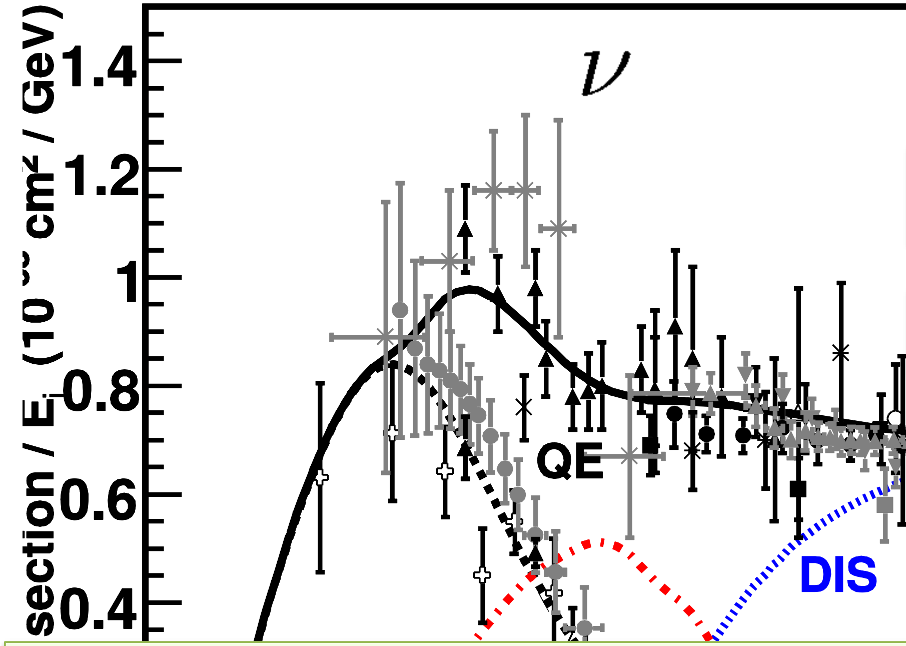
ν-Deuteron Reactions In the Δ(1232) Region

T.-S. Harry Lee
Argonne National Laboratory

Collaborators : Jia-jun Wu, Toru Sato



σ $_{Tot}$ of BNL Neutrino Experiments

J.A.Formaggio G.P.Zeller
RMP84(2012)

Resonance (RES) Excitation is dominated by Δ(1232) at 1-3 GeV

A necessary task for neutrino experiments at few-GeV:

Develop theoretical models for calculating the nuclear effects in the Δ(1232) region

A necessary task for neutrino experiments at few-GeV:

Our approach:

1. Construct a model for the electroweak excitation of the Δ(1232) to describe :

   a. data on the proton target

   b. data on the deuteron target (This talk)

   → determine cross sections on the neutron

2. Apply the constructed model to calculate nuclear effects by using

   a. multiple-scattering theory for deuteron (This talk)

   b. The Δ-hole model for heavy nuclei

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

Excitation of Δ(1232) is dominated by single pion production

Need a model to describe the data of :

$\gamma + p \to \pi^0 + p$

$\gamma + p \to \pi^+ + n$

$\gamma + n \to \pi^0 + n$

$\gamma + n \to \pi^- + p$

$$\nu + p \to l^- + \pi^+ + p$$
$$\nu + n \to l^- + \pi^0 + p$$
$$\nu + n \to l^- + \pi^+ + n$$

$e + p \to e' + \pi^0 + p$

$e + p \to e' + \pi^+ + n$

$e + n \to e' + \pi^0 + n$

$e + n \to e' + \pi^- + p$

$$\bar{\nu} + n \to l^+ + \pi^- + n$$
$$\bar{\nu} + p \to l^+ + \pi^0 + n$$
$$\bar{\nu} + p \to l^+ + \pi^- + p$$

Achieved by the SL Model (1996-2005)

Nucleon target :

T. Sato , T.-S. H. Lee, Phys. Rev. C 54, 2660 (1996)
T. Sato, T.-S. H. Lee, Phys. Rev. C 63, 055201 (2001)
T. Sato, I. Uno, T.-S. H. Lee, Phys, Rev. C67,065201 (2003)
I. Uno, T. Sato, T.-S. H. Lee, Phys. Rev. C72, 025204 (2005)

Deuteron target:

K. Hafidi, T.-S. H. Lee, Phys. Rev. C (2001)
J. Wu, T. Sato, T.-S. H. Lee, Phys. Rev. C 91, 035203 (2014)

Approach of SL model:

Apply the Osaka unitary transformation method

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

→

Construct an energy independent Hamiltonian with π, N, Δ hadronic degrees of freedom from phenomenological Lagrangians of relativistic quantum field theory

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
$N(e,e'\pi) N$

Meson-exchange

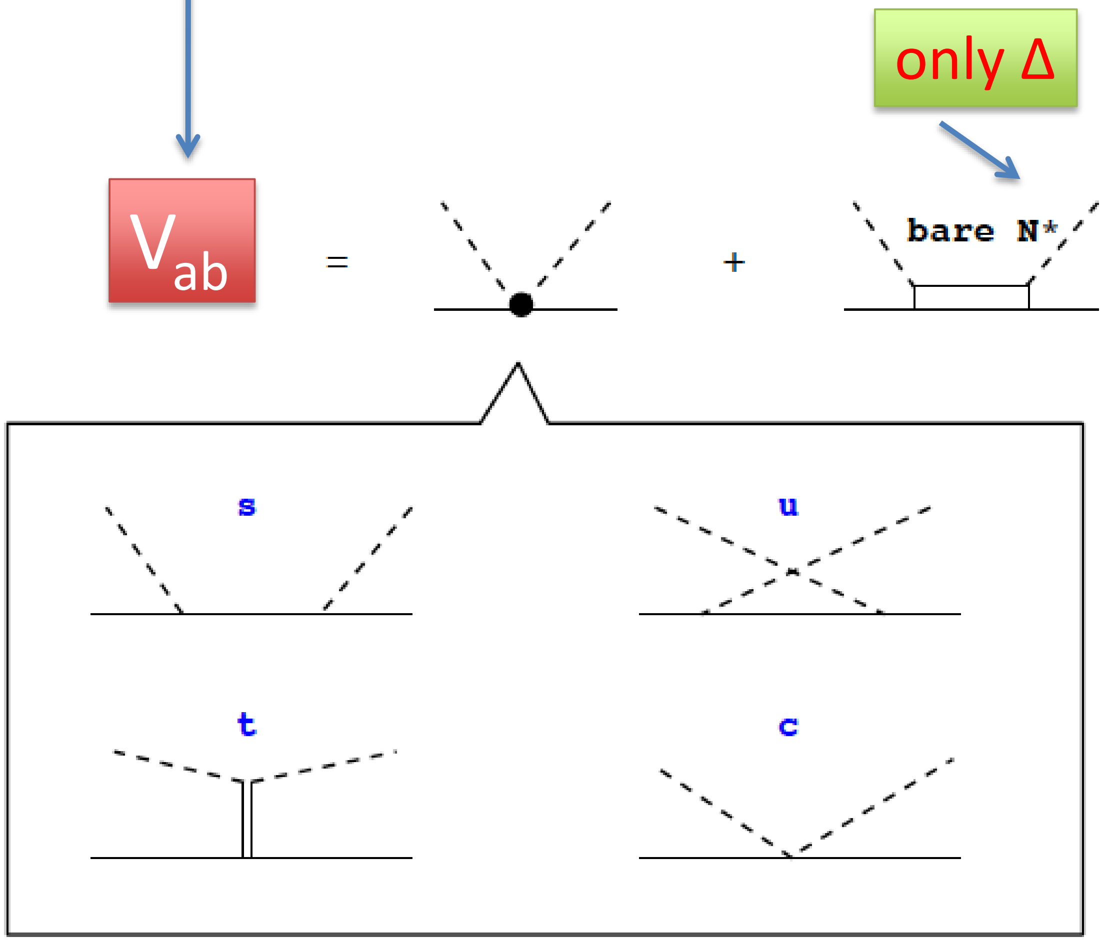
$\langle \Delta | J^{em} | N \rangle$

Determined by data

Solve

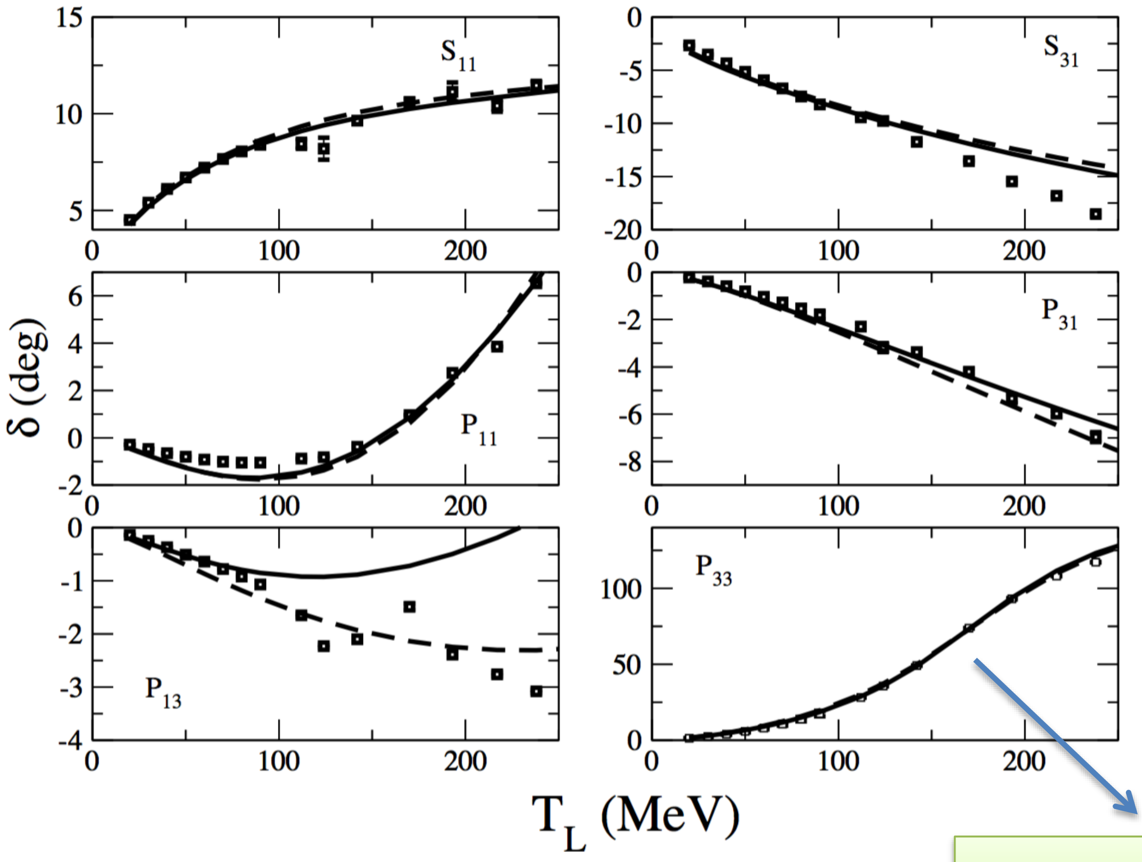
$$T_{ab}(E) = V_{ab} + \sum_{c} V_{ac} G_c(E)\, T_{cb}(E)$$

a ,b, c = πN, γN



Procedures:

- Fit $\pi N \to \pi N$ phase shift



Δ -> πN is determined

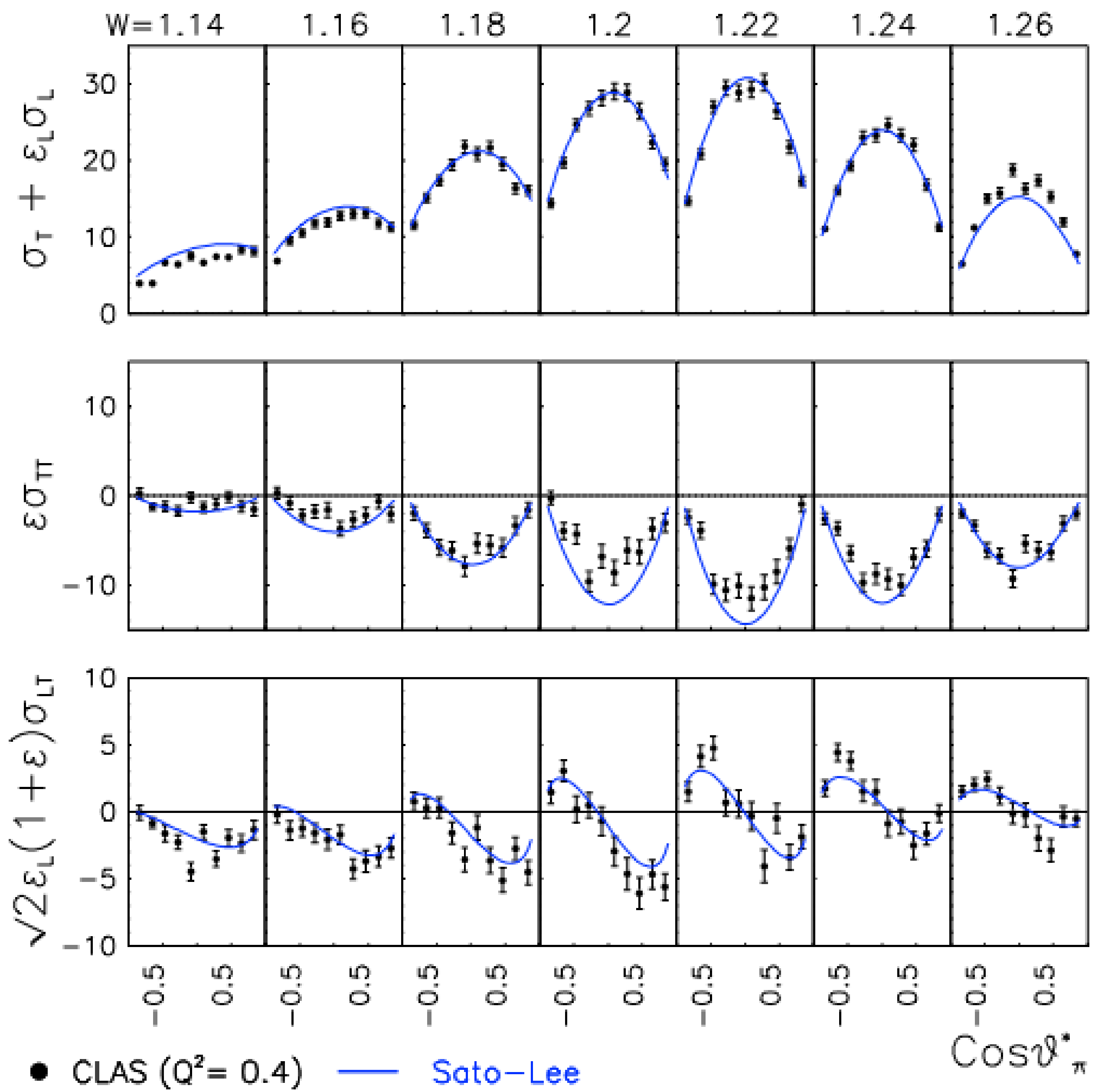
Procedures:

- Fit $\gamma N \rightarrow \pi N$, $N(e,e'\pi)N$ data

$\Rightarrow$

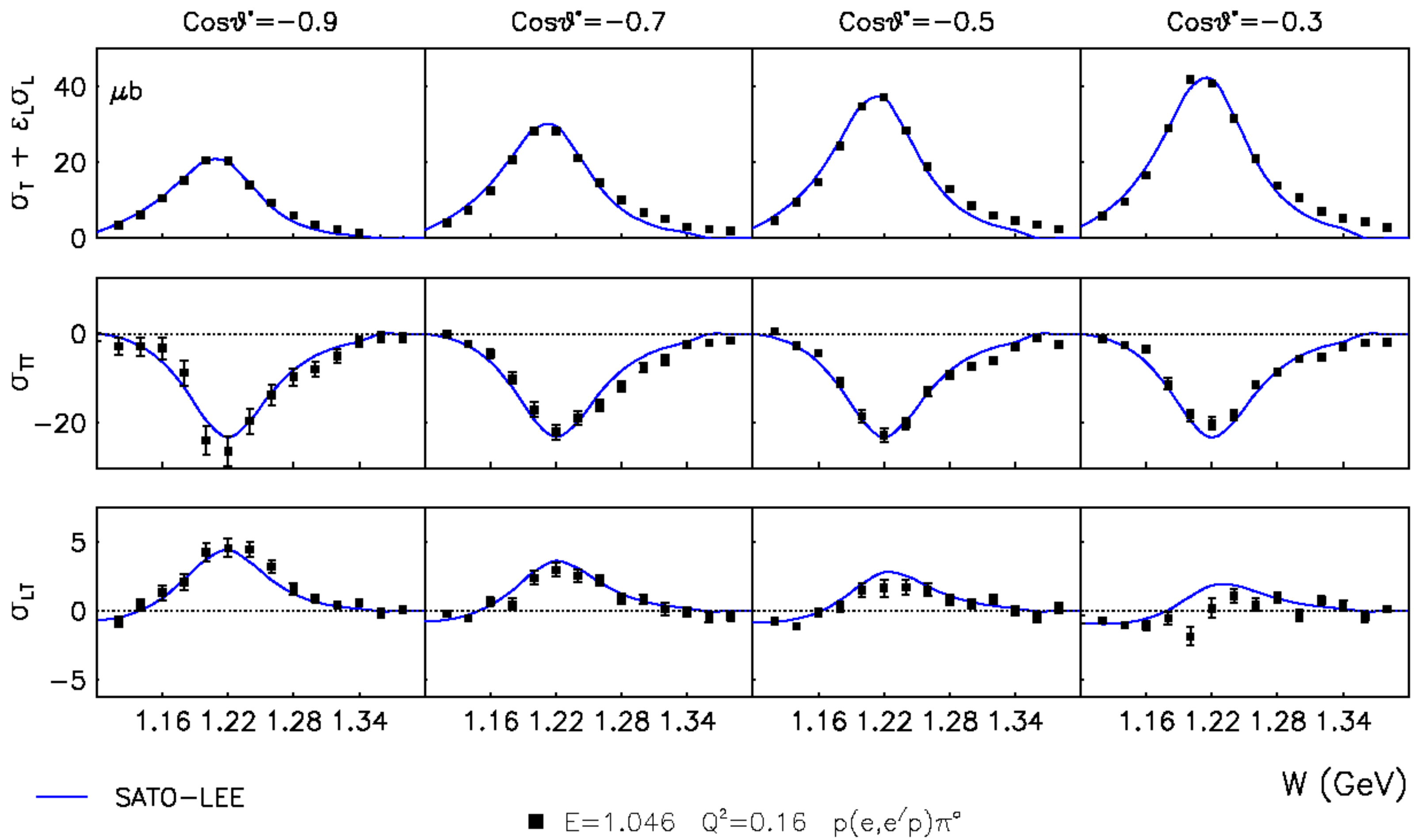
$\Delta \rightarrow \gamma N$ form factors are determined

Structure functions of p(e, e' π^0) p

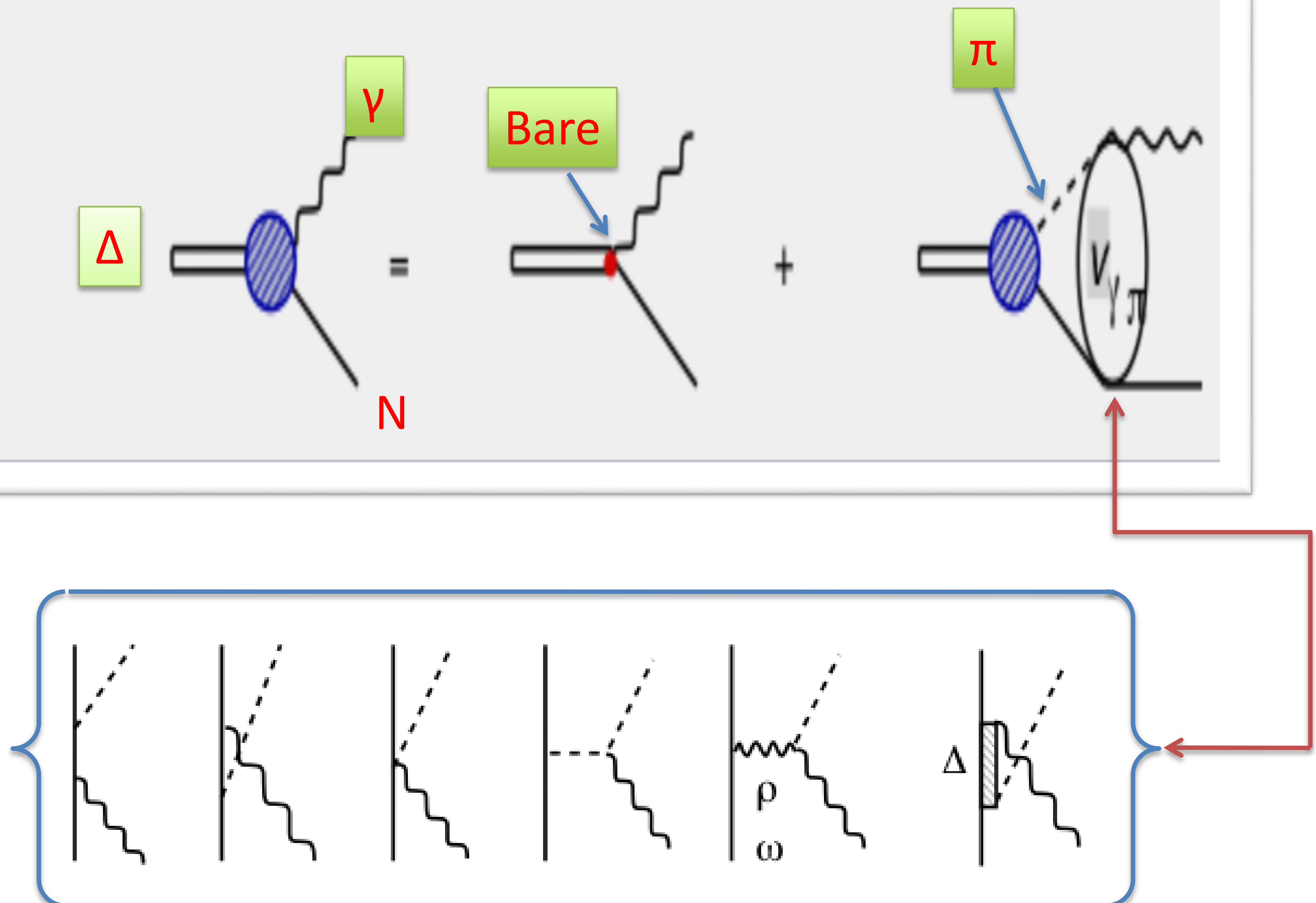


Pion electroproduction Structure functions

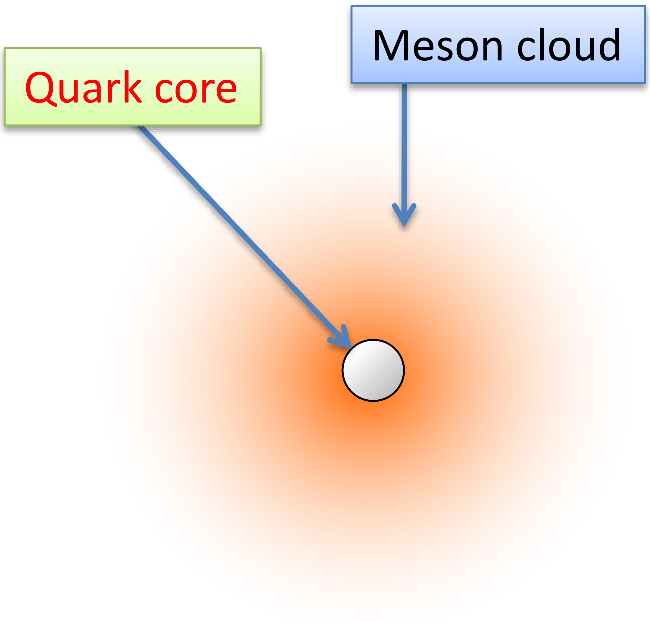
(data CLAS from C. Smith,2004)

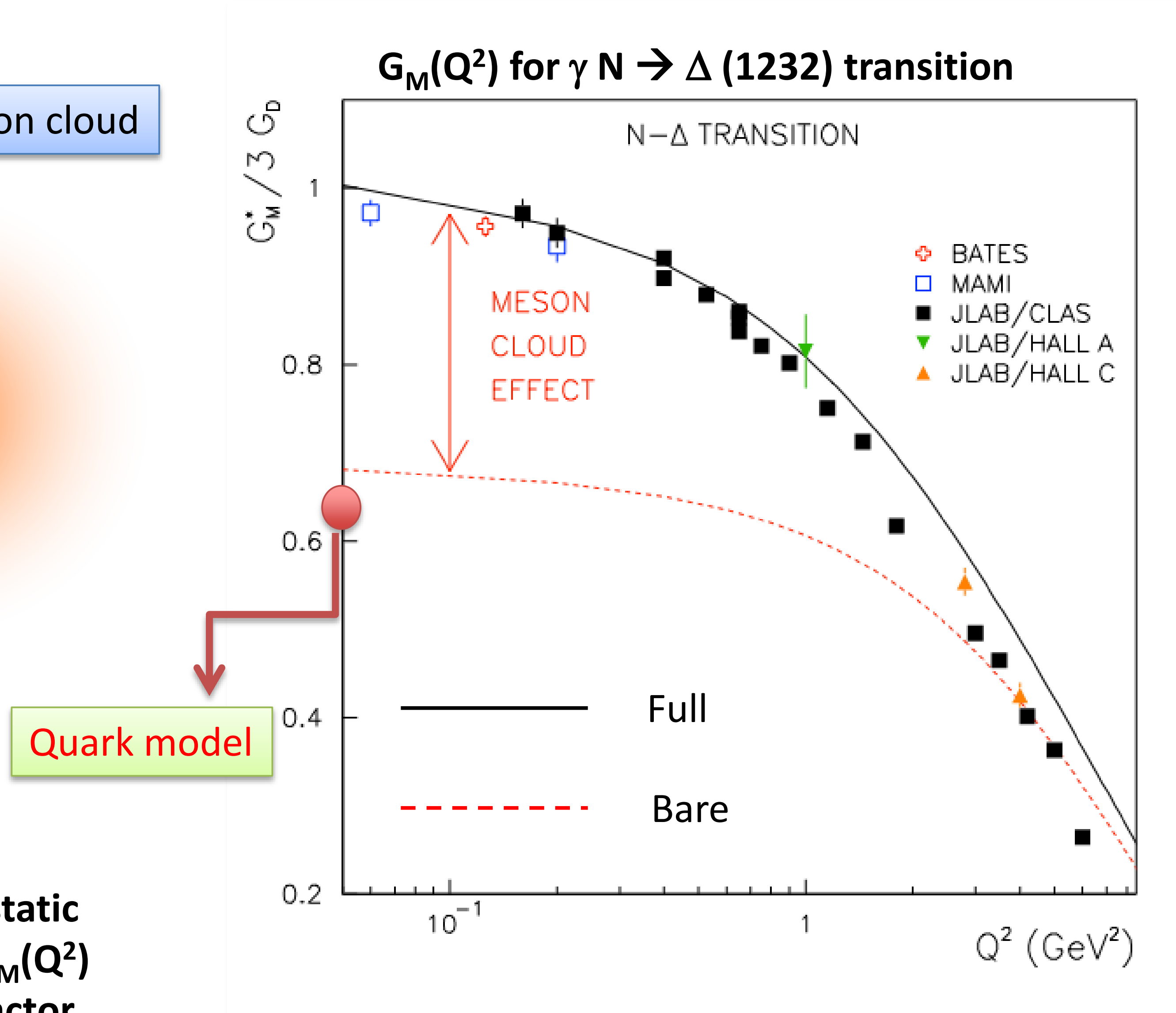


Δ -> γ N Form factor



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)

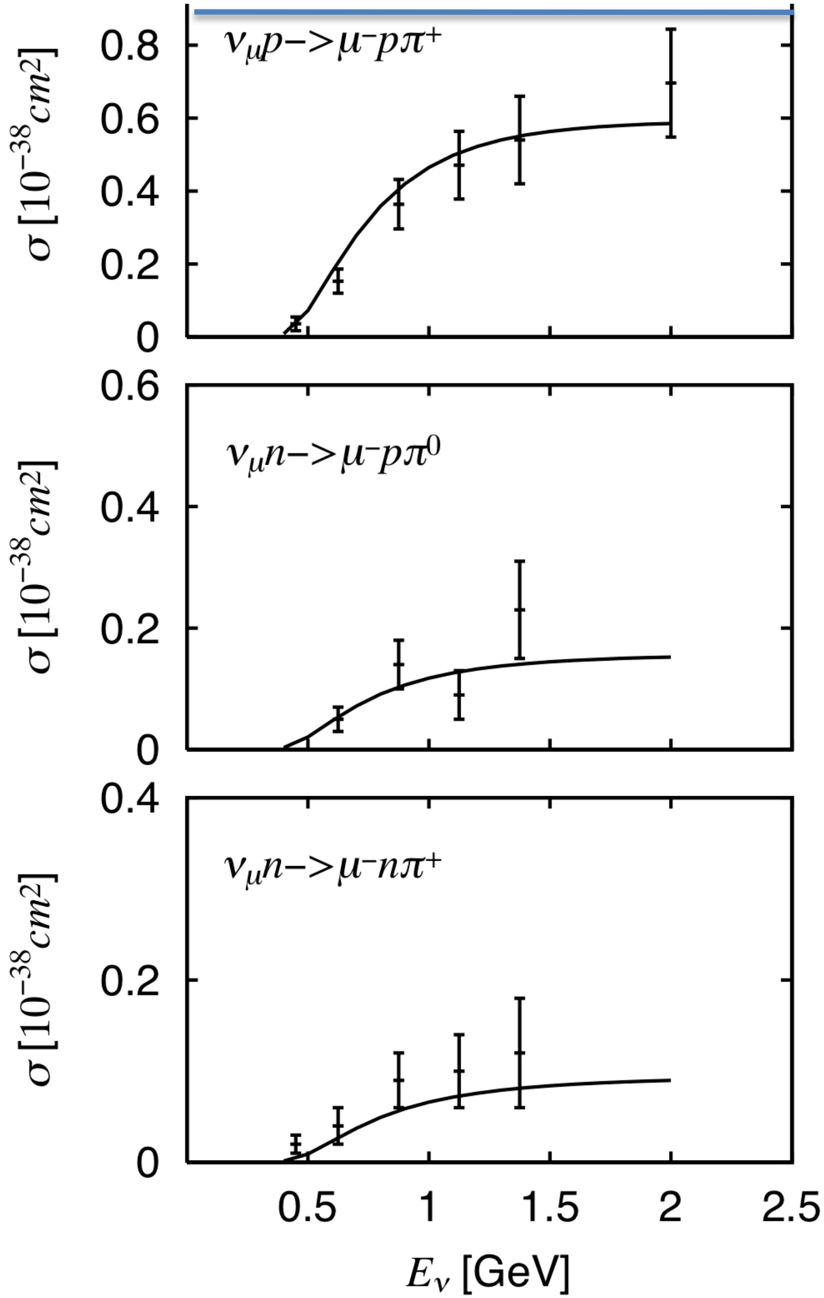
•Non-resonant axial current (A^1, A^2, A^3) are derived from effective Lagrangians

→

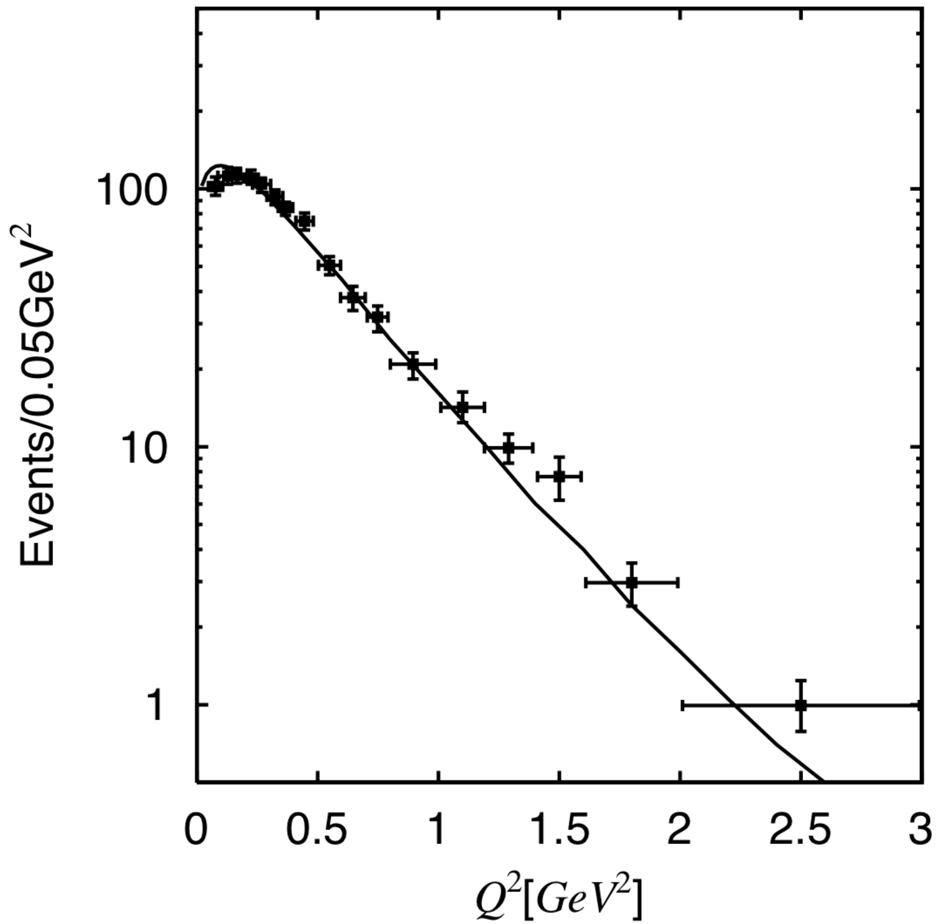
Adjust $G^A_{N,\Delta}(Q^2) = \langle \Delta | (A^1 + iA^2) | N \rangle$ to fit N(ν, μ π) data

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

ν-N Total cross sections



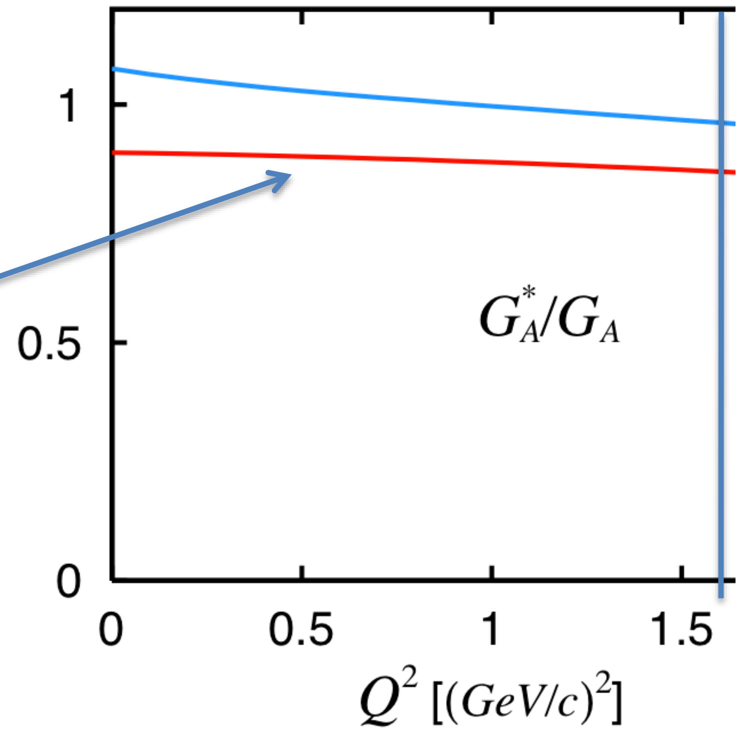
Sato, Uno, Lee, PR C67,065201(2003)



$d\sigma/dQ^2$ 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)

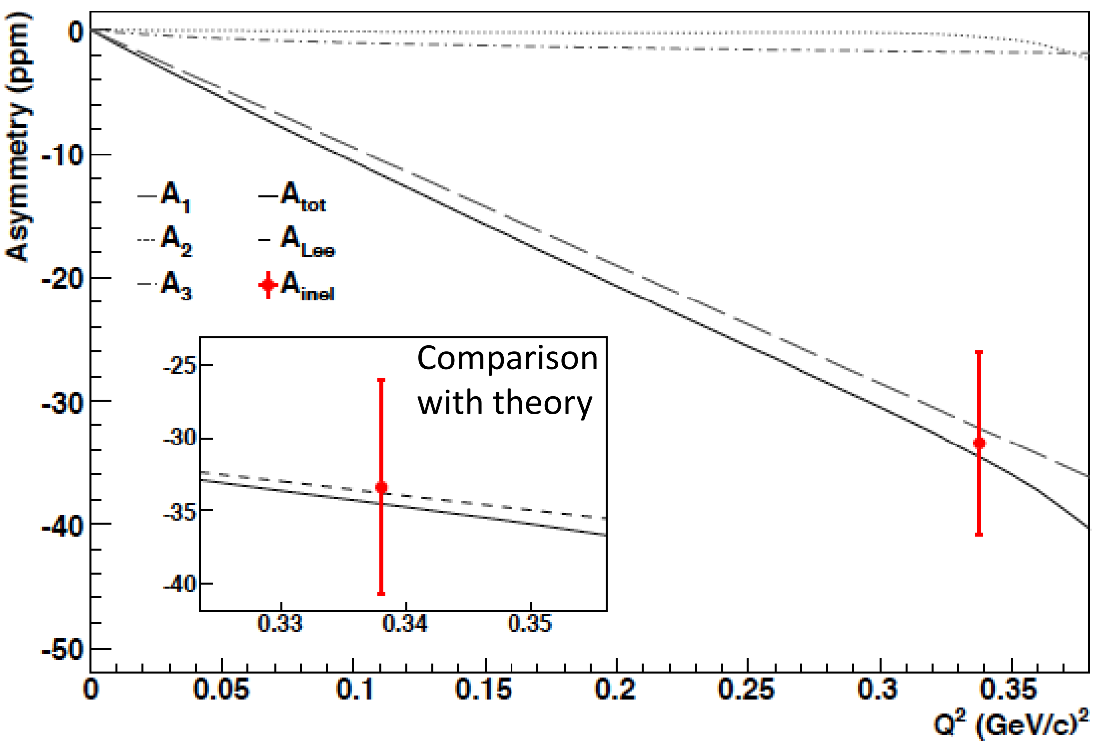
Test A^3 and $G^A_{N,\Delta}(Q^2)$ by Parity-violating inclusive N(e,e′)

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 :

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

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

SL model prediction (2005)

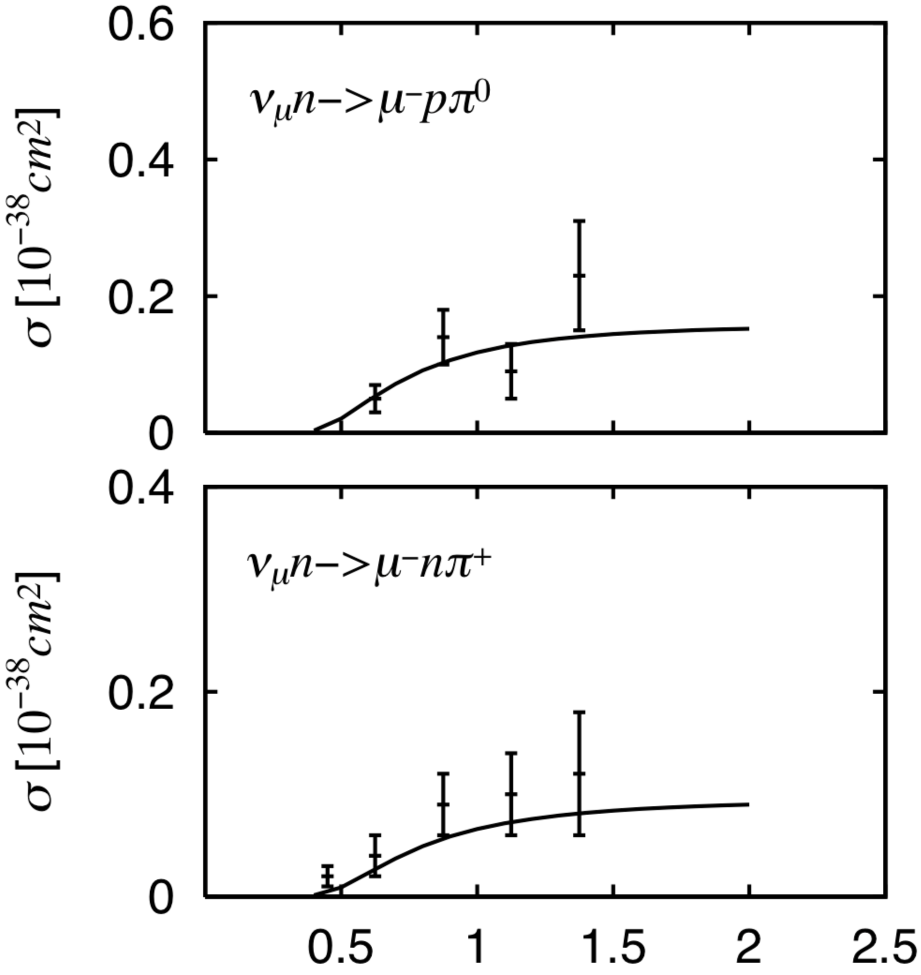
SL Model can describe almost all available data of electroweak pion production in the $\Delta(1232)$ region

→

It can be used to calculate the nuclear effects to analyze neutrino experiments

But

the predicted amplitudes on neutron are not well checked

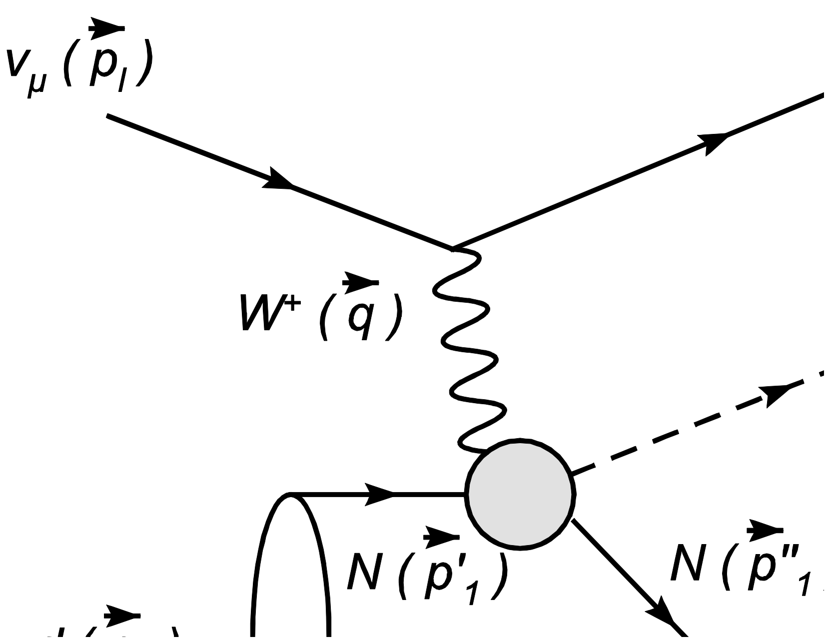


From data on deuteron

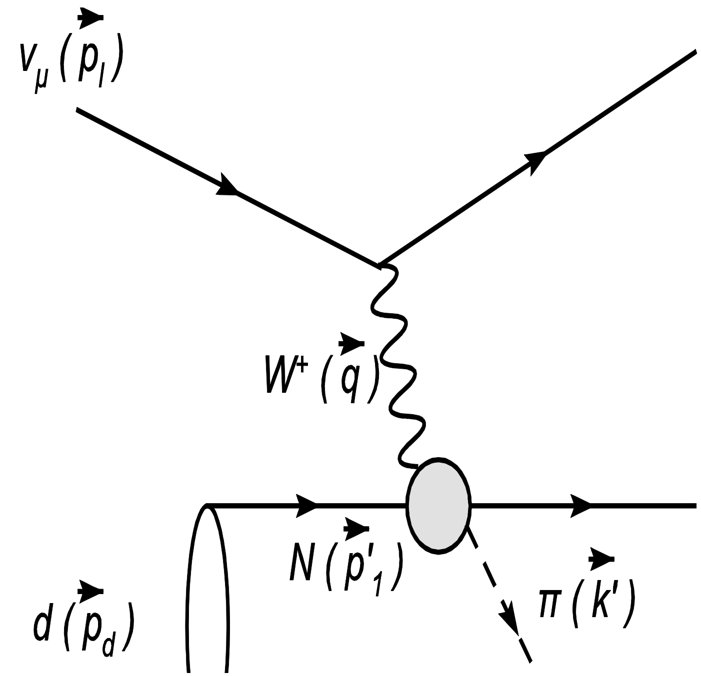
SL model does not describe the data on neutron well

Possible reason:

Previous analysis of data on deuteron target did not include final πNN interaction



NN scattering



πN scattering

Need to study final state interaction (FSI) effects

Study of FSI using SL model:

1. $d(e,e'\pi^+)\,pp$: search for pion excess in nuclei

K. Hafidi, T.-S. H. Lee, Phys. Rev. C (2001)

2. $\gamma + d \rightarrow \pi\ np,\ \pi\ pp$
   $\nu + d \rightarrow \mu\ \pi\ pp,\ \mu\ \pi\ np$

J. Wu, T. Sato, T.-S. H. Lee, Phys. Rev. C 91, 035203 (2014)

Motivated by the neutrino experiments

Approach:

Apply the multiple scattering theory
to calculate γd and νd reaction amplitudes
from a Hamiltonian with N, π and Δ

Model Hamiltonian with N, π, Δ

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

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

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

Lee, Matsuyama (1985-1992)

Determined by
πN -> πN
NN-> NN, πNN

Determined by
γN-> πN
N(e,e'π) N

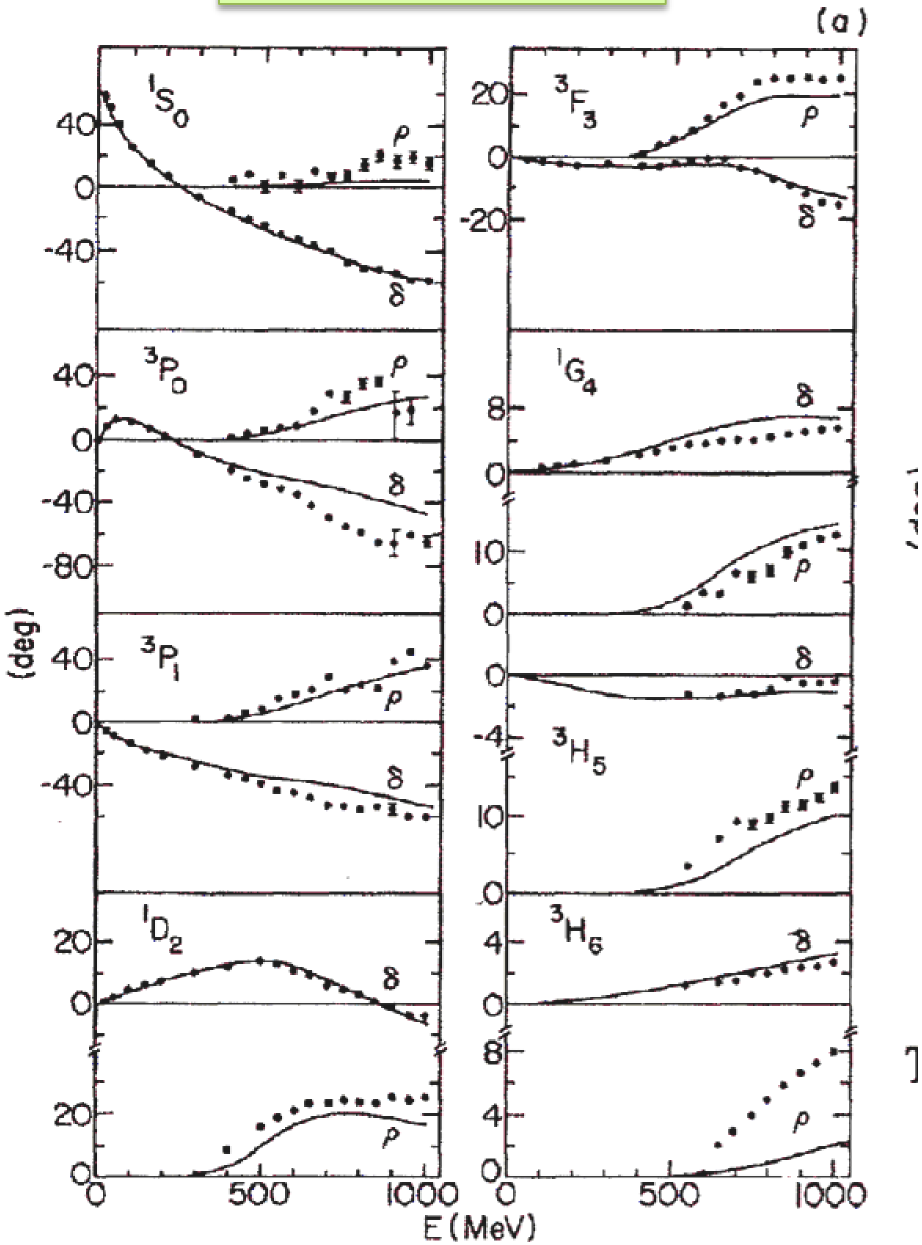
Sato, Lee (1996-2001)

$J^{CC} + J^{NC}$

Determined by νN -> μ π N

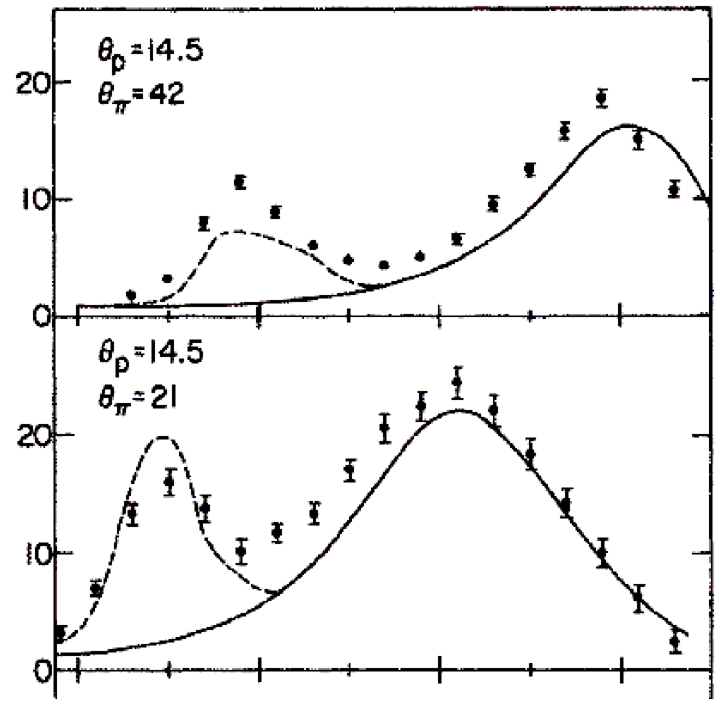
Sato, Uno, Matsui, Lee, (2003-2005)

NN phase shifts



Lee, Matsuyama (1985-1992)

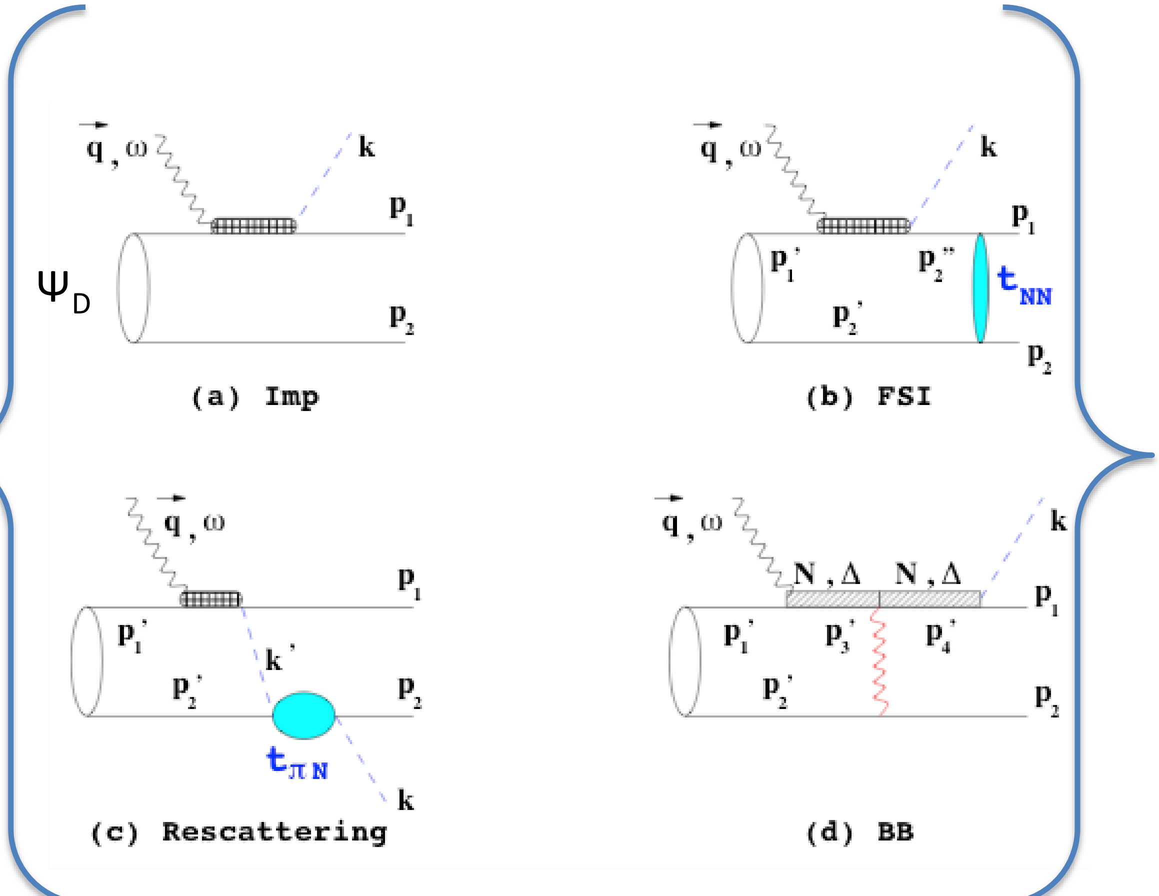
pp -> π^+ np



Model Hamiltonian with N, π, Δ

multiple scattering theory

$\langle \pi NN | T | \gamma^* \Psi_d \rangle$



$\sigma \ (\gamma^* d \to \pi NN)$

Calculations include :

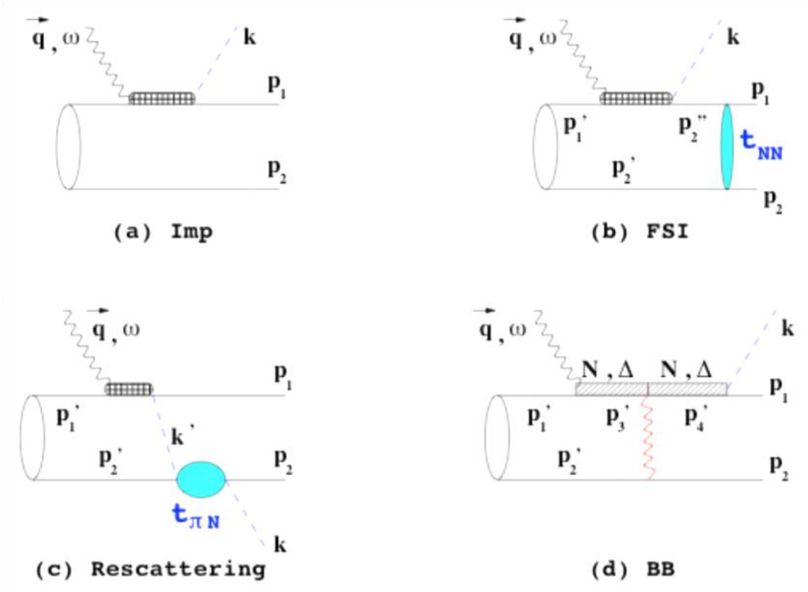
- Fermi motion effects

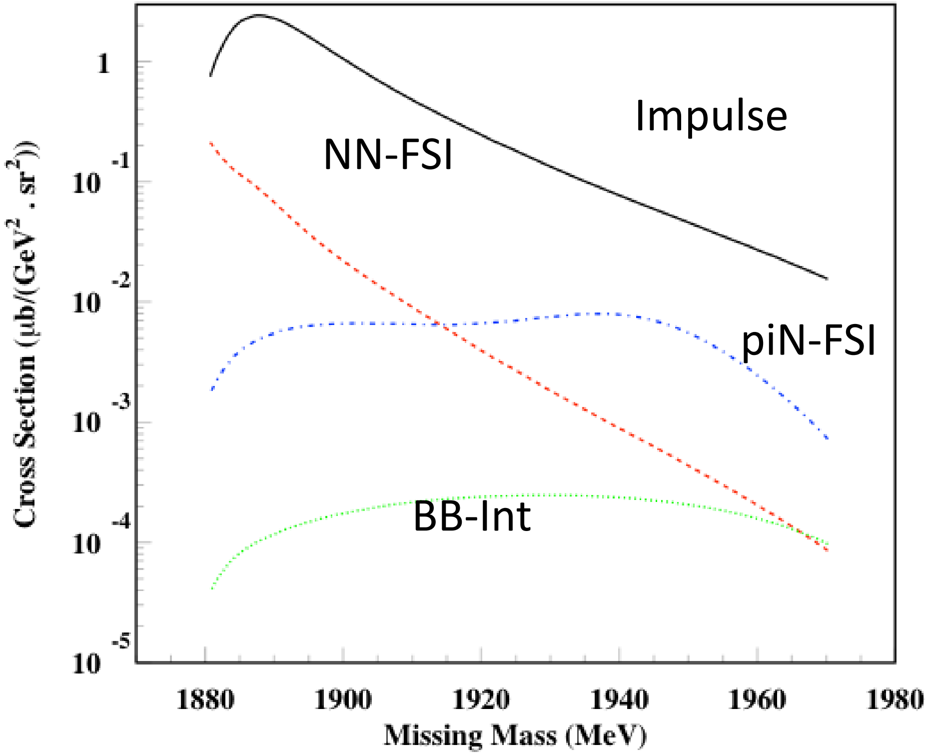
- Spin rotaion effects
  $|p_L,m_s>_d = R_w(\Lambda)\ |p_{c,}m_s>$

- Lorentz transformaion of currents
  $[J]_d\ = \Lambda\ [j]_N\ \Lambda^{-1}$

- Exact loop-integrations of FSI terms

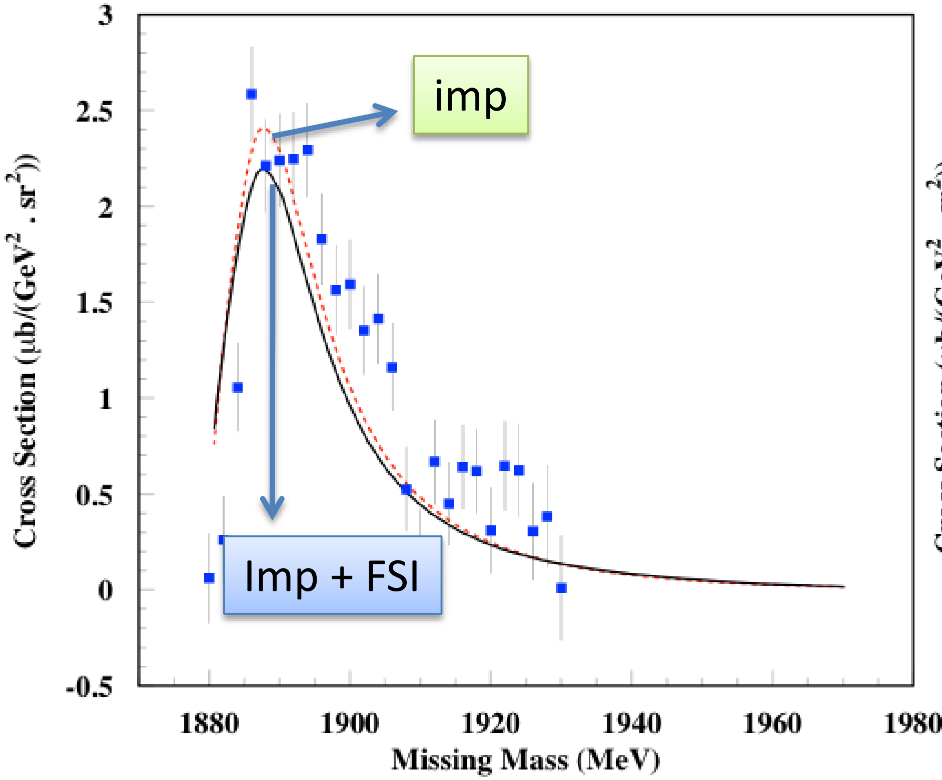
d(e,e'π⁺)nn

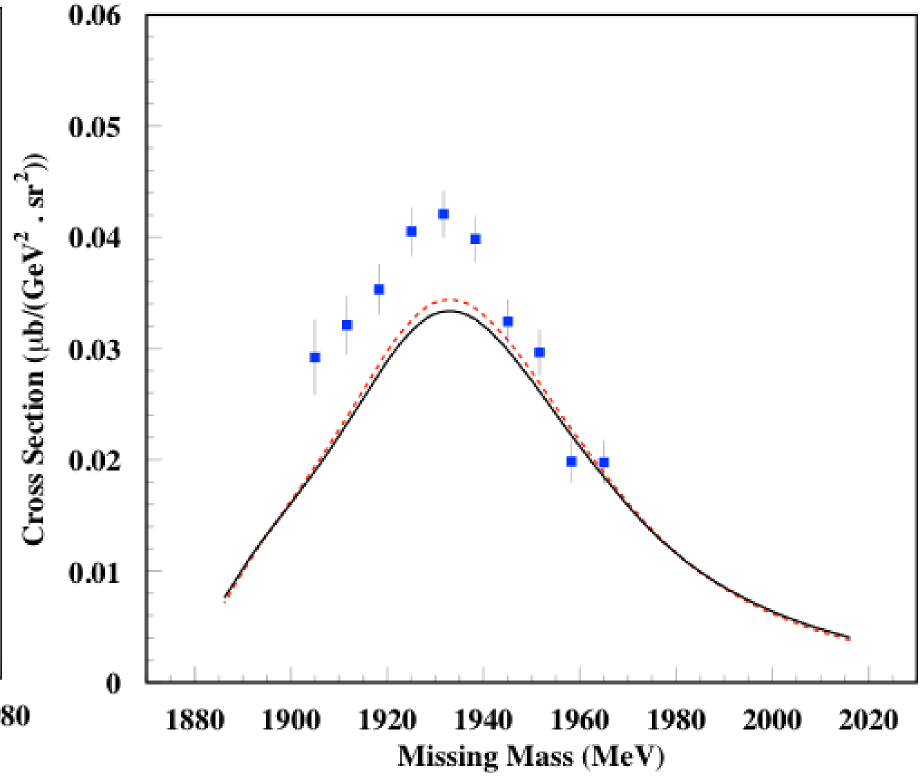




K. Hafidi, T.-S. H. Lee, Phys. Rev. C (2001)

Impluse term dominants
BB Int can be neglected





Saclay data

Q^2=0.08 (GeV/c)^2
W=1.16 GeV
E_e=645 MeV

Jlab data

Q^2=0.4(GeV/c)^2
W=1.16 GeV
E_e=844 MeV

Apply the SL model to study

$\gamma d \rightarrow \pi^- pp$

$\gamma d \rightarrow \pi^0 np$

J. Wu, T. Sato, T.-S. H. Lee Phys. Rv. C91, 035203 (2014)

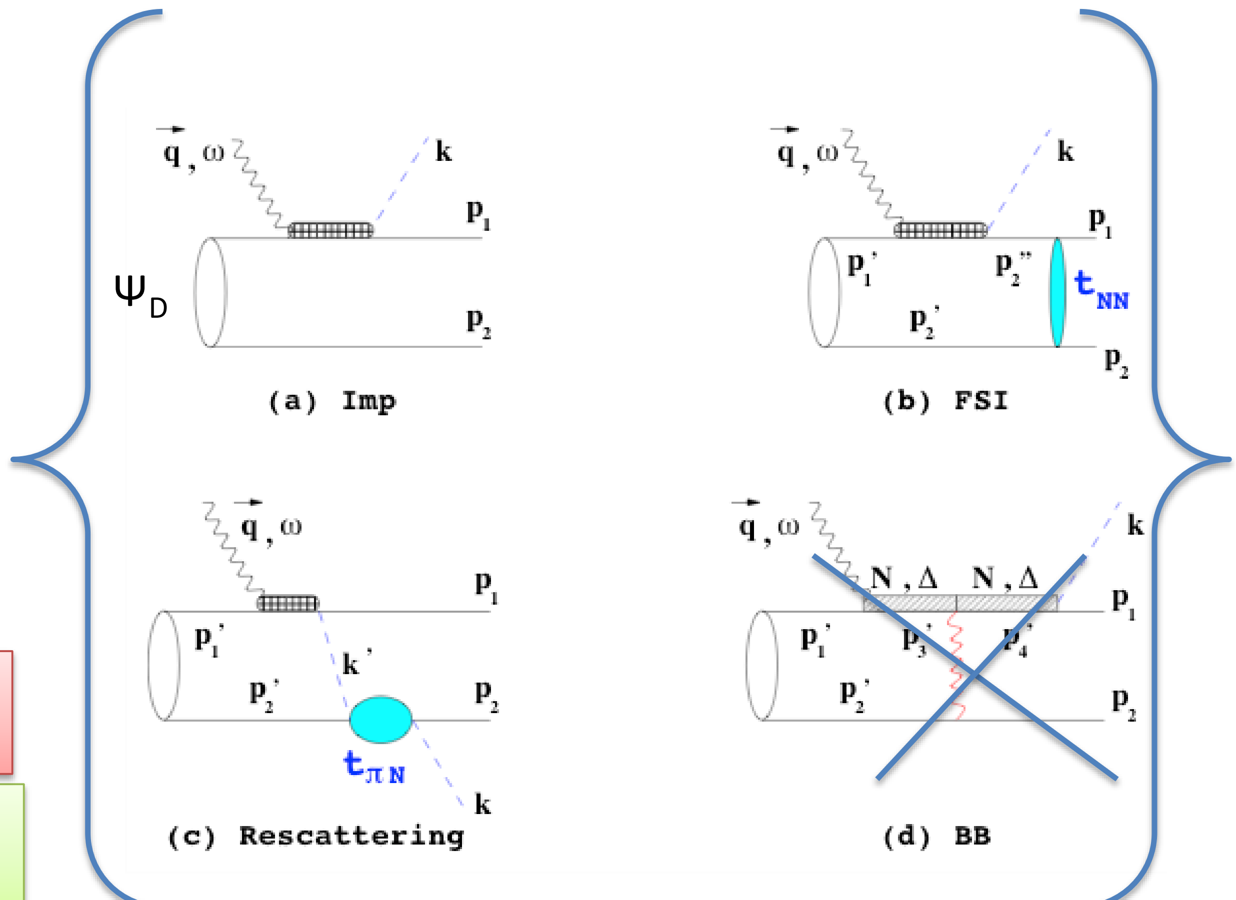
Model Hamiltonian with N, π, Δ

multiple scattering theory

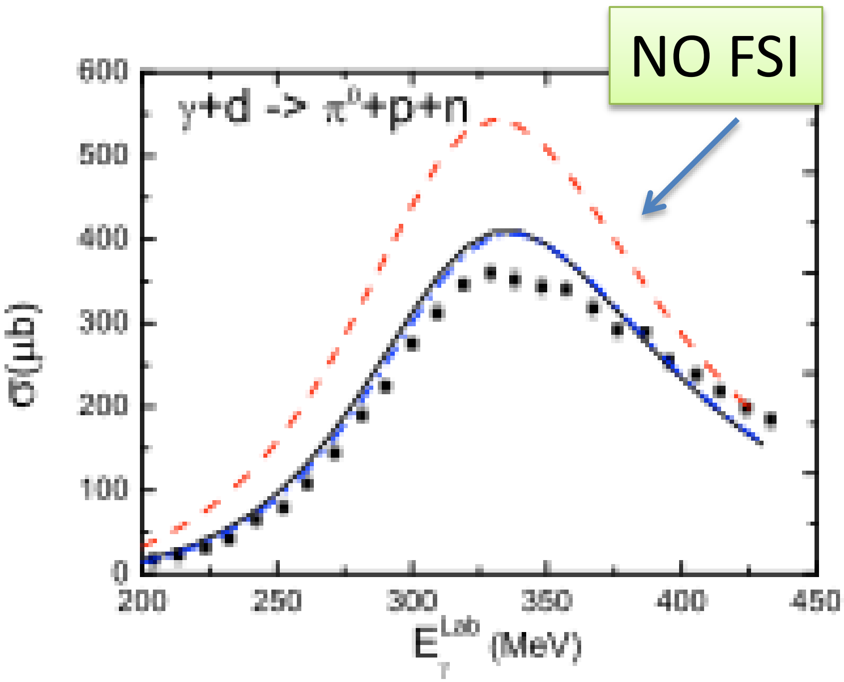
$\langle \pi NN | T | \gamma \Psi_D \rangle$

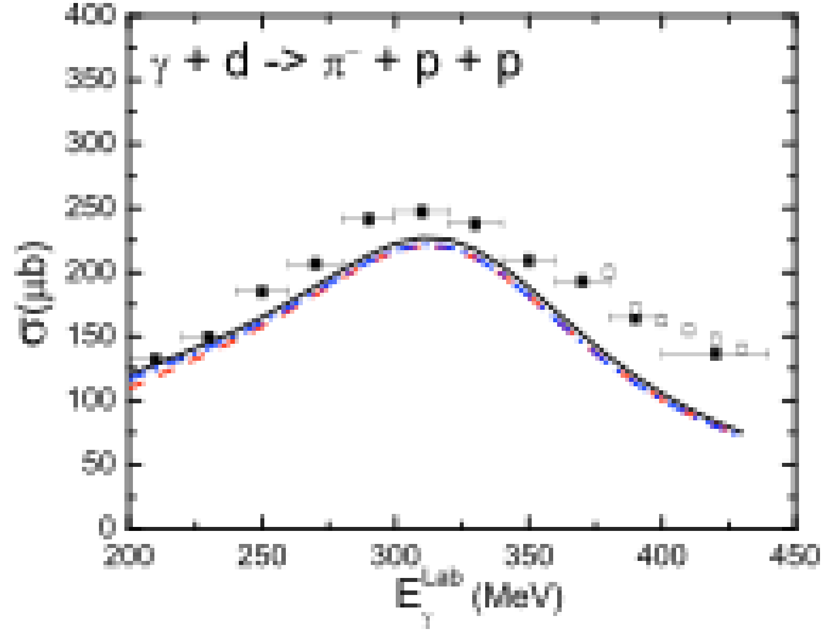
σ (γ d -> π^- pp)

σ (γ d -> π^0 np)

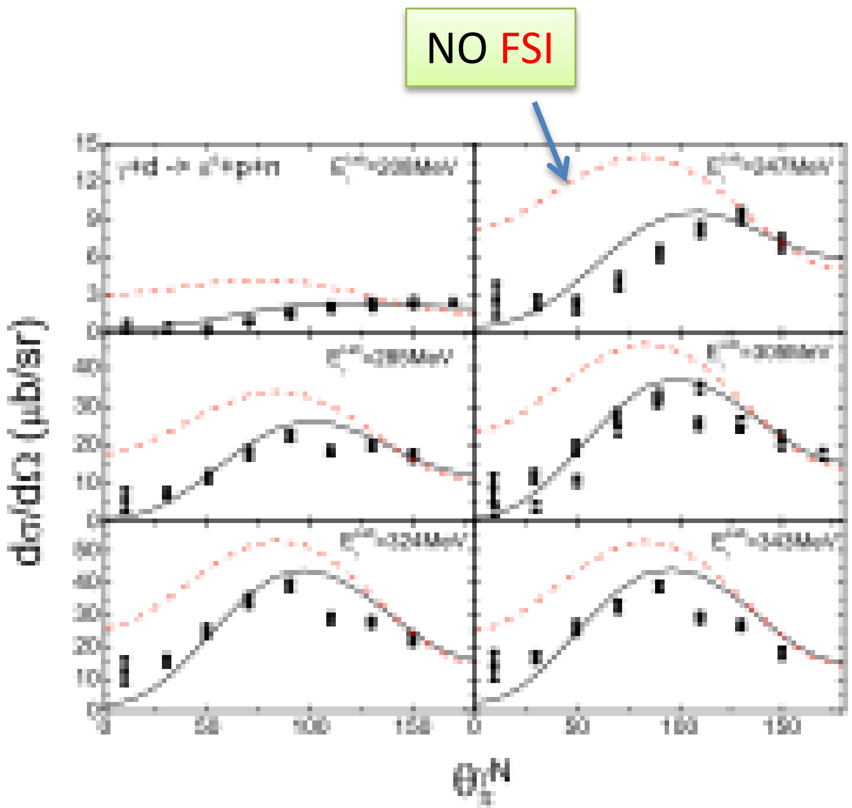


In the Δ(1232) region

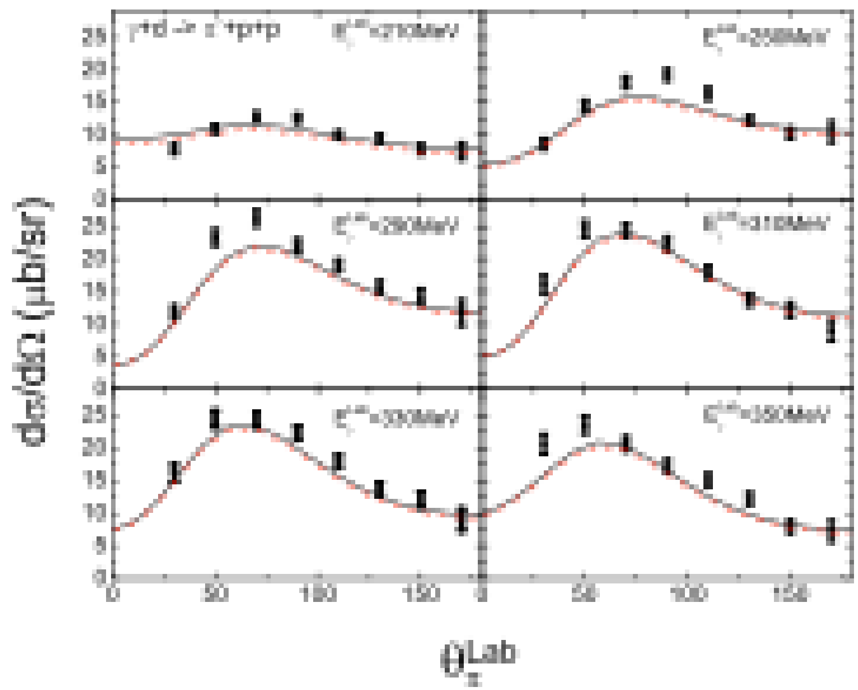




FSI is large for T=0 NN state
FSI is weak for T=1 NN state



γd -> π^0 np



γd -> π^- nn

FSI is large for T=0 NN state
FSI is weak for T=1 NN state

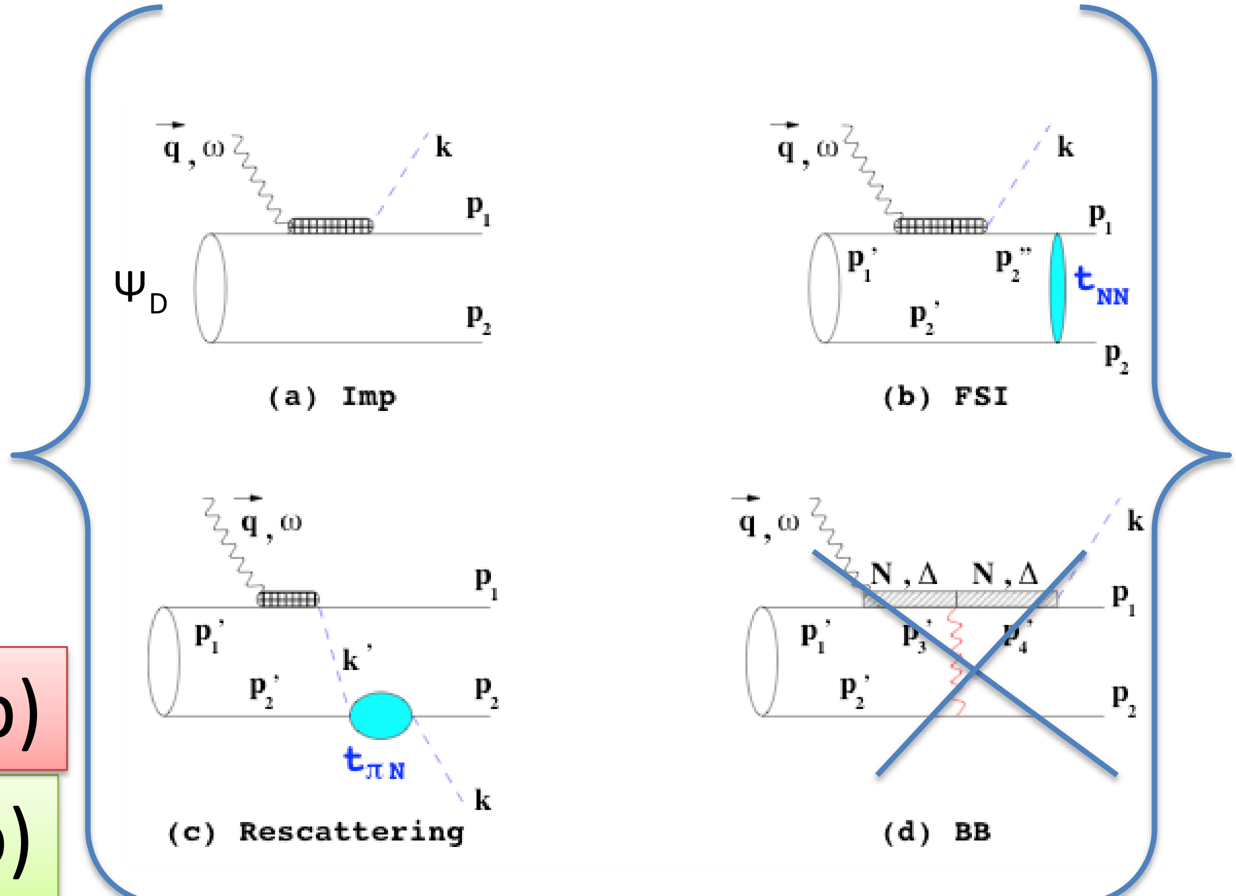
Model Hamiltonian with N, π, Δ

multiple scattering theory

$<\pi NN|T|\nu\Psi_D>$

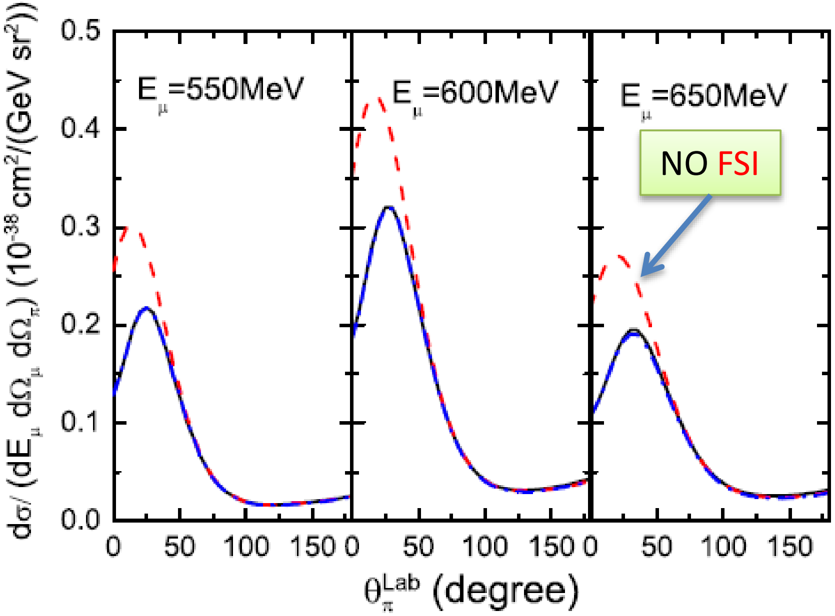
σ (ν d -> $\mu^- \pi^0 pp$)

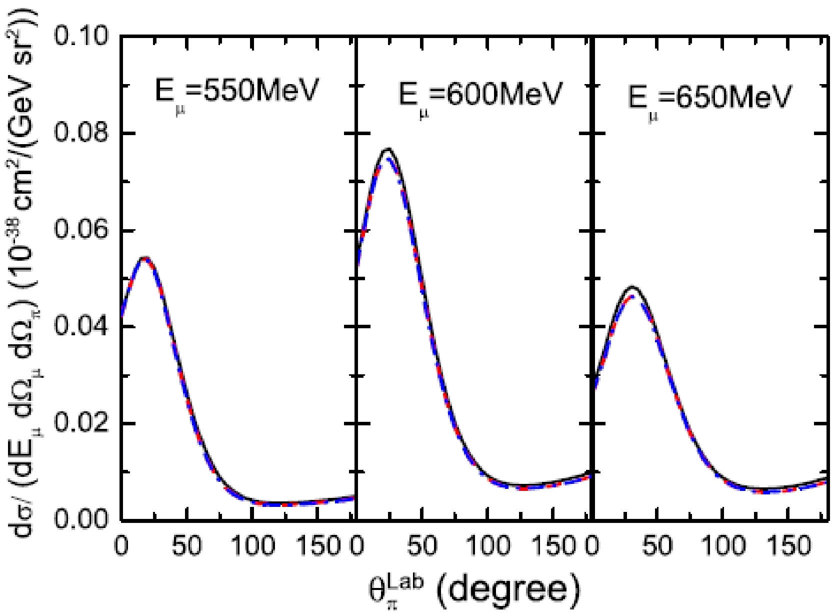
σ (νd -> $\mu^- \pi^+ np$)



$$\nu_\mu d \to \mu^- \pi^+ pn$$

$$\nu_\mu d \to \mu^- \pi^0 pp$$





FSI is large for T=0 NN state

FSI is weak for T=1 NN state

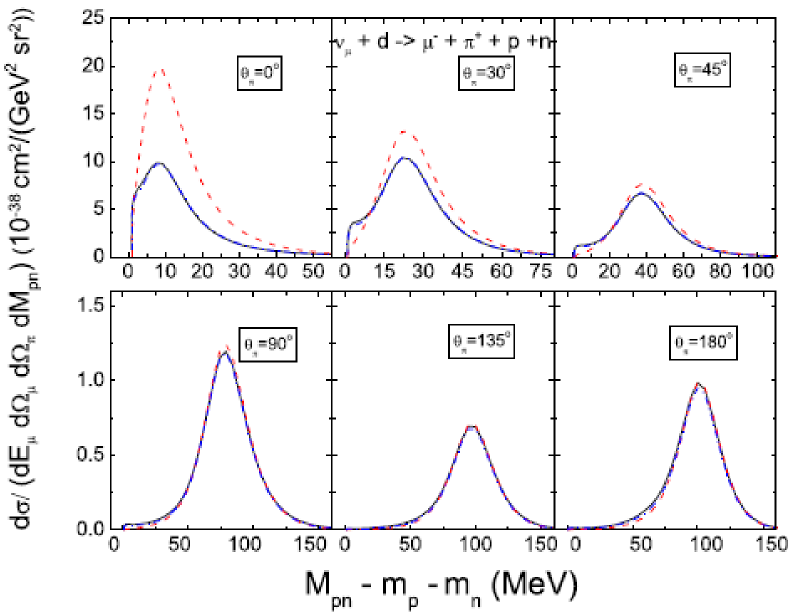
$$E_\nu = 1GeV$$

$$\theta_\mu = 25^o$$

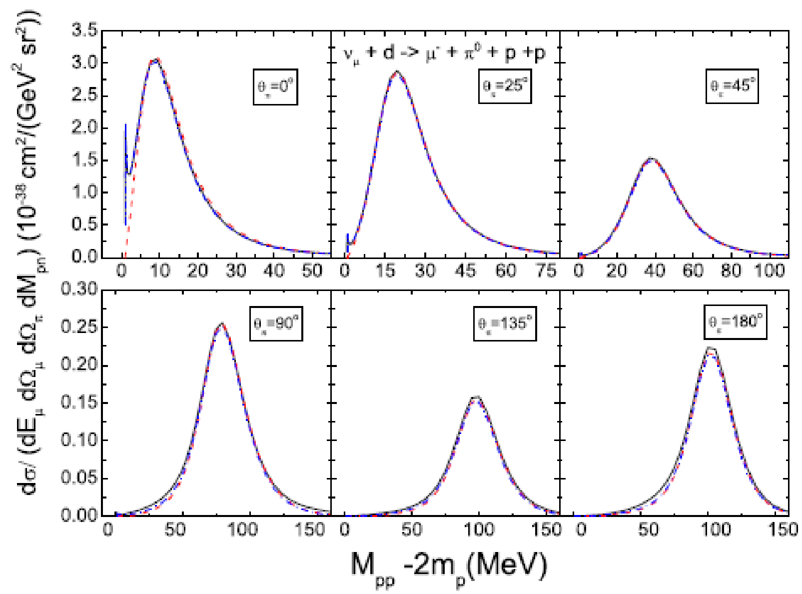
~ Delta-QF kinematics

NN invariant mass distribution

$$\nu_\mu + d \to \mu^- + \pi^+ + p + n$$



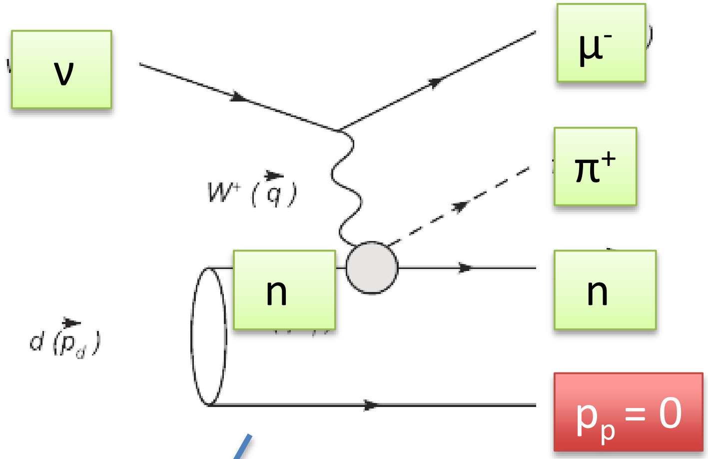
$$\nu_\mu + d \to \mu^- + \pi^0 + p + p$$

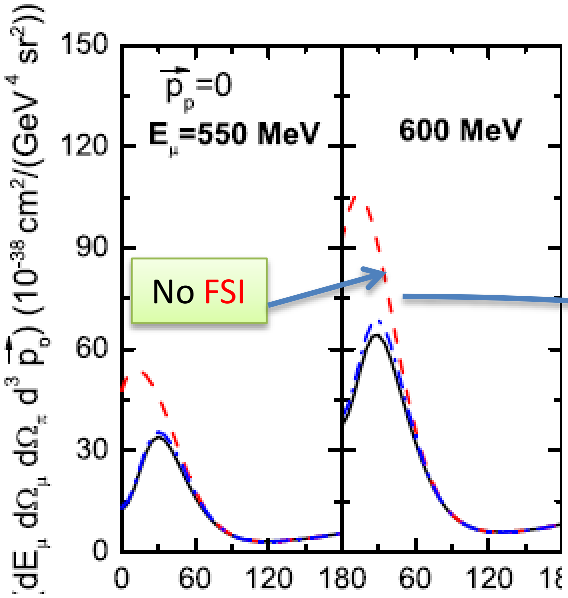


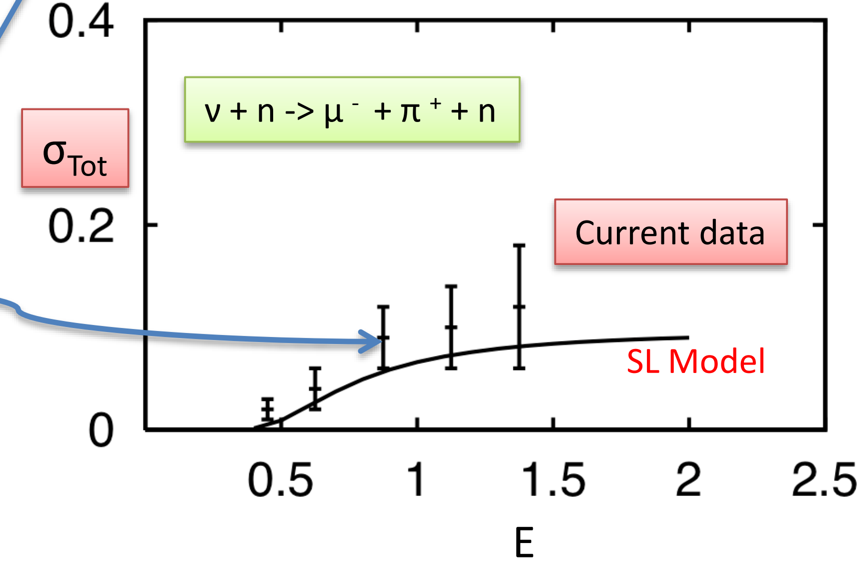
FSI is large for T=0 NN state
FSI is weak for T=1 NN state

spectator approximation

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







Need to re-analyze of ANL and BNL data !

Summary

- For analyzing neutrino experiments at 1-3 GeV, it is necessary to develop theoretical models for calculating nuclear effects in the Δ(1232) region.

- The SL Model can describe almost all electroweak pion production data and has been applied to calculate nuclear effects by using
  a. multiple scattering theory for deuteron target (this talk)
  b. Δ-hole model for heavy nuclei

- The final state interaction effects on γd, νd -> π NN are very large for final T=0 NN state and must be included to extract the cross sections on neutron from data on deuteron

- Our results suggest the need for re-analysis of ANL and BNL data.

Back Up

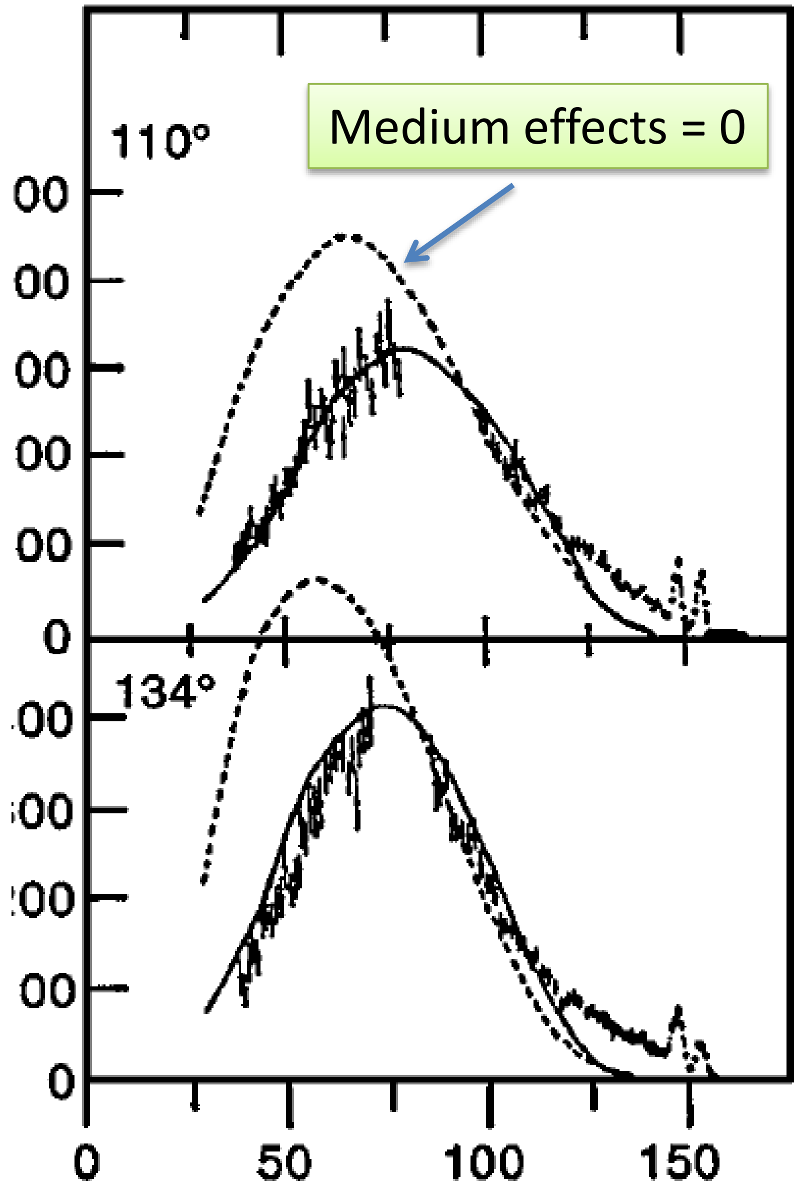
Transition matrix element (radial integral) of two-nucleon wave function

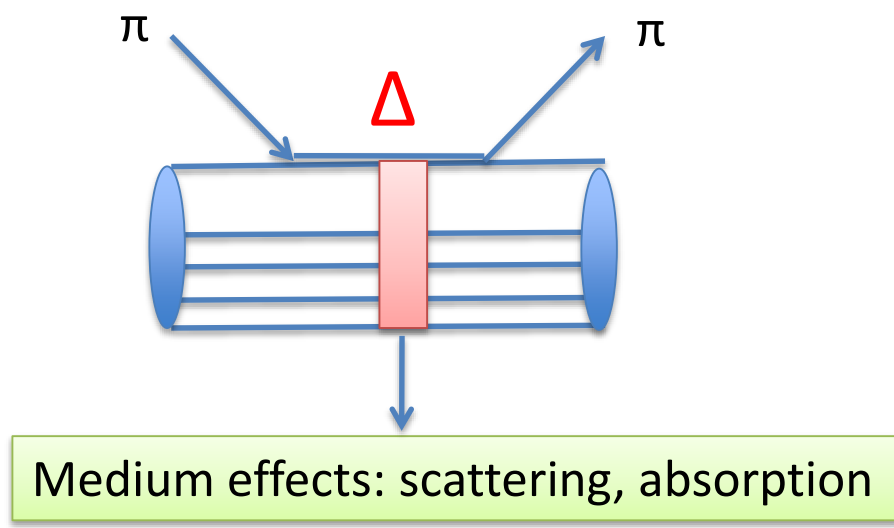
Final state	$\int_0^\infty R_{^{2S+1}L_J}(r) R_d(r) r^2 dr$
$^3S_1(pn)$	0(orthogonality of wave function)
$^1S_0(pn, nn, pp)$	finite

Initial state $\quad ^3S_1(deuteron) \quad$ (S=1,L=0,J=1)

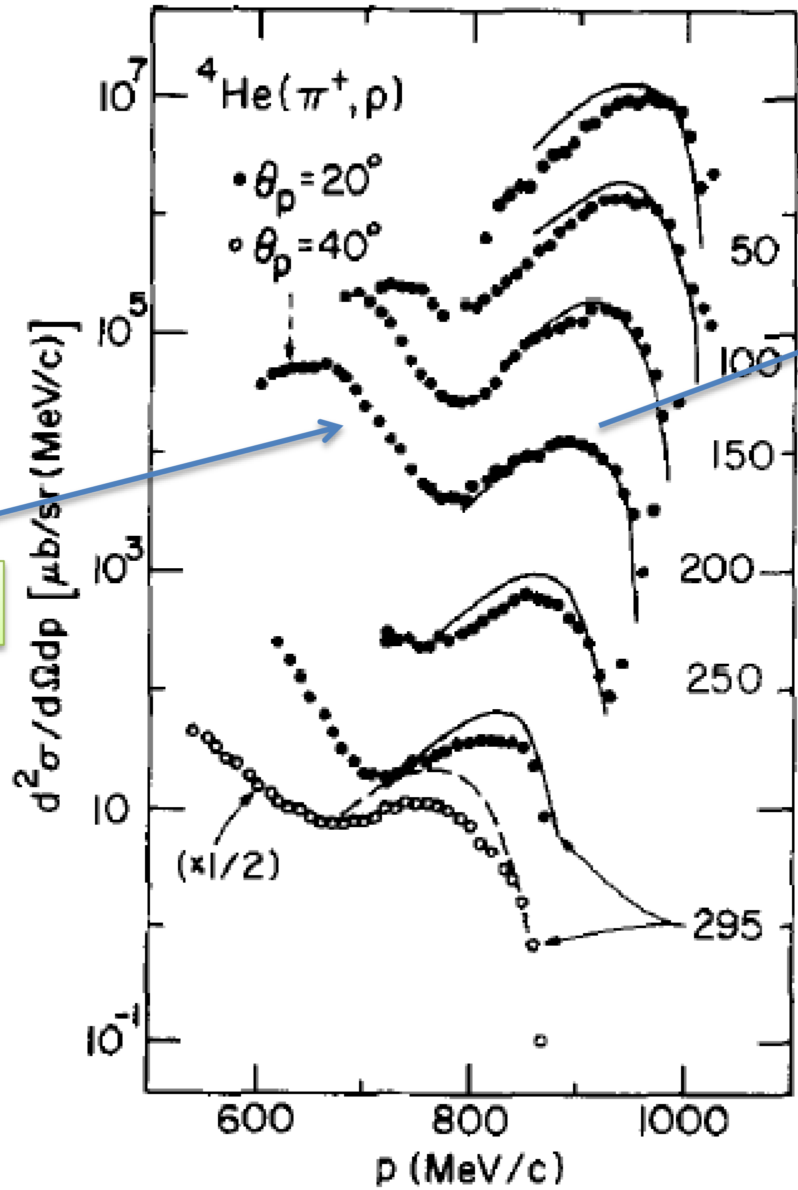
This property can be only taken into account by using distorted wave, not plane wave approximation.

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





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



Absorption

$\pi^+ + {}^4He \to ppn$

$\pi^+ + {}^4He \to \pi\, p\, NN$

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)

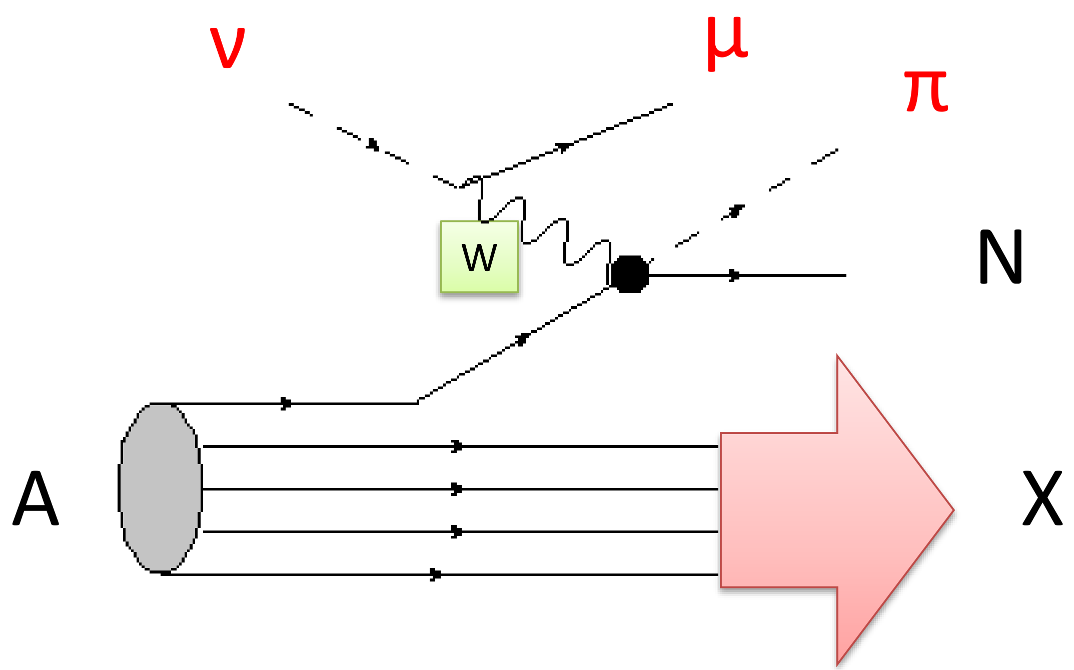
Inclusive A(ν,μ)X

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

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

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

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

$*$ Fermi Gas to Spectral Function

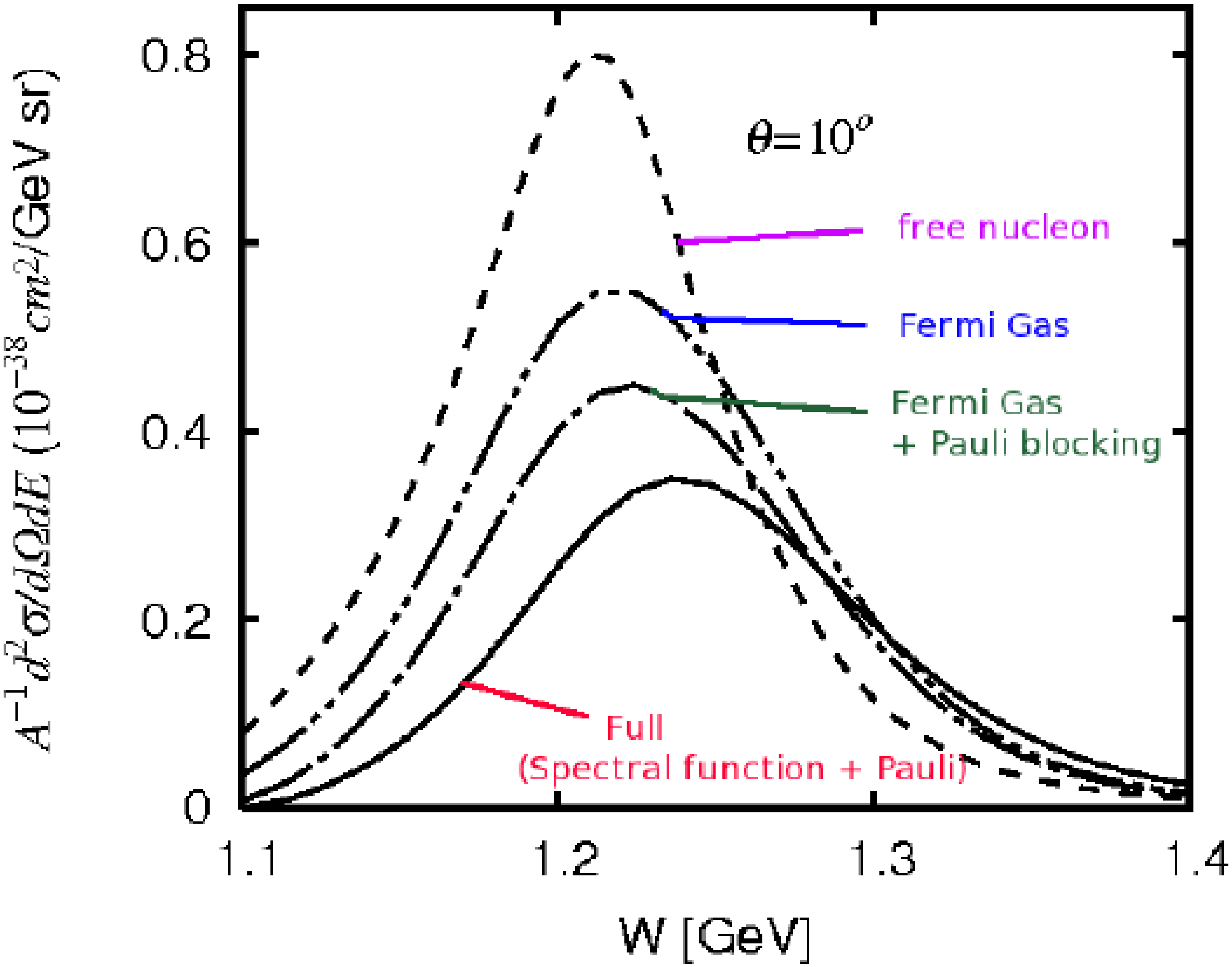
Benhar et al. NPA 579 493 (1994)

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

Include correlations

Nuclear Effect for 1π in Δ-region

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



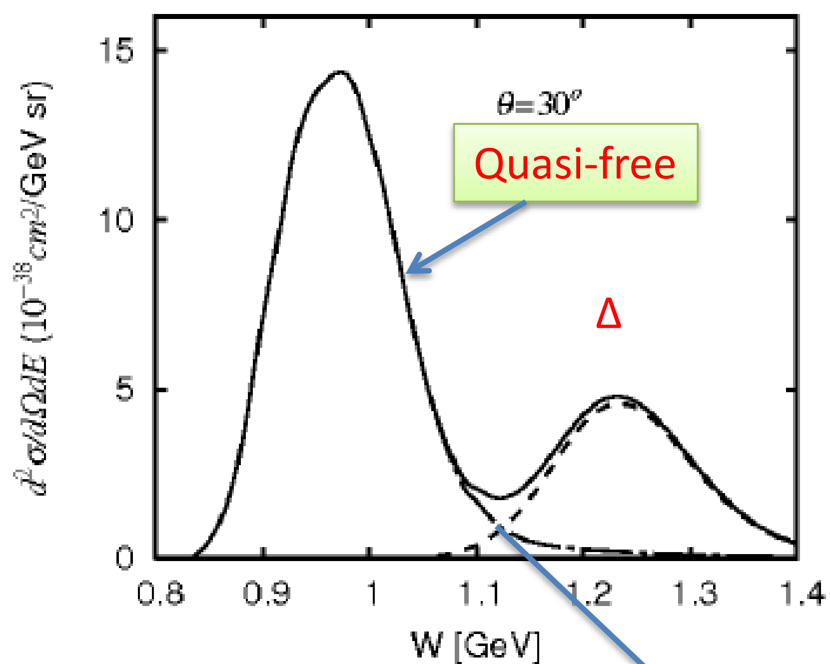
Nuclear correlation and final state interaction must be included in calculating the nuclear effects in analyzing experimental data

Same formula for e + ^{12}C -> e' + π + X

Test the model by the available data

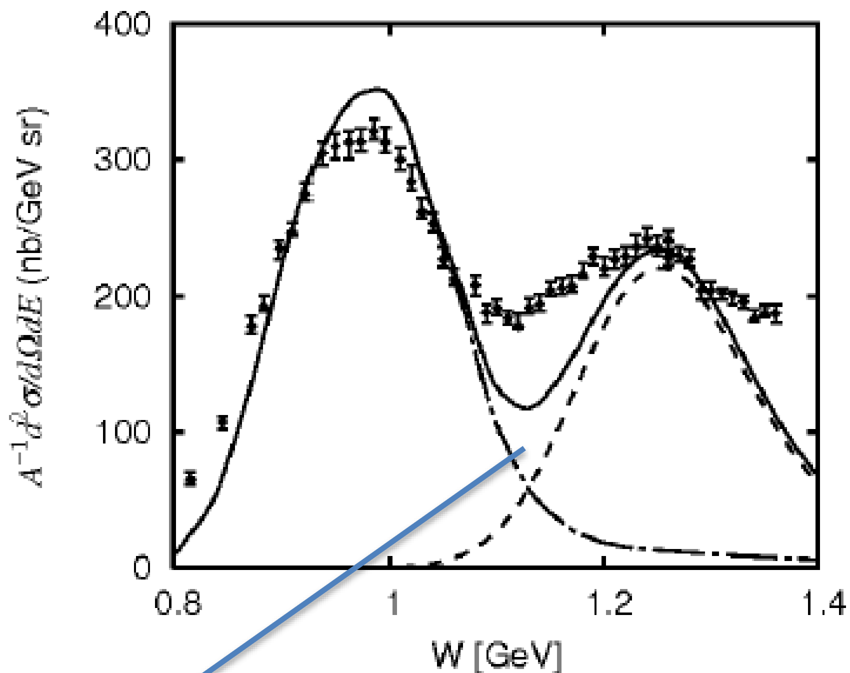
Prediction

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



Compare with data

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

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

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

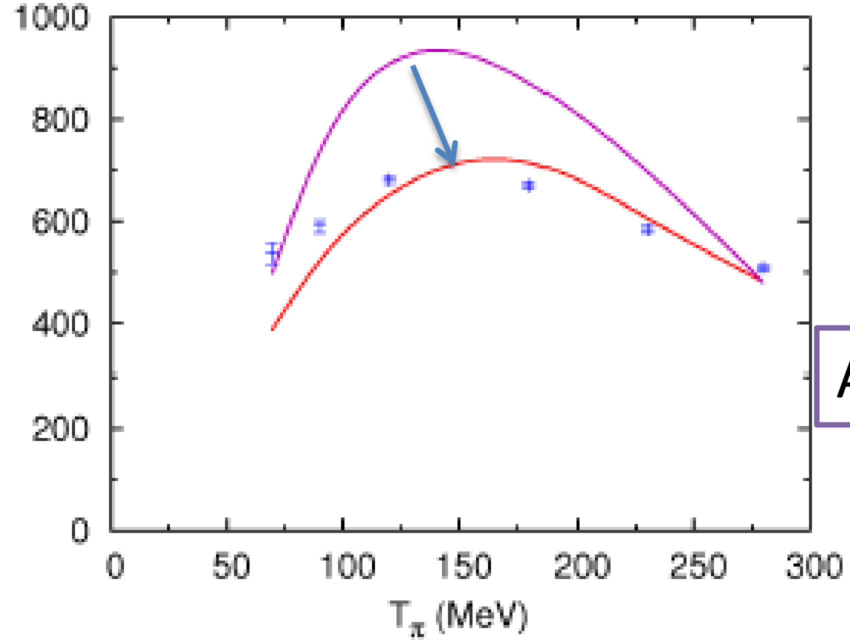
Fit π-A data

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

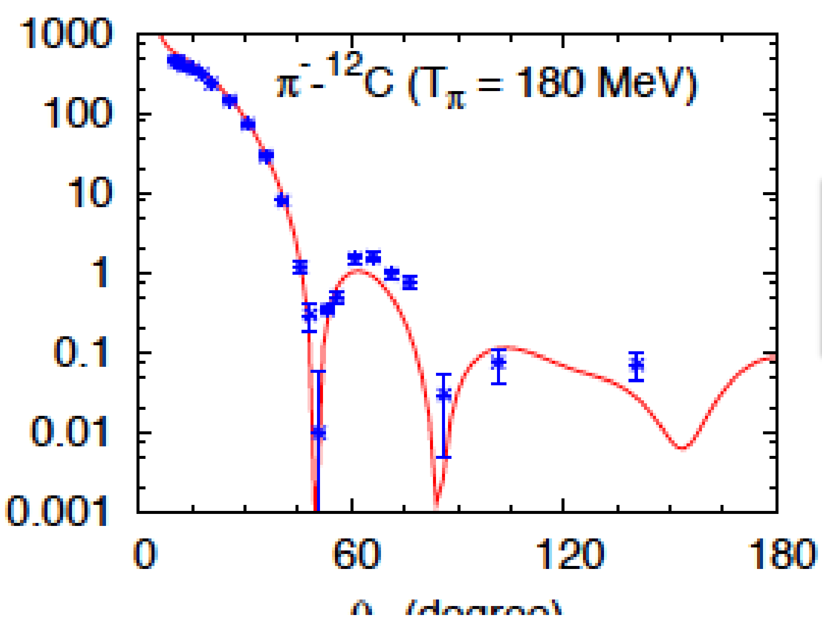
Pion absorption

Δ-hole model for ^{12}C

Nakamura et al., PR C81,035502 (2010

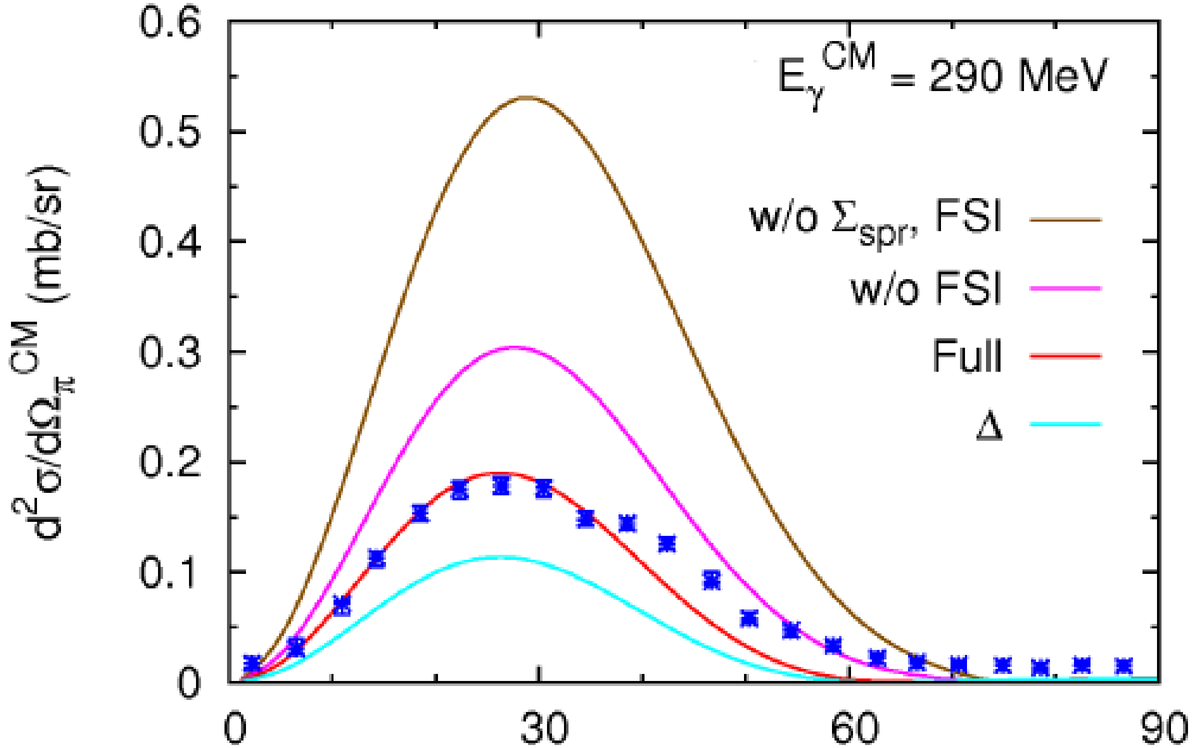


Adjust Σ_{sprd} to fit Total cross section data



Predicted elastic scattering cross section agree well with the data

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



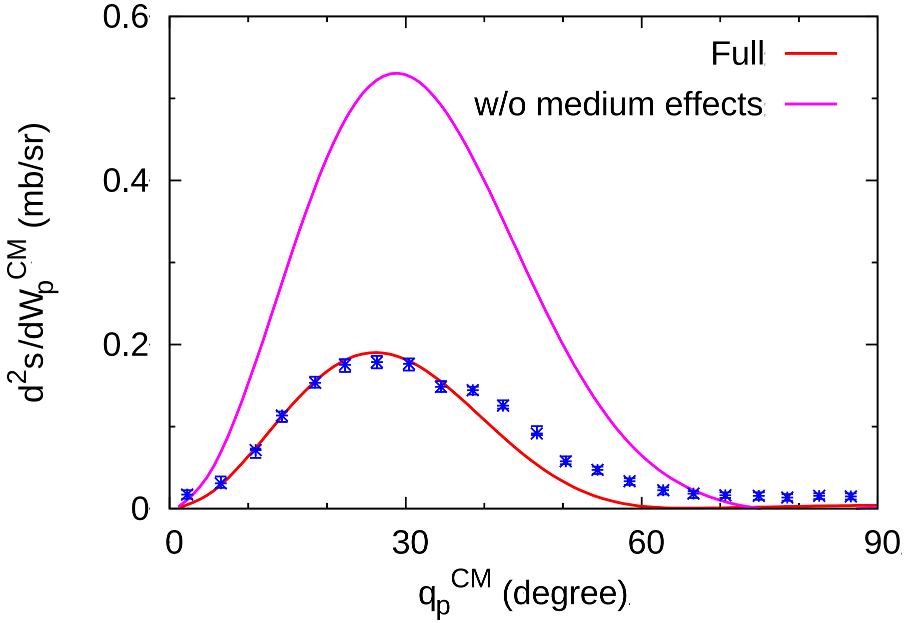
- In agreement with the data
- Medium effects on Δ is large

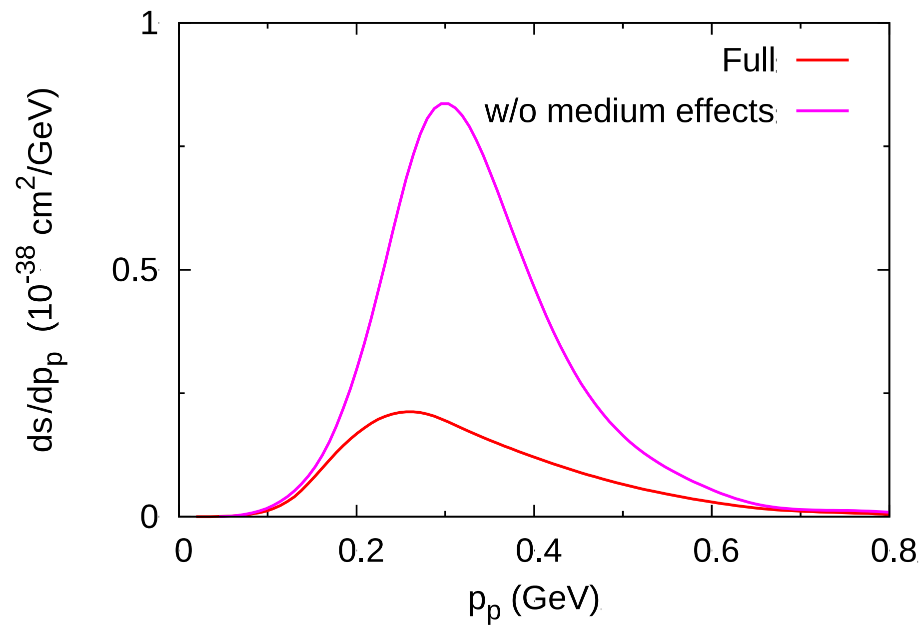
Compare with data

Prediction

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

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





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, $K\Lambda$, $K\Sigma$, ωN

↓

($\pi\Delta$, ρN, σN)

⇒

ANL-Osaka Model has been developed

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

ANL-Osaka Model

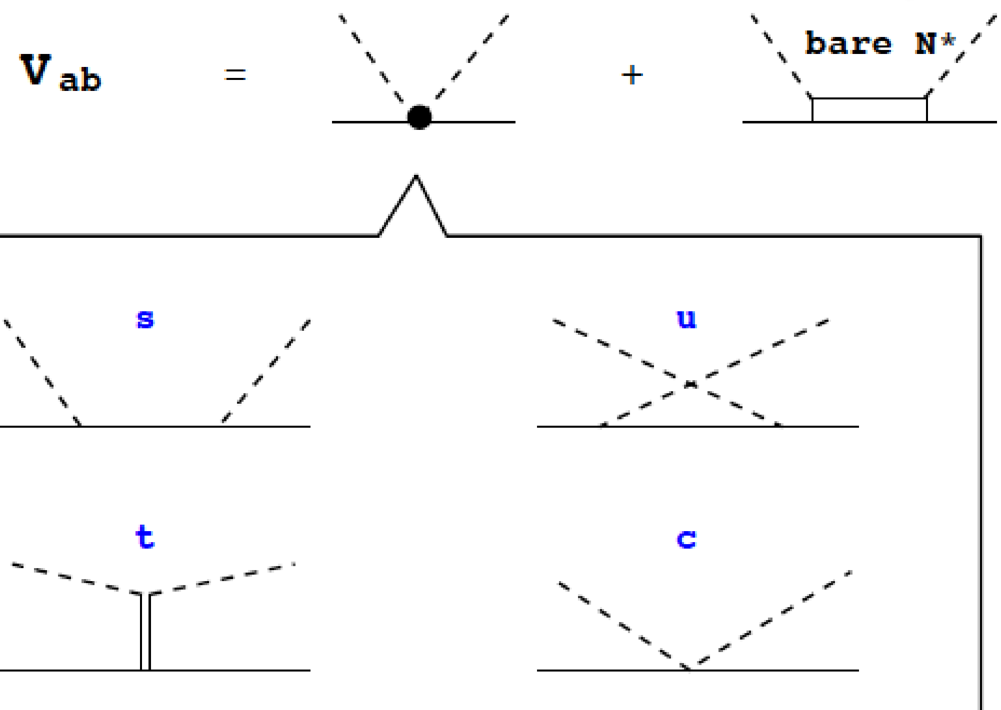
Kamano, Nakamura, Lee, Sato, PRC 88 (2013)

Solve

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

a ,b, c = γN, πN, 2π-N, $K\Lambda$, $K\Sigma$

16 bare N^*



Analysis Database

Pion-induced reactions (purely strong reactions)

SAID

	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

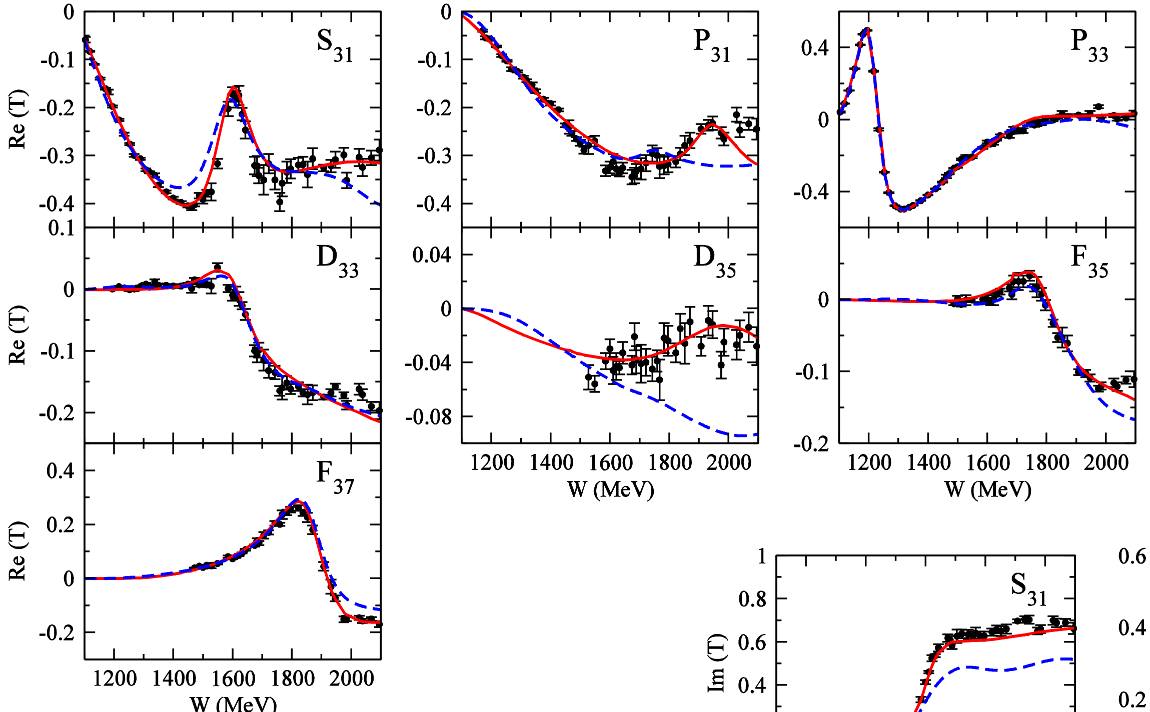
	$d\sigma/d\Omega$	P	R	a	Sum
$\pi^- p \to \eta p$	294	-	-	-	294
$\pi^- p \to K^0 \Lambda$	544	262	-	-	806
$\pi^- p \to K^0 \Sigma^0$	215	70	-	-	285
$\pi^+ p \to K^+ \Sigma^+$	552	312	-	-	864
Sum	1605	644	-	-	2249

~ 28,000 data points to fit

Photo-production reactions

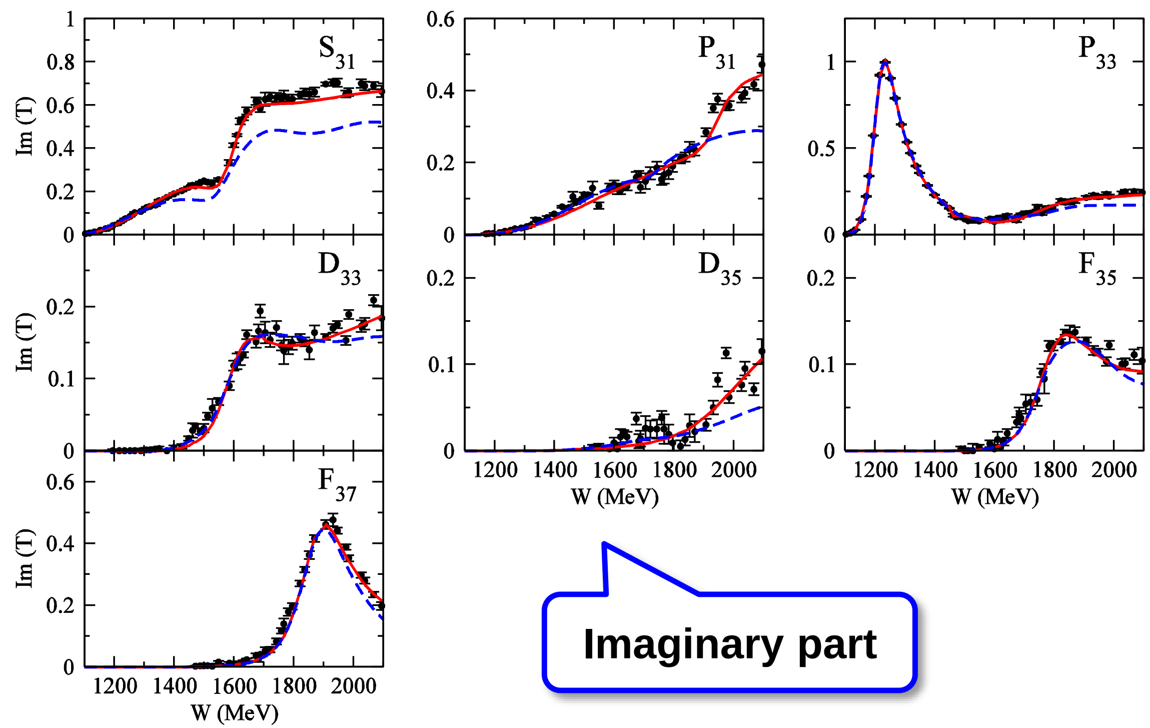
	$d\sigma/d\Omega$	Σ	T	P	G	H	E	F	$O_{x'}$	$O_{z'}$	$C_{x'}$	$C_{z'}$	$T_{x'}$	$T_{z'}$	$L_{x'}$	$L_{z'}$	sum
$\gamma p \to \pi^0 p$	8290	1680	353	557	28	24	-	-	-	-	-	-	-	-	-	-	10860
$\gamma p \to \pi^+ n$	5384	1014	661	221	75	123	-	-	-	-	-	-	-	-	-	-	7478
$\gamma p \to \eta p$	1076	197	50	-	-	-	-	-	-	-	-	-	-	-	-	-	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

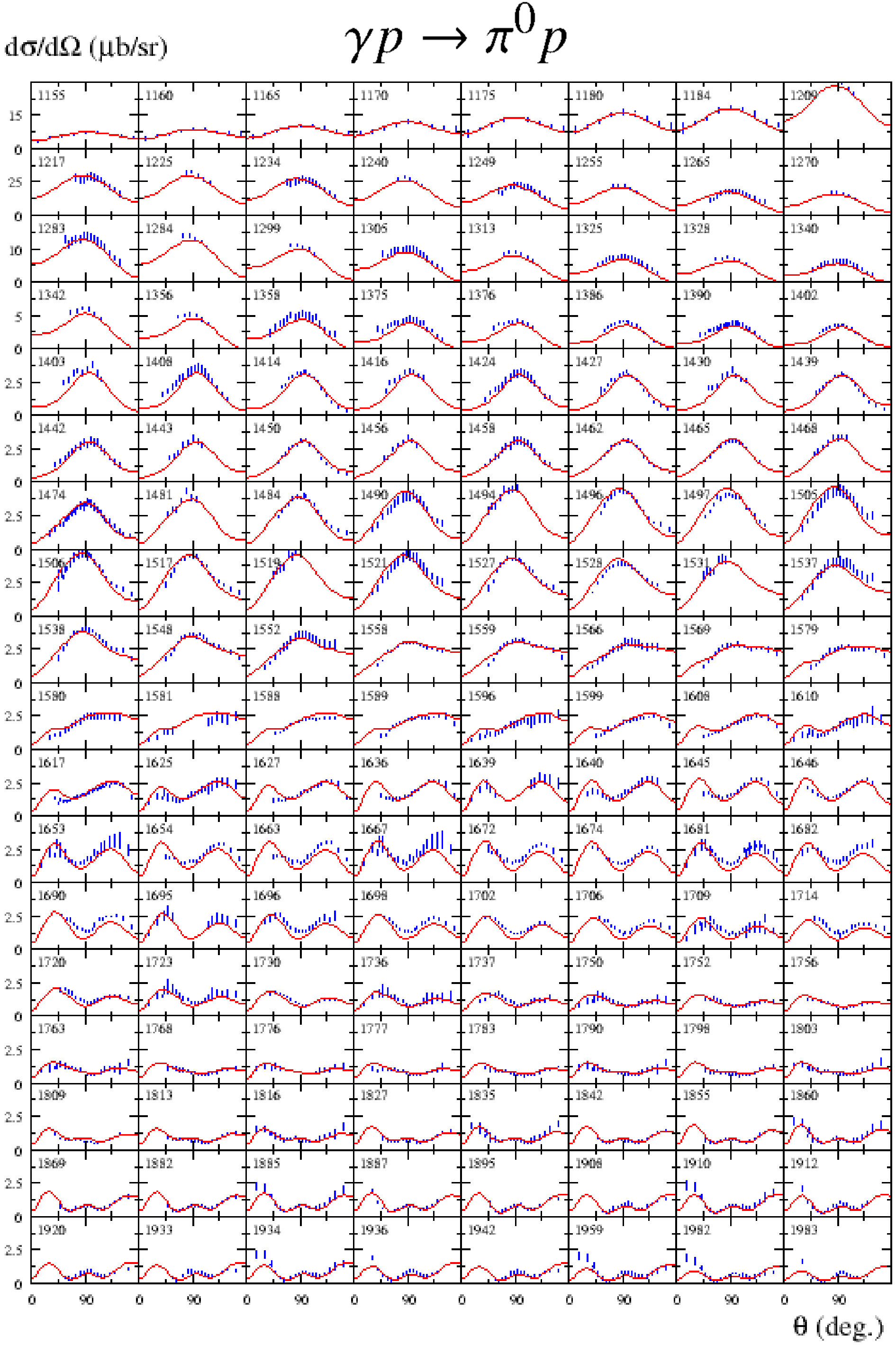
$$I = \frac{3}{2}$$



Imaginary part

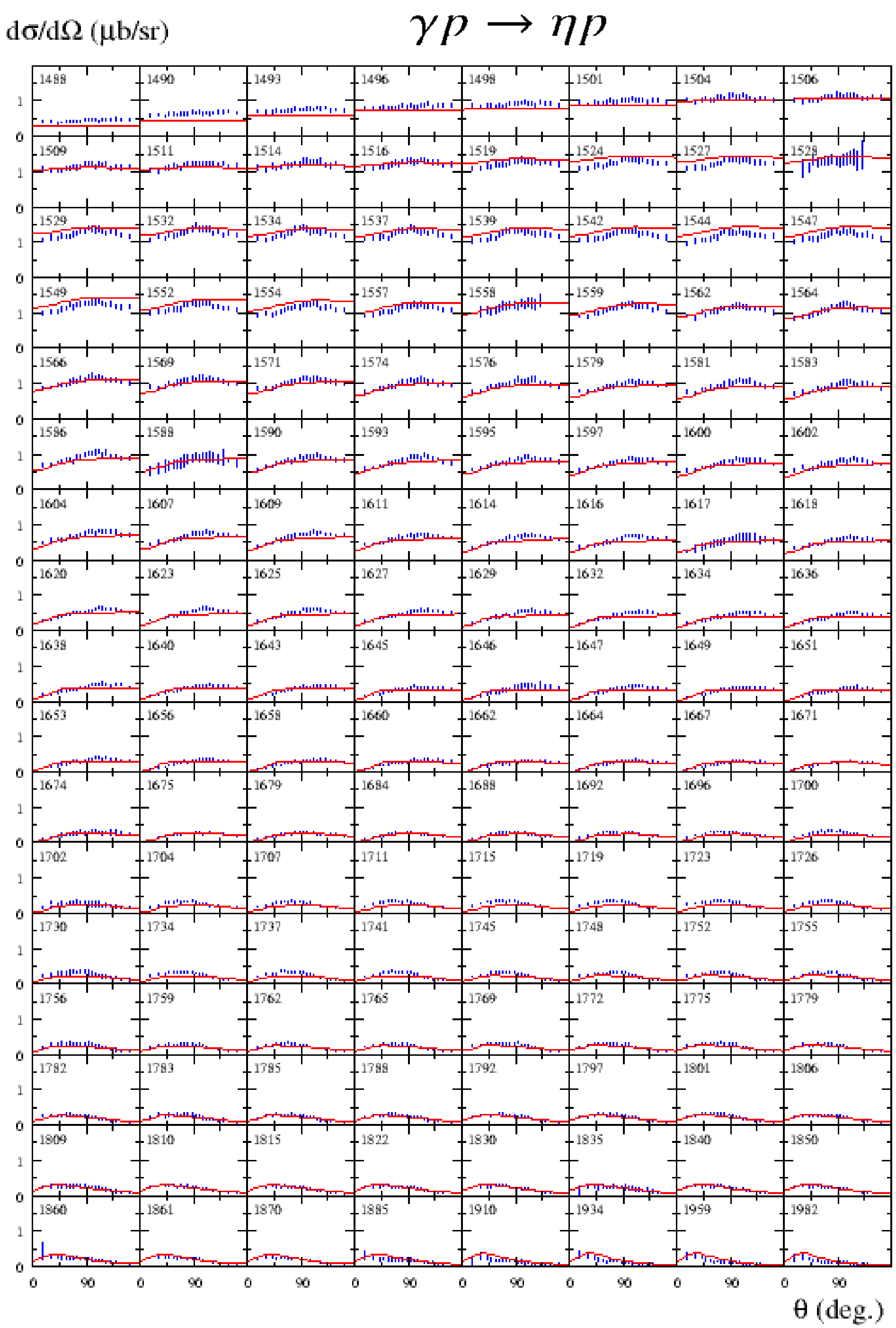
Kamano, Nakamura, Lee, Sato, 2013

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



Vector current (Q^2=0) for 1π

Production is well-tested by data

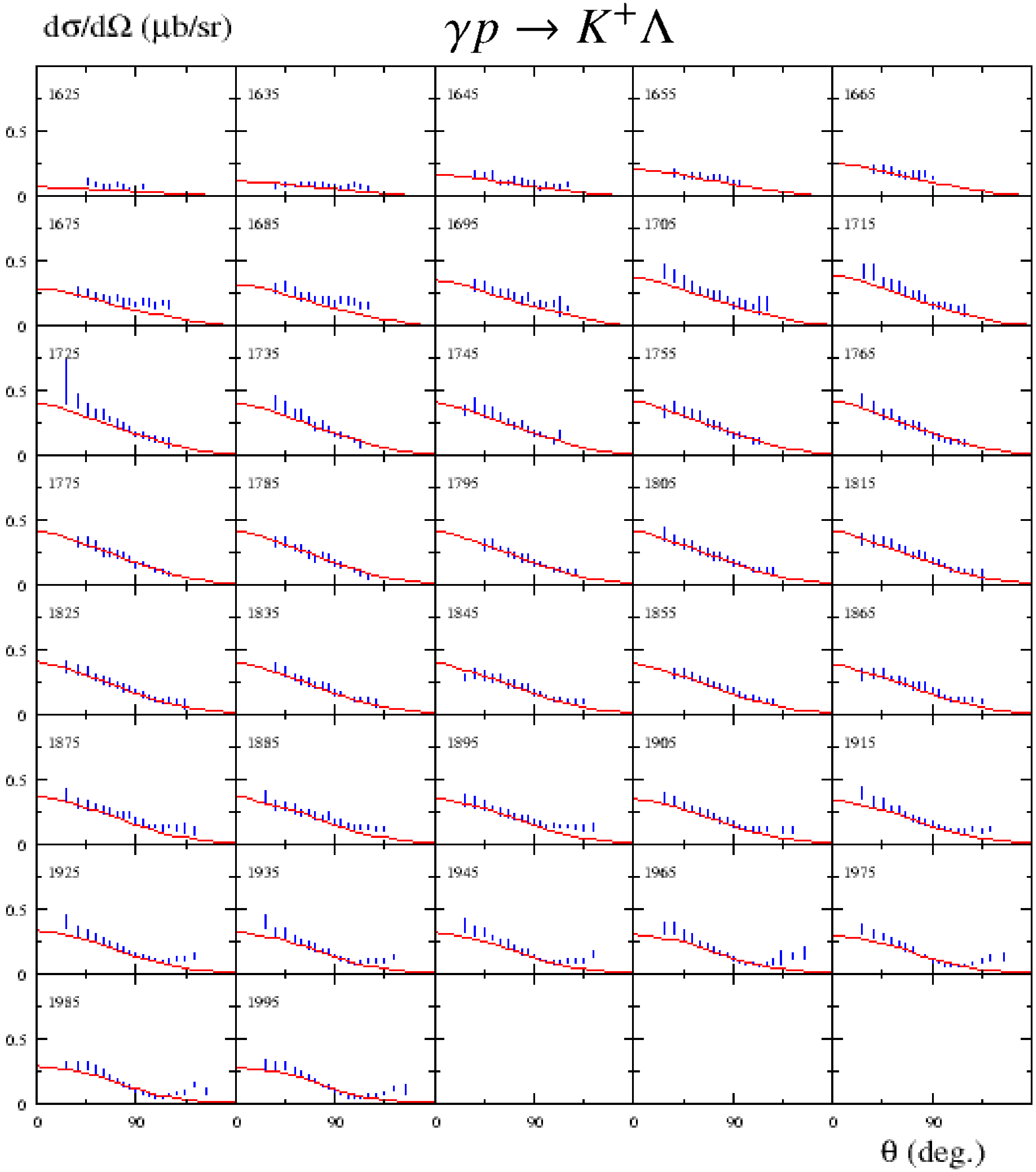


Kamano, Nakamura, Lee, Sato, 2013

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

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

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

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