Recent Developments in Neutrino-Nucleus Scattering (THEORY)

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Introduction

Neutrino-nucleus scattering for ν-oscillation experiments

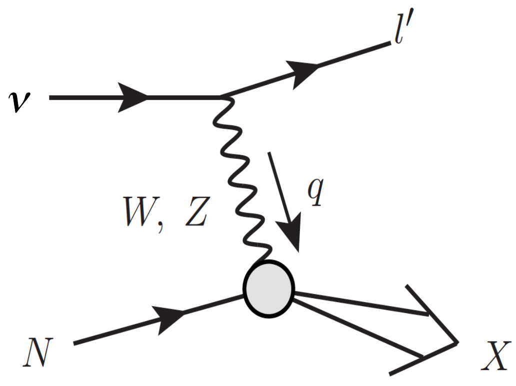
In *all* ν-oscillation experiments, neutrinos are detected through neutrino-nucleus scattering

neutrino detectors (^{16}O, ^{12}C, ^{40}Ar, …)

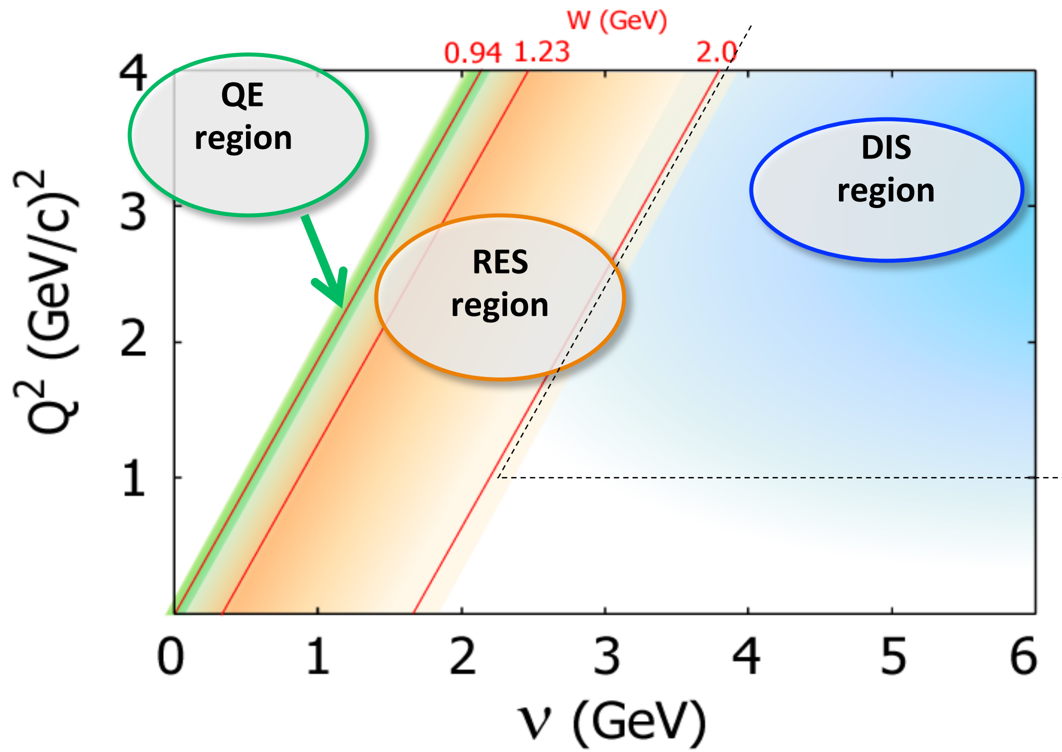
Next-generation exp. ➔ leptonic $\not{CP}$, mass hierarchy

ν–nucleus scattering needs to be understood more accurately (~ 5%)

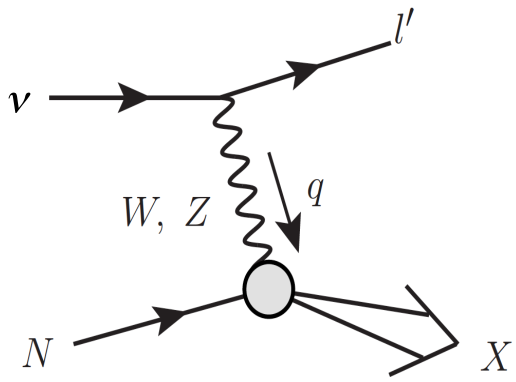
Neutrino-nucleus scattering for ν-oscillation experiments



$$Q^2 = -q^2$$
$$\nu = q^0$$



Neutrino-nucleus scattering for ν-oscillation experiments



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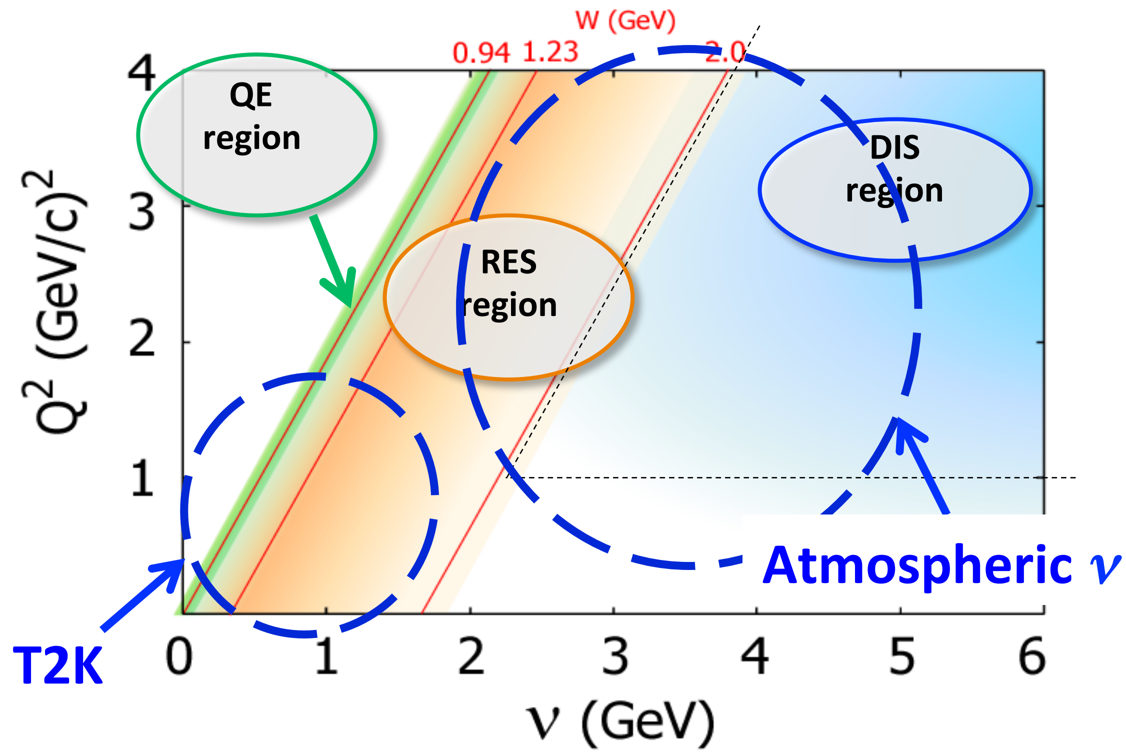
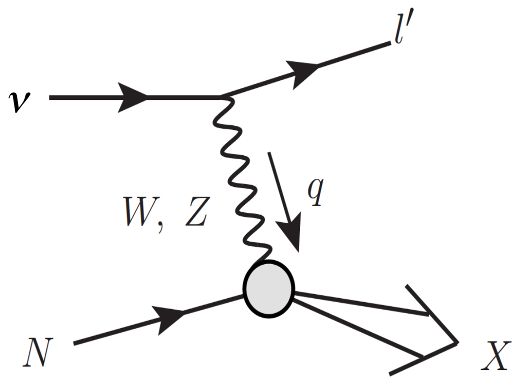


Neutrino-nucleus scattering for ν-oscillation experiments



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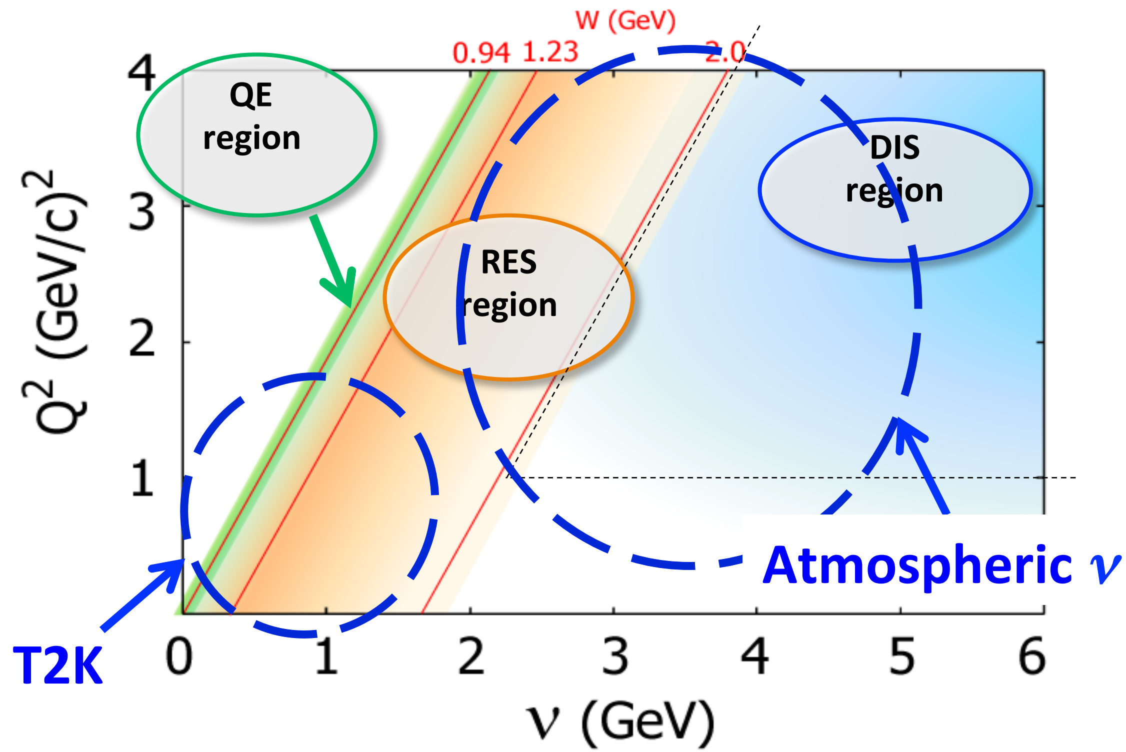
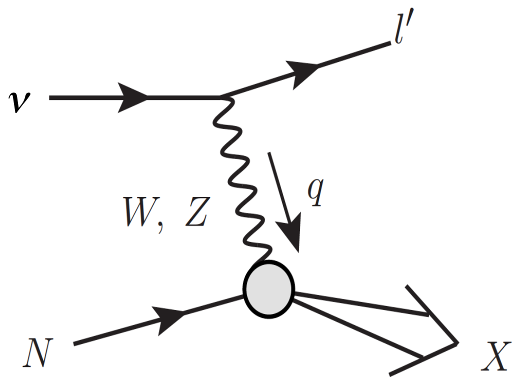


Wide kinematical region with different characteristic

➔ Combination of different expertise is necessary

Neutrino-nucleus scattering for ν-oscillation experiments



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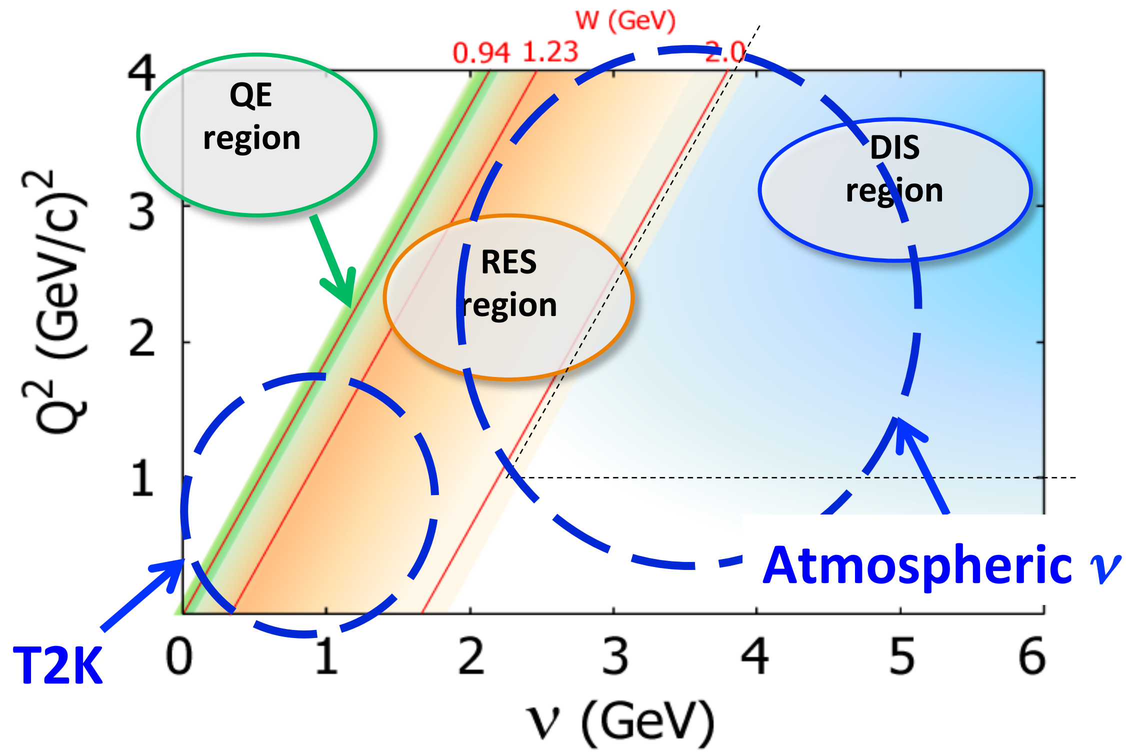


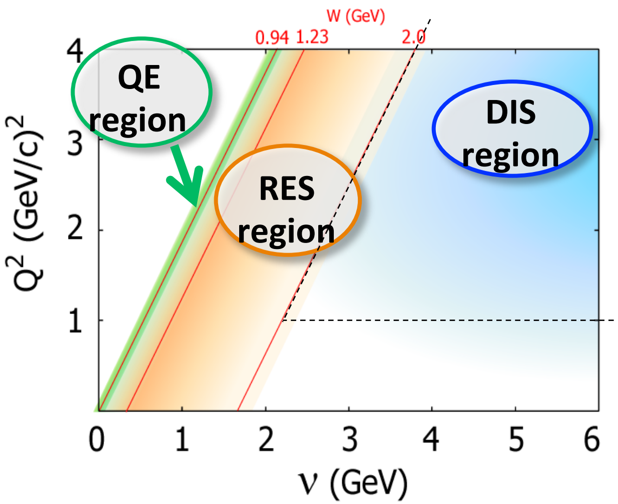
Wide kinematical region with different characteristic

→ Combination of different expertise is necessary

This talk : Very recent and selected developments in neutrino-nucleus scattering in QE and RES regions are reviewed (Sorry, many other recent works !)

QE (quasi-elastic)

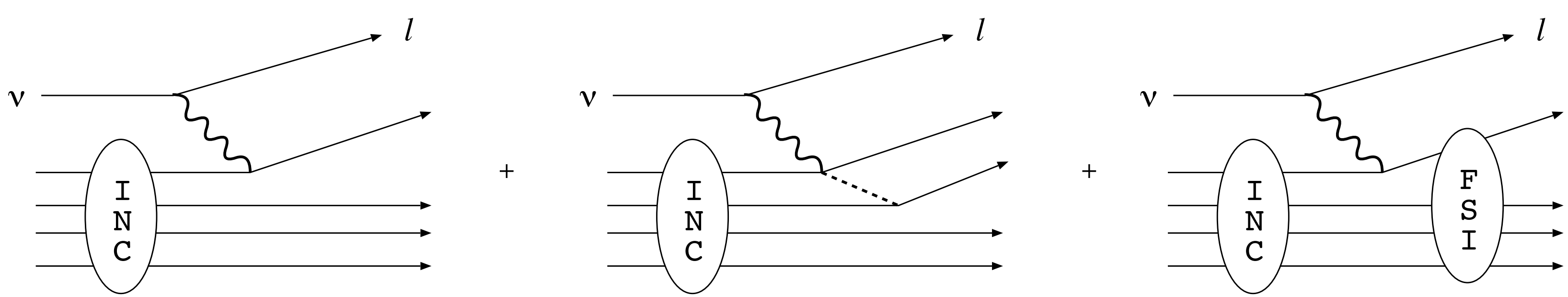
Neutrino-nucleus scattering in QE region



- Crucially relevant to T2K ($E_\nu \sim 1$ GeV)
- E_ν is reconstructed with lepton kinematics assuming QE kinematics and initial nucleon is at rest
- Contamination of CCQE-like event is problematic

INC : initial nucleon correlations
FSI : final state interactions

Mechanisms



Genuine QE

meson exchange current, 2p-2h (QE-like)

General FSI, np-nh (QE-like)

Lots of recent works on QE-like mechanisms (Martini et al., Nieves et al., Amaro et al. …)

Very Recent Update

Ab initio approach to electron inclusive scattering on ^{12}C in QE region

Lovato et al., PRC 91, 062501(R) (2015); PRL **117**, 082501 (2016)

- The best approach in non-relativistic regime (except for computational cost)
- The work is about electron scattering

  but the same method should work as well for neutrino scattering
- The method can be tested by a large amount of electron scattering data

Ab initio approach

$$H\left|\Psi_i\right\rangle = E_i\left|\Psi_i\right\rangle$$

$$H = \sum_i \frac{\mathbf{p}_i^2}{2m} + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk} + \ldots$$

Ab initio approach

$$H|\Psi_i\rangle = E_i|\Psi_i\rangle$$

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Argonne v18 Illinois 7

Ab initio approach

$$H\left|\Psi_i\right\rangle = E_i\left|\Psi_i\right\rangle \qquad H = \sum_i \frac{\mathrm{p}_i^2}{2m} + \sum_{i<j} \underline{v_{ij}} + \sum_{i<j<k} \underline{V_{ijk}} + \ldots$$

GFMC (Green's Function Monte Carlo) method

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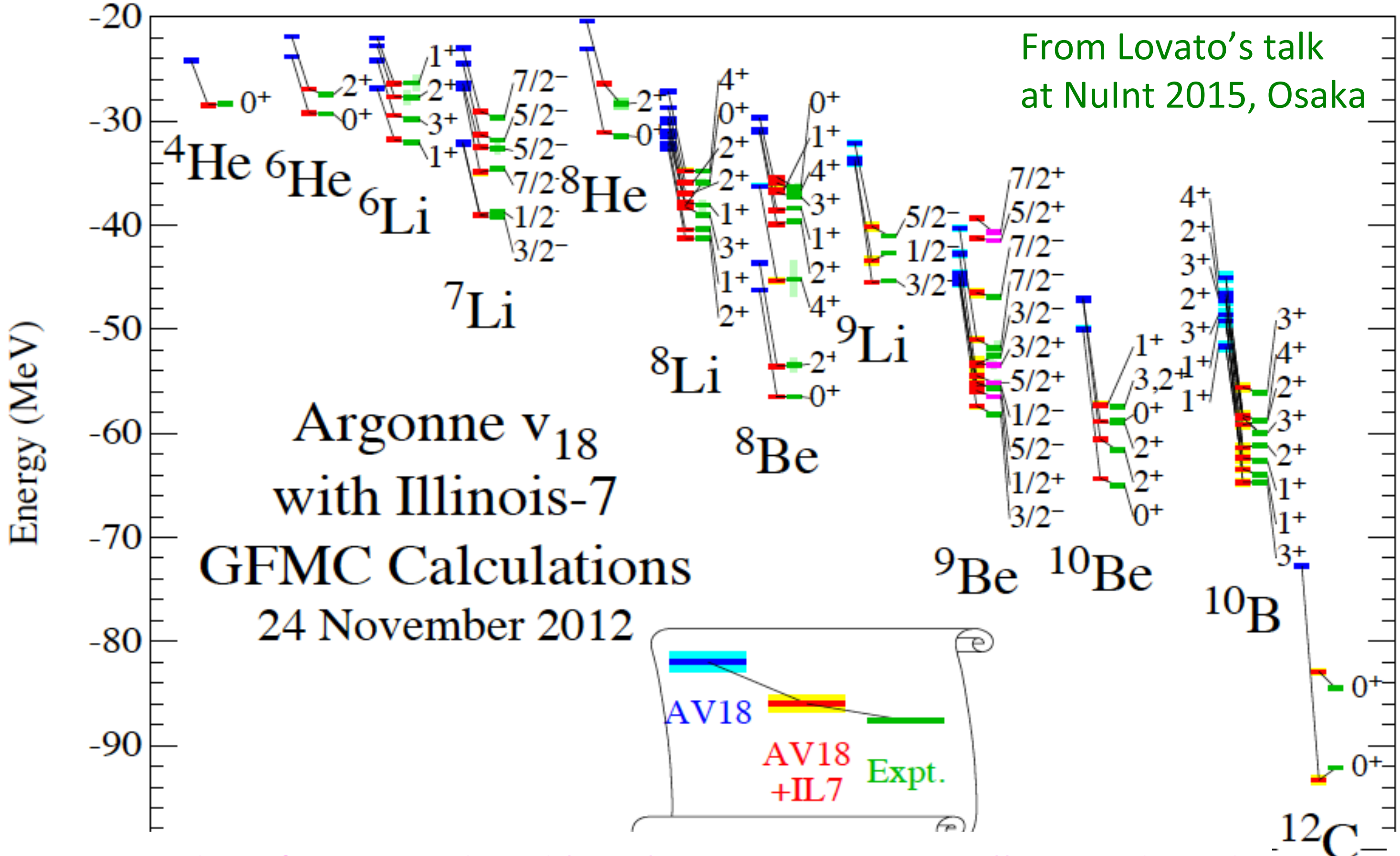


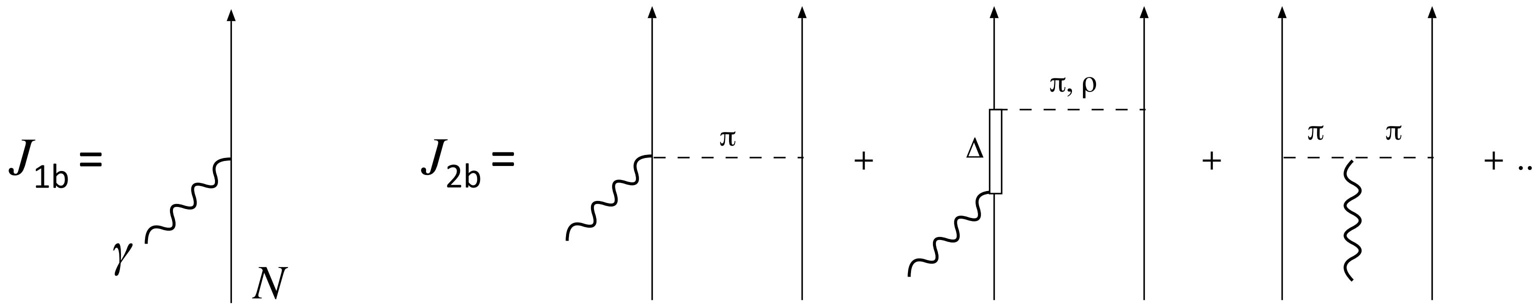
Binding energy data for ground and low-lying states are well reproduced for $A \leq 12$

Ab initio approach

$$H|\Psi_i\rangle = E_i|\Psi_i\rangle \qquad H = \sum_i \frac{\mathbf{p}_i^2}{2m} + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk} + \ldots$$

Electromagnetic current (constrained by current conservation, $\partial_\mu j^\mu = 0$, and data)

$$J_{EM} = J_{1b} + J_{2b}$$



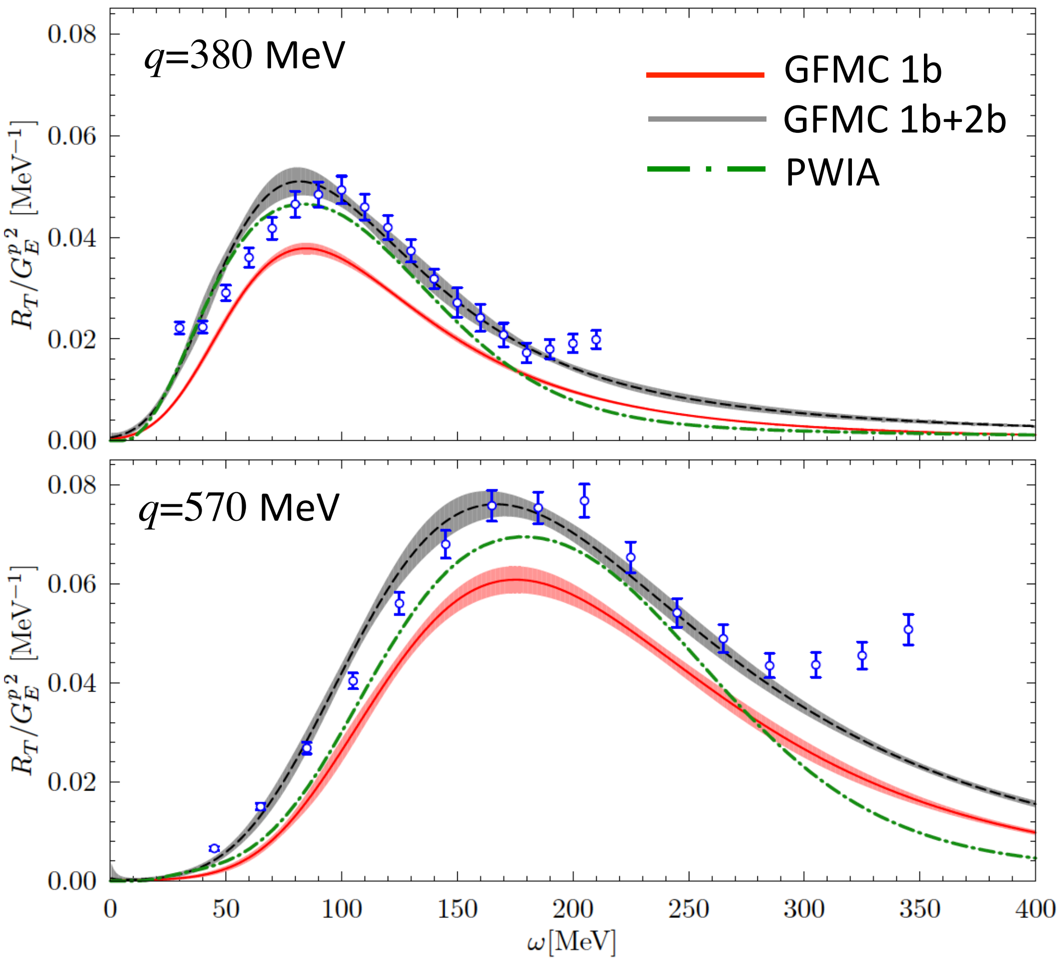
Response functions

$$R_{\alpha\beta}(\omega, \mathbf{q}) = \sum_f \langle\Psi_0|J_\alpha^\dagger(\mathbf{q})|\Psi_f\rangle\langle\Psi_f|J_\beta(\mathbf{q})|\Psi_0\rangle\delta(\omega - E_f + E_0)$$

Cross section is written in terms of $R_{\alpha\beta}$

EM transverse response of ^{12}C

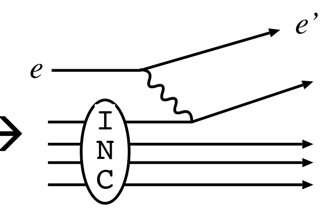
Lovato et al., PRL **117**, 082501 (2016)



Data : Jourdan, NPA 603, 117 (1996)

Conclusions

- Excellent agreement with data in QE region
- PWIA: genuine QE →



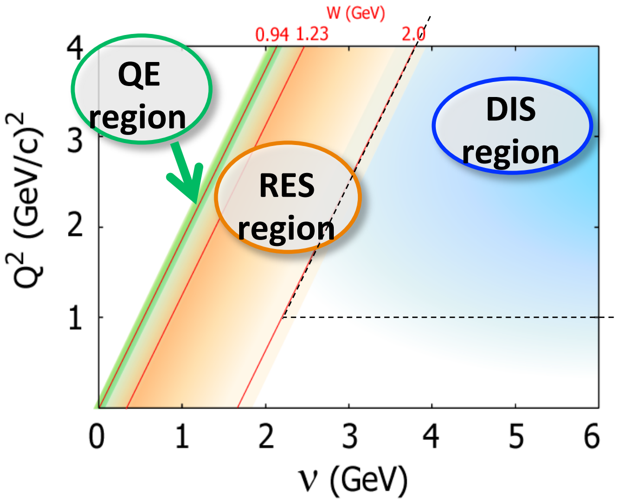
Difference between PWIA and GFMC 1b → importance of FSI

- Large 2b (MEC) enhancement
- Benchmark for other many-body methods

Ab initio approach to heavier nuclei is computationally difficult

RES (resonance)

Neutrino-nucleus scattering in resonance region



Relevance to T2K ($E_\nu \sim 1$ GeV)

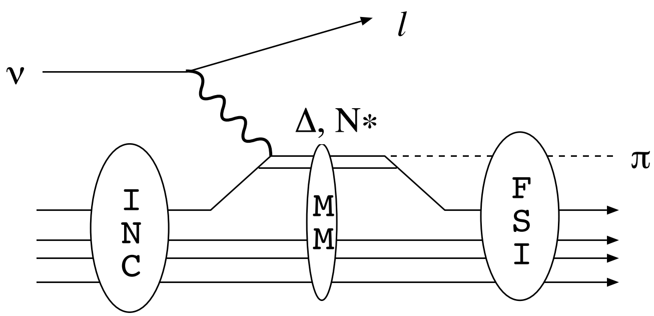
$\Delta(1232)$ excitation → π emission → π absorption

CCQE-like event

Relevance to DUNE ($E_\nu = 2 \sim 4$ GeV)

higher resonance excitations → 1π, 2π emissions

Theoretical description



- Initial nucleon correlations (INC)

  $P(\vec{p}, E)$: spectral function (Fermi gas, shell model)

- Final state interactions (FSI)

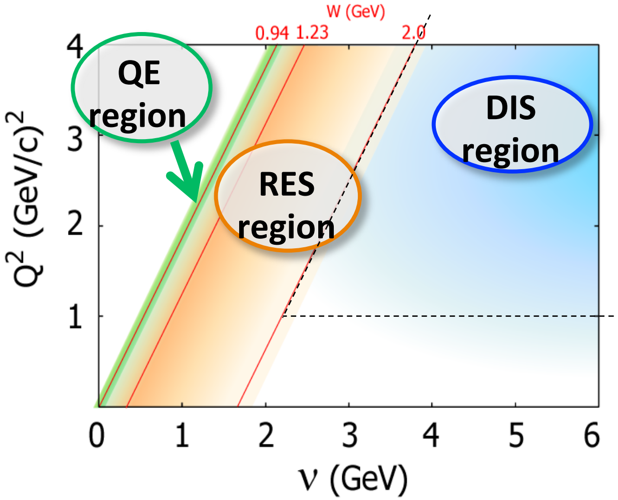
  hadron transport model (GiBUU, cascade)

- Medium modifications (MM)

  Pauli blocking , width broadening

  modified hadron properties

Neutrino-nucleus scattering in resonance region



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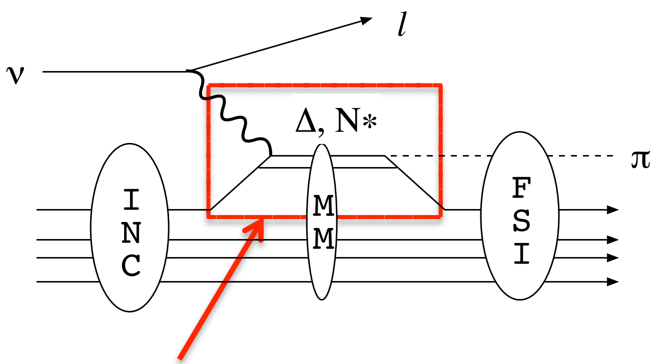

- Elementary amplitude

  to be discussed from now

- Initial nucleon correlations (INC)

  $P(\vec{p},E)$: spectral function (Fermi gas, shell model)

- Final state interactions (FSI)

  hadron transport model (GiBUU, cascade)

- Medium modifications (MM)

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Very Recent Update

- Elementary neutrino-nucleon reaction model from $\Delta(1232)$ up to boundary with DIS region

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

- Possibly important FSI effect in extracting elementary $\nu N \rightarrow \mu^- \pi N$ cross sections from deuterium bubble chamber data

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

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Development of νN-reaction model for whole RES region

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

Strategy

- Dynamical coupled-channels (DCC) model for $\gamma N, \pi N \rightarrow \pi N, \pi\pi N, \eta N, K\Lambda, K\Sigma$
- Extension to $\nu N \rightarrow l^- X$ ($X = \pi N, \pi\pi N, \eta N, K\Lambda, K\Sigma$)

Important improvements over previous models (Breit-Wigner, tree-level non-res)

- Channel-couplings required by unitarity
- 2 π production mechanisms with resonance contributions
- Interference between res and non-res axial amplitudes under control

← consistency between πN interaction and axial current required by PCAC

DCC (Dynamical Coupled-Channel) model

Matsuyama et al., Phys. Rept. 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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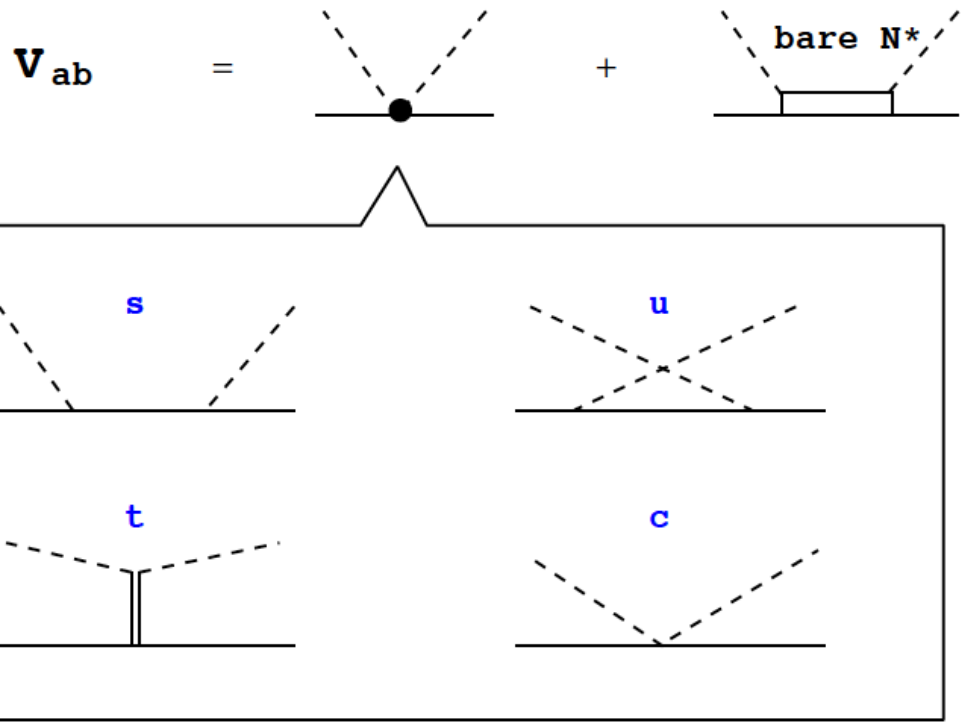

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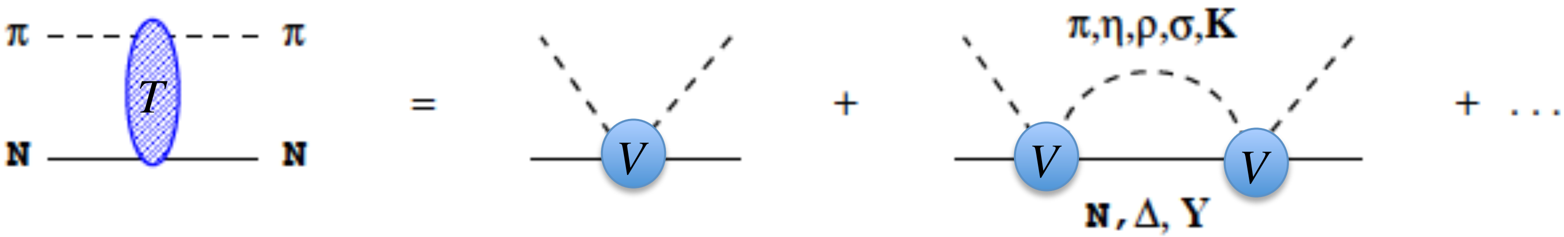
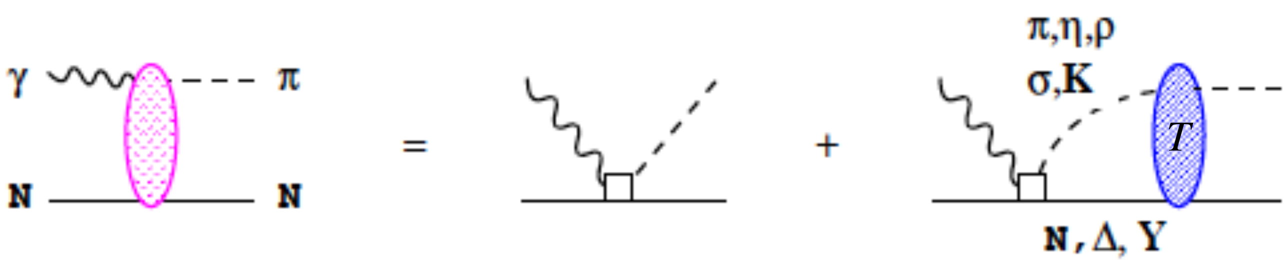


In addition, γN, $W^{\pm}N$, ZN channels are included perturbatively



DCC analysis of meson production data

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

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

~ 23,000 data points are fitted

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

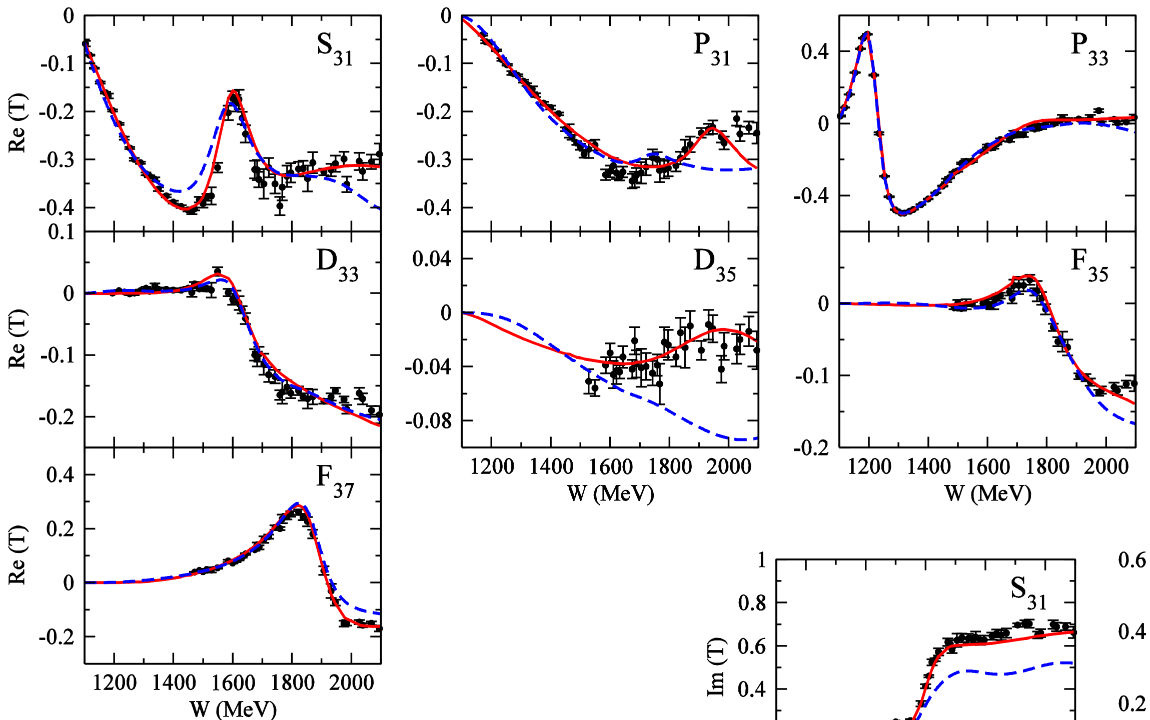
↓

Data for electron scattering on proton and neutron are analyzed

by adjusting $\gamma^* N$ ➔ N^* coupling strength

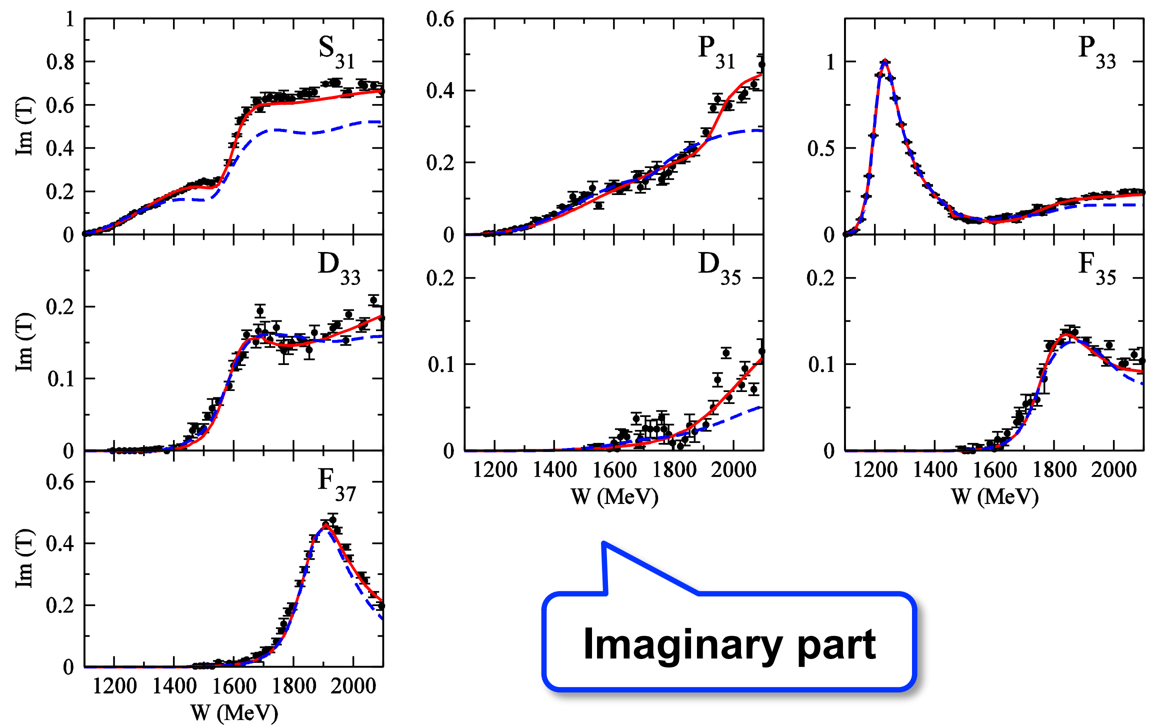
Very small portion of analysis results will be presented next

Partial wave amplitudes of π N scattering



Real part

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



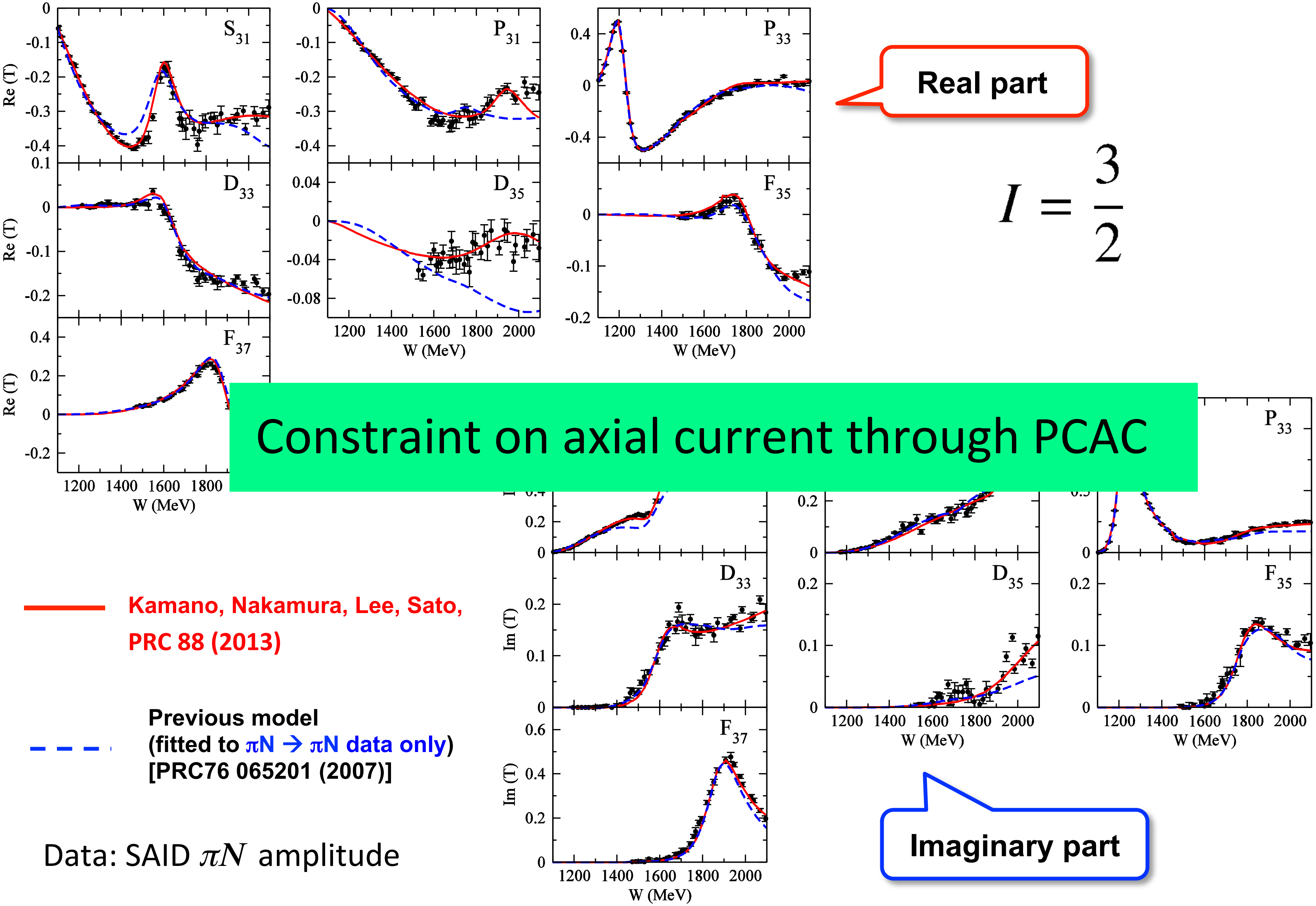
Imaginary part

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

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

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

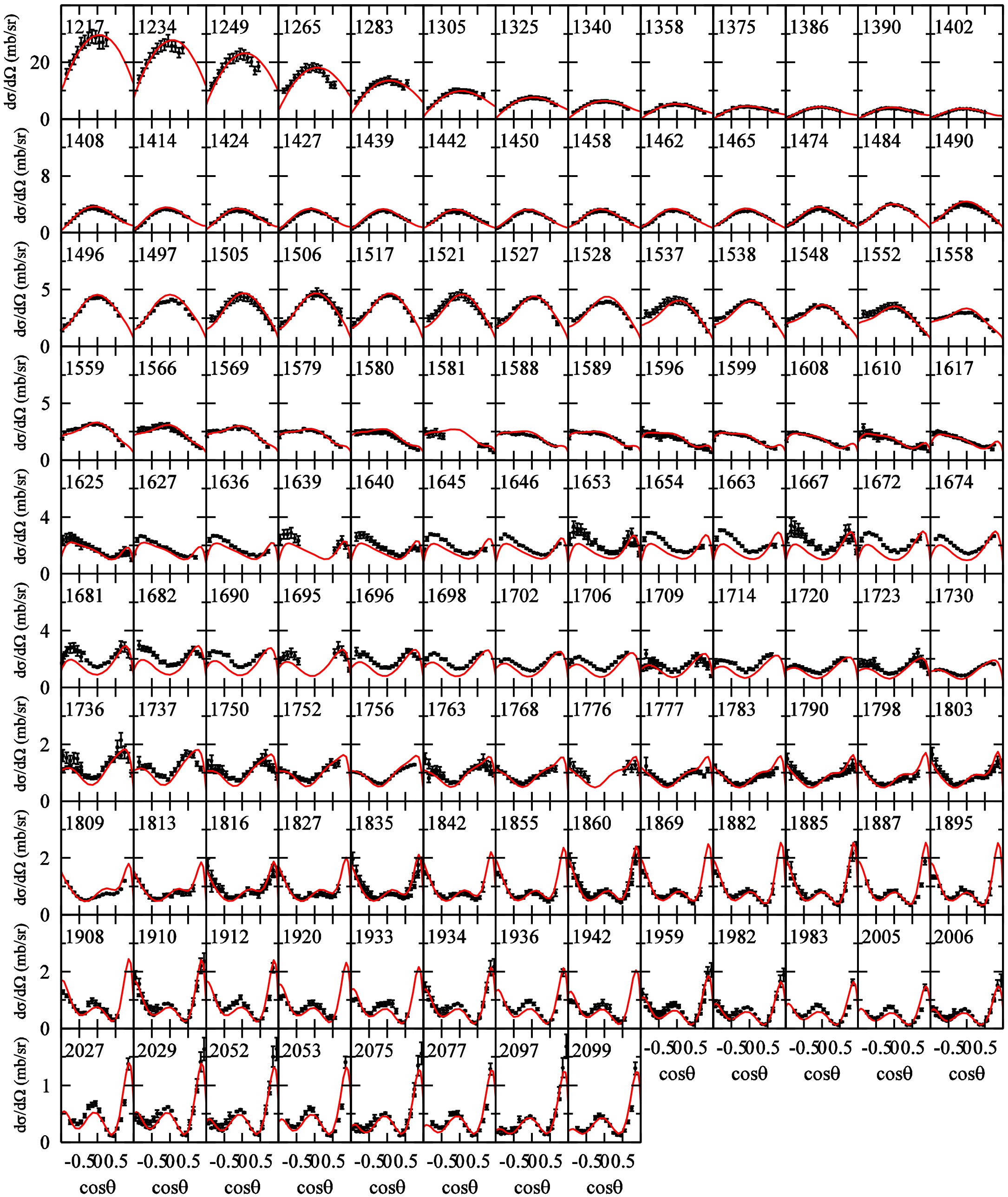
Data: SAID πN amplitude

Imaginary part

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

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

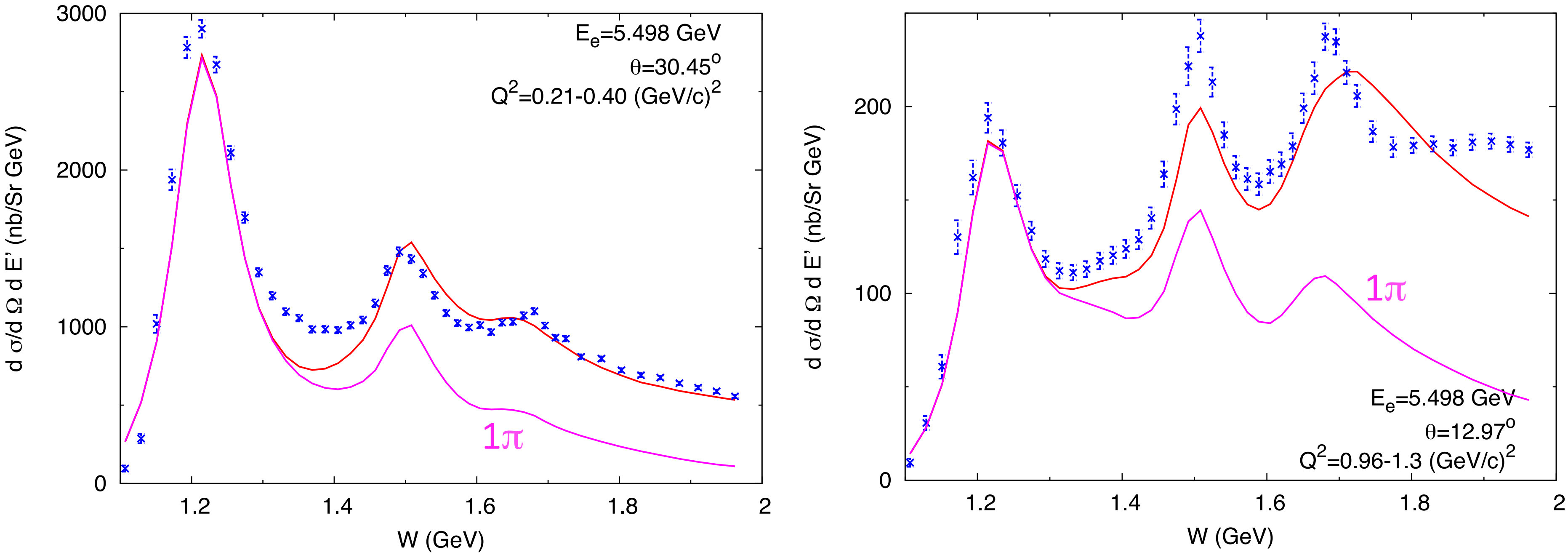
Kamano, Nakamura, Lee, Sato, PRC 88 (2013)



Vector current (Q^2=0) for 1π

Production is well-tested by data

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

Neutrino-induced reactions

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

DCC model for vector current

Vector current for neutrino processes is obtained
by analyzing electron reaction ($Q^2 \neq 0$) data on both proton and neutron targets, and
by isospin separation

Detailed discussion in Kamano's talk today

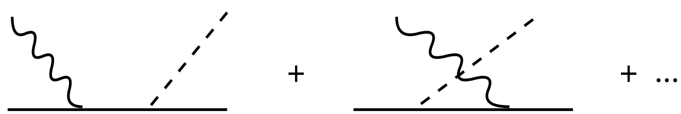
DCC model for axial current

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

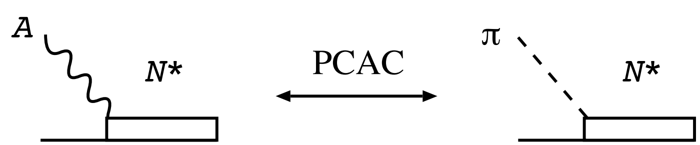
PCAC relation $< X' | q \cdot A | X > \sim i f_\pi < X' | T | \pi X >$

non-resonant mechanisms

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



resonant mechanisms

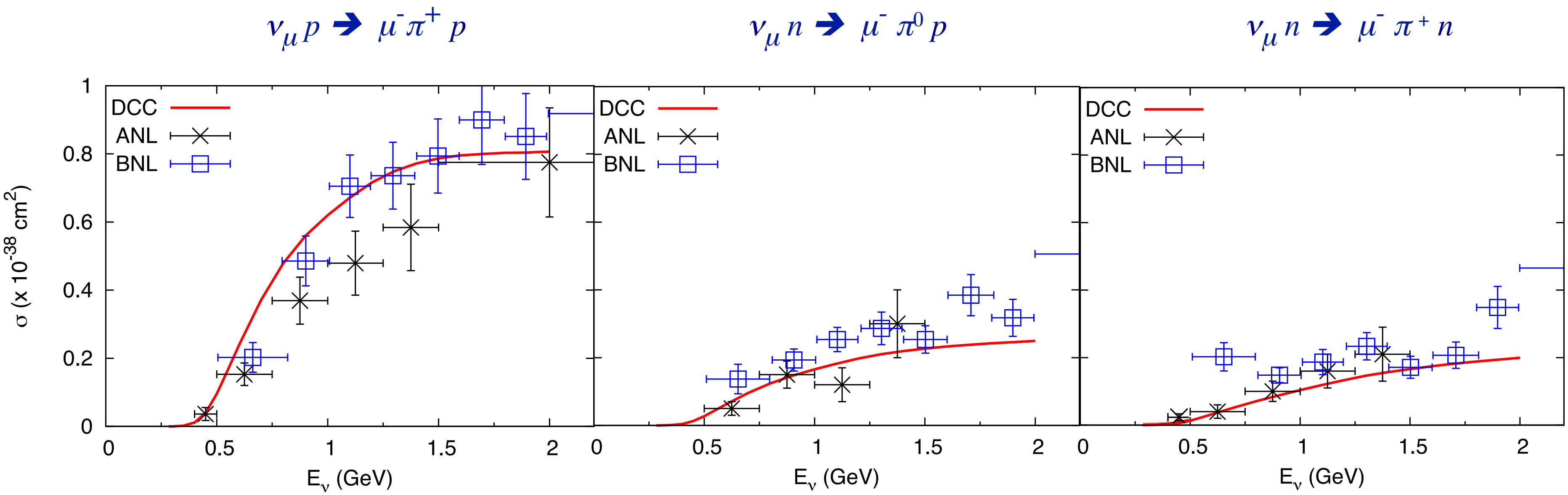


both πN interaction and axial current constructed consistently with PCAC

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

Q^2 –dependence → dipole form is assumed with $M_A \sim$ 1 GeV

Comparison with single pion data



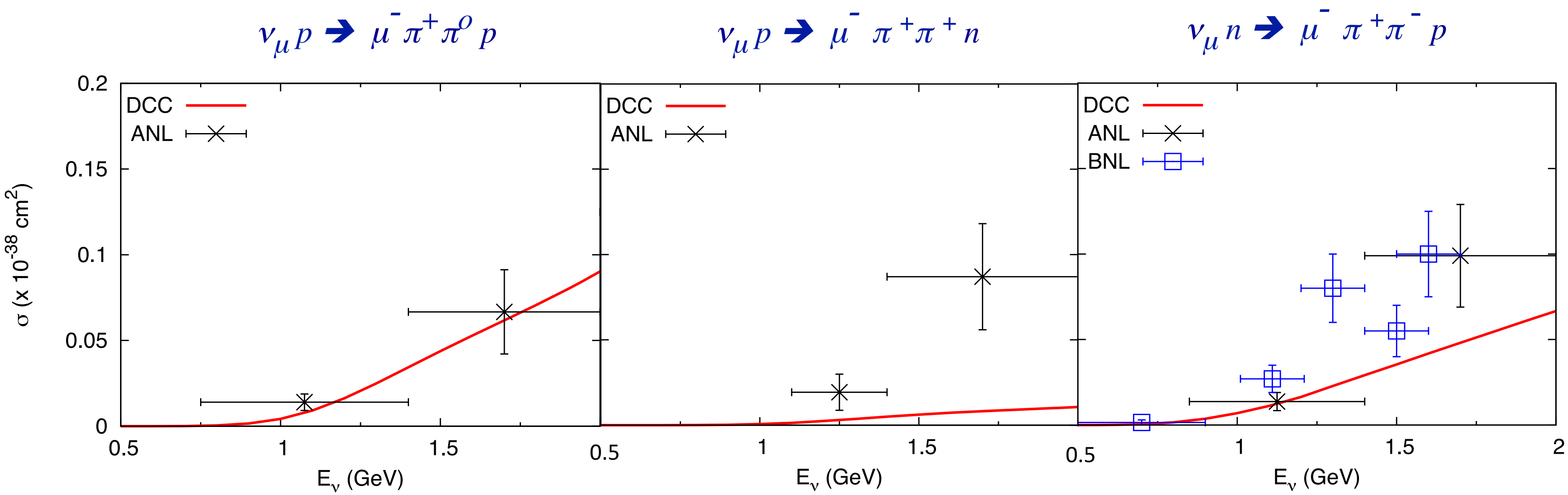
DCC model prediction is consistent with data

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

- DCC model has flexibility to fit data ($ANN^*(Q^2)$)
- Data should be analyzed with nuclear effects

(Wu et al. , PRC91, 035203 (2015))

Comparison with double pion data

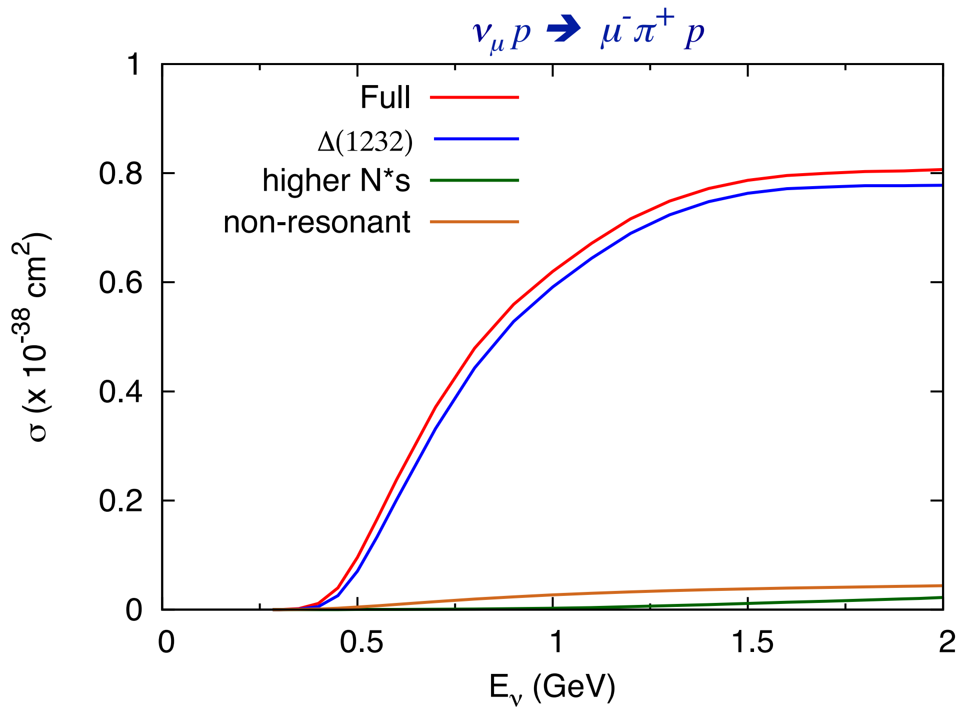


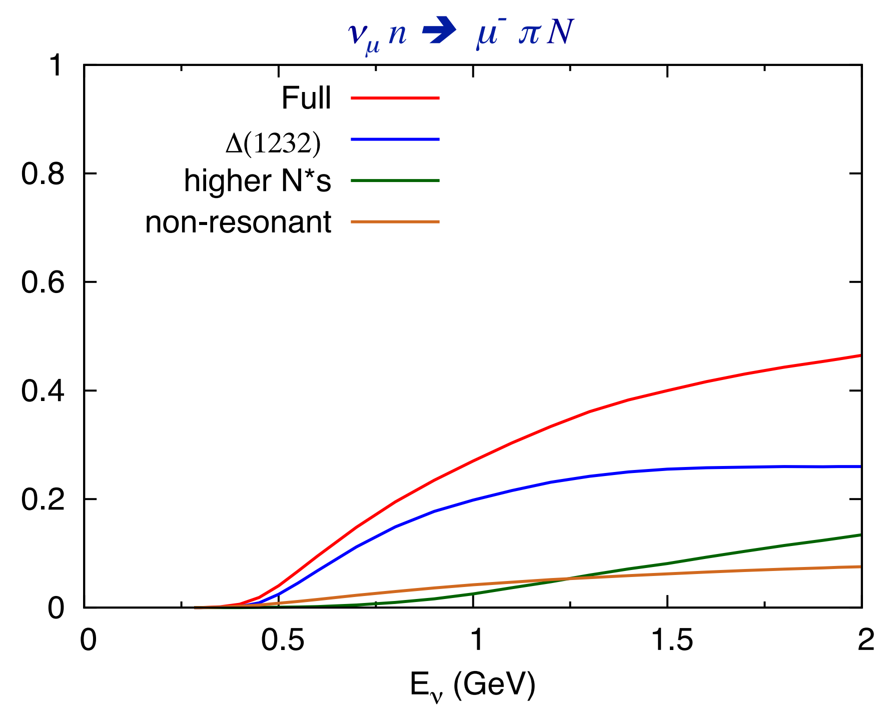
Fairly good DCC predication

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 mechanism and Higher N^*s becomes important towards $E_\nu \approx 2$ GeV for $\nu_\mu n \rightarrow \mu^- \pi N$

→ essential to understand interference pattern among them

→ DCC model can do this; consistency between π interaction and axial current

Very Recent Update

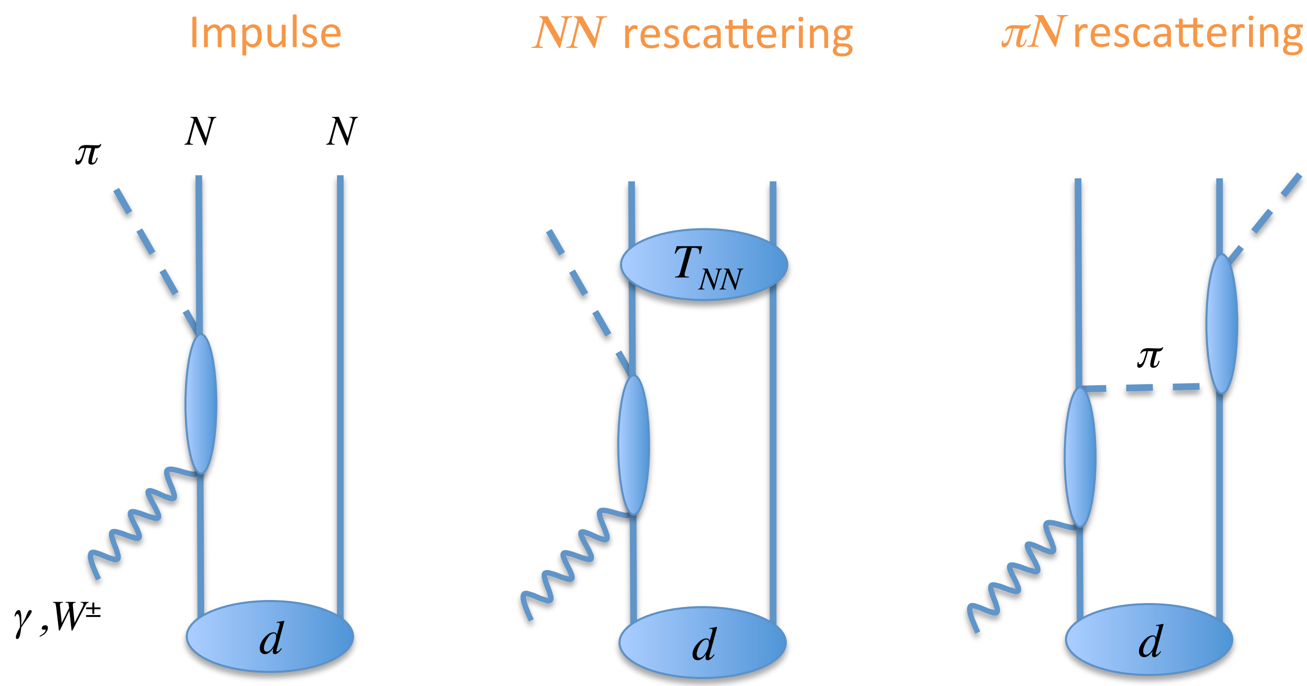
- Elementary neutrino-nucleon reaction model from $\Delta(1232)$ up to boundary with DIS region

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

- Possibly important FSI effect in extracting elementary $\nu N \rightarrow \mu^{-} \pi N$ cross sections from deuterium bubble chamber data

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

Model for $\gamma d, W^{\pm} d \rightarrow \pi N N$



$\gamma N, W^{\pm}N \rightarrow \pi N$ amplitude ← SL model (PRC 54 (1996), PRC 67 (2003))

$\pi N \rightarrow \pi N$ amplitude ← SL model

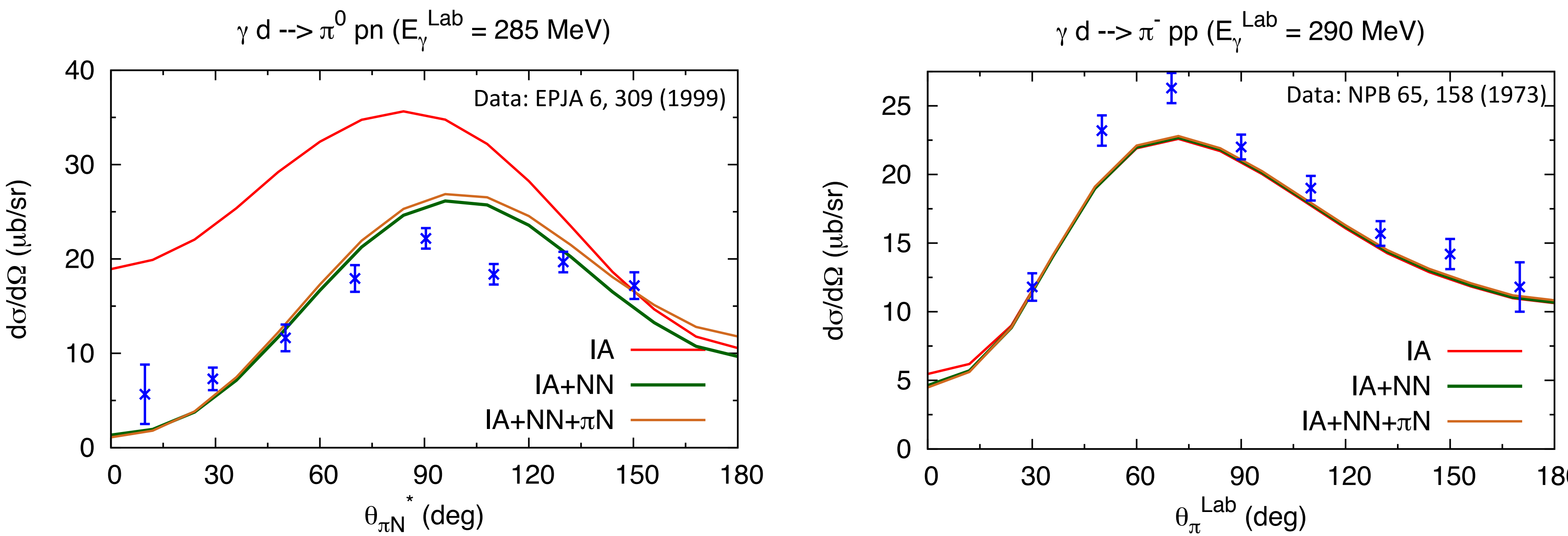
T_{NN}, deuteron w.f. ← CD-Bonn potential (PRC 63 (2001))

SL model is for Δ region and includes πN channel only

$\gamma d \rightarrow \pi N N$

Purpose : test the soundness of the model

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

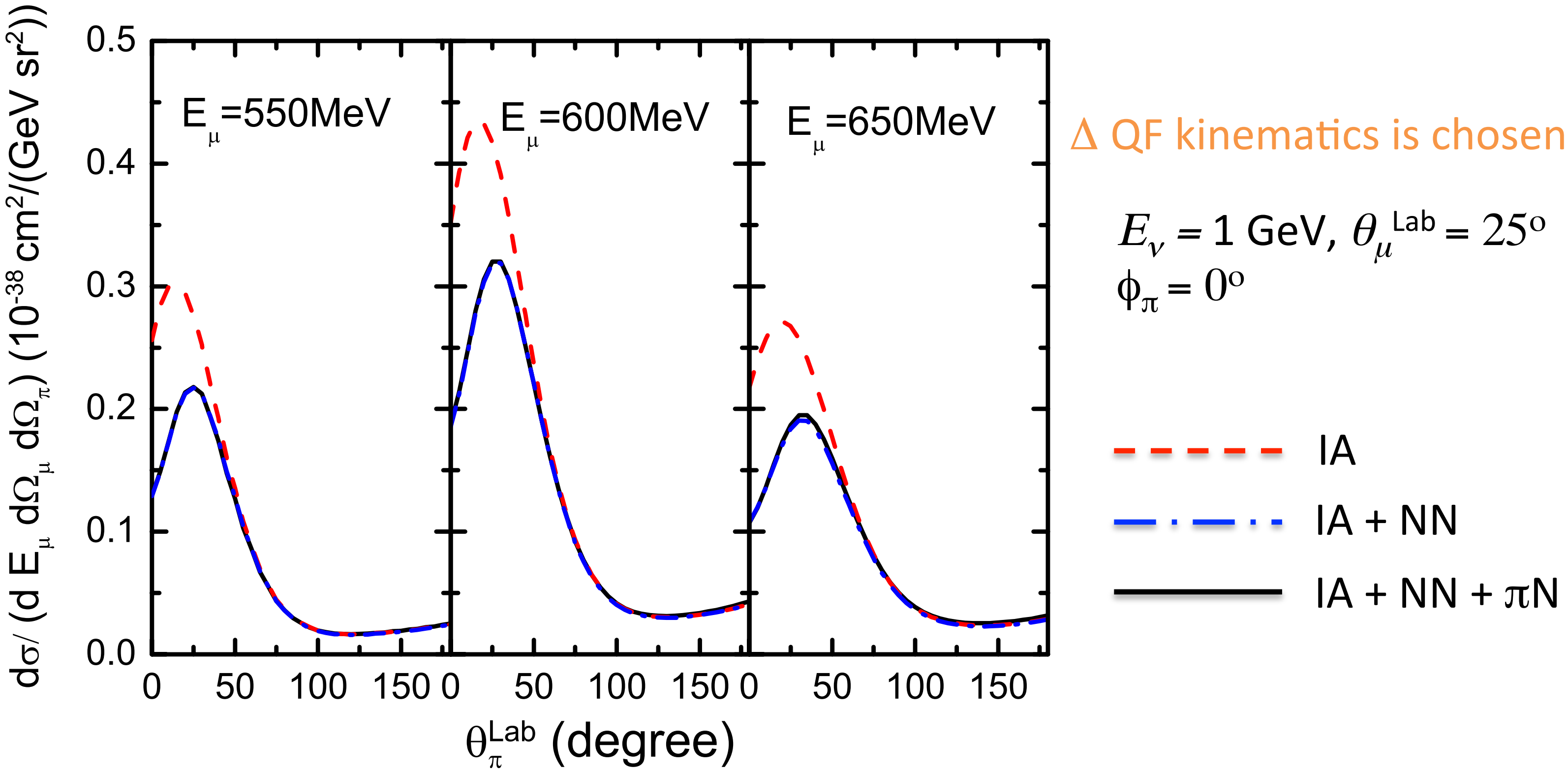


- Model prediction is reasonably consistent with data
- Large NN (small πN) rescattering effect for π^0 production

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

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

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



Δ QF kinematics is chosen

E_ν = 1 GeV, $\theta_\mu^{Lab} = 25^o$

$\phi_\pi = 0^o$

Conclusions

- Large *NN* (small πN) rescattering effect

  orthogonality between deuteron and *pn* scattering wave functions

- ANL and BNL data did not consider FSI

  → calling for reanalysis with FSI taken into account

Summary

Remarkable progress in neutrino-nucleus interaction theory in 2015-2016

QE

First ab initio calculation of electromagnetic response of ^{12}C Lovato et al. (2016)

- Large 2b (MEC) enhancement
- Benchmark for other many-body models

RES

First coupled-channel calculation of neutrino-induced meson productions   SXN et al. (2015)

- First two pion production model for whole RES region
- res and non-res interference are under control by maintaining PCAC

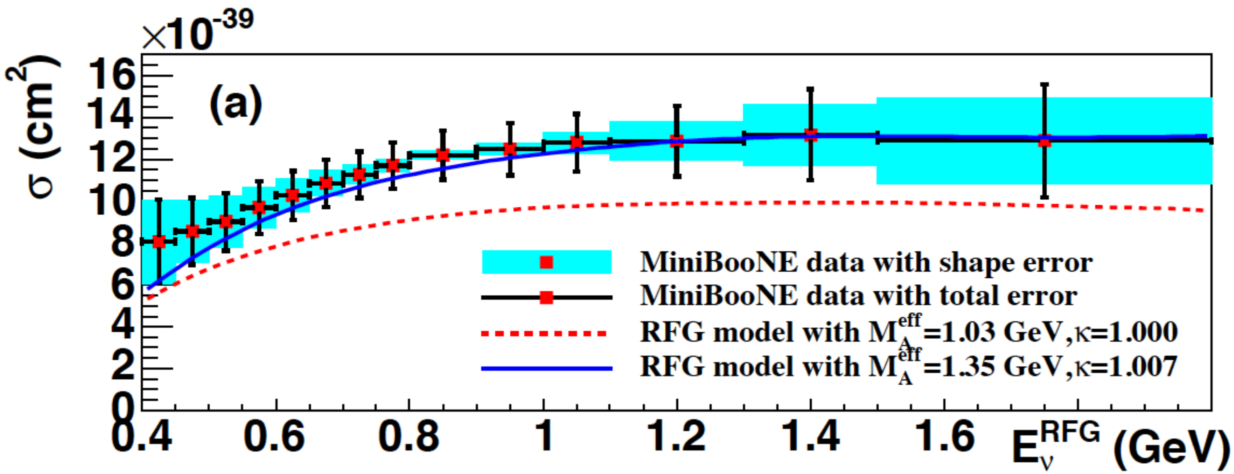
Possibly important FSI effect on pion production in ν-deuteron reactions   Wu et al. (2015)

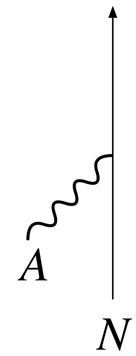
- Large NN rescattering effect
- ANL and BNL bubble chamber data need reanalysis with FSI taken into account

BACKUP

Lots of recent works on QE-like mechanisms

MiniBooNE CCQE data pulled the trigger (PRD 81, 092005 (2010))

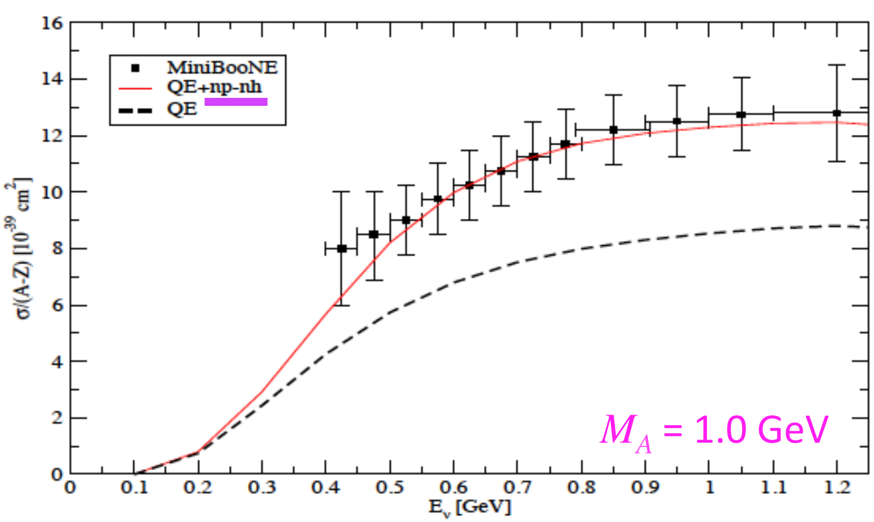




$$= g_A \left(\frac{1}{1 + Q^2 / M_A^2} \right)^2$$

M_A puzzle !

Martini et al.'s answer based on mean field + RPA approach (PRC 80, 065501 (2009) , …)



np-nh (mostly 2p-2h) explains M_A puzzle

Lots of subsequent works

- Valencia model (mean field +RPA)
  Nieves et al., PRC 83 (2011) , …
- (phenomenological) Superscaling + MEC
  Amaro et al., PLB 696 (2011) , …

… and more

Integral transform technique

$$E_{\alpha\beta}(\tau,\vec{q}) \equiv \int d\omega\, e^{-\omega\tau} R_{\alpha\beta}(\omega,\vec{q})$$ (Euclidean response)

With the completeness of final states, $E_{\alpha\beta}$ can be expressed by ground-state expectation value that can be handled with GFMC method

$$E_{\alpha\beta}(\tau,\vec{q}) = \left\langle \Psi_0 \middle| J_\alpha^\dagger(\vec{q})\, e^{-(H-E_0)\tau} J_\beta(\vec{q}) \middle| \Psi_0 \right\rangle$$

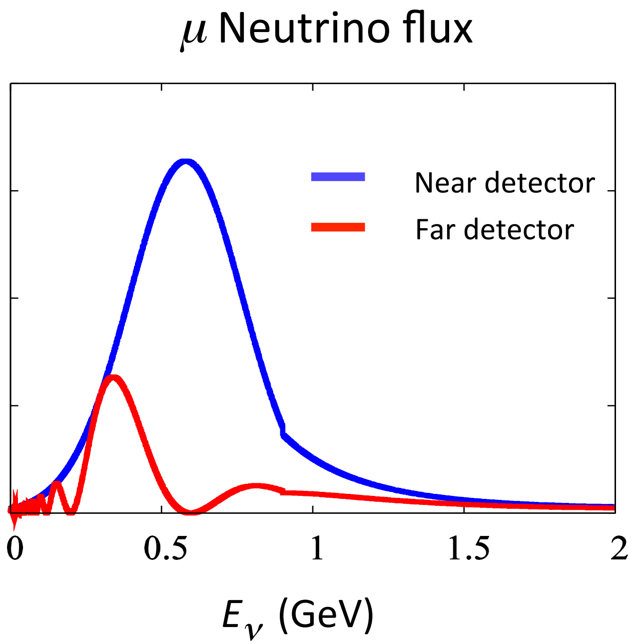
Inversion : $E_{\alpha\beta}(\tau,\vec{q}) \Rightarrow R_{\alpha\beta}(\omega,\vec{q})$ ill-posed problem

Maximum Entropy Method (MEM) can help

Jarrell and Gubernatis, Phys. Rept. 269, 133 (1996)

MEM can reconstruct (infer) information from incomplete and noisy data

Neutrino-nucleus scattering for ν-oscillation experiments



ν_μ survival probability (two-flavor case)

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \, \sin^2\left(\frac{1.27\,\Delta m_{21}^2 L}{E_\nu}\right)$$

θ : mixing angle

$\Delta m_{21}{}^2$ (eV^2) = $m_2{}^2 - m_1{}^2$

L (km) : distance between ν source and detector

E_ν (GeV) : neutrino energy

Next-generation exp. ➔ leptonic $\not{C}\!P$, mass hierarchy

ν−nucleus scattering needs to be understood more precisely (~ 5%)

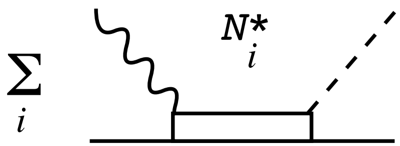
Neutrino-nucleus interactions need to be known for neutrino flux measurement

and then oscillation parameters (θ_{ij} , $\Delta m_{ij}{}^2$, δ_{CP}) are determined

Elementary amplitude for ν–induced 1π production

resonant only

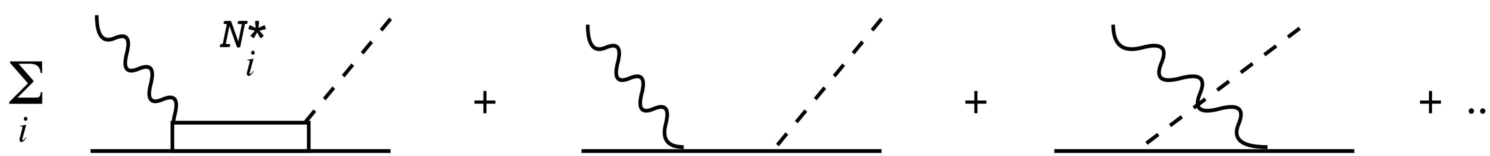
Lalalulich et al. (2005), (2006)



+ non-resonant (tree-level)

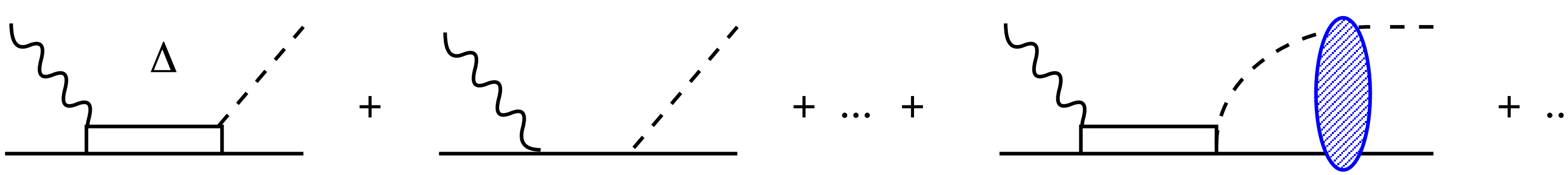
Rein et al.(1981),(1987); Lalakulich et al. (2010); Serot et al.(2012)

Hernandez et al. (2007), (2010), (2016) ; Alam et al. (2016)

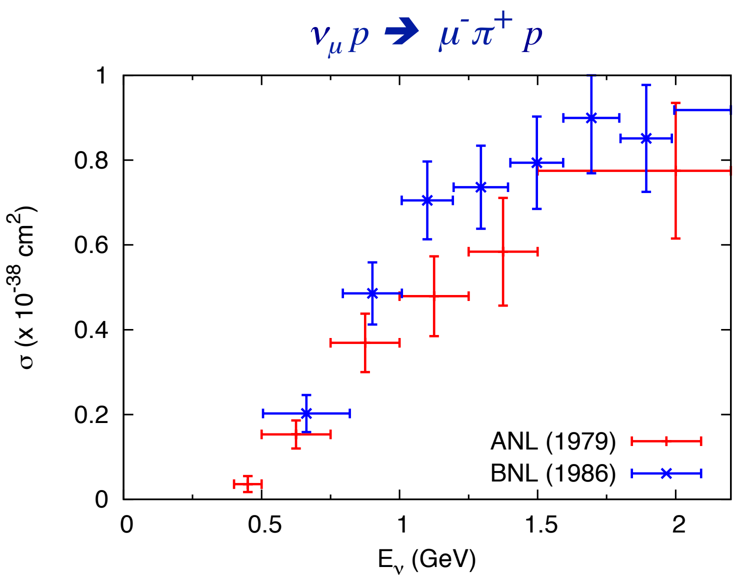


+ rescattering (πN unitarity)

Sato, Lee (2003), (2005)



All elementary process models fit axial N-Δ(1232) coupling strength to bubble chamber data



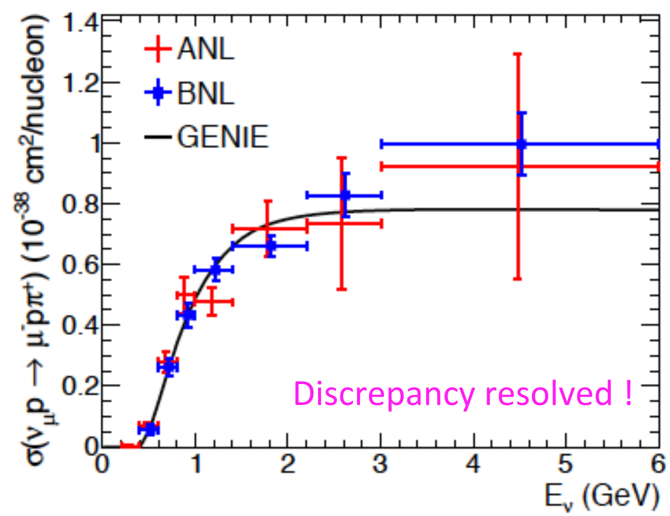
Recent reanalysis

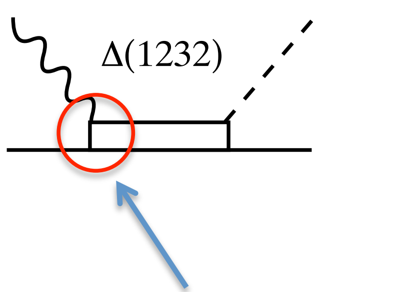
Wilkinson et al.

PRD 90, 112017 (2014)

$$\frac{\sigma(1\pi^+;\text{data})}{\sigma(\text{QE};\text{data})} \times \sigma(\text{QE};\text{GENIE})$$

flux uncertainty eliminated





In Δ(1232) region, all models can be made (more or less) consistent with the bubble chamber data

but this is not the end of the story about elementary amplitude model !

Summary : FSI effects on ν–deuteron reactions in $\Delta(1232)$ region

- Model for photo- and neutrino-induced reactions on the deuteron developed

  impulse, NN and πN rescattering mechanisms

- Model predictions reasonably describe $\gamma d \rightarrow \pi NN$ data (soundness checked)

  NN rescattering significantly reduces cross sections (orthogonality)

- Significant FSI effects on $\nu d \rightarrow \mu^- \pi^+ n p$ differential cross sections at certain kinematics

  NN rescattering significantly reduces cross sections (orthogonality)

- $\nu d \rightarrow \mu^- \pi^+ n p$ total cross sections need to be calculated to analyze ANL and BNL bubble chamber data → ongoing SXN, Kamano, Sato

Summary : DCC model for νN reactions in RES region

Start with DCC model for γN, πN ➔ πN, $\pi\pi N$, ηN, $K\Lambda$, $K\Sigma$

and e^{-}- p & e^{-}-'n' reactions for $W \leq$ 2 GeV , $Q^2 \leq$ 3 (GeV/c)^2

➔ Development of vector current by isospin separation

and axial current for νN interaction; PCAC is maintained

Conclusion

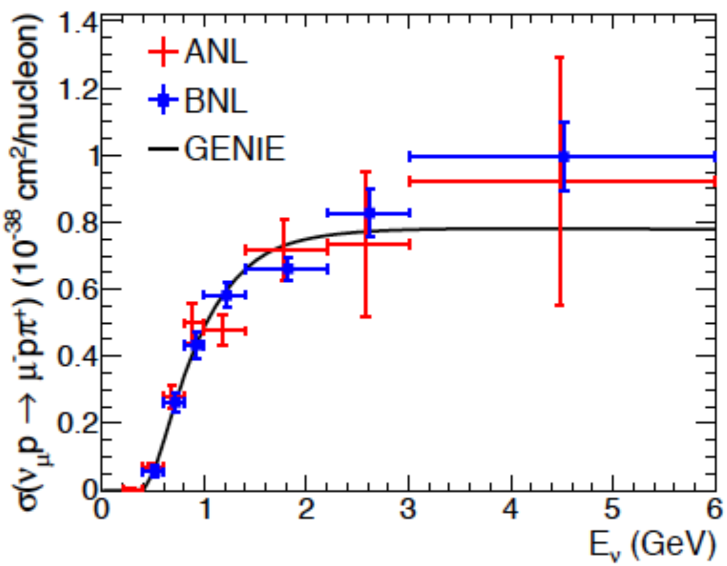
- DCC model prediction is consistent with single pion production data
- Two pion production model for RES region developed for the first time
- Δ, N^*s, non-resonant are all important in few-GeV region (for $\nu_\mu\, n$ ➔ $\mu^- X$)

➔ essential to understand interference pattern among them

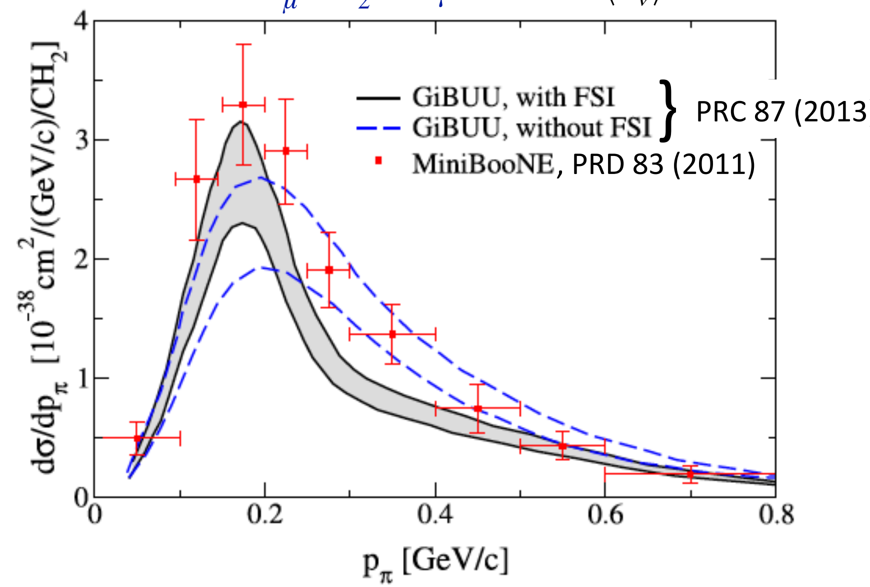
➔ DCC model can do this; consistency between π interaction and axial current

Neutrino interaction data in resonance region

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



$\nu_\mu \mathrm{CH_2} \rightarrow \mu^- \pi^0 X \quad \langle E_\nu \rangle = 0.8$ GeV



- Data to fix nucleon axial current ($g_{AN\Delta}$)
- Discrepancy between BNL & ANL data
- Recent reanalysis of original data

  → discrepancy resolved (!?)

  PRD 90, 112017 (2014)

- Final state interaction (FSI) changes charge, momentum, number of π
- Cross section shape is worse described with FSI
- MINERνA data (PRD92,092008(2015)) favor FSI

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

More data are coming → better understanding of neutrino-nucleus interaction

DCC (Dynamical Coupled-Channel) model

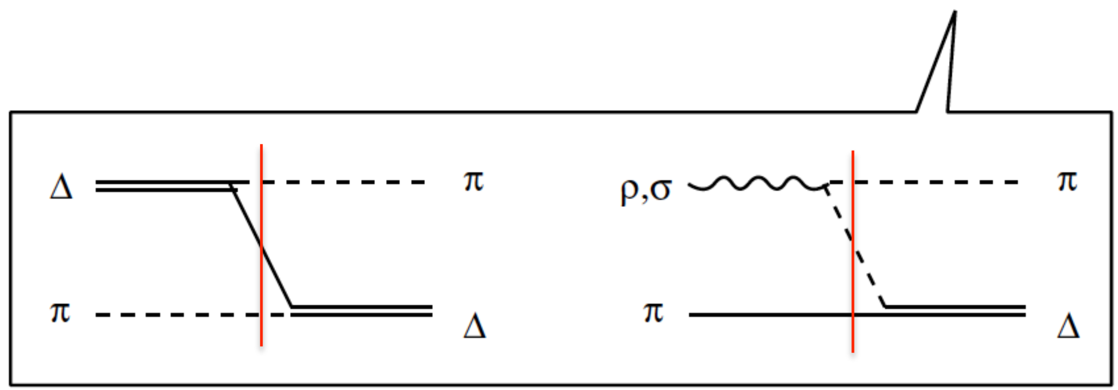
Matsuyama et al., Phys. Rep. **439**, 193 (2007)

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

Coupled-channel Lippmann-Schwinger equation

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

essential for three-body unitarity



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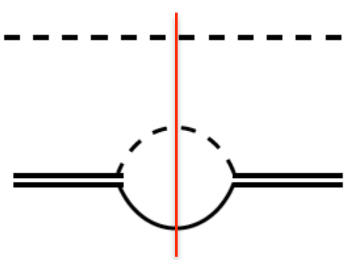
Coupled-channel Lippmann-Schwinger equation

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

$G c$ =

for stable channels



for unstable channels

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:

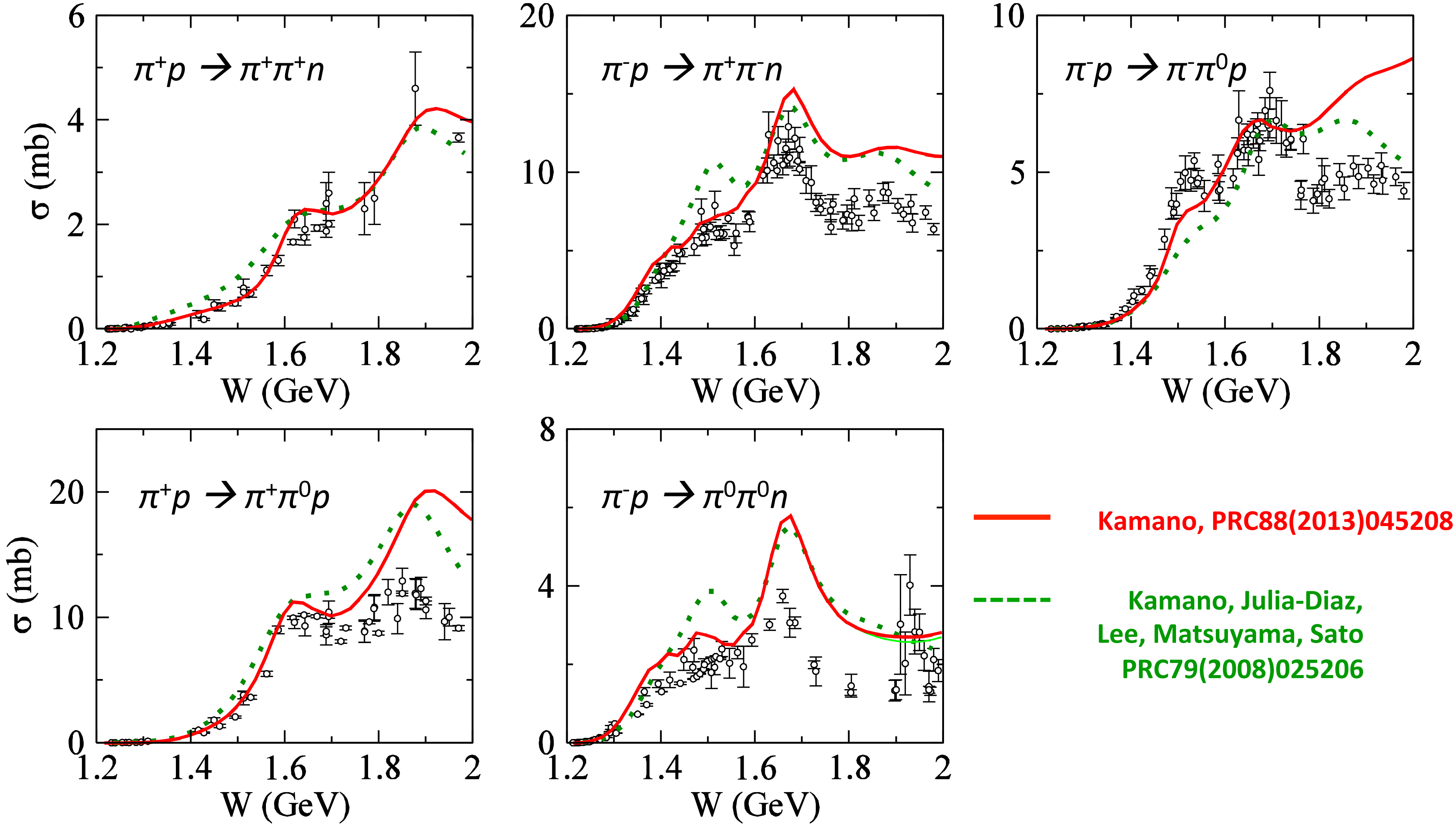
$$< p | V_\lambda | p > = - < n | V_\lambda | n > \qquad < p | V_\lambda^{IS} | p > = < n | V_\lambda^{IS} | n >$$

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

$$< p | V_\lambda | n > = 2 < p | V_\lambda | p >$$

Kamano's talk on Tuesday

Predicted πN → ππN total cross sections with our DCC model

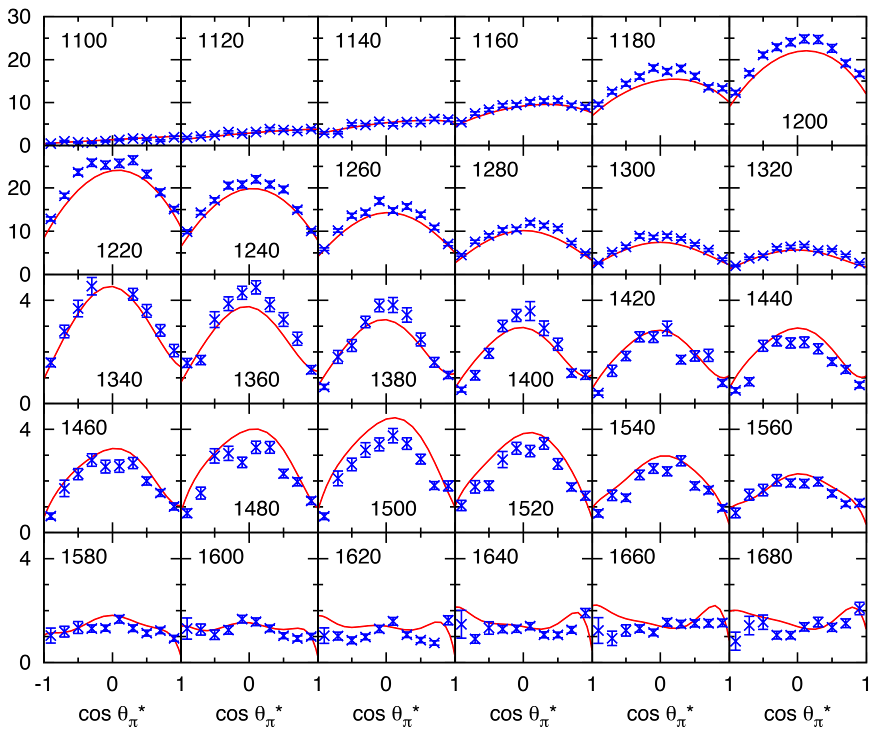


Single π production in electron-proton scattering

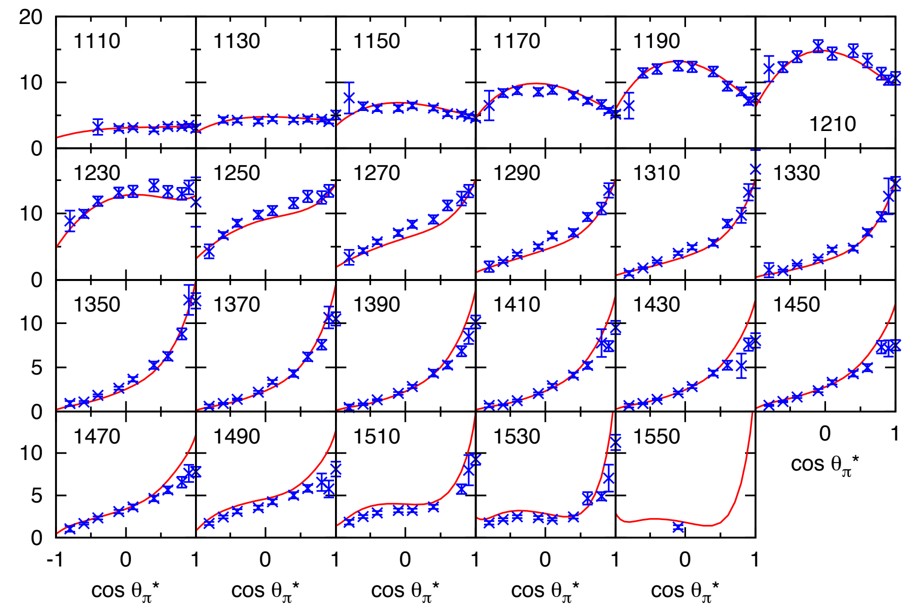
Purpose : Determine Q^2 –dependence of vector coupling of p-N^* : $VpN^*(Q^2)$

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

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



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



DCC model for axial current

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

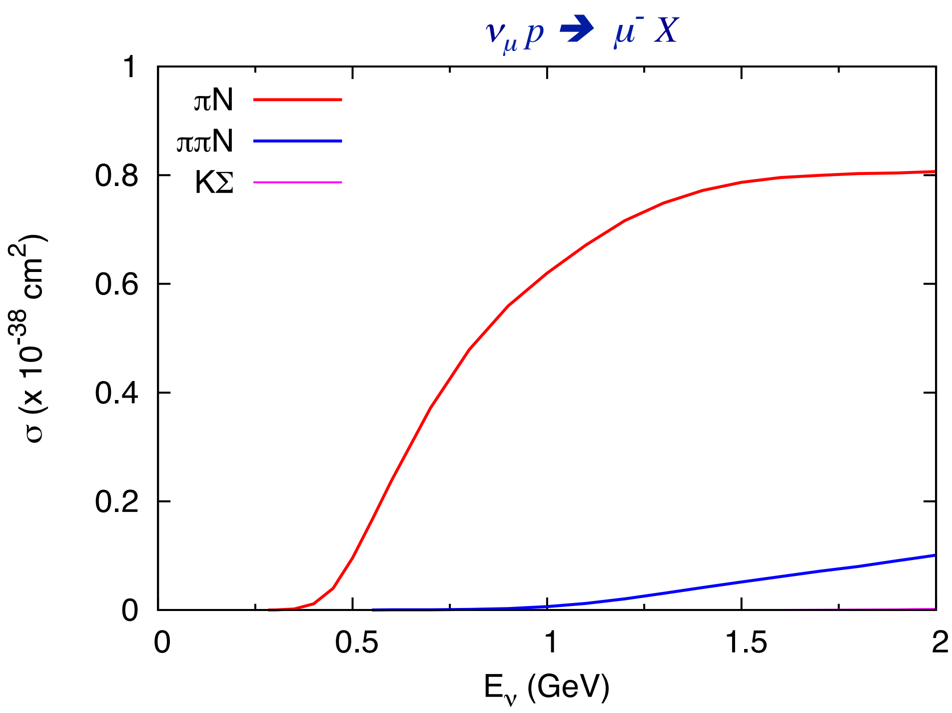
non-resonant mechanisms $$F_A(Q^2) = \left(\frac{1}{1+Q^2/M_A^2}\right)^2$$ M_A=1.02 GeV

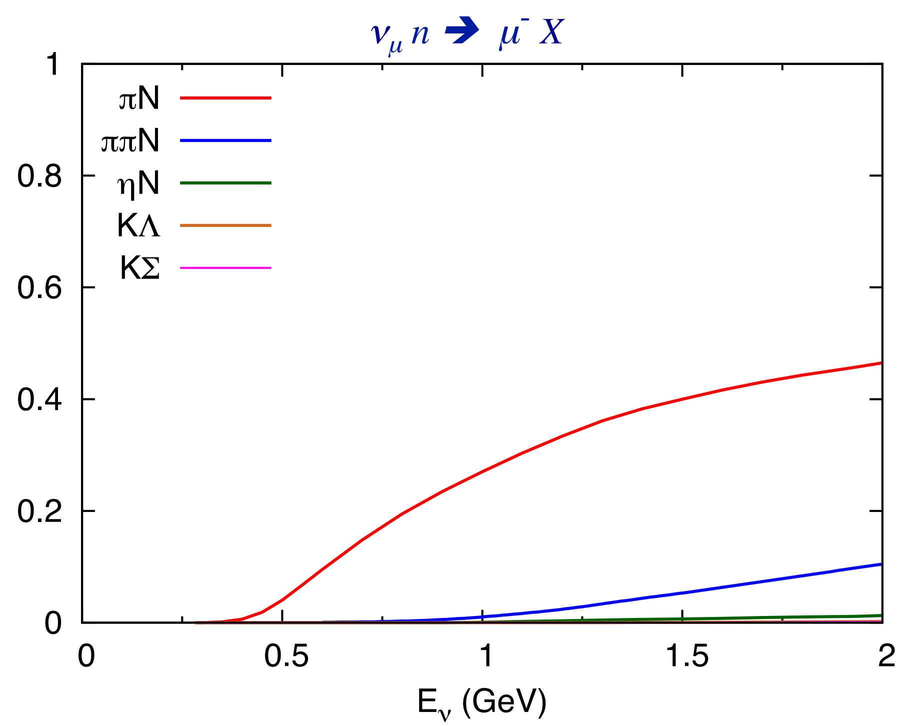
resonant mechanisms $$F_A(Q^2) = \left(\frac{1}{1+Q^2/M_A^2}\right)^2$$

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

Neutrino cross sections will be predicted with this axial current

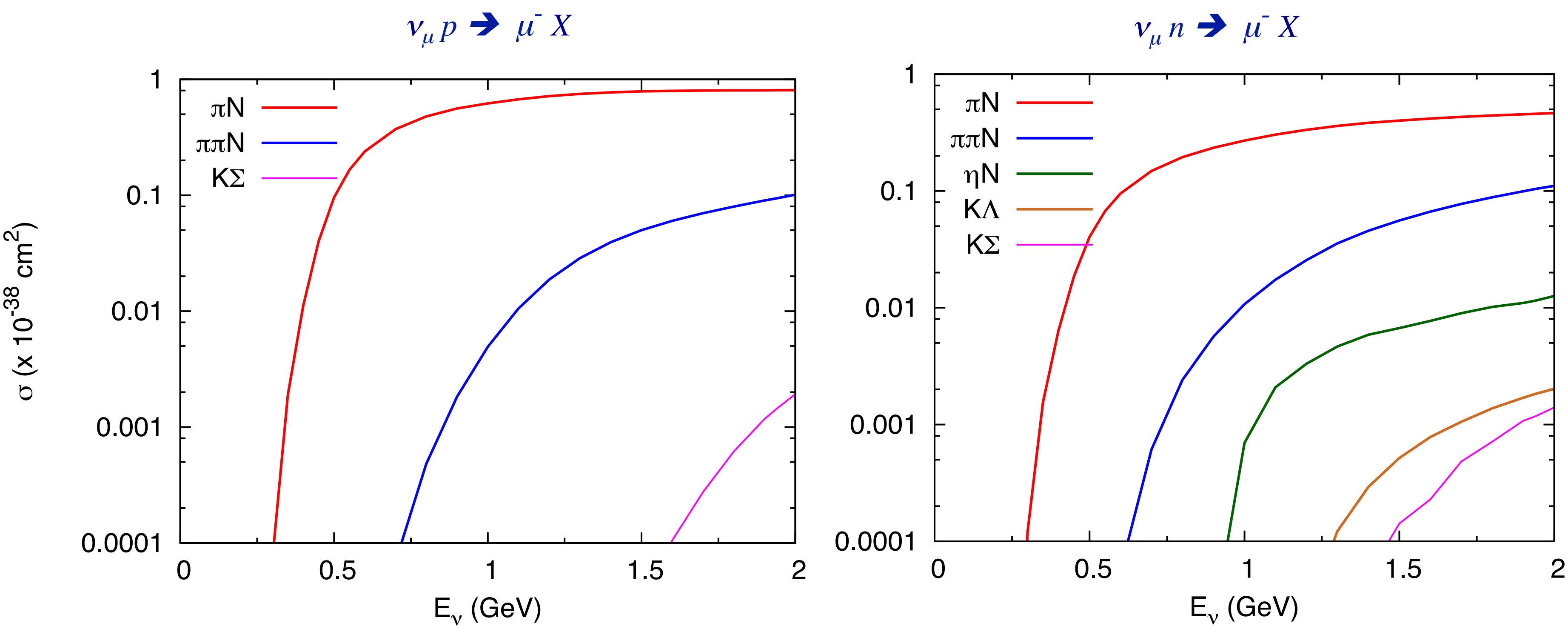
Cross section for $\nu_\mu N \rightarrow \mu^- X$





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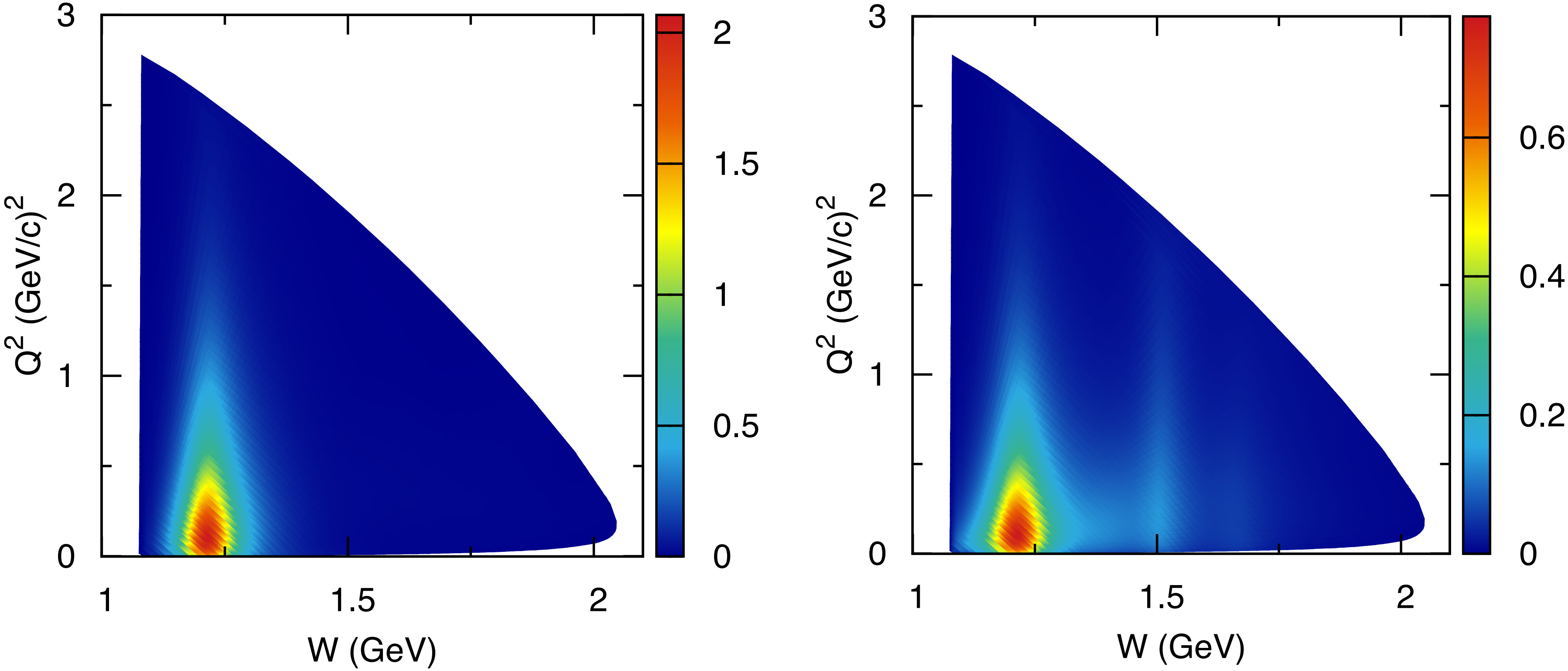
$d\sigma / dW\, dQ^2$ ($\times 10^{-38}$ cm^2 / GeV^2)

E_ν = 2 GeV

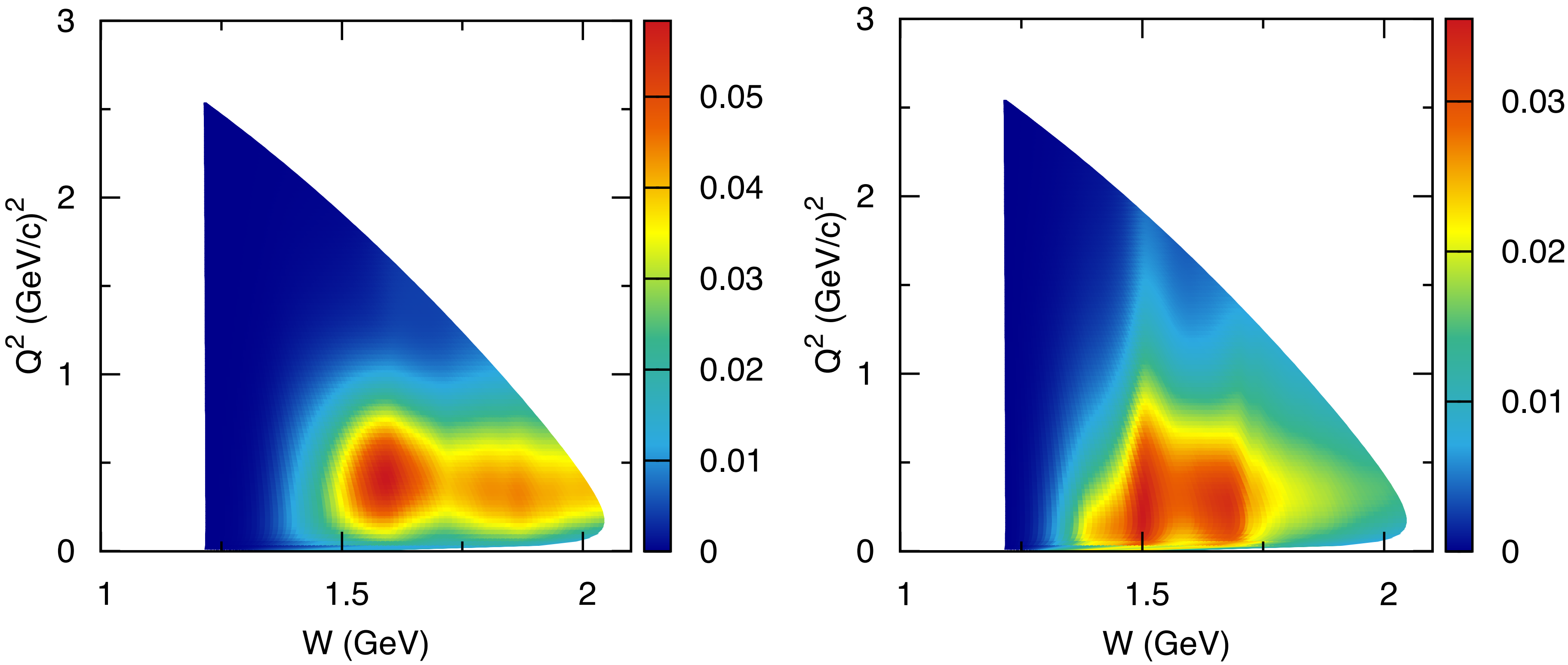
$\nu_\mu p \rightarrow \mu^- \pi^+ p$ $\qquad$ $\nu_\mu n \rightarrow \mu^- \pi N$



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

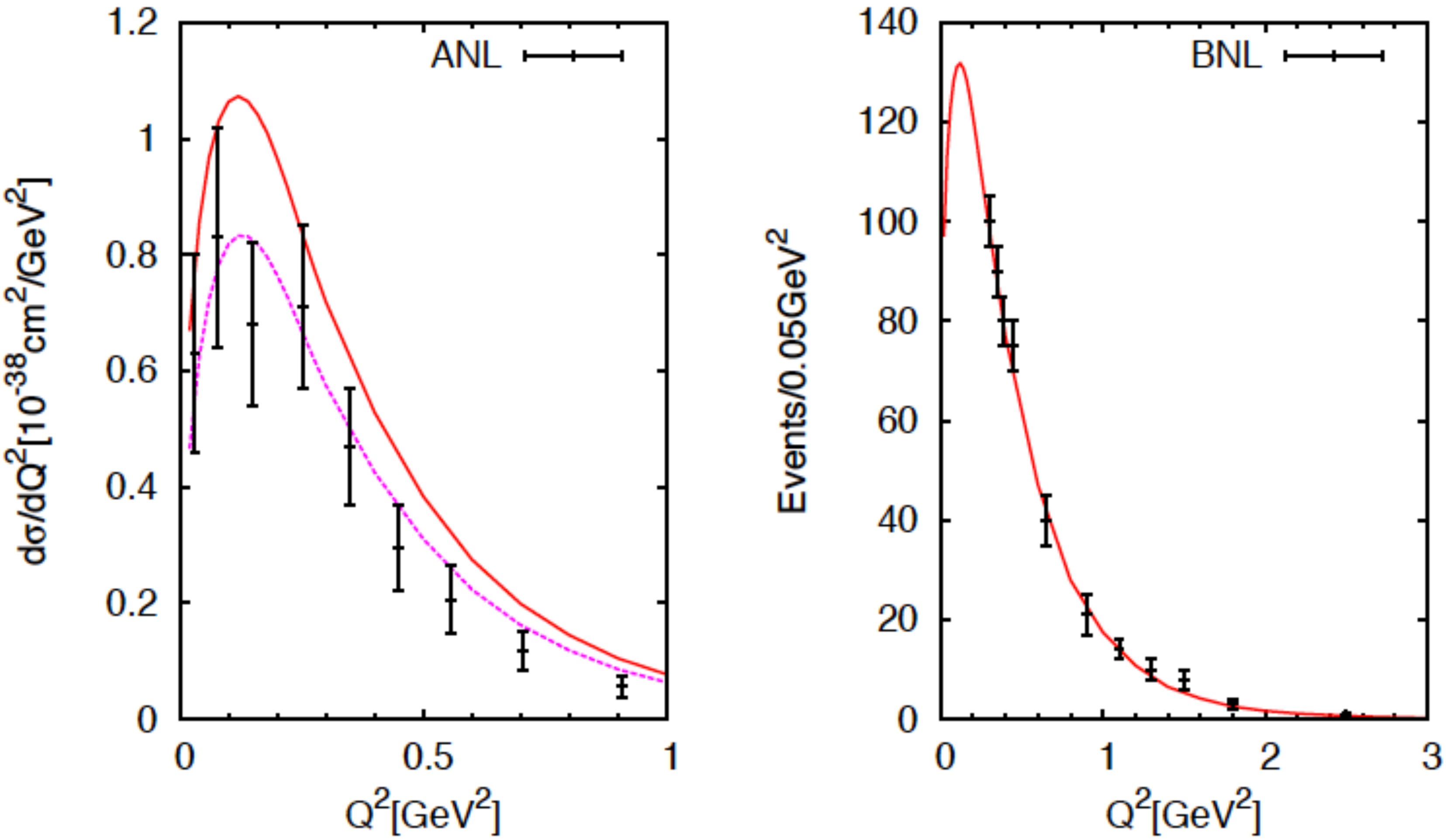
E_ν = 2 GeV

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



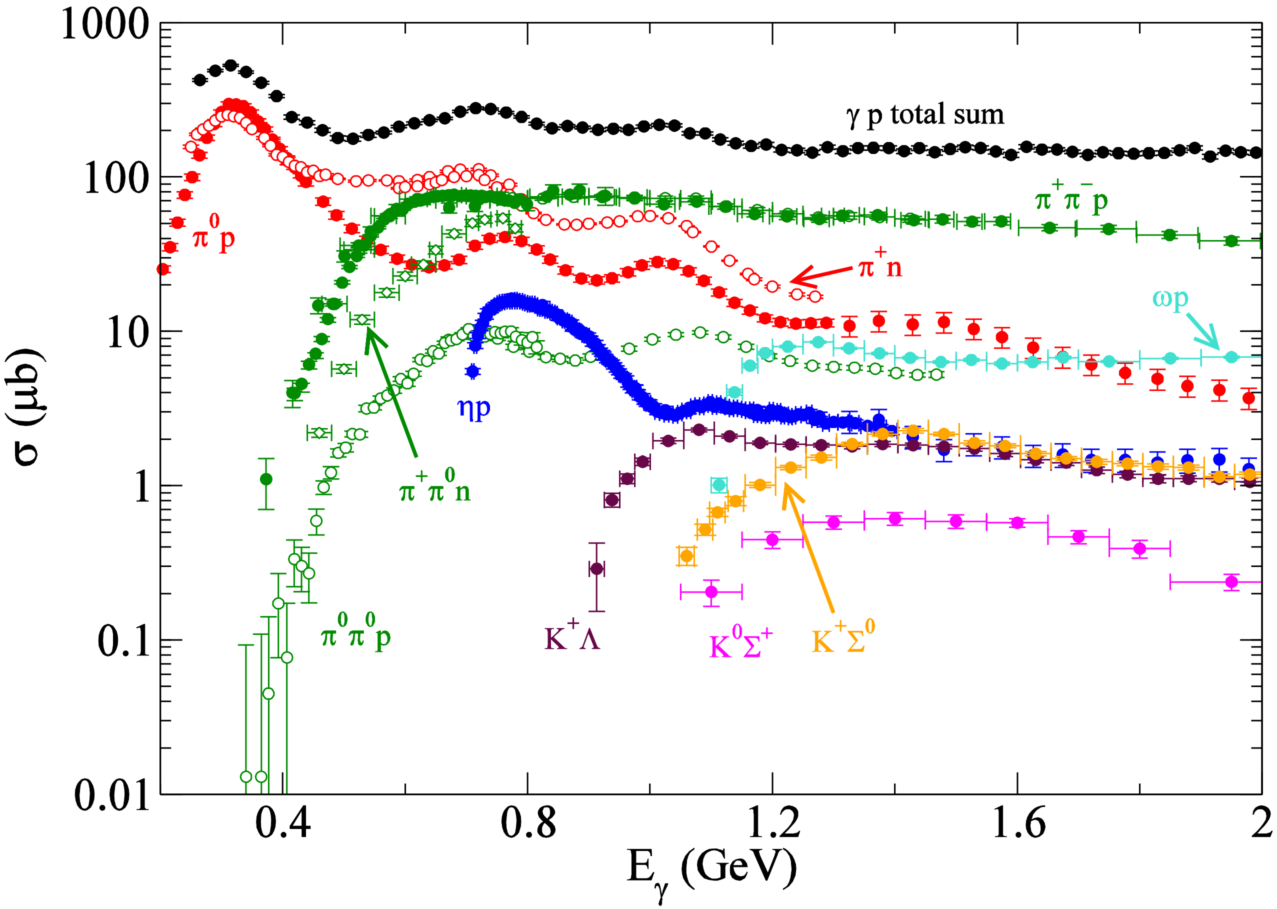
Q^2 – dependence

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



Resonance region (single nucleon)

$\gamma N \rightarrow X$

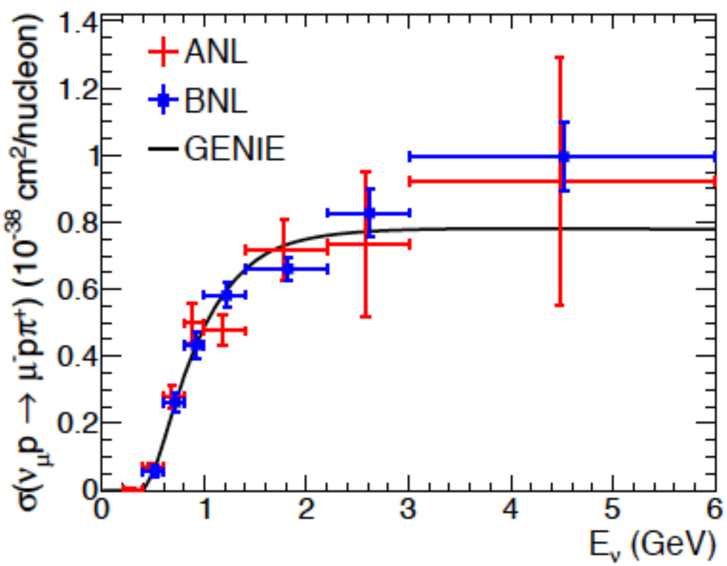


Multi-channel reaction

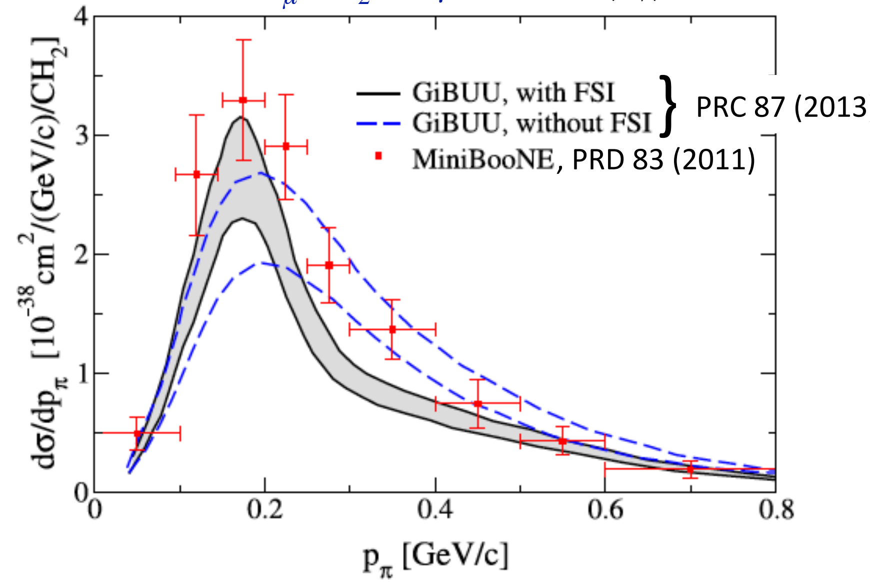
- 2π production is comparable to 1π
- η, K productions ($\boldsymbol{\nu}$ case: background of proton decay exp.)

Neutrino interaction data in resonance region

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



$\nu_\mu CH_2 \rightarrow \mu^- \pi^0 X$ $\langle E_\nu \rangle = 0.8$ GeV



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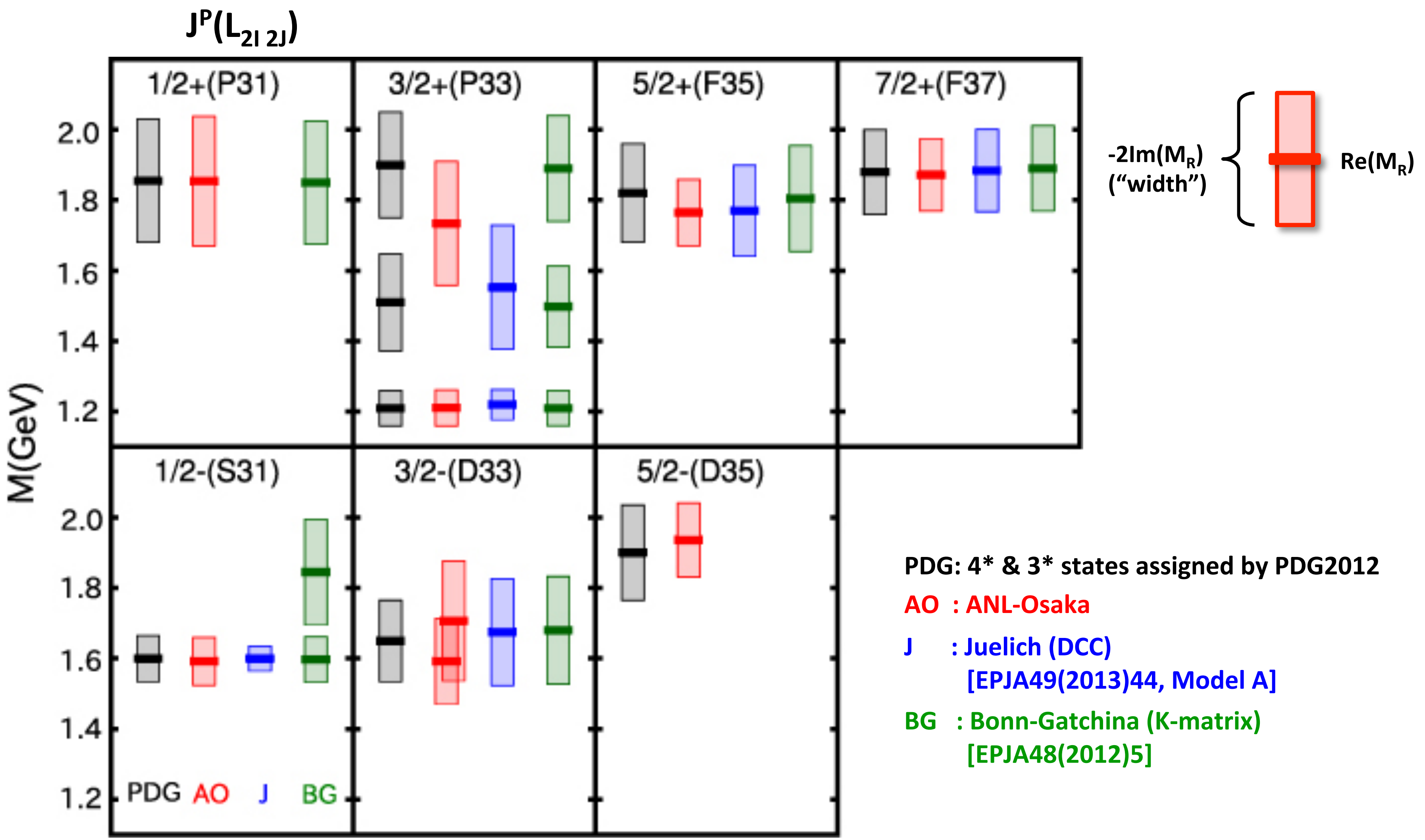
- Discrepancy between BNL & ANL data
- Recent reanalysis of original data
  → discrepancy resolved (!?)
  PRD 90, 112017 (2014)

- Final state interaction (FSI) changes charge, momentum, number of π
- Cross section shape is worse described with FSI
- MINERνA data (arXiv:1406.6415) favor FSI
  $\langle E_\nu \rangle = 4.0$ GeV

More data are coming → better understanding of neutrino-nucleus interaction

"Δ" resonances (I=3/2)

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



PDG: 4* & 3* states assigned by PDG2012

AO : ANL-Osaka

J : Juelich (DCC) [EPJA49(2013)44, Model A]

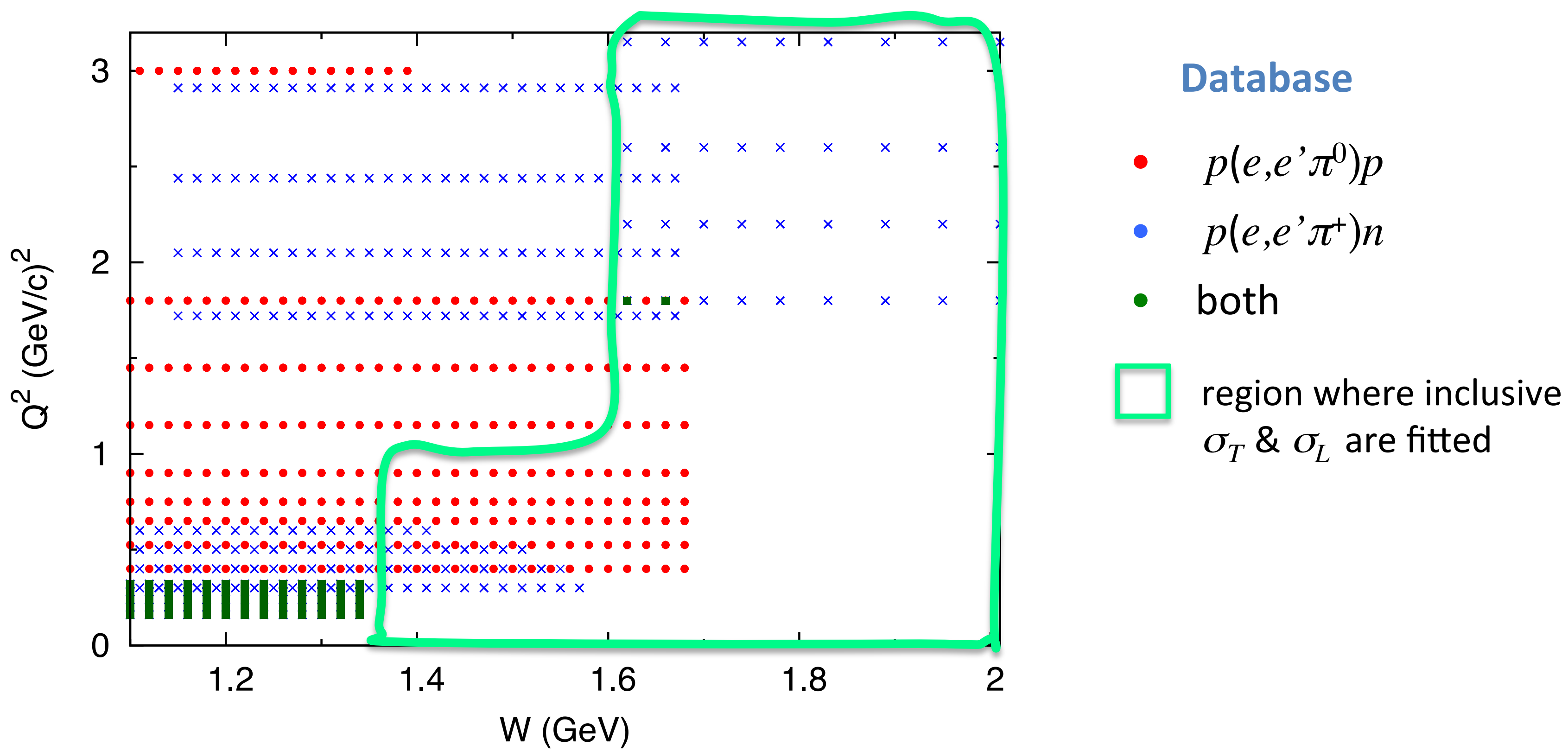
BG : Bonn-Gatchina (K-matrix) [EPJA48(2012)5]

Analysis of electron-proton scattering data

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

Data : * 1π electroproduction

* Empirical inclusive inelastic structure functions σ_T, σ_L ← Christy et al, PRC 81 (2010)



Analysis of electron-'neutron' scattering data

Purpose : Vector coupling of neutron-N^* and its Q^2 –dependence : $VnN^*(Q^2)$ $(I=1/2)$

$I=3/2$ part has been fixed by proton target data

Data : * 1π photoproduction ($Q^2=0$)

* Empirical inclusive inelastic structure functions σ_T, σ_L ($Q^2\neq0$)

← Christy and Bosted, PRC 77 (2010), 81 (2010)

Done

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

Formalism

Cross section for $\nu N \rightarrow l X$ ($X = \pi N, \pi\pi N, \eta N, K\Lambda, K\Sigma$)

$\theta \rightarrow 0$

$$\frac{d\sigma}{dE_\ell d\Omega_\ell} = \frac{G_F^2}{2\pi^2} E_\ell^2 \left(\cancel{2W_1 \sin^2\frac{\theta}{2}} + W_2 \cos^2\frac{\theta}{2} \pm \cancel{W_3 \frac{E_\nu + E_\ell}{m_N} \sin^2\frac{\theta}{2}} \right)$$

$Q^2 \rightarrow 0$

$$W_2 = \frac{Q^2}{\vec{q}^2} \sum \left[\cancel{\frac{1}{2}\left(|\langle J^x\rangle|^2 + |\langle J^y\rangle|^2\right)} + \frac{Q^2}{\vec{q}_c^2} \left| \left\langle \cancel{J^0} + \frac{\omega_c}{Q^2} q \cdot J \right\rangle \right|^2 \right]$$

CVC & PCAC

$$\langle q \cdot J \rangle = \langle q \cdot V \rangle - \langle q \cdot A \rangle = i f_\pi m_\pi^2 \langle \hat{\pi} \rangle$$

LSZ & smoothness

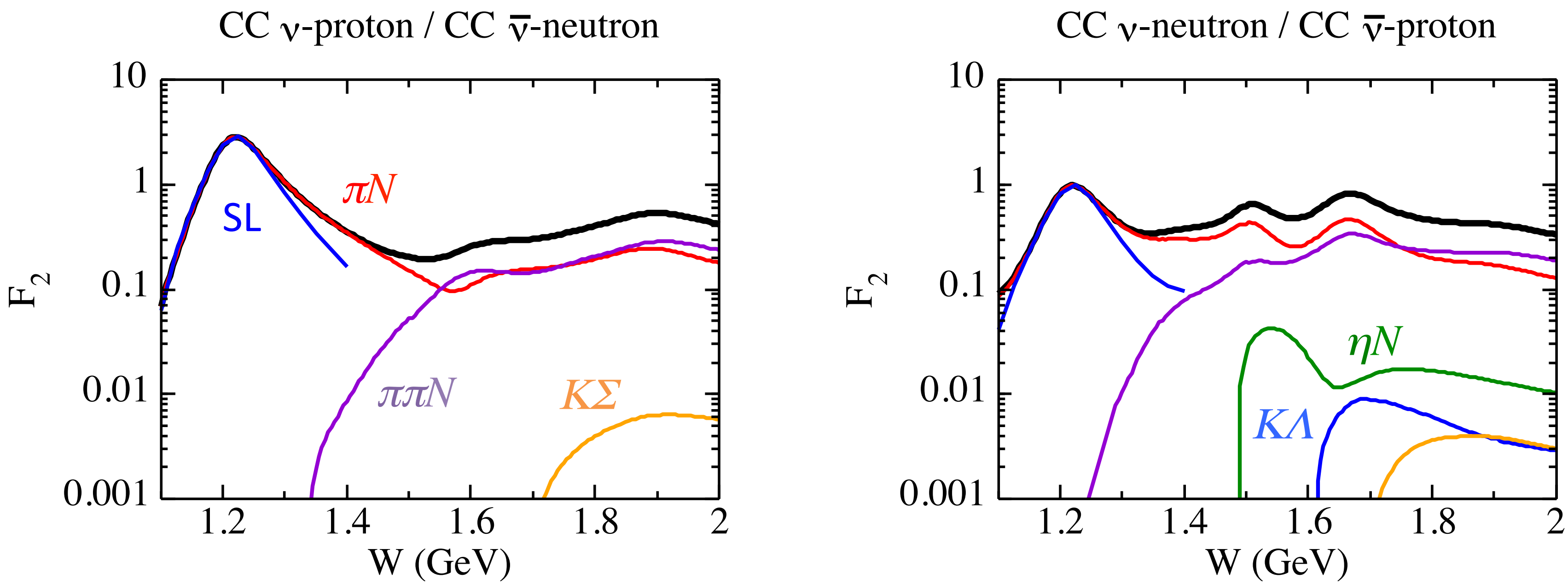
$$\langle X | \hat{\pi} | N \rangle = \frac{\sqrt{2\omega_c}}{m_\pi^2} \mathcal{T}_{\pi N \to X}(0) \sim \frac{\sqrt{2\omega_c}}{m_\pi^2} \mathcal{T}_{\pi N \to X}(m_\pi^2)$$

Finally

$$F_2 \equiv \omega W_2 = \frac{2 f_\pi^2}{\pi} \sigma_{\pi N \to X}$$

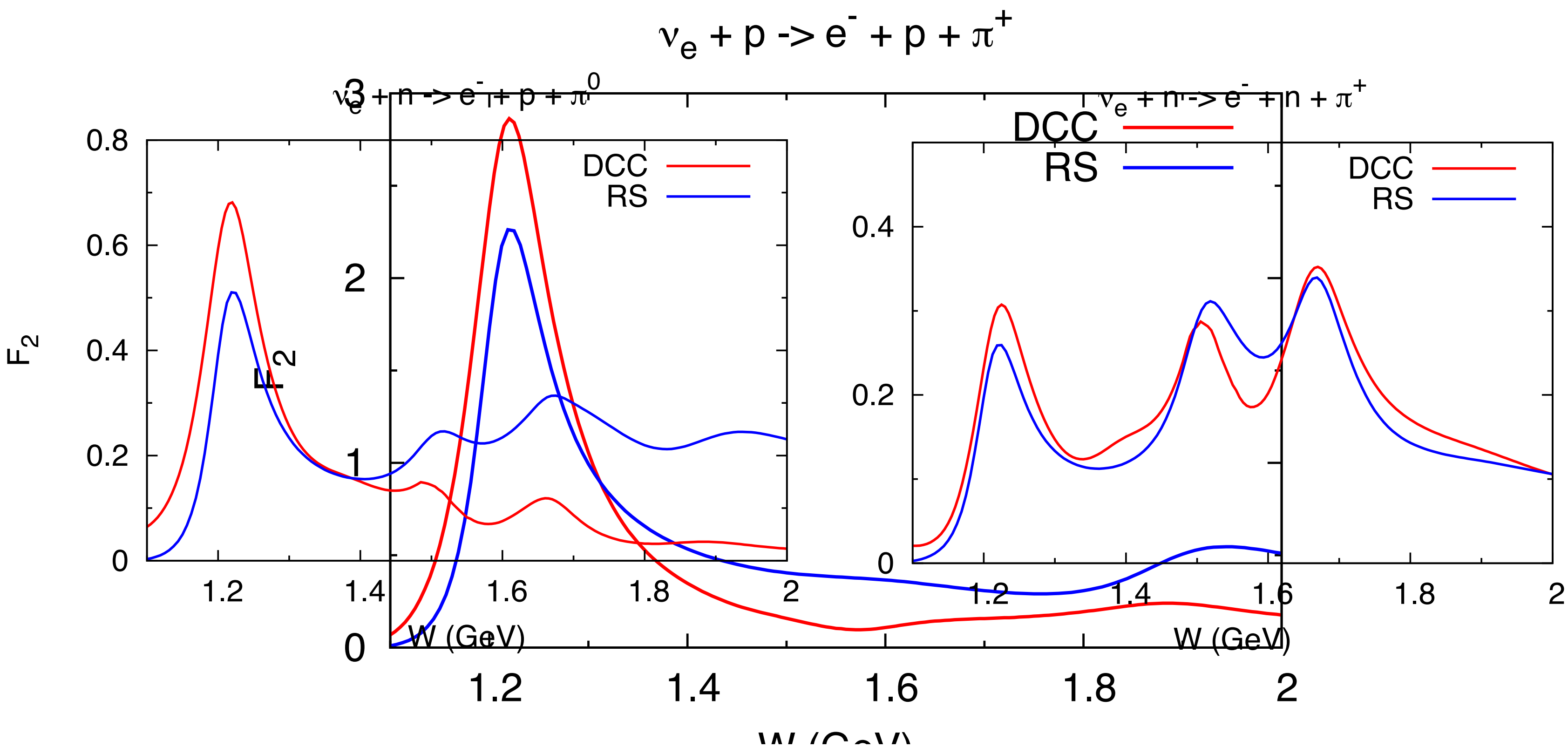
$\sigma_{\pi N \rightarrow X}$ is from our DCC model

Results



- Prediction based on model well tested by data (first $\nu N \rightarrow \pi\pi N$)
- πN dominates for $W \leq 1.5$ GeV
- $\pi\pi N$ becomes comparable to πN for $W \geq 1.5$ GeV
- Smaller contribution from ηN and KY $O(10^{-1})$ - $O(10^{-2})$
- Agreement with SL (no PCAC) in Δ region

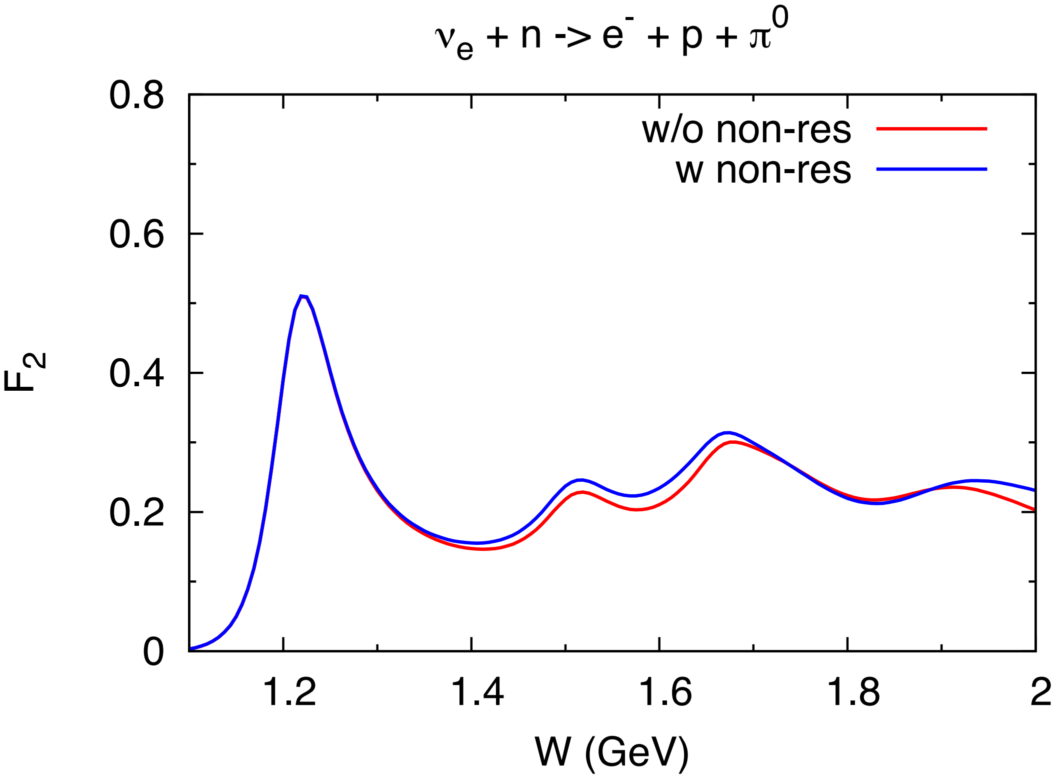
Comparison with Rein-Sehgal model



Comparison in whole kinematical region will be done

after axial current model is developed

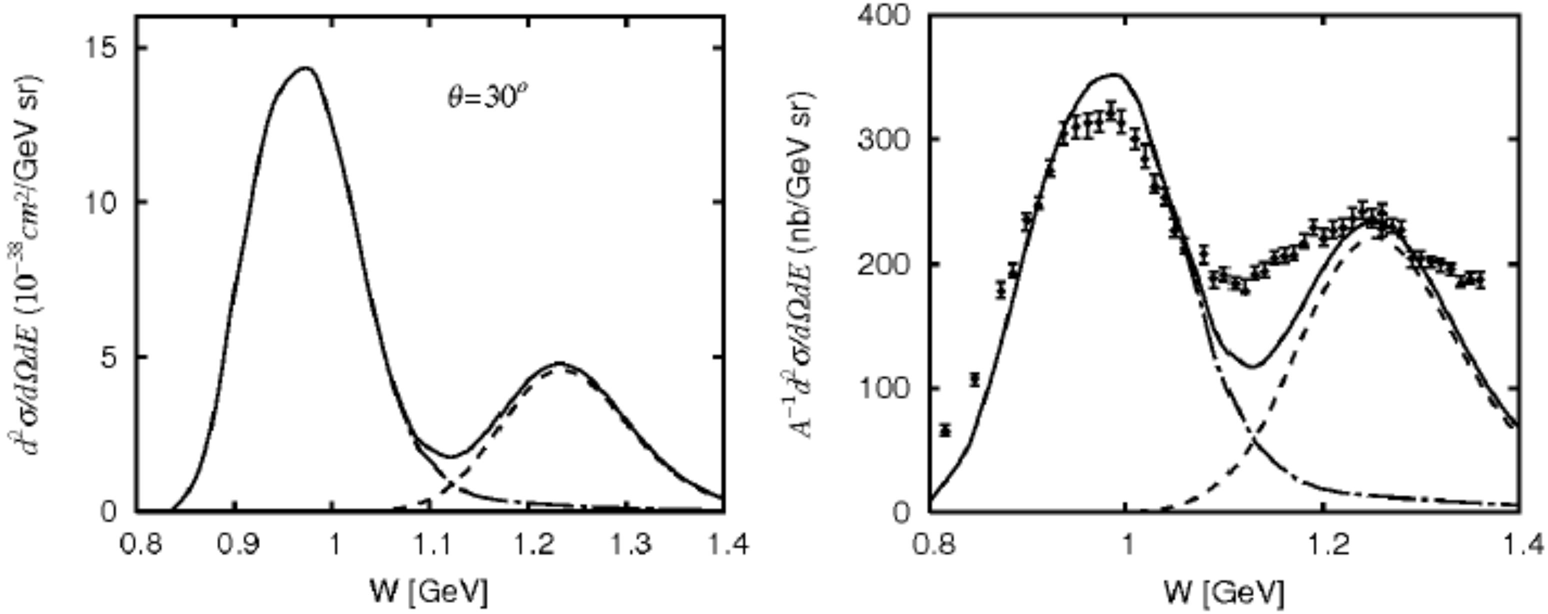
F_2 from RS model



SL model applied to ν−nucleus scattering

1 π production

$\nu_e + {}^{12}\mathrm{C} \rightarrow e^- + X$ ($E_\nu = 1$ GeV) $\quad$ $e^- + {}^{12}\mathrm{C} \rightarrow e^- + X$ ($E_e = 1.1$ GeV)

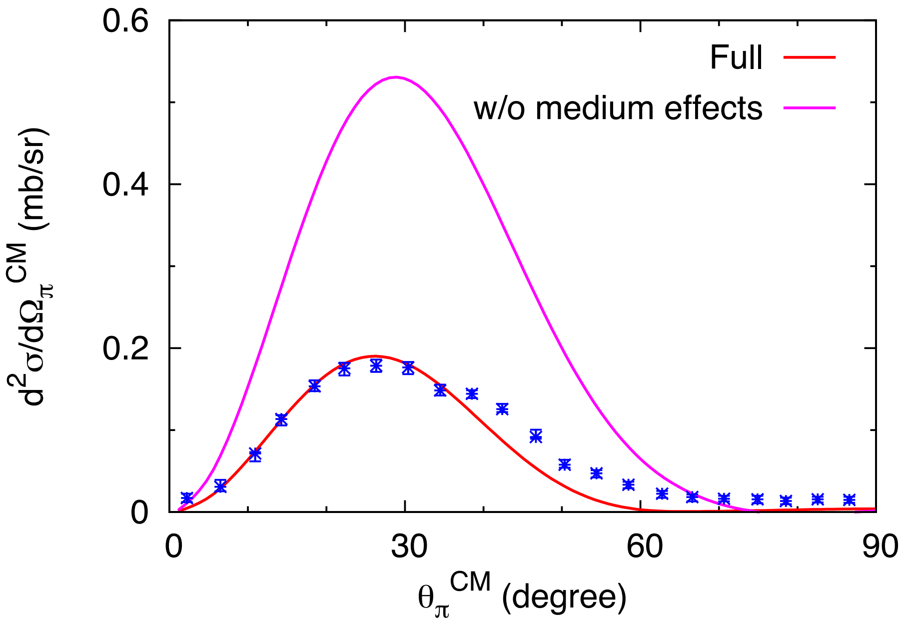


Szczerbinska et al. (2007)

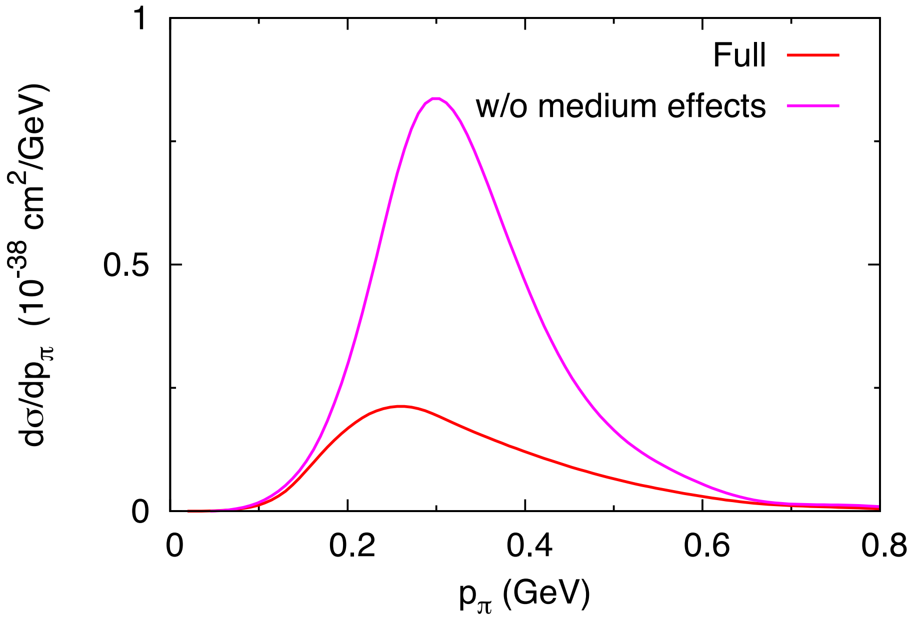
SL model applied to ν−nucleus scattering

coherent π production

$\gamma + {}^{12}C \rightarrow \pi^0 + {}^{12}C$



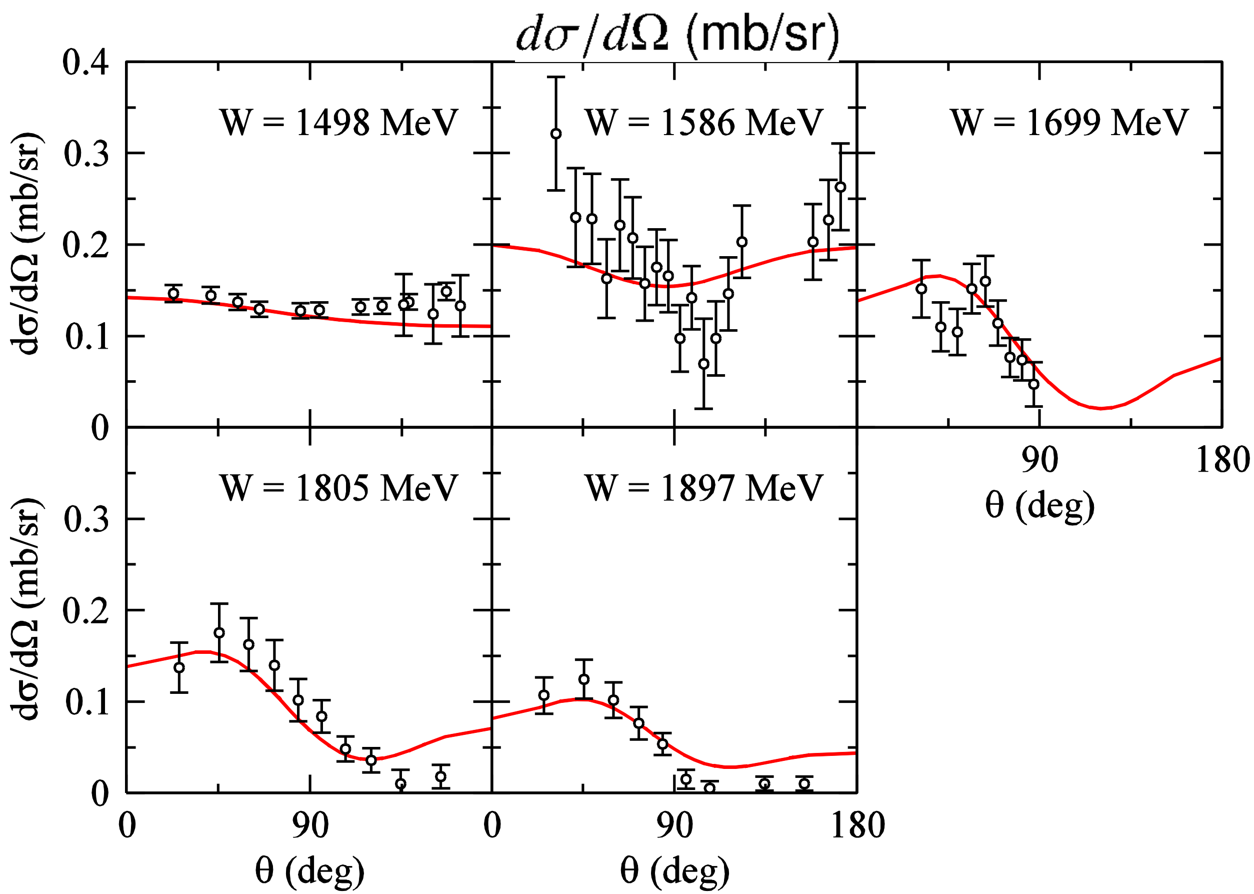
$\nu_\mu + {}^{12}C \rightarrow \mu^- + \pi^0 + {}^{12}C$



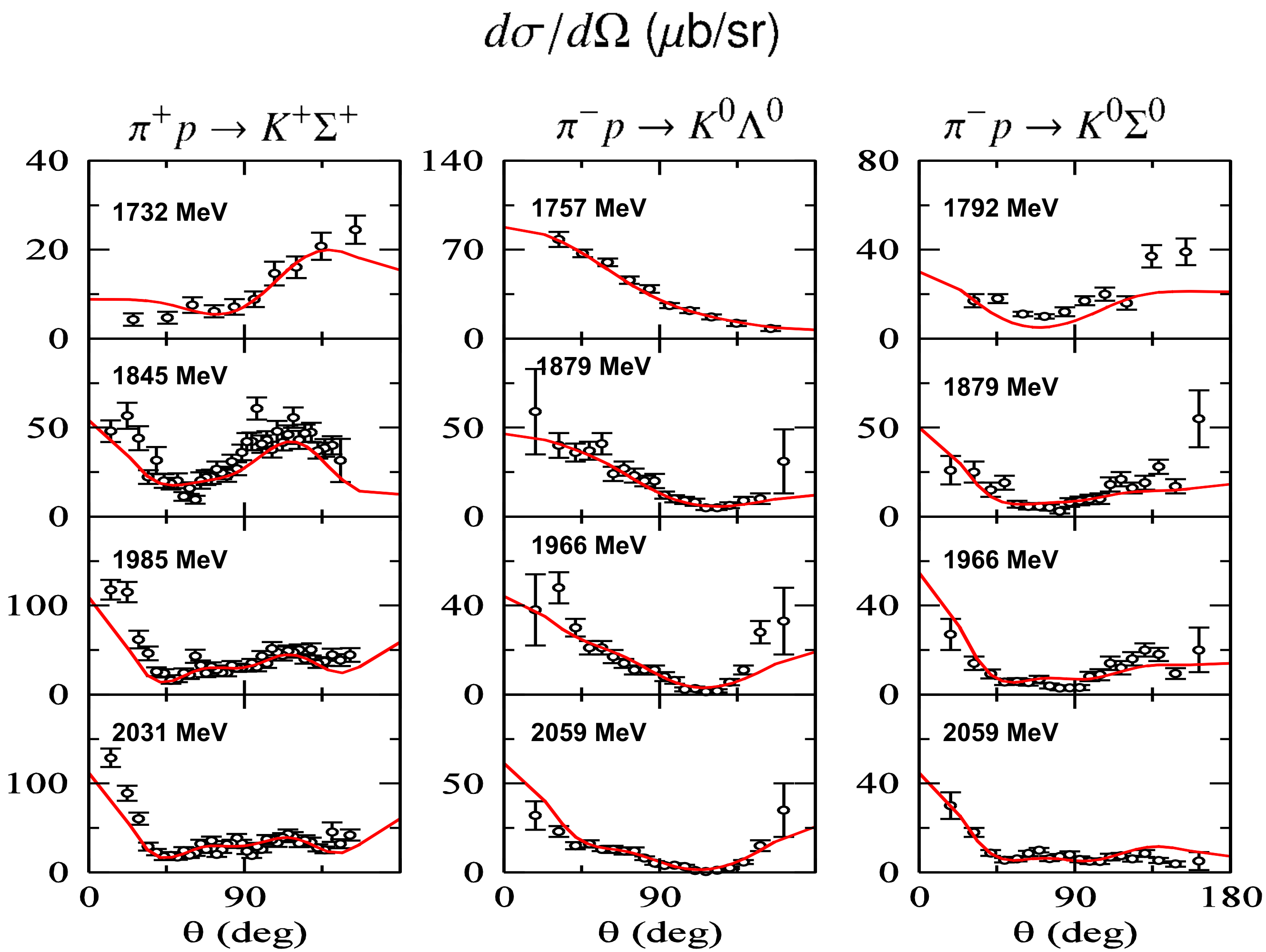
Nakamura et al. (2010)

Eta production reactions

$$\pi^- p \to \eta n$$



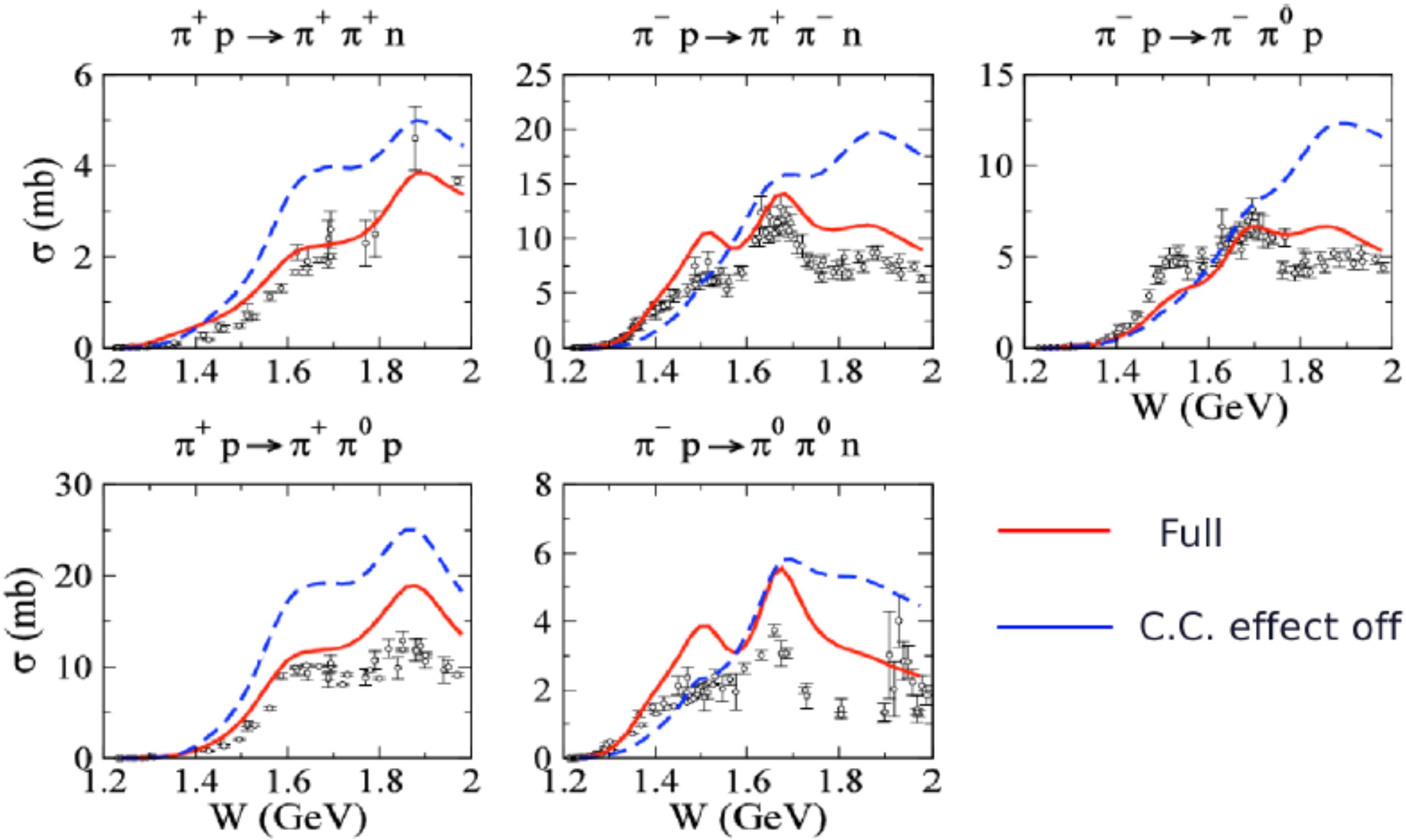
KY production reactions

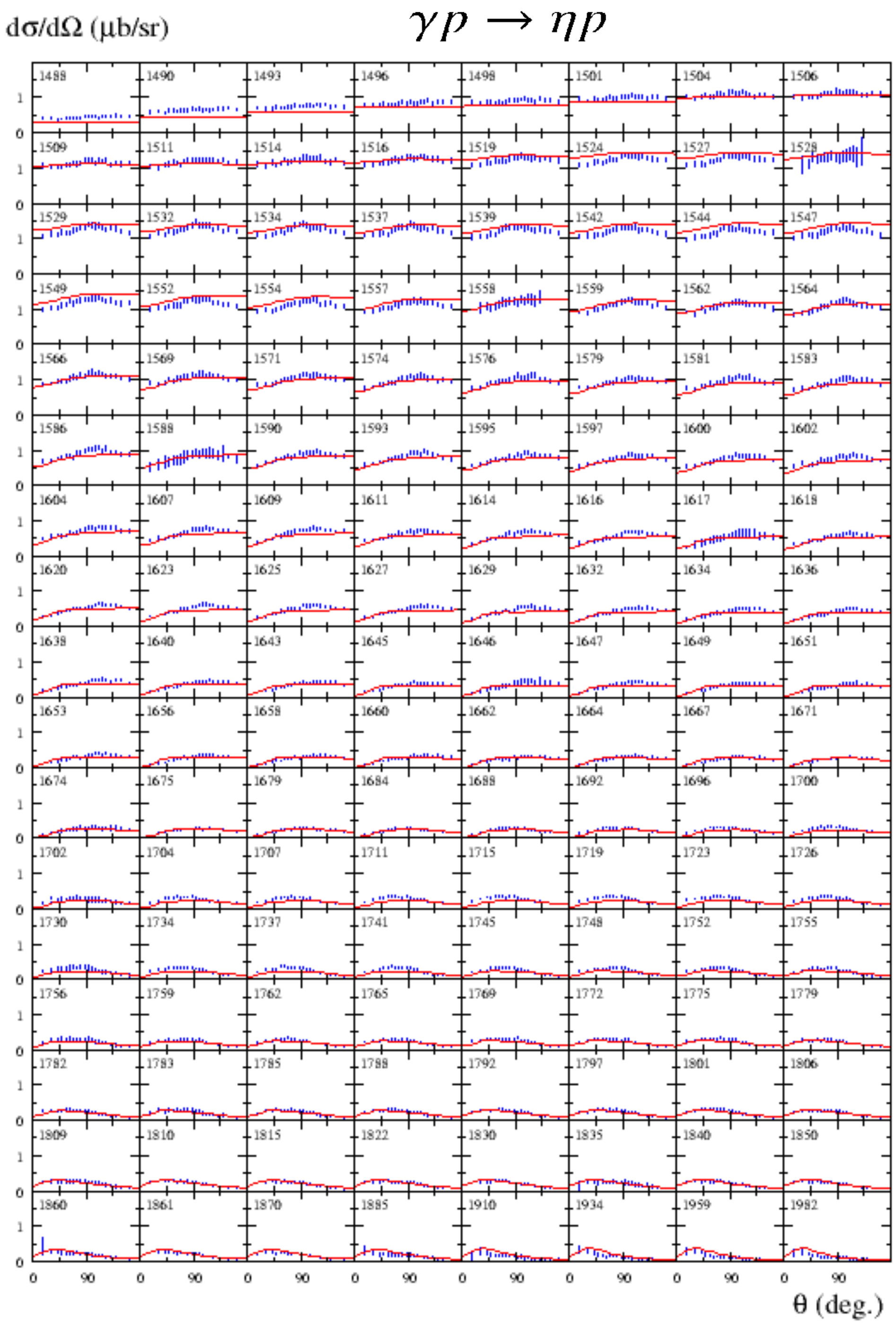


$\pi N \to \pi\pi N$

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

Kamano, Julia-Diaz, Lee, Matsuyama, Sato, PRC79 025206 (2009)





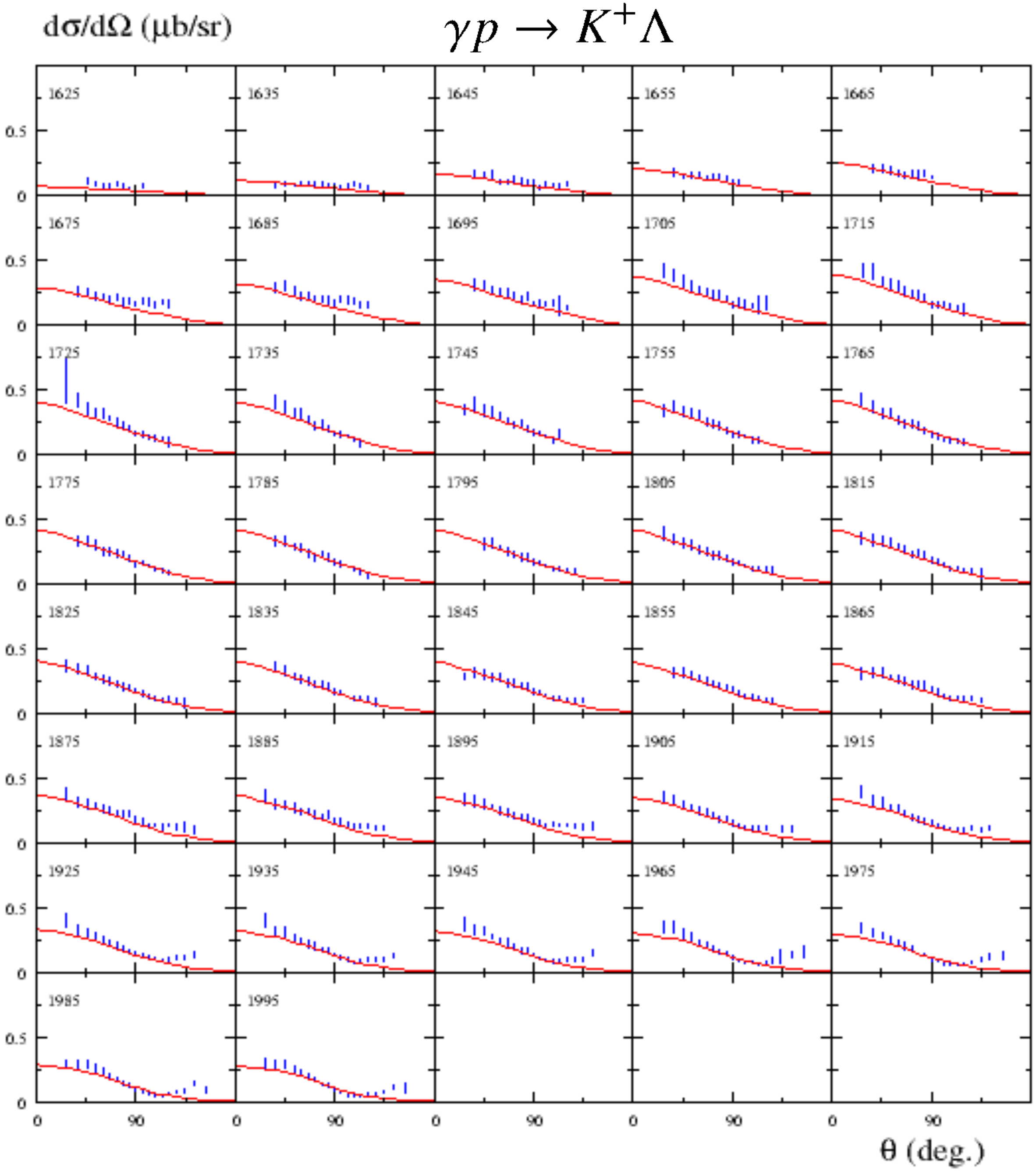
Kamano, Nakamura, Lee, Sato, arXiv:1305.4351

Vector current (Q^2=0) for η

Production is well-tested by data

$\gamma p \rightarrow K^+ \Lambda$

Kamano, Nakamura, Lee, Sato, arXiv:1305.4351



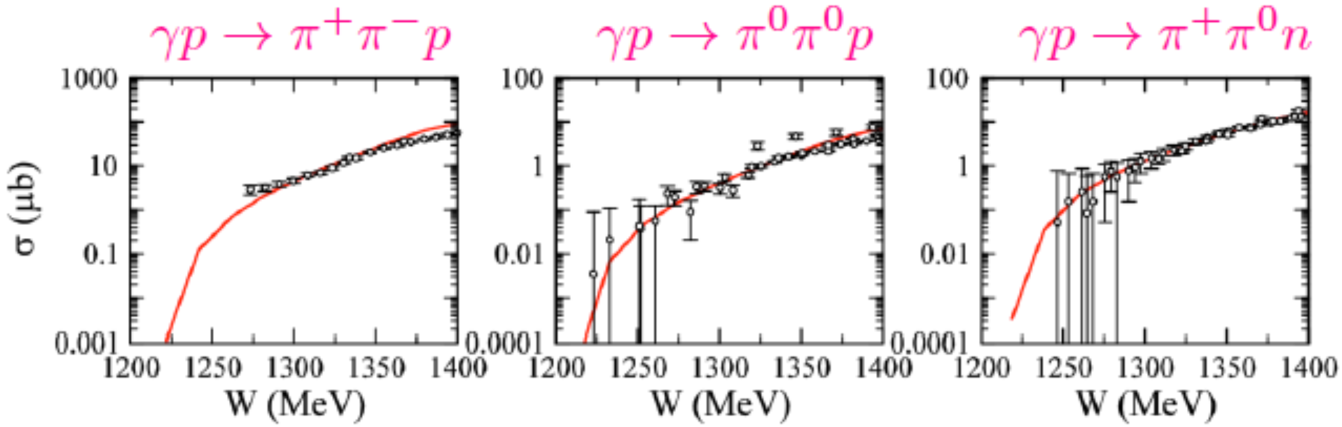
Vector current (Q^2=0) for K

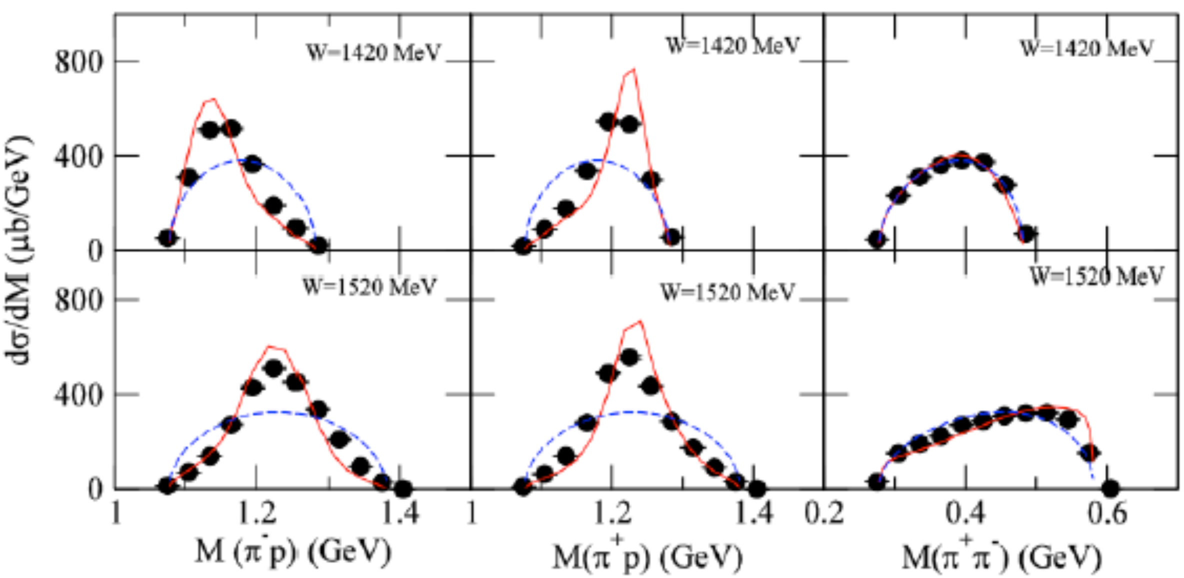
Production is well-tested by data

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

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

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





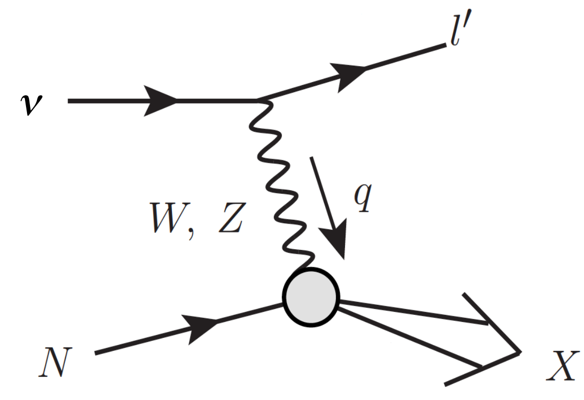
- ∗ Good description near threshold
- ∗ Good shape of invariant mass distribution
- ∗ Total cross sections overestimate data for $W \geq 1.5$ GeV

DCC model for neutrino interaction

$\nu N \rightarrow l\,X \quad (X = \pi N, \pi\pi N, \eta N, K\Lambda, K\Sigma)$

at forward limit Q^2=0

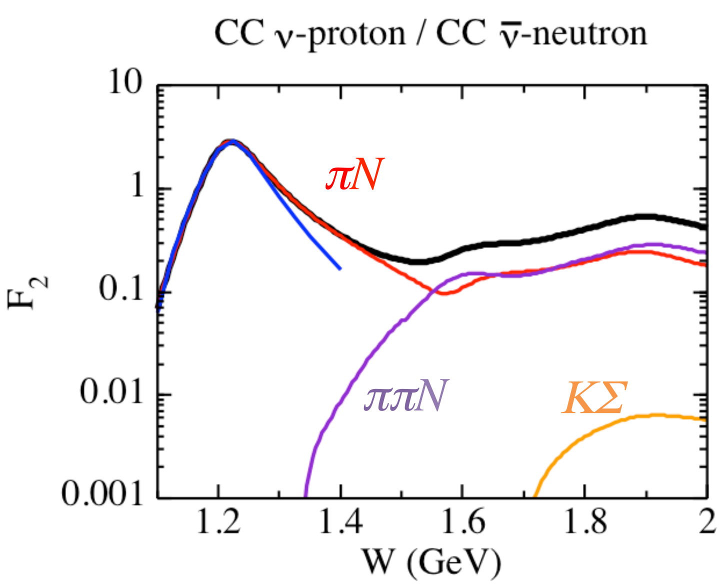
Kamano, Nakamura, Lee, Sato, PRD 86 (2012)



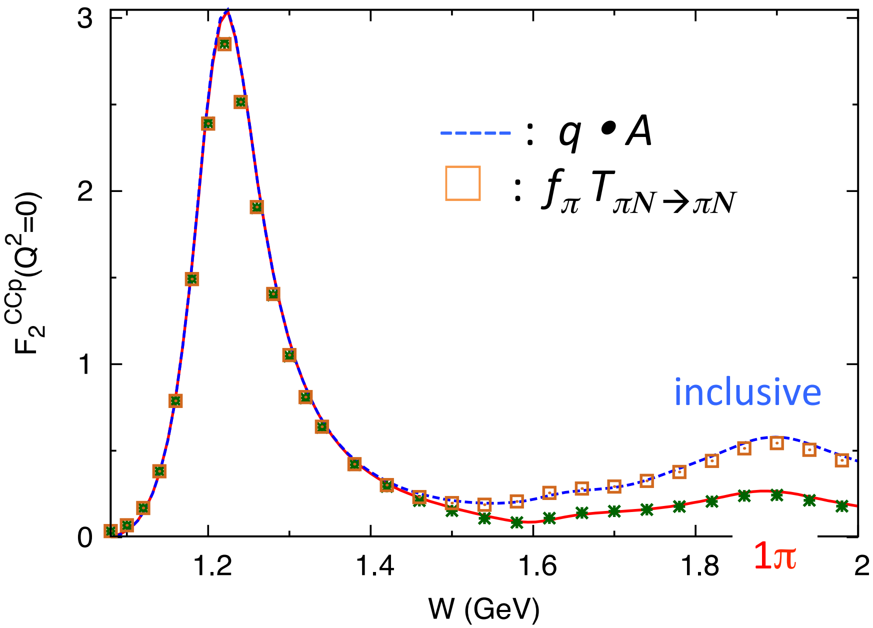
$$\frac{d\sigma}{dE_\ell d\Omega_\ell} = \frac{G_F^2}{2\pi^2} E_\ell^2\, W_2$$

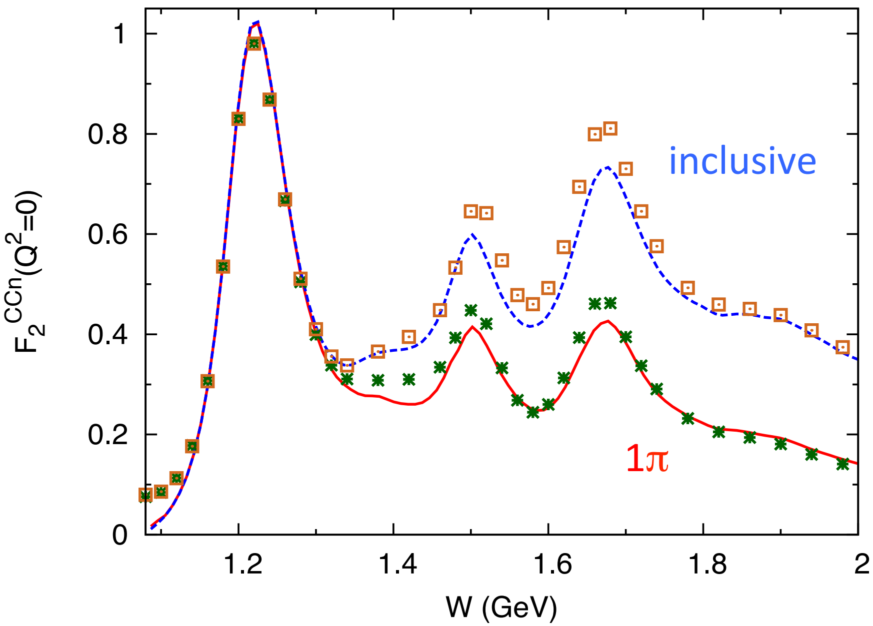
via PCAC $$F_2 \equiv \omega W_2 = \frac{2 f_\pi^2}{\pi} \sigma_{\pi N \to X}$$

$\sigma_{\pi N \rightarrow X}$ is from our DCC model



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

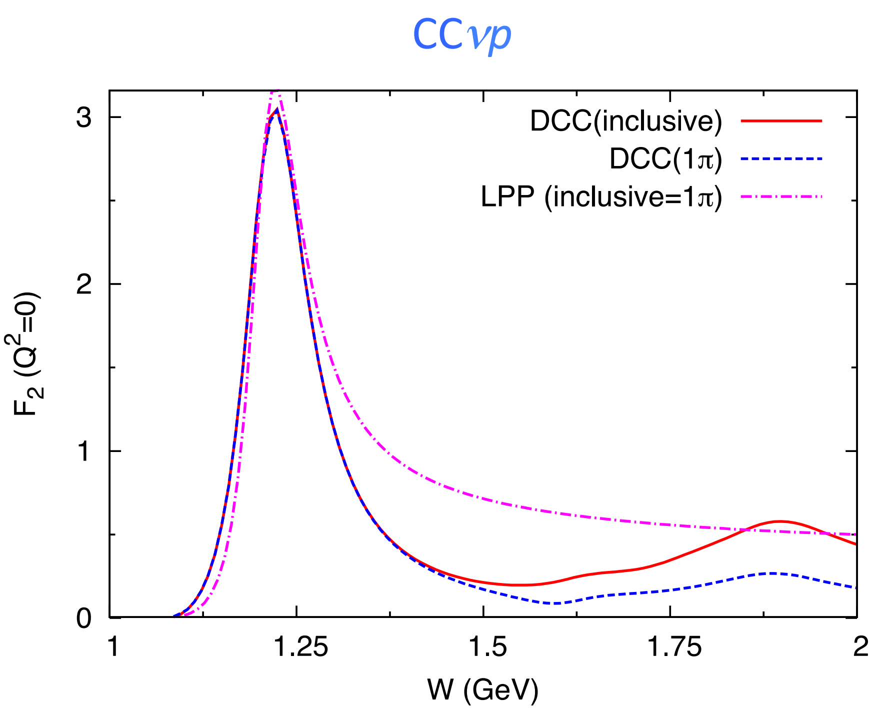


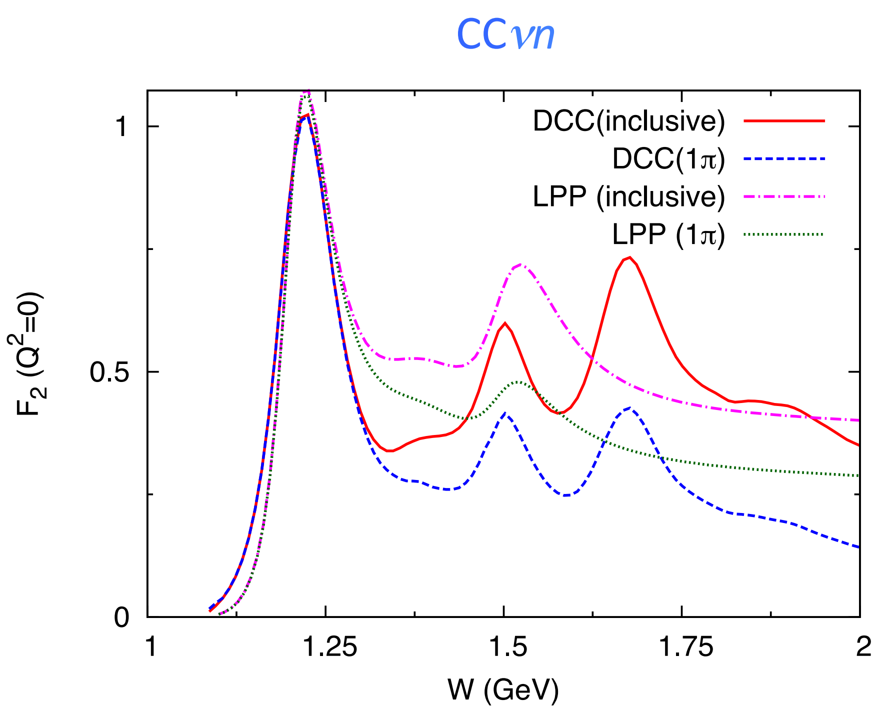


DCC model keeps good consistency with PCAC

Comparison with LPP model

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



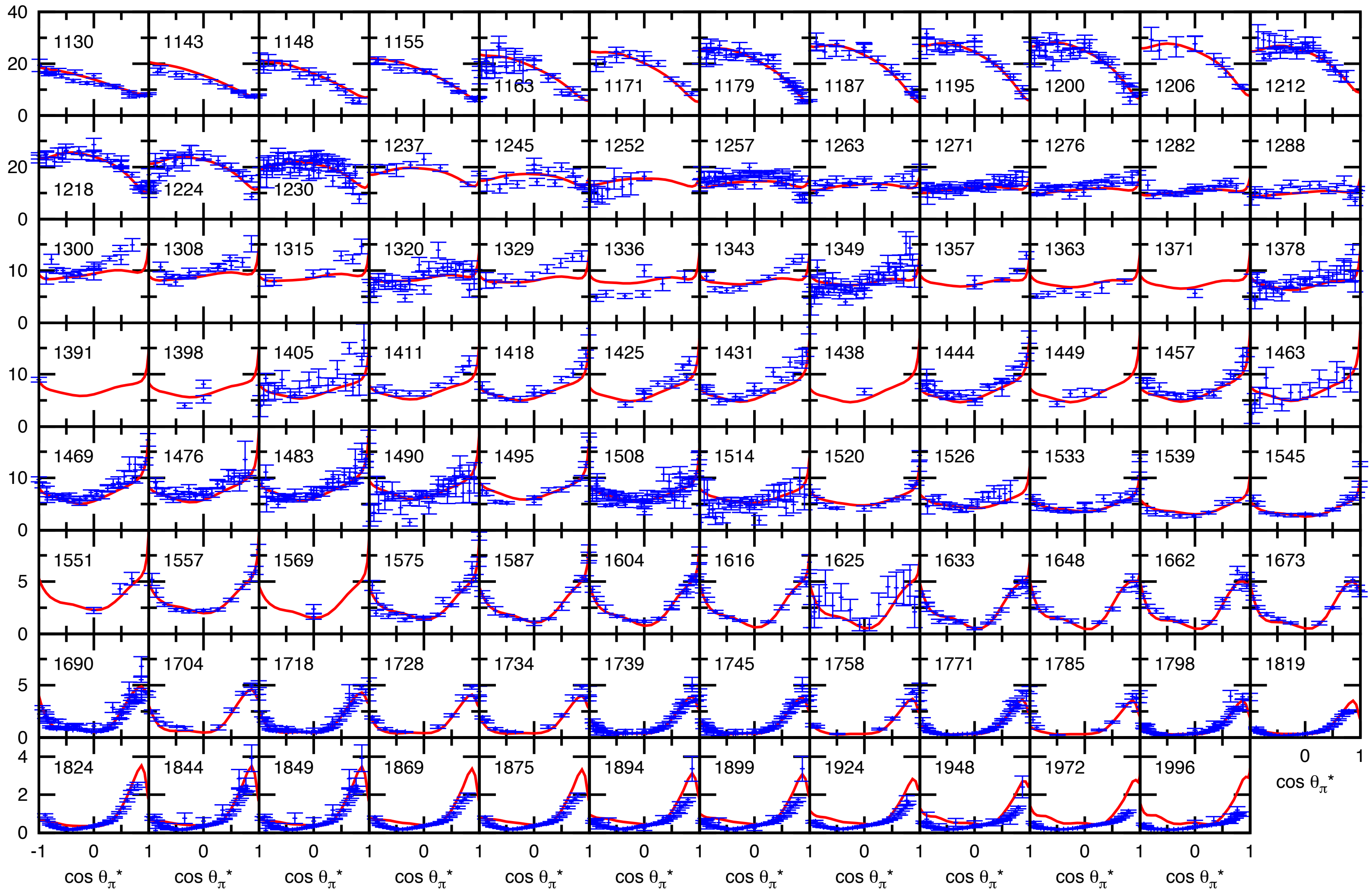


- Large difference beyond $\Delta(1232)$ region
- Importance of consistency between axial-current and πN interaction

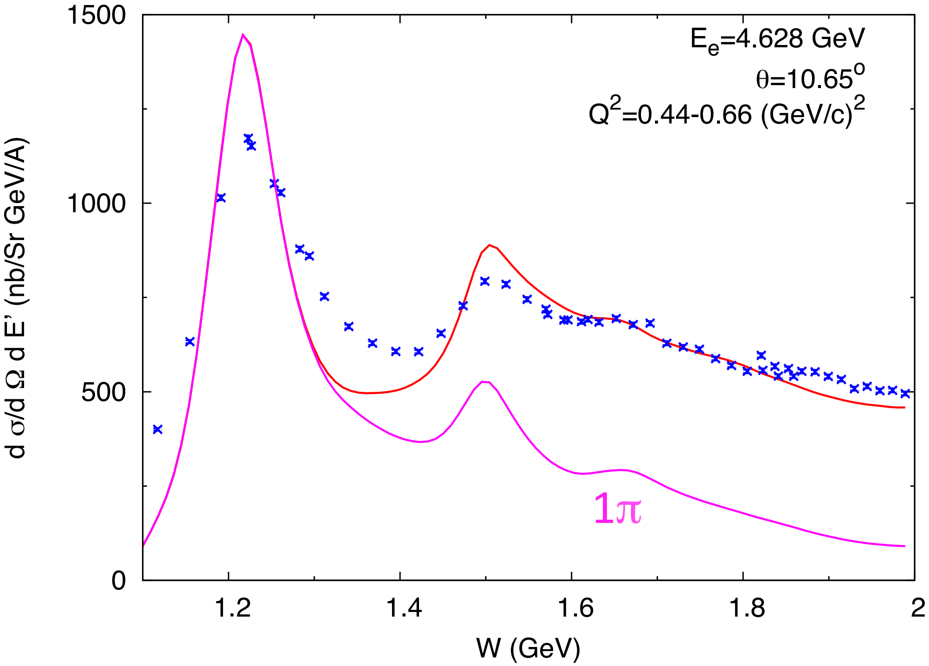
Analysis result (single π)

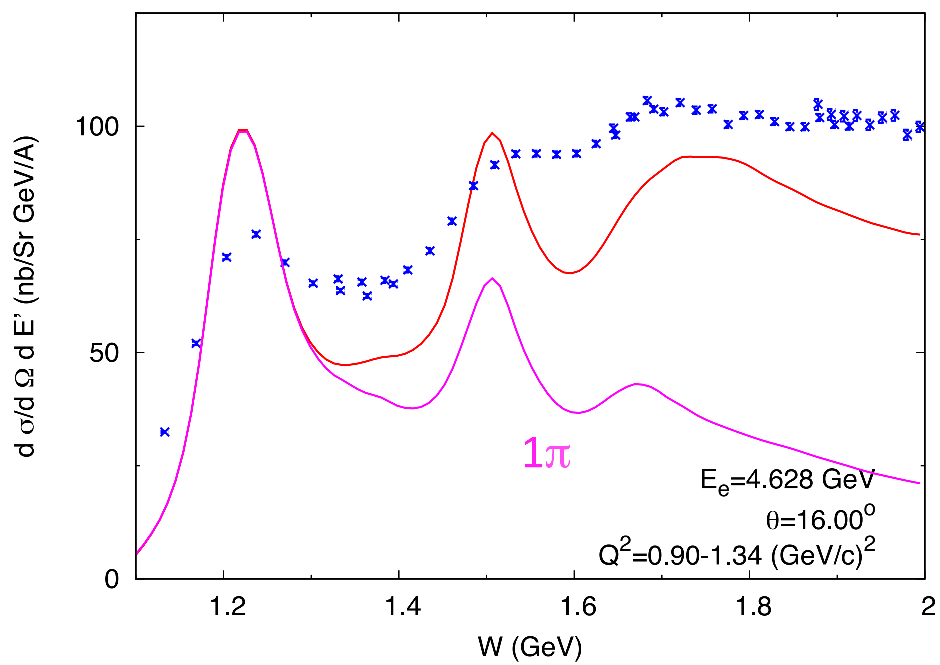
Q^2=0

$d\sigma / d\Omega$ $(\gamma n \rightarrow \pi^- p)$ for W=1.1 – 2.0 GeV



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

For application to neutrino interactions

Analysis of electron scattering data

➔ $VpN^*(Q^2)$ & $VnN^*(Q^2)$ fixed for several Q^2 values

➔ Parameterize $VpN^*(Q^2)$ & $VnN^*(Q^2)$ with simple analytic function of Q^2

I=3/2	:	$VpN^*(Q^2) = VnN^*(Q^2)$	➔	CC, NC
I=1/2 isovector part	:	$(\, VpN^*(Q^2) - VnN^*(Q^2)\,)\,/\,2$	➔	CC, NC
I=1/2 isoscalar part	:	$(\, VpN^*(Q^2) + VnN^*(Q^2)\,)\,/\,2$	➔	NC

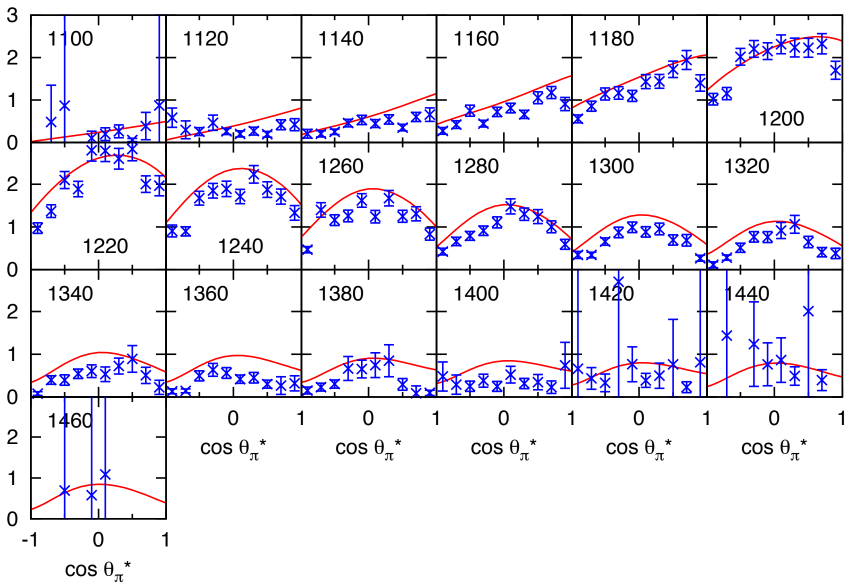
DCC vector currents has been tested by data for whole kinematical region relevant to neutrino interactions of $E_\nu \leq 2$ GeV

Analysis result (single π)

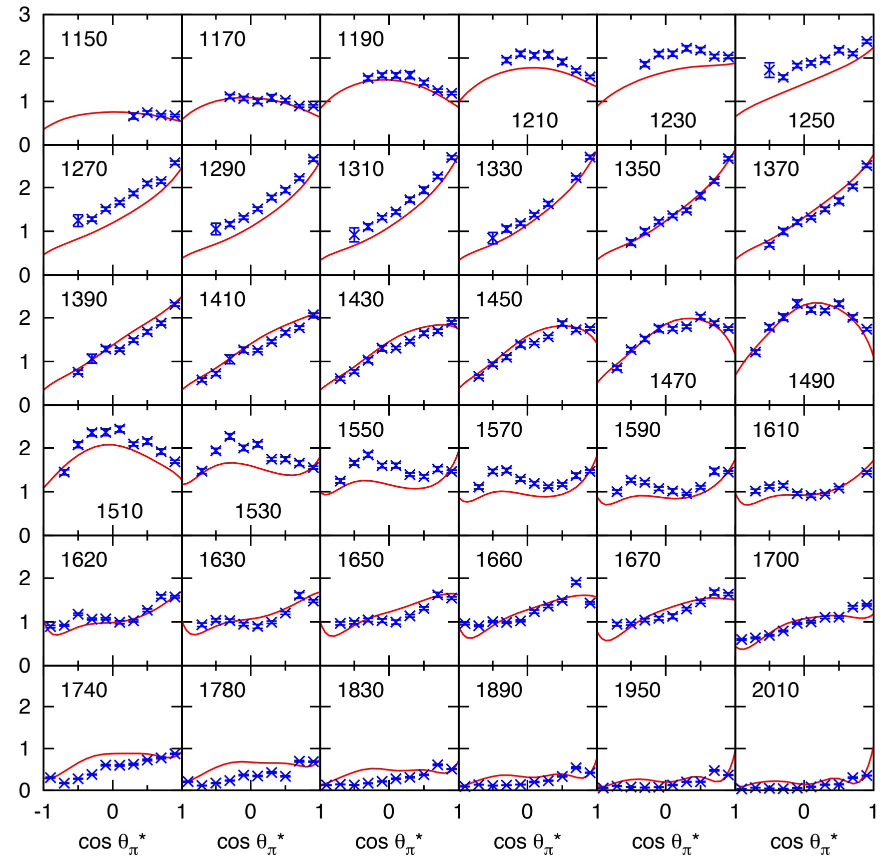
Q^2=1.76 (GeV/c)^2

$\sigma_T + \varepsilon\, \sigma_L$ for W=1.10 – 2.01 GeV

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



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

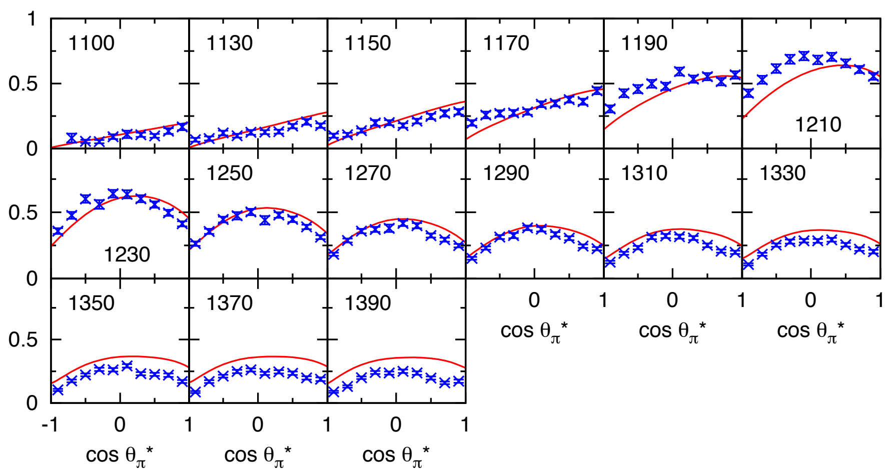


Analysis result (single π)

Q^2=2.91-3.00 (GeV/c)^2

$\sigma_T + \varepsilon\, \sigma_L$ for W=1.10 – 1.67 GeV

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



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