Neutrino-induced forward meson productions in nucleon resonance region

(arXiv:1207.5724; to appear in PRD)

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★ Dynamical coupled-channels (DCC) model for

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

Vector current is developed and tested by data

★ PCAC-based application of DCC model to

$$\nu N \rightarrow \pi N,\ \pi\pi N,\ \eta N,\ K\Lambda,\ K\Sigma \quad (Q^2=0)$$

Axial current is derived with PCAC from $\pi N \rightarrow X$ amplitudes

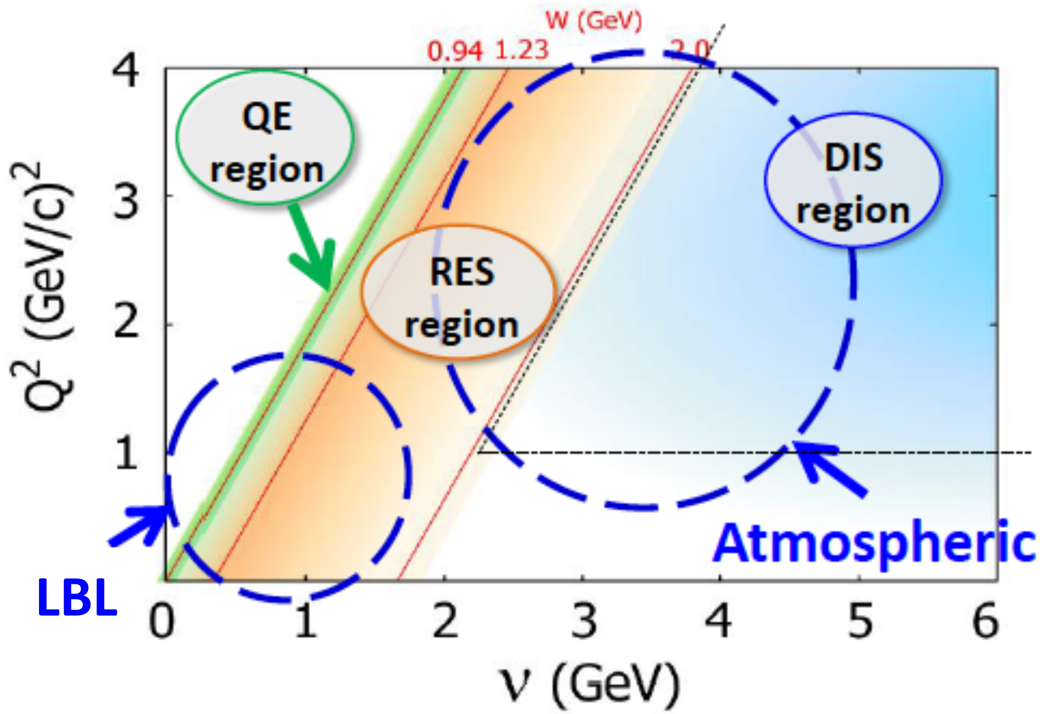
$\theta_{13} \neq 0$ (Daya-Bay, RENO, T2K, MINOS, Double-Chooz)

Next-generation exp. ➔ leptonic $\cancel{CP}$, mass hierarchy

ν–nucleus scattering needs to be understood more precisely

$\theta_{13} \neq 0$ (Daya-Bay, RENO, T2K, MINOS, Double-Chooz)

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

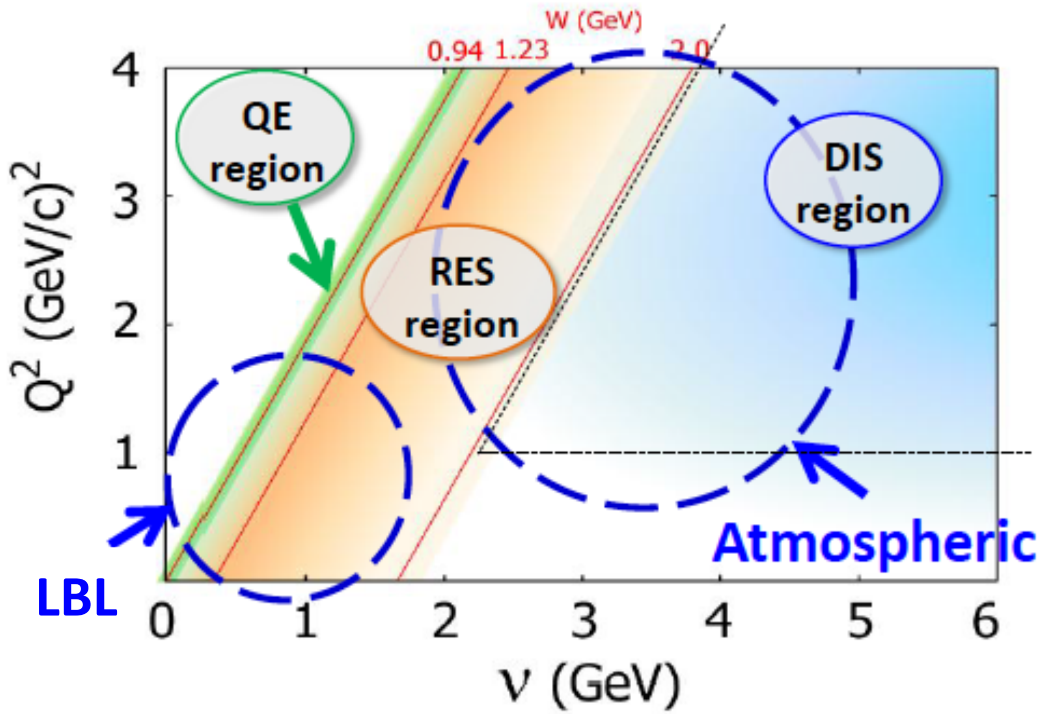


Wide kinematical region with different characteristic

➔ Combination of different expertise is necessary

$\theta_{13} \neq 0$ (Daya-Bay, RENO, T2K, MINOS, Double-Chooz)

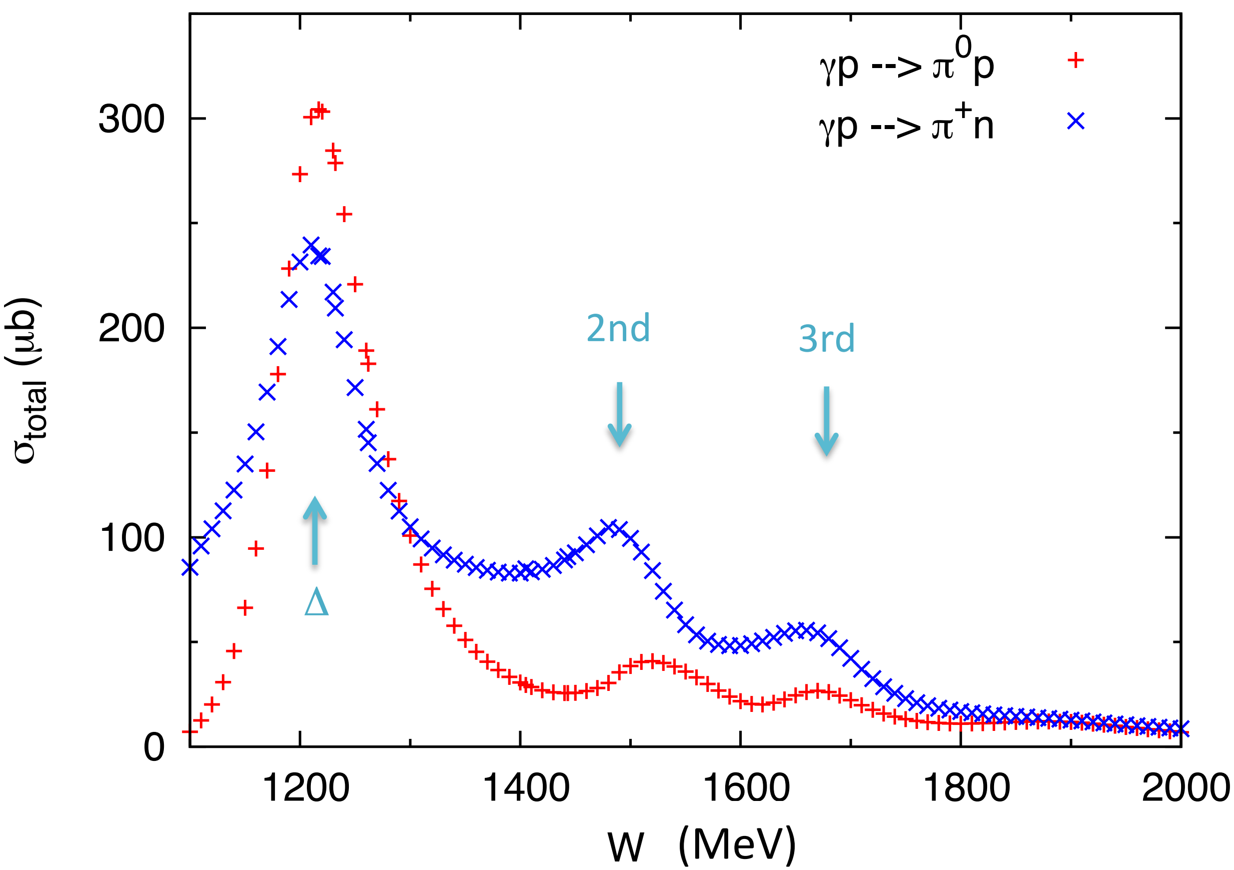
Next-generation exp. ➔ leptonic $\not{C}\not{P}$, mass hierarchy



Collaboration at J-PARC Branch of KEK Theory Center

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

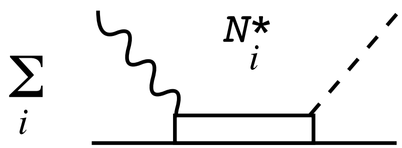
Resonance region



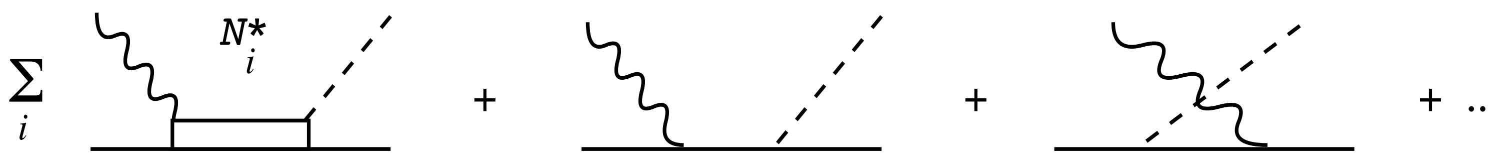
Many nucleon resonances in 2nd and 3rd resonance region

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

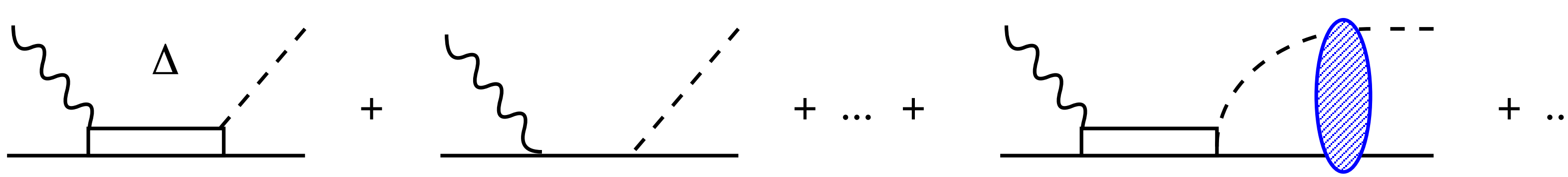
resonant only   Rein et al. (1981), (1987) ; Lalalulich et al. (2005), (2006)



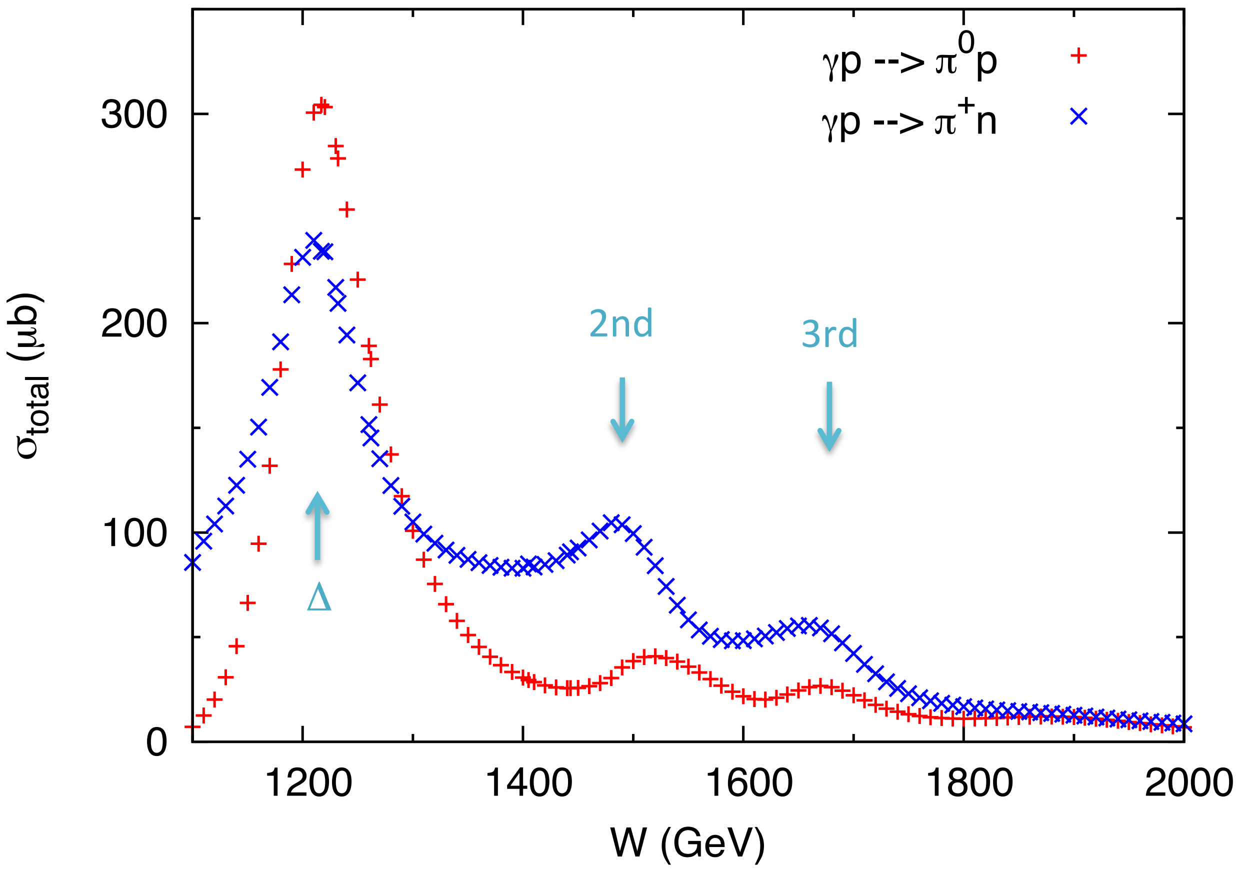
+ non-resonant (tree-level)   Hernandez et al. (2007), (2010) ; Lalakulich et al. (2010)



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

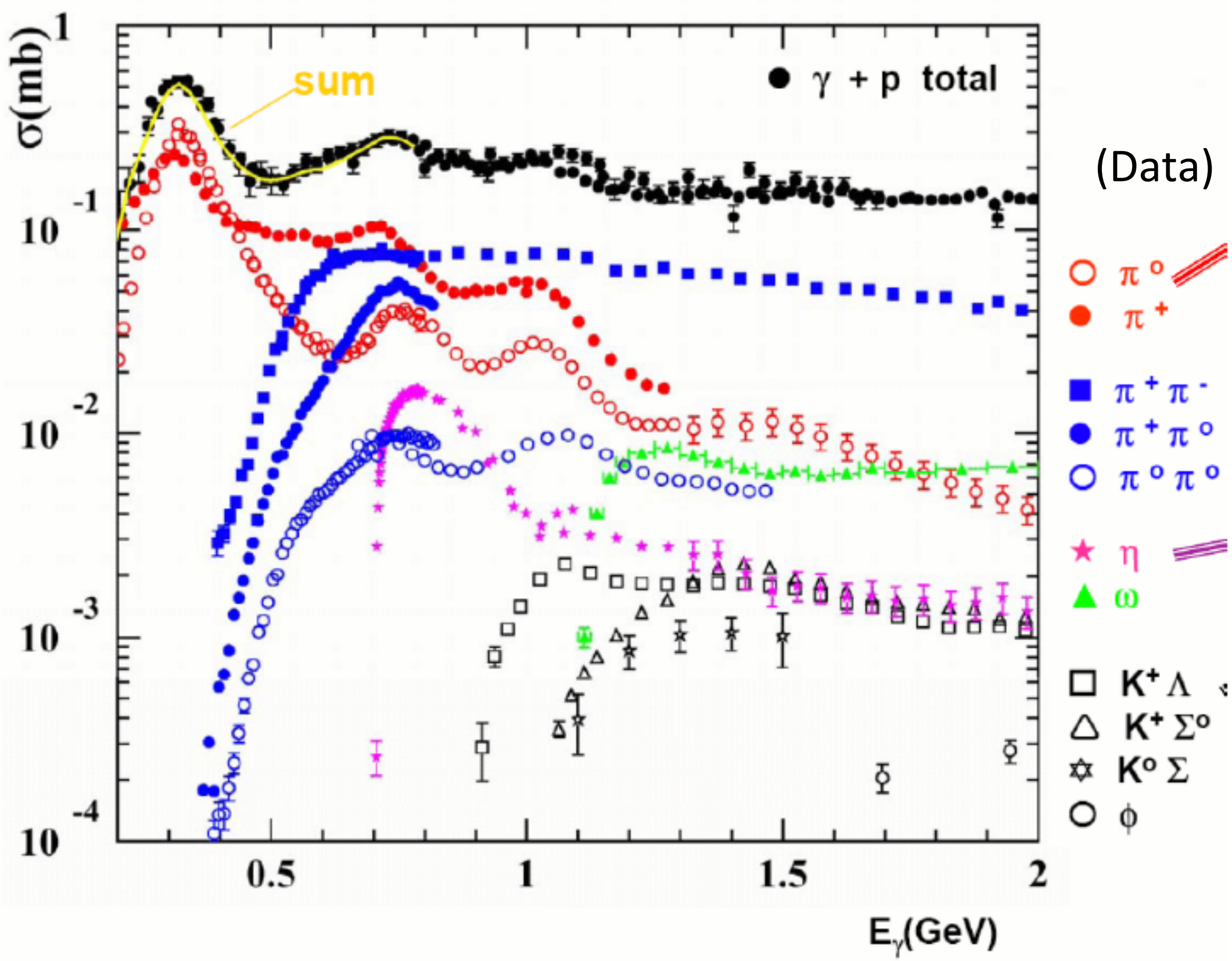


Resonance region



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.)

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

Unitary coupled-channel model needs to be developed

★ Dynamical coupled-channels (DCC) model for

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

★ Application 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

DCC (Dynamical Coupled-Channel) model

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

Coupled-channel Lippmann-Schwinger equation

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

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

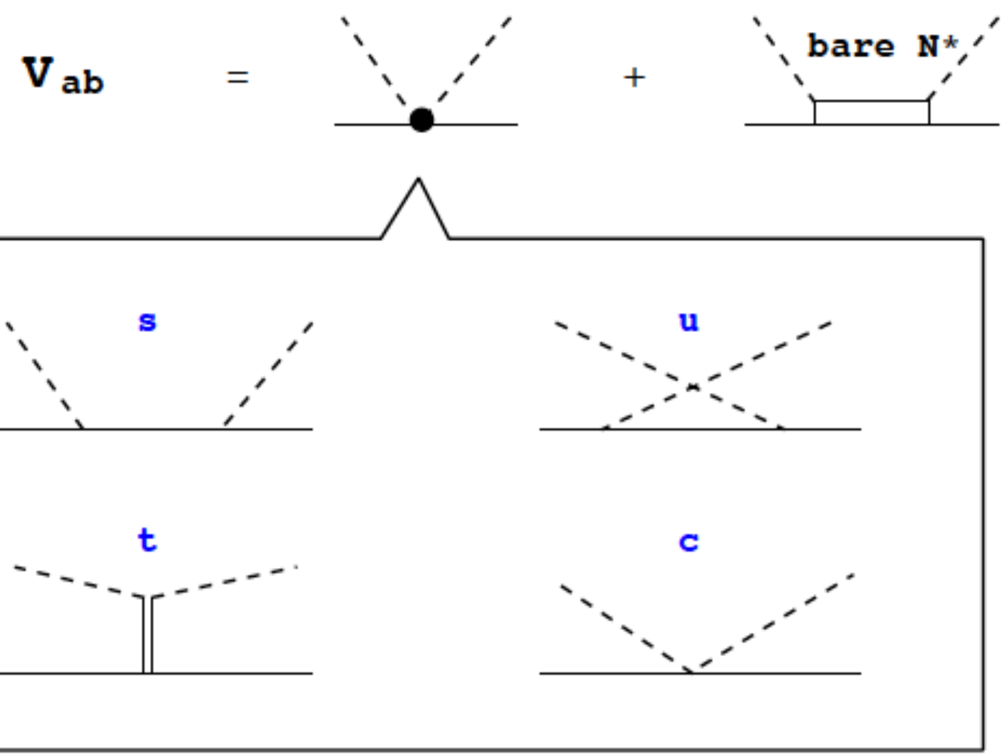
Coupled-channel unitarity is fully taken into acount

DCC (Dynamical Coupled-Channel) model

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

Coupled-channel Lippmann-Schwinger equation

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



DCC analysis of meson production data

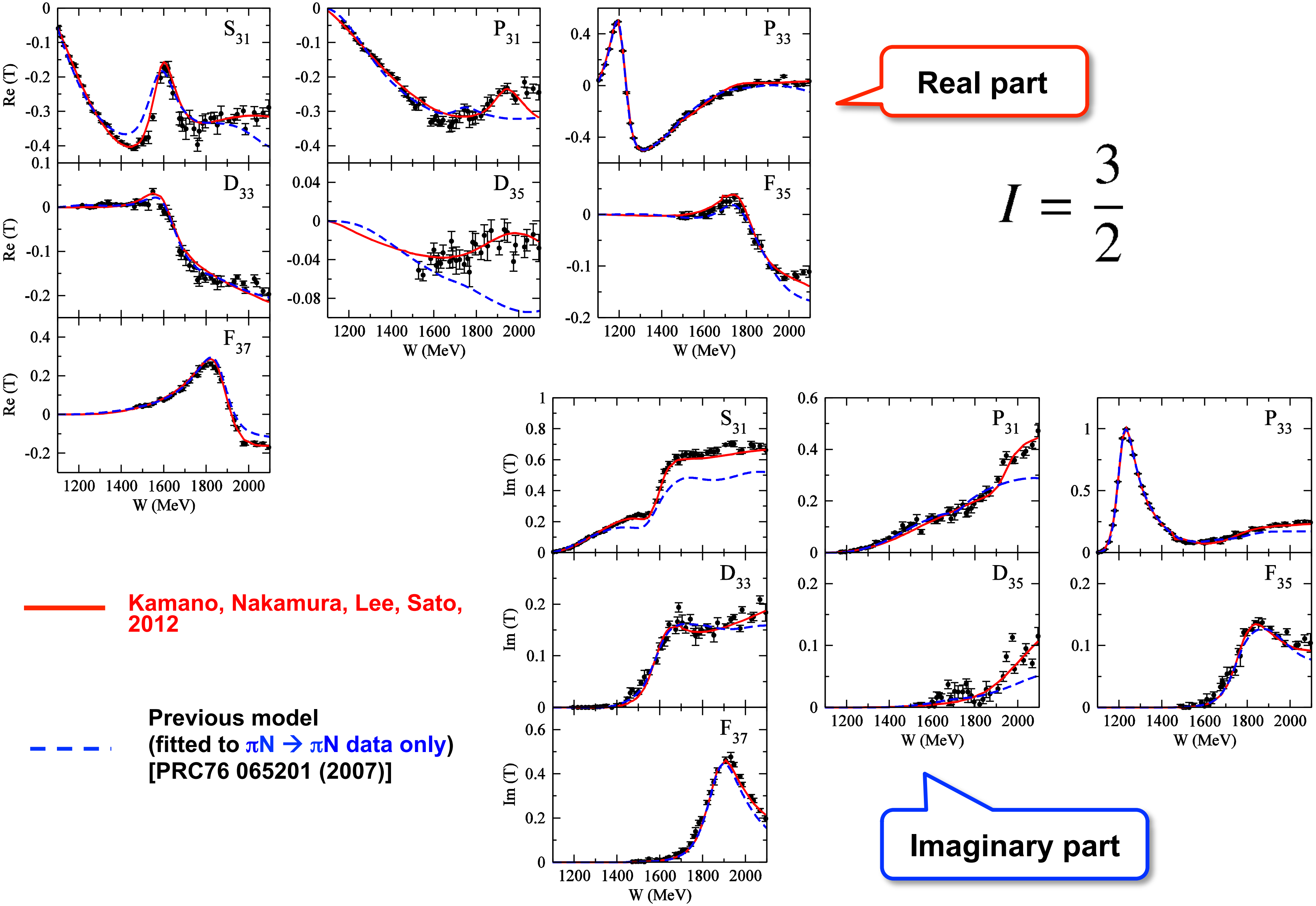
Fully combined analysis of $\gamma N, \pi N \rightarrow \pi N, \eta N, K\Lambda, K\Sigma$

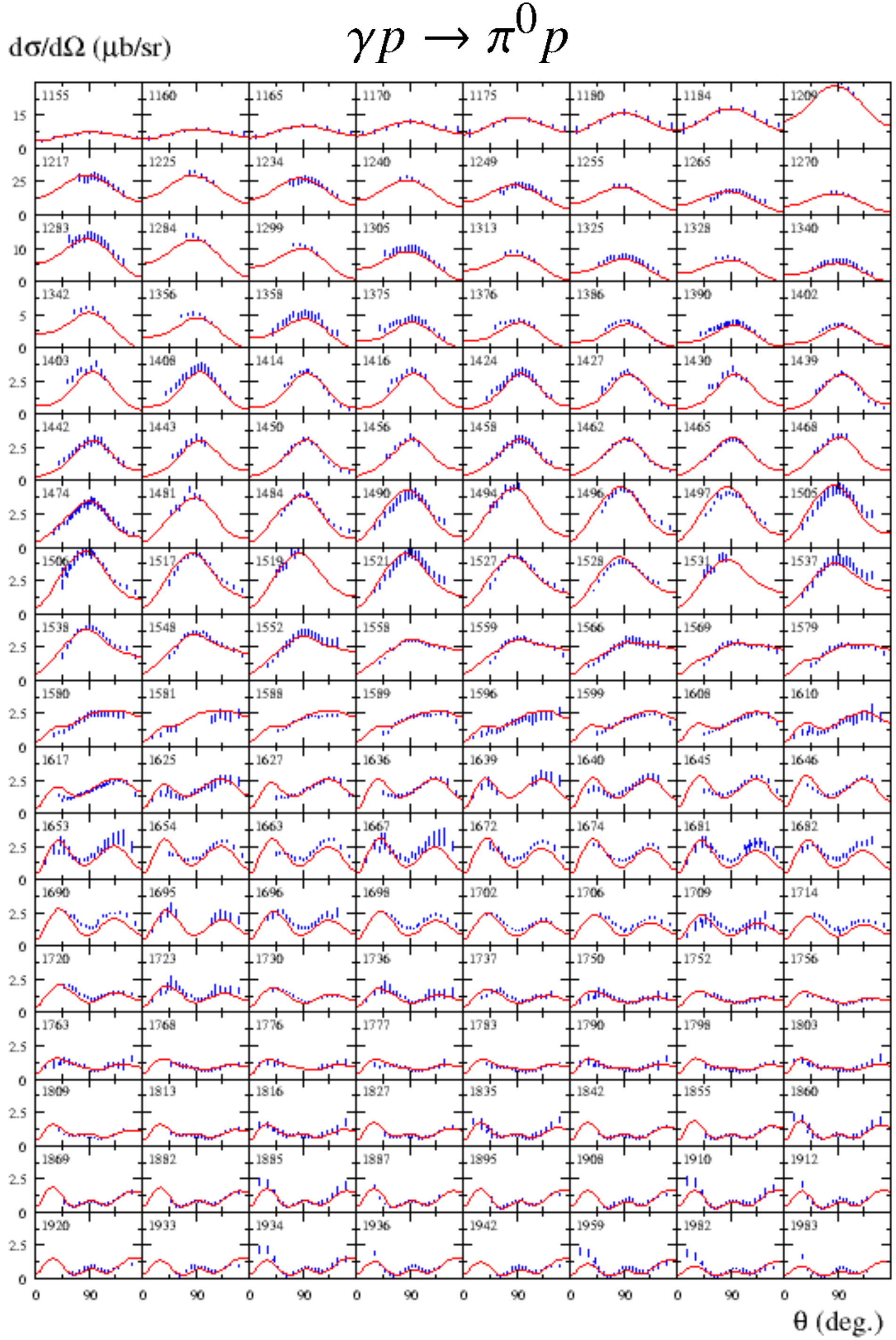
(W ≤ 2.1 GeV)

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

to fit ~ 20,000 data points

Partial wave amplitudes of pi N scattering



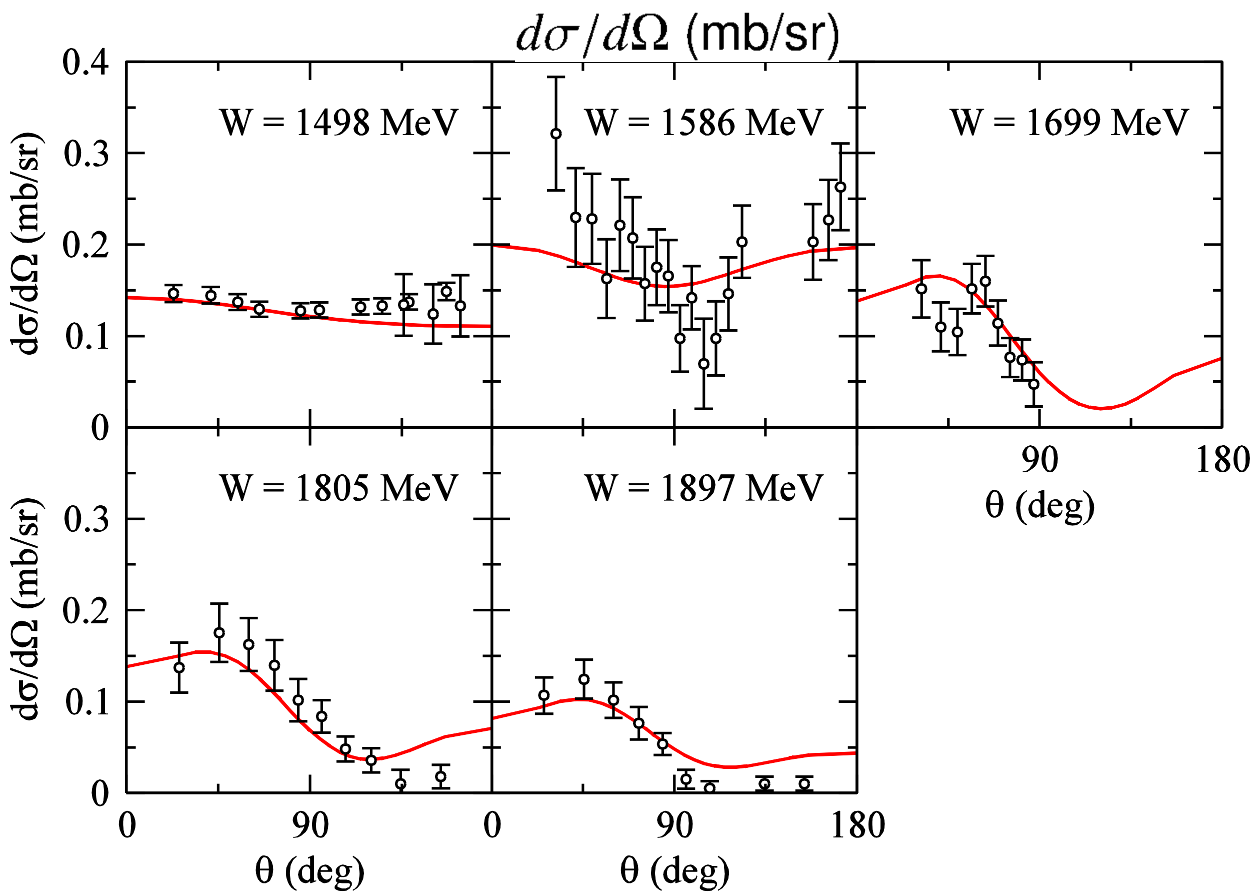


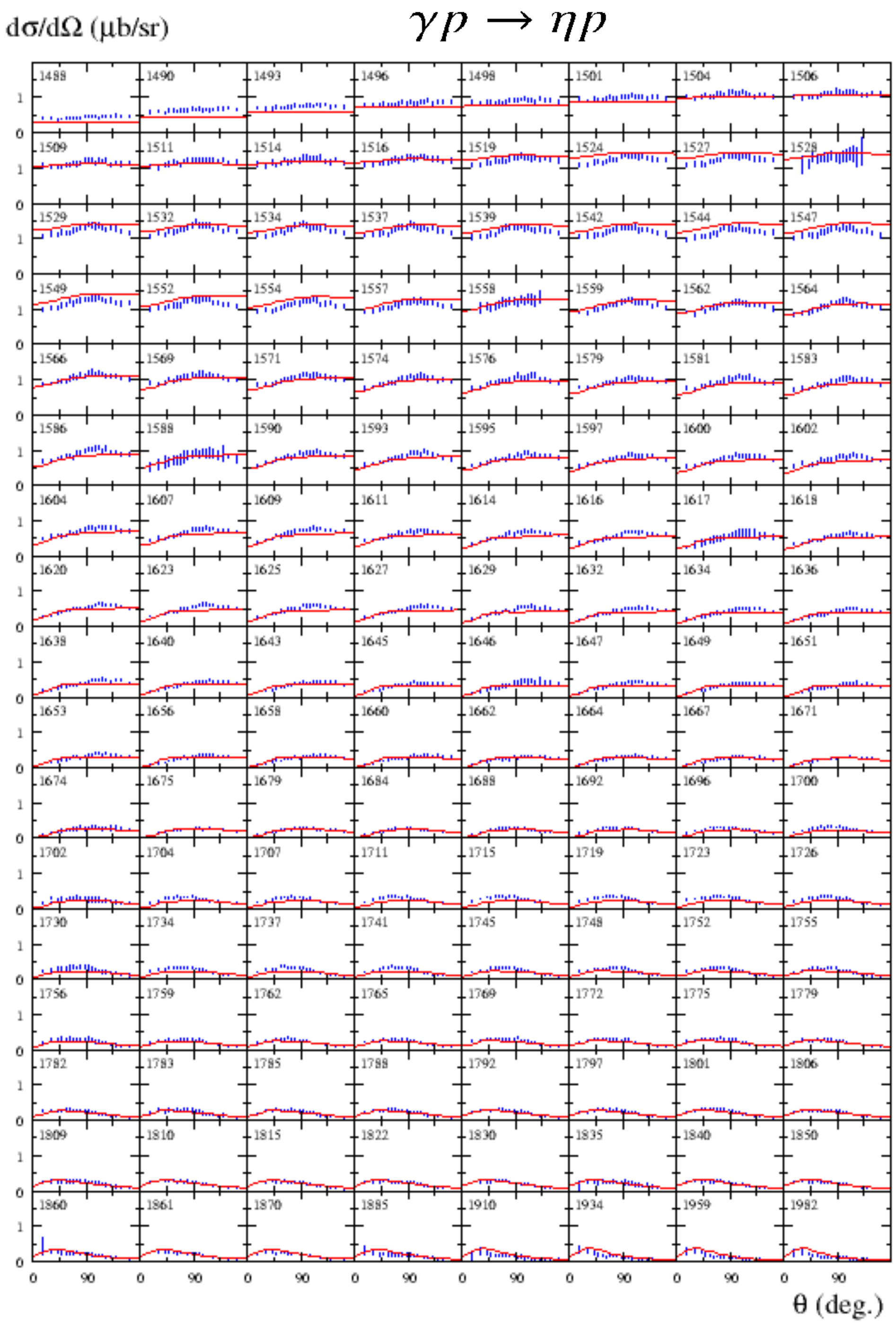
Vector current (Q^2=0) for 1π

Production is well-tested by data

Eta production reactions

$\boxed{\pi^- p \rightarrow \eta n}$



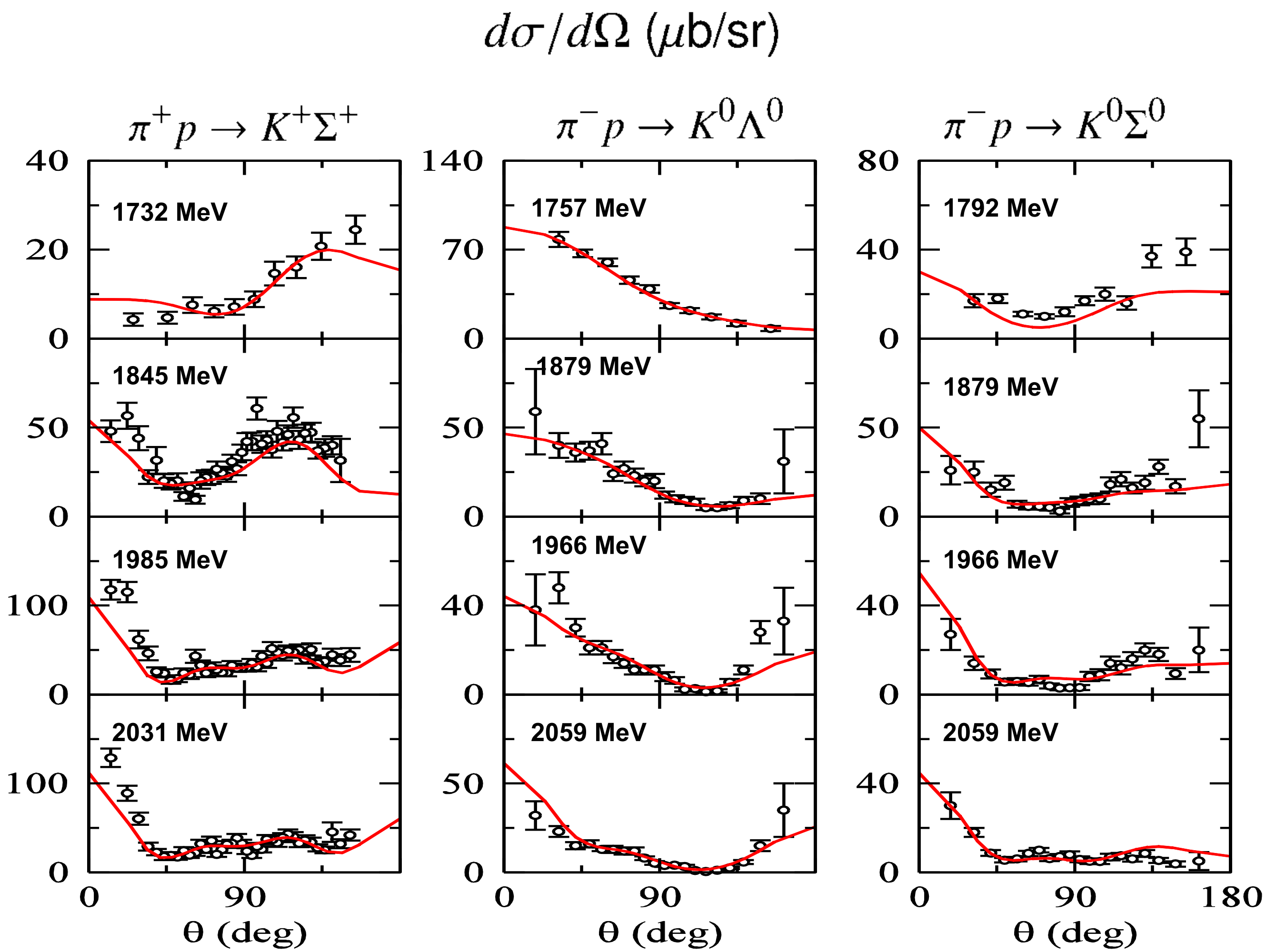


Kamano, Nakamura, Lee, Sato, 2012

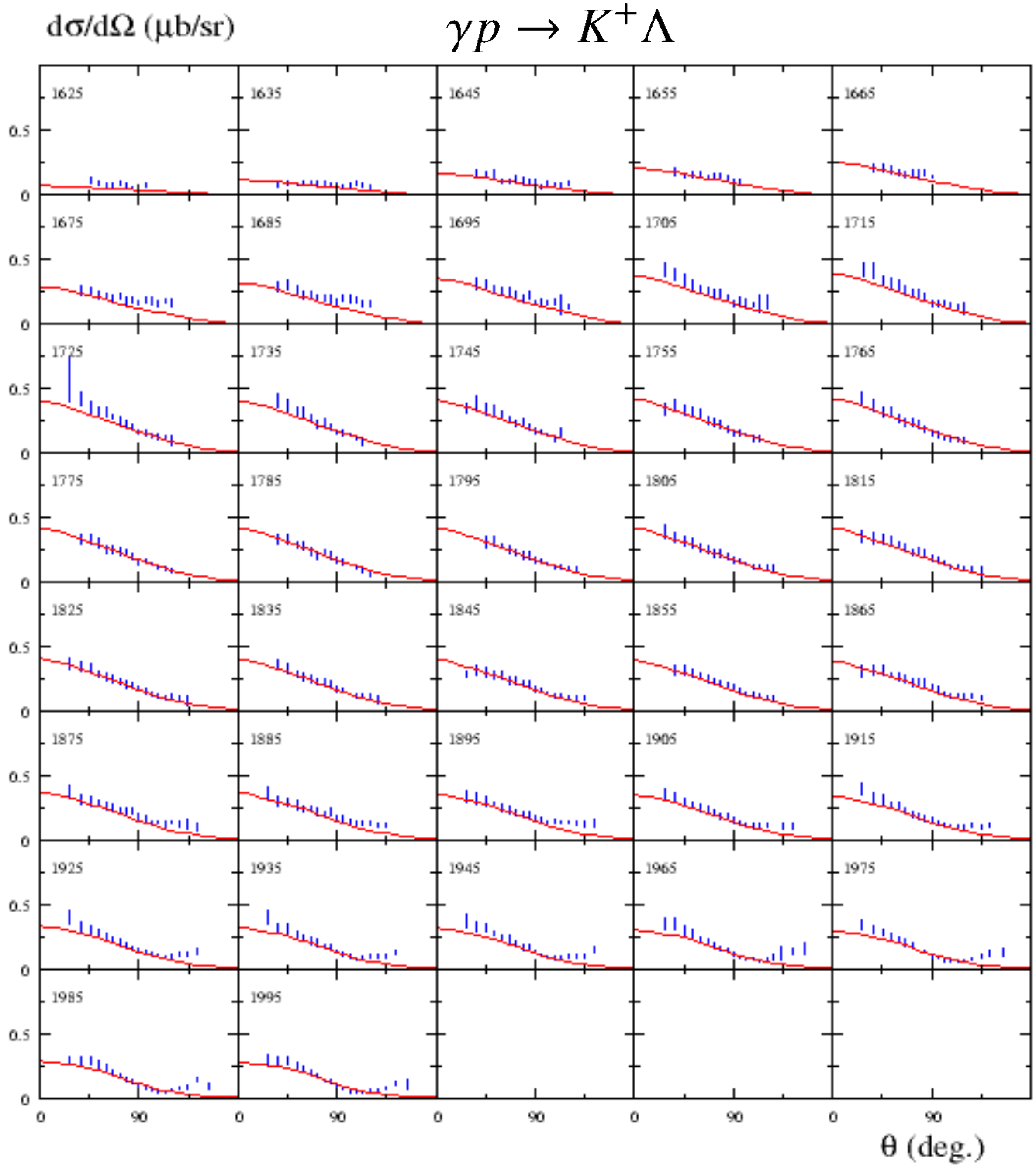
Vector current (Q^2=0) for η

Production is well-tested by data

KY production reactions



Kamano, Nakamura, Lee, Sato, 2012



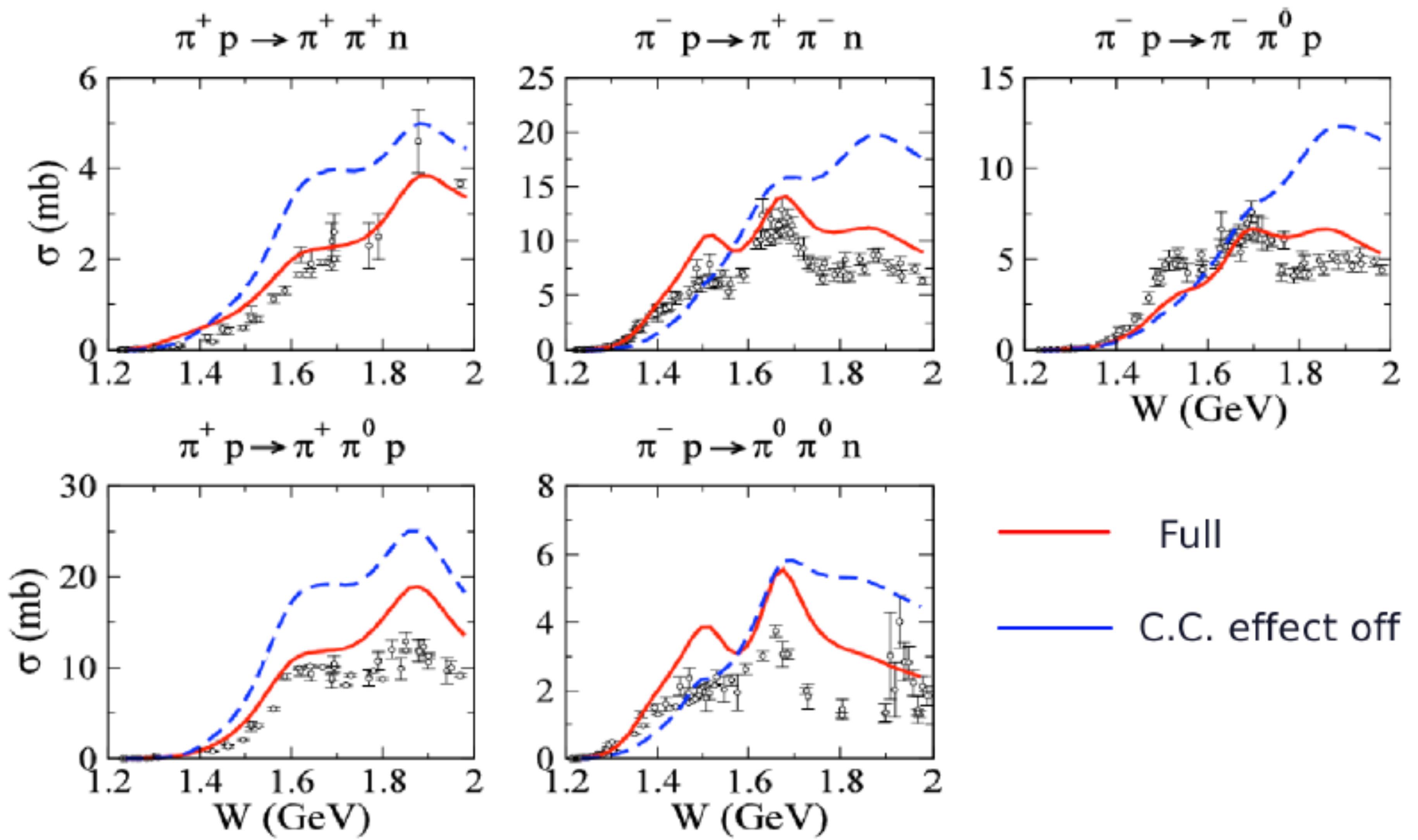
Vector current (Q^2=0) for K

Production is well-tested by data

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

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

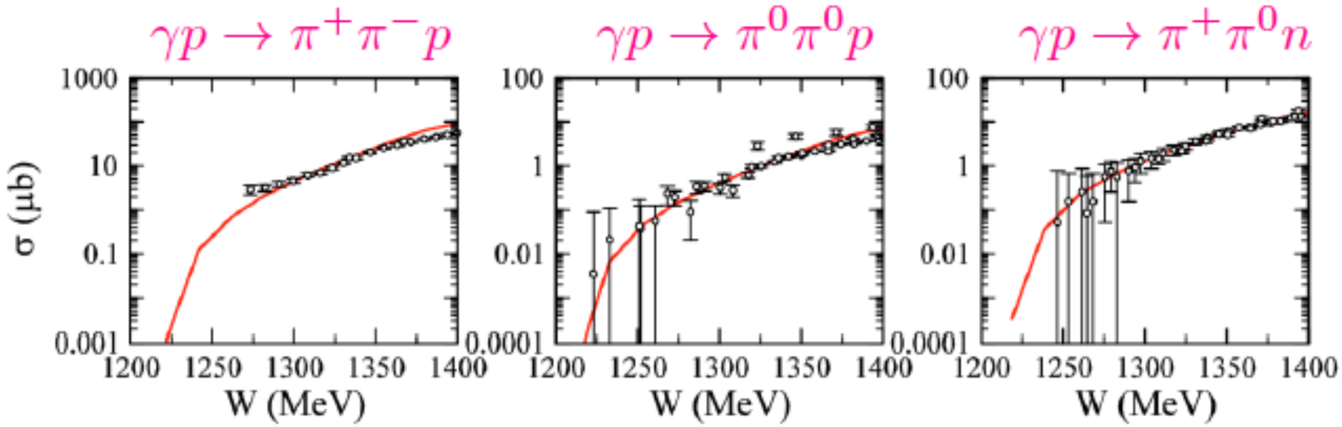
Kamano, Julia-Diaz, Lee, Matsuyama, Sato, PRC79 025206 (2009)

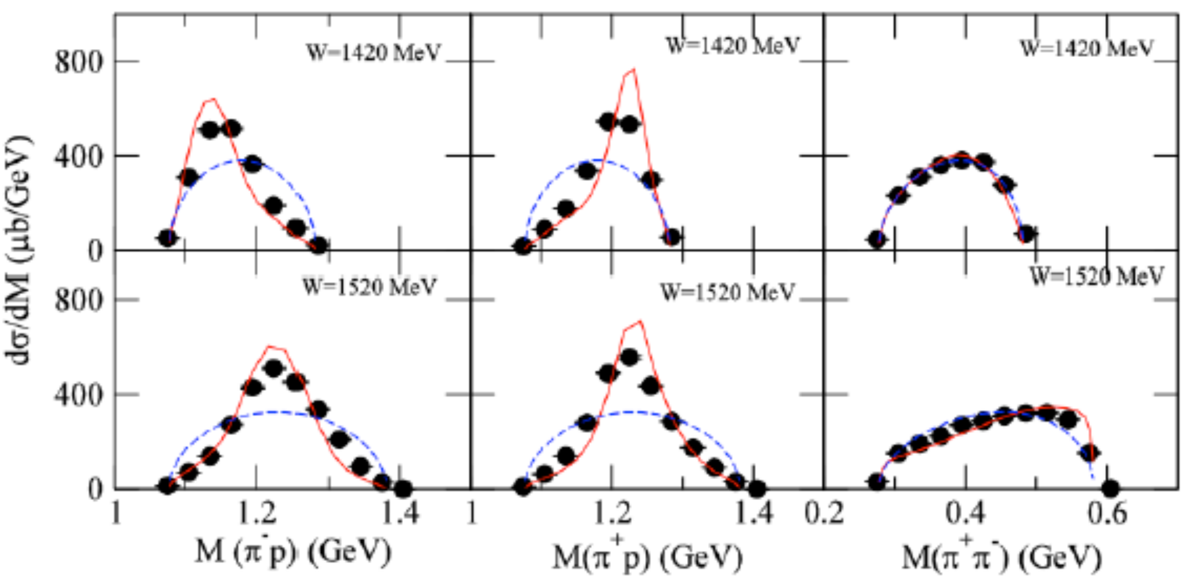


$\gamma N \to \pi\pi N$

(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 $\gamma N,\ \pi N \rightarrow \pi N, \pi\pi N, \eta N, K\Lambda, K\Sigma$ is developed
- Model is extensively tested by $\gamma N,\ \pi N \rightarrow \pi N, \pi\pi N, \eta N, K\Lambda, K\Sigma$

  data $\rightarrow$ reliable vector current to be applied to ν-scattering

PCAC-based application of DCC model to forward νN → $\pi N, \pi\pi N, \eta N, K\Lambda, K\Sigma$

Kamano, Nakamura, Lee, Sato, PRD, arXiv:1207.5724

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

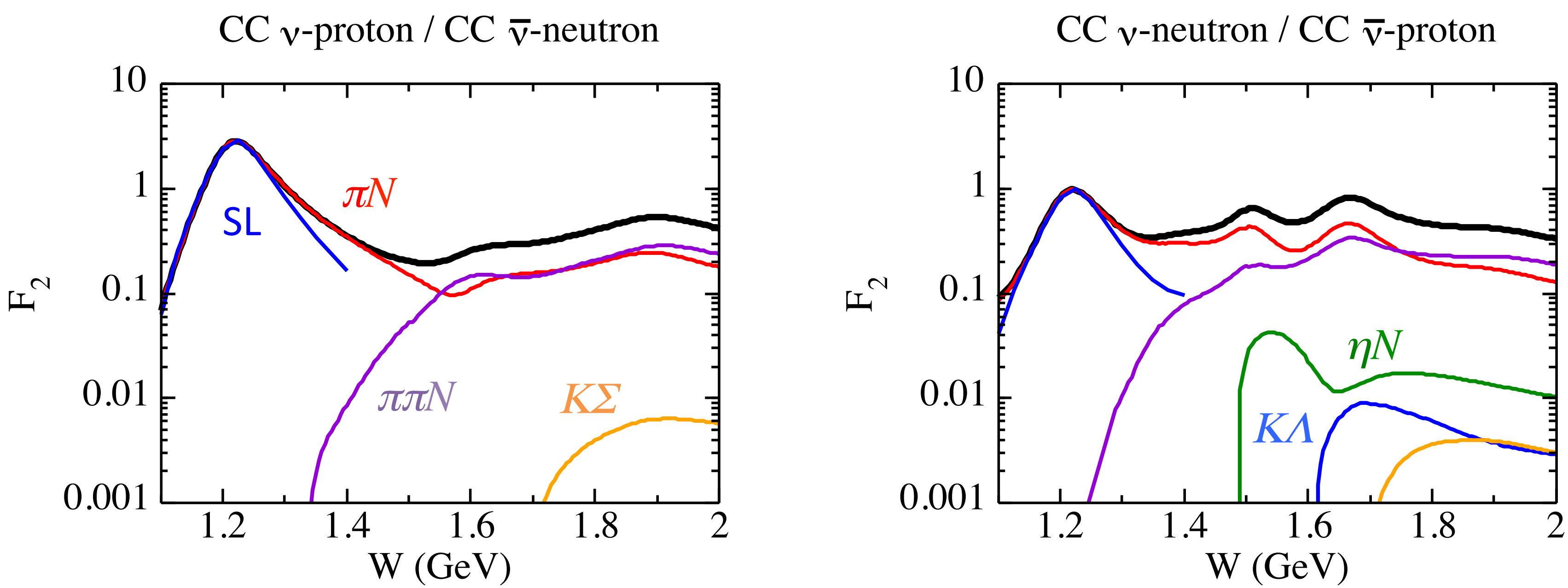
$$\langle X | \hat{\pi} | N \rangle = \frac{\sqrt{2\omega_c}}{m_\pi^2} \mathcal{T}_{\pi N \to X}(0) \sim \frac{\sqrt{2\omega_c}}{m_\pi^2} \mathcal{T}_{\pi N \to X}(m_\pi^2)$$

Finally

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

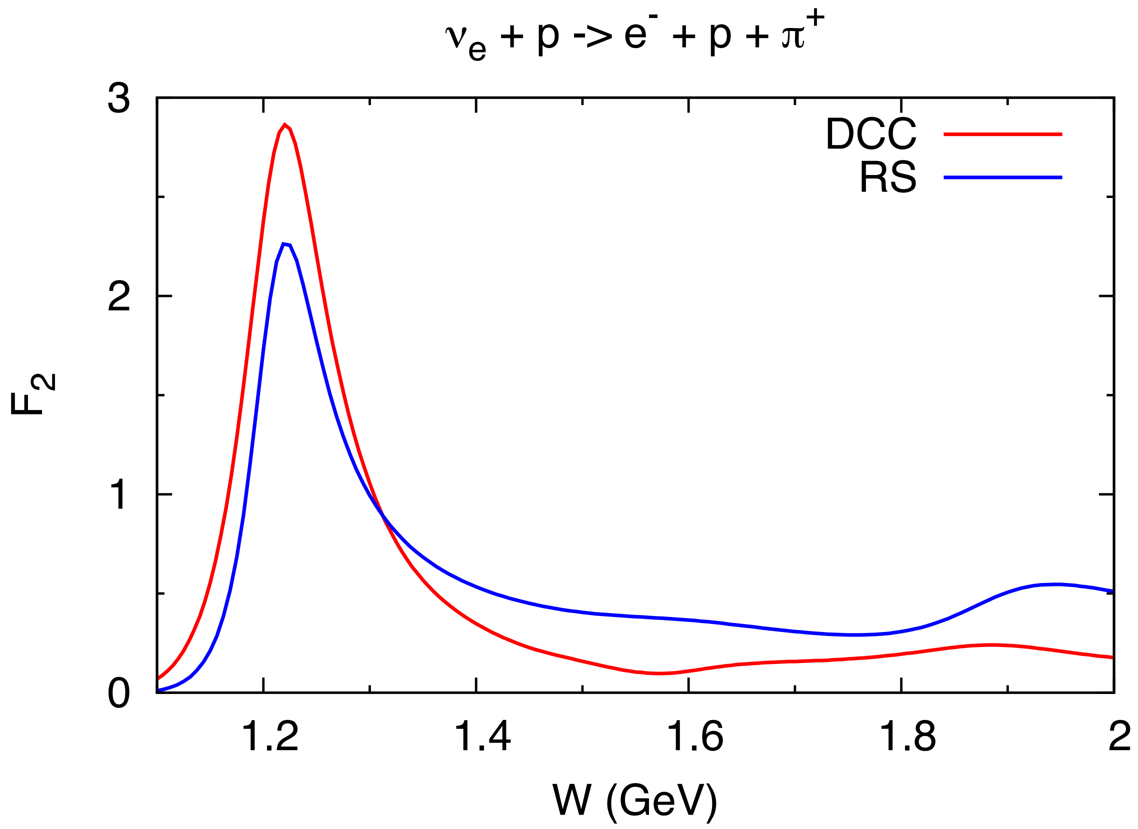
$\sigma_{\pi N \rightarrow X}$ is from our DCC model

Results



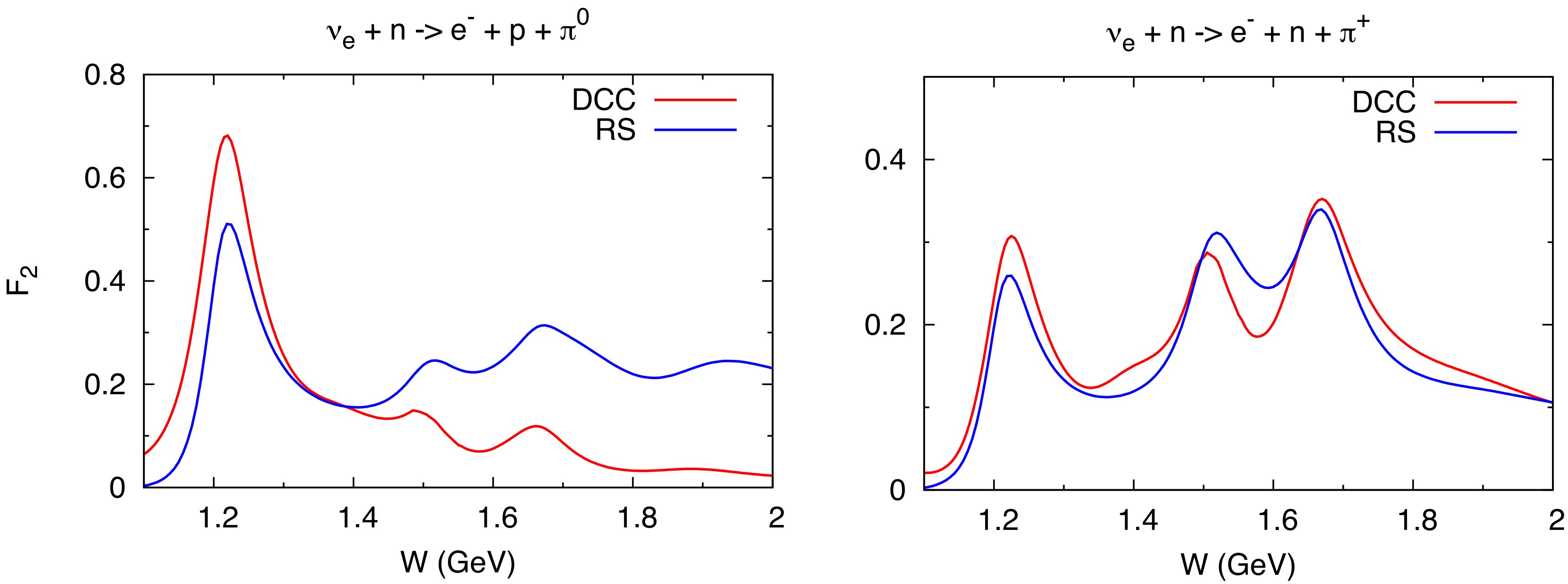
- Prediction based on model well tested by data
- πN dominates for $W \leq 1.5$ GeV
- $\pi\pi N$ becomes comparable to πN for $W \geq 1.5$ GeV
- Smaller contribution from ηN and KY $O(10^{-1})$ - $O(10^{-2})$
- Agreement with SL (no PCAC) in Δ region

Comparison with Rein-Sehgal model



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

Comparison with Rein-Sehgal model



Comparison in whole kinematical region will be done

after axial current model is developed

Summary

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 development of dynamical axial current is underway

BACKUP

J-PARC proposal

$\pi N \rightarrow \pi\pi N$ in high-mass N* region

(K. Hicks, K. Imai et al.)

→ There is *NO* practical data that can be used for testing models for $\pi N \rightarrow \pi\pi N$ above $W > 1.5$ GeV.

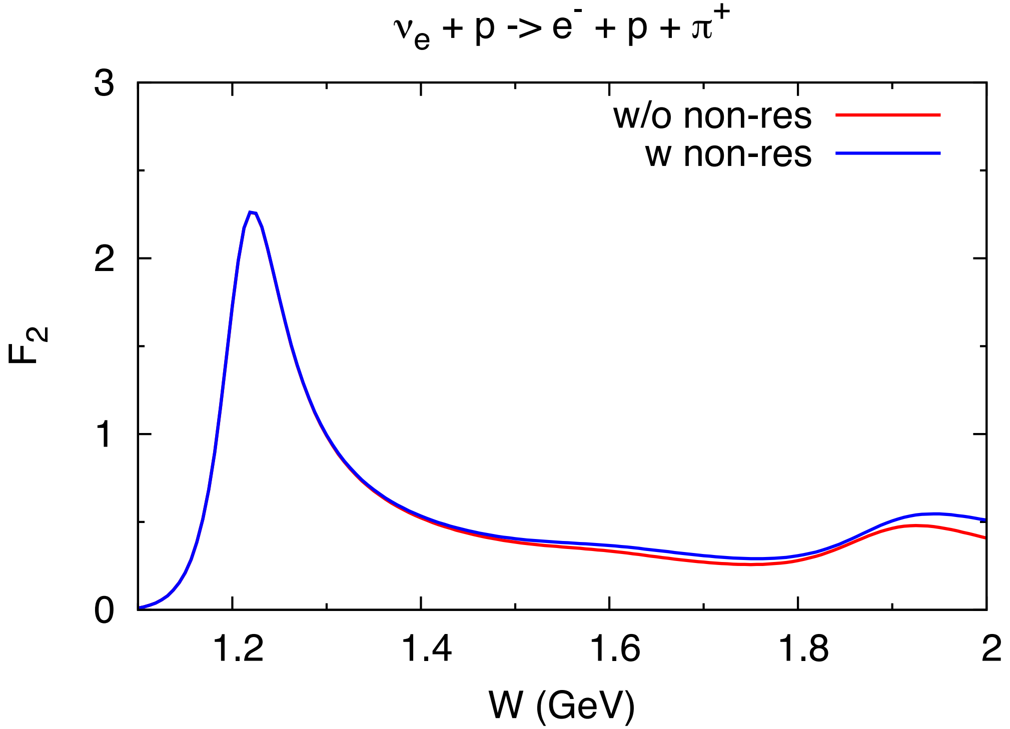
→ For $W > 1.5$ GeV, $\pi N \rightarrow \pi\pi N$ becomes the dominant process of the πN reactions. (same applied to ν-scattering)

Model for $\nu N \rightarrow \pi\pi N$ will be essetial piece in MC

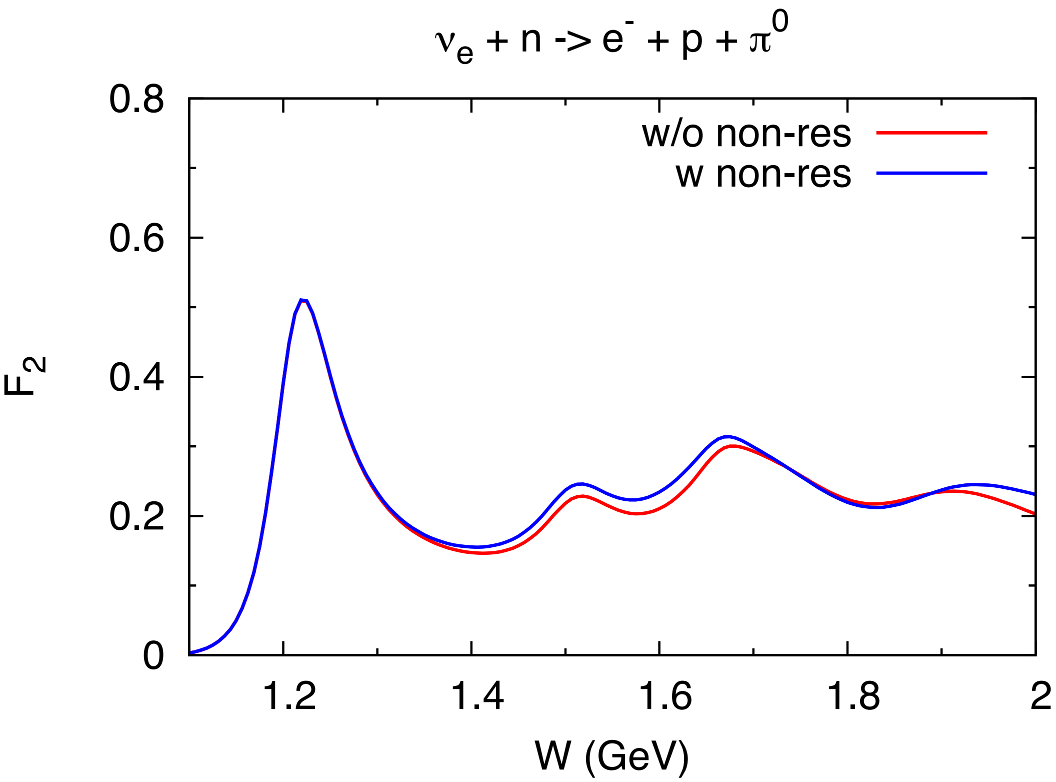
$\pi N \rightarrow \pi\pi N$ data are essential to develop $\nu N \rightarrow \pi\pi N$ model

Please support the proposal !

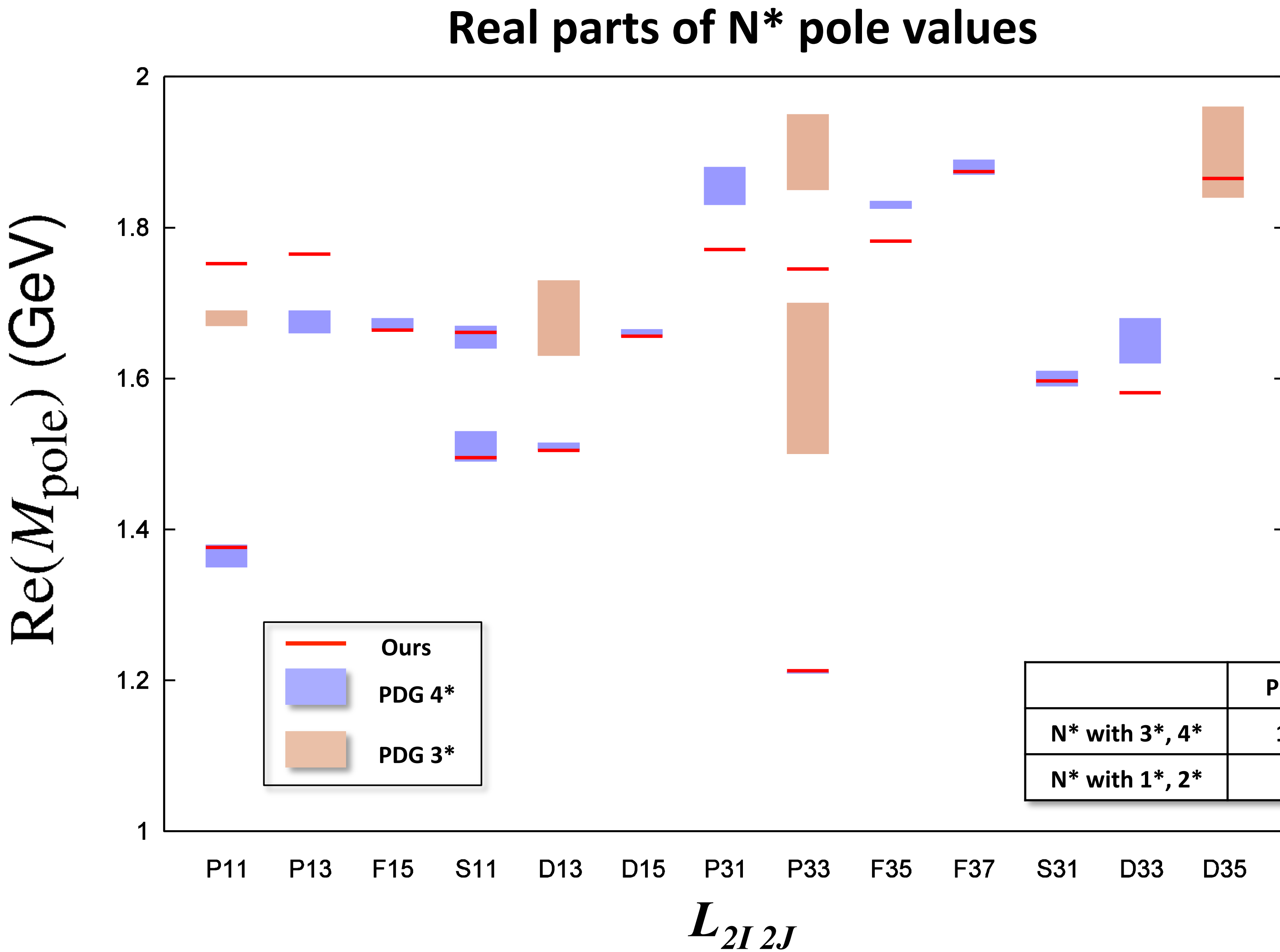
F_2 from RS model



F_2 from RS model



Spectrum of N* resonances

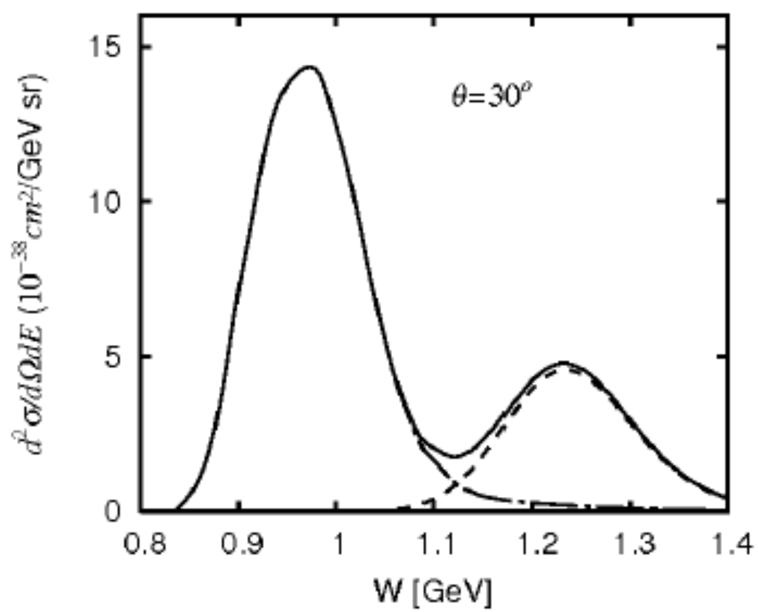


	PDG	Ours
N* with 3*, 4*	18	16
N* with 1*, 2*	5	

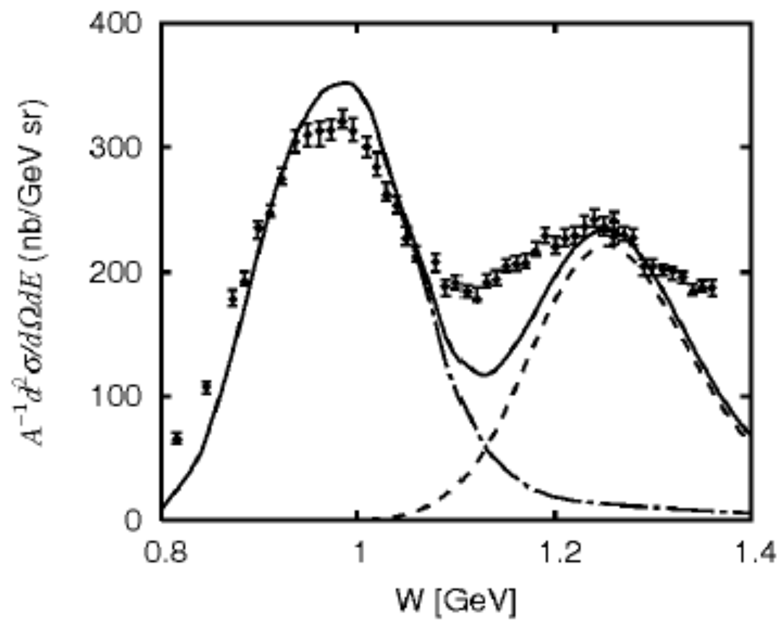
SL model applied to ν−nucleus scattering

1 π production

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



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

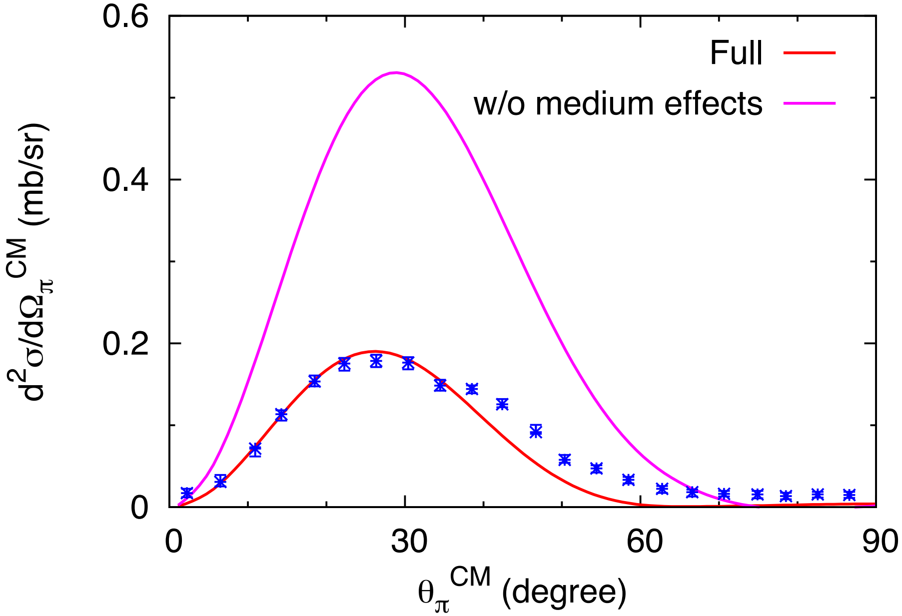


Szczerbinska et al. (2007)

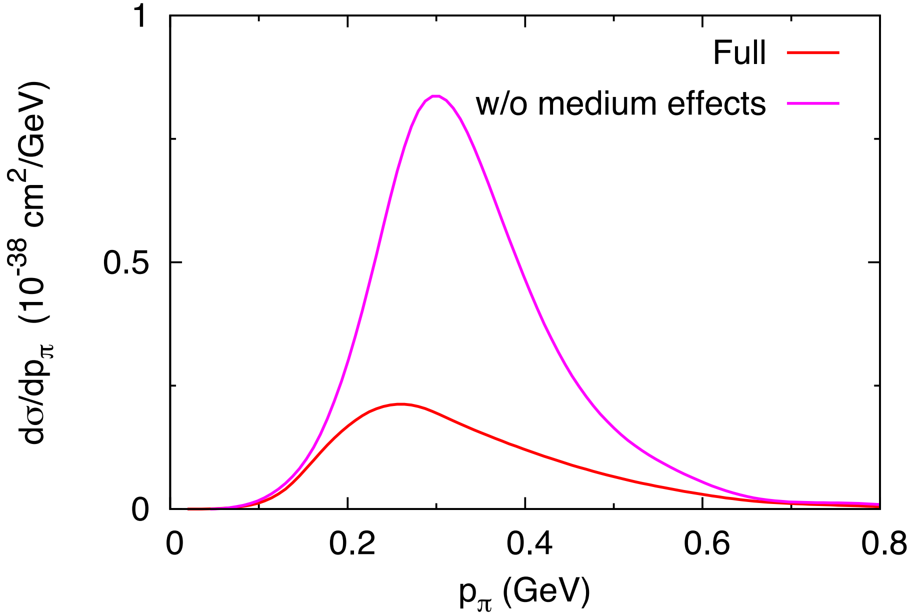
SL model applied to ν−nucleus scattering

coherent π production

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



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



Nakamura et al. (2010)

Dealing with multi-channel reaction

e.g., ν-induced K production

Tree-level models

ΔS=0 : Adera et al., (2010)

ΔS=1 : Rafi Alam et al., (2010), (2012)

DCC model for γN, πN → πN, ηN, $K\Lambda$, $K\Sigma$ reactions

* Well-established meson-exchange mechanism for meson-baryon interactions

* Description of nucleon resonance (N^*)

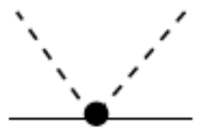
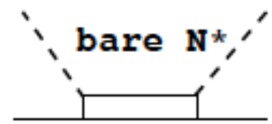
* Unitarity → γN, πN, ηN, $\pi\pi N$ ($\pi\Delta$, ρN, σN), $K\Lambda$, $K\Sigma$ coupled-channels

DCC (Dynamical Coupled-Channel) model

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

Coupled-channel Lippmann-Schwinger equation

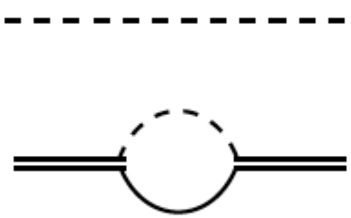
$$T_{ab} = V_{ab} + \sum_c V_{ac}\, G_c\, T_{cb}$$

$\mathbf{V}_{\mathbf{ab}}$ =  + 

+ **Z**

$G\,c$ =

for stable channels



for unstable channels