Neutrino-interaction in the resonance region (transition)

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T.-S.H. Lee (Argonne Nat'l Lab).

Contents

★ Introduction ν interaction in resonance region

★ Dynamical coupled-channels (DCC) model for

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

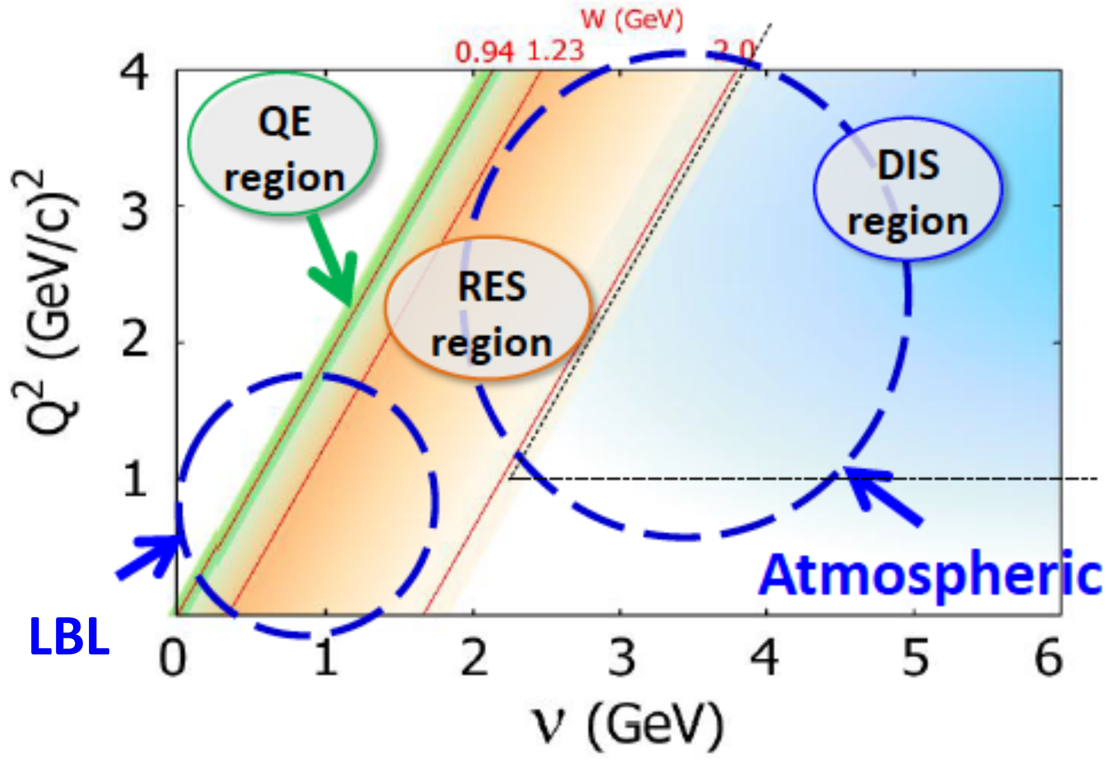
extended to $\nu N \rightarrow \pi N, \pi\pi N, \eta N, K\Lambda, K\Sigma$

★ Future plan

matching with DIS cf. quark-hadron duality

ν −nucleus interaction

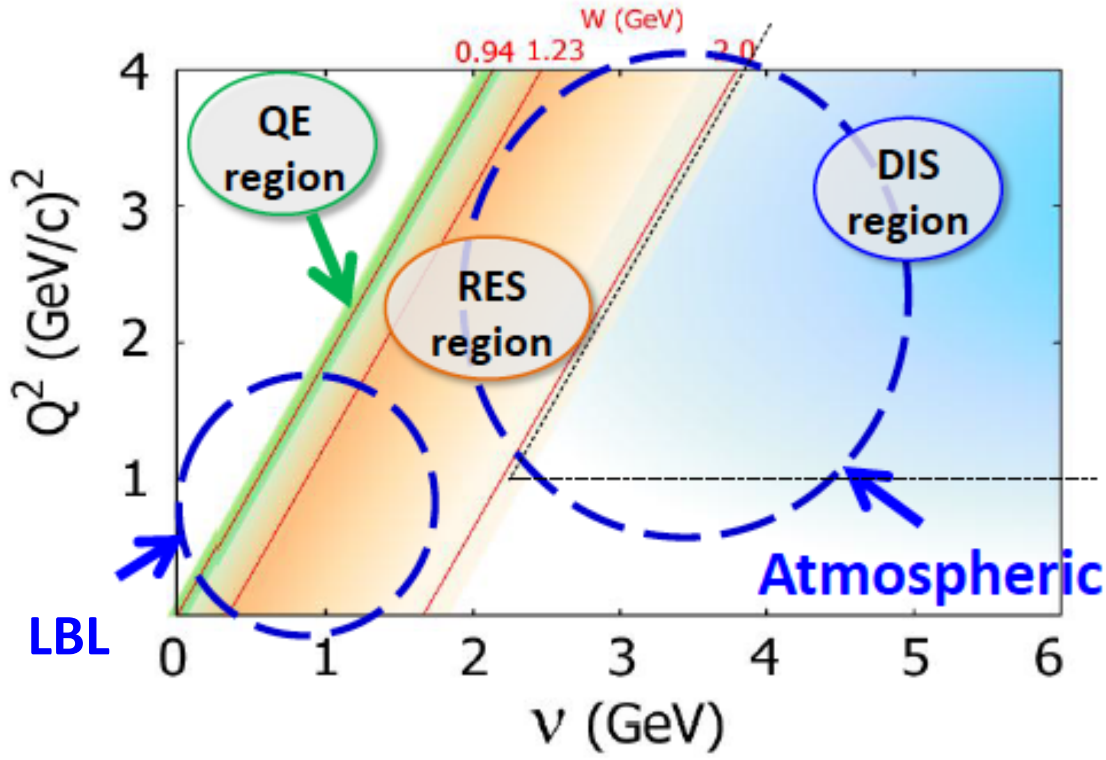
ν-interaction (kinematics & characteristics)



Collaboration at J-PARC Branch of KEK Theory Center

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

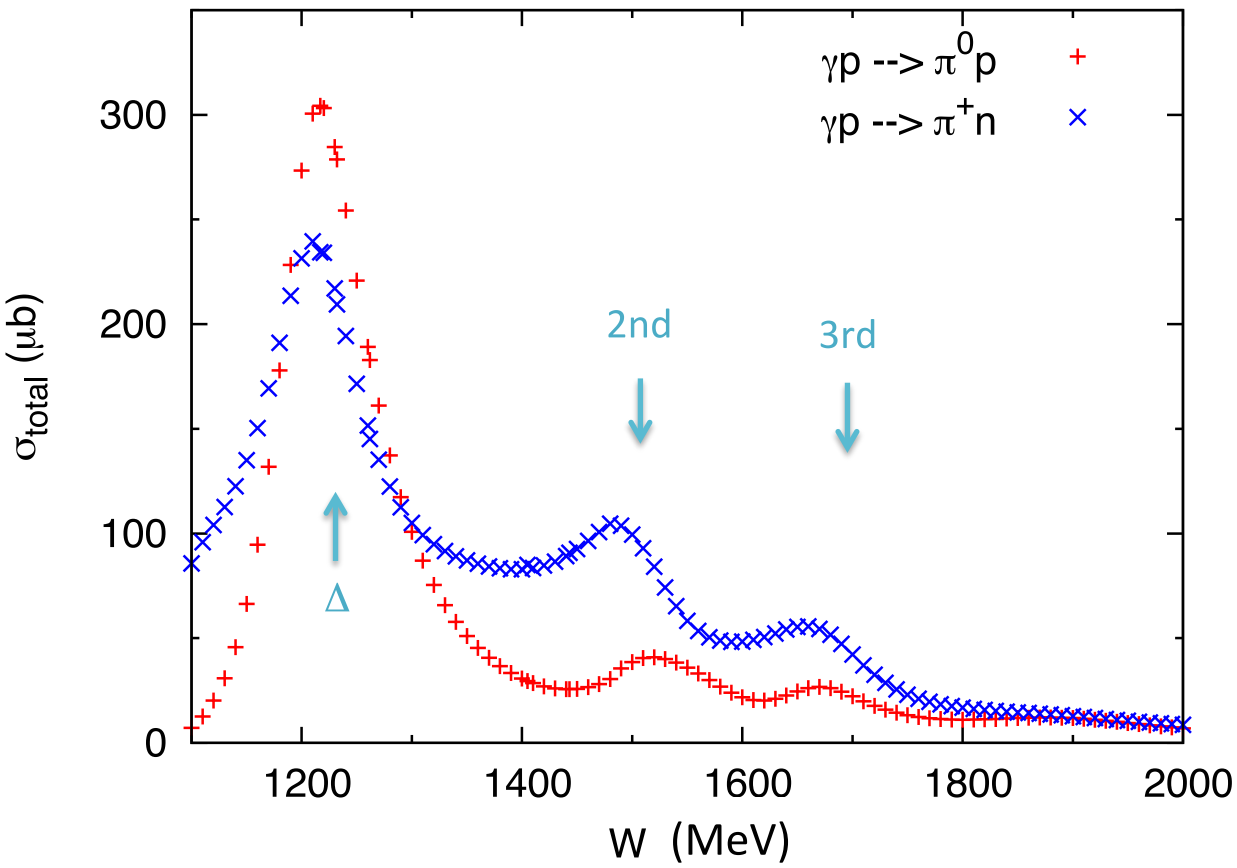
ν-interaction (kinematics & characteristics)



Wide kinematical region with different characteristic

➔ Combination of different expertise is necessary

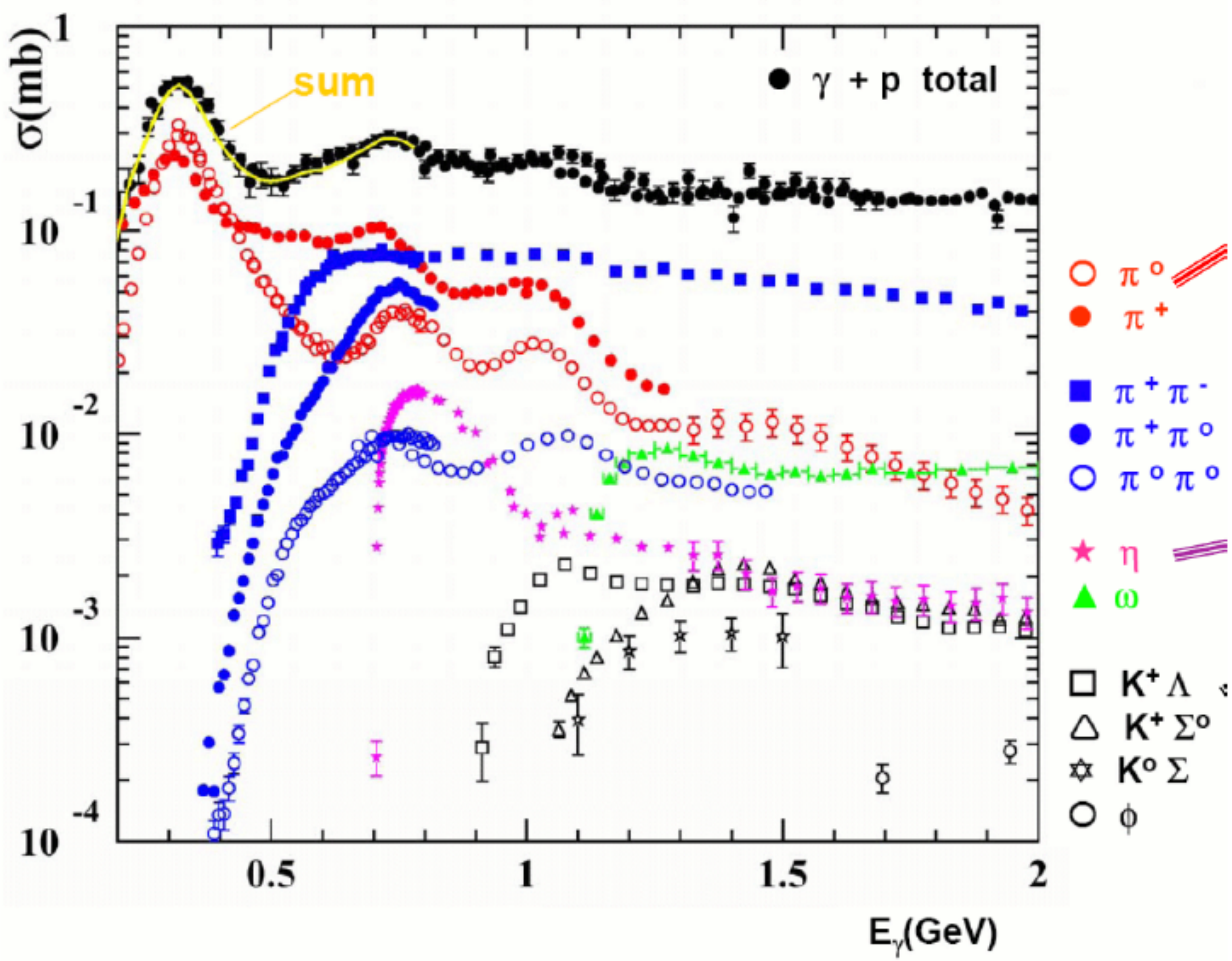
Resonance region



Many nucleon resonances in 2nd and 3rd resonance region

Not only 1π production but also …

Resonance region



Multi-channel reaction

- 2π production is comparable to 1π
- η, K productions (background of proton decay exp.)

Theoretical approach to ν -interaction in resonance region

- PCAC (partially conserved axial current)

  at $Q^2=0$, axial coupling ➔ pion coupling

  Paschos et al. (2011); Kamano et al. (2012)

- Microscopic model

  resonant and non-resonant hadronic interactions

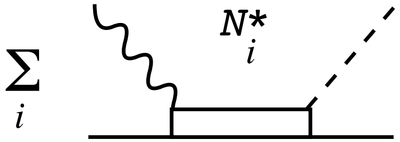
  Rein et al. (1981), (1987) ; Lalalulich et al. (2005), (2006) ;

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

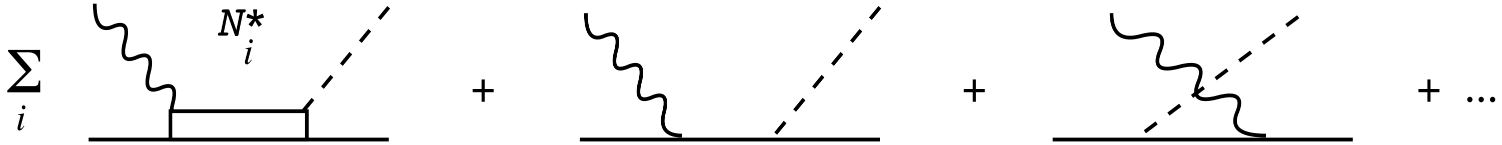
  Sato et al. (2003), (2005) ; …

Microscopic models for ν–induced 1π production

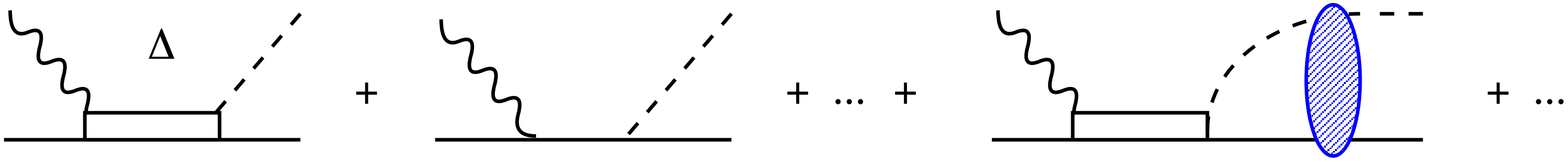
resonant only   Rein et al. (1981), (1987) ;   Lalalulich et al. (2005), (2006)



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



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



Dealing with multi-channel reaction

Problems

- Unitarity is missing in previous models
- Important 2 π production model is missing
- Previous models for K and η production are not well tested by data

to overcome the problems…

We develop Unitary coupled-channel 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 $\nu N \rightarrow \pi N, \pi\pi N, \eta N, K\Lambda, K\Sigma$

DCC model for

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

Kamano, Nakamura, Lee, Sato, PRC 88, 035209 (2013)

DCC (Dynamical Coupled-Channel) model

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

Coupled-channel Lippmann-Schwinger equation

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

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

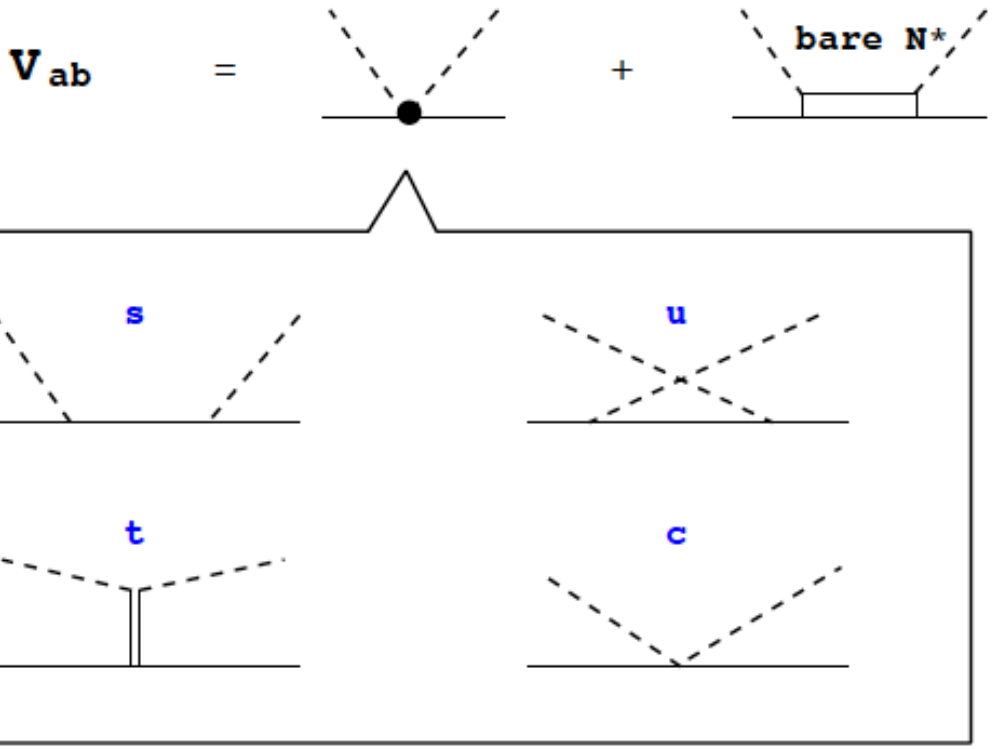
Coupled-channel, 2&3-body unitarity is taken into acount

DCC (Dynamical Coupled-Channel) model

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

Coupled-channel Lippmann-Schwinger equation

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



DCC analysis of meson production data

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

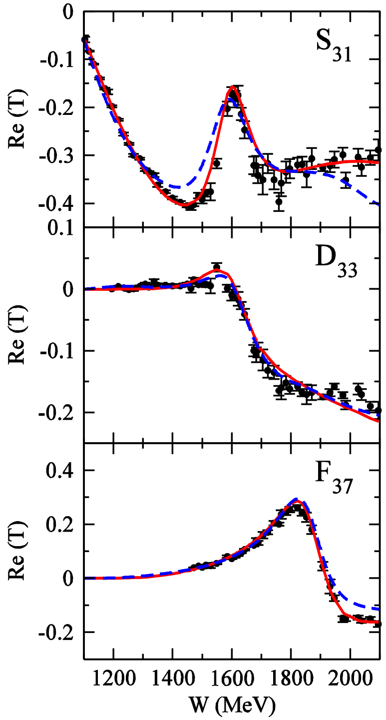
Fully combined analysis of $\gamma N, \pi N \rightarrow \pi N, \eta N, K\Lambda, K\Sigma$

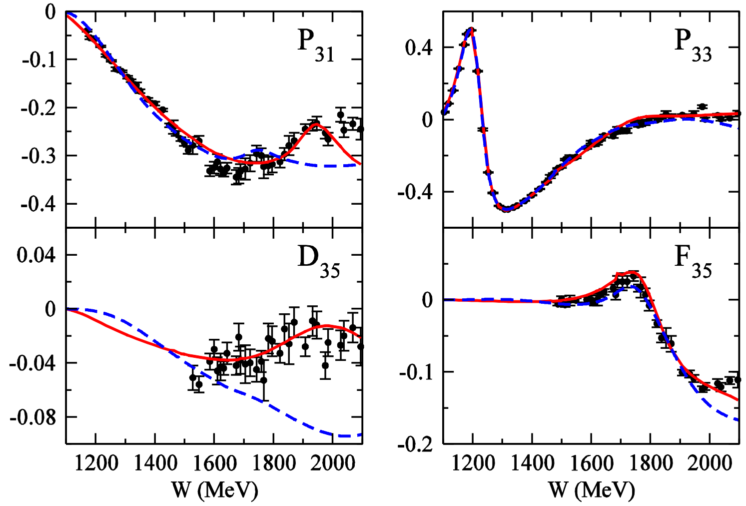
(W ≤ 2.1 GeV)

~380 parameters (N^* mass, $N^* \rightarrow MB$ couplings, cutoffs)

to fit ~ 20,000 data points

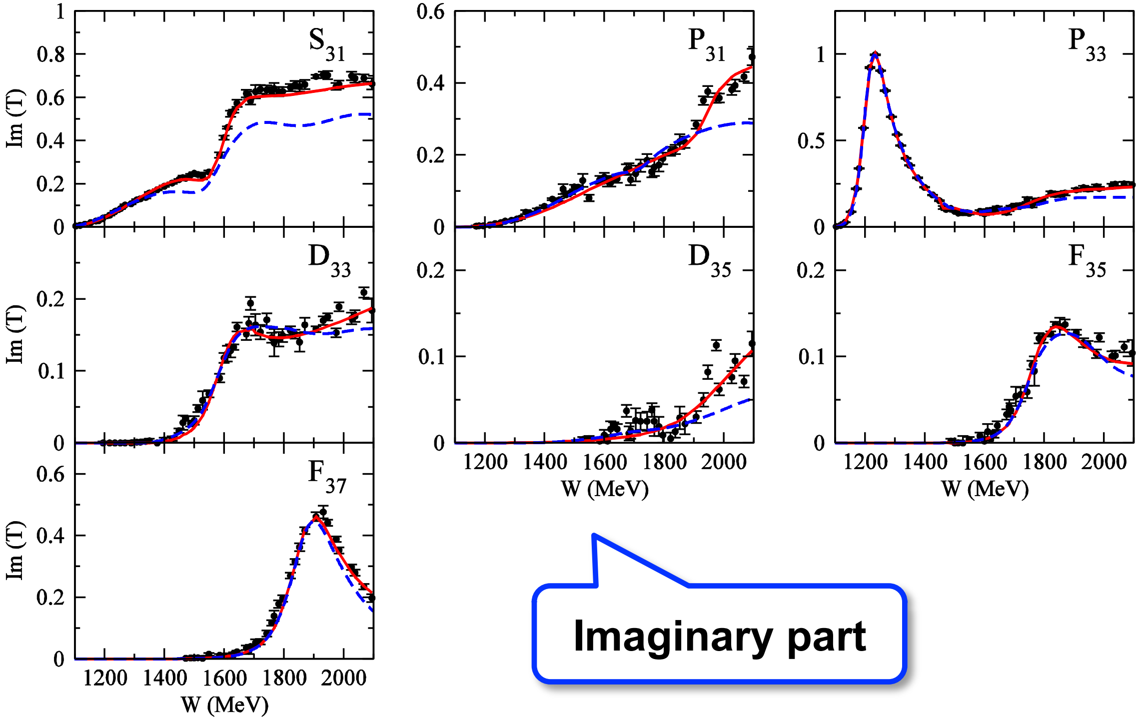
Partial wave amplitudes of pi N scattering





Real part

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

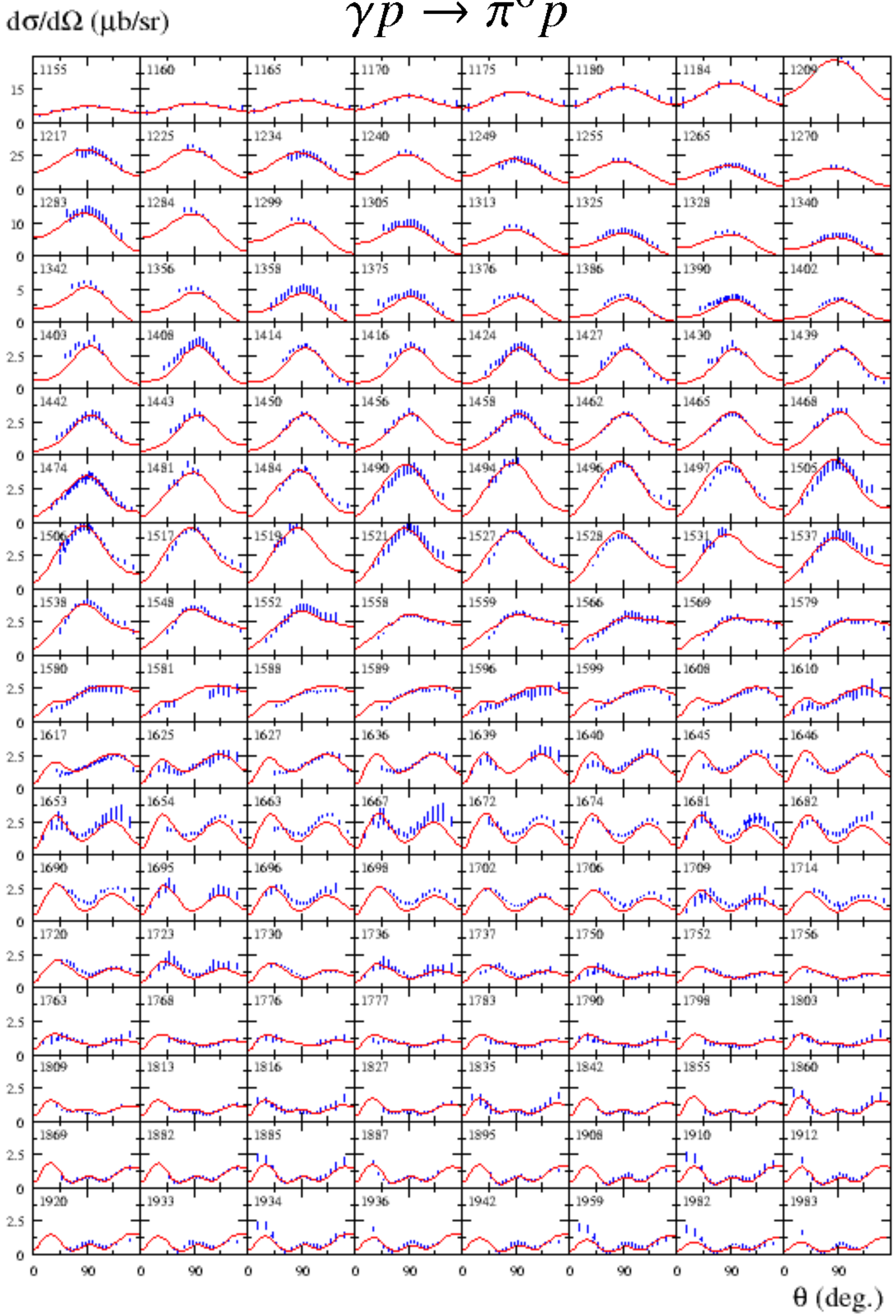


— **Kamano, Nakamura, Lee, Sato, 2013**

- - - **Previous model**
(fitted to $\pi N \to \pi N$ data only)
[PRC76 065201 (2007)]

Imaginary part

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



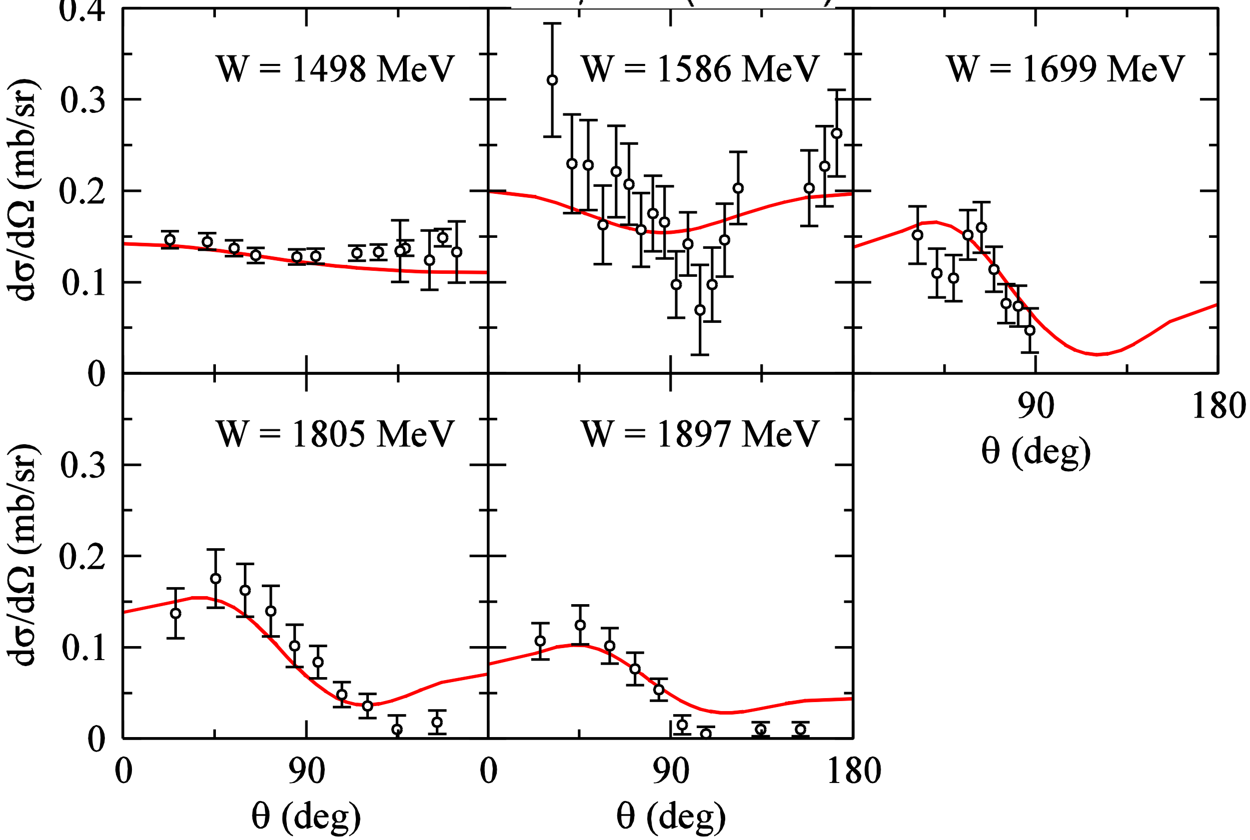
Vector current ($Q^2=0$) for 1π

Production is well-tested by data

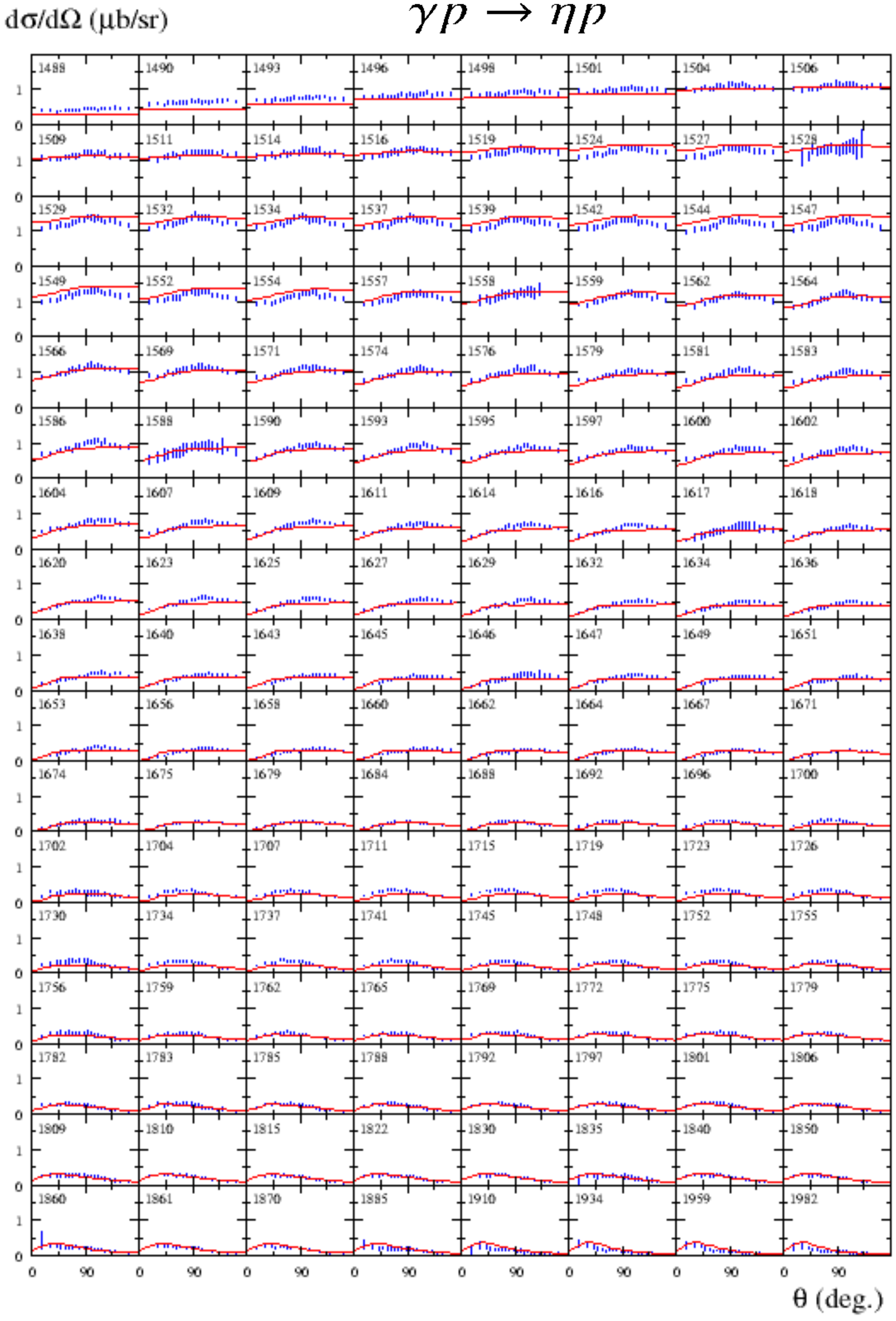
Eta production reactions

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

$d\sigma/d\Omega$ (mb/sr)



$\gamma p \to \eta p$

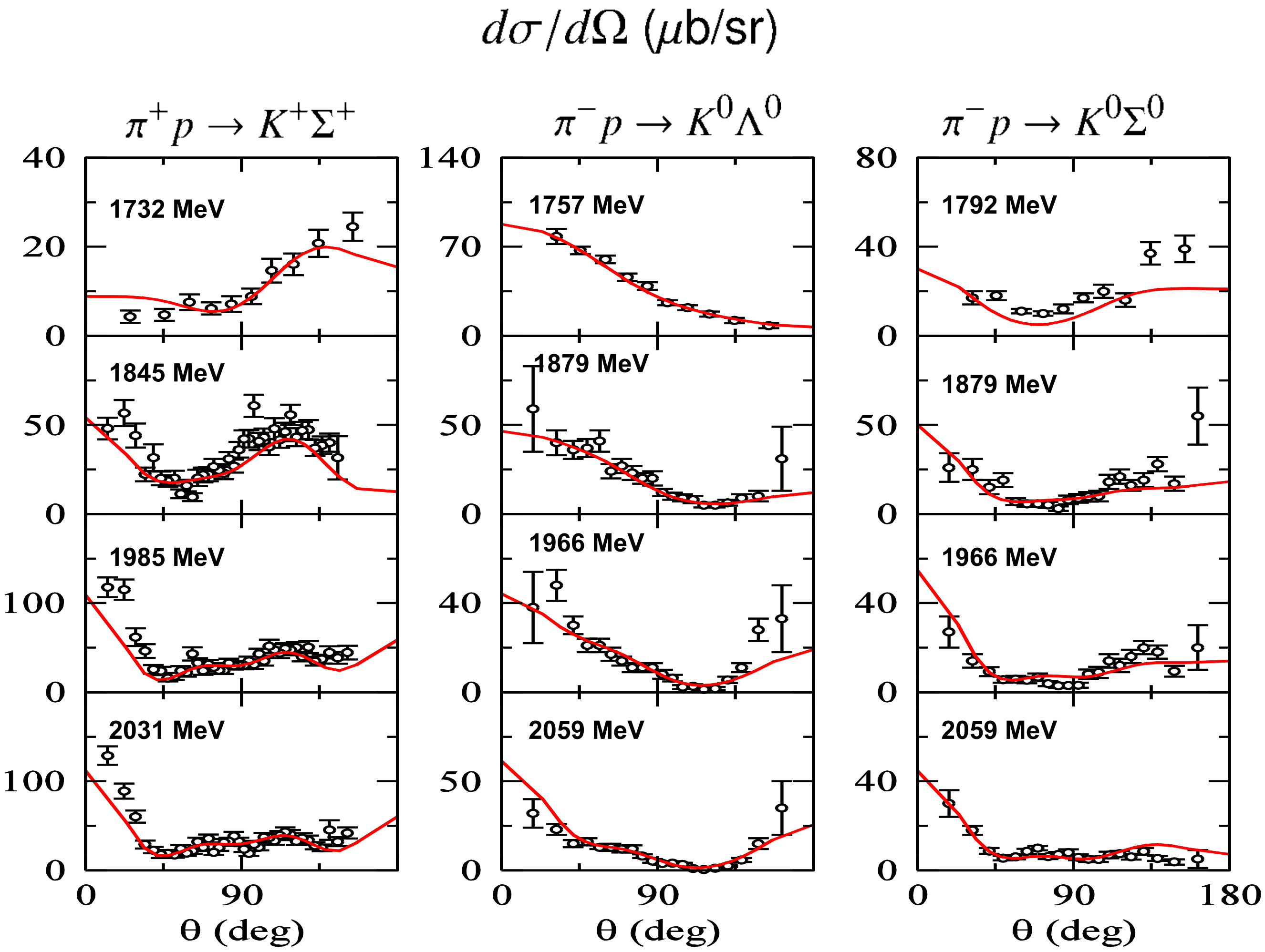


Kamano, Nakamura, Lee, Sato, 2013

Vector current (Q^2=0) for η

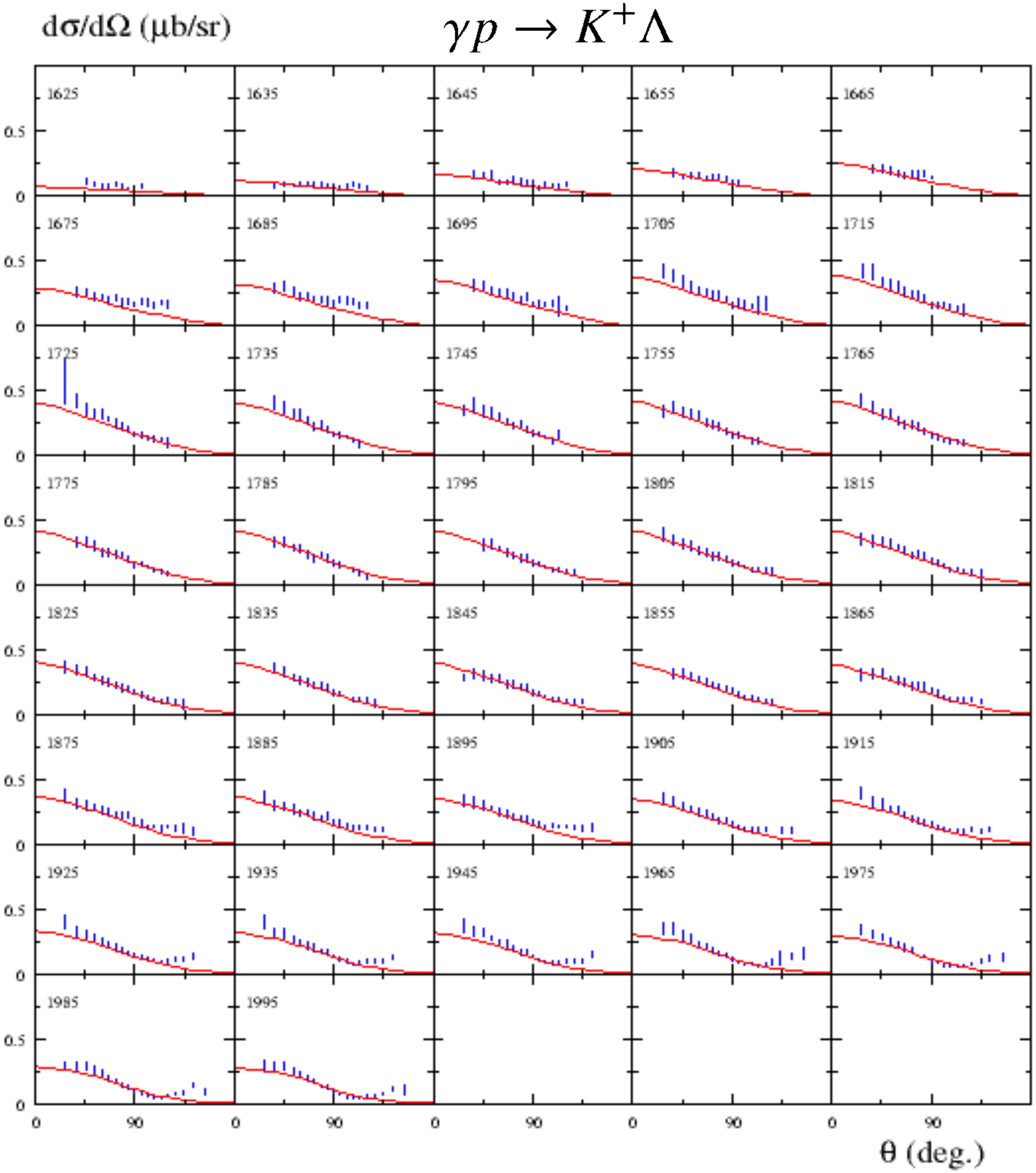
Production is well-tested by data

KY production reactions



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

Kamano, Nakamura, Lee, Sato, 2013



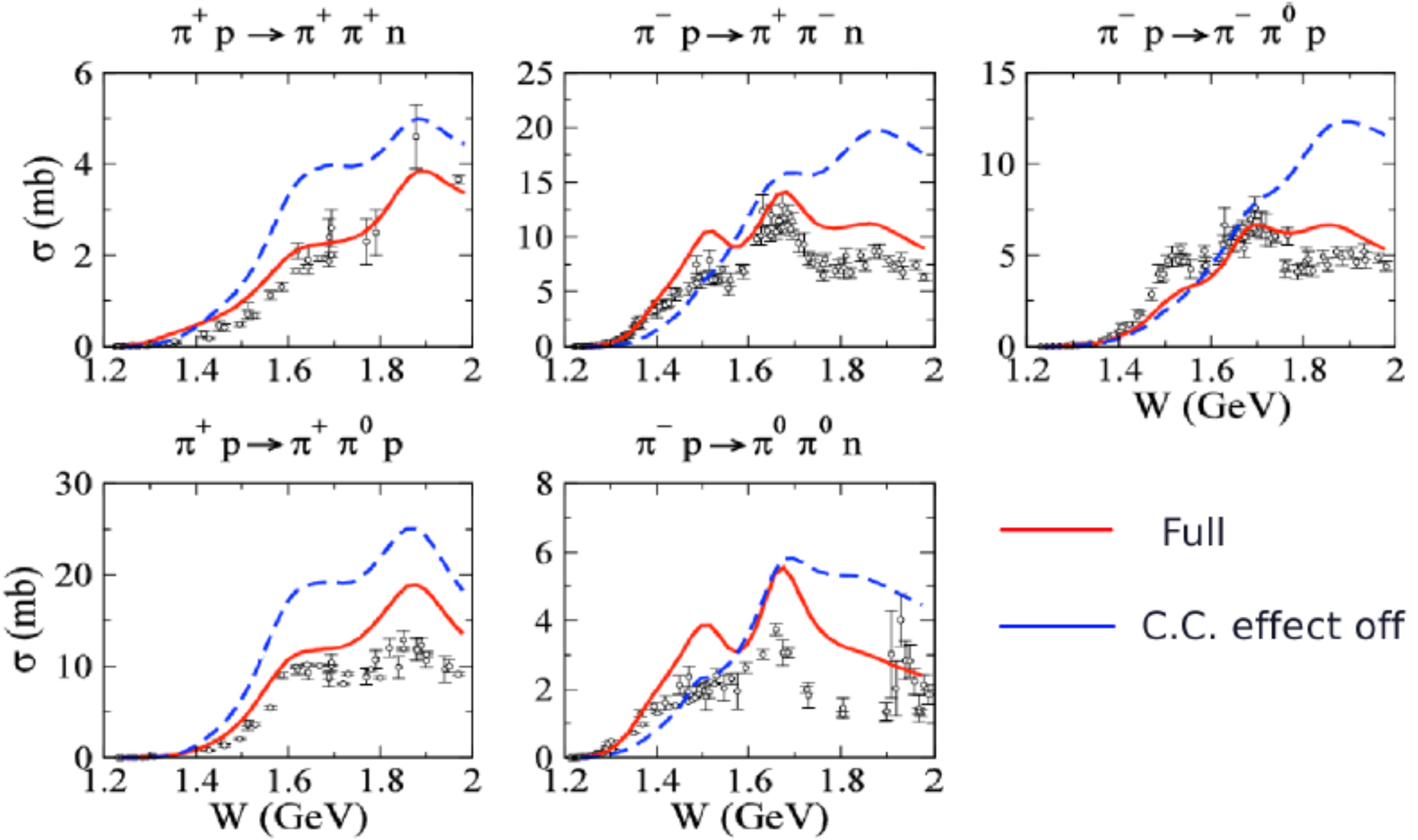
Vector current ($Q^2=0$) for K

Production is well-tested by data

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

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

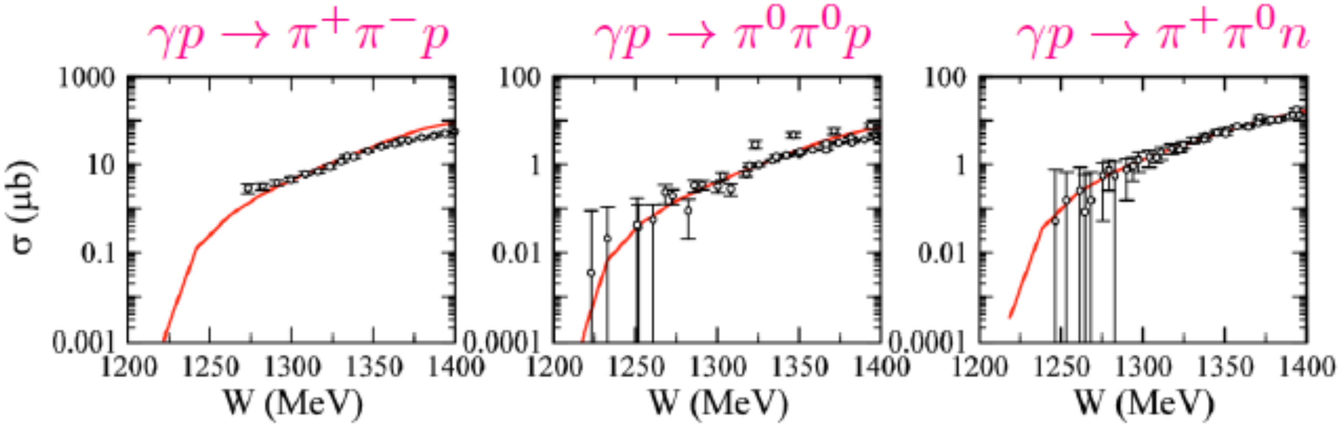
Kamano, Julia-Diaz, Lee, Matsuyama, Sato, PRC79 025206 (2009)

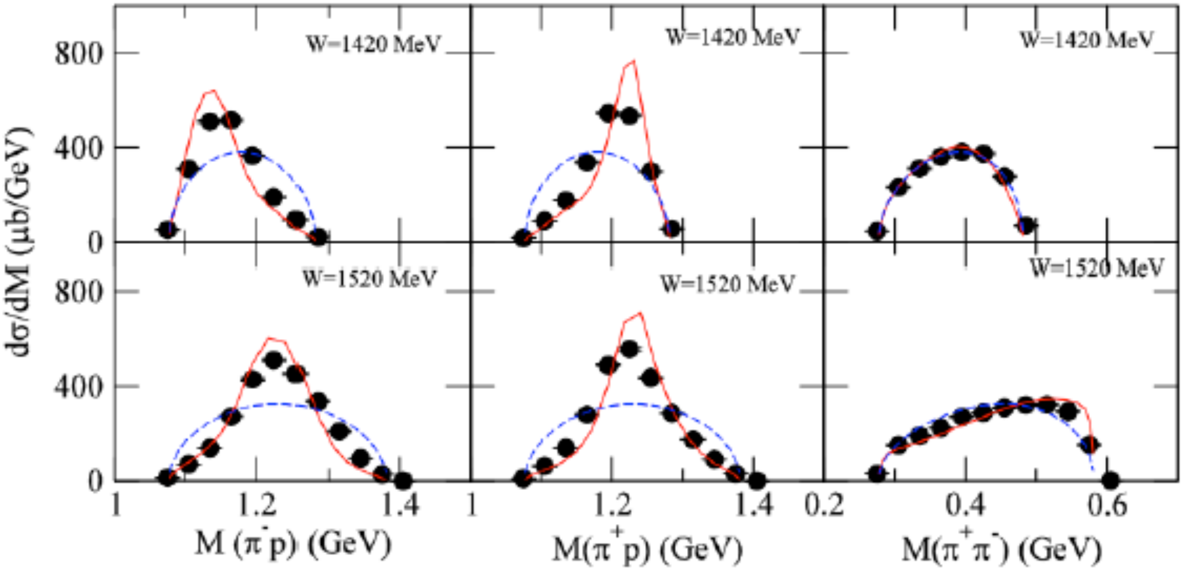


$\gamma N \to \pi\pi N$

(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

Short Summary

- νN scattering in resonance region is multi-channel reaction
- Unitary coupled-channels model is ideal
- DCC model for γN, πN → πN, $\pi\pi N$, ηN, $K\Lambda$, $K\Sigma$ is developed
- Model is extensively tested by γN, πN → πN, $\pi\pi N$, ηN, $K\Lambda$, $K\Sigma$

  data → reliable vector current to be applied to ν-scattering

Extended DCC model for

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

1. PCAC-based calculation (Q^2=0) Kamano, Nakamura, Lee, Sato, PRD 86, 097503 (2012)
2. Dynamical axial current (strategy)
3. Photon emission in NC process (some comments)

PCAC-based calculation for forward scattering of

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

Kamano et al., PRD 86, 097503 (2012)

Cf. Paschos et al., arXiv:1212.4662

Objectives

- Set a starting point for full dynamical model
- Relative importance of different channels
- Comparison with Rein-Sehgal model

Formalism

Cross section for $\nu N \rightarrow X$ ($X = \pi N, \pi\pi N, \eta N, K\Lambda, K\Sigma$)

$\theta \rightarrow 0$

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

$Q^2 \rightarrow 0$

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

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

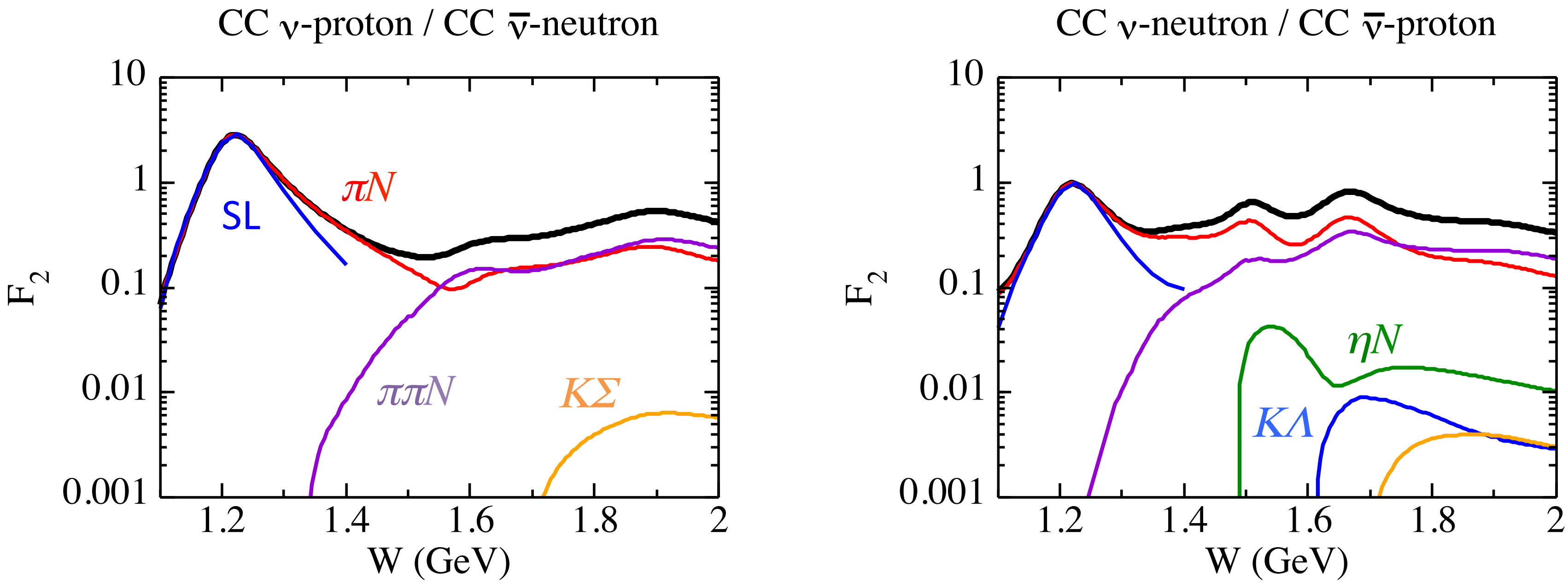
$$\langle X|\hat{\pi}|N\rangle = \frac{\sqrt{2\omega_c}}{m_\pi^2}T_{\pi N\to X}(0) \sim \frac{\sqrt{2\omega_c}}{m_\pi^2}T_{\pi N\to X}(m_\pi^2)$$

Finally

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

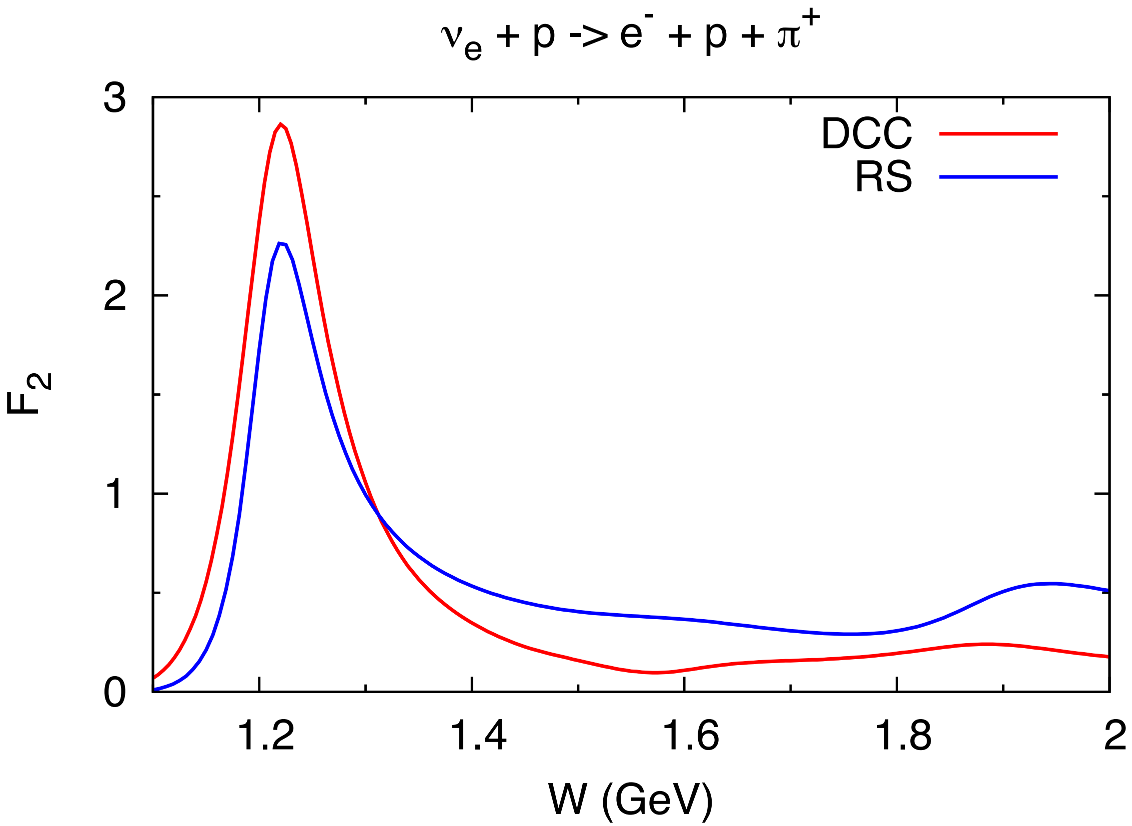
$\sigma_{\pi N \rightarrow X}$ is from our DCC model

Results



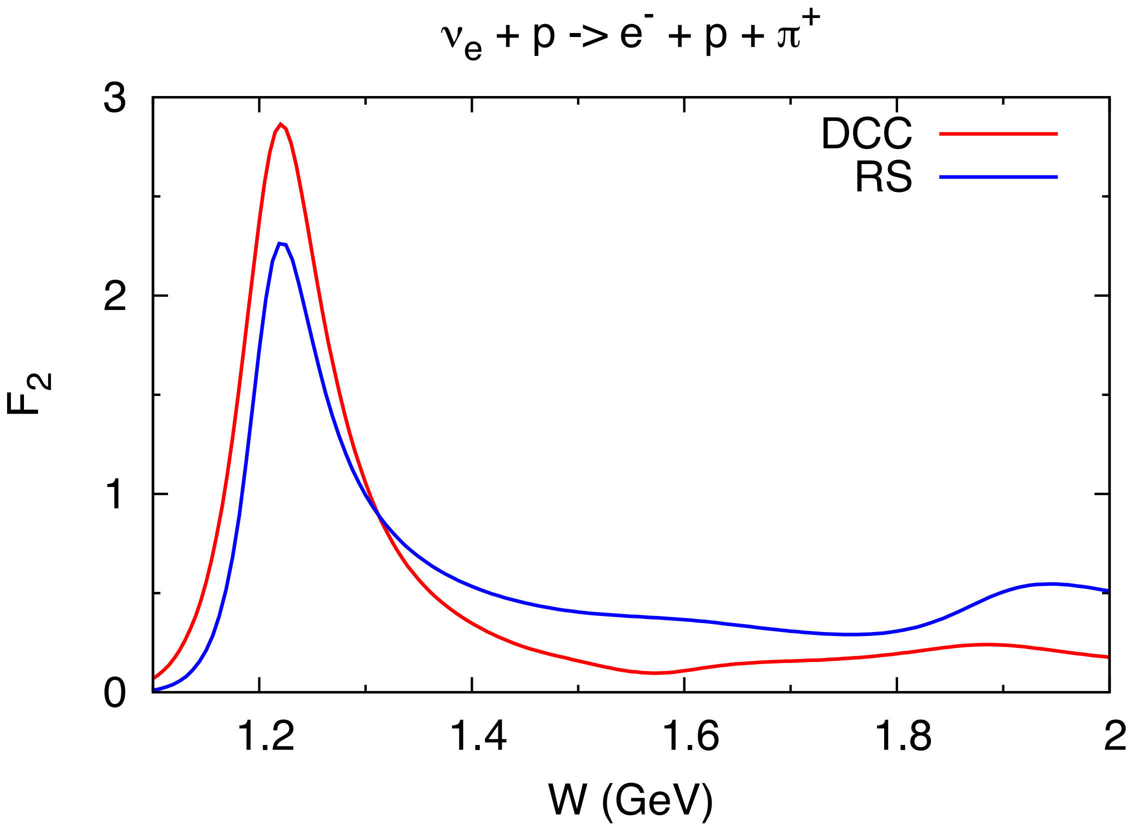
- Prediction based on model well tested by data
- πN dominates for $W \leq$ 1.5 GeV
- $\pi\pi N$ becomes comparable to πN for $W \geq$ 1.5 GeV
- Smaller contribution from ηN and KY $O(10^{-1})$ - $O(10^{-2})$
- Agreement with SL (no PCAC) in Δ region

Comparison with Rein-Sehgal model



- Lower Δ peak of RS model
- RS overestimate in higher energy regions (DCC model is tested by data)

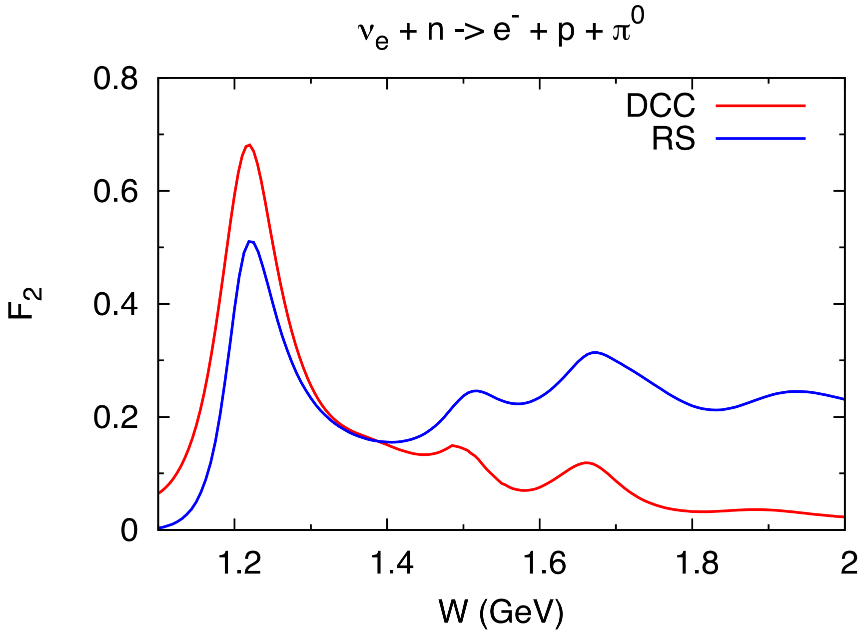
Comparison with Rein-Sehgal model

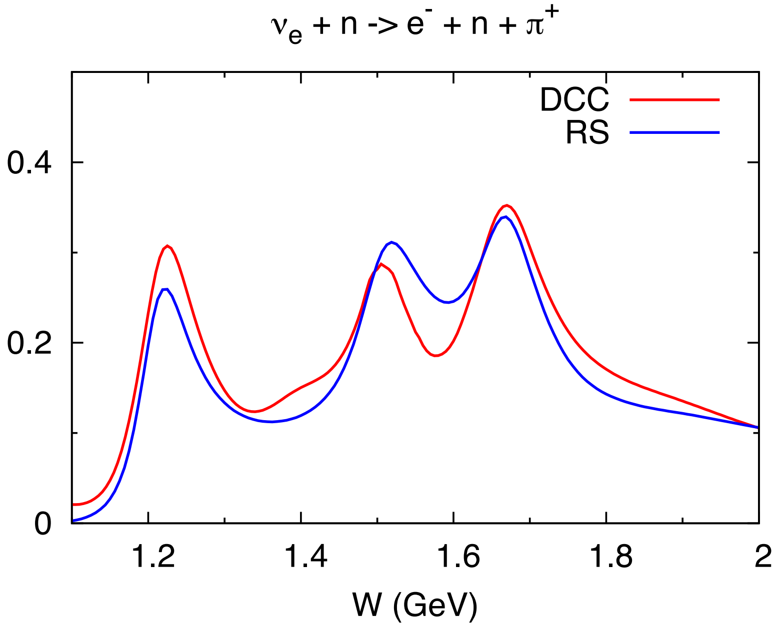


Similar findings by Leitner et al., PoS NUFACT08 (2008) 009

Graczyk et al., Phys.Rev. D77 (2008) 053001

Comparison with Rein-Sehgal model





Comparison in whole kinematical region will be done

after axial current model is developed

Short summary 2

DCC model for forward νN ➔ $\pi N, \pi\pi N, \eta N, K\Lambda, K\Sigma$ via PCAC

- Prediction based on model well tested by data
- $\pi\pi N$ comparable to πN for $W \geq 1.5$ GeV (first νN ➔ $\pi\pi N$)
- First νN ➔ $\eta N, KY$ based on data

Comparison with Rein-Sehgal model :

- RS has Lower Δ peak
- RS overestimates cross section at higher energies

Full DCC model for νN ➔ $\pi N, \pi\pi N, \eta N, K\Lambda, K\Sigma$

Kamano, Nakamura, Lee, Sato, in progress

Vector current

$Q^2=0$

γp ➔ MB analysis has been done

γn ➔ $\pi N, \eta n$ analysis is ongoing ➔ isospin separation

necessary for calculating ν-interaction

$Q^2\neq0$ (electromagnetic form factors for VNN^* couplings)

obtainable from $(e,e'\pi)$ data analysis (will be done soon)

Previous analysis of 1π electroproduction data

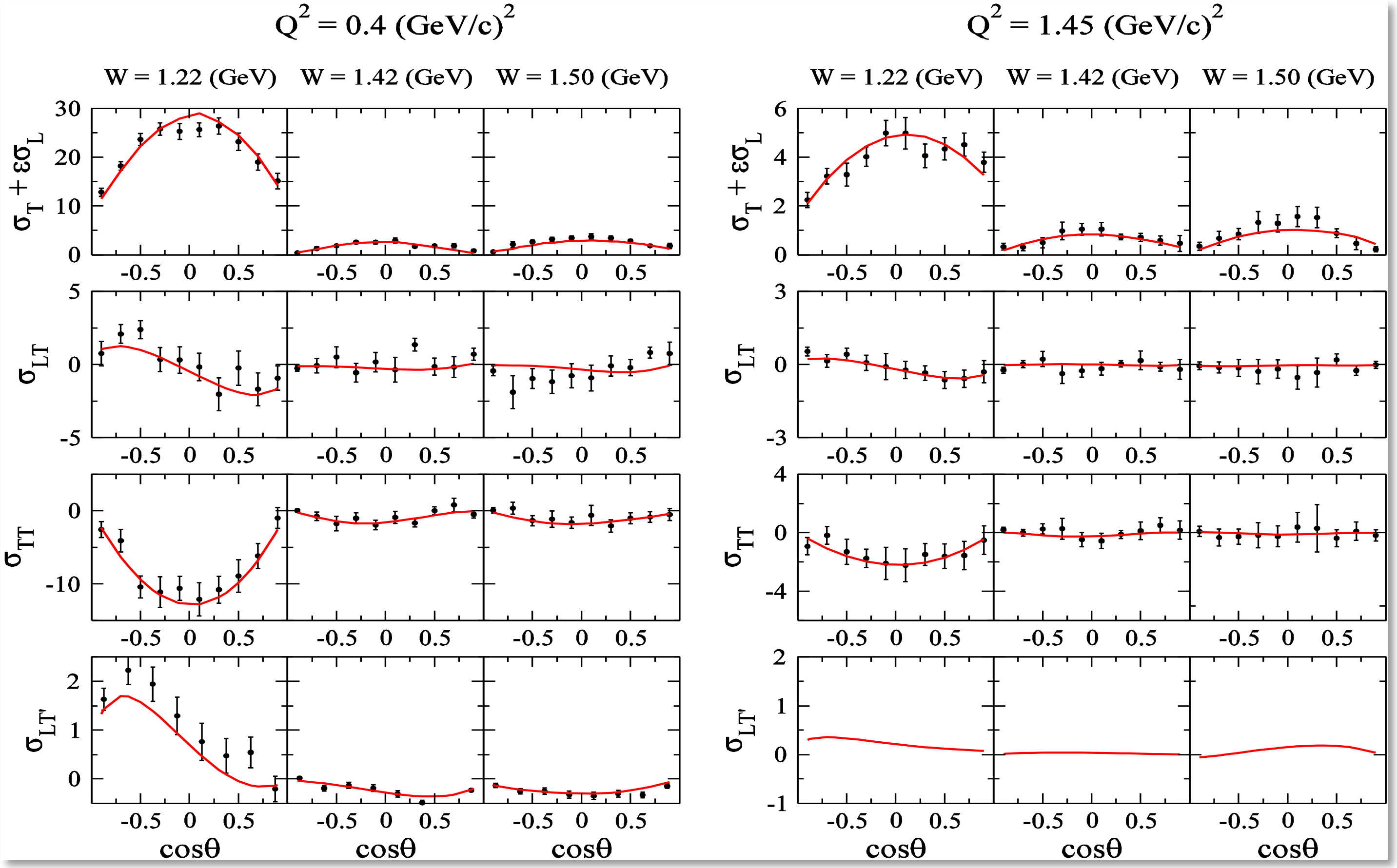
Juliz-Diaz et al., PRC 80, 025207 (2009)

Fit to structure functions from CLAS for $p\,(e,e'\,\pi)\,p$

$$\frac{d\sigma^5}{dE_{e'}d\Omega_{e'}d\Omega_\pi^*} = \Gamma_\gamma\left[\sigma_T + \epsilon\sigma_L + \sqrt{2\epsilon(1+\epsilon)}\sigma_{LT}\cos\phi_\pi^* + \epsilon\sigma_{TT}\cos 2\phi_\pi^* + h_e\sqrt{2\epsilon(1-\epsilon)}\sigma_{LT'}\sin\phi_\pi^*\right].$$

W < 1.6 GeV

$Q^2 < 1.5$ (GeV/c)^2



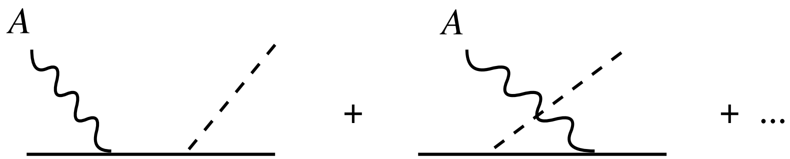
Full DCC model for νN ➔ $\pi N, \pi\pi N, \eta N, K\Lambda, K\Sigma$

Kamano, Nakamura, Lee, Sato, in progress

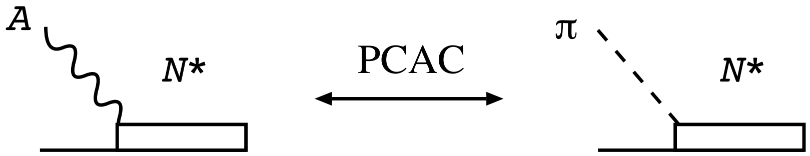
Axial current

Q^2=0

non-resonant mechanisms



resonant mechanisms

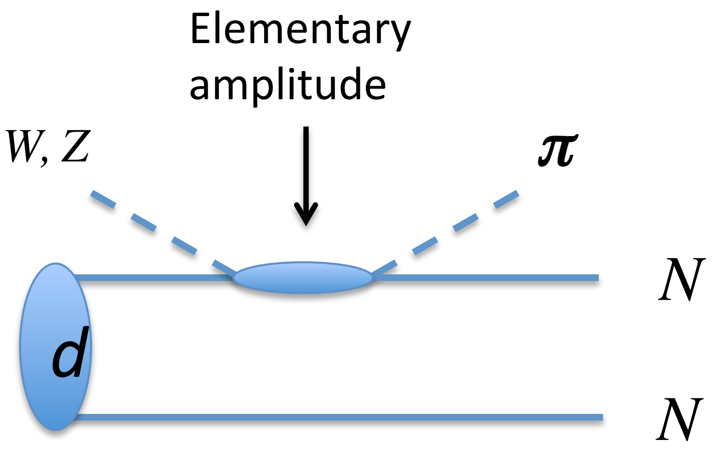


$Q^2 \neq 0$ (axial form factors of ANN^*)

experimental information is necessary to fix this

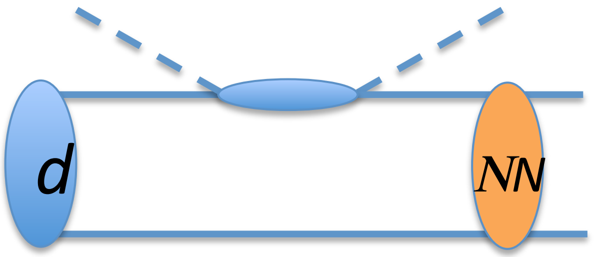
How to fix axial form factors of ANN^*

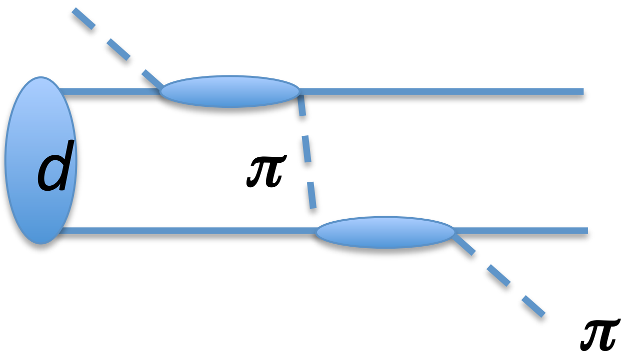
Neutrino data on deuteron from ANL and BNL $\nu_\mu d \rightarrow \mu^- NN \pi$



Fermi motion of deuteron
Hernandez et al., PRD 81 (2010)

Fermi motion of deuteron
+ rescattering effects
Jiajun and Lee in progress

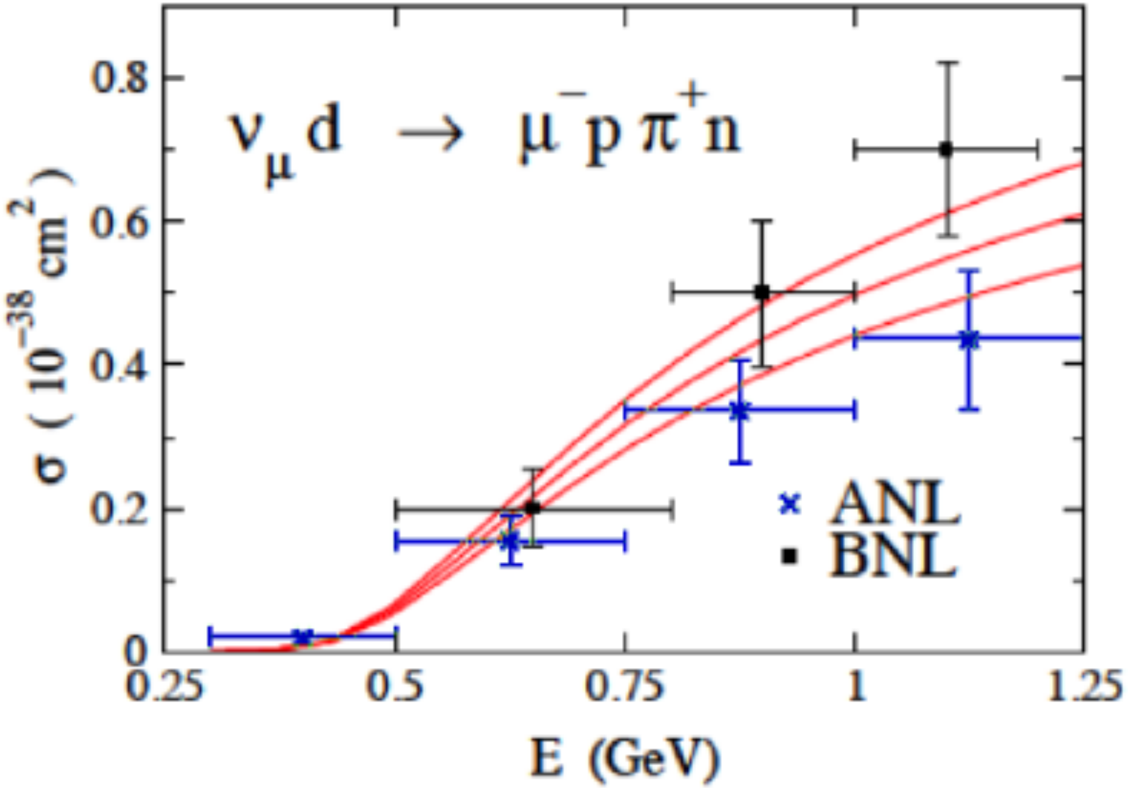




How to fix axial form factors of *ANN**

Neutrino data

Discrepancy of ANL and BNL data ➔ new deuterium data are highly hoped



$C_5^A(0)$ = 1.00 ± 0.11

$M_{A\Delta}$ = 0.93 ± 0.07 (GeV)

Hernandez et al., PRD 76 (2006); 81 (2010)

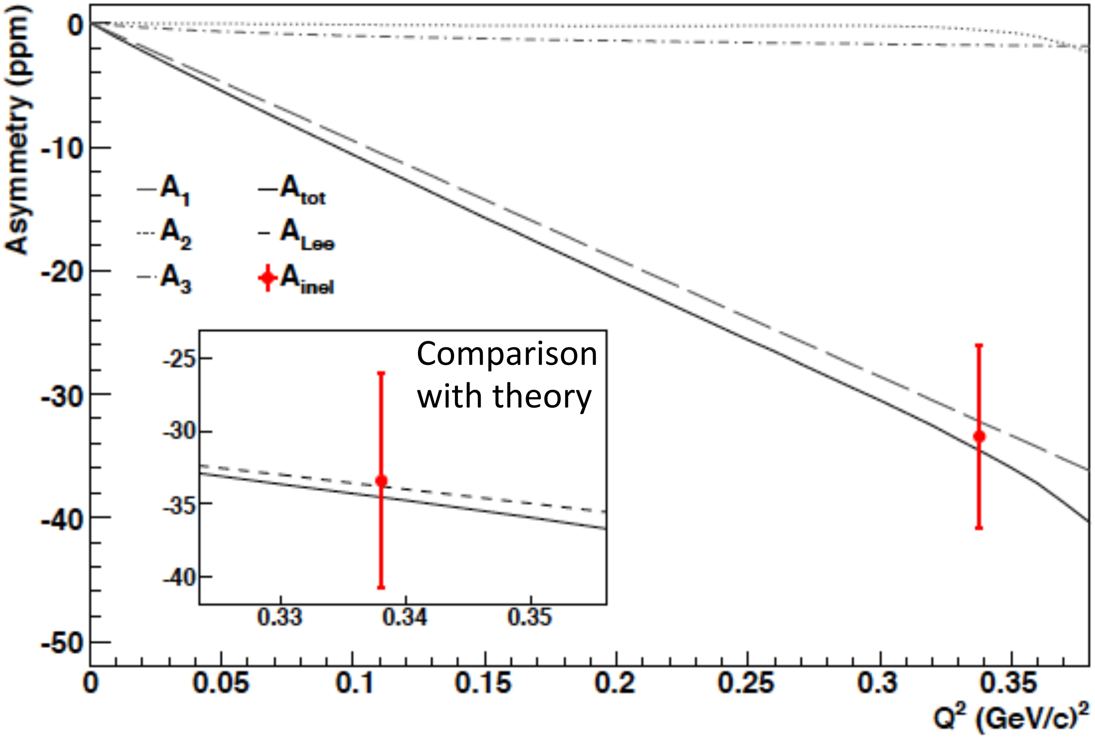
How to fix axial form factors of *ANN**

Electron data : parity violation asymmetry

G⁰@JLab, arXiv:1212.163

$$A = \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L}$$

$$G^A_{N\Delta}(Q^2) = \frac{1}{2}[M^2 - M^2_\Delta + Q^2]C^A_4(Q^2) - M^2 C^A_5(Q^2)$$



$$G^A_{N\Delta}(Q^2) = -0.05 \pm (0.35)_{\rm stat} \pm (0.34)_{\rm sys} \pm (0.06)_{\rm th}$$

Theory

$$G^A_{N\Delta}(Q^2) = -0.196$$

How to fix axial form factors of ANN^*

Quark-hadron duality : coming back to this later

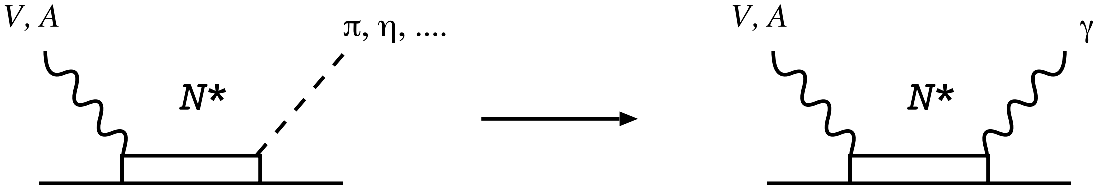
Photon emission in NC

Δ−Region : Hill (2010), Zhang et al. (2012)

Δ+2nd resonance : Wang et al. (2013)

Relevant to T2K and MiniBooNE

With our DCC model



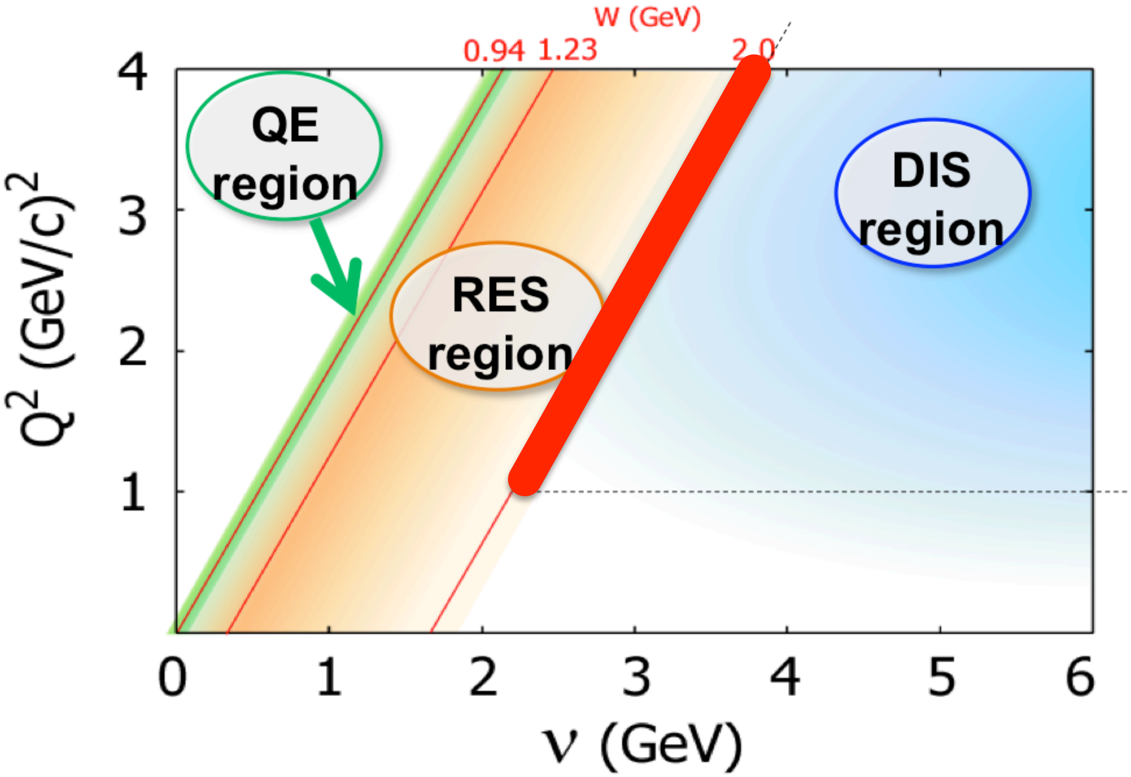
Photon emission in higher N region relevant to future experiments ??*

Matching with DIS

Purposes:

- Make sure smooth transition from RES to DIS (electron scattering)
- Fix axial form factors of ANN^* (neutrino scattering)

Matching with DIS



Matching with DIS

N(e, e')

$$\frac{d\sigma}{d\Omega dE'} = \frac{4\alpha^2 E'^2}{Q^4}[2W_1 \sin^2\frac{\theta}{2} + W_2 \cos^2\frac{\theta}{2}]$$

N(ν, l')

$$\frac{d\sigma^{\nu,\bar{\nu}}}{dE'd\Omega'} = \frac{G_F^2 \mid V_{ud} \mid^2}{2\pi^2} E'^2[2W_1 \sin^2\frac{\theta}{2} + W_2 \cos^2\frac{\theta}{2} \pm W_3 \frac{E+E'}{m_N} \sin^2\frac{\theta}{2}]$$

In terms of matrix elements of hadronic currents

$$\begin{aligned} W_1 &= \frac{1}{2}\sum[\mid < f \mid J^x_\alpha \mid i > \mid^2 + \mid < f \mid J^y_\alpha \mid i > \mid^2]\,, \\ W_2 &= \frac{Q^2}{\mathbf{q}^2}\sum[\frac{1}{2}(\mid < f \mid J^x_\alpha \mid i > \mid^2 + \mid < f \mid J^y_\alpha \mid i > \mid^2) + \frac{Q^2}{\mathbf{q}_c^2}\mid < f \mid \bar{J}_\alpha \mid i > \mid^2] \\ W_3 &= -\frac{2m_N}{\mid \mathbf{q} \mid}\sum Im[< f \mid J^x_\alpha \mid i >< f \mid J^y_\alpha \mid i >^*]\,, \end{aligned}$$

Matching with DIS

N(e, e')
$$\frac{d\sigma}{d\Omega dE'} = \frac{4\alpha^2 E'^2}{Q^4}[2W_1 \sin^2\frac{\theta}{2} + W_2 \cos^2\frac{\theta}{2}]$$

N(ν, l')
$$\frac{d\sigma^{\nu,\bar{\nu}}}{dE'd\Omega'} = \frac{G_F^2 \mid V_{ud} \mid^2}{2\pi^2} E'^2[2W_1 \sin^2\frac{\theta}{2} + W_2 \cos^2\frac{\theta}{2} \pm W_3 \frac{E+E'}{m_N} \sin^2\frac{\theta}{2}]$$

$$\begin{aligned} F_1(x,Q^2) &= m_N W_1(x,Q^2) \\ F_2(x,Q^2) &= \omega W_2(x,Q^2)\,, \\ F_3(x,Q^2) &= \omega W_3(x,Q^2)\,, \end{aligned}$$

In terms of parton distribution functions (PDF)

For *N(e, e')*
$$\begin{aligned} F_2(x,Q^2) &= x[\frac{4}{9}(u(x,Q^2)+\bar{u}(x,Q^2)) + \frac{1}{9}(d(x,Q^2)+\bar{d}(x,Q^2))] \\ F_1(x,Q^2) &= F_2(x,Q^2)/2x\,, \end{aligned}$$

For CC *ν*
$$\begin{aligned} F_2(x,Q^2) &= 2xF_1(x,Q^2) = 2x(d(x,Q^2)+\bar{u}(x,Q^2)) \\ F_3(x,Q^2) &= 2(d(x,Q^2)-\bar{u}(x,Q^2))\,. \end{aligned}$$

Matching with DIS

N(e, e')

$$\frac{d\sigma}{d\Omega dE'} = \frac{4\alpha^2 E'^2}{Q^4}[2W_1 \sin^2\frac{\theta}{2} + W_2 \cos^2\frac{\theta}{2}]$$

N(ν, l')

$$\frac{d\sigma^{\nu,\bar{\nu}}}{dE'd\Omega'} = \frac{G_F^2 \mid V_{ud} \mid^2}{2\pi^2} E'^2[2W_1 \sin^2\frac{\theta}{2} + W_2 \cos^2\frac{\theta}{2} \pm W_3 \frac{E+E'}{m_N} \sin^2\frac{\theta}{2}]$$

$$\begin{aligned} F_1(x,Q^2) &= m_N W_1(x,Q^2) \\ F_2(x,Q^2) &= \omega W_2(x,Q^2)\,, \\ F_3(x,Q^2) &= \omega W_3(x,Q^2)\,, \end{aligned}$$

Matching F_i^{DCC} ←→ F_i^{PDF} at $W \approx 2$ GeV, $Q^2 > 1$ (GeV/c)^2

(overlapping region)

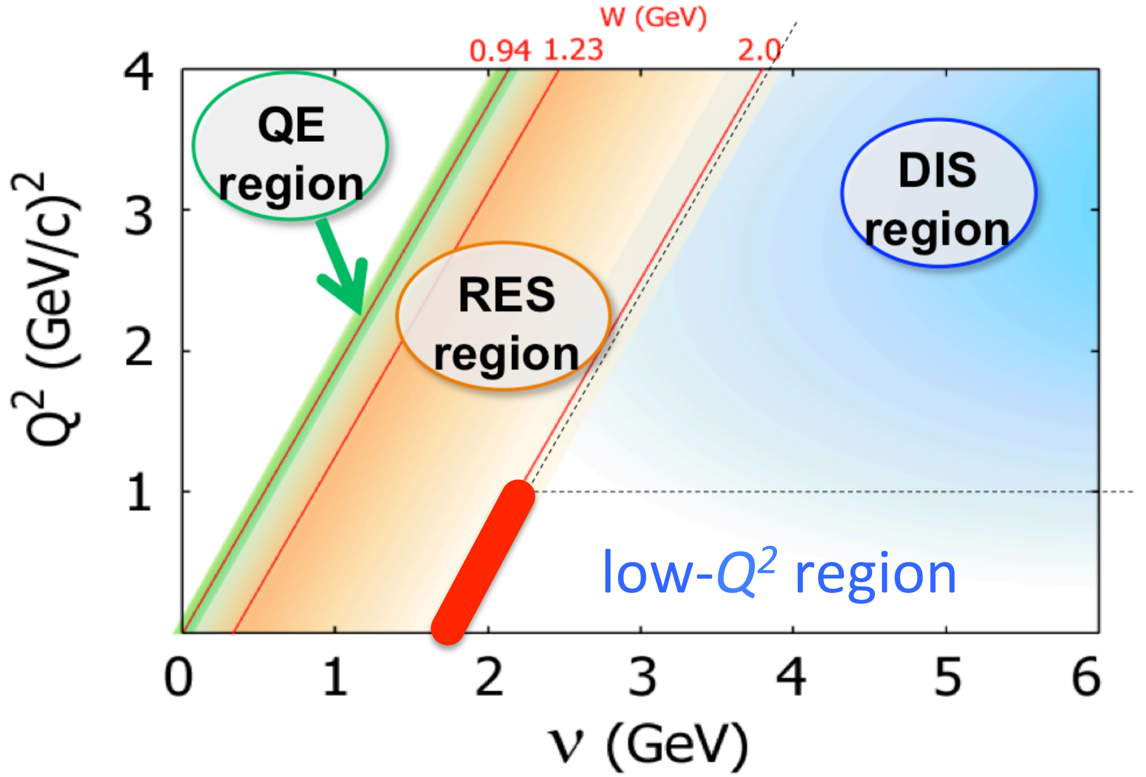
Matching with DIS

- Make sure smooth transition for electron scattering
- Some axial form factors of ANN^* can be fixed for neutrino scattering
- Unitarity, coupled-channels are essential for matching

  only inclusive structure functions can be matched

  2 π contribution is large

Matching with low-Q^2 region

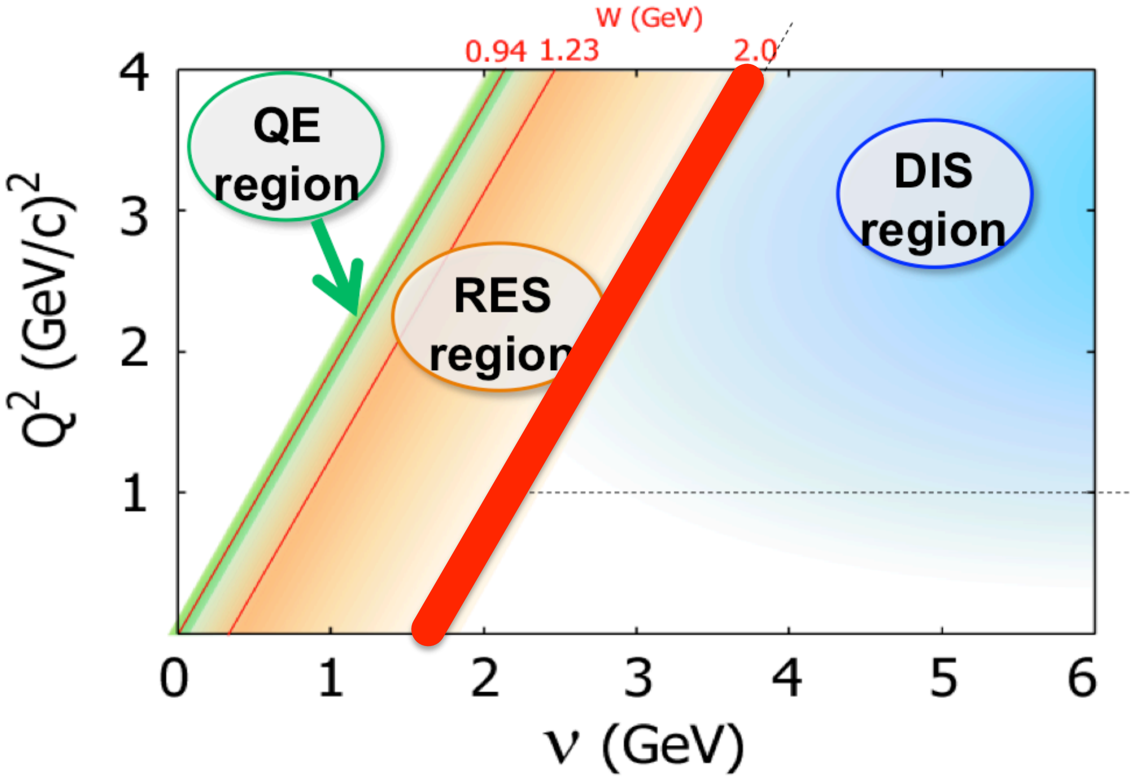


Model for low-Q^2 region

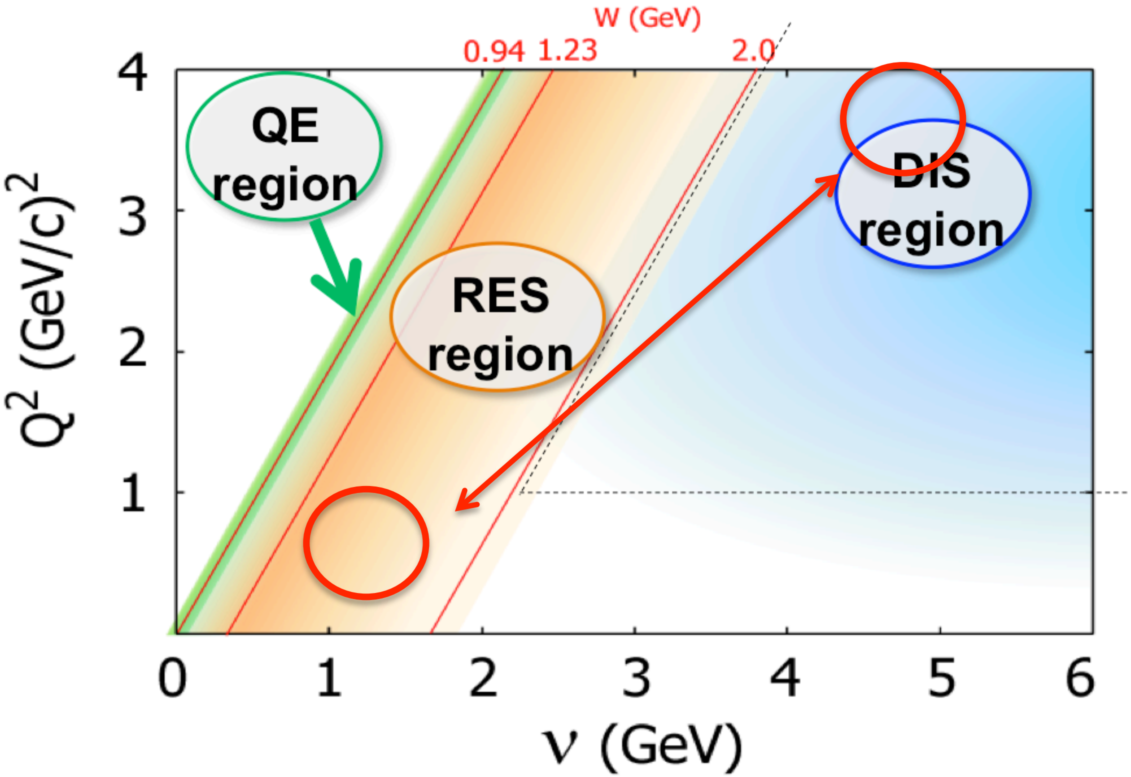
Kulagin and Petti, PRD 76, 094023 (2007) PCAC + extrapolation to finite Q^2 from 0

Bodek and Yang, arXiv:1011.6592 PDF extrapolated to lower Q^2 from DIS region

Matching on the boundary

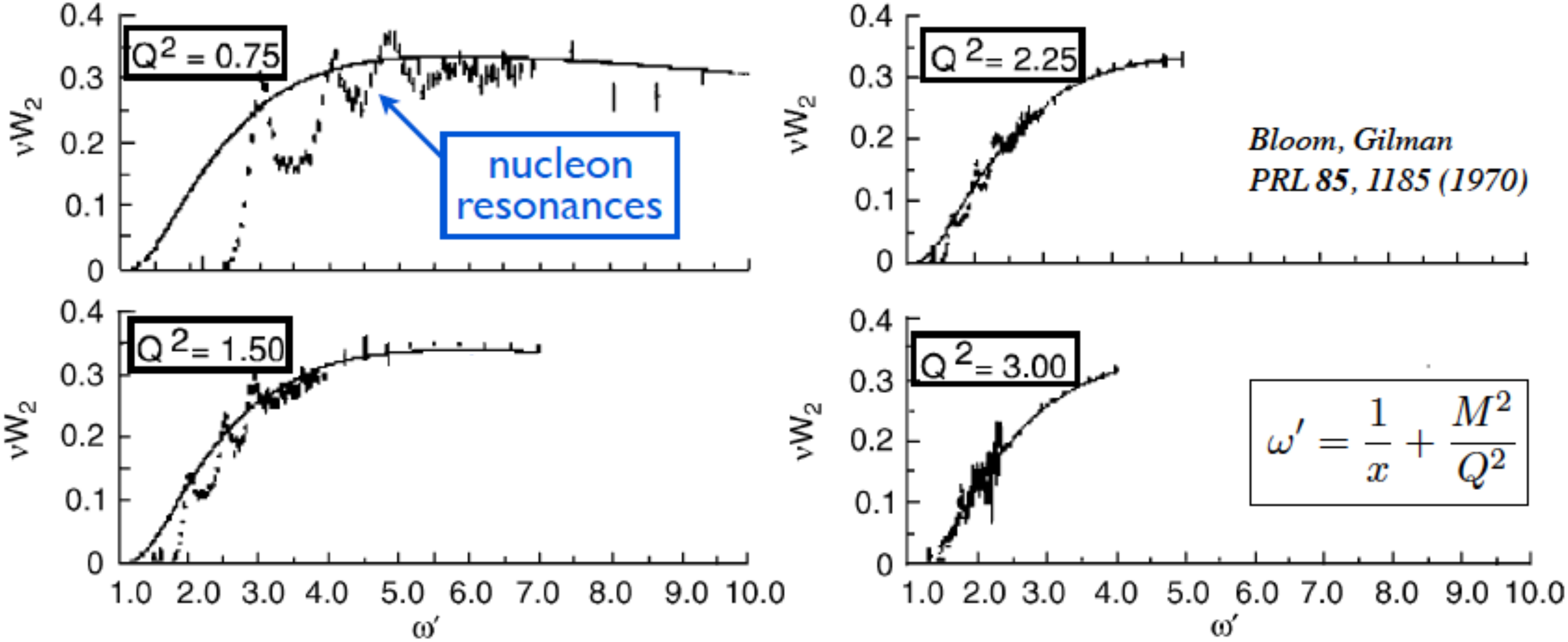


Quark-hadron duality



Quark-hadron duality

Global duality in electron-nucleon scattering



nucleon resonances

Bloom, Gilman
PRL ***85****, 1185 (1970)*

$$\omega' = \frac{1}{x} + \frac{M^2}{Q^2}$$

Ex. PDF from W≈3 GeV, Q^2≈ 10 (GeV/c)^2

$$x = Q^2/(2m_N\omega)$$

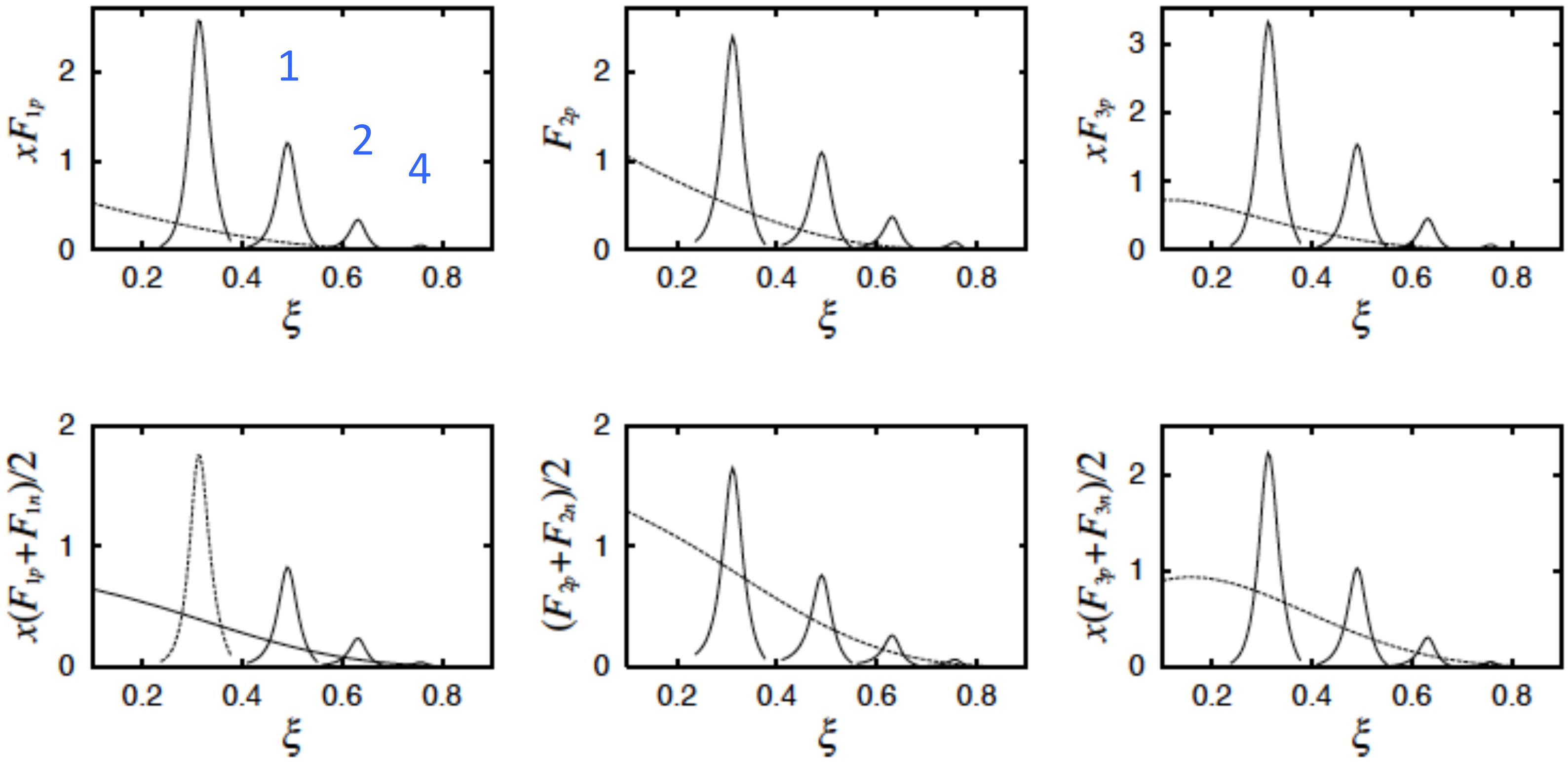
Quark-hadron duality

Matsui, Sato, Lee, PRC 72 (2005)

Local duality in Neutrino-nucleon scattering in Δ region

CTEQ06 vs. SL model

Q^2=0.4 (GeV/c)^2



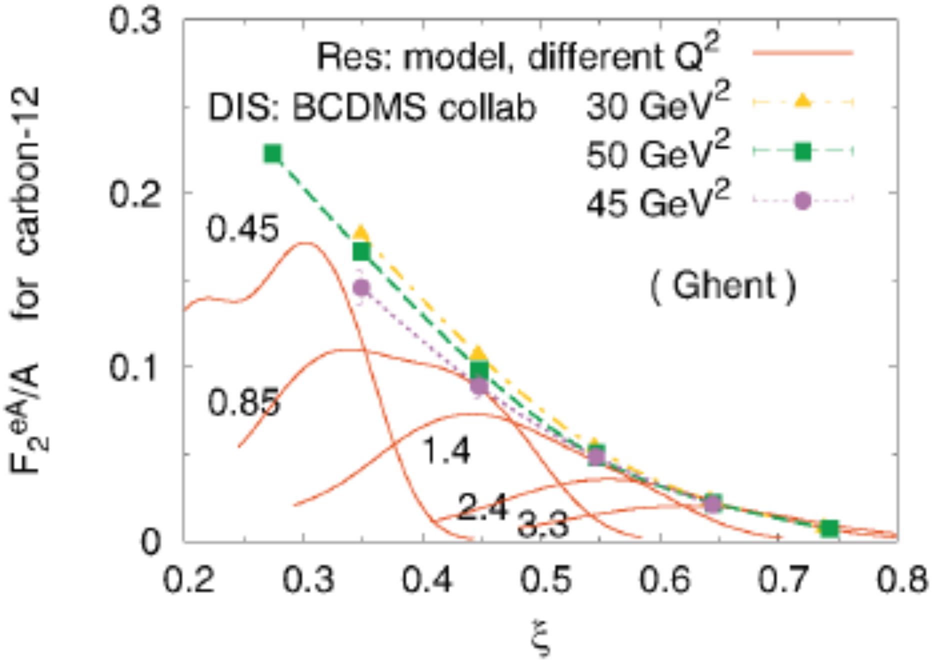
Nachtman variable : $$\xi = \frac{2x}{1+(1+4x^2m_N^2/Q^2)^{1/2}}$$

QH duality holds for isoscalar target

Quark-hadron duality

Electron-nucleus scattering

Lalakulich et al, PRC 79 (2009)



Broadening of resonance peaks 🡐 Fermi motion, many-body correlation, FSI

Quark-hadron duality

HOPE : Utilize QH duality practically

PDF ←→ Structure functions in resonance region

Electron scattering Res SF → PDF (in kinematics where data are scarce)

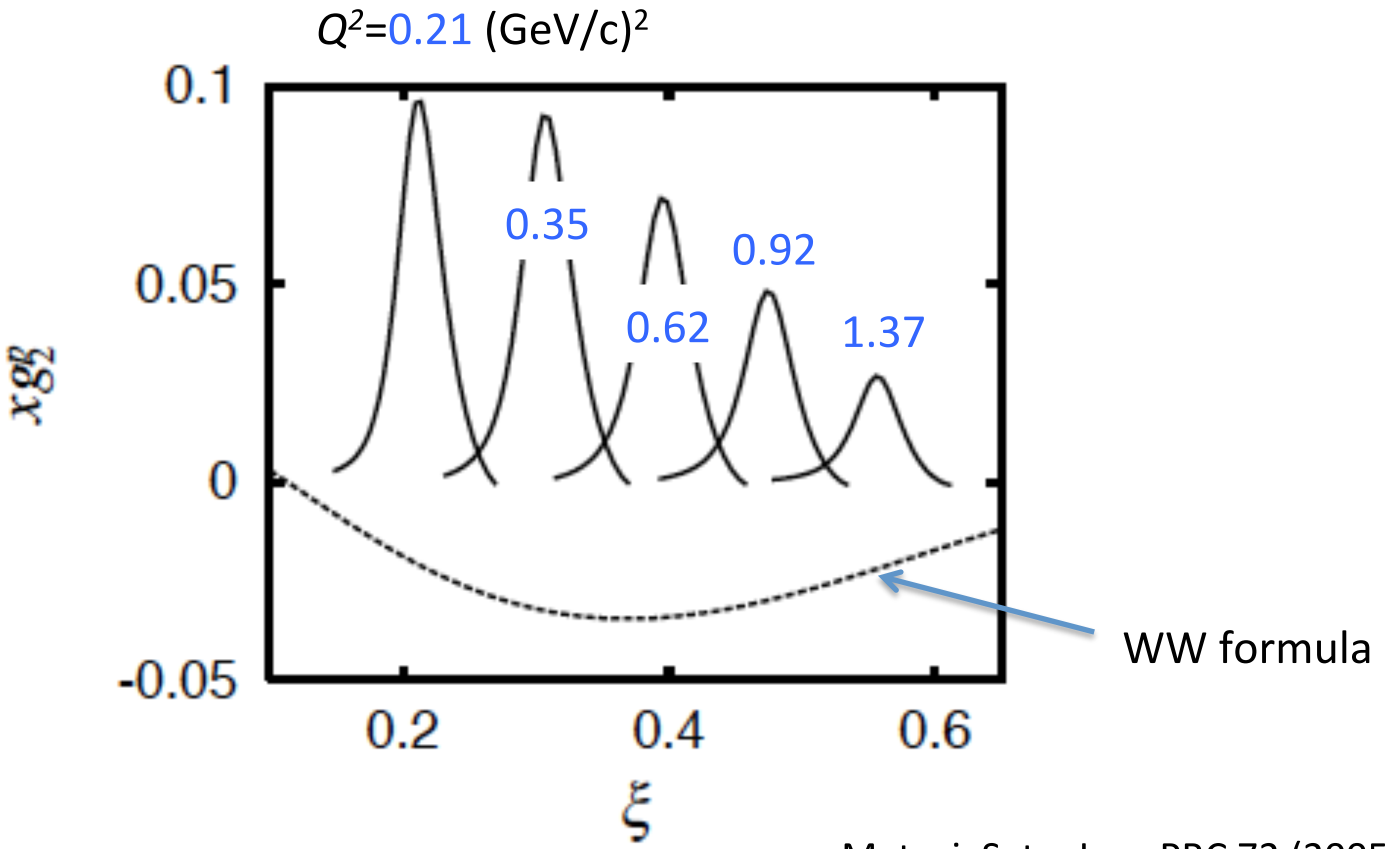
Neutrino scattering PDF → axial form factor of ANN^*

1π &2π model is necessary → DCC model can do

Quantitative (theoretical) understanding of QH duality is prerequisite

Sometimes, QH duality could do a very bad job

Comparison of SL model and Wandzura-Wilczek formula for electron scattering



Matsui, Sato, Lee, PRC 72 (2005)

Quark-hadron duality

HOPE : Utilize QH duality practically

PDF ←→ Structure functions in resonance region

Electron scattering Res SF → PDF (in kinematics where data are scarce)

Neutrino scattering PDF → axial form factor of ANN^*

1π &$2\ \pi$ model is necessary → DCC model can do

Quantitative (theoretical) understanding of QH duality is prerequisite

Can be (has been ?) studied in electron scattering

critical comments are welcome

Neutrino-nucleus interaction

Neutrino-nucleus interaction

To be done with DCC model

Our previous experience with Sato-Lee model   PRC 54 2660 (1996)

- πN channel only
- Δ only

✔ Incoherent 1 π production

✔ Coherent 1 π production

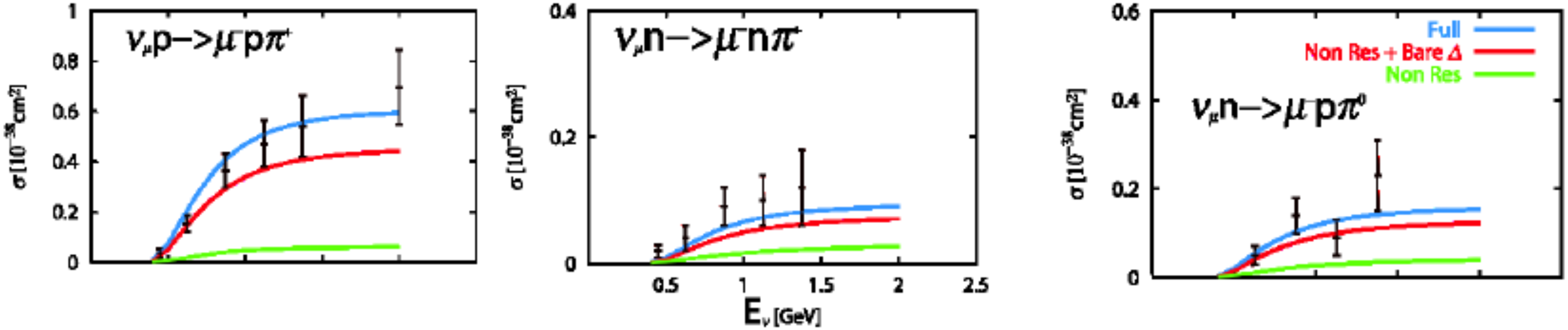
Difficult remaining issues

- Final state interactions
- Medium effects (width broadening of resonances)

Sato-Lee (SL) model

Sato and Lee, PRC 54 2660 (1996)

- πN channel only
- Δ only

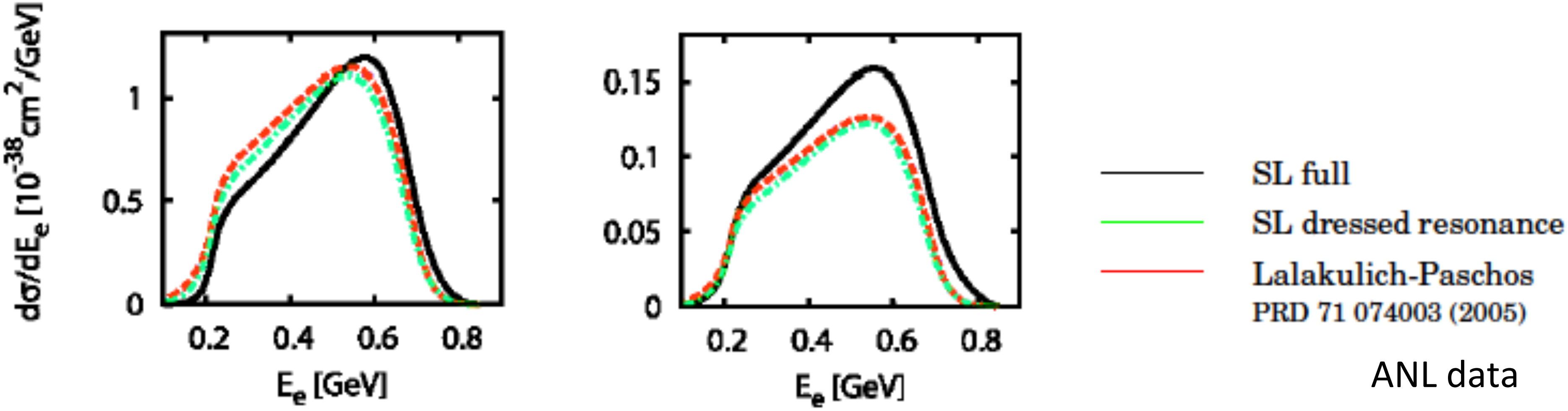


ANL data

Sato-Lee (SL) model

Sato and Lee, PRC 54 2660 (1996)

- πN channel only
- Δ only



$\nu p \rightarrow e^- \pi^+ p$

$\nu n \rightarrow e^- \pi^+ n$

ANL data

Inclusive *ν-A* scattering in Δ region

Szczerbinska et al., PLB 649 132 (2007)

- Quasi-elastic (QE)
- Δ-excitation (1π)

$$\frac{d\sigma}{dE_\ell d\Omega_\ell} = \frac{p_\ell}{p_\nu} \frac{G_F^2 \cos\theta_C^2}{8\pi^2} L_{\mu\nu} W^{\mu\nu}$$

$L_{\mu\nu}$: Leptonic tensor

$W^{\mu\nu}$: Hadronic tensor

1π

$$\begin{aligned} W^{\mu\nu} \quad &\sim \quad \int d\vec{p'}\, d\vec{k}\, d\vec{p}\, \theta(p_F - |\vec{p'}|)\, \theta(|\vec{p}| - p_F) && \Leftarrow \text{Fermi Gas} \\ &\times \quad \Lambda^{\mu\mu'} \langle \pi N(p')|\, j_{\mu'}\, |N(p)\rangle_{\pi N-\mathrm{cm}} && \Leftarrow \text{SL} \\ &\times \quad \Lambda^{\nu\nu'} \langle \pi N(p')|\, j_{\nu'}\, |N(p)\rangle^{*}_{\pi N-\mathrm{cm}} \end{aligned}$$

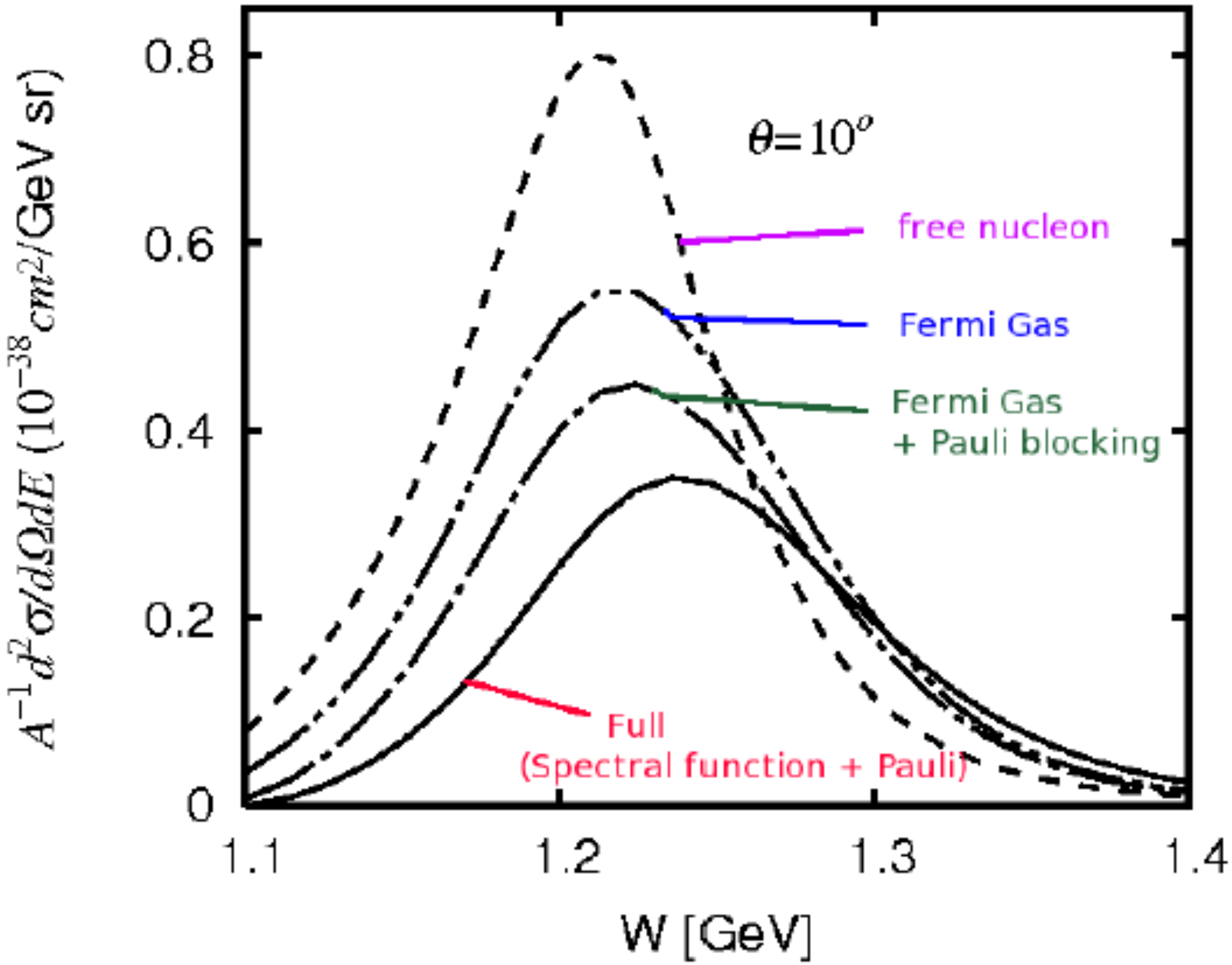
$*$ Fermi Gas to Spectral Function

Benhar et al. NPA 579 493 (1994)

$$\frac{3}{4\pi\, p_F^3} \int d\vec{p}\, \theta(p_F - |\vec{p}|) \rightarrow \int d\vec{p}\, dE\, P(\vec{p}, E)$$

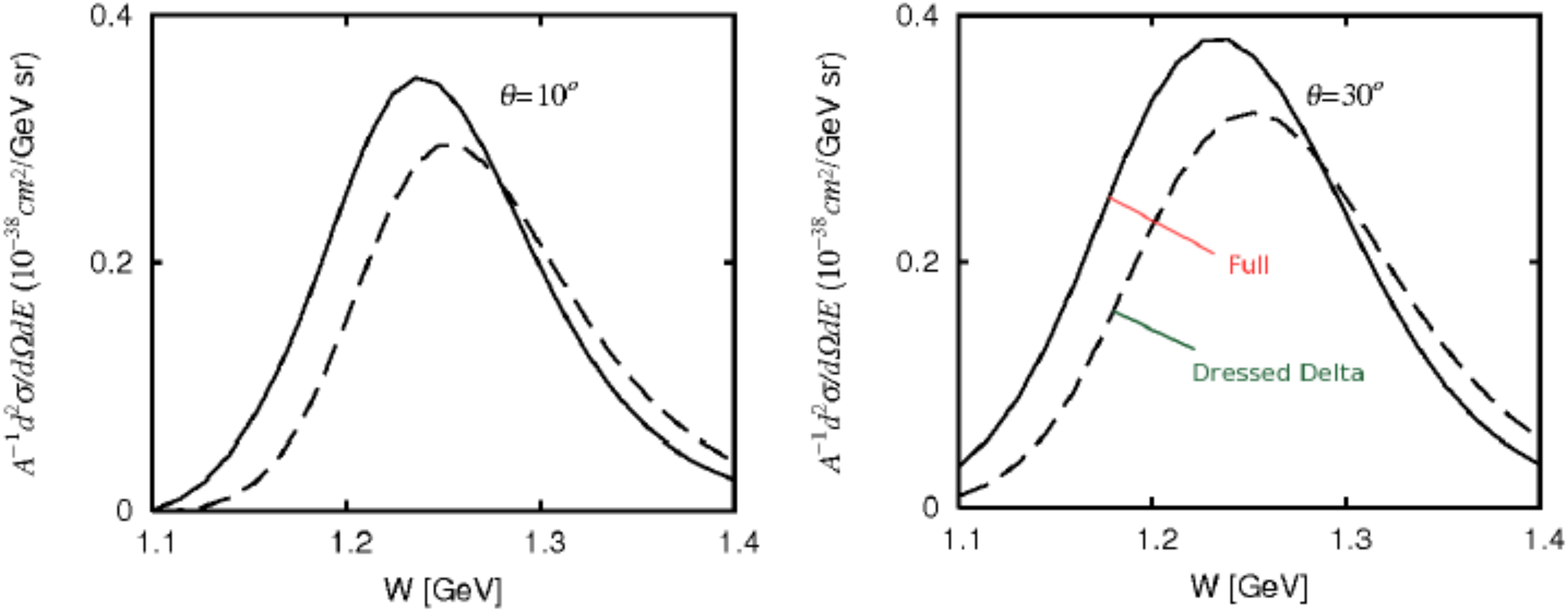
Nuclear Effect for 1π in Δ-region

$\nu_e + {}^{12}\mathrm{C} \to e^- + \pi + X$ $\qquad E_\nu = 1$ GeV



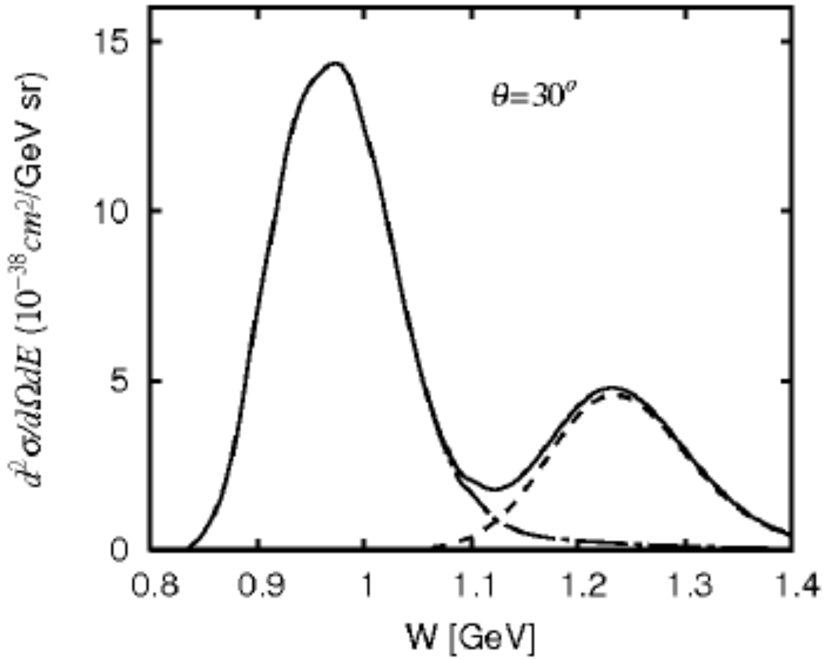
Non-resonant effect for 1π

$\nu_e + {}^{12}\mathrm{C} \rightarrow e^- + \pi + X$ $E_\nu = 1$ GeV

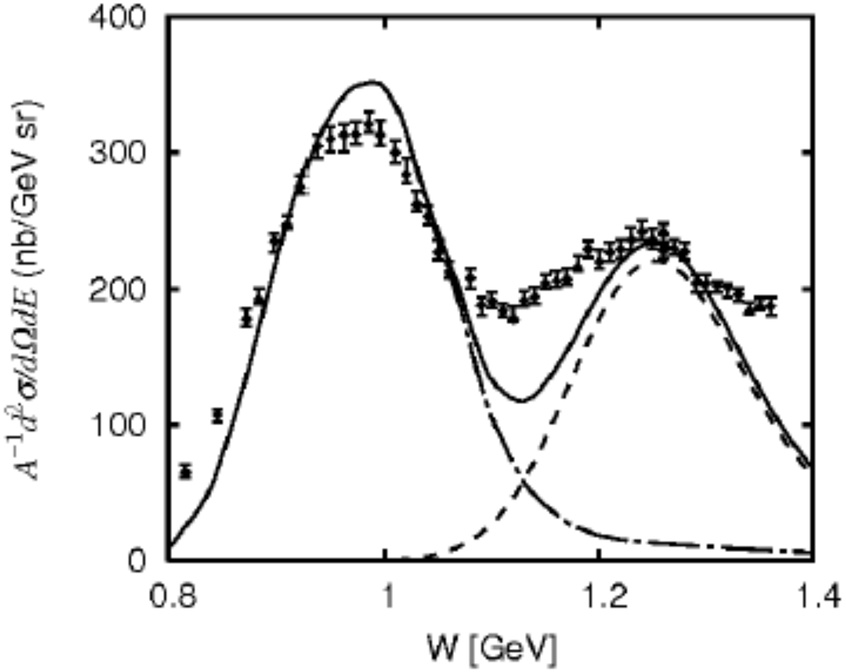


Confronting with Data (Inclusive)

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



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



[Data: Sealock et al. PRL 62 1350 (1989)]

- ∗ Dip region : Beyond impulse approximation, another nuclear correlation
- ∗ Higher W : Higher mass resonances (To be done with DCC model)

Another big issue

- Final state interaction

  transport model

  optical potential

- Medium effects on resonance properties (shift of mass, width)

  pion-nucleus scattering data

Coherent π production in ν-A scattering in Δ region

Nakamura et al., PRC 81 035502 (2010)

Motivation

- NC π^0 can fake $(\nu_\mu \rightarrow \nu_e)$ event
- Puzzling experimental situation

No evidence for CC K2K (2005), SciBooNE (2008)

Signature for NC MiniBooNE

Naive expectation from isospin matrix element : $\sigma_{CC} \sim 2\ \sigma_{NC}$

Theoretical approaches to coherent π production

∗ PCAC (Partially Conserved Axial Current)-based model

- Rein, Sehgal, NPB 223 (1983)
- Kartavtsev et al., PRD 74 (2006)
- Berger, Sehgal, PRD 79, (2009)
- Paschos, Schalla, PRD 80 (2009)

∗ Dynamical microscopic model

- Kelkar et al., PRC 55 (1997) • Singh et al., PRL 96 (2006)
- Alvarez-Ruso et al., PRC 7576 (2007) • Amaro et al., PRD 79 (2009)
- Hernandez et al., PRD 82 (2010) • Leitner et al., PRC 79 (2009)
- Martini et al., PRC 80 (2009) • Nakamura et al, PRC 81 (2010)

Dynamical model for coherent production

Nakamura et al, PRC 81 (2010)

Ingredients

- ∗ Elementary amplitudes ($\nu N \rightarrow \mu^- \pi^+ N$, $\nu N \rightarrow \nu \pi^0 N$) SL model

- ∗ Medium effect on Δ (mass, width, non-locality)

- ∗ Final state interaction

} Δ-hole model

Medium effect on Δ

$$\frac{1}{E - m_\Delta^0 - \Sigma_\Delta} \quad \Longrightarrow \quad \frac{1}{E - m_\Delta^0 - \Sigma_\Delta - H_\Delta - \Sigma_{Pauli} - \Sigma_{spr}}$$

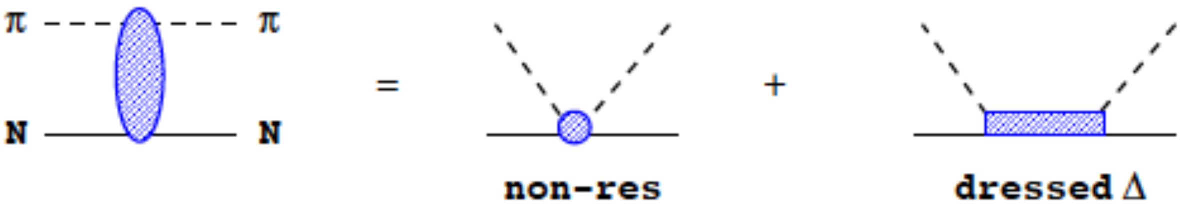
$$H_\Delta = T_\Delta + V_\Delta + H_{A-1} \; , \quad T_\Delta \Rightarrow \text{non-local effect}$$

Spreading potential $\quad \Sigma_{spr} = V_C \, \rho(r) + V_{LS}(r) \, \vec{L}_\Delta \cdot \vec{S}_\Delta$

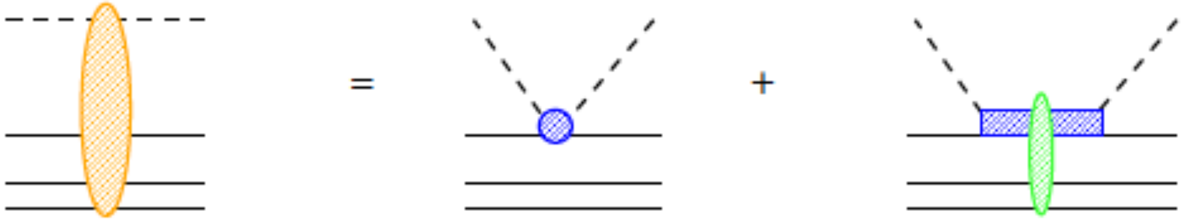
Parameters (complex) : $V_C, V_{LS} \;\; \rightarrow \;\; \pi$-nucleus (total & elastic) scattering data

Final State Interaction

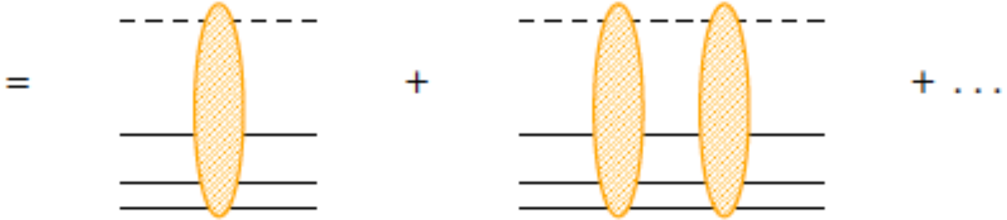
πN t-matrix (SL model)



πA potential



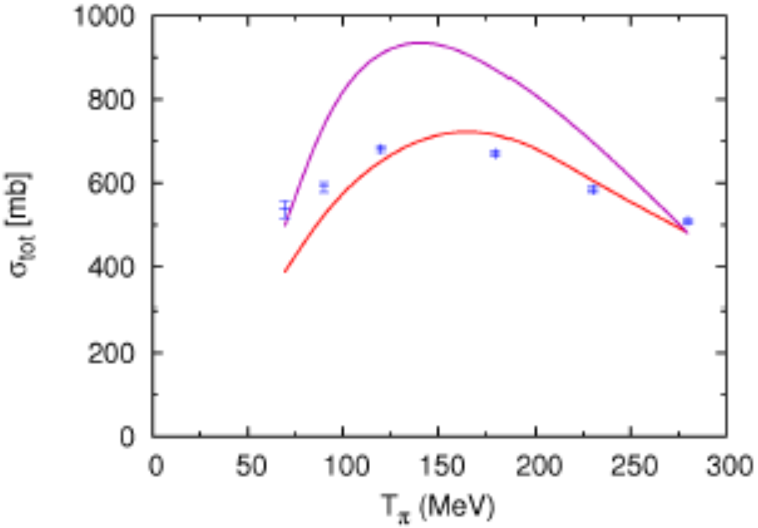
πA t-matrix (Lippmann-Schwinger equation)

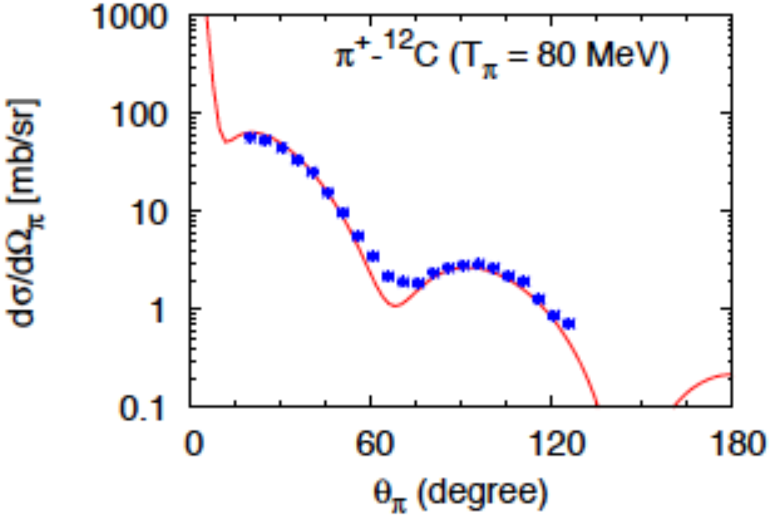


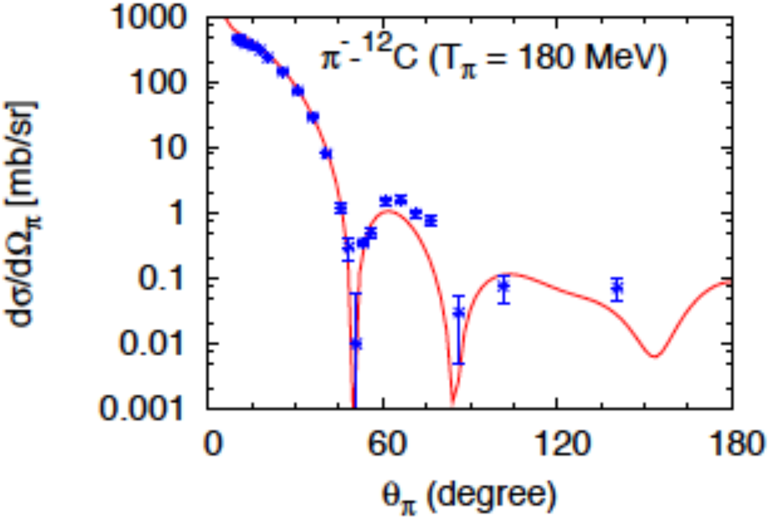
Final State Interaction

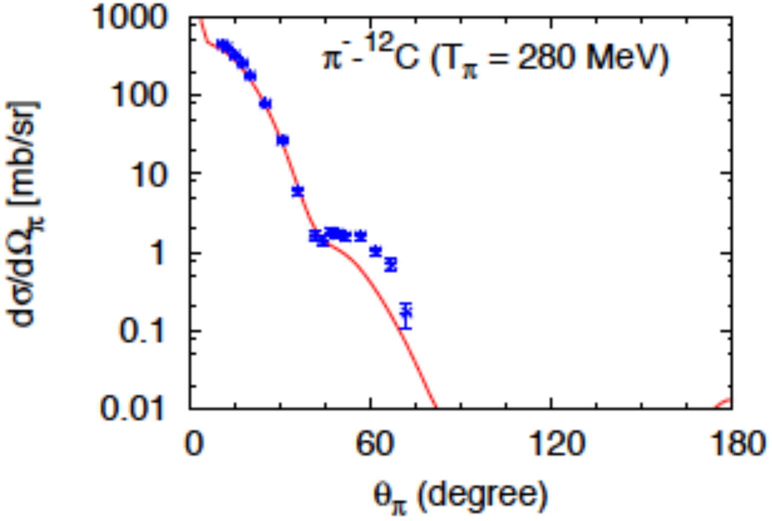
$\pi^{\pm}$ - ^{12}C scattering

[Data : NPB **17**, 168 (1970), PRC **29**, 561 (1984)]



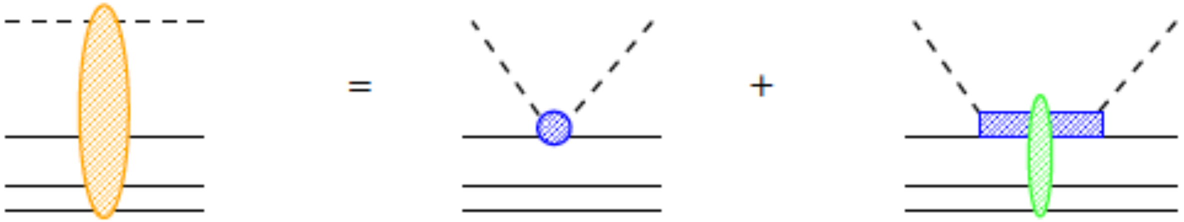




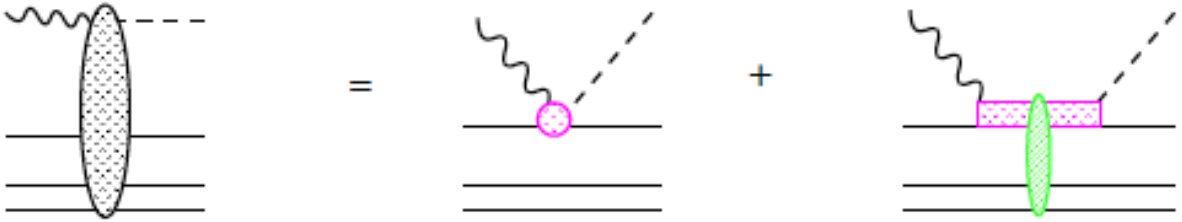


Coherent π production

πA potential



$\gamma A \longrightarrow \pi A$ potential



$\gamma A \longrightarrow \pi A$ amplitude

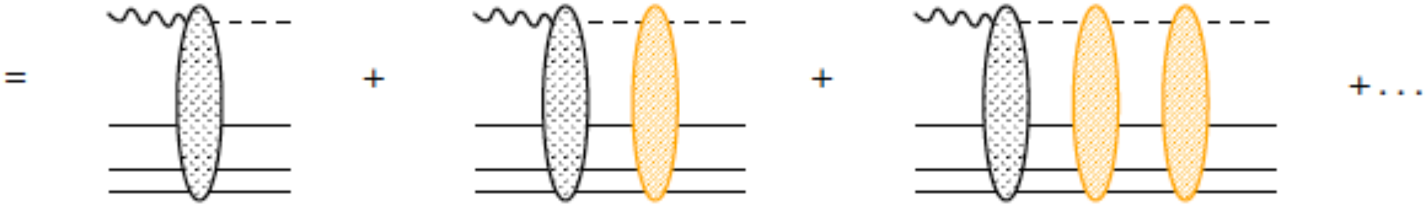
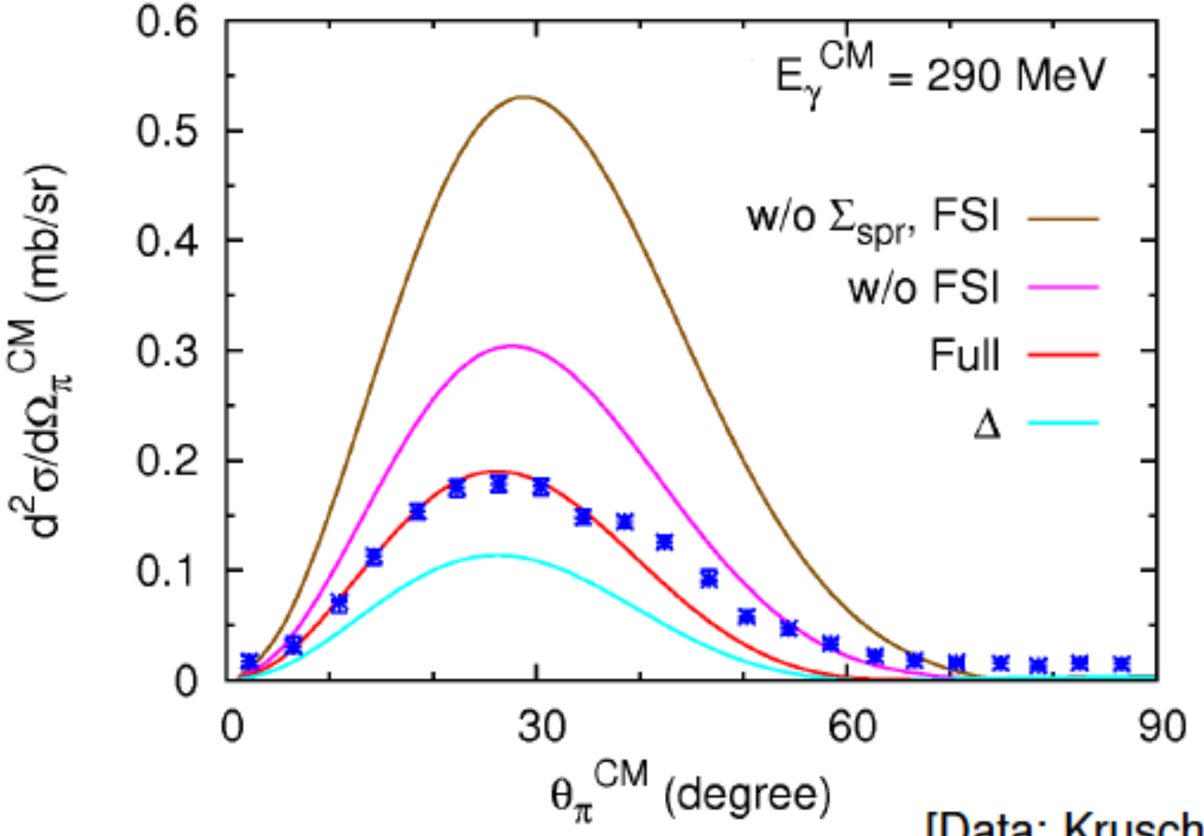


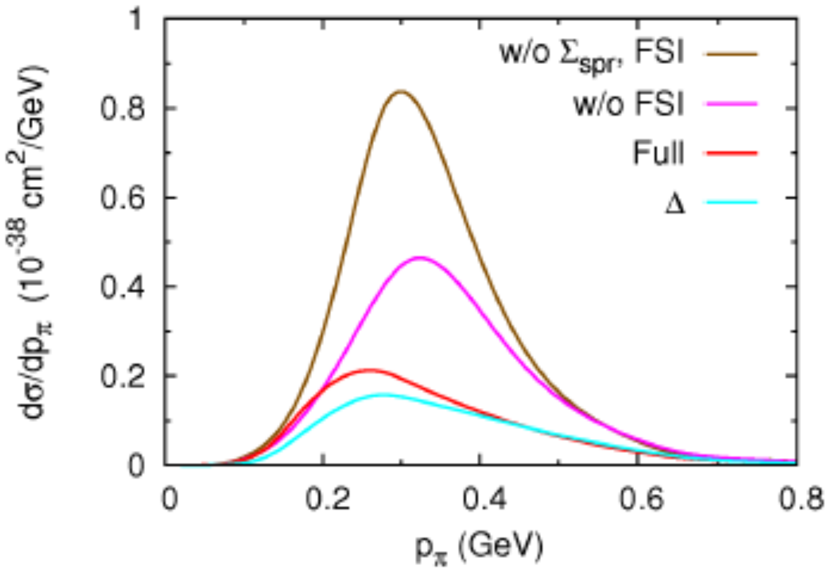
Photo coherent π production on ^{12}C



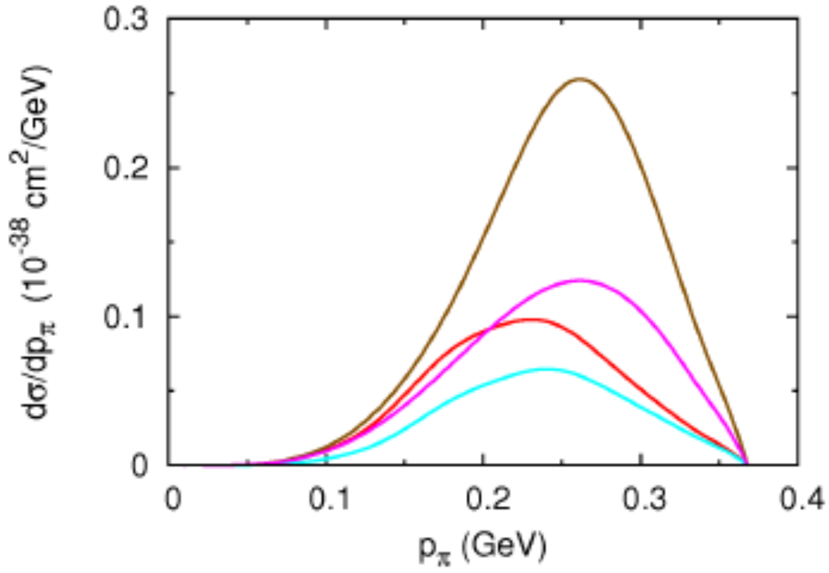
[Data: Krusche et al., PLB**526** (2002)]

- Parameter-free prediction
- Good testing ground for microscopic models
- Important medium effects

CC Coherent π production on ^{12}C



CC E_ν = 1 GeV



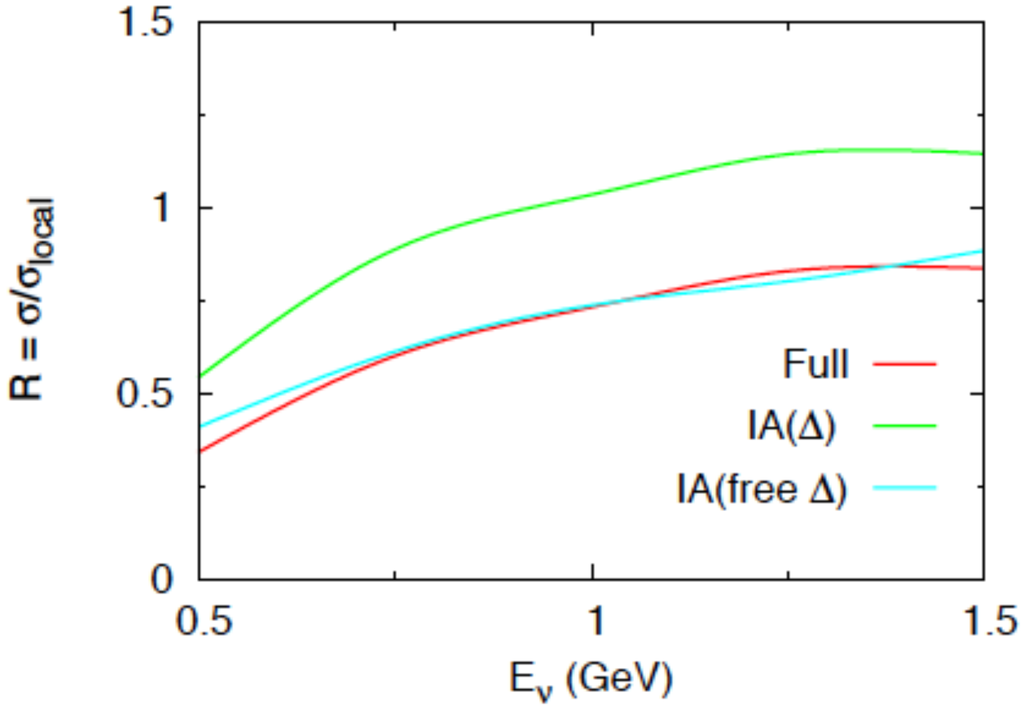
CC E_ν = 0.5 GeV

- Large medium effects in Δ region
- Enhancement due to non-resonance (interference with Δ)
  32 (10) % at E_ν = 0.5 (1) GeV
- No contribution from (tree-level) non-resonant mechanism

Amaro et al., PRD **79** (2009); Hernandez et al., PRD **82** (2010)

Non-locality of Δ-propagation

Leitner et al., PRC **79**,057601 (2009)



- 60, 30, 20 % reduction for E_ν = 0.5, 1, 1.5 GeV for free Δ and Full
- Non-local effect is still important after including medium effects
- All previous microscopic calculations used local approximation

Comparison with Data

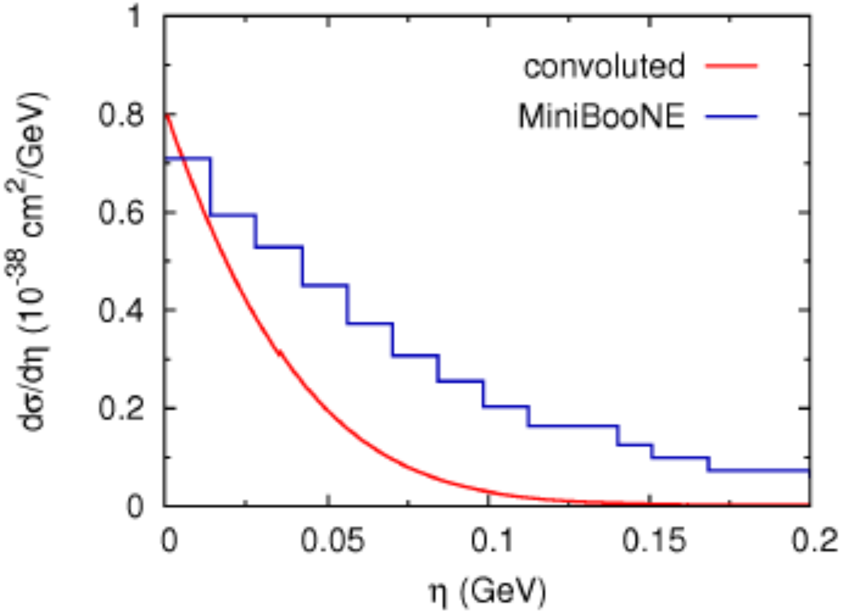
Large discrepancy between data and theory in $\mathrm{CC}\pi^+$ / $\mathrm{NC}\pi^0$

$\sigma(\mathrm{CC}\pi^+)$ / $\sigma(\mathrm{NC}\pi^0)$ = $0.14^{+0.30}_{-0.28}$ Kurimoto et al., PRD **81** (2010)

$\sigma(\mathrm{CC}\pi^+)$ / $\sigma(\mathrm{NC}\pi^0)$ = $1 \sim 2$ all theoretical calculations

Data analysis of coherent NCπ^0 with Rein-Sehgal model

$\eta \equiv E_\pi(1 - \cos\theta_\pi)$ distribution



[MC from MiniBooNE PLB **664**, 41 (2008)]

- η is useful to break degeneracy of several pion productions in data
- Discrepancy between Monte Carlo (RS model) and microscopic models

  Amaro et al., PRD **79** (2009); Hernandez et al., PRD **80** (2009);**82** (2010)

  Nakamura et al, PRC **81** (2010)

  $\Rightarrow$ possible overestimation of NC cross section

Summary

★ Dynamical coupled-channels (DCC) model for

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

extended to $\nu N \rightarrow \pi N,\ \pi\pi N,\ \eta N,\ K\Lambda,\ K\Sigma$ (ongoing)

★ Matching with DIS and low-Q^2 regions

cf. quark-hadron duality

★ ν −nucleus interaction

SL model-based calculation for (in)coherent π production

Questions/comments

- DCC model for νN ➔ $\pi N, \pi\pi N, \eta N, K\Lambda, K\Sigma$ being developed (done for Q^2=0)

  first serious 2 π production model (1 π and $2\,\pi$ are comparable in resonance region)
- Rein-Sehgal model needs to be improved (replaced)
- New deuterium experiment is highly hoped

  deuteron reaction model being developed
- NC photon emission in higher resonance region relevant ?
- Matching with DIS (low-Q^2) needs all coupled-channels ➔ DCC model can do this
- Is making use of QH duality a promising direction to fix axial form factors ?
- Nuclear effects are another difficult problem