ニュートリノ原子核反応

－　理論の現状　－

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JPARCで展開されるハドロン原子核物理

Contents

- Motivation

- Inclusive neutrino-nucleus reaction

$$d\sigma/dT_\mu d\cos\theta_\mu$$

- Neutrino induced pion production reaction

$$A(\nu_\mu, \mu^- \pi^+) A,\ A(\nu, \nu\pi^0) A$$

- Summary

Motivation:

Why we are interested in neutrino cross sections on complex nuclei:

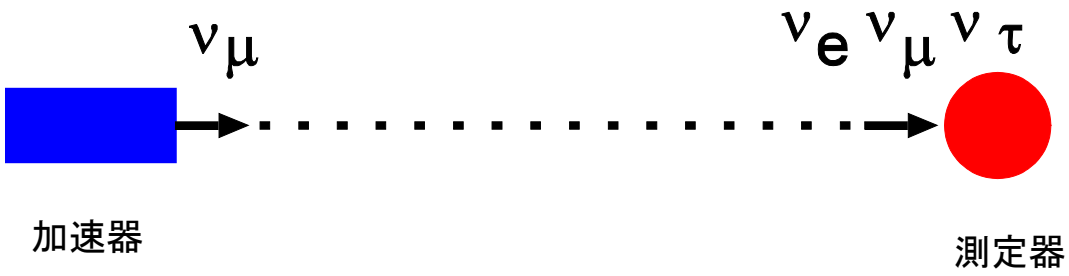
$0 < E_\nu \leq 100 MeV$

Supernova explosion(heating) and cooling
nucleosynthesis
detection of supernova, solar neutrino on Earth
……

$100 MeV \leq E_\nu \leq$ a few GeV

Tools to study neutrino oscillations with accelerator
atmospheric neutrino
Axial vector response of nuclei and nucleon

ニュートリノ振動

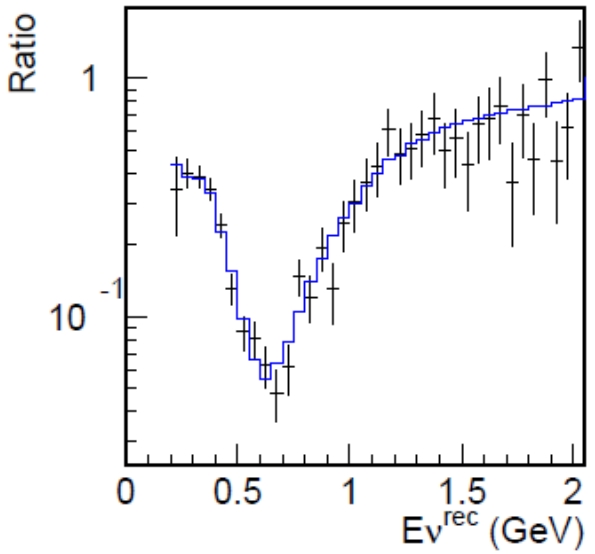


ν_μ disappearance $(\nu_\mu \to \nu_\tau)$

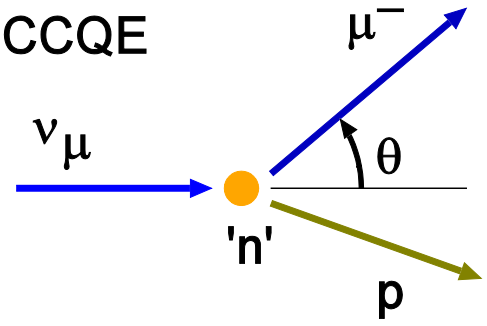
$\theta_{23}, \Delta m^2_{23}$

ν_e appearance $(\nu_\mu \to \nu_e)$ θ_{13}, δ

Ratio of reconstructed neutrino energy distribution (Hiraide thesis)



- Reconstruct E_ν from Quasi-elastic scattering



$$\nu_\mu +' N' \rightarrow \mu^- + N$$

$$E_\nu^{rec} = \frac{2E_\mu M'_n - (M'^2_n + m^2_\mu - M^2_p)}{2(M'_n - E_\mu p_\mu \cos\theta)}$$

true only for reaction on free nucleon

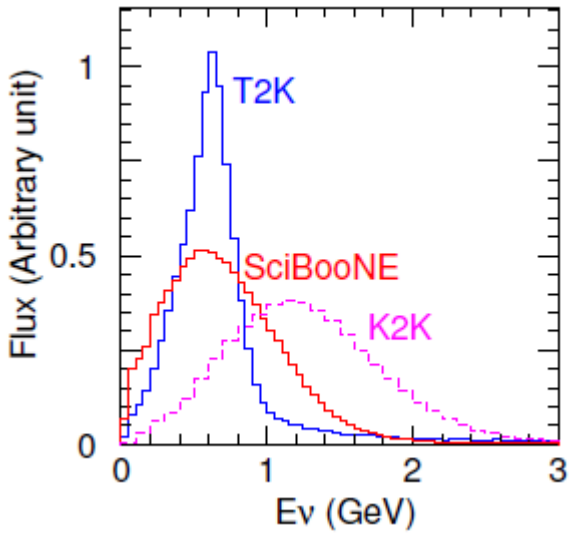
- Pion production reaction

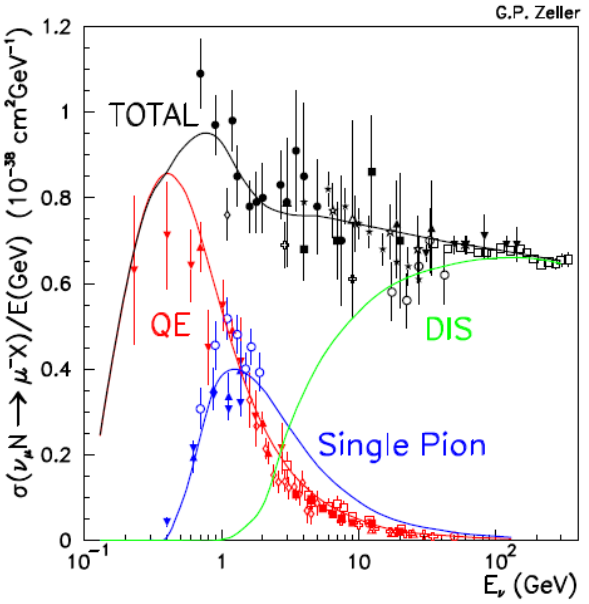
$$\nu_\mu +' n' \rightarrow \mu^- + \pi^+ + p \qquad \text{CCpi+}$$

$$\nu +' N' \rightarrow \nu + \pi^0 + N \qquad \text{NCpi0}$$

$$\nu_\mu + A_{gr} \rightarrow \nu_\mu + \pi^0 + A_{gr} \qquad \text{Coherent pion production}$$

pi0: electron like event for disappearance exp.





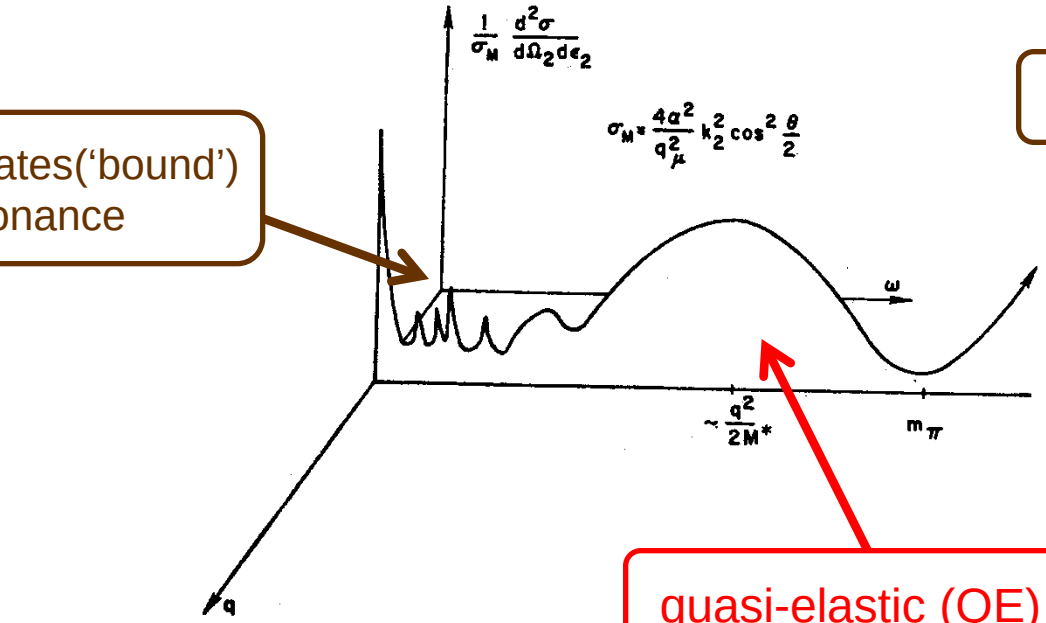
Understanding of neutrino-nucleus reaction around a few GeV region is crucial

Int. workshop on ‘neutrino-nucleus interactions in the few-GeV region’

2001 KEK Sakuda, Morfin, …. 2011 India 7th

lepton-nucleus double differential electron scattering cross section

T. deForest Jr, J. D. Walecka Adv. in Phys. (1964)



excited states('bound')
Giant resonance

Delta_33, pion production

energy transfer

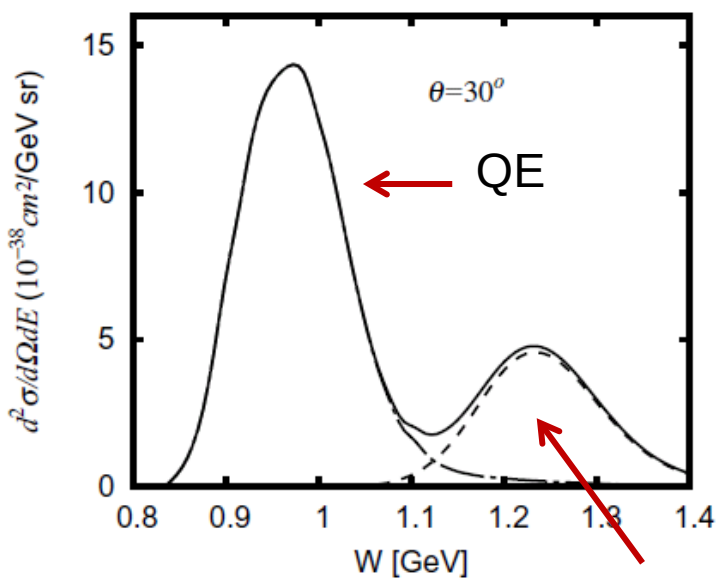
quasi-elastic (QE)

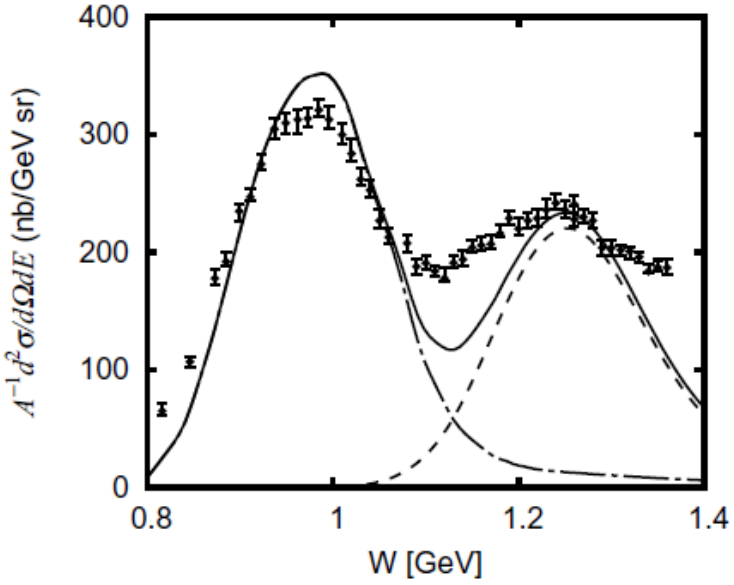
spatial momentum transfer

$$\omega = E_e - E'_e, \vec{q} = \vec{p}_e - \vec{p}'_e$$

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

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





Pion production

Sealock et al.(89)

Inclusive neutrino-nucleus reaction in QE region

Large M_A in nuclei?

$$g_A(Q^2) = g_A/(1 + Q^2/M_A^2)^2$$

$$M_A = 1.2 \pm 0.12 GeV(K2K'06), 1.23 \pm 0.2 GeV(BiniBooNE'08)$$

一方

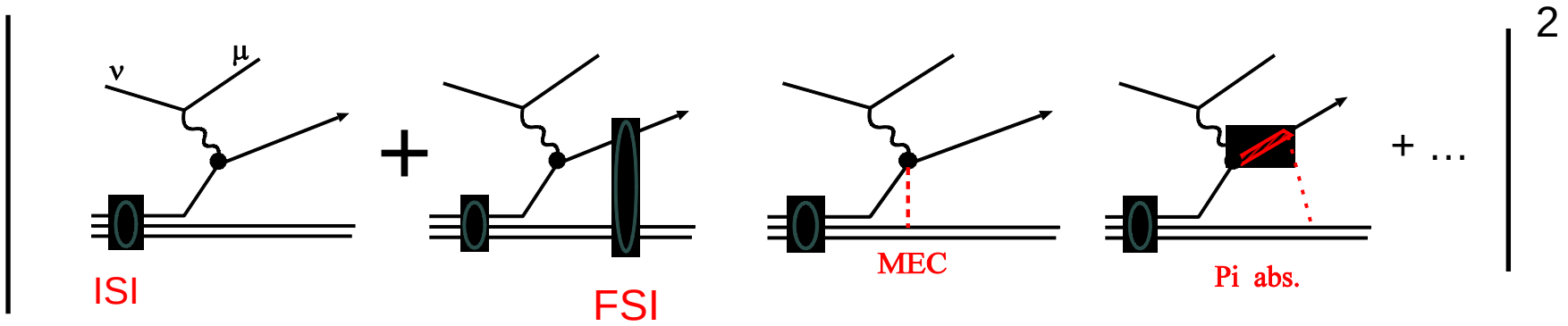
$$\begin{aligned} M_A &= 1.026 \pm 0.021(\nu - N) \\ &= 1.069 \pm 0.016((e, e'\pi) + \chi PT) \end{aligned}$$

$$\nu_\mu + A \rightarrow \mu^- + X$$

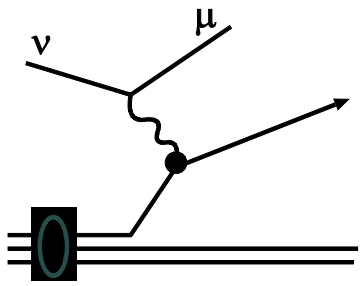
$$\frac{d\sigma}{dE_l d\Omega_l} = \frac{p_l}{p_\nu}\frac{G_F^2 V_{ud}^2}{8\pi^2} L_{\mu\nu} W^{\mu\nu}$$

$$W^{\mu\nu} = \sum_{\bar{i},f} (2\pi)^3 \delta^4(p + p_\nu - p' - p_l) < f|J^\nu|i >^* < f|J^\mu|i >$$

‘QE’



Theoretical approaches



- Relativistic Fermi gas: most of the simulation codes

- ‘Impulse approximation’ using spectral function (P(p)) + FSI Benhar et al.(05)

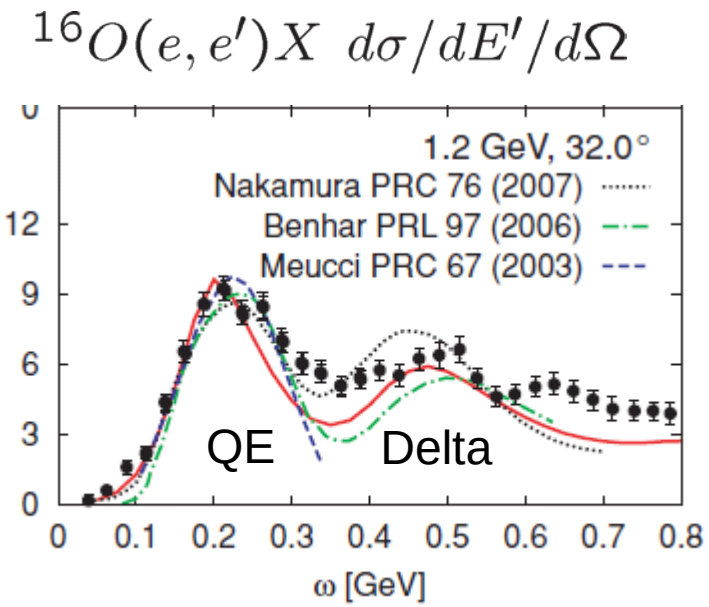
ground state correlation

$$d\sigma_{\nu A} = \int dp P(\vec{P}, E) d\sigma_{\nu N} \qquad P(\vec{P}, E) = \sum_n | < n|a_p|0 > |^2 \delta(E - E_n + E_0)$$

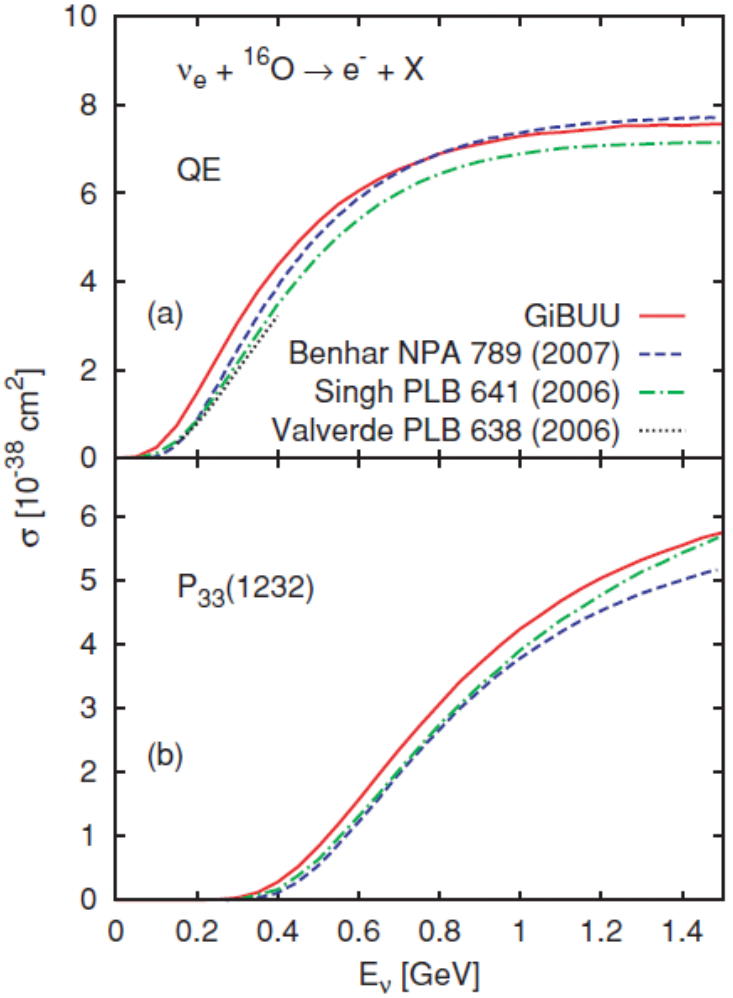
FSI using ‘Glauber’

- Giessen-Boltzmann-Uehling-Uhlenbeck(GiBUU) transport eq. Leitner et al.(09)

Stability of theoretical results



Leitner et al. PRC79 (09)

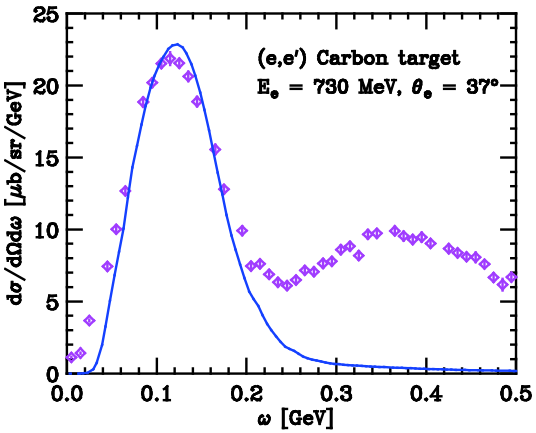


Test theoretical approaches with electron scattering and predict neutrino reaction

Inclusive double differential cross section: electron vs neutrino

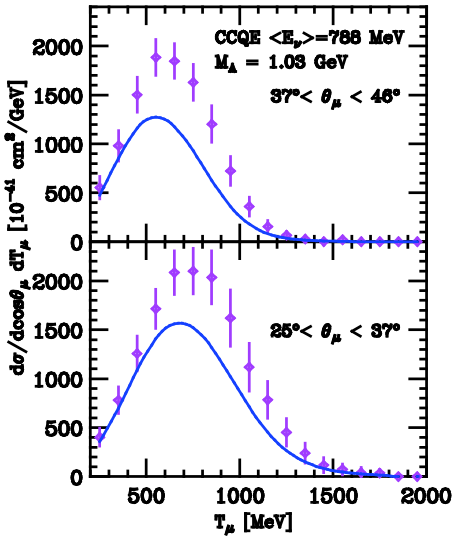
IA+Spectral Func+ FSI O.Benhar,P. Coletti, D. Meloni PRL105(10)

$^{12}C(e,e')X \quad d\sigma/dE'/d\Omega$



O'Connell et al. PRC35(1987)

$^{12}C(\nu_\mu,\mu^-)X \quad d\sigma/d\cos\theta/dT_\mu$



A. A. Aguilar-Arevalo et al. PRD81(10)

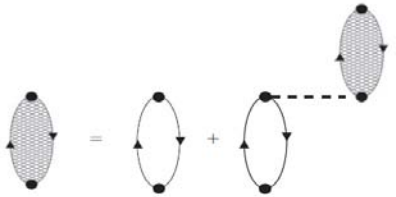
First double diff. cross data

IA+FSI (e,e')QE :OK but under estimate neutrino-reaction

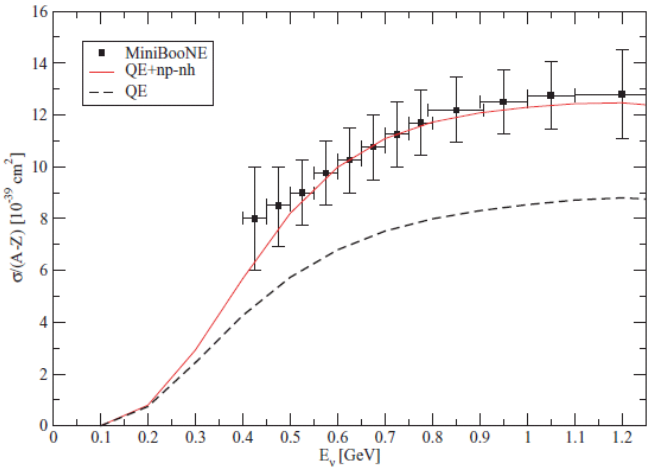
Possible Solution: RPA sum of ph-Δ h polarization: long range correlation

Nieves et al.(04,11),Martini et al.(09,10)

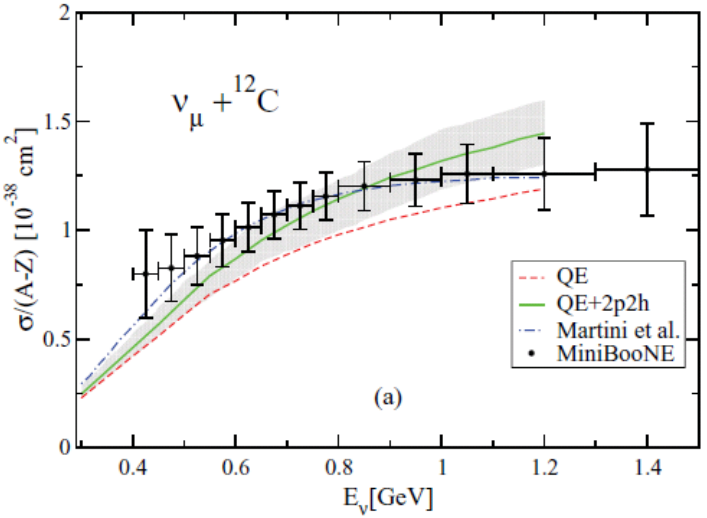
$$W_s^{\mu\sigma} = -\Theta(q^0)\left(\frac{2\sqrt{2}}{g}\right)^2 \int \frac{d^3r}{2\pi} \mathrm{Im}\left[\Pi_W^{\mu\sigma} + \Pi_W^{\sigma\mu}\right](q;\rho)$$



Integrated 'QE' cross section



Martini et al.



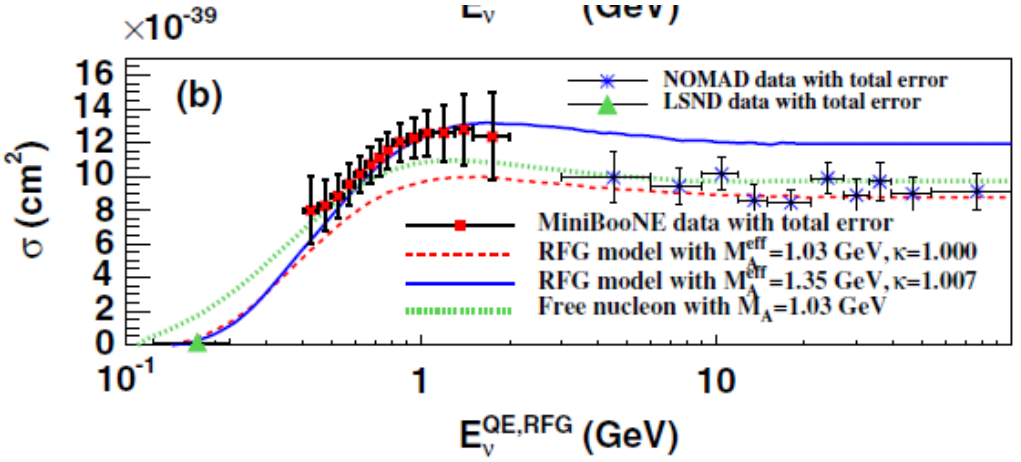
Nieves et al.

QE: data ←→ theory

Solved?

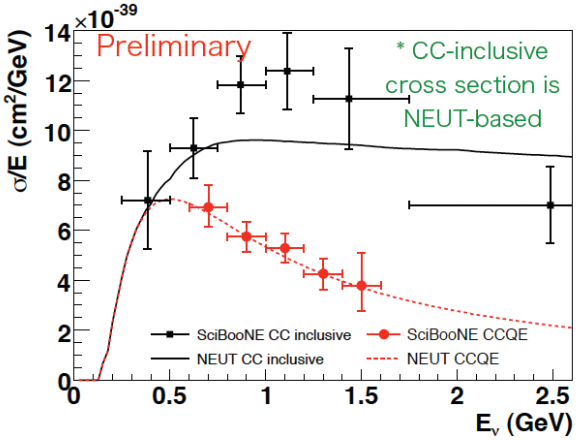
electron scattering OK?, double differential cross section?

NOMAD high energy data?



Inclusive CC cross section

(SciBooNE Nakajima NUINT11)



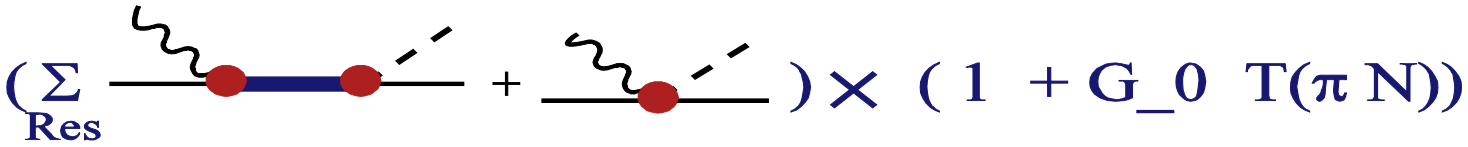
Pion production reaction

- Model of neutrino-nucleon reaction in N*, Detla resonance region
- Neutrino-nucleus reaction

  inclusive reaction

  coherent pion production

Model of neutrino-nucleon reaction in the nucleon resonance region



Isobar model

Rein Sehgal AP133(80)
Alvarez-Ruso et al. PRC57(98)
Paschos et al. PRD65(02)
Lalakulich et al. PRD71(05), PRD74(06)

+ non-res. (chiral Lagrangian)

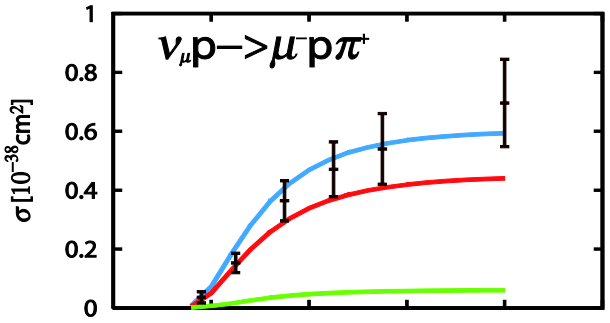
Hernandez et al. PRD76 (07),PRD81(10)
Lalakulich et al. arXiv 1007.0925

+ non-res + unitarity

SL PRC67(03),PRC72(05)

- E_nu < 1GeV, Delta(33) dominance
- Detail of mechanism should be tested by extensive data of pion electroproduction

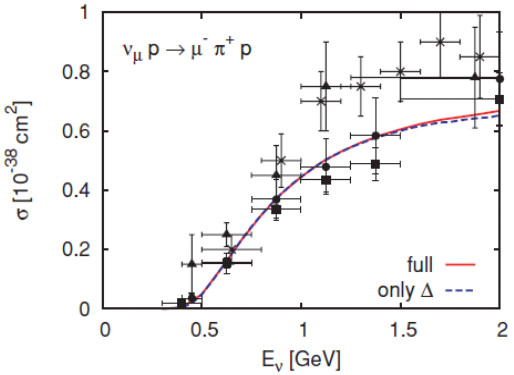
SL PRC67(03)



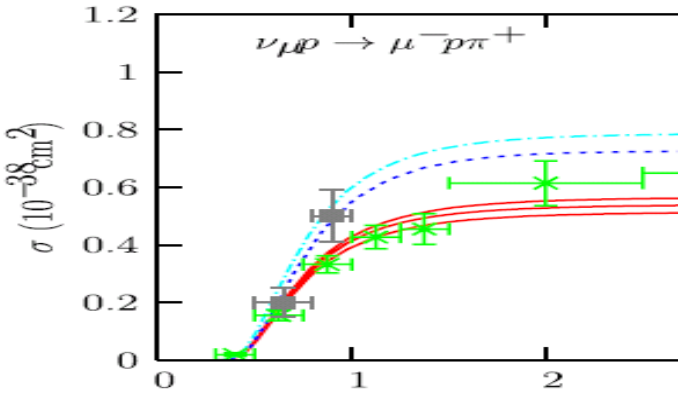
full

Delta_33

Leitner et al. RPC79(09)



Hernandez et al PRD76(07)

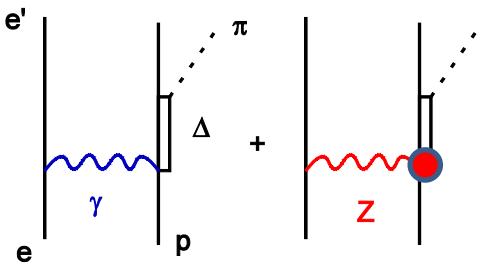


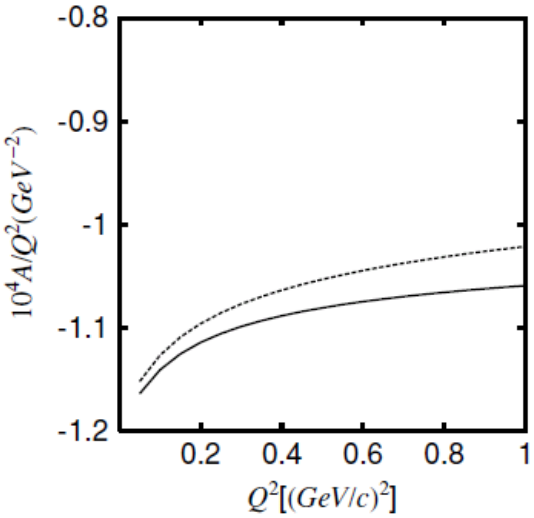
Models explain integrated cross section (mainly delta)
need more data on proton and deuteron on resonance region

Information on g_A(ND) (Q^2) from PV electron scattering (Matsui et al. 05)

Parity violating asymmetry

$$A = \frac{d\sigma(h_e = +1) - d\sigma(h_e = -1)}{d\sigma(h_e = +1) + d\sigma(h_e = -1)}$$





Kitagaki et al.

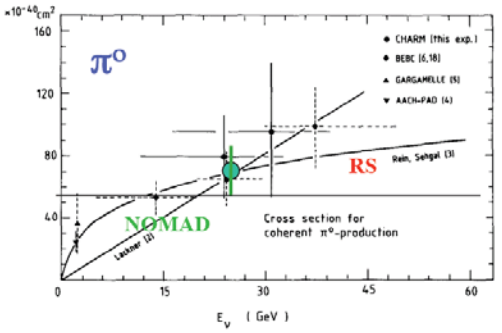
SL

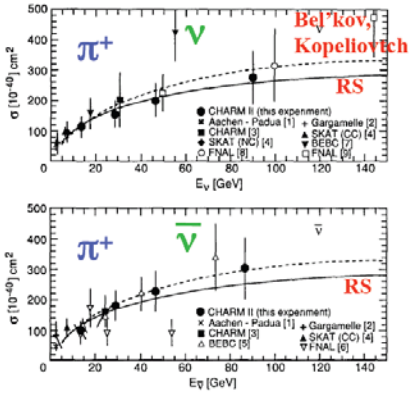
W=1.232, theta=110 deg

Coherent pion production

Camilleri Neutrino 2010

$$\nu_\mu + A_{gr} \rightarrow \mu^- + \pi^+ + A_{gr}$$
$$\nu_\mu + A_{gr} \rightarrow \nu_\mu + \pi^0 + A_{gr}$$





Puzzle: Rein-Sehgal (83)model based on PCAC works well for higher energy region but not 1~2 GeV region

K2K,SciBooNE upper limit on CCpi+ << RS
MiniBooNE evidence for NCpi0

Theoretical point of view

final two-body hadron system
spin-isospin non-flip transition amplitude contributes ($0^+ \rightarrow 0^+$)

→theoretical models of pion production mechanism, medium effects can be tested

PCAC approach

$$\frac{d\sigma}{dxdydt}|_{Q^2=0} = \frac{G^2 M E}{\pi^2}\frac{f_\pi^2}{2}(1-y)\frac{d\sigma(\pi^0 A \to \pi^0 A)}{dt}$$ RS (83)

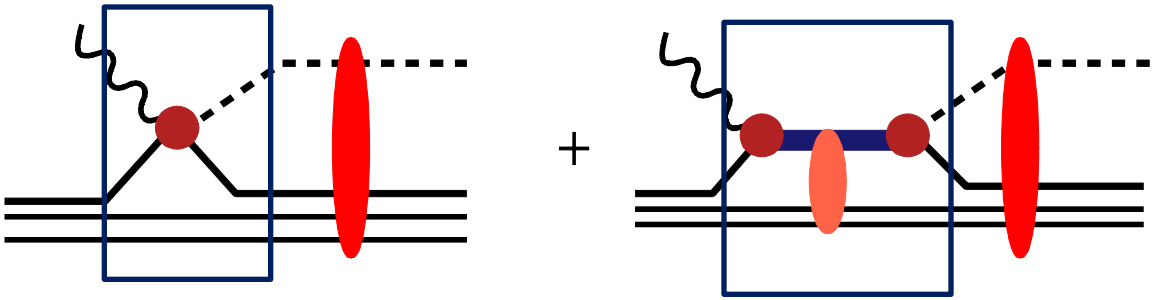
PACA + forward, Q^2 ~ 0 approximation + simple pi-nuclear cross section

$$q_\lambda < \beta|A^\lambda|\alpha > \; = \; \sqrt{4q_0}\frac{M_N g_A}{g_r}[1 - \frac{q^2}{M_\pi^2 - q^2}]T(\pi^+ + \alpha \to \beta)$$ Adler 64

$$\frac{d\sigma(\pi^0 A \to \pi^0 A)}{dt} = A^2 F_{abs}^2 \frac{d\sigma(\pi^0 N \to \pi^0 N)}{dt}$$

Pion-nuclear dynamics must be examined carefully
(pion rescattering, absorption, propagation in nuclei, non-forward scattering)

Our model of coherent pion production (Nakamura et al.)



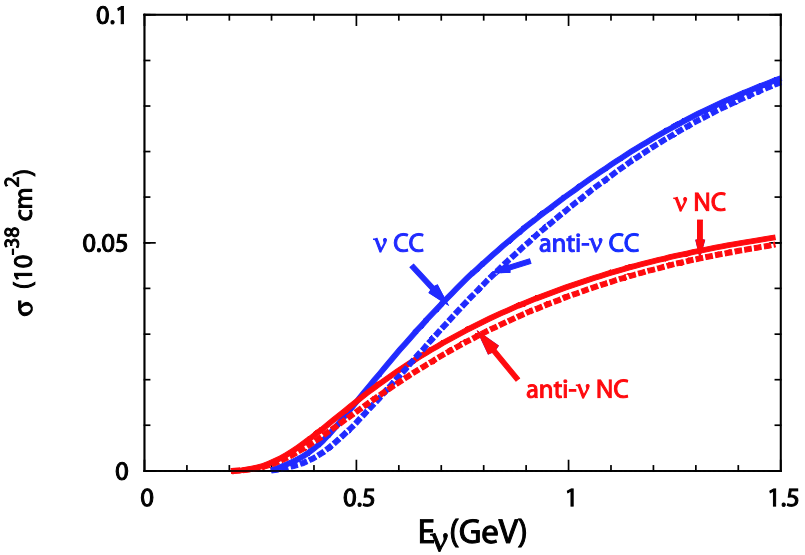
Non-res res

medium modification of pion production mechanism

$$G^{-1}_{\Delta h} = W - (m^0_\Delta + \frac{p^2_\Delta}{2\mu_\Delta} + \Sigma(W) + \Sigma_{Pauli} + \Sigma_{sp} + V_\Delta + e_h)$$

final state interaction of pion: optical potential within the same model as weak pion production

- use t-matrix from dynamical model of piN and weak pion production for both transition operator and pi-Nucleus optical potential
- check : pion-nucleus(elastic, total, inelastic), coherent gamma-pi0



CCpi+ $\sigma_{K2K} < 7.7 \times 10^{-40} cm^2$

NCpi0 $\sigma_{MiniBooNE} = 7.7 \pm 1.6 \pm 3.6 \times 10^{-40} cm^2$

Flux averaged cross section

	Alvarez-Ruso et al.(07)	Hernandez et. al(10)	Nakamura et al.(10)	Berger Sehgal (09)
CCpi+(K2K)	10.8/5.7	6.1+/-1.3	6.3	0.62x12
NCpi0(MiniBooNE)	5.0/2.6	2.6+/-0.5	2.8	

- agreement among recent theoretical results
- pi+/pi0 ration ~ 2 due to Delta_33 dominance

($\sigma(CC\pi^+)/\sigma(NC\pi^0) = 0.14^{+0.30}_{-0.28}$ Kurimoto et al. PRD81(10))

Summary

Neutrino-nucleus reaction around ~GeV has been studied various theoretical approaches

QE
- model describe well (e,e')
- missing strength could be related to long range correlation

Coherent pion production
- agreement of integrated cross sections among models
- but details are different.

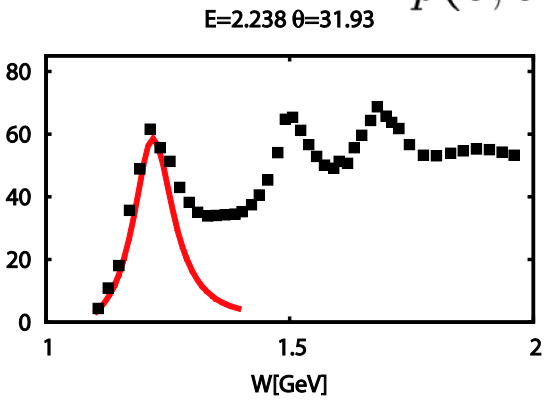
Need for further study,
- crucial to monitor theory by using electron induced reactions as far as possible

meson production reactions
- need to be extended beyond delta including two pion production

summary

beyond Delta_33 (N*,Delta region) and DIS

$p(e,e')X$



Kamano, Nakamura (Excited Baryon Analysis Center at Jlab)

Kumano, Saito, Hirai

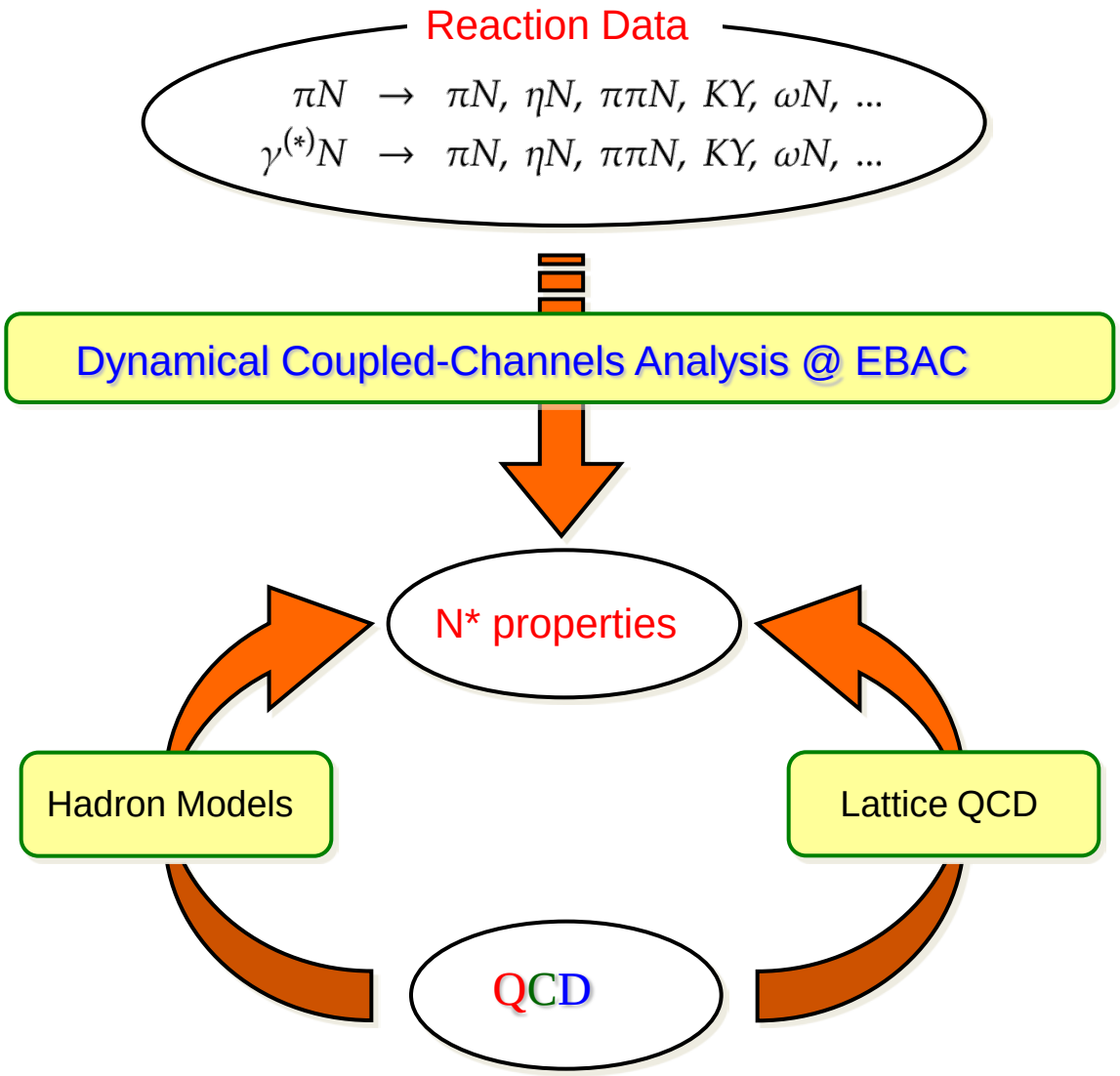
low energy neutrino-nucleus reaction and supernova $d^2\sigma/d\Omega dE[nb/(srGeV)]$

Sumiyoshi, Nasu, Nakamura, Horiuchi, Suzuki

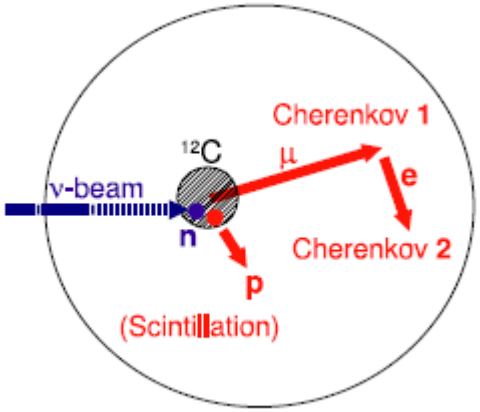
close contact with data analysis

NEUT, … Hayato, Sakuda

Electroweak meson production above Delta (W<2GeV)
coupled-channel approach of Excited Baryon Analysis Center



MiniBooNE



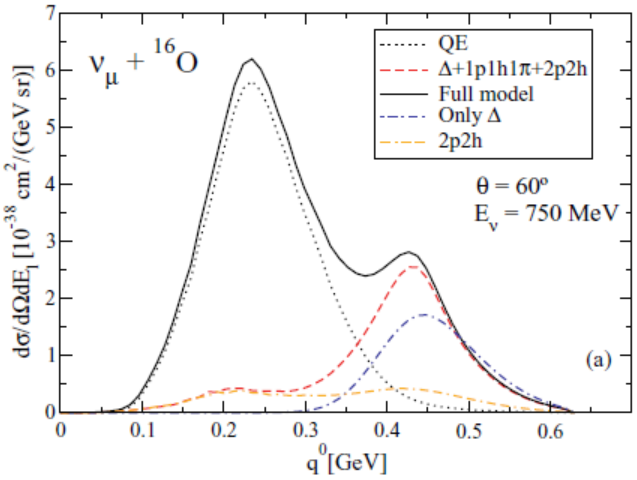
QE

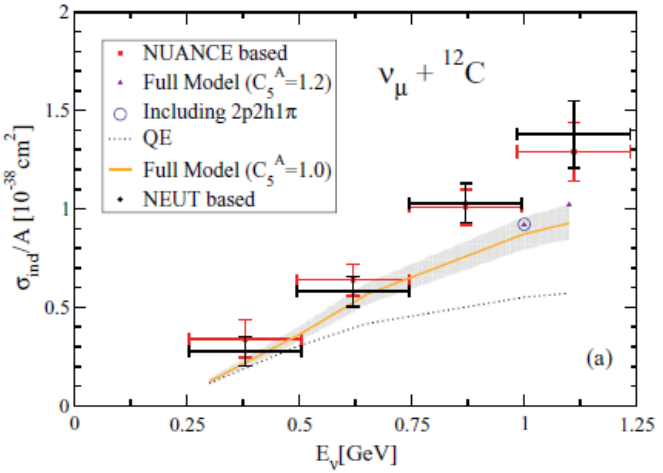
$$1:\ \nu_\mu + n \rightarrow \mu^- + p$$
$$2:\ \hookrightarrow e^- + \bar{\nu}_e + \nu_\mu.$$

CC1pi+

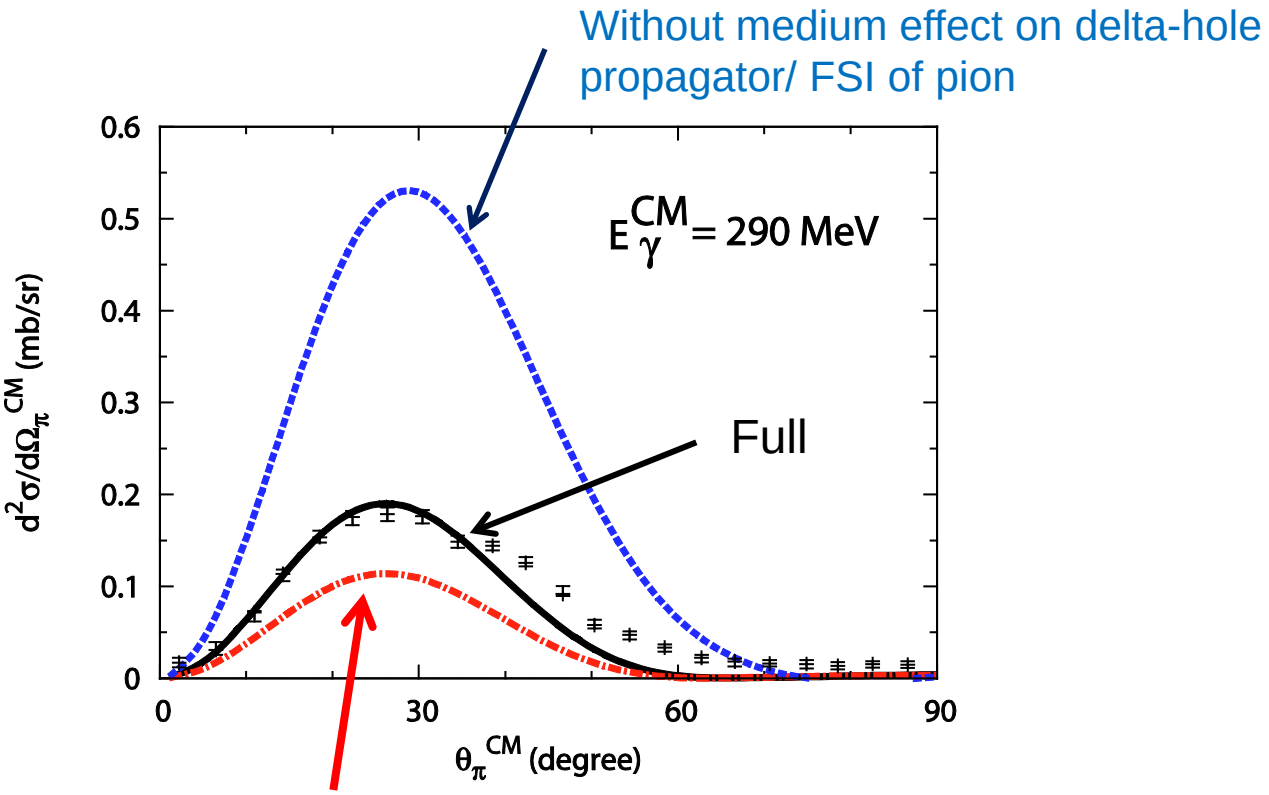
$$1:\ \nu_\mu + p(n) \rightarrow \mu^- + p(n) + \pi^+$$
$$\hookrightarrow \mu^+ + \nu_\mu$$
$$2:\ \hookrightarrow e^- + \bar{\nu}_e + \nu_\mu$$
$$3:\ \hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu.$$

Nieves et al.



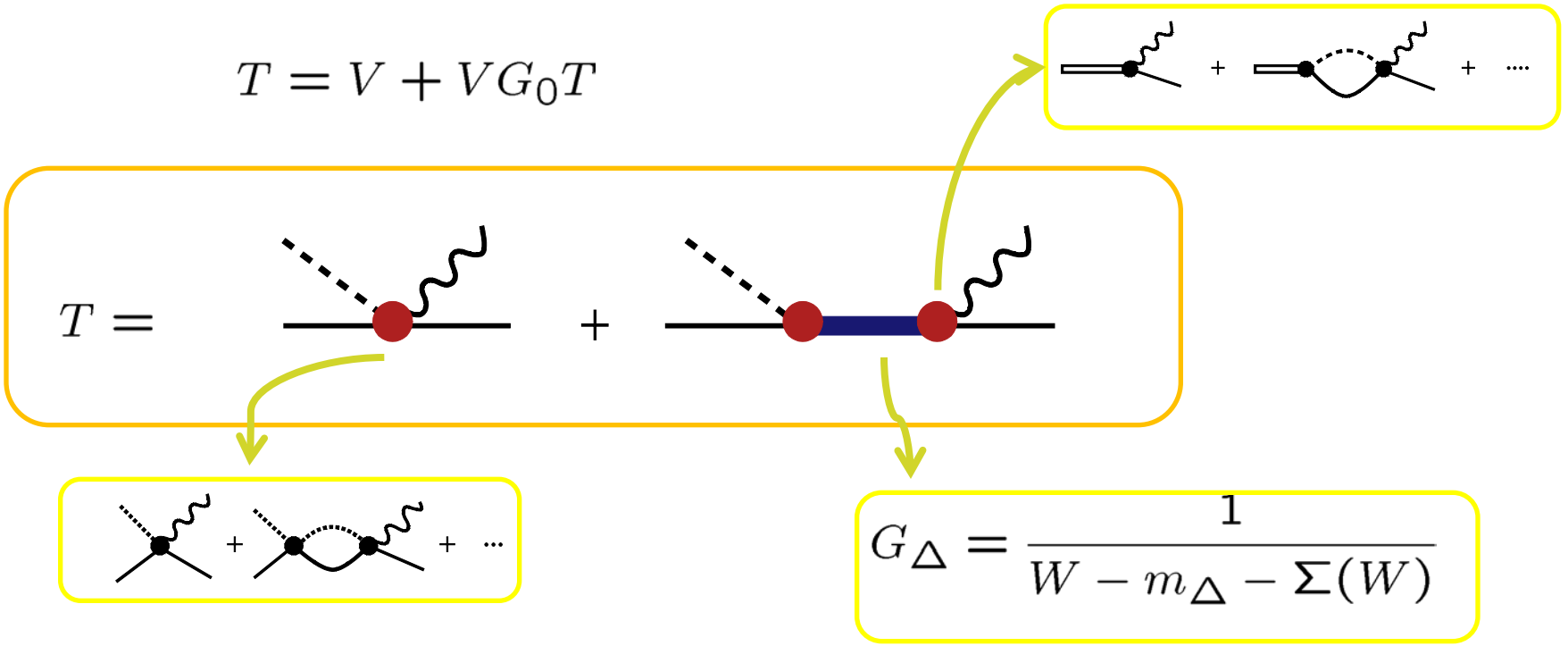


prediction of coherent pion photoproduction $^{12}C(\gamma,\pi^0)^{12}C$



Solve Lippman-Schwinger Eq.

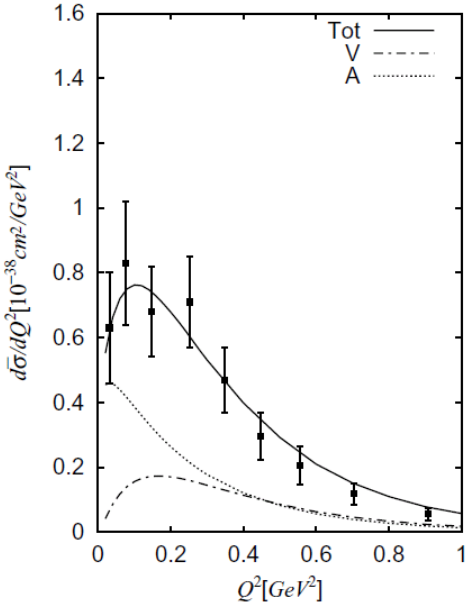
$$T = V + VG_0T$$



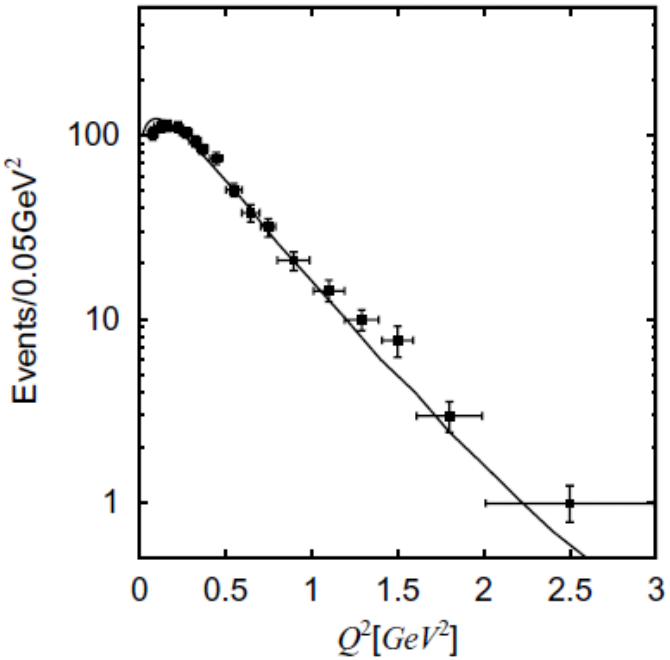
Effects of rescattering , unitarity

renormalize ND coupling
soft component of ND transition form factor

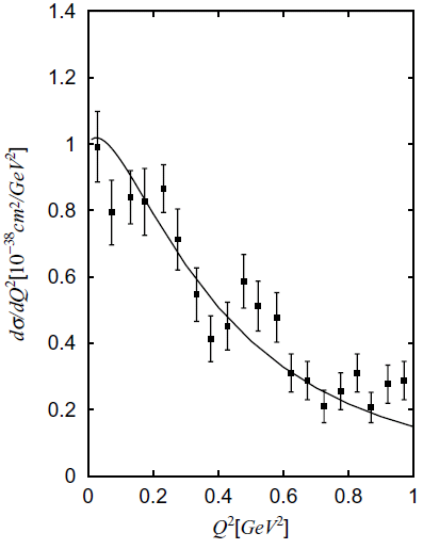
better to compare $Im(\mathcal{E}_{1+}^{3/2})|_{W=1.232}$ than C_5^A



$0.5 < E_\nu < 6GeV$ Barish et al.(79) ANL



Kitagaki et al. (90) BNL



$p(\nu_\mu, \mu^- \pi^+)p$

Jones et al. (89) CERN

$E_\nu = 15GeV$

Muon energy distribution $\nu_\mu + {}^{12}C \rightarrow \mu^- + X(E_\nu = 1\text{GeV})$