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Unified approach for nucleon knock-out and coherent and incoherent pion production in neutrino interactions with nuclei

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Outline

- Introduction
  - relevant channels for accelerator exp.
  - link with ν oscillation physics
  - why nuclear physics is important?

- Our model: nuclear response functions

- Comparison with other microscopical models and with commonly used Monte Carlo

- Comparison with experimental results
  - pion production, quasielastic (MiniBooNE)
  - importance of multi-nucleon emission

In collaboration with:

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IPN Lyon

Phys. Rev. C 80 065501 (2009)
Phys. Rev. C 81 045502 (2010)

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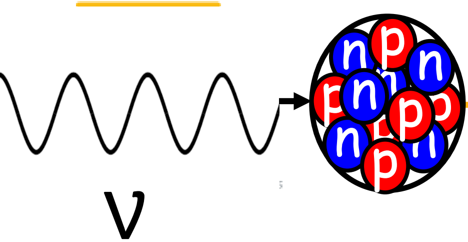
Neutrino-nucleus interaction
and
ν oscillation physics

Neutrino - nucleus interaction @ $E_\nu \sim \mathcal{O}$ (1 GeV)

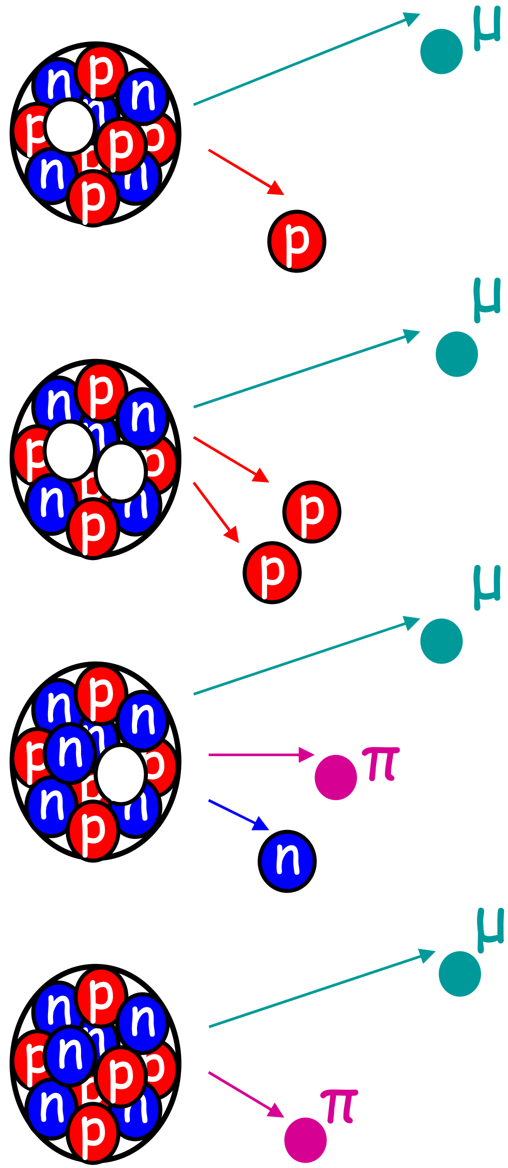


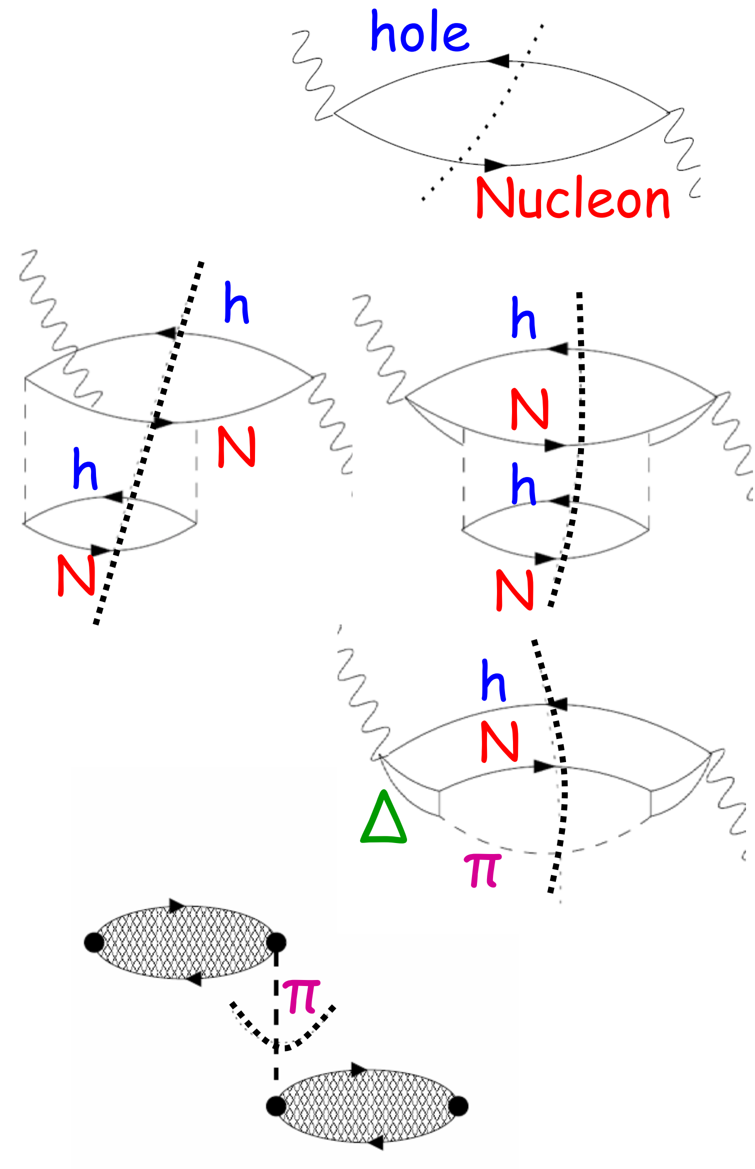
Quasielastic (QE)

Two Nucleons knock-out (2p-2h)

Incoherent π production

Coherent π production

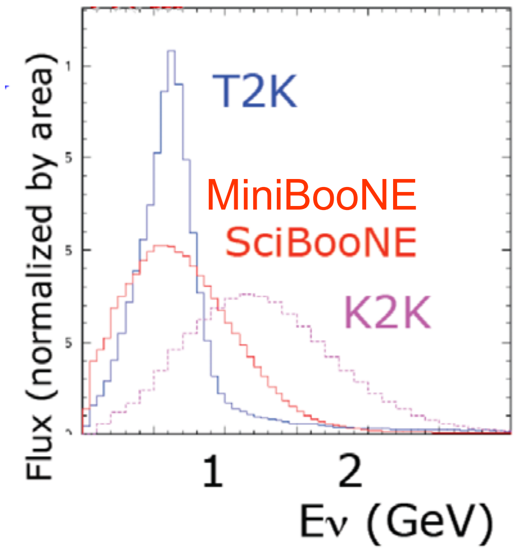




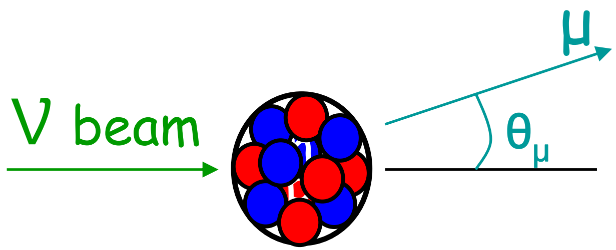
ν_μ Disappearance - 2-3 sector - QE channel

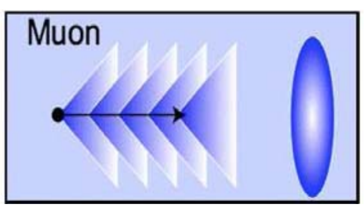
The measurement of θ_{23} and Δm^2_{23} is based on comparing the initial energy spectrum of ν_μ measured at a near detector to the final spectrum measured at a far detector

The ability to reconstruct neutrino energy, which is not known for broad fluxes, is crucial



E_ν from (ν_μ n $\rightarrow$ μ^- p) CCQE





Cherenkov:
μ,π detected
n,p not detected

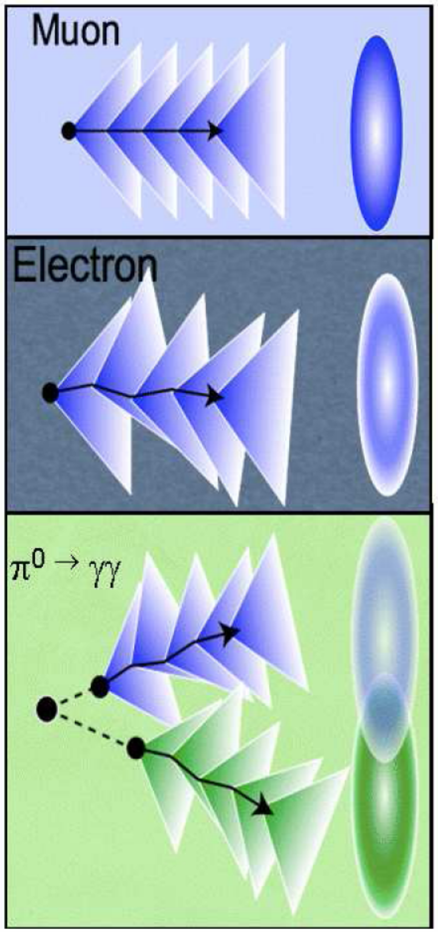
E_μ and θ_μ measured

E_ν reconstructed with two-body kinematics

but:

- This is exact only for free neutrons
- Detector are composed of nuclei
- E_ν is smeared due to momentum distribution of n
- Events not CCQE but look identical to them:
- Two nucleons knock-out
- CC1π production if π is not detected

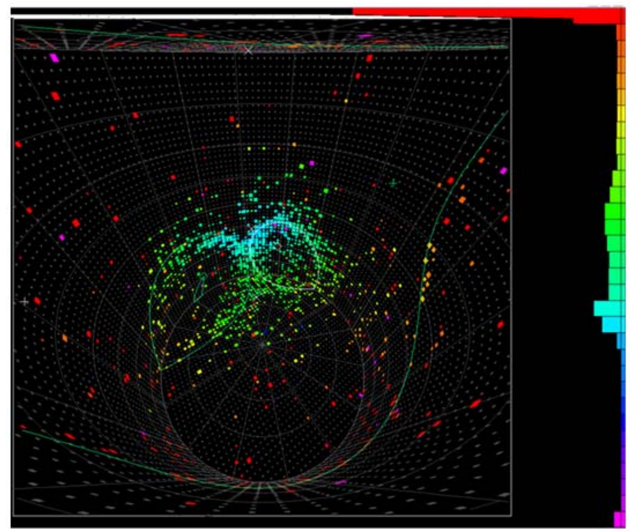
ν_e Appearance - 1-3 sector - NC π^0 production



High sensitivity searches for $\nu_\mu \to \nu_e$ appearance associated with θ_{13} and CP violation

NC π^0 most important background

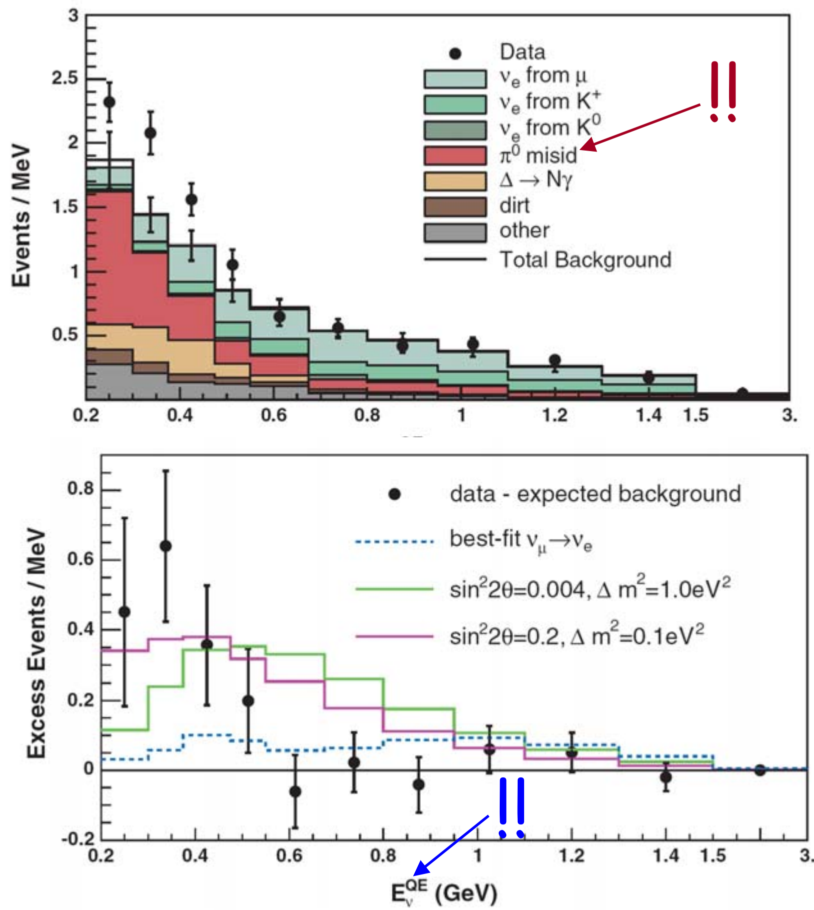
NC π^0 events can mimic CCQE ν_e signal events when 1 of the 2 γ associated with $\pi^0 \to \gamma\gamma$ decay is not detected



24/02/2010 First T2K event seen is Super-Kamiokande

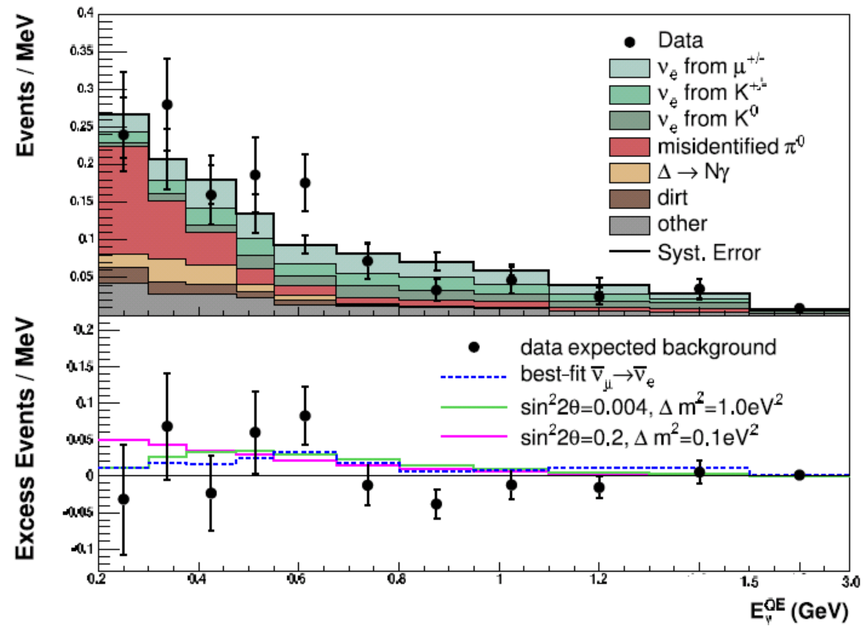
ν_e Appearance

$\bar{\nu}_e$ Appearence



MiniBooNE, PRL 102, 101802 (2009)

« MiniBooNE observes an unexplained excess of electronlike events in the energy region 200<E_ν^{QE}<475 MeV. These events are consistent with being either electron events produced by CC scattering or photon events produced by NC scattering. »



MiniBooNE, PRL 103, 111801 (2009)

« MiniBooNE observes no significant excess of $\bar{\nu}_e$ events in the low energy region 200<E_ν^{QE}<475 MeV. The absence of an excess at low energy in antineutrino mode should help distinguish between several hypotheses suggested as explanation for the low energy excess observed in neutrino mode. »

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Our model:
Nuclear response functions

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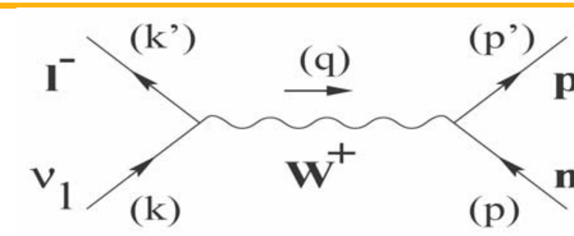
Neutrino-nucleus cross-section



$$\mathcal{L}_W = \frac{G_F}{\sqrt{2}} \cos(\theta_C) l_\mu h^\mu$$

lepton

$$\langle k', s' | l_\mu | k, s \rangle = e^{-iqx} \bar{u}(k', s') \, [\gamma_\mu (1 - \gamma_5)] \, u(k, s)$$

$$\langle p', s' | h^\mu | p, s \rangle \;=\; e^{iqx} \bar{u}(p', s') \, [F_1(t) \gamma^\mu \;+\; F_2(t) \sigma^{\mu\nu} \frac{i q_\nu}{2 M_N}$$

hadron

$$+ G_A(t) \gamma^\mu \gamma_5 \;+\; G_P(t) \gamma_5 \frac{q^\mu}{2 M_N}] \; u(p, s)$$

$$t = q^2 = \omega^2 - \boldsymbol{q}^2$$

$$G_A(t) = g_A \, [1 - \frac{t}{M_A^2}]^{-2}$$

After non-relativistic reduction:

$$\frac{\partial^2 \sigma}{\partial \Omega \, \partial k'} = \frac{G_F^2 \, \cos^2 \theta_c \, (\boldsymbol{k}')^2}{2 \, \pi^2} \cos^2 \frac{\theta}{2} \Bigg[G_E^2 \, (\frac{q_\mu^2}{\boldsymbol{q}^2})^2 \, R_\tau^{NN}$$

charge nuclear response

$$+ \; G_A^2 \frac{(M_\Delta - M_N)^2}{2 \, \boldsymbol{q}^2} R_{\sigma\tau(L)}^{N\Delta} + G_A^2 \frac{(M_\Delta - M_N)^2}{\boldsymbol{q}^2} R_{\sigma\tau(L)}^{\Delta\Delta}$$

isospin spin-longitudinal

$$+ \; \left(G_M^2 \frac{\omega^2}{\boldsymbol{q}^2} + G_A^2 \right) \left(- \frac{q_\mu^2}{\boldsymbol{q}^2} + 2 \tan^2 \frac{\theta}{2} \right) \left(R_{\sigma\tau(T)}^{NN} + 2 R_{\sigma\tau(T)}^{N\Delta} + R_{\sigma\tau(T)}^{\Delta\Delta} \right)$$

isospin spin-transverse

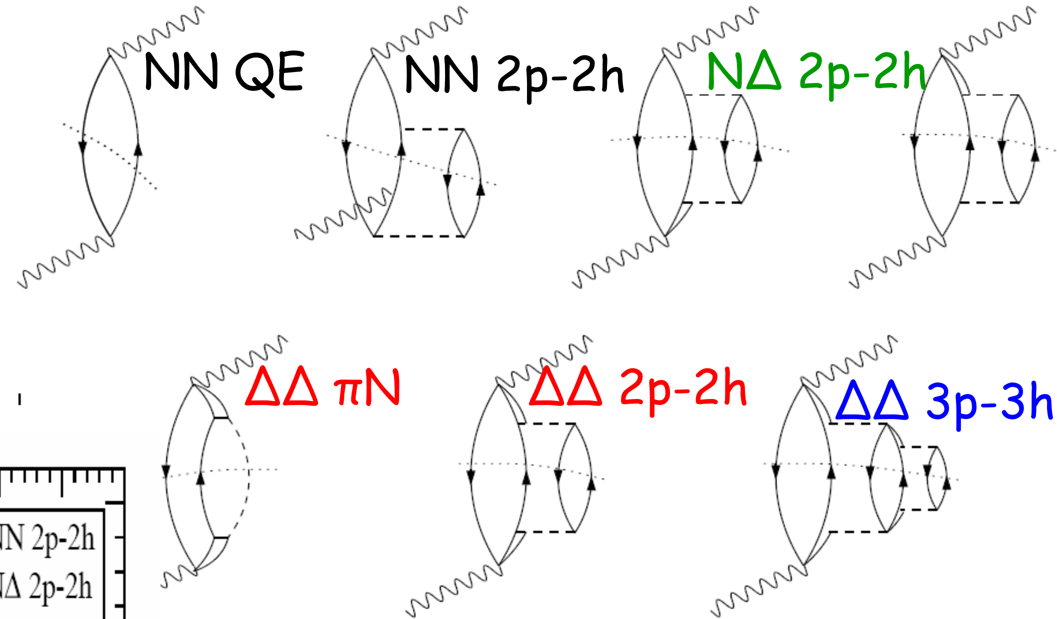
$$\left\{ \begin{array}{ll} + & (\nu) \\ - & (\bar{\nu}) \end{array} \right. \; \pm \; 2 \, G_A \, G_M \frac{k + k'}{M_N} \tan^2 \frac{\theta}{2} \left(R_{\sigma\tau(T)}^{NN} + 2 R_{\sigma\tau(T)}^{N\Delta} + R_{\sigma\tau(T)}^{\Delta\Delta} \right) \Bigg]$$

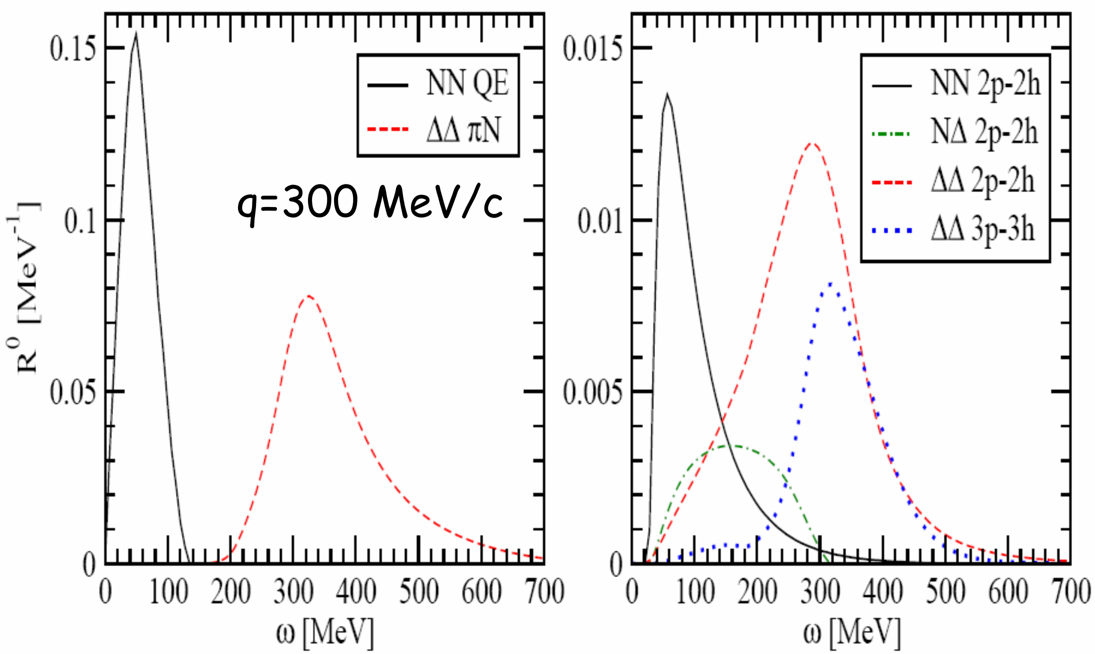
interference V-A

Bare nuclear responses

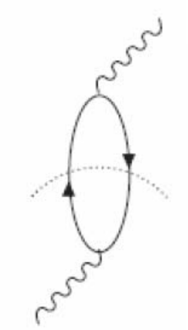
Several partial components
(final state channels)

- QE (1 nucleon knock-out)
- Pion production
- Multinucleon emission





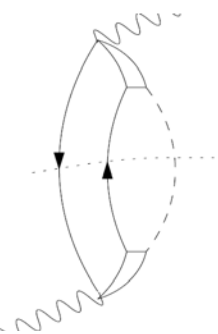
Bare polarization propagators



Nucleon-hole

$$\Pi^0(\vec{q},\omega) = g\int \frac{\mathrm{d}\vec{k}}{(2\pi)^3}\left[\frac{\theta(|\vec{k}+\vec{q}|-k_F)\theta(k_F-k)}{\omega-(\omega_{\vec{k}+\vec{q}}-\omega_{\vec{k}})+i\eta}-\frac{\theta(k_F-|\vec{k}+\vec{q}|)\theta(k-k_F)}{\omega+(\omega_{\vec{k}}-\omega_{\vec{k}+\vec{q}})-i\eta}\right]$$

$\longrightarrow$ Quasielastic



Delta-hole

$$\Pi_{\Delta-h}(q) = \frac{32\tilde{M}_\Delta}{9}\int \frac{d^3k}{(2\pi)^3}\theta(k_F-k)\left[\frac{1}{s-\tilde{M}_\Delta^2+i\tilde{M}_\Delta\Gamma_\Delta}-\frac{1}{u-\tilde{M}_\Delta^2}\right]$$

$\longrightarrow$ Pion production

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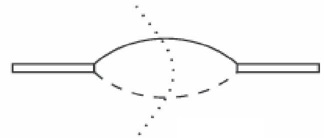
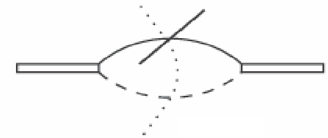
Delta in the medium

Mass

$$\tilde{M}_\Delta = M_\Delta + 40(MeV)\frac{\rho}{\rho_0}$$

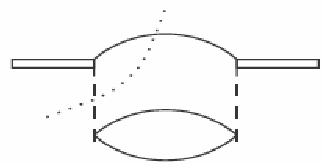


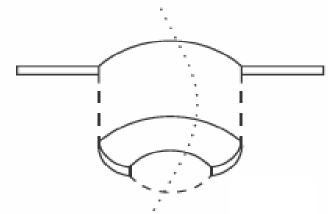
$\Delta \to \pi$ N



Pauli correction (F_P)

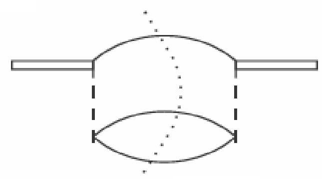
Width



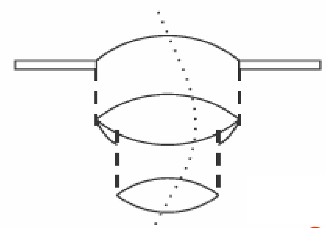


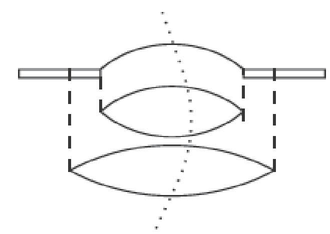
Pion distortion (C_Q)

$$\widetilde{\Gamma_\Delta} = \Gamma_\Delta \; F_P - 2\mathrm{Im}(\Sigma_\Delta)$$



2p-2h





3p-3h

Self energy

$$\mathrm{Im}(\Sigma_\Delta(\omega)) = -\left[C_Q\left(\frac{\rho}{\rho_0}\right)^\alpha + C_{2p2h}\left(\frac{\rho}{\rho_0}\right)^\beta + C_{3p3h}\left(\frac{\rho}{\rho_0}\right)^\gamma\right]$$

E. Oset and L. L. Salcedo, Nucl. Phys. A 468, 631 (1987)

Other 2p -2h contributions

Not reducible to a modification of the Delta width

Initial state nucleon correlation

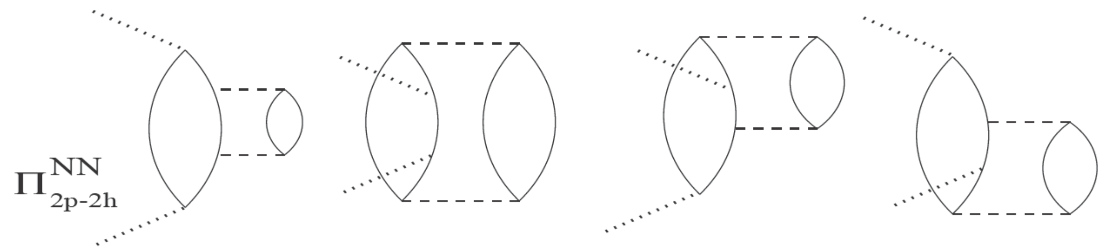
Mostly n-p pairs correlated by tensor interaction

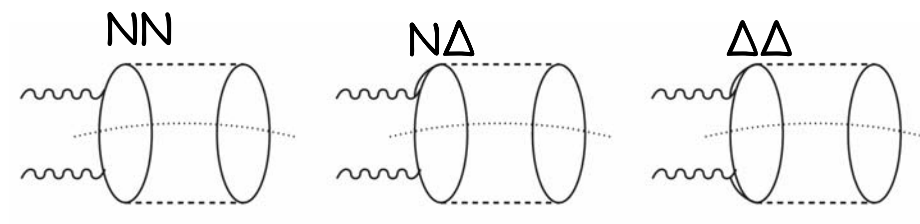
2p-2h π absorption at threshold

Shimizu Faessler, NPA 333,495 (1980)

extrapolation

Delorme, Guichon, 2 proceedings (1989)





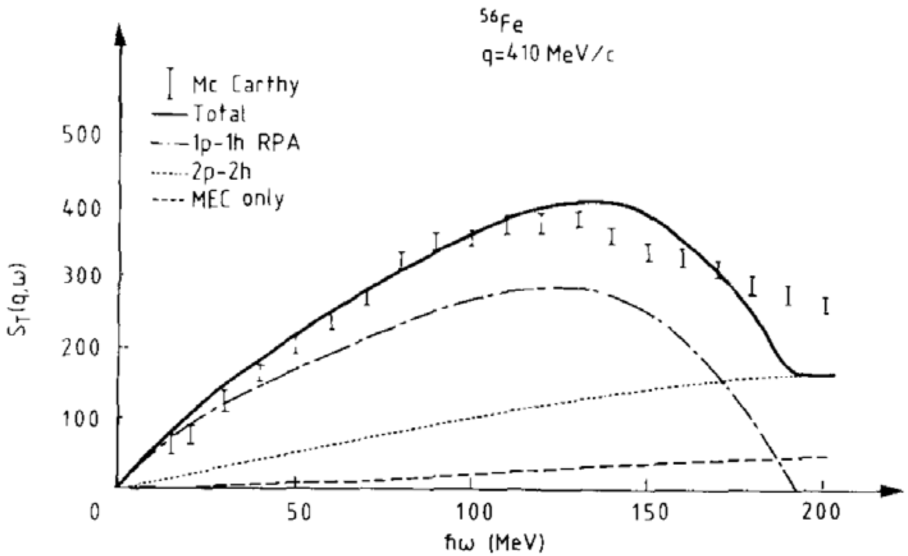
$$Im(\Pi^0_{NN}) = 4\pi\rho^2 \frac{(2M_N+m_\pi)^2}{(2M_N+\omega)^2} C_1\,\Phi_1(\omega)\left[\frac{1}{\omega^2}\right]$$

$$Im(\Pi^0_{N\Delta}) = -4\pi\rho^2 \frac{(2M_N+m_\pi)^2}{(2M_N+\omega)^2} C_2\,\Phi_2(\omega)\,\mathrm{Re}\left[\frac{1}{\omega(\omega-\tilde{M}_\Delta+M_N+i\frac{\Gamma_\Delta}{2})}+\frac{1}{\omega(\omega+\tilde{M}_\Delta-M_N)}\right]$$

$$Im(\Pi^0_{\Delta\Delta}) = -4\pi\rho^2 \frac{(2M_N+m_\pi)^2}{(2M_N+\omega)^2} C_3\,\Phi_3(\omega)\left[\frac{1}{(\omega+\tilde{M}_\Delta-M_N)^2}\right]$$

2p -2h: an alternative treatment

Microscopic evaluation: Alberico, Ericson, Molinari, Ann. Phys. 154, 356 (1984)



Transverse magnetic response of (e,e') ,

but:

^{56}Fe, few q and ω, too large Im C_0

•Parametrization of the responses in terms of $x = \frac{q^2-\omega^2}{2M_N\omega}$ $\longrightarrow$ Extrapolation to cover V region

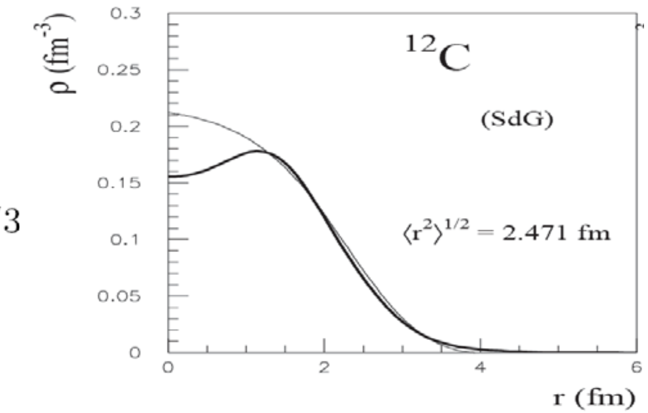
•Absorptive p-wave π-A optical potential $\mathrm{Im}C_0 \simeq 0.18 m_\pi^{-6} \longrightarrow \mathrm{Im}C_0 \simeq 0.11 m_\pi^{-6}$

•Levinger factor $^{56}Fe \rightarrow {}^{12}C$ $\longrightarrow$ Global reduction ≈ 0.5

From nuclear matter to finite nuclei

Semi-classical approximation

$$\Pi^0(\omega, \boldsymbol{q}, \boldsymbol{q}') = \int d\boldsymbol{r}\, e^{-i(\boldsymbol{q}-\boldsymbol{q}')\cdot\boldsymbol{r}}\, \Pi^0\left(\omega, \frac{1}{2}(\boldsymbol{q}+\boldsymbol{q}'), \boldsymbol{r}\right)$$



Local density approximation $\quad k_F(r) = (3/2\,\pi^2\,\rho(r))^{1/3}$

$$\Pi^0\left(\omega, \frac{\boldsymbol{q}+\boldsymbol{q}'}{2}, \boldsymbol{r}\right) = \Pi^0_{k_F(r)}\left(\omega, \frac{\boldsymbol{q}+\boldsymbol{q}'}{2}\right)$$

e.g. Lindhard funct. for QE

$$\Pi^{0(L)}_{k_F(R)}(\omega, q, q') = 2\pi \int du\, P_L(u)\Pi^0_{k_F(R)}(\omega, \frac{\boldsymbol{q}+\boldsymbol{q}'}{2})$$

$$\Pi^{0(L)}(\omega, q, q') = 4\pi \sum_{l_1,l_2}(2l_1+1)(2l_2+1)\begin{pmatrix} l_1 & l_2 & L \\ 0 & 0 & 0 \end{pmatrix}^2 \times \int dR R^2\, j_{l_1}(qR)\, j_{l_1}(q'R)\Pi^{0(l_2)}_{k_F(R)}(\omega, q, q')$$

N, Δ

$$R^{0PP'}_{(k)\,xy}(\omega, q) = -\frac{\mathcal{V}}{\pi}\sum_J \frac{2J+1}{4\pi}\,\mathrm{Im}[\Pi^{0(J)}_{(k)xy_{PP'}}(\omega, q, q)]$$

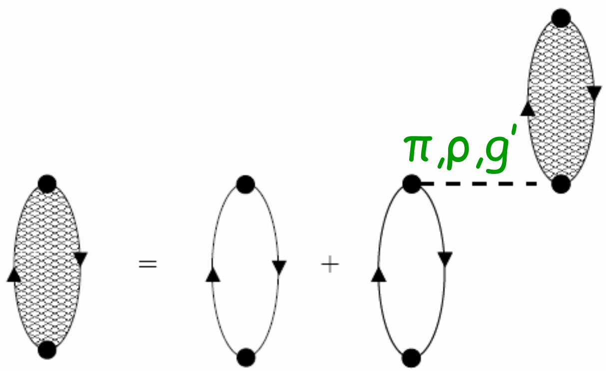
QE,2p-2h,...

Longit., Transv., Charge

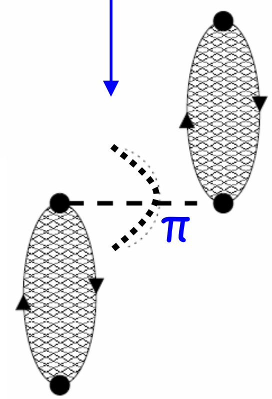
Switching on the interaction

RPA

$$\Pi = \Pi^0 + \Pi^0 V \Pi$$



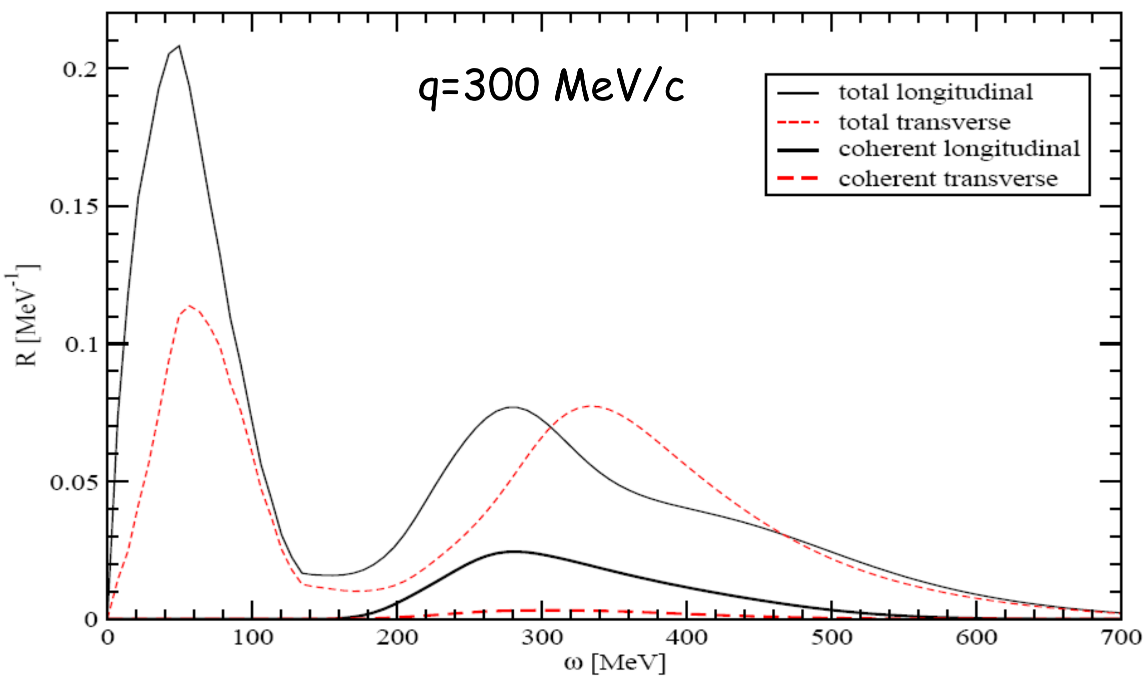
$$\mathrm{Im}\Pi = |\Pi|^2 \,\mathrm{Im}V + |1 + \Pi V|^2 \,\mathrm{Im}\Pi^0$$



coherent π production

$$\Pi^0 = \sum_{k=1}^{N_k} \Pi^0_{(k)}$$

exclusive channels:
QE, 2p-2h, Δ→πN ...



Several partial components treated in self-consistent, coupled and coherent way

Details: p-h effective interaction

$$
\begin{aligned}
V_{NN} &= (f' + V_\pi + V_\rho + V_{g'})\, \boldsymbol{\tau}_1 . \boldsymbol{\tau}_2 \\
V_{N\Delta} &= (V_\pi + V_\rho + V_{g'})\, \boldsymbol{\tau}_1 . \boldsymbol{T}_2^\dagger \\
V_{\Delta N} &= (V_\pi + V_\rho + V_{g'})\, \boldsymbol{T}_1 . \boldsymbol{\tau}_2 \\
V_{\Delta\Delta} &= (V_\pi + V_\rho + V_{g'})\, \boldsymbol{T}_1 . \boldsymbol{T}_2^\dagger .
\end{aligned}
$$

$$f' = 0.6 \qquad g'_{NN} = 0.7 \;\; g'_{N\Delta} = g'_{\Delta\Delta} = 0.5$$

$$G^*_M / G_M = G^*_A / G_A = f^* / f = 2.2$$

$$
\begin{aligned}
V_\pi &= \left(\frac{g_r}{2M_N}\right)^2 F_\pi^2 \frac{\boldsymbol{q}^2}{\omega^2 - \boldsymbol{q}^2 - m_\pi^2}\, \boldsymbol{\sigma}_1 . \widehat{q}\; \boldsymbol{\sigma}_2 . \widehat{q} \\
V_\rho &= \left(\frac{g_r}{2M_N}\right)^2 C_\rho F_\rho^2 \frac{\boldsymbol{q}^2}{\omega^2 - \boldsymbol{q}^2 - m_\rho^2}\, \boldsymbol{\sigma}_1 \times \widehat{q}\; \boldsymbol{\sigma}_2 \times \widehat{q} \\
V_{g'} &= \left(\frac{g_r}{2M_N}\right)^2 F_\pi^2\, g'\; \boldsymbol{\sigma}_1 . \boldsymbol{\sigma}_2
\end{aligned}
$$

$$C_\rho = 1.5 \quad F_\pi(q) = (\Lambda_\pi^2 - m_\pi^2)/(\Lambda_\pi^2 - q^2)$$

$$\Lambda_\pi = 1 \;\text{GeV} \quad \Lambda_\rho = 1.5 \;\text{GeV}$$

RPA

$$\Pi = \Pi^0 + \Pi^0\, V\, \Pi$$

$$(1 + \Pi\, V)^*\, \Pi = (1 + \Pi\, V)^*\, \Pi^0 + (1 + \Pi\, V)^*\, \Pi^0\, V\, \Pi$$

$$\Pi + \Pi^*\, V^*\, \Pi = (1 + \Pi\, V)^*\, \Pi^0\, (1 + V\, \Pi)$$

$$\mathrm{Im}\,(\Pi) = |\Pi|^2\, \mathrm{Im}\,(V) + |1 + V\, \Pi|^2\, \mathrm{Im}\,(\Pi^0)$$

coherent

exclusive channels:
QE, 2p-2h, $\Delta \to \pi N$ ...

Details: RPA resolution

$$\Pi_{\mu\nu_{PP'}}(\omega,\boldsymbol{q},\boldsymbol{q}') = \Pi^0_{\mu\nu_{PP'}}(\omega;\boldsymbol{q},\boldsymbol{q}') + \sum_{QQ'=N\Delta}\int\frac{d^3k}{(2\pi)^3}\Pi^0_{\mu l_{PQ}}(\omega,\boldsymbol{q},\boldsymbol{k})W_l^{QQ'}(k)\Pi_{l\nu_{Q'P'}}(\omega,\boldsymbol{k},\boldsymbol{q}') + \sum_{QQ'=N\Delta}\sum_{i=\pm1}\int\frac{d^3k}{(2\pi)^3}\Pi^0_{\mu t_{i\,PQ}}(\omega,\boldsymbol{q},\boldsymbol{k})W_t^{QQ'}(k)\Pi_{t_i\nu_{Q'P'}}(\omega,\boldsymbol{k},\boldsymbol{q}')$$

$$U(i) = -\frac{k(i)^2}{(2\pi)^3}\,w_k(i)\,V(k(i))$$

$$\Pi^0(i,j) = \sum_k(\delta_{ik}+\Pi^0(i,k)U(k))\,\Pi(k,j) \equiv \sum_k\mathcal{K}(i,k)\,\Pi(k,j)$$

$$\left(\begin{array}{cc|cc}
\Pi^{0ll}{}_{NN} & \Pi^0_{lt_{NN}} & \Pi^0_{ll_{N\Delta}} & \Pi^0_{lt_{N\Delta}} \\
\Pi^0_{tl_{NN}} & \Pi^0_{tt_{NN}} & \Pi^0_{tl_{N\Delta}} & \Pi^0_{tt_{N\Delta}} \\
\hline
\Pi^0_{ll_{\Delta N}} & \Pi^0_{lt_{\Delta N}} & \Pi^0_{ll_{\Delta\Delta}} & \Pi^0_{lt_{\Delta\Delta}} \\
\Pi^0_{tl_{\Delta N}} & \Pi^0_{tt_{\Delta N}} & \Pi^0_{tl_{\Delta\Delta}} & \Pi^0_{tt_{\Delta\Delta}}
\end{array}\right) = \mathcal{K}\times\left(\begin{array}{cc|cc}
\Pi_{ll_{NN}} & \Pi_{lt_{NN}} & \Pi_{ll_{N\Delta}} & \Pi_{lt_{N\Delta}} \\
\Pi_{tl_{NN}} & \Pi_{tt_{NN}} & \Pi_{tl_{N\Delta}} & \Pi_{tt_{N\Delta}} \\
\hline
\Pi_{ll_{\Delta N}} & \Pi_{lt_{\Delta N}} & \Pi_{ll_{\Delta\Delta}} & \Pi_{lt_{\Delta\Delta}} \\
\Pi_{tl_{\Delta N}} & \Pi_{tt_{\Delta N}} & \Pi_{tl_{\Delta\Delta}} & \Pi_{tt_{\Delta\Delta}}
\end{array}\right)$$

Neutrino-nucleus cross-sections

ν-Nucleus Quasielastic scattering

QE totally dominated by isospin spin-transverse response $R_{\sigma\tau(T)}$

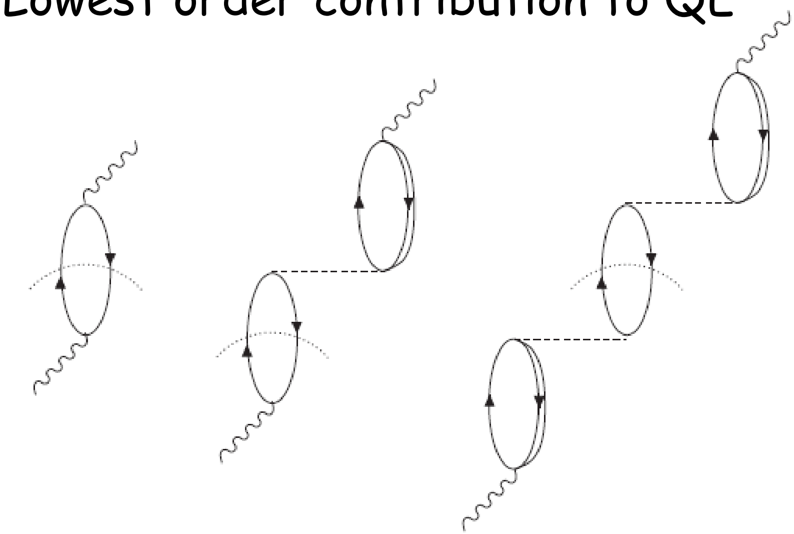
RPA reduction

- expected from the repulsive character of p-h interaction in T channel
- mostly due to interference term $R^{N\Delta} < 0$

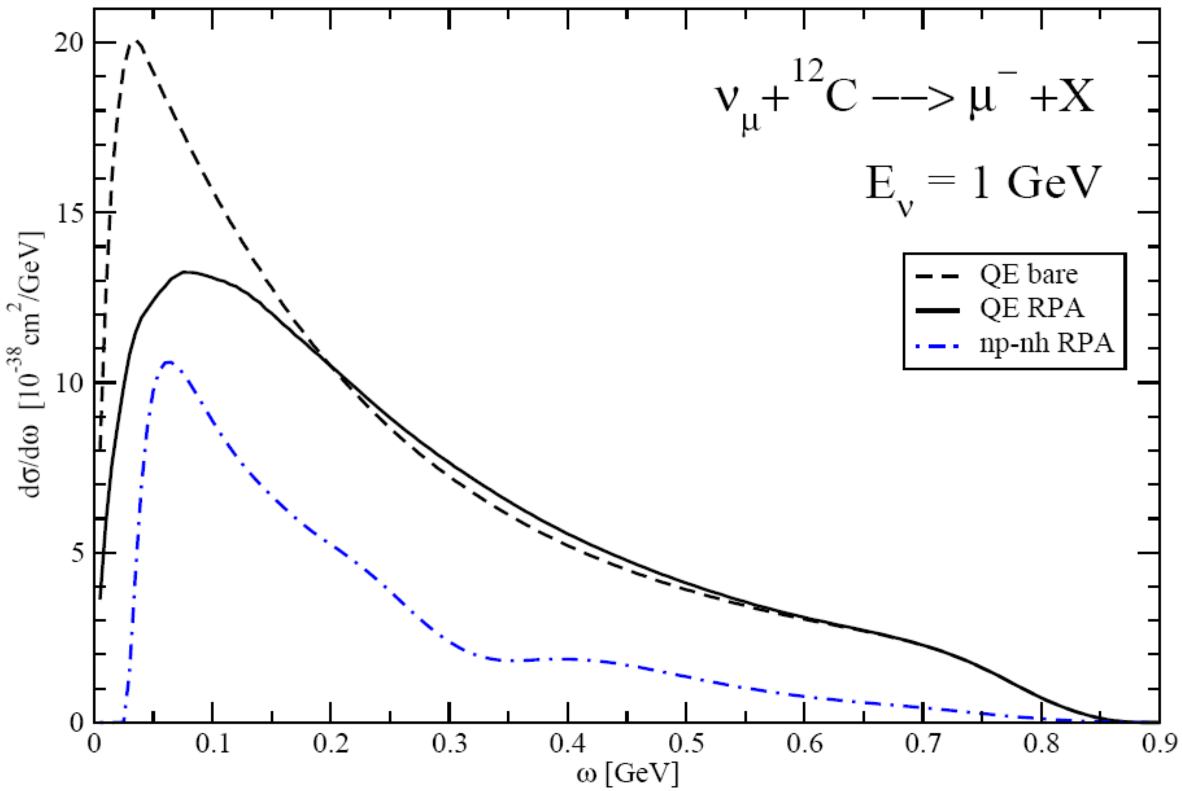
(Lorentz-Lorenz or Ericson-Ericson effect)

Test: electron-nucleus scattering

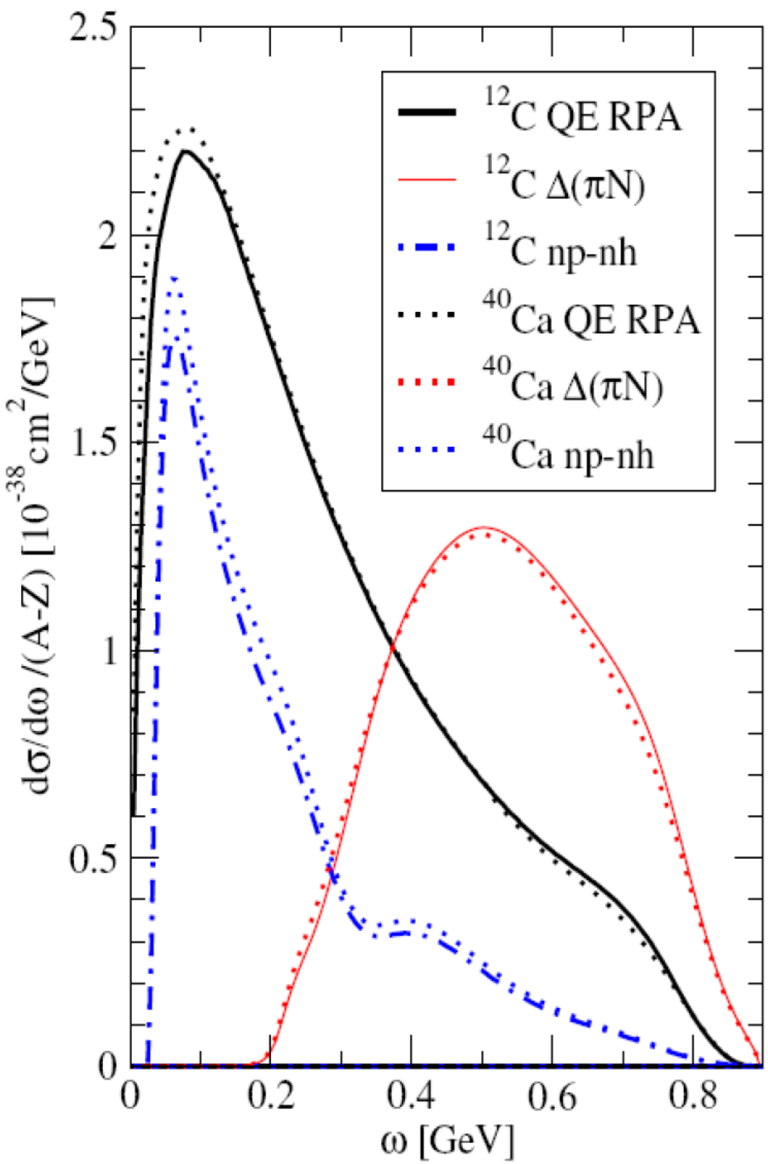
Lowest order contribution to QE



R^{NN}_{QE} $R^{N\Delta}_{QE}$ $R^{\Delta\Delta}_{QE}$

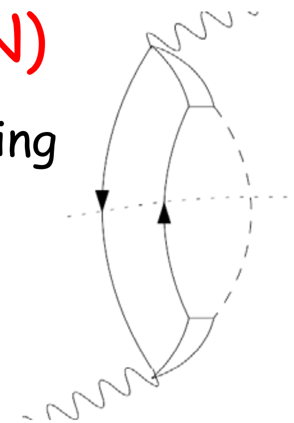


π production and np-nh ; nuclear mass dependence



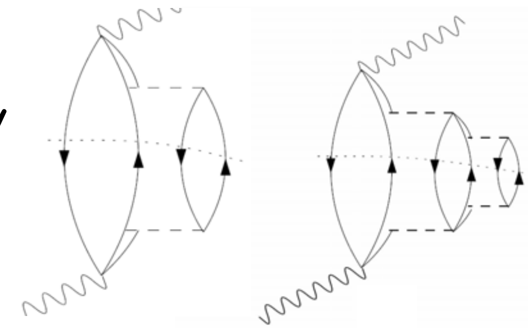
Pion production: Δ(πN)

- from π-A and γ-A scattering
- Test: π-A

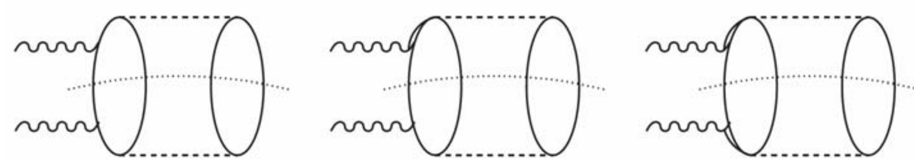


np-nh channel

- non pionic Δ decay in nuclear medium ΔN→NN



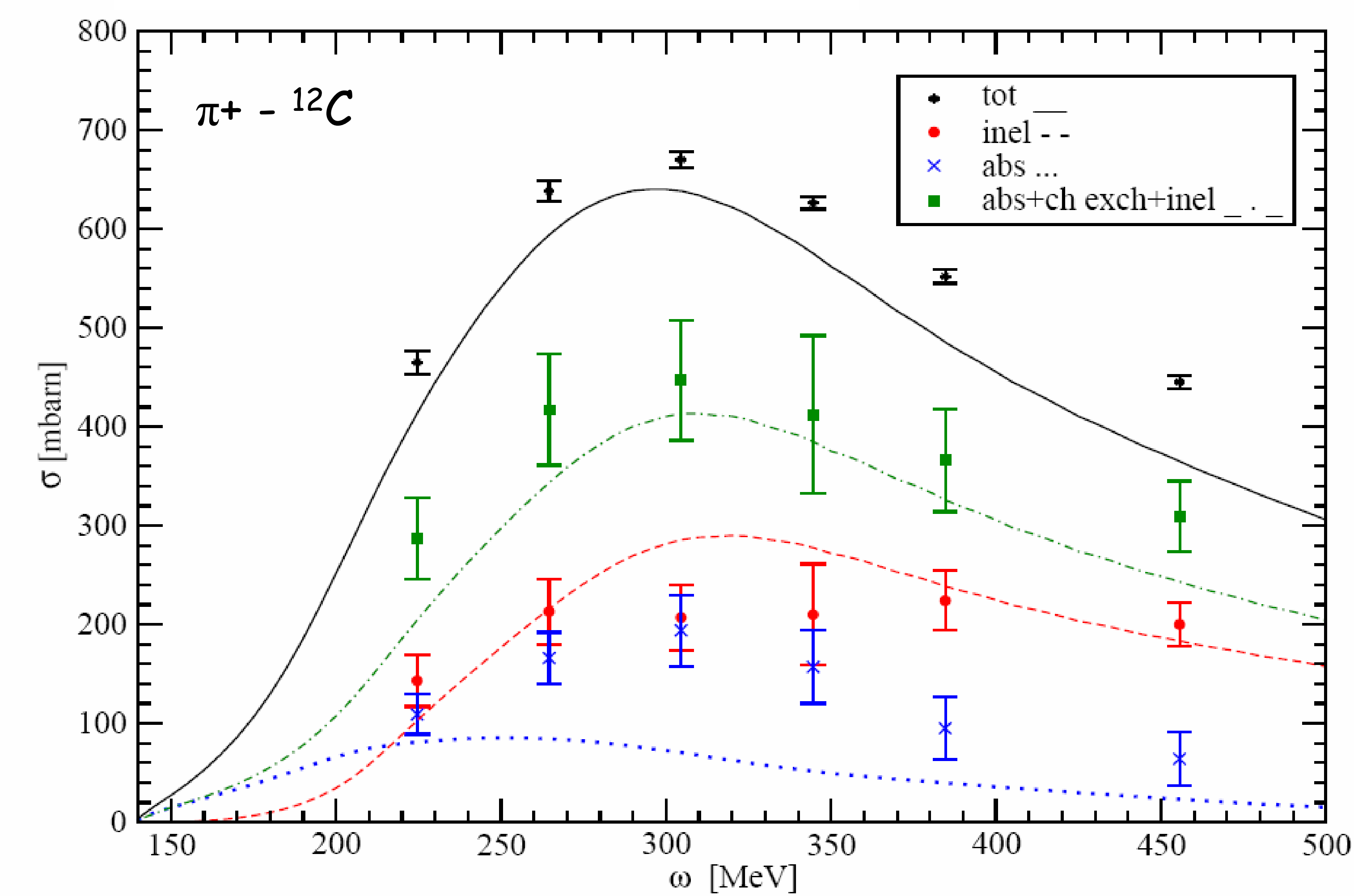
- Initial state nucleon correlation



Scaling with A

Pion-nucleus cross section

$$\sigma^{tot}(\omega) = \left(\frac{g_r}{2M_N}\right)^2 \pi q_\pi \, R_L(\omega, q_\pi)$$

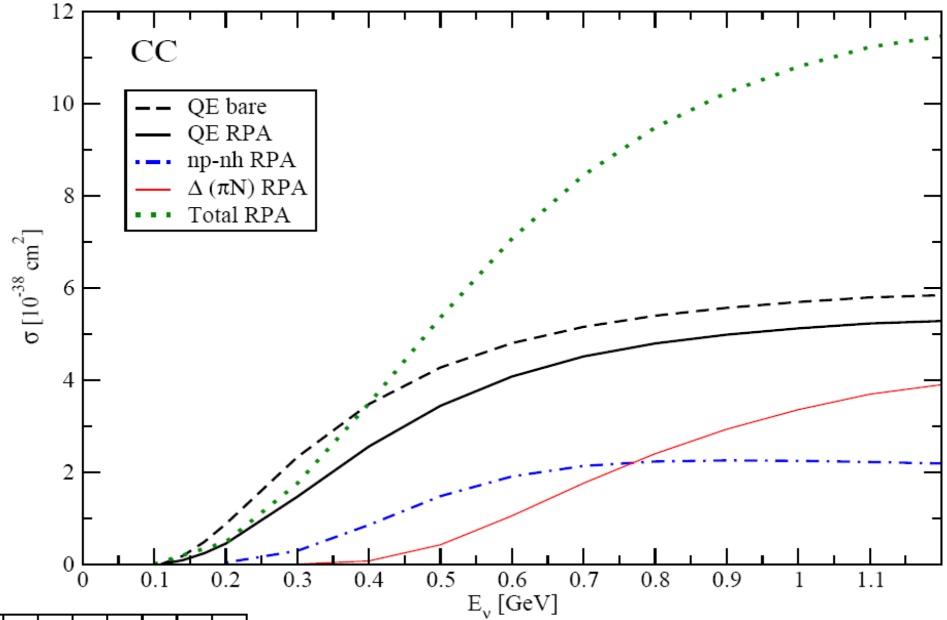


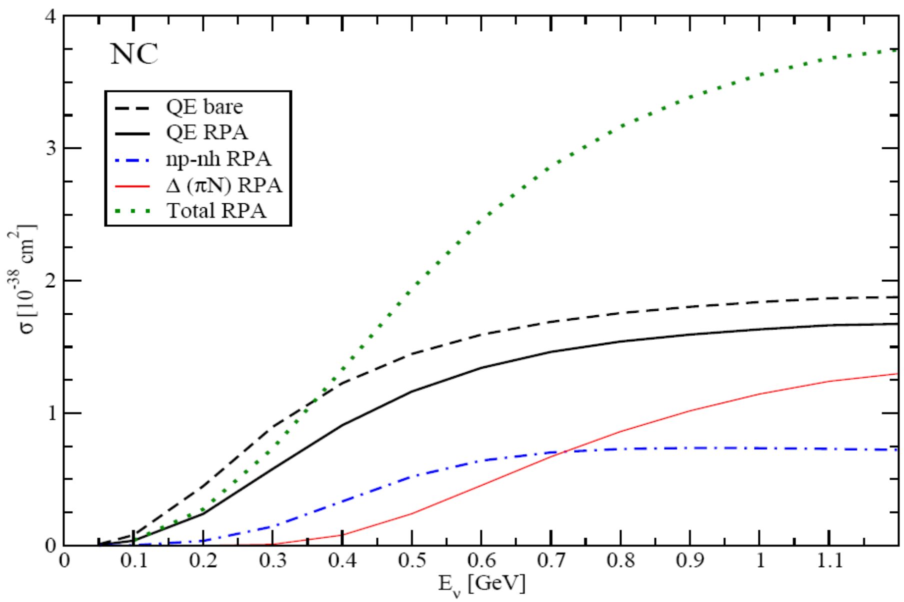
Overestimation of inelastic ch. in the peak region

Underestimation of absorption

Absence of π FSI

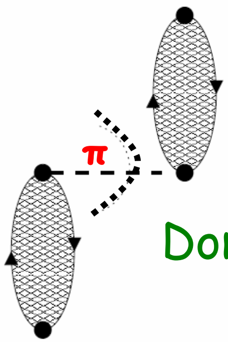
ν_μ-^{12}C Cross sections





as a function of ν energy

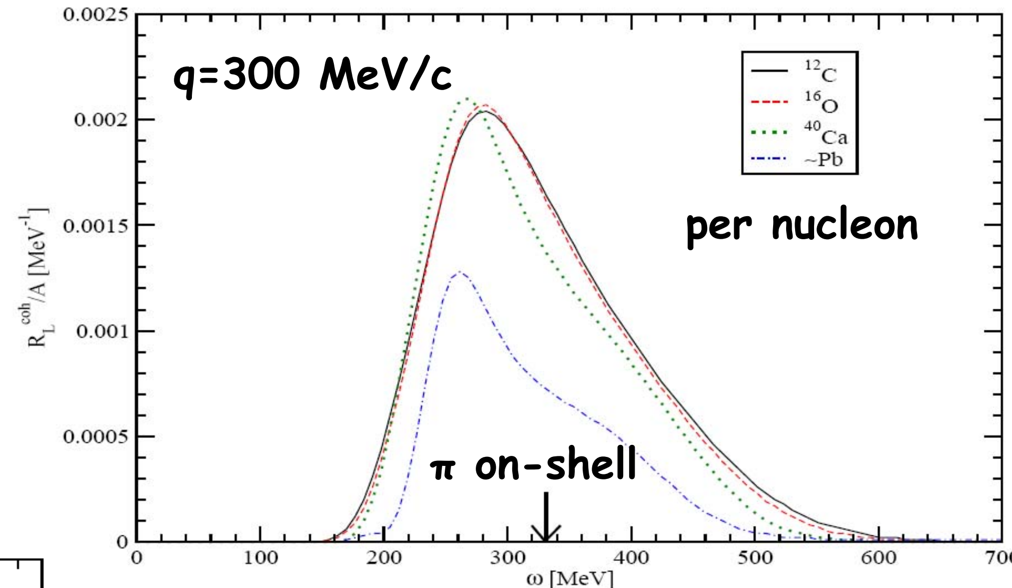
Coherent channel

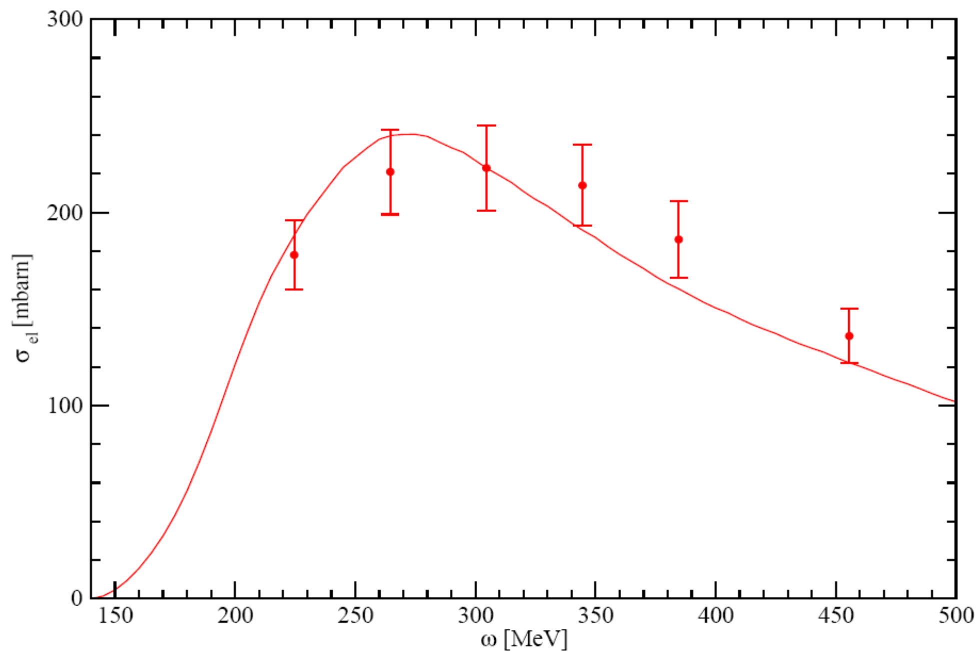


Dominated by $R_{\sigma\tau}$ longitudinal

Reshaped by collective effects

Softening of the responses





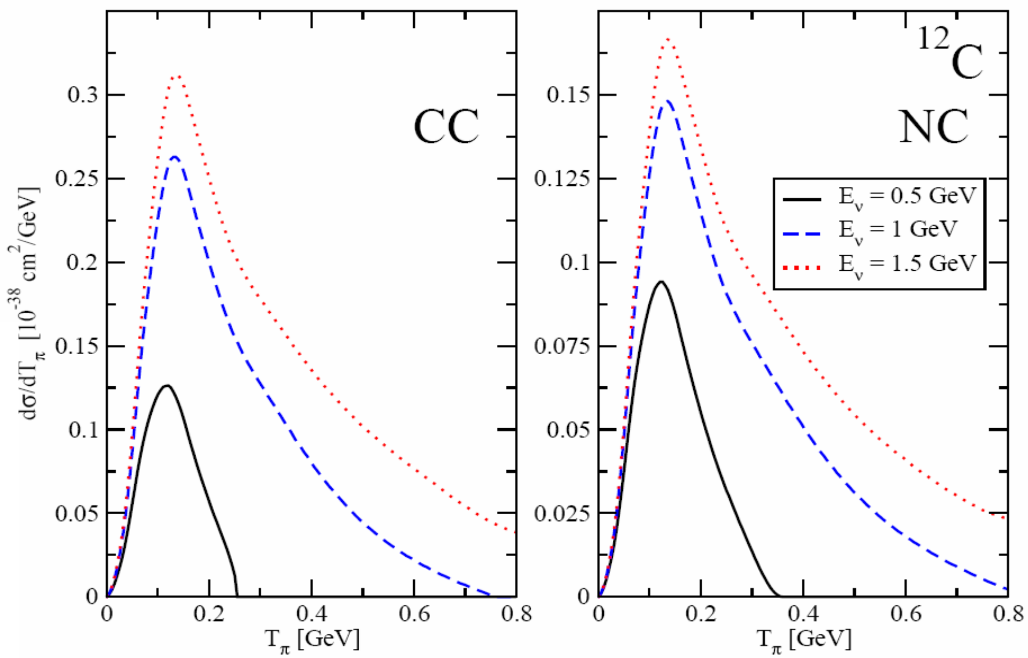
Test: π - ^{12}C elastic cross-section

$$\sigma^{elas}(\omega) = \left(\frac{g_r}{2M_N}\right)^2 \pi q_\pi \, R_L^{coh}(\omega, q_\pi)$$

$$q_\pi^2 = \omega^2 - m_\pi^2$$

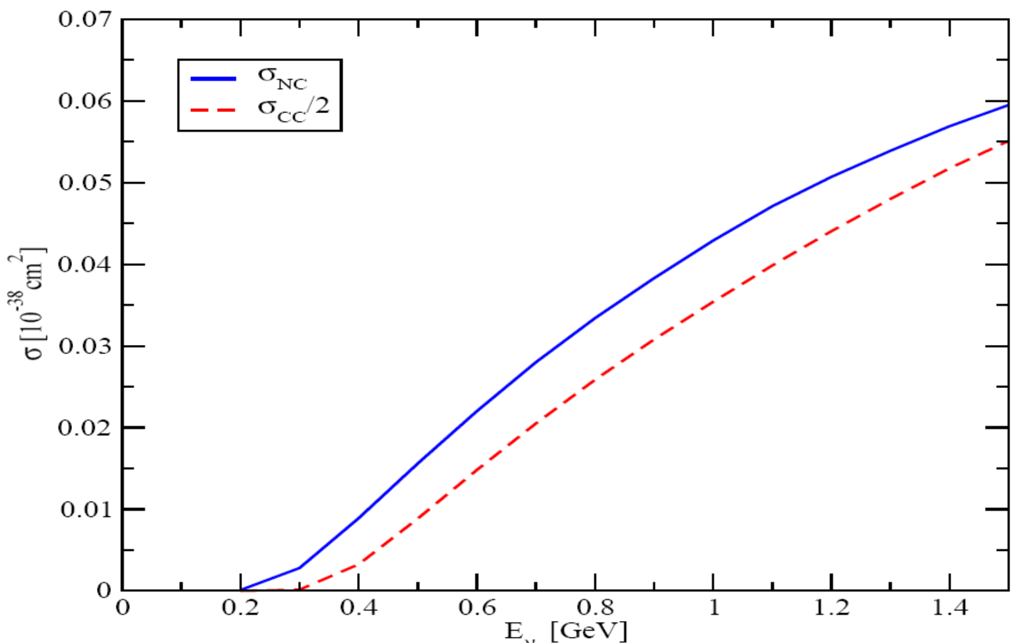
ν_μ induced coherent pion production off ^{12}C

Differential cross section



pion kinetic energy

Total cross section



neutrino energy

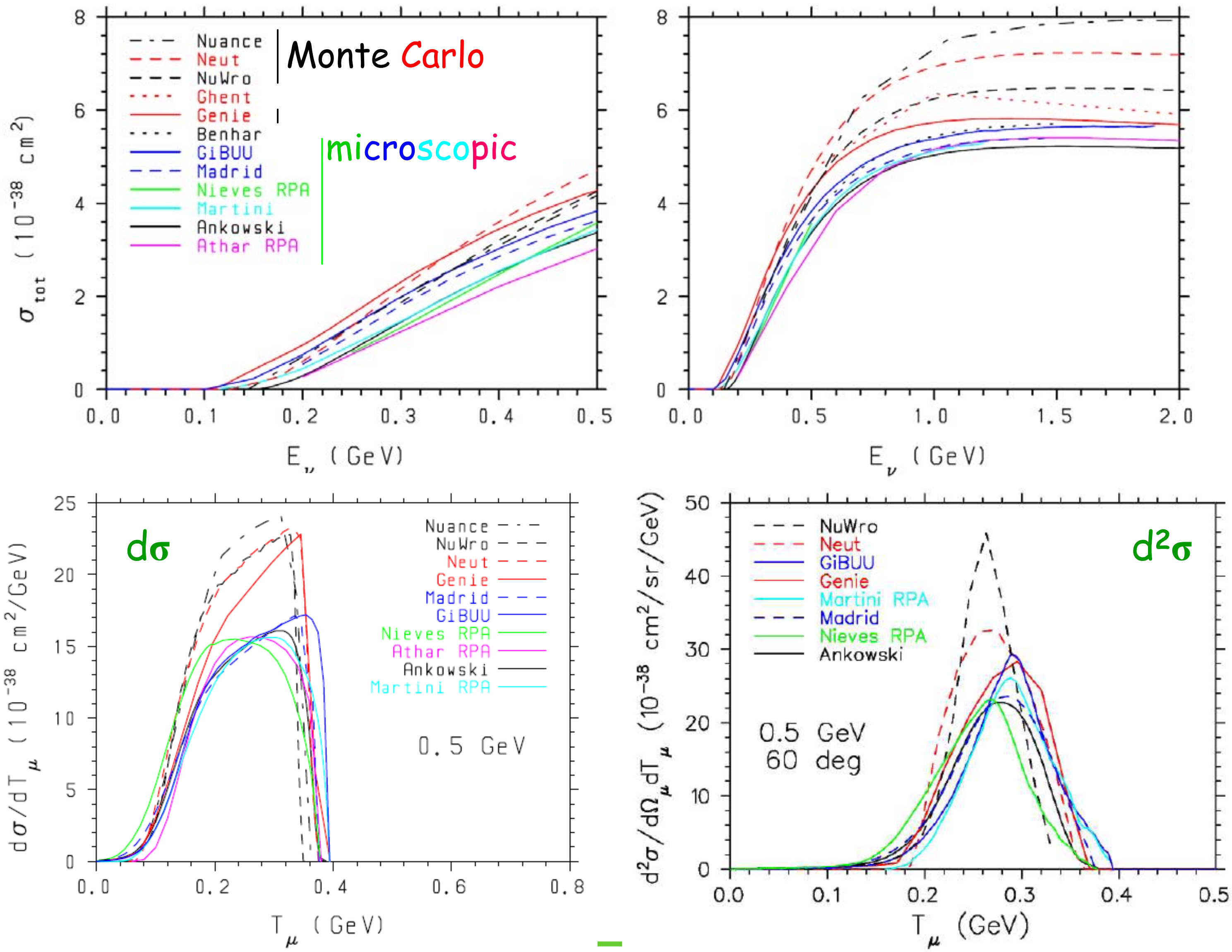
energie atomique • energies alte

Comparison of Models of Neutrino-Nucleus Interactions

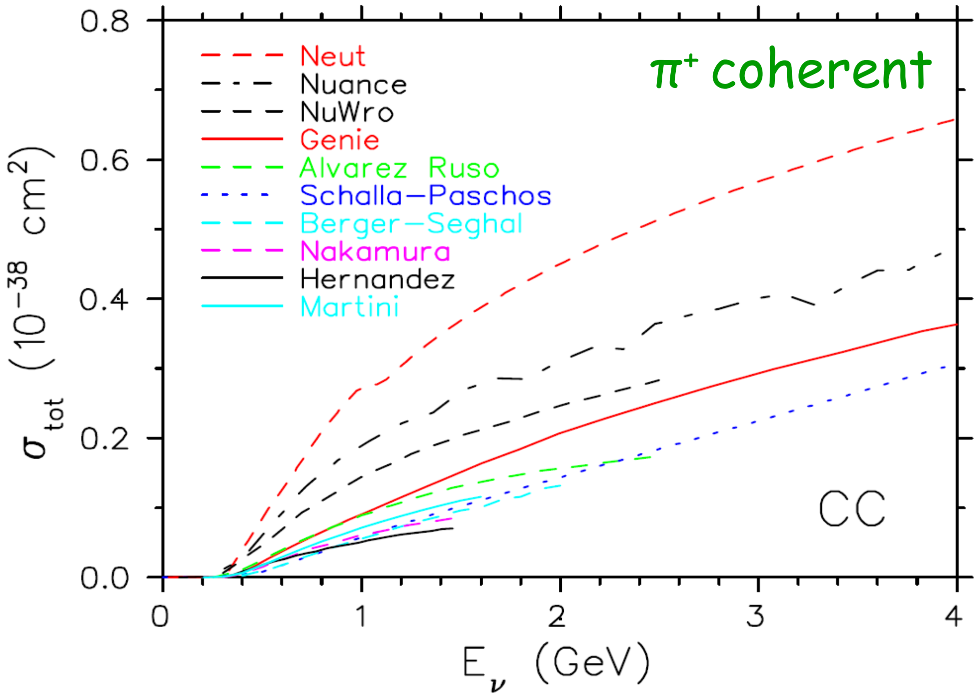
S. Boyd*, S. Dytman†, E. Hernández**, J. Sobczyk‡ and R. Tacik§

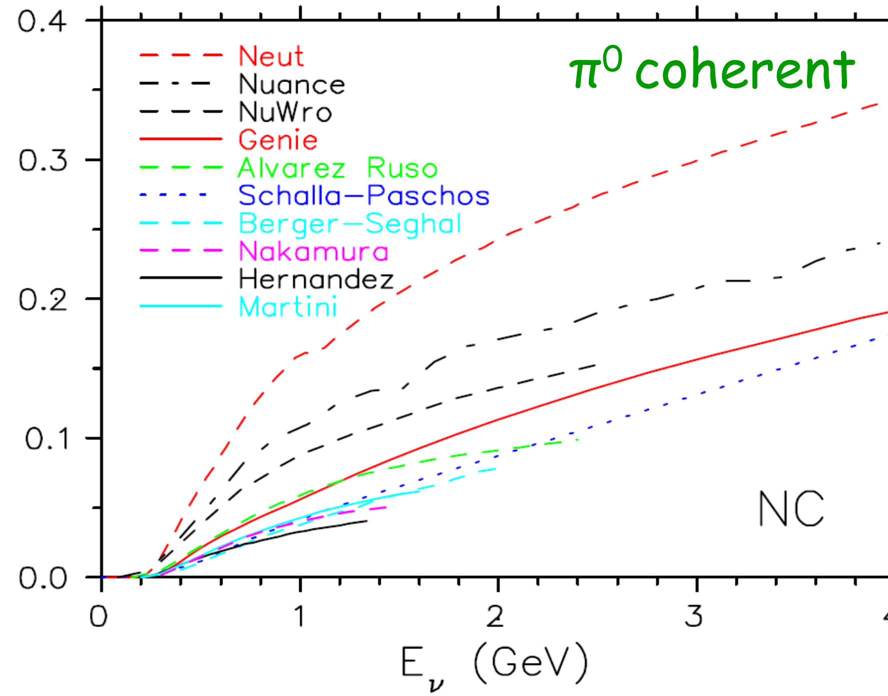
QE tot

QE diff

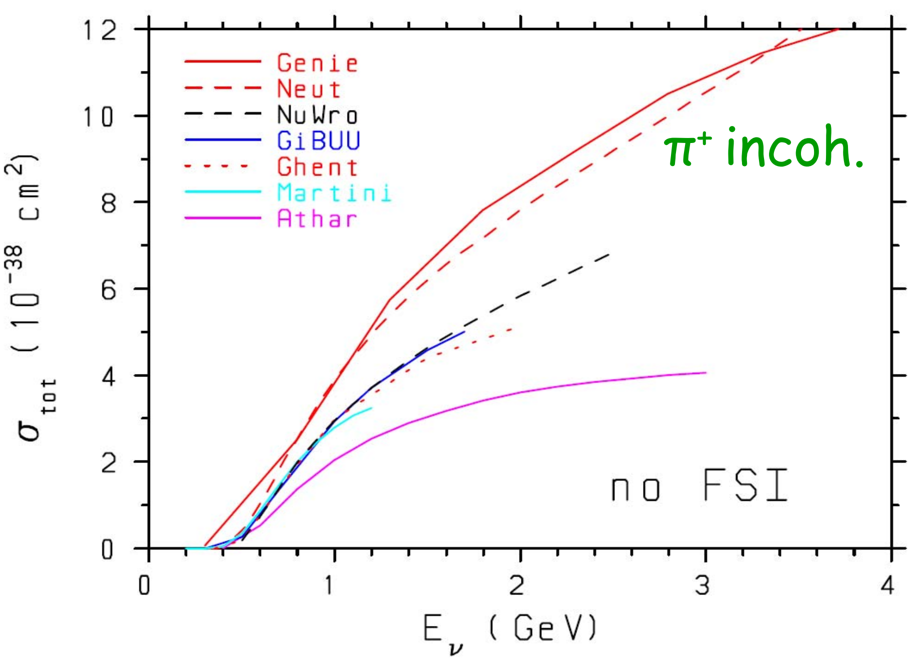


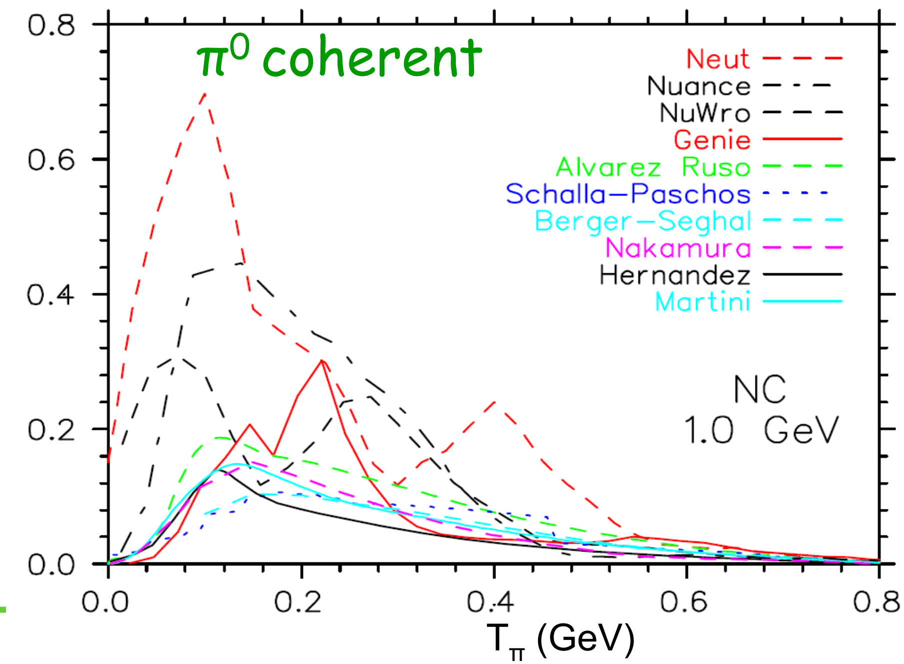
NUINT09


π+ coherent
Neut
Nuance
NuWro
Genie
Alvarez Ruso
Schalla−Paschos
Berger−Seghal
Nakamura
Hernandez
Martini
CC
σtot (10−38 cm2)
Eν (GeV)
0.0
0.2
0.4
0.6
0.8
0
1
2
3
4


π0 coherent
Neut
Nuance
NuWro
Genie
Alvarez Ruso
Schalla−Paschos
Berger−Seghal
Nakamura
Hernandez
Martini
NC
Eν (GeV)
0.0
0.1
0.2
0.3
0.4
0
1
2
3
4

NUINT09


π+ incoh.
Genie
Neut
NuWro
GiBUU
Ghent
Martini
Athar
no FSI
σtot (10−38 cm2)
Eν (GeV)
0
2
4
6
8
10
12
0
1
2
3
4


π0 coherent
Neut
Nuance
NuWro
Genie
Alvarez Ruso
Schalla−Paschos
Berger−Seghal
Nakamura
Hernandez
Martini
NC
1.0 GeV
Tπ (GeV)
0.0
0.2
0.4
0.6
0.8
0.0
0.2
0.4
0.6
0.8

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Comparison with data

- Ratios of cross sections

- Absolute cross sections
  (last months)

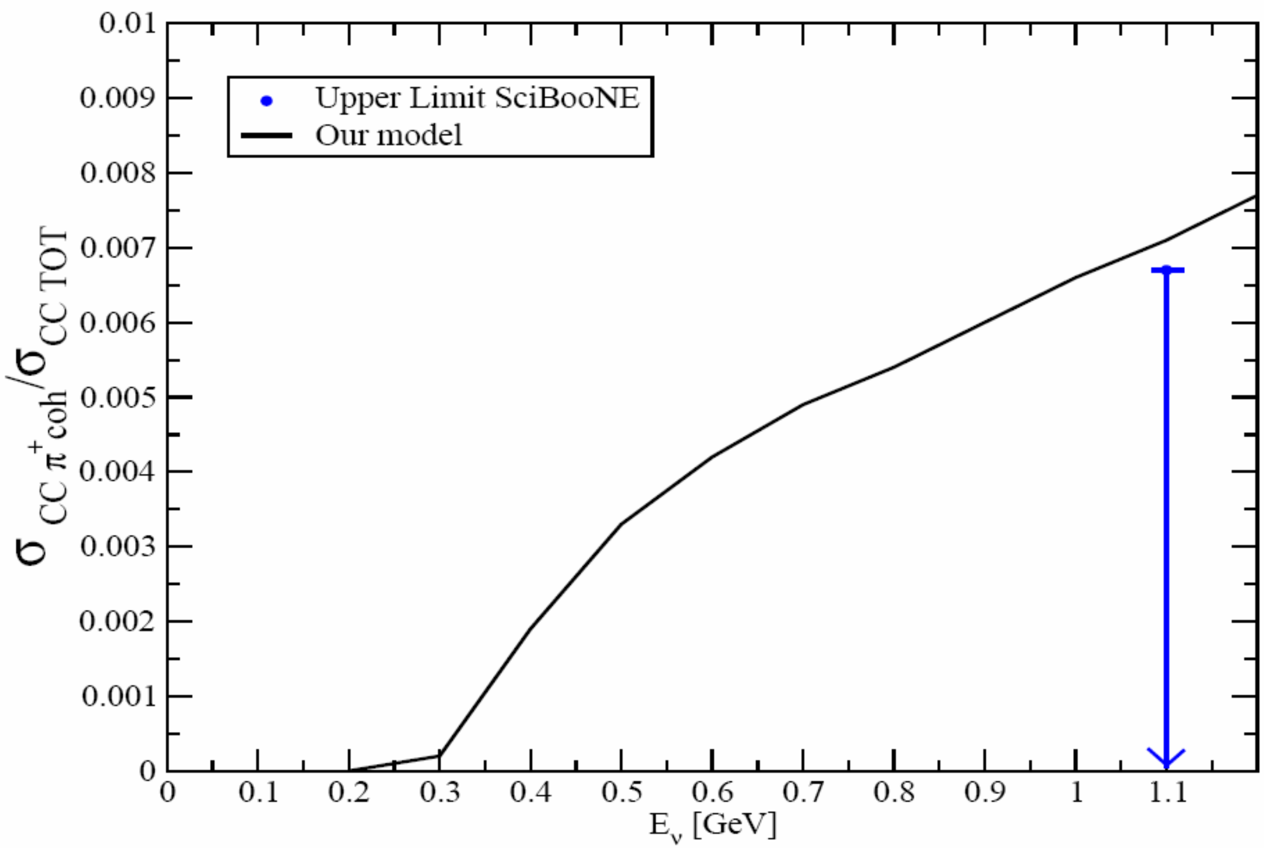
Charged current coherent π^+ production

Upper limits

$$\frac{\sigma\ CC\ \pi^+_{coherent}}{\sigma\ CC\ total}$$

K2K: 0.60 10^{-2} averaged over ν flux $\langle E_\nu \rangle$ 1.3 GeV PRL 95 252301 (2005)

SciBooNE: 0.67 10^{-2} @ E_ν =1.1 GeV
1.36 10^{-2} @ E_ν =2.2 GeV PRD 78 112004 (2008)



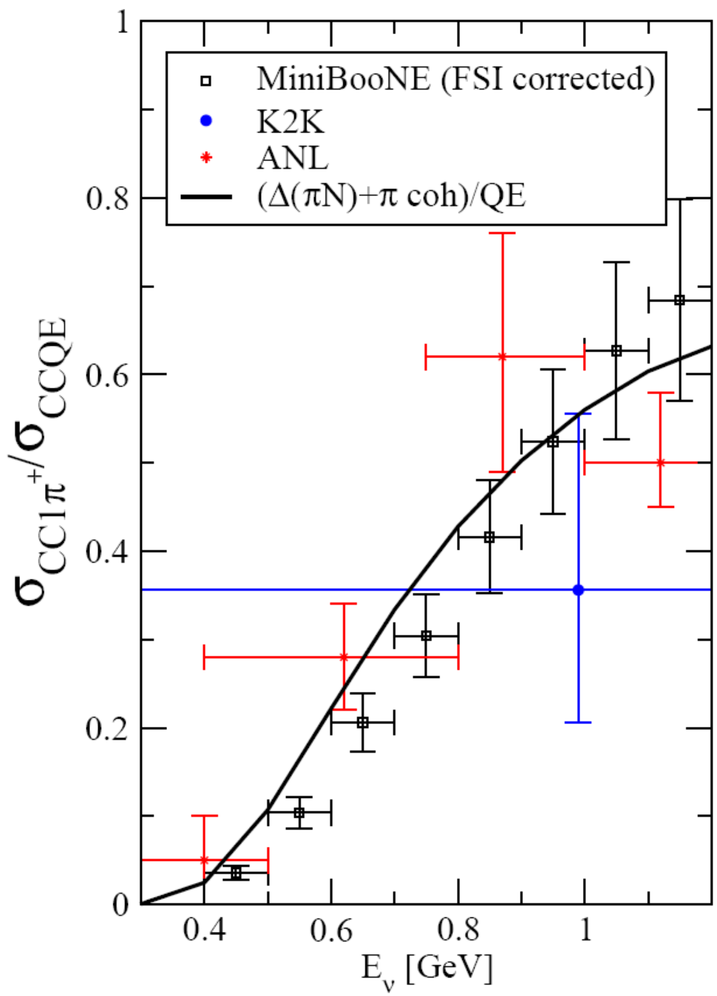
Our model @
E_ν=1.1 GeV
0.71 10^{-2}
Just compatible

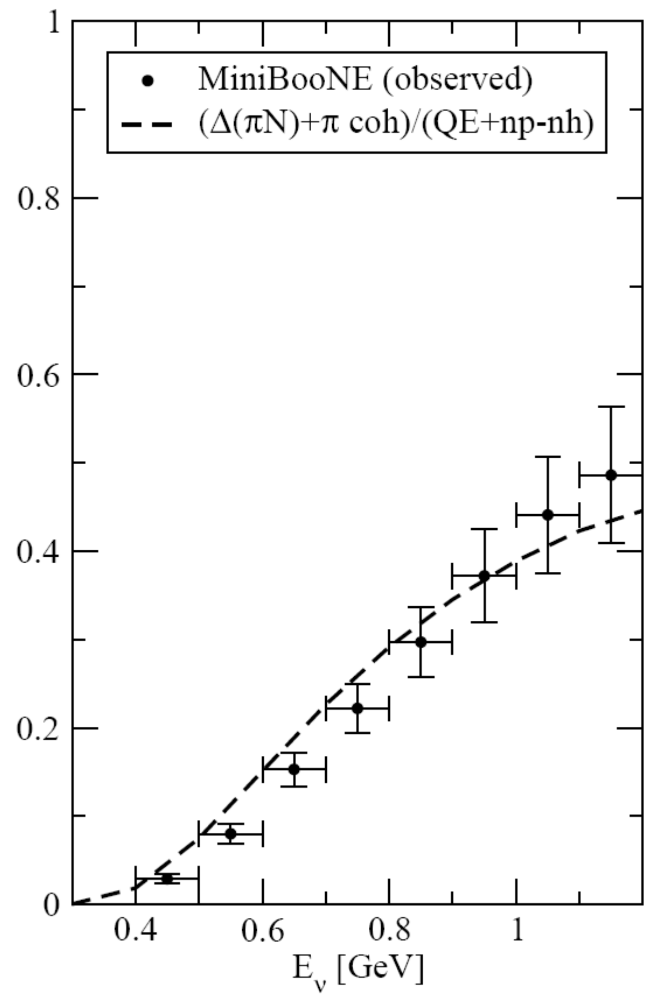
Without np-nh
in σ CC total

0.89 10^{-2}
Appreciably above u.l.

Charged current total $1\pi^+$ production over QE ratio

MiniBooNE, Phys. Rev. Lett. 103, 081801 (2009)





In our model π FSI are not included; a reduction of ~ 15 % is expected

NC π^0 production over CC total cross-section

Total π^0

Phys. Rev. D 81, 033004 (2010)

$$\frac{\sigma(NC\ \pi_0)}{\sigma(CC_{TOT})} = (7.7 \pm 0.5(\text{stat.}) \pm 0.5(\text{sys.})) \cdot 10^{-2}$$

SciBooNE @ E_ν = 1.1 GeV

Our model

$$\frac{\sigma(NC\ \pi_0)}{\sigma(CC_{TOT})} = 7.9 \cdot 10^{-2}$$

Suppressing np-nh in $\sigma\ CC_{TOT}$

$$\frac{\sigma(NC\ \pi_0)}{(\sigma(CC_{TOT}) - \sigma(CC_{np-nh}))} = 9.8 \cdot 10^{-2}$$

Coherent π^0

$$\frac{\sigma(NC\ \pi_0\ \text{coh})}{\sigma(CC_{TOT})} = (0.7 \pm 0.4) \cdot 10^{-2}$$

SciBooNE @ E_ν = 1 GeV

Our model

$$\frac{\sigma(NC\ \pi_0\ \text{coh})}{\sigma(CC_{TOT})} = 0.4 \cdot 10^{-2}$$

Suppressing np-nh in $\sigma\ CC_{TOT}$

$$\frac{\sigma(NC\ \pi_0\ \text{coh})}{(\sigma(CC_{TOT}) - \sigma(CC_{np-nh}))} = 0.5 \cdot 10^{-2}$$

NC π^0 production absolute cross sections

Total cross section

	MiniBooNE σ [10^-40 cm^2/nucleon]	Our model σ [10^-40 cm^2/nucleon]
ν @ 808 MeV	4.76 ± 0.05 st ± 0.76 sy	5.42
$\overline{\nu}$ @ 664 MeV	1.48 ± 0.05 st ± 0.23 sy	1.37

Incoherent exclusive NC $1\pi^0$

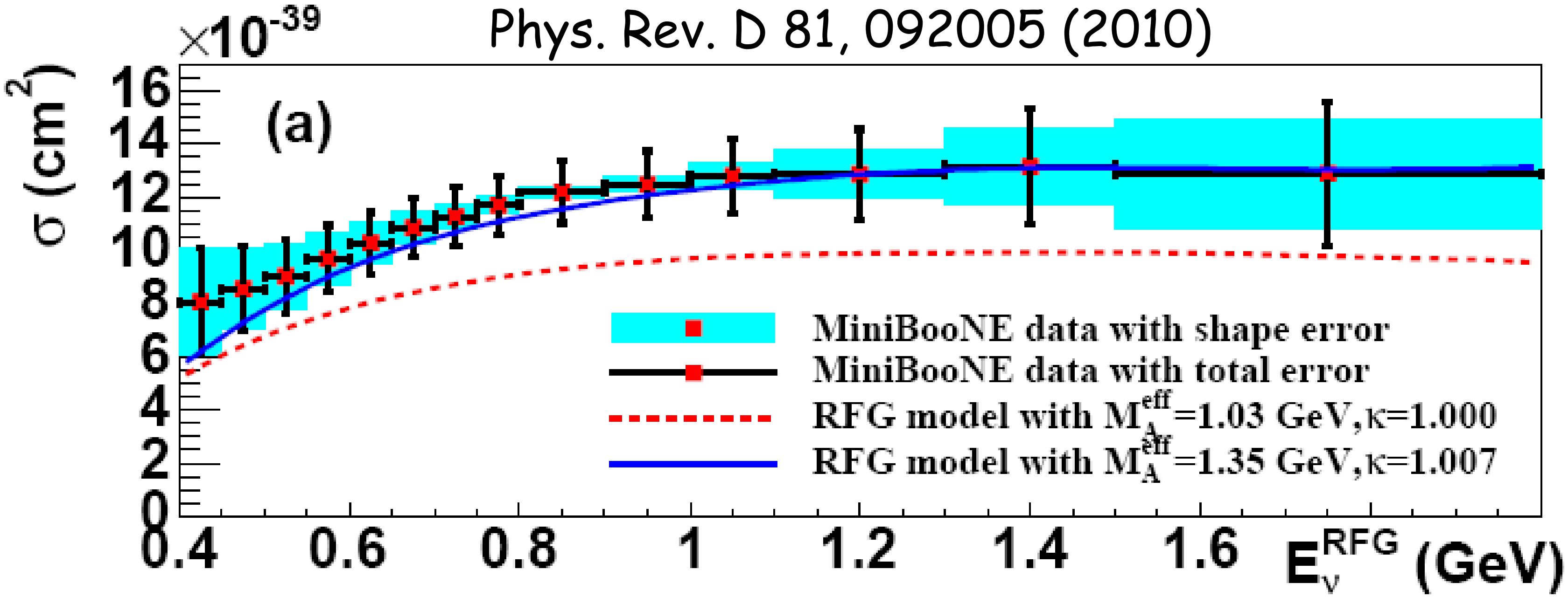
	MiniBooNE corrected for FSI effects	Our model
ν @ 808 MeV	5.71 ± 0.08 st ± 1.45 sy	5.14
$\overline{\nu}$ @ 664 MeV	1.28 ± 0.07 st ± 0.35 sy	1.17

MiniBooNE, Phys. Rev. D 81, 013005 (2010)

P.S. Our model: $\Delta N \rightarrow NN$ absorption process, but not absorption once π_{inco} is placed on-shell

Quasielastic cross section

MiniBooNE,
AIP Conf. Proc. 1189: 139-144 (2009);
Phys. Rev. D 81, 092005 (2010)



Comparison with a prediction based on RFG with M_A=1.03 GeV (standard value) reveals a discrepancy

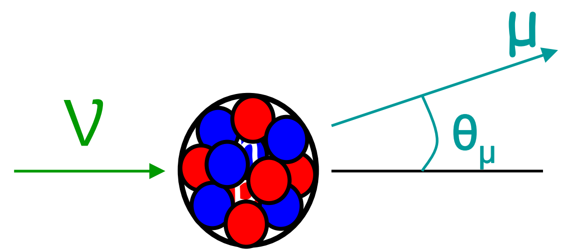
In RFG an axial mass of 1.35 GeV is needed to account for data

The introduction of a realistic spectral function does not alter this conclusion (Benhar and Meloni, Phys. Rev. D80: 073003, 2009)

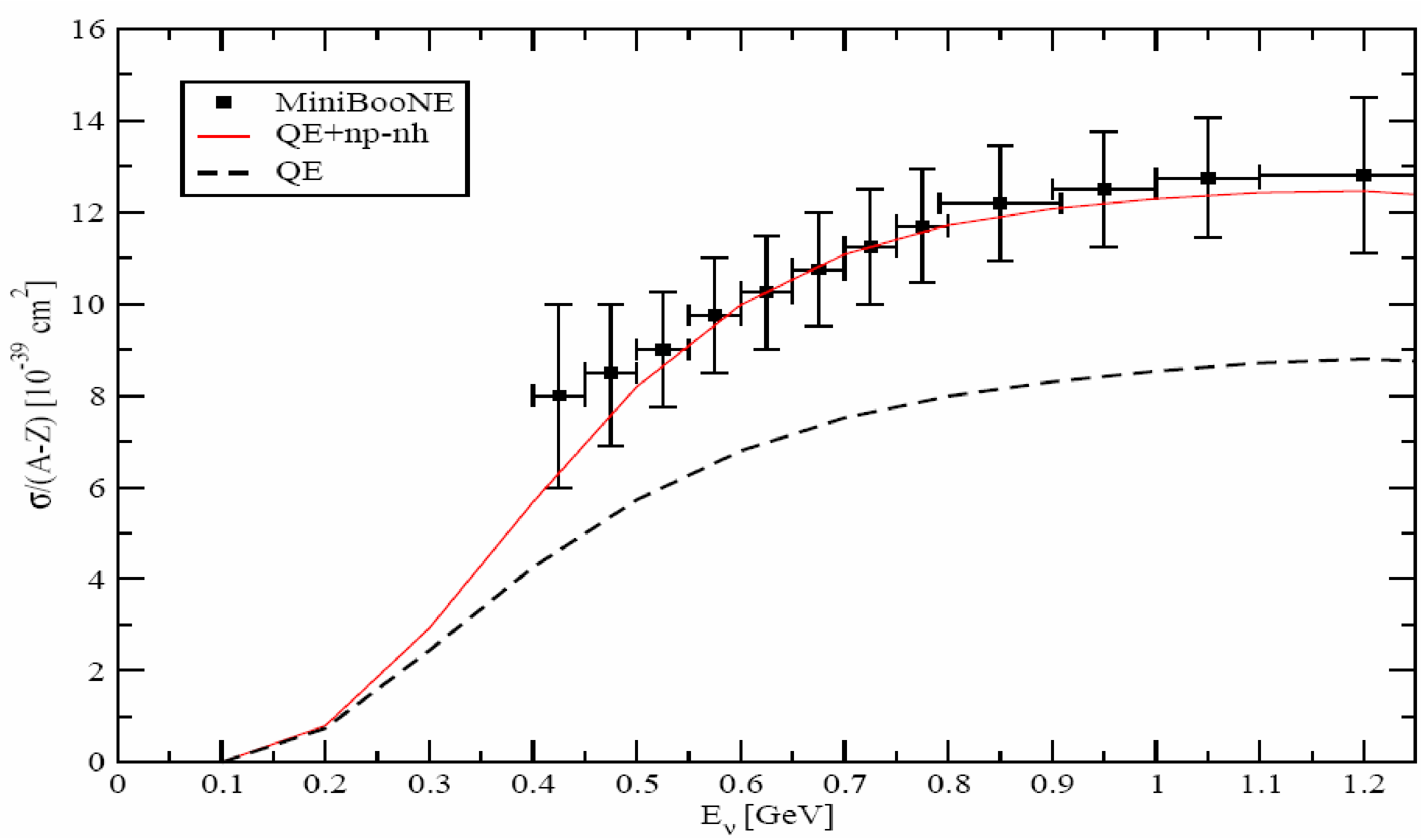
We proposed a possible alternative interpretation…

"Quasielastic" events if just μ is detected

- Ejection of a single nucleon (1N): "genuine" QE event



- Events involving a correlated nucleon pair: 2N ejected



Flux averaged:

MiniBooNE

$9.4\ 10^{-39} cm^2 \pm 11\%$

Our model QE+np-nh

$9.1\ 10^{-39}\ cm^2$

Our model genuine QE

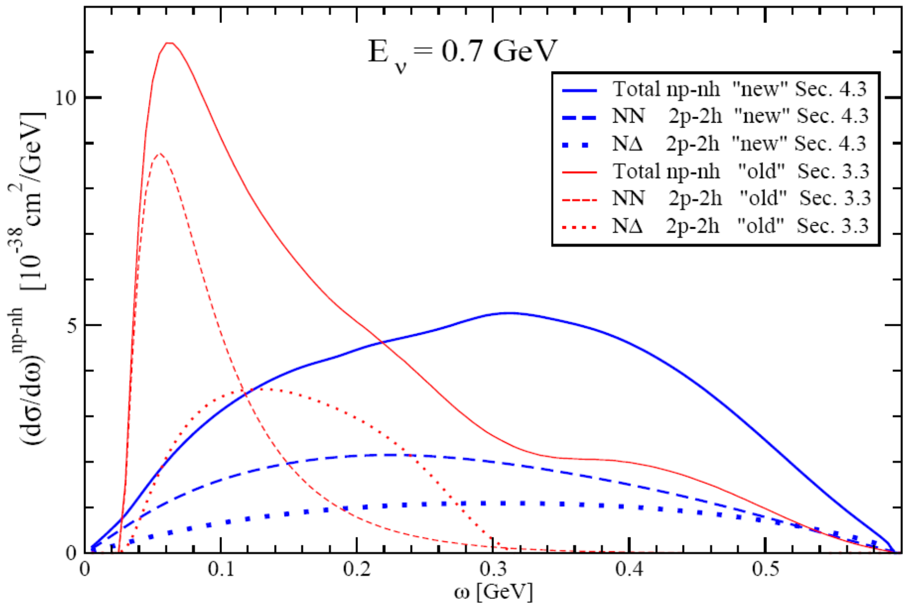
$6.4\ 10^{-39}\ cm^2$

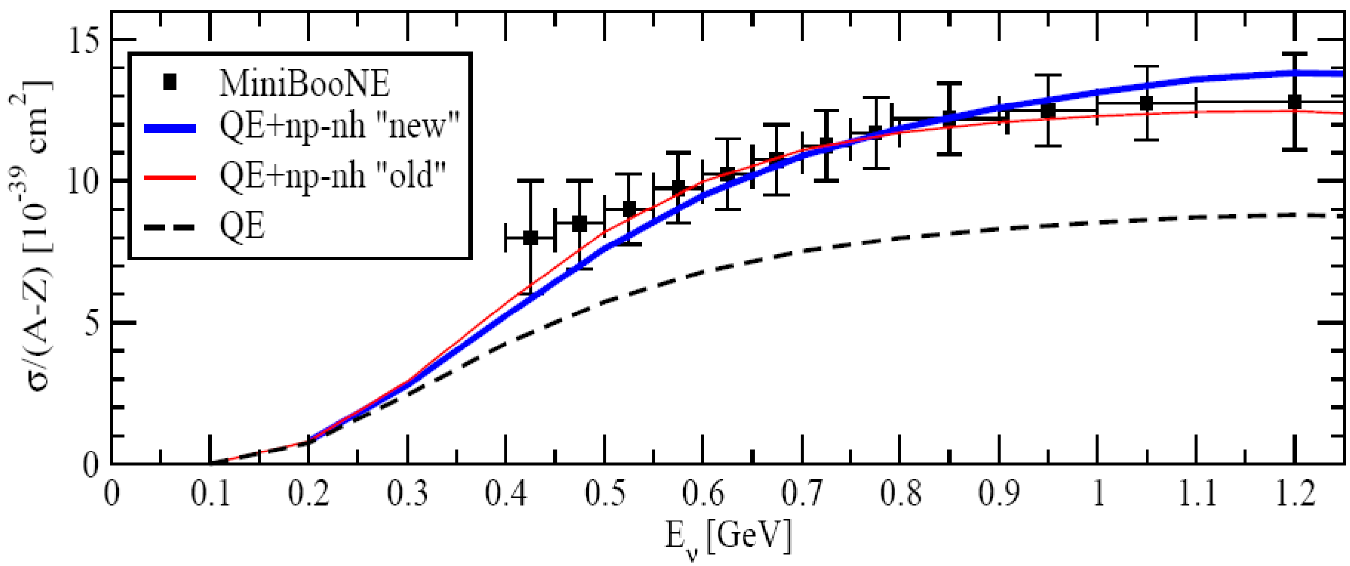
2p-2h contribution: comparison of the two parametrizations

Red: from Delorme et al.
(2p-2h π absorption)

Blue: from Alberico et al.
(R_T of (e,e') ^{56}Fe)

Energy behaviors different, but...

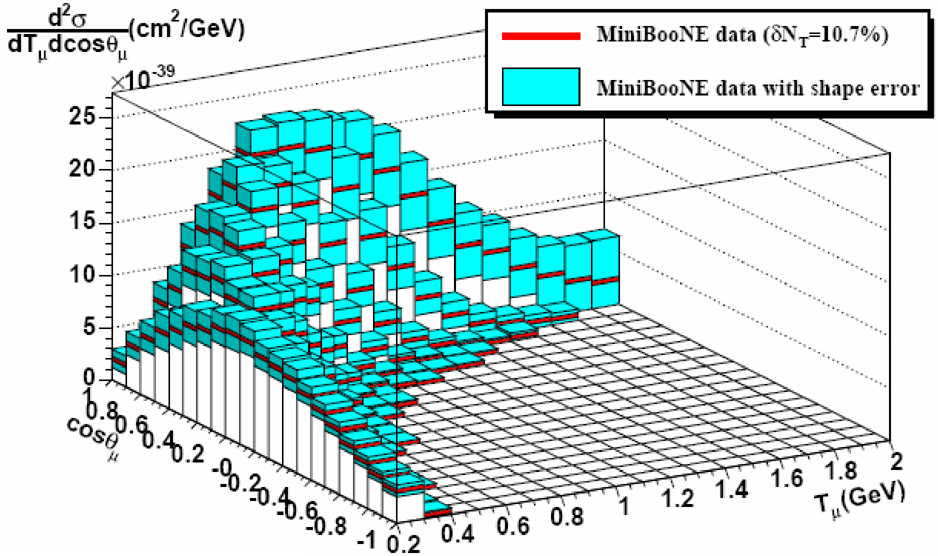




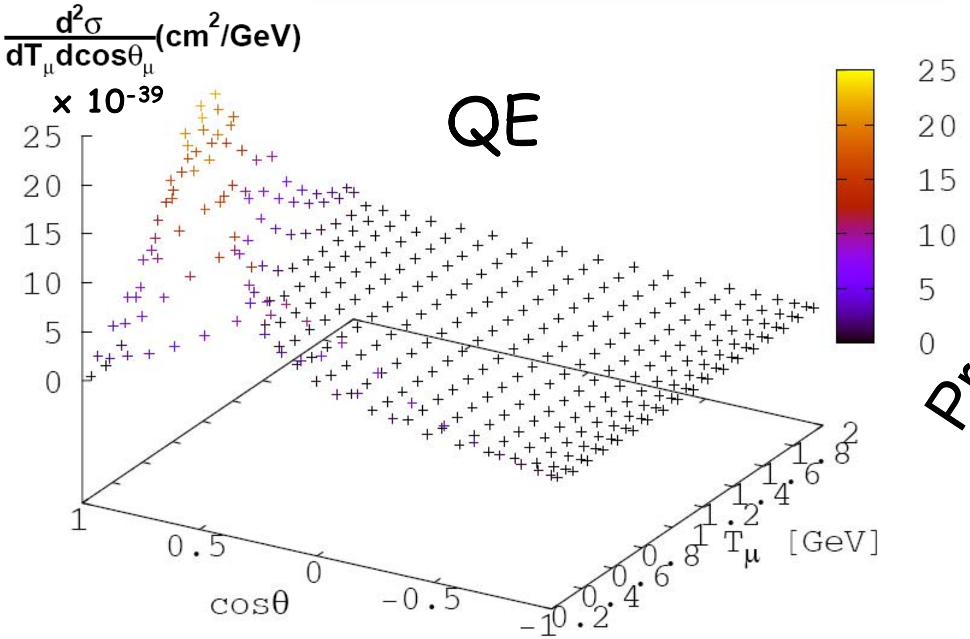
Similar conclusion:
important role of the multinucleon channel

Neutrino do not interact only with individual nucleons but also with pairs (mostly n-p)

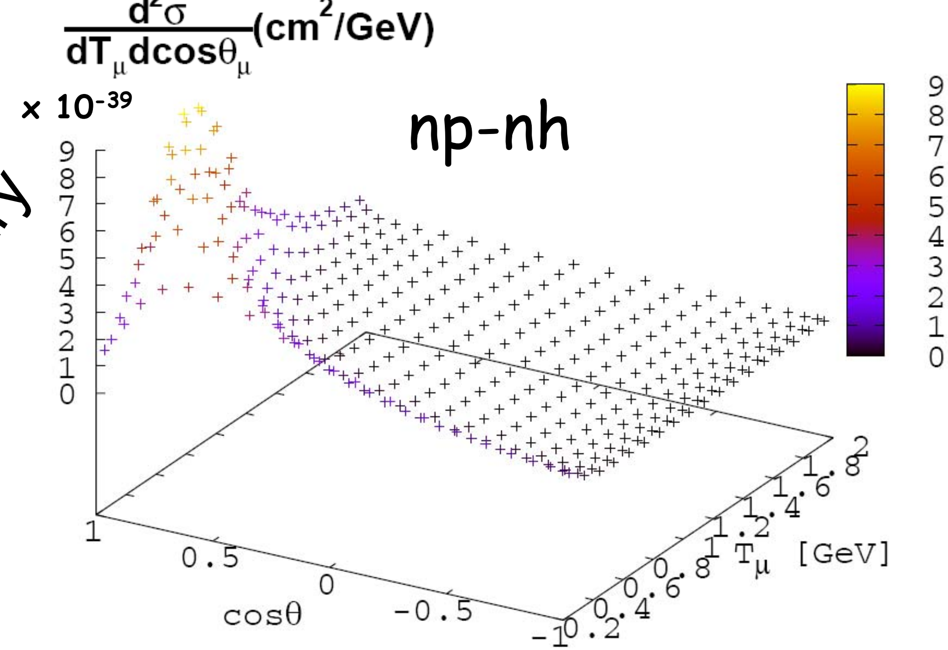
MiniBooNE CCQE flux-integrated double differential X section



MiniBooNE,
Phys. Rev. D 81, 092005 (2010)



Preliminary



MiniBooNE CCQE flux-integrated double differential X section

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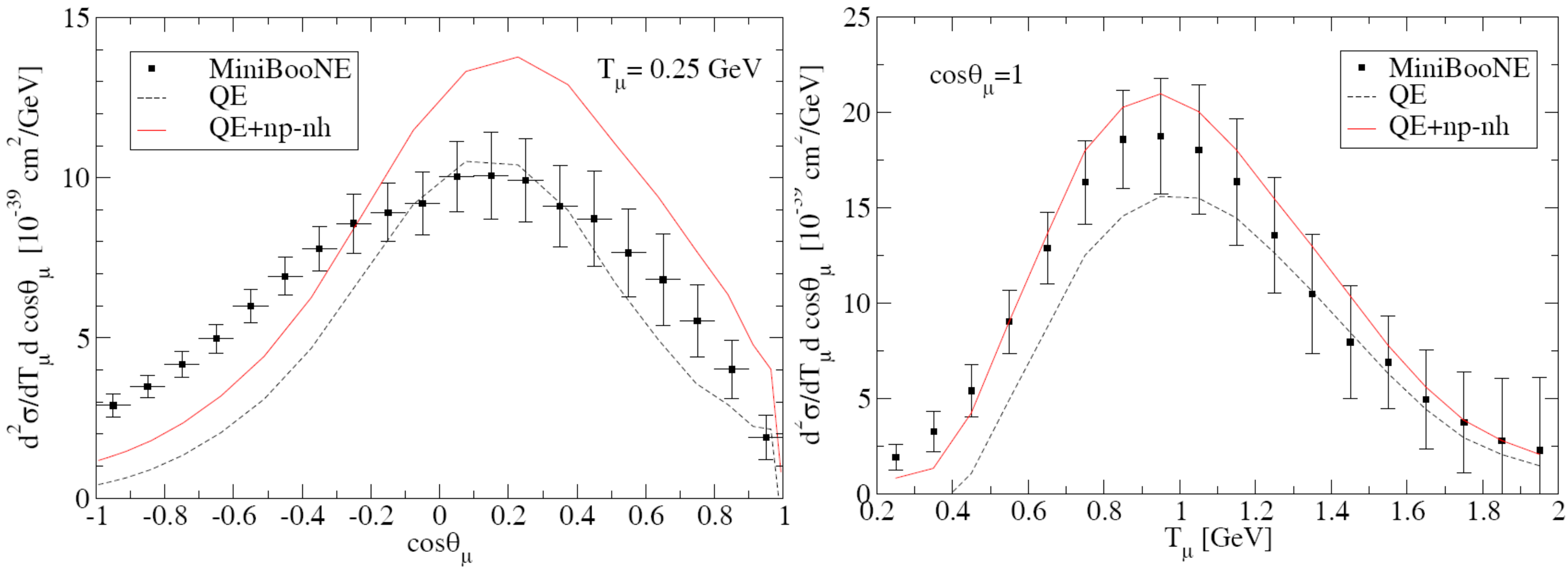
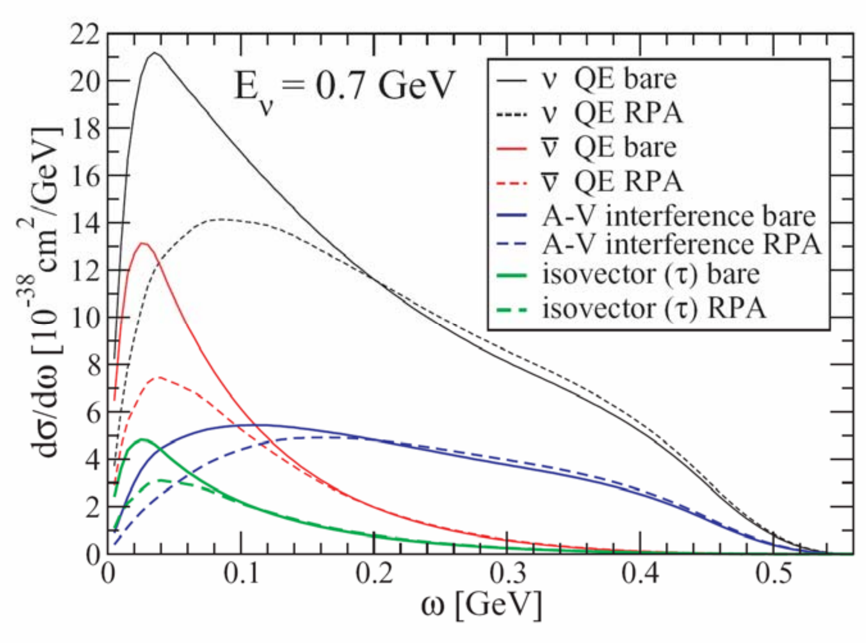
Fixed muon energy

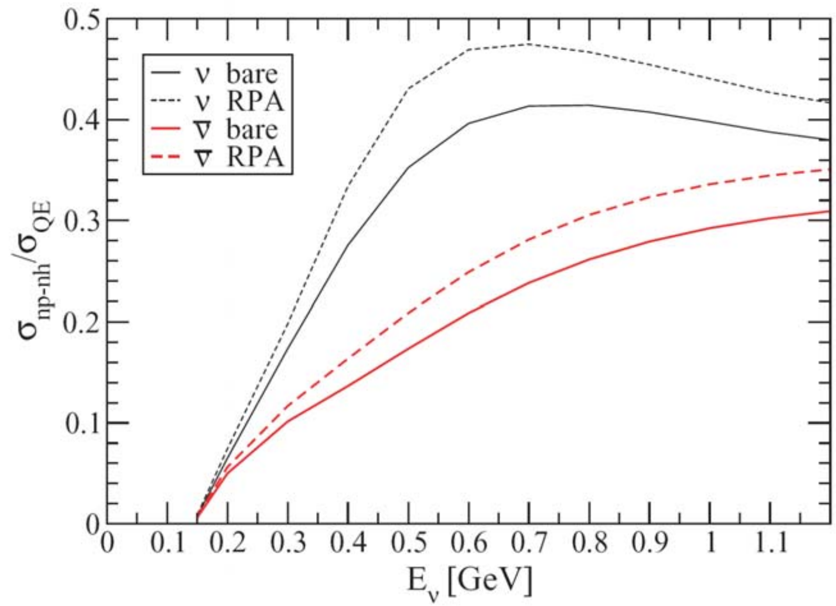
Fixed angle



N.B.
Final State Interaction for the outgoing nucleon not included

Neutrino vs Antineutrino QE scattering



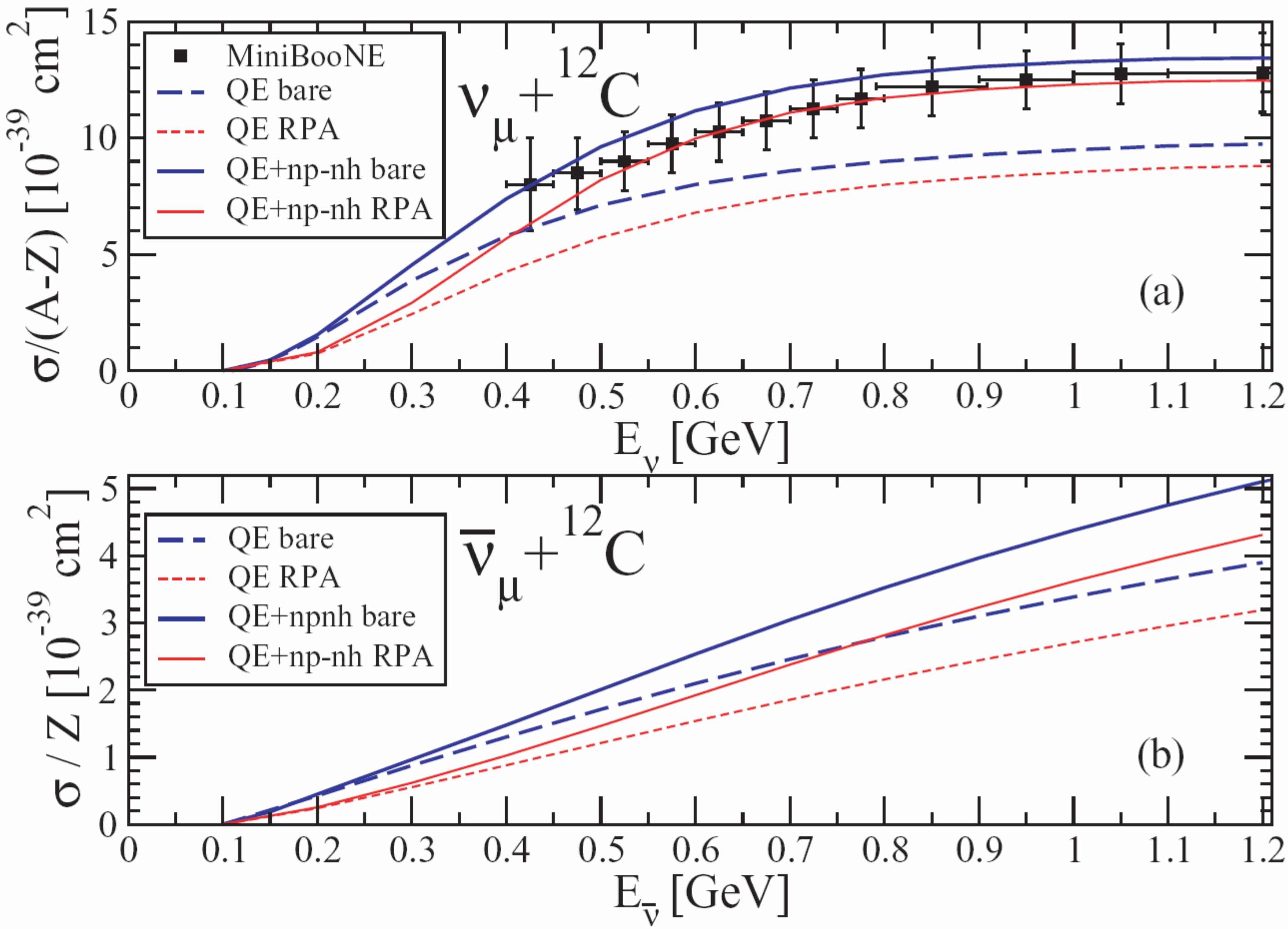


$$\frac{\partial^2\sigma}{\partial\Omega\,\partial k'} = \frac{G_F^2\,\cos^2\theta_c\,(\boldsymbol{k}')^2}{2\,\pi^2}\,\cos^2\frac{\theta}{2}\,\left[G_E^2\,(\frac{q_\mu^2}{\boldsymbol{q}^2})^2\,R_\tau^{NN}\right.$$
$$+\;G_A^2\,\frac{(M_\Delta - M_N)^2}{2\,\boldsymbol{q}^2}\,R_{\sigma\tau(L)}^{N\Delta} + G_A^2\,\frac{(M_\Delta - M_N)^2}{\boldsymbol{q}^2}R_{\sigma\tau(L)}^{\Delta\Delta}$$
$$+\;\left(G_M^2\,\frac{\omega^2}{\boldsymbol{q}^2} + G_A^2\right)\left(-\frac{q_\mu^2}{\boldsymbol{q}^2} + 2\tan^2\frac{\theta}{2}\right)\left(R_{\sigma\tau(T)}^{NN} + 2R_{\sigma\tau(T)}^{N\Delta} + R_{\sigma\tau(T)}^{\Delta\Delta}\right)$$
$$\left.\pm\;2\,G_A\,G_M\,\frac{k+k'}{M_N}\,\tan^2\frac{\theta}{2}\,\left(R_{\sigma\tau(T)}^{NN} + 2R_{\sigma\tau(T)}^{N\Delta} + R_{\sigma\tau(T)}^{\Delta\Delta}\right)\right]$$

np-nh only affects magnetics and axial responses; no isovector

Interference: suppression for $\bar\nu$

Test of "Quasielastic" anomaly: antineutrino scattering



The role of the np-nh is smaller for antineutrinos

Summary

Theory of neutrino interactions with nuclei

Nuclear responses treated in RPA

Unified description of several channels:

- Quasielastic ⇔ E_ν reconstruction
- Pion production ⇔ CC1π backgr. of CCQE; NC π^0 backgr. of ν_e appearance
- Multi-nucleon emission ⇔ QE like scattering

Evolution with the mass number (12→40): partial cross-sections scales with *A*

Collective effects in the coherent channel

Successful comparison to the available experimental data
(K2K, MiniBooNE, SciBooNE)

Multi-nucleon component quite relevant for the interpretation of the experiments, in particular for the QE of MiniBooNE

Test of "Quasielastic" anomaly: antineutrino scattering

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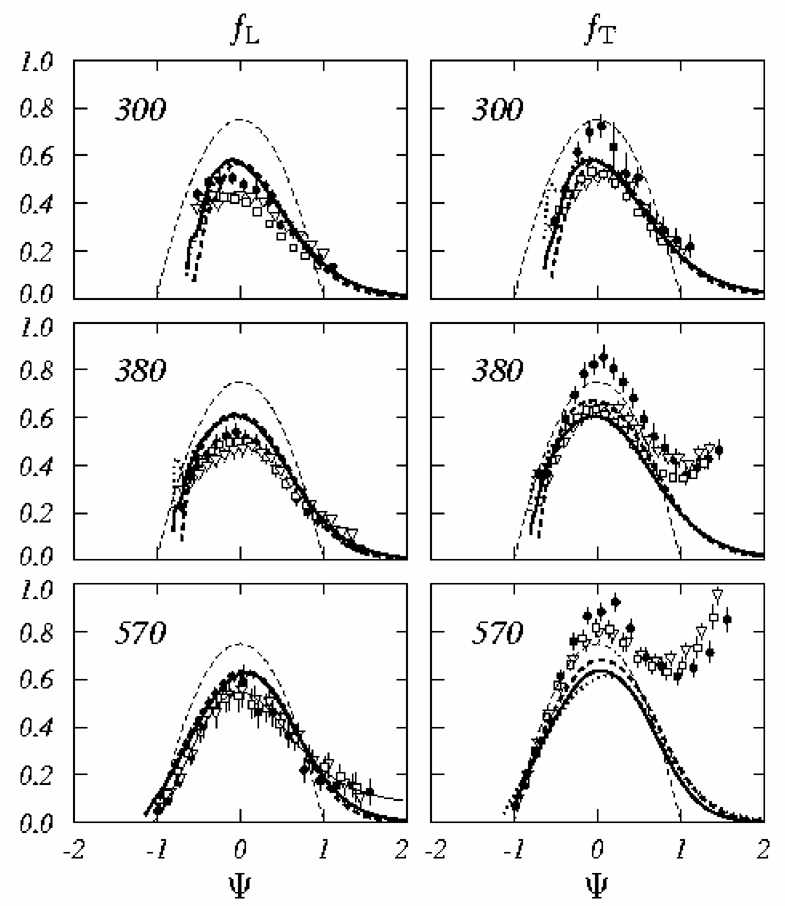
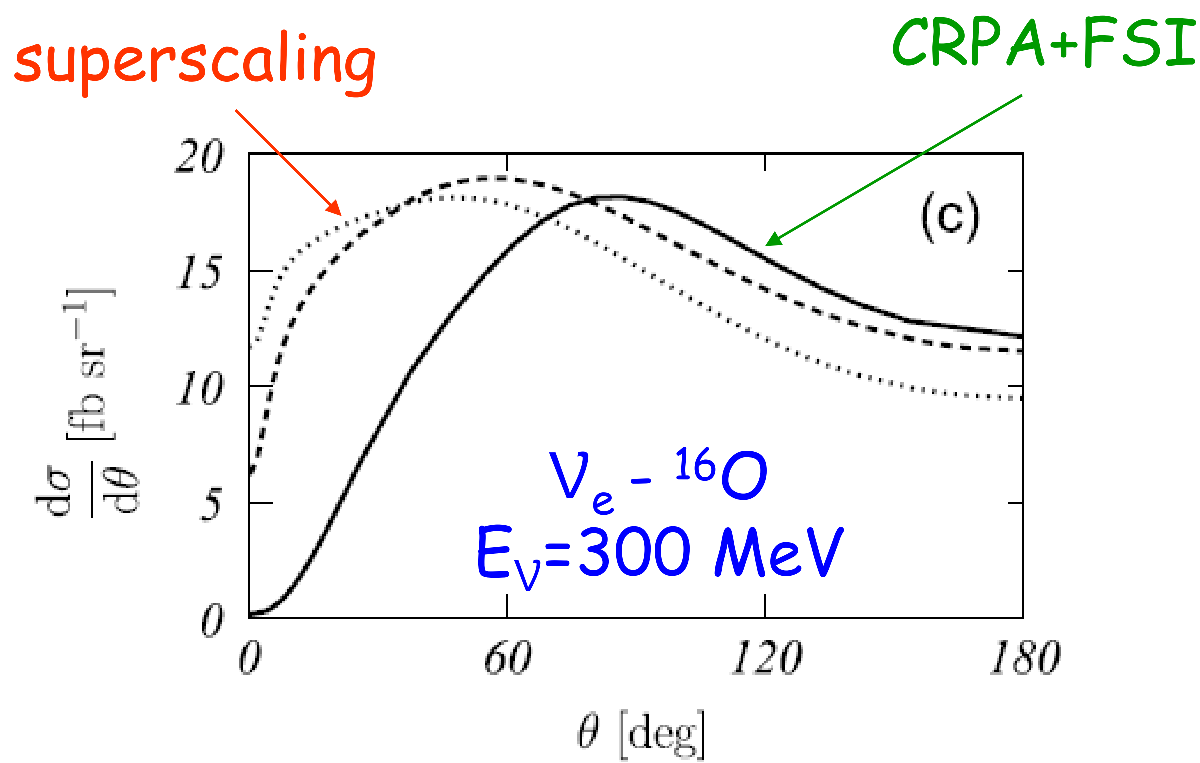
Spares

energie atomique • energies alternatives

Superscaling approach



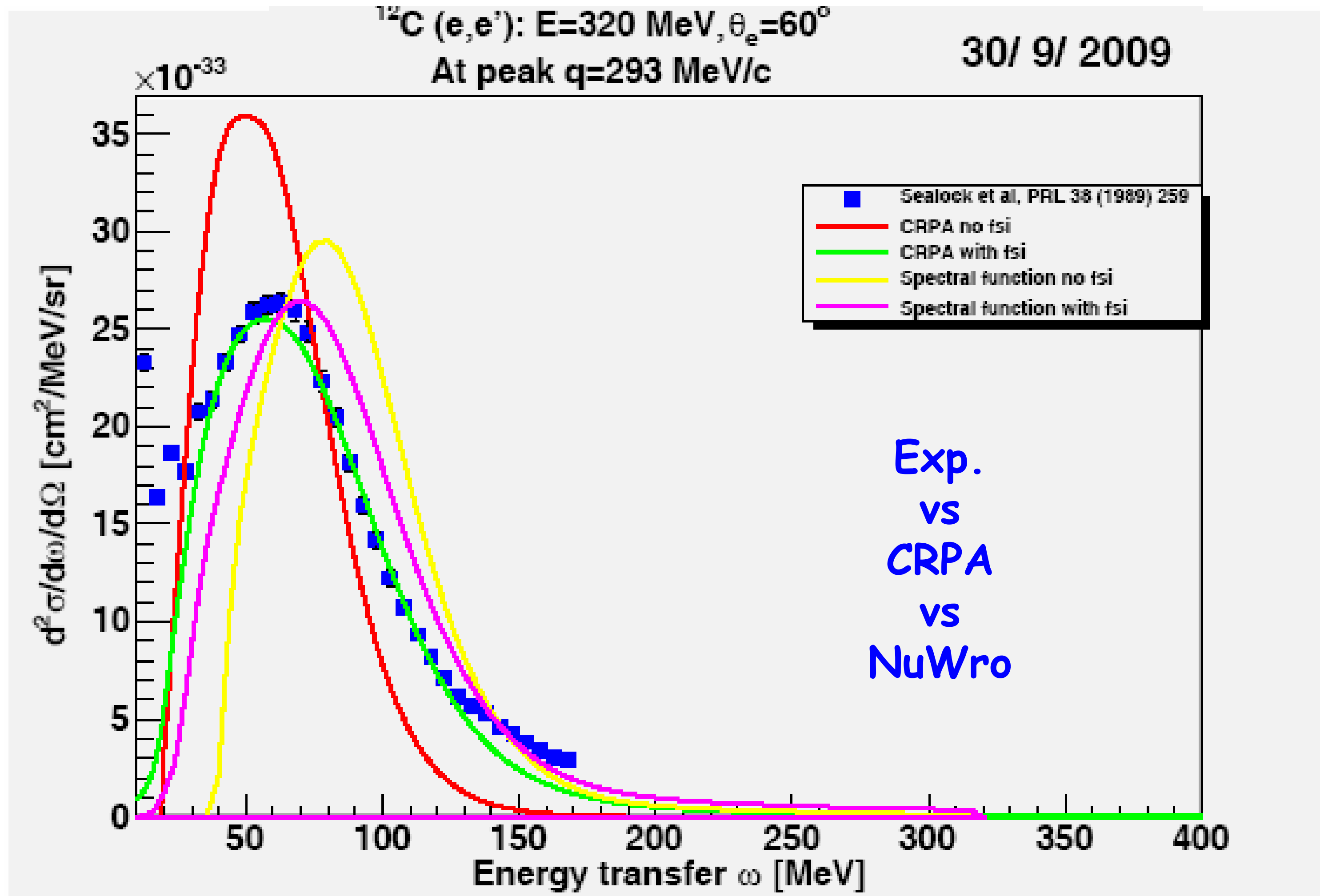


Experimental points:
^{12}C, ^{40}Ca, ^{56}Fe

M. Martini, G. Co', M. Anguiano, A. Lallena, Phys. Rev. C 75, 034604 (2007)

Electron-nucleus scattering

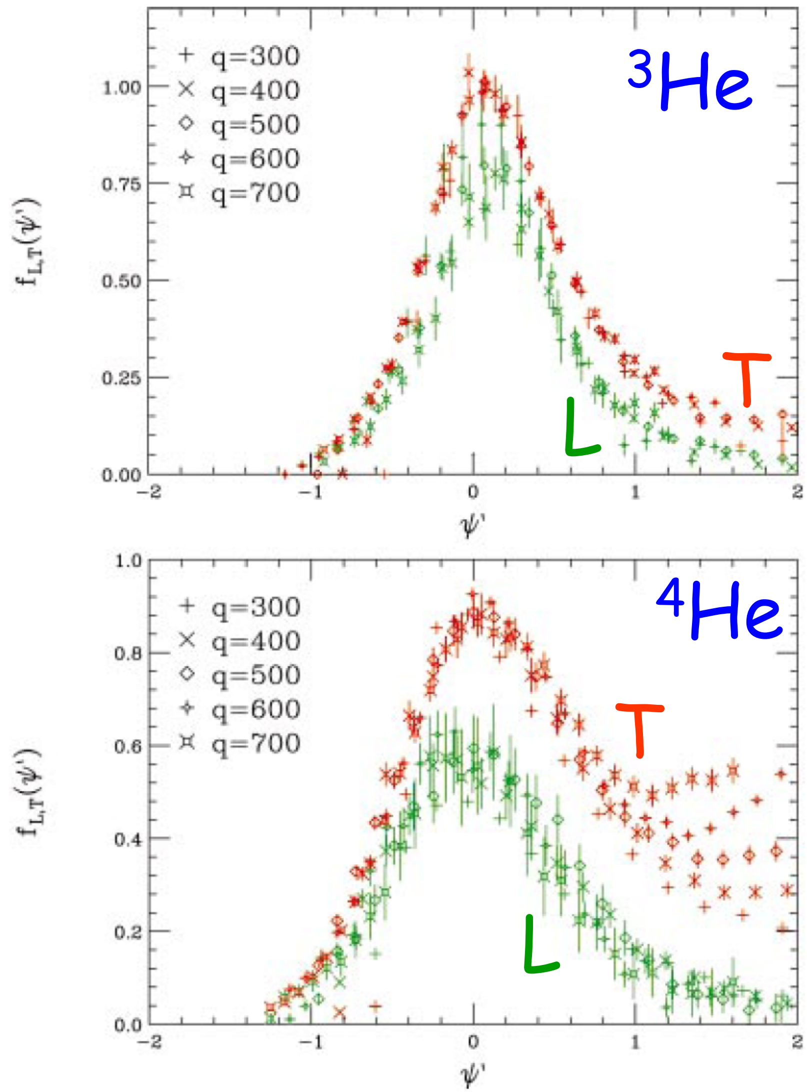
Role of FSI



PHYSICAL REVIEW C, VOLUME 65, 024002

Longitudinal and transverse quasielastic response functions of light nuclei

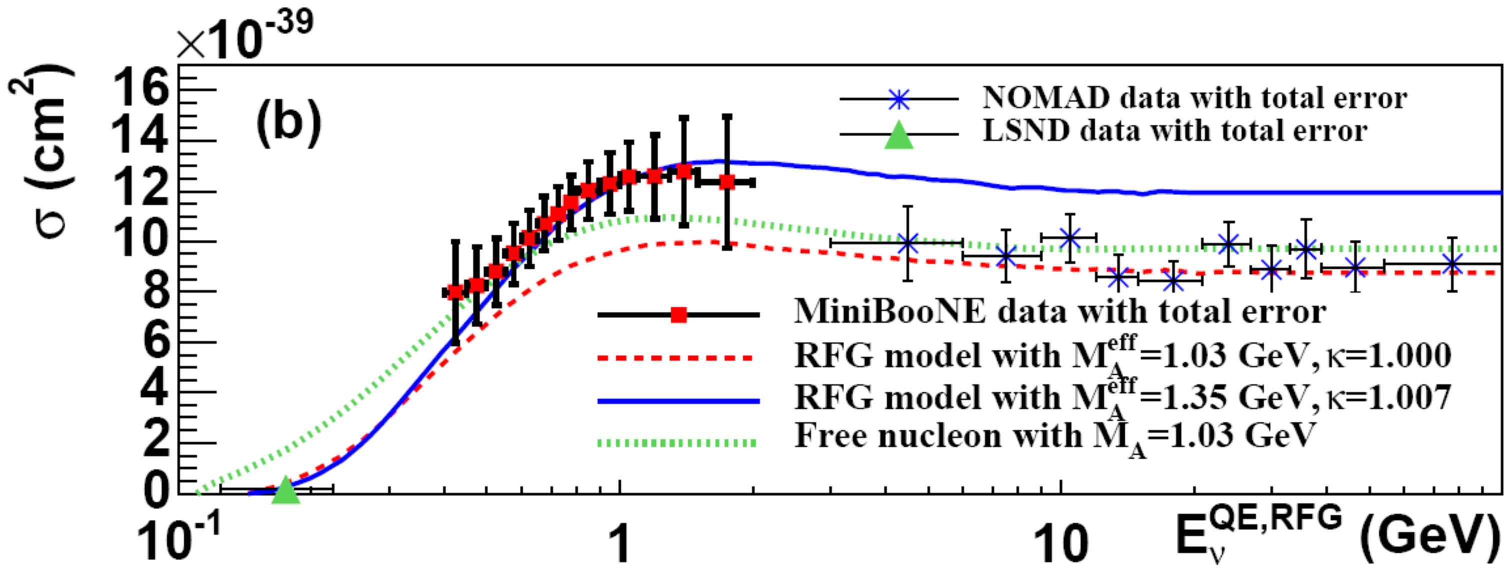
J. Carlson,[1] J. Jourdan,[2] R. Schiavilla,[3,4] and I. Sick[2]



Finally, the role of tensor interactions and correlations has been investigated via model studies of the ^{4}He Euclidean transverse response function, using simplified interactions, currents, and wave functions. In contrast to earlier speculations [21] that the large enhancement from two-body currents was due to the presence of strong tensor correlations in the ground state, it is now clear that this enhancement arises from the concerted interplay of tensor interactions and correlations in both ground and scattering states. A successful prediction of the longitudinal and transverse response functions in the quasielastic region demands an accurate description of nuclear dynamics, based on realistic interactions and currents.

Observed increase of the quasielastic cross section

might reflect the underlying nuclear (rather than nucleon's) physics



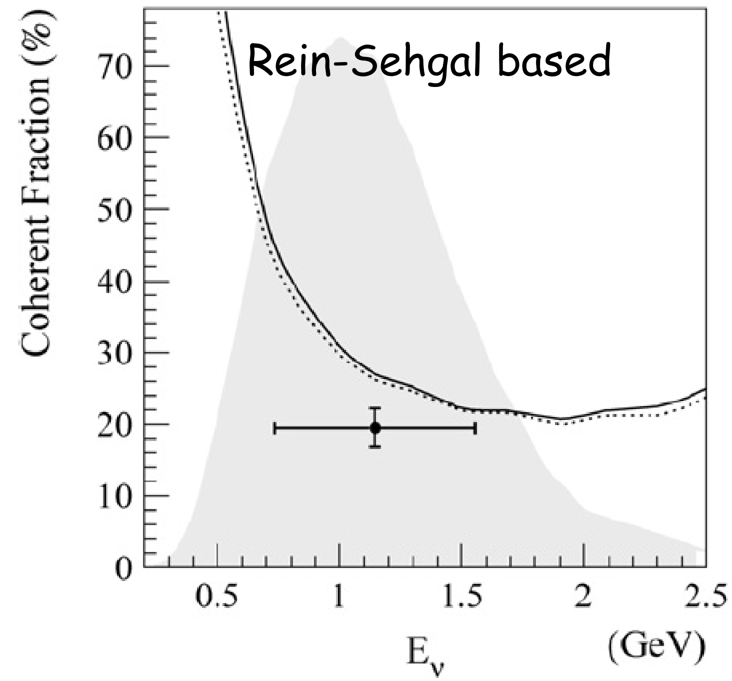
It is interesting that the MiniBooNE measurement is also larger than this free nucleon value (at least at higher energies). This may indicate a significant contribution from neglected mechanisms for CCQE-like scattering from a nucleus such as multi-nucleon processes (for example, Ref. [17]). This may explain both the higher cross section and the harder Q^2 spectrum, but has not yet been explicitly tested. It may also be relevant for the difference between these results and those of NOMAD (or other experiments) where the observation of recoil nucleons enter the definition of a CCQE event.

MiniBooNE,
Phys. Rev. D 81, 092005 (2010)

Neutral current coherent π^0 production

MiniBooNE, Phys. Lett. B 664, 41 (2008)

$$\frac{\sigma\ \pi^0_{\text{coherent}}}{\sigma\ \pi^0_{\text{total}}} = 19.5 \pm 1.1(\text{stat}) \pm 2.5(\text{sys})\ \%$$



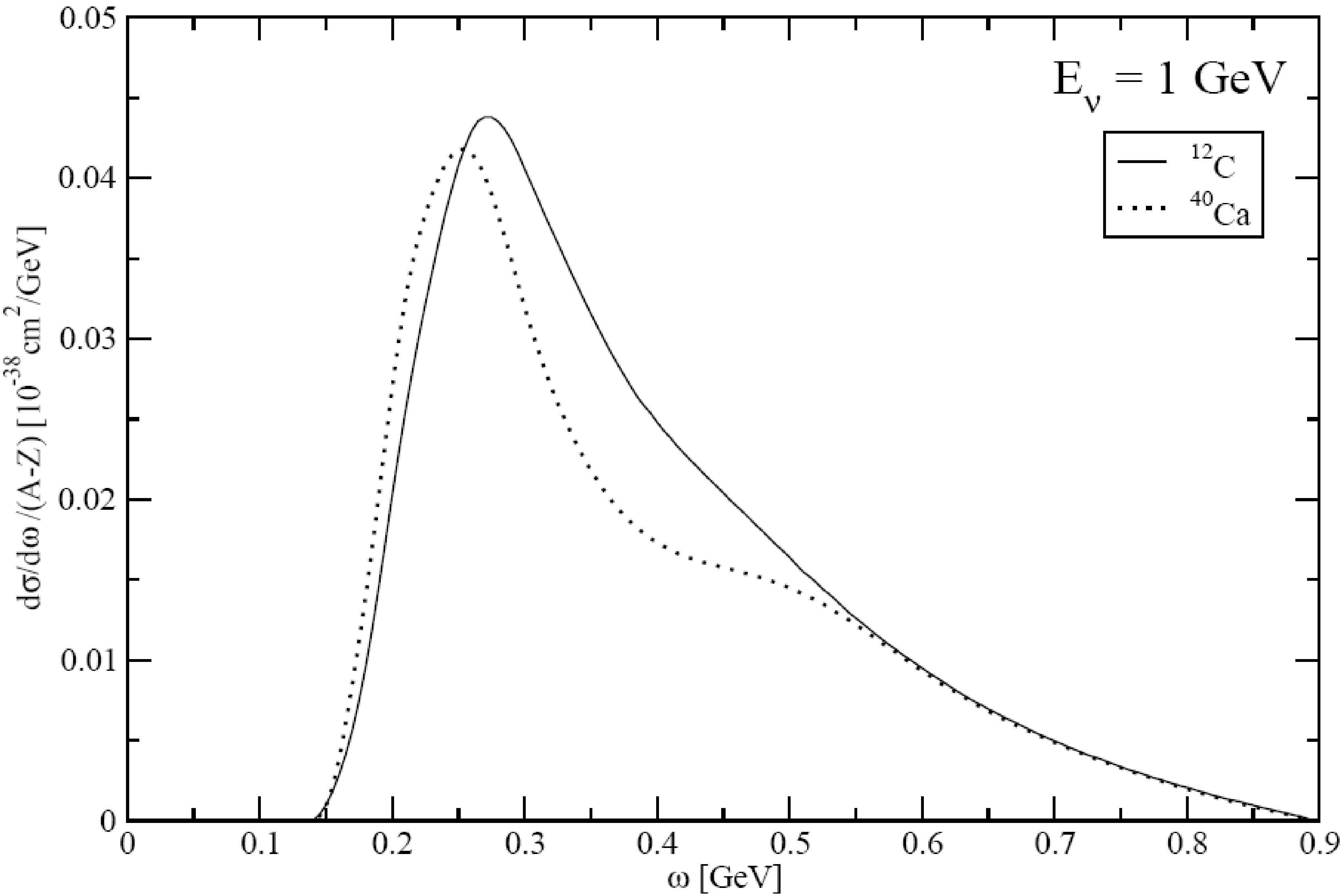
Our ratio: 6%

Difficult to reconcile with data

A problem that other groups also face

Compatibility with π^+ coherent production ?

ν_μ induced coherent pion production



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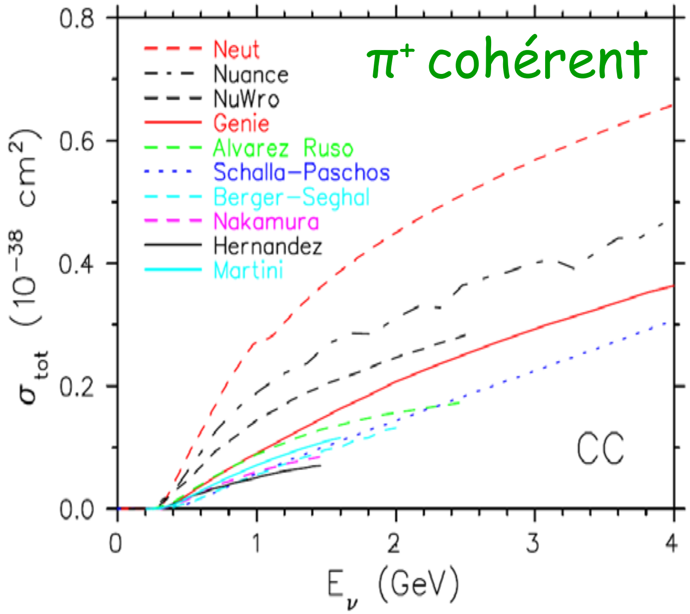

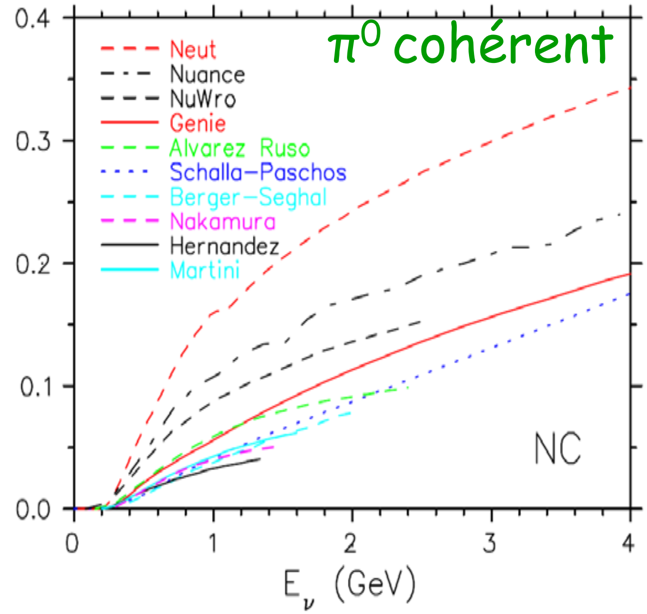

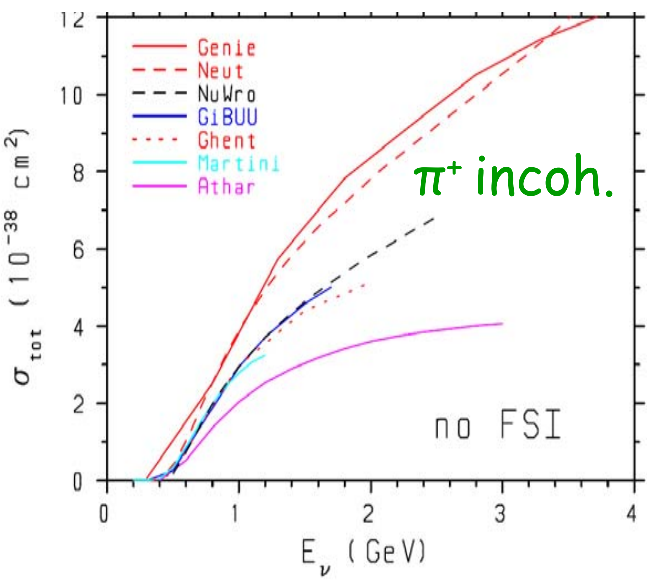

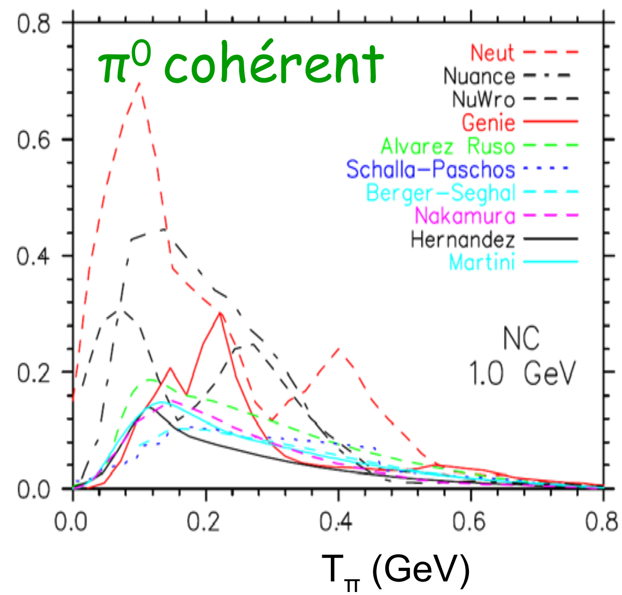

Monte Carlo

QE: Fermi Gas

π prod:Rein-Sehgal

- Neut: SuperKamiokande, K2K, T2K, SciBooNE
- Nuance: SuperKamiokande, MINOS, MiniBooNE
- Genie: T2K, MINOS, Minerva, NOvA, ArgoNEUT
- NuWro: Wroclaw theo. group

MC larger than microscopic models

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2.E

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THE ABSORPTIVE PION-NUCLEUS OPTICAL POTENTIAL

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Abstract: We calculate s-wave and p-wave absorptive pion-nucleus optical potentials assuming that a pion is absorbed by a pair of nucleons. Employing a model which takes into account both a single nucleon absorption with nucleon-nucleon correlations and rescattering, we obtain simple analytic expressions for Im B_0 and Im C_0 of the pion-nucleus optical potential. The off-shell effect on the s-wave pion absorption is examined and shown to be strongly modified by short range correlations. The result for the p-wave absorptive part Im C_0 clearly shows the importance of the tensor correlations. The enhanced nn emission after π^- absorption is shown to be related with a large p-wave πN scattering length a_{33} via the tensor correlations.

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Microscopic evaluation: Alberico, Ericson, Molinari, Ann. Phys. 154, 356 (1984)

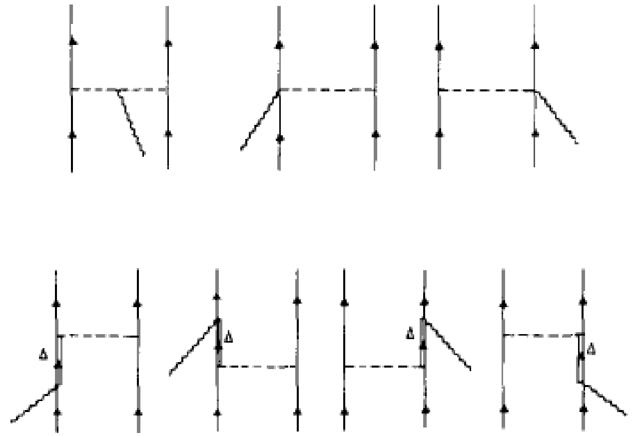

FIG. 2. The meson exchange current diagrams. In the upper graphs the pion-in-flight and contact terms are shown; in the lower graphs the pionic current is coupled to a Δ intermediate state.

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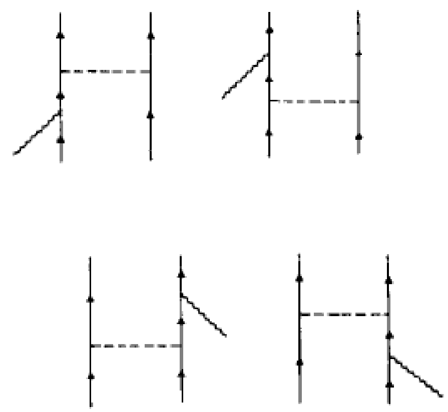
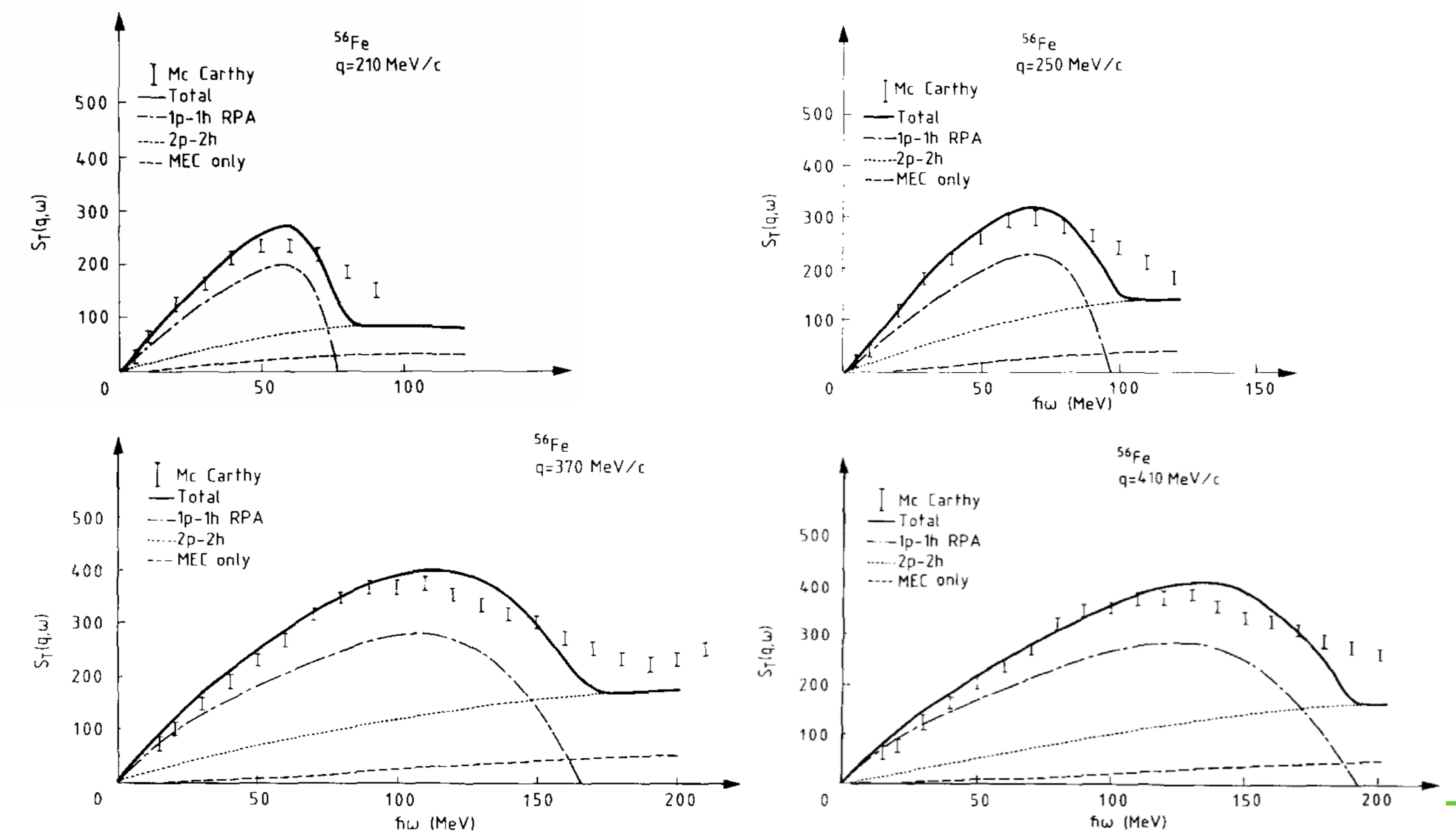


FIG. 5. Diagrams for the coupling of a photon to a pair of correlated nucleons (correlation "current").

Microscopic 2p-2h evaluation: Alberico et al. Ann. Phys. 154, 356 (1984)



Fully relativistic framework (but not NN 2p-2h contribution)

De Pace, Nardi, Alberico, Donnelly, Molinari
"Role of 2p - 2h MEC excitations in superscaling"
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