Meson Productions in Neutrino-Nucleon Scattering

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and electron scattering data

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★ Results for νN → $l^- X$

Introduction

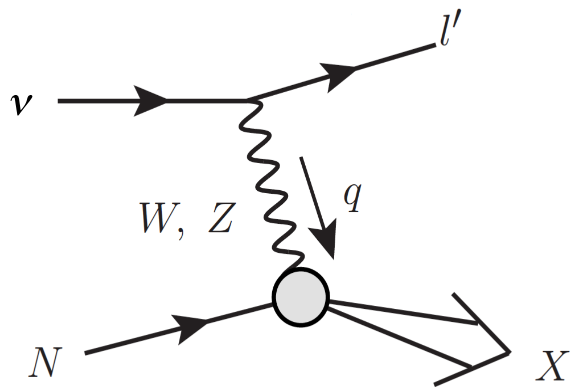
Neutrino-nucleus scattering for ν-oscillation experiments

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

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

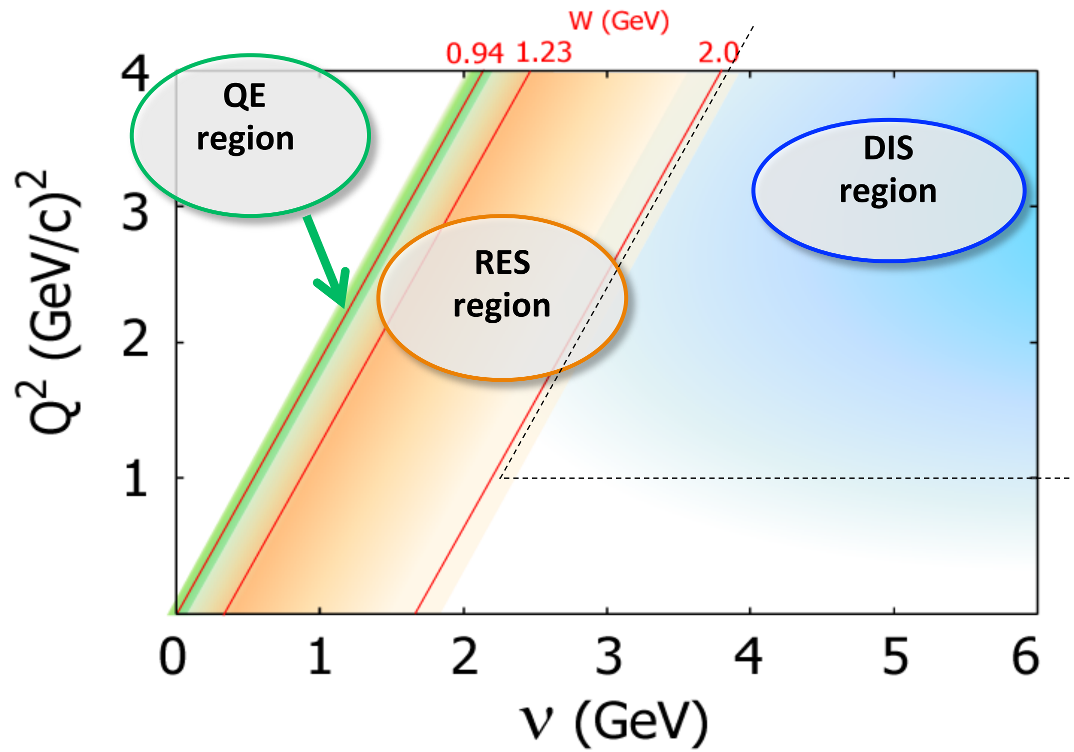
All ν-oscillation experiments measure ν-flux through ν-nucleus interaction

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



Neutrino-nucleus scattering for ν-oscillation experiments

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



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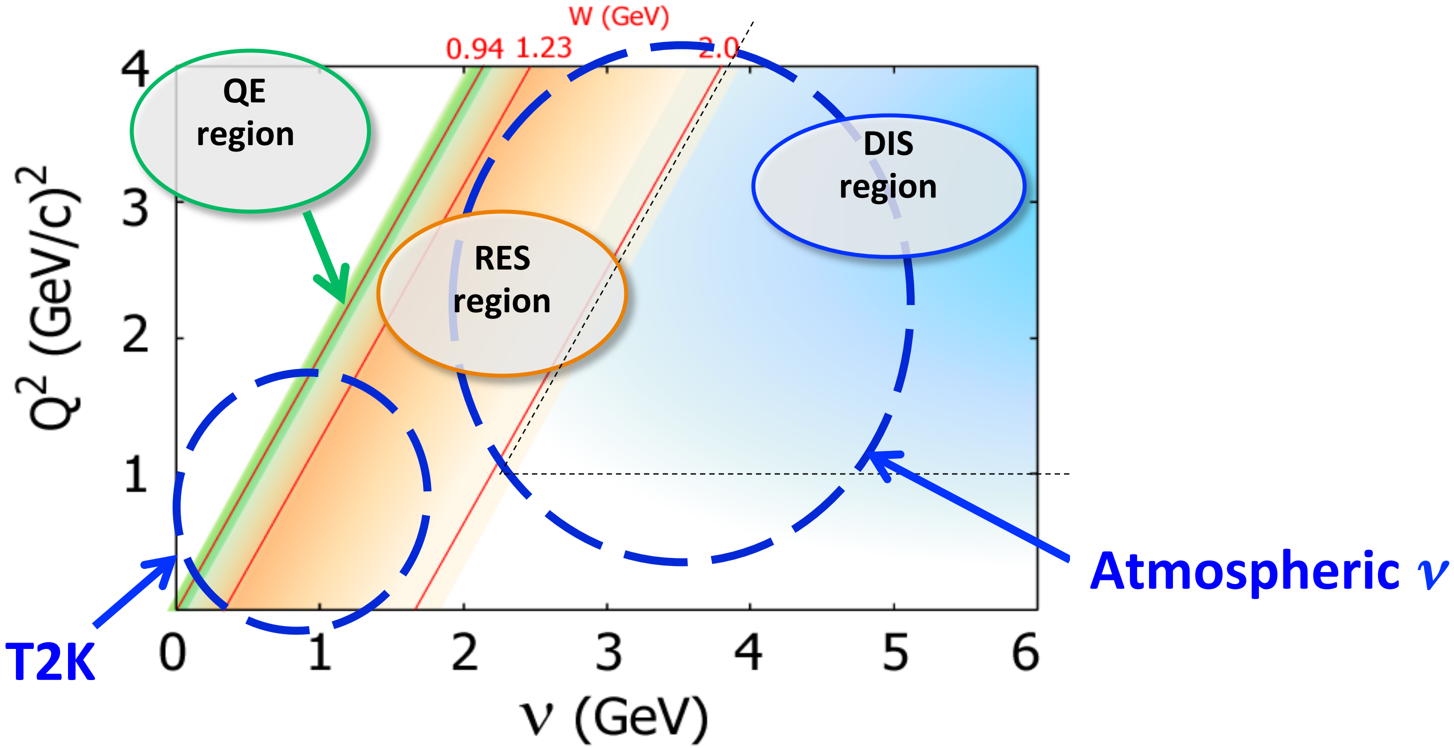
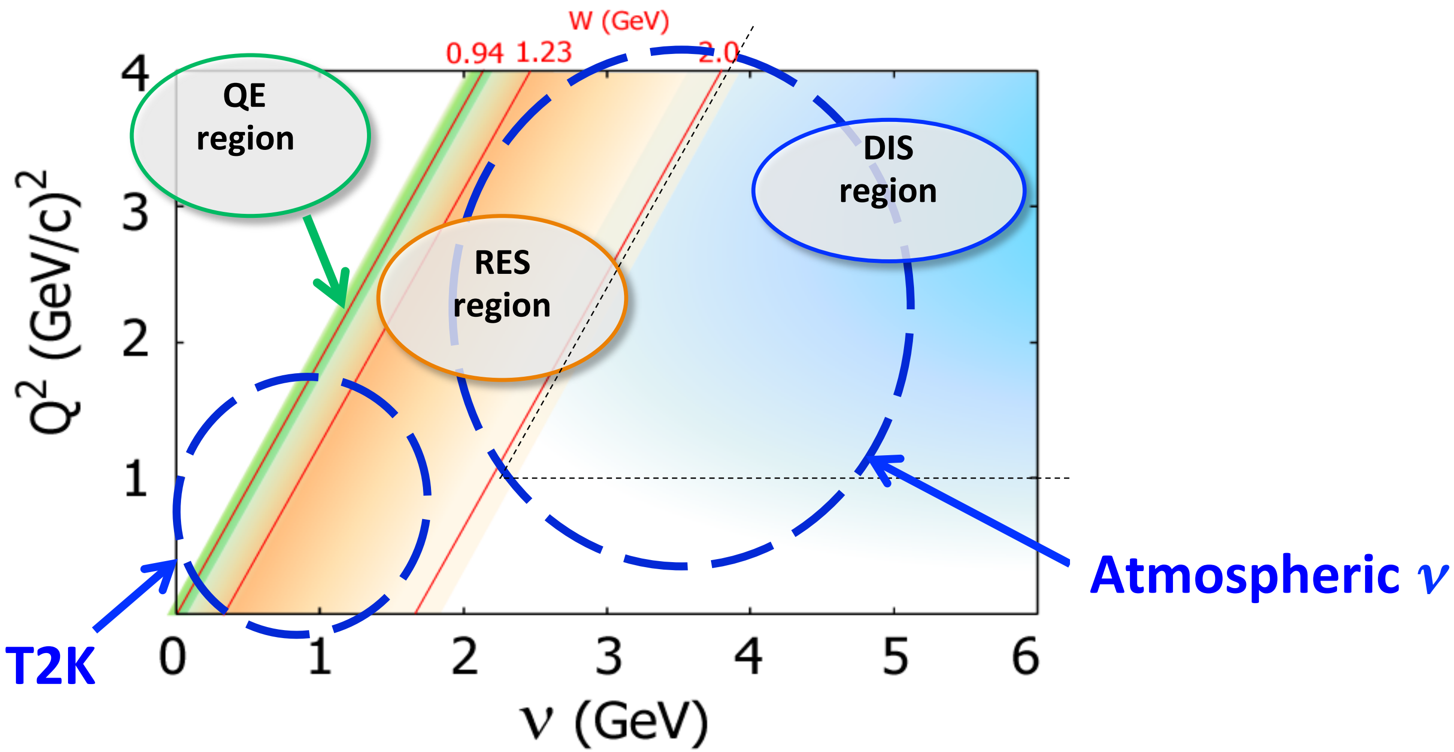


Neutrino-nucleus scattering for ν-oscillation experiments

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

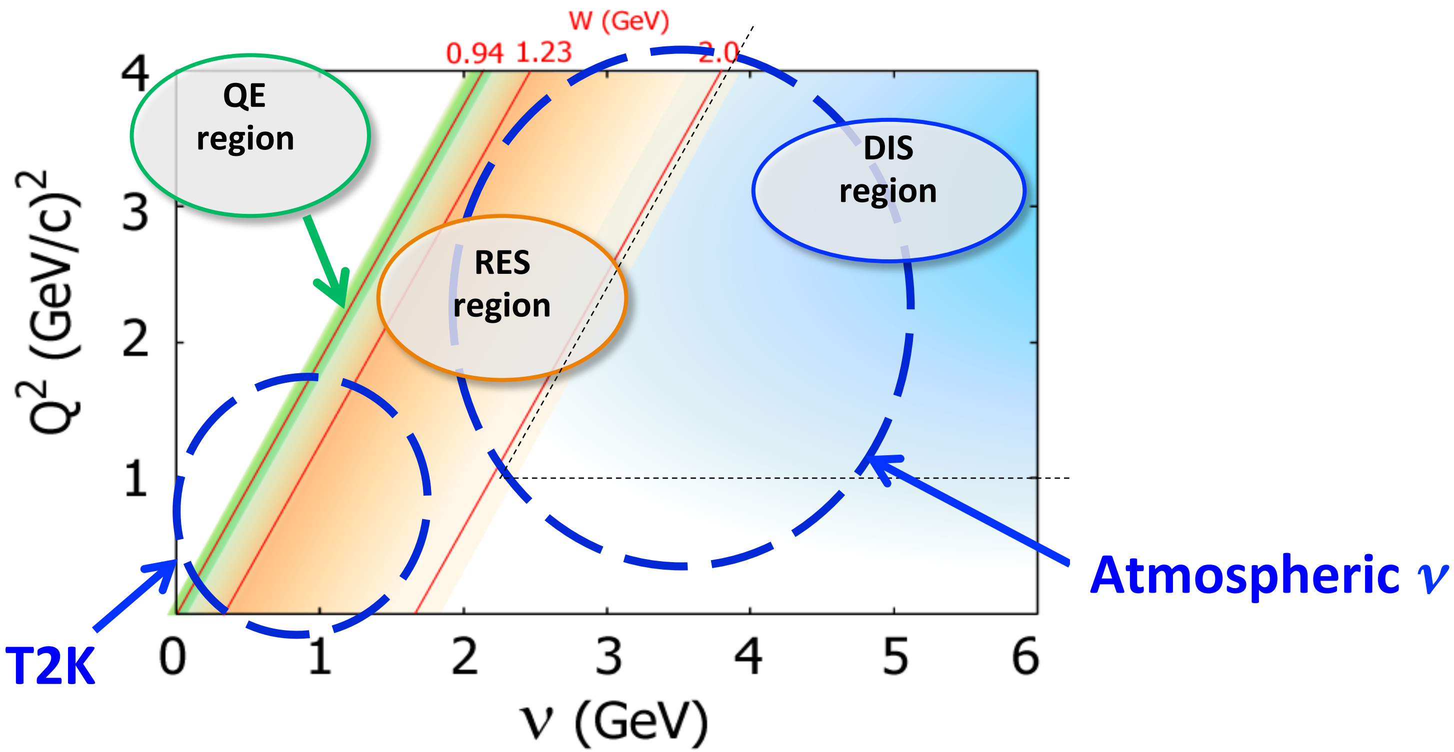


Wide kinematical region with different characteristic

➔ Combination of different expertise is necessary

Neutrino-nucleus scattering for ν-oscillation experiments

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

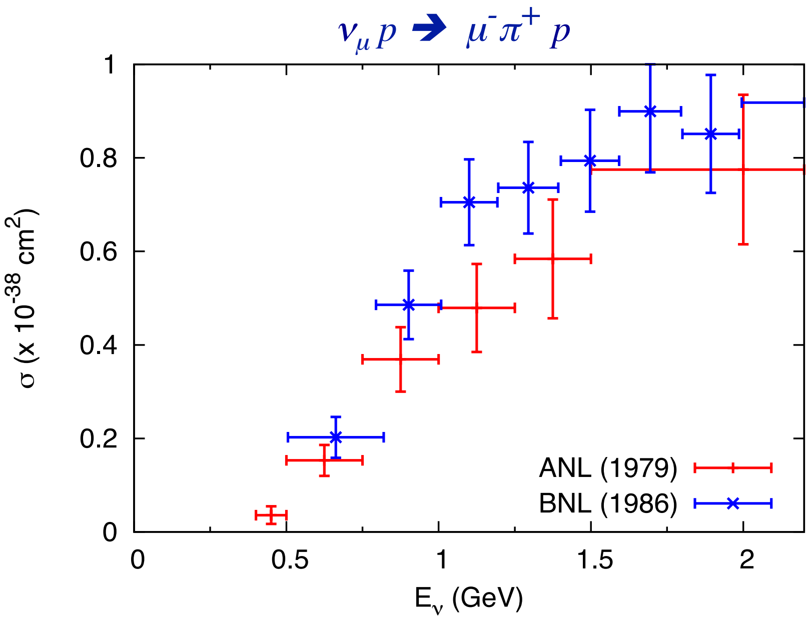


Collaboration at J-PARC Branch of KEK Theory Center

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

A review article to be published in *Reports on Progress in Physics*

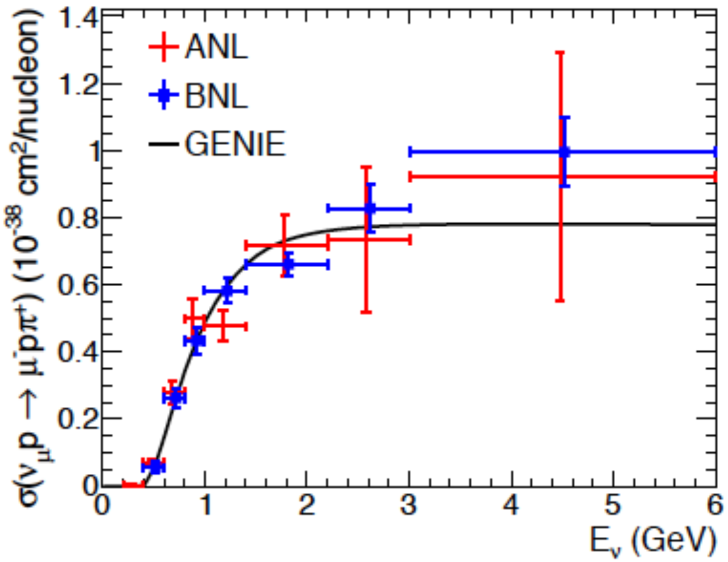
Neutrino interaction data in resonance region



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

Neutrino interaction data in resonance region

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



- 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)

Neutrino interaction data in resonance region

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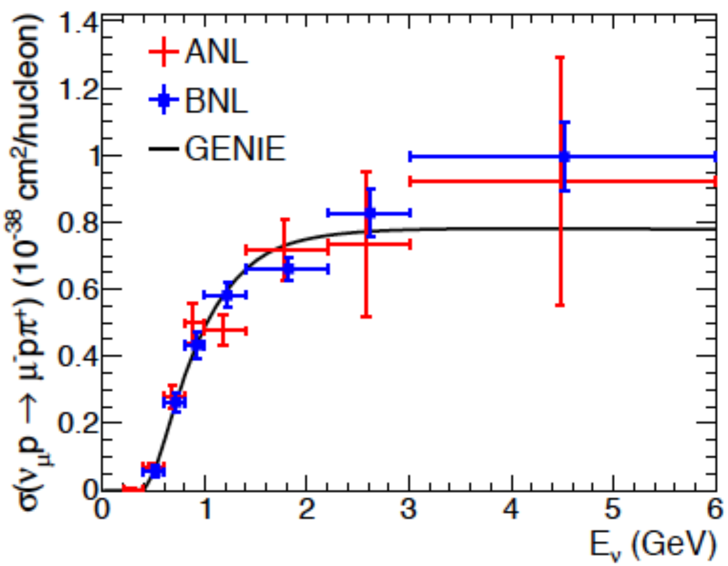
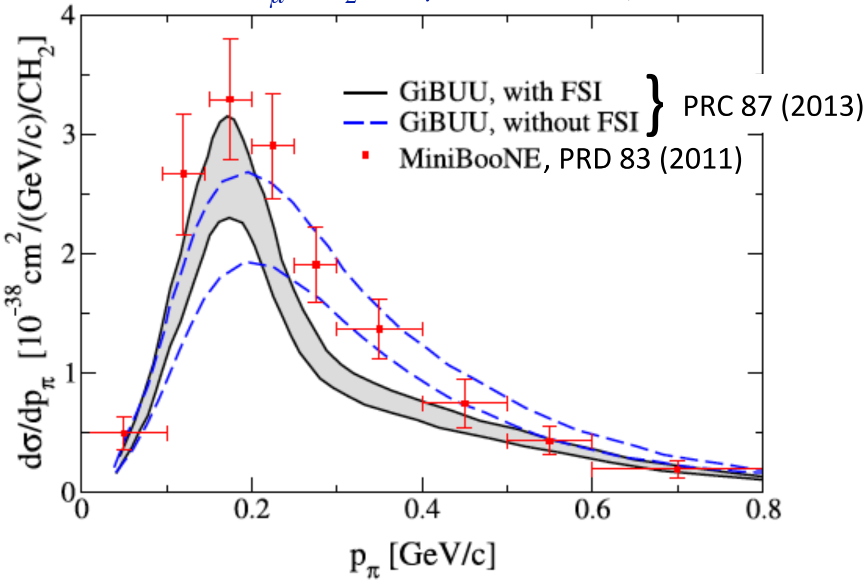


$\nu_\mu CH_2 \rightarrow \mu^- \pi^0 X \quad \langle E_\nu \rangle = 0.8$ GeV



- 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

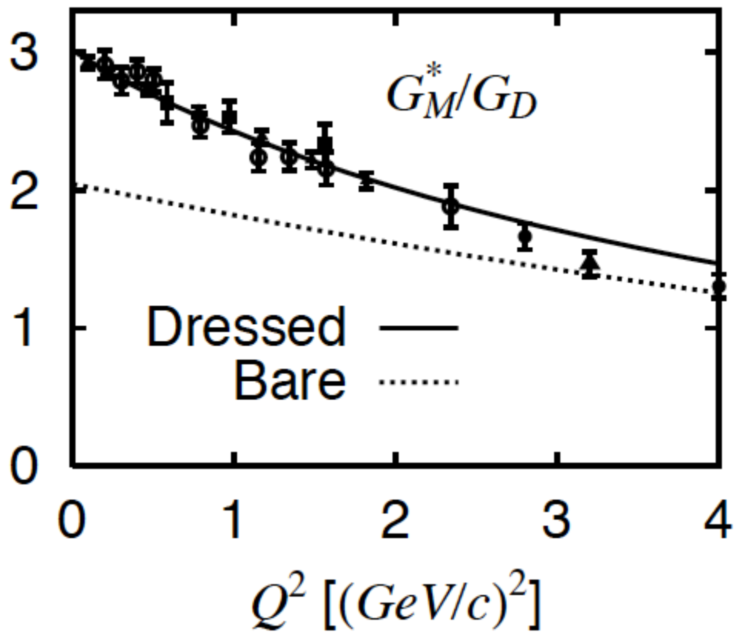
More data are coming → better understanding of neutrino-nucleus interaction

Relevance to baryon spectroscopy

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

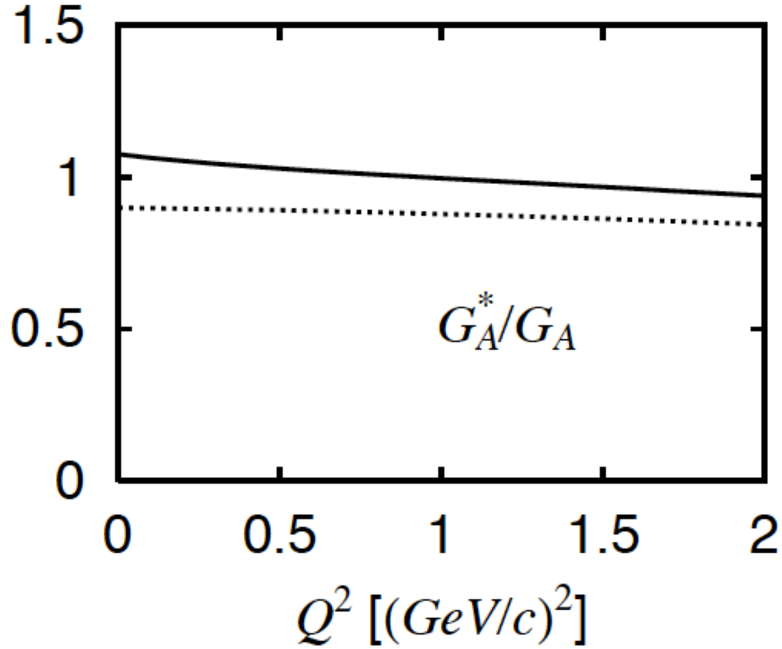
Sato et al., PRC 63 (2001); PRC 67 (2003)

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

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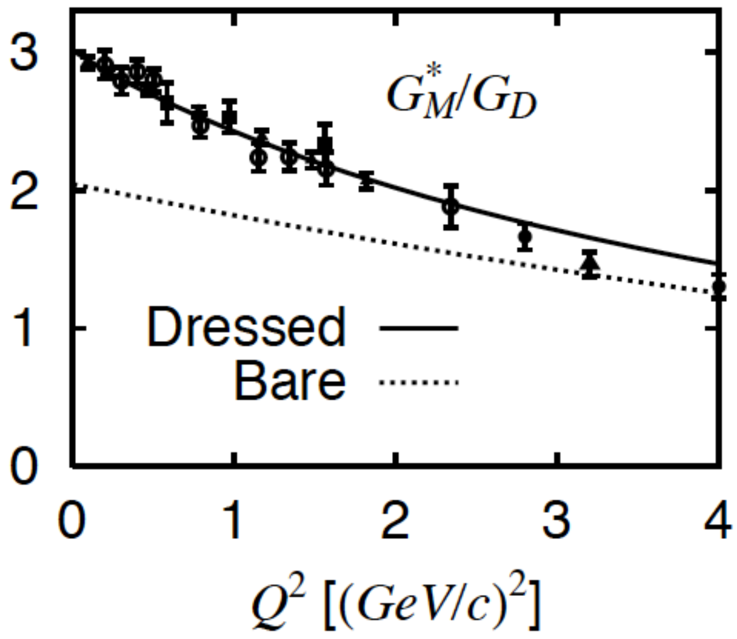
Vector (magnetic) form factor
from electron reactions



Axial form factor
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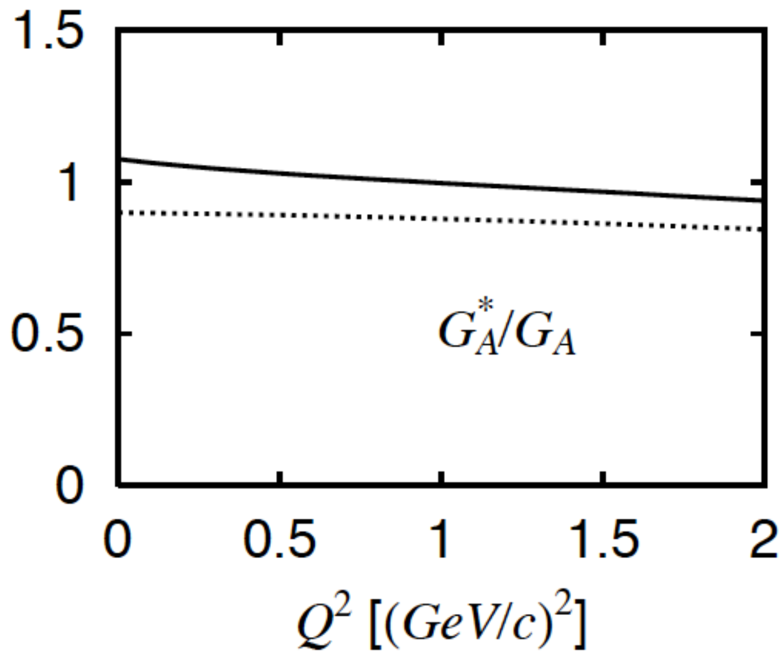

- Axial structure of bayrons can be learned from neutrino reaction data
- Different pion cloud contributions to magnetic and axial form factors (slope)

GOAL : Develop νN-interaction model in resonance region

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

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

- Channel-couplings required by unitarity
- Important 2 π production mechanisms

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

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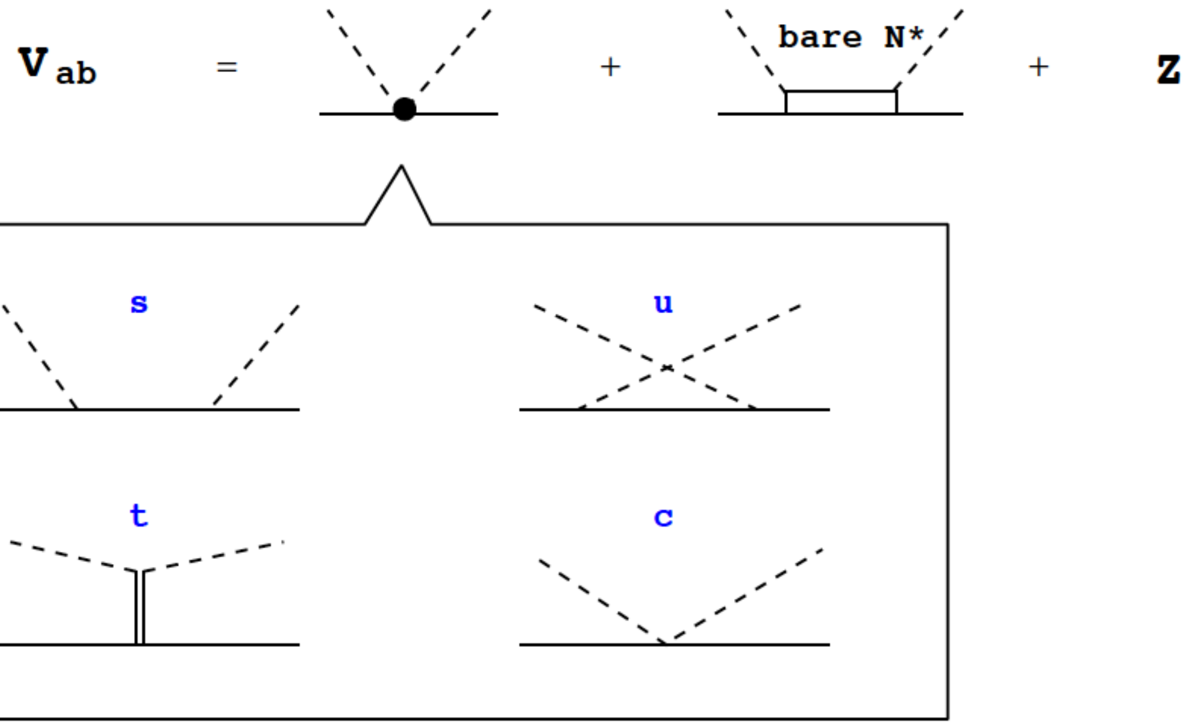

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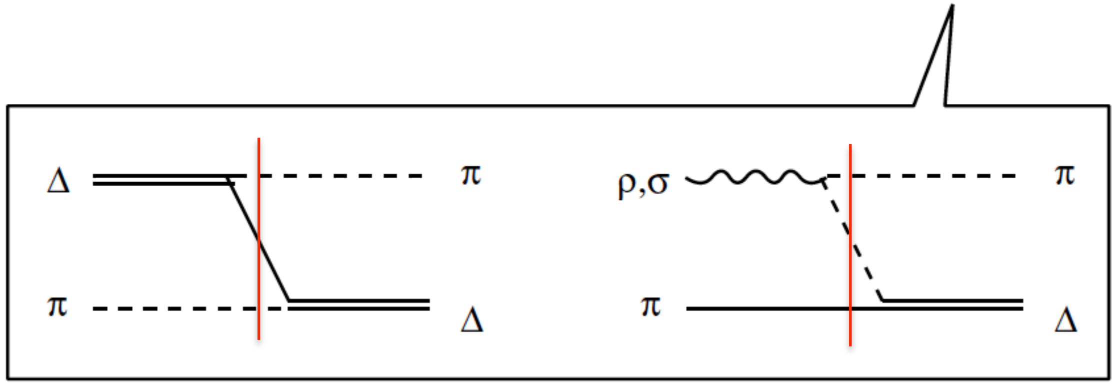
Coupled-channel Lippmann-Schwinger equation

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

V ab =

essential for three-body unitarity



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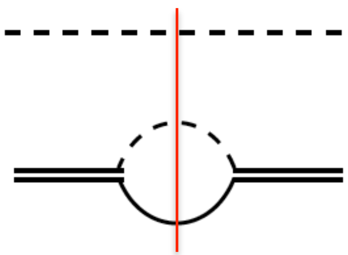
$G c =$

for stable channels



for unstable channels

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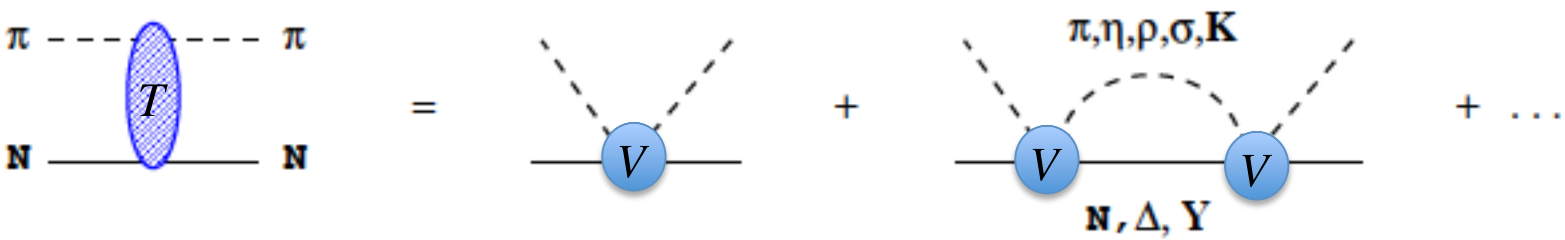
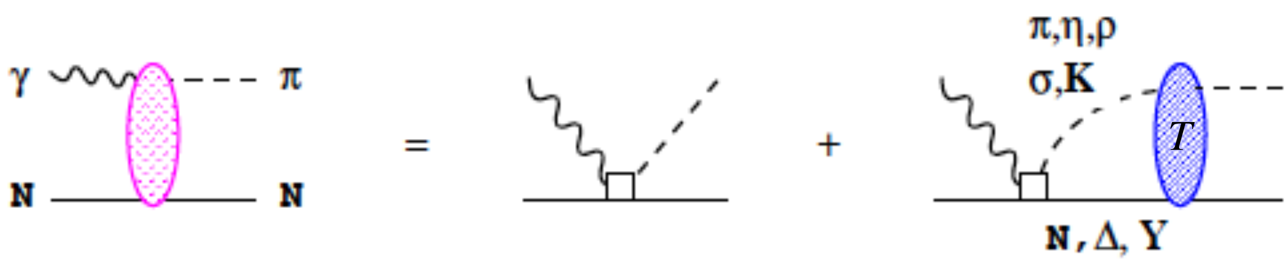


In addition, γN, $W^{\pm}N$, ZN channels are included perturbatively



Relation between neutrino and electron (photon) interactions

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

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

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

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

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

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

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

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

DCC model for axial current

Because neutrino reaction data are scarce, axial current cannot be determined phenomenologically

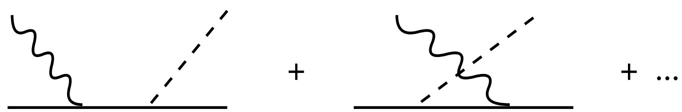
→ Chiral symmetry and PCAC (partially conserved axial current) are guiding principle

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

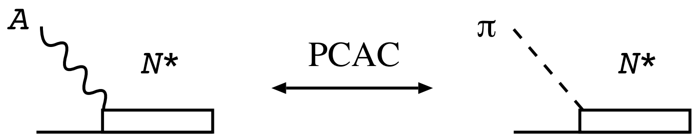
Q^2=0

non-resonant mechanisms

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



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 ($Q^2 \leq 3\ (\mathrm{GeV}/c)^2$)

DCC analysis results

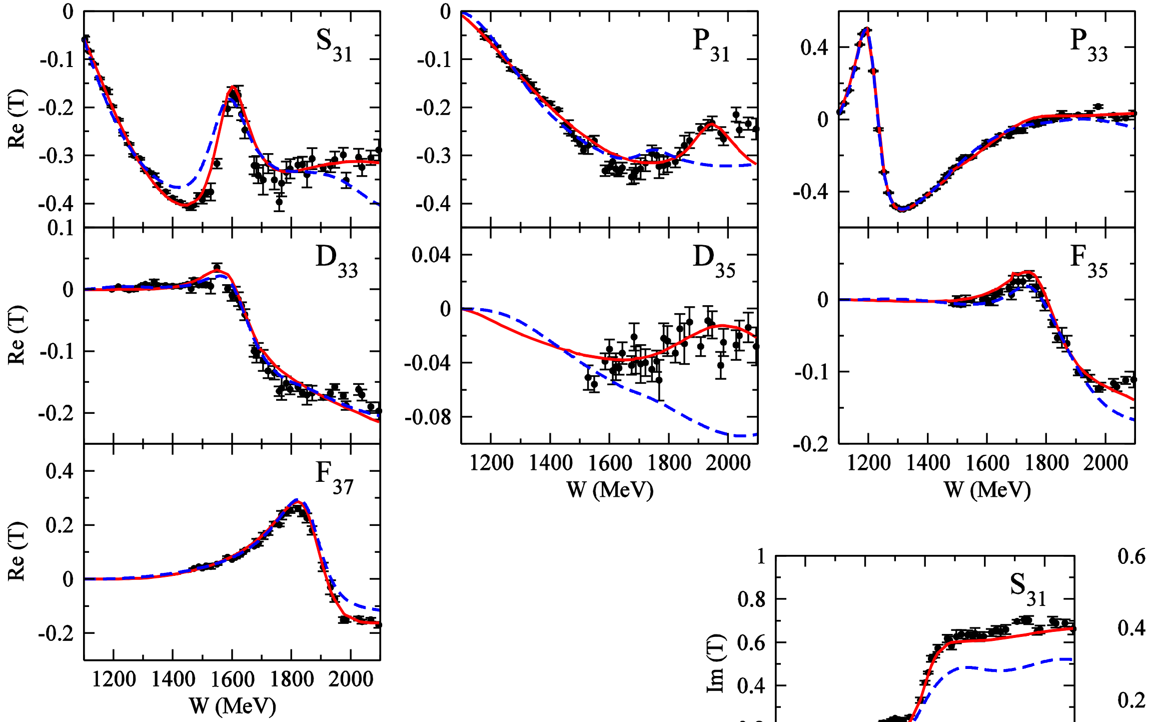
Caveat

Due to time limitation, small portion of analysis results are presented.

More analysis results including extracted resonance parameters,

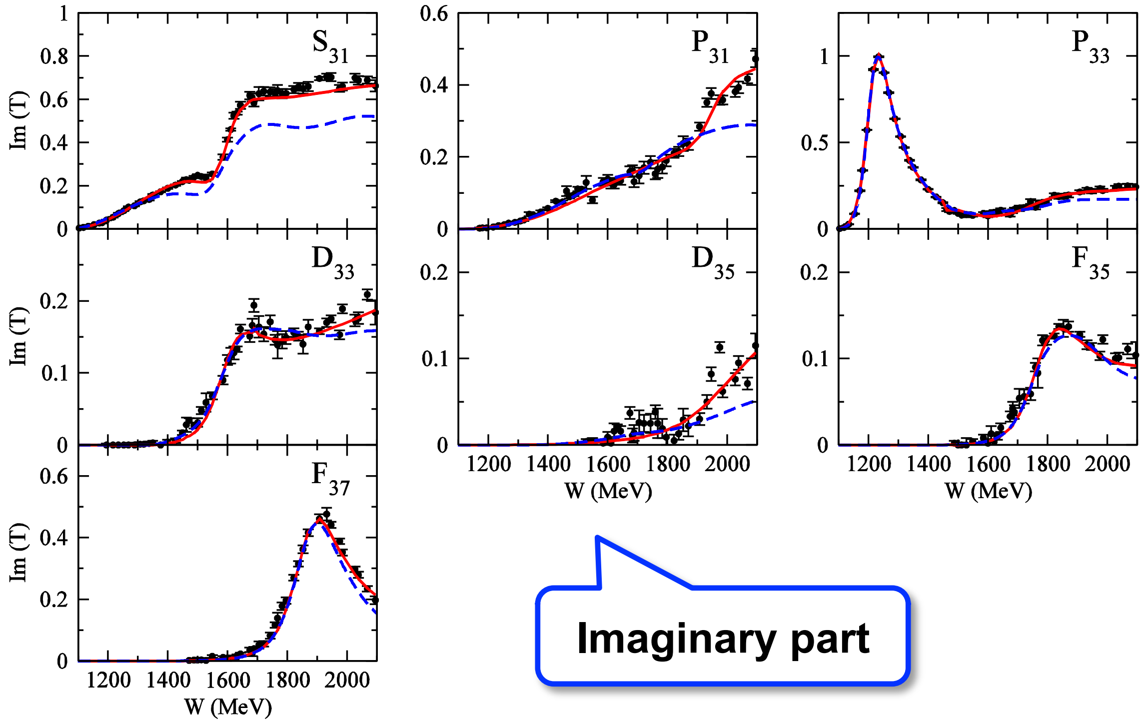
see Kamano's plenary talk on Friday.

Partial wave amplitudes of π N scattering



Real part

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



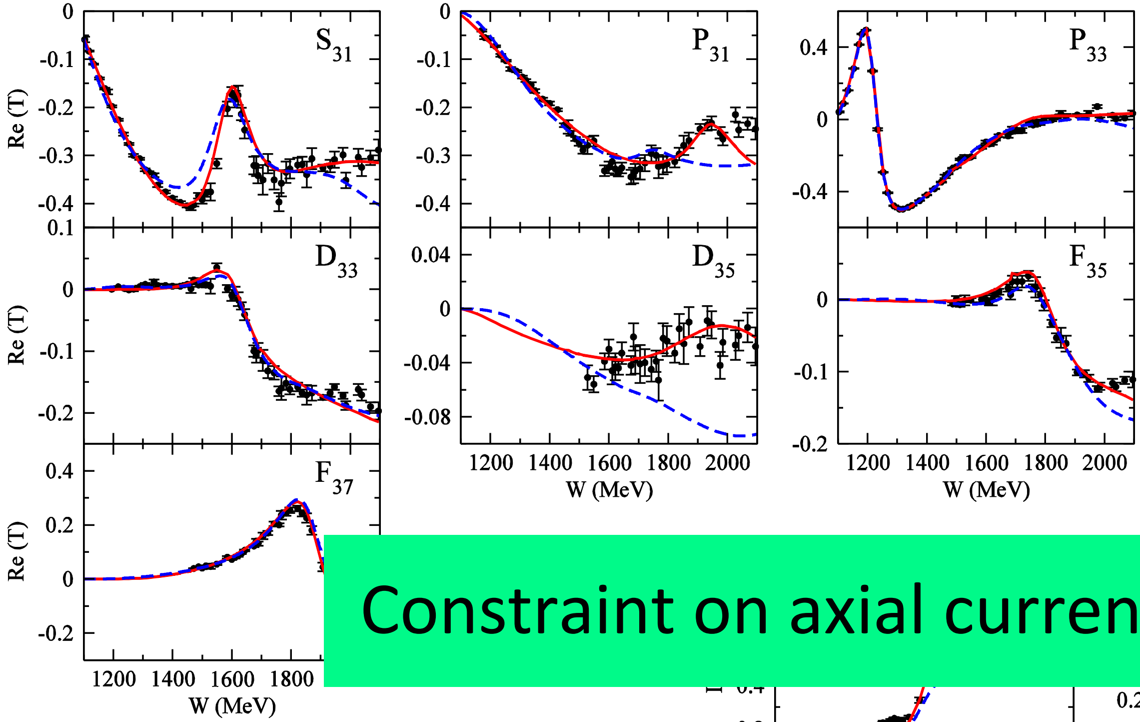
Imaginary part

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

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

Data: SAID πN amplitude

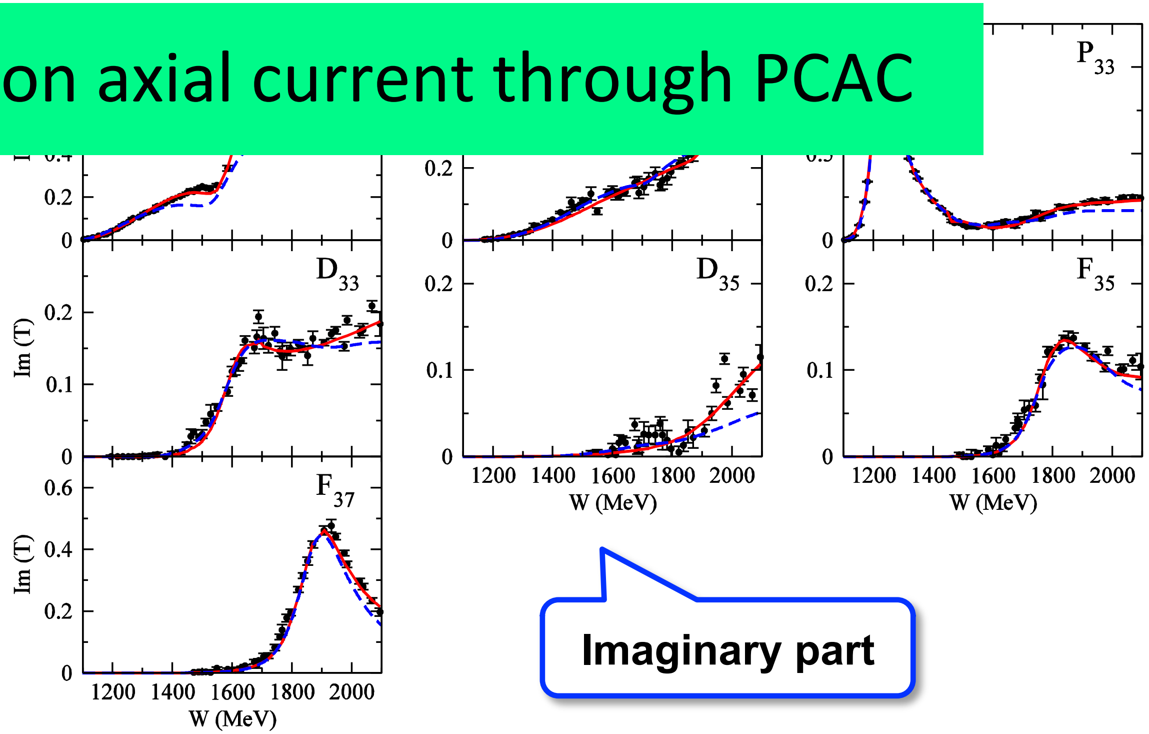
Partial wave amplitudes of π N scattering



Real part

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

Constraint on axial current through PCAC



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Previous model
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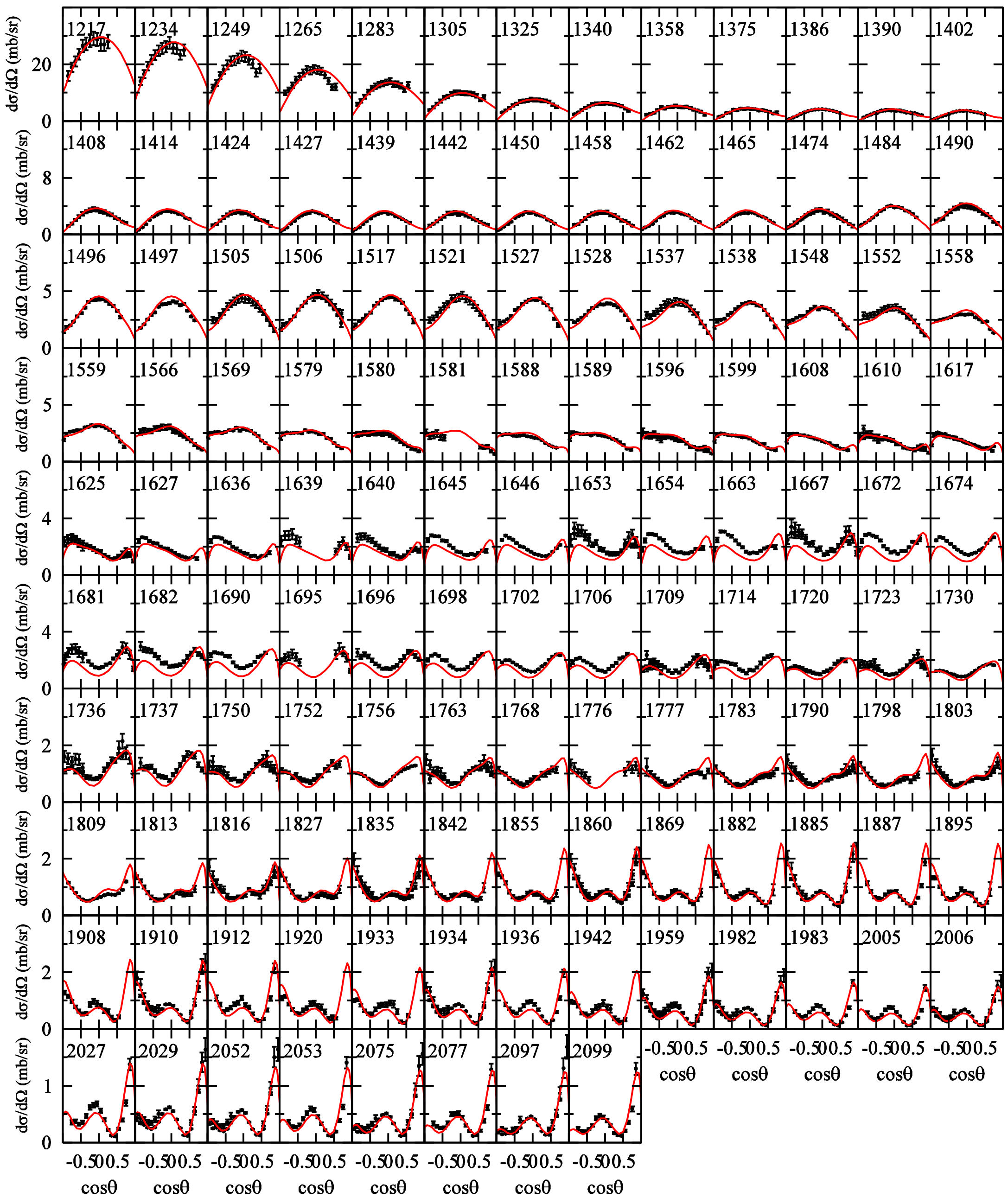
Data: SAID πN amplitude

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

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

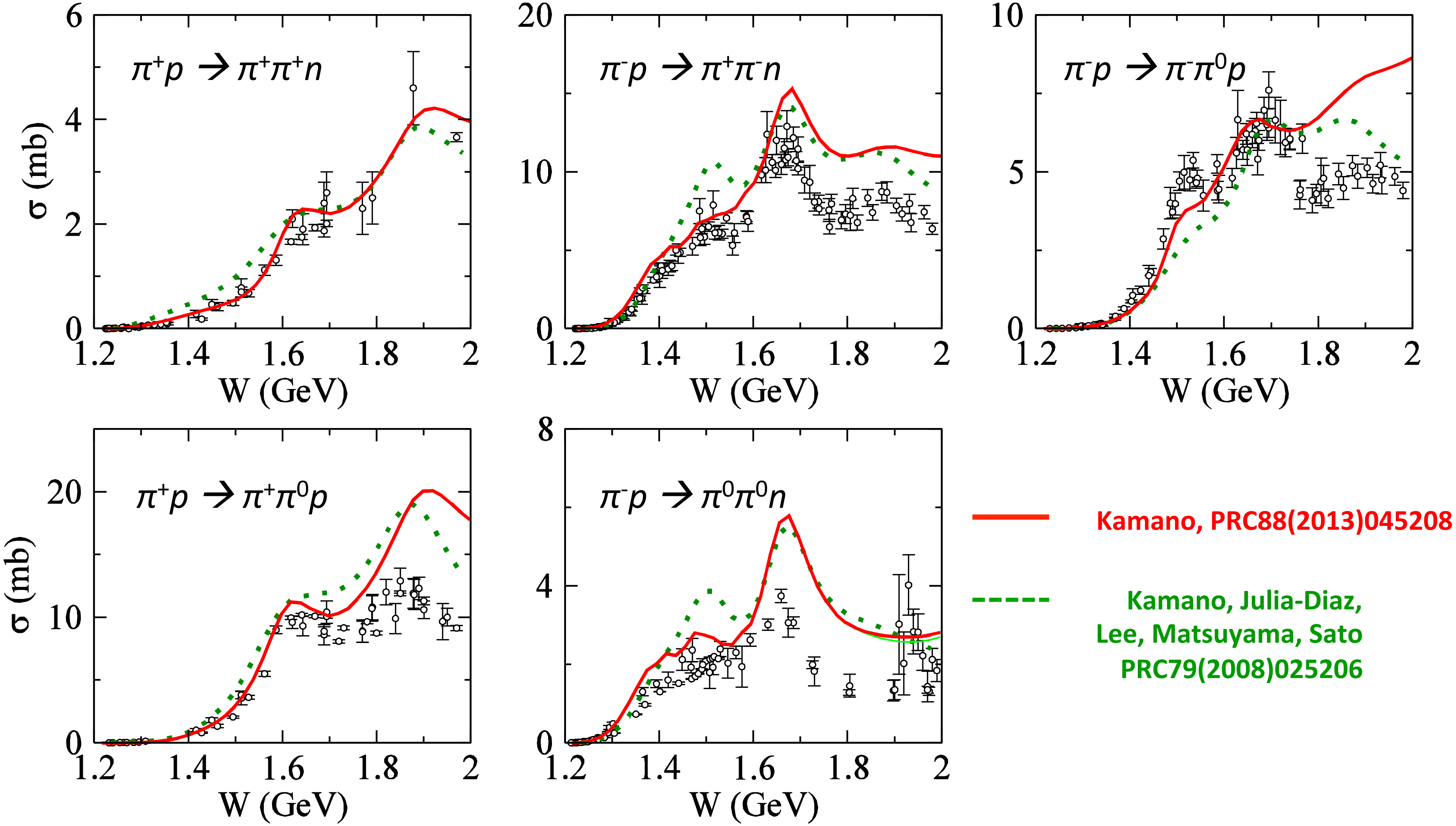
Kamano, Nakamura, Lee, Sato, PRC 88 (2013)



Vector current (Q^2=0) for 1π

Production is well-tested by data

Predicted πN → ππN total cross sections with our DCC model

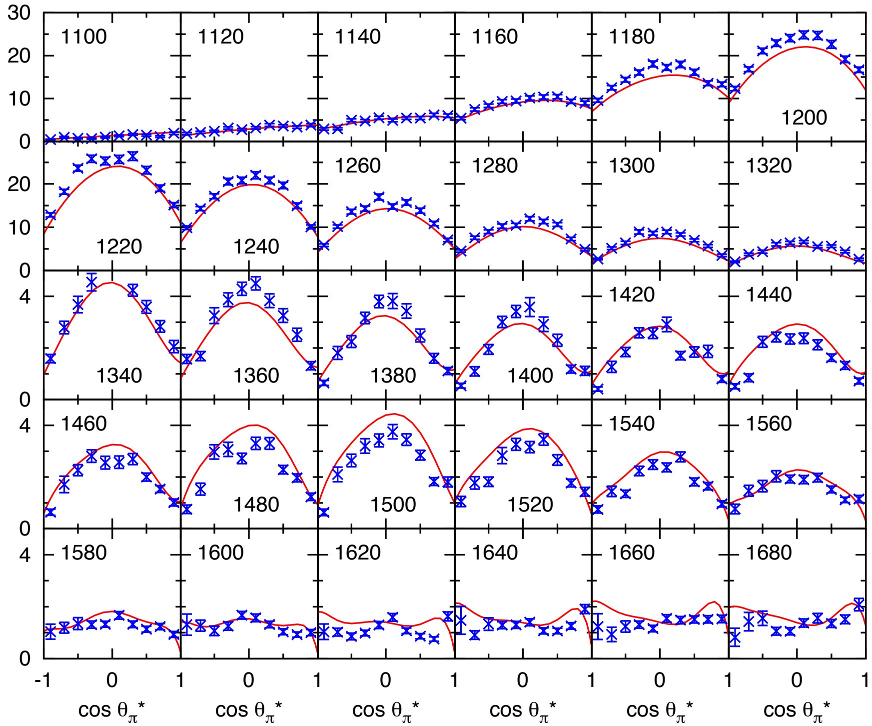


Single π production in electron-proton scattering

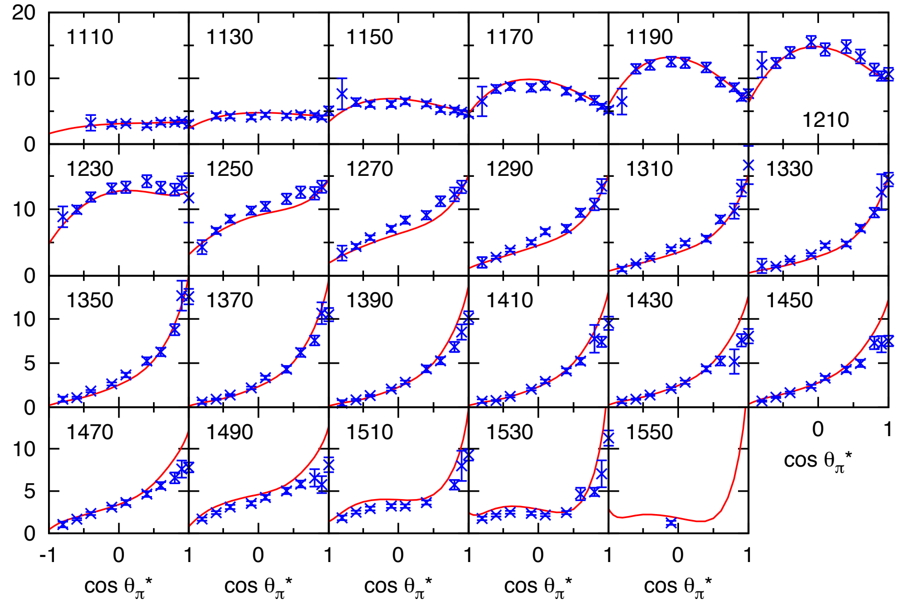
Purpose : Determine Q^2–dependence of vector coupling of p-N^* : $VpN^*(Q^2)$

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

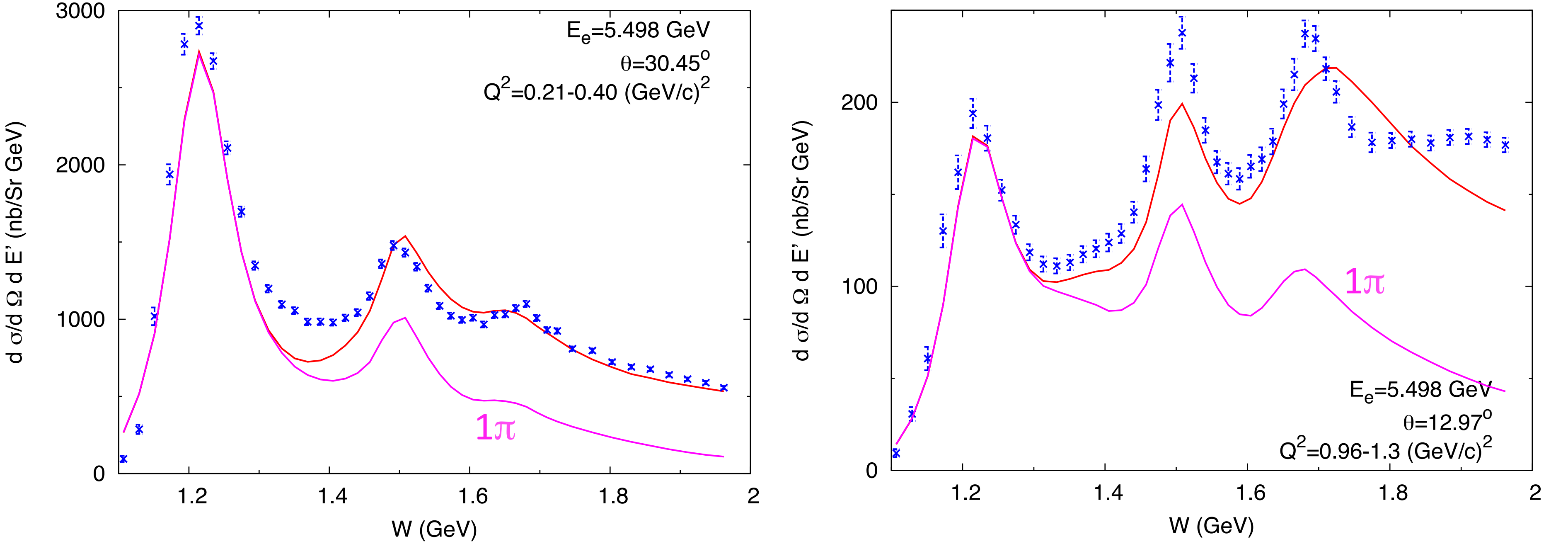
$p(e,e'\pi^0)p$



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



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

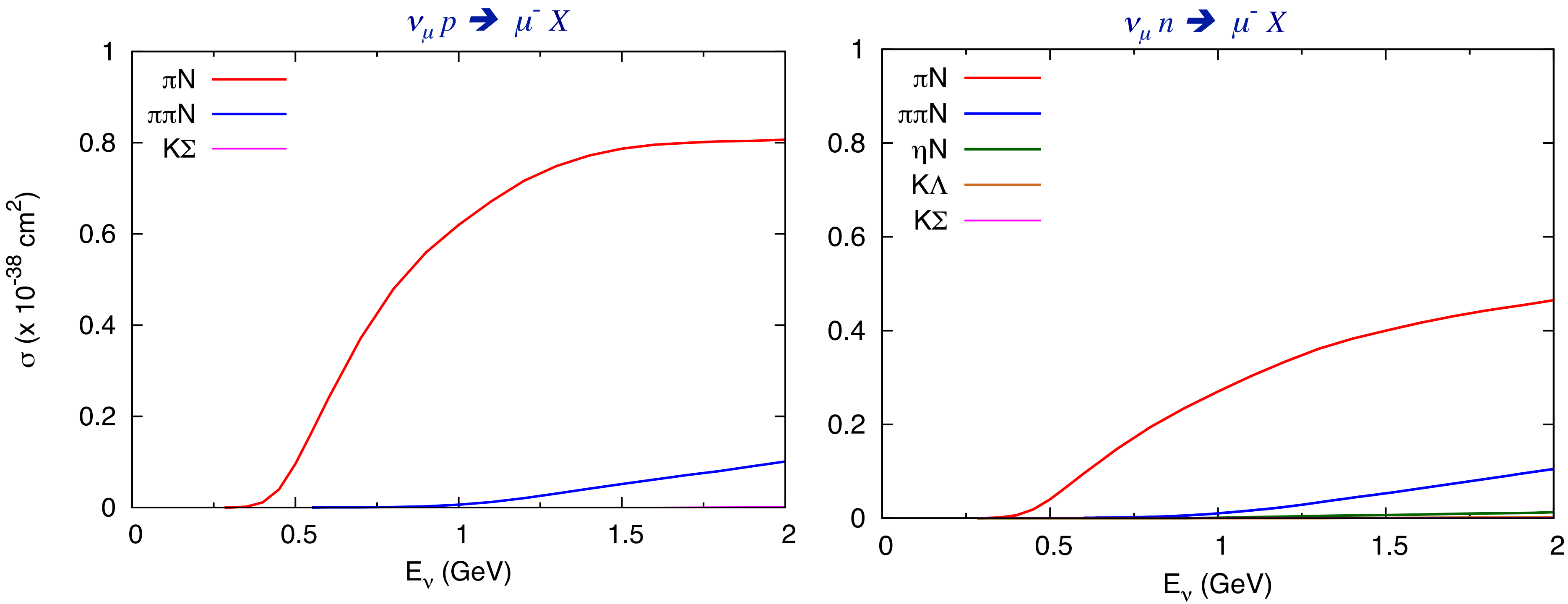
Similar analysis of electron-neutron scattering data has also been done

DCC vector currents has been tested by data for whole kinematical region

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

Neutrino Results

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

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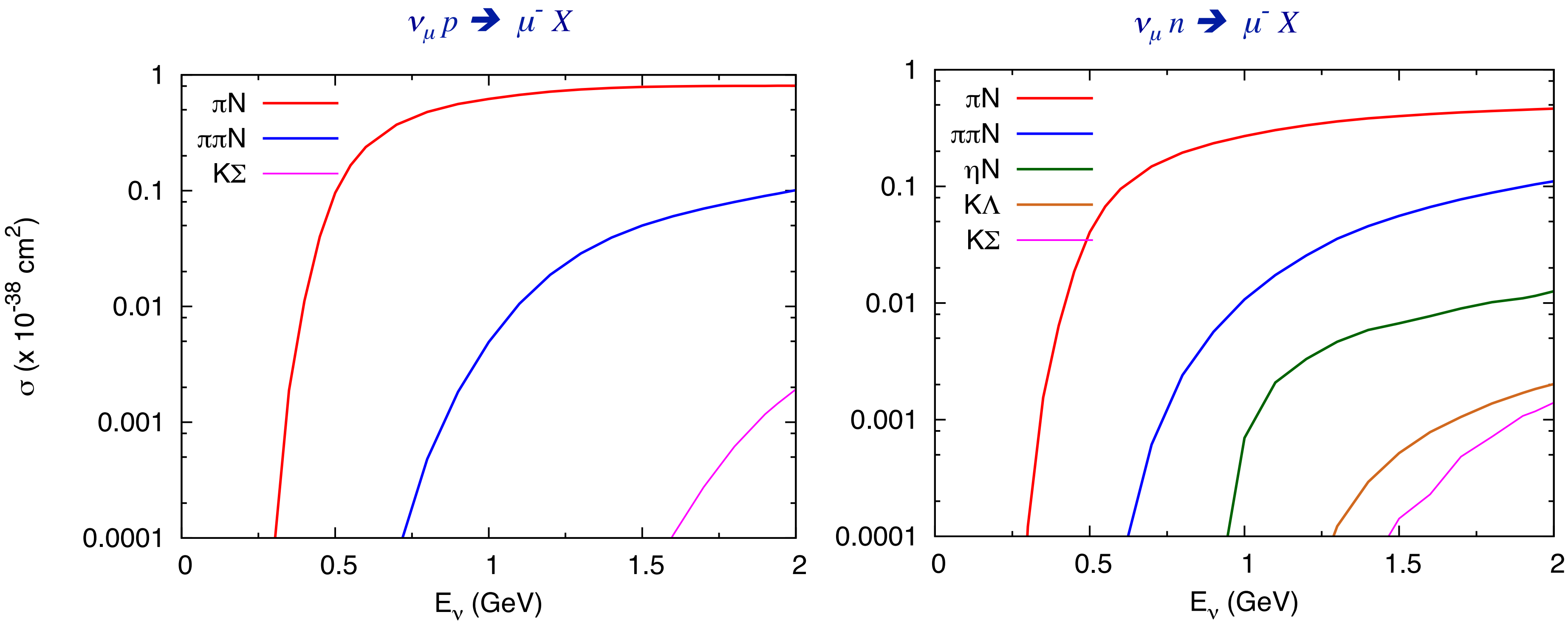

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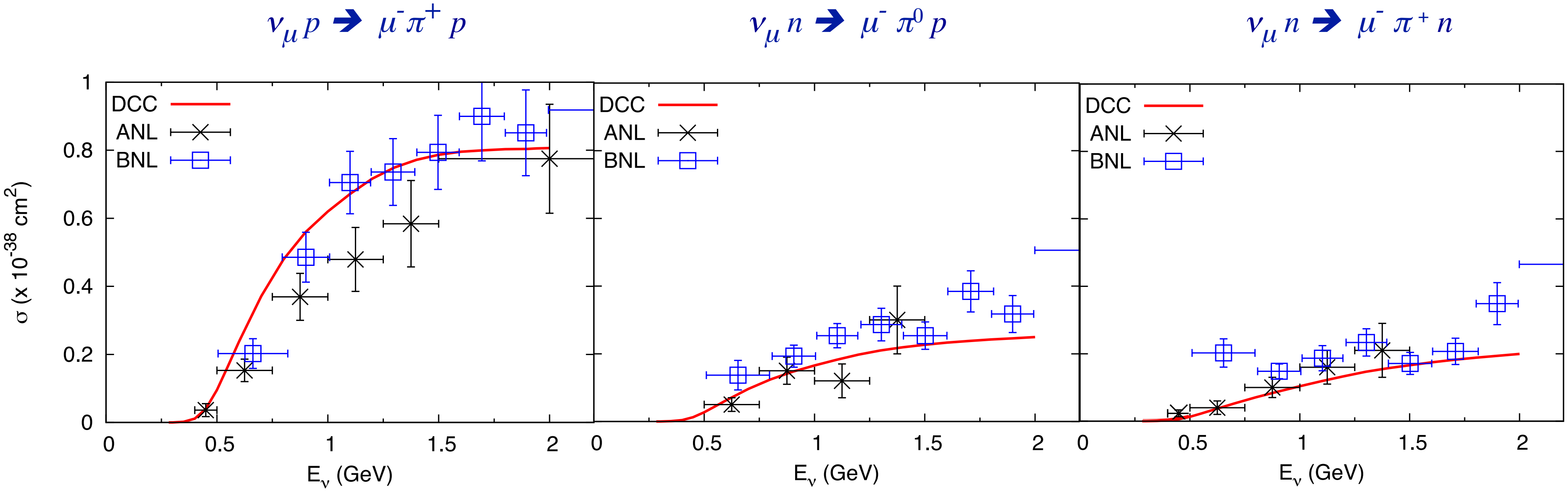
Comparison with single pion data



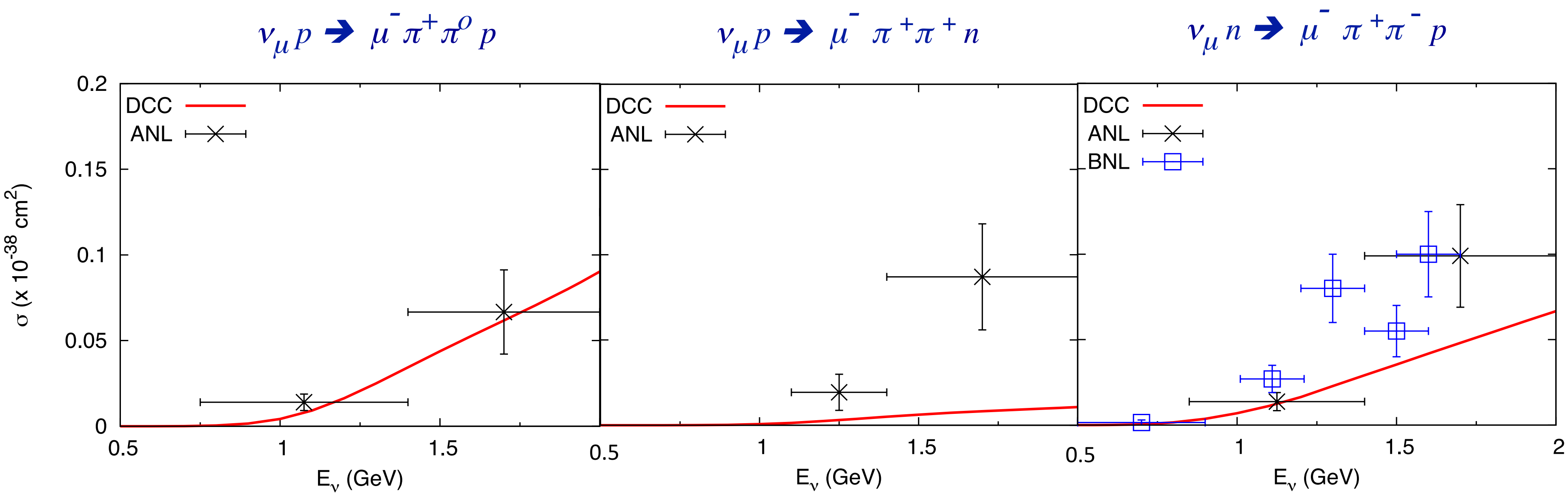
DCC model prediction is consistent with data

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))

Comparison with double pion data

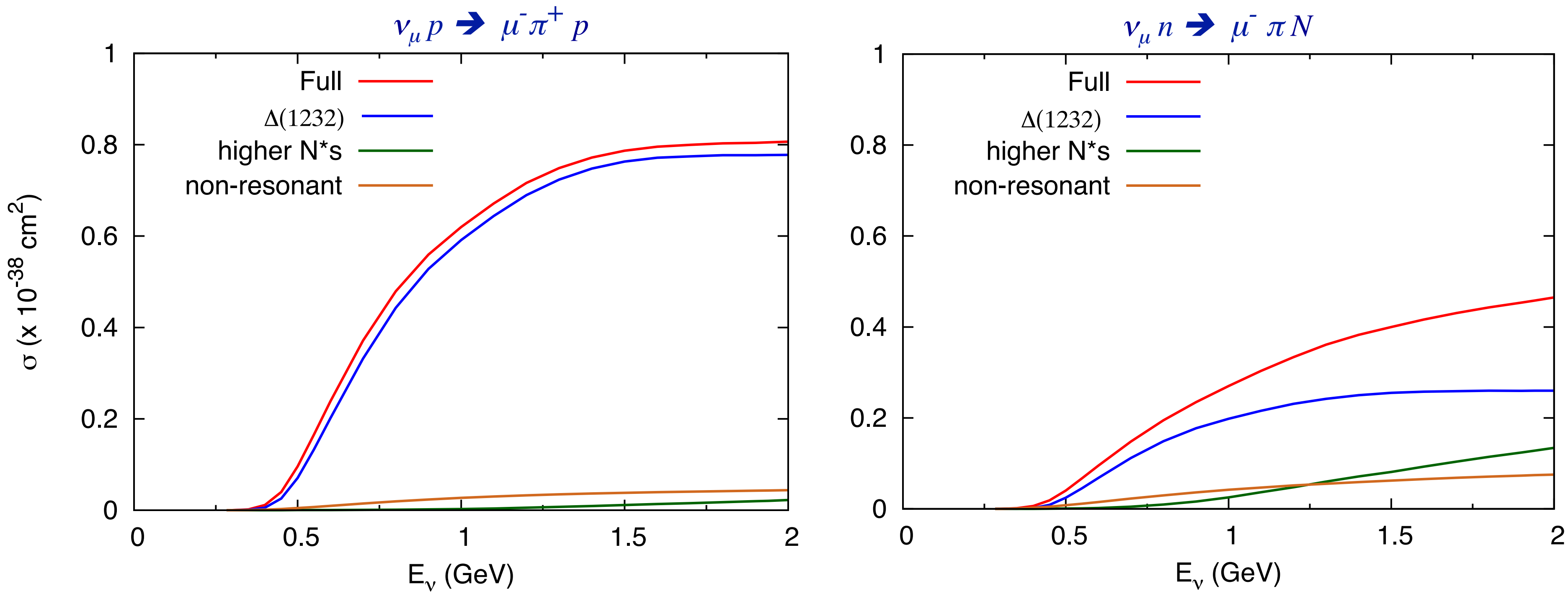


Fairly good DCC predication

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

First dynamical model for 2 π production in resonance region

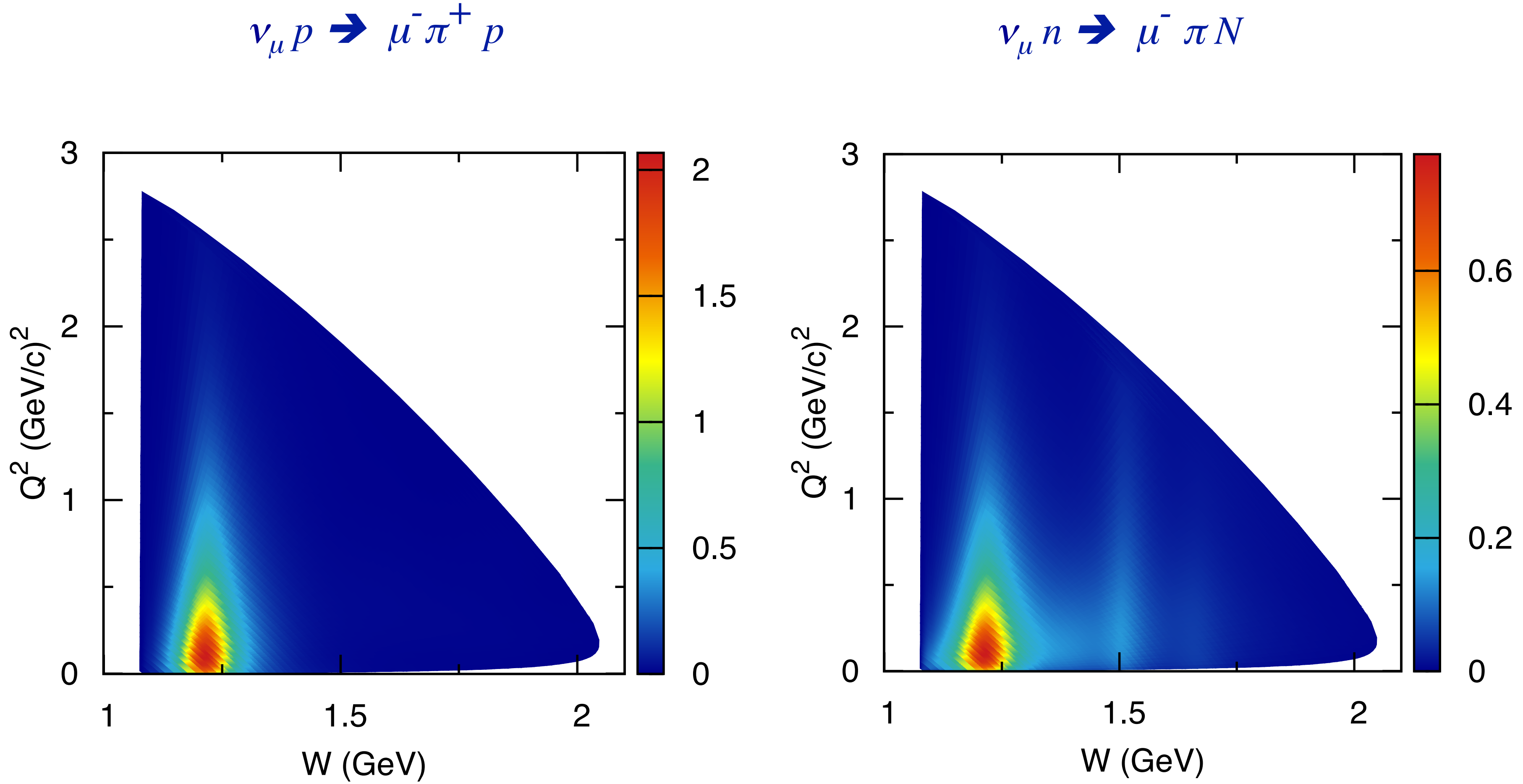
Mechanisms for $\nu_\mu N \rightarrow \mu^- \pi N$



- 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)

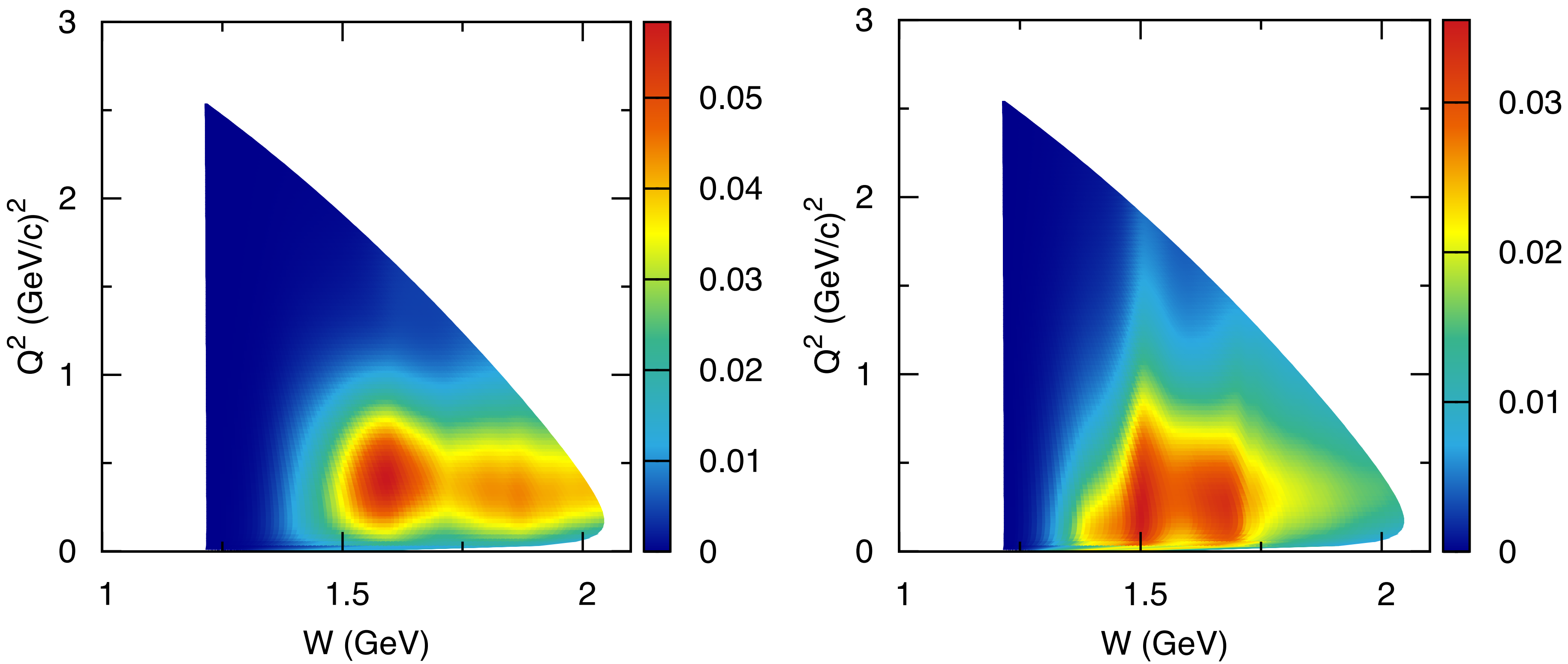
E_ν = 2 GeV



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

E_ν = 2 GeV

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



Conclusion

Development of DCC model for νN interaction in resonance region

Start with DCC model for $\gamma N,\ \pi N$ ➔ $\pi N, \pi\pi N, \eta N, K\Lambda, K\Sigma$

➔ 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 $\nu_\mu\, n$ ➔ $\mu^- X$)

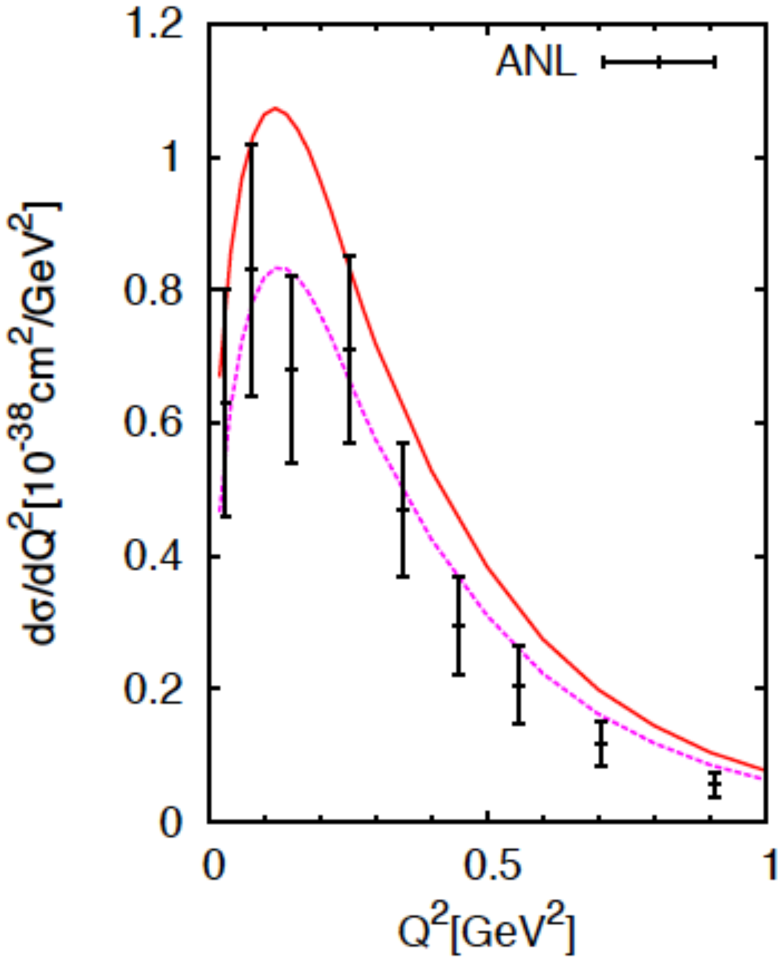
➔ essential to understand interference pattern among them

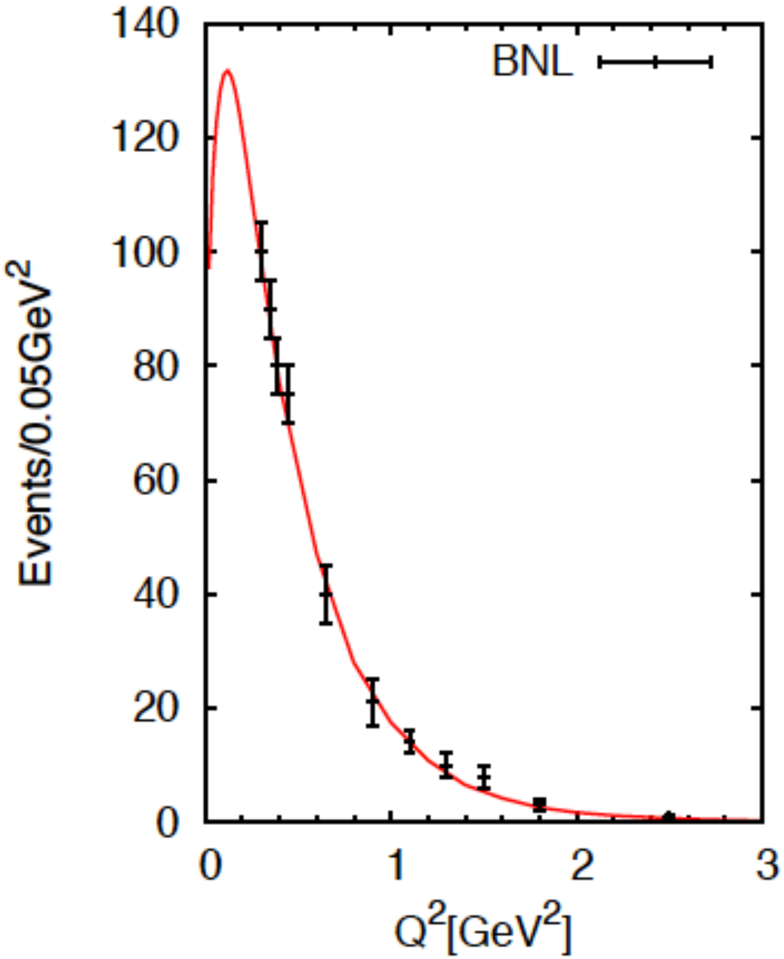
➔ DCC model can do this; consistency between π interaction and axial current

BACKUP

Q^2 – dependence

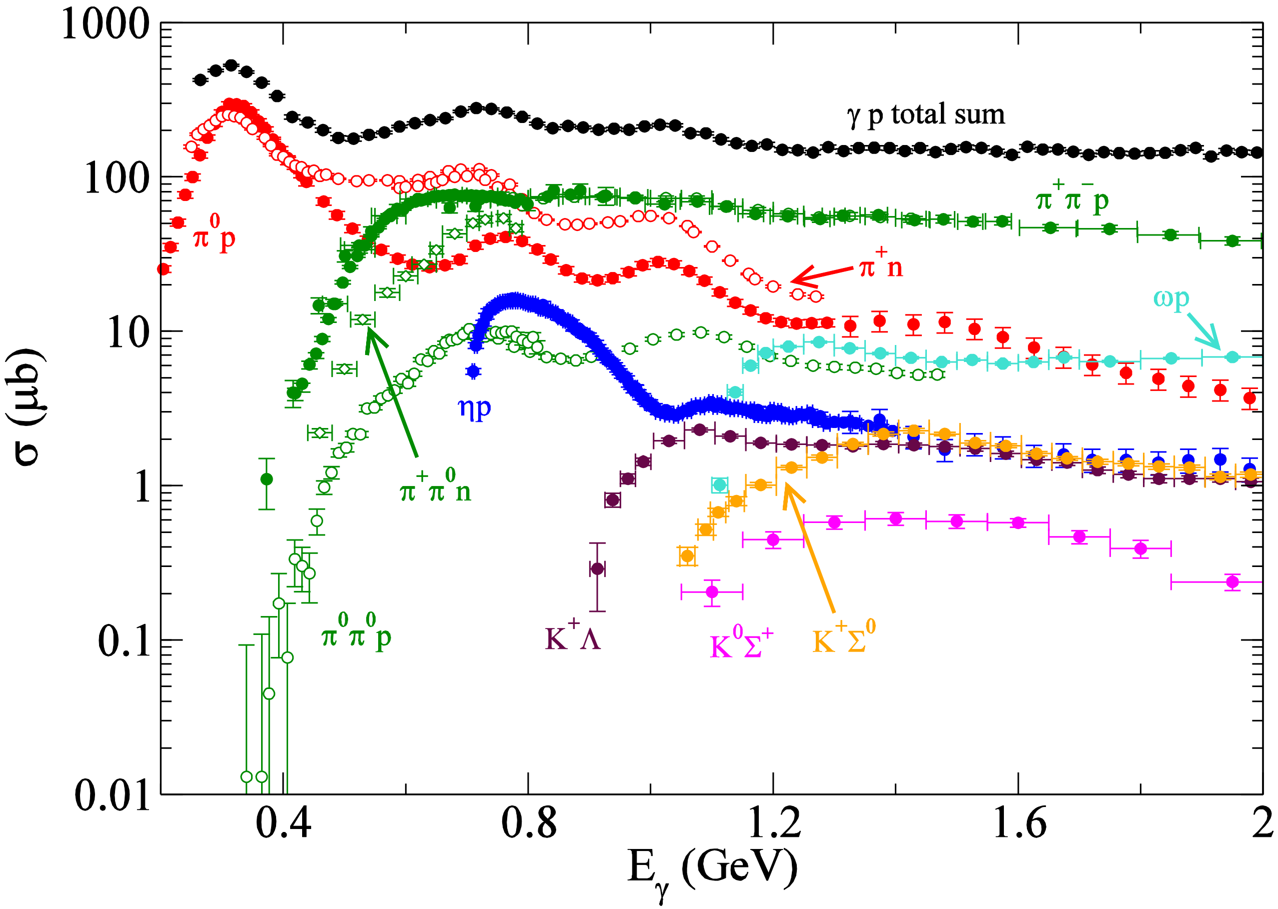
$\nu_\mu p \rightarrow \mu^- \pi^+ p$





Resonance region (single nucleon)

$\gamma N \rightarrow X$

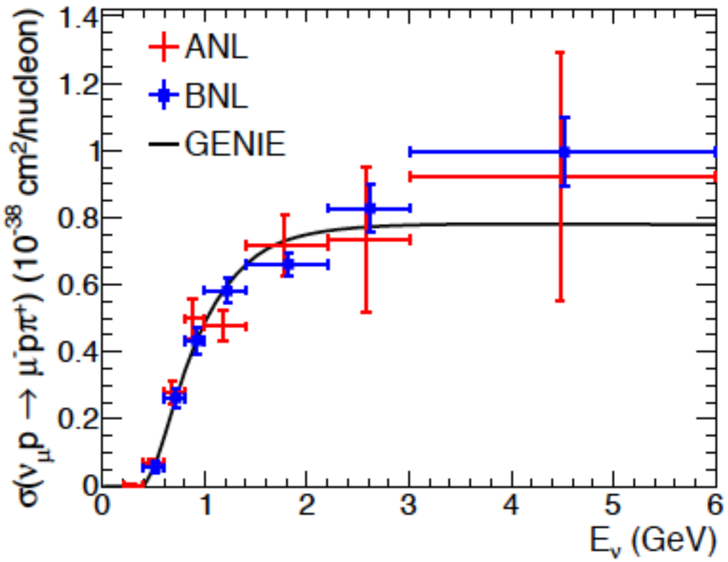


Multi-channel reaction

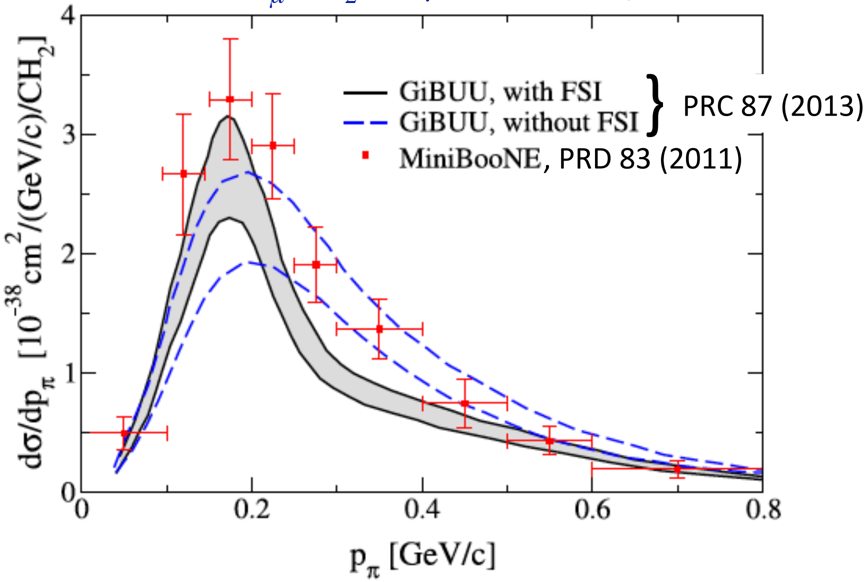
- 2π production is comparable to 1π
- η, K productions ($\boldsymbol{\nu}$ case: background of proton decay exp.)

Neutrino interaction data in resonance region

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



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

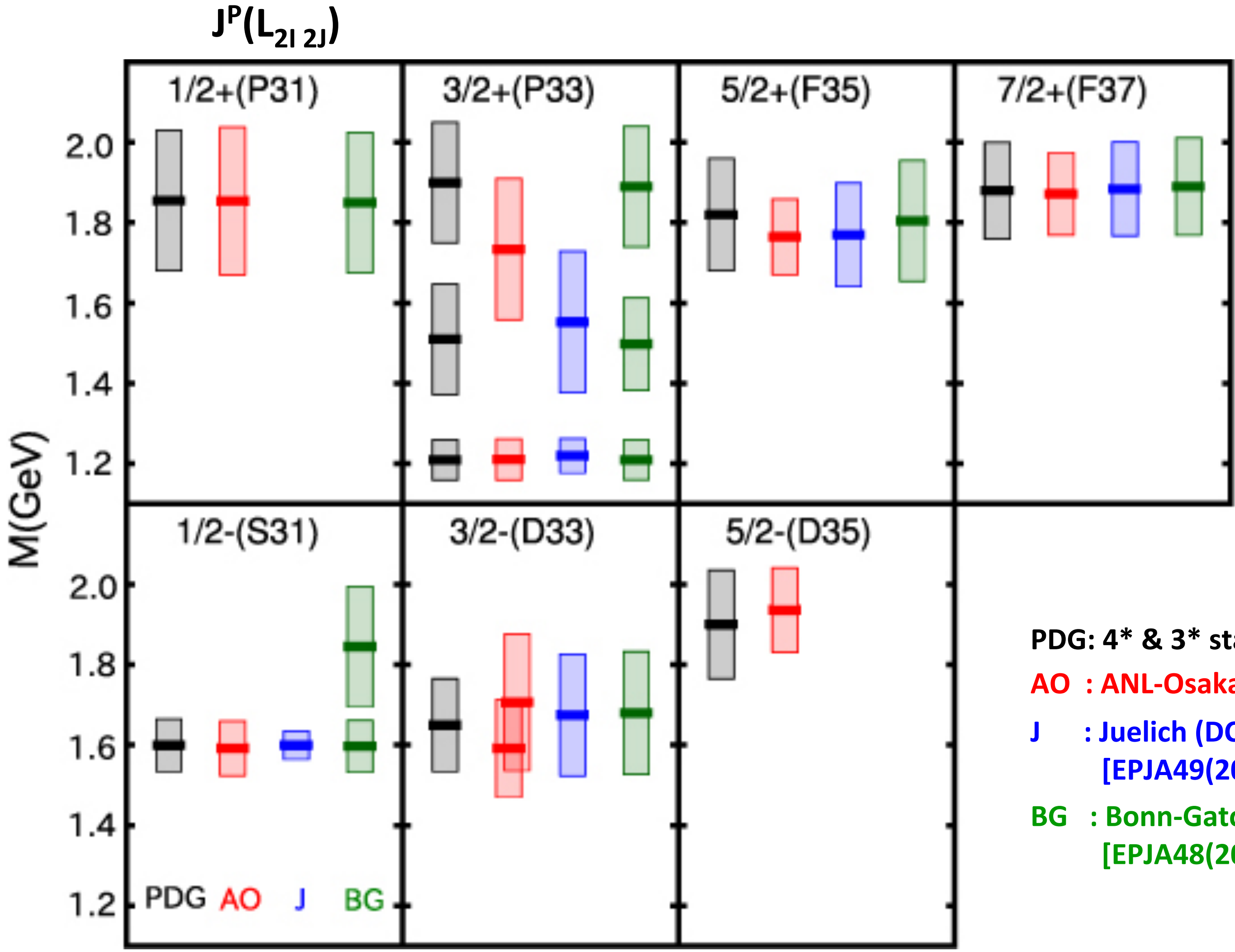
- Final state interaction (FSI) changes charge, momentum, number of π
- Cross section shape is worse described with FSI
- MINERνA data (arXiv:1406.6415) favor FSI

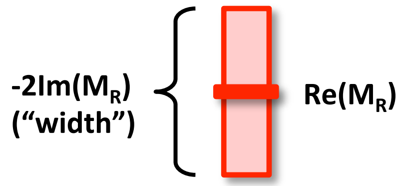
  $\langle E_\nu \rangle = 4.0$ GeV

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]

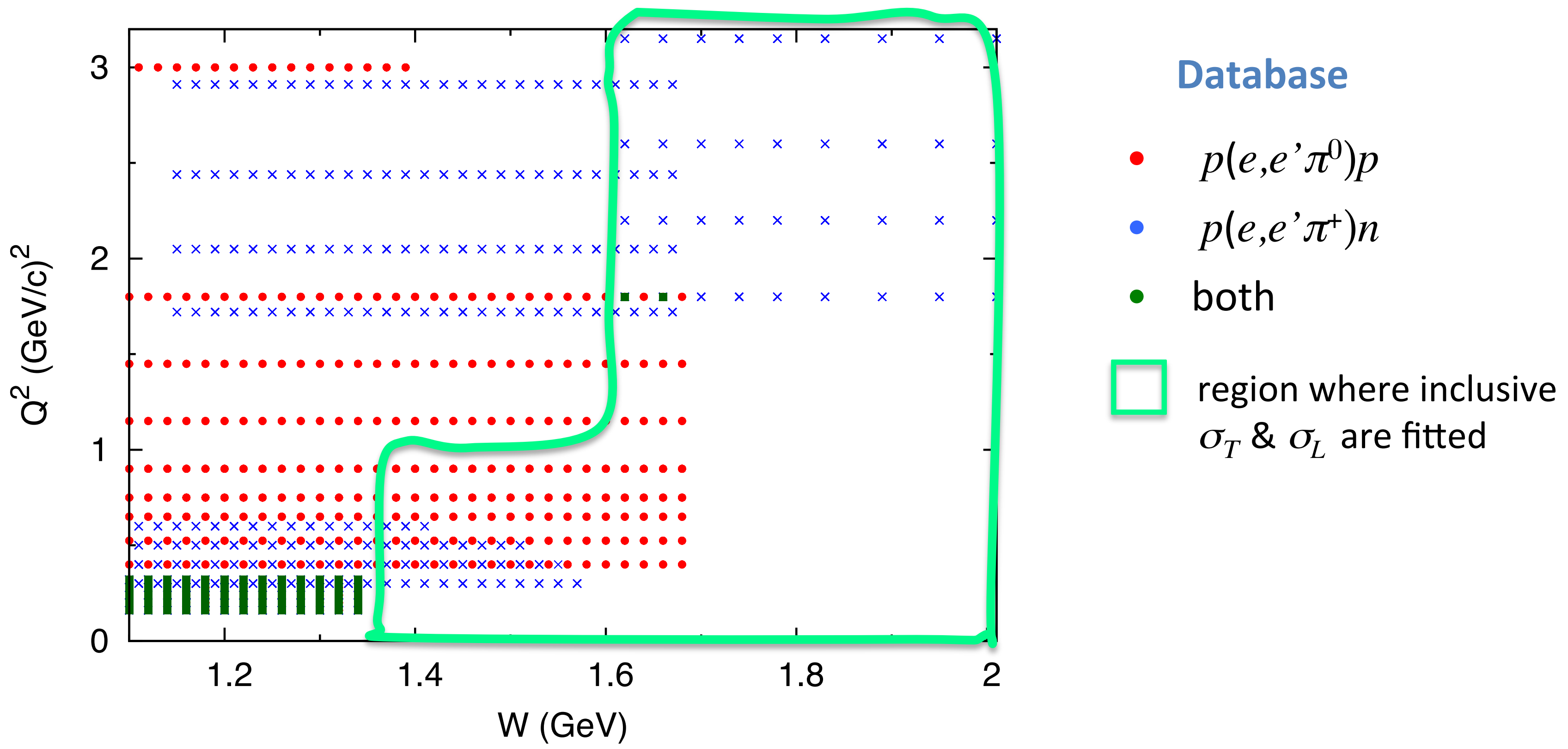
BG : Bonn-Gatchina (K-matrix) [EPJA48(2012)5]

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 ($Q^2\neq 0$)

← 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

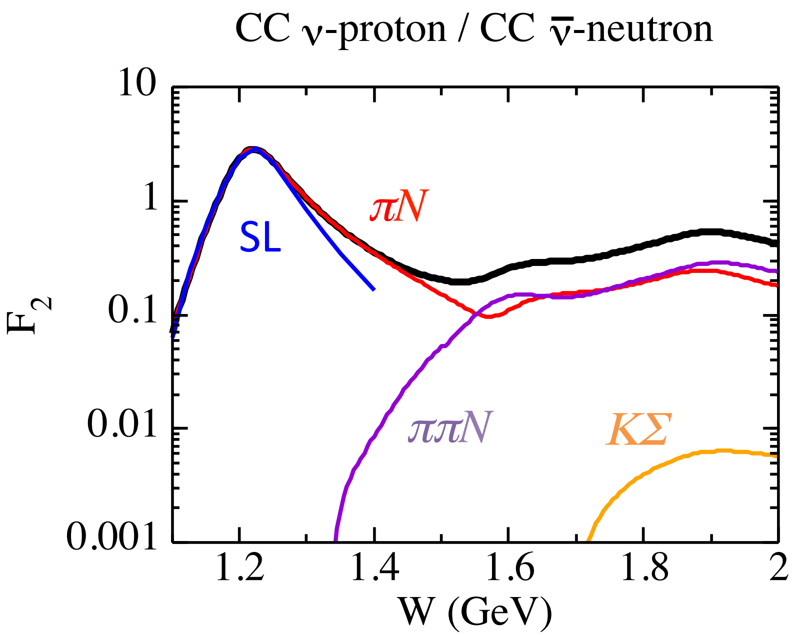
$$\langle X | \hat{\pi} | N \rangle = \frac{\sqrt{2\omega_c}}{m_\pi^2} \mathcal{T}_{\pi N \to X}(0) \sim \frac{\sqrt{2\omega_c}}{m_\pi^2} \mathcal{T}_{\pi N \to X}(m_\pi^2)$$

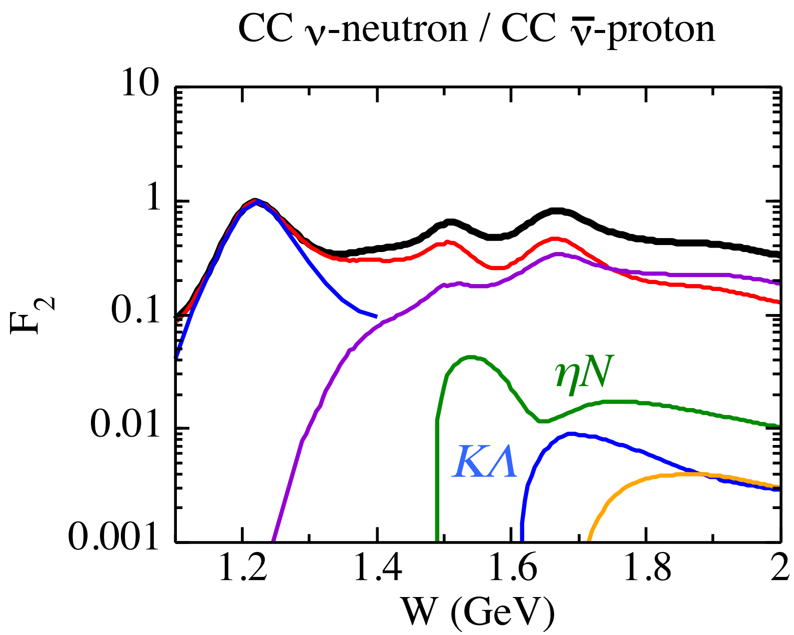
Finally

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

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

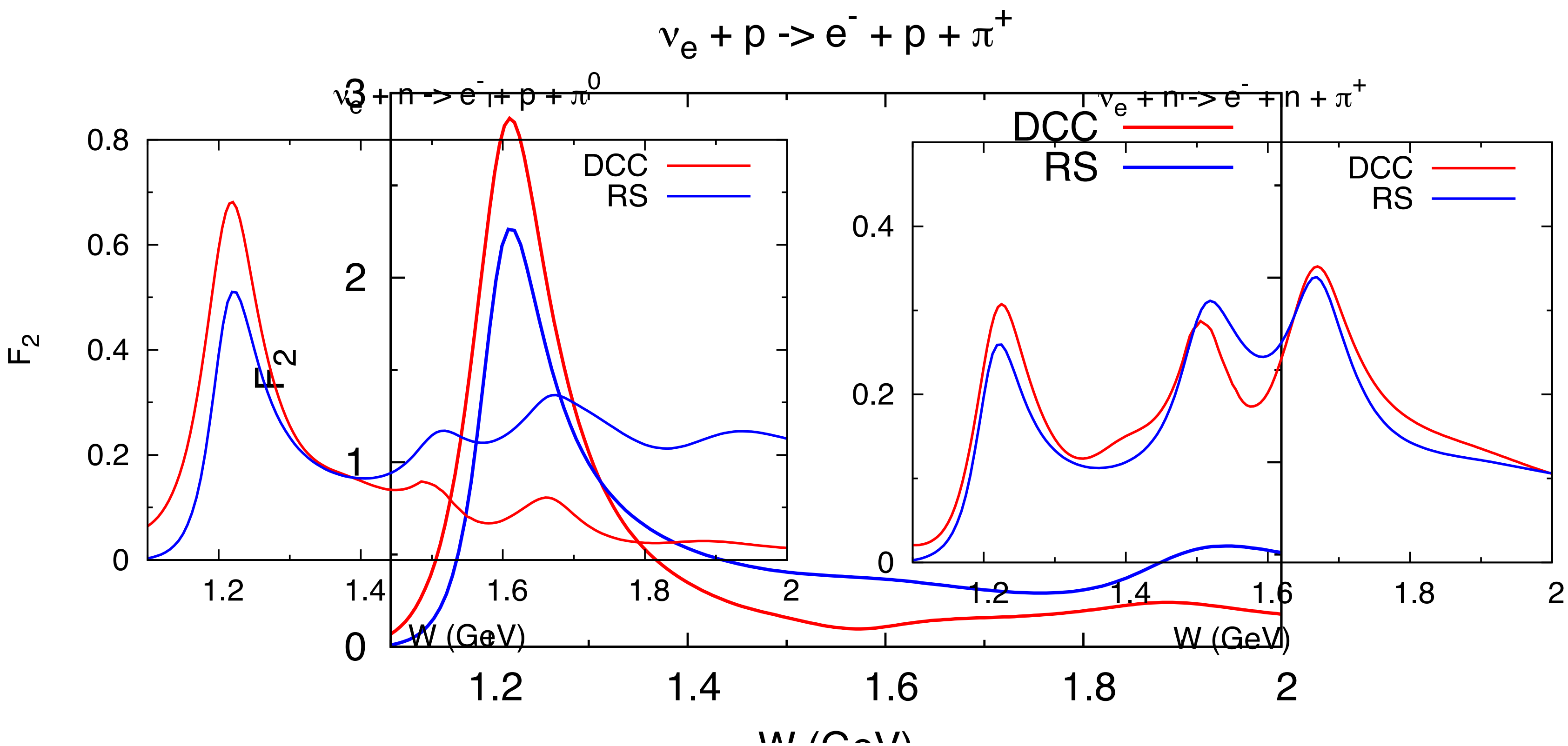
Results





- 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

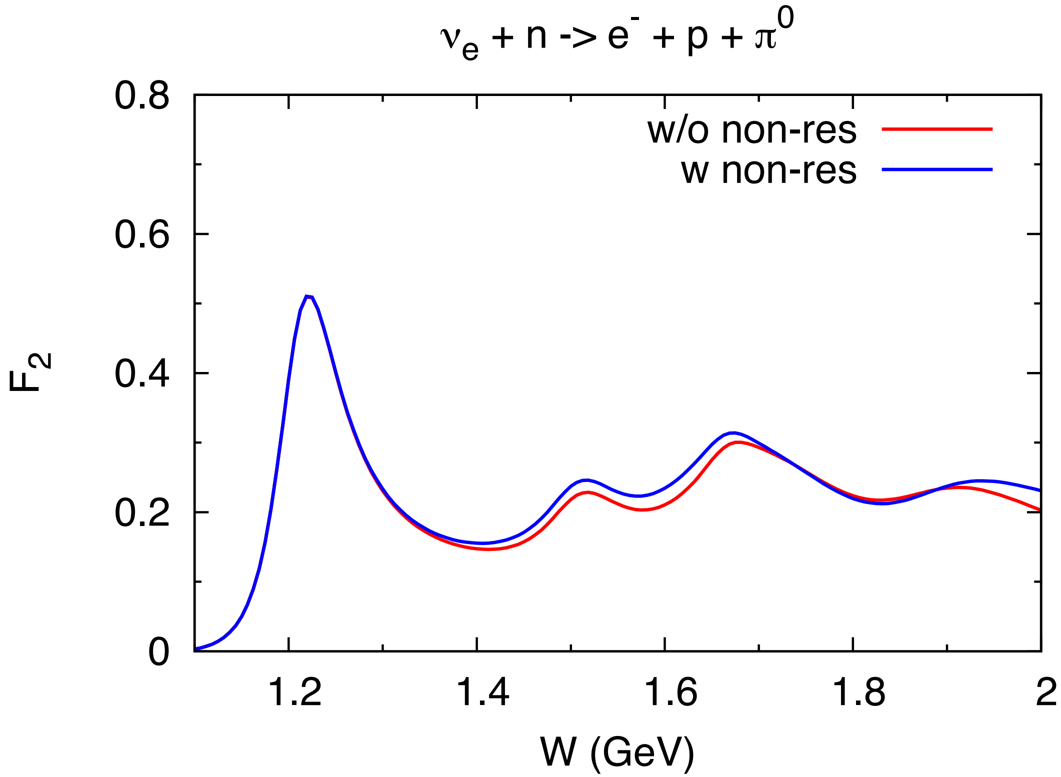
Comparison with Rein-Sehgal model



Comparison in whole kinematical region will be done

after axial current model is developed

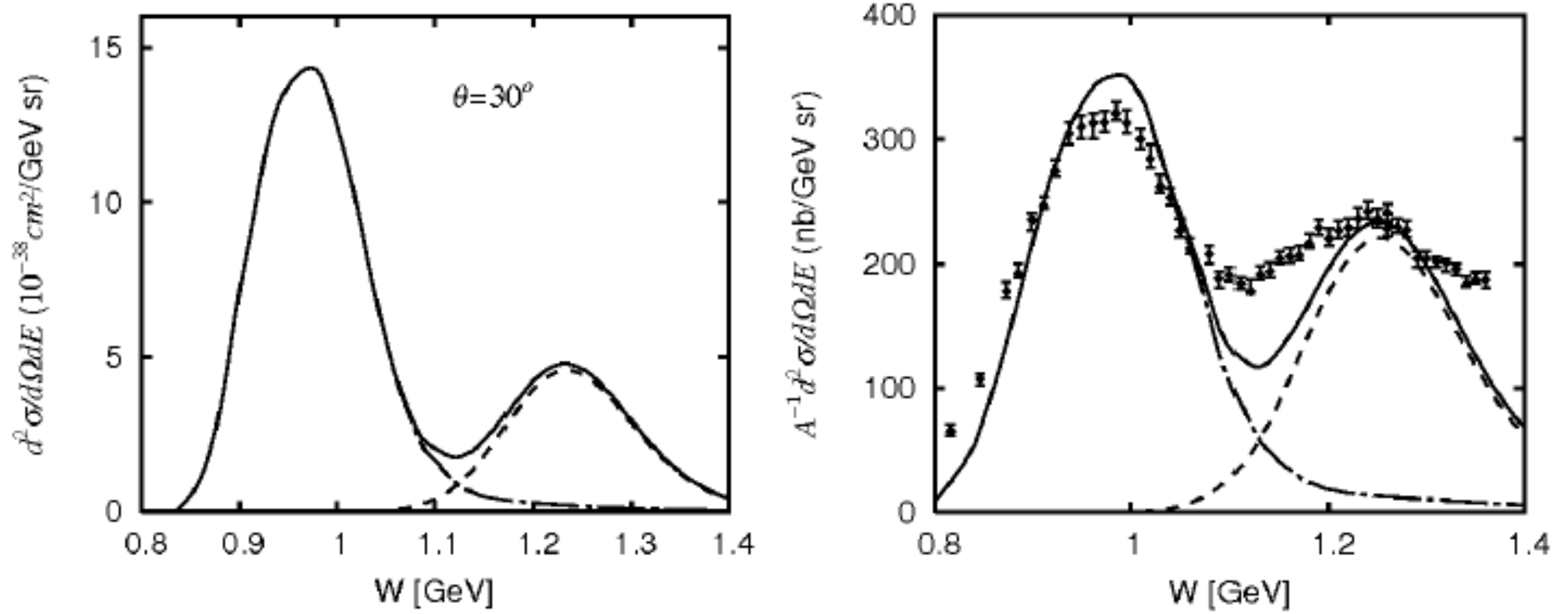
F_2 from RS model



SL model applied to ν−nucleus scattering

1 π production

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



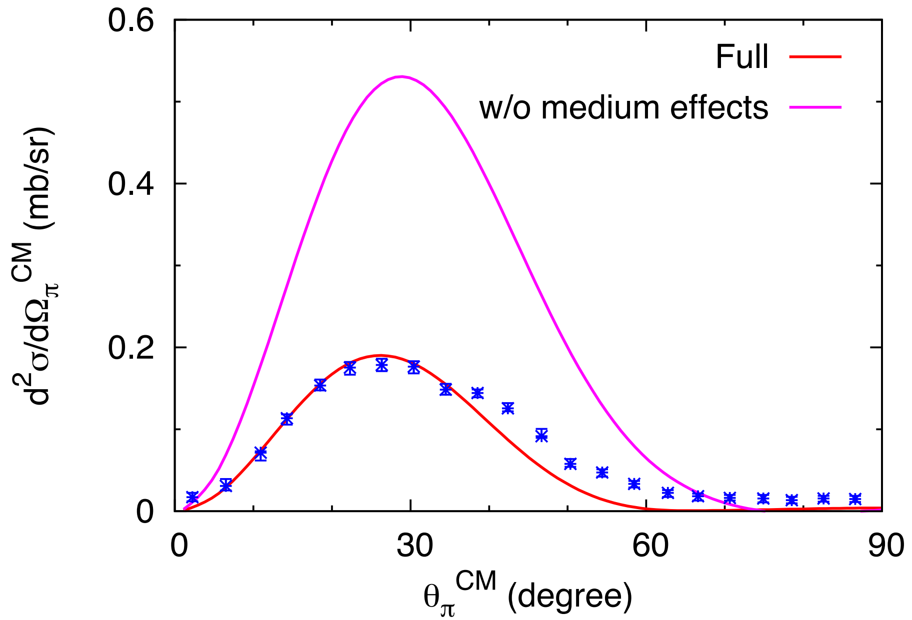
Szczerbinska et al. (2007)

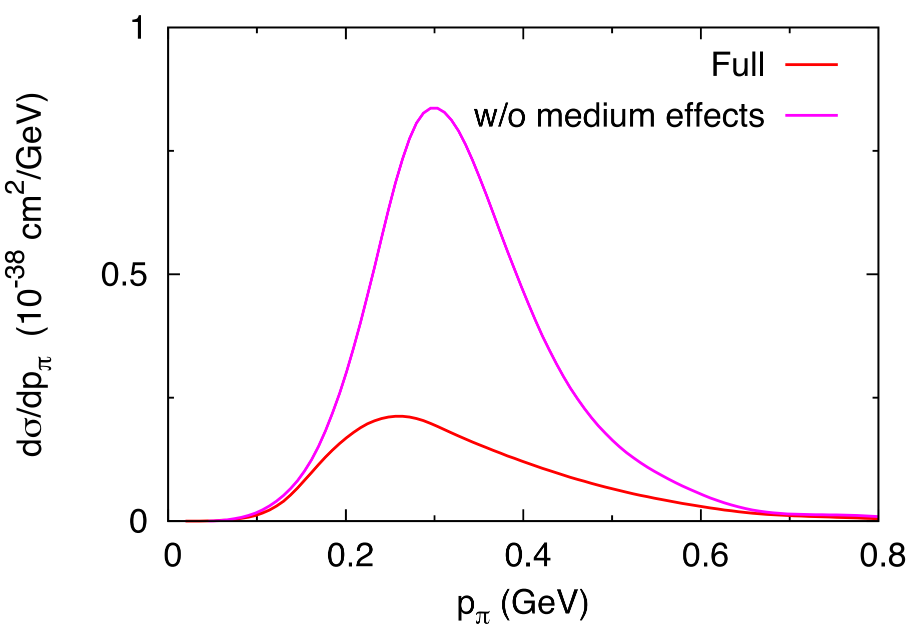
SL model applied to ν−nucleus scattering

coherent π production

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

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



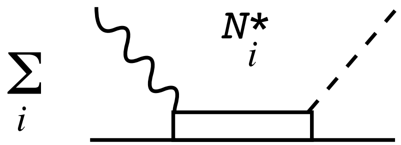


Nakamura et al. (2010)

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

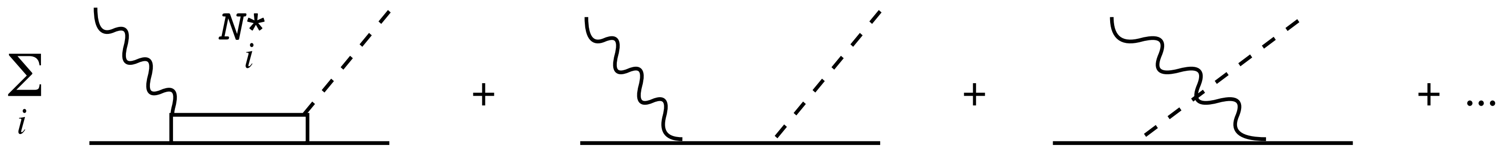
resonant only

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



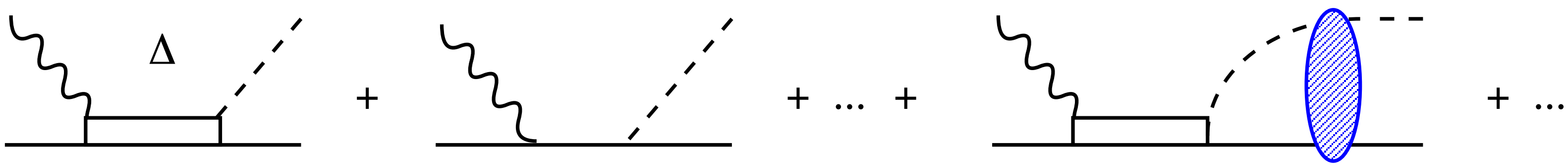
+ non-resonant (tree-level)

Hernandez et al. (2007), (2010) ; Lalakulich et al. (2010)



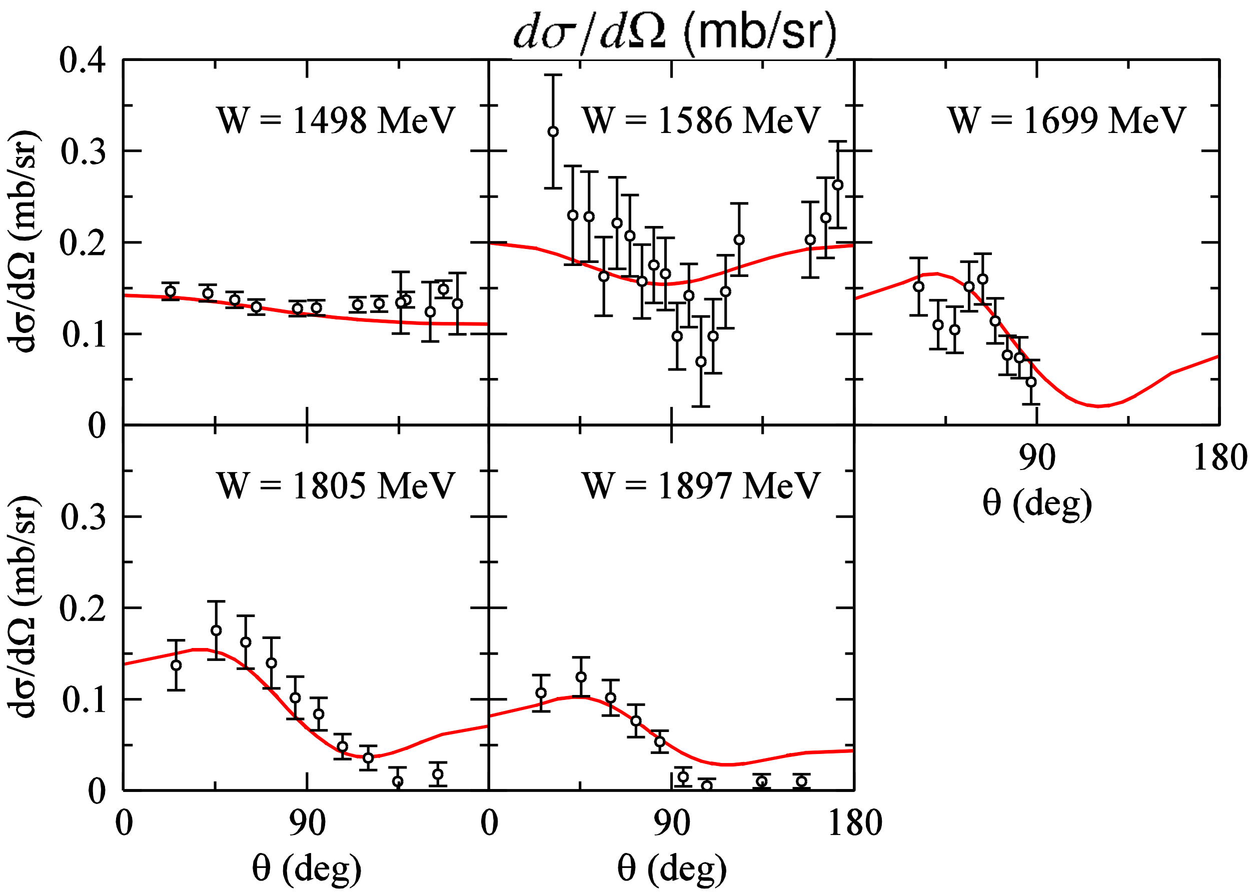
+ rescattering (πN unitarity)

Sato, Lee (2003), (2005)

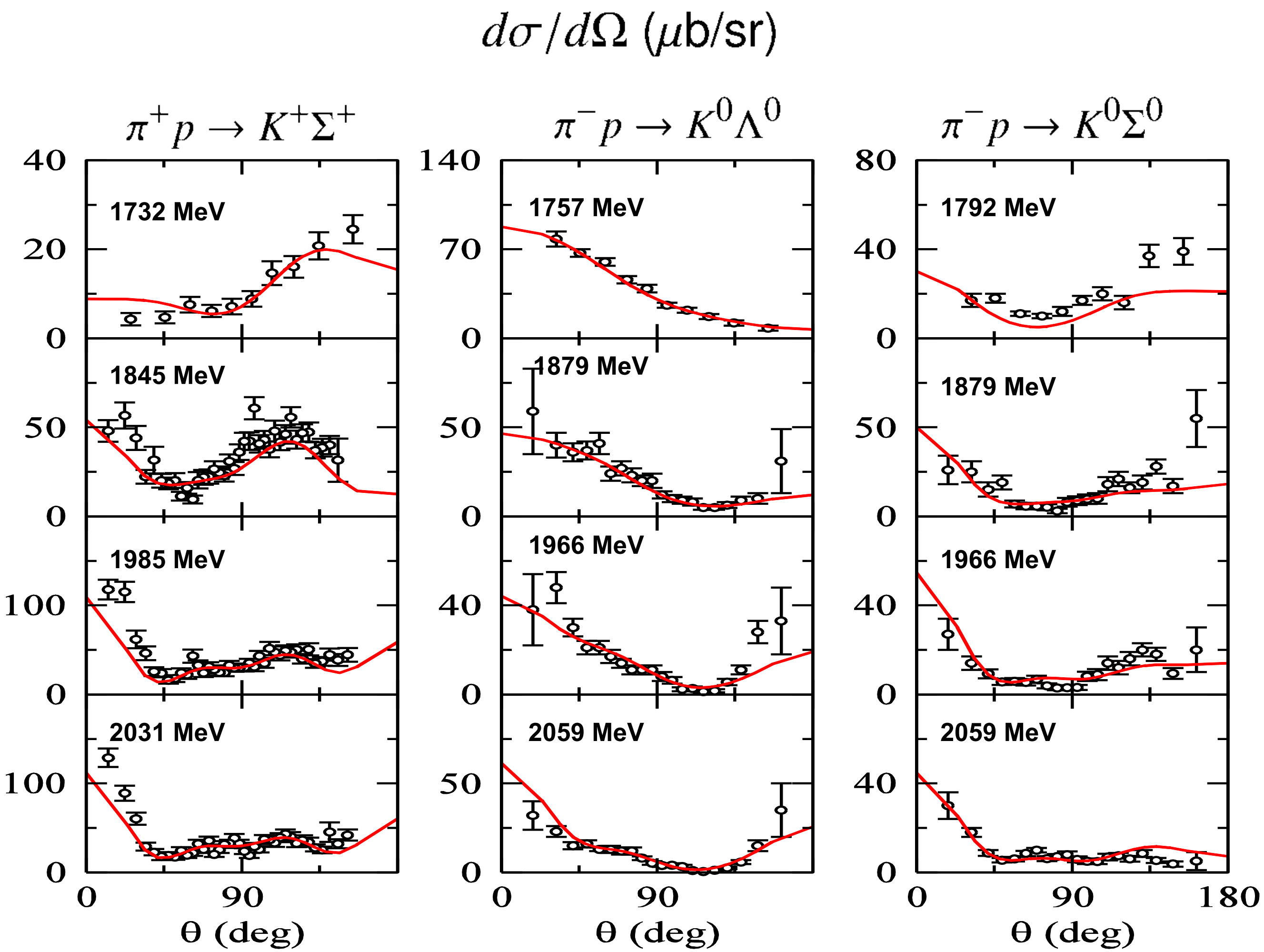


Eta production reactions

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



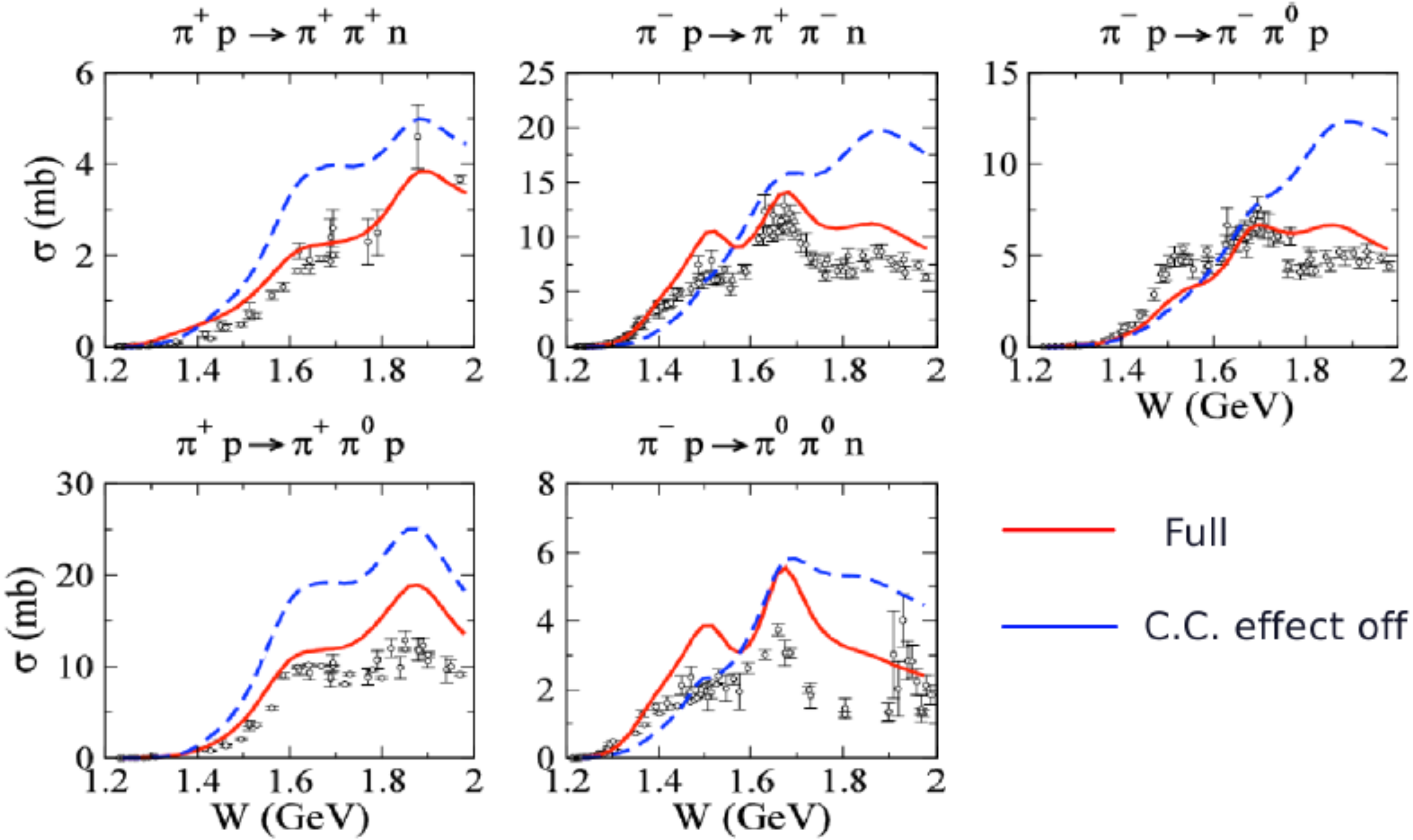
KY production reactions

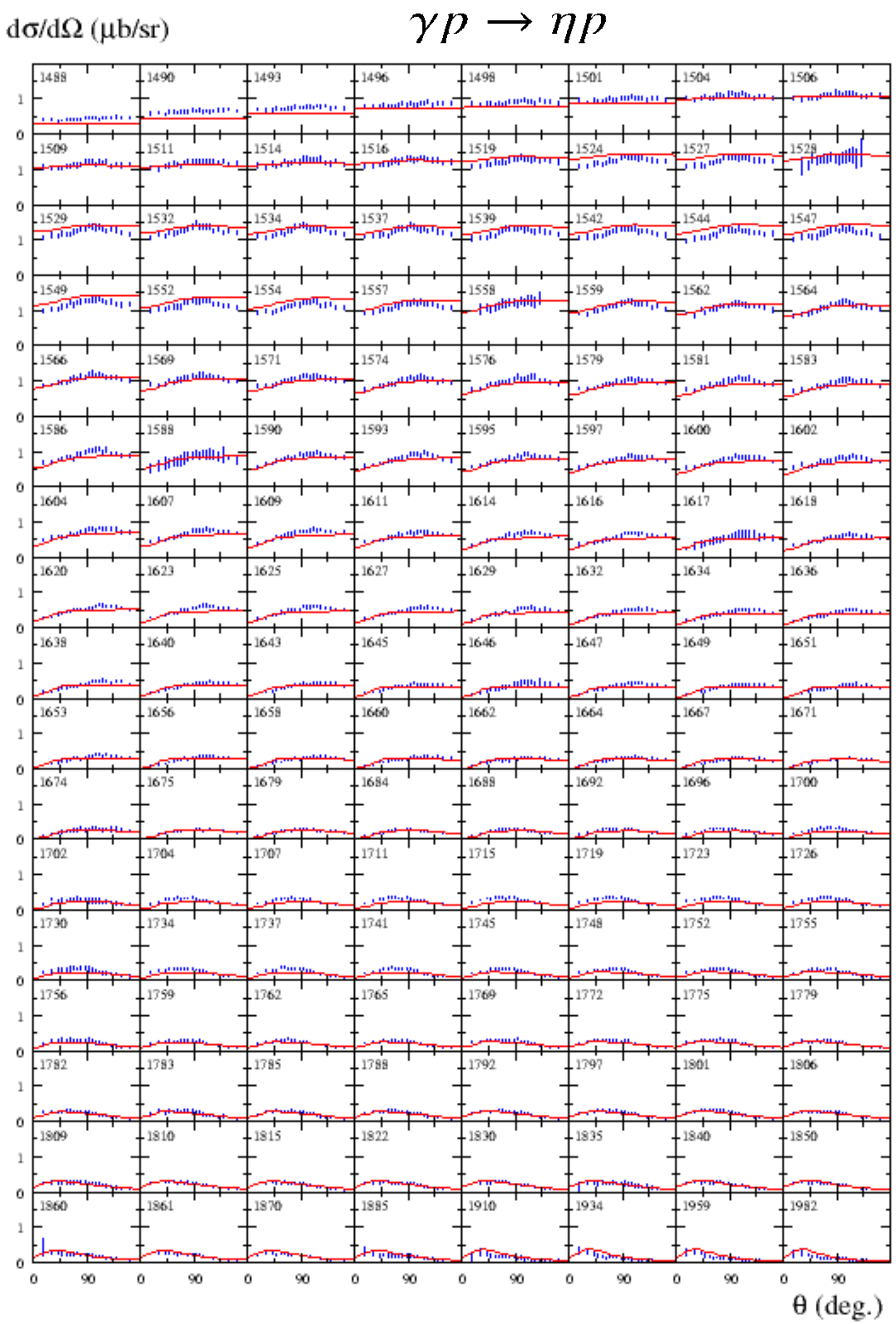


$\pi N \to \pi\pi N$

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

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



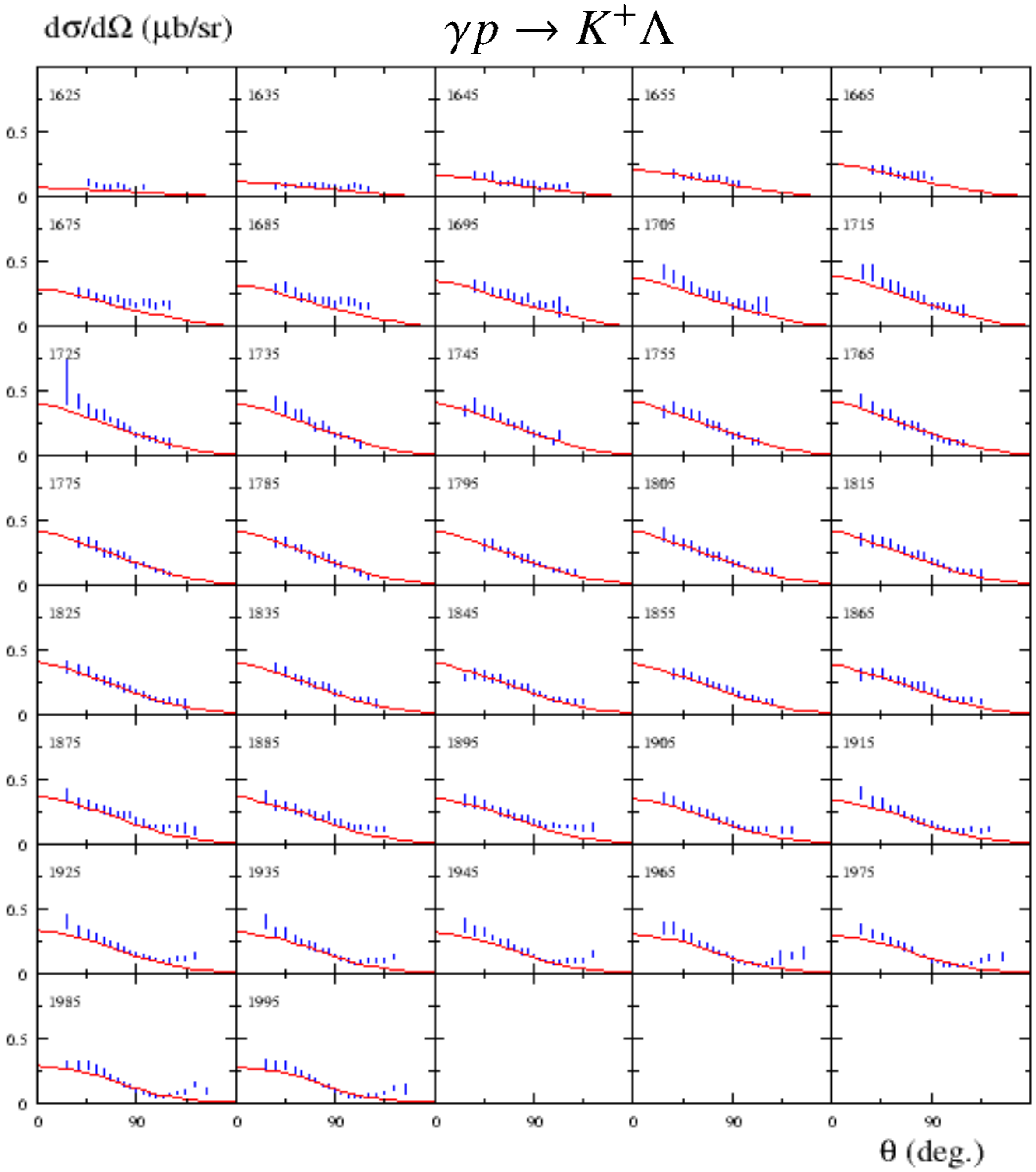


Kamano, Nakamura, Lee, Sato, arXiv:1305.4351

Vector current (Q^2=0) for η

Production is well-tested by data

Kamano, Nakamura, Lee, Sato, arXiv:1305.4351



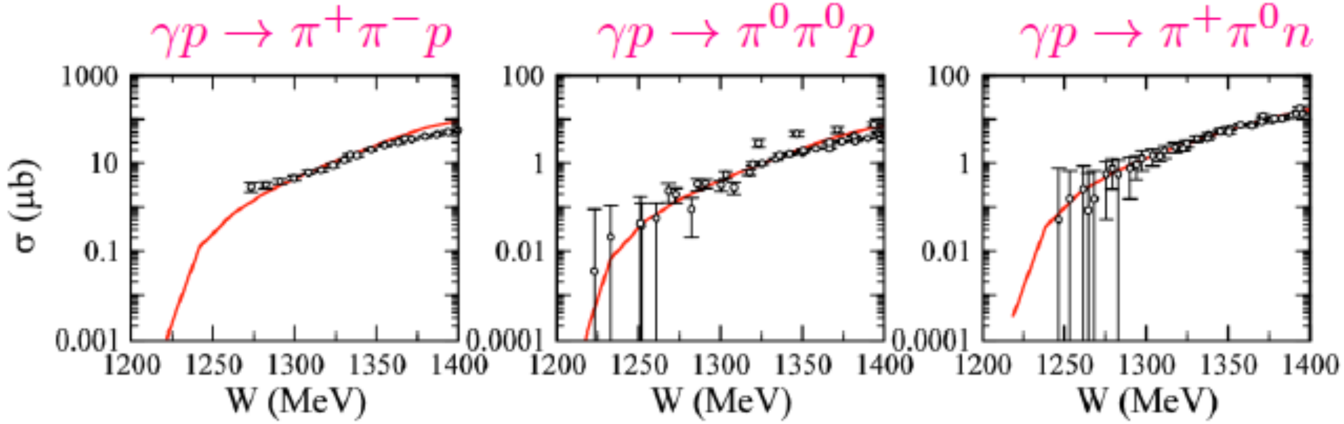
Vector current (Q^2=0) for K

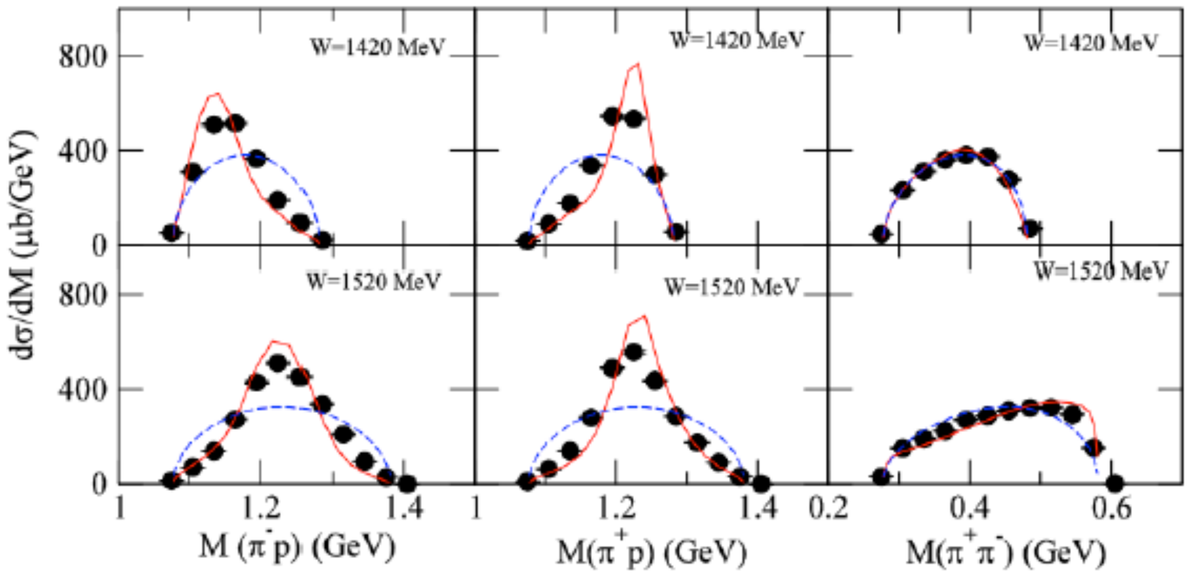
Production is well-tested by data

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

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

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



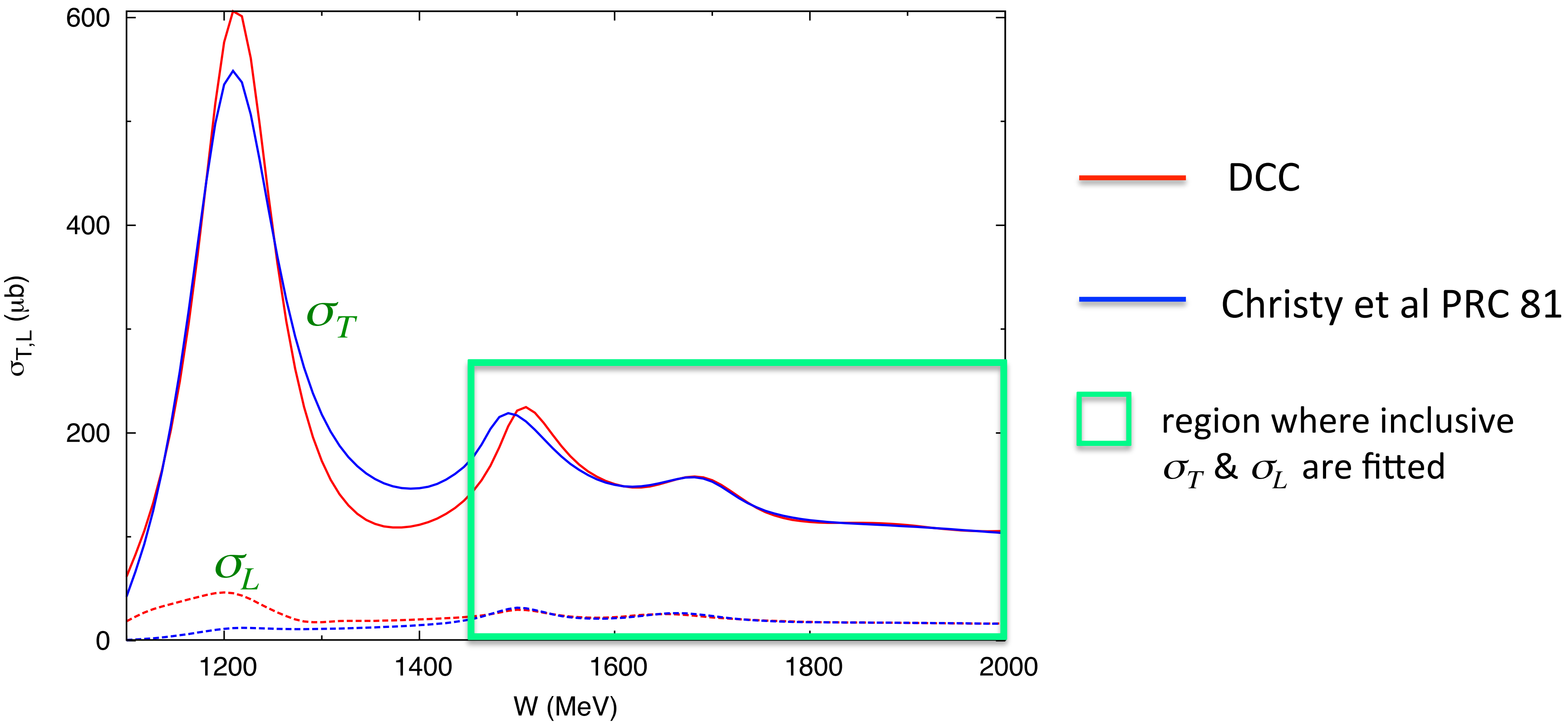


* Good description near threshold
* Good shape of invariant mass distribution
* Total cross sections overestimate data for $W \geq 1.5$ GeV

Analysis result

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

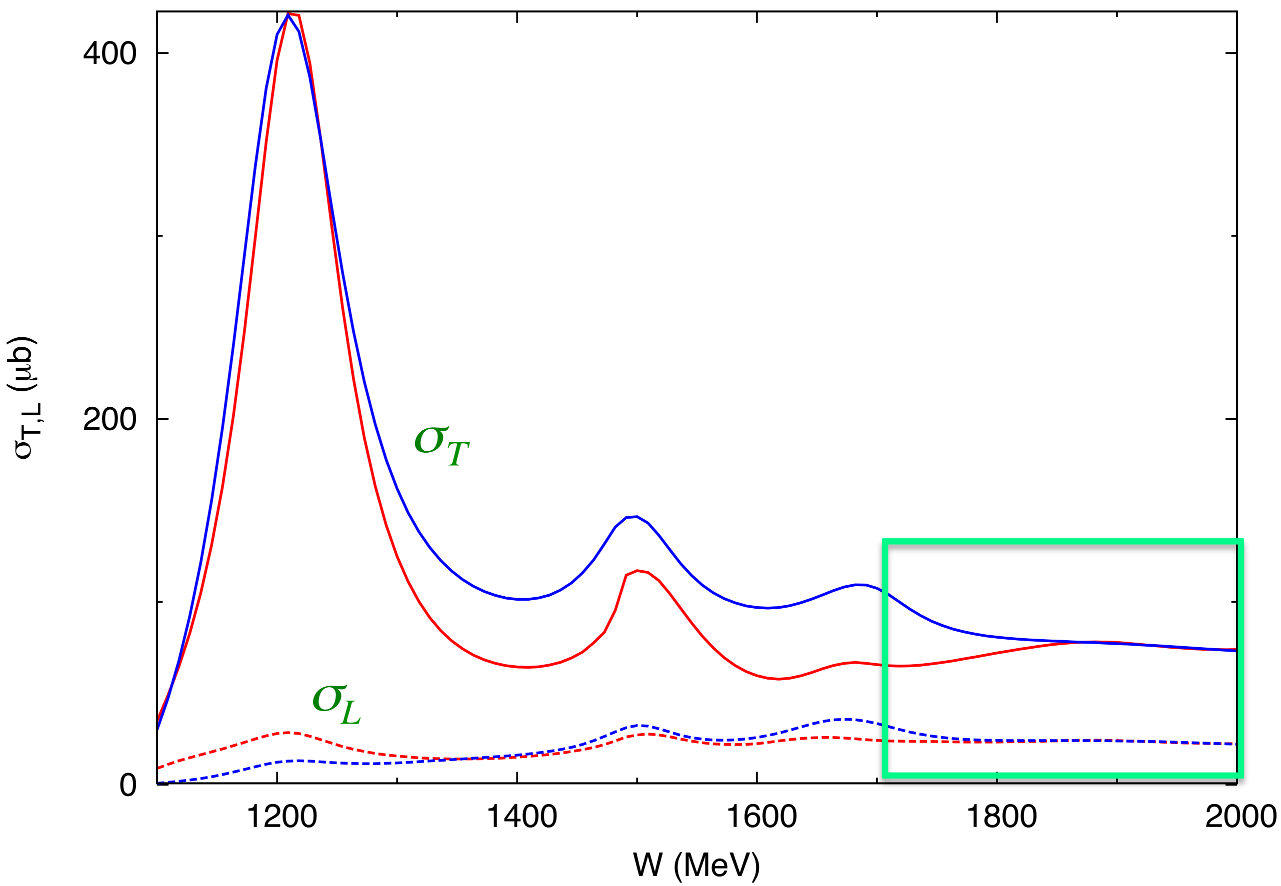
σ_T & σ_L (inclusive inelastic)



Analysis result

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

σ_T & σ_L (inclusive inelastic)



DCC

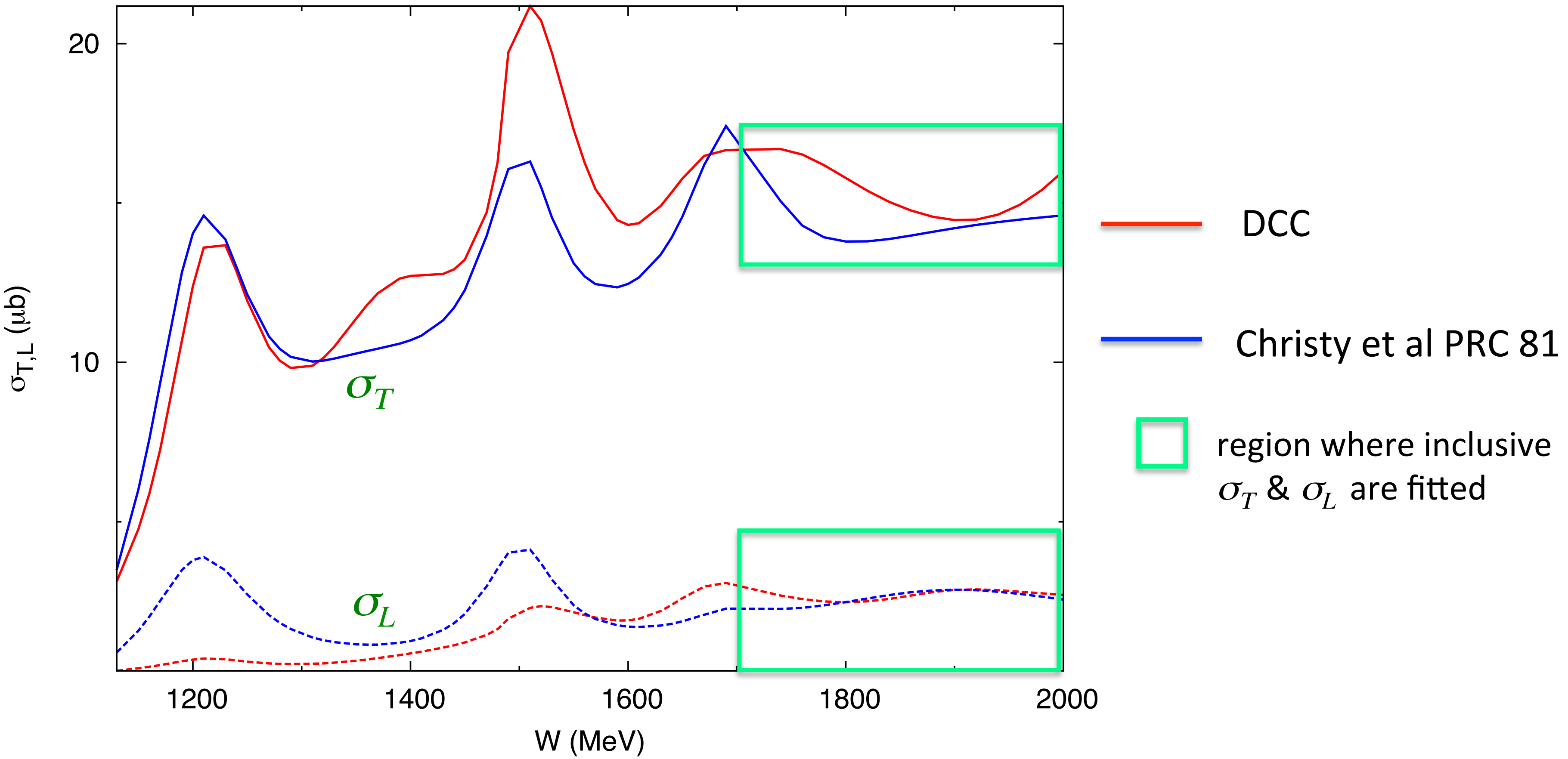
Christy et al PRC 81

region where inclusive σ_T & σ_L are fitted

Analysis result

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

σ_T & σ_L (inclusive inelastic)

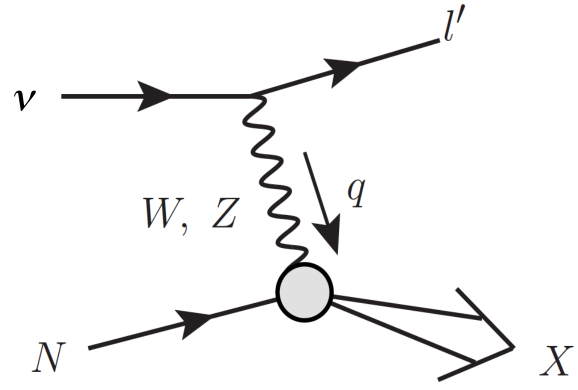


DCC model for neutrino interaction

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

at forward limit Q^2=0

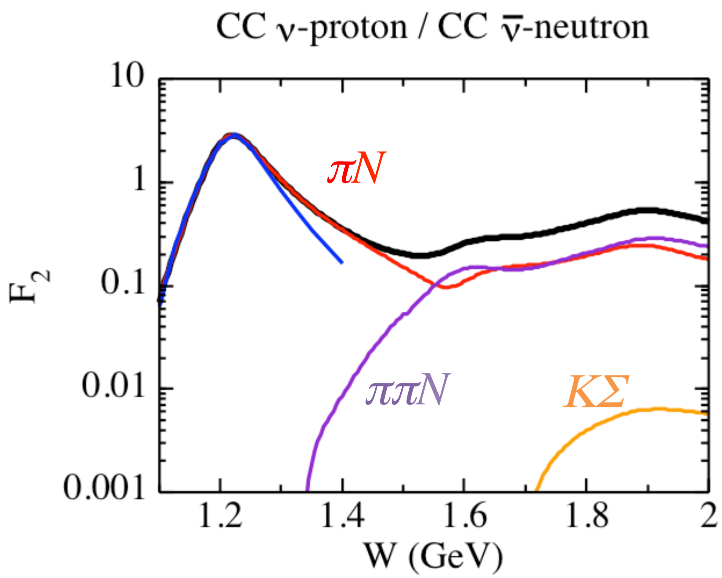
Kamano, Nakamura, Lee, Sato, PRD 86 (2012)



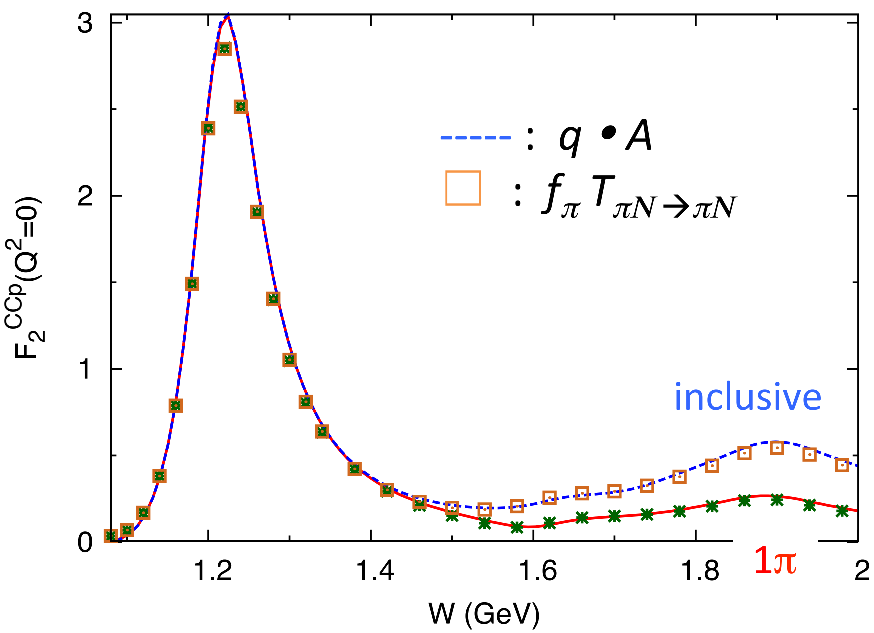
$$\frac{d\sigma}{dE_\ell d\Omega_\ell} = \frac{G_F^2}{2\pi^2} E_\ell^2\, W_2$$

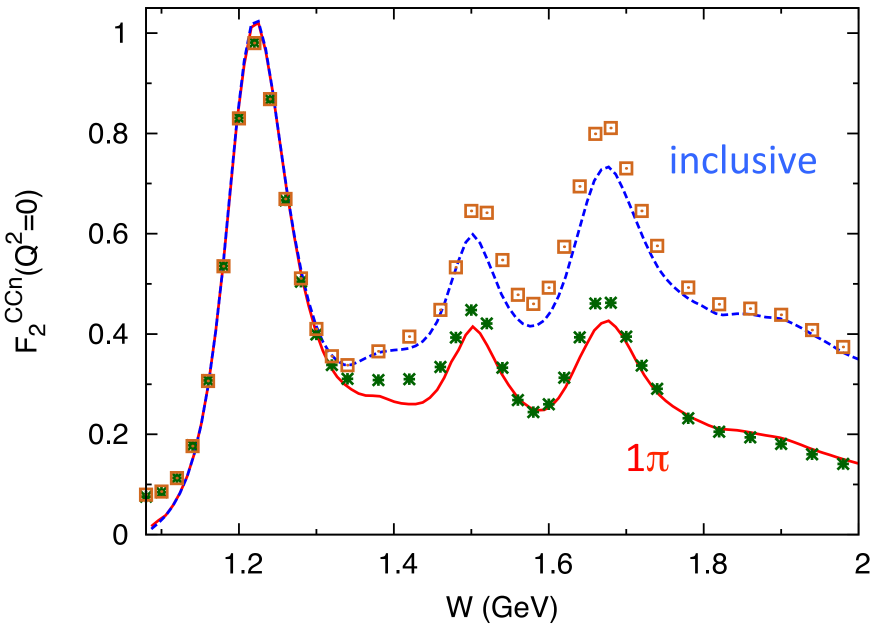
via PCAC $$F_2 \equiv \omega W_2 = \frac{2 f_\pi^2}{\pi} \sigma_{\pi N \to X}$$

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



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

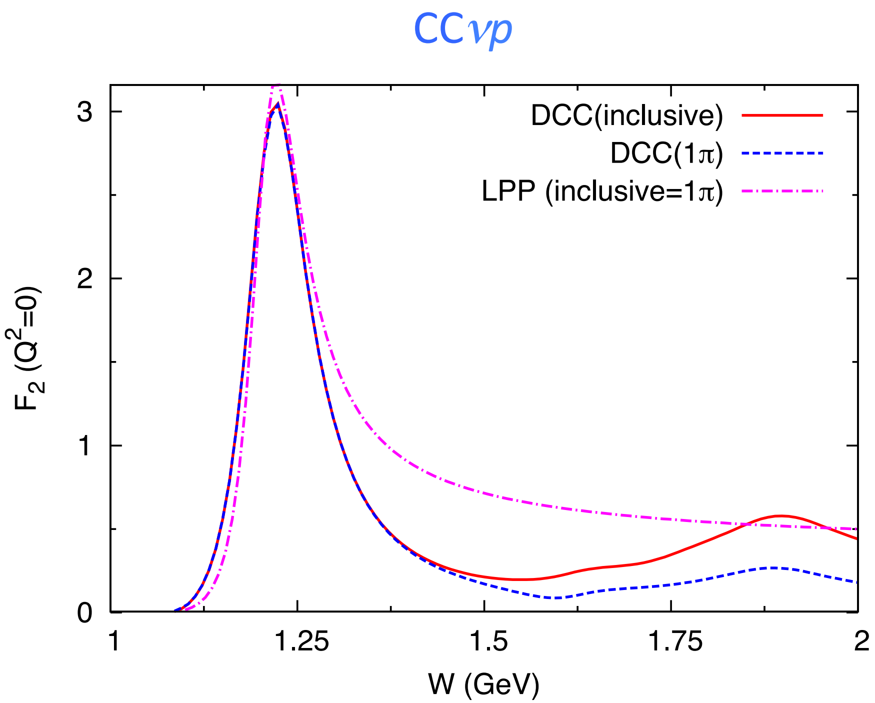


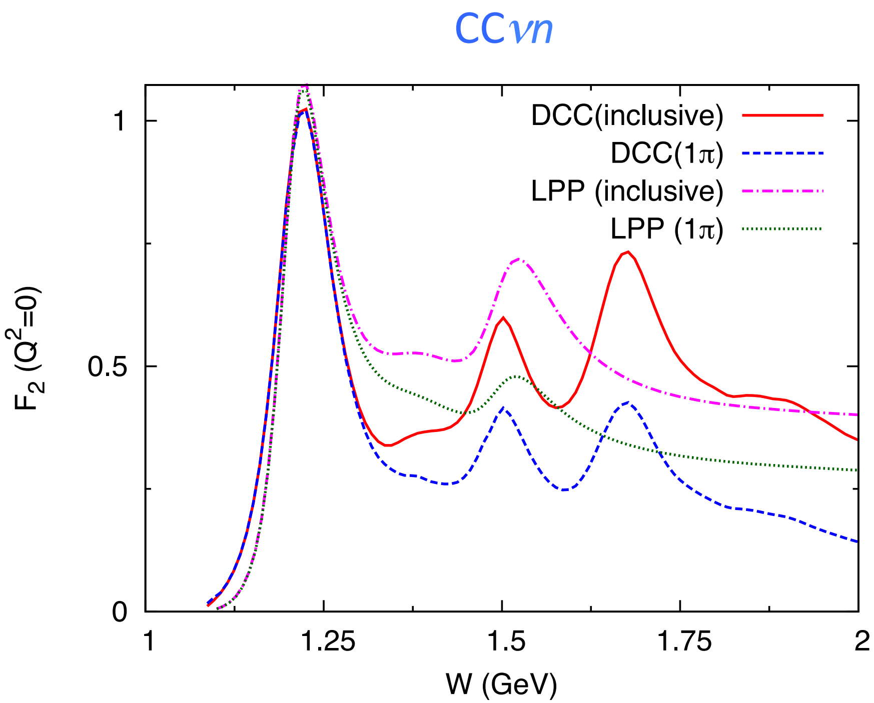


DCC model keeps good consistency with PCAC

Comparison with LPP model

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



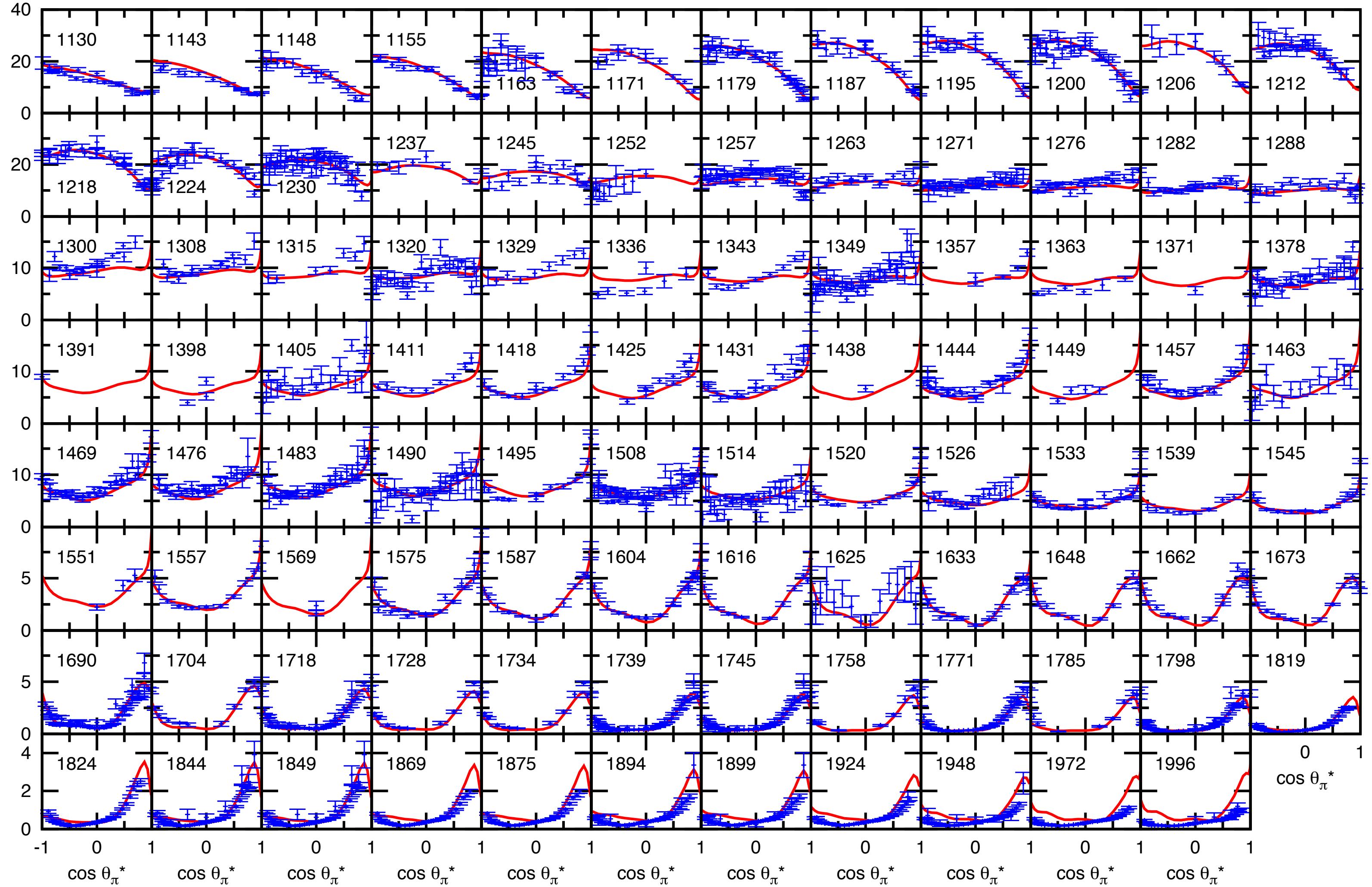


- Large difference beyond $\Delta(1232)$ region
- Importance of consistency between axial-current and πN interaction

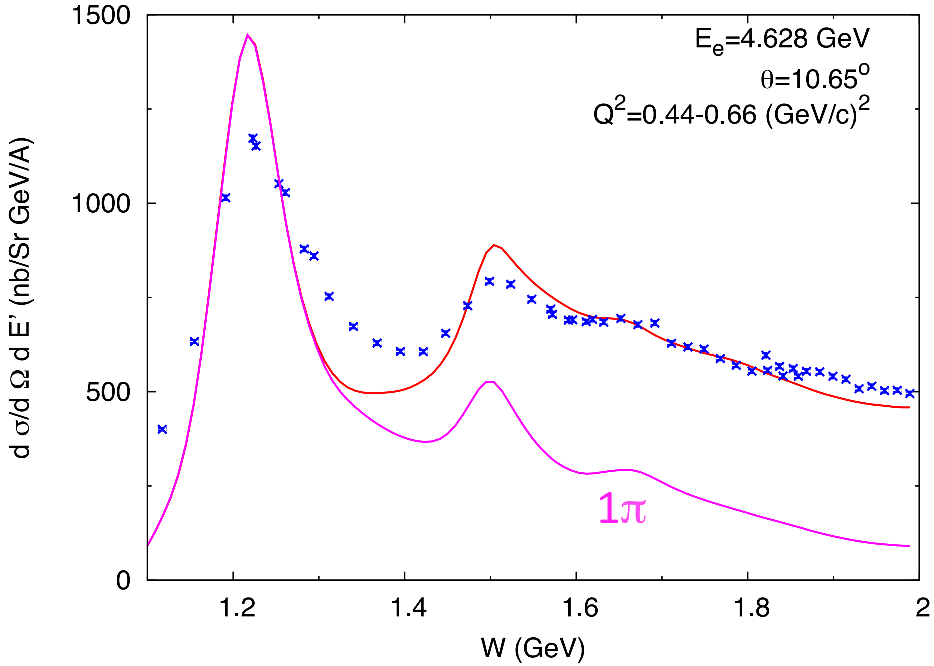
Analysis result (single π)

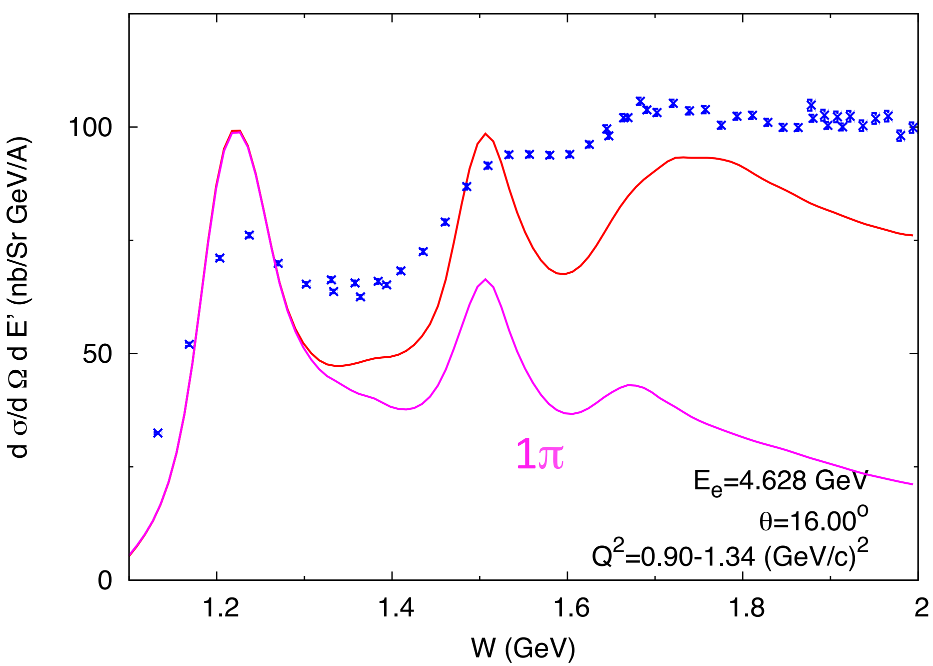
Q^2=0

$d\sigma / d\Omega$ $(\gamma n \rightarrow \pi^- p)$ 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

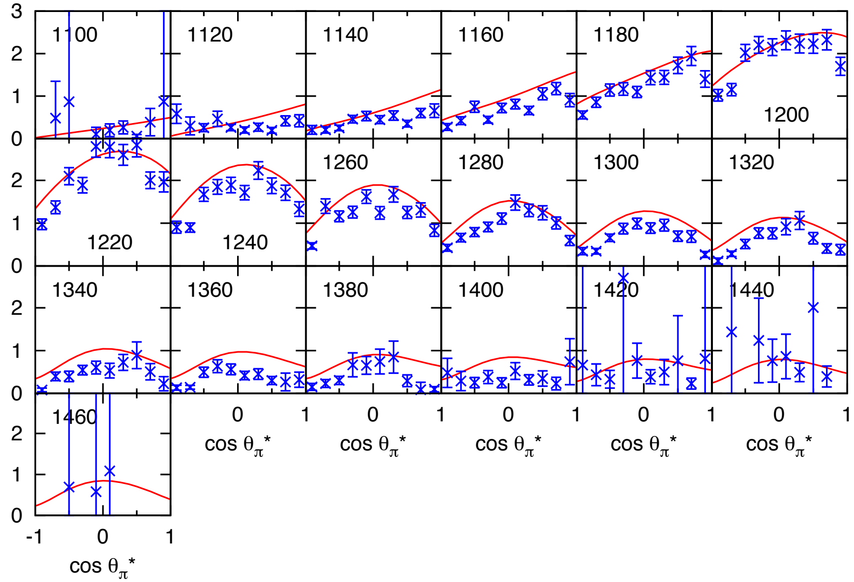
relevant to neutrino interactions of $E_\nu \leq 2$ *GeV*

Analysis result (single π)

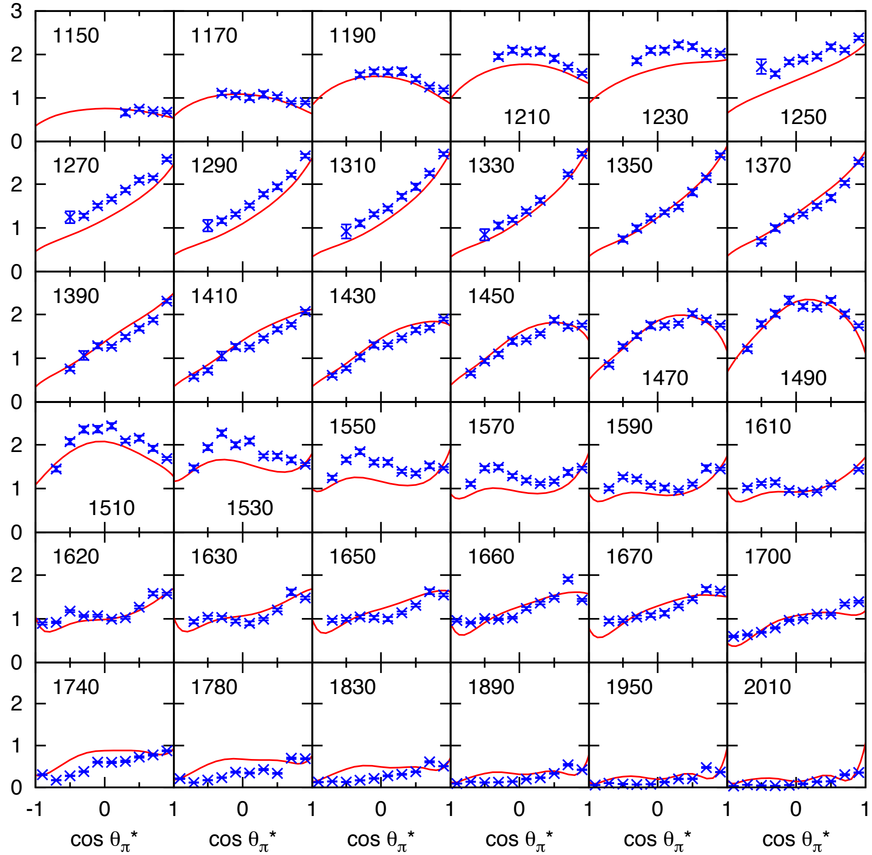
Q^2=1.76 (GeV/c)^2

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

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



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

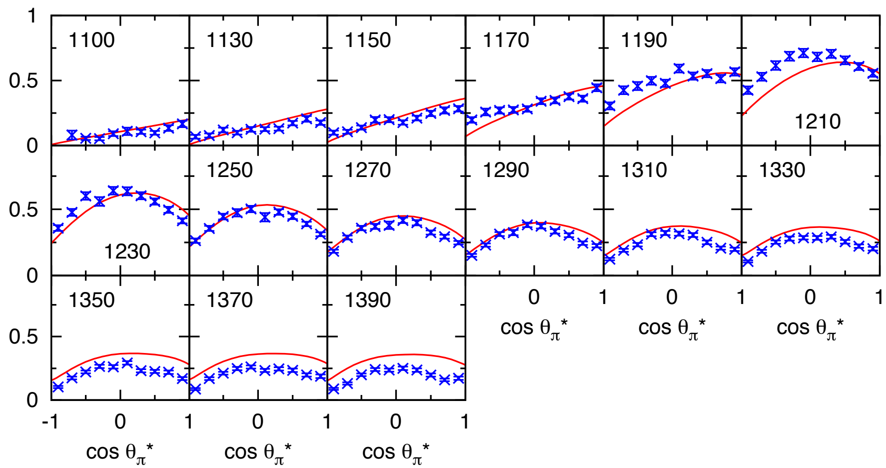


Analysis result (single π)

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

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

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



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