ν-Nucleus Interactions in ANL-Osaka Model

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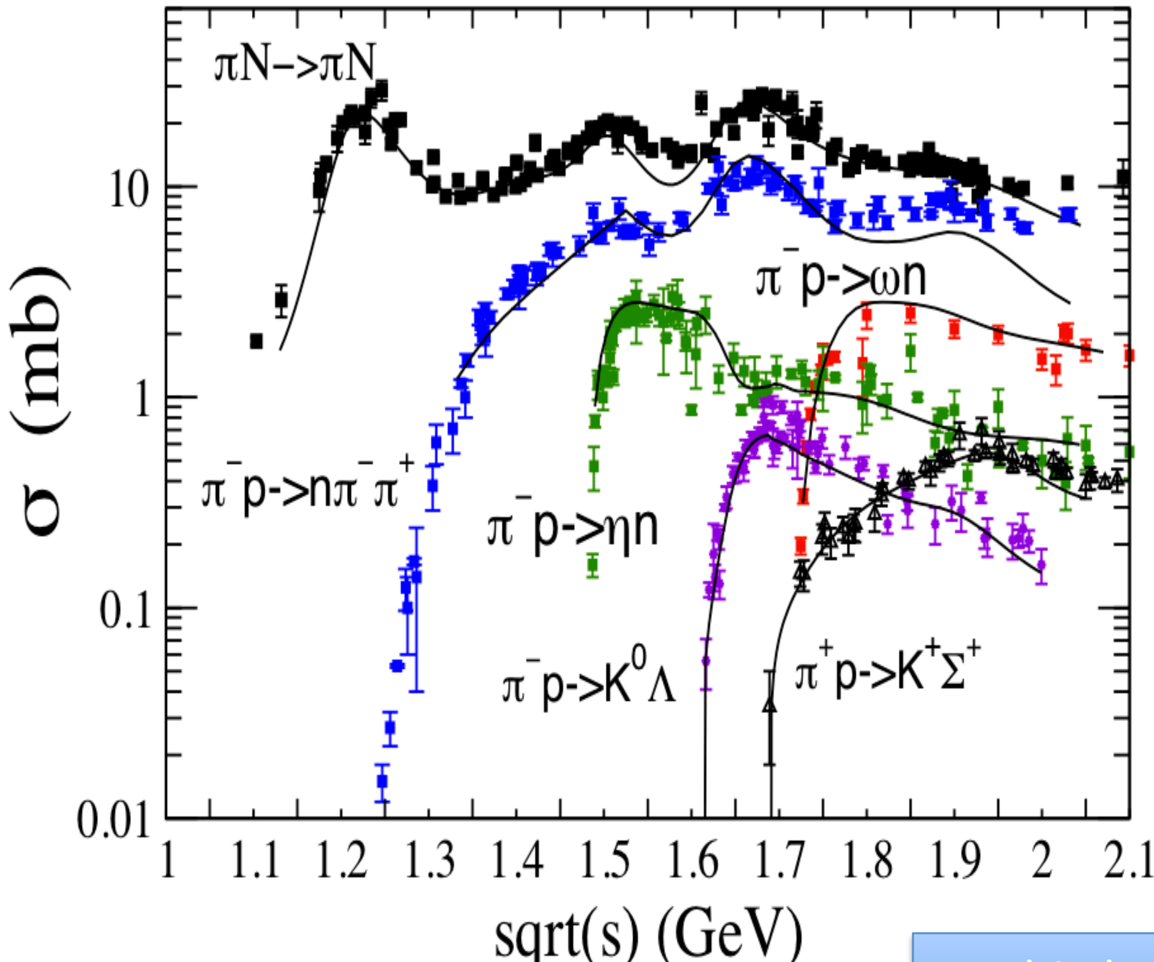
Objectives of ANL-Osaka Model:

- Analyze the data of meson production on the nucleon in the nucleon resonance region
- Apply the model to predict electroweak meson production from nuclei

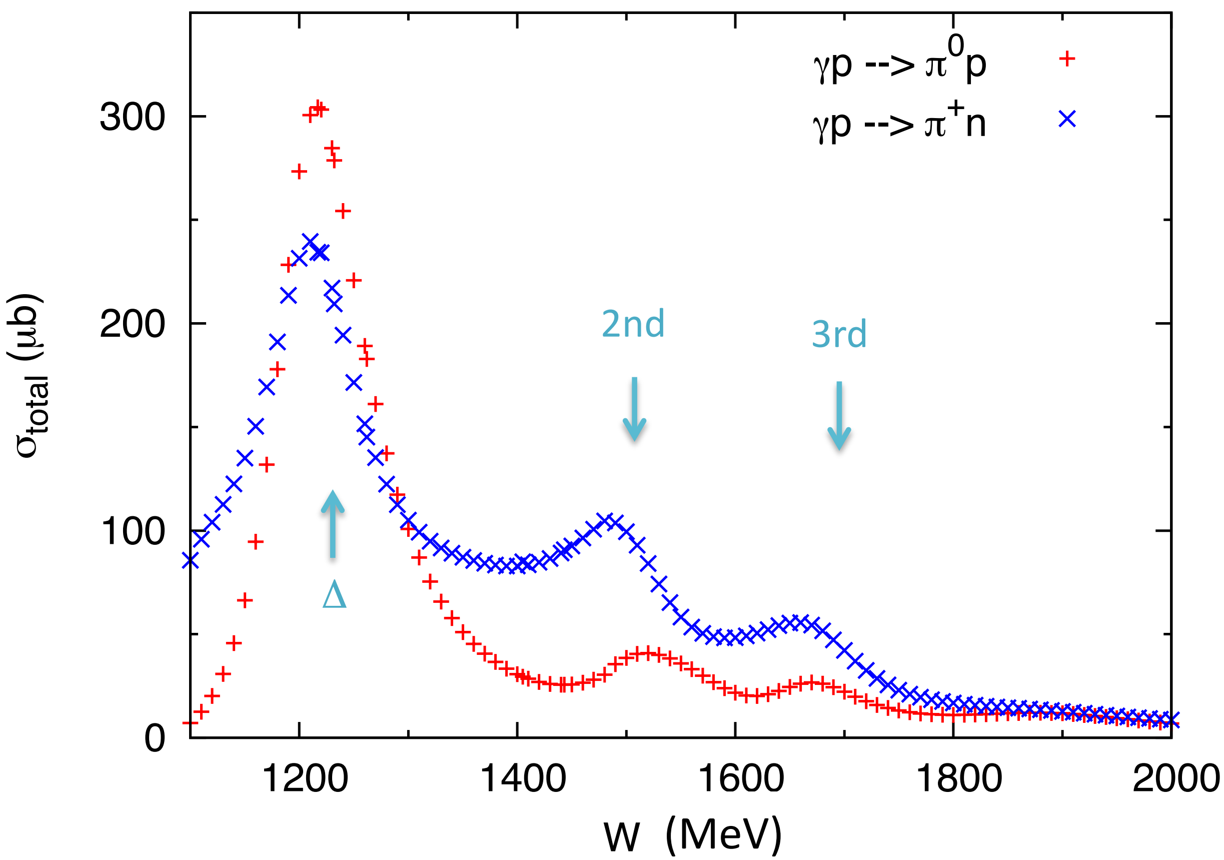
Total cross sections of πp reaction



Complications in resonance region:

- Multi-channel problem
- Many resonances
- 2π is comparable to 1π

Resonances in γN reactions



Δ(1232) is isolated

- First step: Focus on the $\Delta(1232)$ region (1996-2005)

Objectives:

1. Determine electroweak N -> $\Delta(1232)$ form factors

2. Perform consistent many-body calculations of electroweak π production on nuclei

→

Construct energy independent Hamiltonian from Lagrangian of quantum field theory using Osaka unitary transformation method

M. Kobayashi, T.Sato, H.Ohtsubo, Prog. Theor. Phys. 98 927 (1997)

Model Hamiltonians with N, π and Δ

$$H = H_0 + H'_1 + H'_2$$

$$H'_2 = V_{NN,NN} + V_{N\Delta,NN} + V_{N\Delta,N\Delta}$$

$$H'_1 = v_{\pi N,\pi N} + h_{\Delta,\pi N}$$

$$+ v_{\pi N,\gamma N} + h_{\Delta,\gamma N}$$

Determined by
πN -> πN
NN-> NN, πNN

Determined by
γN-> πN
N(e,e'π) N

SL Model

(Sato, Lee, PR C 54, 2660 (1996);C63,055201 (2001))

$$H'_1 = v_{\pi N,\pi N} + h_{\Delta,\pi N} + v_{\pi N,\gamma N} + h_{\Delta,\gamma N}$$

Determined by
πN -> πN
γN-> πN
N(e,e'π) N

Meson-exchange

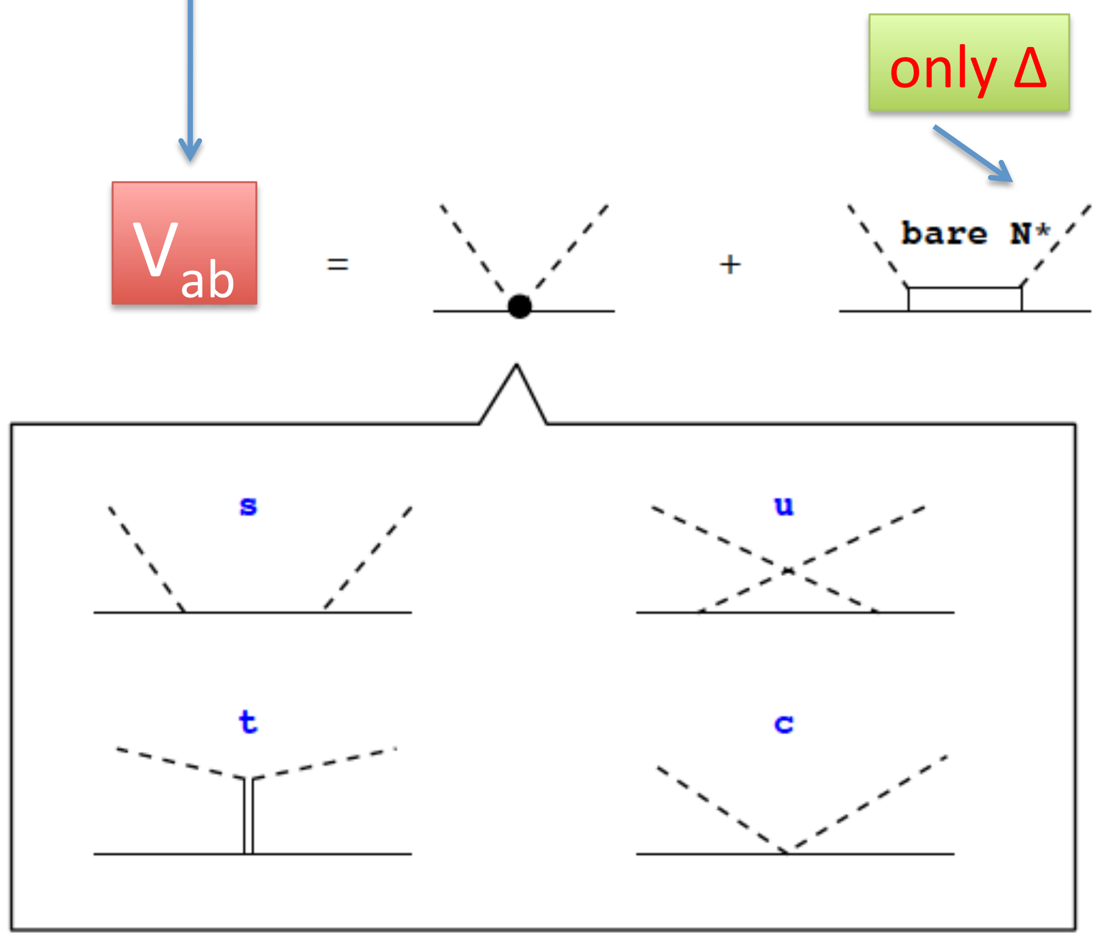
$\langle \Delta | J^{em} | N \rangle$

Determined by data

Solve

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

a ,b, c = πN, γN



Procedures:

- Fit πN -> π N phase shifts data

→

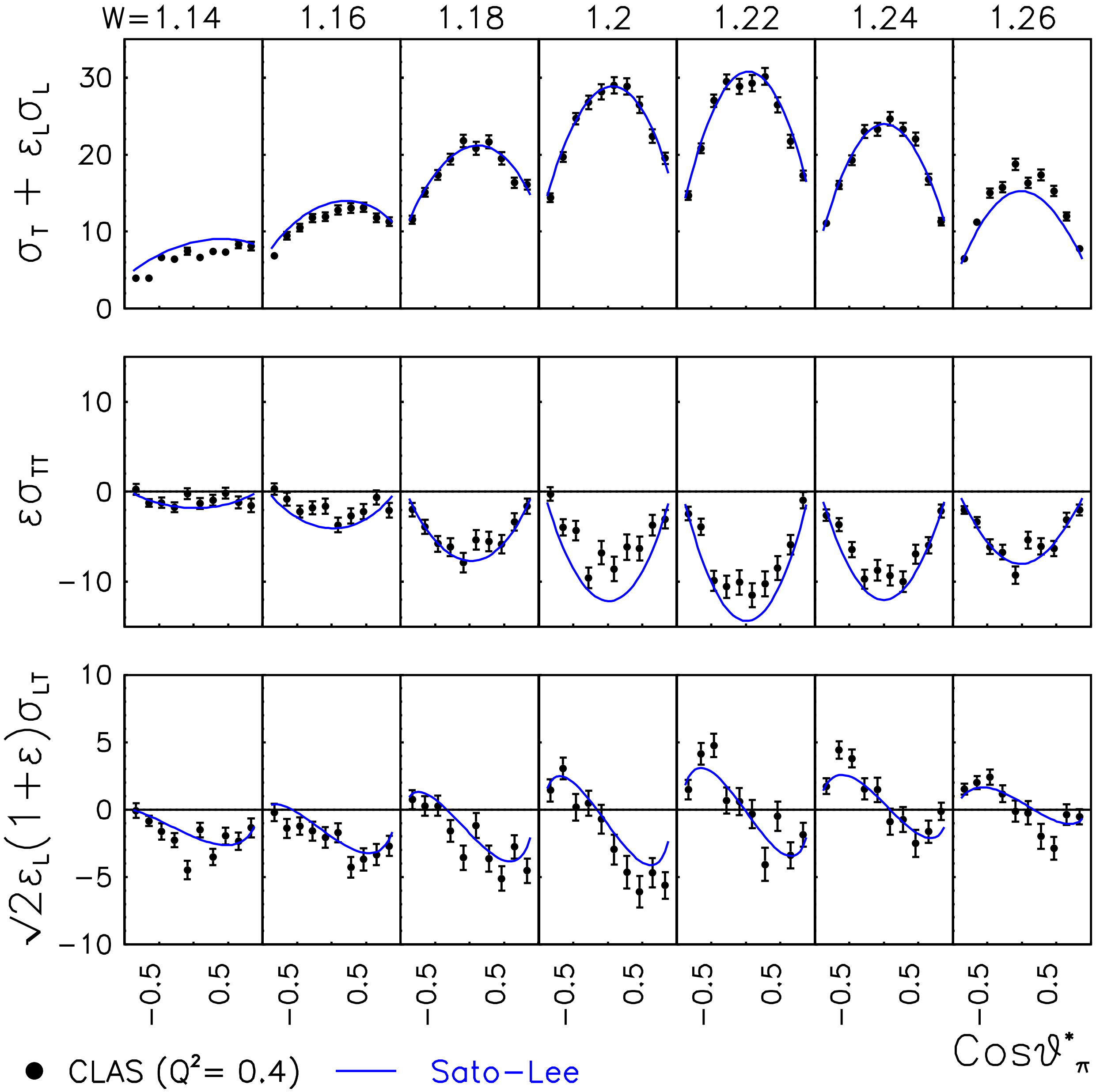
Δ -> π N is determined

- Fit γ N -> π N, N(e,e' π)N data

→

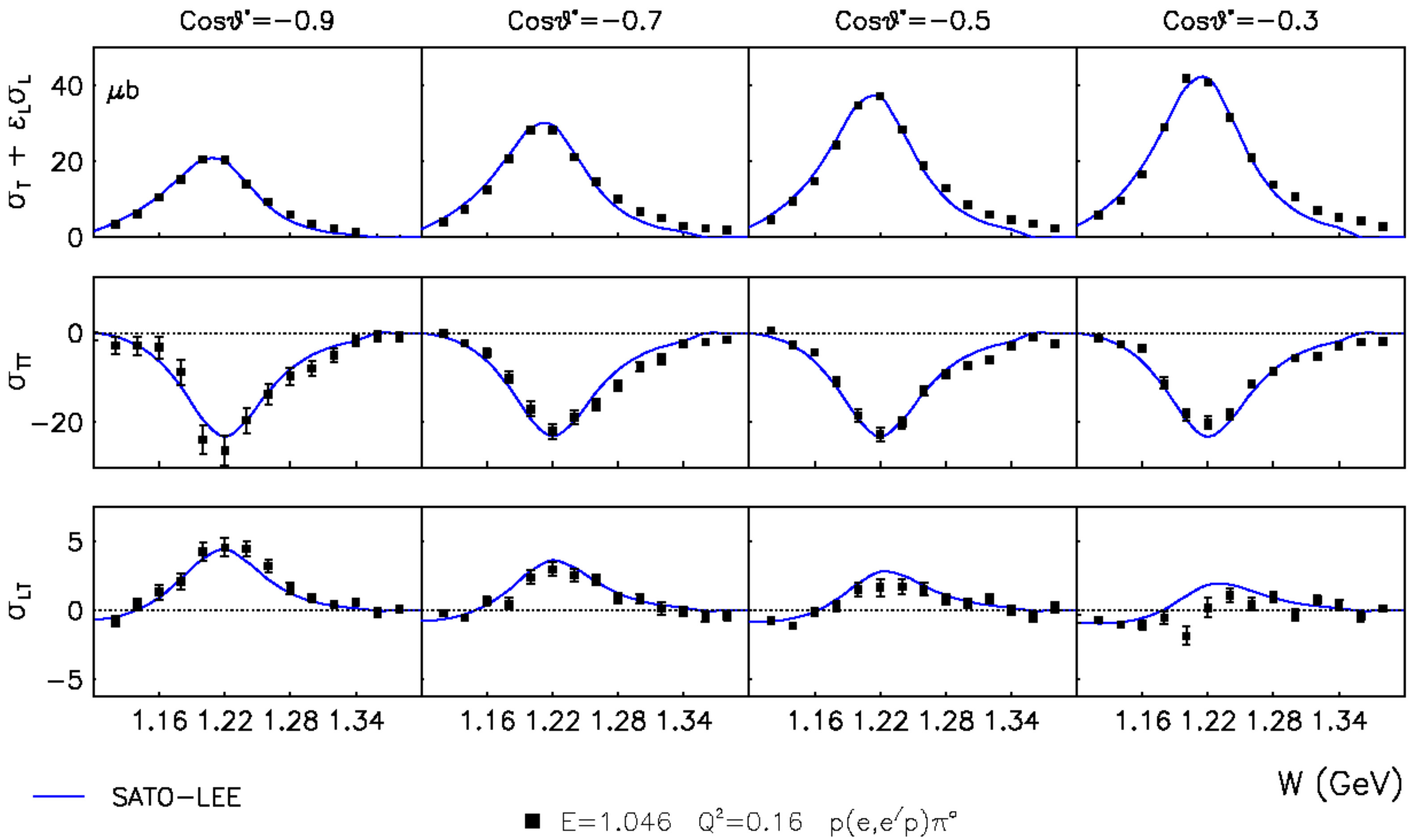
Δ -> γ N form factors are determined

Structure functions of p(e, e' π^0) p

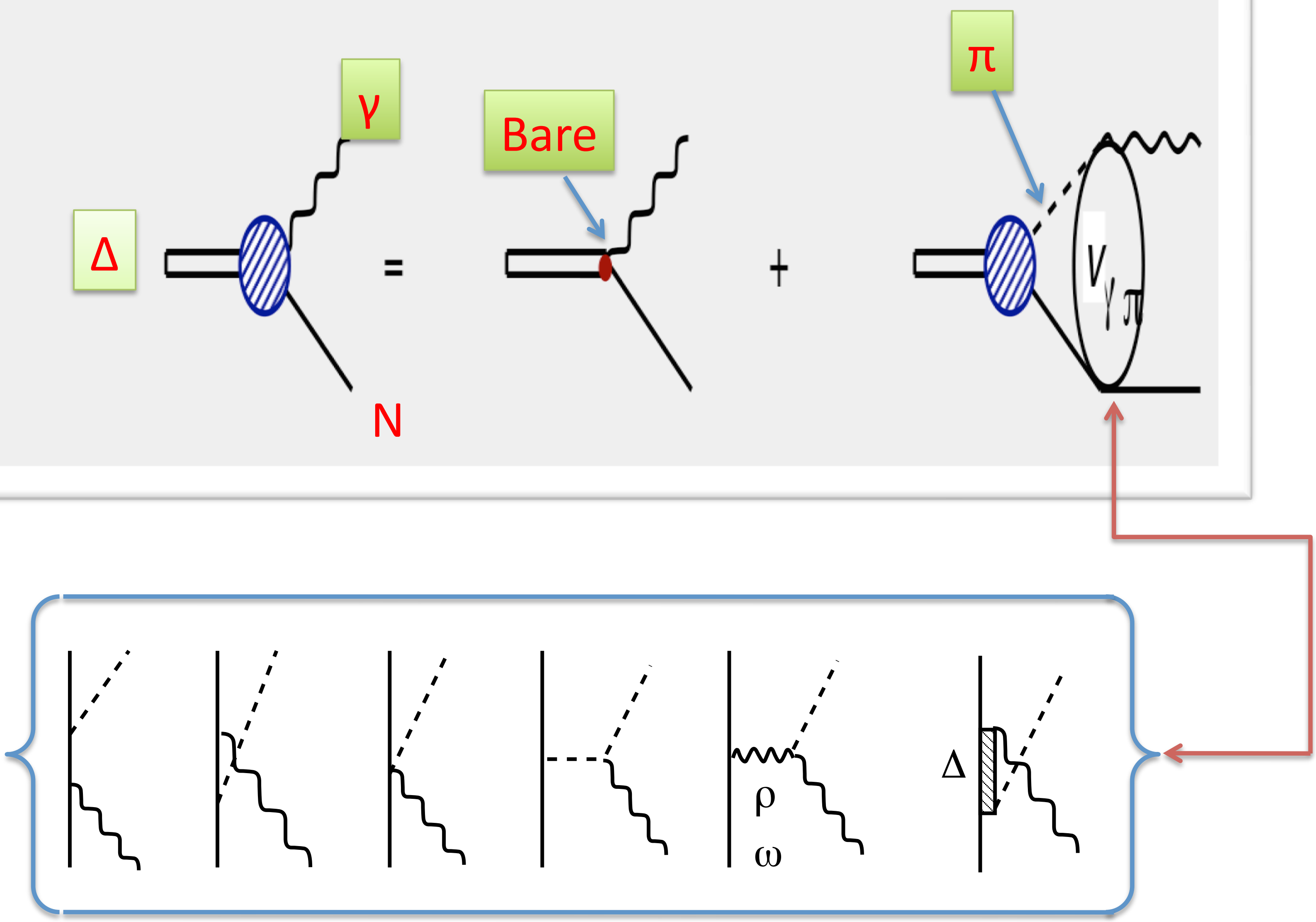


Pion electroproduction Structure functions

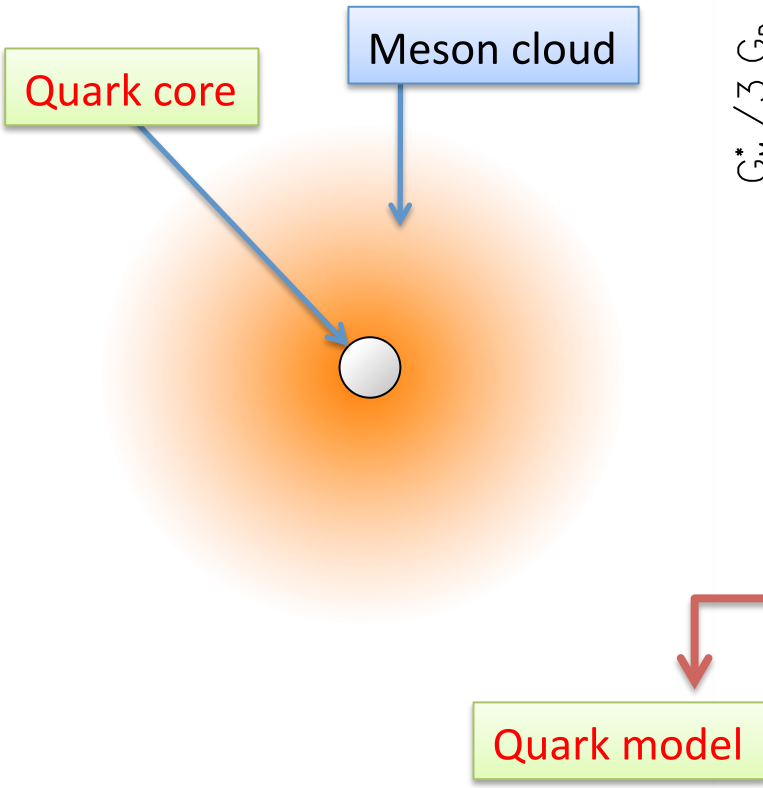
(data CLAS from C. Smith,2004)

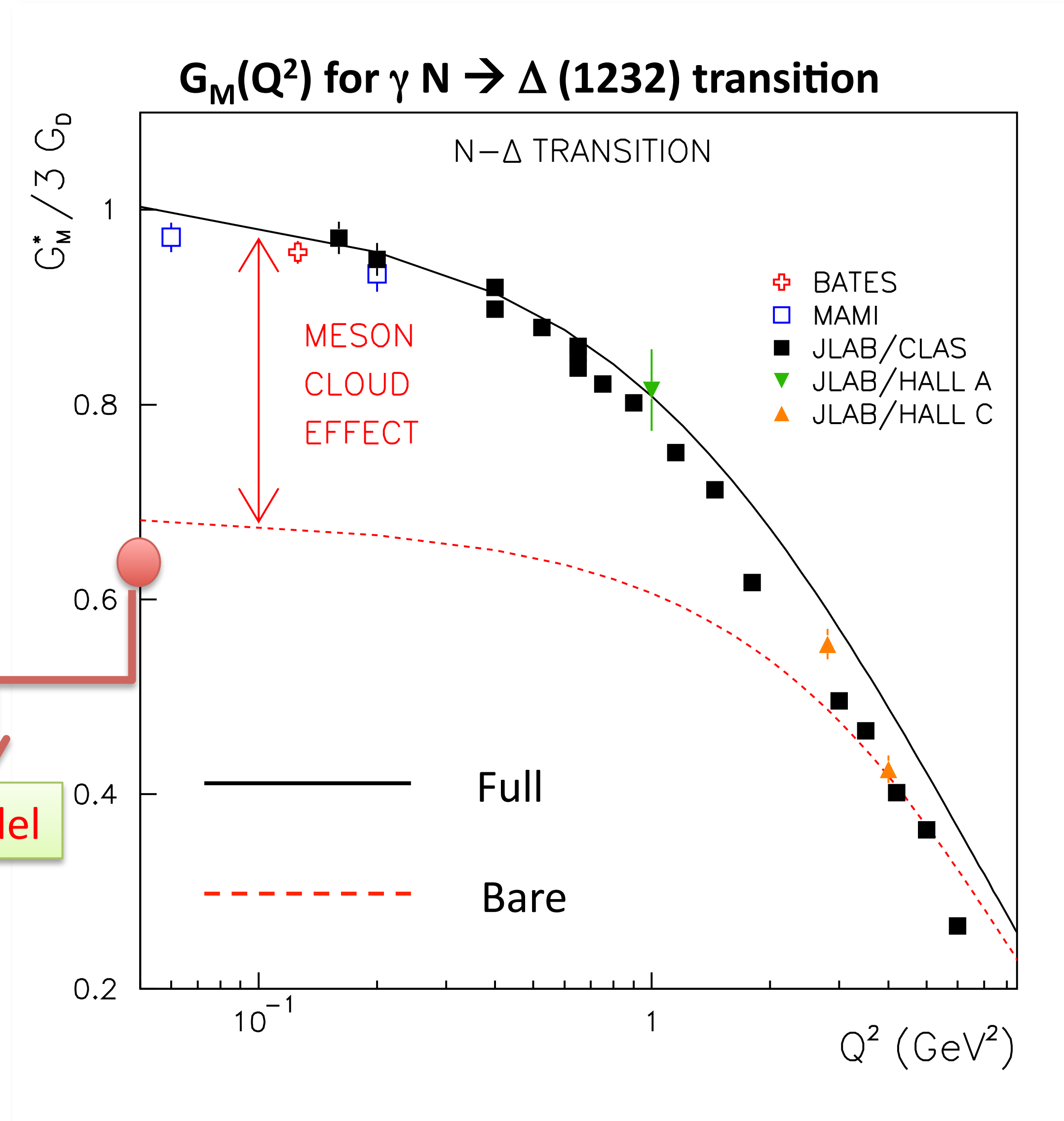


Δ -> γ N Form factor



Meson cloud effect in
γ N → Δ(1232) form factors





Note:
Most of the available static hadron models give $G_M(Q^2)$ close to "Bare" form factor.

Extend SL Model to include J^{CC} and J^{NC}

- Charged current

$$J^{CC} = (V^1 + i\,V^2) - (A^1 + i\,A^2)$$

- Neutral current

$$J^{NC} = (1-2\sin^2\theta_W)\,J^{em} - V_{isoscalar} - A^3$$

Objective:

Extract N – Δ axial form factors from

- N(ν, μ π) reactions
- Parity-iolating asymmetry of inclusive N(e,e')

Procedures:

- Charged current

$J^{CC} = (V^1 + i V^2) - (A^1 + iA^2)$

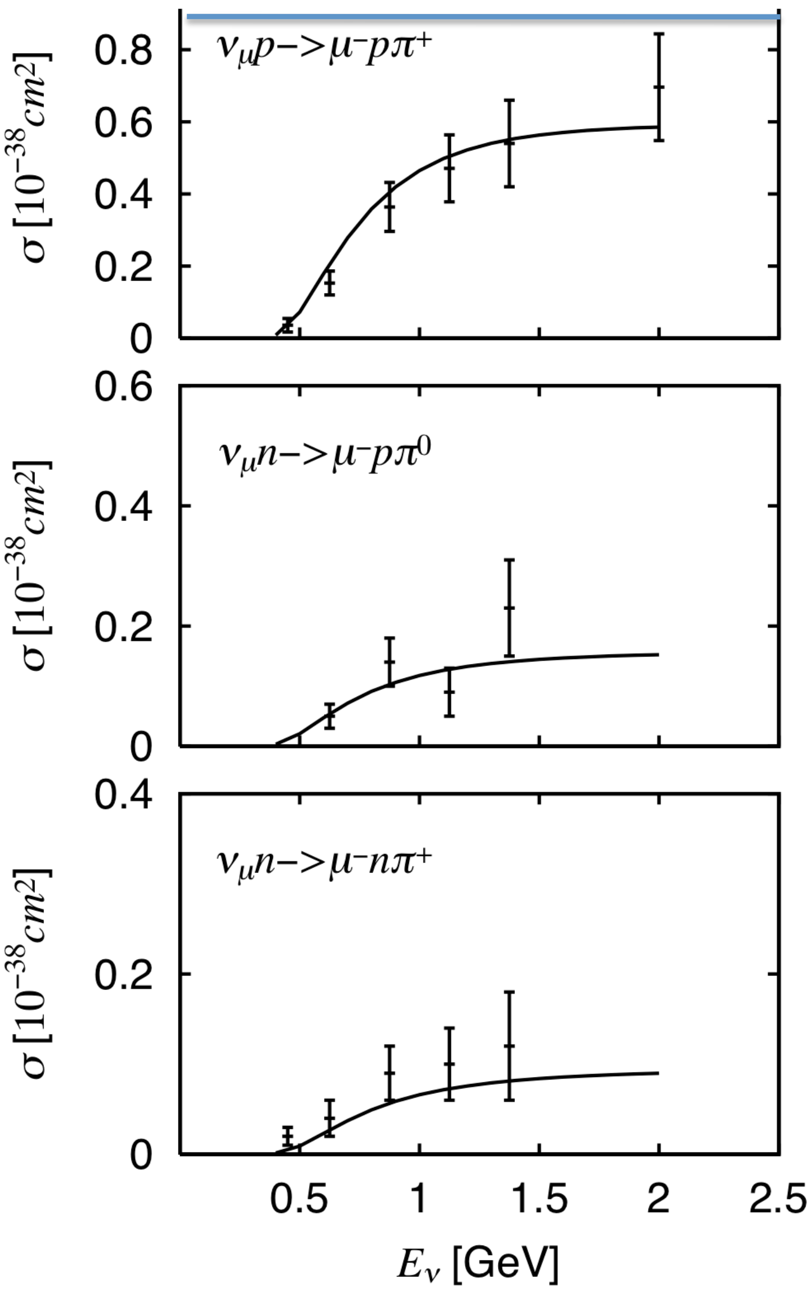
determined in (e, e' π)

•Non-resonant axial current (A^1, A^2, A^3) are derived from effective Lagrangians

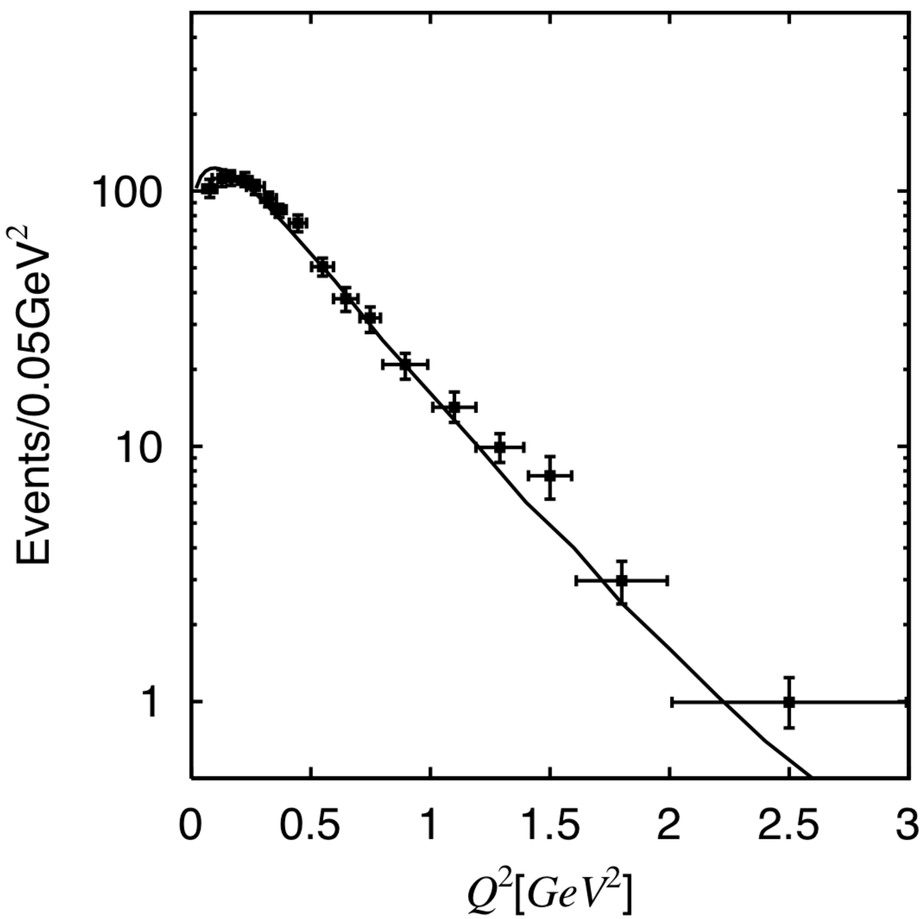
Adjust $G^A_{N,\Delta}(Q^2) = \langle\Delta|(A^1 + iA^2)|N\rangle$ to fit N(ν, μ π) data

Sato, Uno, Lee, PR C67,065201 (2003)

ν-N Total cross sections



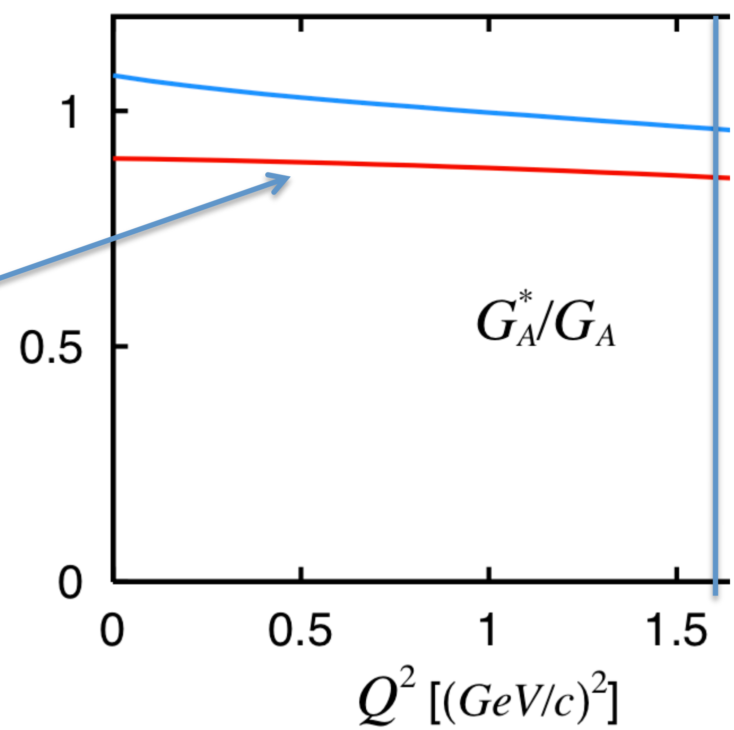
Sato, Uno, Lee, PR C67,065201(2003)



$d\sigma/dQ^2$ of $p(\nu,\mu^- \pi^+)$

$G^{A}_{N,\Delta}(Q^2)$= <N|A^1+iA^2|Δ> is determined

Bare <N|A^{CC} |Δ>



Neutral current

$$J^{NC} = (1-2\sin^2\theta_W)\ J^{em} - V_{isoscalar} - A^3$$

determined in (e, e' π)

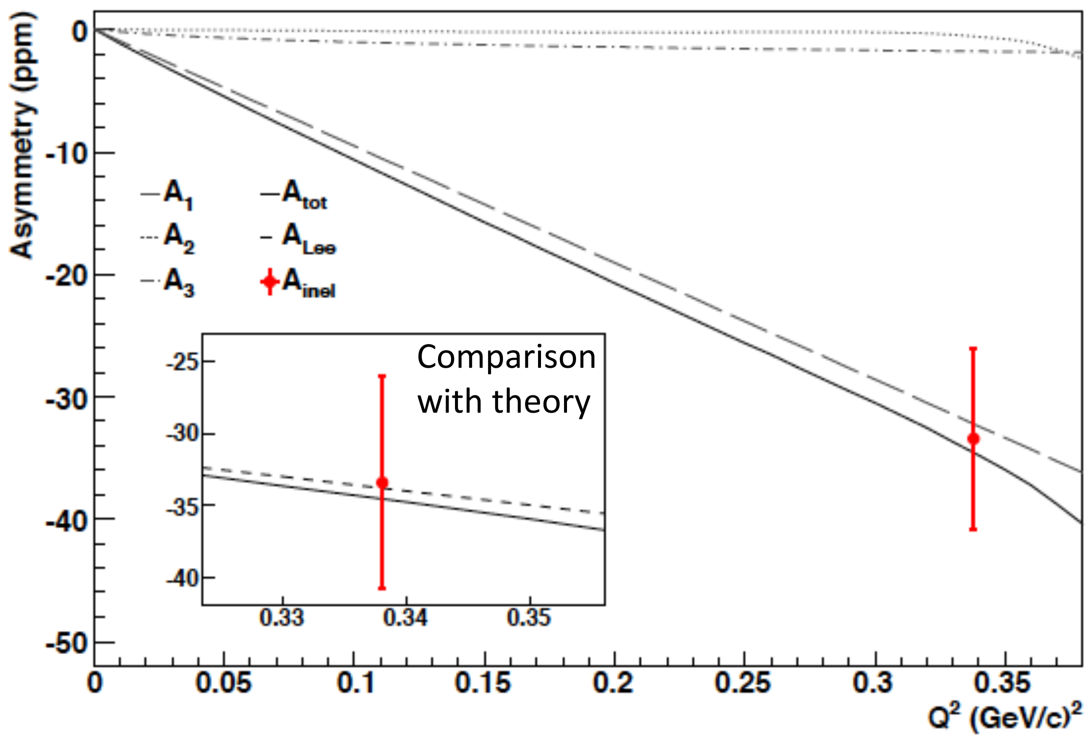
Test A^3 and $G^A_{N,\Delta}(Q^2)$ by Parity-violating inclusive N(e,e')

Experimental test (2011) of SL prediction(2005)

Electron data : parity violation asymmetry

G^0@JLab, arXiv:1212.1637

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



Exp :

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

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

Hamiltonian for many-body calculations of electroweak pion production on nuclei In Δ(1232) region has been constructed

↓

Predict ν-nucleus reactions

Hamiltonian with N, π and Δ

$$H = H_0 + H'_1 + H'_2 + J^{CC} + J^{NC}$$

Determined by νN -> μ π N

$$H'_2 = V_{NN,NN} + V_{N\Delta,NN} + V_{N\Delta,N\Delta}$$

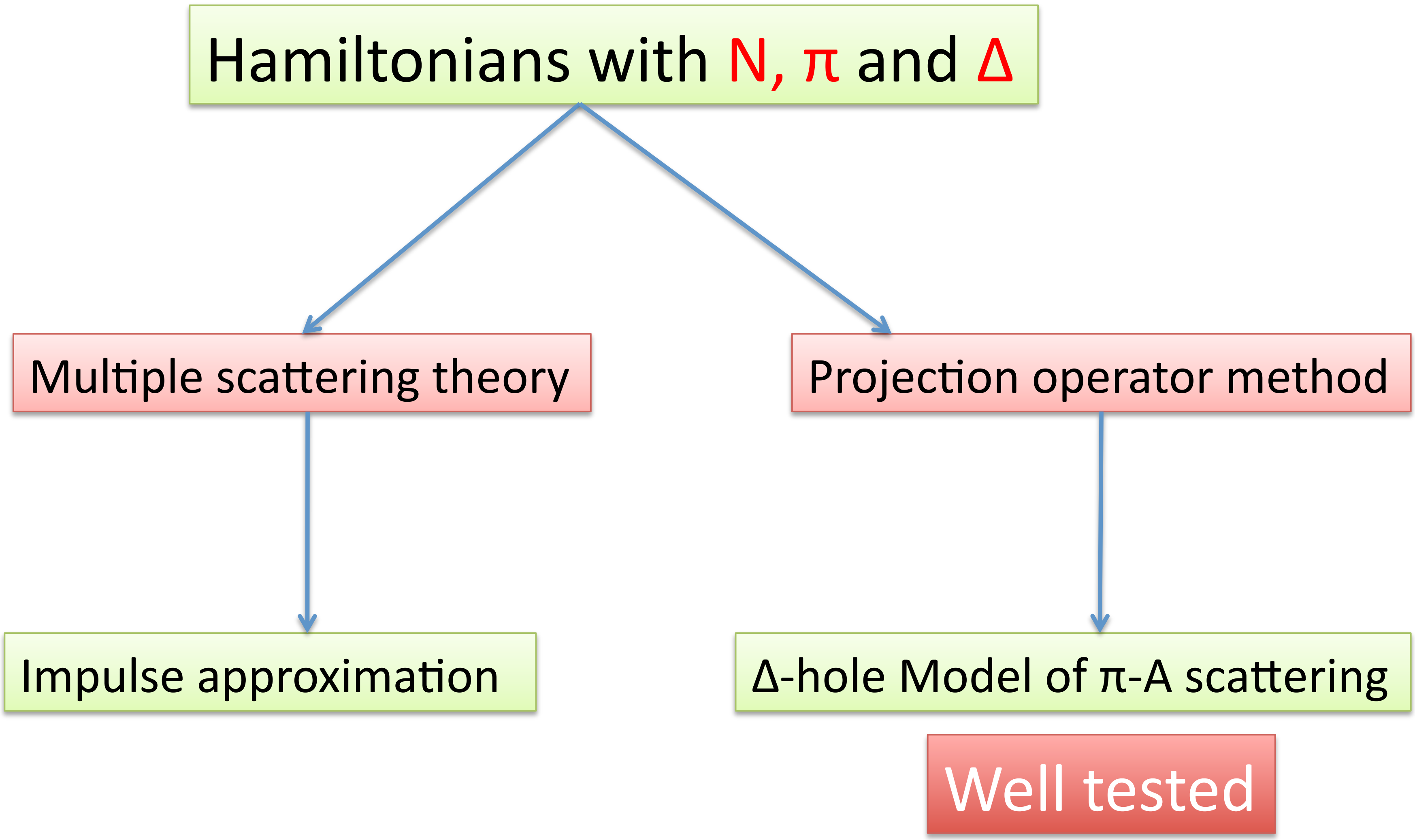
$$H'_1 = v_{\pi N,\pi N} + h_{\Delta,\pi N}$$

Determined by
πN -> πN
NN-> NN, πNN

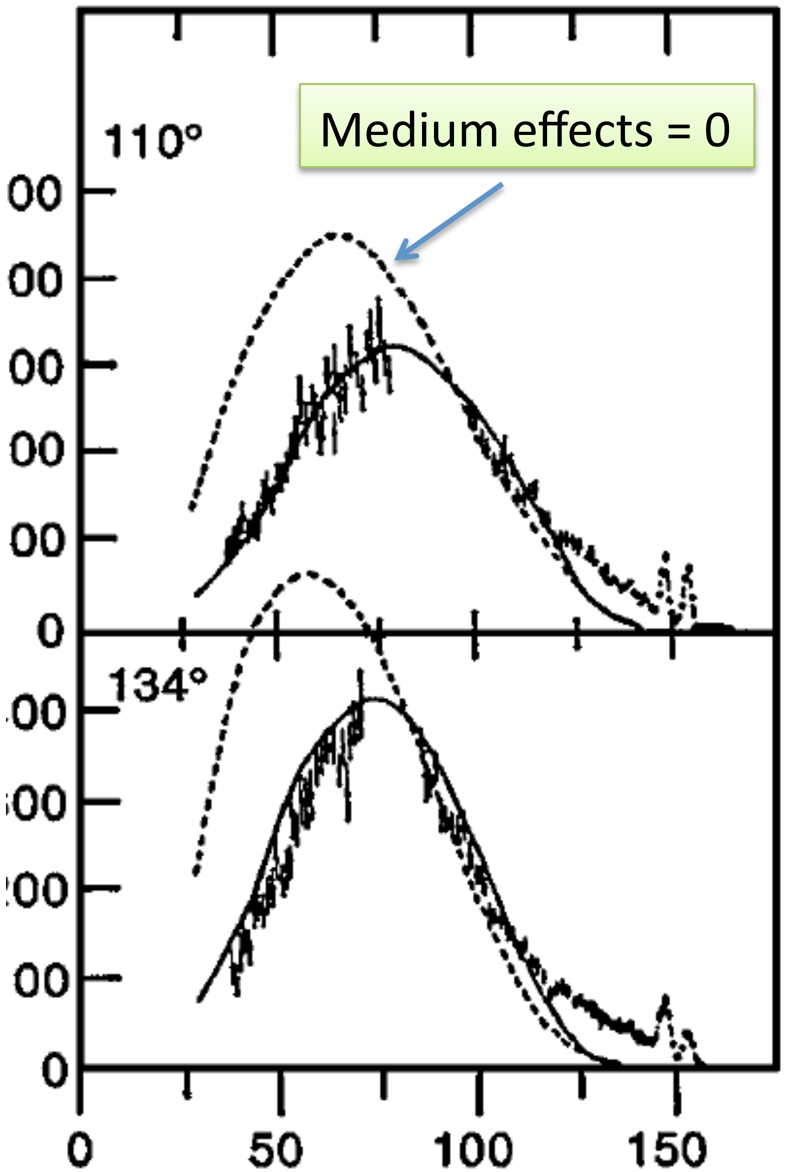
$$+ v_{\pi N,\gamma N} + h_{\Delta,\gamma N}$$

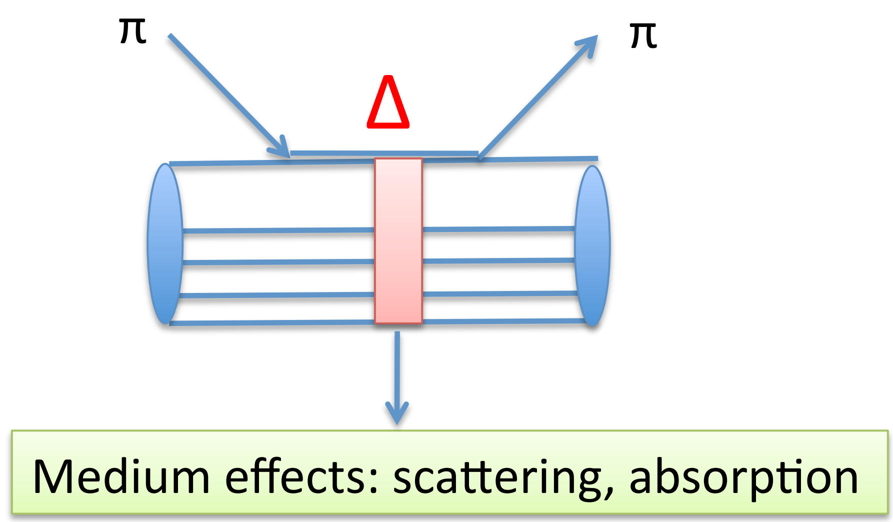
Determined by
γN-> πN
N(e,e'π) N

Many-body (microscopic) approach

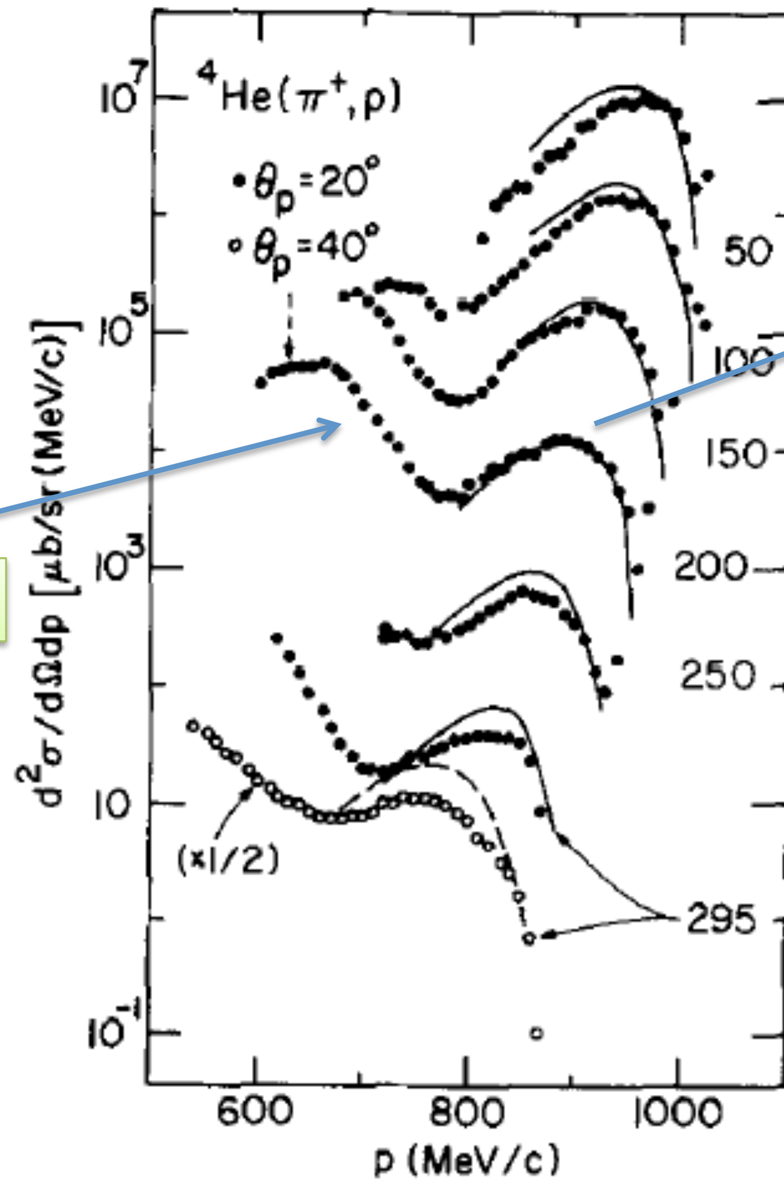


Δ-Hole model calculation of $^{12}C(\pi, \pi')X$





Δ-hole model calculation of ^{4}He (π^+, p)NN



Absorption

π^+ + ^{4}He-> ppn

π^+ + ^{4}He-> π p NN

Quasi-free scattering

Predict :

- Inclusive $^{12}C(\nu, \mu)\ X$

Szczerbinska, Sato, Kubodera, Lee et al., PLB 649 132 (2007)

- Coherent $^{12}C(\nu, \mu, \pi^0)^{12}C$

Nakamura, Sato, Lee,Szczerbinska, Kubodera, PR C81,035502 (2010)

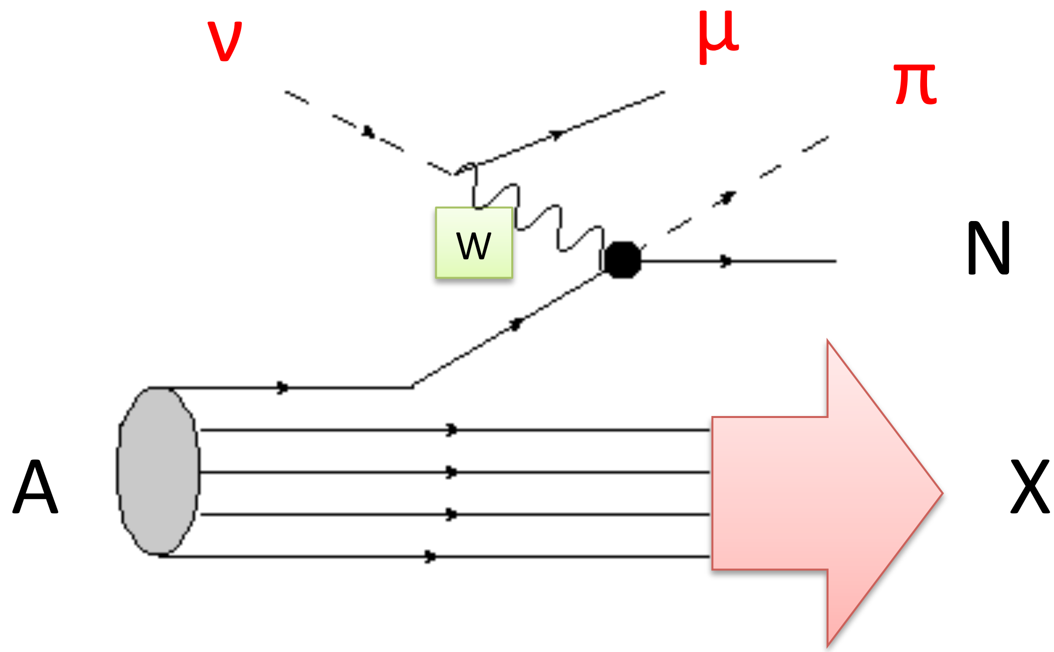
Inclusive A(ν,μ)X

Szczerbinska, Sato, Kubodera, Lee et al., PLB 649 132 (2007)

- Impulse approximation : $T = \sum_i t(i)$

amplitude on N

- Objectives:
  a. Examine Fermi Gas Model
  b. Make prediction using Spectral function



$$W^{\mu\nu} = \sum_X \langle A|J^\mu|\pi N X\rangle\langle X N \pi|J^\nu|A\rangle$$

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

1π

$$W^{\mu\nu} \sim \int d\vec{p}'\, d\vec{k}\, d\vec{p}\, \theta(p_F - |\vec{p}'|)\, \theta(|\vec{p}| - p_F) \quad \Leftarrow \text{Fermi Gas}$$

$$\times \quad \Lambda^{\mu\mu'} \langle \pi N(p') |\, j_{\mu'}\, | N(p) \rangle_{\pi N-\text{cm}} \quad \Leftarrow \text{SL}$$

$$\times \quad \Lambda^{\nu\nu'} \langle \pi N(p') |\, j_{\nu'}\, | N(p) \rangle^{*}_{\pi N-\text{cm}}$$

$*$ Fermi Gas to Spectral Function

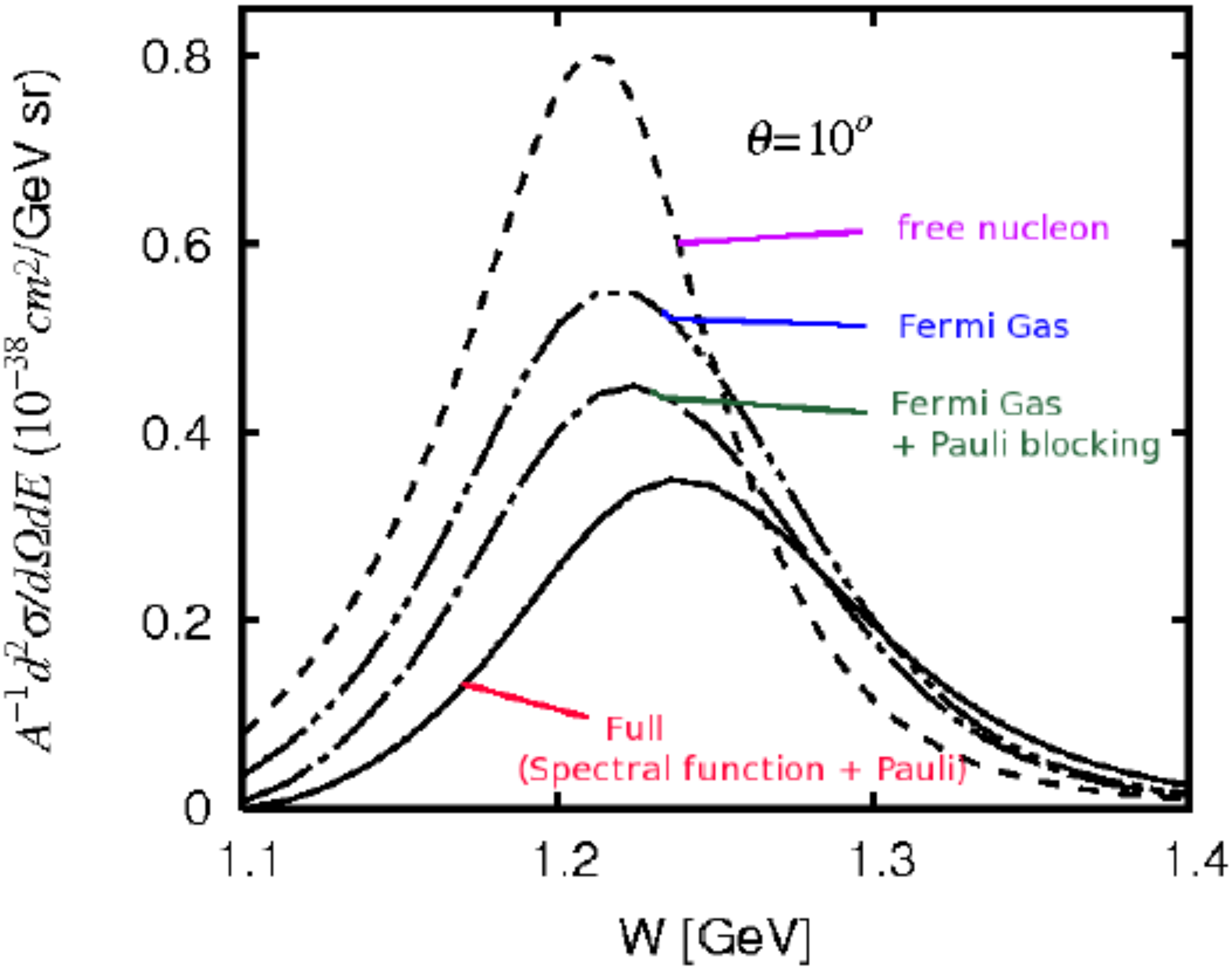
Benhar et al. NPA 579 493 (1994)

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

Include correlations

Nuclear Effect for 1π in Δ-region

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



Nuclear correlation and final state interaction must be included in calculating the nuclear effects in analyzing experimental data

Same formula for $e + {}^{12}C \rightarrow e' + \pi + X$

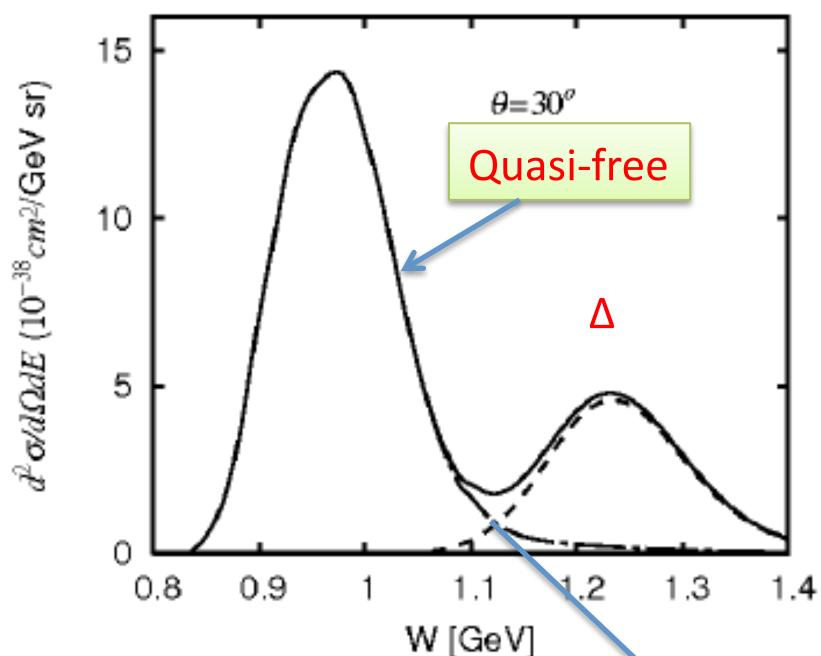
Test the model by the available data

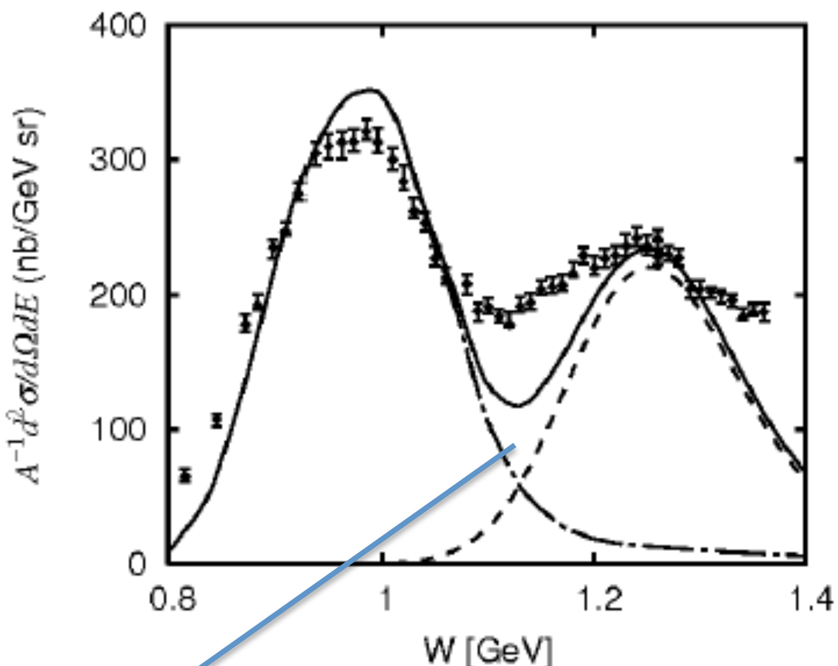
Prediction

Compare with data

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

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





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

Dip region : need to include two-body mechanisms which are beyond the impulse approximation calculations

*

Coherent $A(\nu,\mu\pi^0)A$ reactions

Nakamura, Sato, Lee,Szczerbinska, Kubodera, PR C81,035502 (2010)

Main motivation:

Remove π^0 which could fake $\nu_\mu \to \nu_e$ oscillation events

Δ-hole Model

$$\langle A|\, J\, |\pi, A\rangle = \sum_{I,j} \langle \phi_A \,|\, j_{N,\Delta}(i)\;\; G_{\Delta\text{-}h}(E)\;\; h_{\Delta,\pi N}(j) \,|\, \pi\, \phi_A \rangle$$

$$G_{\Delta\text{-}h}(E) = \frac{|\phi_{A-1}\,\Delta\rangle\langle\Delta\,\phi_{A-1}|}{E - M_\Delta - T_\Delta - V_\Delta - H_{A-1} - \Sigma_{pauli} - \Sigma_{sprd}}$$

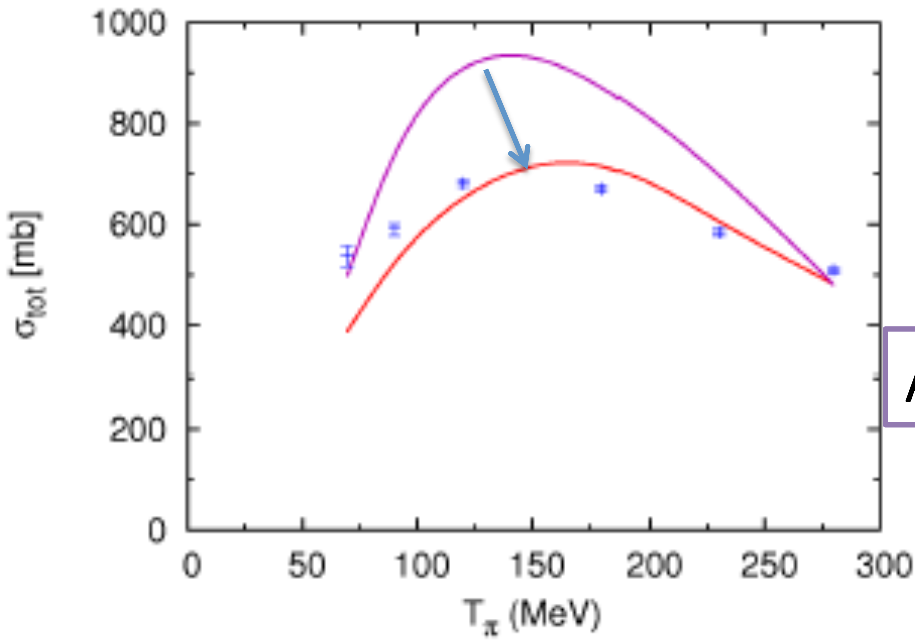
Fit π-A data

$$\Sigma_{sprd} = V_c(r) + V_{s.o}(r)\, \vec{S}_\Delta \cdot \vec{L}_\Delta$$

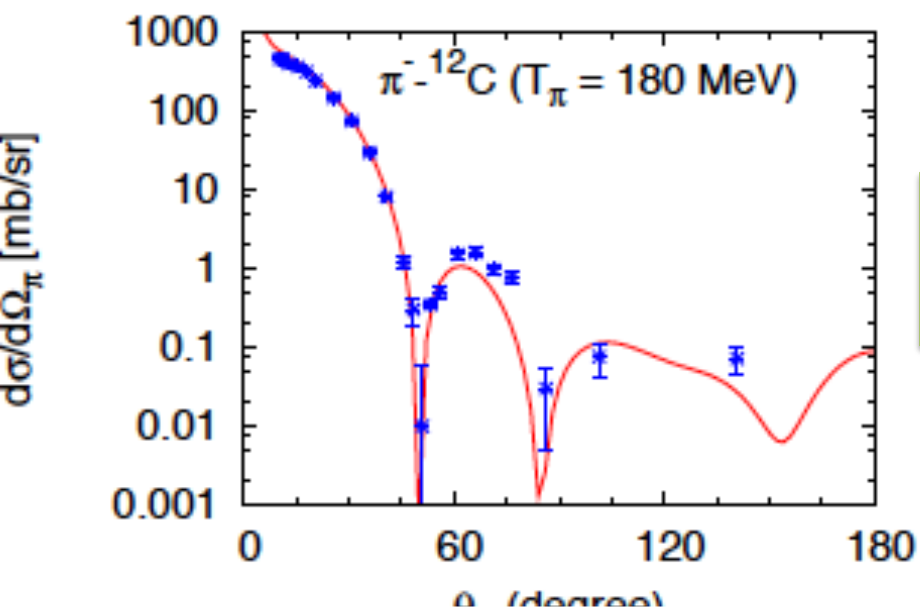
Pion absorption

Δ-hole model for ^{12}C

Nakamura et al., PR C81,035502 (2010

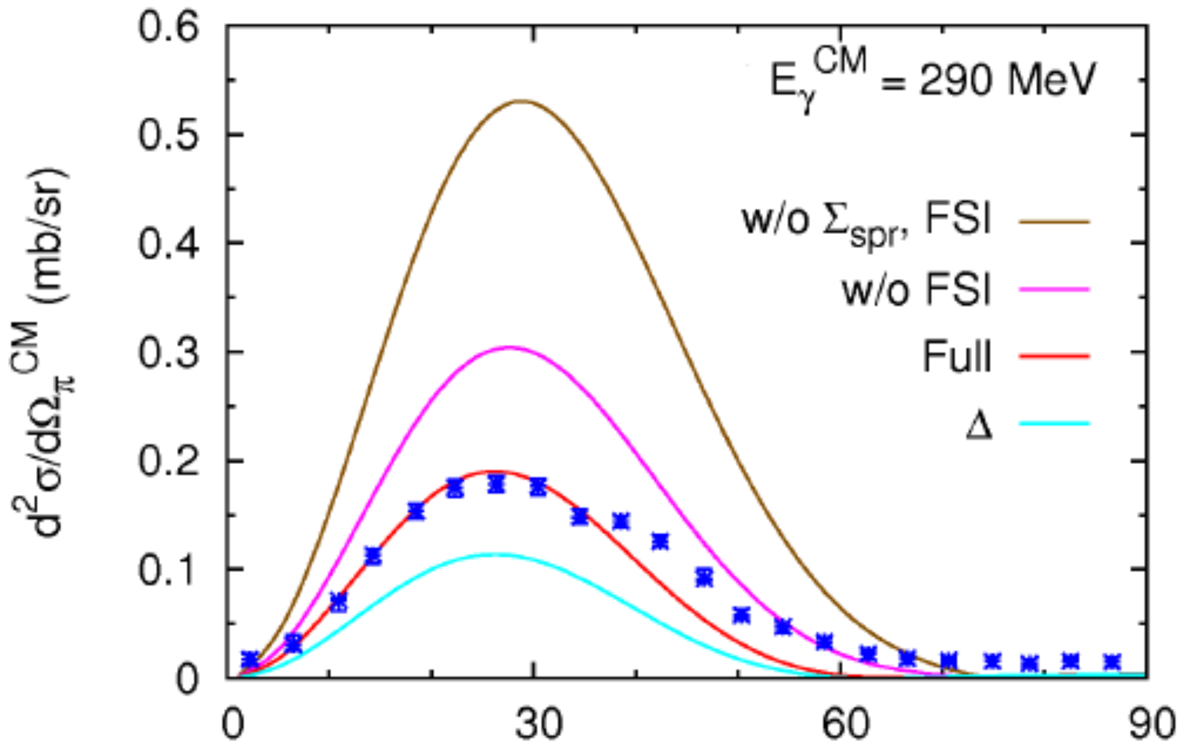


Adjust Σ_{sprd} to fit Total cross section data



Predicted elastic scattering cross section agree well with the data

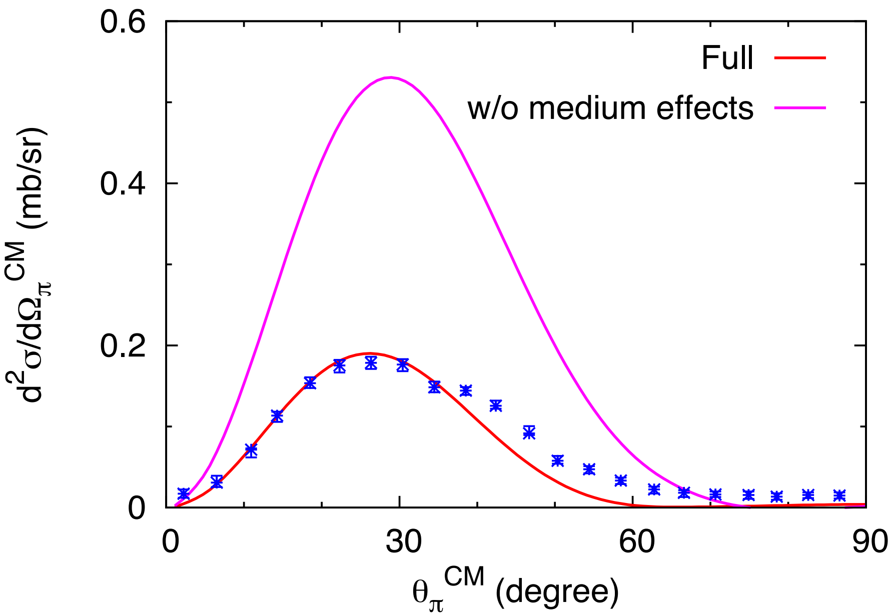
Δ-hole model prediction of $^{12}C(\gamma,\pi^0)^{12}C$



- In agreement with the data
- Medium effects on Δ is large

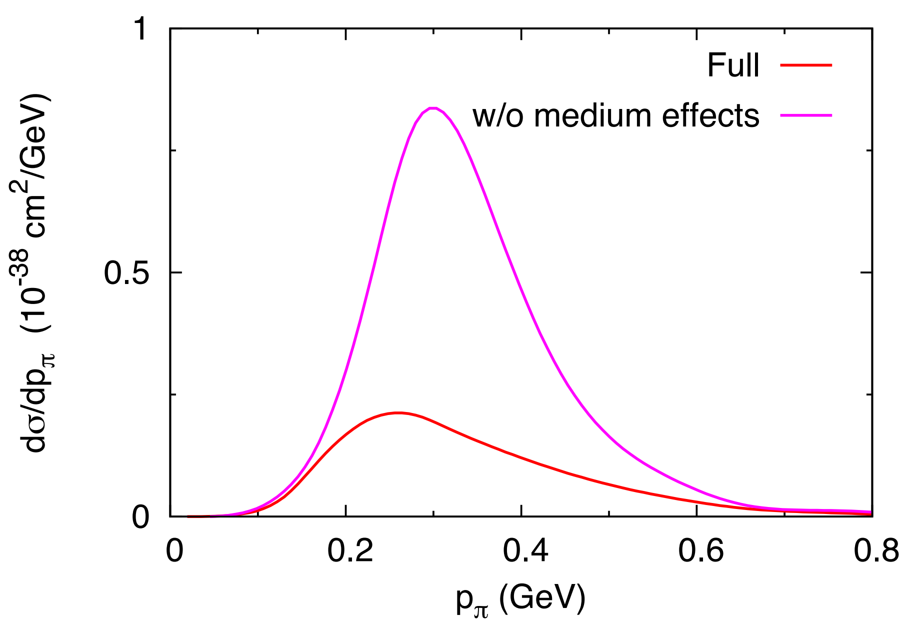
Compare with data

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



Prediction

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



Nakamura et al. (2010)

Current effort:

Extend SL model to include higher mass nucleon resonances (N^*) to predict ν-nucleus reactions

→

Starting point :

Hamiltonian with excited nucleons

Hamiltonian with excited nucleons

(Matsuyama, Sato, Lee, Phys. Rept, 2007

$$H_{int} = h_{N^*,\ MB} + v_{MB,M'B'}$$

N* : Confined quark-gluon core

MB : : γN, πN, 2π-N, ηN, KΛ, KΣ, ωN

↓

($\pi\Delta$, ρN, σN)

⇨

ANL-Osaka Model has been developed

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

ANL-Osaka Model

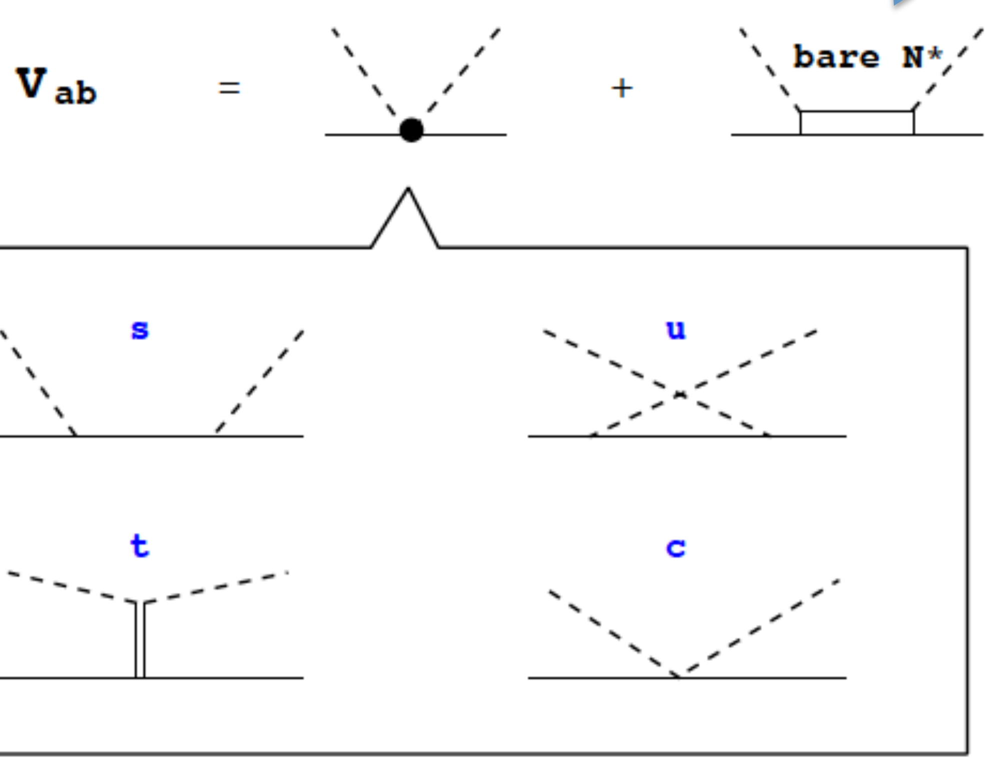
Kamano, Nakamura, Lee, Sato, PRC 88 (2013)

Solve

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

a ,b, c = γN, πN,2π-N, KΛ, KΣ

16 bare N^*



Analysis Database

Pion-induced reactions (purely strong reactions)

	Waves	# of data	Waves	# of data
$\pi N \to \pi N$ PWA	S_{11}	56×2	D_{13}	52×2
	S_{31}	56×2	D_{15}	52×2
	P_{11}	56×2	D_{33}	50×2
	P_{13}	52×2	D_{35}	31×2
	P_{31}	52×2	F_{15}	39×2
	P_{33}	56×2	F_{17}	23×2
			F_{35}	34×2
			F_{37}	35×2
			Sum	1288

SAID

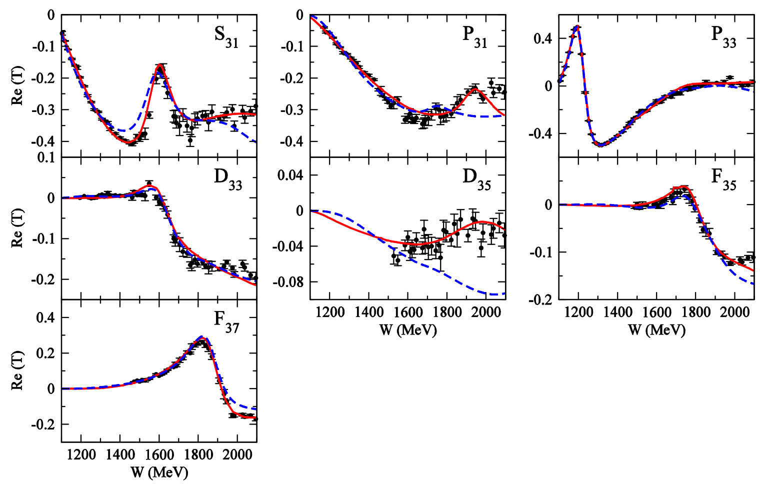
	$d\sigma/d\Omega$	P	R	a	Sum
$\pi^- p \to \eta p$	294	-	-	-	294
$\pi^- p \to K^0\Lambda$	544	262	-	-	806
$\pi^- p \to K^0\Sigma^0$	215	70	-	-	285
$\pi^+ p \to K^+\Sigma^+$	552	312	-	-	864
Sum	1605	644	-	-	2249

~ 28,000 data points to fit

Photo-production reactions

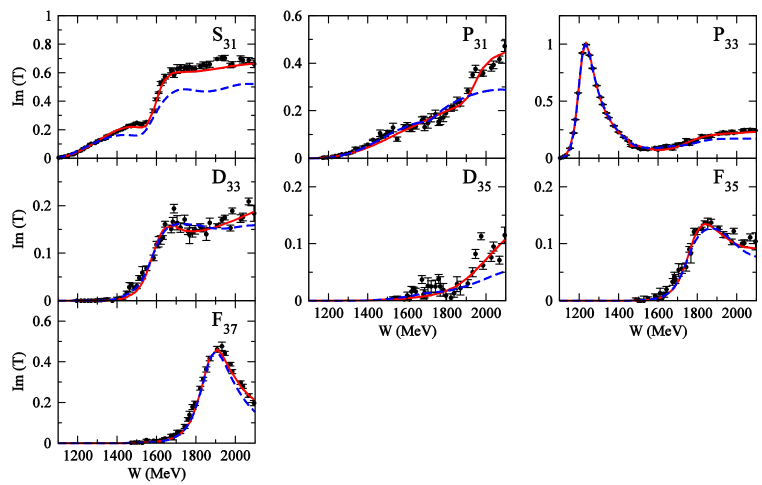
	$d\sigma/d\Omega$	Σ	T	P	G	H	E	F	$O_{x'}$	$O_{z'}$	$C_{x'}$	$C_{z'}$	$T_{x'}$	$T_{z'}$	$L_{x'}$	$L_{z'}$	sum
$\gamma p \to \pi^0 p$	8290	1680	353	557	28	24	-	-	-	-	-	-	-	-	-	-	10860
$\gamma p \to \pi^+ n$	5384	1014	661	221	75	123	-	-	-	-	-	-	-	-	-	-	7478
$\gamma p \to \eta p$	1076	197	50	-	-	-	-	-	-	-	-	-	-	-	-	-	1323
$\gamma p \to K^+\Lambda$	611	118	69	410	-	-	-	-	66	66	89	89	-	-	-	-	1518
$\gamma p \to K^+\Sigma^0$	2949	116	-	320	-	-	-	-	-	-	52	52	-	-	-	-	3489
Sum	18310	3043	1133	1508	103	147	-	-	66	66	141	141	-	-	-	-	24668

Partial wave amplitudes of pi N scattering



Real part

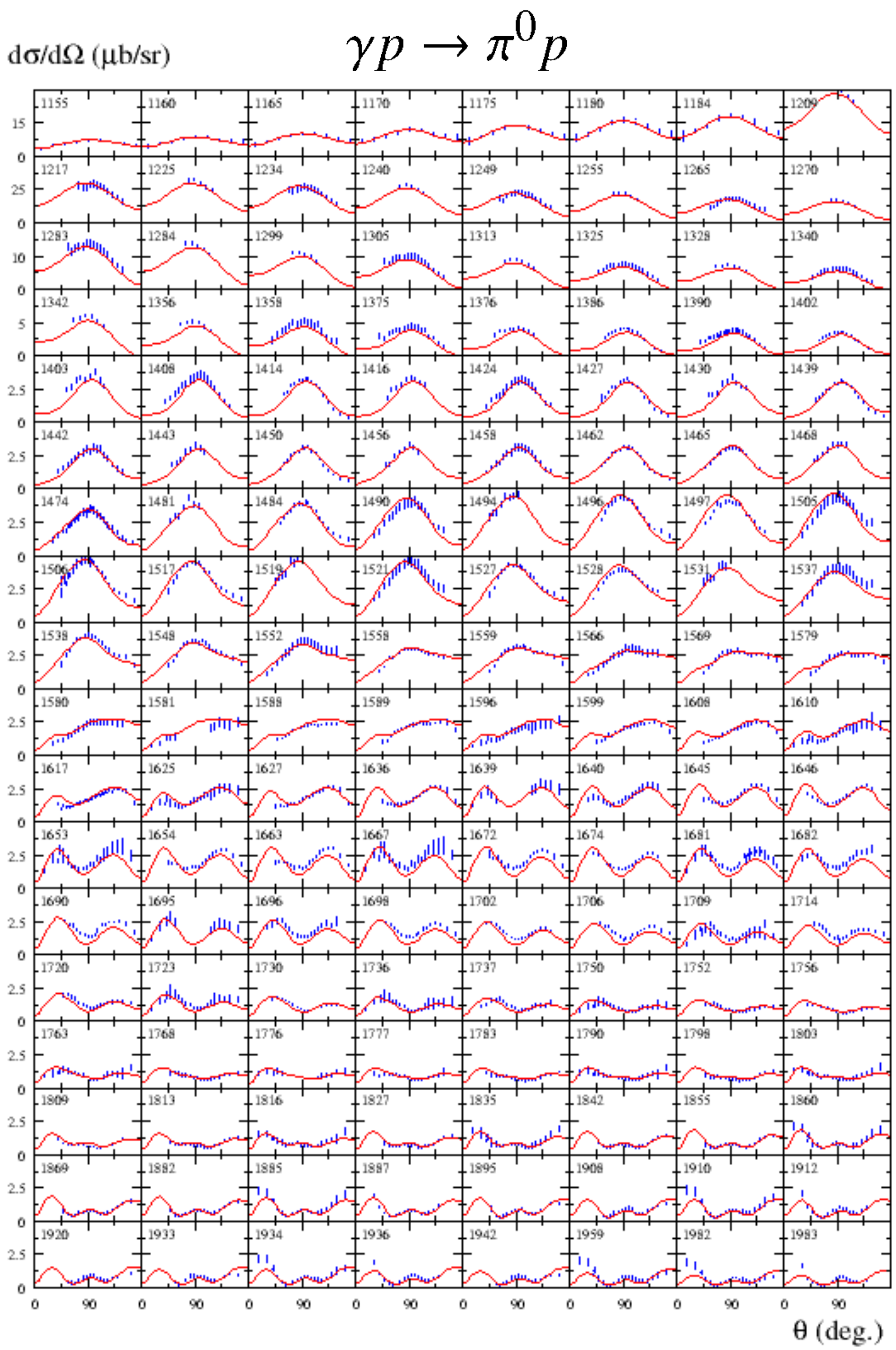
$$I = \frac{3}{2}$$



Kamano, Nakamura, Lee, Sato, 2013

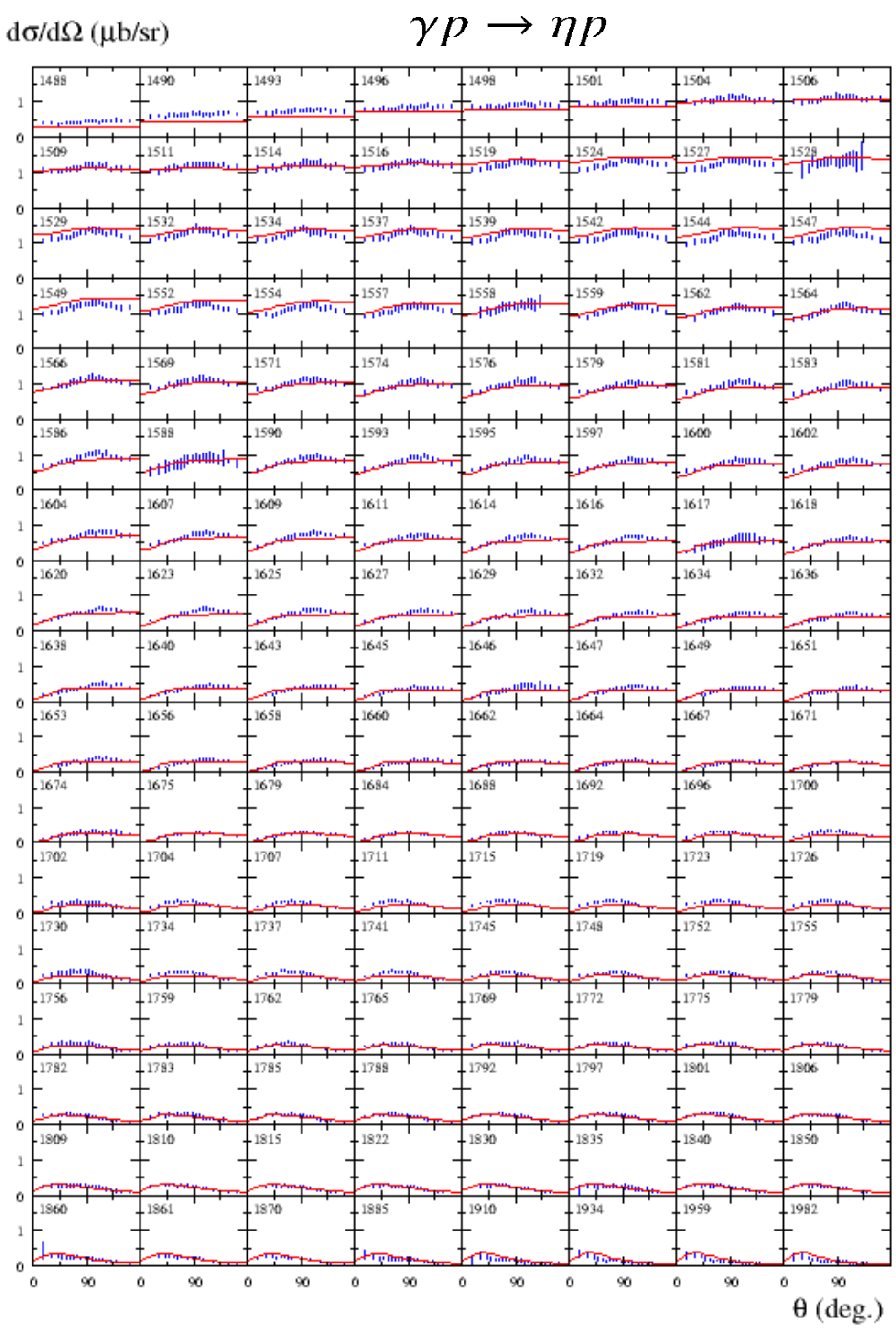
Previous model
(fitted to πN → πN data only)
[PRC76 065201 (2007)]

Imaginary part



Vector current (Q^2=0) for 1π

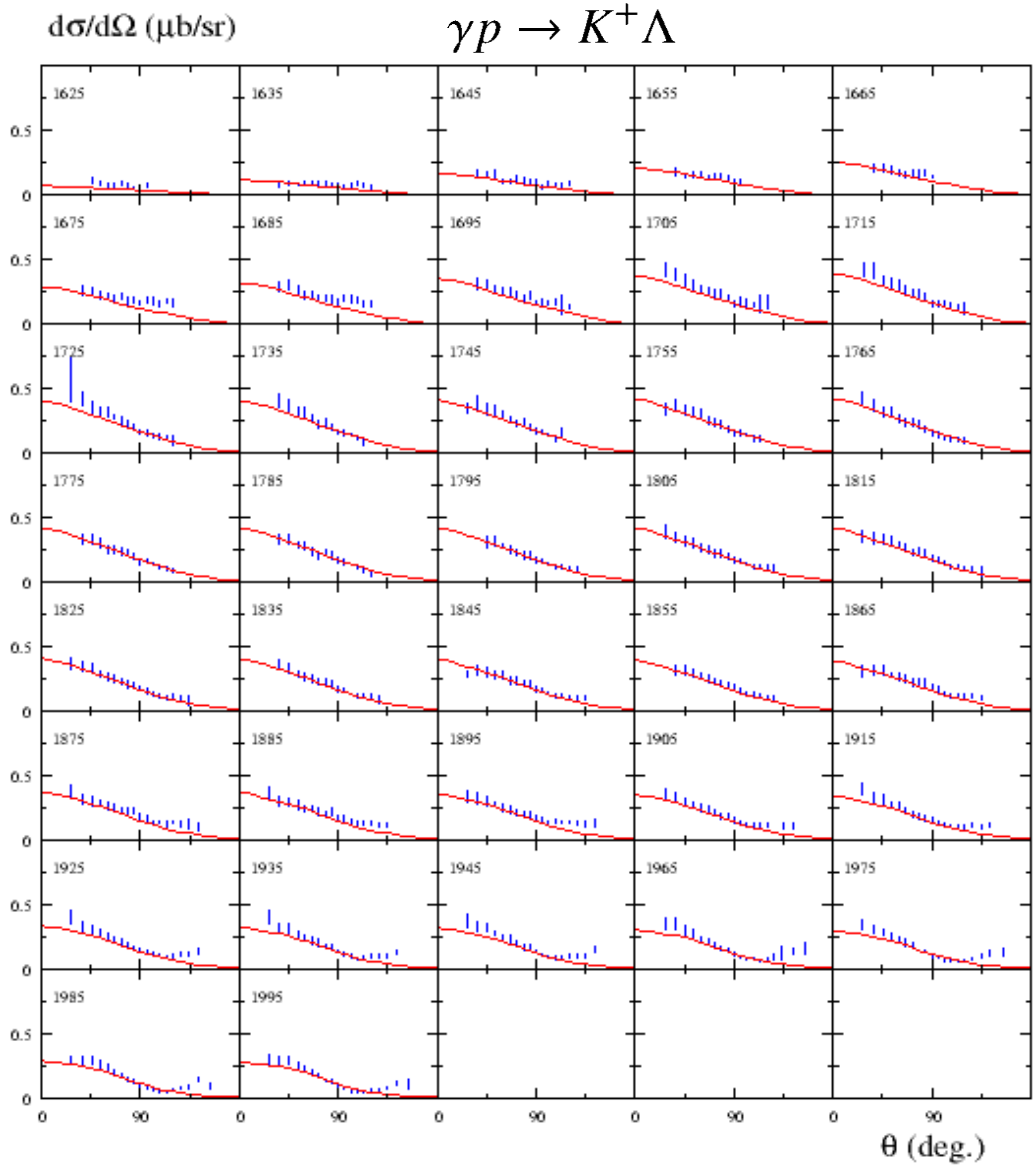
Production is well-tested by data



Kamano, Nakamura, Lee, Sato, 2013

Vector current (Q^2=0) for η

Production is well-tested by data



Kamano, Nakamura, Lee, Sato, 2013

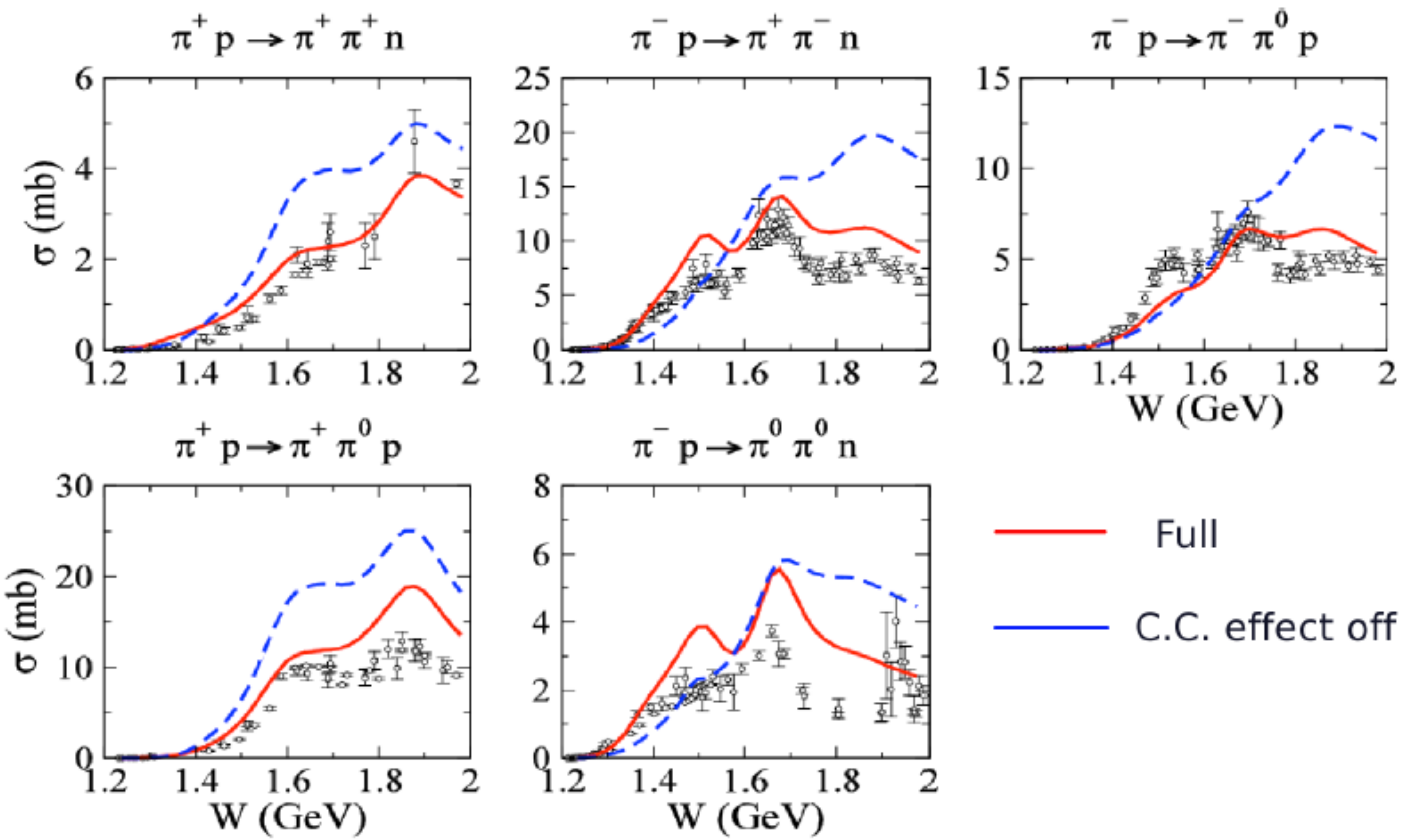
Vector current (Q^2=0) for K

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)



More detailed results from ANL-Osaka Model will be presented in the Workshop on Hadron physics at J-PARC

Current effort:

Extend ANL-Osaka model to include

- Charged current

$J^{CC} = (V^1 + i\, V^2) - (A^1 + i\, A^2)$

- Neutral current

$J^{NC} = (1-2\sin^2\theta_W)\, J^{em} - V_{isoscalar} - A^3$

Task:

Construct axial current (A^1, A^2, A^3) for

a. N^*

b. channels : πN, 2π-N, ηN, $K\Lambda$, $K\Sigma$

First attemp:

PCAC-based calculation of forward angle cross Sections of ν N -> πN, 2π-N, ηN, KΛ, KΣ

Objectives:

- Examine the importance of each channel
- Compare with Rein-Sehgal model

Formalism

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

$\theta \rightarrow 0$

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

$Q^2 \rightarrow 0$

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

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

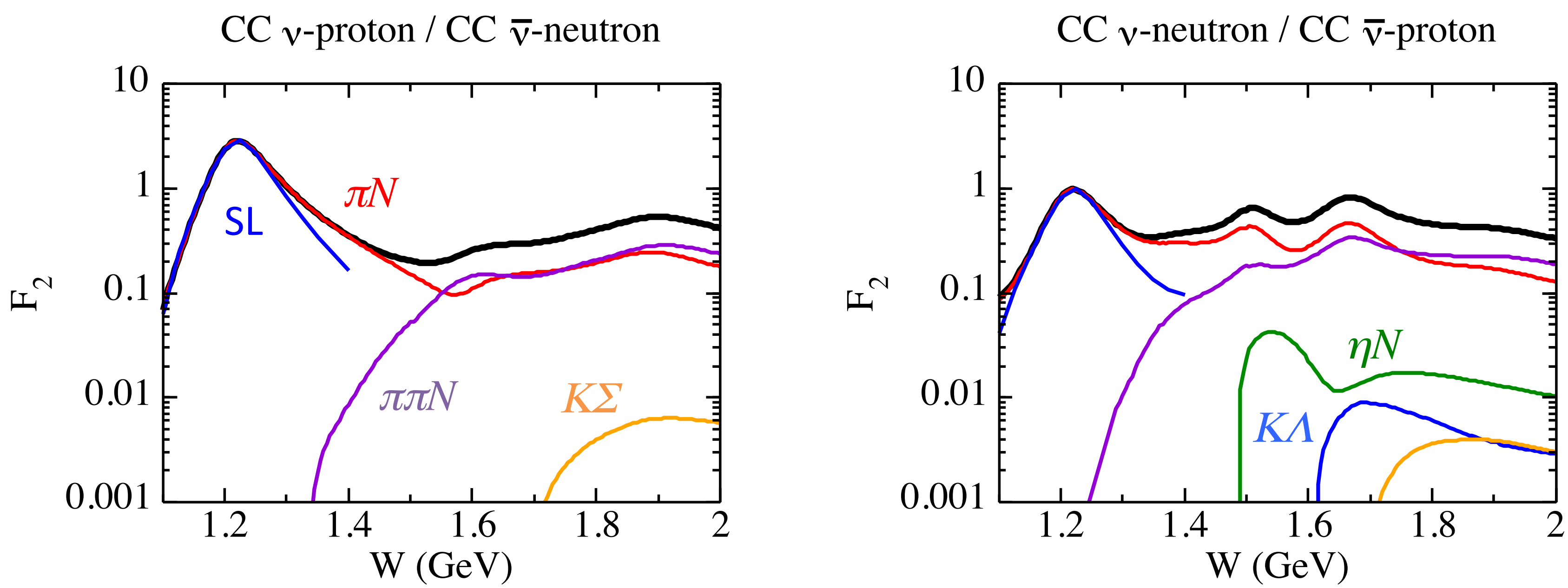
$$\langle X | \hat{\pi} | N \rangle = \frac{\sqrt{2\omega_c}}{m_\pi^2} T_{\pi N \to X}(0) \sim \frac{\sqrt{2\omega_c}}{m_\pi^2} T_{\pi N \to X}(m_\pi^2)$$

Finally

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

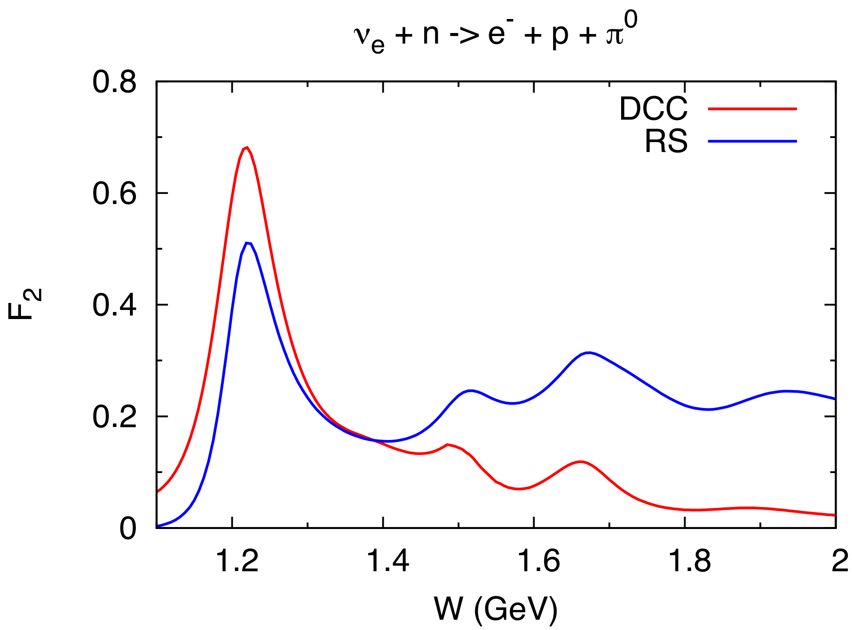
$\sigma_{\pi N \rightarrow X}$ is from our DCC model

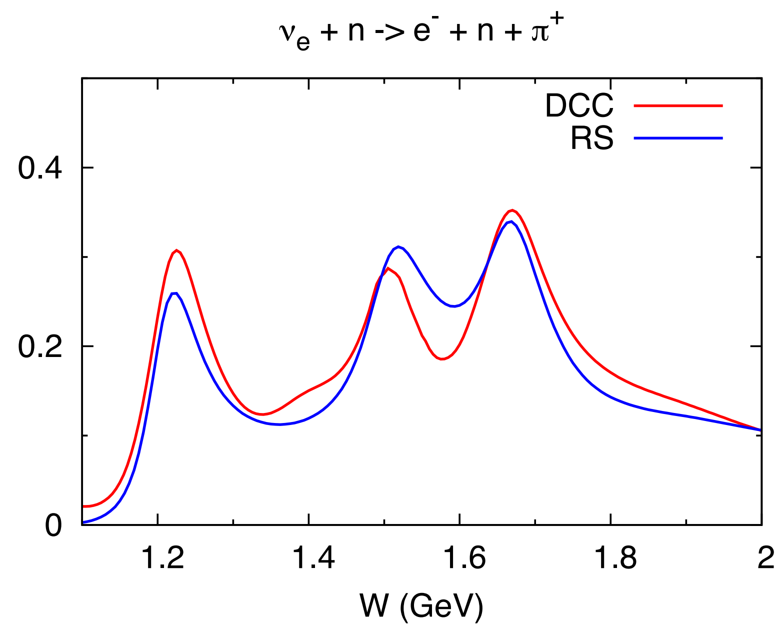
Results



- 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





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

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

in progress

Vector current V:

Q^2=0

γp ➔ MB analysis has been done

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

isospin separation necessary for calculating ν-interaction

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

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

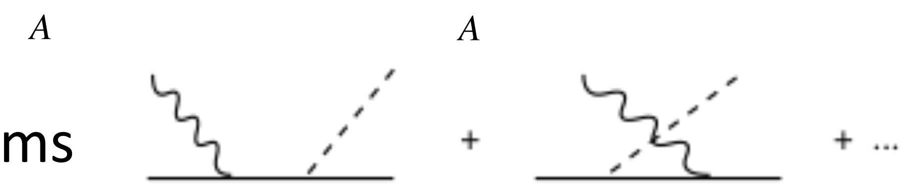
Full DCC model for νN → $\pi N, \pi\pi N, \eta N, K\Lambda, K\Sigma$

in progress

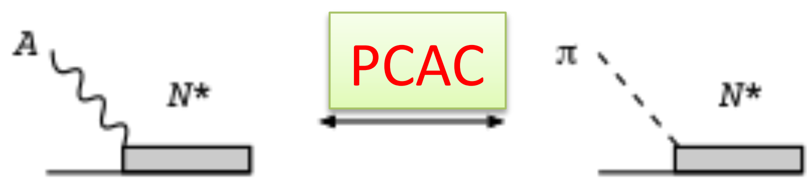
Axial current A :

$Q^2=0$

non-resonant mechanisms



resonant mechanisms



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

experimental information is necessary to fix this

Summary

- A dynamical model for $\Delta(1232)$ is ready for analyzing the nuclear effects on experiments measuring neutrino properties
- The ANL-Osaka model is being extended to include N^* in the analysis of experiments measuring neutrino properties