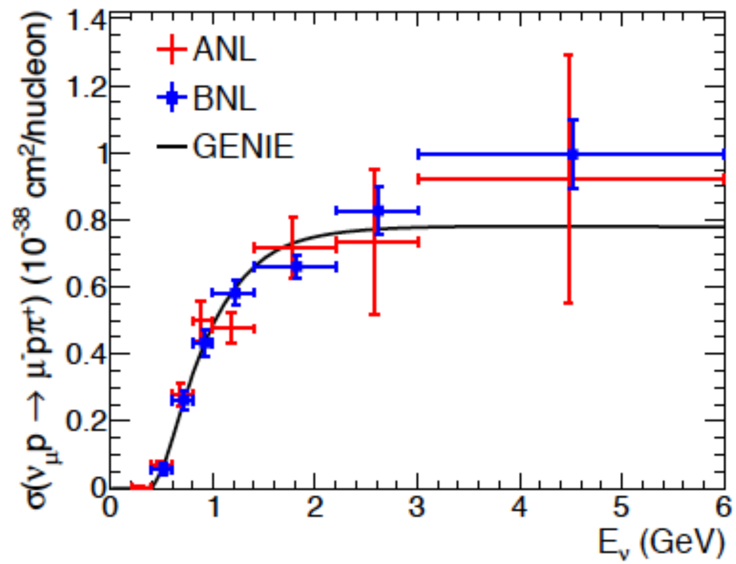
Vector current : photon- and electron-nucleon 1π production data

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

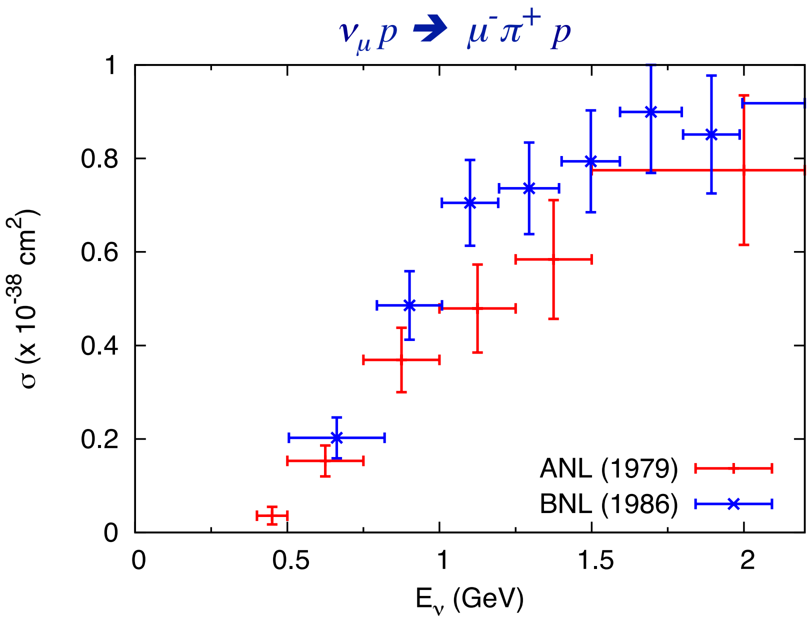
Reanalysis of original data

→ 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

Neutrino interaction data in Δ(1232) region



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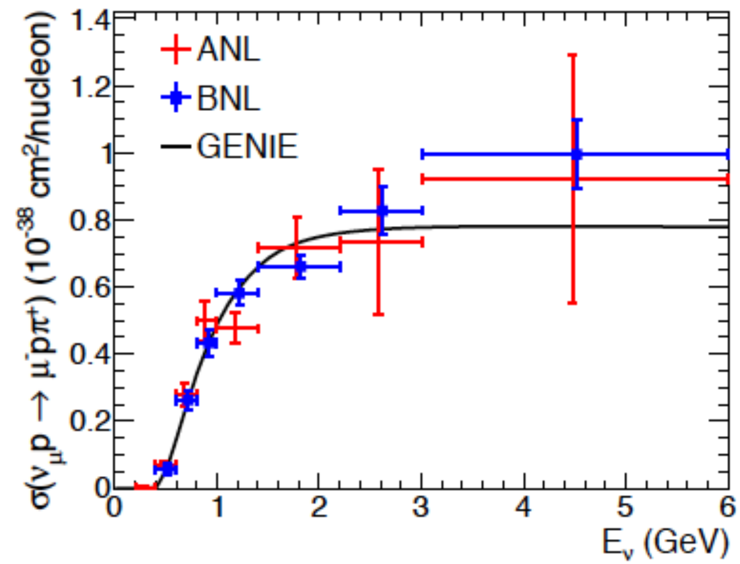

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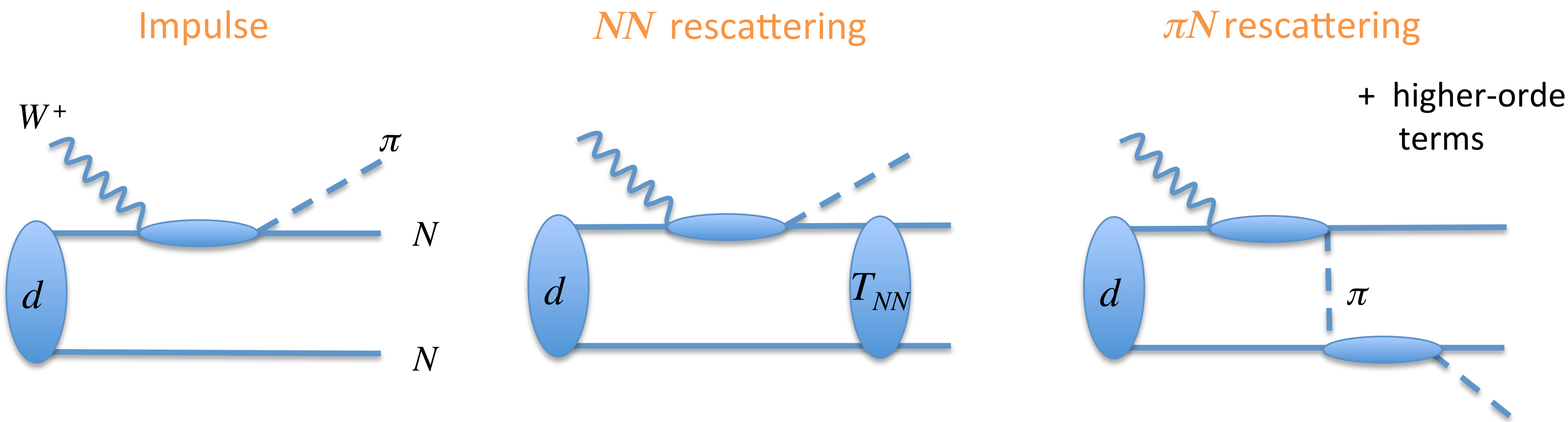
$\nu_\mu p$ ➔ $\mu^- \pi^+ p$ data were extracted from $\nu_\mu d$ ➔ $\mu^- \pi^+ p\, n$ data   Nuclear effects matter ?

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



Nuclear effect managements

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

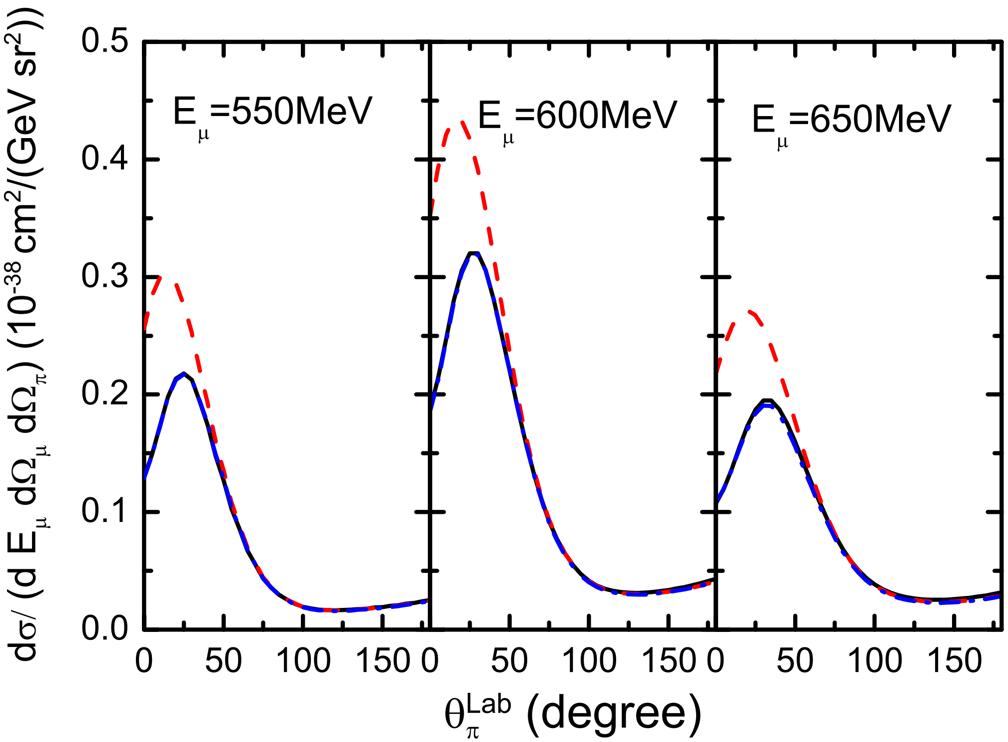
Theory Fermi motion considered in fixing $g_{AN\Delta}$ Hernandez et al. (2010), Alam et al. (2016)

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

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

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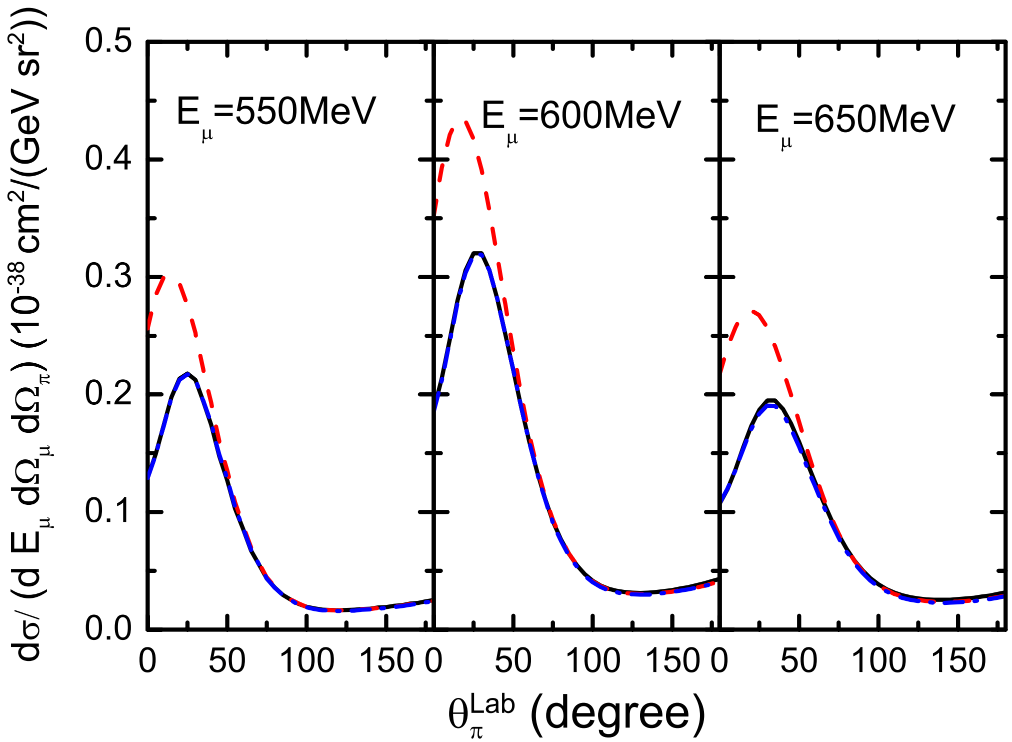

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Orthogonality of *pn* and *d* wave functions

Limitation of Wu et al.'s work : A 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)

Numerically challenging problem

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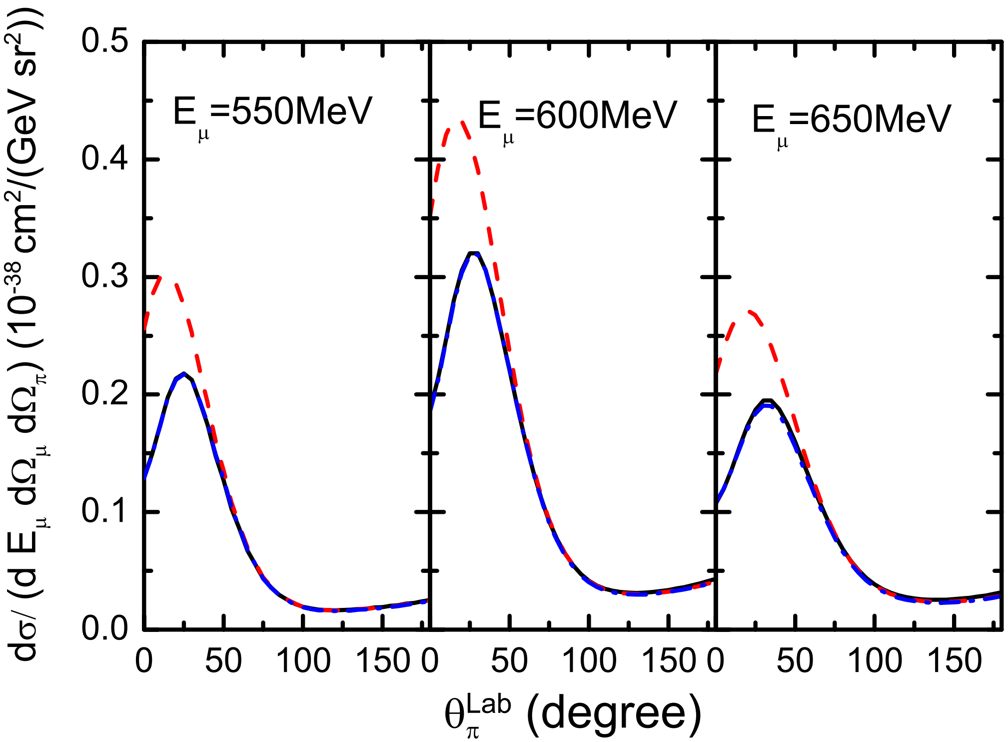

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Numerically challenging problem *will be managed in this work*

This work

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

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

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

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

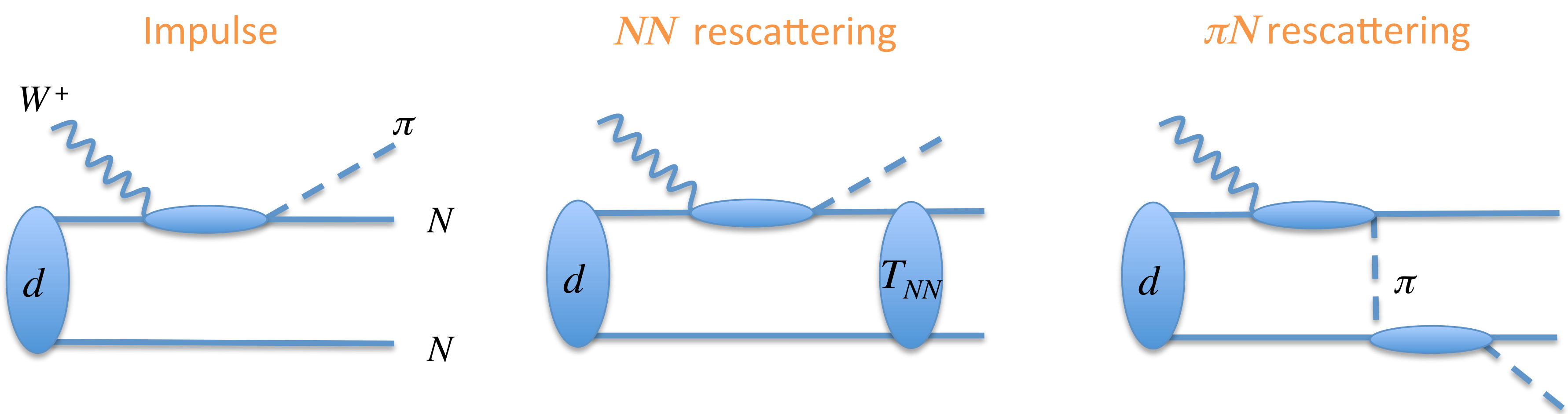
$\nu_\mu d \rightarrow \mu^- \pi^+ p\, n$ reaction model

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



Elementary amplitudes

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

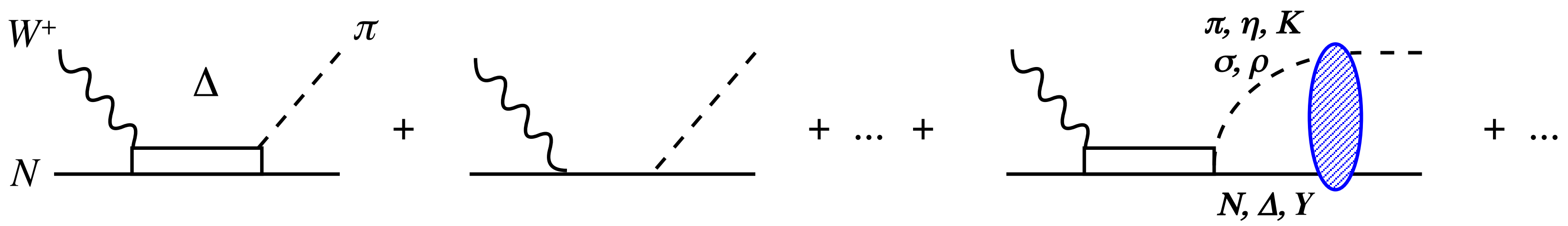
T_{NN}, deuteron w.f. ← CD-Bonn potential (Machleidt et al., PRC 63 (2001))

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

The model has been validated in photo-induced pion productions

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 (~25,000 data pts.)

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

Unique features

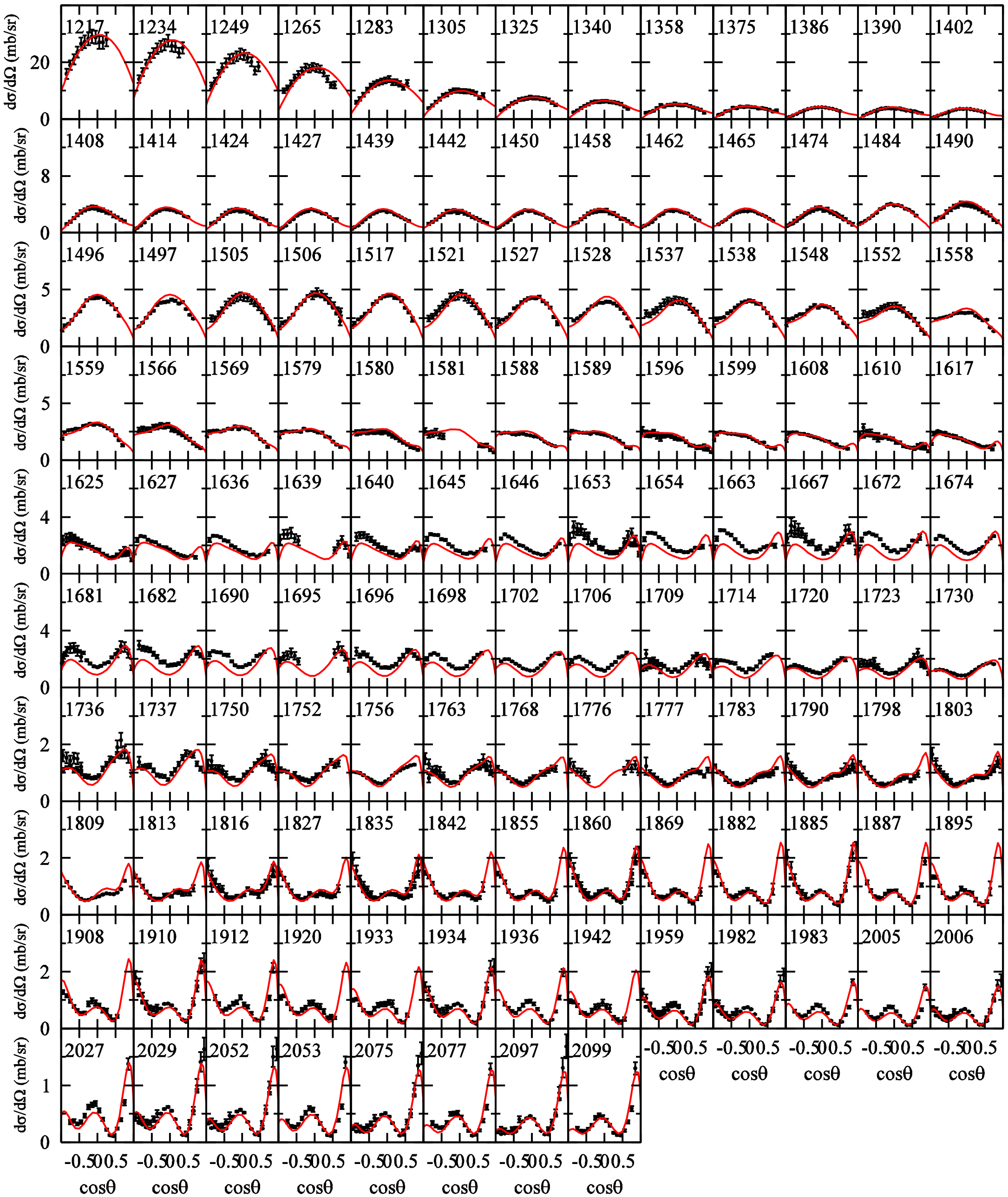
- Hadronic rescattering and channel-couplings are taken into account
  ← requirement from the unitarity
- Interference among resonant and non-resonant mechanisms are under control
  within the model
- One-pion AND two-pion productions for the whole resonance region are described

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

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

Comparison of DCC model with data

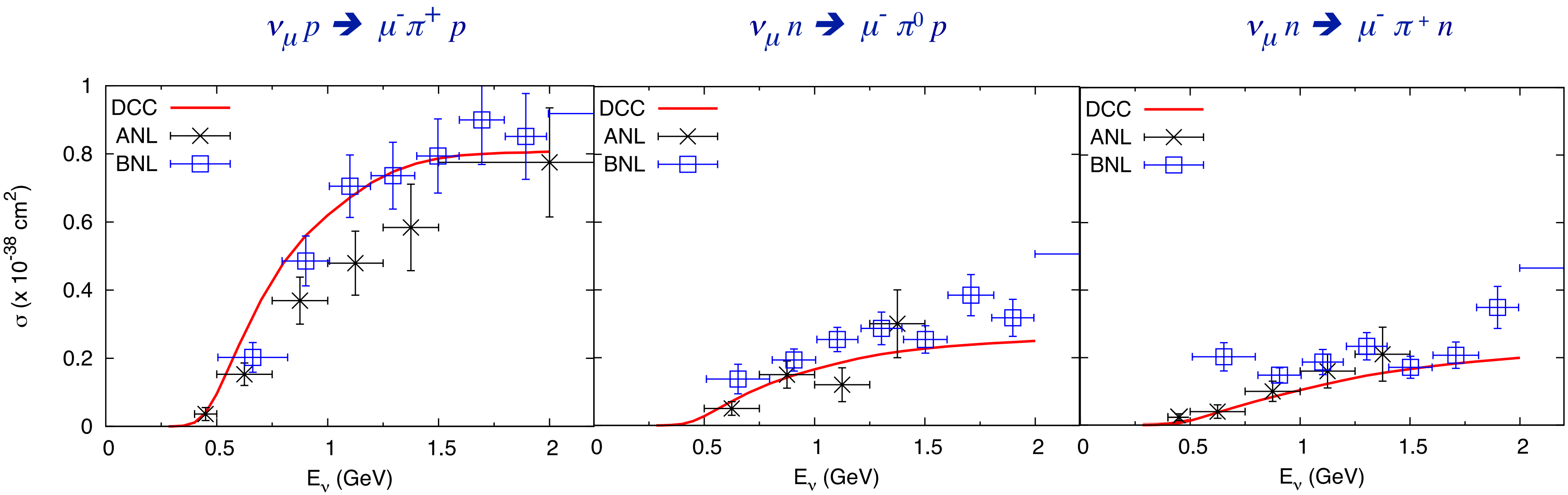
Kamano, Nakamura, Lee, Sato, PRC 88 (2013)



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)

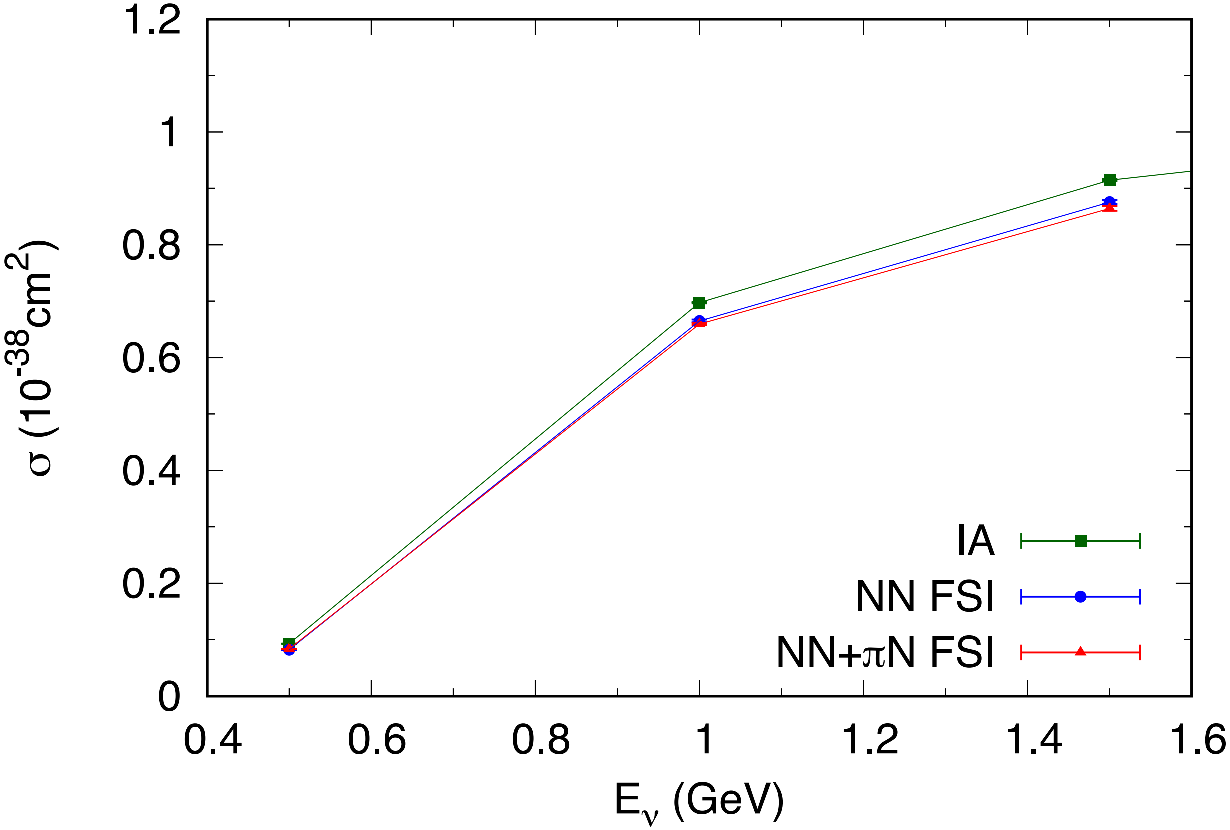
DCC model prediction is consistent with BNL data (before flux correction)

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

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

Results

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



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

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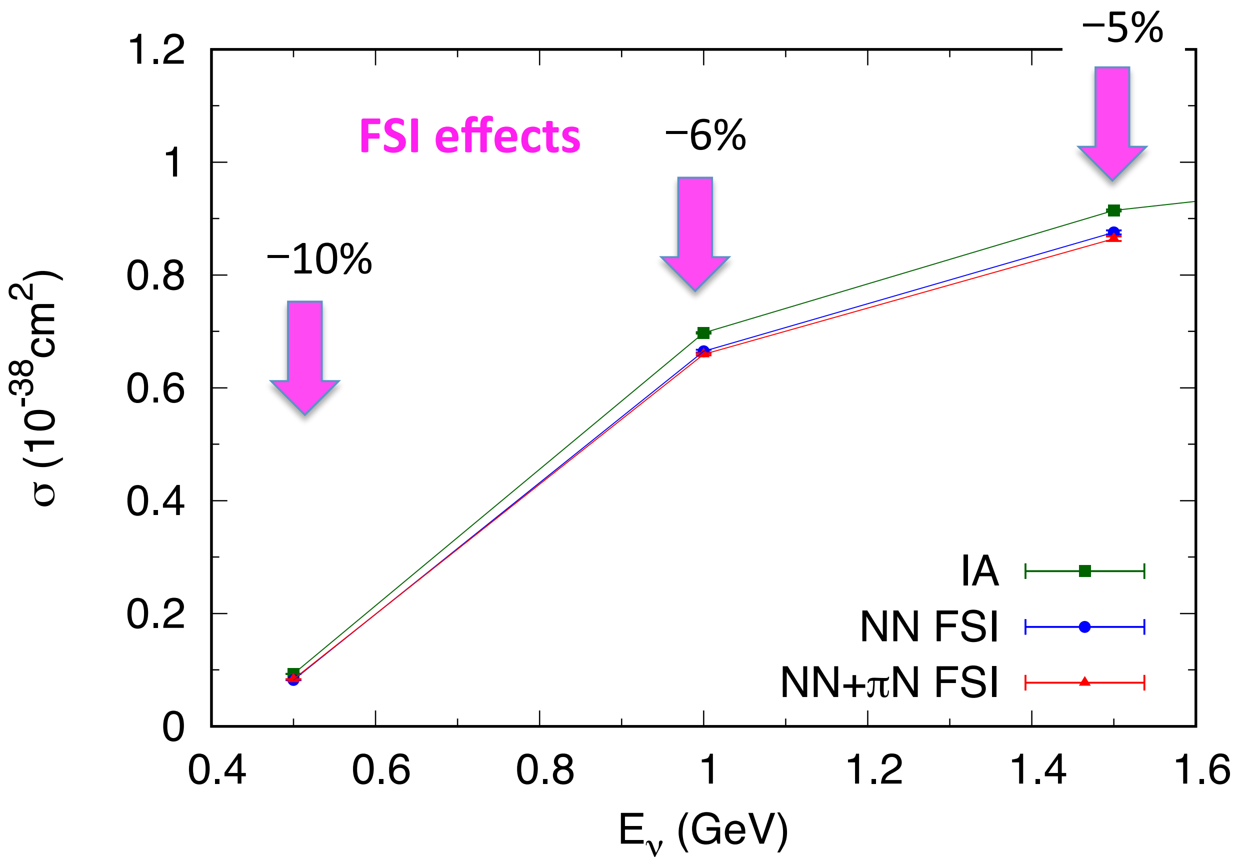

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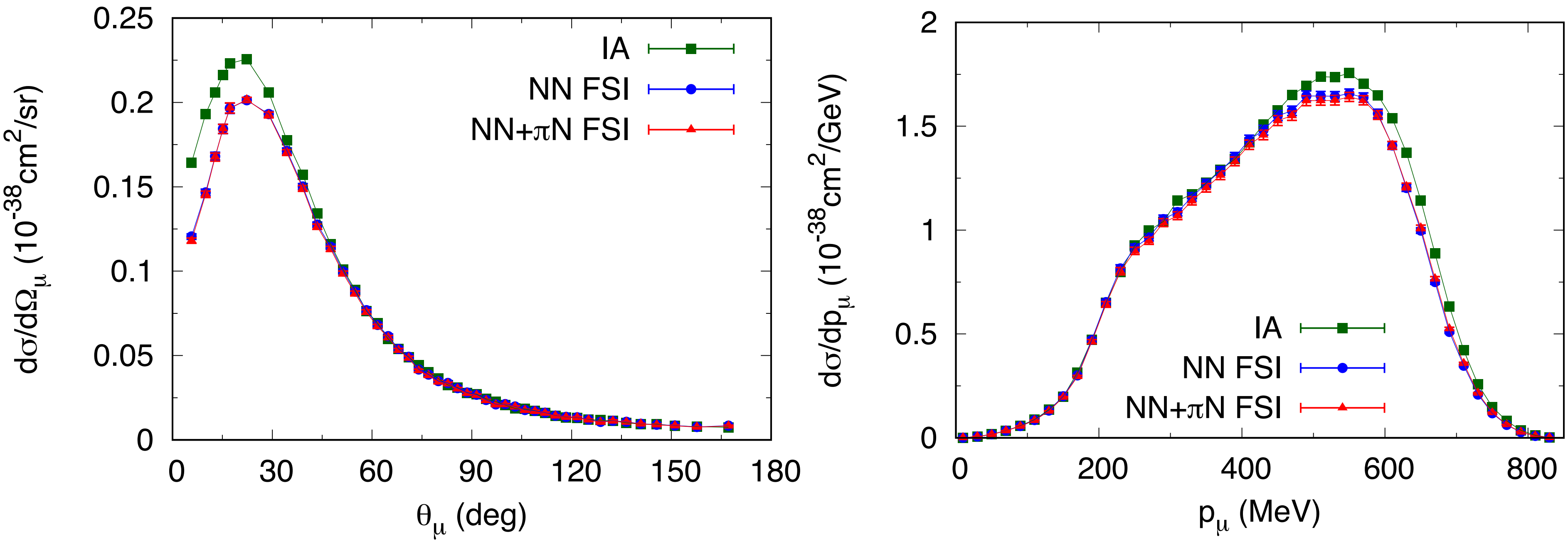
- (Mostly NN) FSI reduces σ by 10%, 6%, 5% at E_ν = 0.5, 1, 1.5 GeV
- πN FSI hardly changes $\sigma(\nu_\mu\, d \rightarrow \mu^- \pi^+\, p\, n)$
- Much smaller FSI effects than what you might have expected from Wu et al.'s result ?

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



- Significant FSI effects are seen in narrow kinematical windows

  → moderate reduction of total cross sections

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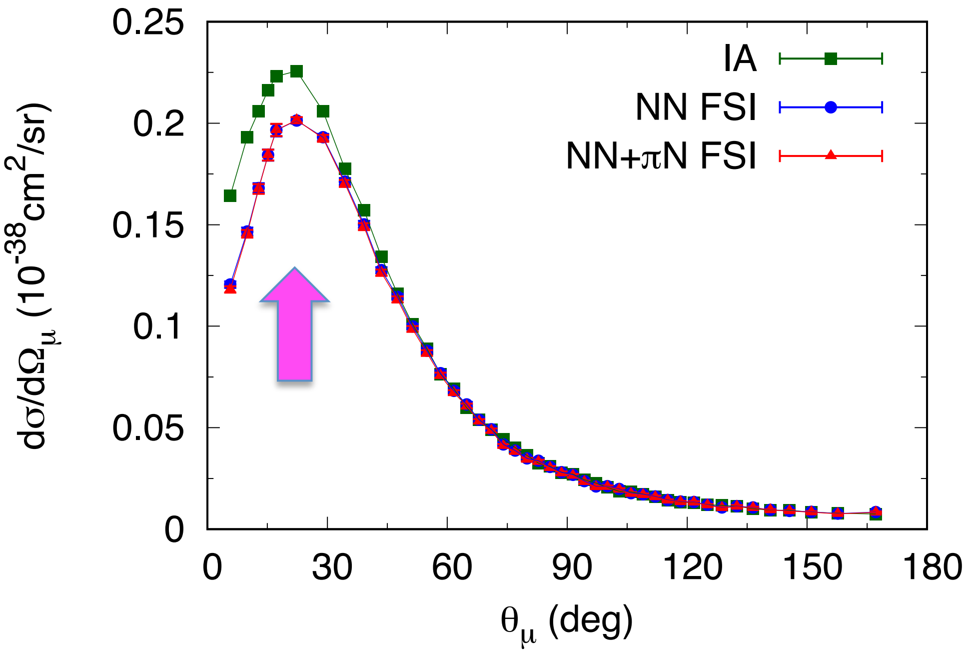

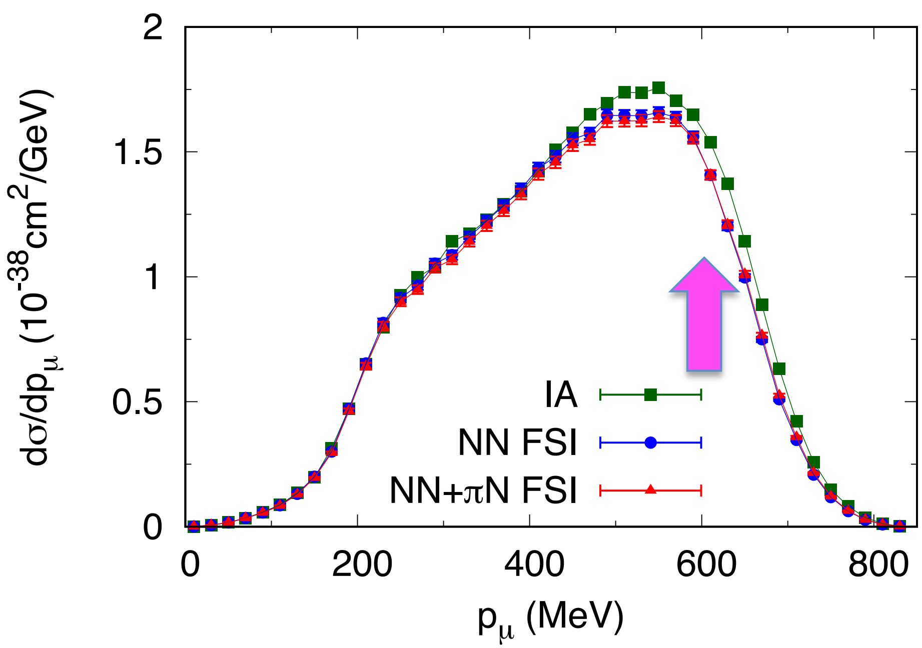

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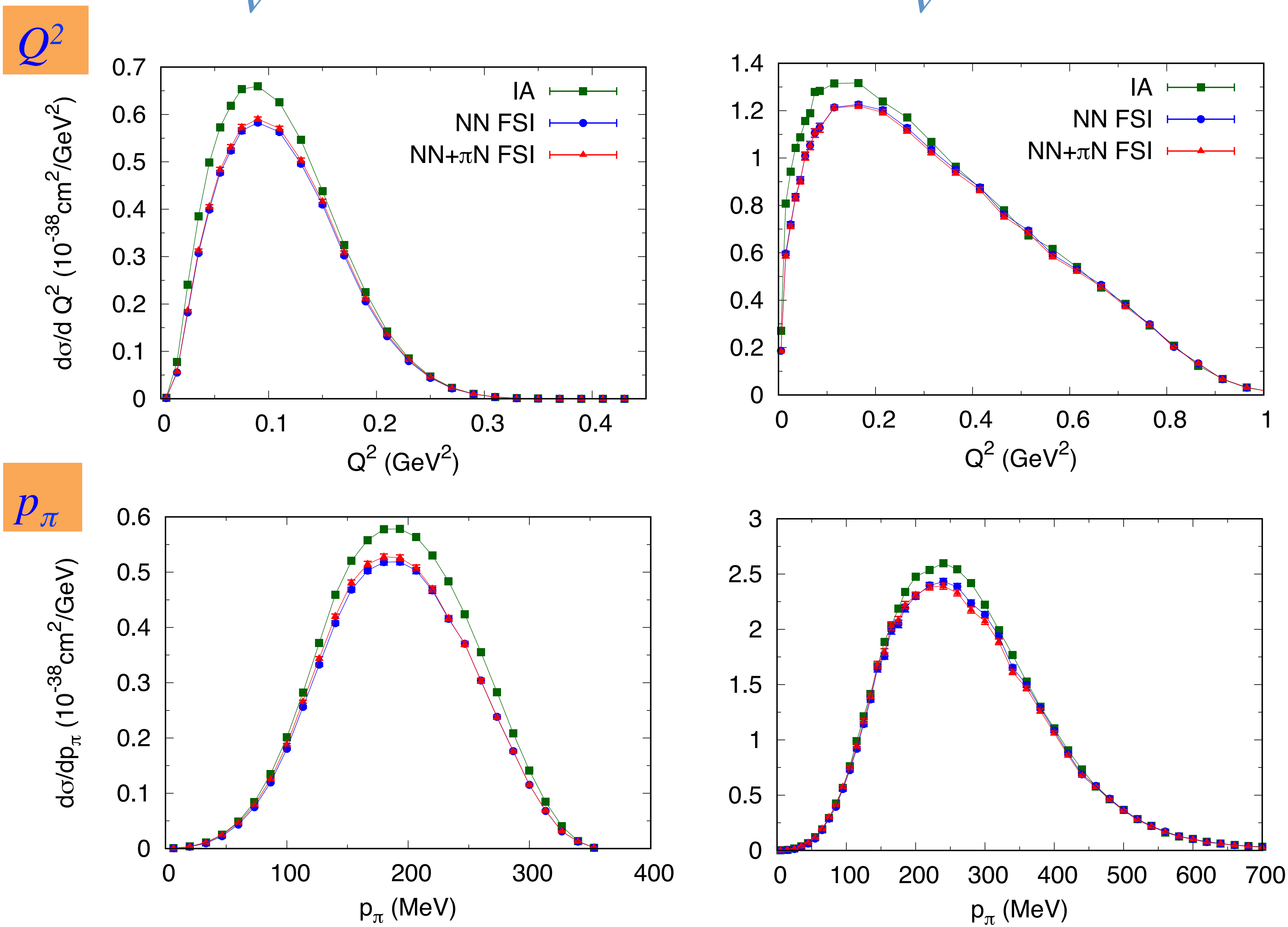
- Wu et al.'s calculation was at $\theta_\mu = 25°$ and $E_\mu = 550, 600, 650$ MeV

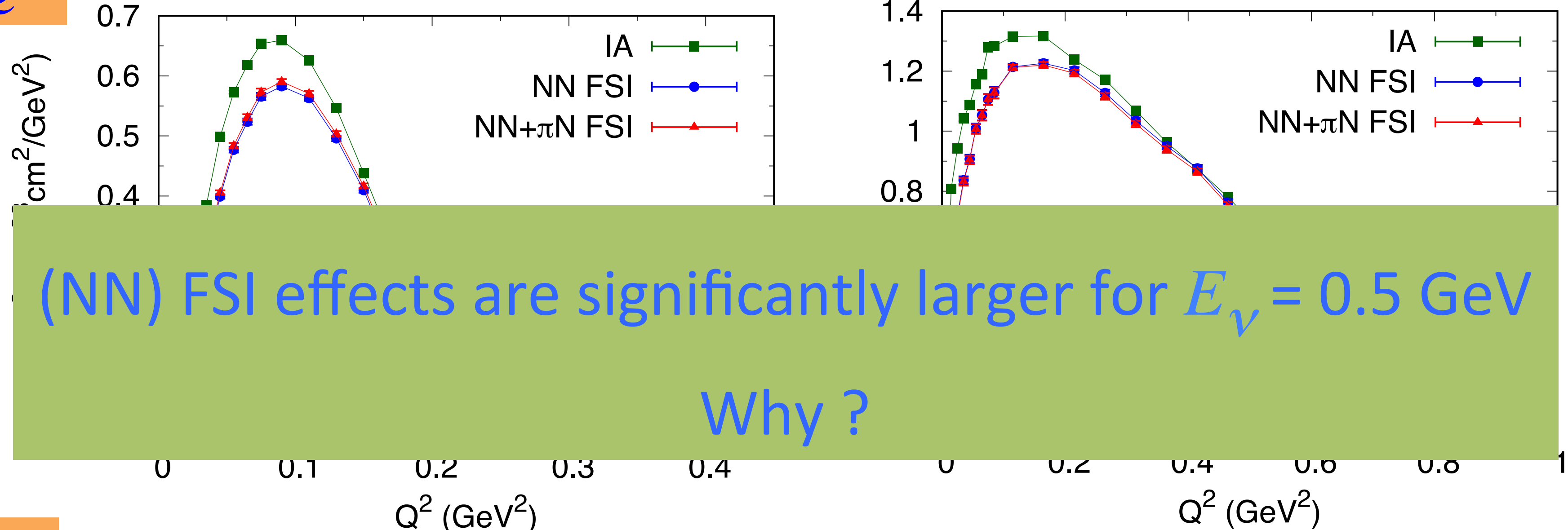
  (region where quasi-free kinematics is important)

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



E_ν = 0.5 GeV vs E_ν = 1 GeV

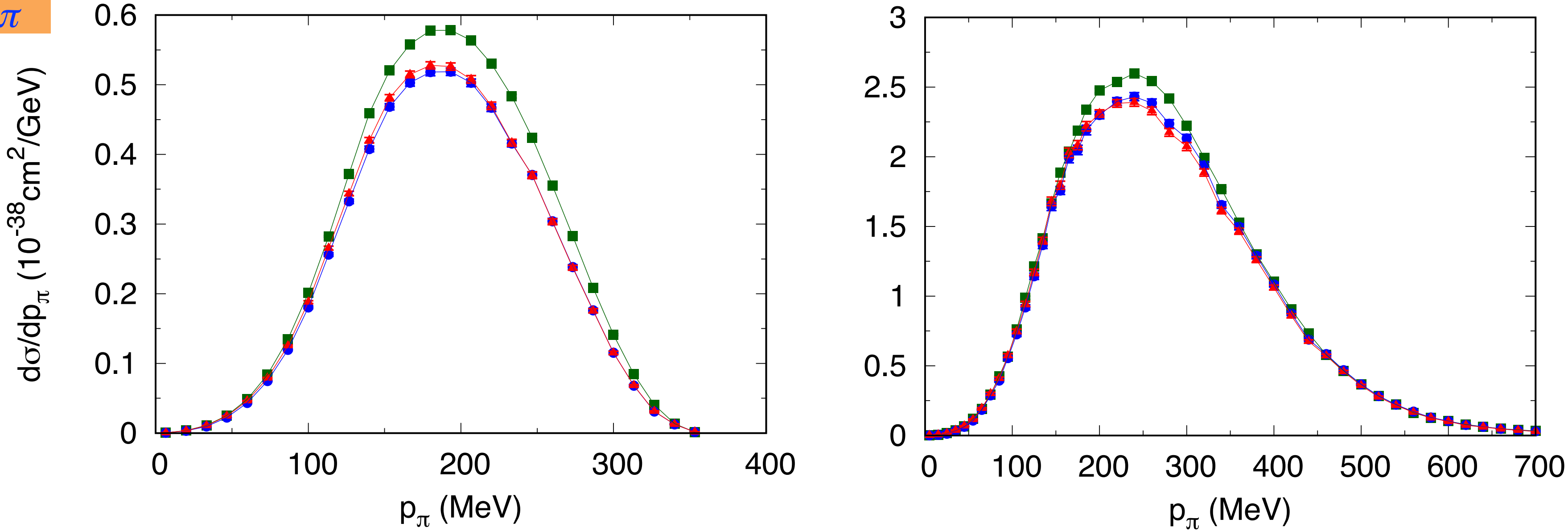
Q^2



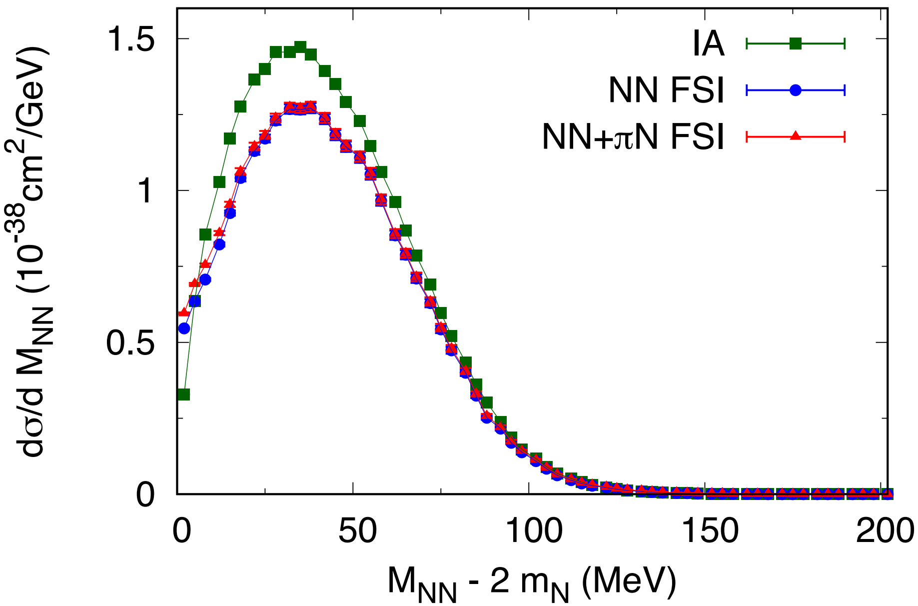
(NN) FSI effects are significantly larger for E_ν = 0.5 GeV

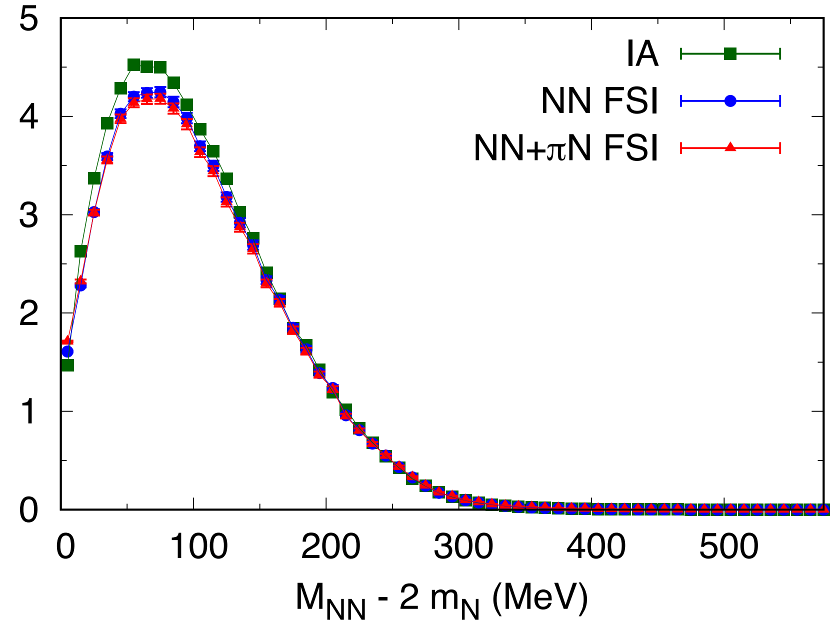
Why ?

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 low E_ν

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 $\sigma(\nu_\mu d \rightarrow \mu^- \pi^+ pn)$?

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- A correct procedure

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

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

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- More common (and practical) procedure

  Cutting out FSI-free $\nu_\mu p \to \mu^- \pi^+ p$ and $\nu_\mu n \to \mu^- \pi^+ n$ events ($\to$ cross sections)

  Easier ! Great ! But how ?

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  (i) Follow ANL and BNL analyses → details lost in history ☹

  (ii) Our own *rough estimate* for here; more elaborate estimate under way

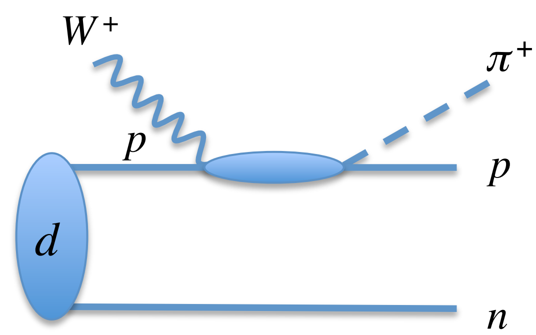
  → How cutting-out procedure would make a mistake in the presence of FSI

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

How ?

Cutting out FSI-free $\nu_\mu p \rightarrow \mu^- \pi^+ p$ cross section

≈ Cutting out contribution from this mechanism →



For doing this, we need to know how

a cross section of this guy behaves …

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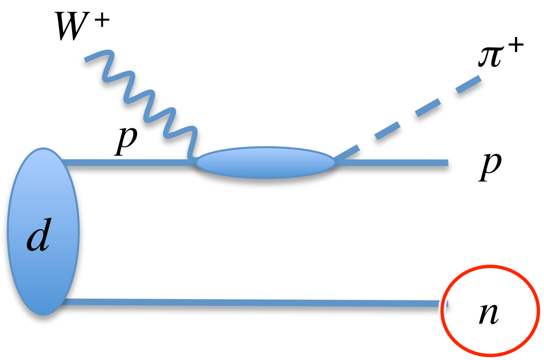

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⇨

Momentum distribution of the spectator neutron should follow the Fermi motion ?

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

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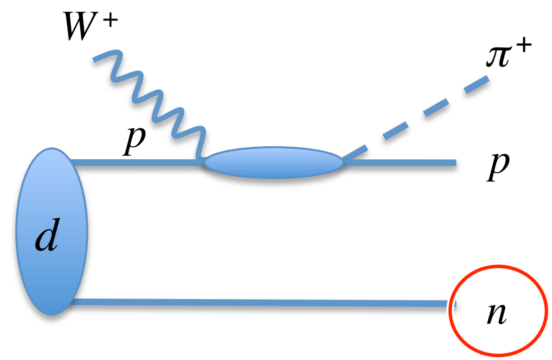

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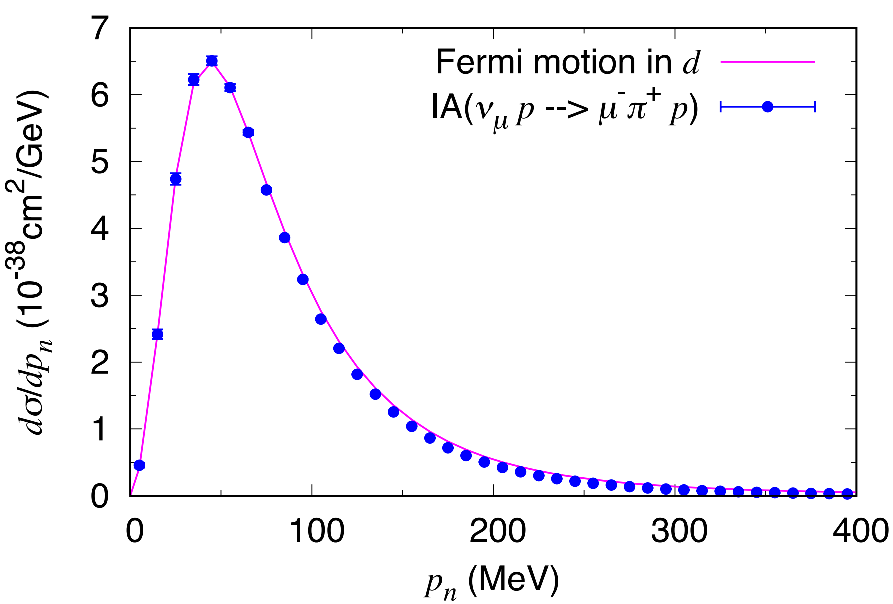


That's right !

IA ($\nu_\mu p \rightarrow \mu^- \pi^+ p$) contribution behaves:

$$\frac{d\sigma}{dp_n} = \underbrace{N(p_n)}_{\approx 1} \, \sigma(\nu_\mu p \rightarrow \mu^- \pi^+ p) \left|\psi_d(p_n)\right|^2$$

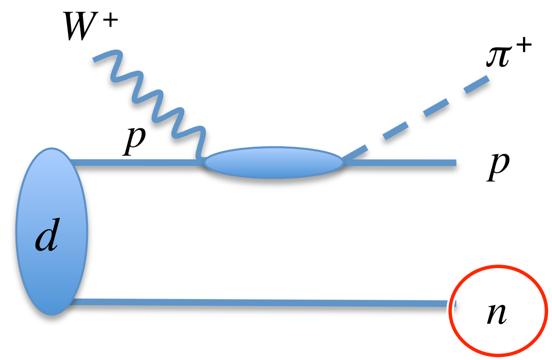
But this is a phenomenological finding because $\nu_\mu p \rightarrow \mu^- \pi^+ p$ amplitude depends on $\vec{p}_n$.

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

How ?

Cutting out FSI-free $\nu_\mu p \rightarrow \mu^- \pi^+ p$ cross section

≈ Cutting out contribution from this mechanism →



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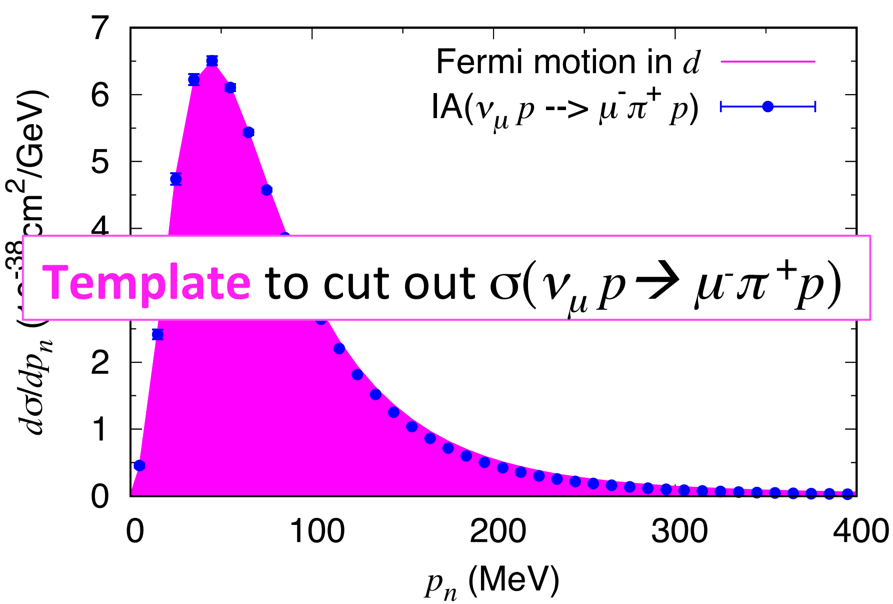

Template to cut out $\sigma(\nu_\mu p \rightarrow \mu^- \pi^+ p)$

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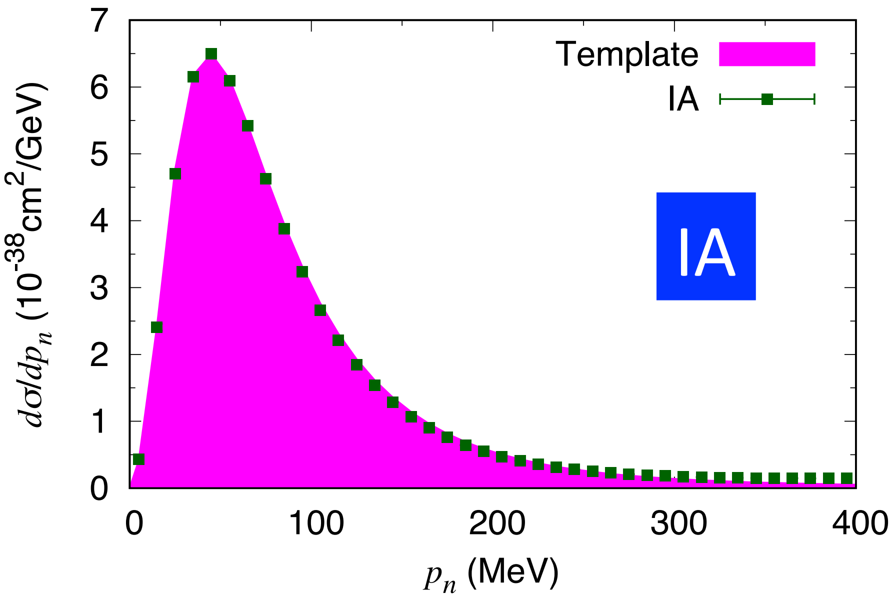
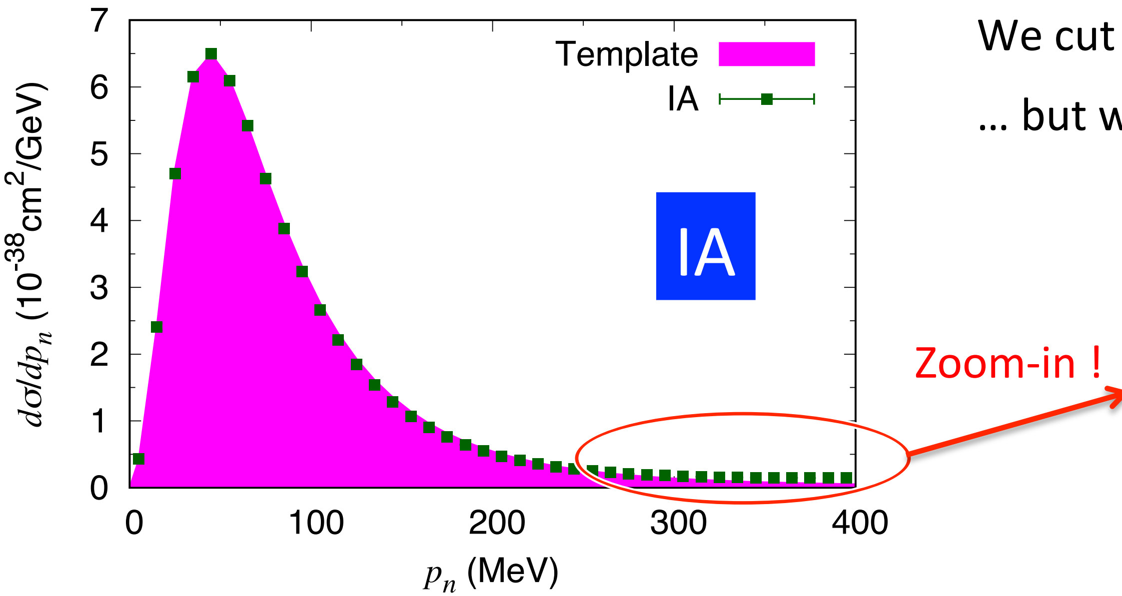


We cut out $\sigma(\nu_\mu p \rightarrow \mu^- \pi^+ p)$ (< 1 % accuracy)

… but where is $\sigma(\nu_\mu n \rightarrow \mu^- \pi^+ n)$?

$\sigma(\nu_\mu p \rightarrow \mu^- \pi^+ p)$ from $\sigma(\nu_\mu d \rightarrow \mu^- \pi^+ p n)$ at E_ν = 1 GeV



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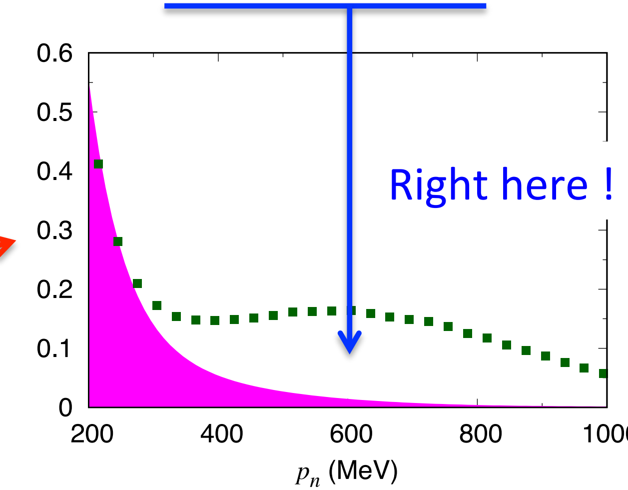

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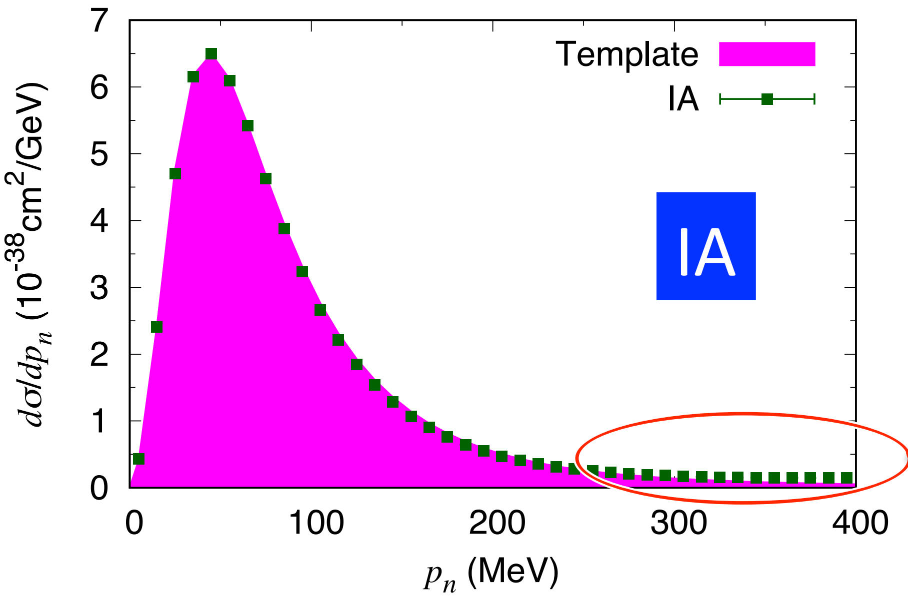

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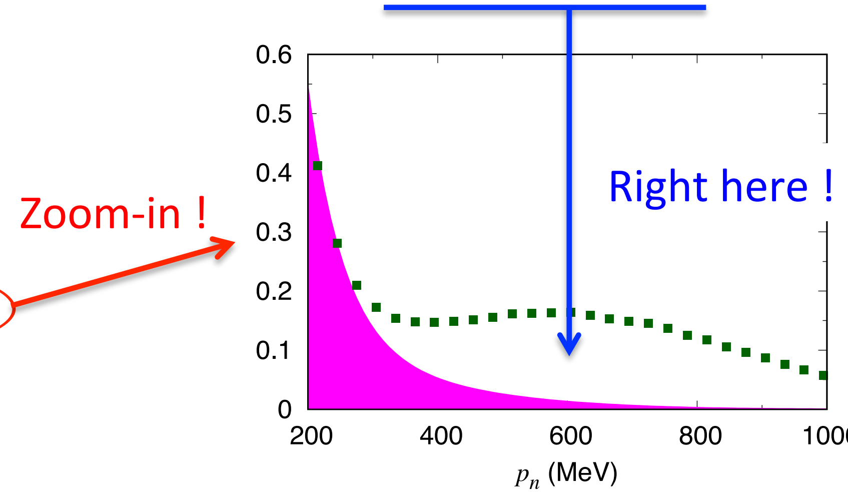
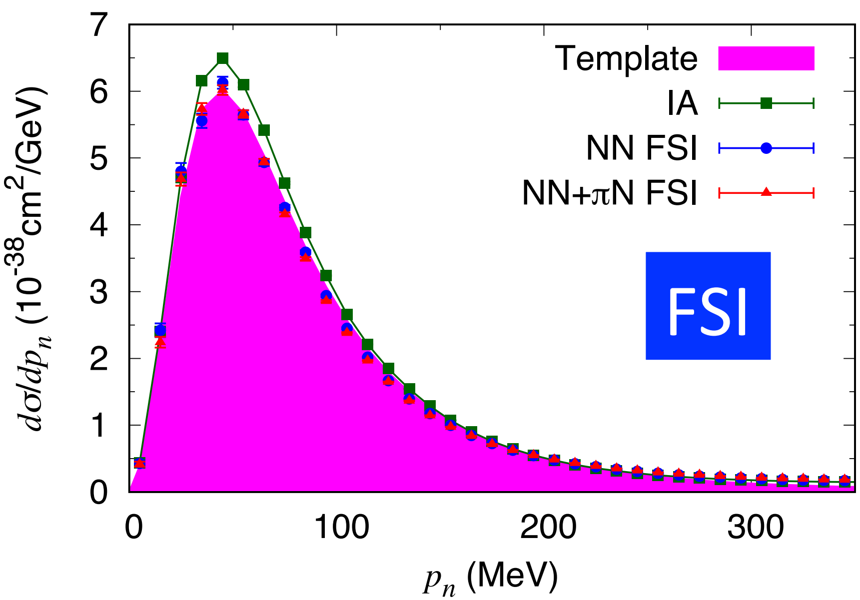
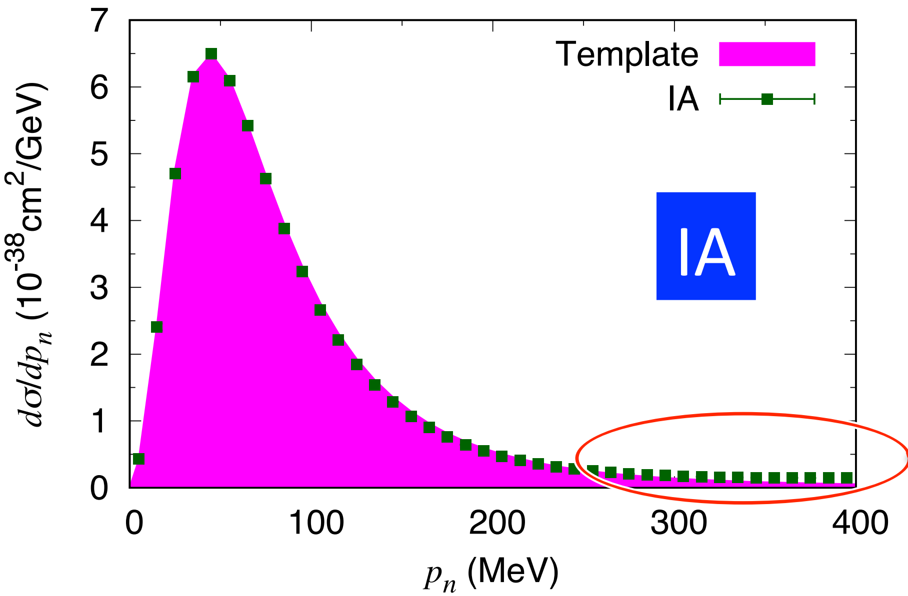




$\sigma(\nu_\mu p \rightarrow \mu^- \pi^+ p)$ from $\sigma(\nu_\mu d \rightarrow \mu^- \pi^+ p n)$ at $E_\nu = 1$ GeV



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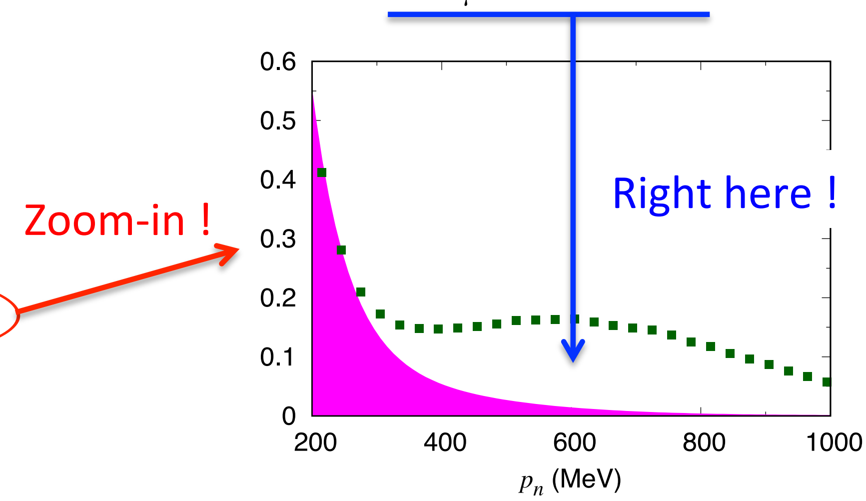
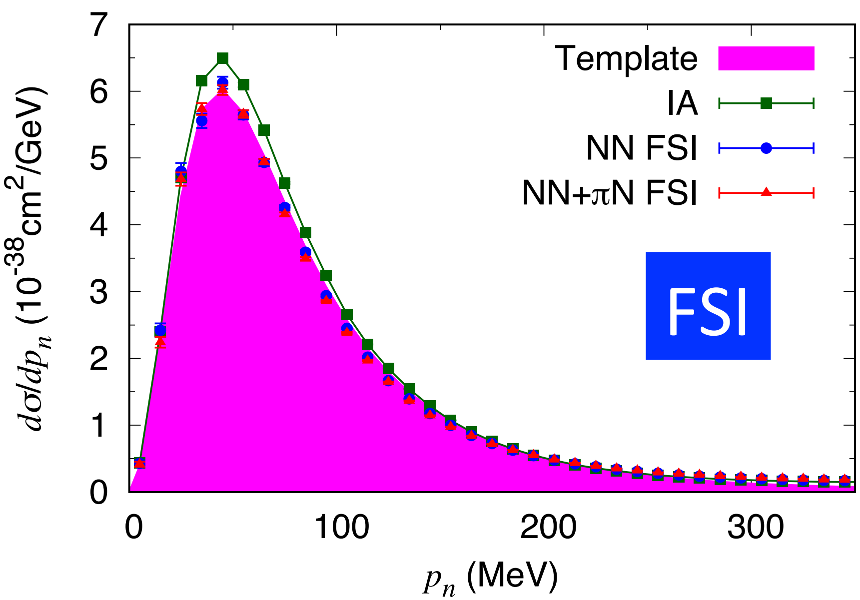
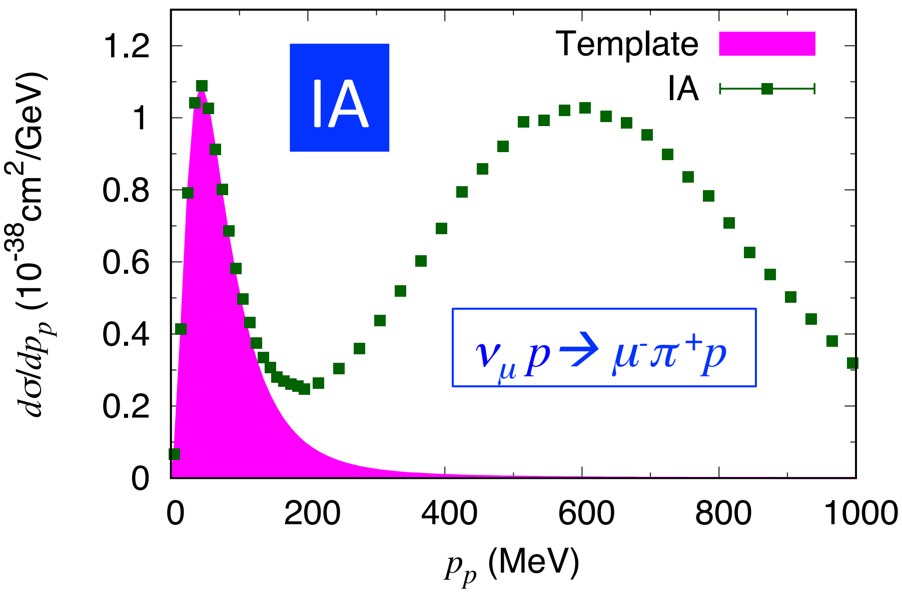




In the presence of FSI, the template method underestimates $\sigma(\nu_\mu p \rightarrow \mu^- \pi^+ p)$ by 8 %. Why ?

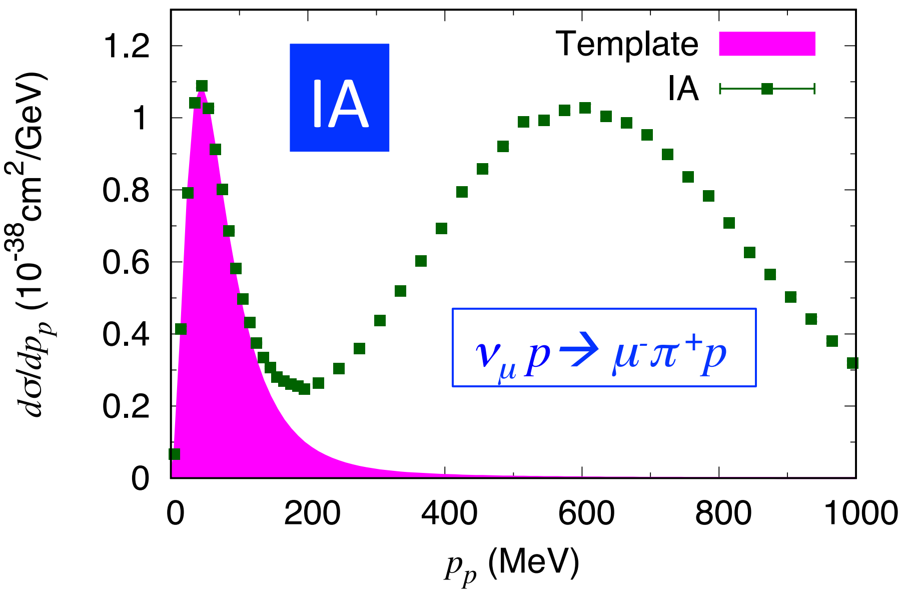
- FSI create events with large spectator momentum → the template can remove it
- FSI reduce events with low spectator momentum → the template can't compensate

$\sigma(\nu_\mu n \rightarrow \mu^- \pi^+ n)$ from $\sigma(\nu_\mu d \rightarrow \mu^- \pi^+ pn)$ at E_ν = 1 GeV



Method : The template analysis done for spectator-proton momentum distribution

$\sigma(\nu_\mu n \to \mu^- \pi^+ n)$ from $\sigma(\nu_\mu d \to \mu^- \pi^+ p n)$ at E_ν = 1 GeV

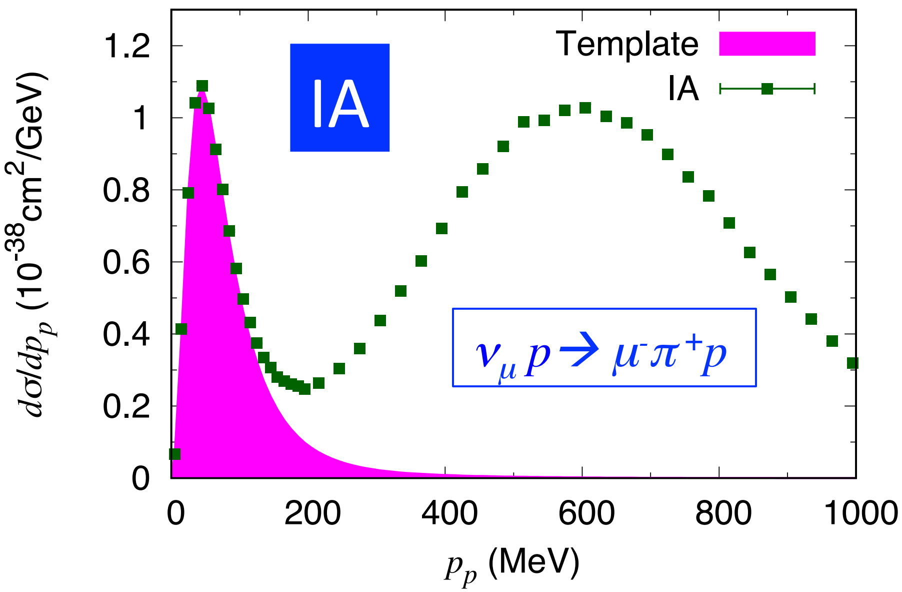


Method : The template analysis done for spectator-proton momentum distribution

$\sigma(\nu_\mu n \to \mu^- \pi^+ n)$ is cut out at 1% precision !

Unexpectedly successful because mixture of $\nu_\mu p \to \mu^- \pi^+ p$ inside the template should have been removed; interference is hard to handle

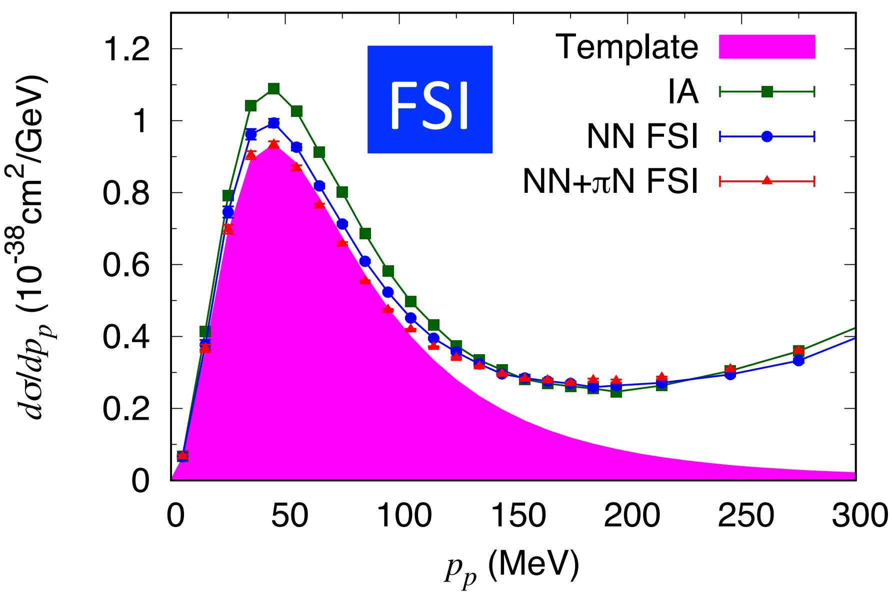
$\sigma(\nu_\mu n \to \mu^- \pi^+ n)$ from $\sigma(\nu_\mu d \to \mu^- \pi^+ pn)$ at $E_\nu = 1$ GeV



Method : The template analysis done for spectator-proton momentum distribution

$\sigma(\nu_\mu n \to \mu^- \pi^+ n)$ is cut out at 1% precision !

Unexpectedly successful because mixture of $\nu_\mu p \to \mu^- \pi^+ p$ inside the template should have been removed; interference is hard to handle



πN and NN FSI effects are comparable size

πN FSI is visible only where ν-p is suppressed

In the presence of FSI, the template method underestimates $\sigma(\nu_\mu n \to \mu^- \pi^+ n)$ by 15%

Conclusion

Conclusions

- Total (σ) and single differential ($d\sigma/dX$) cross sections for $\nu_\mu d \rightarrow \mu^- \pi^+ p\, n$ 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 10%, 6%, and 5% at E_ν = 0.5, 1, and 1.5 GeV

- $\sigma(\nu_\mu p \rightarrow \mu^- \pi^+ p)$ and $\sigma(\nu_\mu n \rightarrow \mu^- \pi^+ n)$ are extracted from $\sigma(\nu_\mu d \rightarrow \mu^- \pi^+ pn)$ using Fermi motion-based template (temporary exercise)

  If FSI is absent, the template method works well

  If FSI is present, the template method significantly underestimates $\sigma(\nu_\mu p \rightarrow \mu^- \pi^+ p)$ by 8%, and $\sigma(\nu_\mu n \rightarrow \mu^- \pi^+ n)$ by 15%.

  Very likely, other kinematical cut-based methods have the same problem because we cannot infer from data amount of reduction caused by FSI

Thank you very much for your attention

Acknowledgments

- Financial support for this work

  KAKENHI JP25105010

  FAPESP 2016/15618-8

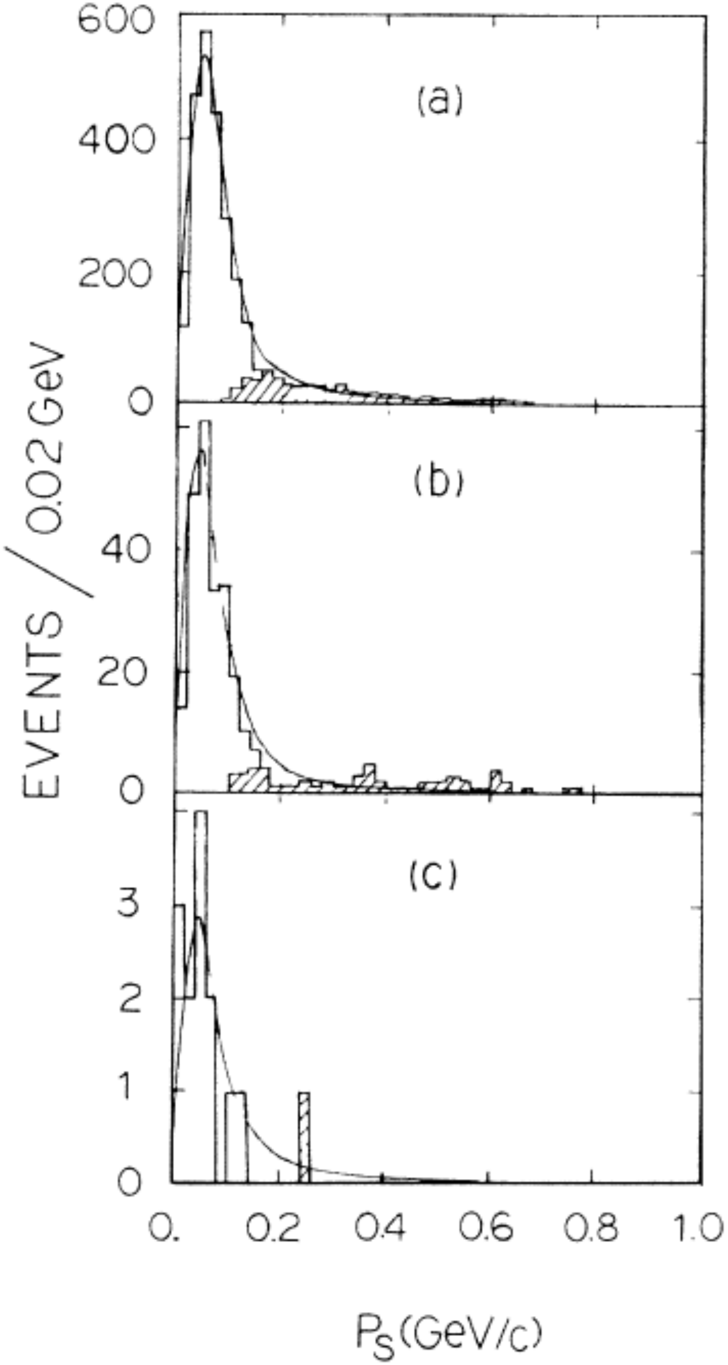
- Computing resource

  Blues: Laboratory Computing Resource Center at Argonne National Laboratory

BACKUP

BNL analysis

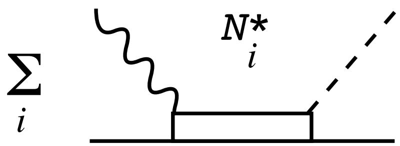
PRD 34, 2554 (1986)



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

resonant only

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

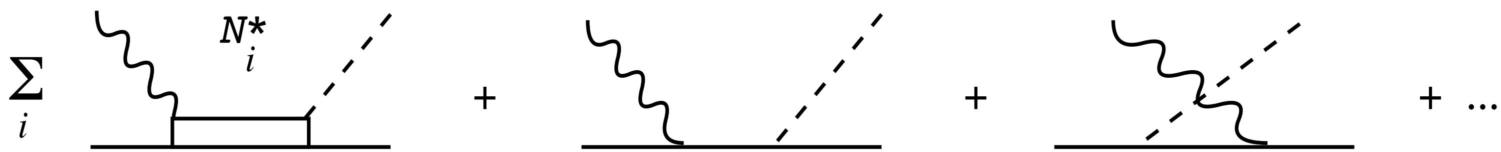


VNN^* : helicity amplitudes listed in PDG

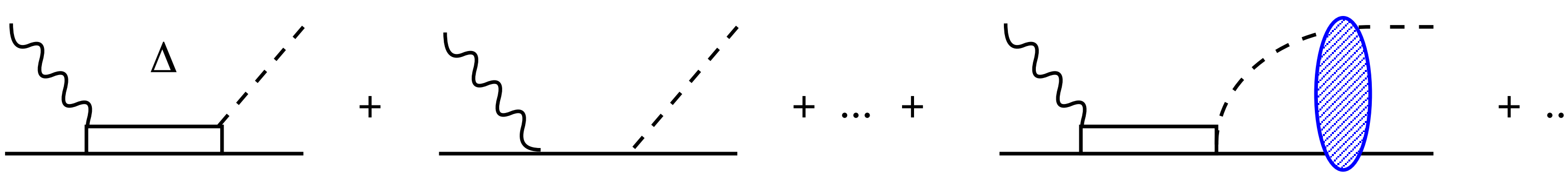
ANN^* : quark model, PCAC relation to $|\pi NN^*|$ (PDG)

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

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

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

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

DCC (Dynamical Coupled-Channel) model

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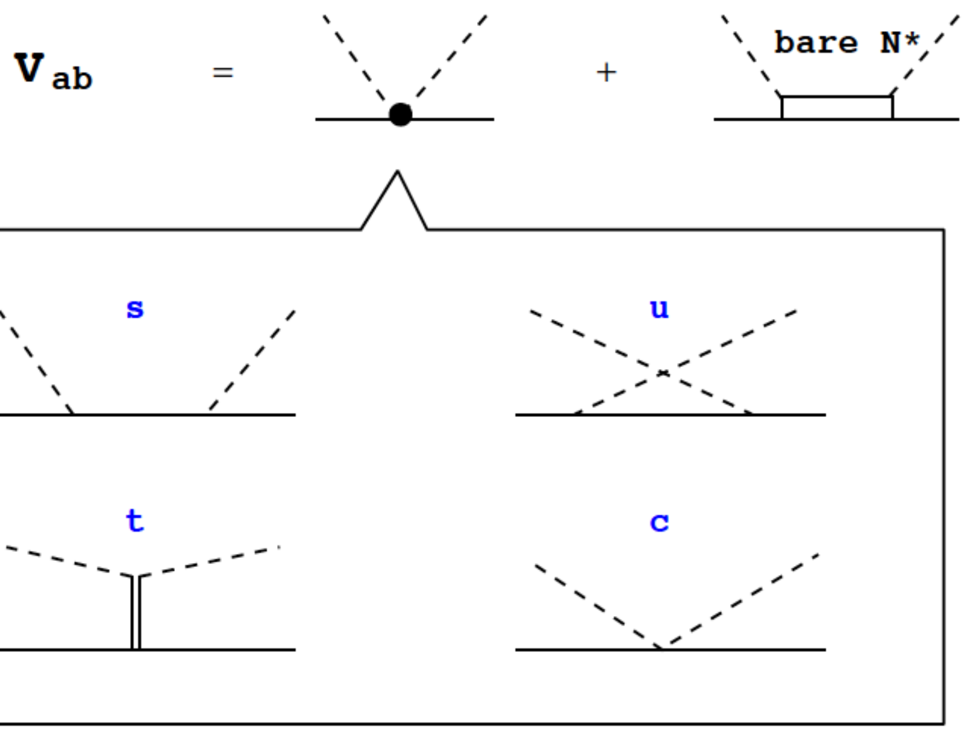

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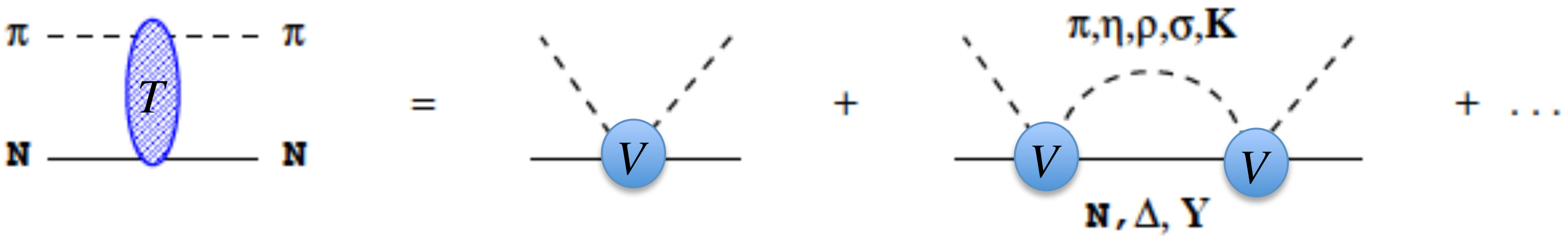
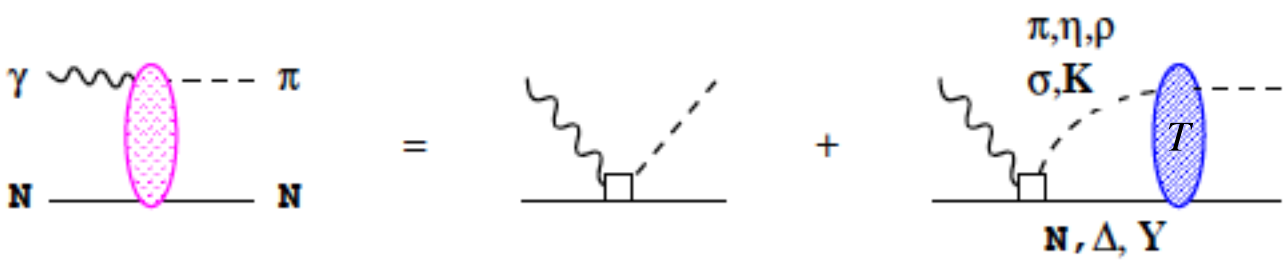


In addition, γN, $W^{\pm}N$, ZN channels are included perturbatively



Relation between neutrino and electron (photon) interactions

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

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

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

$$L^{em} = e\ J_\lambda^{em} A_{em}^\lambda \qquad J_\lambda^{em} = V_\lambda + V_\lambda^{IS}$$

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:

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

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

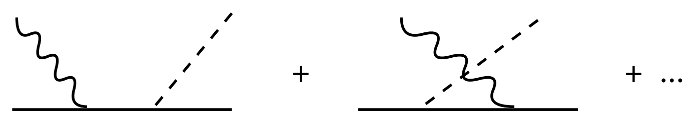
Because neutrino reaction data are scarce, axial current cannot be determined phenomenologically
→ Chiral symmetry and PCAC (partially conserved axial current) are guiding principle

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

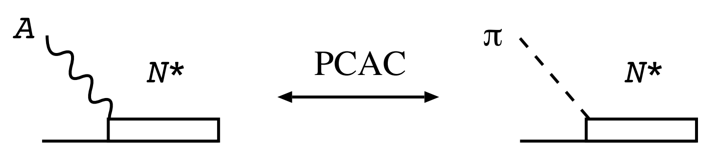
Q^2=0

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 $F_A(Q^2) = \left(\frac{1}{1+Q^2/M_A^2}\right)^2$ $M_A = 1.02$ GeV

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

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 γN, πN → πN, ηN, $K\Lambda$, $K\Sigma$

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

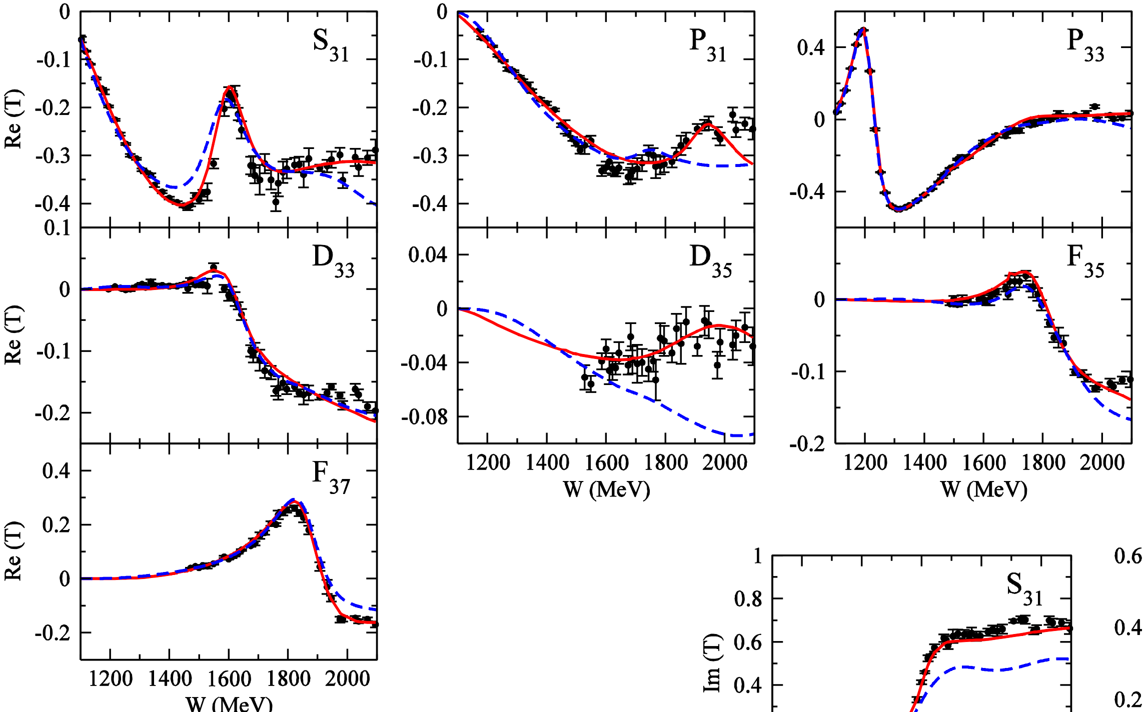
by adjusting parameters (*N** mass, *N** ➔ *MB* couplings, cutoffs)

↓

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

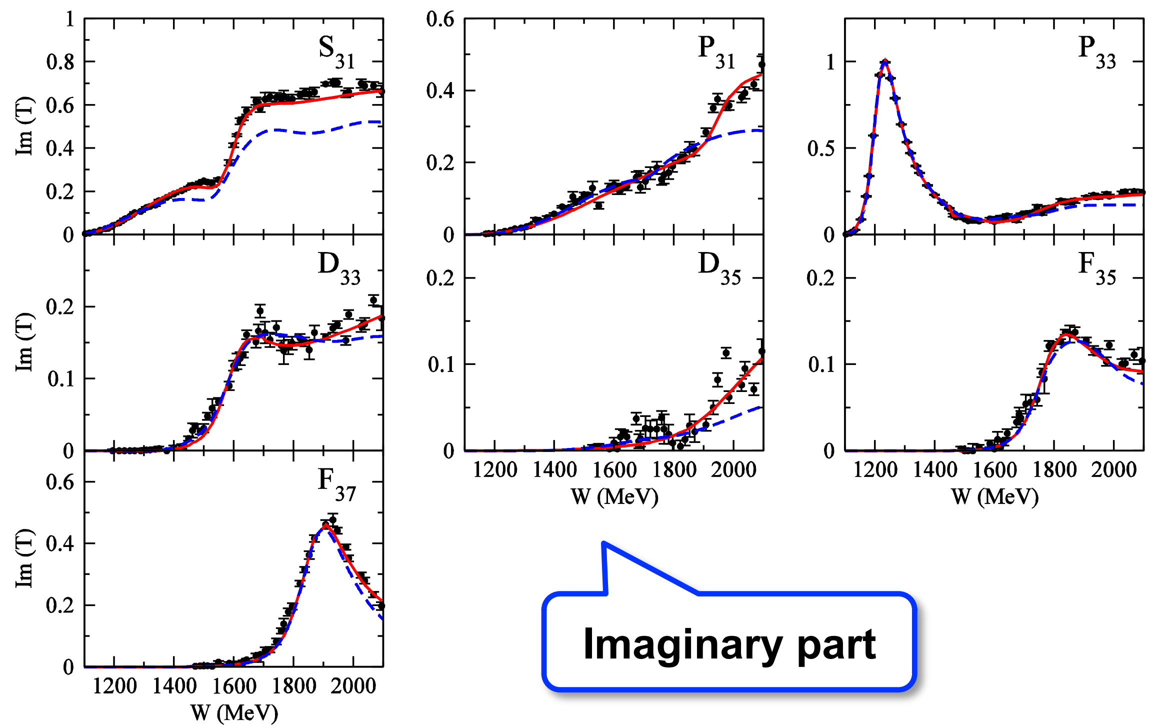
$\gamma^* N$ ➔ N^* coupling strength at different Q^2 values ($Q^2 \leq 3\ (\mathrm{GeV}/c)^2$)

Partial wave amplitudes of π N scattering



Real part

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



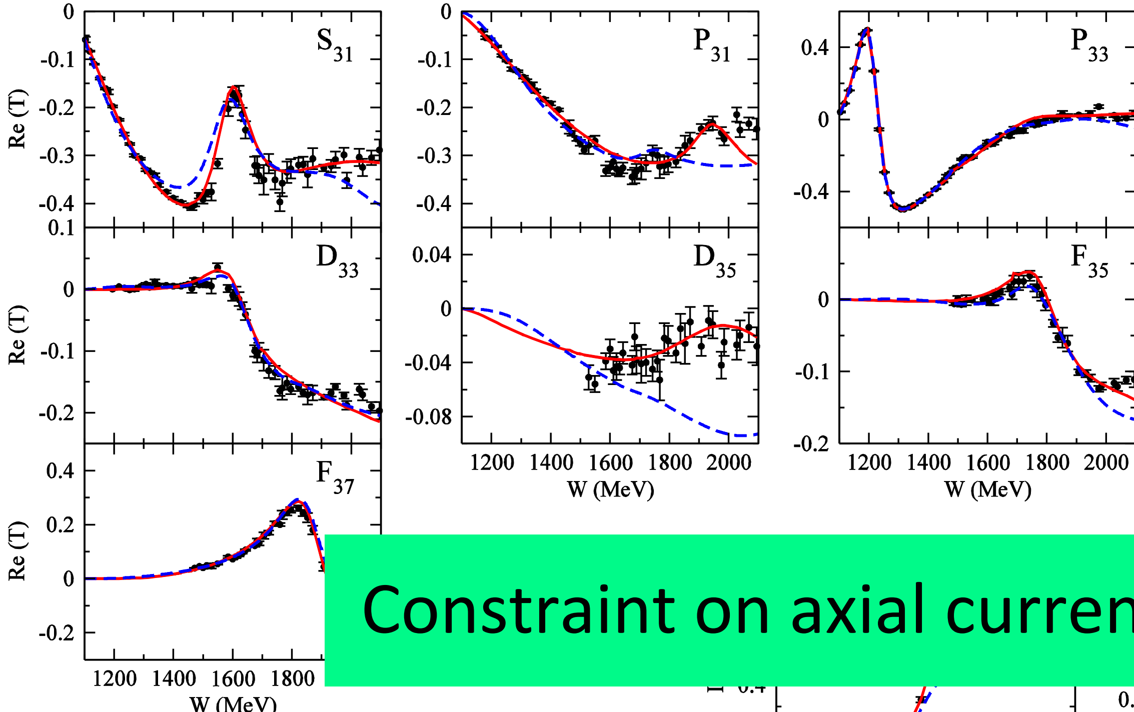
Imaginary part

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

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

Data: SAID πN amplitude

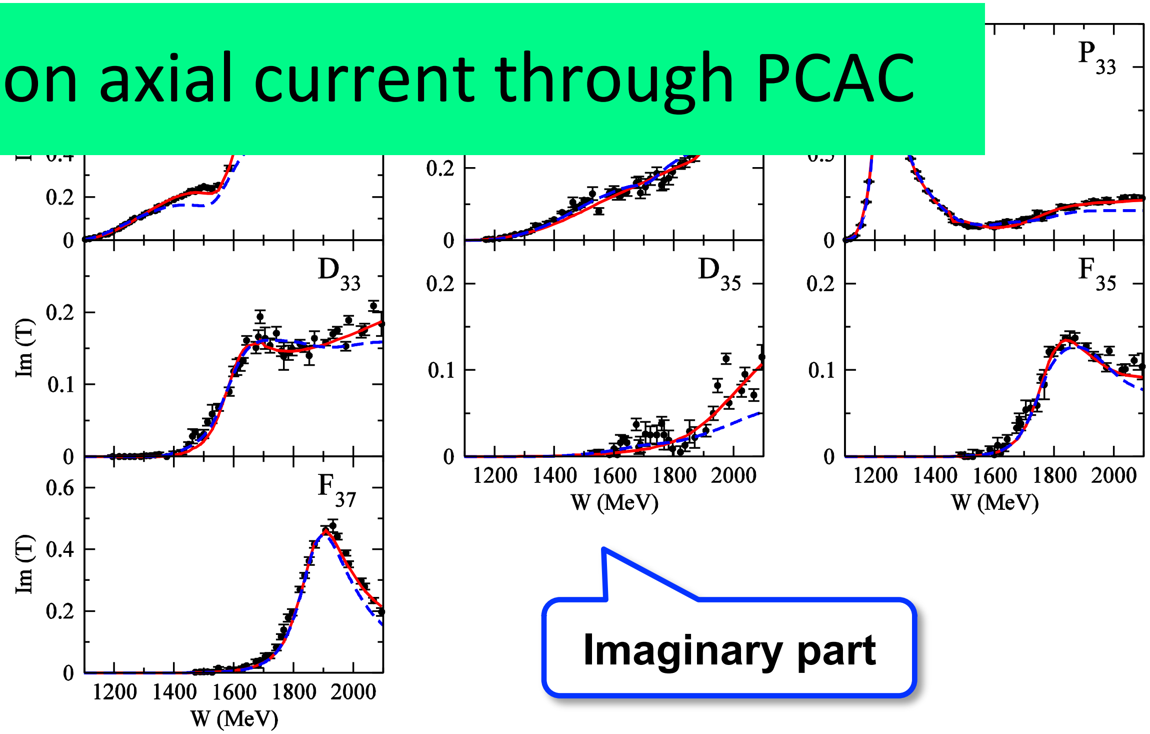
Partial wave amplitudes of π N scattering



Real part

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

Constraint on axial current through PCAC



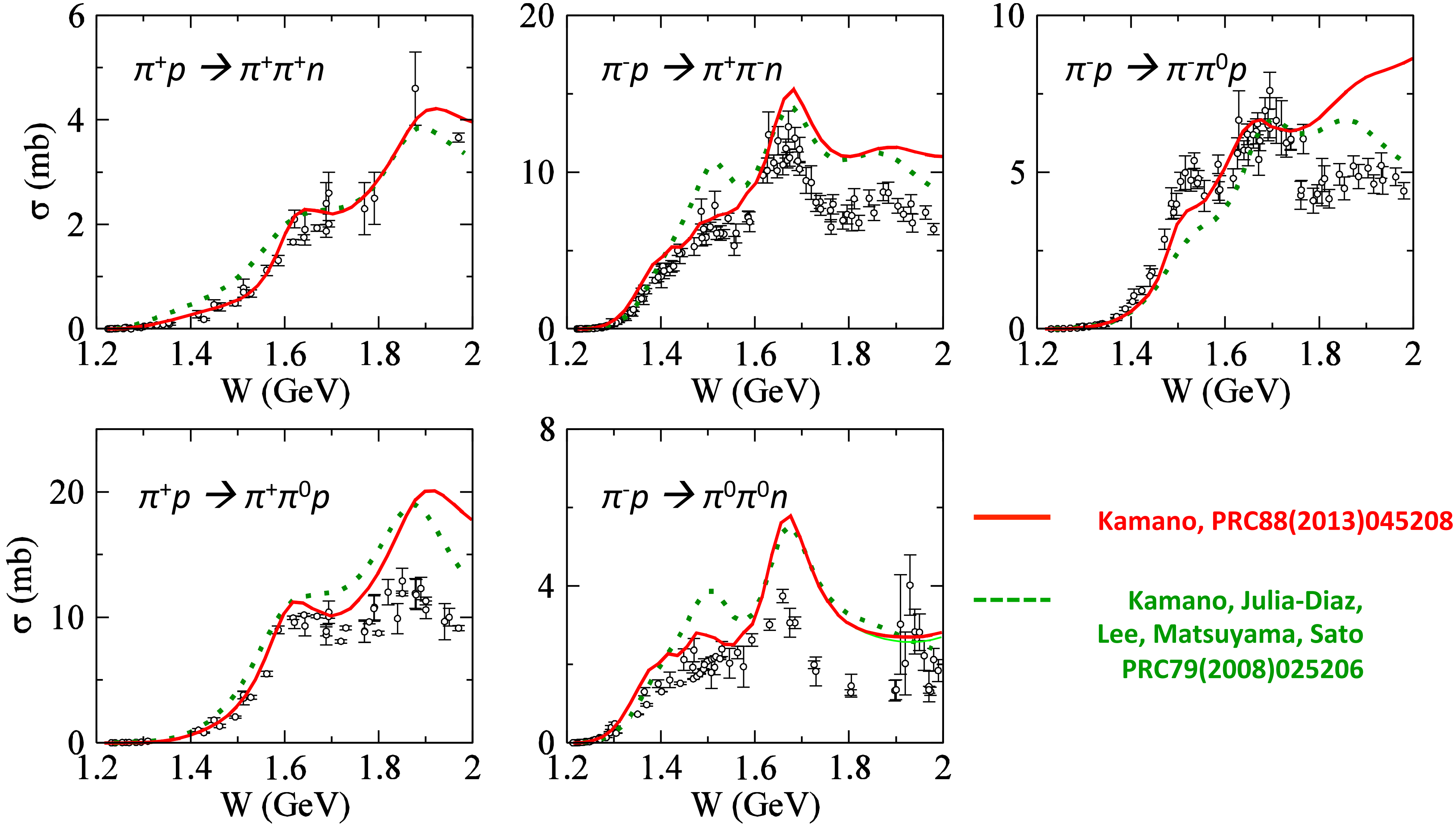
Imaginary part

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

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

Data: SAID πN amplitude

Predicted πN → ππN total cross sections with our DCC model



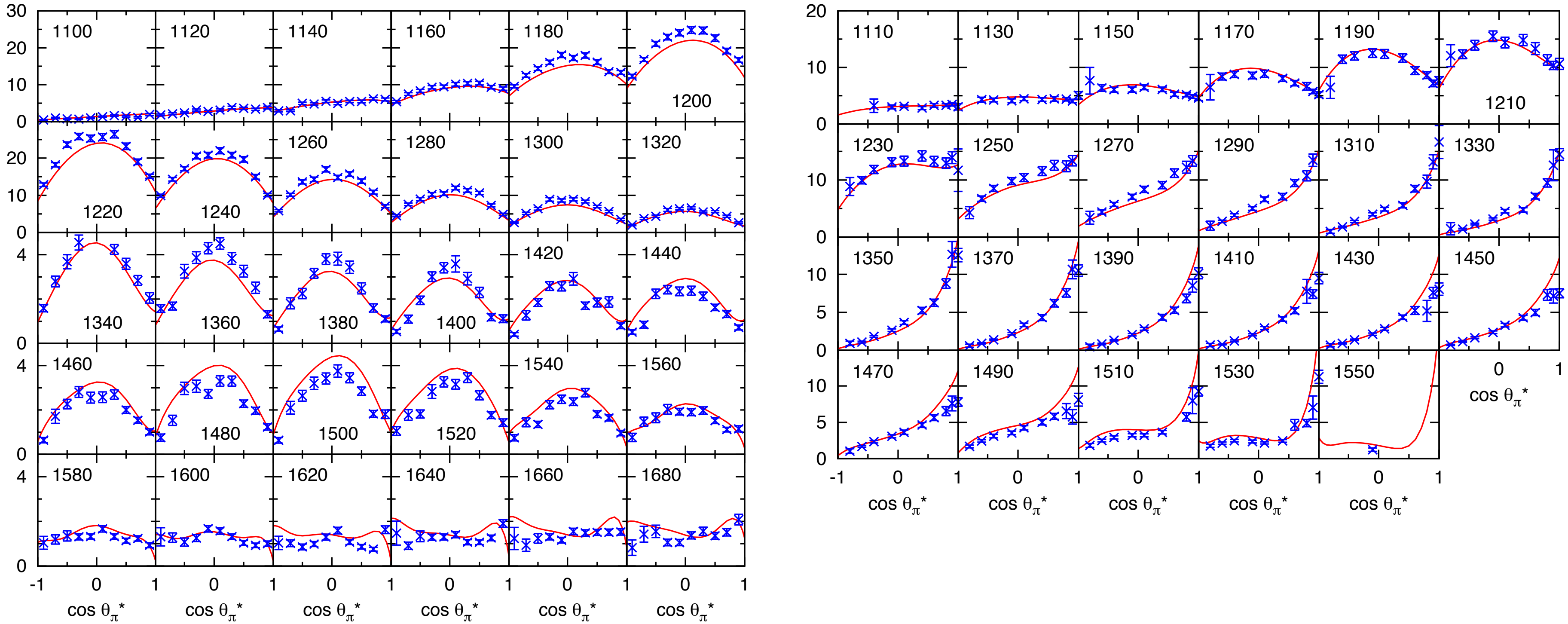
Single π production in electron-proton scattering

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

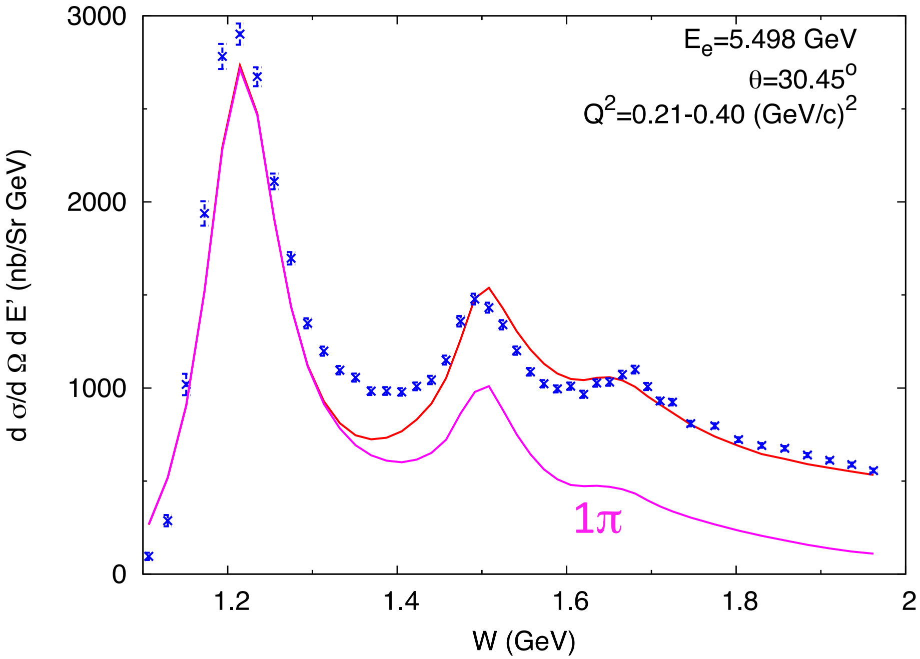
$\sigma_T + \varepsilon\, \sigma_L$ for Q^2=0.40 (GeV/c)^2 and W=1.1 – 1.68 GeV

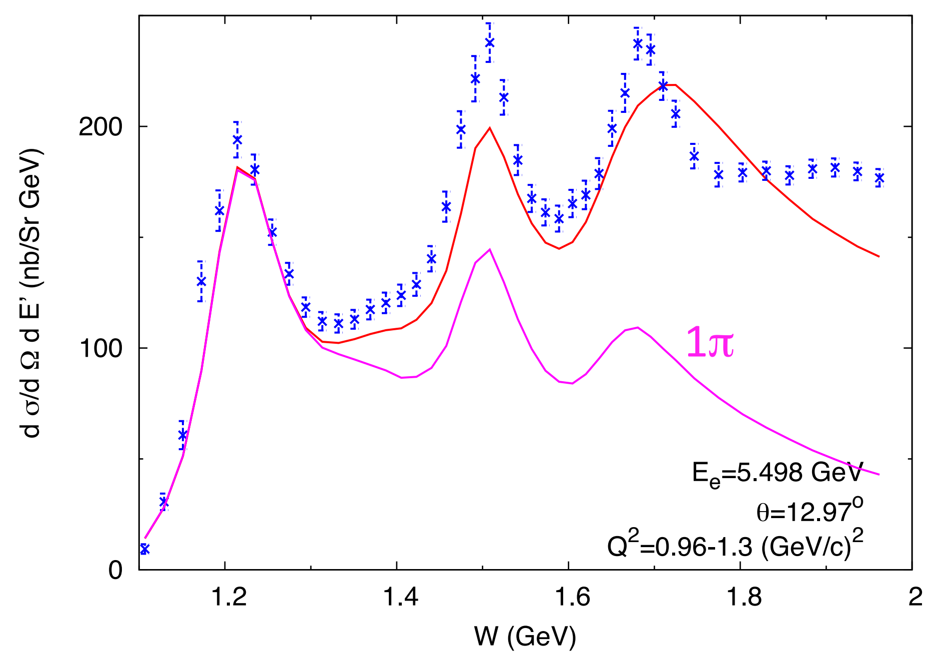
$p(e,e'\pi^0)p$

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



Inclusive electron-proton scattering





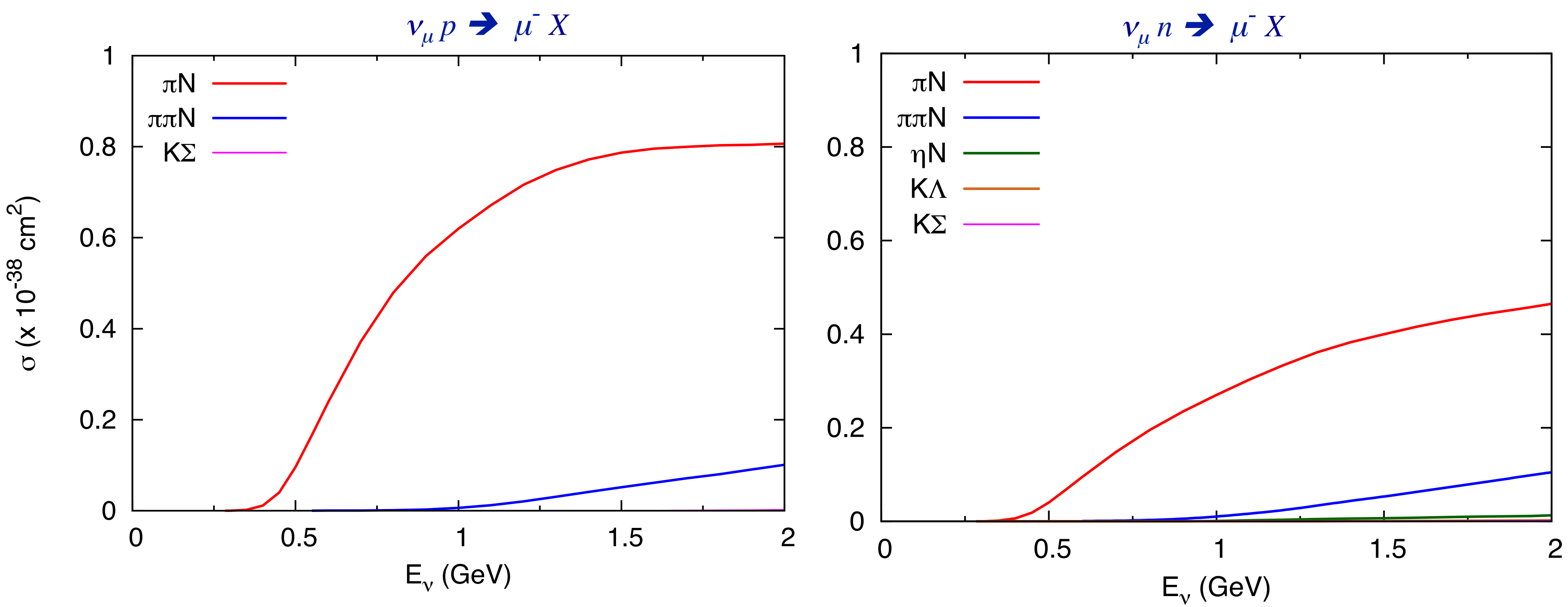
Data: JLab E00-002 (preliminary)

- 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

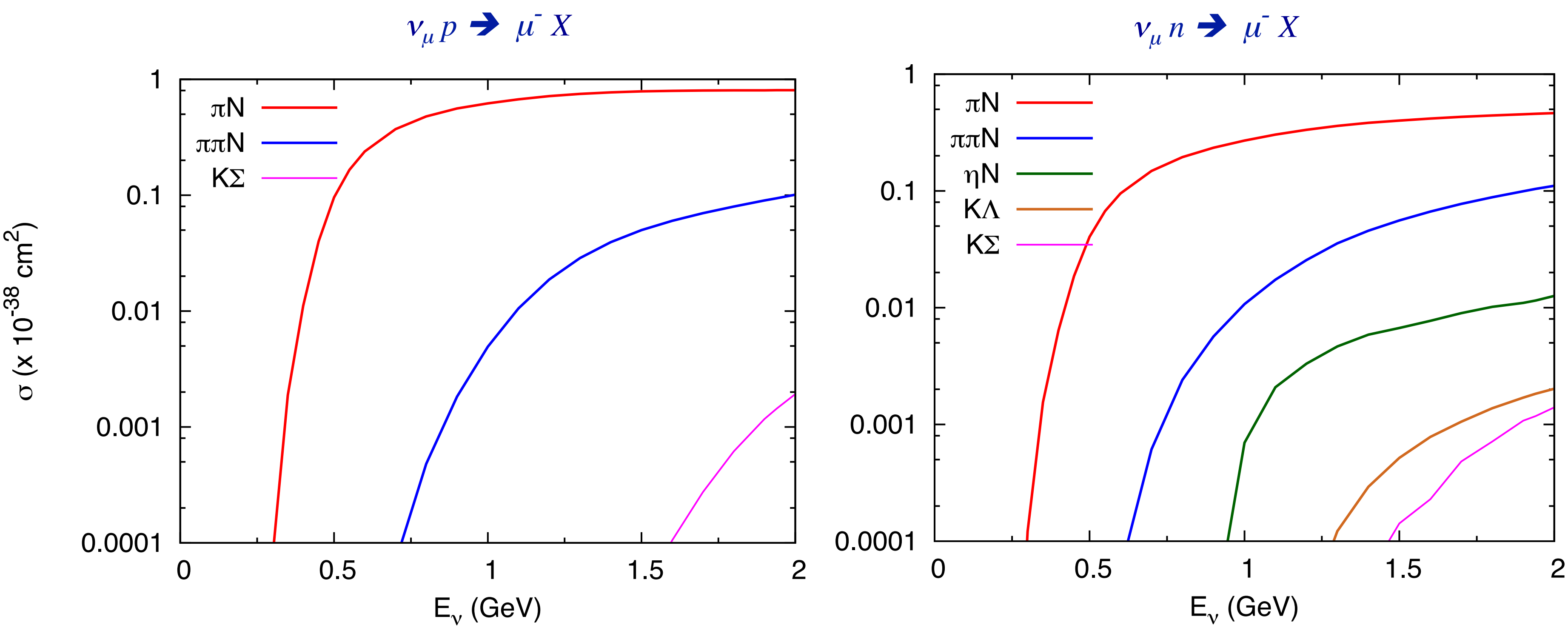
DCC vector currents has been tested by data for whole kinematical region relevant to neutrino interactions of $E_\nu \leq 2$ GeV

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 $\nu_\mu N \rightarrow \mu^- X$



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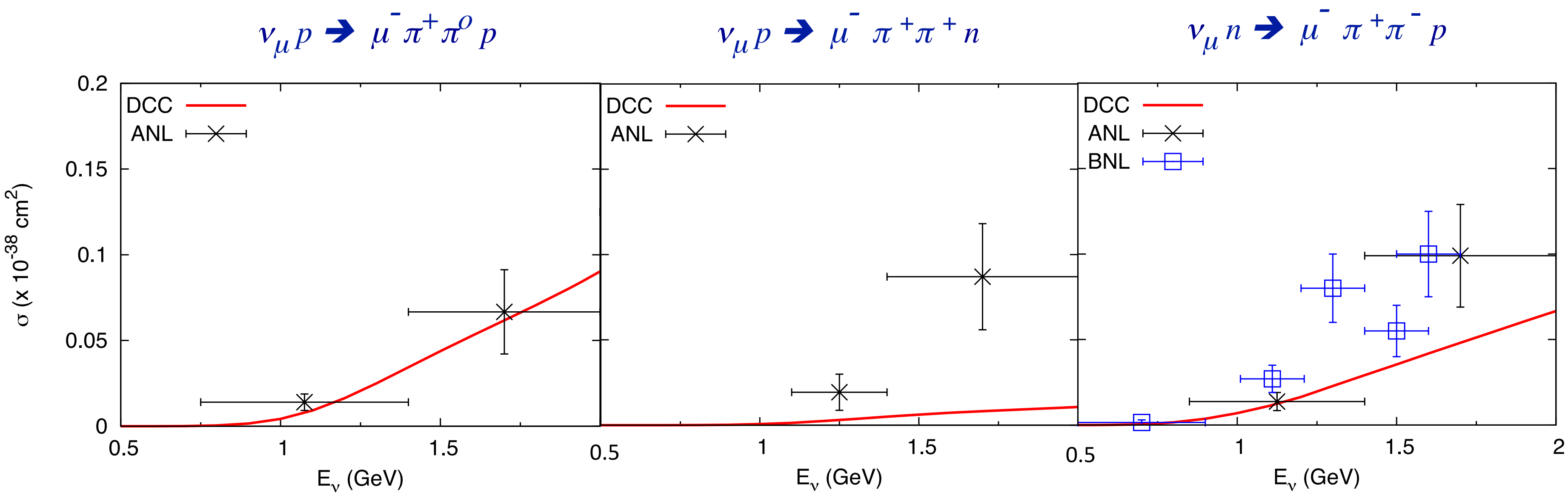
Comparison with double pion data

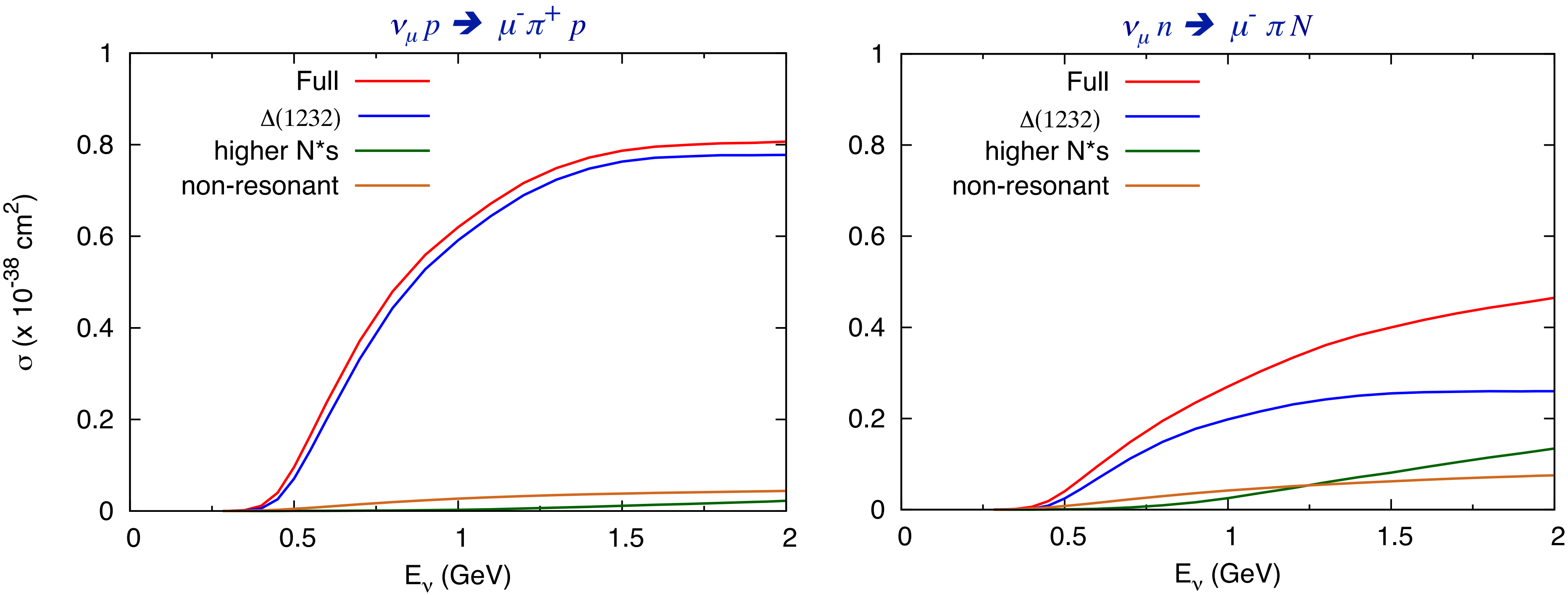


Fairly good DCC predication

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

First dynamical model for 2 π production in resonance region

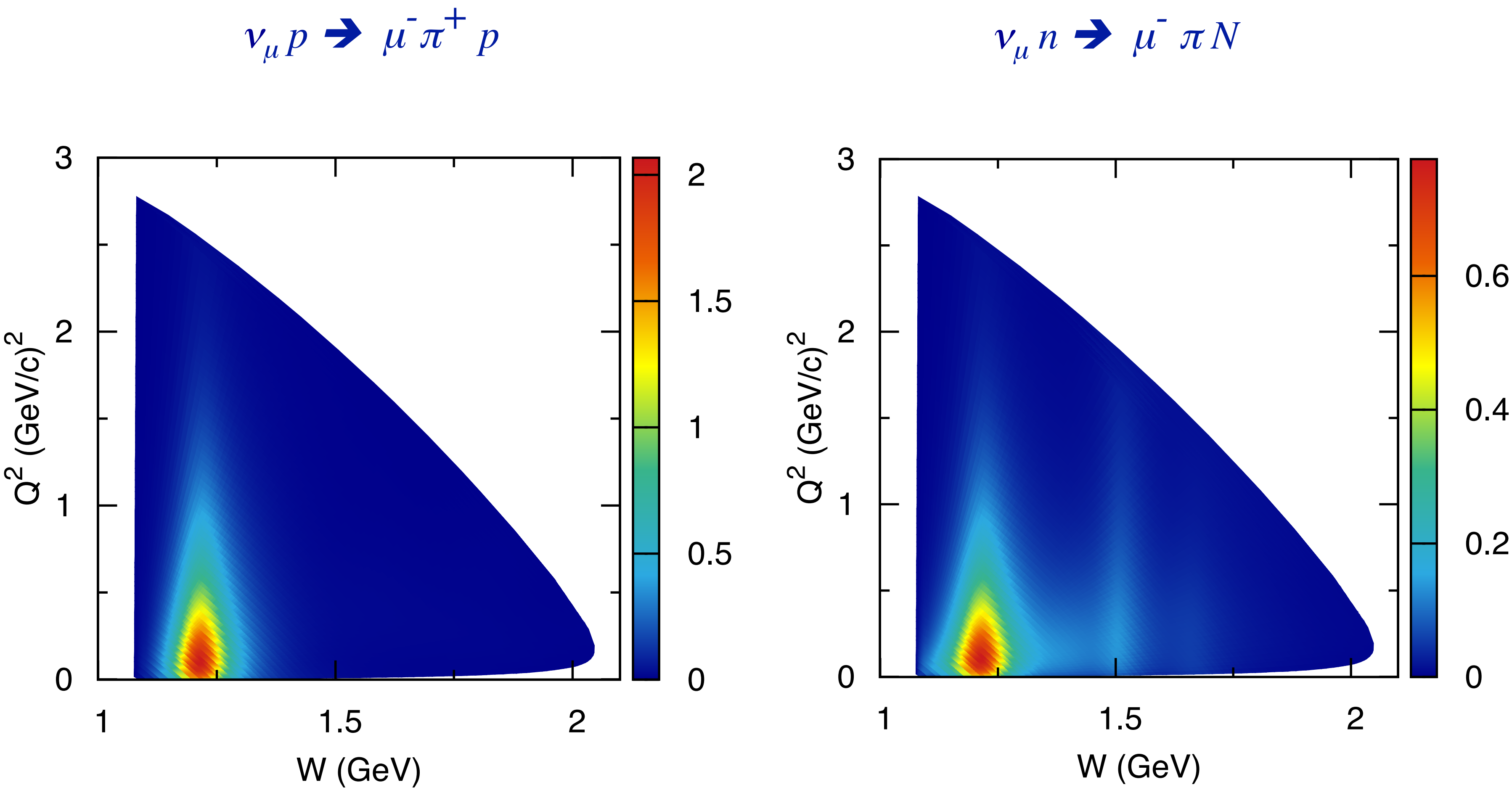
Mechanisms for $\nu_\mu N \rightarrow \mu^- \pi N$



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

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

E_ν = 2 GeV



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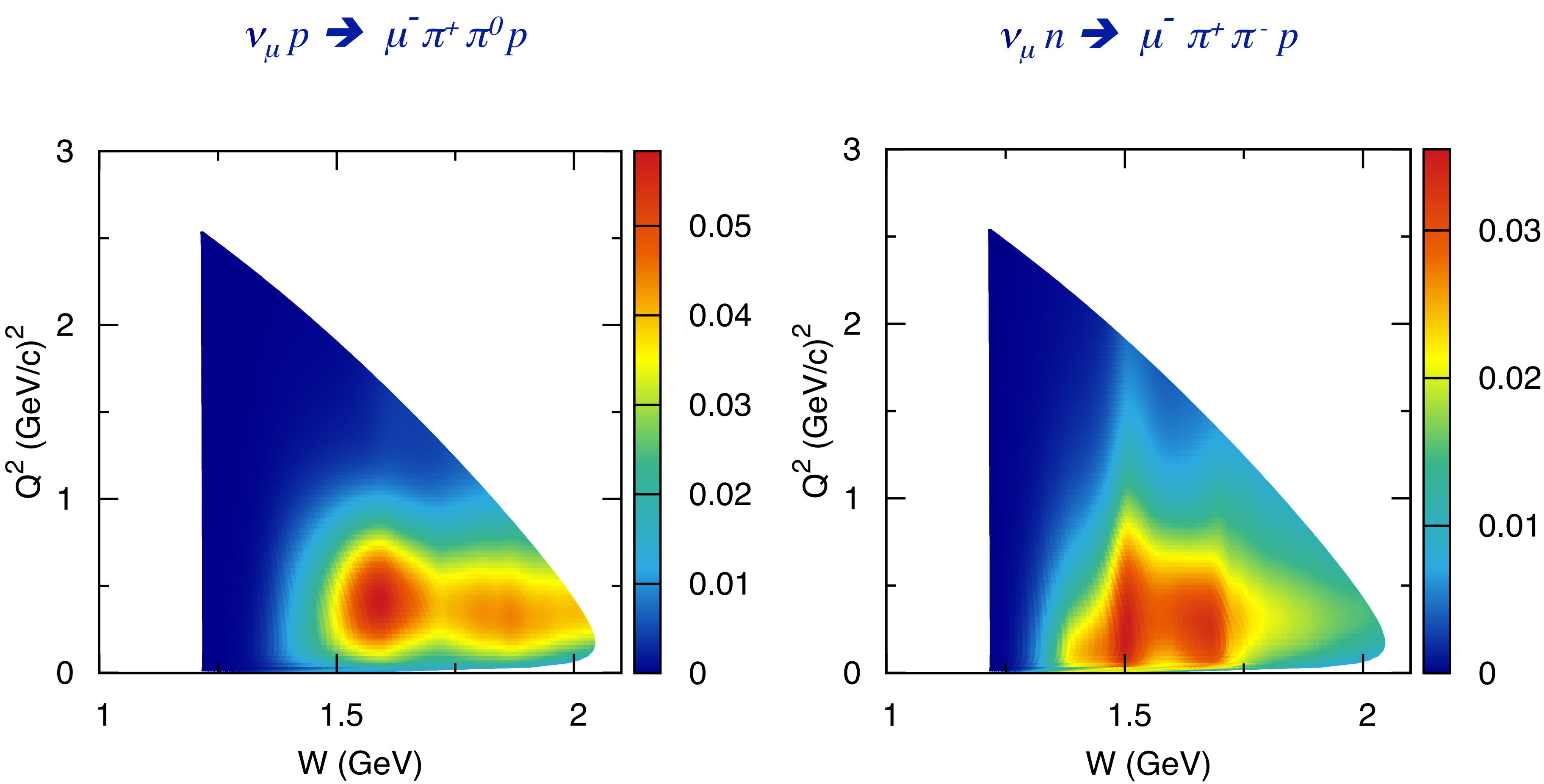
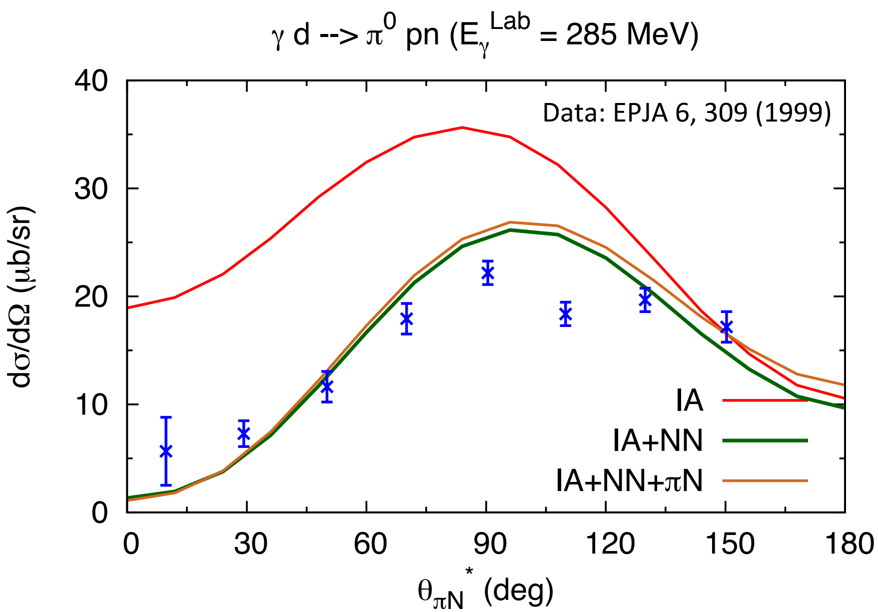
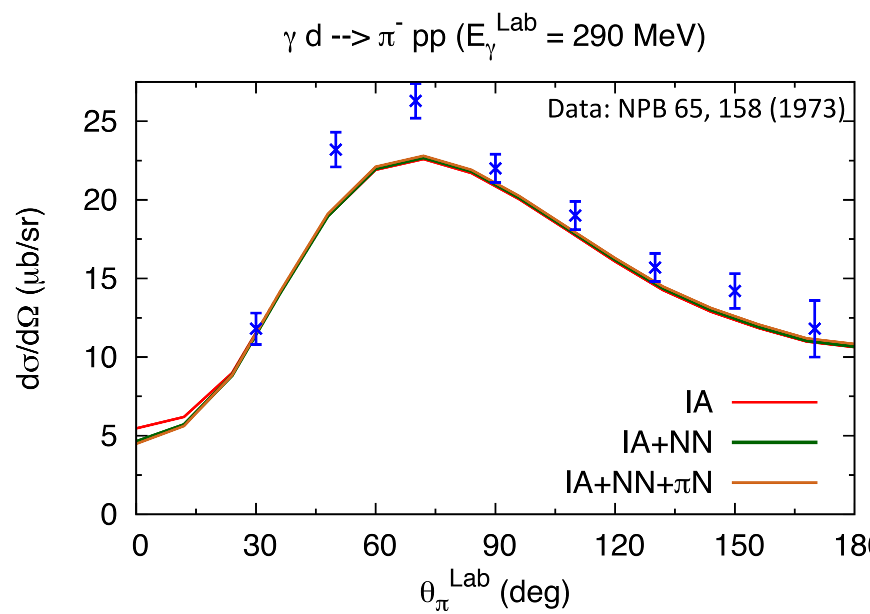


$\gamma d \rightarrow \pi N N$

Purpose : test the soundness of the model

Wu, Sato, and Lee , PRC 91, 035203 (2015)



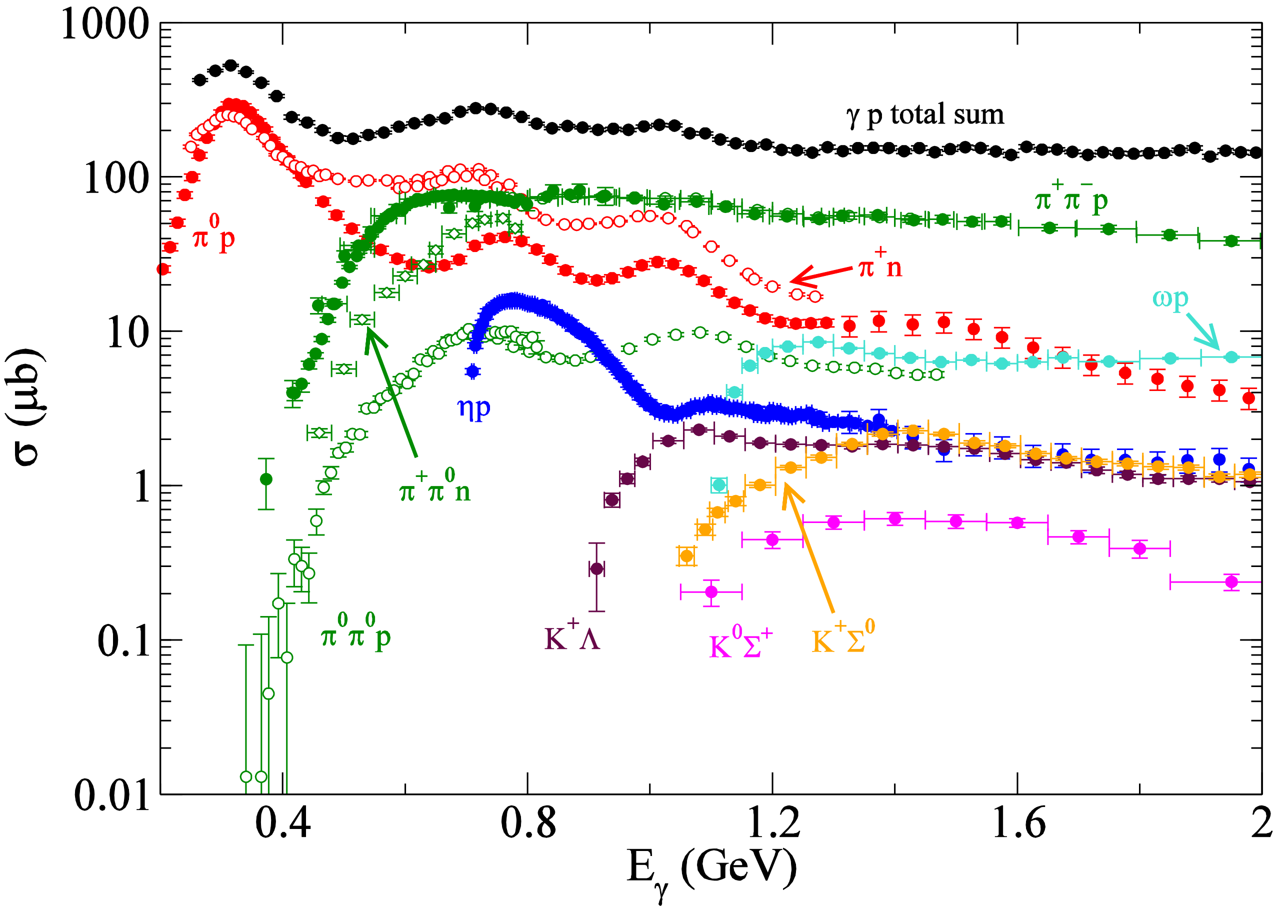


- Model prediction is reasonably consistent with data
- Large NN (small πN) rescattering effect for π^0 production

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

Resonance region (single nucleon)

$\gamma N \rightarrow X$



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

DCC (Dynamical Coupled-Channel) model

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

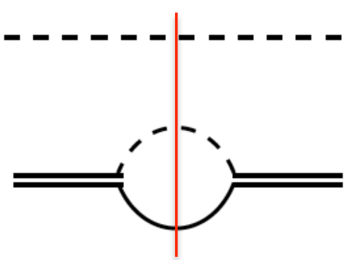
Kamano et al., PRC 88, 035209 (2013)

Coupled-channel Lippmann-Schwinger equation

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

$G\,c$ =

for stable channels



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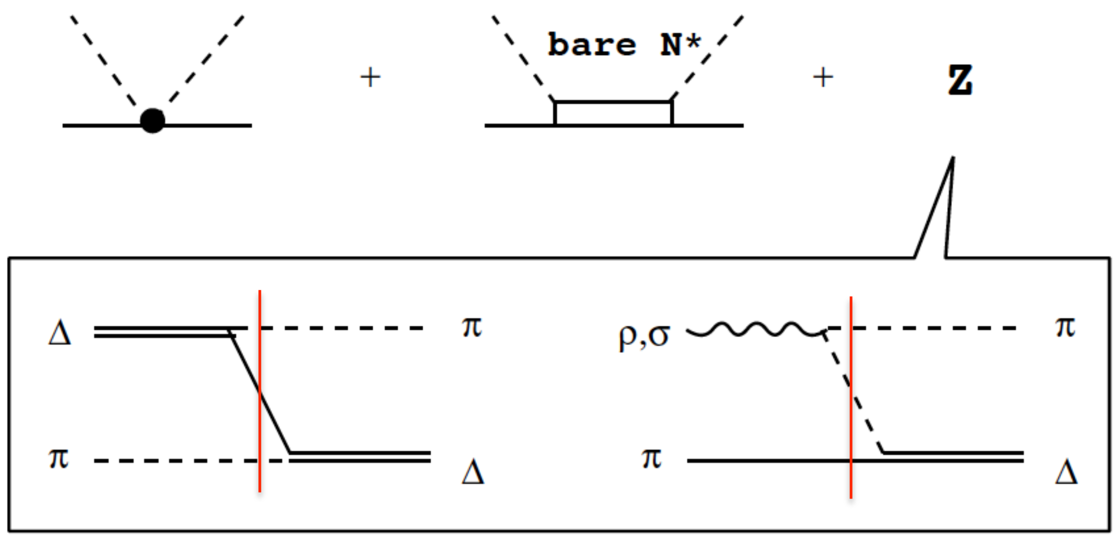
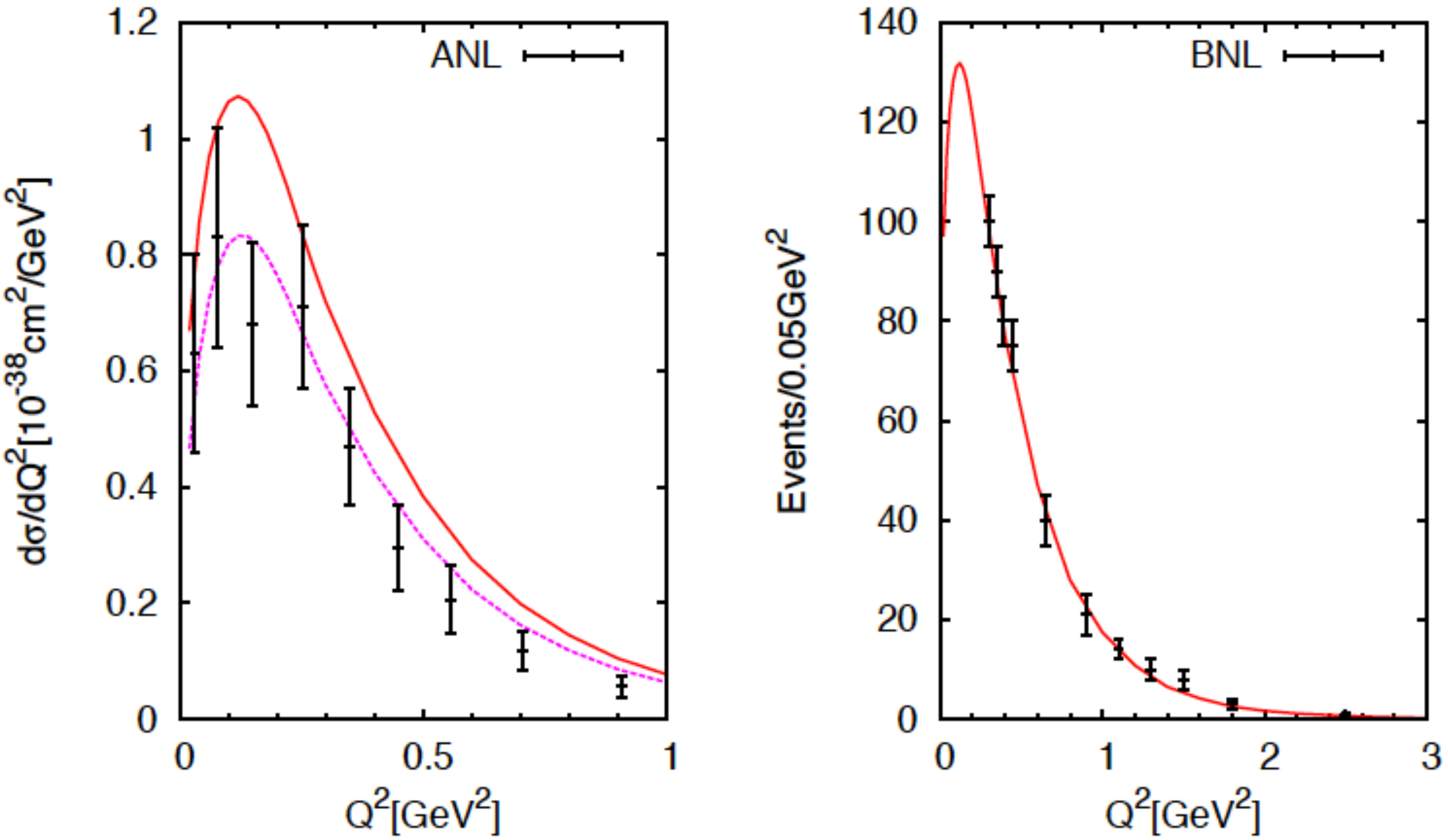


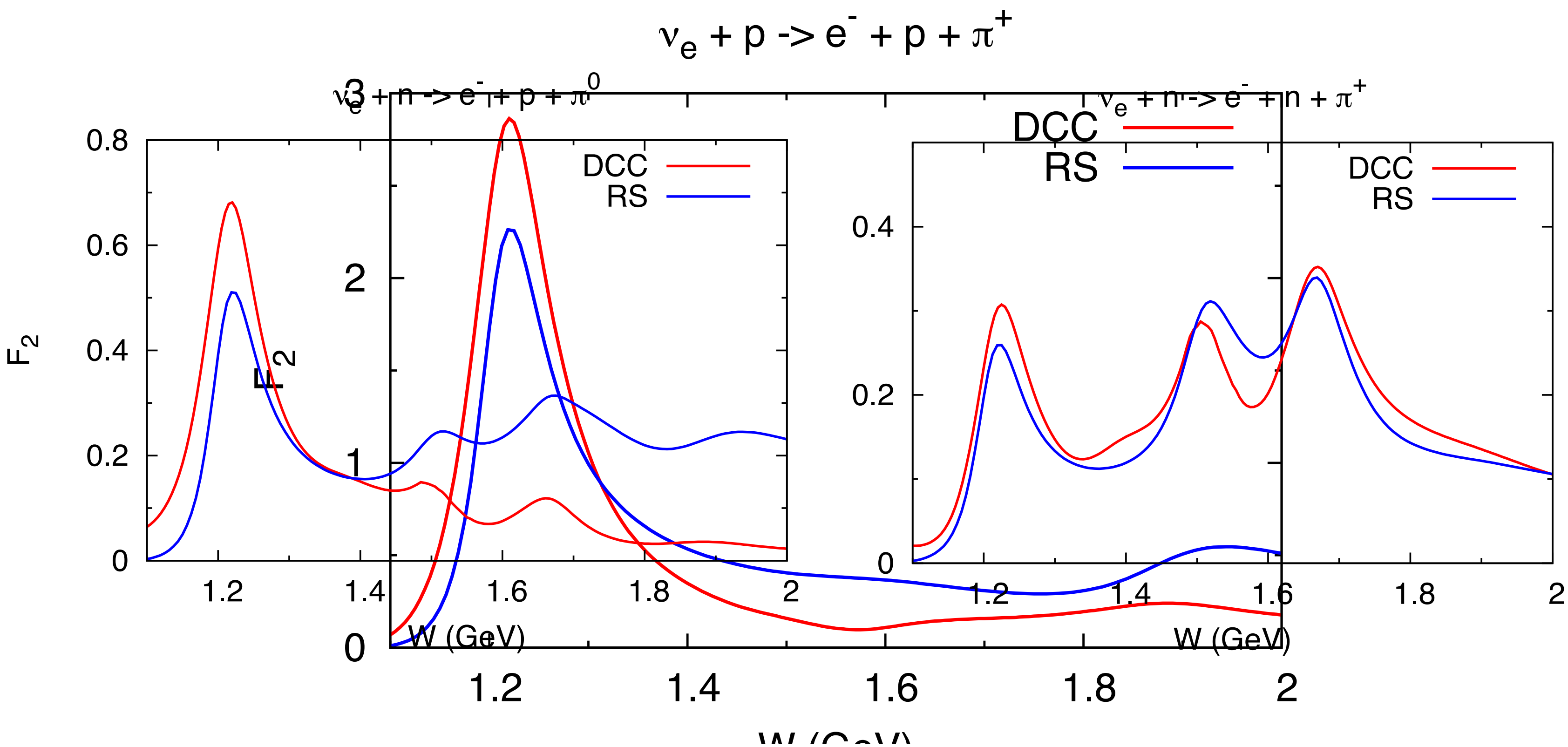
essential for three-body unitarity

Q^2 – dependence

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



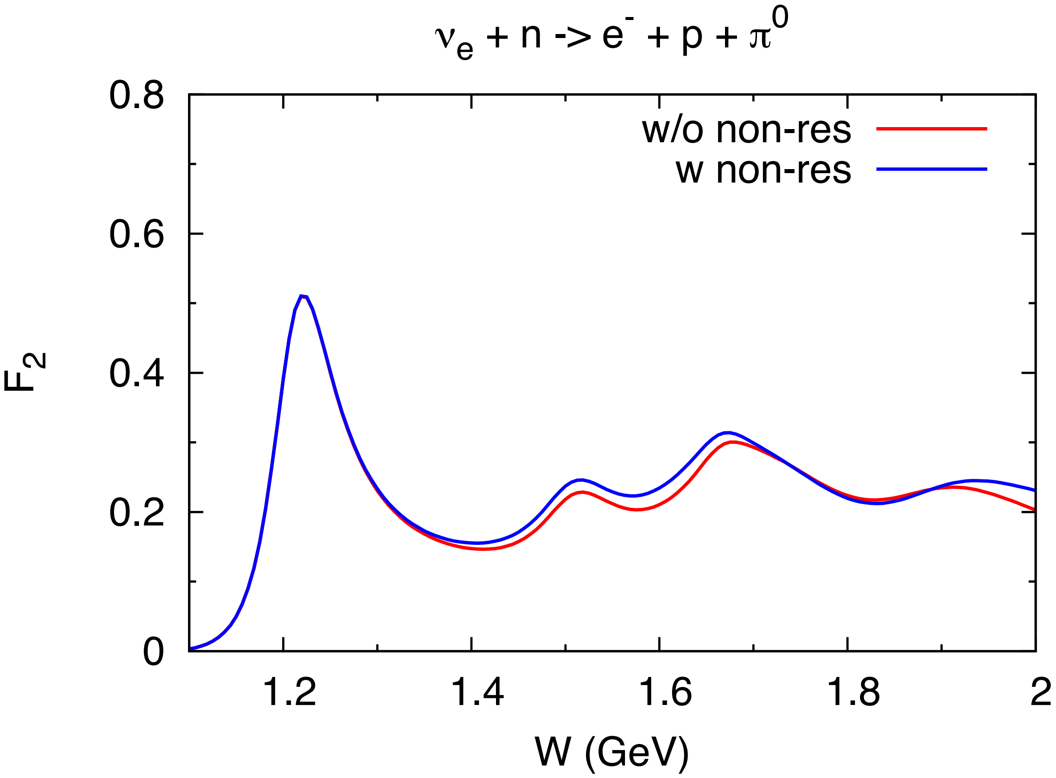
Comparison with Rein-Sehgal model

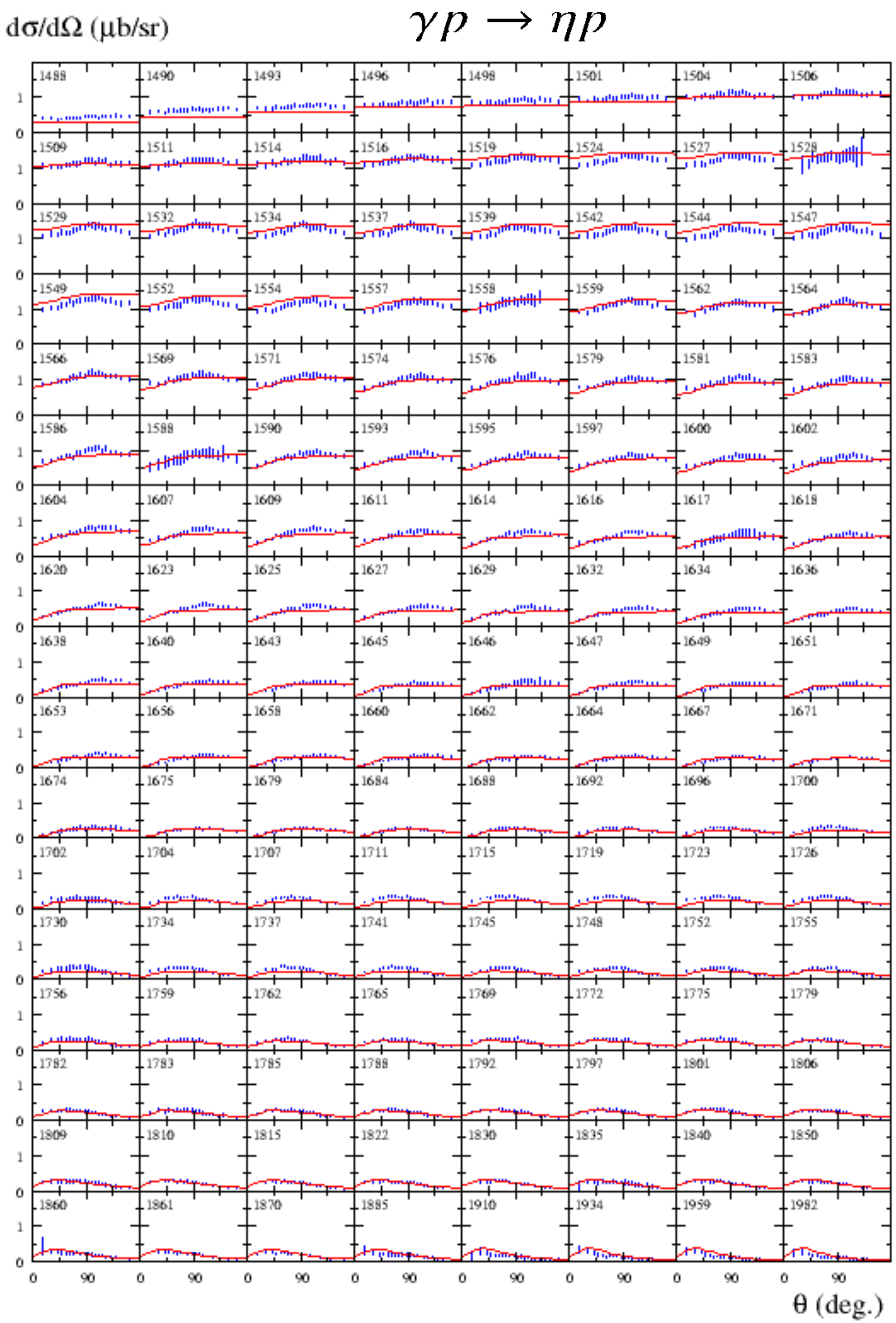


Comparison in whole kinematical region will be done

after axial current model is developed

F_2 from RS model



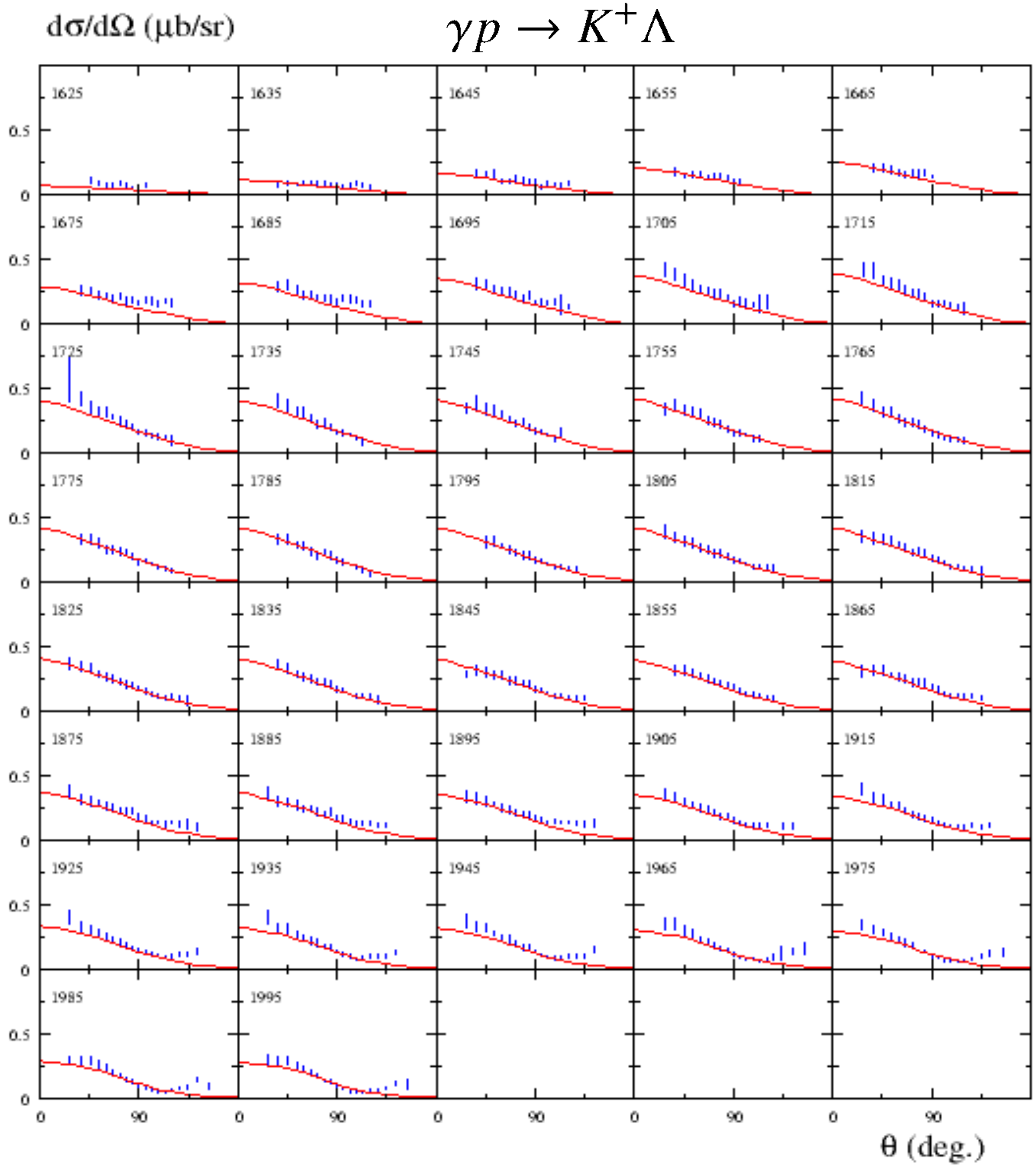


Kamano, Nakamura, Lee, Sato, arXiv:1305.4351

Vector current (Q^2=0) for η

Production is well-tested by data

Kamano, Nakamura, Lee, Sato, arXiv:1305.4351



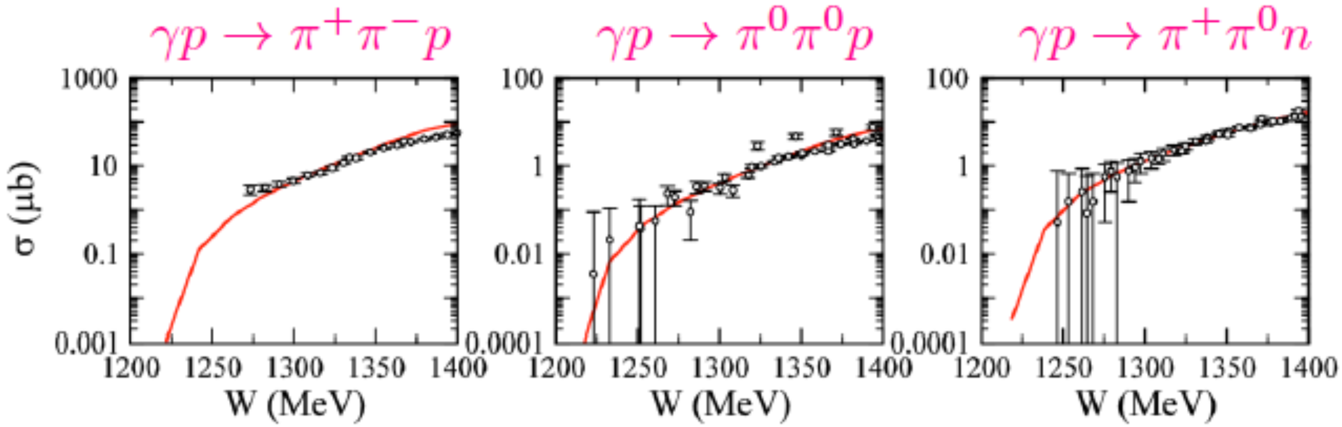
Vector current (Q^2=0) for K

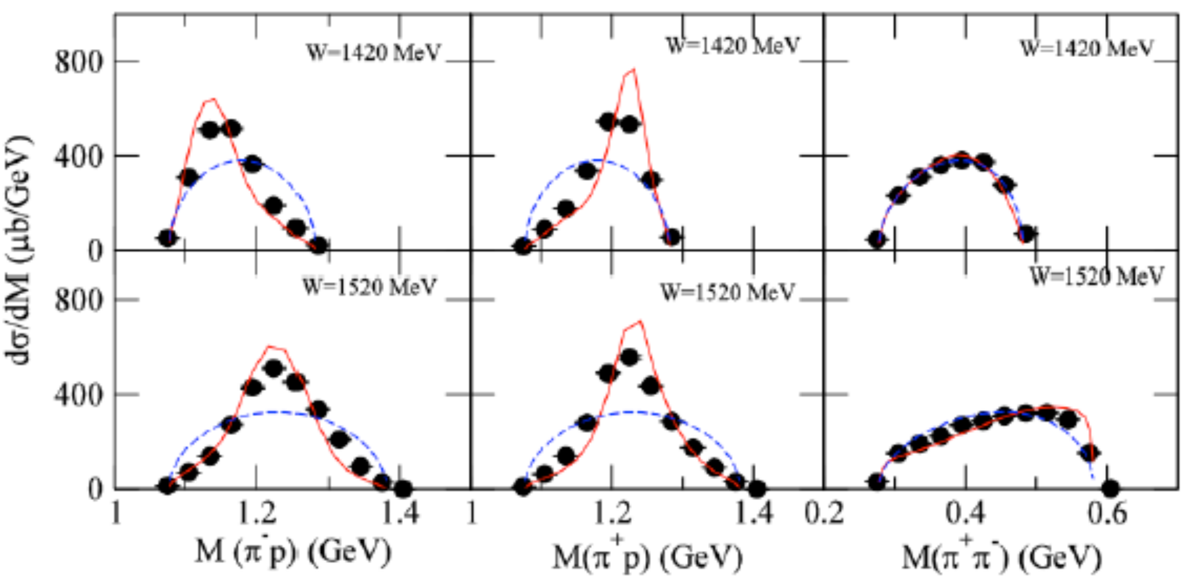
Production is well-tested by data

$\gamma N \to \pi\pi N$

(parameters had been fitted to $\pi N, \gamma N \to \pi N$)

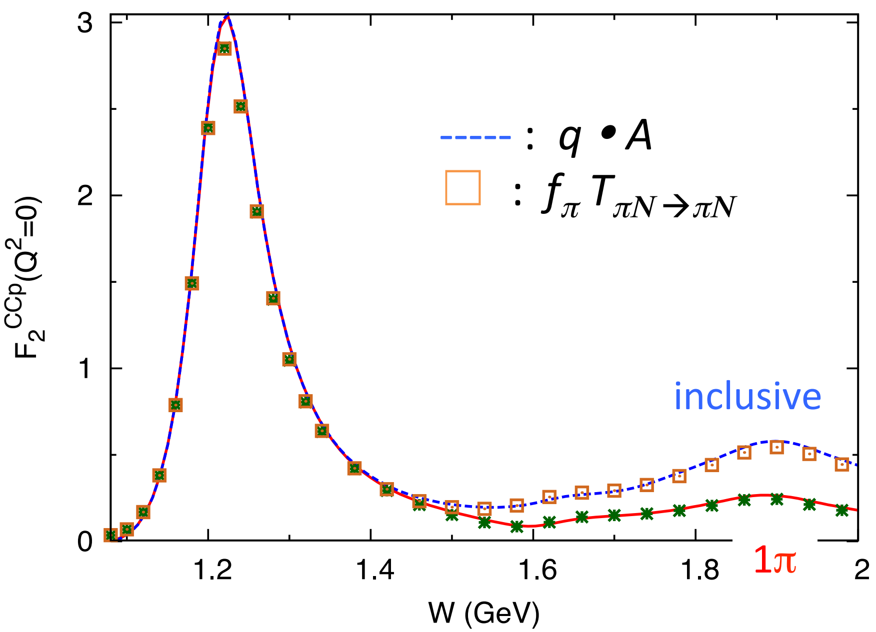
Kamano, Julia-Diaz, Lee, Matsuyama, Sato, PRC80 065203 (2009)

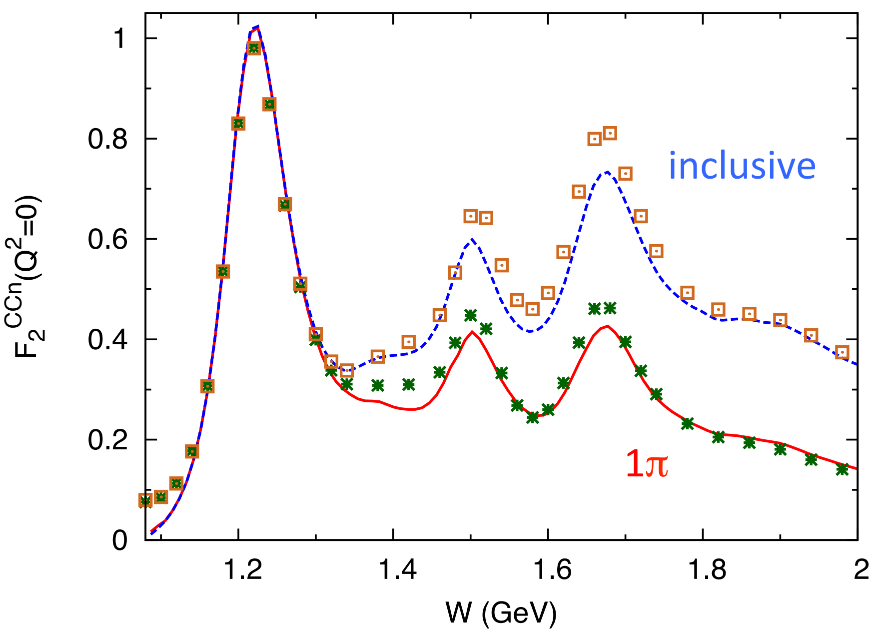




- ∗ Good description near threshold
- ∗ Good shape of invariant mass distribution
- ∗ Total cross sections overestimate data for $W \geq 1.5$ GeV

$F_2(Q^2=0)$ from DCC model and PCAC



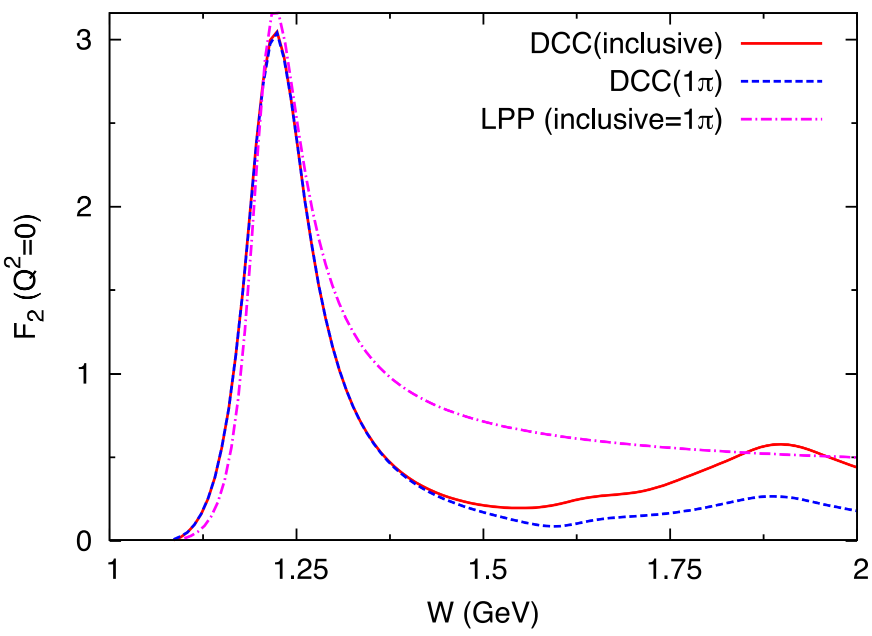


DCC model keeps good consistency with PCAC

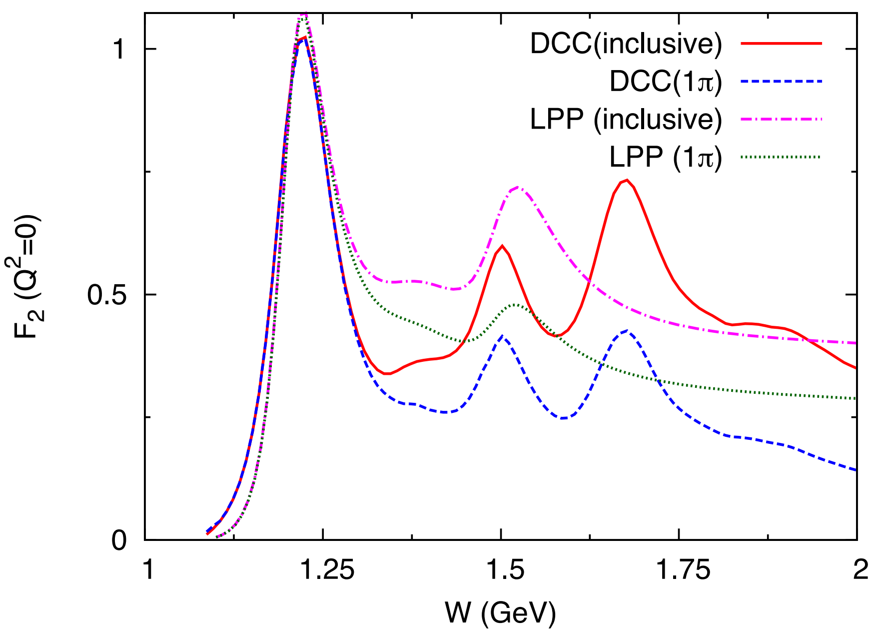
Comparison with LPP model

LPP model : Lalakulich et al, PRD 74 (2006)

CCνp

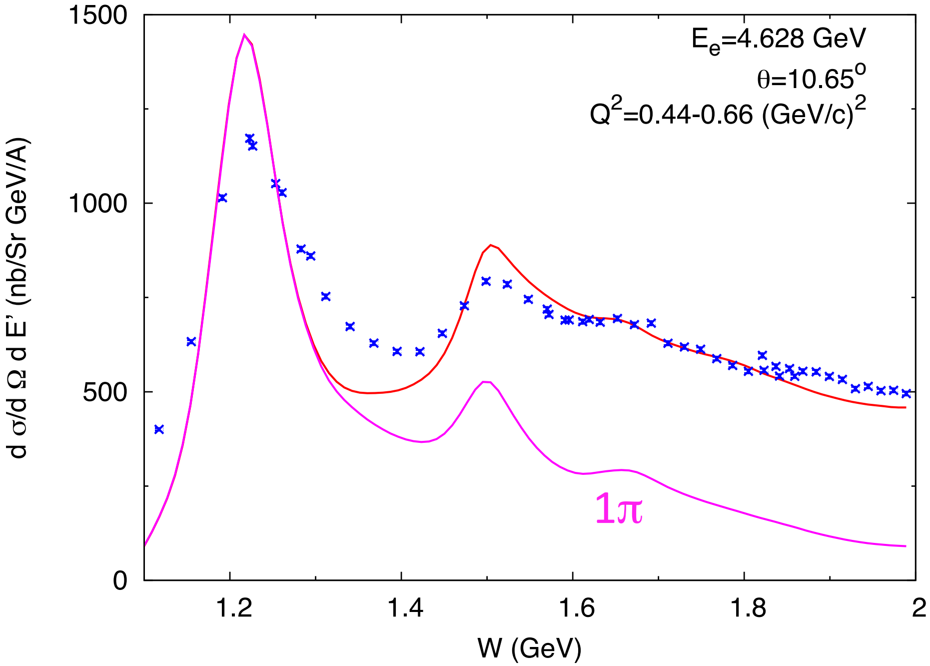


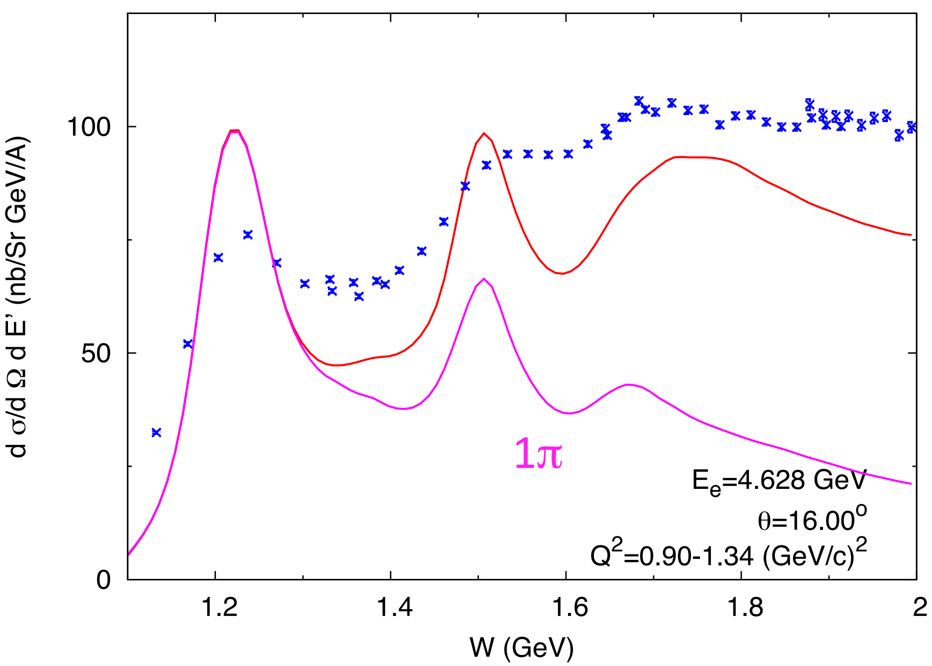
CCνn



- Large difference beyond $\Delta(1232)$ region
- Importance of consistency between axial-current and πN interaction

Analysis result (inclusive e^--d)





Data: NP Proc. Suppl. 159, 163 (2006)

- Our calculation : $[\ \sigma(e^-\text{-}p) + \sigma(e^-\text{-}n)\ ] / 2$
- Too sharp resonant peaks → fermi motion smearing, other nuclear effects needed
- Reasonable starting point for application to neutrino interactions