Neutrino-induced meson productions

Satoshi Nakamura

Osaka University, Japan

Collaborators : H. Kamano (RCNP, Osaka Univ.), T. Sato (Osaka Univ.)

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Introduction

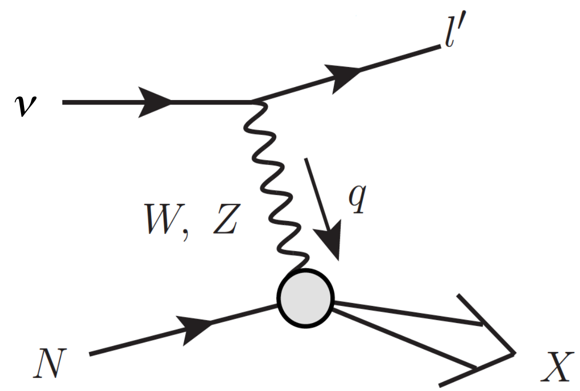
Neutrino-nucleus scattering for ν-oscillation experiments

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

ν–nucleus scattering needs to be understood more precisely

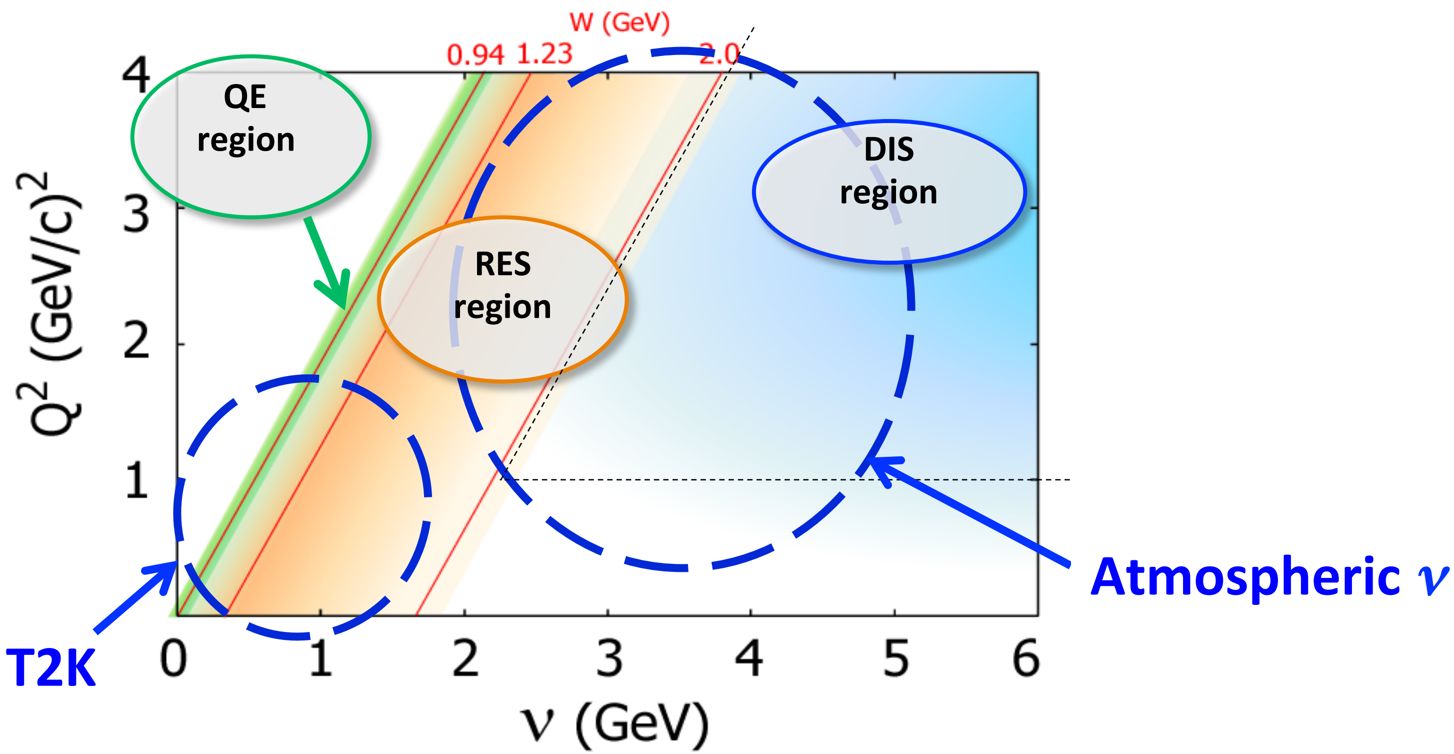
All ν-oscillation experiments measure ν-flux through ν-nucleus interaction

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



Neutrino-nucleus scattering for ν-oscillation experiments

Next-generation exp. ➔ leptonic CP̸, mass hierarchy

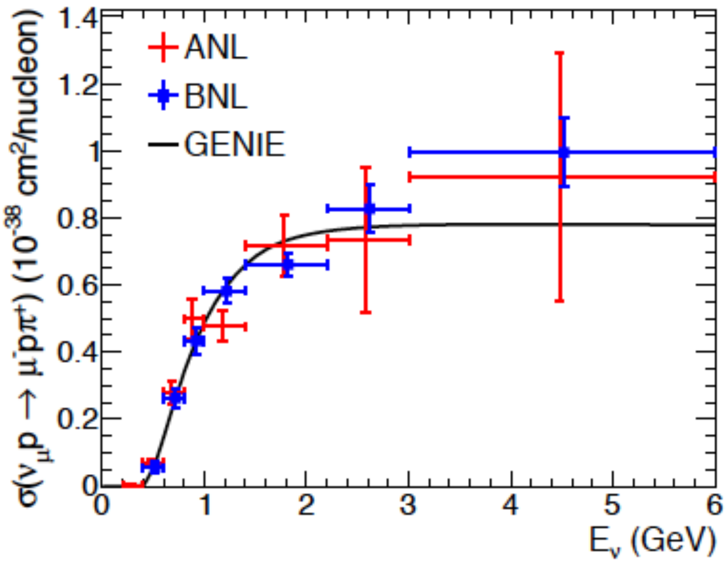


Collaboration at J-PARC Branch of KEK Theory Center

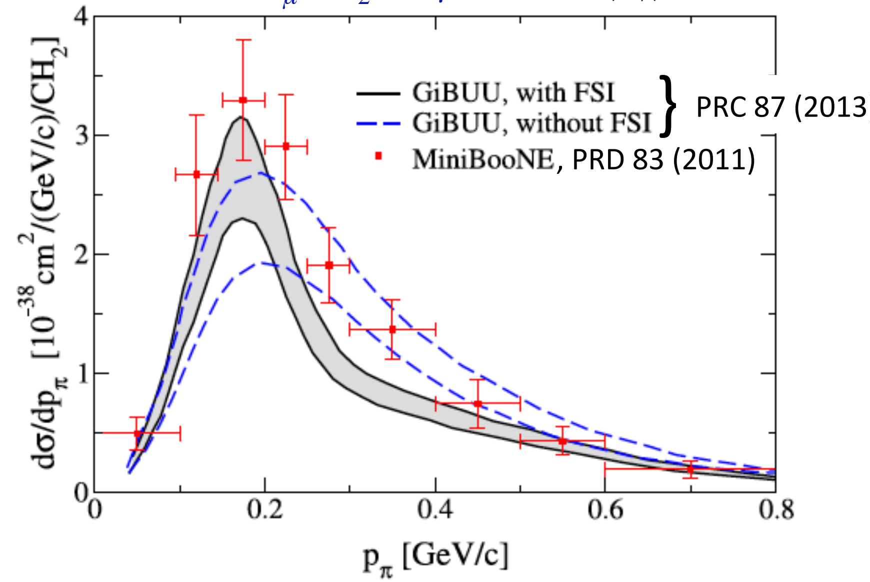
http://j-parc-th.kek.jp/html/English/e-index.html

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)

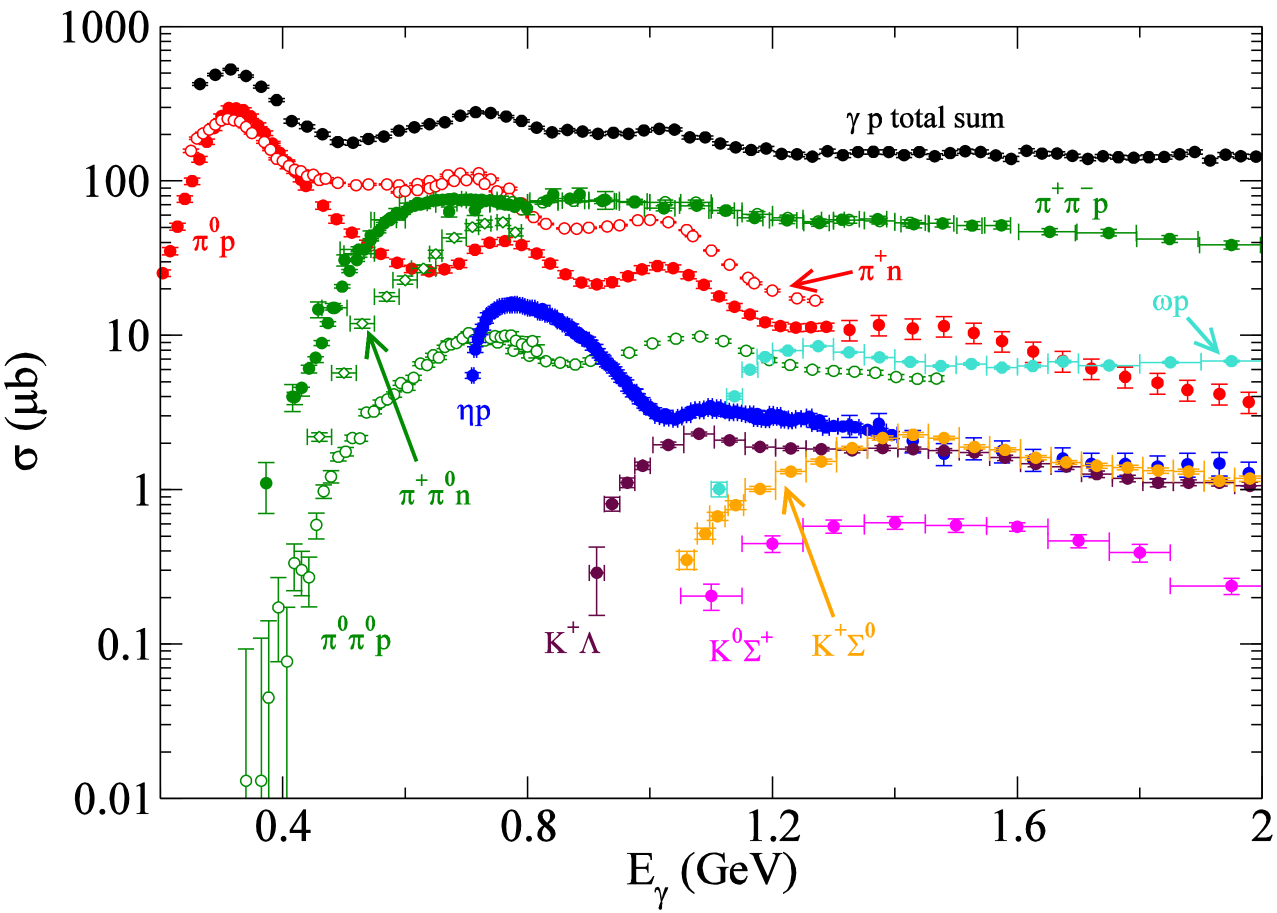
- Final state interaction (FSI) changes charge, momentum, number of π
- Cross section shape is worse described with FSI
- MINERνA data (arXiv:1406.6415) favor FSI

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

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

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.)

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

Our strategy to overcome the problems…

We develop a dynamical coupled-channels model

★ Dynamical coupled-channels (DCC) model for $\gamma N, \pi N \rightarrow \pi N, \pi\pi N, \eta N, K\Lambda, K\Sigma$

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

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

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

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

Coupled-channel unitarity is fully taken into account

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

DCC (Dynamical Coupled-Channel) model

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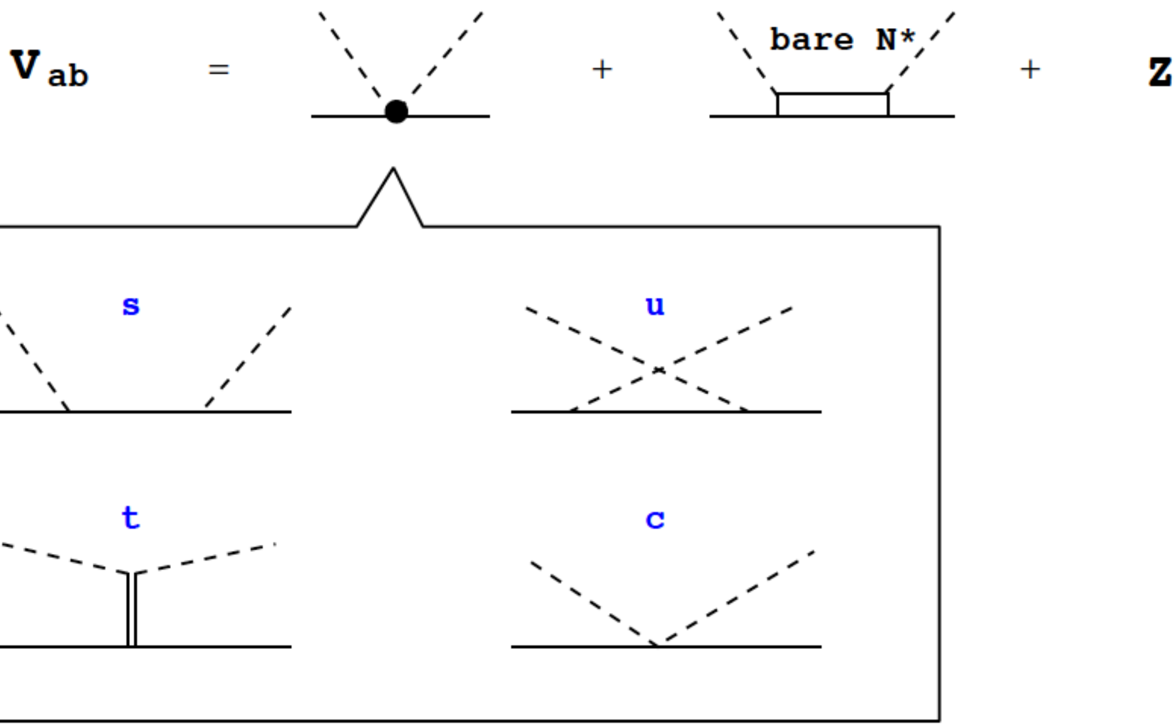

DCC (Dynamical Coupled-Channel) model

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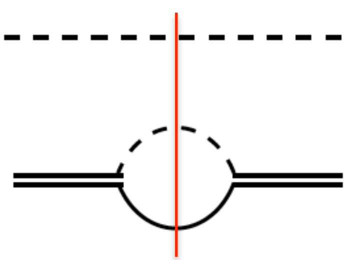
Coupled-channel Lippmann-Schwinger equation

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

$Gc =$

for stable channels



for unstable channels

DCC analysis of meson production data

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

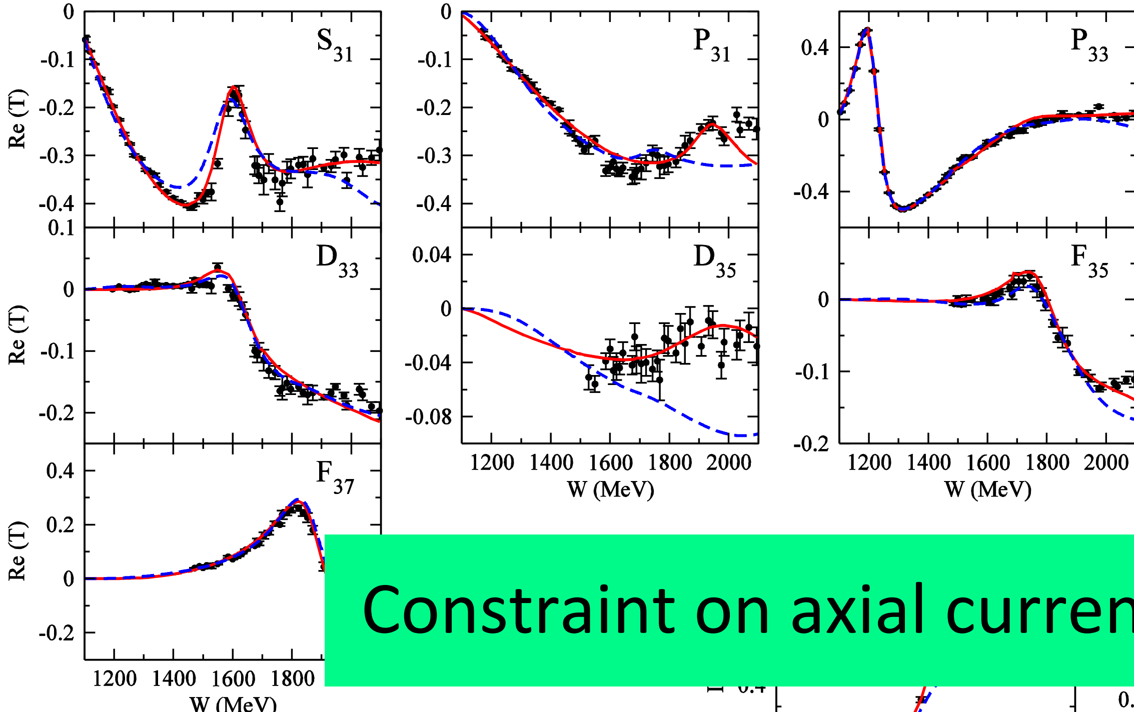
Fully combined analysis of $\gamma N, \pi N$ ➔ $\pi N, \eta N, K\Lambda, K\Sigma$ data

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

~ 23,000 data points are fitted

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

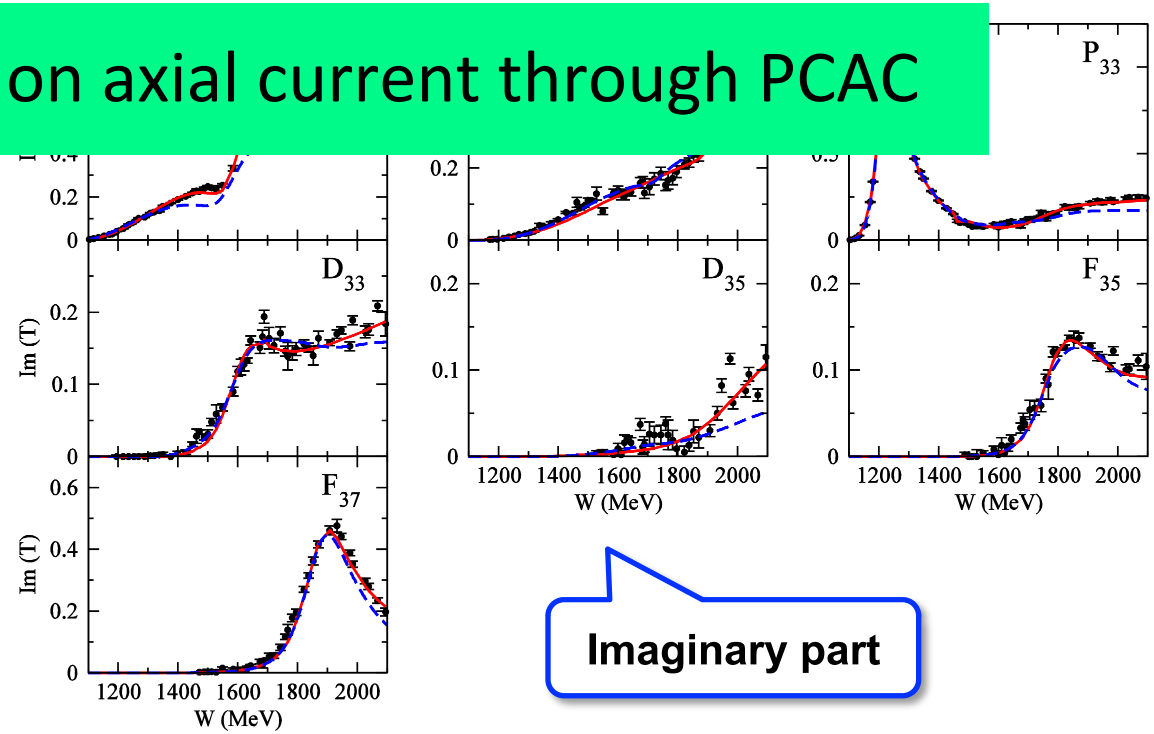
Partial wave amplitudes of π N scattering



Real part

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

Constraint on axial current through PCAC



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

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

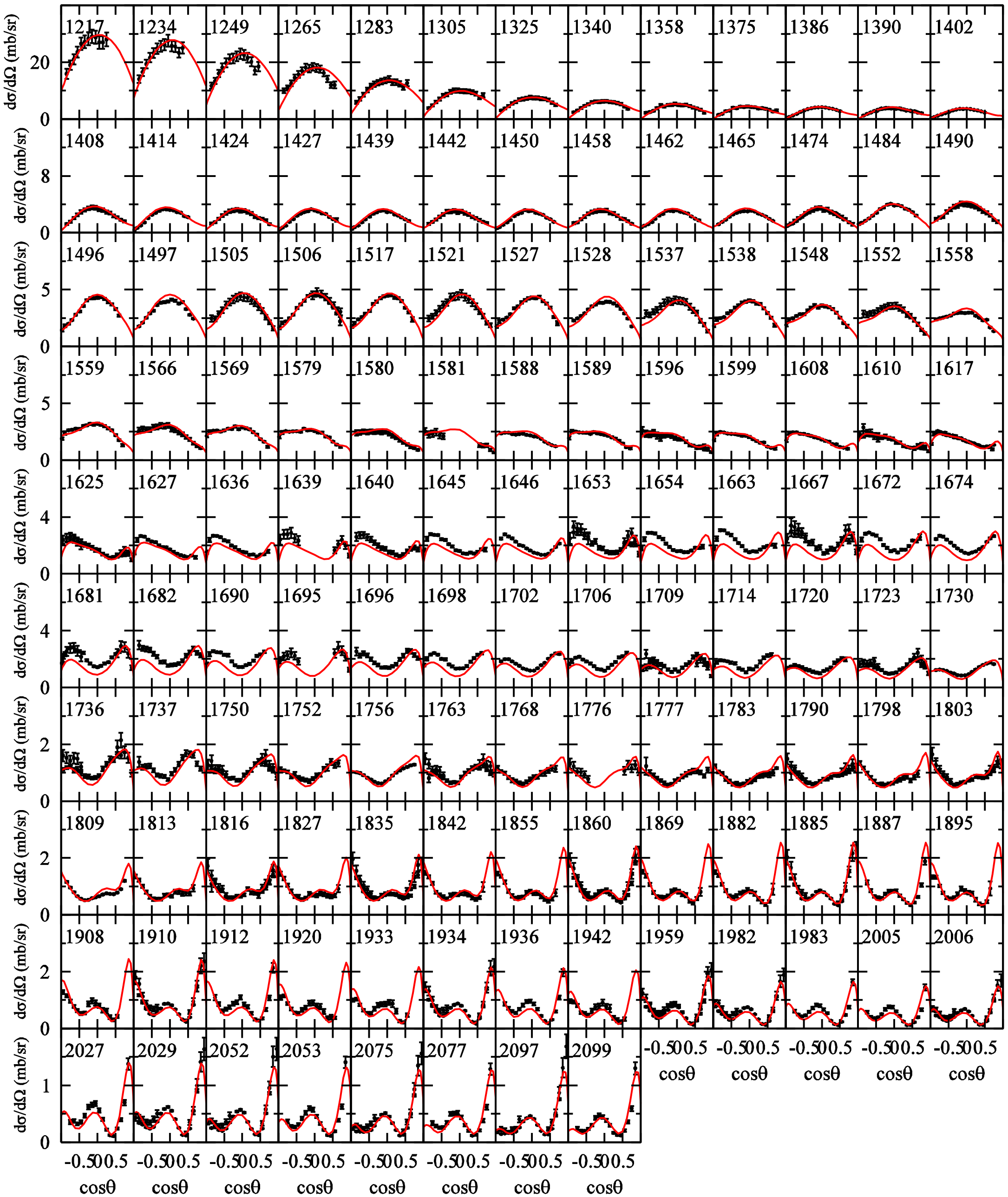
Imaginary part

Data: SAID πN amplitude

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

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

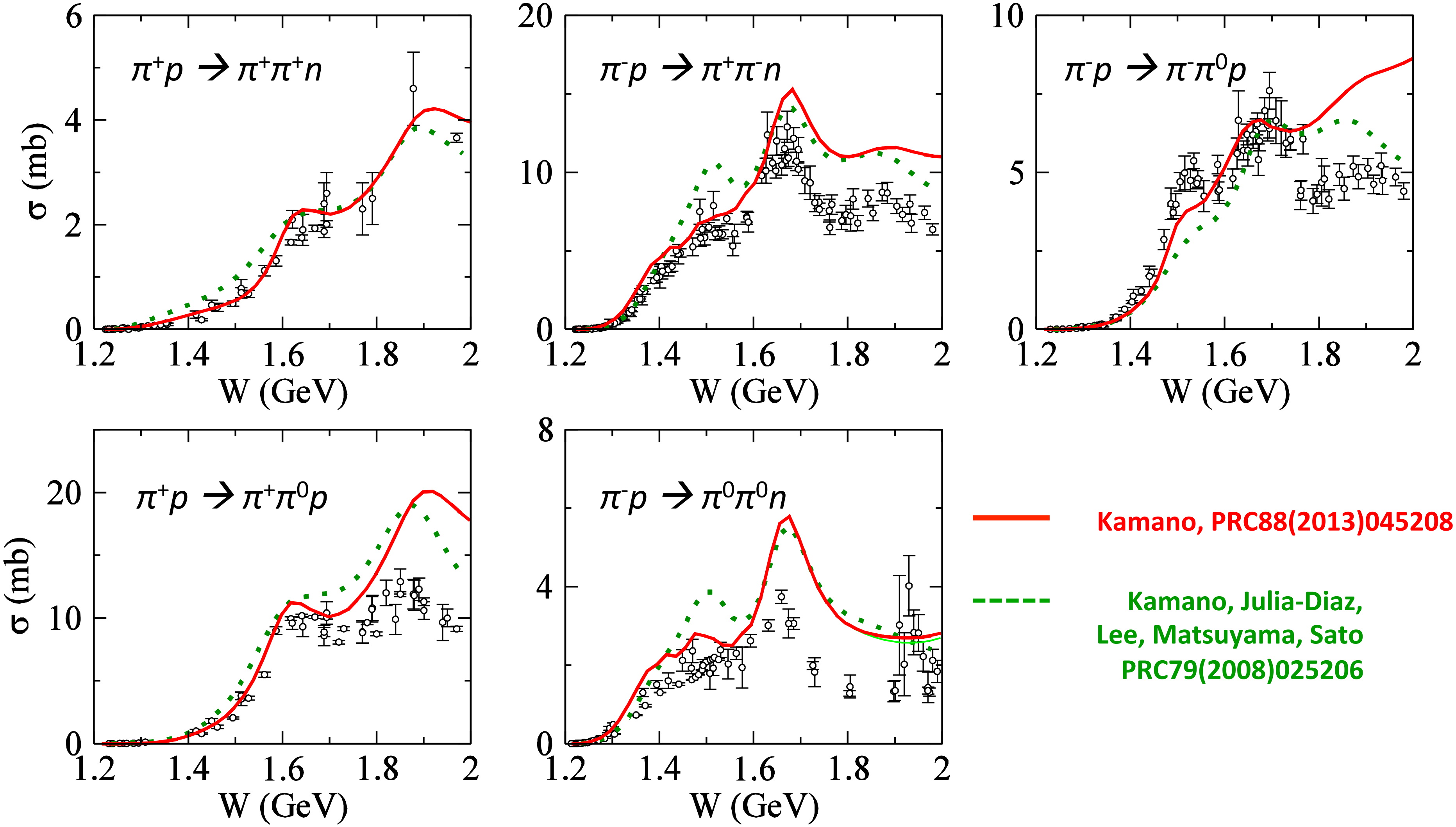
Kamano, Nakamura, Lee, Sato, PRC 88 (2013)



Vector current (Q^2=0) for 1π

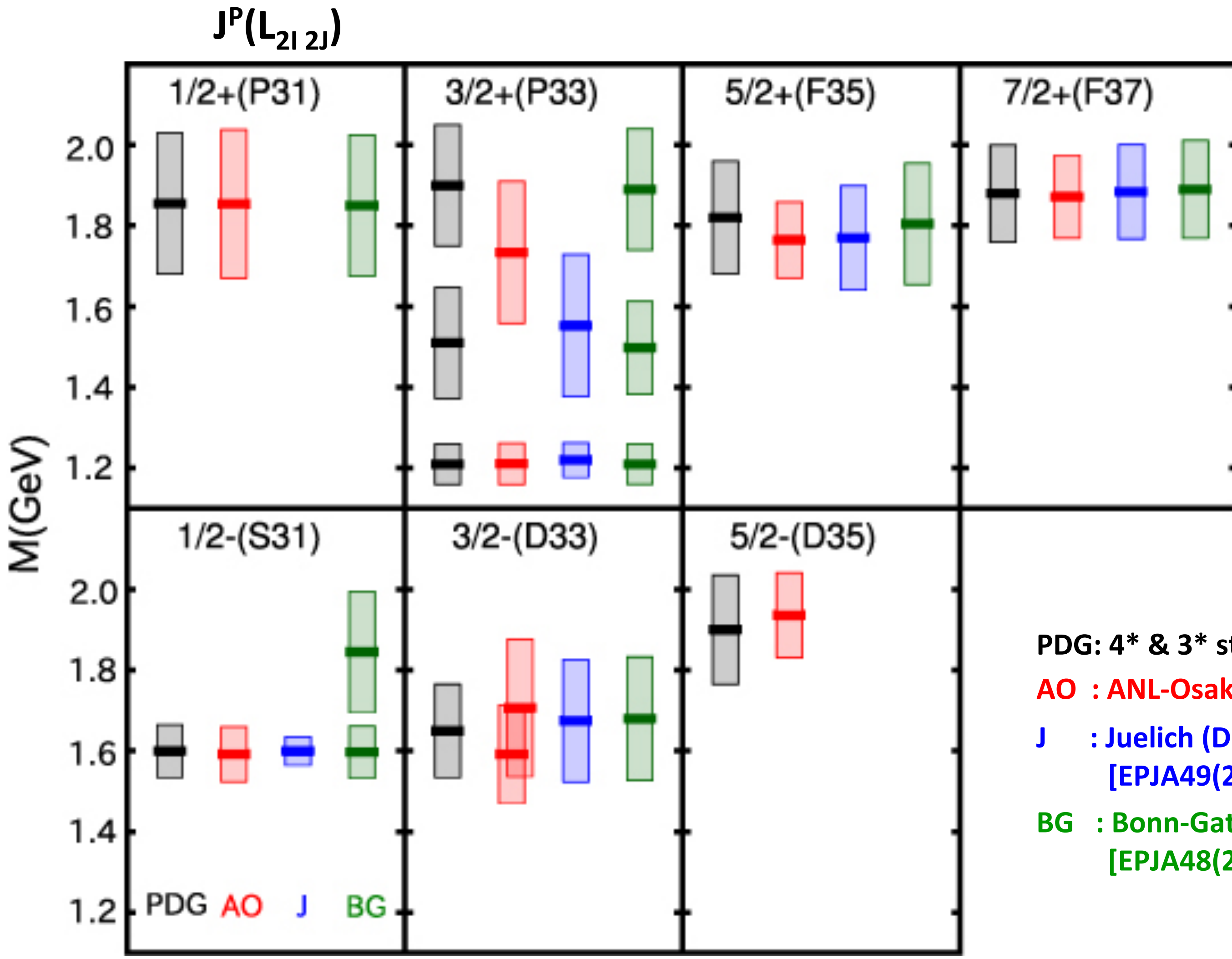
Production is well-tested by data

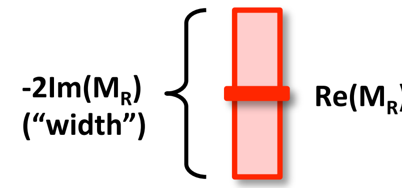
Predicted πN → ππN total cross sections with our DCC model



"Δ" resonances (I=3/2)

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





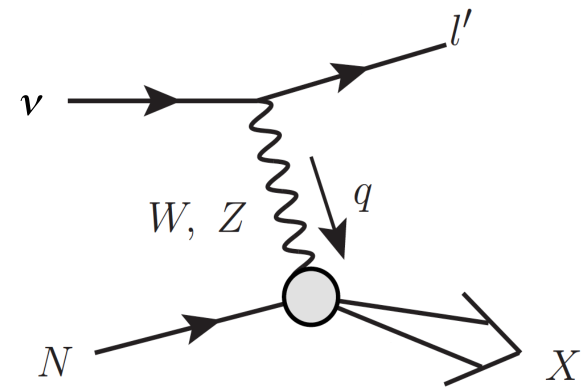
PDG: 4* & 3* states assigned by PDG2012

AO : ANL-Osaka

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

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

DCC model for neutrino interaction



Extension to full kinematical region $Q^2 \neq 0$

➔ Model for vector & axial currents is necessary

DCC model for neutrino interaction

Vector current

$Q^2=0$

γp ➔ MB

γn ➔ πN ➔ isospin separation

necessary for calculating ν-interaction

$Q^2 \neq 0$ (electromagnetic form factors for N-N^* transitions)

obtainable from $(e,e'\ \pi)$, $(e,e'\ X)$ data analysis

We've done first analysis of all these reactions ➔ $VNN^*(Q^2)$ fixed ➔ neutrino reactions

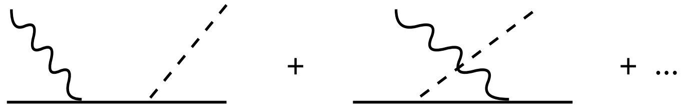
DCC model for neutrino interaction

Axial current

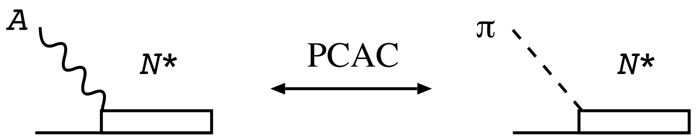
Q^2=0

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

Caveat : phenomenological axial currents are added to maintain PCAC relation

$$q \cdot A_{AN \rightarrow \pi N} \sim i f_\pi T_{\pi N \rightarrow \pi N}$$

to be improved in future

DCC model for neutrino interaction

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 for this presentation

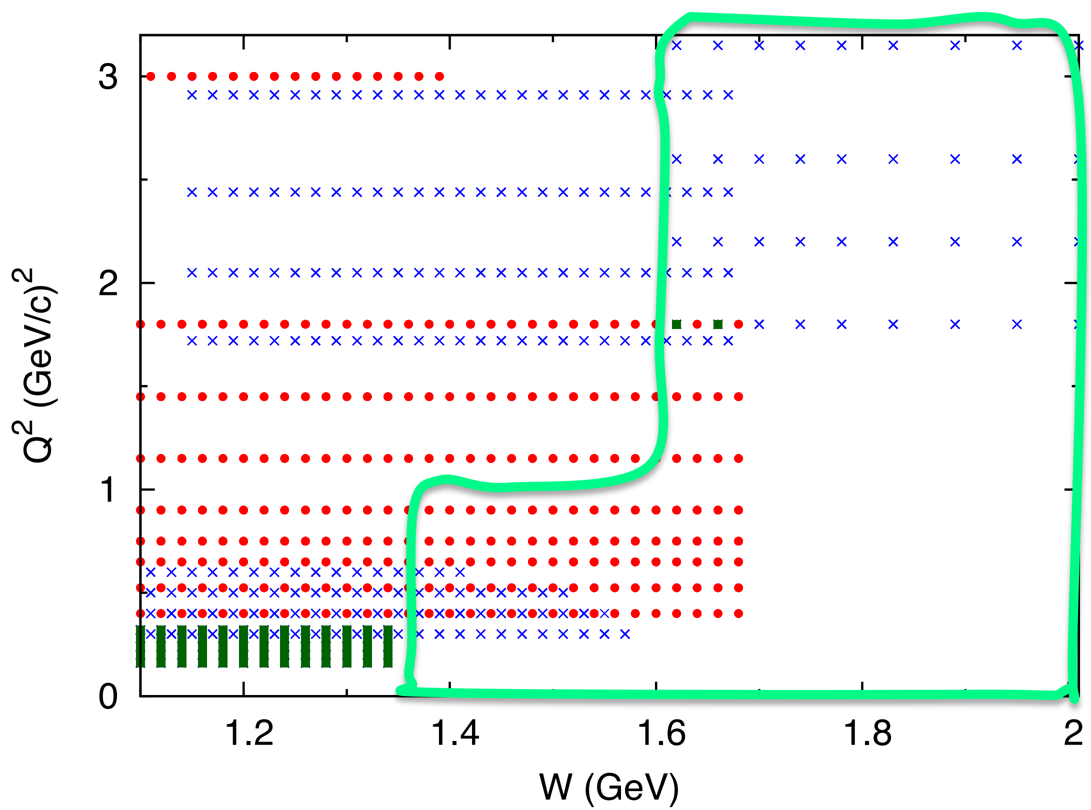
Analysis of electron scattering data

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)



Database

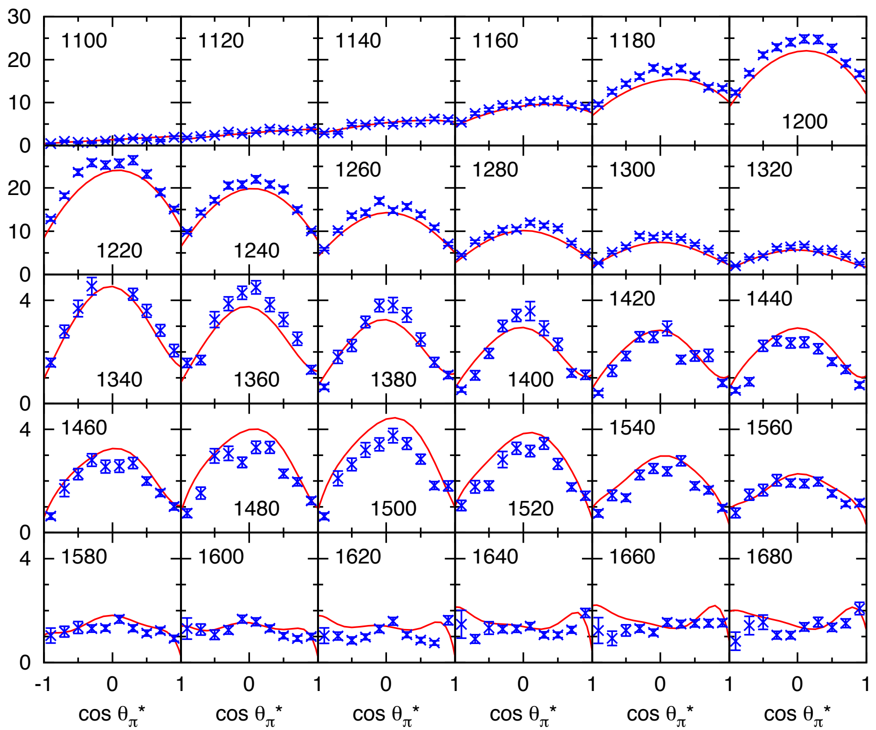
- $p(e,e'\pi^0)p$
- $p(e,e'\pi^+)n$
- both
- region where inclusive σ_T & σ_L are fitted

Analysis result (single π)

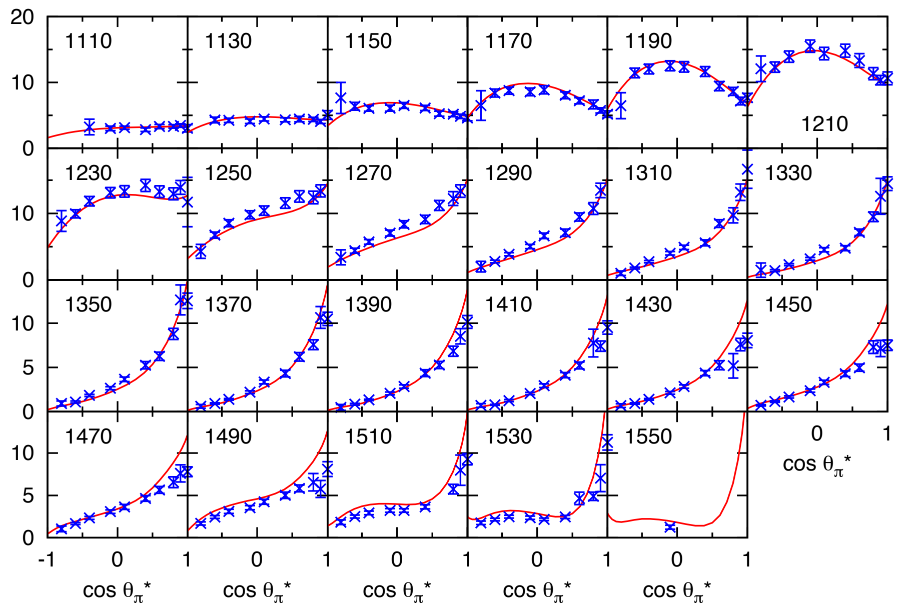
Q^2=0.40 (GeV/c)^2

$\sigma_T + \varepsilon\, \sigma_L$ for W=1.1 – 1.68 GeV

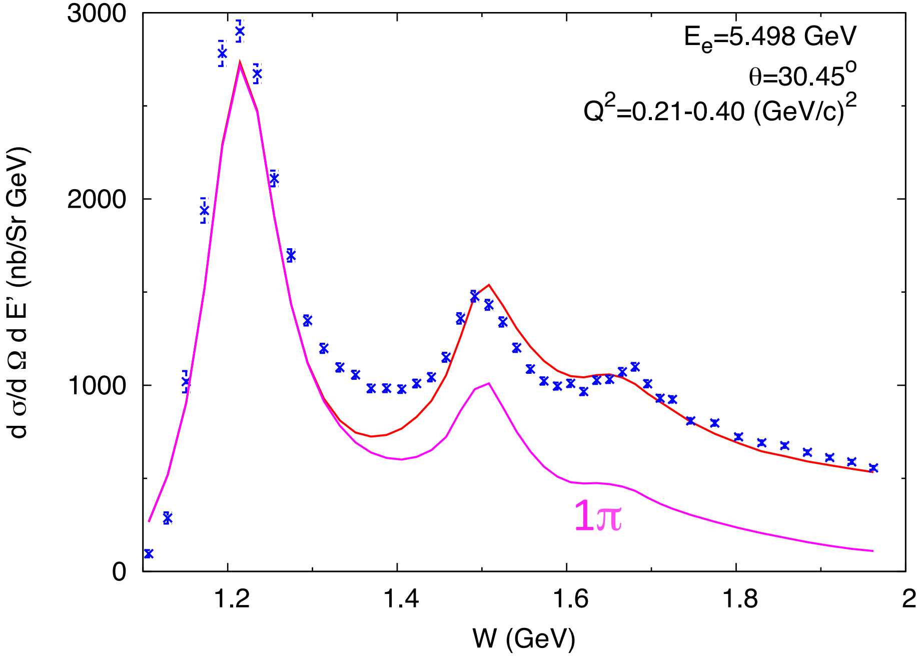
$p(e,e'\pi^0)p$

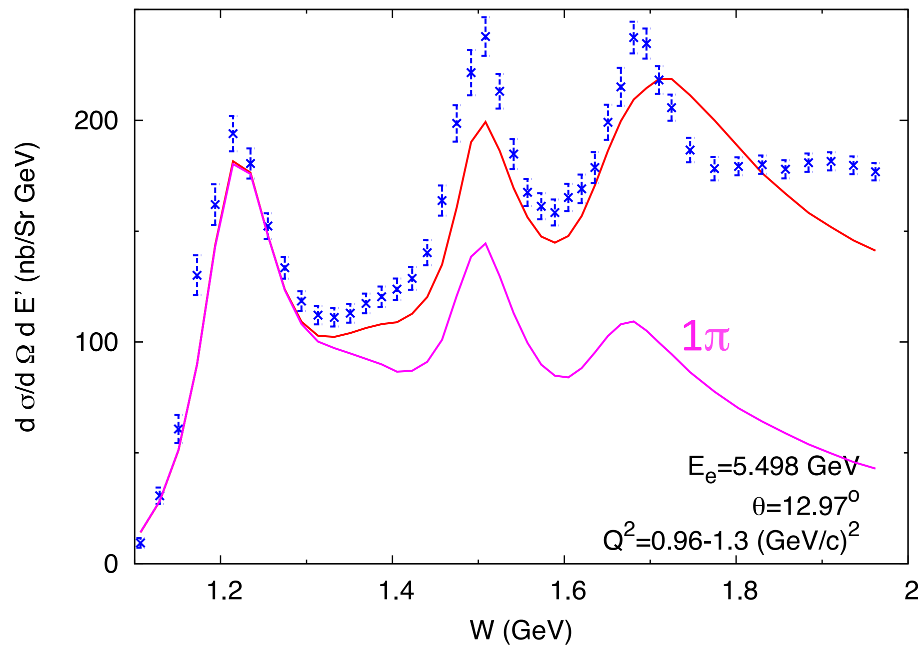


$p(e,e'\pi^+)n$



Analysis result (inclusive)





Data: JLab E00-002 (preliminary)

- Reasonable fit to data for application to neutrino interactions
- Important 2π contributions for high W region

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 ($Q^2\neq 0$)

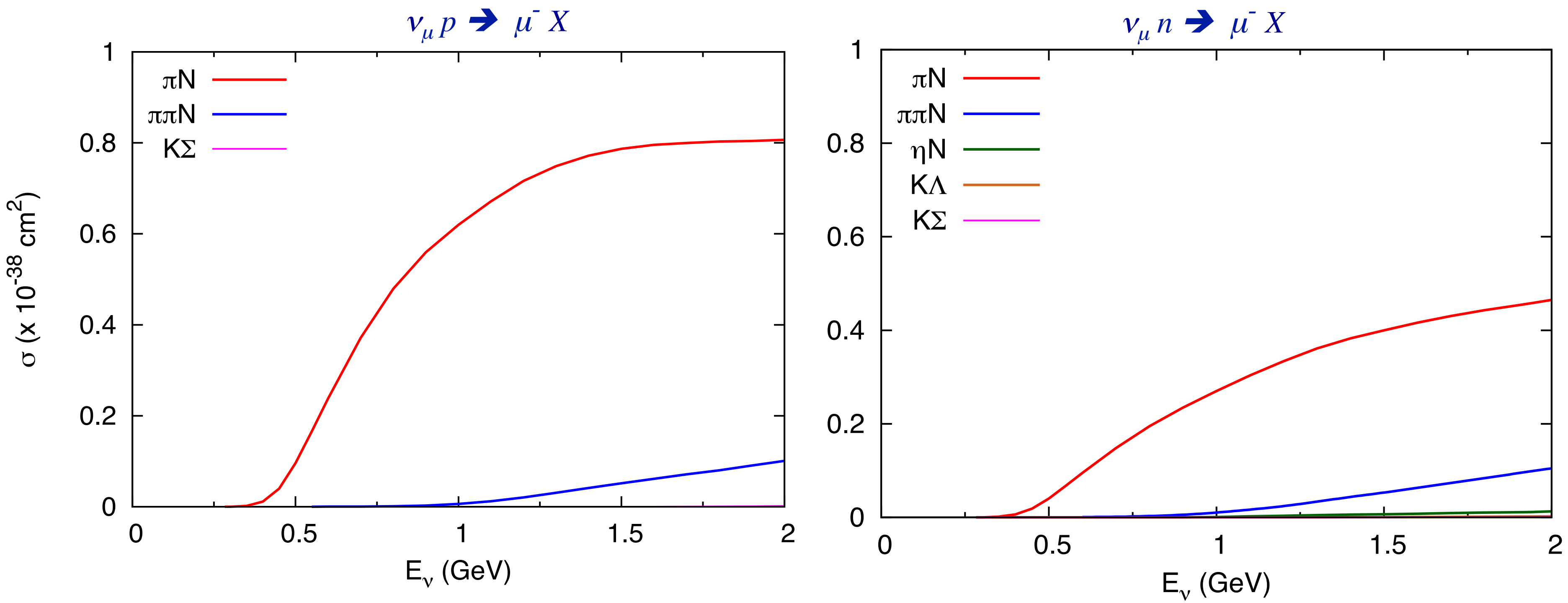
← Christy and Bosted, PRC 77 (2010), 81 (2010)

Done

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

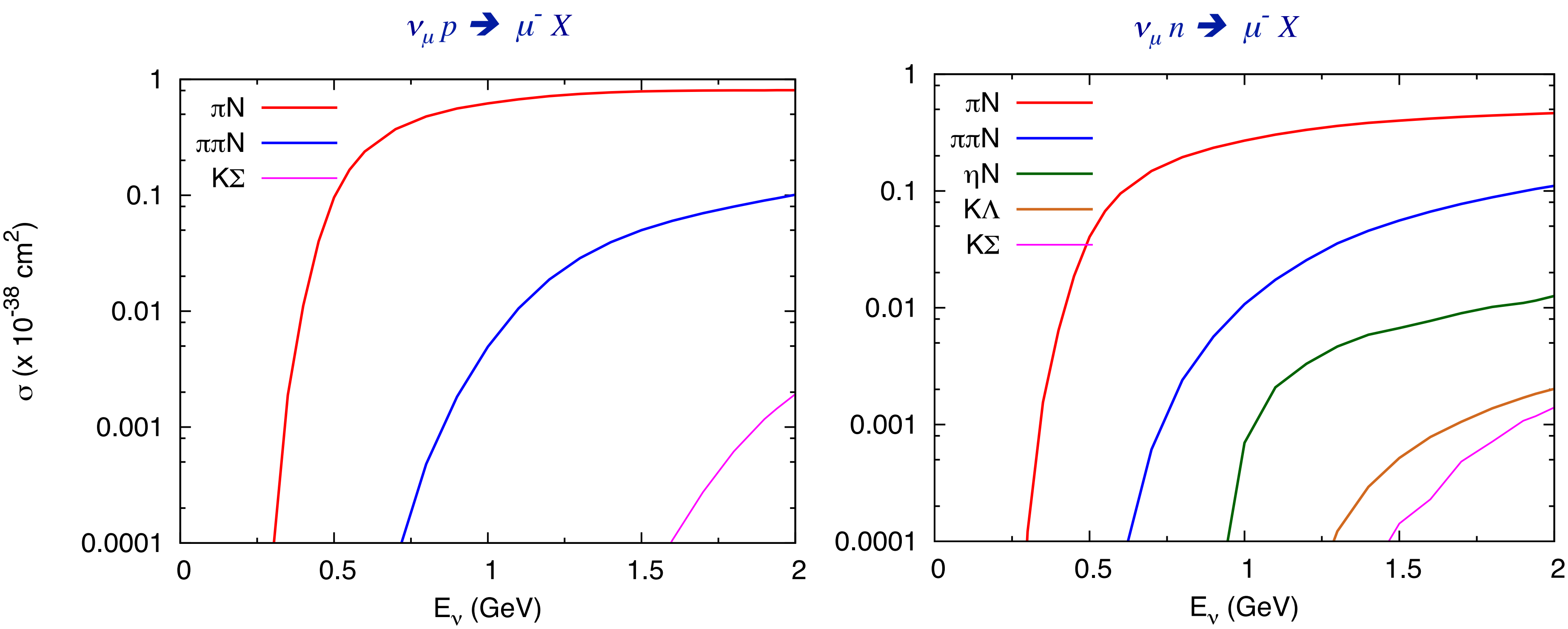
Neutrino Results

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

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



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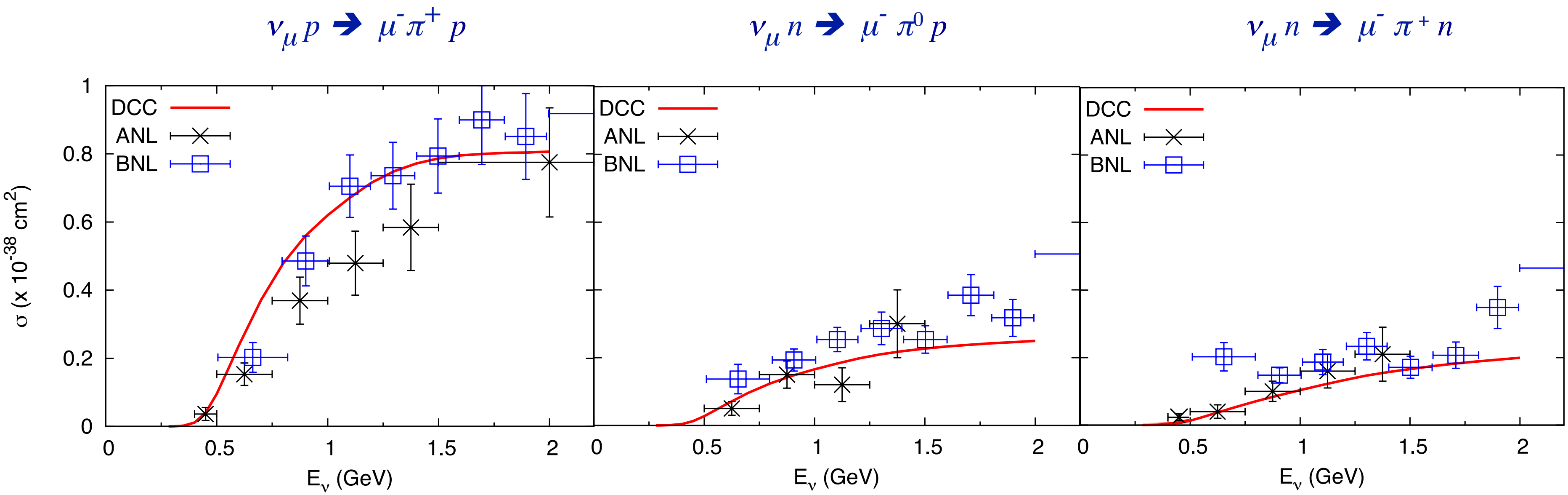
Comparison with single pion data



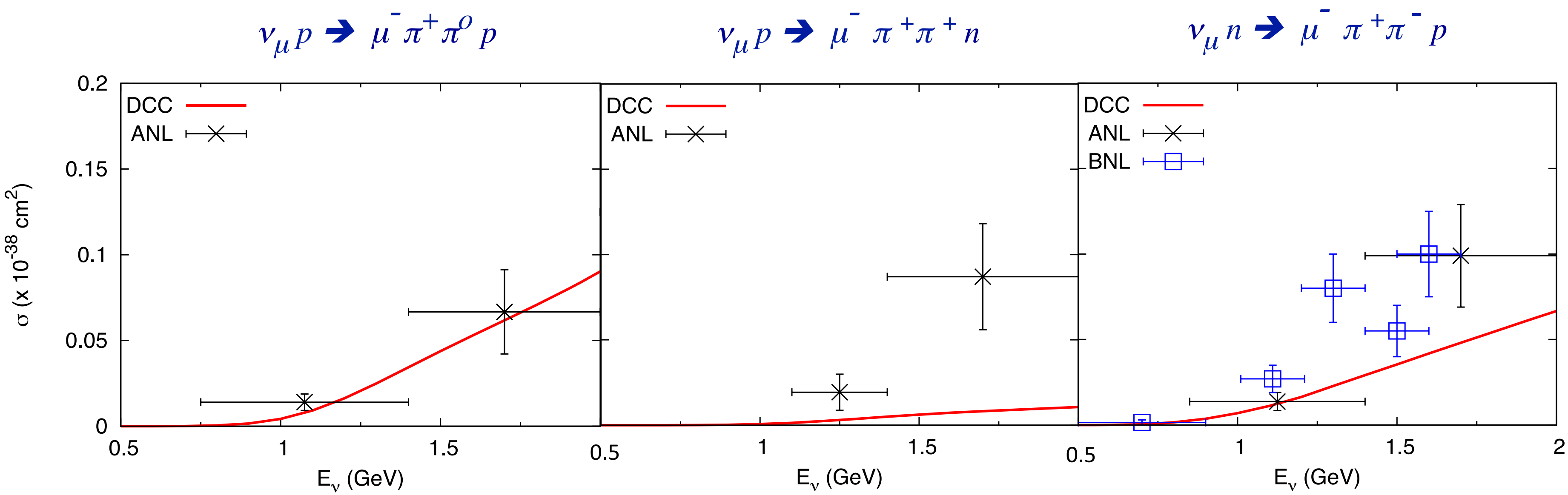
DCC model prediction is consistent with data

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. , arXiv:1412:2415)

Comparison with double pion data

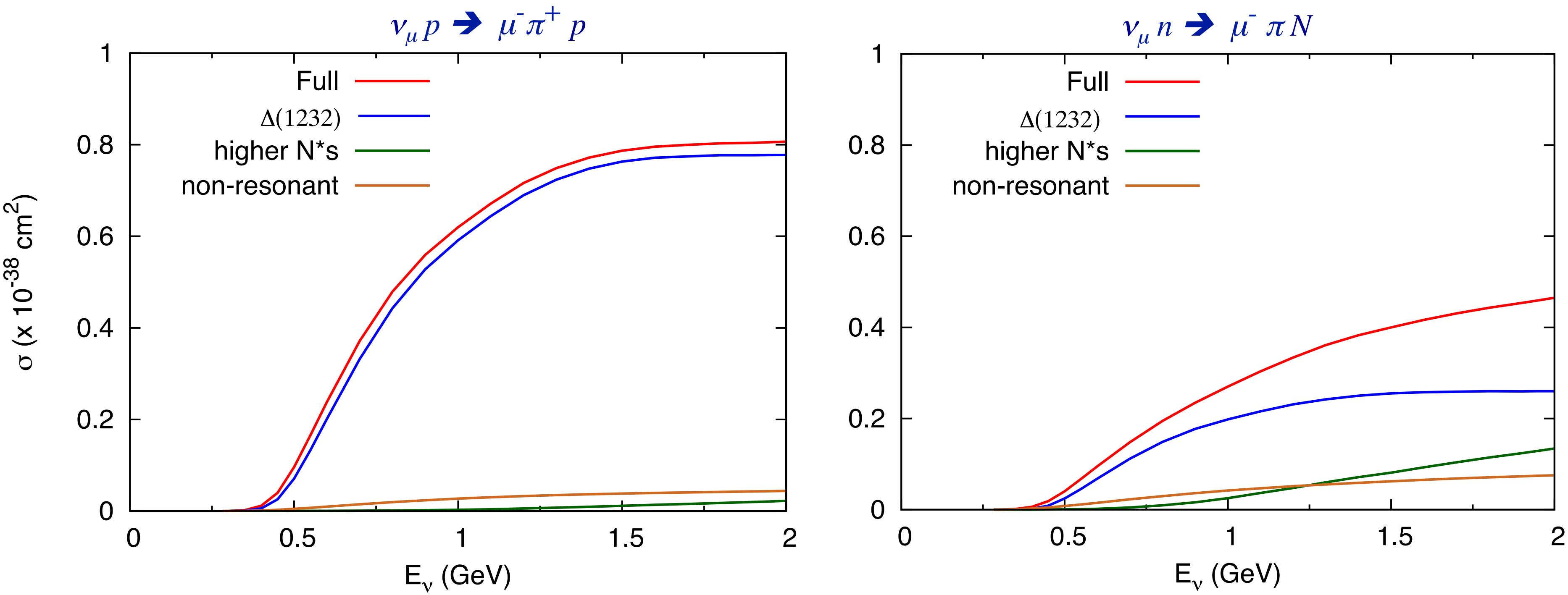


Fairly good DCC predication

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

First dynamical model for 2 π production in resonance region

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

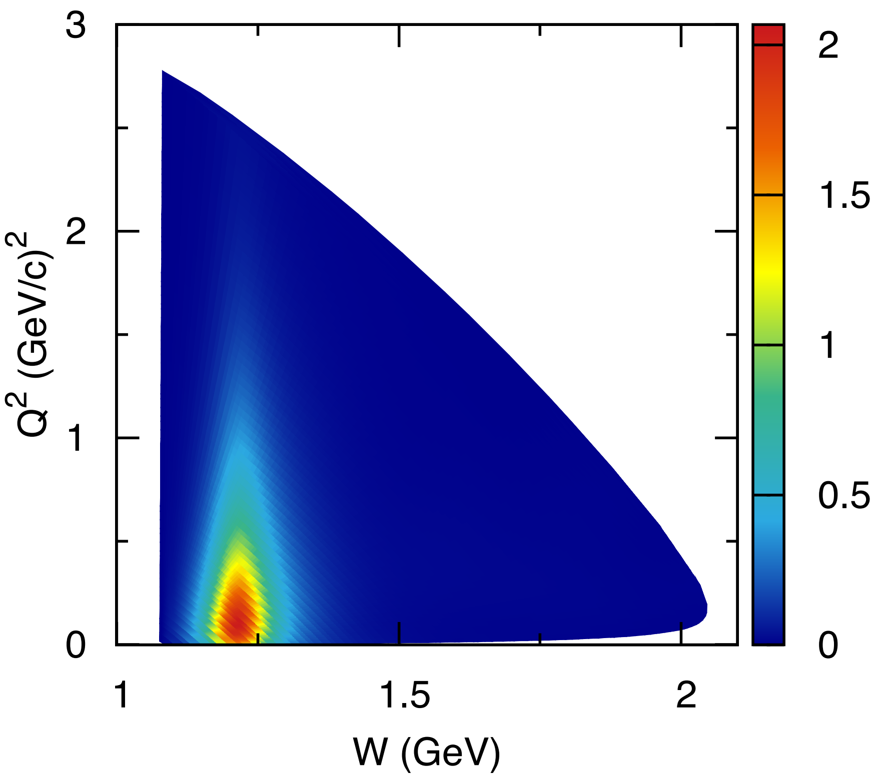


- Δ(1232) dominates for $\nu_\mu p \rightarrow \mu^- \pi^+ p$ $(I=3/2)$ for $E_\nu \leq 2$ GeV
- Non-resonant mechanisms contribute significantly
- Higher N^*s becomes important towards $E_\nu \approx 2$ GeV for $\nu_\mu n \rightarrow \mu^- \pi N$

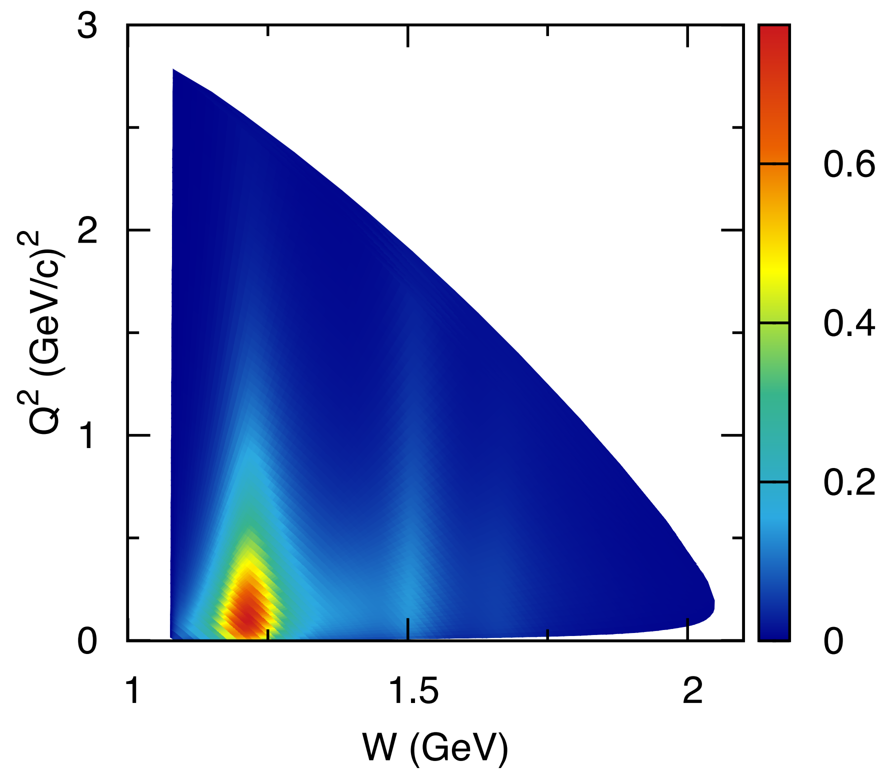
$d\sigma / dW\, dQ^2$ ($\times 10^{-38}$ cm^2 / GeV^2)

E_ν = 2 GeV

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



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



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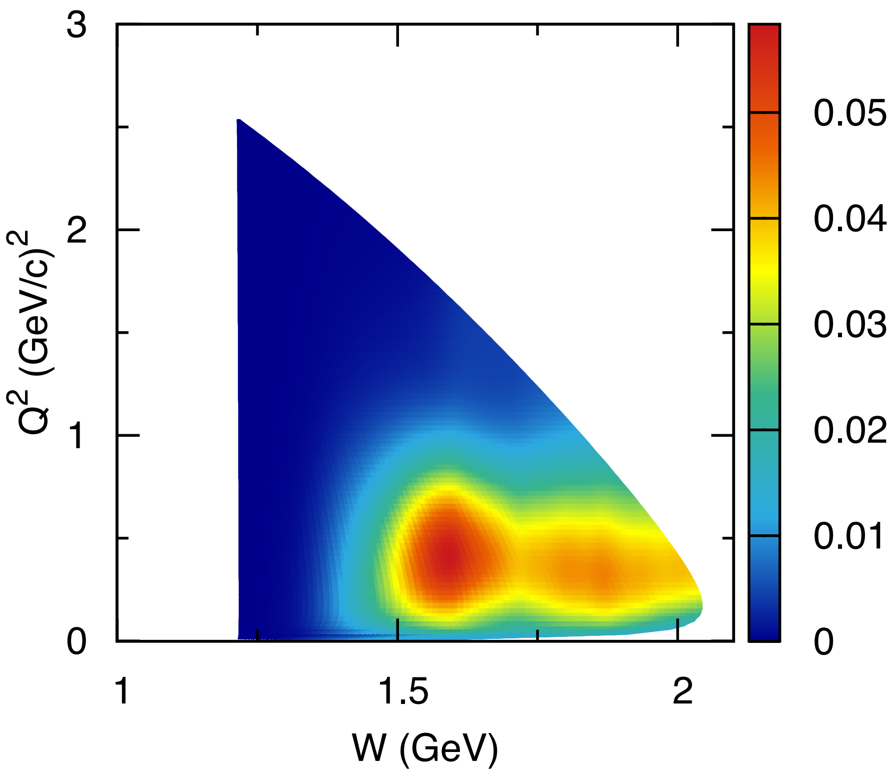
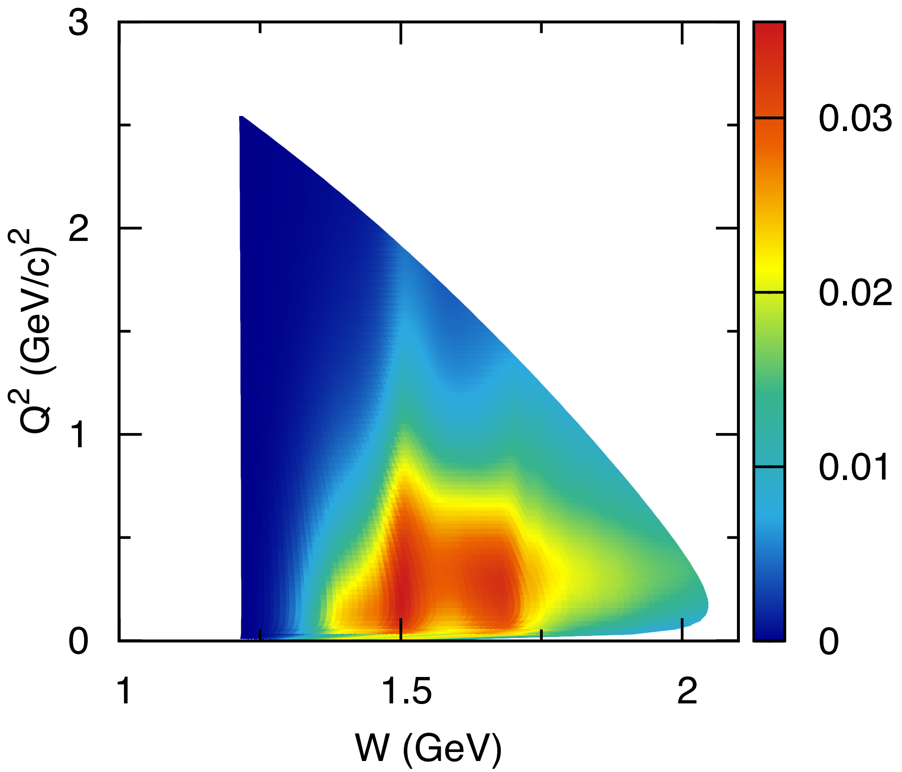


$\nu_\mu n \rightarrow \mu^- \pi^+ \pi^- p$



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

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

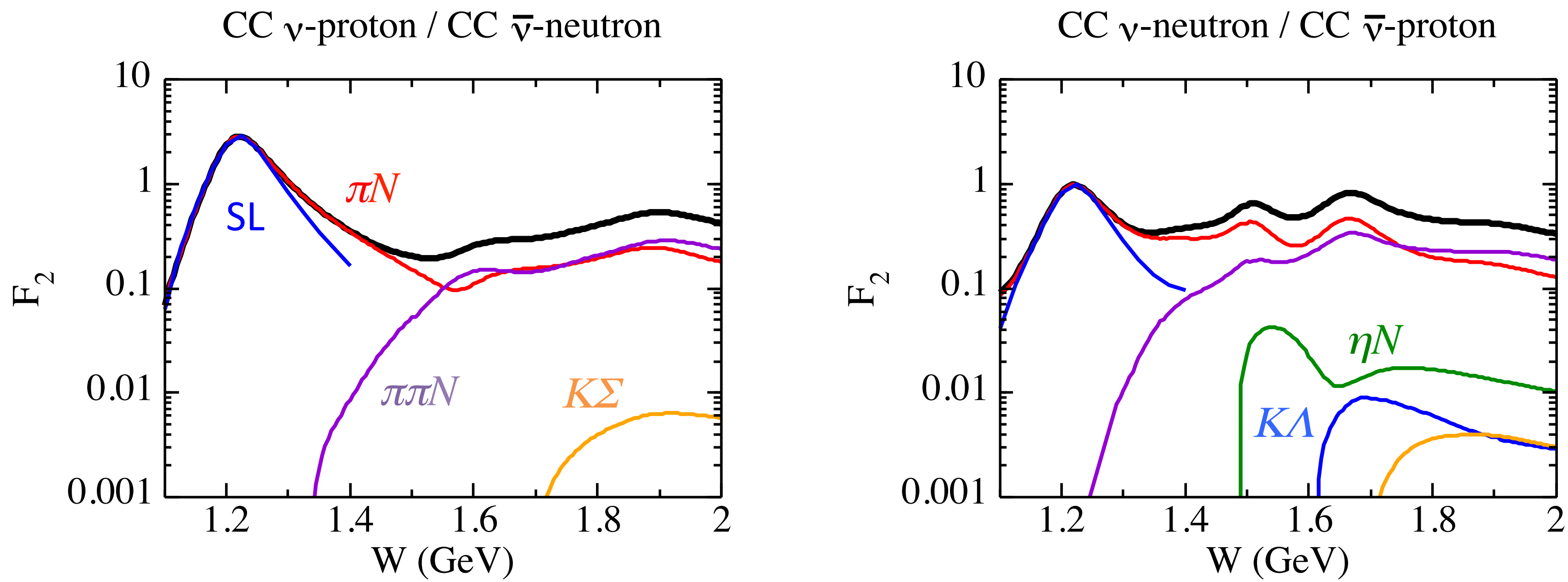
$$\langle X|\hat{\pi}|N\rangle = \frac{\sqrt{2\omega_c}}{m_\pi^2} \mathcal{T}_{\pi N \to X}(0) \sim \frac{\sqrt{2\omega_c}}{m_\pi^2} \mathcal{T}_{\pi N \to X}(m_\pi^2)$$

Finally

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

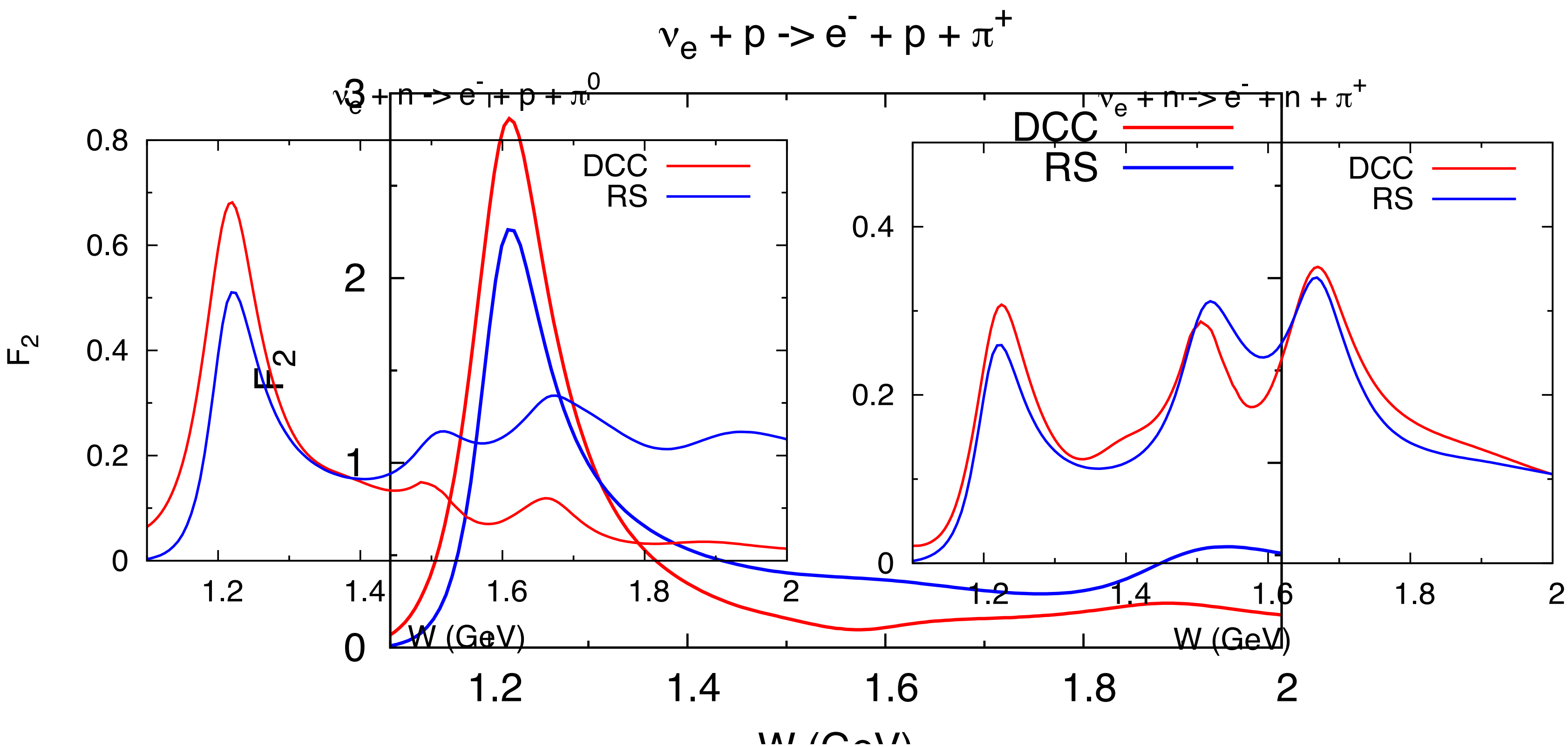
$\sigma_{\pi N \rightarrow X}$ is from our DCC model

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

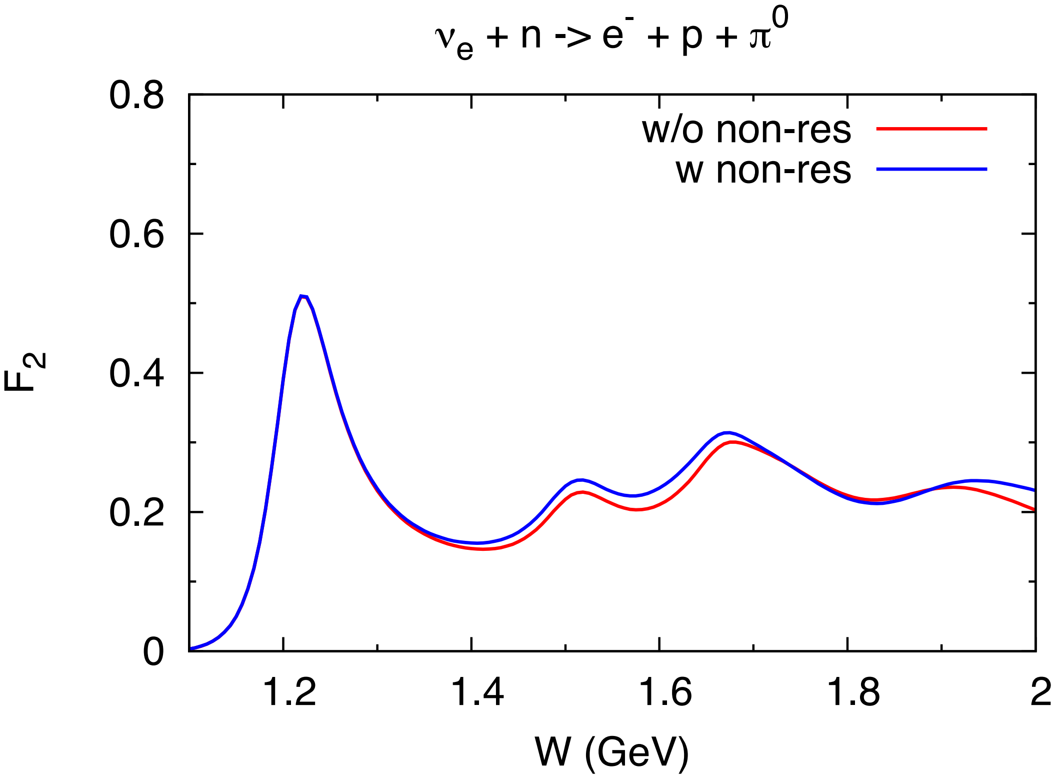
Comparison with Rein-Sehgal model



Comparison in whole kinematical region will be done

after axial current model is developed

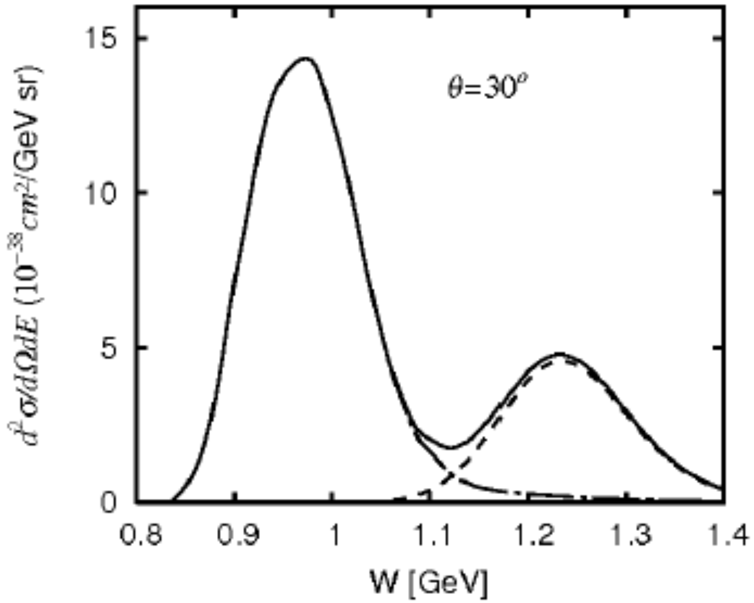
F_2 from RS model



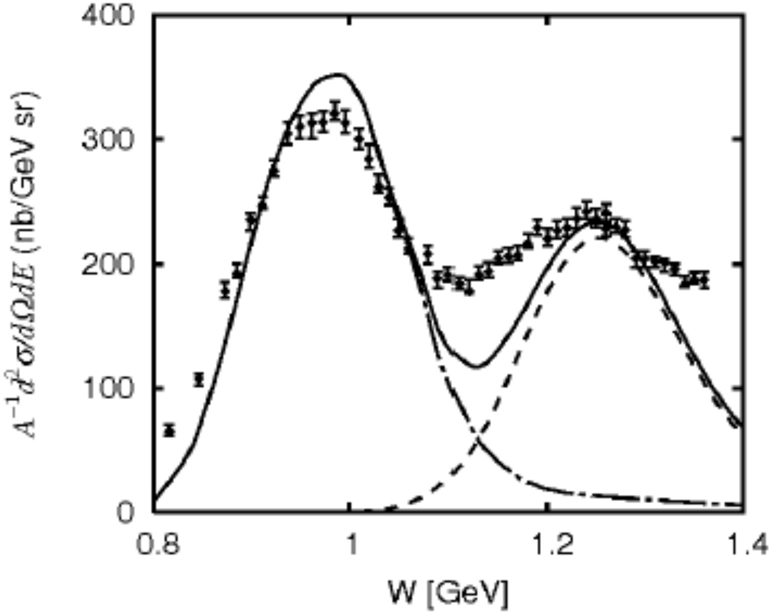
SL model applied to ν−nucleus scattering

1 π production

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



$e^- + {}^{12}\mathrm{C} \to e^- + X \; (E_e = 1.1 \text{ GeV})$

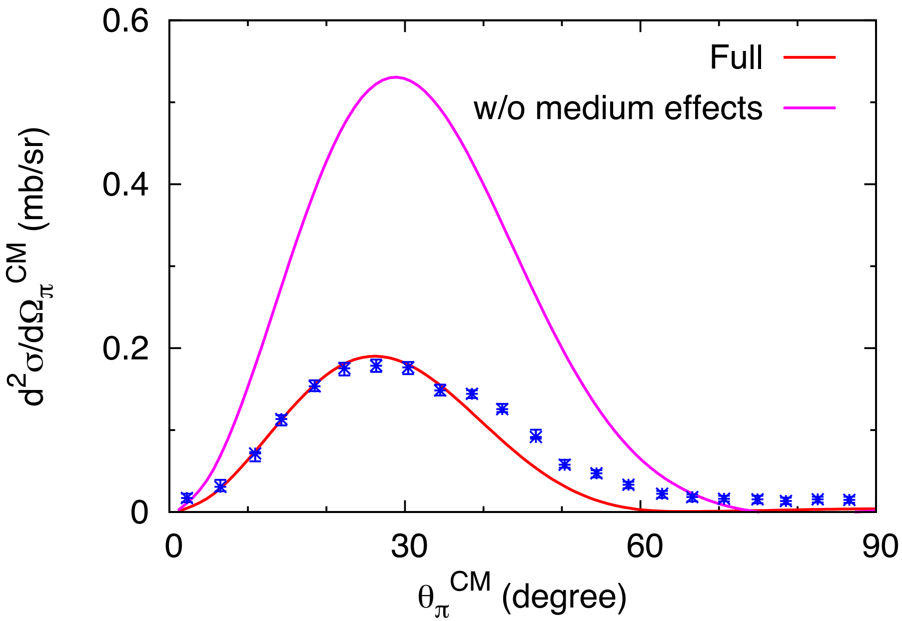


Szczerbinska et al. (2007)

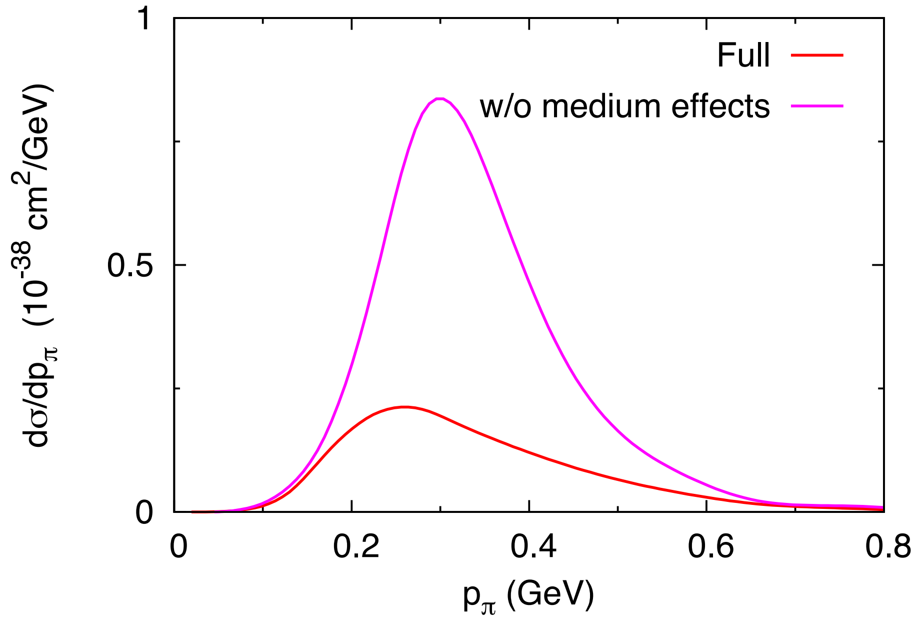
SL model applied to ν−nucleus scattering

coherent π production

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



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



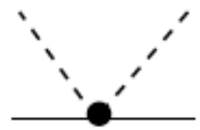
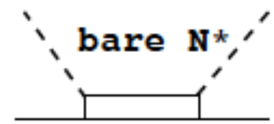
Nakamura et al. (2010)

DCC (Dynamical Coupled-Channel) model

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

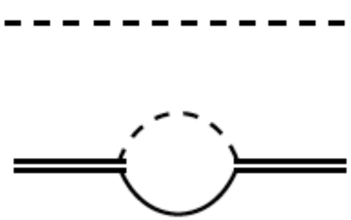
Coupled-channel Lippmann-Schwinger equation

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

V ab =  + 

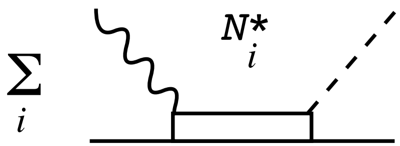
+ **Z**

Gc = for stable channels

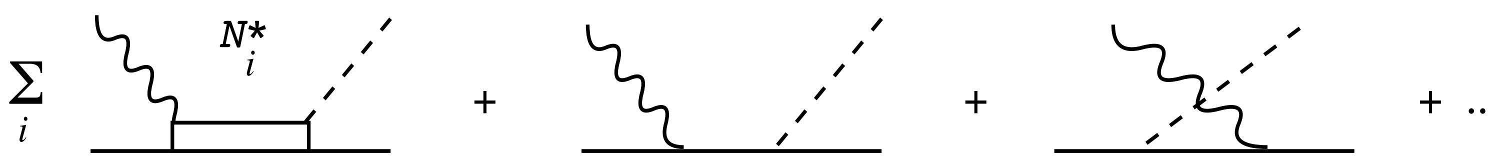
 for unstable channels

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

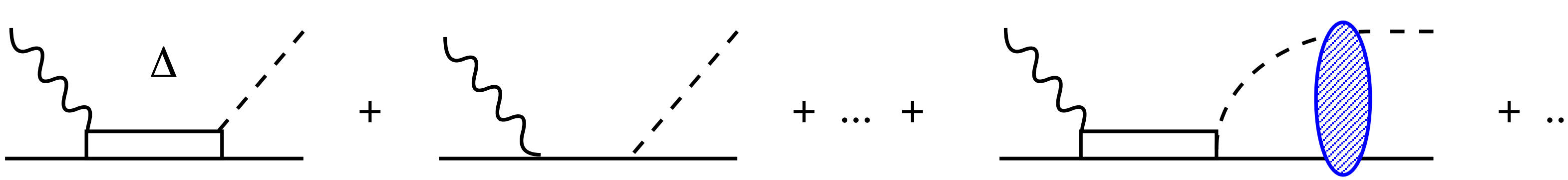
resonant only — Rein et al. (1981), (1987) ; Lalalulich et al. (2005), (2006)



+ non-resonant (tree-level) — Hernandez et al. (2007), (2010) ; Lalakulich et al. (2010)

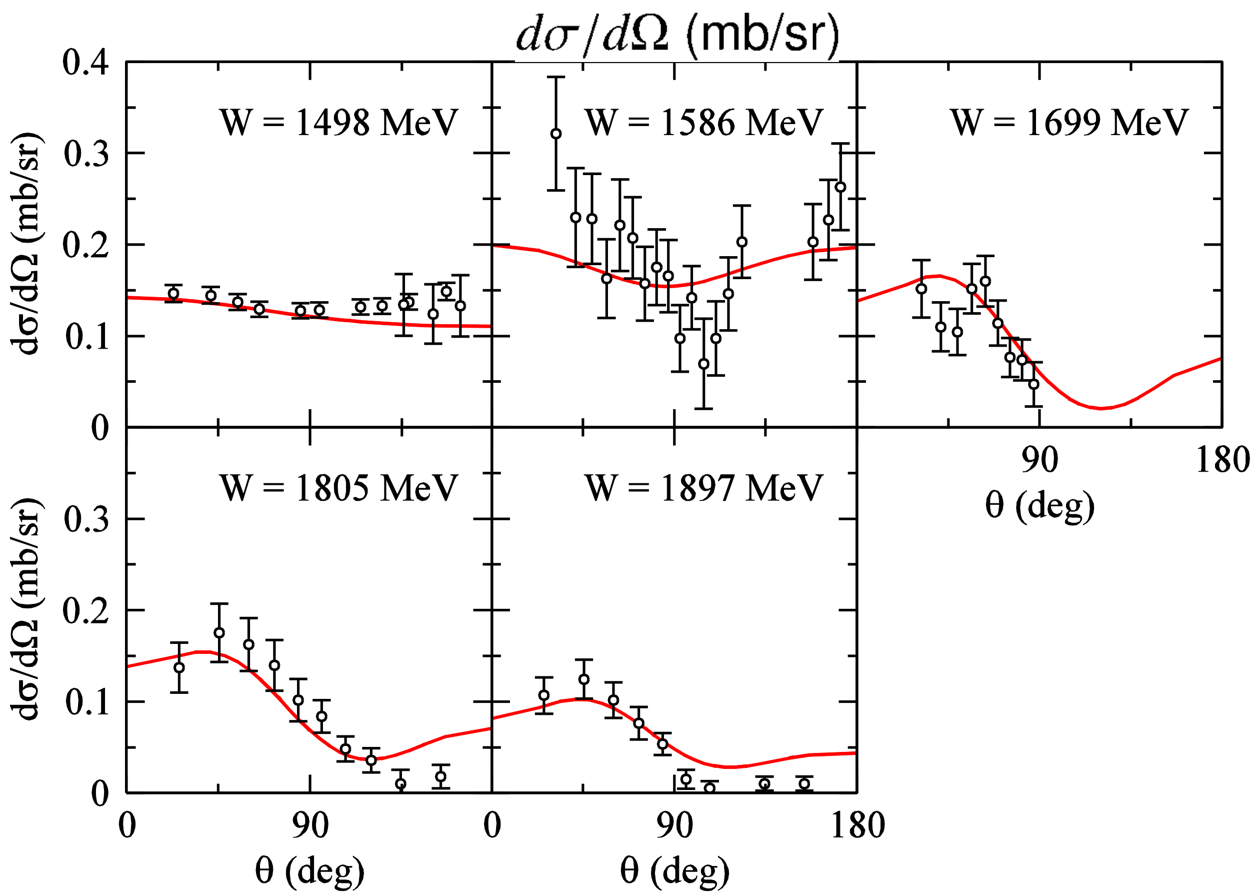


+ rescattering (πN unitarity) — Sato, Lee (2003), (2005)

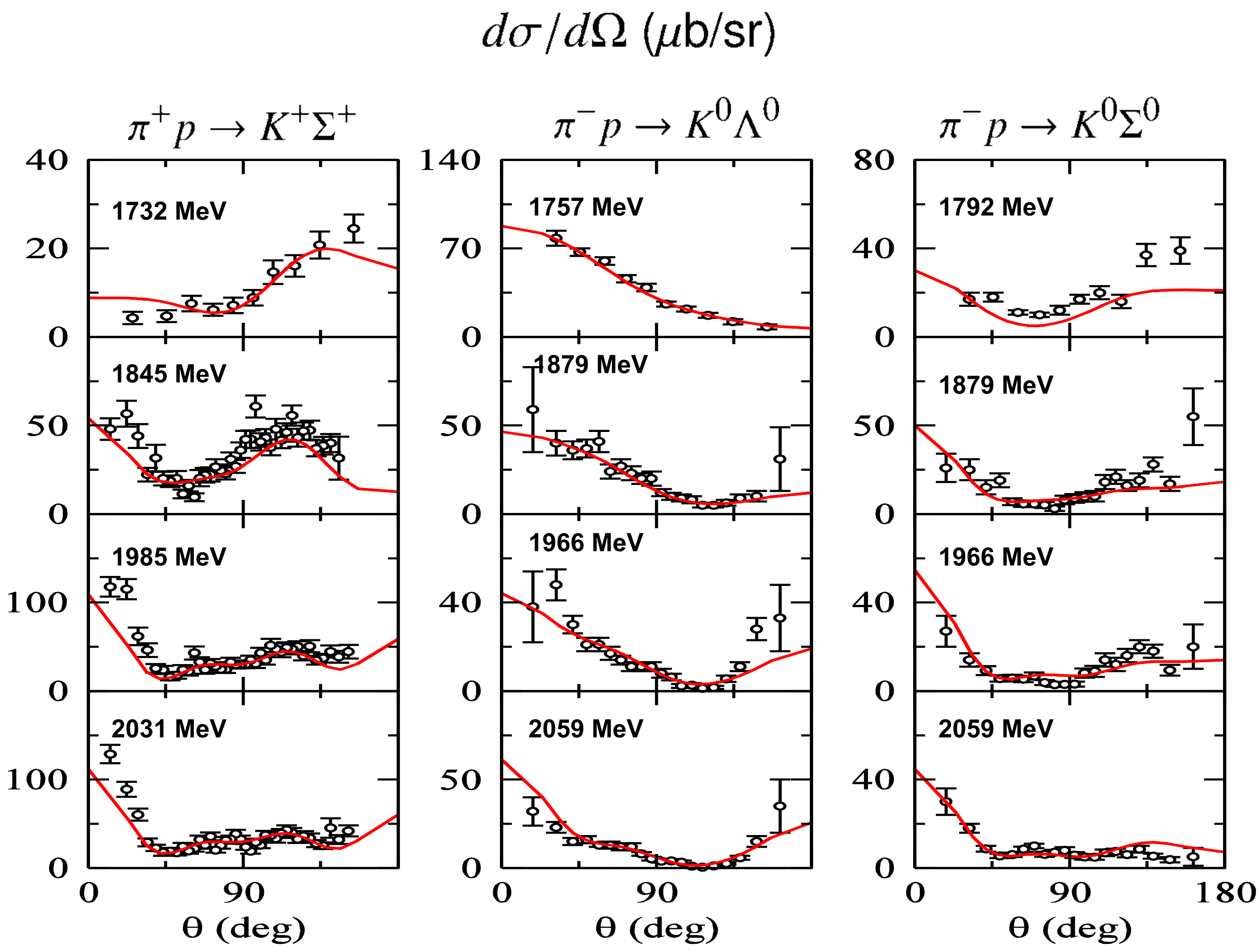


Eta production reactions

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



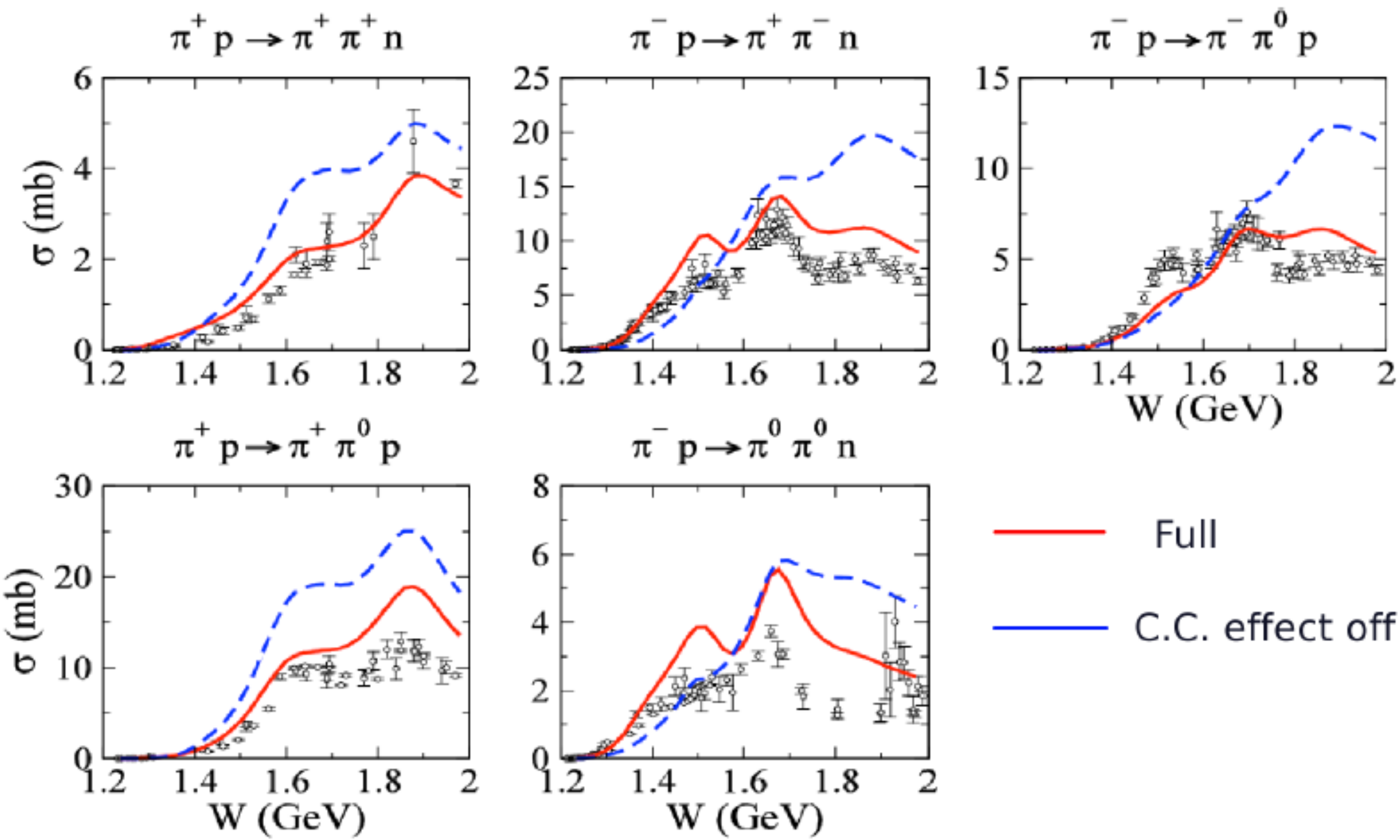
KY production reactions



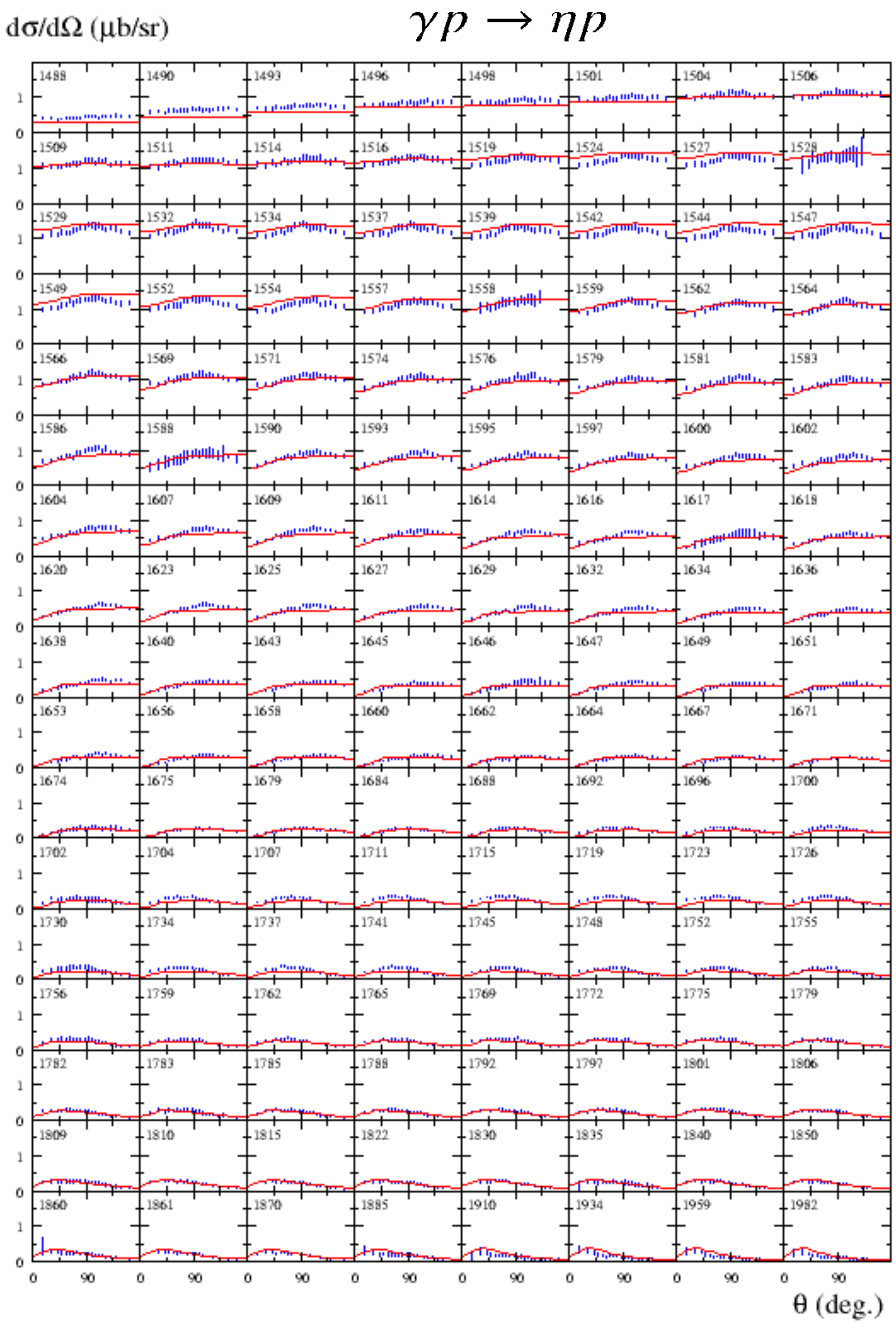
$\pi N \rightarrow \pi\pi N$

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

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



Kamano, Nakamura, Lee, Sato, arXiv:1305.4351

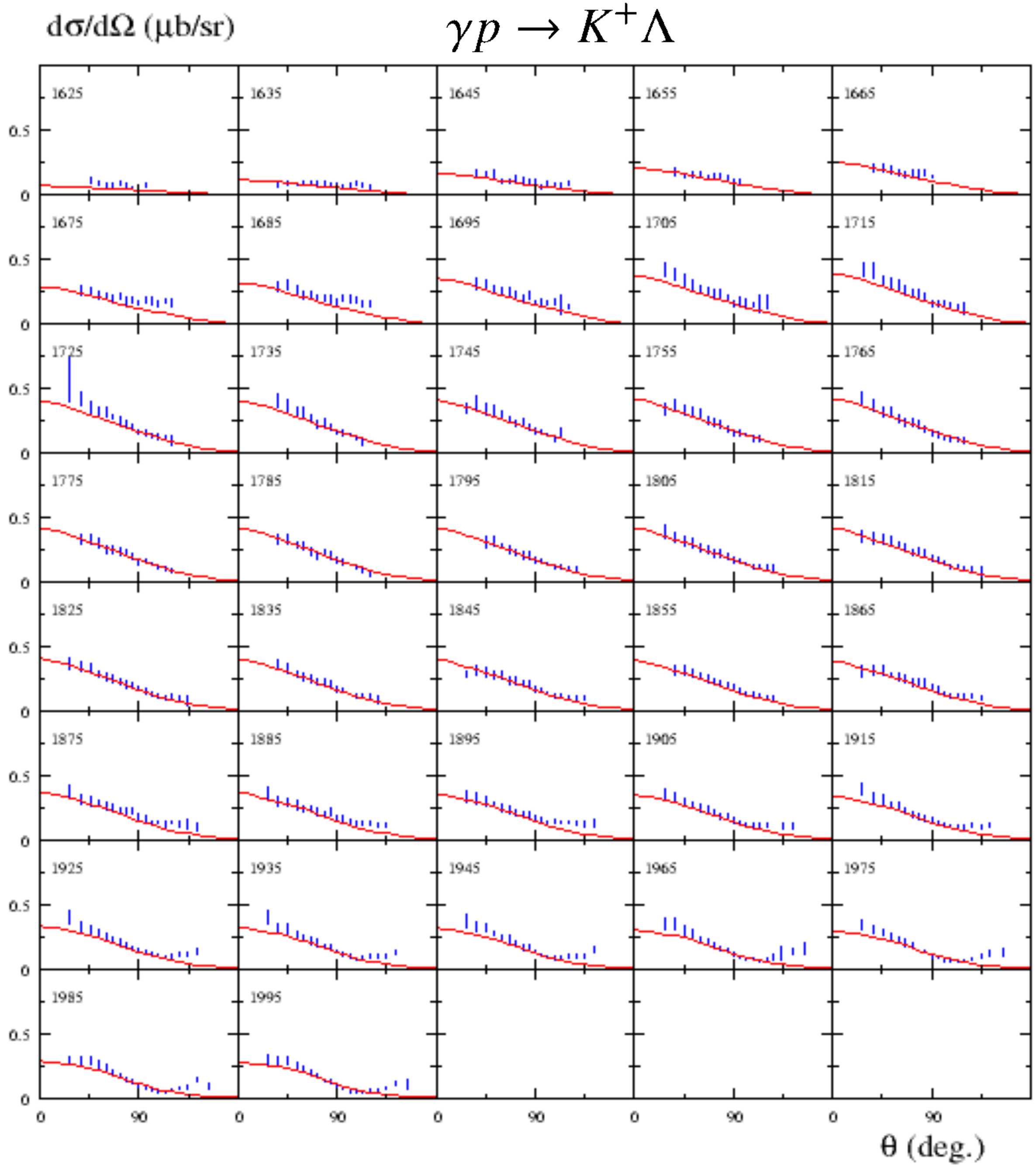


Vector current (Q^2=0) for η

Production is well-tested by data

Kamano, Nakamura, Lee, Sato, arXiv:1305.4351

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



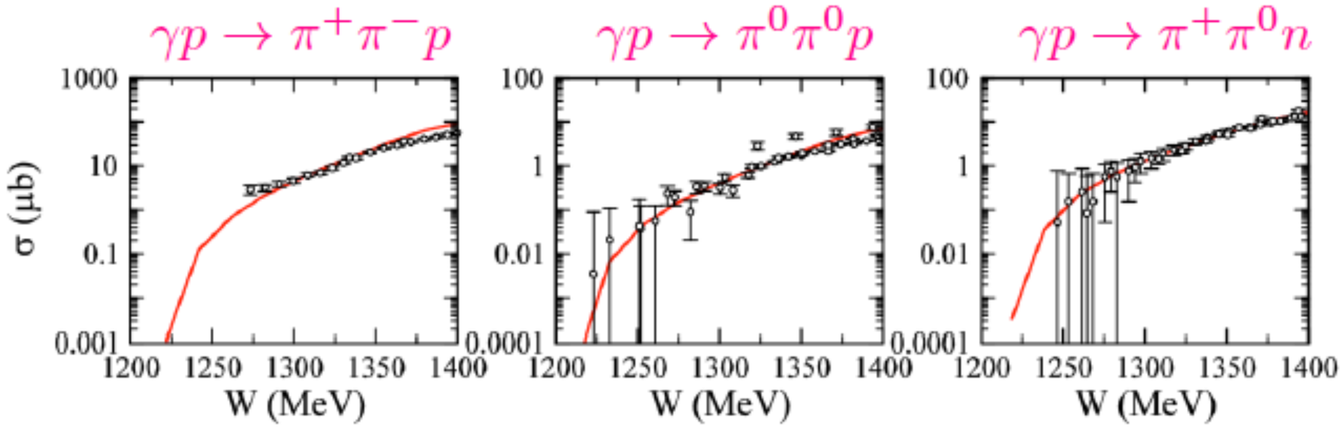
Vector current (Q^2=0) for K

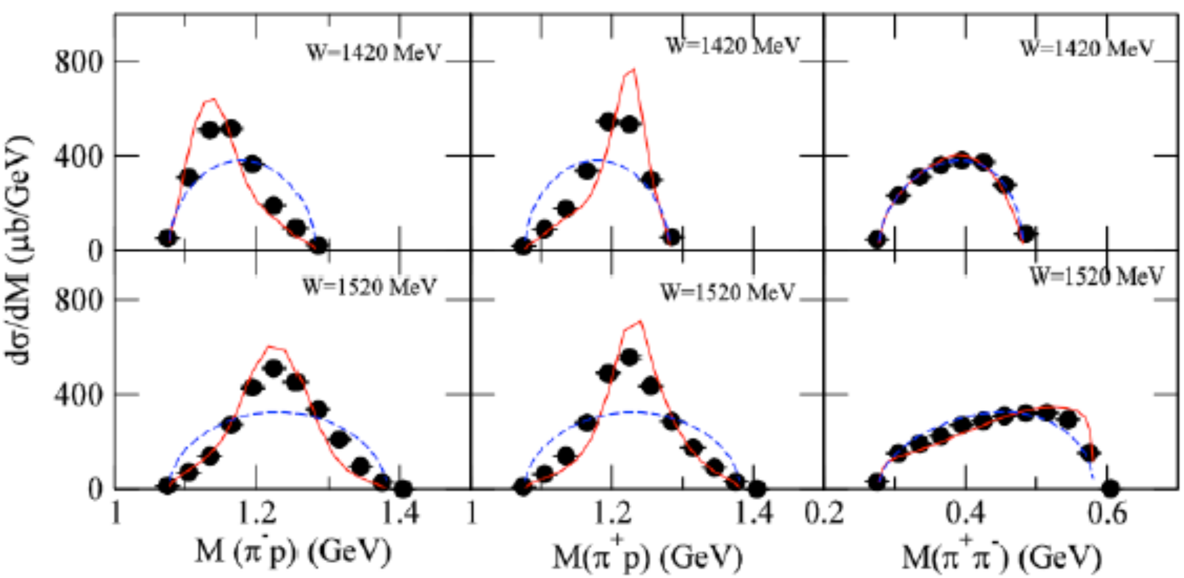
Production is well-tested by data

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

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

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



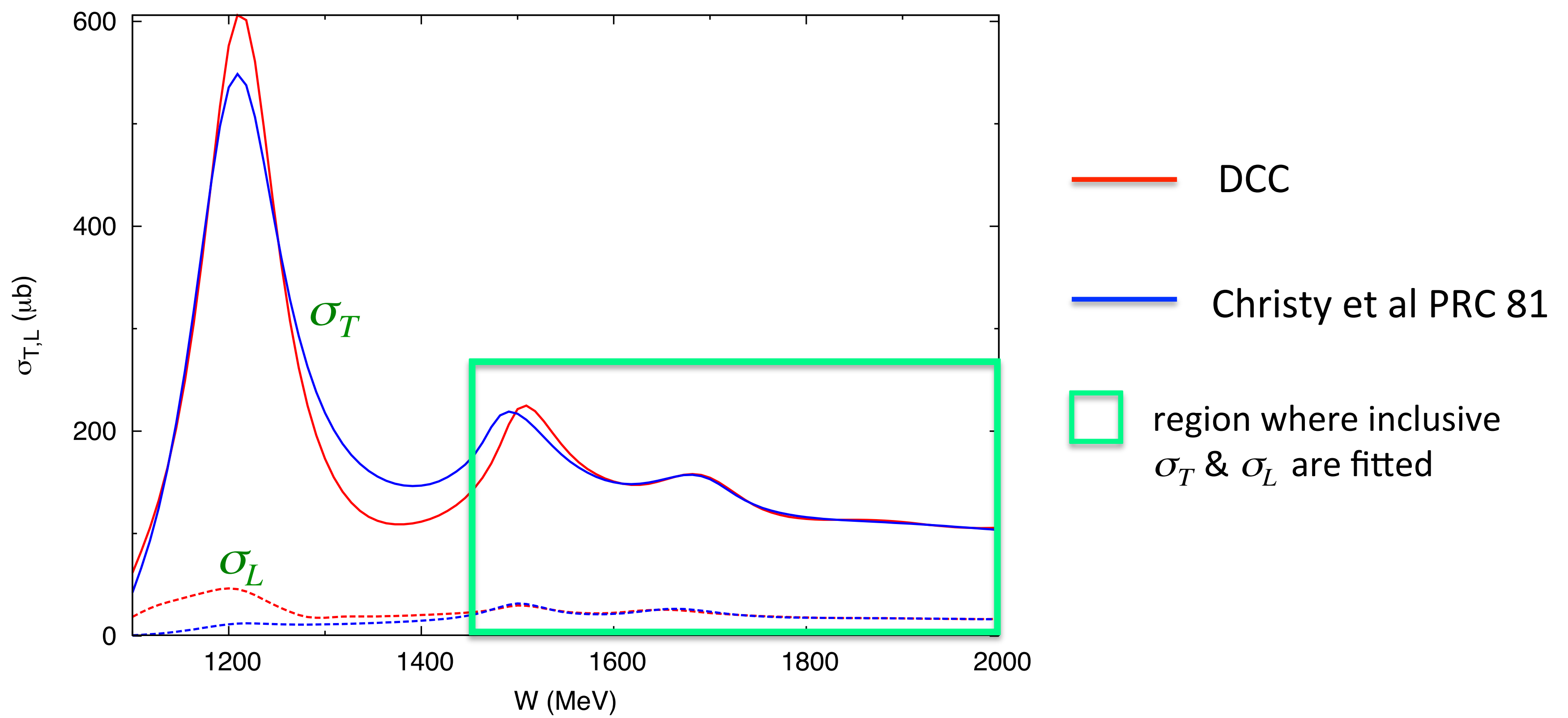


* Good description near threshold
* Good shape of invariant mass distribution
* Total cross sections overestimate data for $W \geq 1.5$ GeV

Analysis result

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

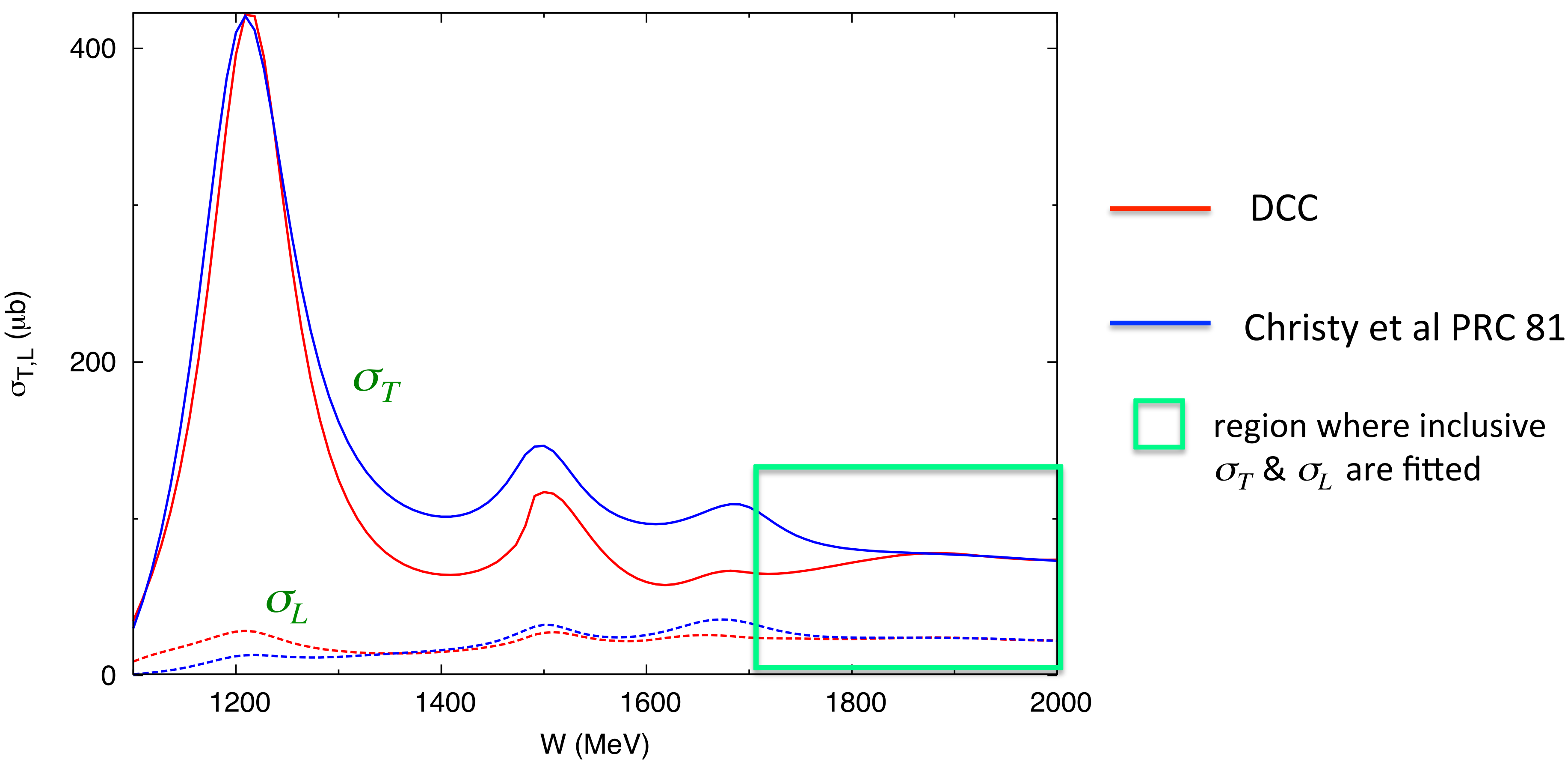
σ_T & σ_L (inclusive inelastic)



Analysis result

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

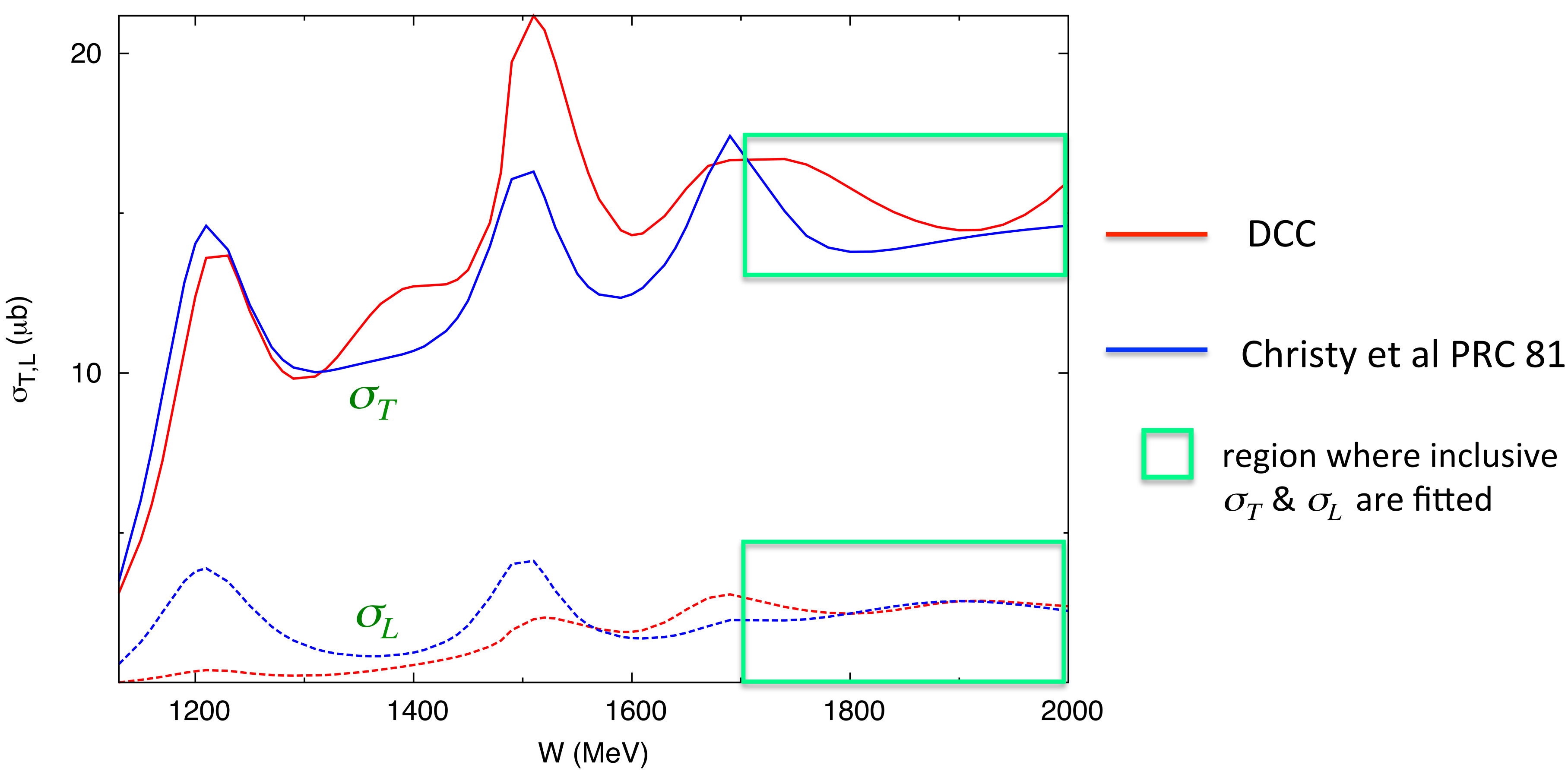
σ_T & σ_L (inclusive inelastic)



Analysis result

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

σ_T & σ_L (inclusive inelastic)



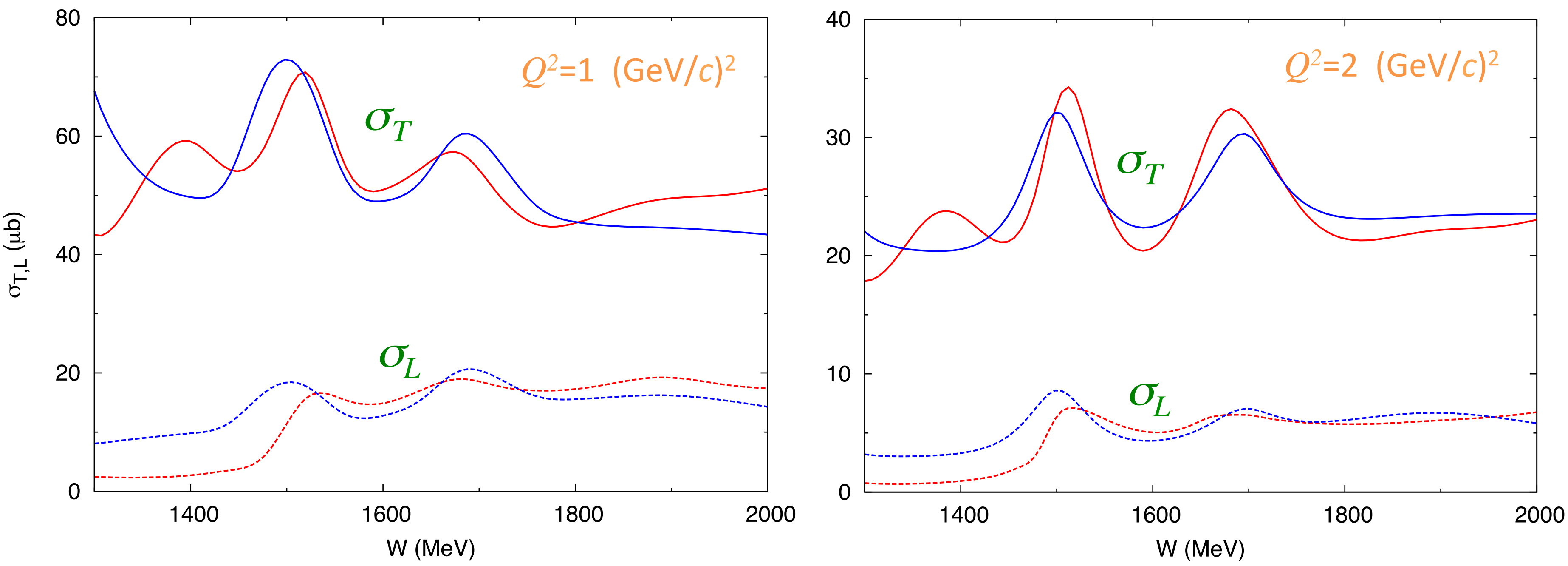
Analysis result (inclusive)

$Q^2 \neq 0$

σ_T & σ_L (inclusive inelastic e^--'n')

DCC

Christy and Bosted PRC 77; 81

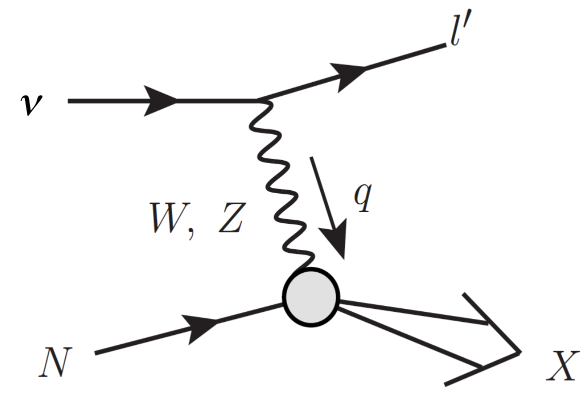


DCC model for neutrino interaction

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

at forward limit $Q^2=0$

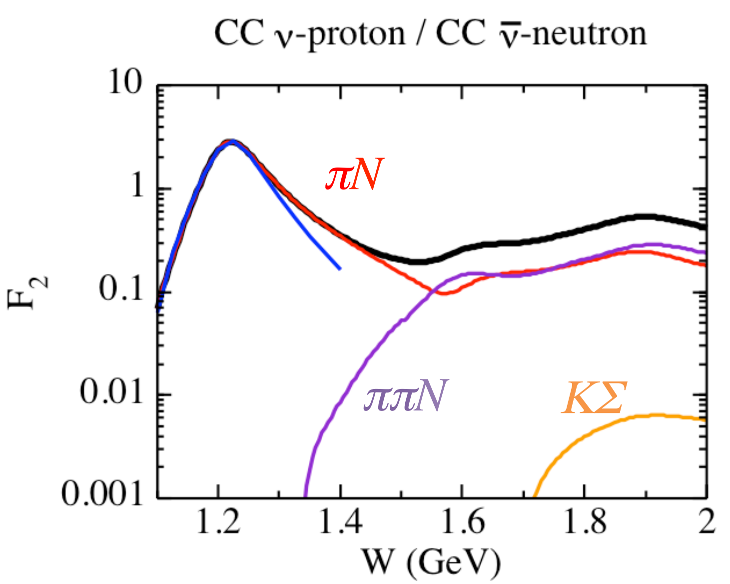
Kamano, Nakamura, Lee, Sato, PRD 86 (2012)



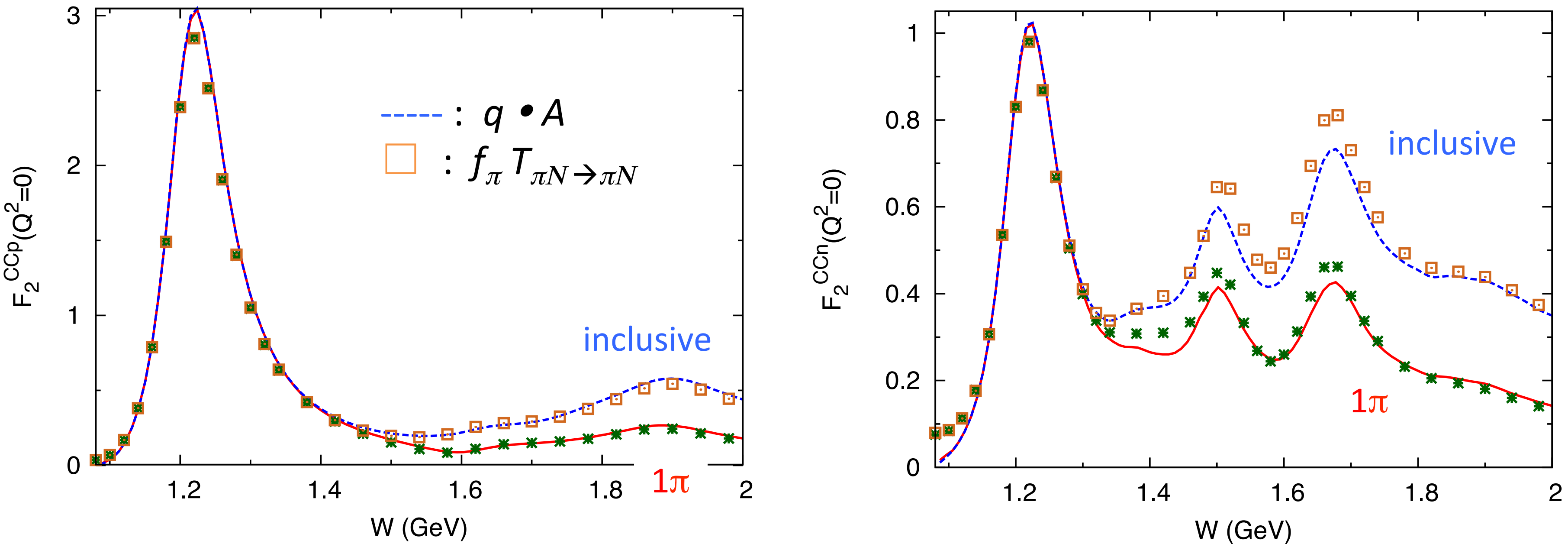
$$\frac{d\sigma}{dE_\ell d\Omega_\ell} = \frac{G_F^2}{2\pi^2} E_\ell^2\, W_2$$

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

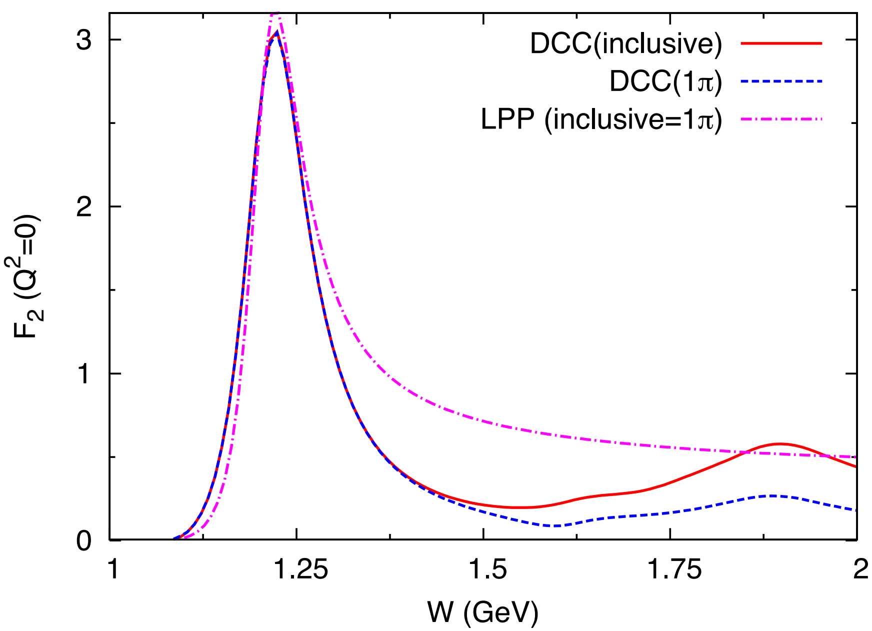


DCC model keeps good consistency with PCAC

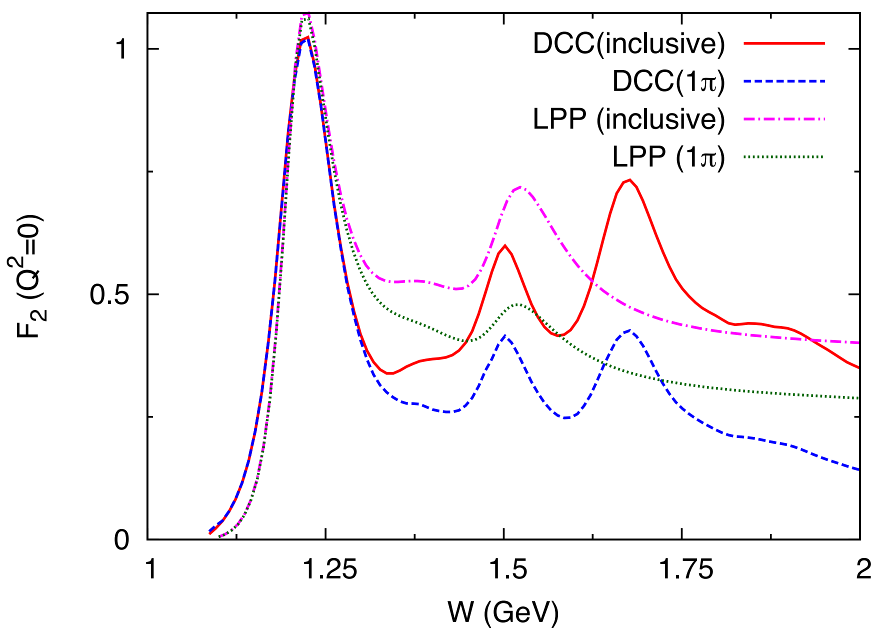
Comparison with LPP model

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

CCνp



CCνn



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

Future development

- Axial form factor

  more neutrino data is ideal

  $\pi N \rightarrow \rho N$ (t-ch π) (maybe possible at J-PARC)

- $\pi\pi N$ channel

  $\pi N \rightarrow \pi\pi N$ experiment (J-PARC, K. Hicks et al.)

  $\gamma N \rightarrow \pi\pi N$ experiment (ELPH, JLab)

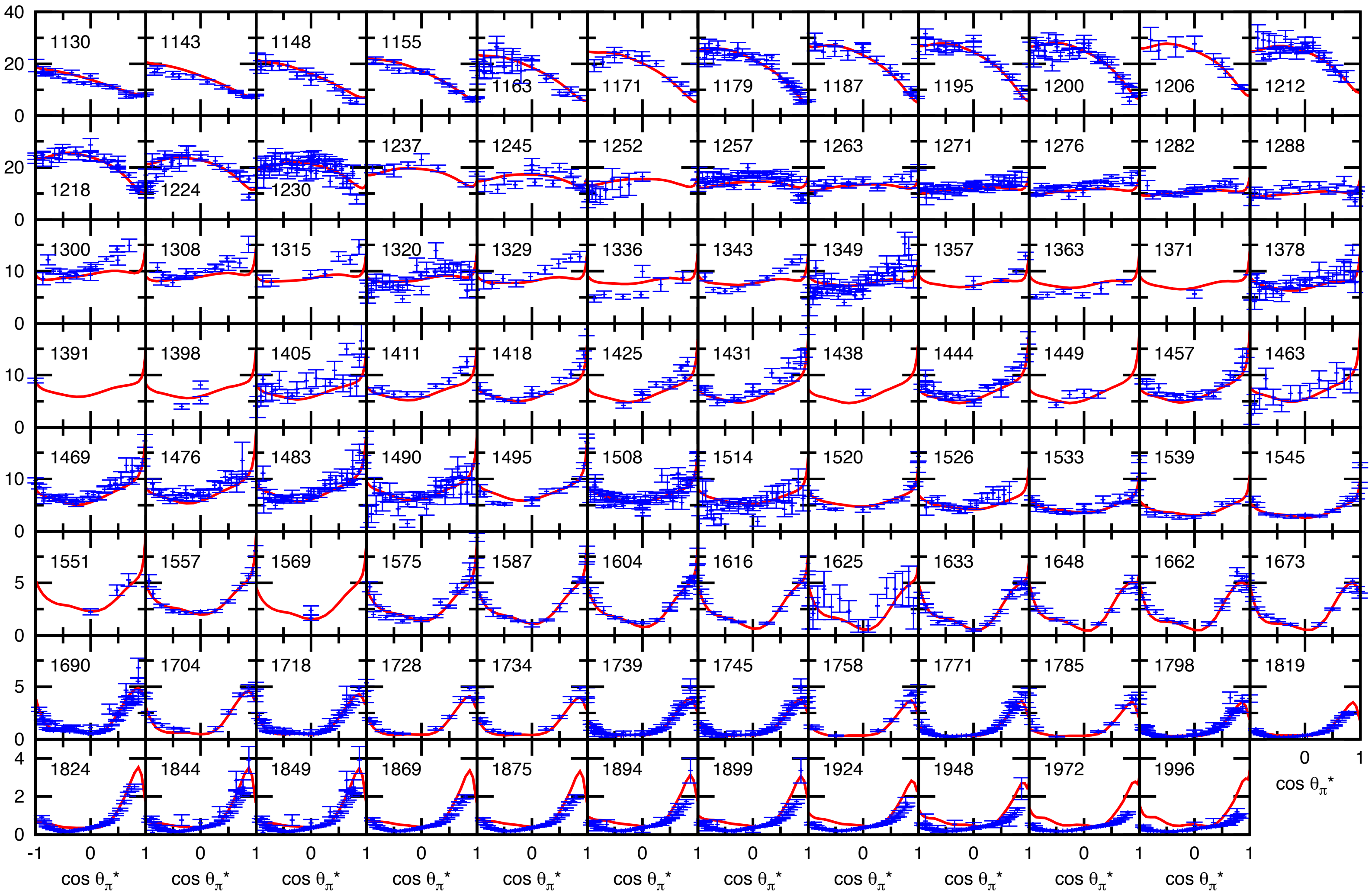
- Nuclear models

  deuteron model , Δ-hole type model

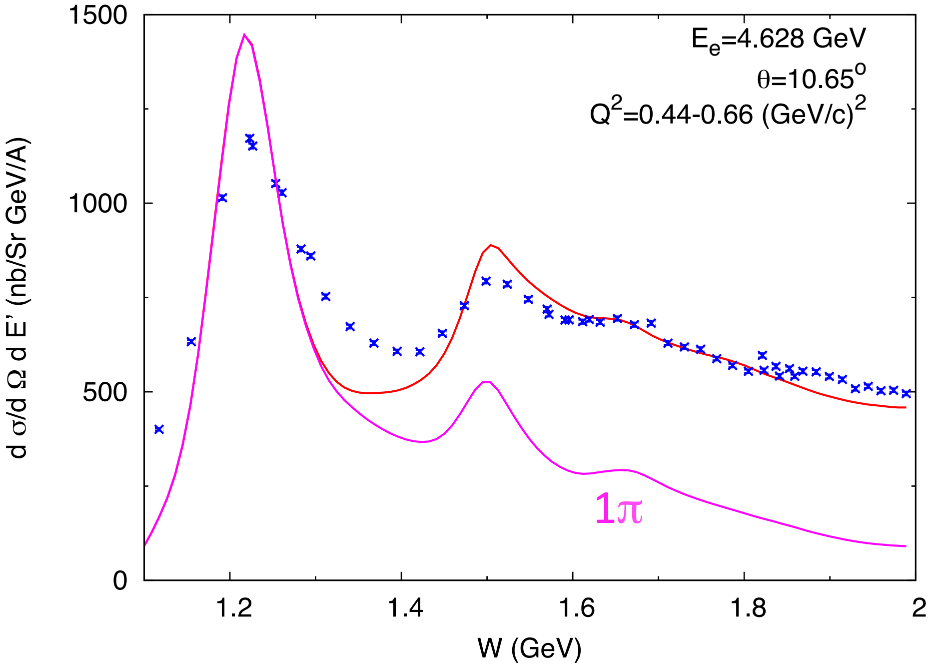
Analysis result (single π)

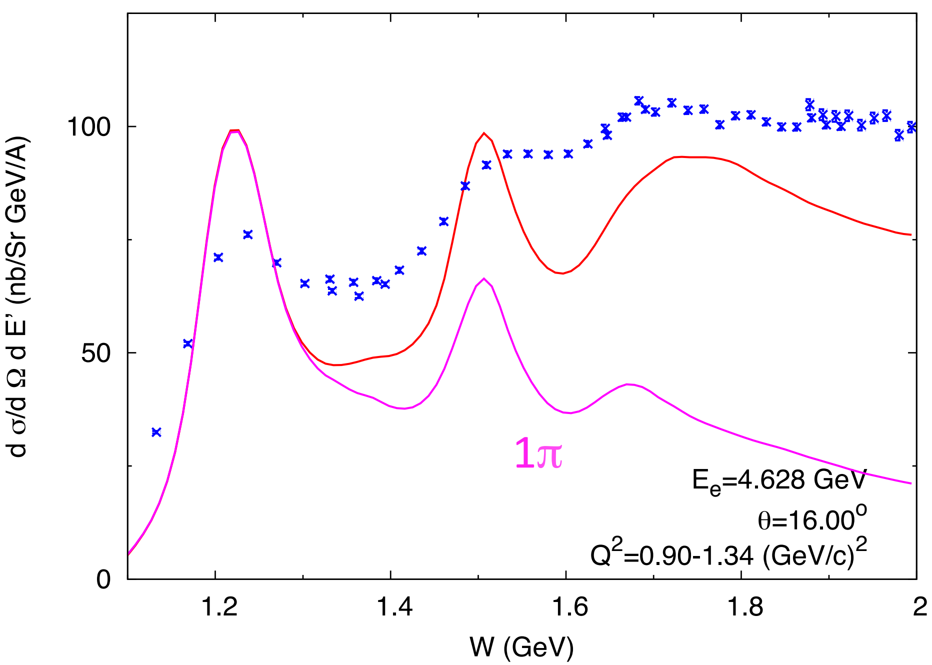
Q^2=0

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

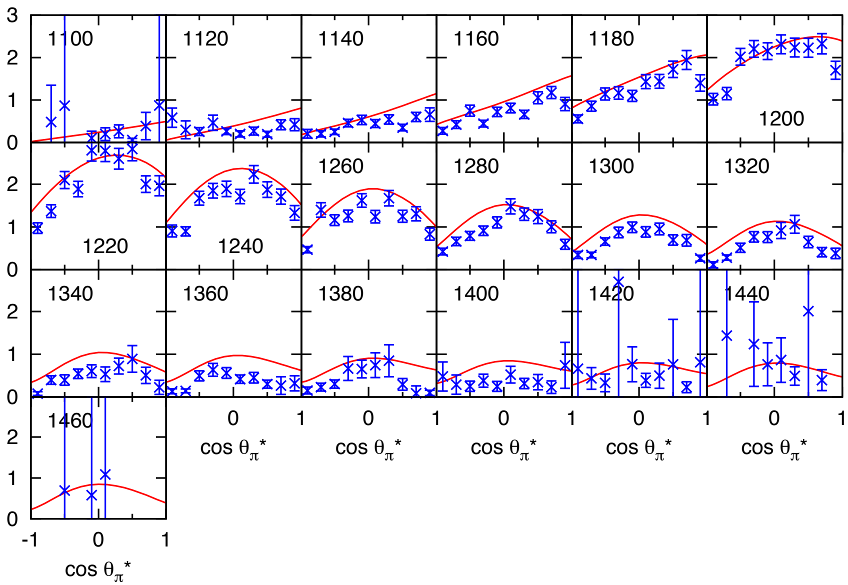
relevant to neutrino interactions of $E_\nu \leq 2$ *GeV*

Analysis result (single π)

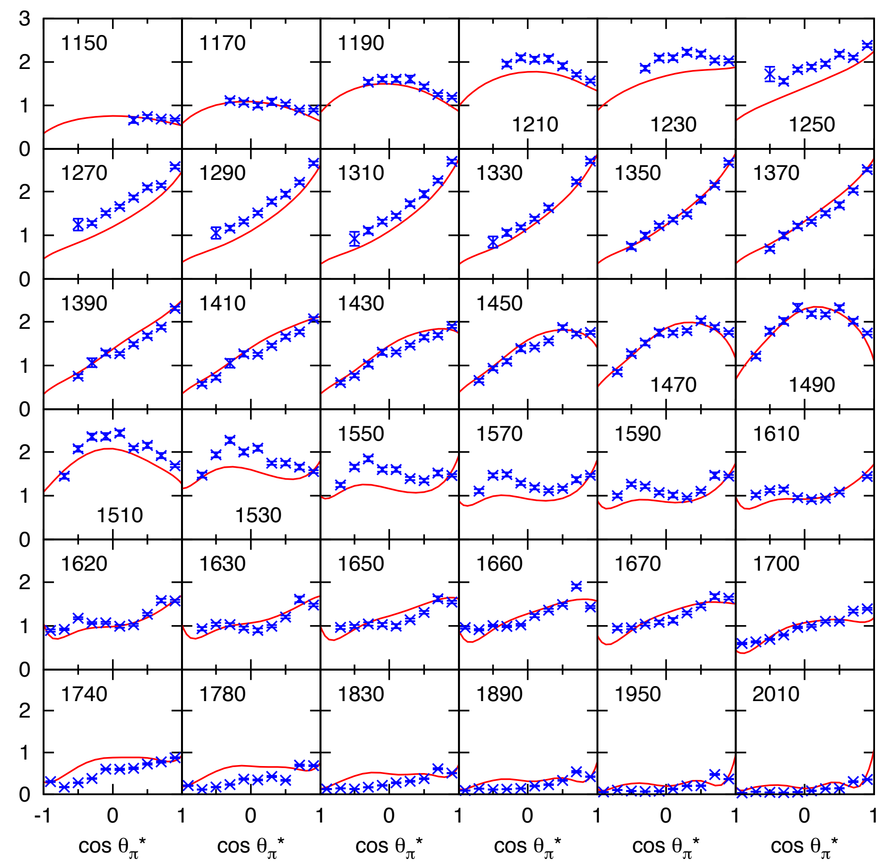
Q^2=1.76 (GeV/c)^2

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

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



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

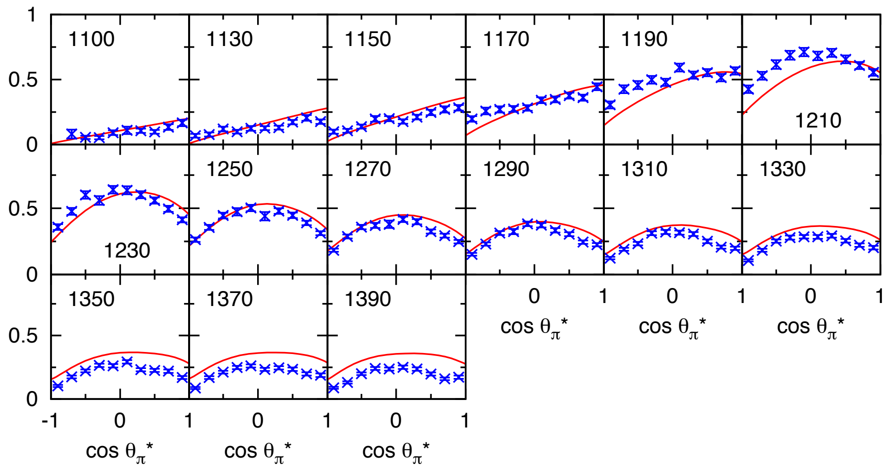


Analysis result (single π)

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

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

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



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