Neutrino-induced meson productions

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→ baryon resonance properties extracted

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★ Results for νN → $l^- X$

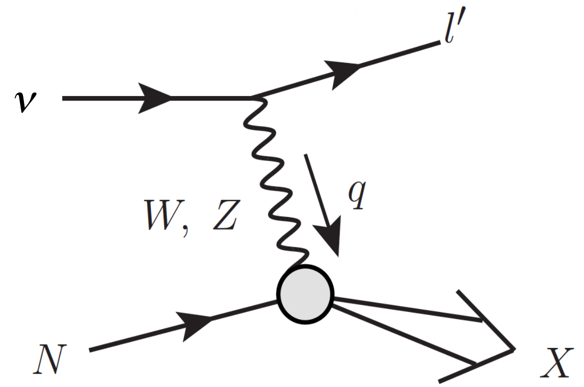
Introduction

Neutrino-nucleus scattering for ν-oscillation experiments

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

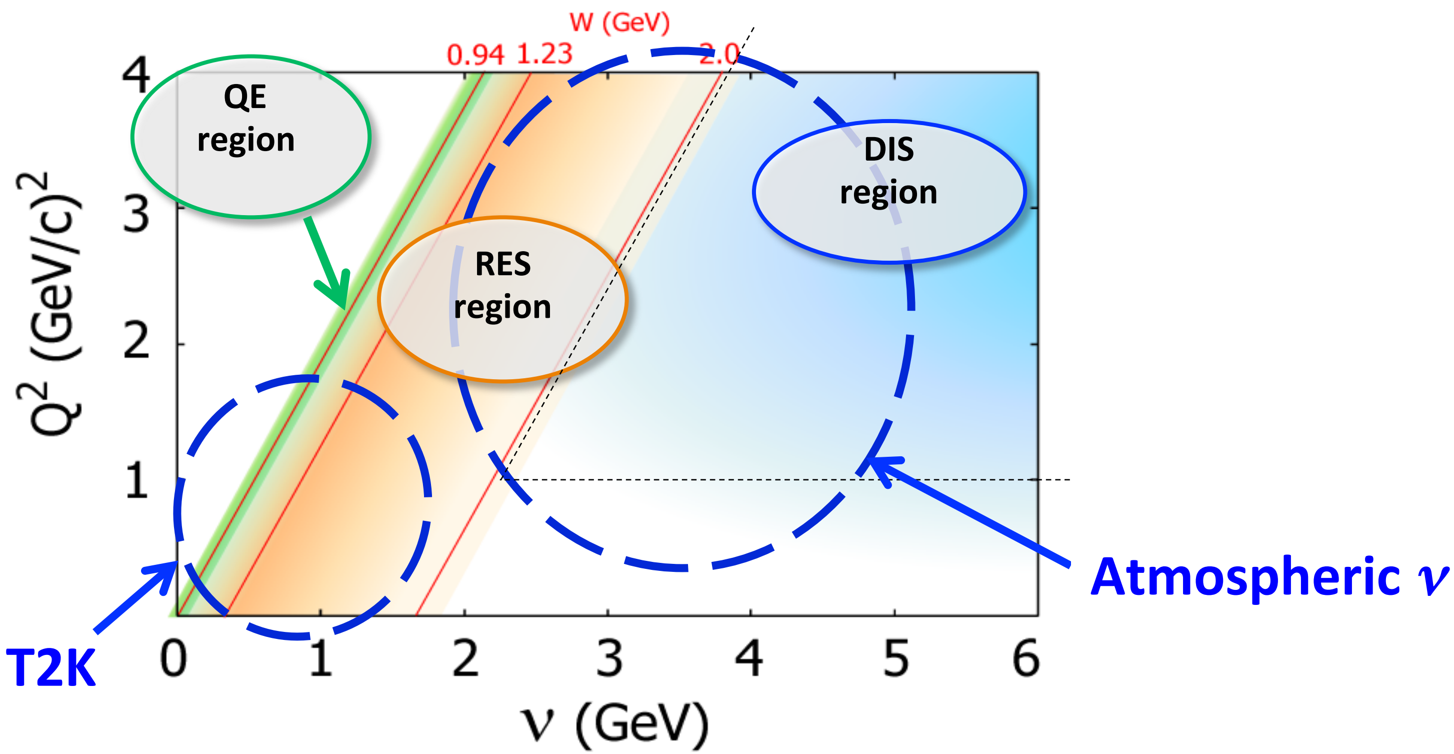
ν–nucleus scattering needs to be understood more precisely

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



Neutrino-nucleus scattering for ν-oscillation experiments

Next-generation exp. ➔ leptonic C̸P, mass hierarchy

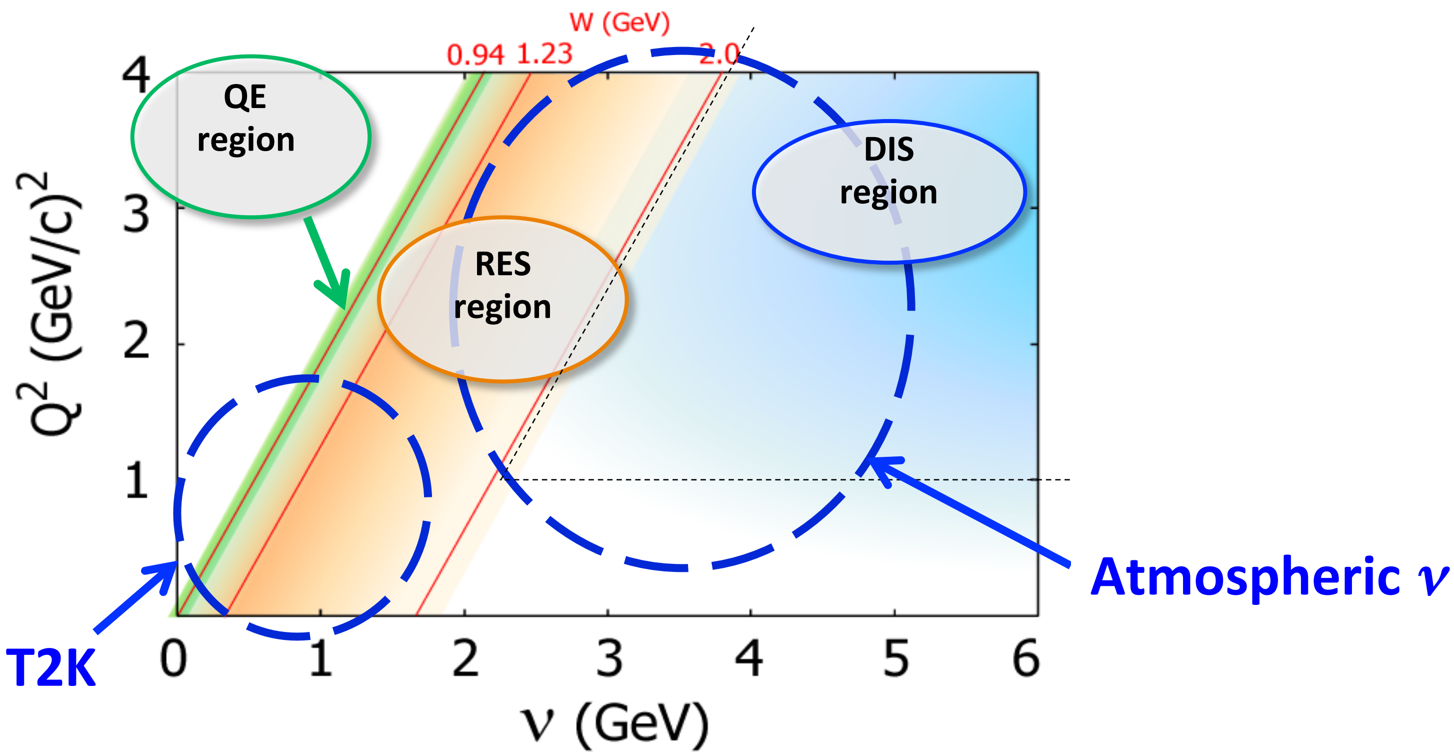


Wide kinematical region with different characteristic

➔ Combination of different expertise is necessary

Neutrino-nucleus scattering for ν-oscillation experiments

Next-generation exp. ➔ leptonic CP̸, mass hierarchy

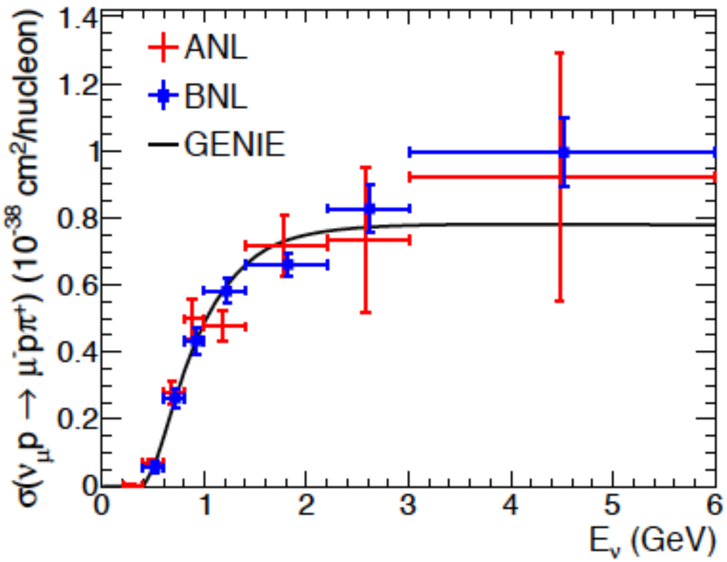


Collaboration at J-PARC Branch of KEK Theory Center

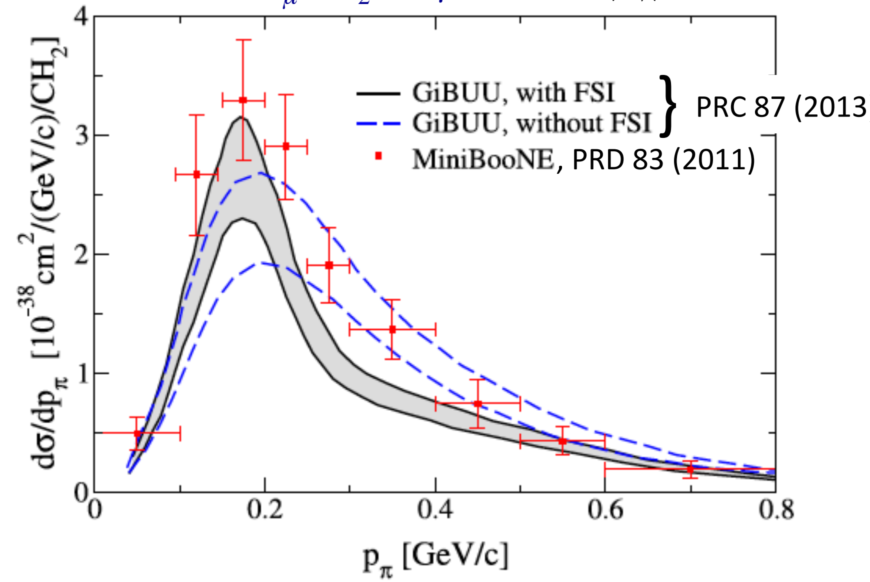
http://j-parc-th.kek.jp/html/English/e-index.html

Neutrino interaction data in resonance region

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



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



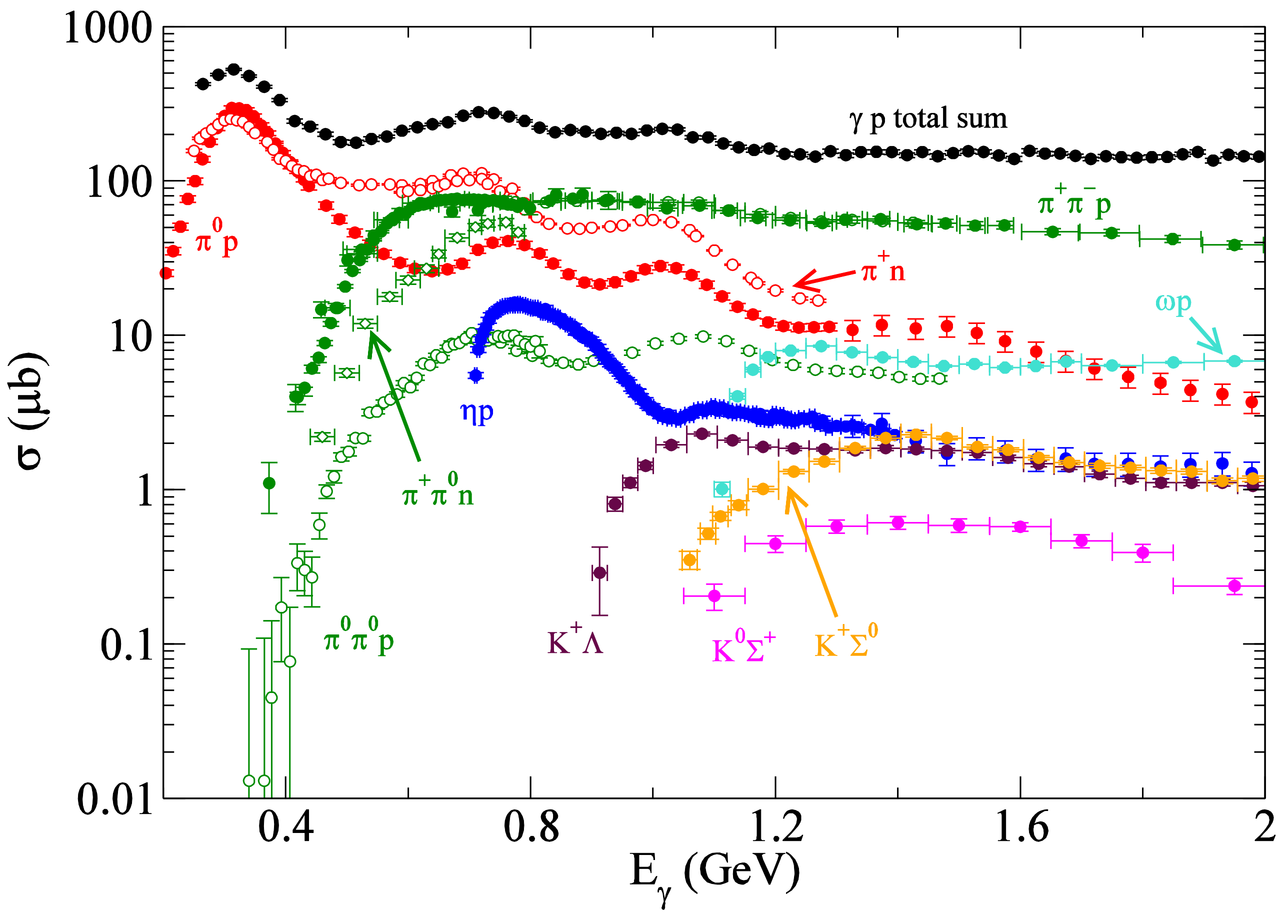
- Data to fix nucleon axial current ($g_{AN\Delta}$)
- Discrepancy between BNL & ANL data
- Recent reanalysis of original data
  → discrepancy resolved (!?)
  PRD 90, 112017 (2014)

- 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

- (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

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

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

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

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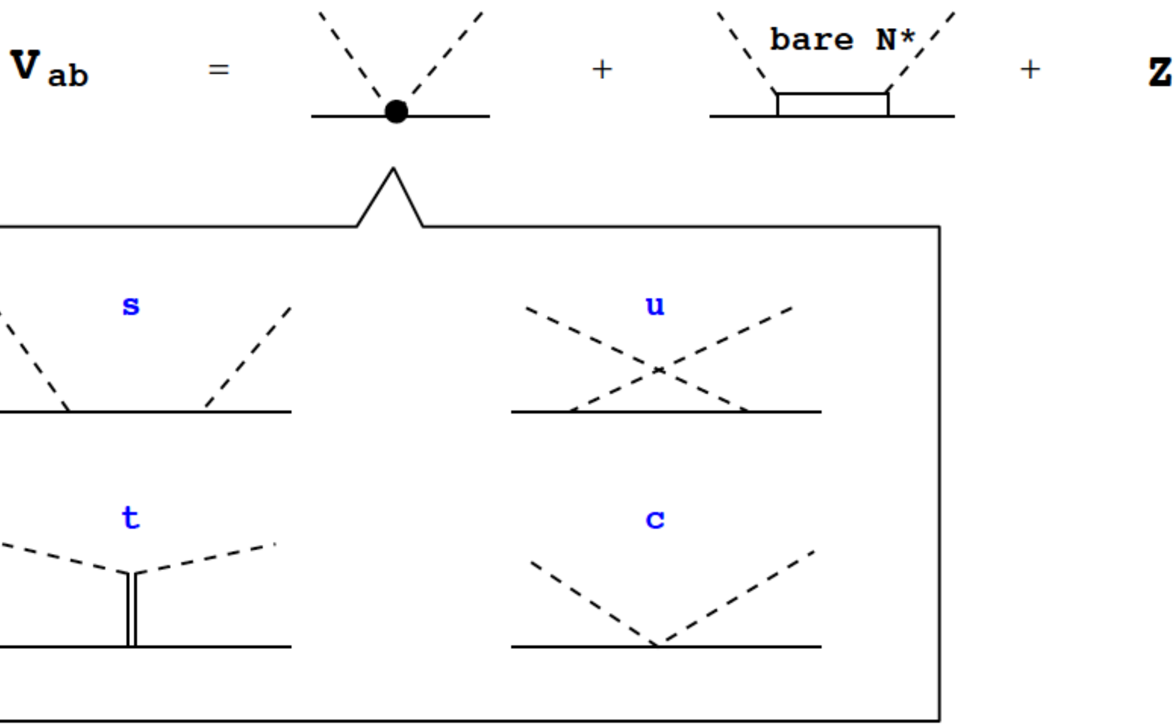

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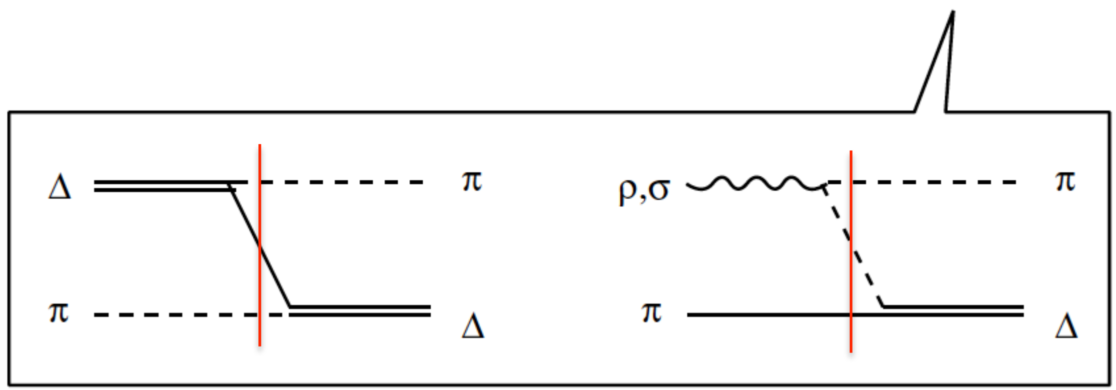
Coupled-channel Lippmann-Schwinger equation

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

V ab =

Z

essential for three-body unitarity



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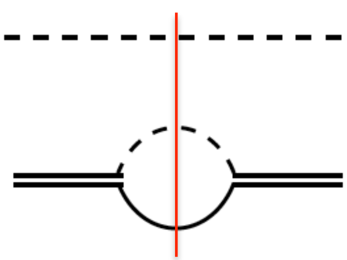
$G c$ =

for stable channels



for unstable channels

DCC analysis of meson production data

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

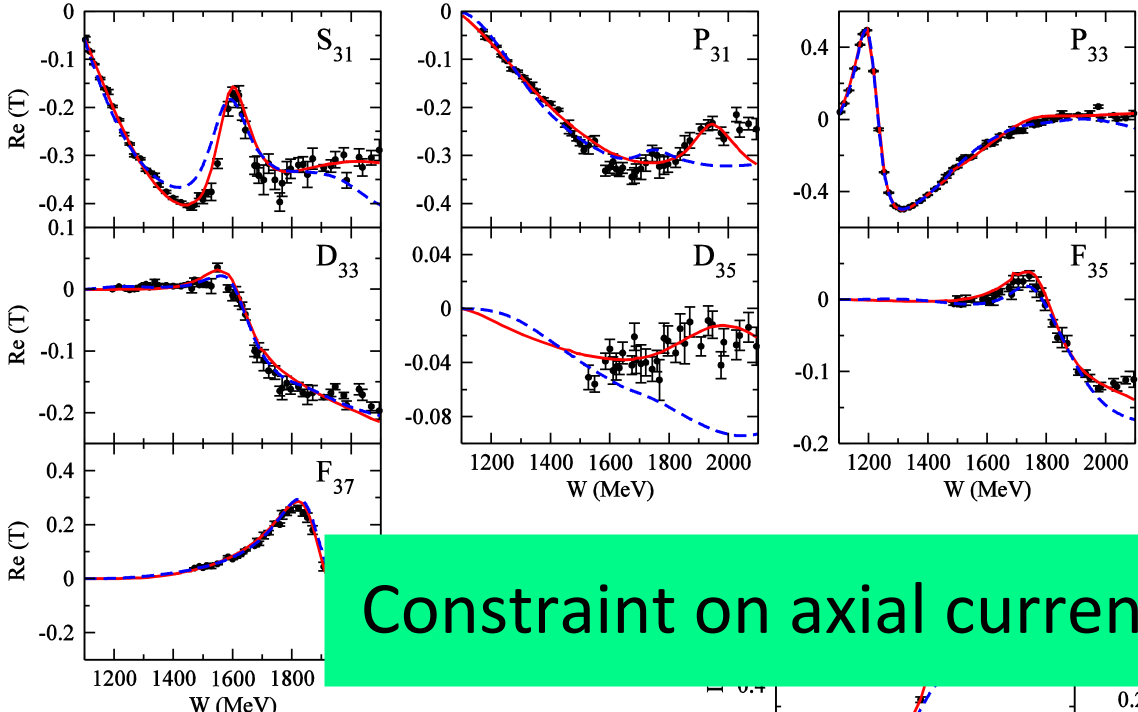
Fully combined analysis of $\gamma N, \pi N$ ➔ $\pi N, \eta N, K\Lambda, K\Sigma$ data

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

~ 20,000 data points are fitted

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

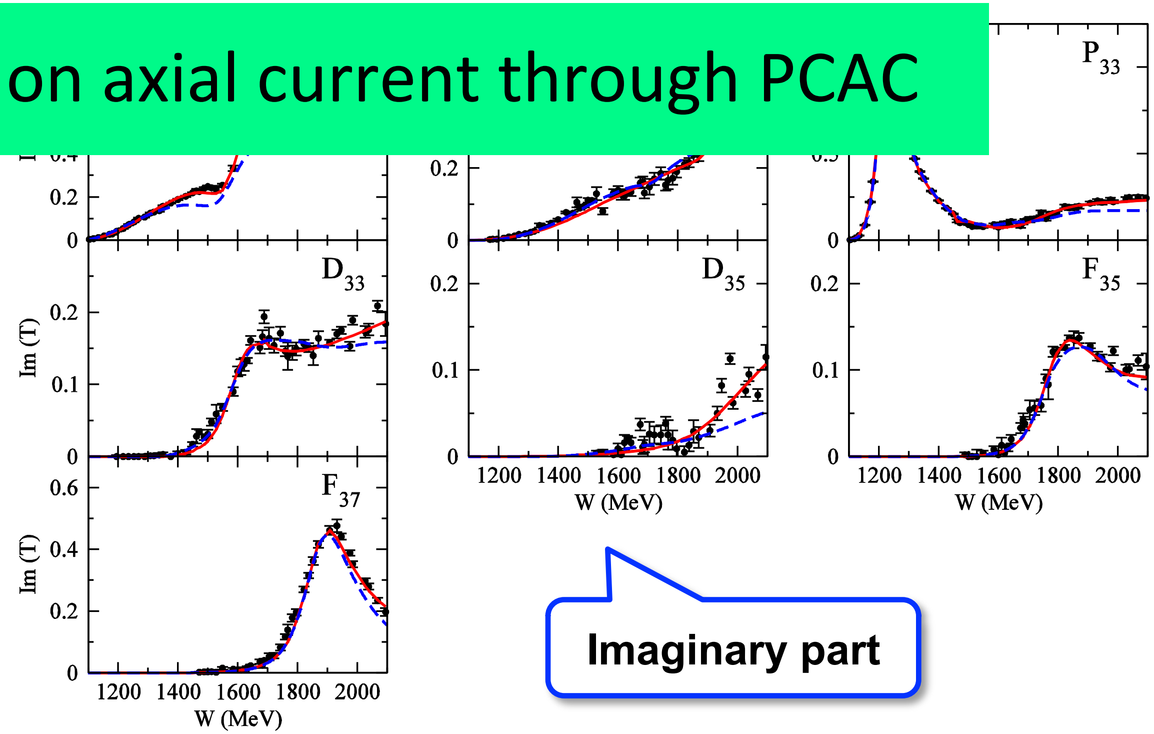
Partial wave amplitudes of π N scattering



Real part

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

Constraint on axial current through PCAC



Imaginary part

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

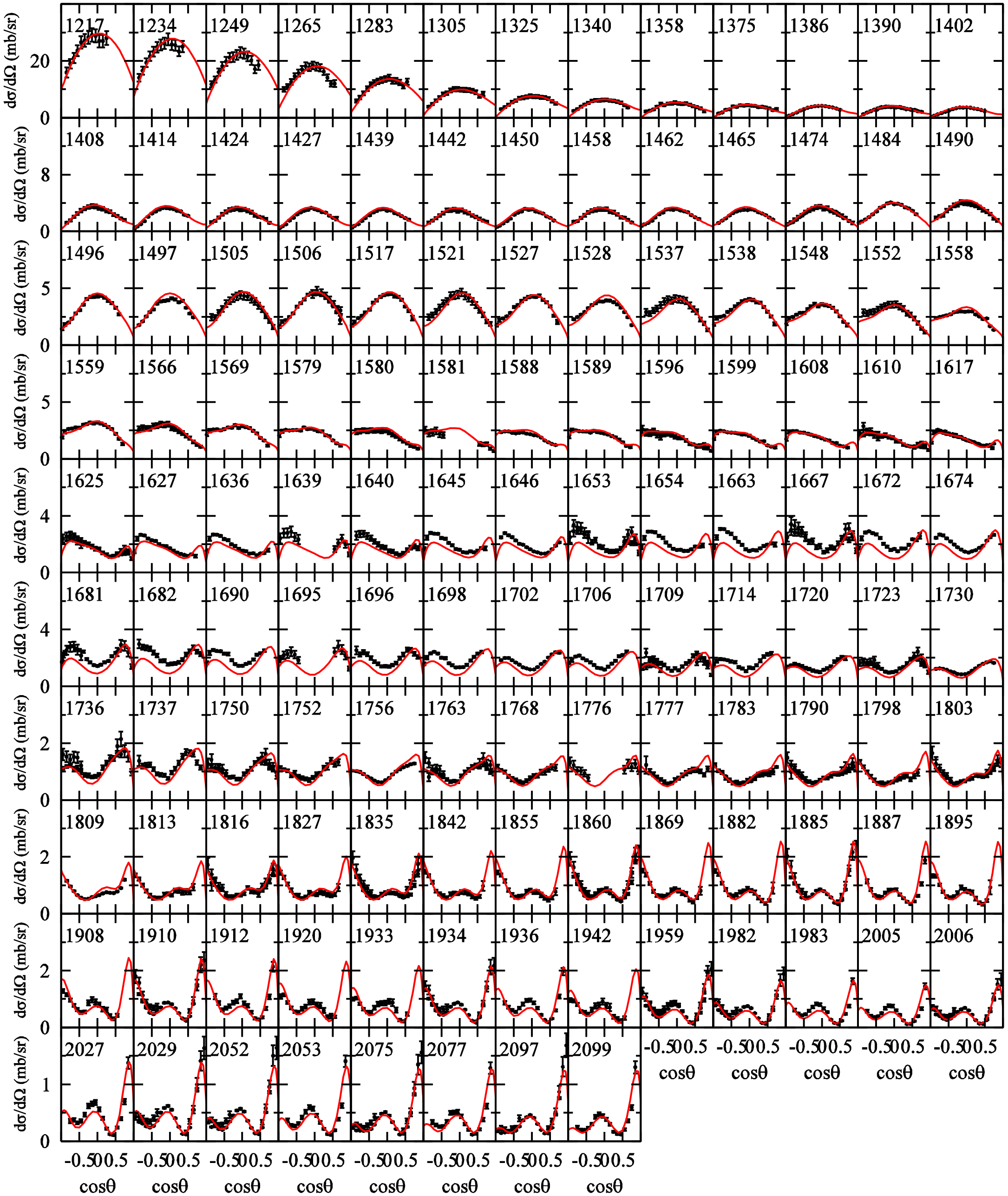
Previous model
(fitted to πN → πN data only)
[PRC76 065201 (2007)]

Data: SAID πN amplitude

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

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

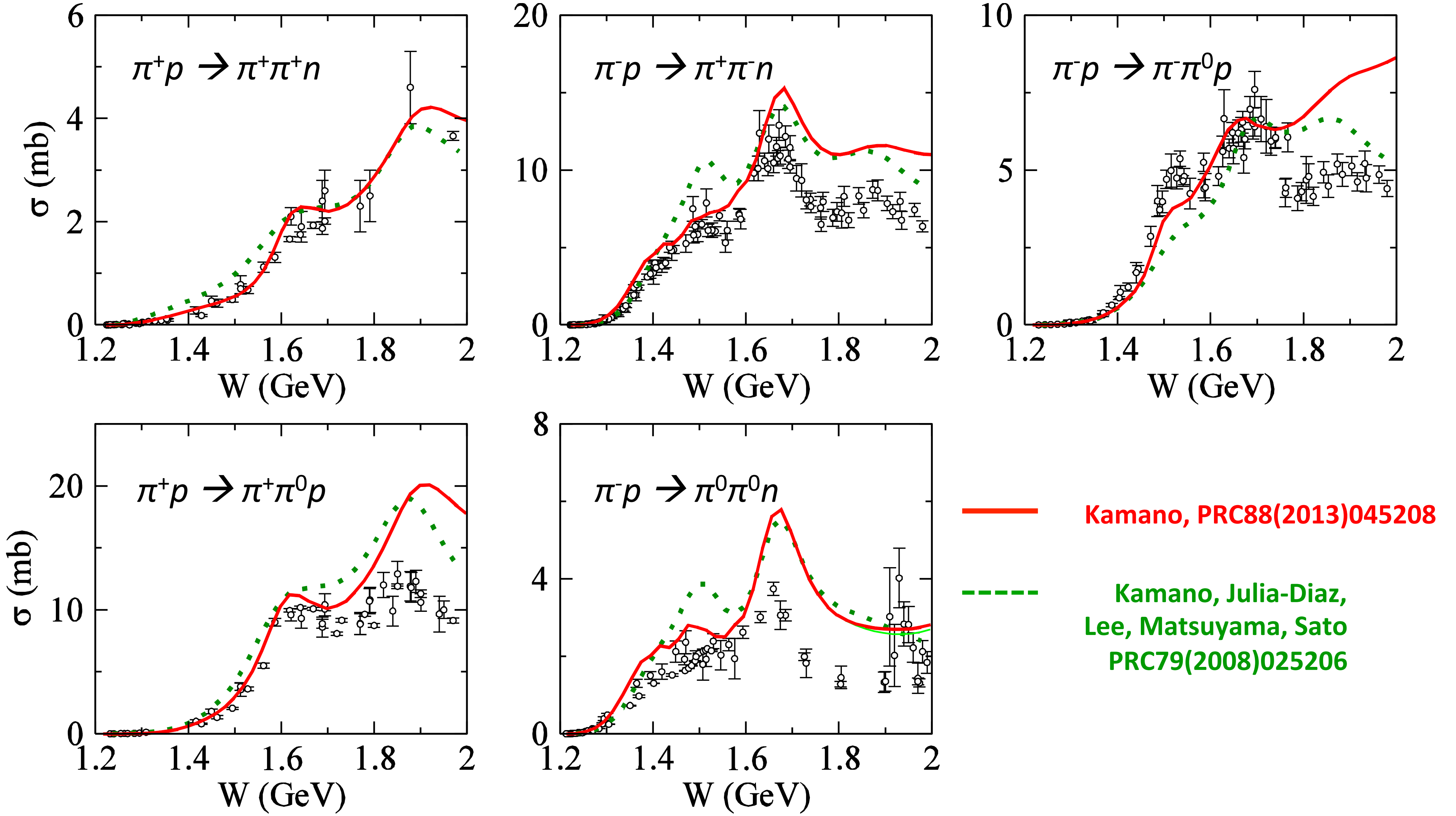
Kamano, Nakamura, Lee, Sato, PRC 88 (2013)



Vector current (Q^2=0) for 1π

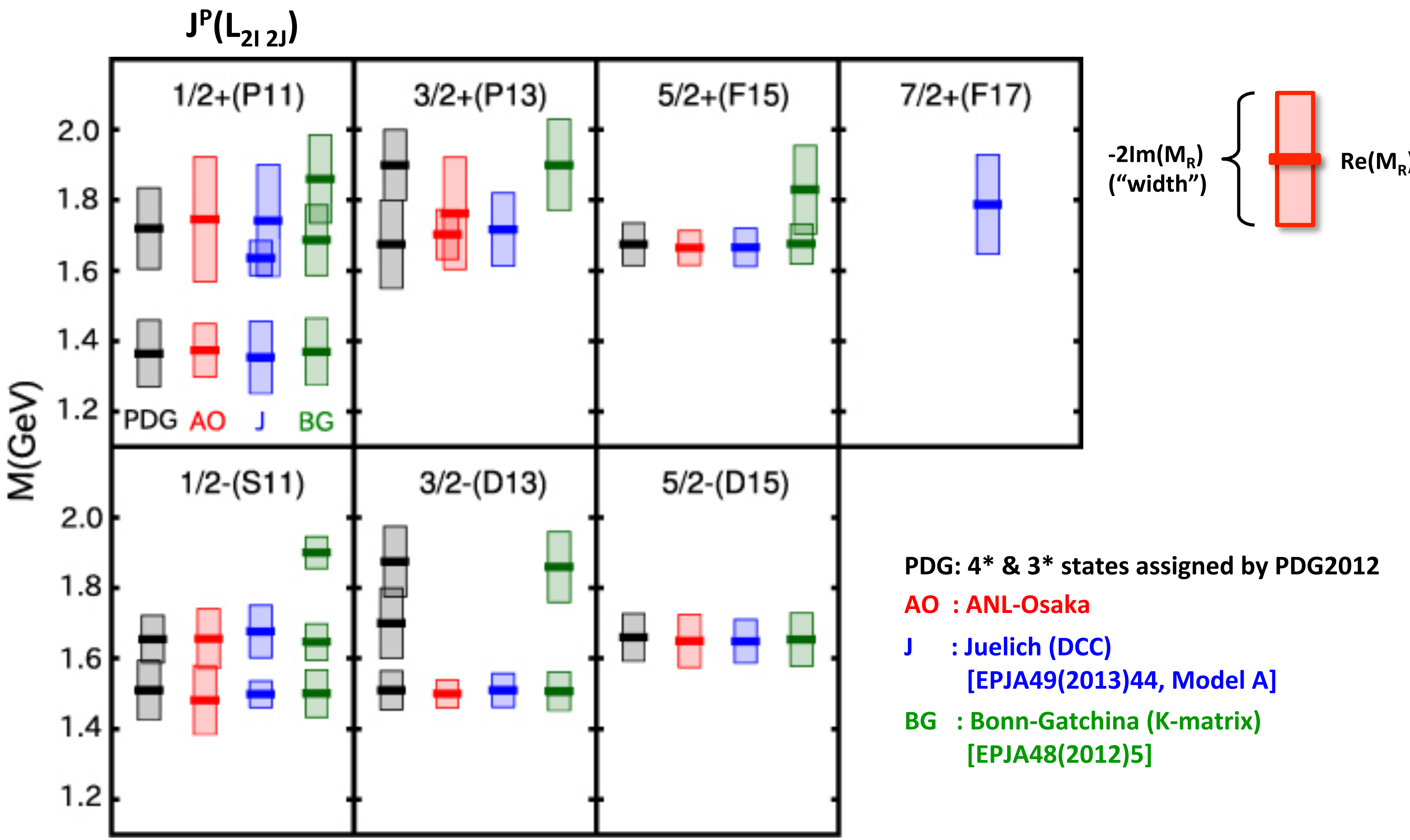
Production is well-tested by data

Predicted πN → ππN total cross sections with our DCC model



“N” resonances (I=1/2)

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



PDG: 4* & 3* states assigned by PDG2012

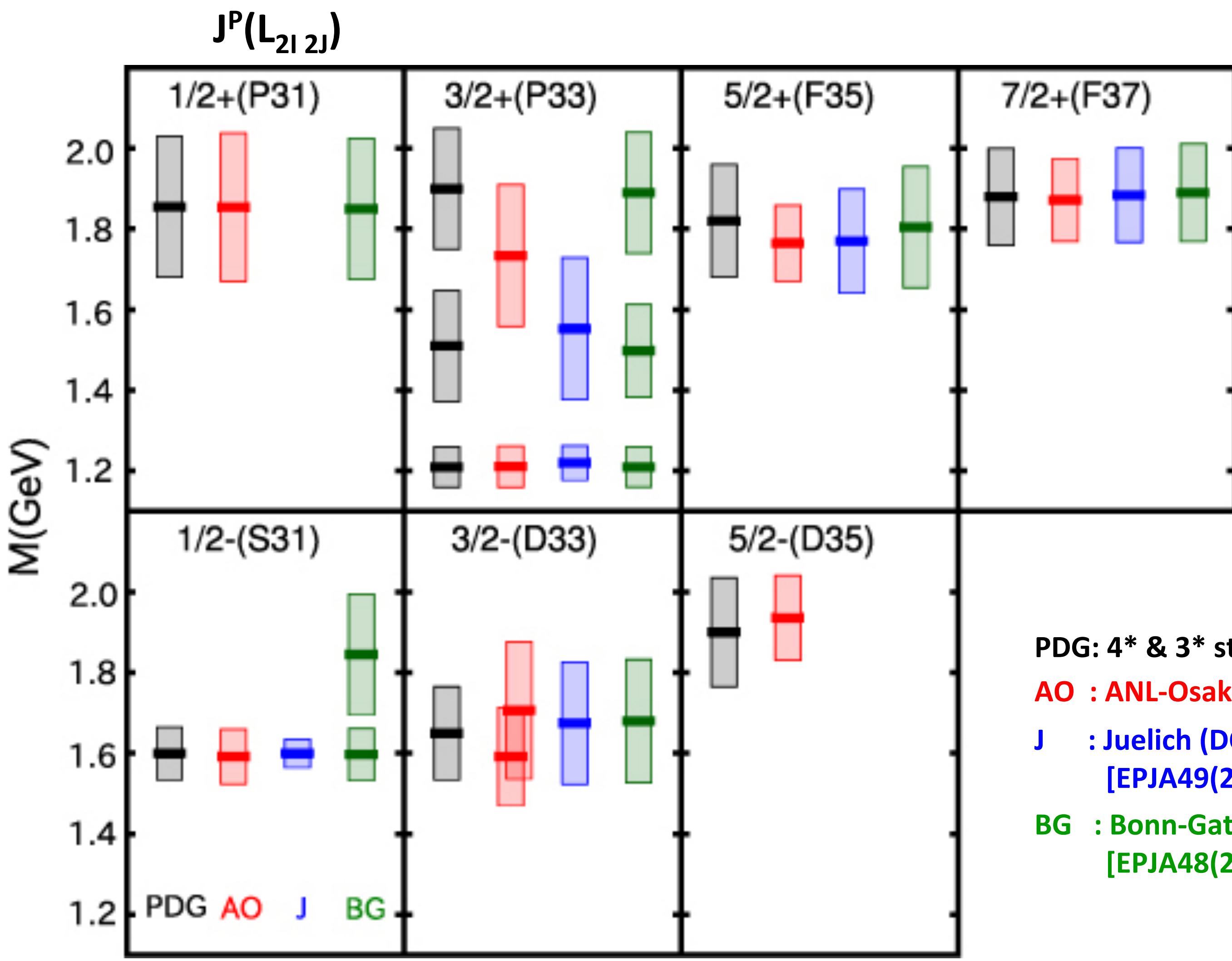
AO : ANL-Osaka

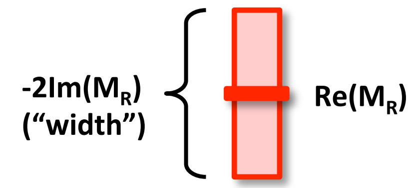
J : Juelich (DCC) [EPJA49(2013)44, Model A]

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

"Δ" resonances (I=3/2)

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





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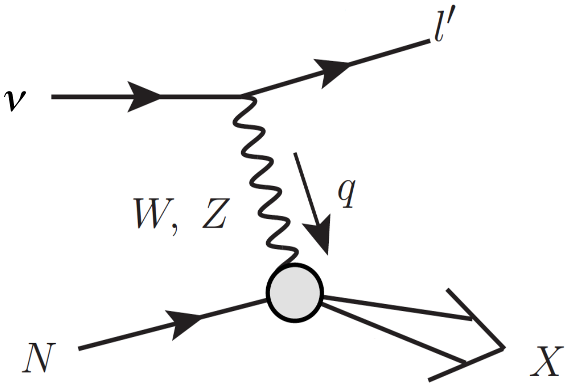
[EPJA48(2012)5]

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

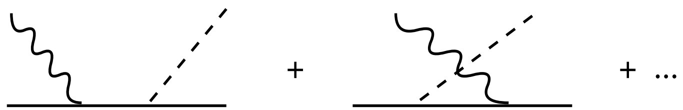
DCC model for neutrino interaction

Axial current

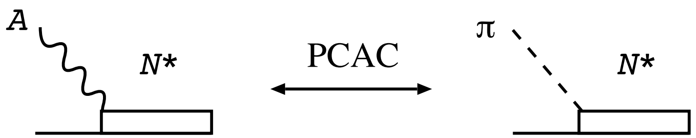
Q^2=0

non-resonant mechanisms

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



resonant mechanisms



Interference among resonances and background can be made under control 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 $F_A(Q^2) = (1 + aQ^2)\exp(-bQ^2)\left(\frac{1}{1 + Q^2 / M_A^2} \right)^2$ 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

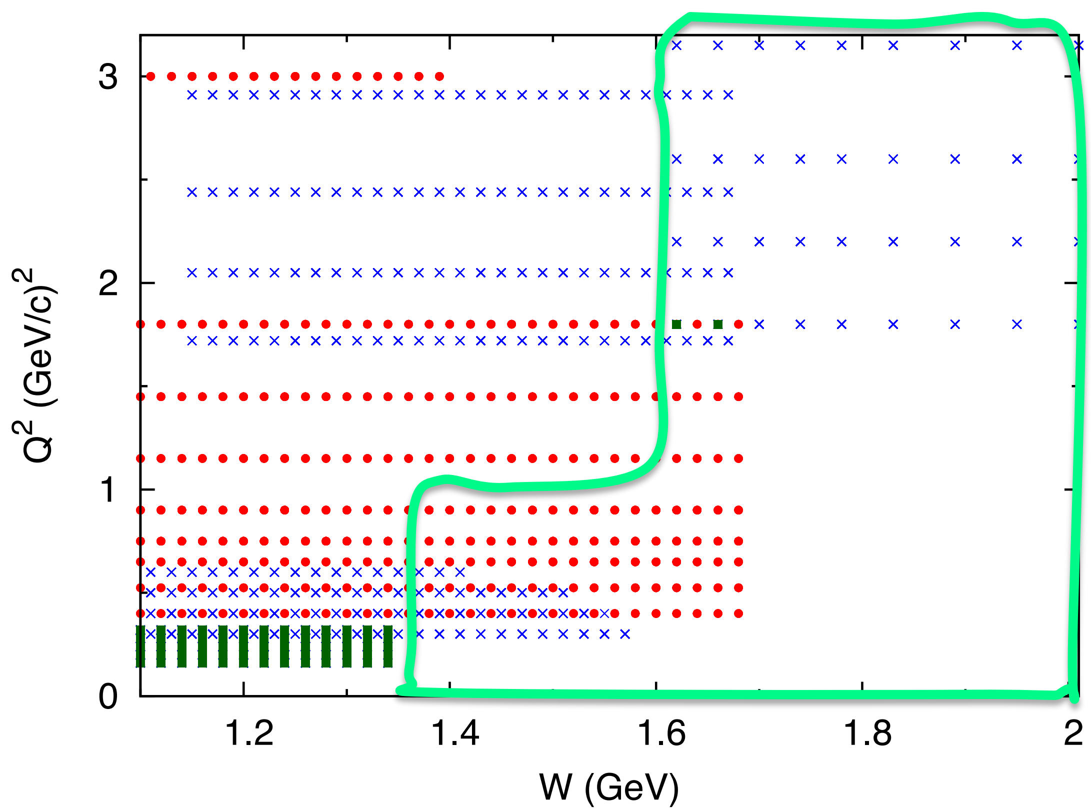
Analysis of electron scattering data

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

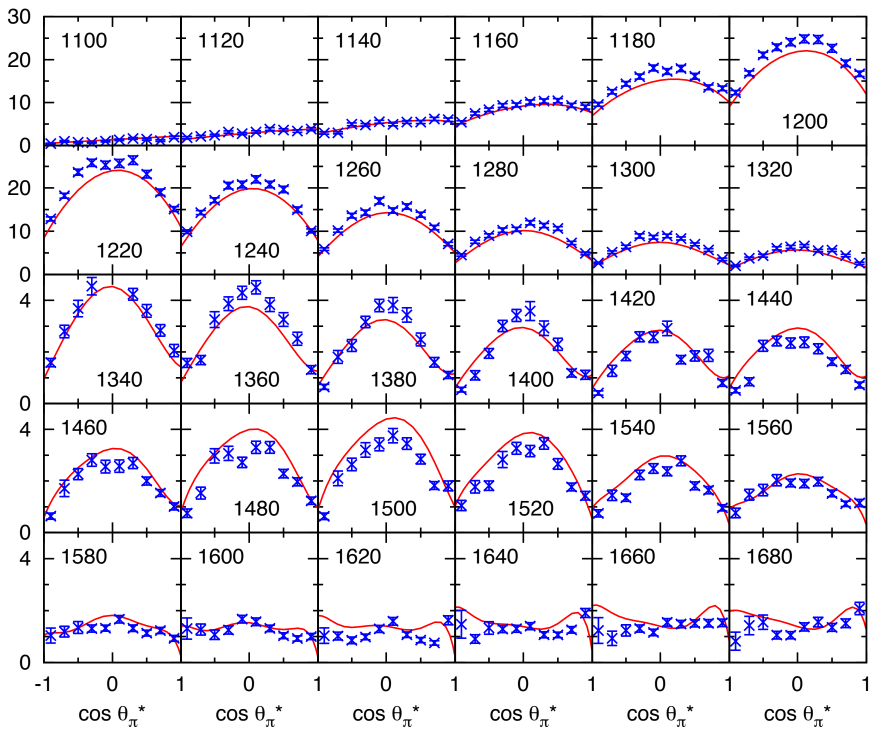
- $p(e,e'\pi^0)p$
- $p(e,e'\pi^+)n$
- both
- region where inclusive σ_T & σ_L are fitted

Analysis result (single π)

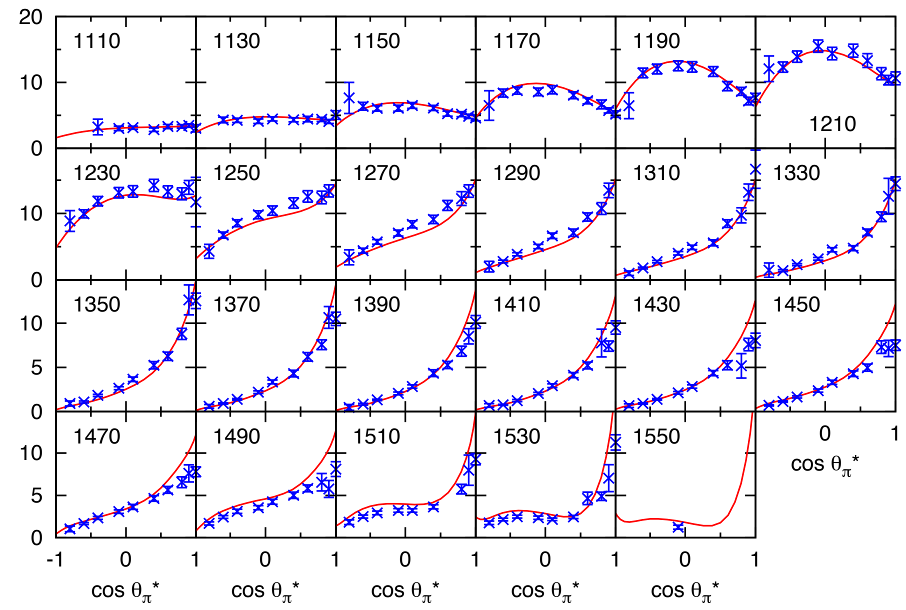
Q^2=0.40 (GeV/c)^2

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

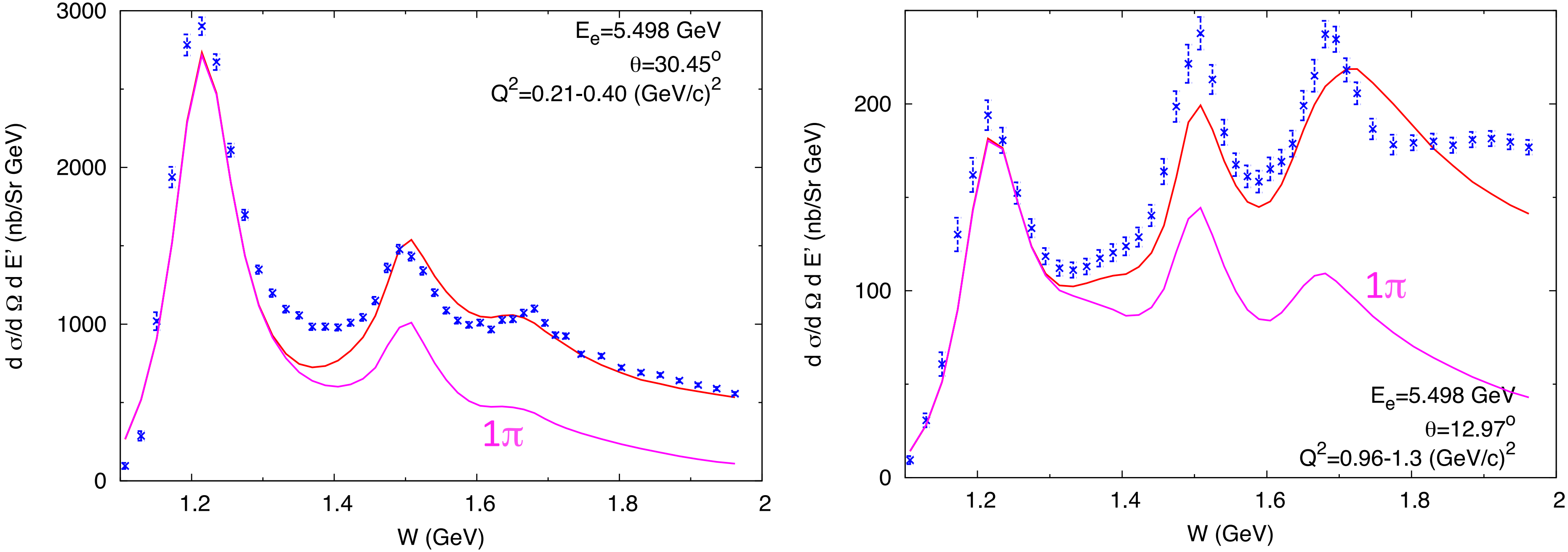
$p(e,e'\pi^0)p$



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



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

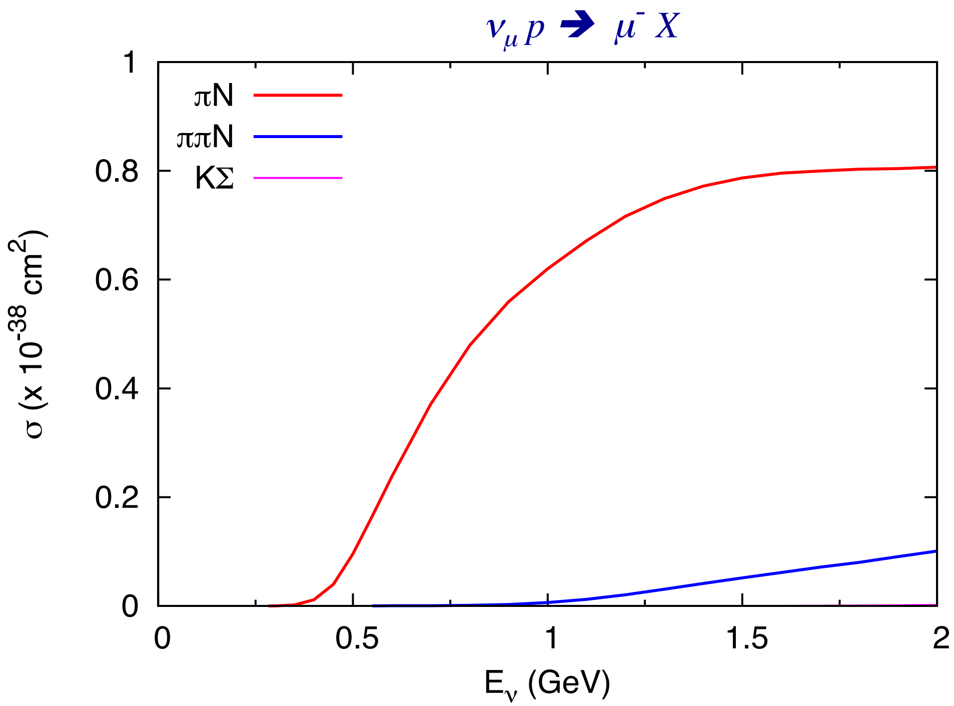
relevant to neutrino interactions of $E_\nu \leq 2$ GeV

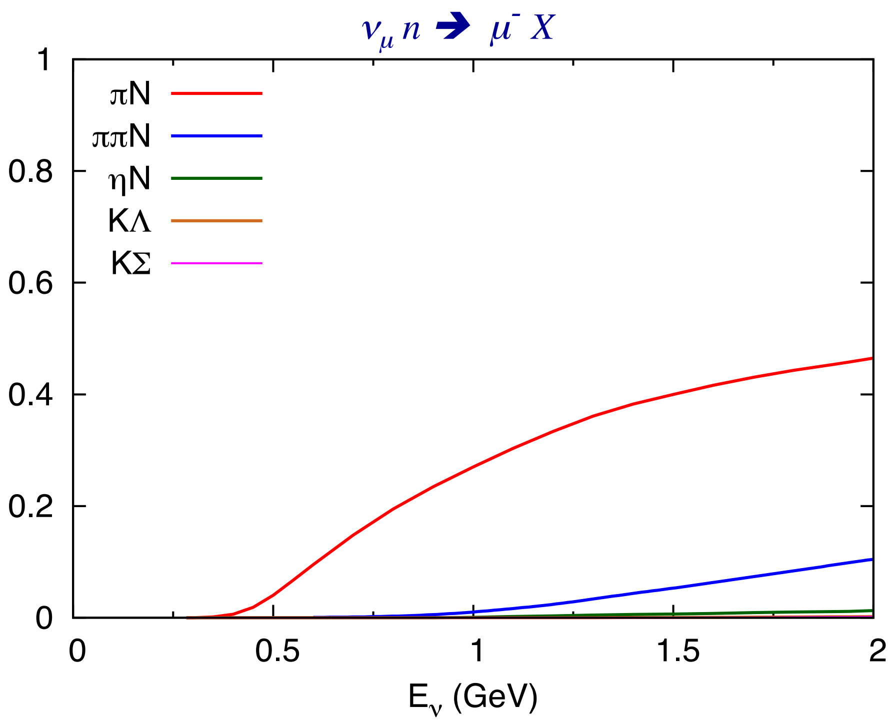
Neutrino Results

Caveat

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

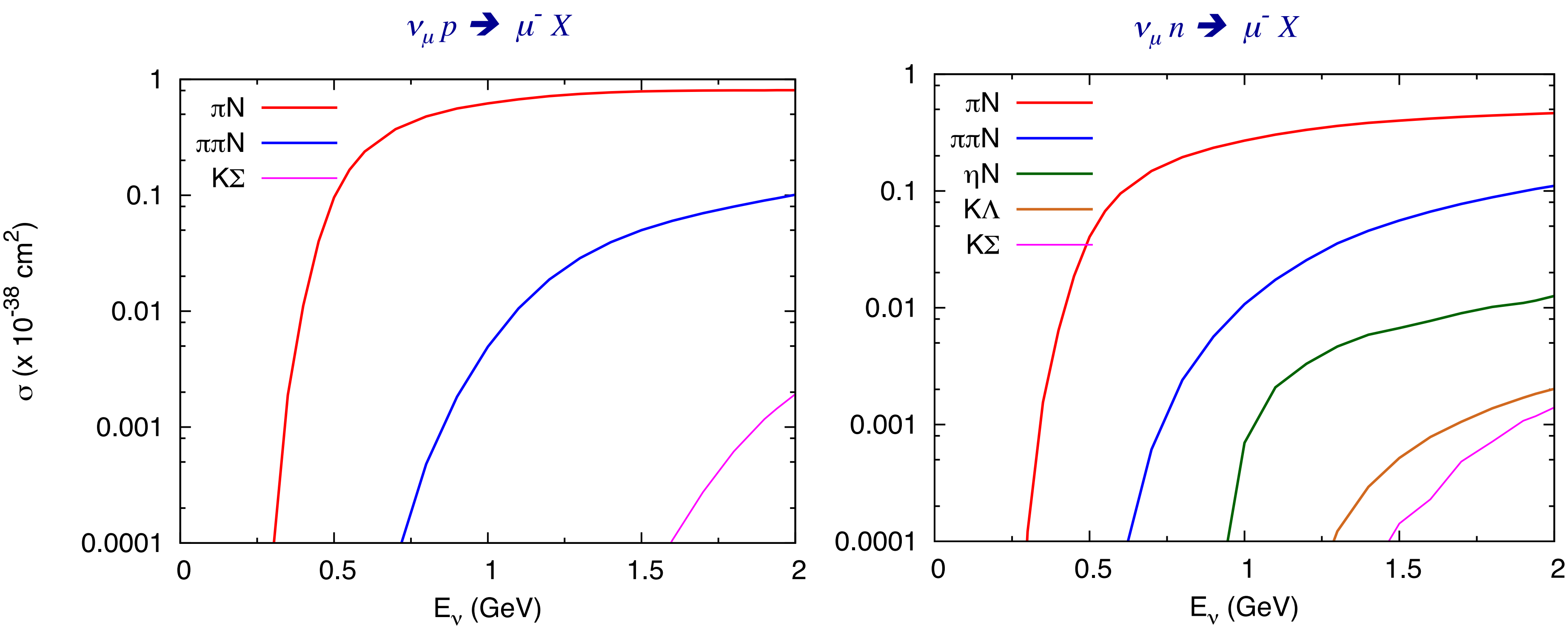
Cross section for $\nu_\mu N \rightarrow \mu^- X$





- πN & $\pi\pi N$ are main channels in few-GeV region
- 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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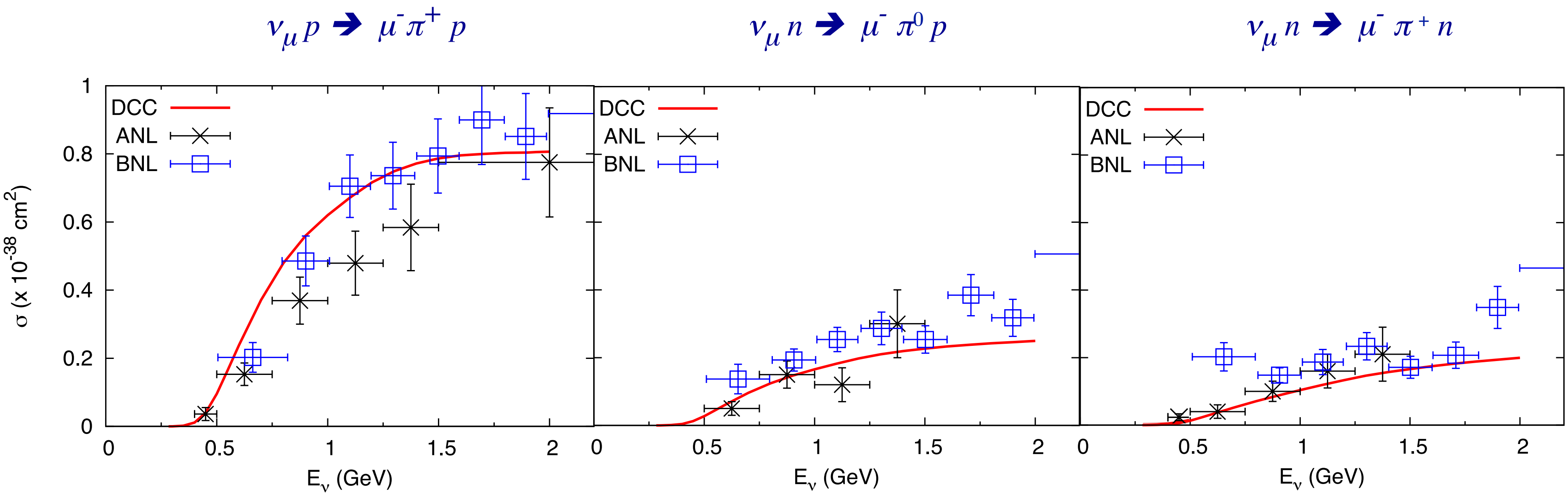
Comparison with single pion data



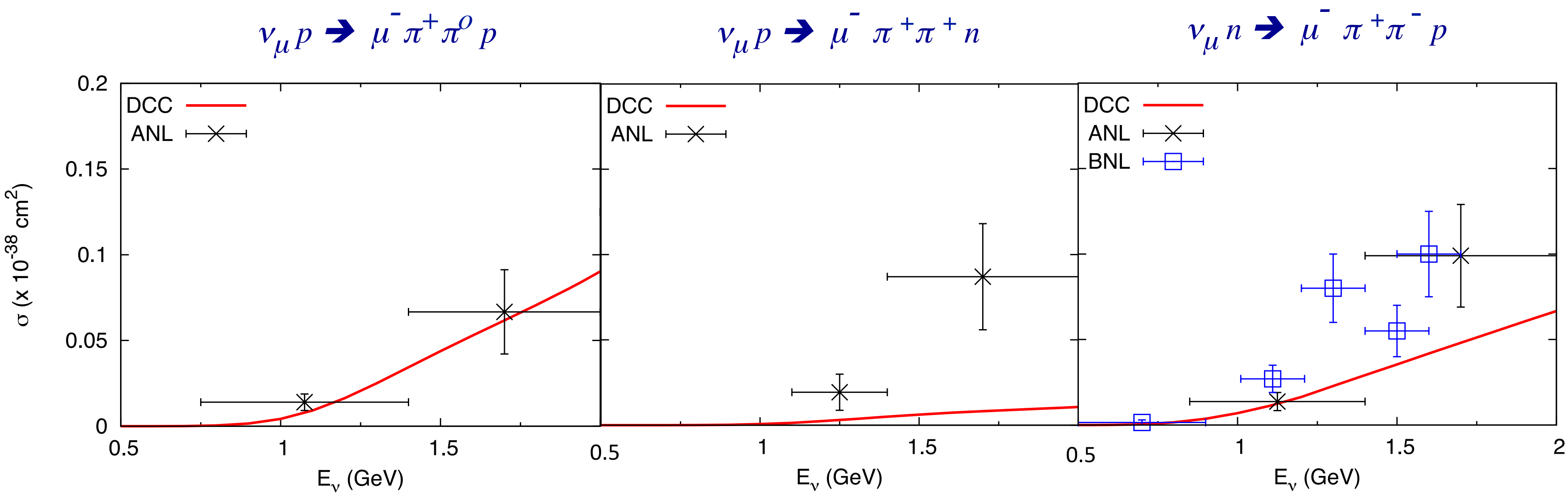
DCC model prediction is consistent with data

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

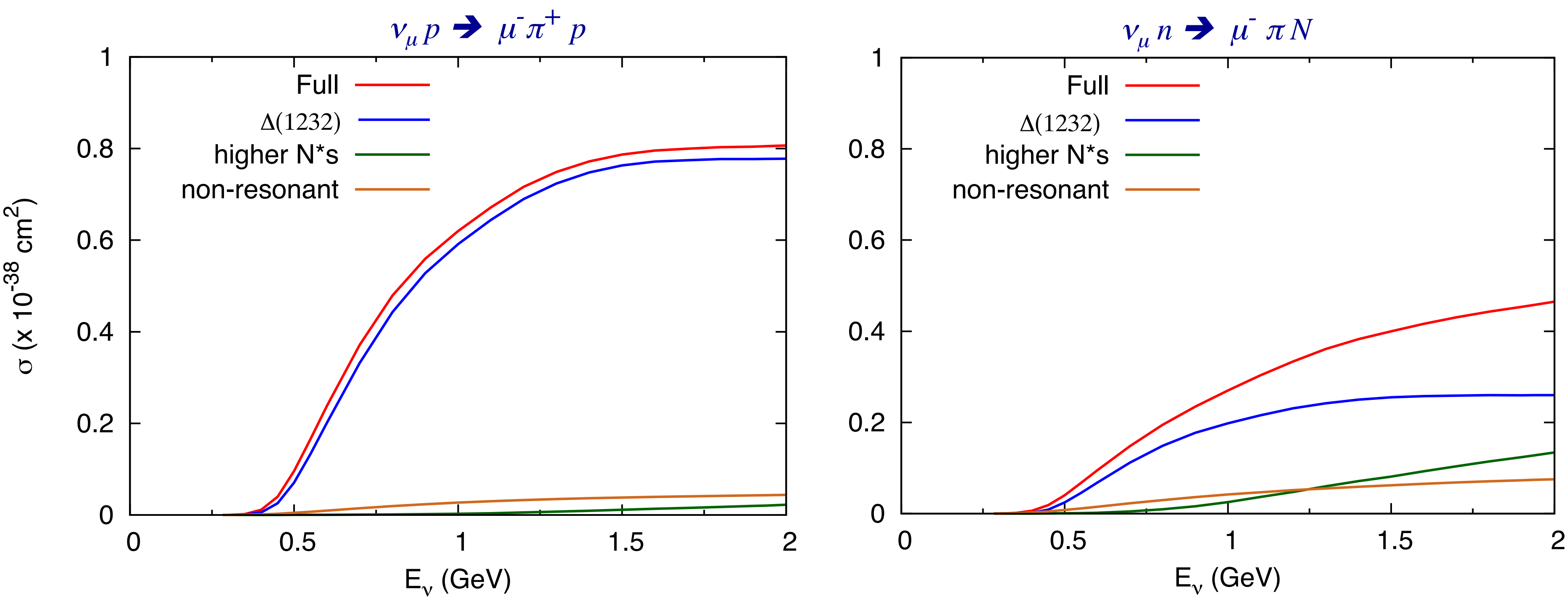


Fairly good DCC predication

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

- First microscopic model for 2 π production in resonance region
- 2 π production model is becoming available

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

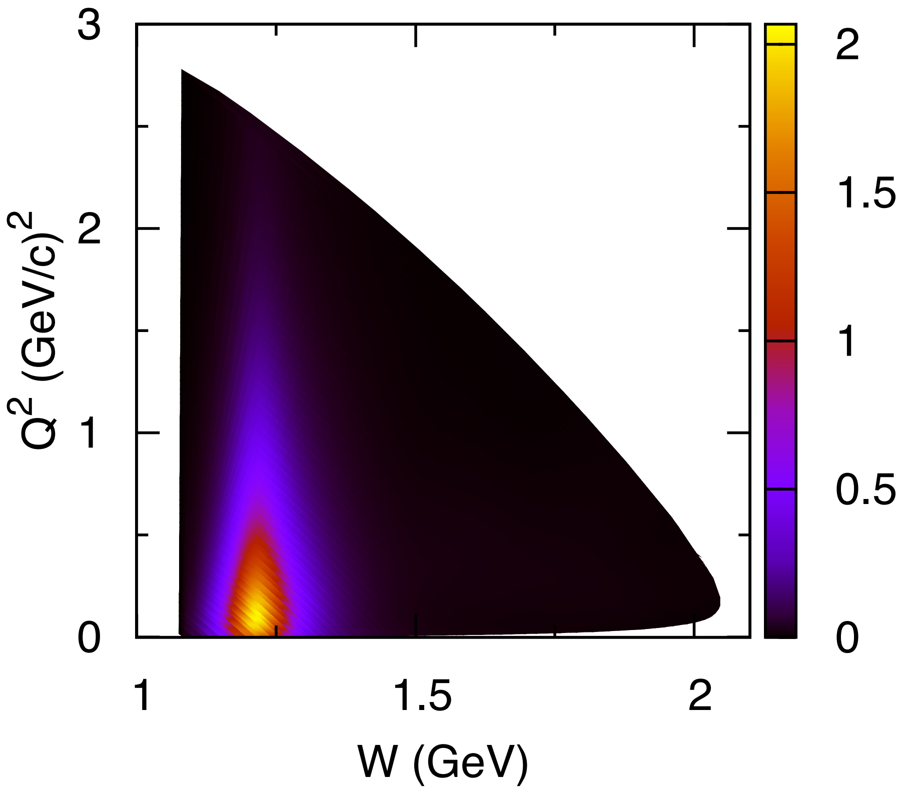


- Δ(1232) dominates for $\nu_\mu p \rightarrow \mu^- \pi^+ p$ $(I=3/2)$ for $E_\nu \leq 2$ GeV
- Non-resonant mechanisms contribute significantly
- Higher N^*s becomes important towards $E_\nu \approx 2$ GeV for $\nu_\mu n \rightarrow \mu^- \pi N$

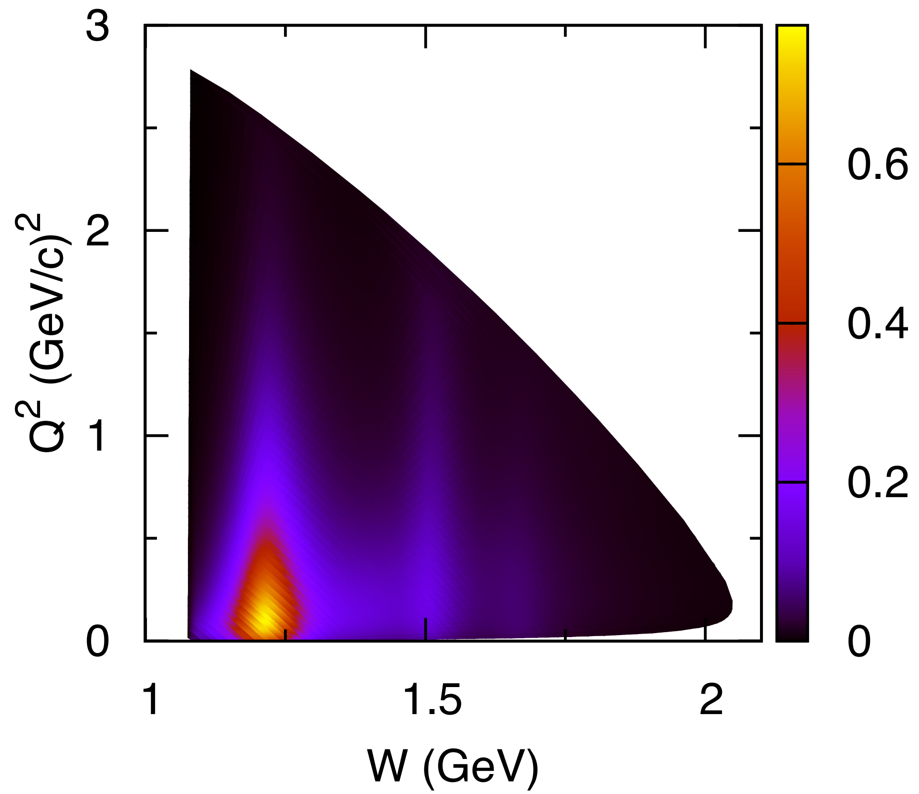
$d\sigma / dW\, dQ^2$ ($\times 10^{-38}$ cm^2 / GeV^2)

E_ν = 2 GeV

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



$\nu_\mu n \rightarrow \mu^- \pi\pi N$



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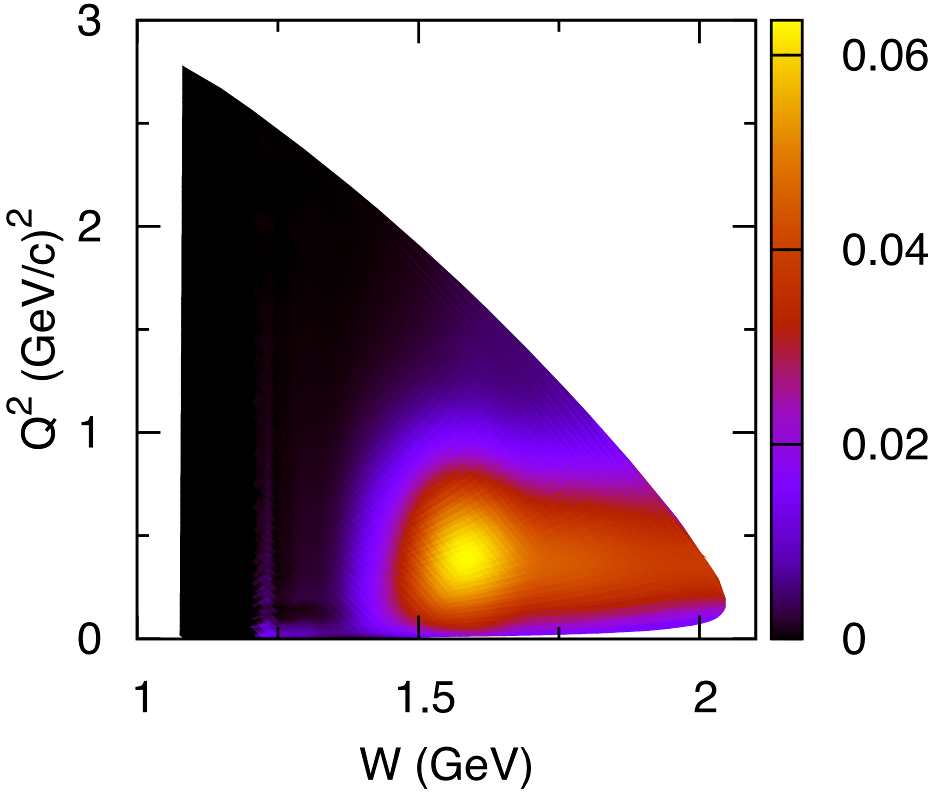
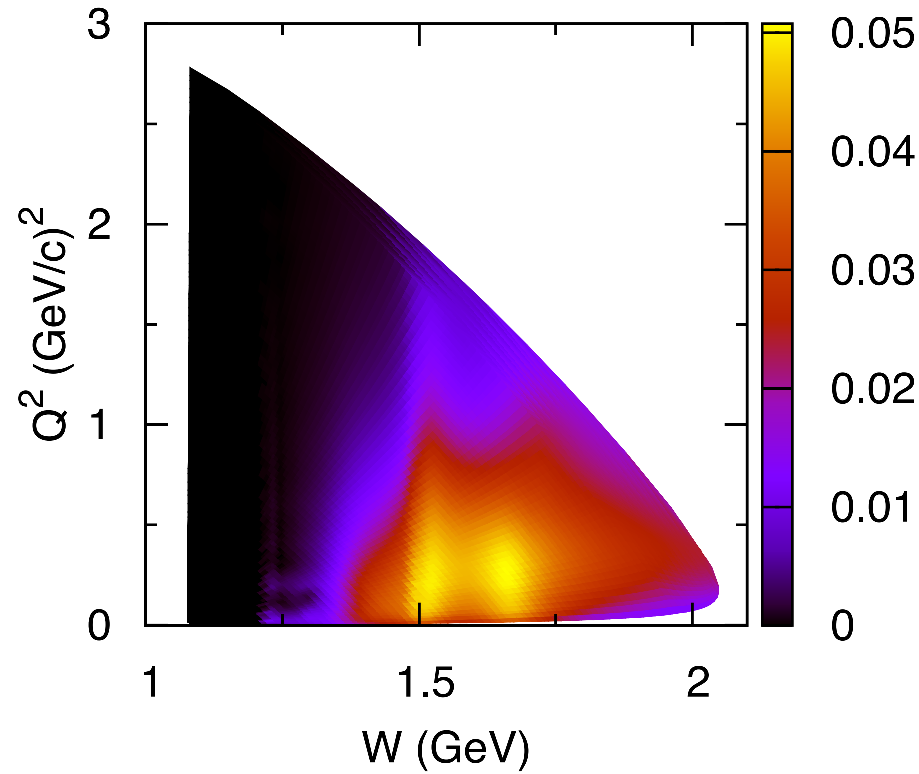


$\nu_\mu n \rightarrow \mu^- \pi\pi N$



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