Neutrino-interactions in resonance region

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Introduction

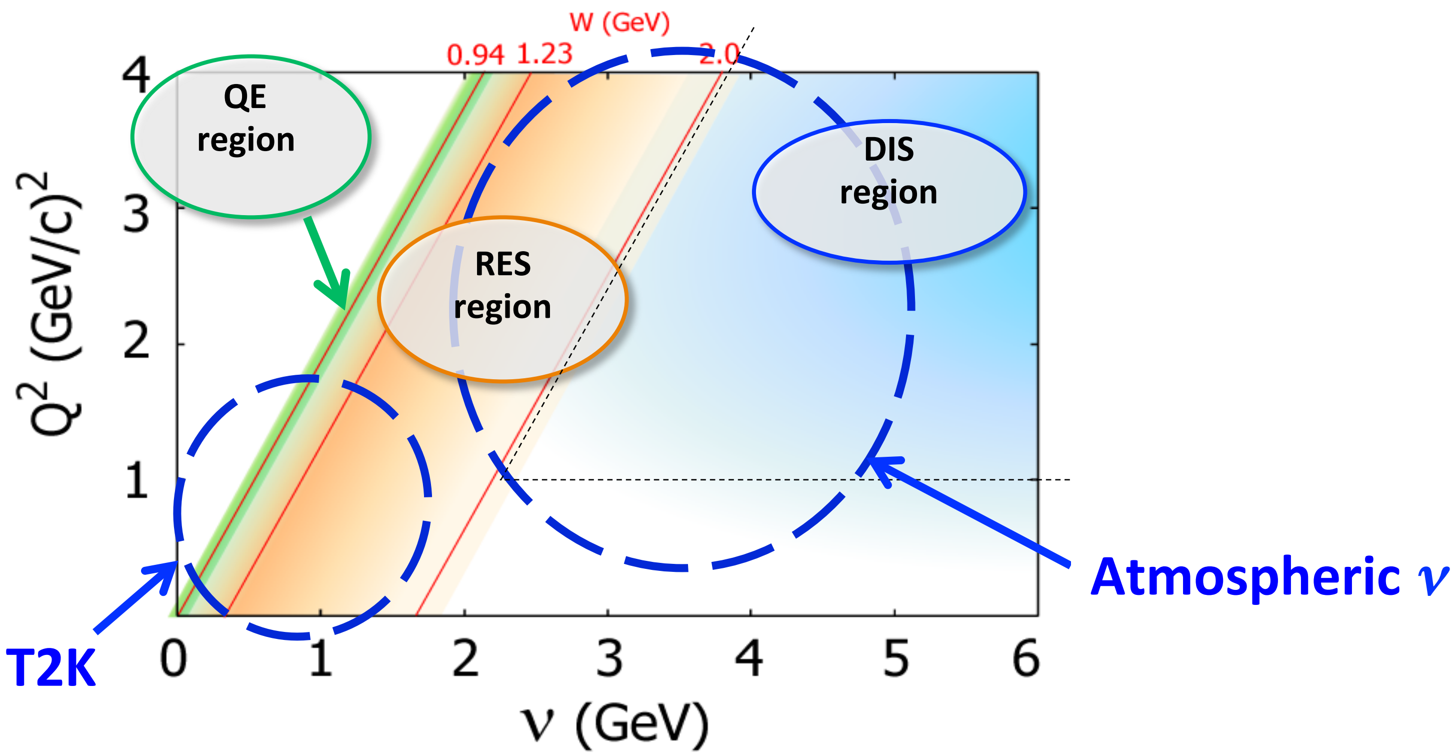
Neutrino-nucleus scattering for ν-oscillation experiments

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

$\nu-$nucleus scattering needs to be understood more precisely

Neutrino-nucleus scattering for ν-oscillation experiments

Next-generation exp. ➔ leptonic CP̸, mass hierarchy

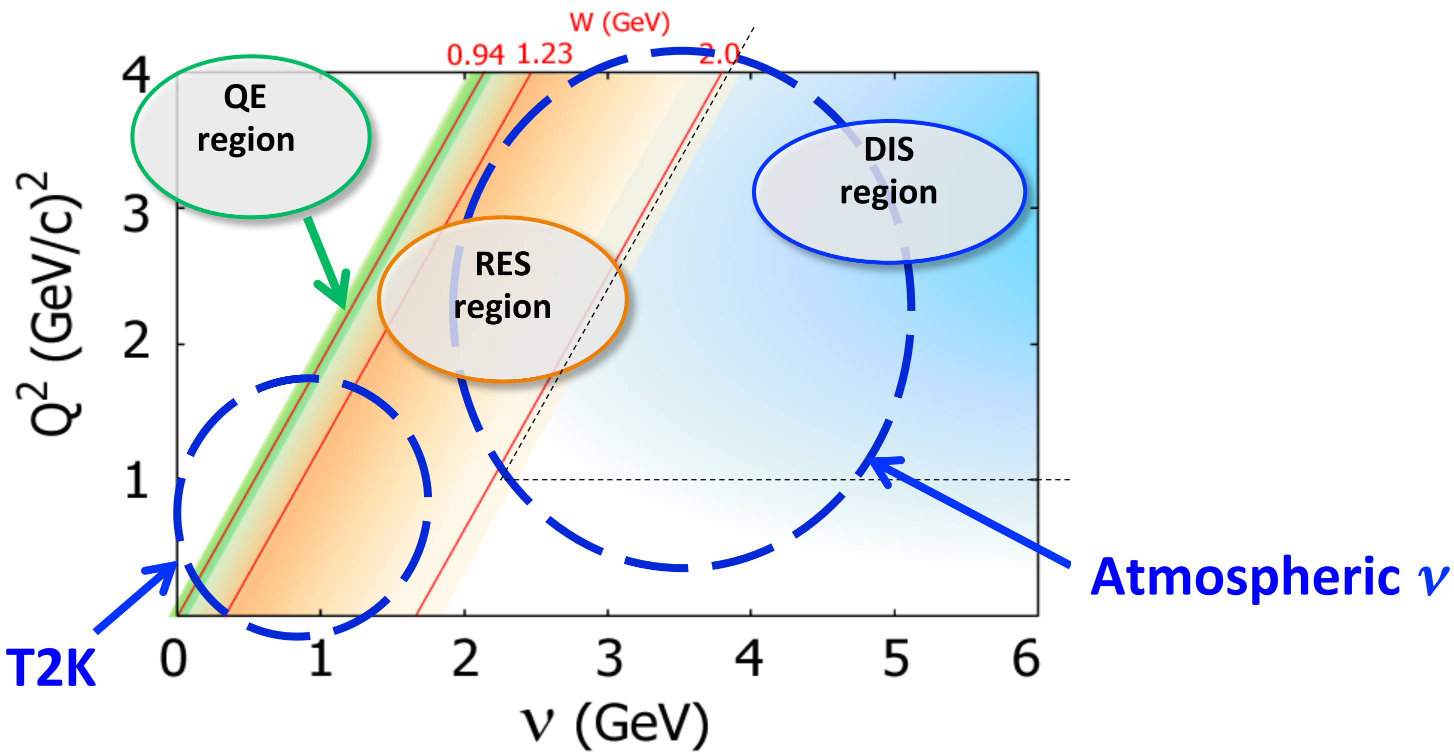


Wide kinematical region with different characteristic

➔ Combination of different expertise is necessary

Neutrino-nucleus scattering for ν-oscillation experiments

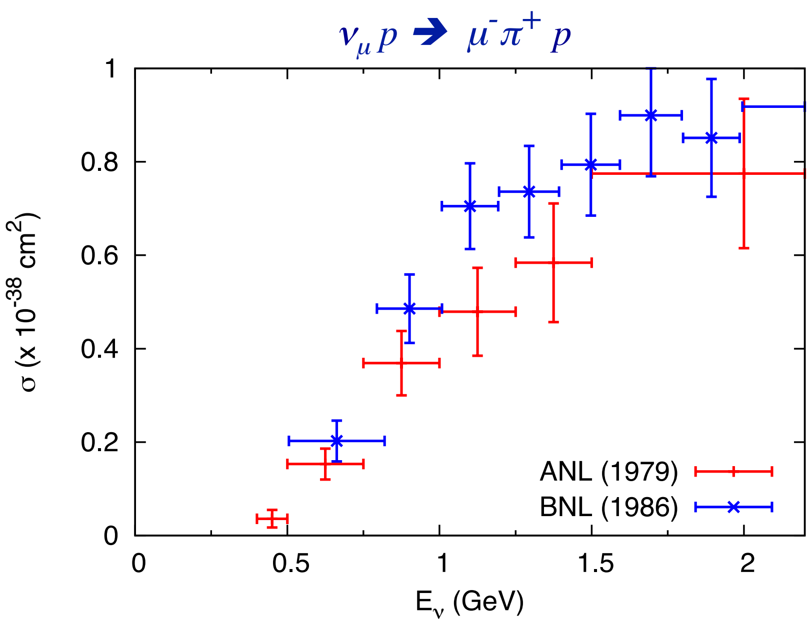
Next-generation exp. ➔ leptonic $\not{C}P$, mass hierarchy

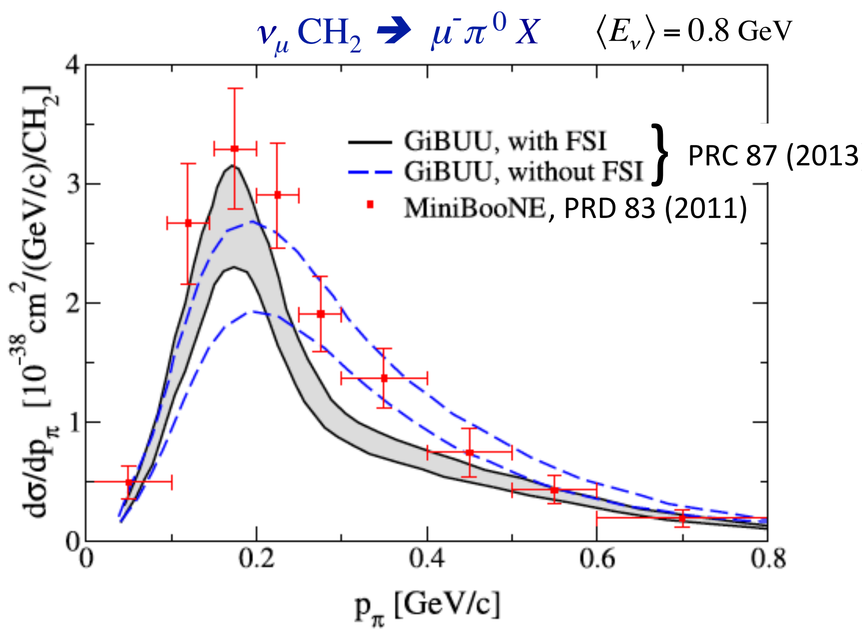


Collaboration at J-PARC Branch of KEK Theory Center

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

Neutrino interaction data in resonance region





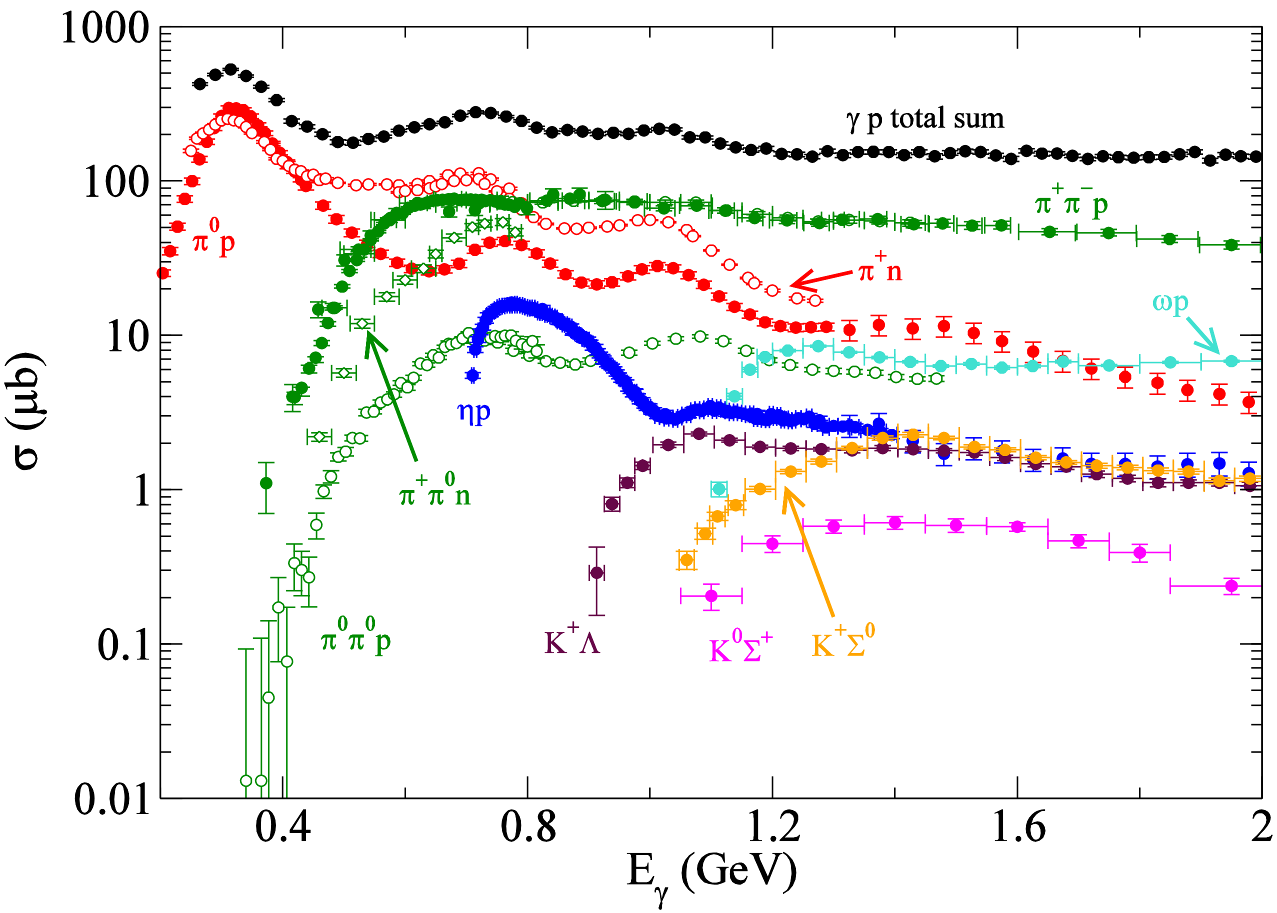
- Data to fix nucleon axial current ($g_{AN\Delta}$)
- Discrepancy between BNL & ANL data
- Recent reanalysis (arXiv:1411.4482) flux uncertainty → discrepancy resolved (!?)

- 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

- (multi-channel) Unitarity is missing
- Important 2 π production model is missing

Our strategy to overcome the problems…

We develop a Unitary coupled-channels model

Contents of this talk

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

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

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

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

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

Coupled-channel unitarity is fully taken into account

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

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

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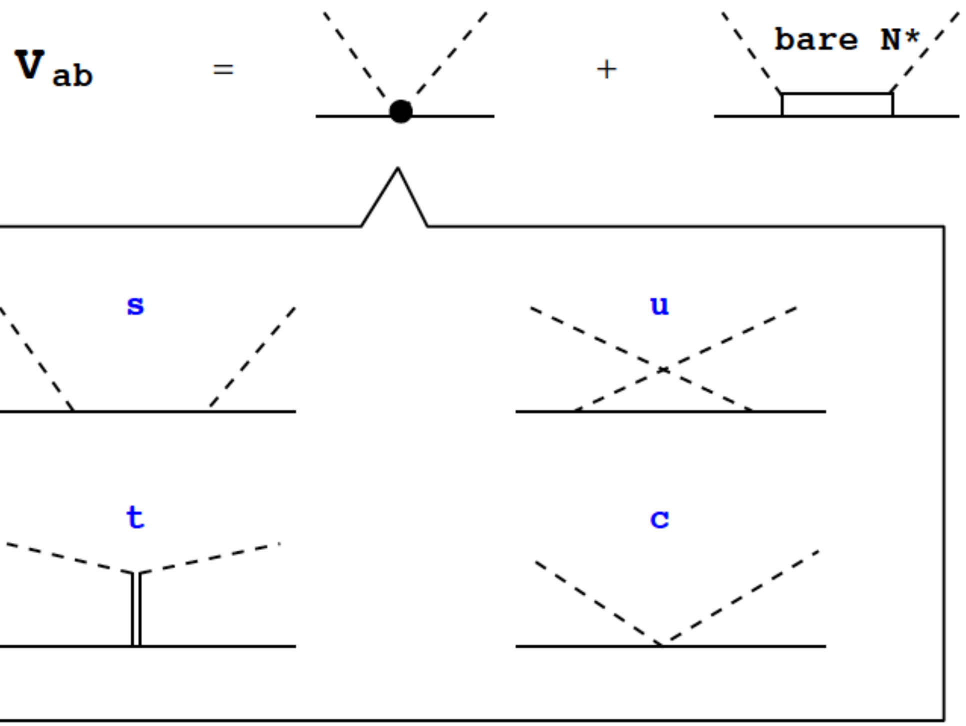


DCC analysis of meson production data

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

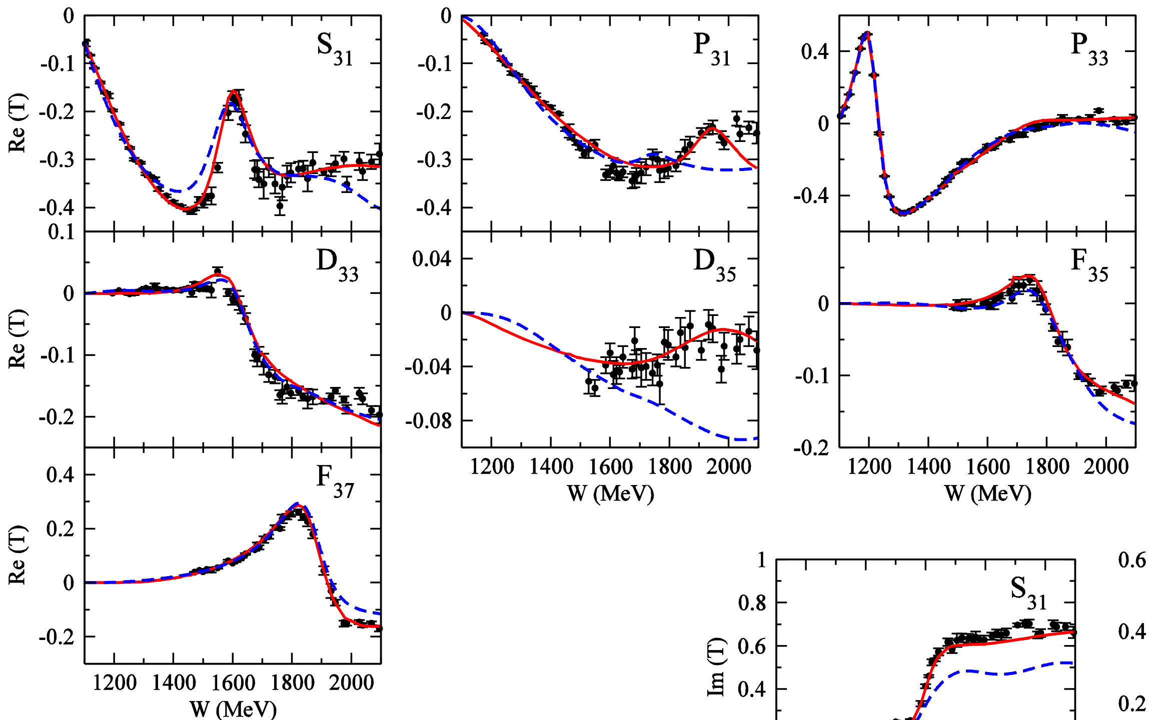
Fully combined analysis of $\gamma N, \pi N$ ➔ $\pi N, \eta N, K\Lambda, K\Sigma$ data

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

~380 parameters (N^* mass, N^* ➔ MB couplings, cutoffs)

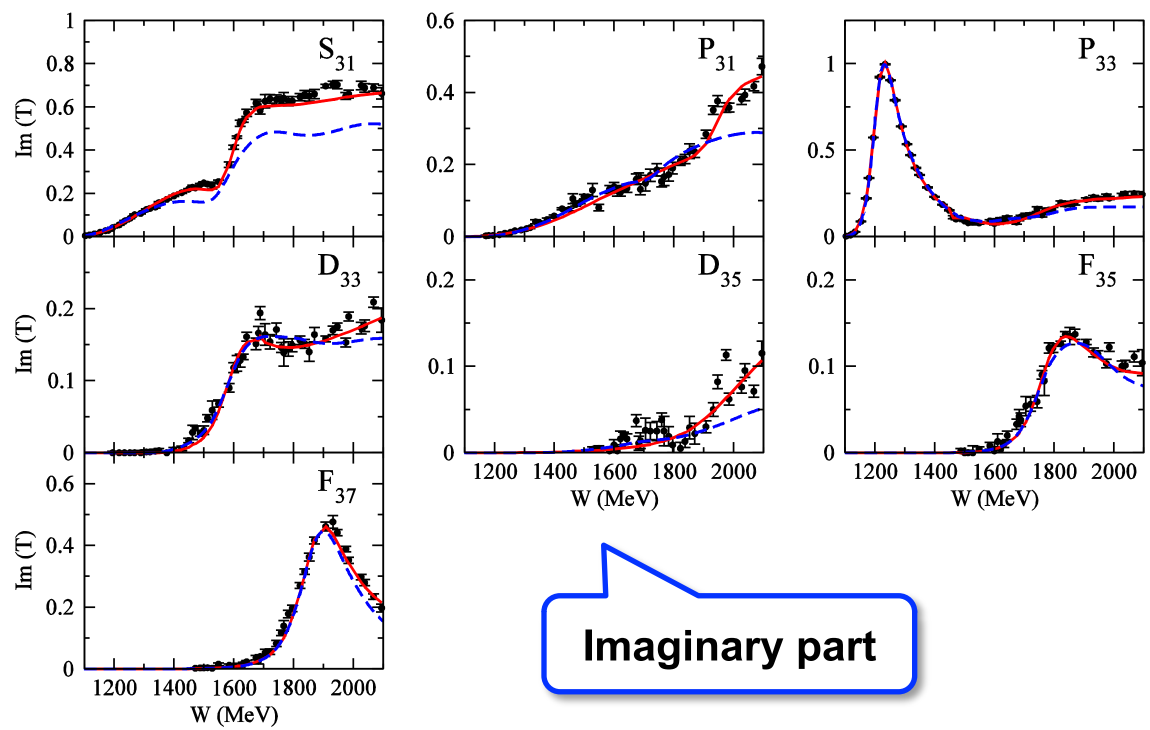
to fit ~ 20,000 data points

Partial wave amplitudes of π N scattering



Real part

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



Imaginary part

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

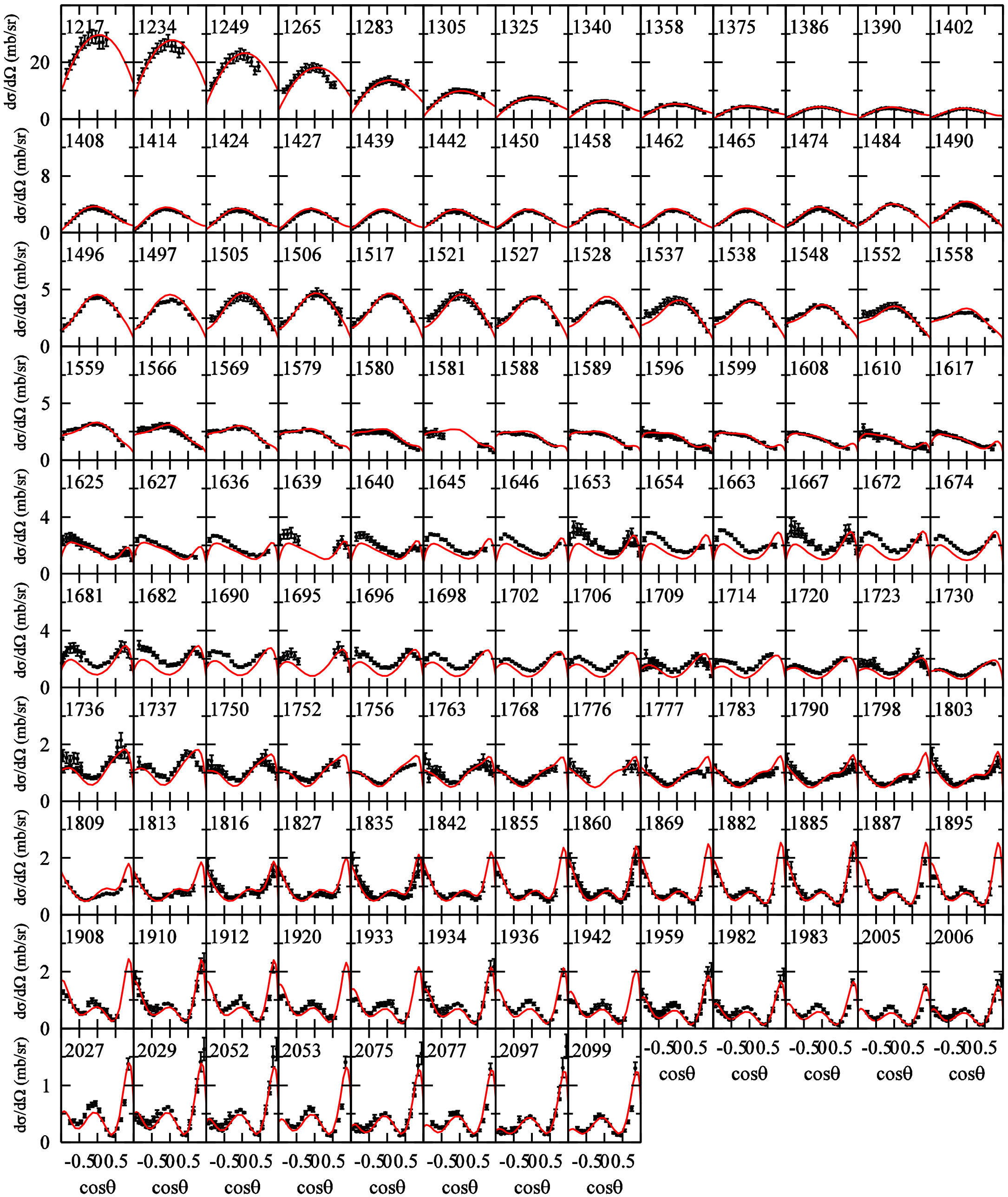
Previous model (fitted to πN → πN data only) [PRC76 065201 (2007)]

Data: SAID πN amplitude

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

dσ/dΩ 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

DCC model for neutrino interaction

Vector current

Q^2=0

γp ➔ MB

γn ➔ πN ➔ isospin separation

necessary for calculating ν-interaction

$Q^2 \neq 0$ form factors (Q^2-dependence) for VNN^* couplings

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

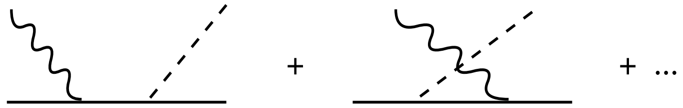
DCC model for neutrino interaction

Axial current

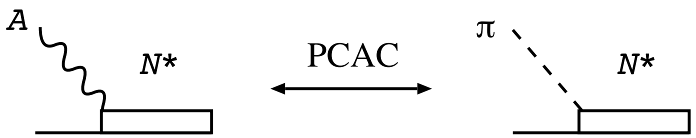
Q^2=0

non-resonant mechanisms

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



resonant mechanisms



Interference among resonances and background can be made under control within DCC model

Caveat : phenomenological axial currents are added to maintain PCAC relation

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

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

resonant mechanisms $$F_A(Q^2) = (1+aQ^2)\exp(-bQ^2)\left(\frac{1}{1+Q^2/M_A^2}\right)^2$$ Sato et al. PRC 67 (2003)

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

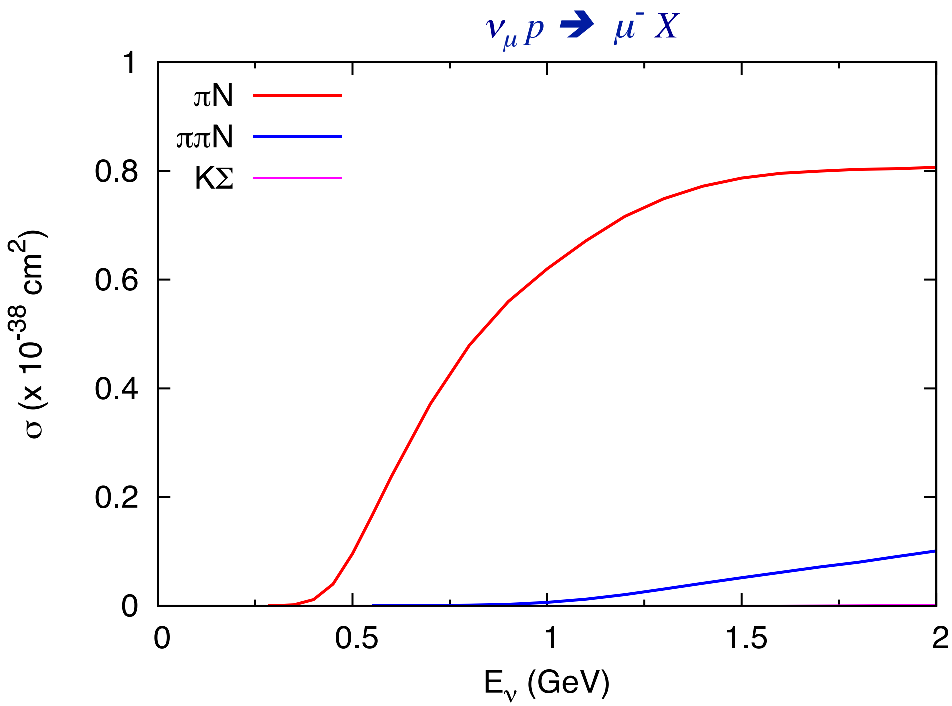
Neutrino cross sections will be predicted with this axial current for this presentation

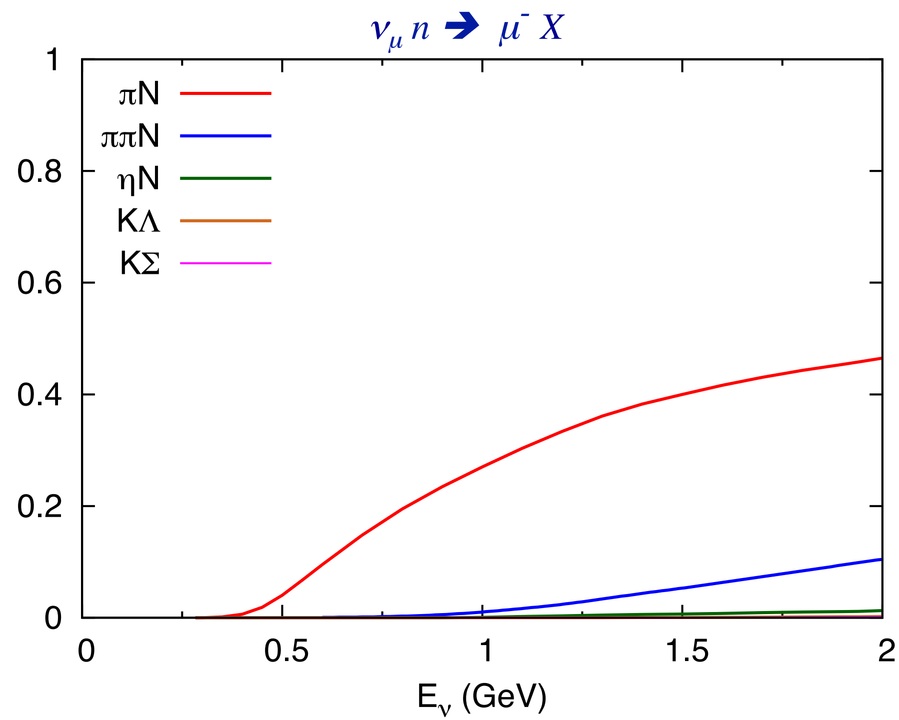
Results

Caveat

- Results presented here are still preliminary
- Careful examination needs to be made to obtain a final result

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





- πN & $\pi\pi N$ are main channels in few-GeV region
- ηN, KY cross sections are $10^{-1} - 10^{-2}$ smaller

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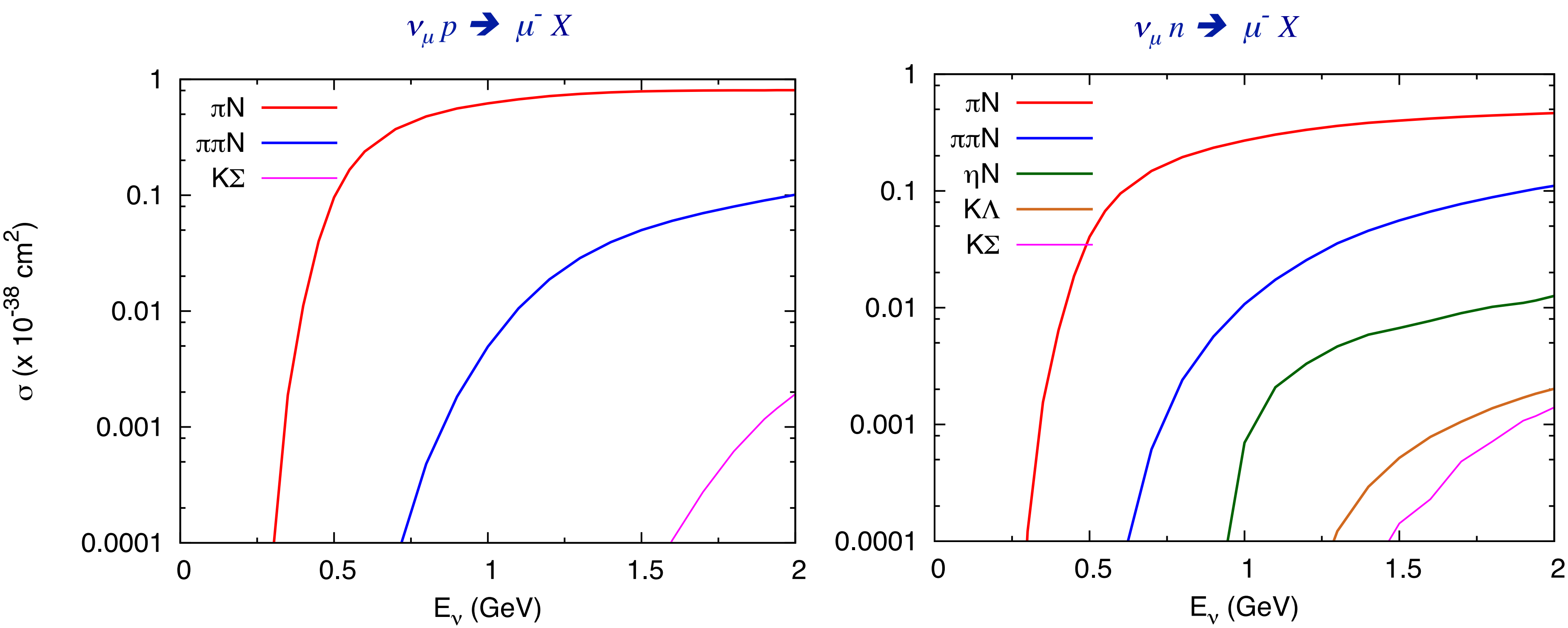

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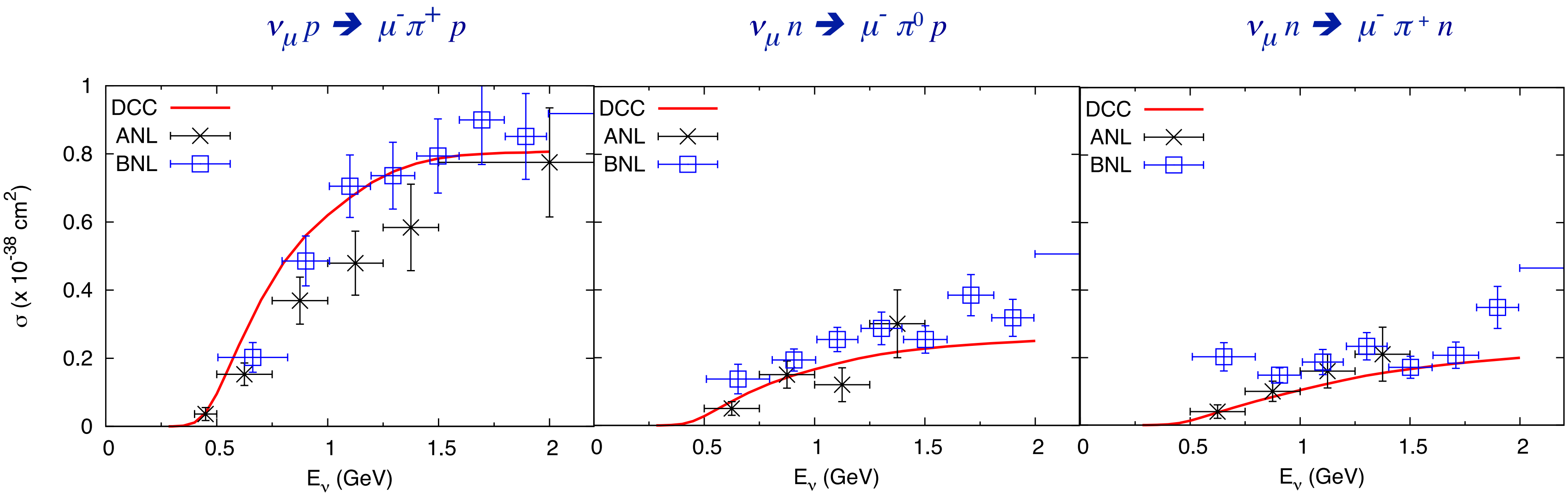
Comparison with single pion data



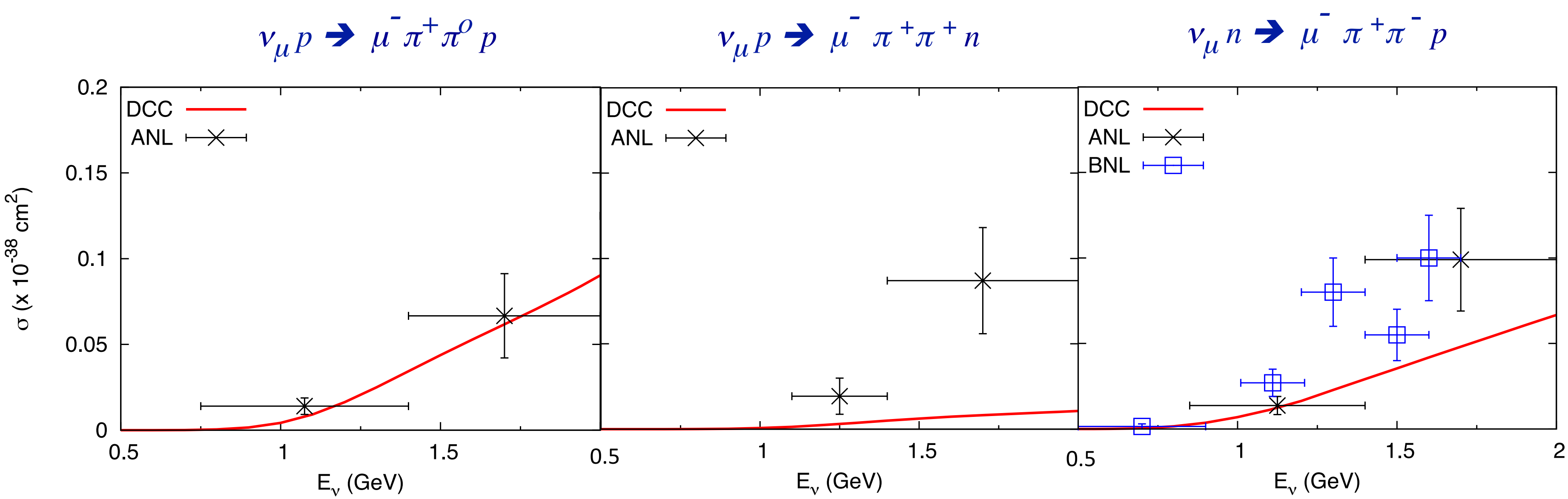
DCC model prediction is consistent with data

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. , arXiv:1412:2415)

Comparison with double pion data

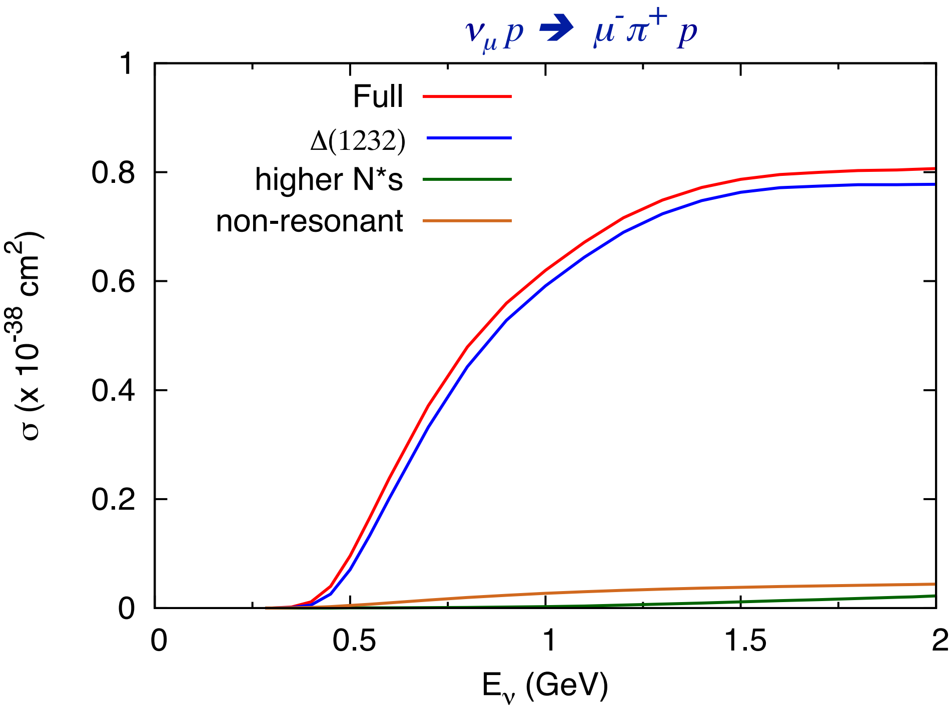


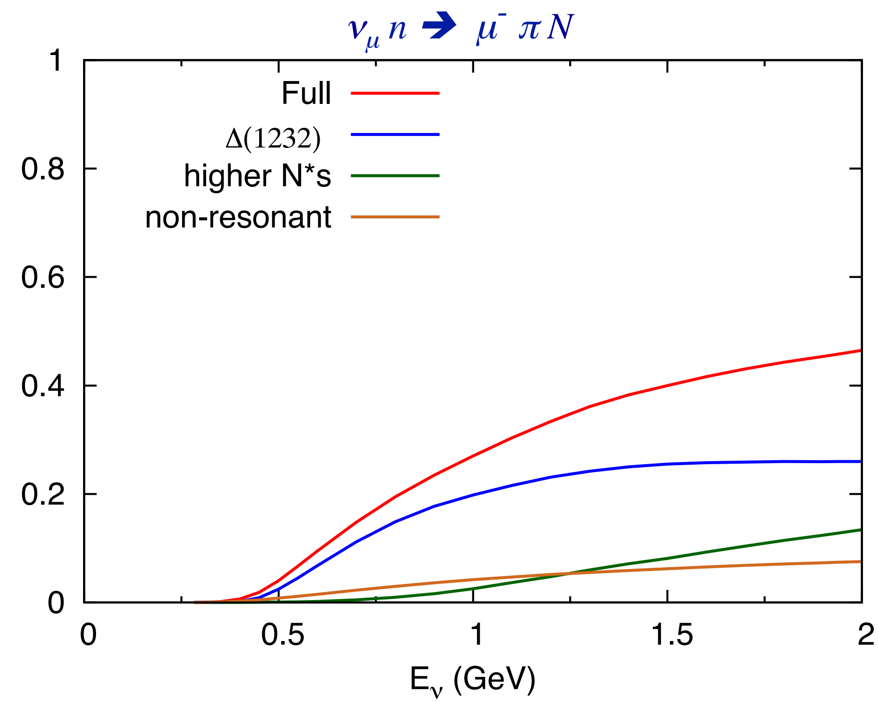
Fairly good DCC predication

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

- First serious comparison between theory and double pion data
- 2 π production model is becoming available

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

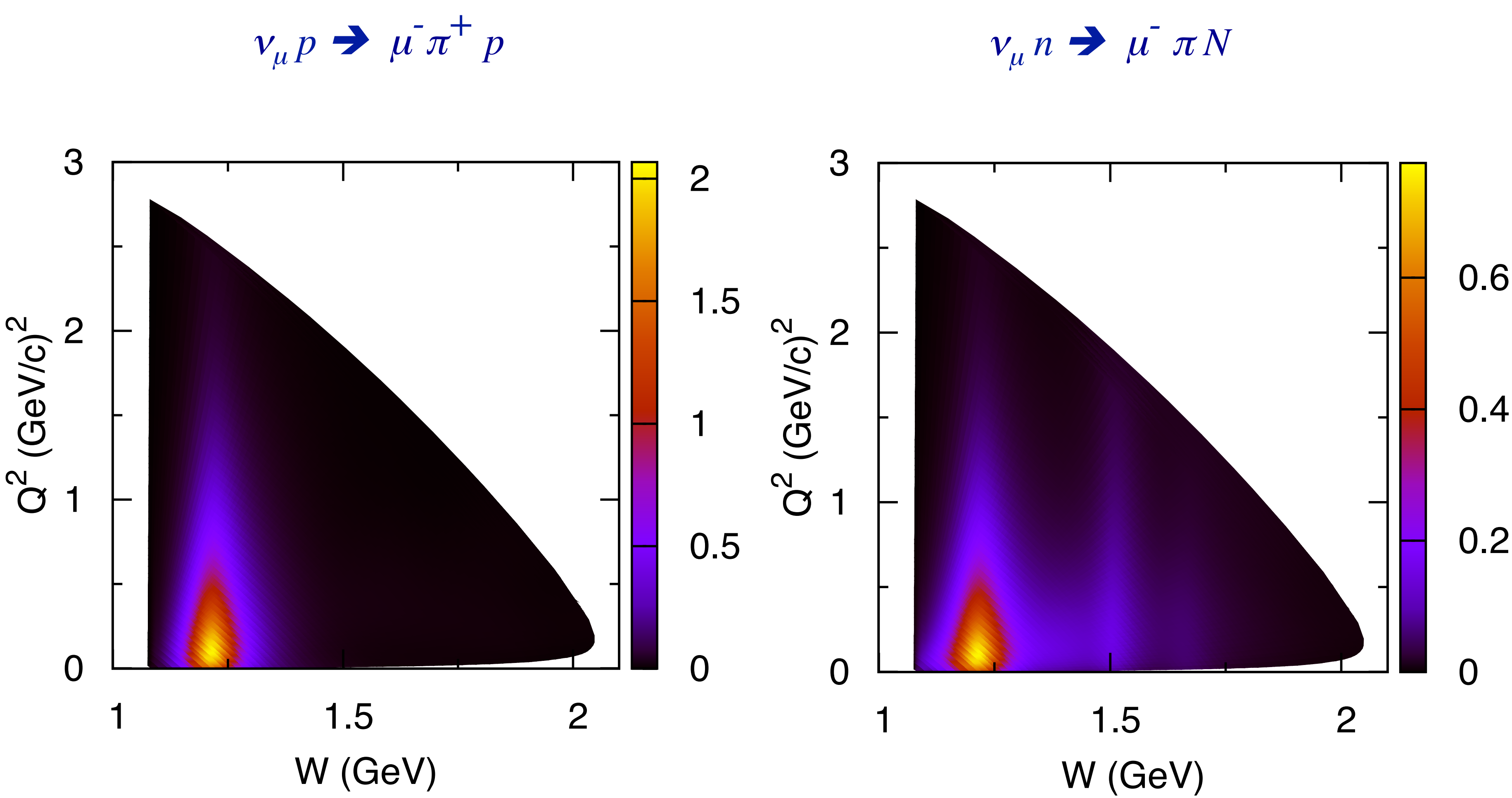




- Δ(1232) dominates for $\nu_\mu p \rightarrow \mu^- \pi^+ p$ $(I=3/2)$ for $E_\nu \leq 2$ GeV
- Non-resonant mechanisms contribute significantly
- Higher N^*s becomes important towards $E_\nu \approx 2$ GeV for $\nu_\mu n \rightarrow \mu^- \pi N$

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

E_ν = 2 GeV



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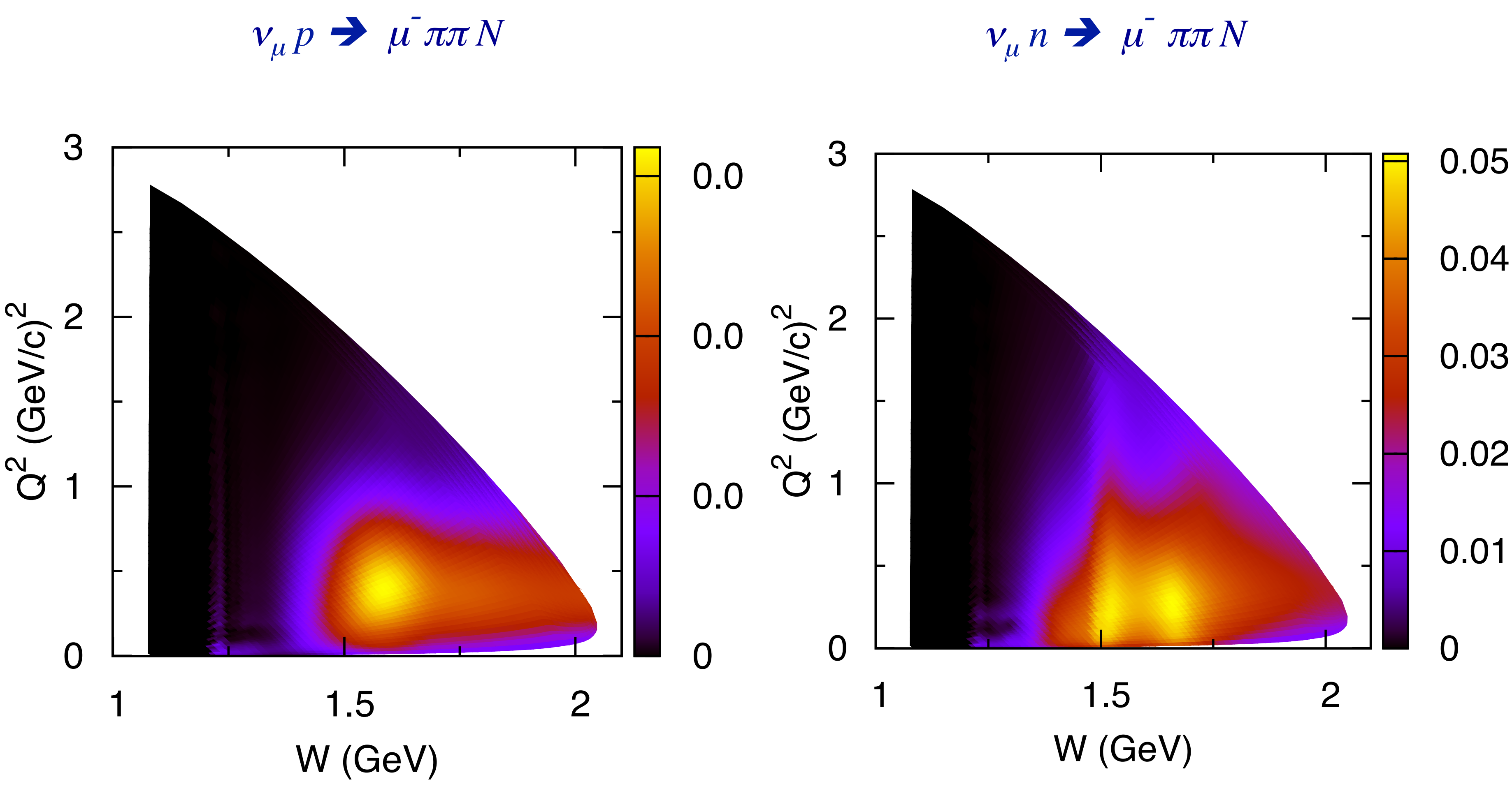

Conclusion

Development of DCC model for νN interaction in resonance region

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

➔ 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 for 1π (2π) production is (fairly) consistent with 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