Meson Productions in Neutrino-Nucleon Reactions in Resonance Region

中村　聡

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Introduction

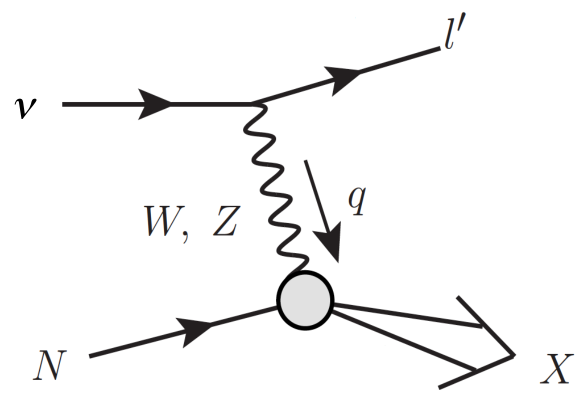
Neutrino-nucleus scattering for ν-oscillation experiments

All ν-oscillation experiments measure ν-flux through ν-nucleus interaction

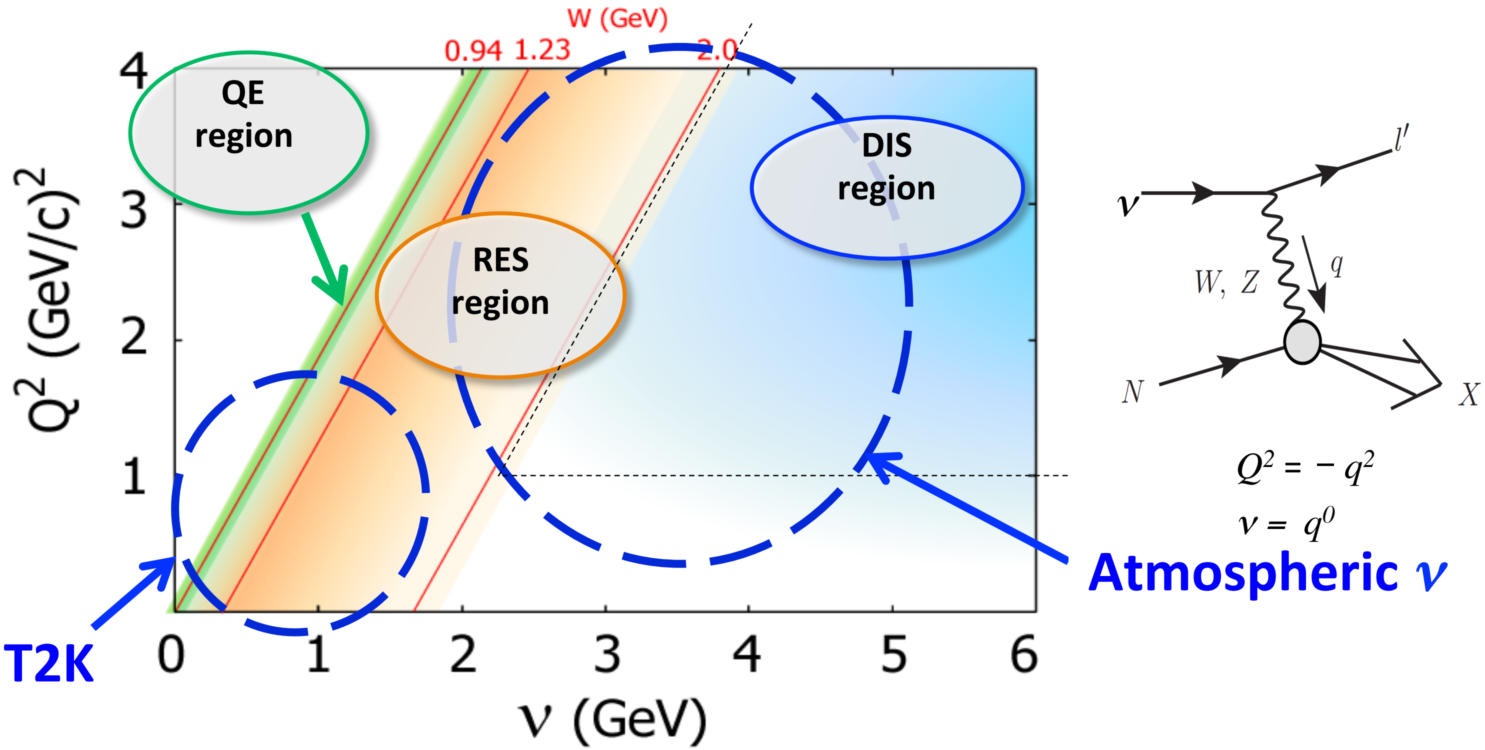
Next-generation exp. ➔ leptonic $\not{C}P$, mass hierarchy,
sterile neutrinos

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

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



Neutrino-nucleus scattering for ν-oscillation experiments



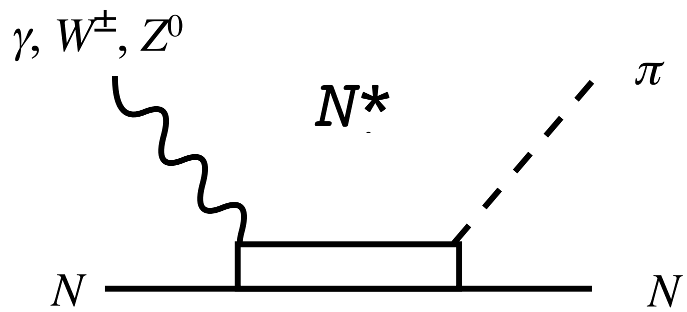
Collaboration at J-PARC Branch of KEK Theory Center

http://j-parc-th.kek.jp/html/English/e-index.html

A review article to be published in *Reports on Progress in Physics* (**arXiv:1610.01464**)

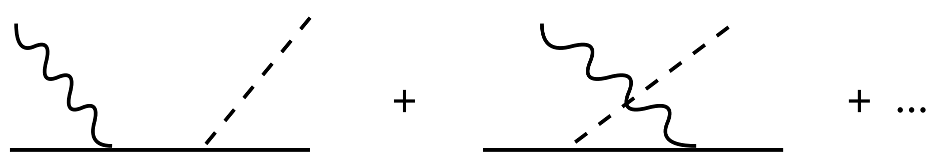
Resonance region

Main reaction mechanism : resonance excitations



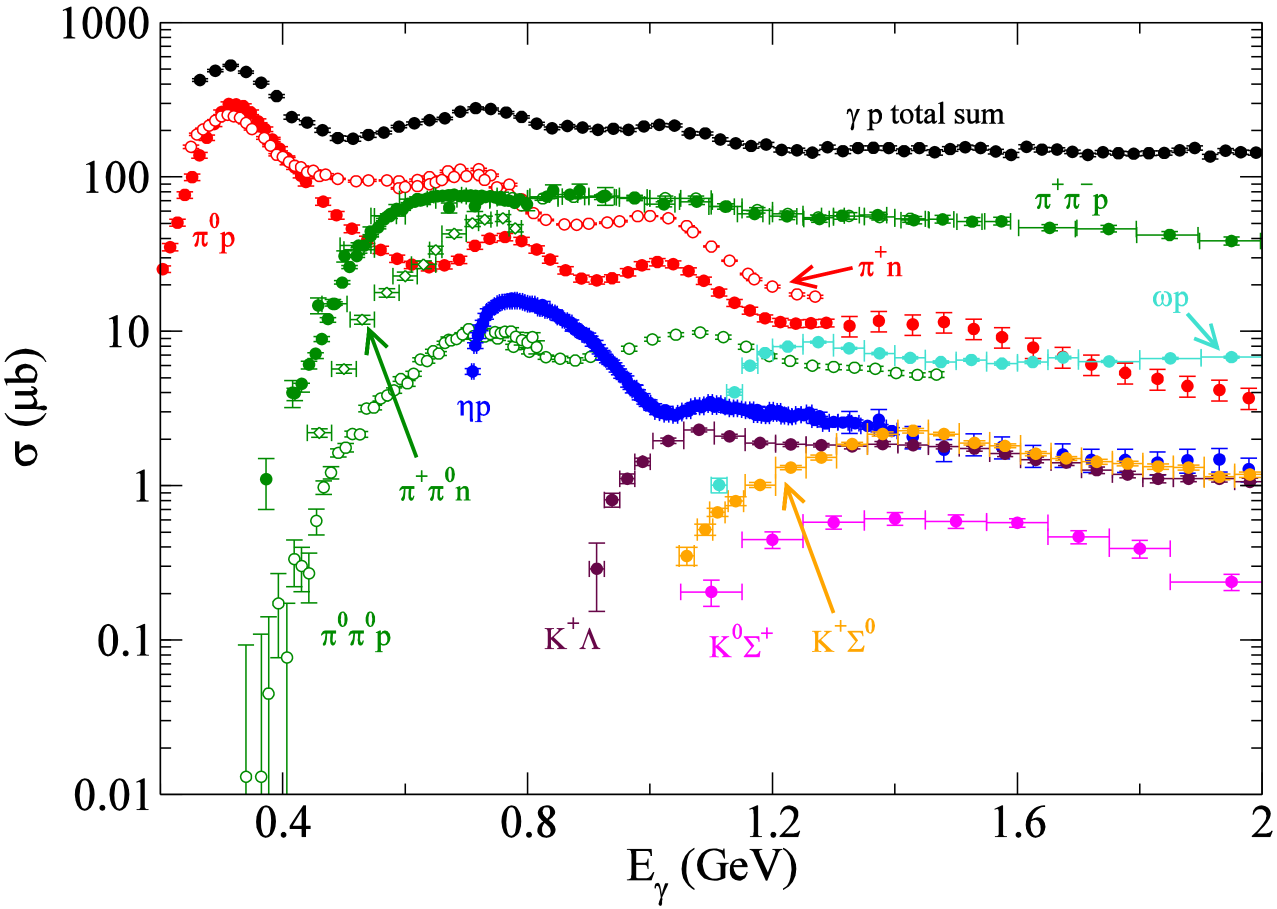
- N^* are unstable and strongly couple to meson-baryon continuum states
- Width ~ 100 MeV, several N^*'s are overlapping

(Sub-leading) non-resonant mechanisms



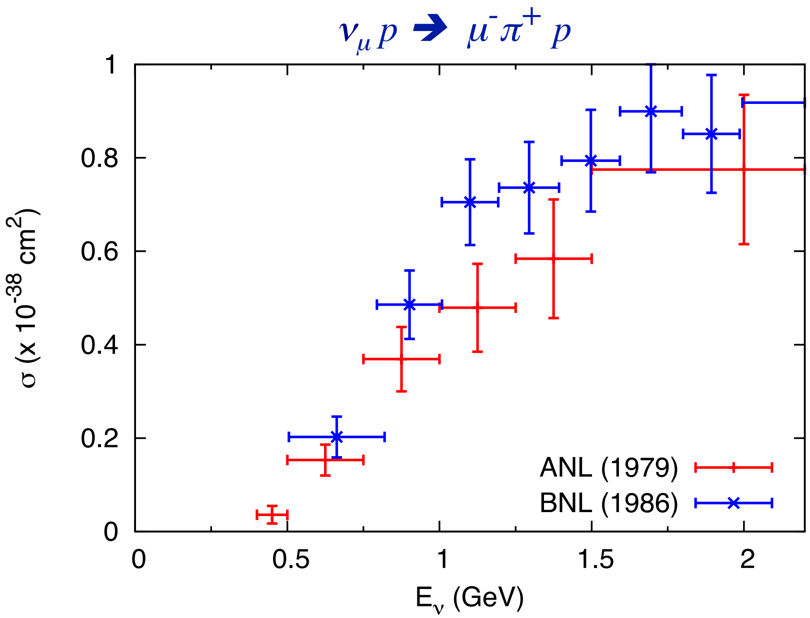
Resonance region (single nucleon)

$\gamma N \rightarrow X$

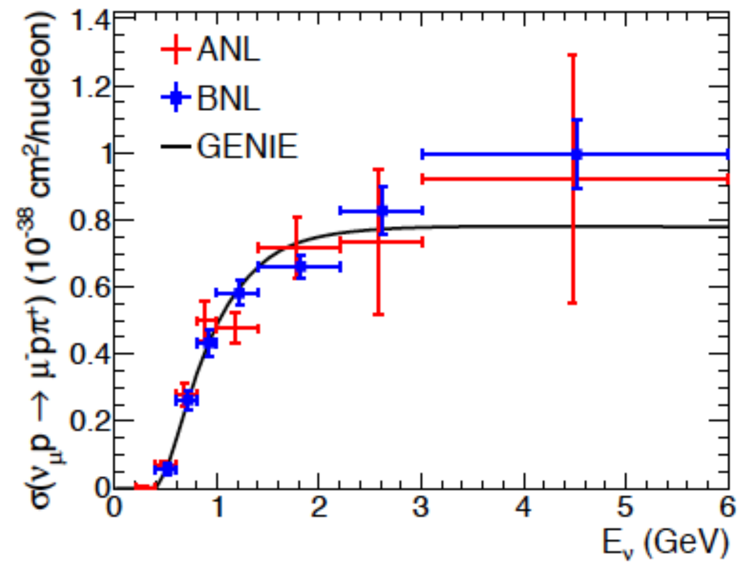


- Several resonances form characteristic peaks
- 2π production is comparable to 1π
- η, K productions (multi-channel reaction)

Neutrino interaction data in Δ(1232) region



Wilkinson et al. PRD 90 (2014)



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

  → theoretical uncertainty in neutrino-nucleus cross sections

Recent reanalysis of original data

→ discrepancy resolved (probably)

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

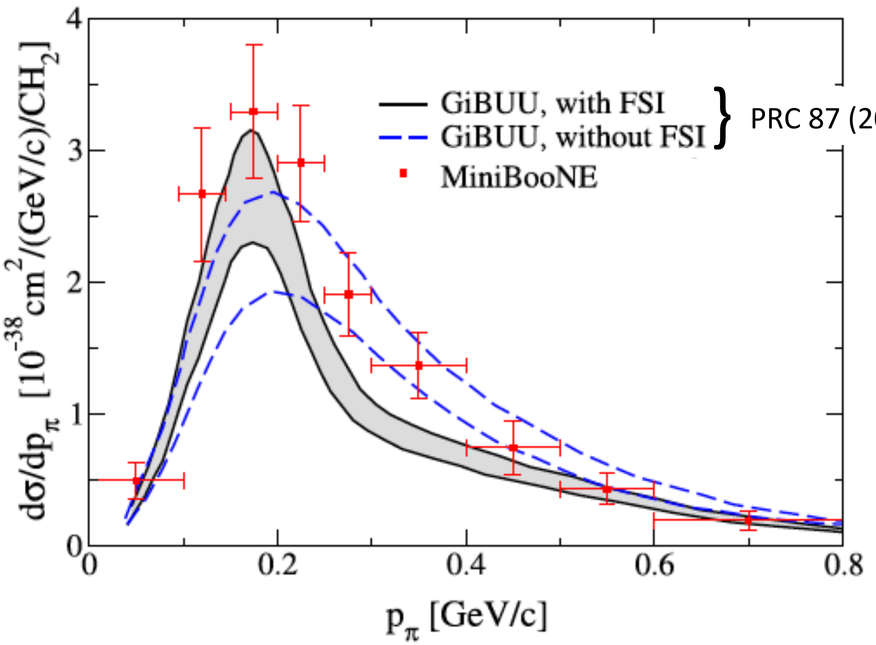
Flux uncertainty is cancelled out

FSI matters ? → to be discussed later

Neutrino interaction data in Δ(1232) region

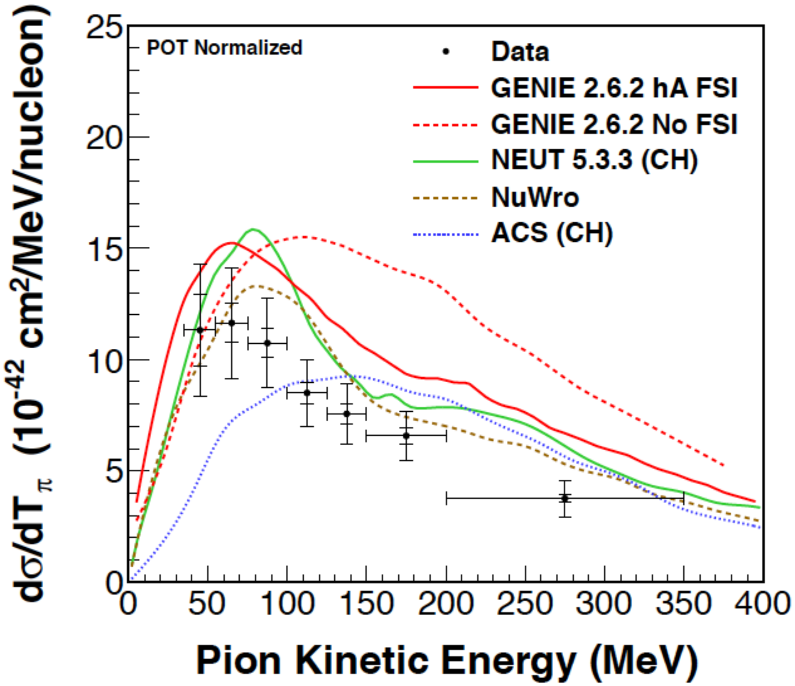
MiniBooNE PRD 83 (2011)

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



MINERvA PRD 92 (2015)

$\nu_\mu CH \rightarrow \mu^- \pi^\pm X \quad \langle E_\nu \rangle = 4.0$ GeV $, W < 1.4$ GeV



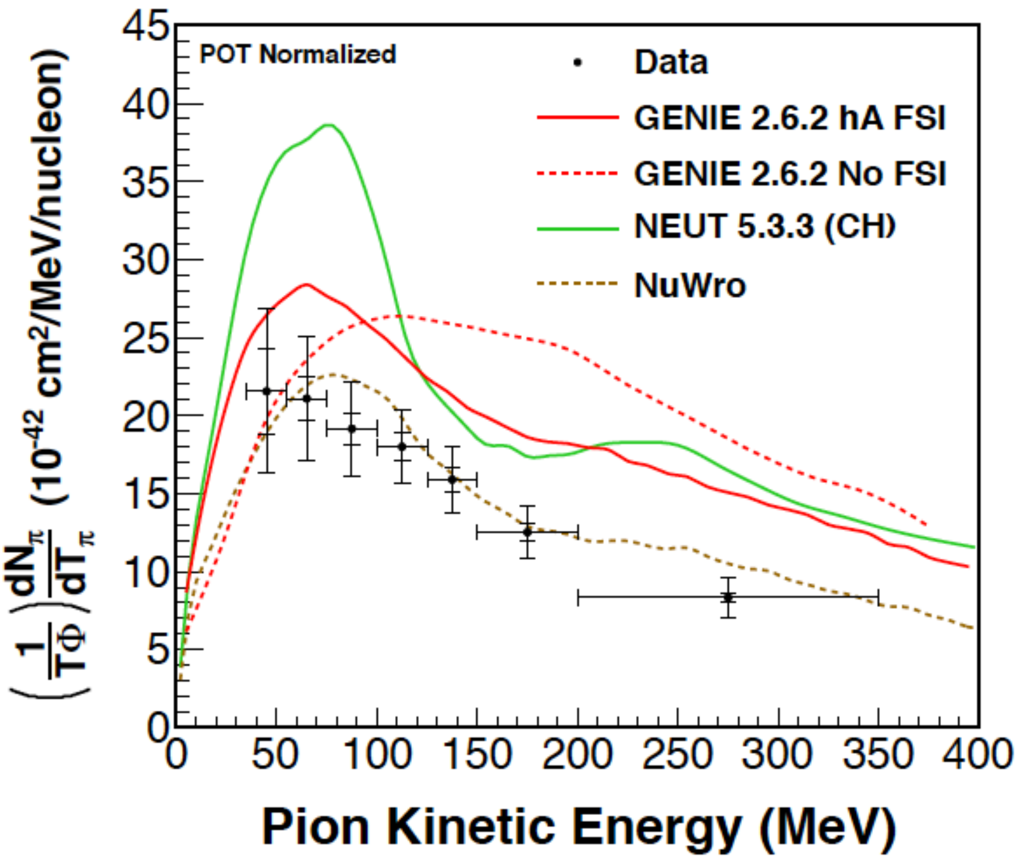
- Final state interaction (FSI) changes charge, momentum, number of π
- Current FSI models are classical (cascade) models
- MiniBooNE cross section shape is worse described with FSI
- MINERvA data favor FSI

Current FSI models are not satisfactory

Neutrino interaction beyond $\Delta(1232)$ region

MINERvA PRD 92 (2015)

ν_μ CH → $\mu^- \, N \, \pi^\pm X$ (N=1,2,3, ...) $\langle E_\nu \rangle = 4.0$ GeV , $W <$ 1.8 GeV



Main decay mode of higher resonances

→ Two pions

→ Described with DIS model in common neutrino interaction generators (GENIE, etc.) not correct

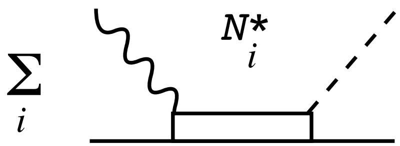
Development of a reaction model on single nucleon is still an issue

T : # of nucleons in fiducial volume

Φ : integrated flux

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

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

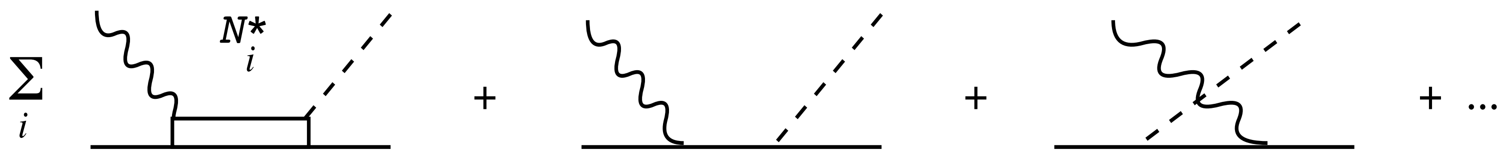


VNN^* : helicity amplitudes listed in PDG

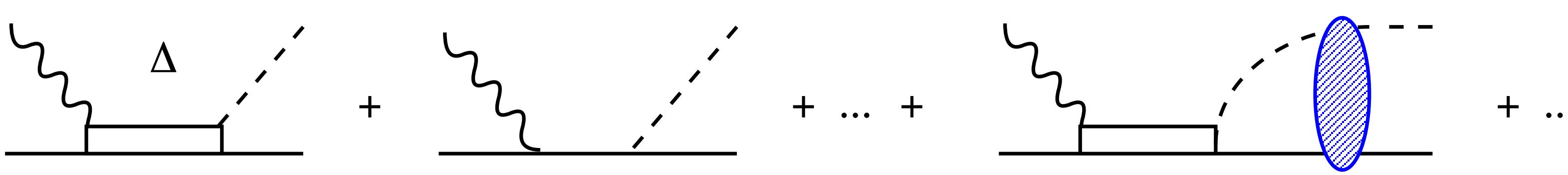
ANN^* : quark model, PCAC relation to $|\pi NN^*|$ (PDG)

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)



GOAL : Develop νN-interaction model in resonance region

Problems in previous models

- Channel-couplings required by unitarity is missing
- Important 2 π production model is missing
- Relative phases among different ANN^* are out of control

Our strategy to overcome the problems…

We develop a dynamical coupled-channels model

★ Dynamical coupled-channels (DCC) model for $\gamma^{(*)}N$, $\pi N \rightarrow \pi N$, $\pi\pi N$, ηN, $K\Lambda$, $K\Sigma$

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

Dynamical Coupled-Channels model

for meson productions

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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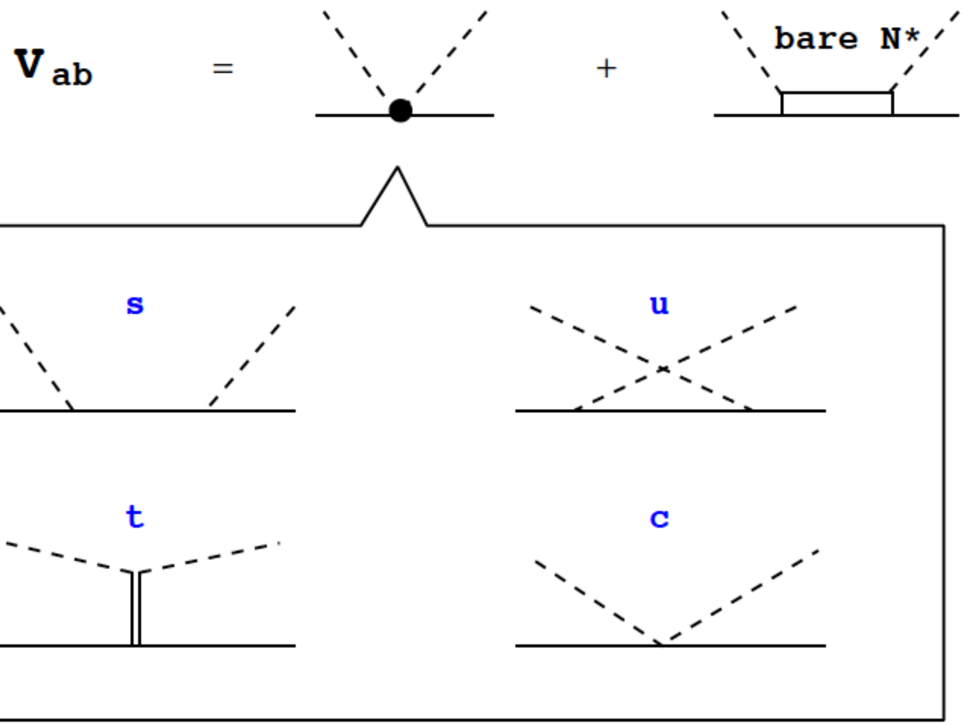

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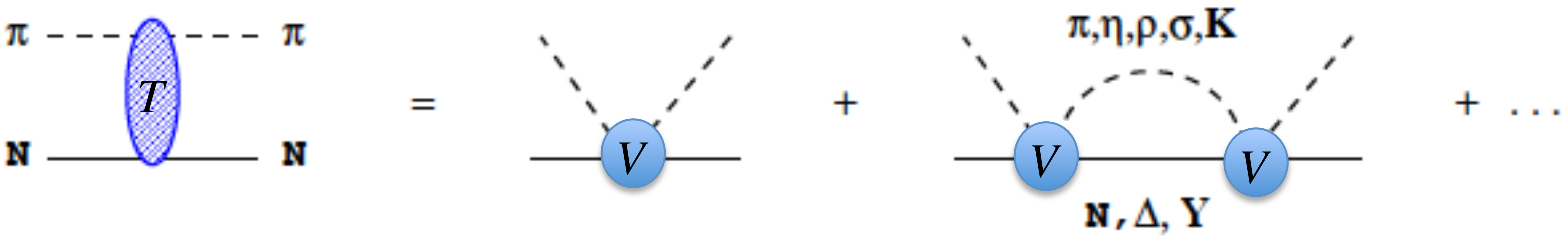
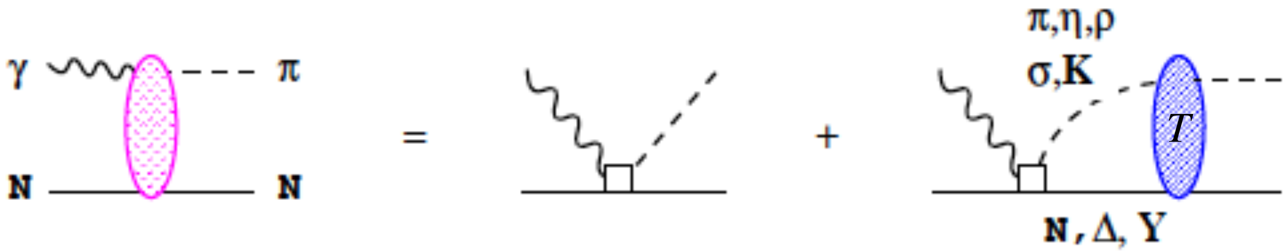


In addition, γN, $W^{\pm}N$, ZN channels are included perturbatively



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

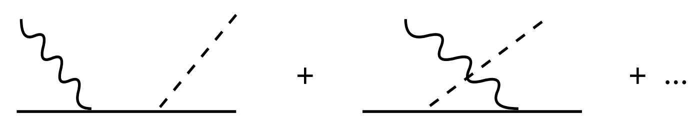
Because neutrino reaction data are scarce, axial current cannot be determined phenomenologically
→ Chiral symmetry and PCAC (partially conserved axial current) are guiding principle

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

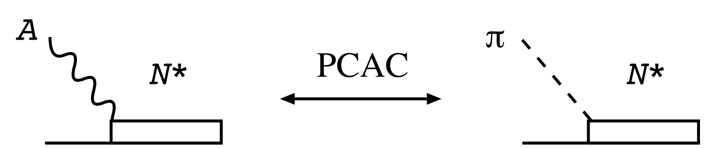
Q^2=0

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 $\gamma N, \pi N \rightarrow \pi N, \eta N, K\Lambda, K\Sigma$

and electron scattering data

DCC analysis of meson production data

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

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

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

~ 23,000 data points are fitted

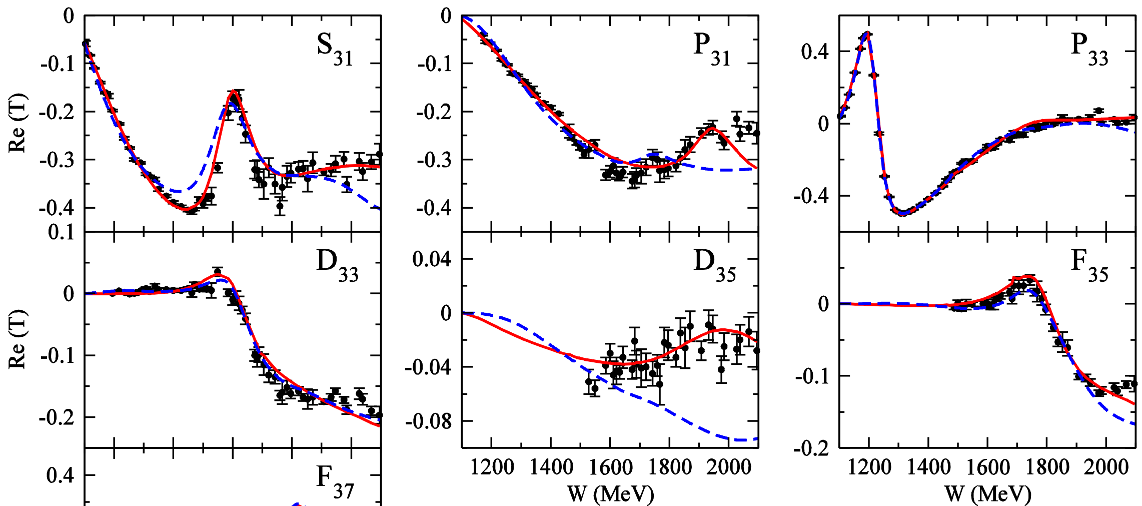
by adjusting parameters (N^* mass, N^* → MB couplings, cutoffs)

↓

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

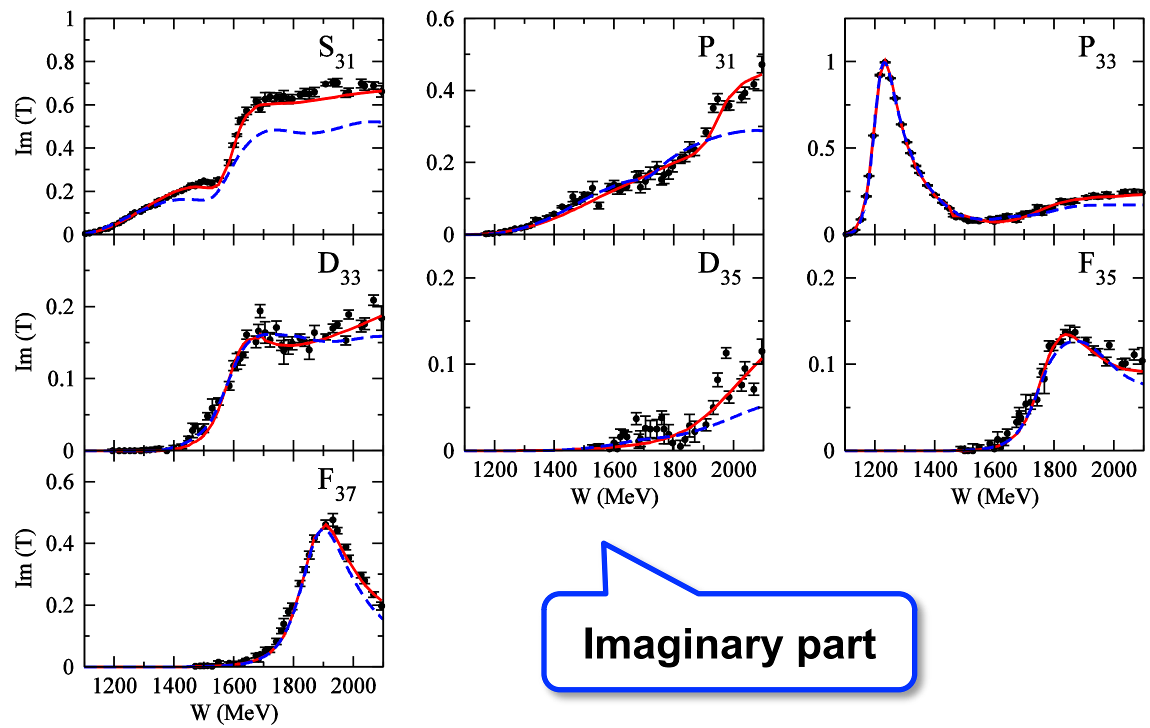
$\gamma^* N$ → N^* coupling strength at different Q^2 values ($Q^2 \leq 3\ (\mathrm{GeV}/c)^2$)

Partial wave amplitudes of π N scattering



Real part

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



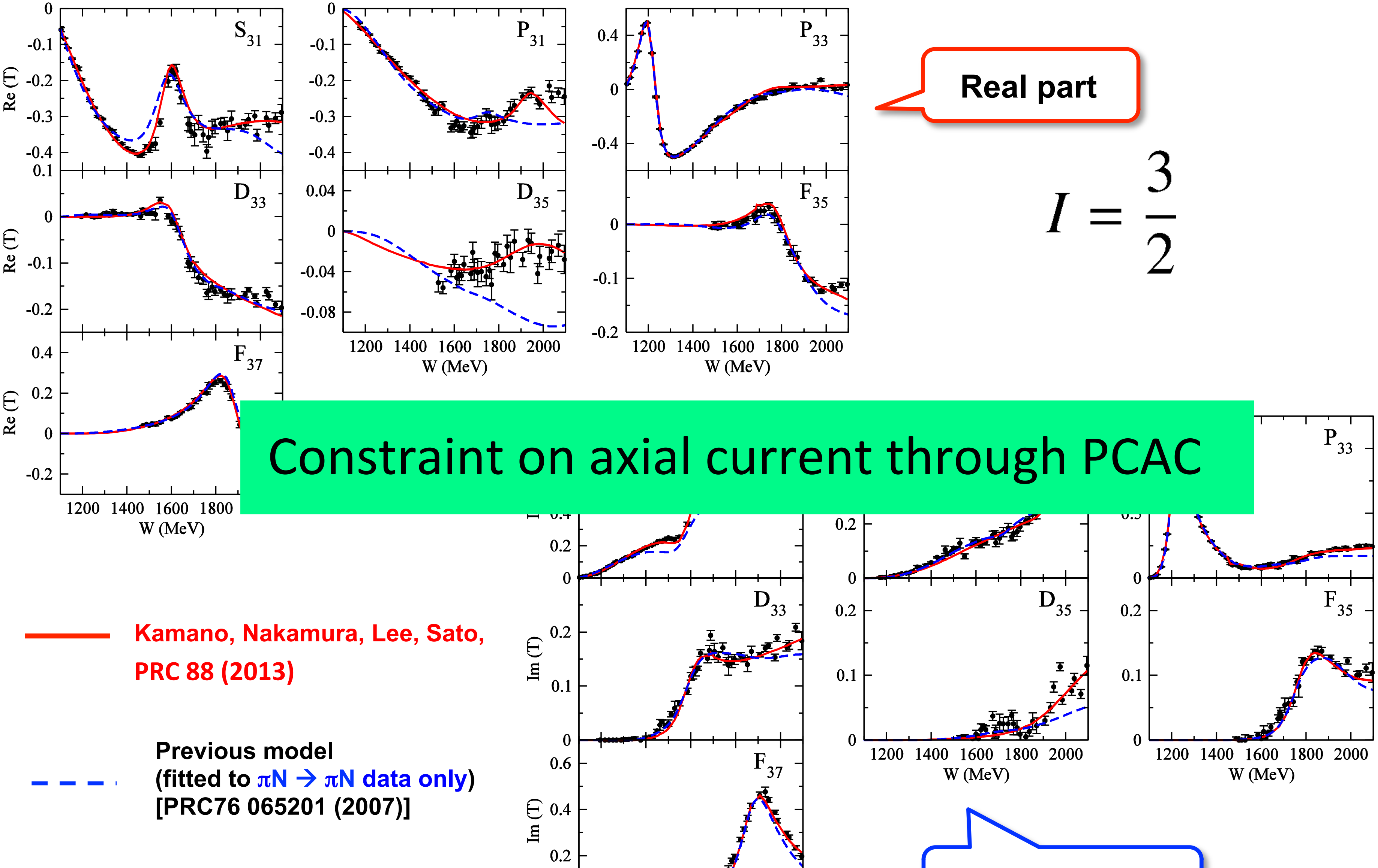
Imaginary part

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

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

Data: SAID πN amplitude

Partial wave amplitudes of π N scattering

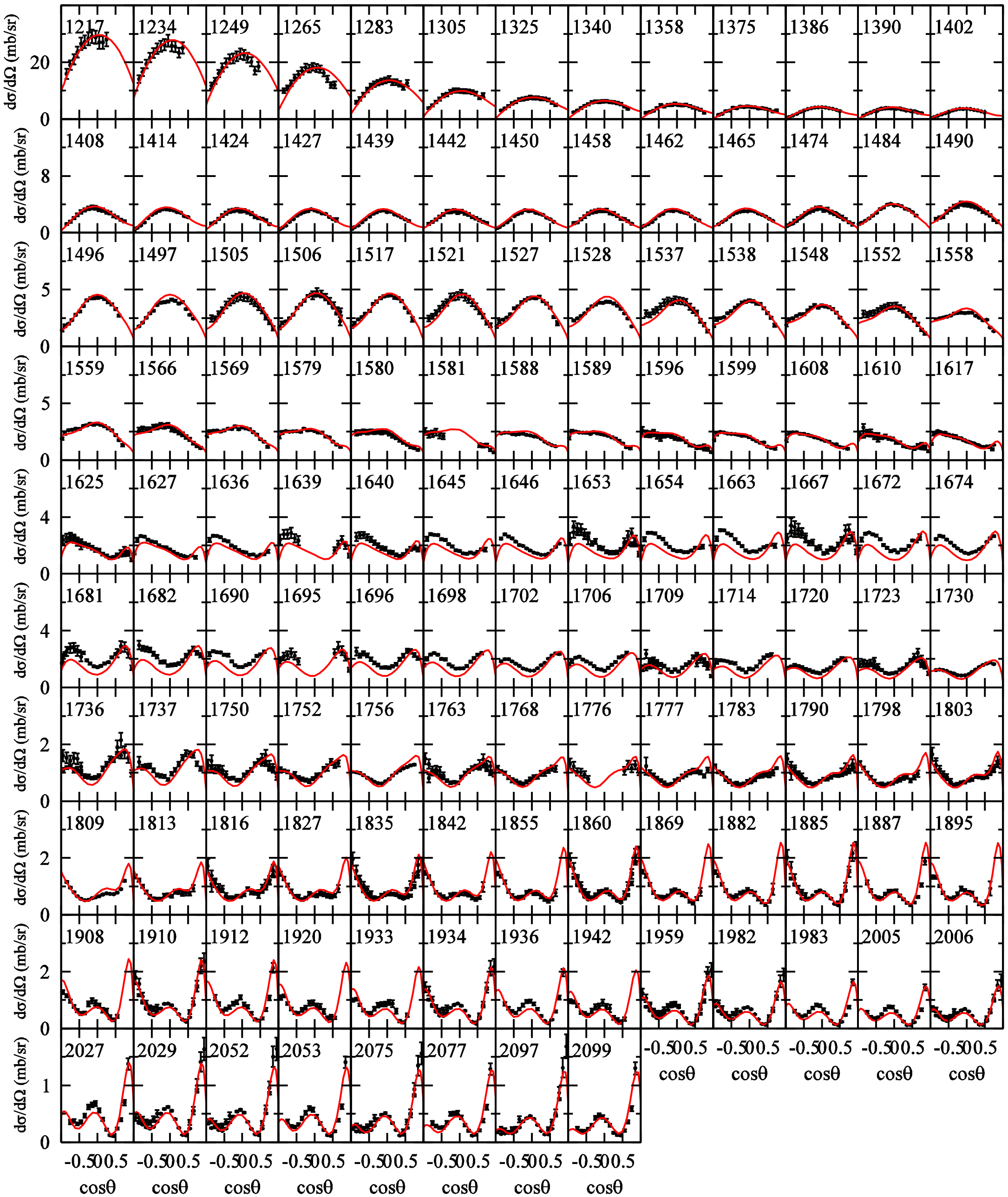


Data: SAID πN amplitude

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

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

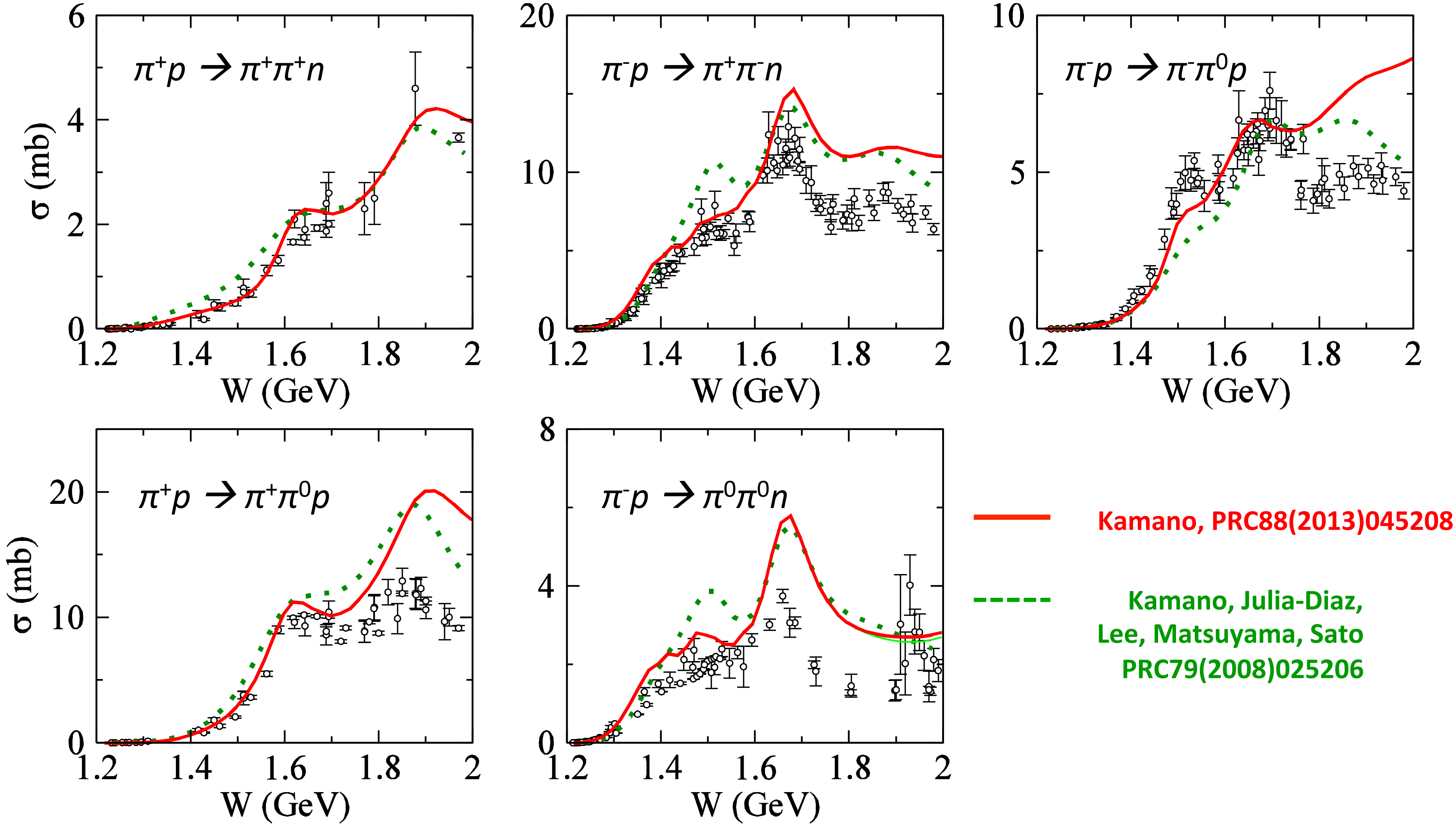
Kamano, Nakamura, Lee, Sato, PRC 88 (2013)



Vector current (Q^2=0) for 1π

Production is well-tested by data

Predicted πN → ππN total cross sections with our DCC model

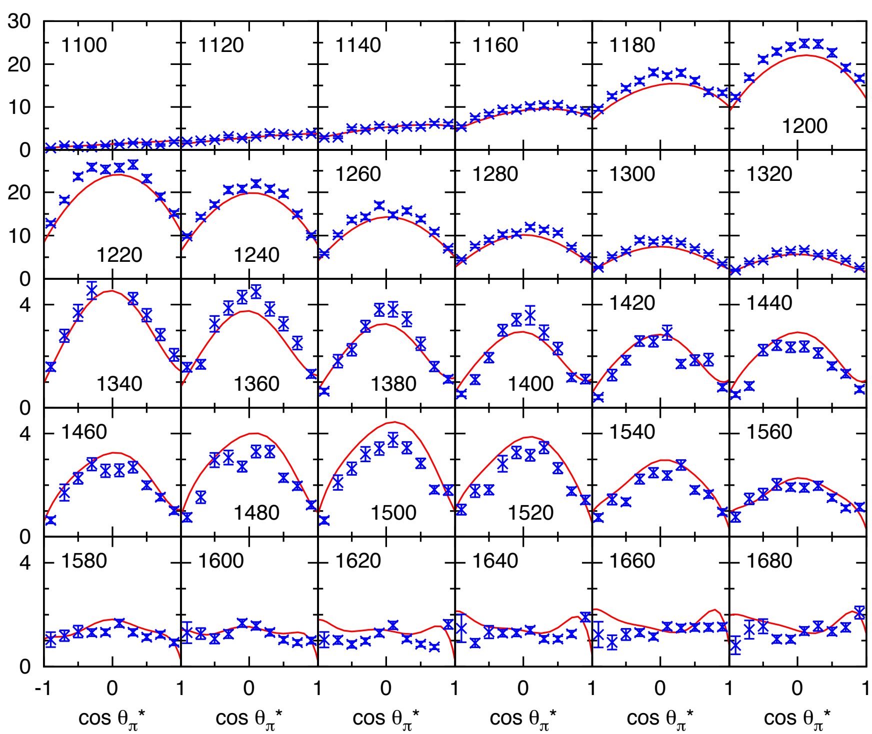


Single π production in electron-proton scattering

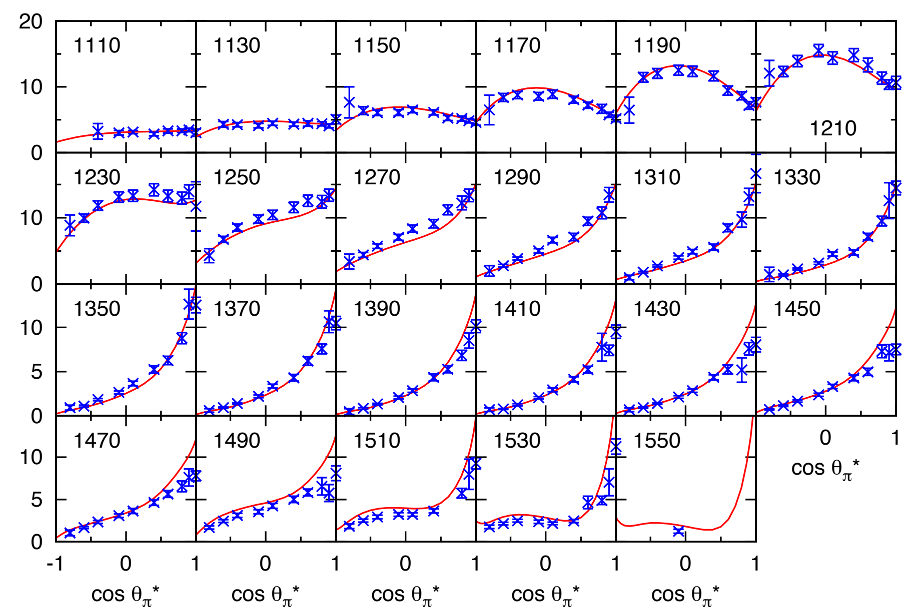
Purpose : Determine Q^2 –dependence of vector coupling of p-N^* : $VpN^*(Q^2)$

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

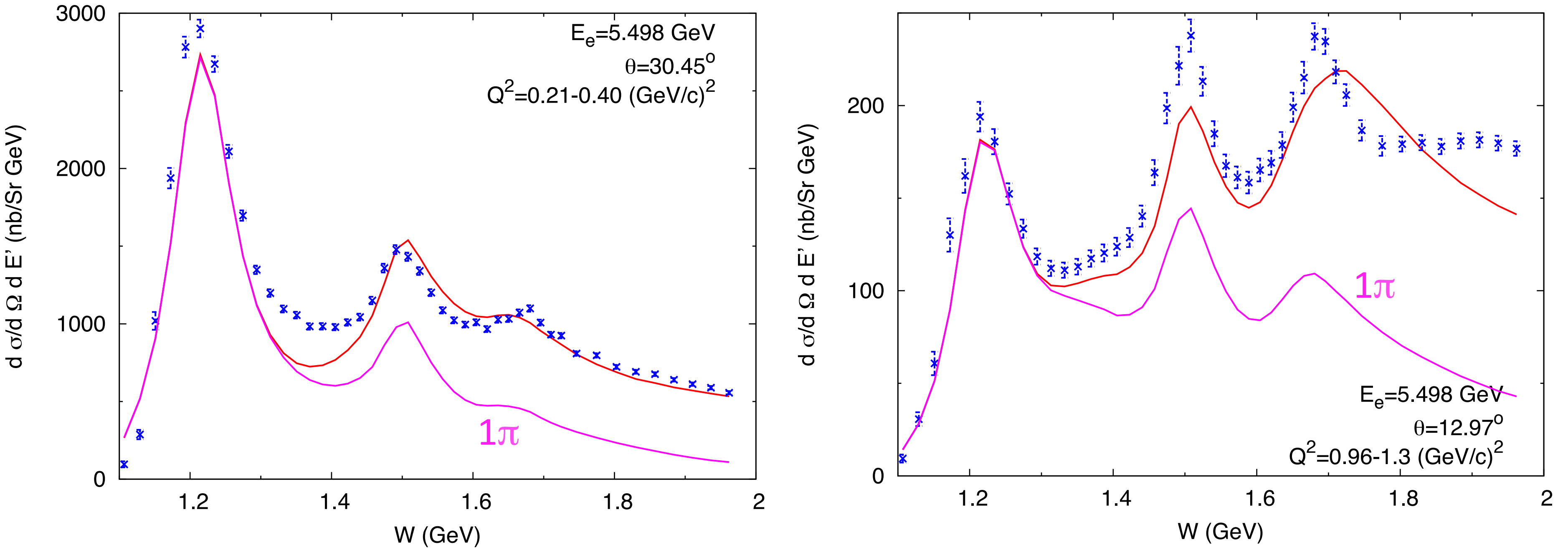
$p(e,e'\pi^0)p$



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



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

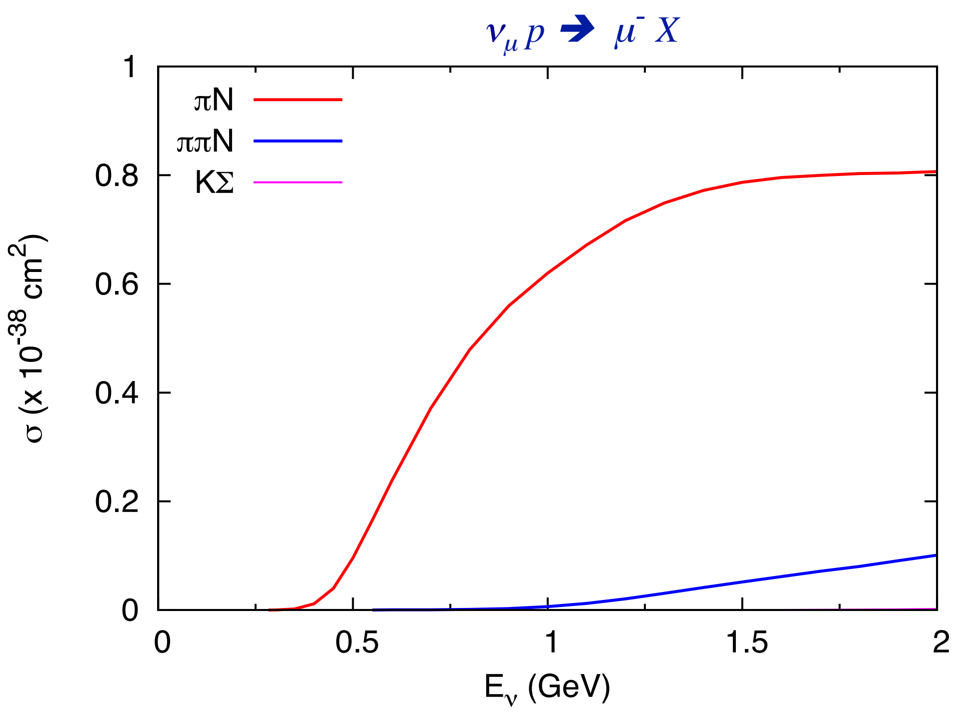
Similar analysis of electron-neutron scattering data has also been done

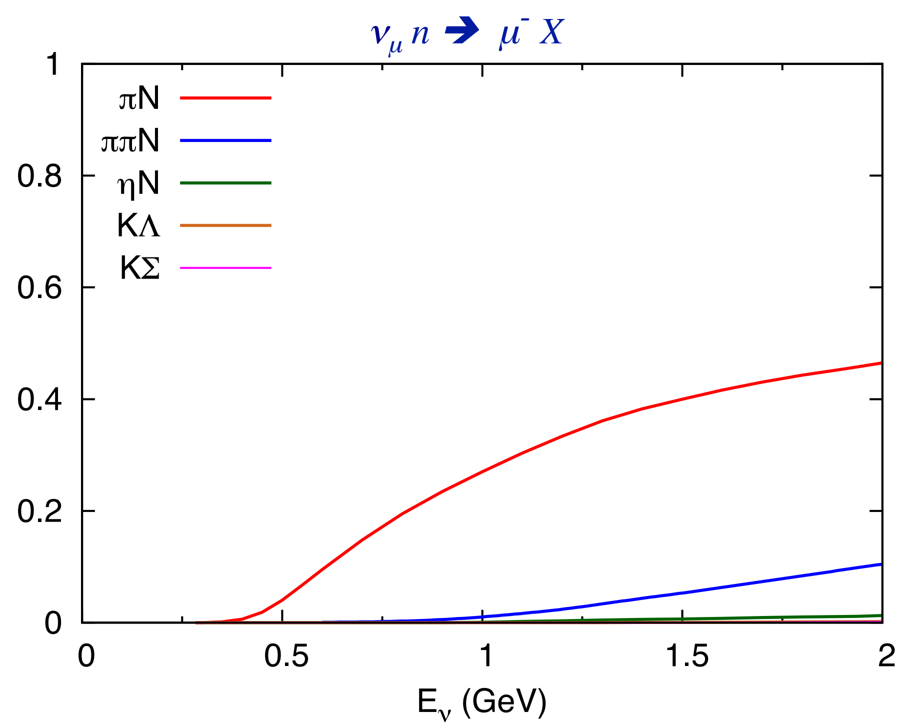
DCC vector currents has been tested by data for whole kinematical region relevant to neutrino interactions of $E_\nu \leq 2$ GeV

Neutrino Results

SXN et al., Phys. Rev. D **92**, 074024 (2015)

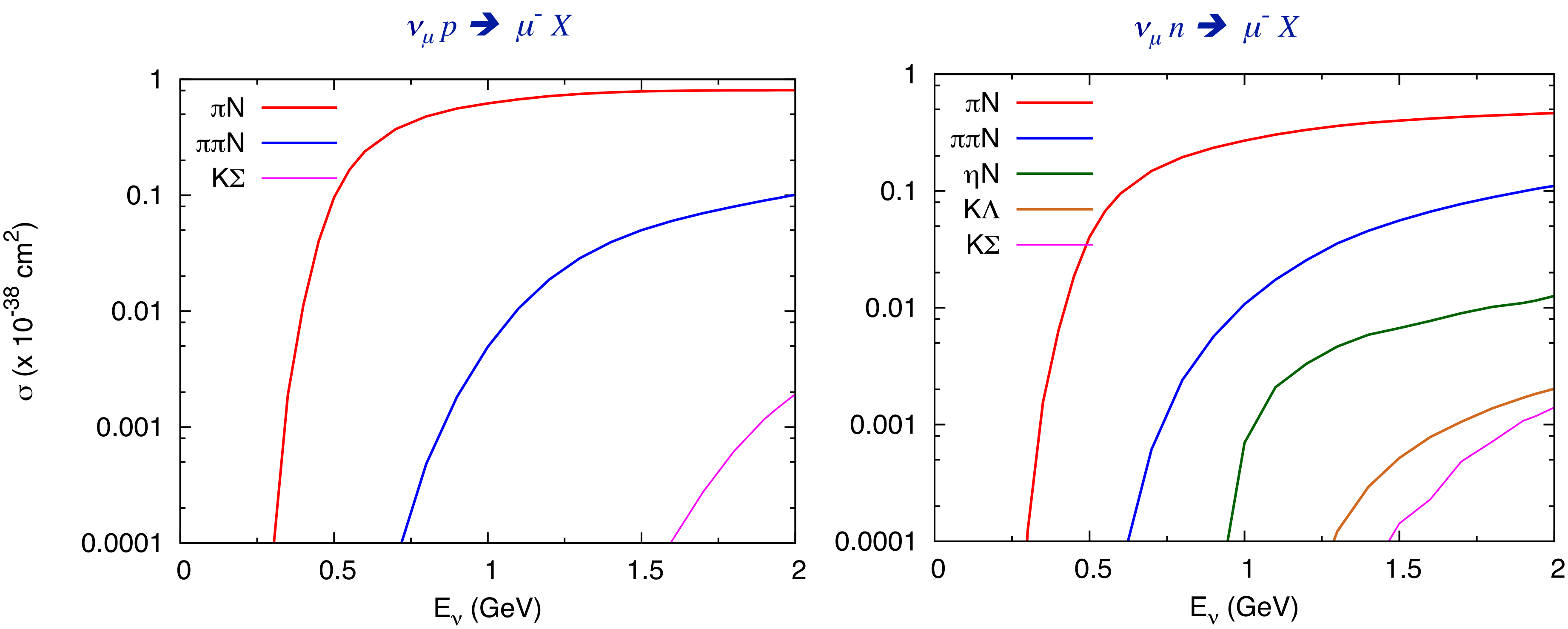
Cross section for $\nu_\mu N \rightarrow \mu^- X$





- 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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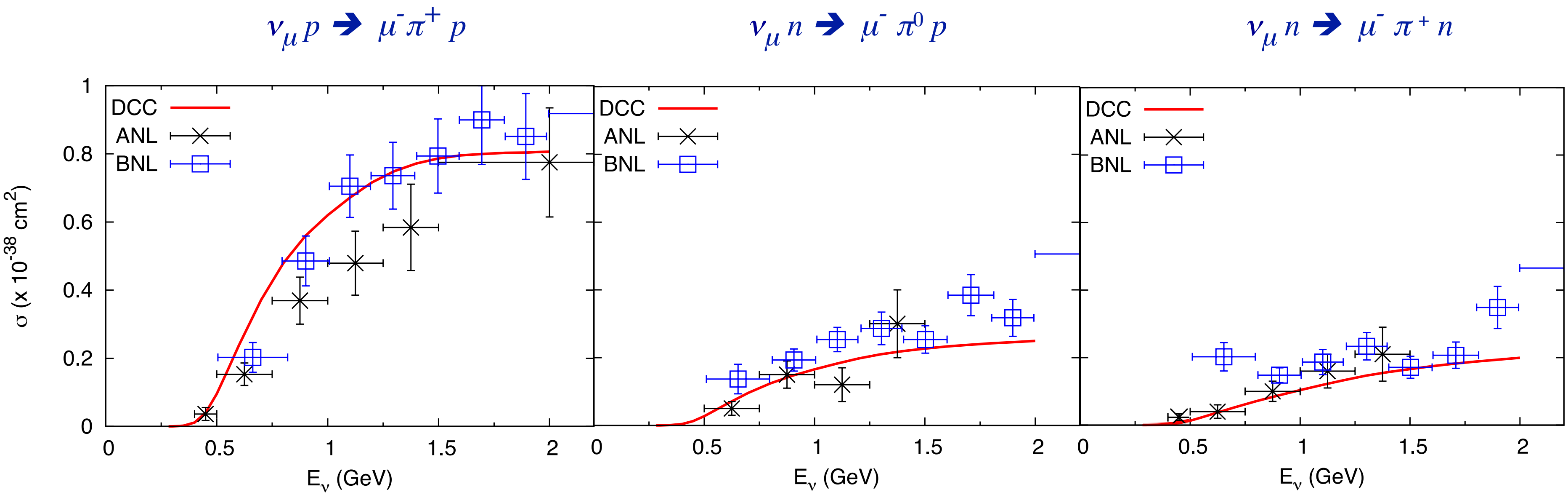
Comparison with single pion data



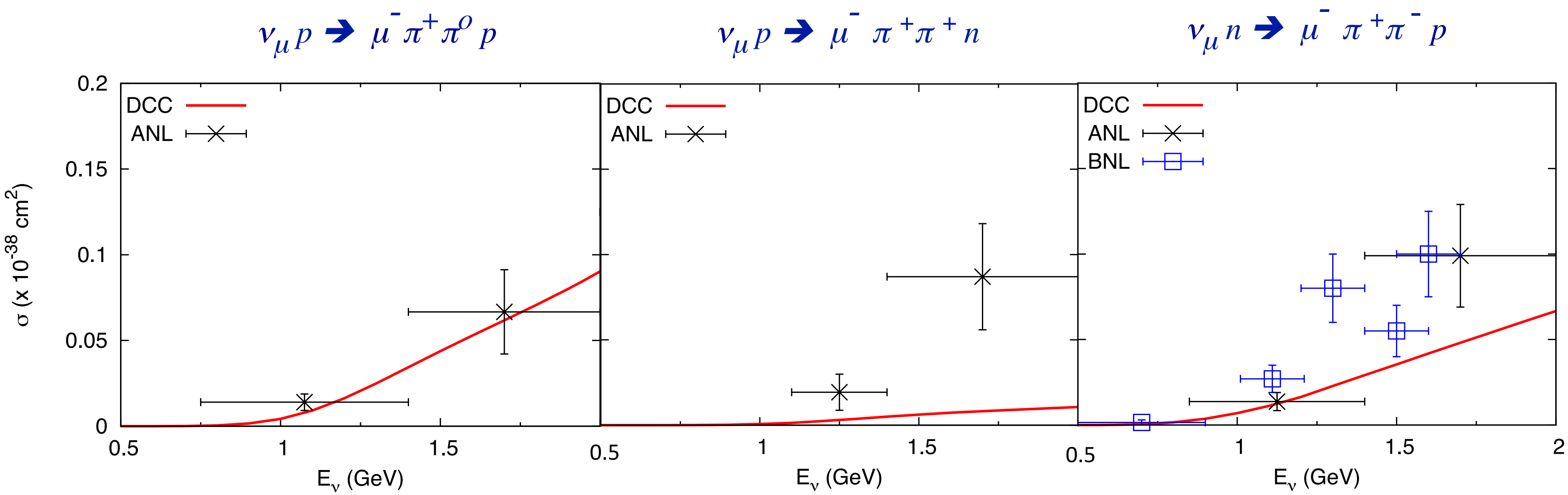
DCC model prediction is consistent with data

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); to be discussed later)

Comparison with double pion data

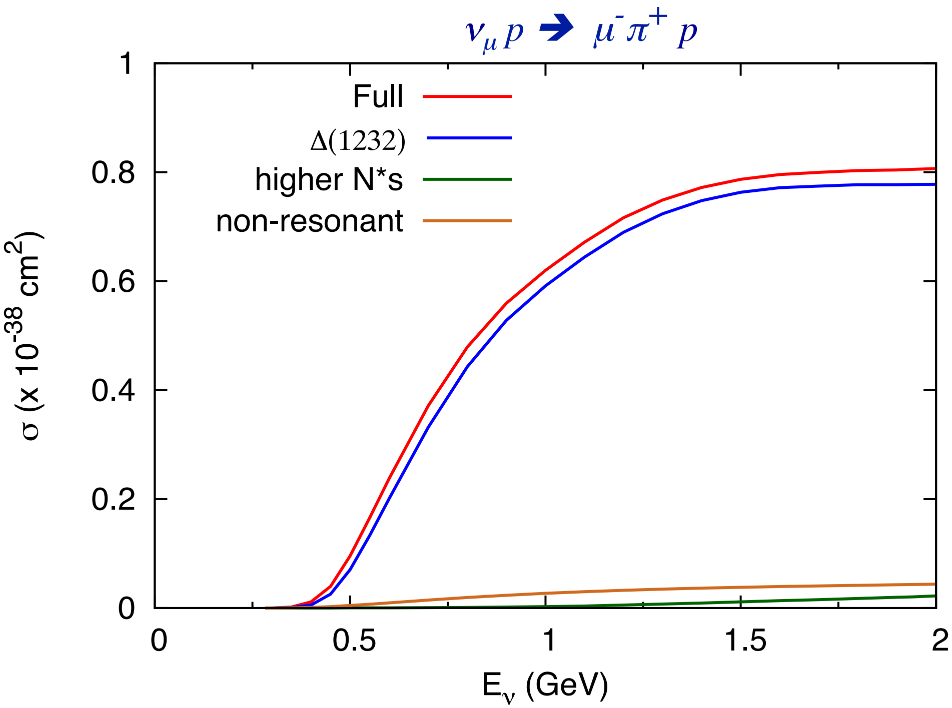


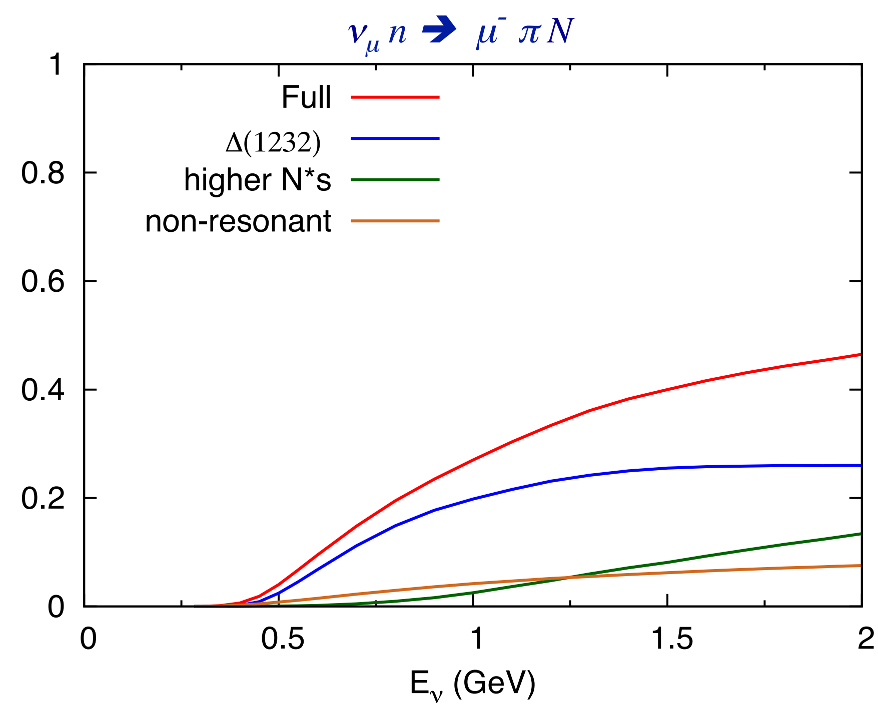
Fairly good DCC predication

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

First dynamical model for 2 π production in resonance region

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



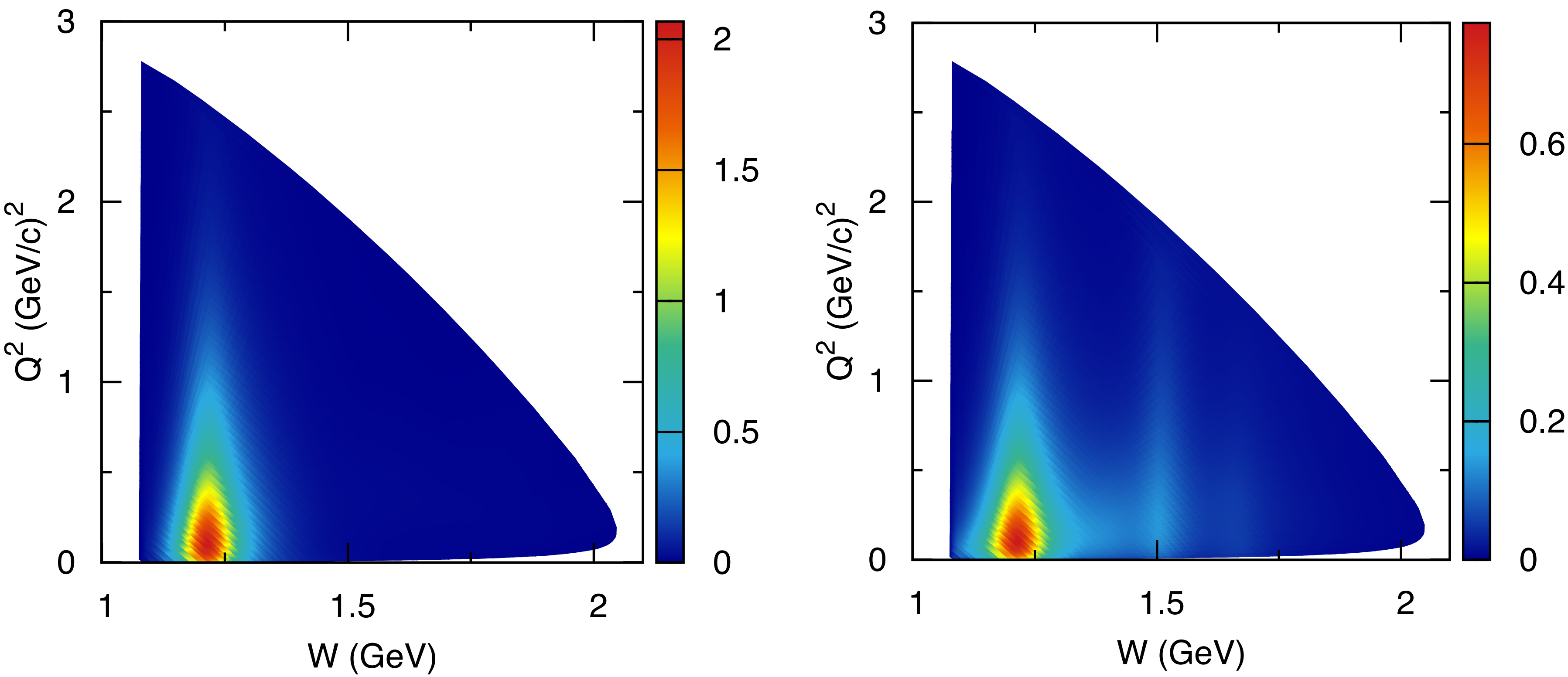


- Δ(1232) dominates for $\nu_\mu p \rightarrow \mu^- \pi^+ p$ $(I=3/2)$ for $E_\nu \leq 2$ GeV
- Non-resonant mechanisms contribute significantly
- Higher N^*s becomes important towards $E_\nu \approx 2$ GeV for $\nu_\mu n \rightarrow \mu^- \pi N$

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

E_ν = 2 GeV

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



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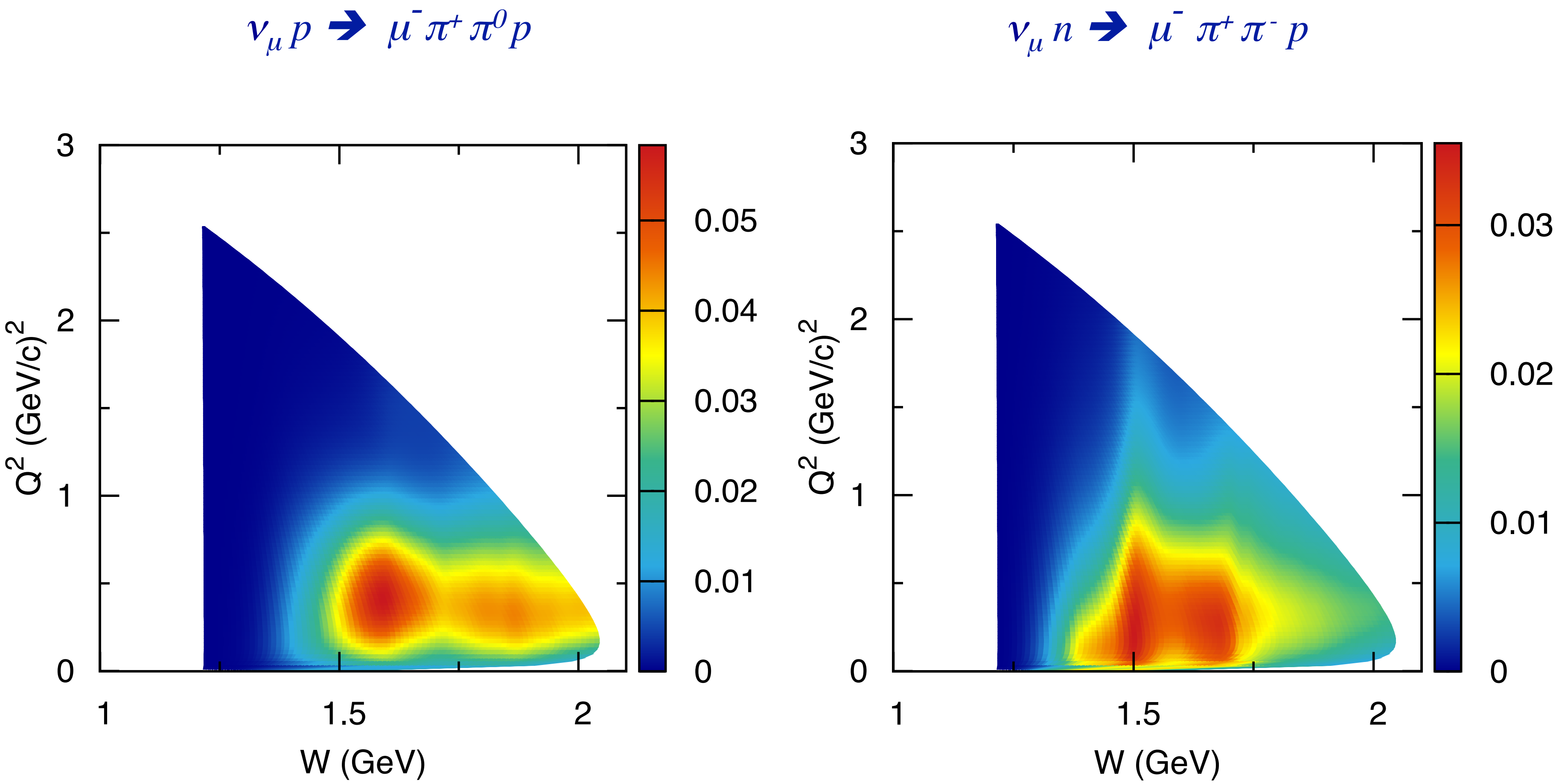
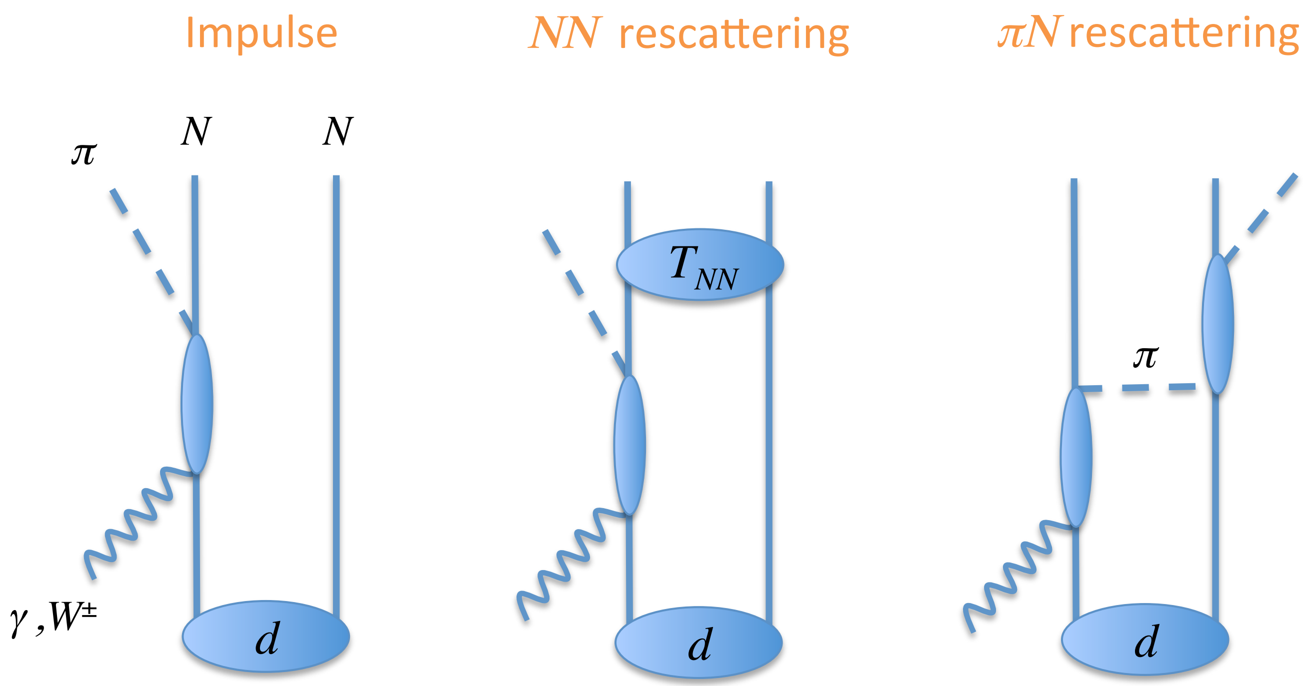


Further development of DCC model for neutrino reactions

Neutrino reactions on the deuteron

- ANL and BNL data on $\nu_\mu N \rightarrow \mu^- \pi N$ are actually from $\nu_\mu d \rightarrow \mu^- \pi NN$ data
- Quasi-free kinematics is chosen but possible FSI effects are concern
- First step has been taken by Wu et al. PRC91, 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

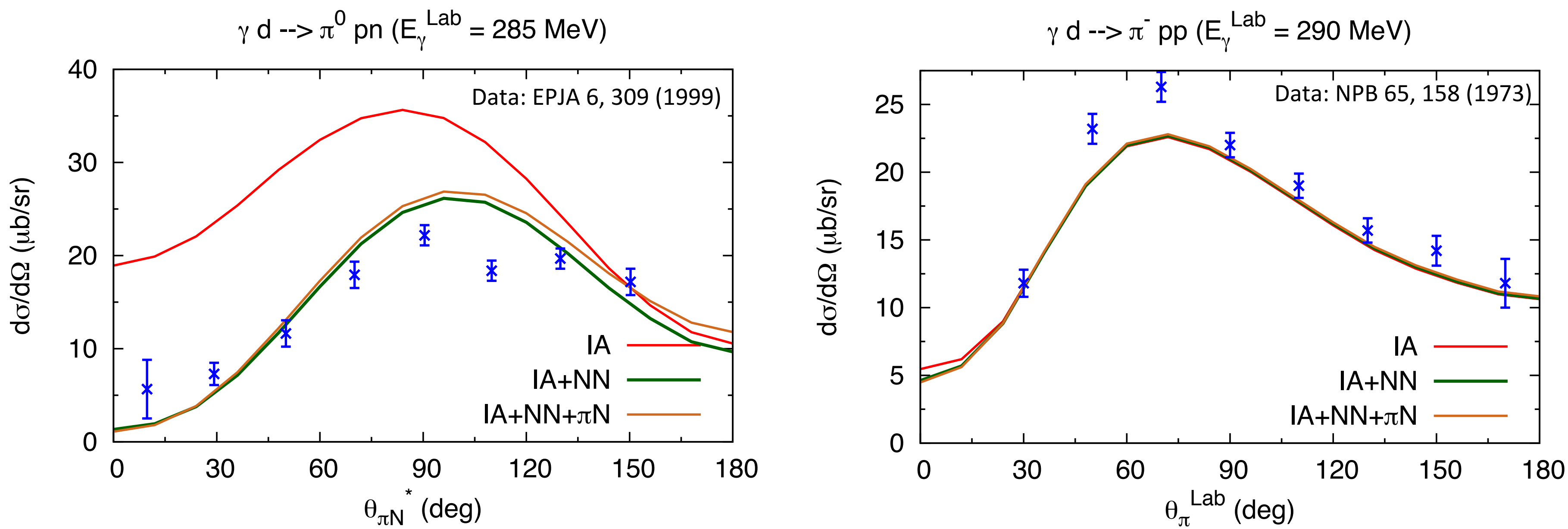
T_{NN}, deuteron w.f. ← CD-Bonn potential (PRC 63 (2001))

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)

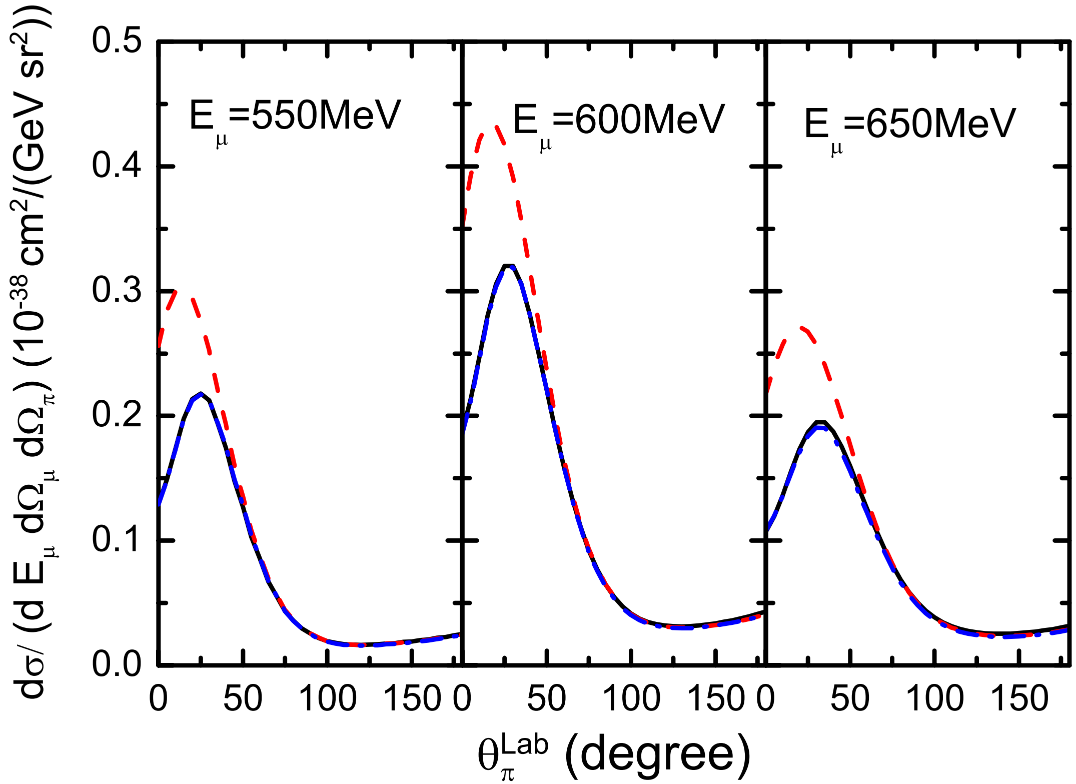


- Model prediction is reasonably consistent with data
- Large NN (small πN) rescattering effect for π^0 production

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

$\phi_\pi = 0^o$

IA

IA + NN

IA + NN + πN

Conclusions

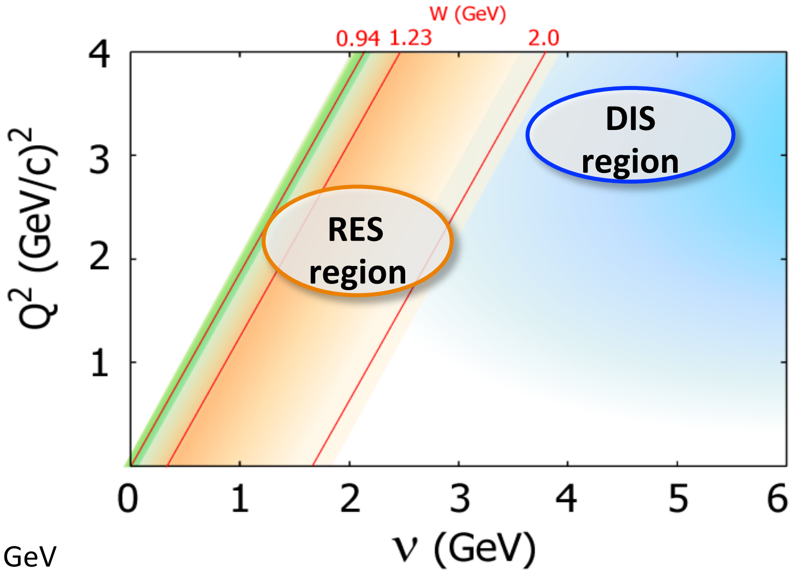
- Large NN (small πN) rescattering effect

  orthogonality between deuteron and pn scattering wave functions

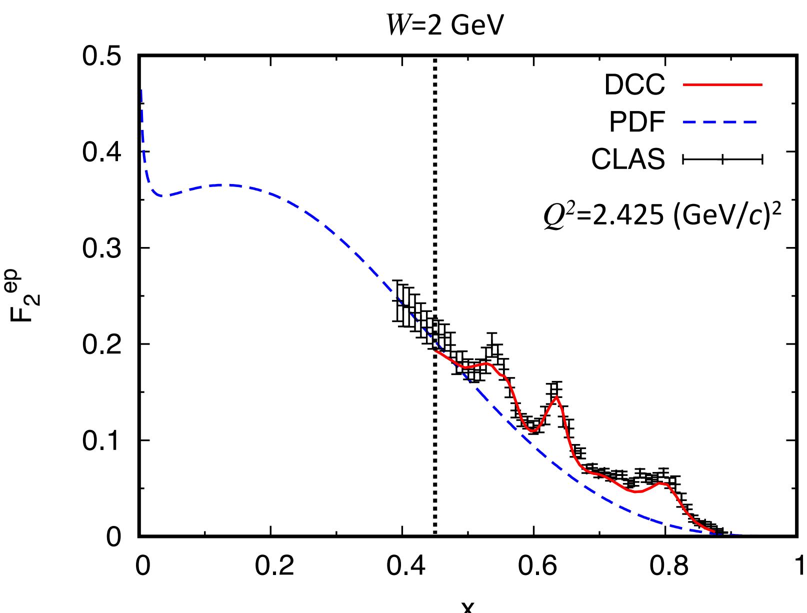
- ANL and BNL data did not consider FSI

  → calling for reanalysis with FSI taken into account → ongoing with DCC model

Matching with DIS



Vector current



arXiv:1610.01464

We are currently working on the axial current

Conclusion

Development of DCC model for νN interaction in resonance region

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

➔ extension of vector current to $Q^2 \neq 0$ region, isospin separation

through analysis of e^{-}- p & e^{-}-'n' data for $W \leq 2$ GeV , $Q^2 \leq 3$ (GeV/c)^2

➔ Development of axial current for νN interaction; PCAC is maintained

Conclusion

- πN & $\pi\pi N$ are main channels in few-GeV region
- DCC model prediction is consistent with BNL data
- 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

Further development

- Neutrino reactions on the deuteron → reanalysis of ANL and BNL data with FSI effects
- Matching with DIS region

BACKUP

DCC (Dynamical Coupled-Channel) model

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

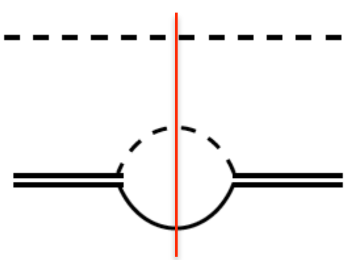
Kamano et al., PRC 88, 035209 (2013)

Coupled-channel Lippmann-Schwinger equation

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

$G c$ =

for stable channels



for unstable channels

DCC (Dynamical Coupled-Channel) model

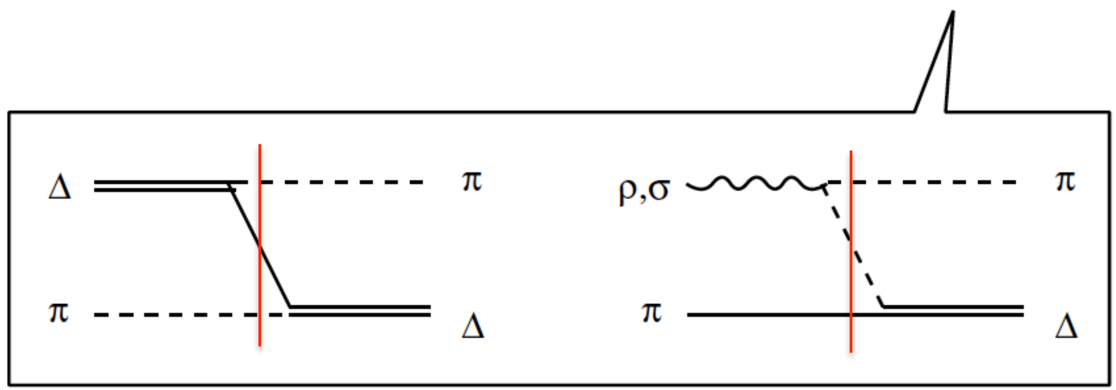
Matsuyama et al., Phys. Rep. **439**, 193 (2007)

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



Contents

★ Introduction

νN scattering in resonance region and relevance to baryon spectroscopy

★ Dynamical coupled-channels (DCC) model

Analysis of γN, πN ➔ πN, ηN, $K\Lambda$, $K\Sigma$ data

and electron scattering data

Extension to νN ➔ $l^- X$ ($X = \pi N$, $\pi\pi N$, ηN, $K\Lambda$, $K\Sigma$)

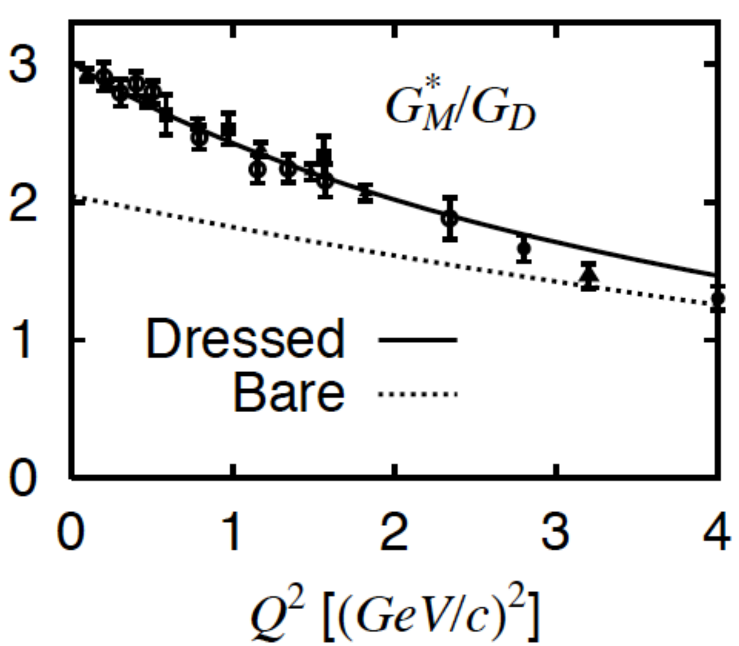
★ Results for νN ➔ $l^- X$

Relevance to baryon spectroscopy

e.g. N-$\Delta(1232)$ transition form factors

Sato et al., PRC 63 (2001); PRC 67 (2003)

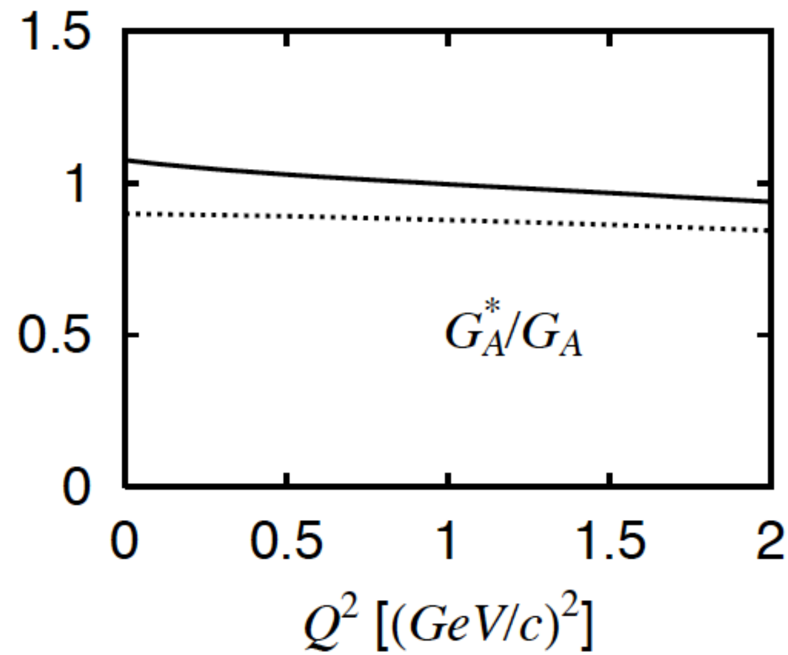
Vector (magnetic) form factor
from electron reactions



$$G_D = 1/(1 + Q^2/M_V^2)^2$$

$$M_V = 0.84 \text{ GeV}$$

Axial form factor
from neutrino reactions



$$G_A = 1/(1 + Q^2/M_A^2)^2$$

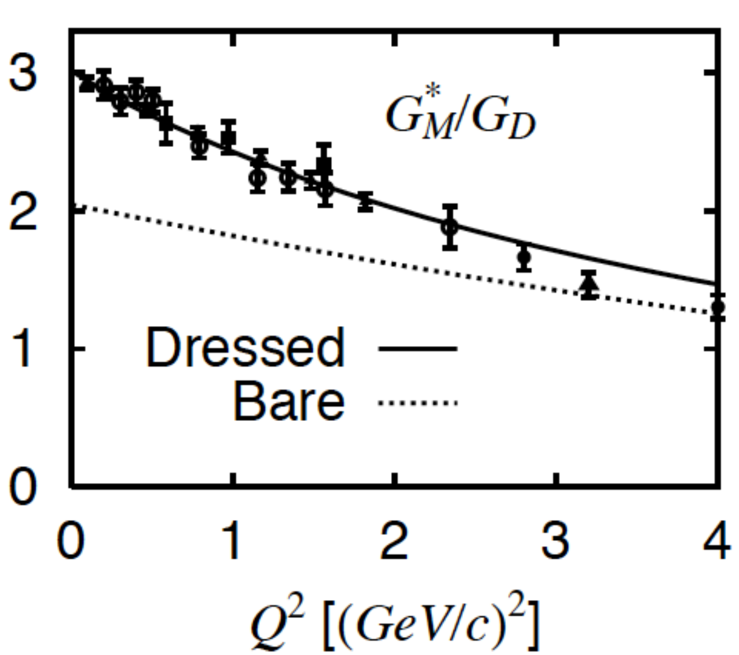
$$M_A = 1.02 \text{ GeV}$$

Relevance to baryon spectroscopy

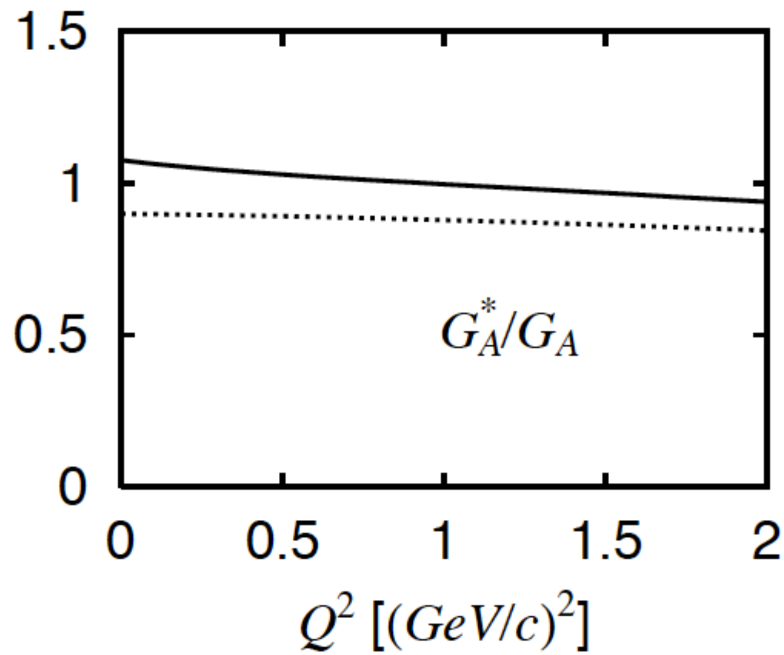
e.g. N-$\Delta(1232)$ transition form factors

Sato et al., PRC 63 (2001); PRC 67 (2003)

Vector (magnetic) form factor from electron reactions



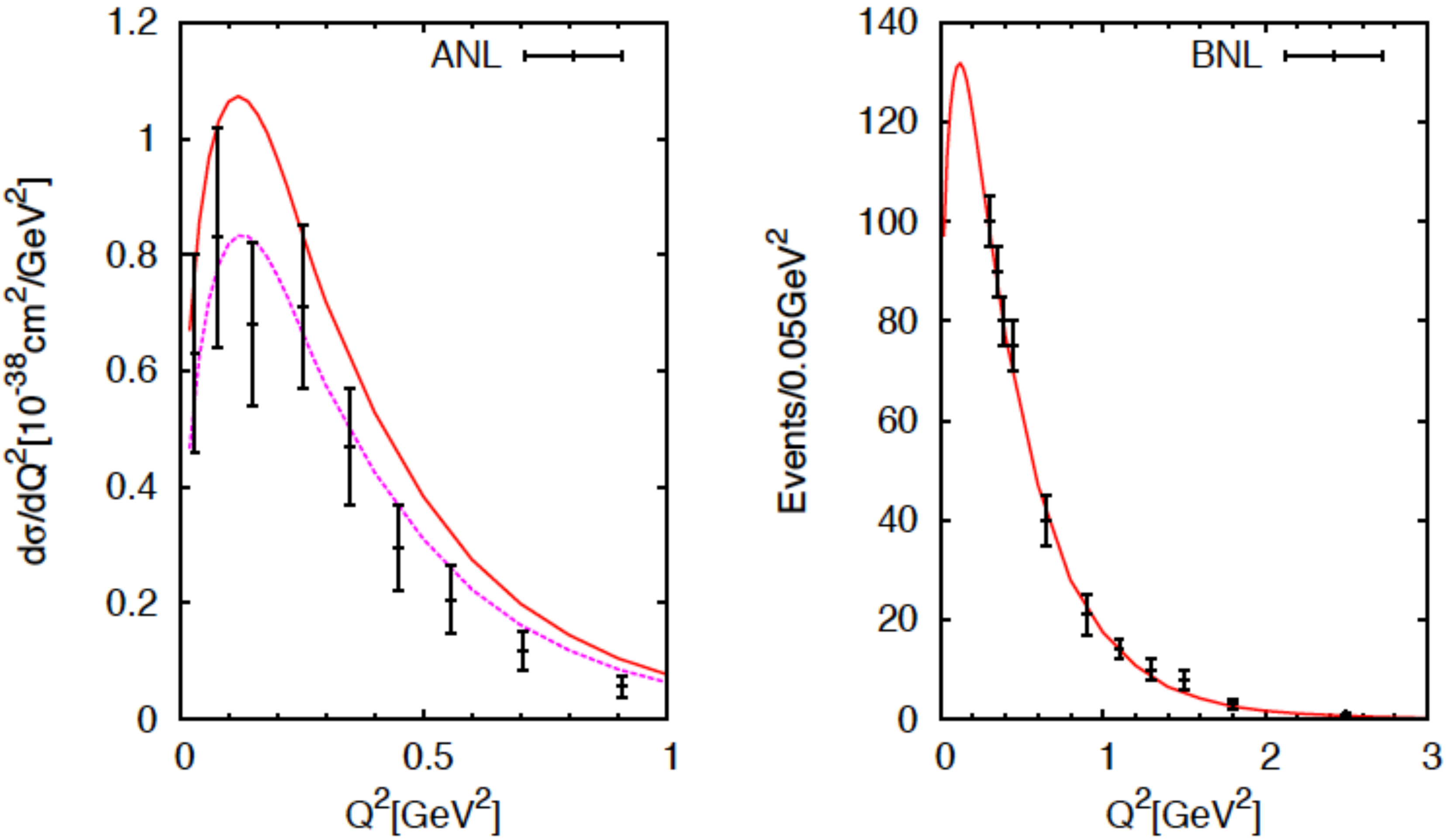
Axial form factor from neutrino reactions



- Axial structure of bayrons can be learned from neutrino reaction data
- Different pion cloud contributions to magnetic and axial form factors (slope)

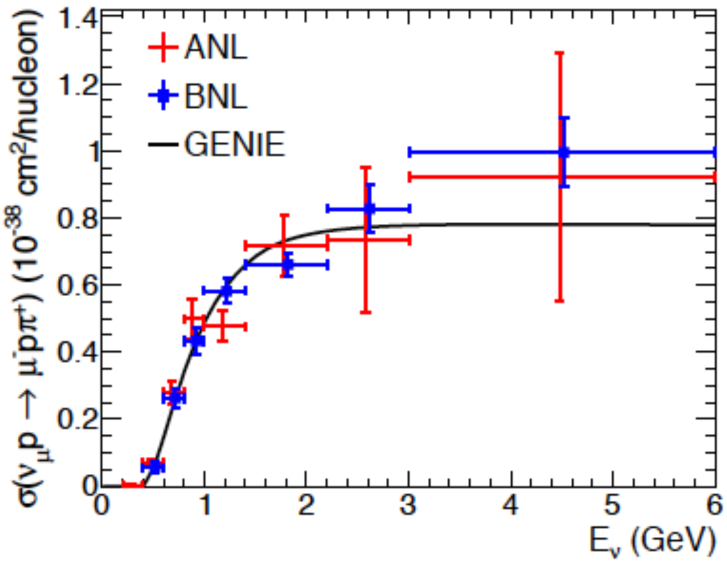
Q^2 – dependence

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

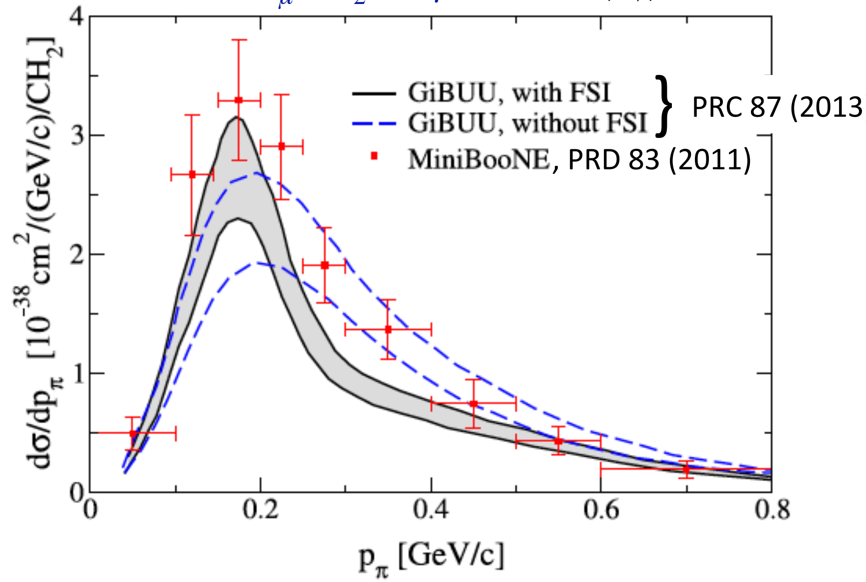


Neutrino interaction data in resonance region

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



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



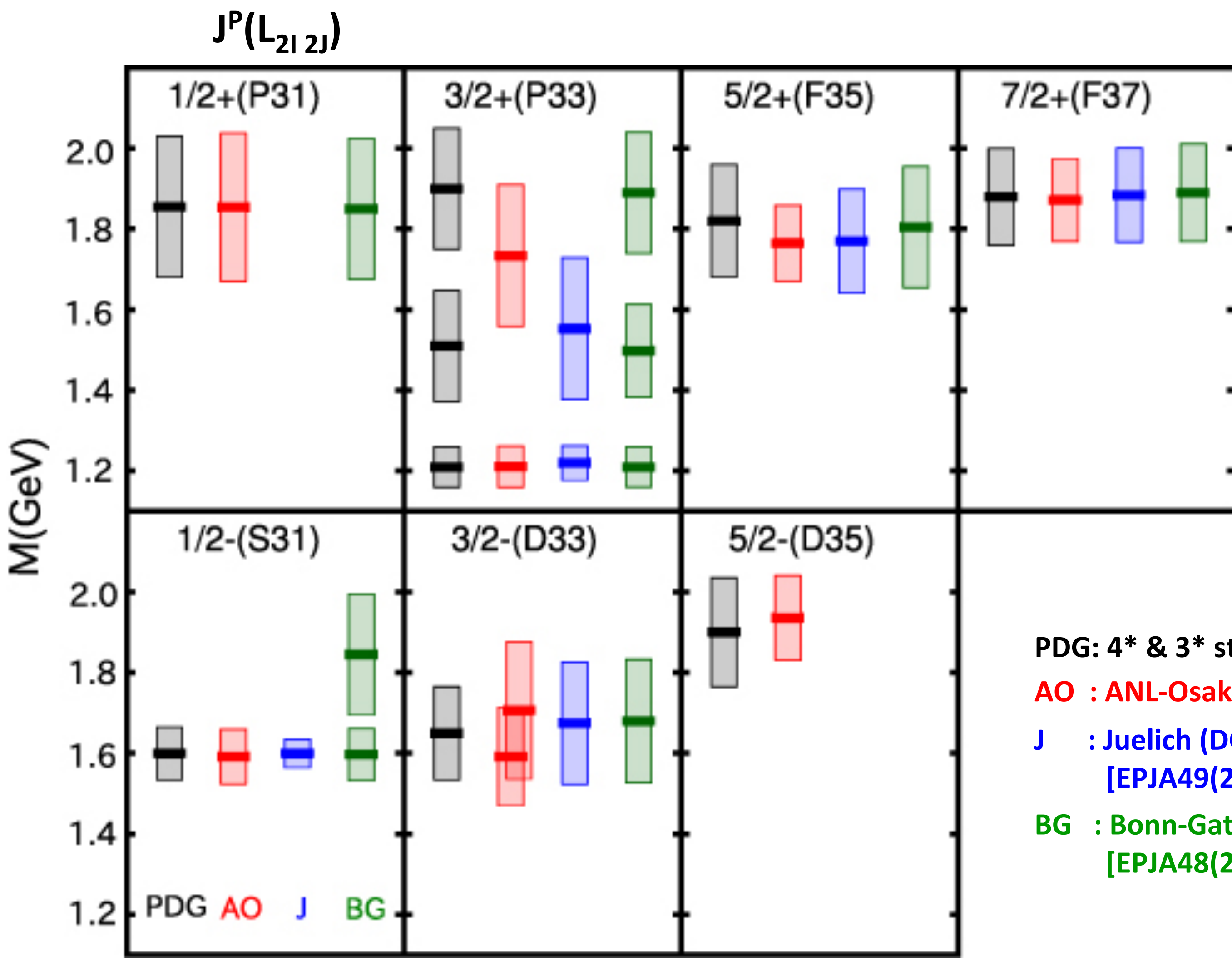
- Data to fix nucleon axial current ($g_{AN\Delta}$)
- Discrepancy between BNL & ANL data
- Recent reanalysis of original data
  → discrepancy resolved (!?)
  PRD 90, 112017 (2014)

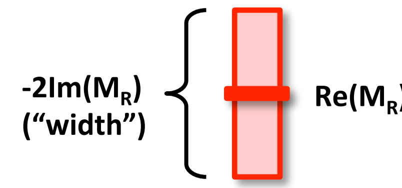
- Final state interaction (FSI) changes charge, momentum, number of π
- Cross section shape is worse described with FSI
- MINERνA data (arXiv:1406.6415) favor FSI
  $\langle E_\nu \rangle = 4.0$ GeV

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]

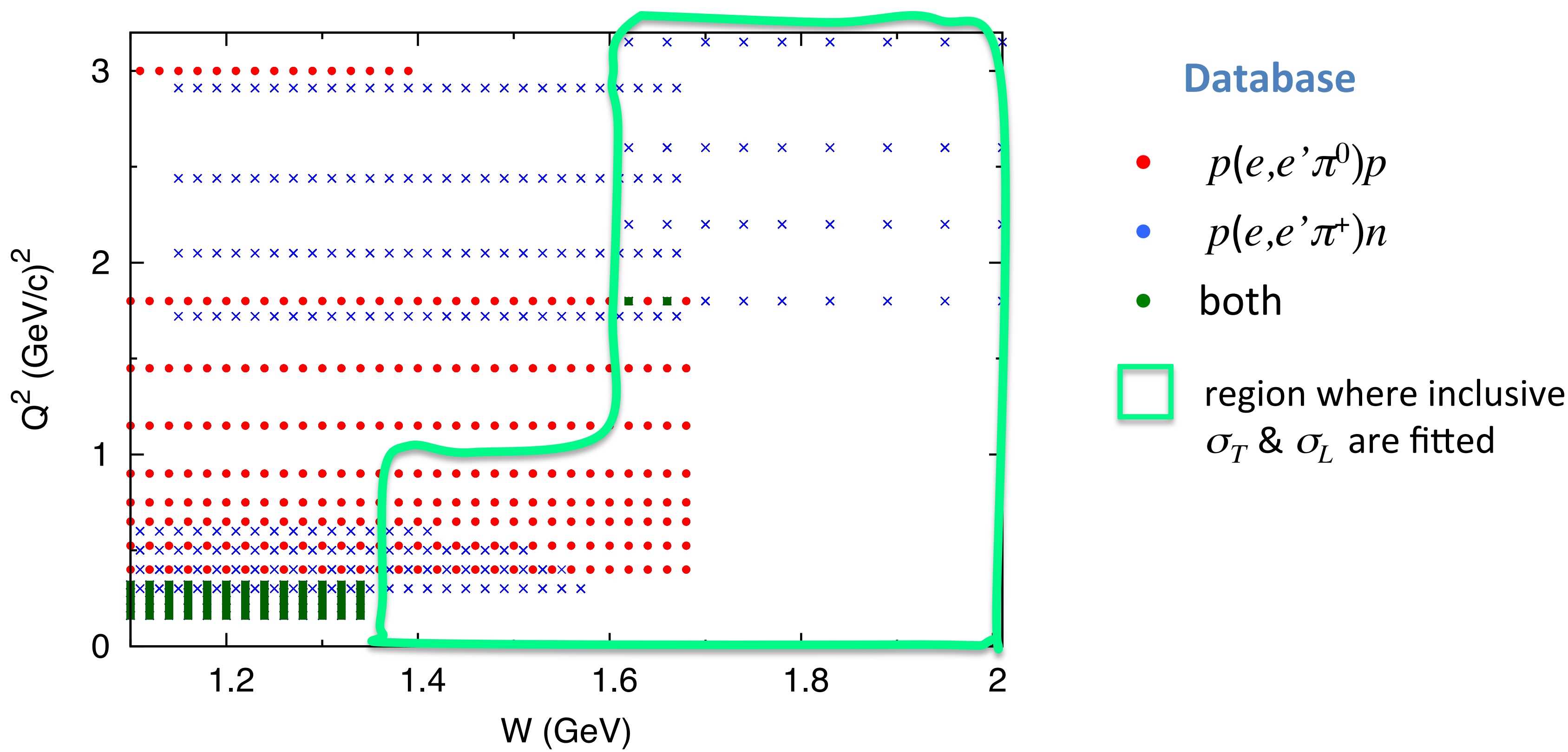
BG : Bonn-Gatchina (K-matrix) [EPJA48(2012)5]

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

$\theta \rightarrow 0$

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

$Q^2 \rightarrow 0$

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

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

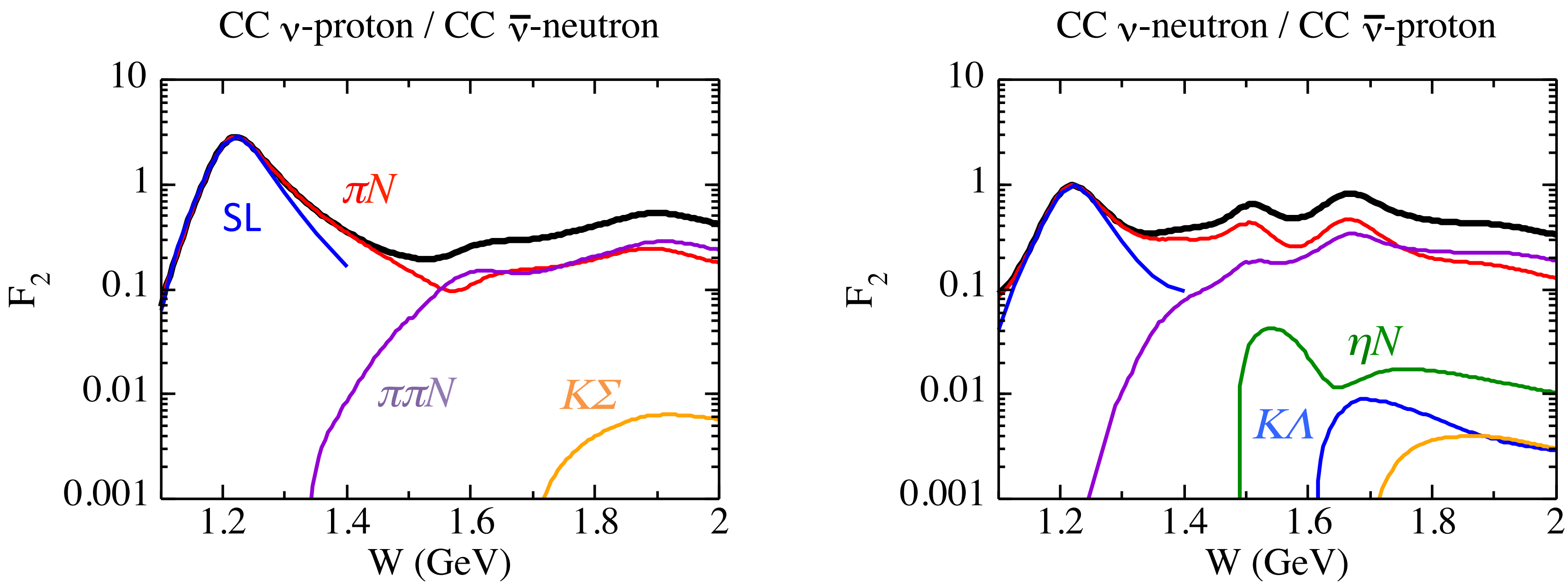
$$\langle X | \hat{\pi} | N \rangle = \frac{\sqrt{2\omega_c}}{m_\pi^2} \mathcal{T}_{\pi N \rightarrow X}(0) \sim \frac{\sqrt{2\omega_c}}{m_\pi^2} \mathcal{T}_{\pi N \rightarrow X}(m_\pi^2)$$

Finally

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

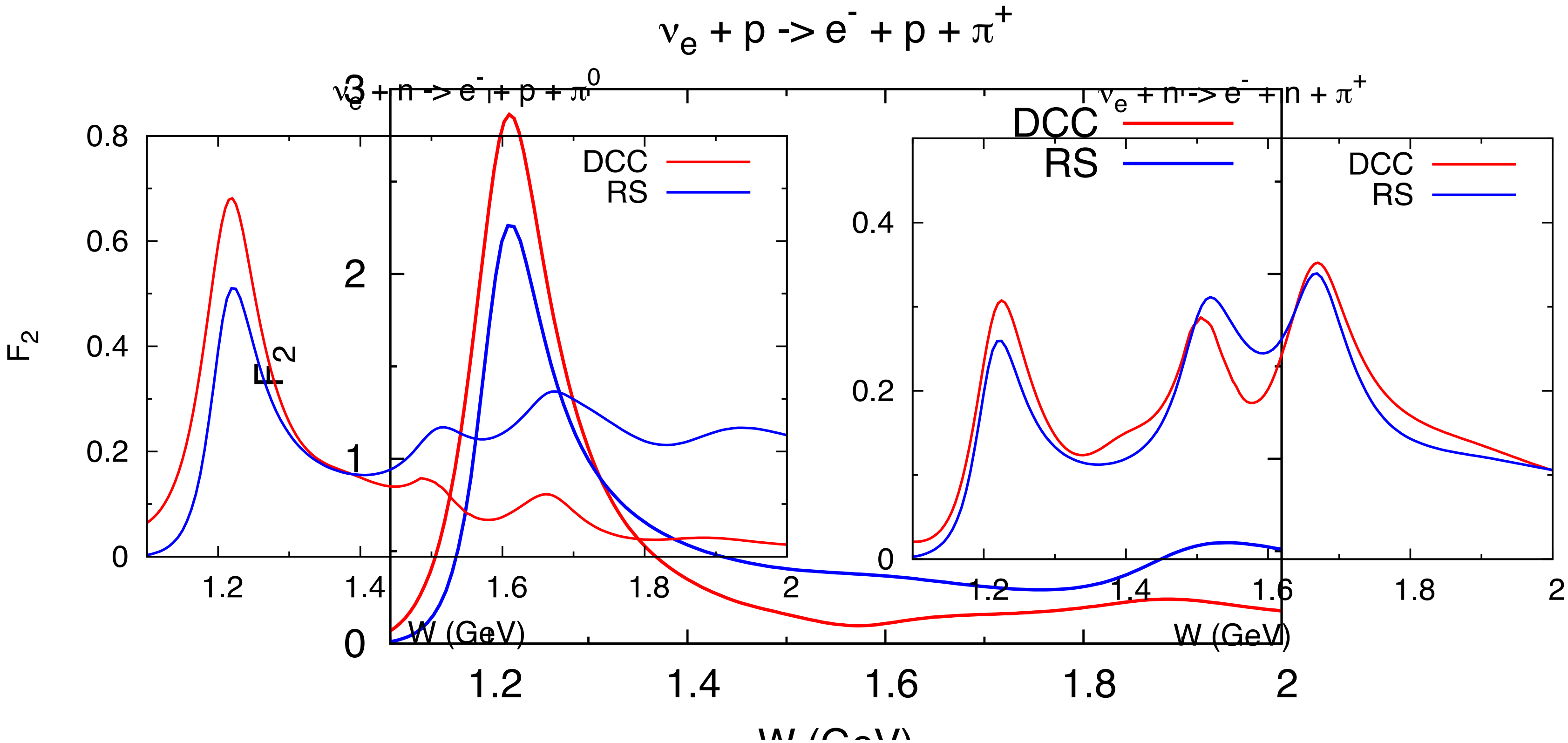
$\sigma_{\pi N \rightarrow X}$ is from our DCC model

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

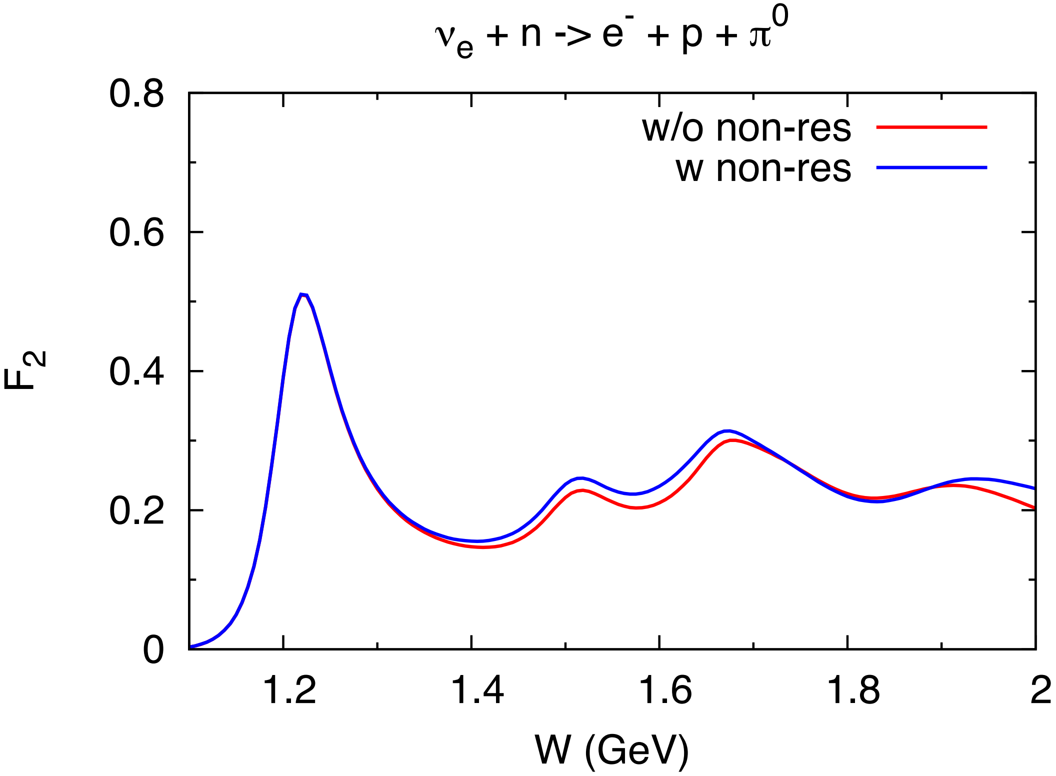
Comparison with Rein-Sehgal model



Comparison in whole kinematical region will be done

after axial current model is developed

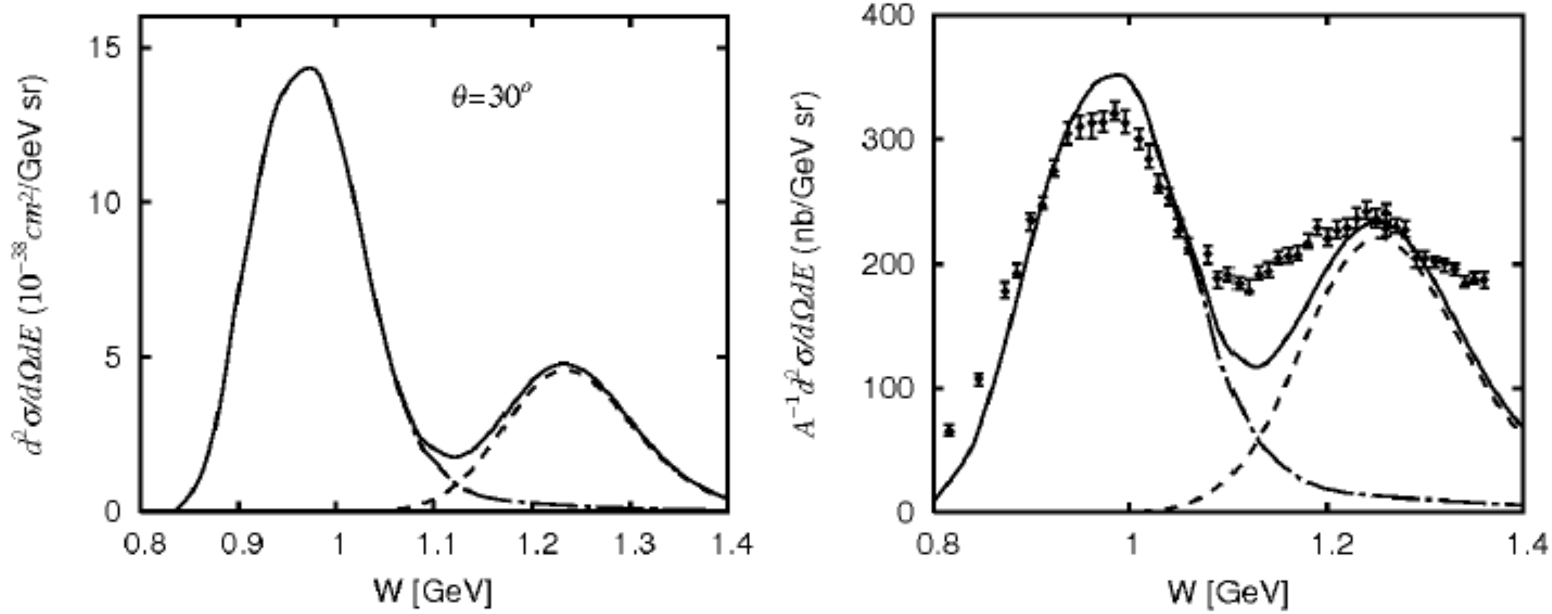
F_2 from RS model



SL model applied to ν−nucleus scattering

1 π production

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

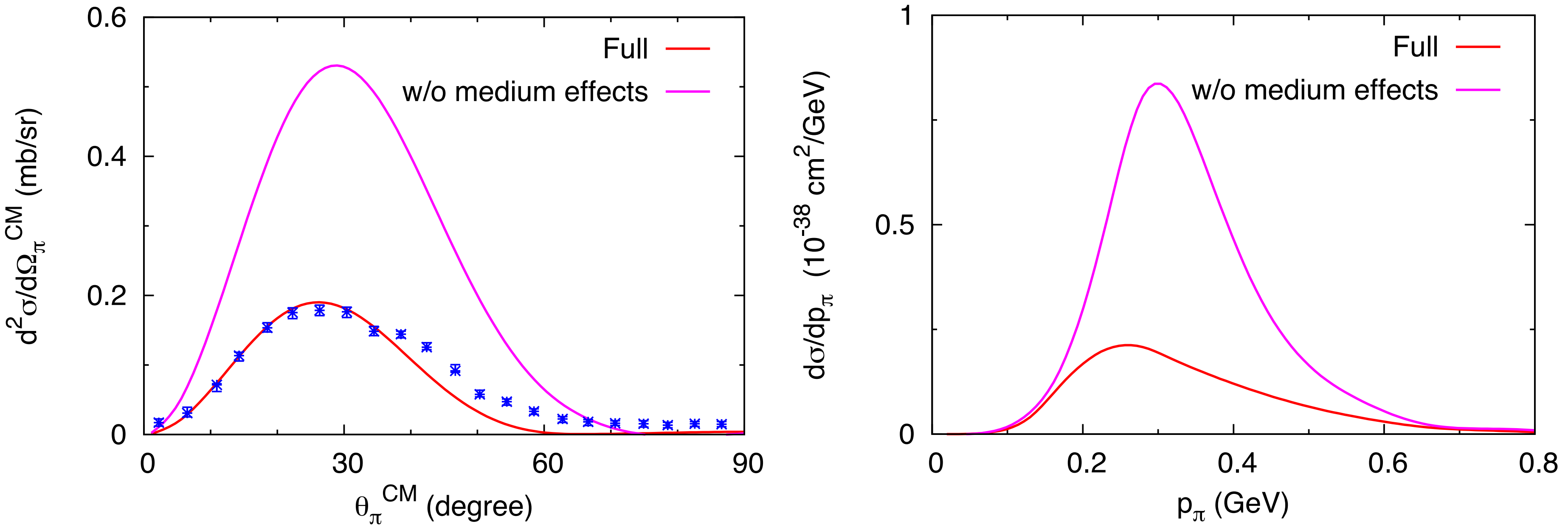


Szczerbinska et al. (2007)

SL model applied to ν−nucleus scattering

coherent π production

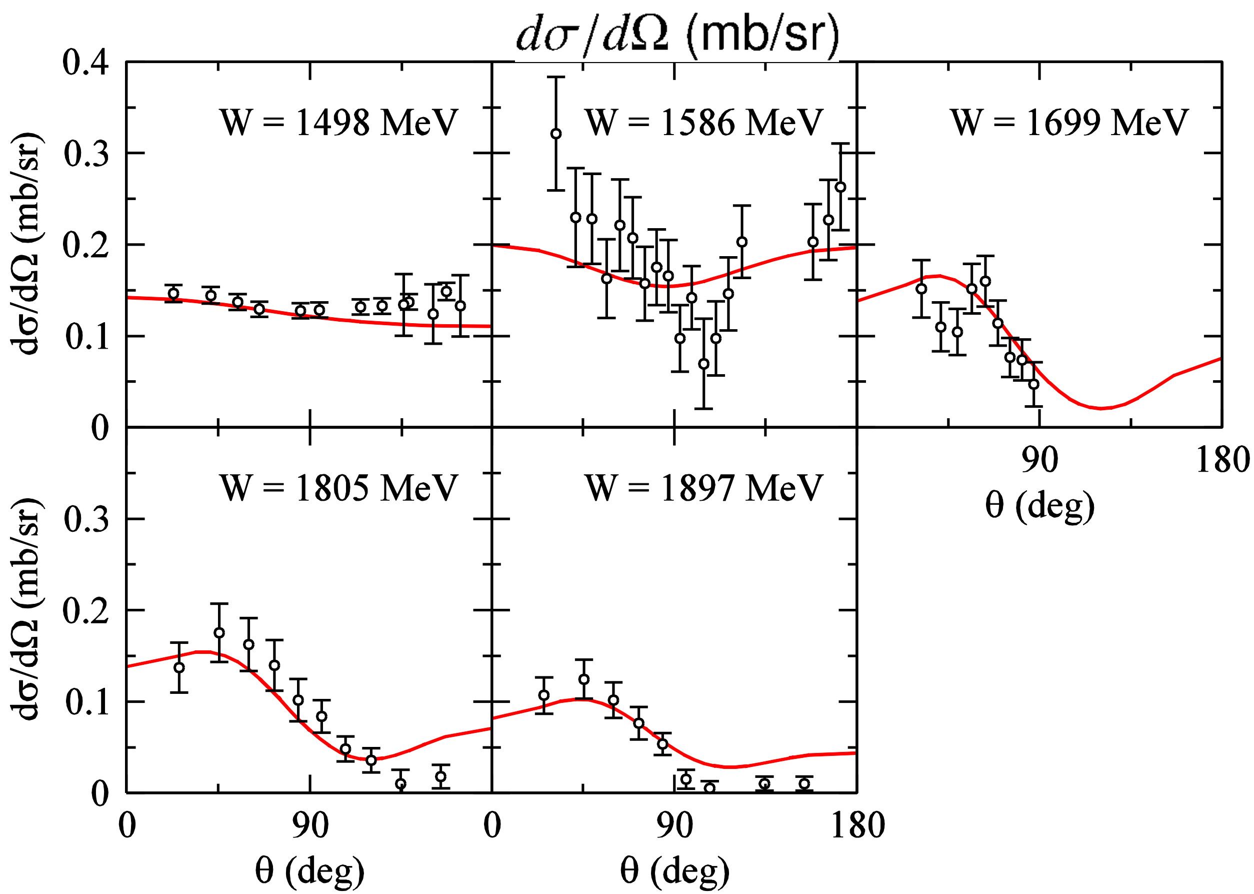
$\gamma + {}^{12}C \rightarrow \pi^0 + {}^{12}C$ $\nu_\mu + {}^{12}C \rightarrow \mu^- + \pi^0 + {}^{12}C$



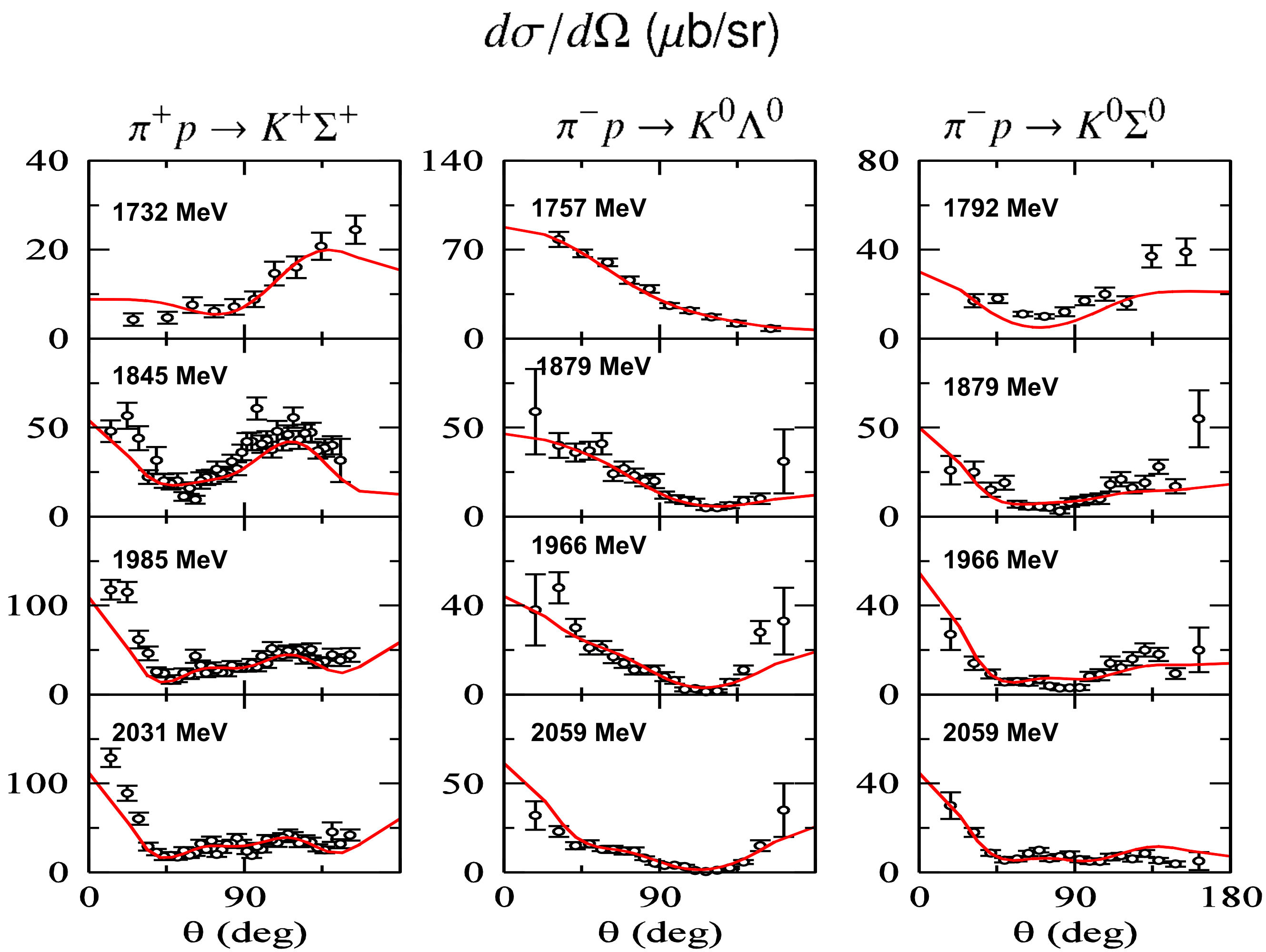
Nakamura et al. (2010)

Eta production reactions

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



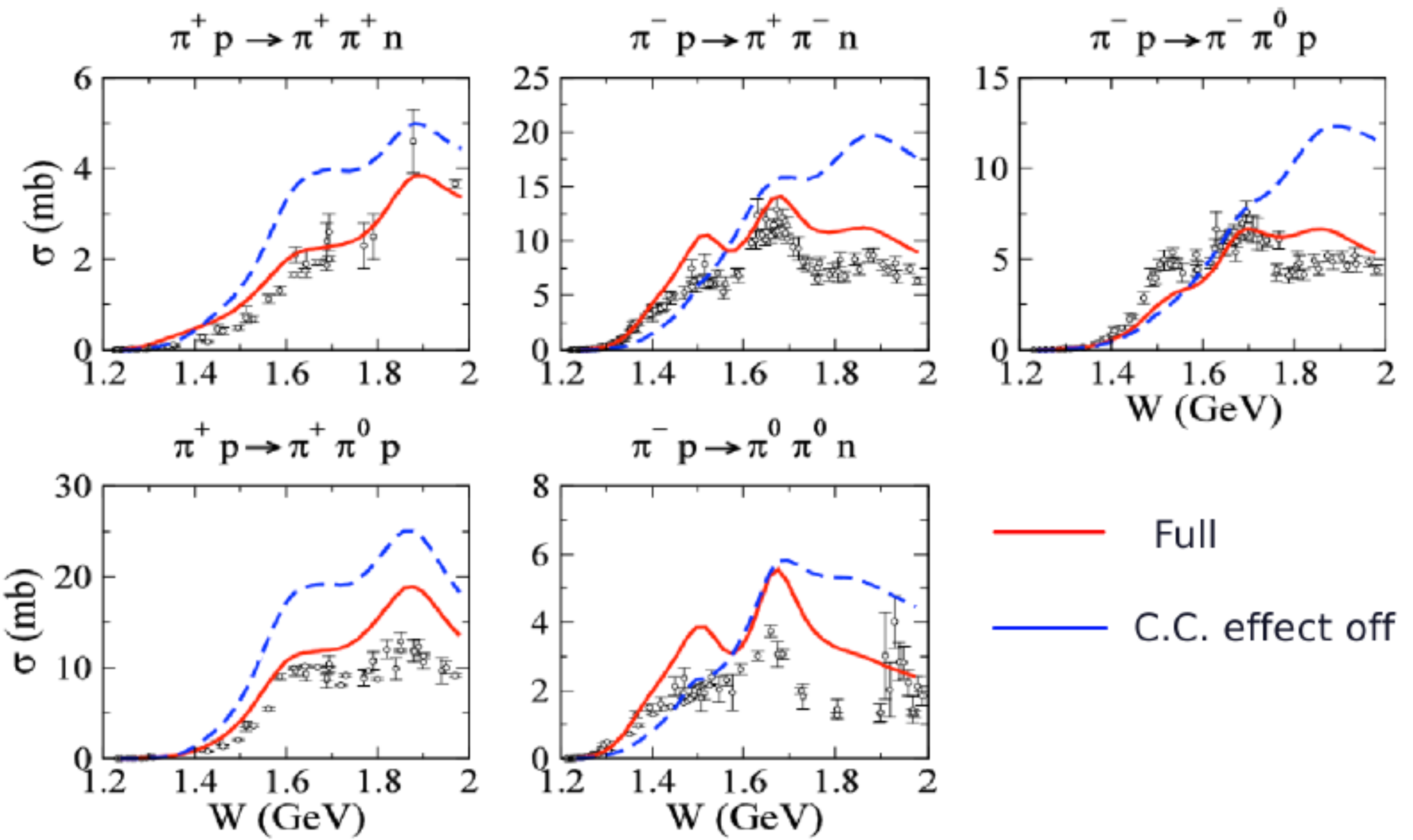
KY production reactions

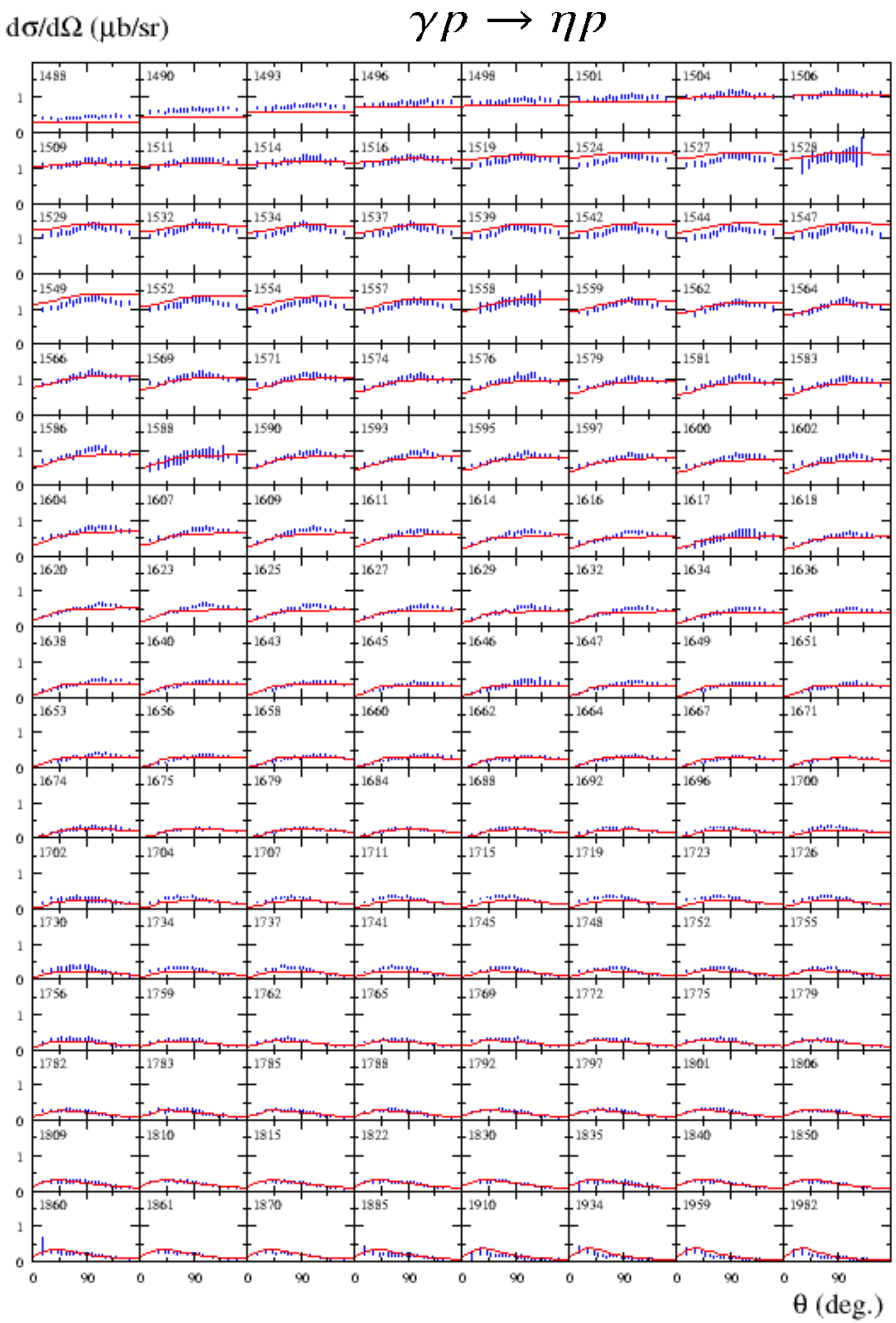


$\pi N \to \pi\pi N$

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

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





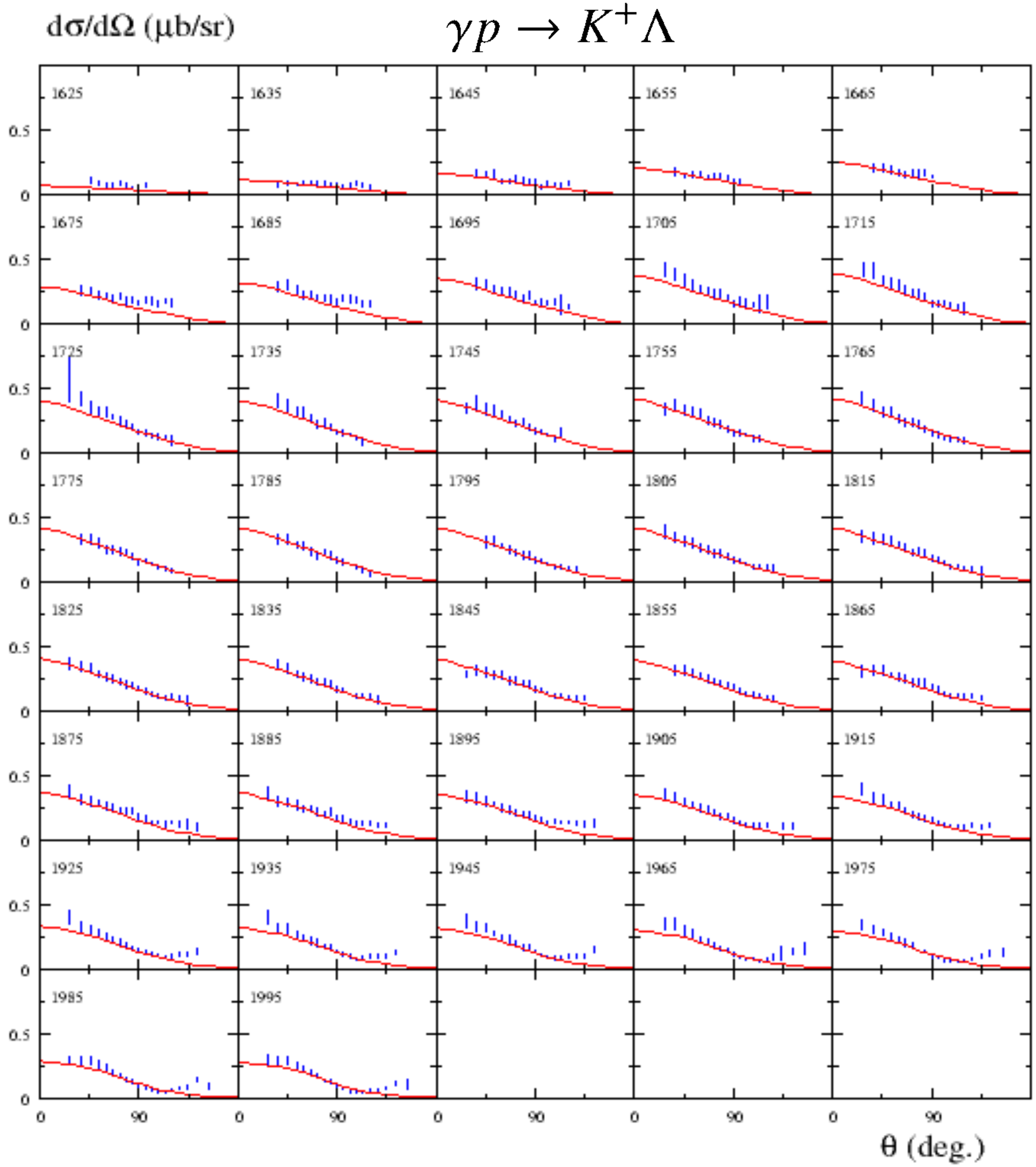
Kamano, Nakamura, Lee, Sato, arXiv:1305.4351

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



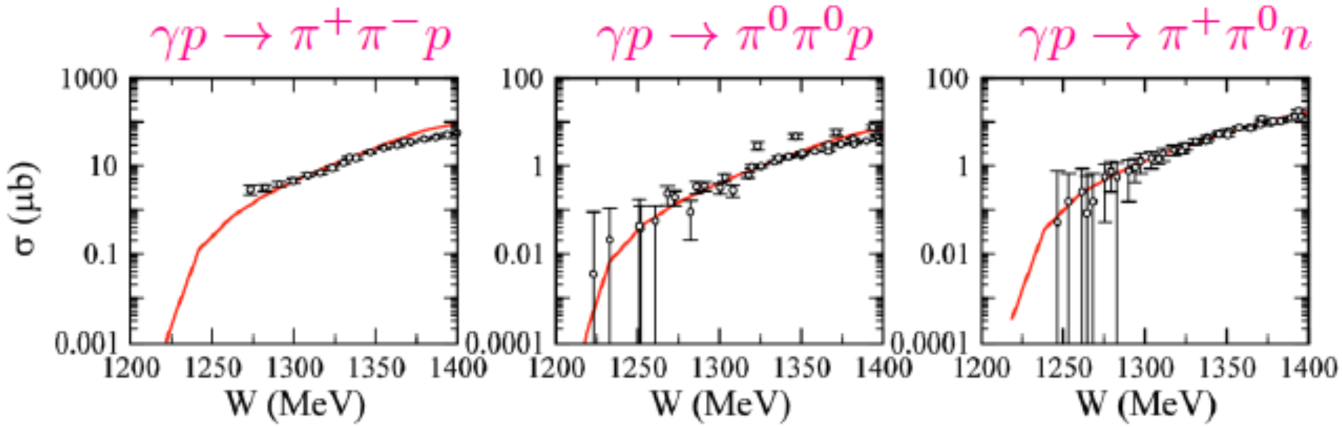
Vector current (Q^2=0) for K

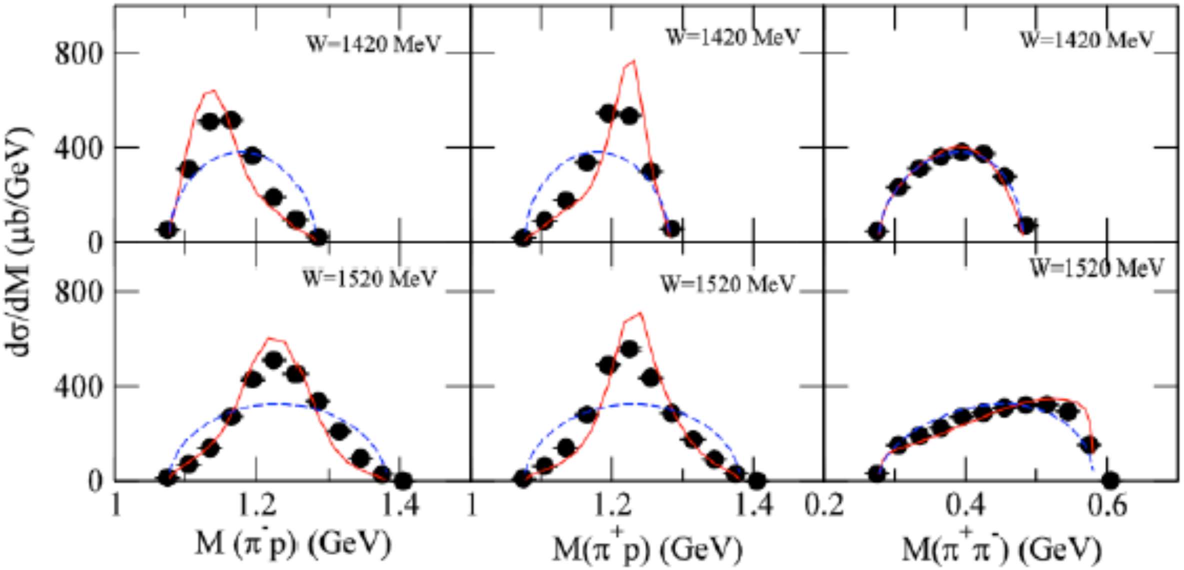
Production is well-tested by data

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

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

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



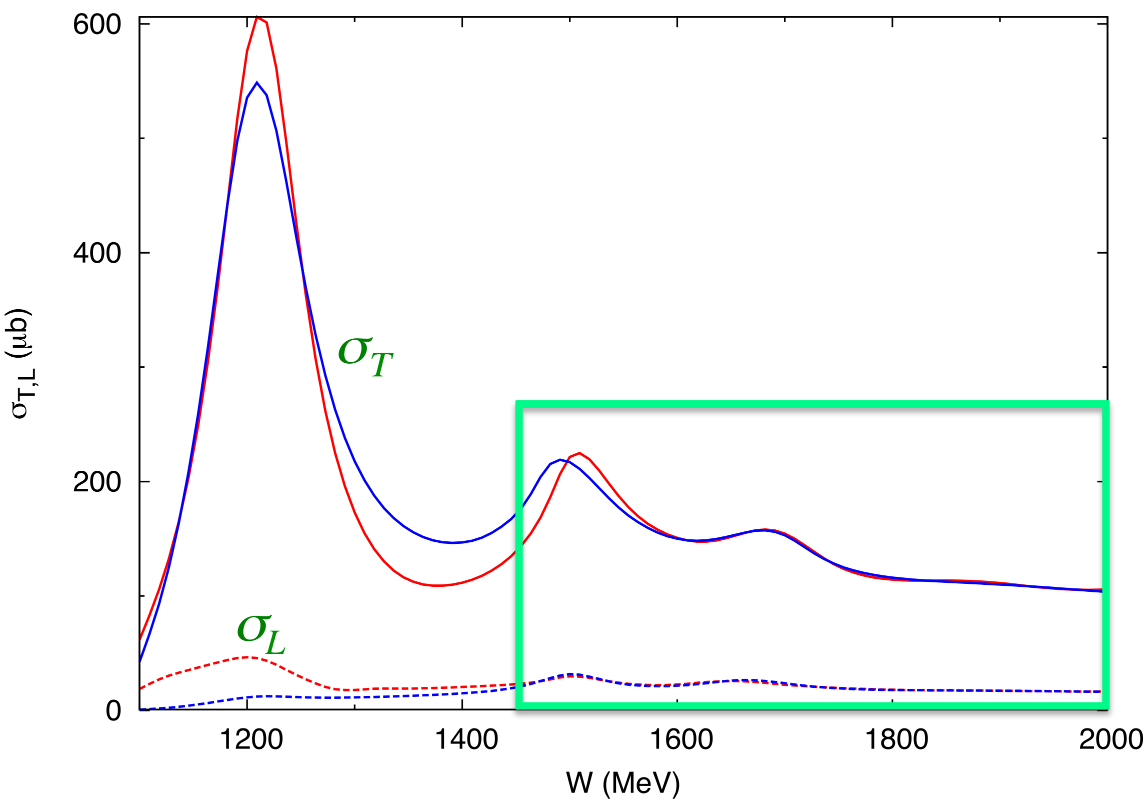


- $*$ Good description near threshold
- $*$ Good shape of invariant mass distribution
- $*$ Total cross sections overestimate data for $W \geq 1.5$ GeV

Analysis result

Q^2=0.16 (GeV/c)^2

σ_T & σ_L (inclusive inelastic)



DCC

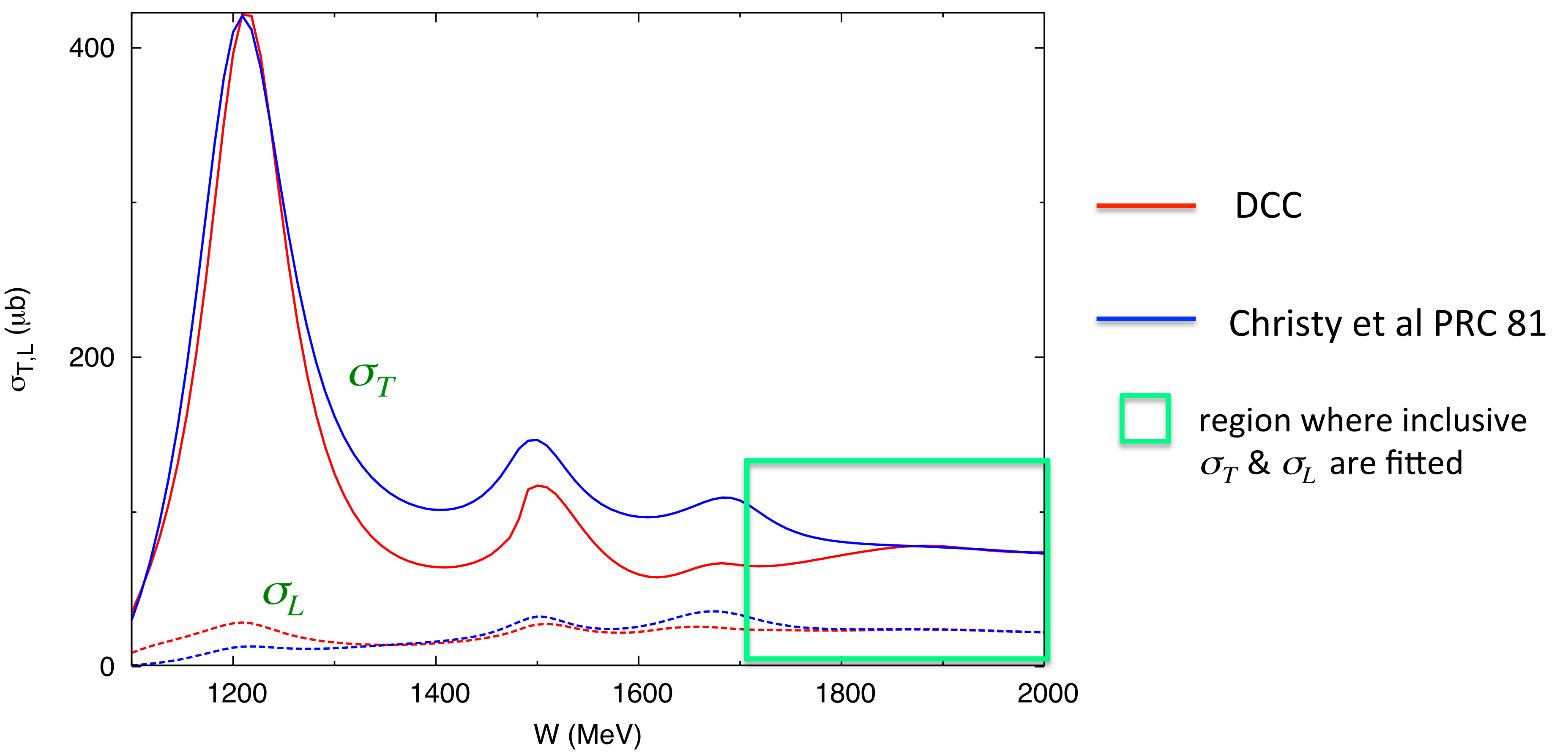
Christy et al PRC 81

region where inclusive σ_T & σ_L are fitted

Analysis result

Q^2=0.40 (GeV/c)^2

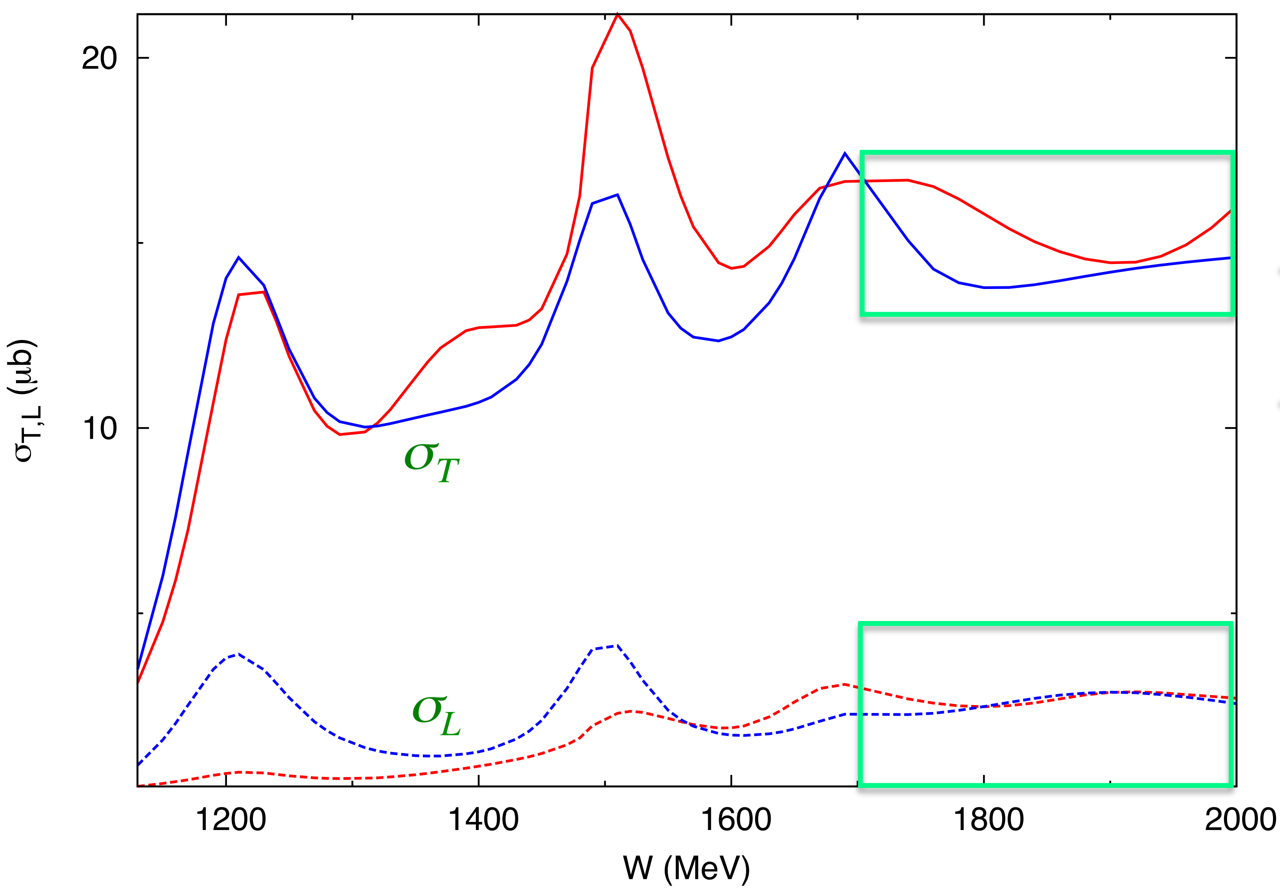
σ_T & σ_L (inclusive inelastic)



Analysis result

Q^2=2.95 (GeV/c)^2

σ_T & σ_L (inclusive inelastic)



DCC

Christy et al PRC 81

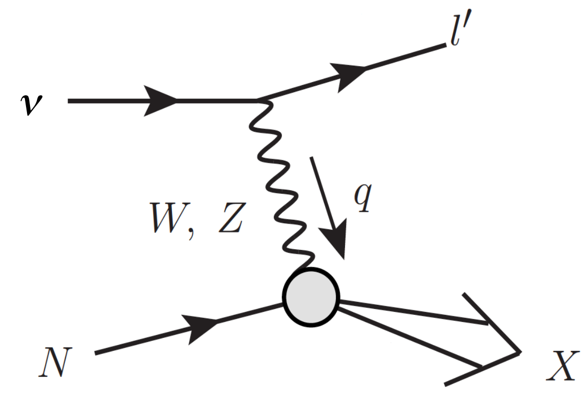
region where inclusive σ_T & σ_L are fitted

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

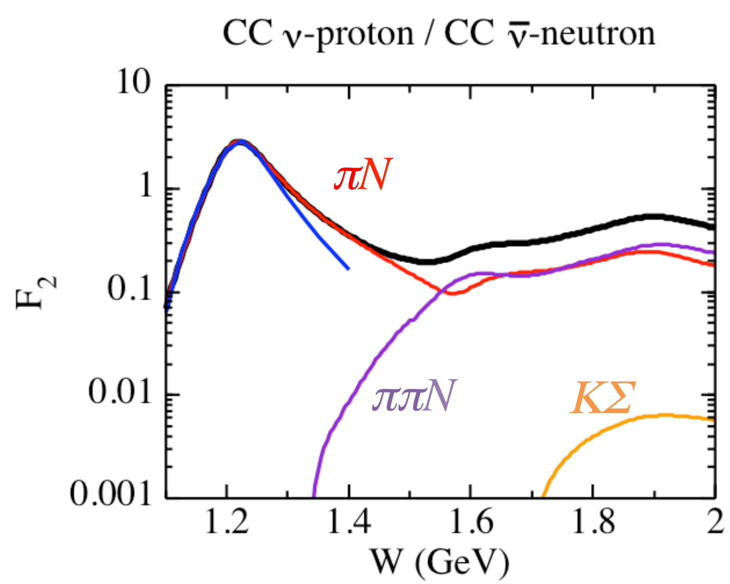
Kamano, Nakamura, Lee, Sato, PRD 86 (2012)



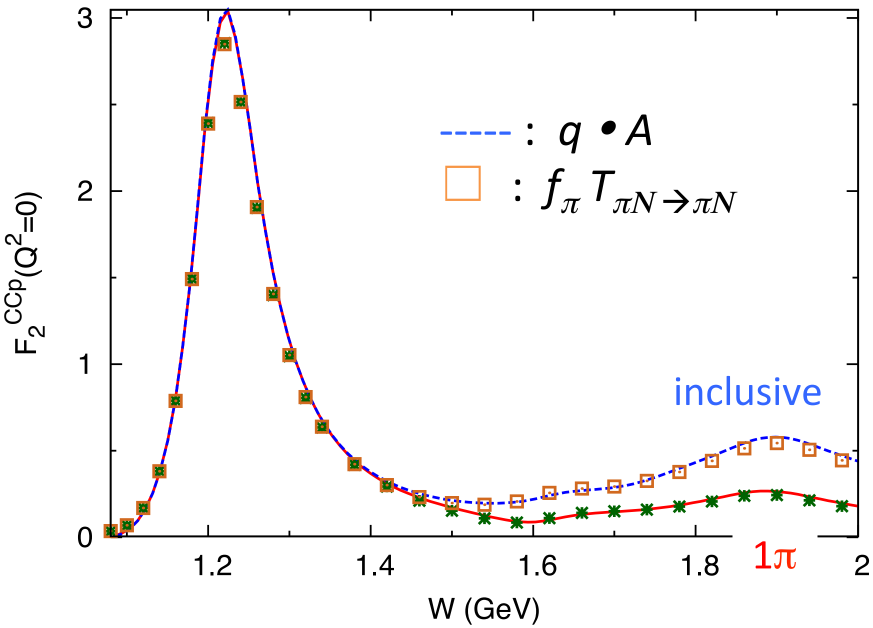
$$\frac{d\sigma}{dE_\ell d\Omega_\ell} = \frac{G_F^2}{2\pi^2} E_\ell^2\, W_2$$

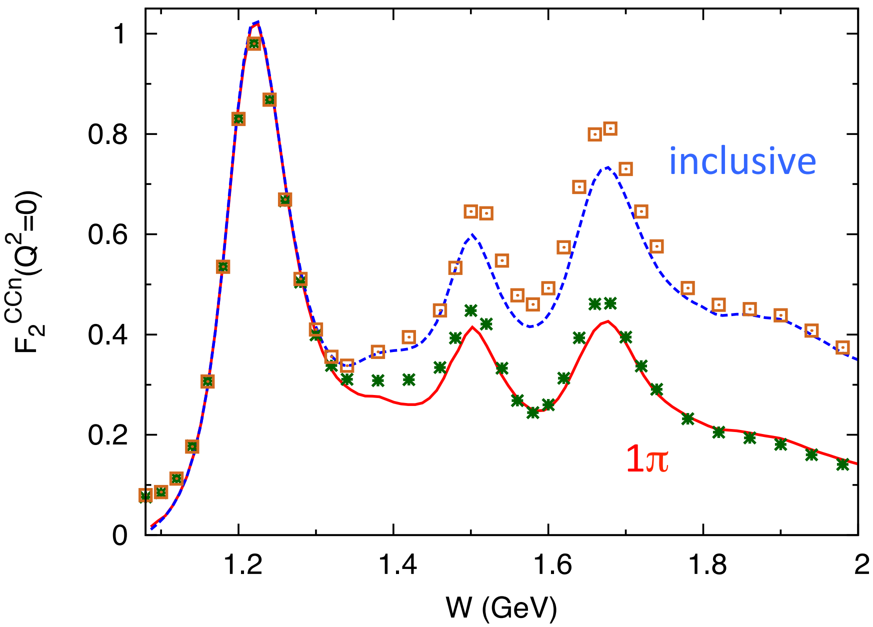
via PCAC $$F_2 \equiv \omega W_2 = \frac{2 f_\pi^2}{\pi} \sigma_{\pi N \rightarrow X}$$

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



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



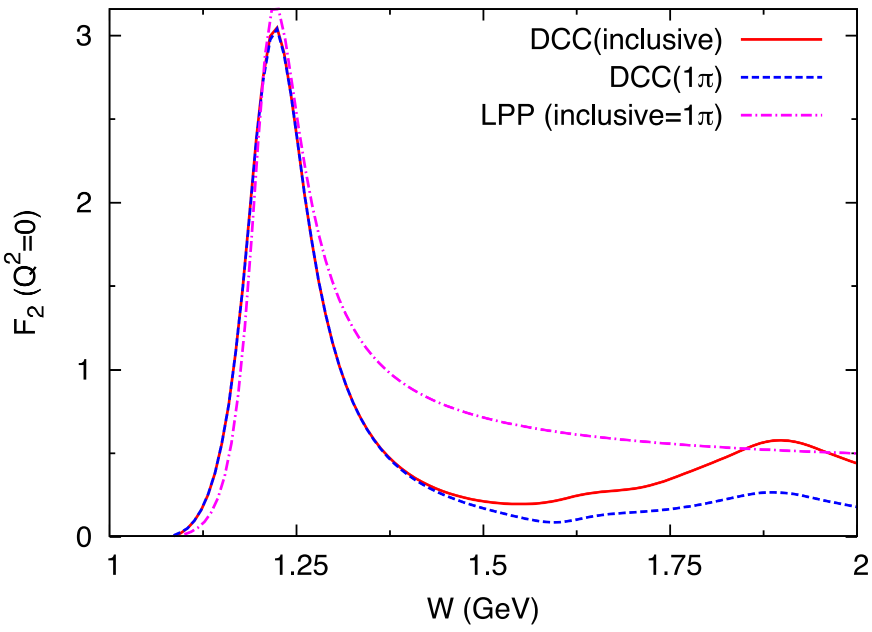


DCC model keeps good consistency with PCAC

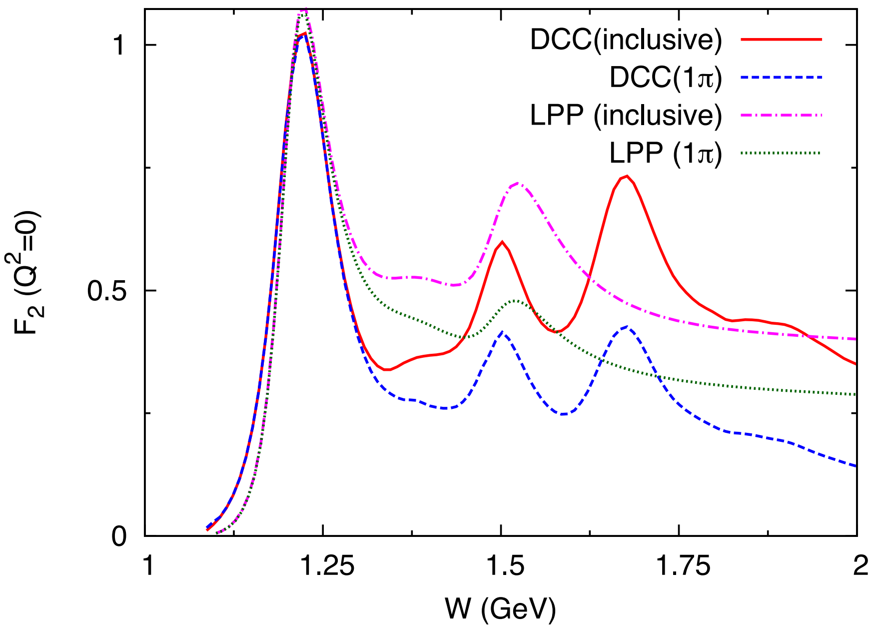
Comparison with LPP model

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

CCνp



CCνn

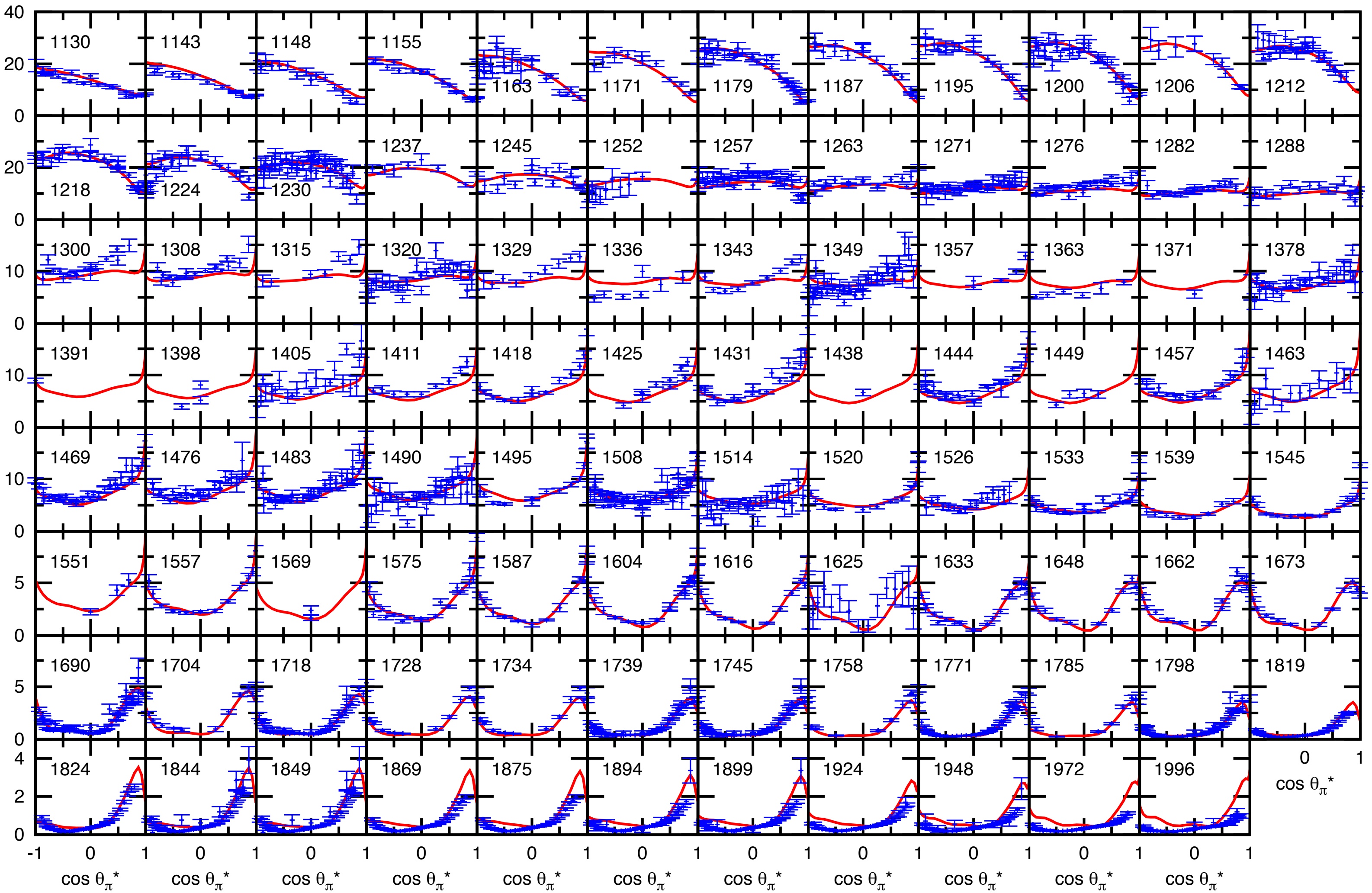


- Large difference beyond $\Delta(1232)$ region
- Importance of consistency between axial-current and πN interaction

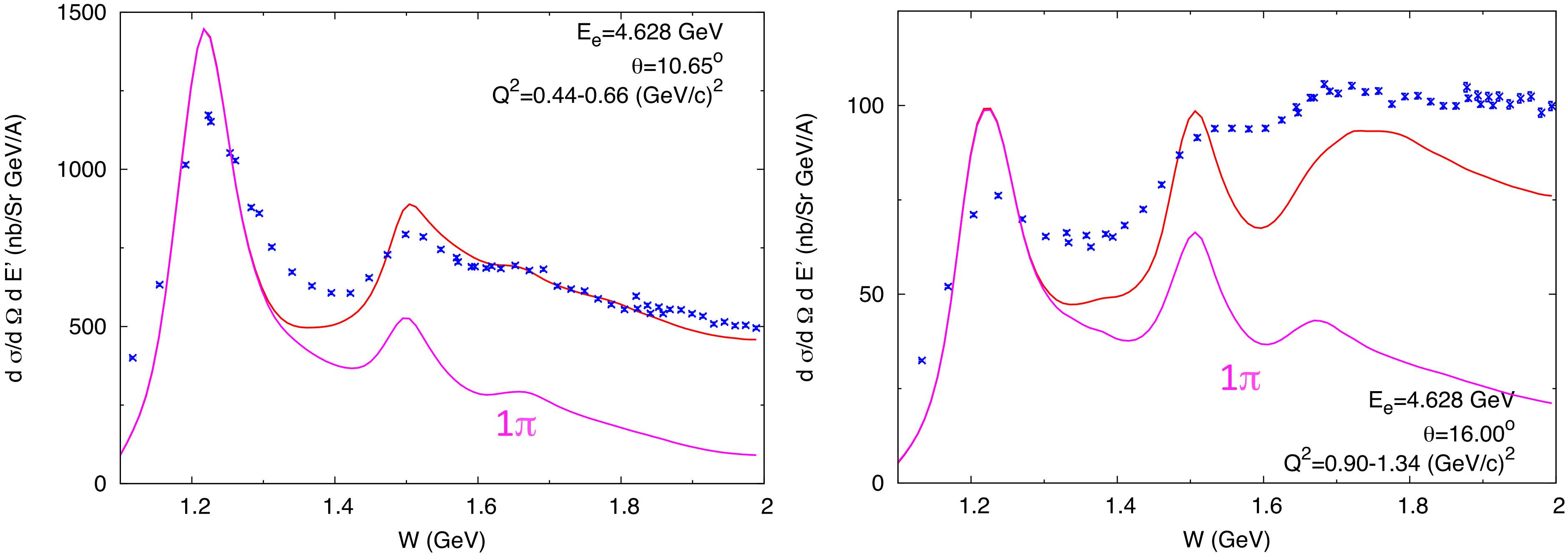
Analysis result (single π)

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

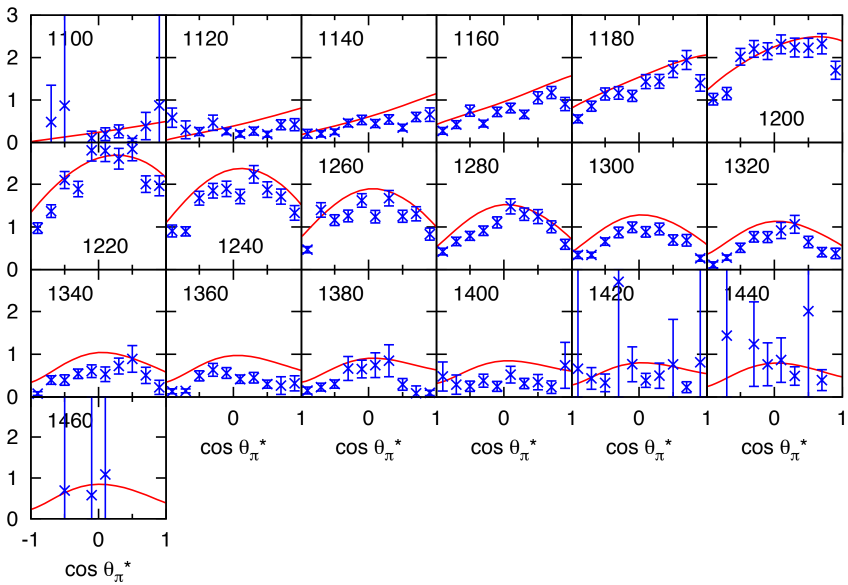
relevant to neutrino interactions of $E_\nu \leq 2$ *GeV*

Analysis result (single π)

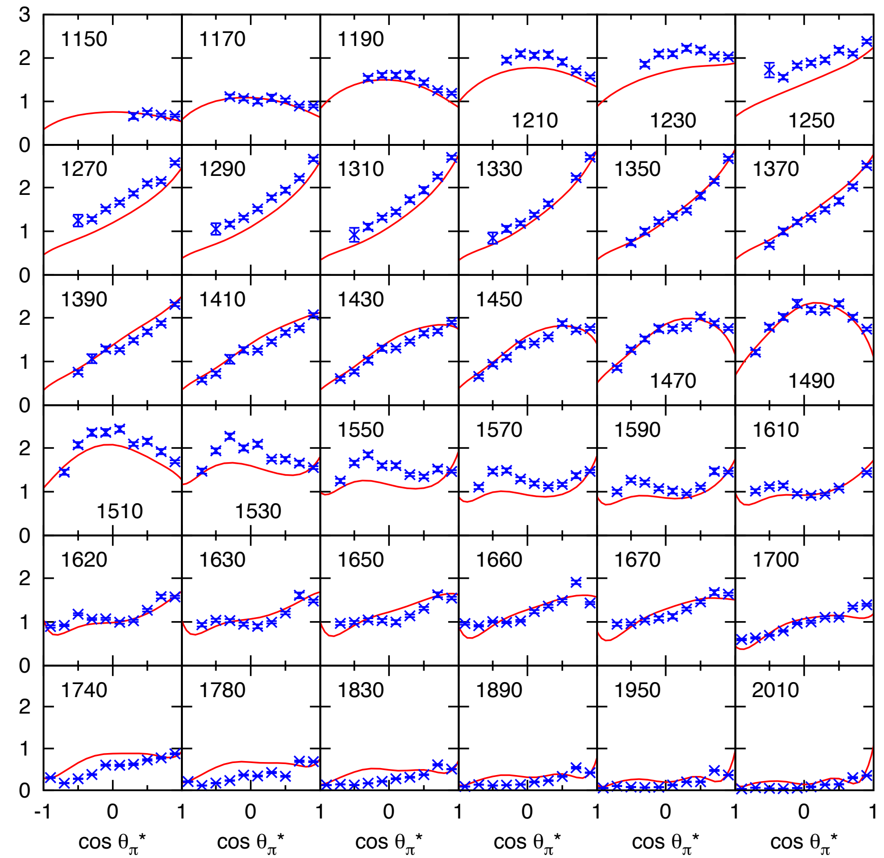
Q^2=1.76 (GeV/c)^2

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

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



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

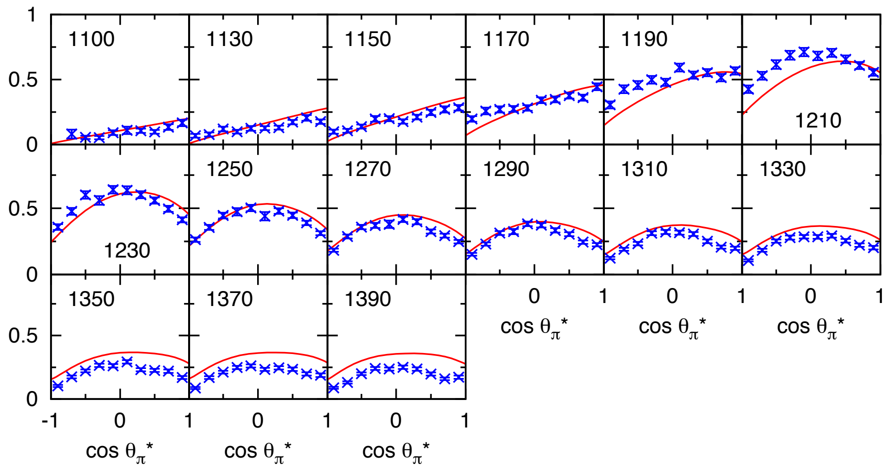


Analysis result (single π)

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

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

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



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