energie atomique • energies alternatives

Quasielastic and two-body currents in neutrino interactions with nuclei

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

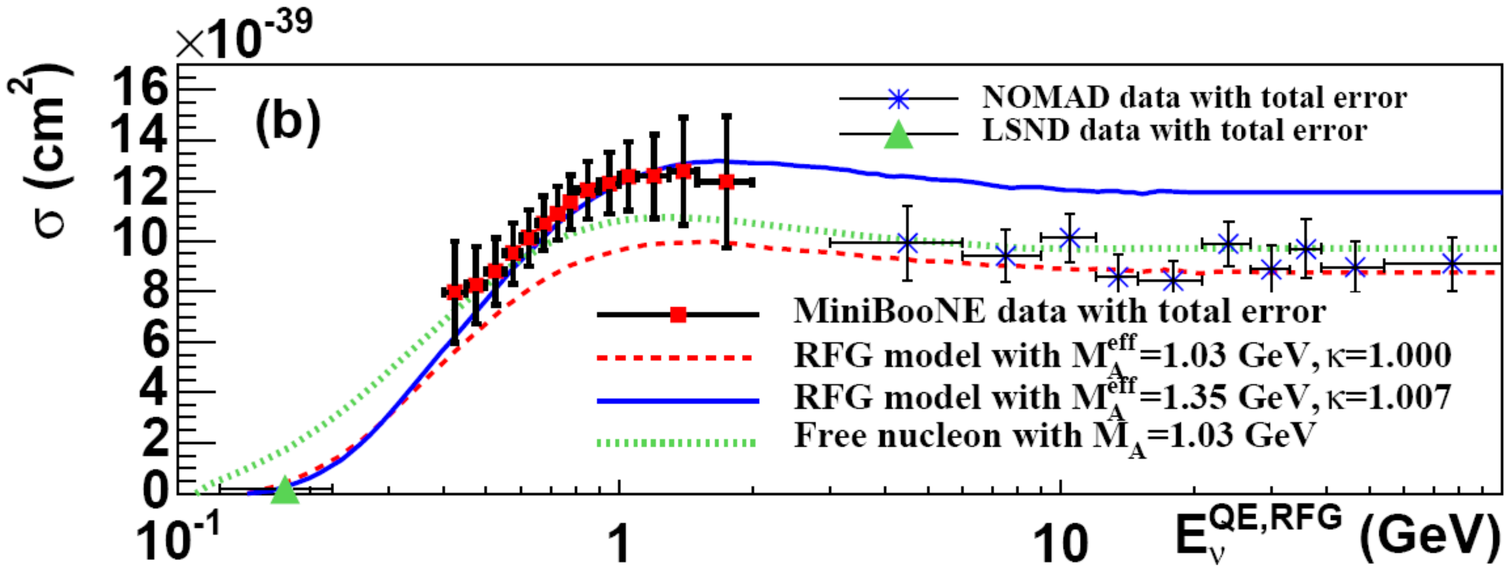
Outline

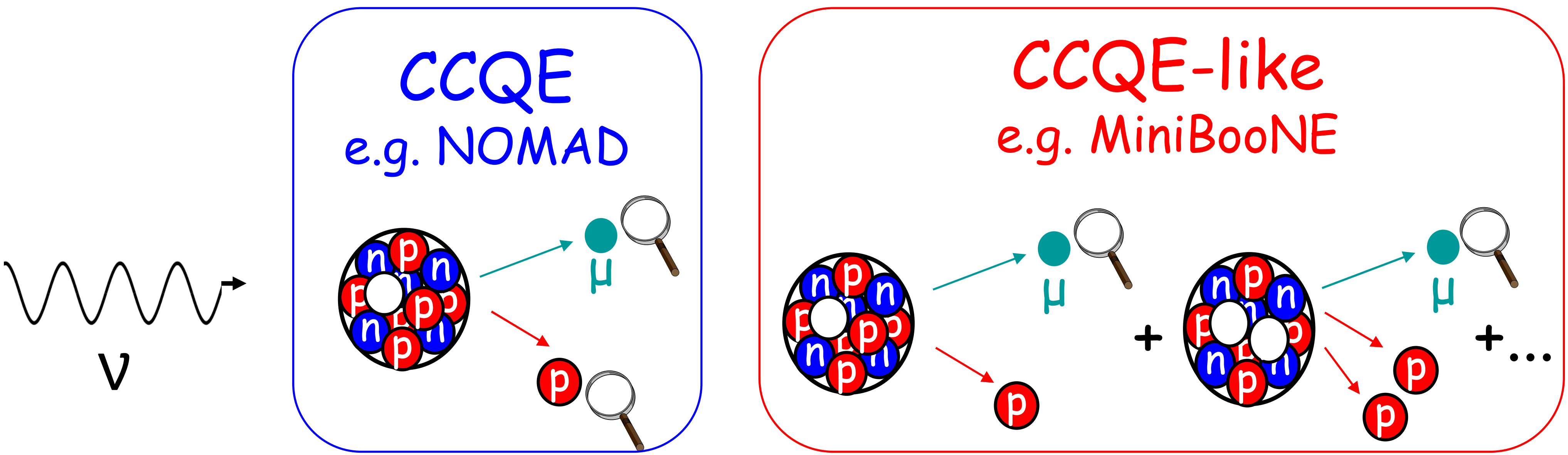
- Introduction
  - CCQE, CCQE-like and multinucleon emission
- Two body currents and 2p-2h excitations
  - phenomenology and microscopic calculations
  - tests of our parameterizations
  - effects in neutrino and antineutrino scattering
- Comparison with experiments
- Conclusions

Introduction

…starting from the end

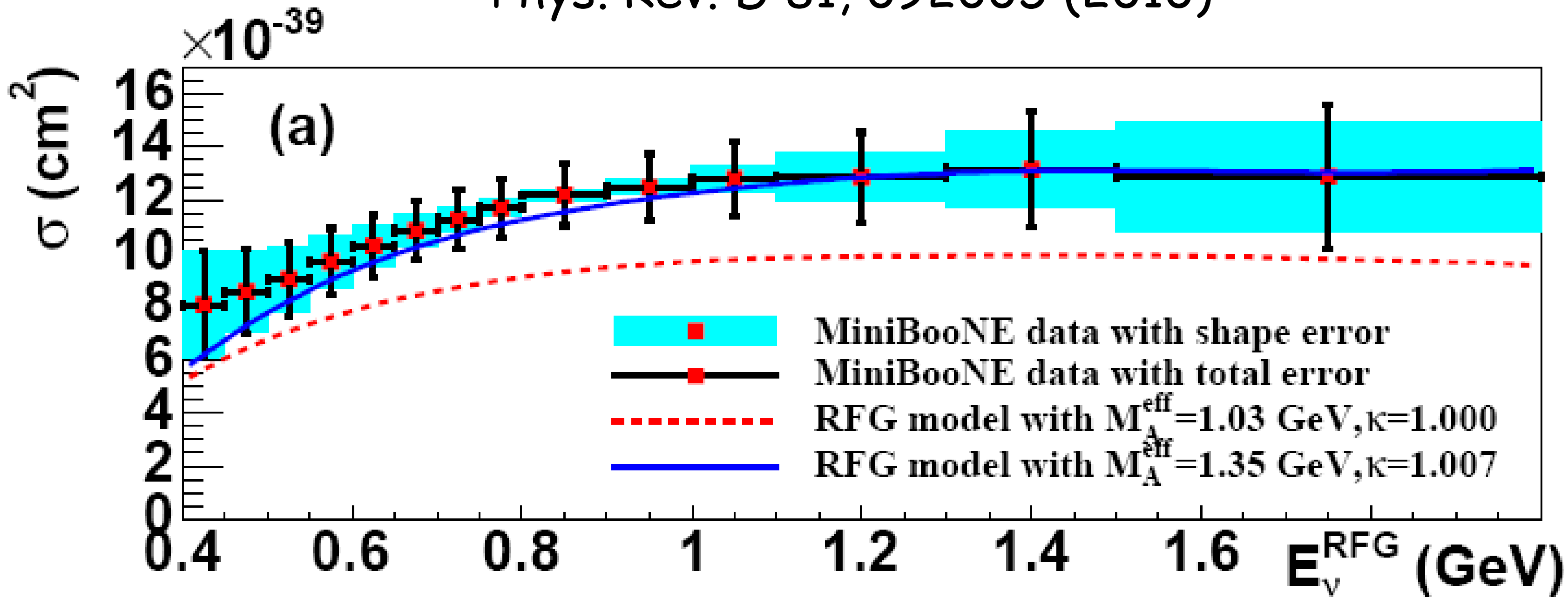
CCQE and CCQE-like





MiniBooNE analysis

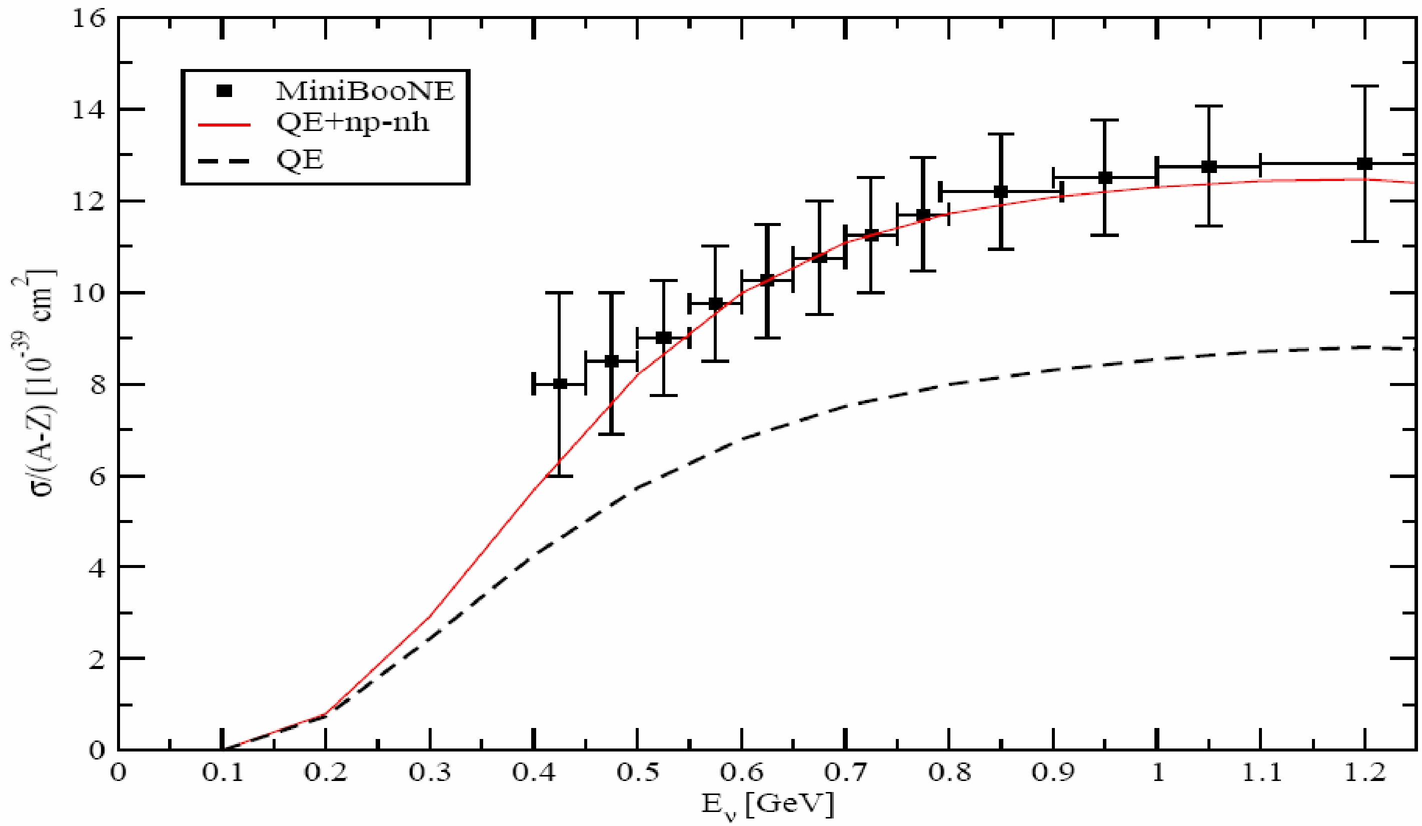
AIP Conf. Proc. 1189: 139-144 (2009);
Phys. Rev. D 81, 092005 (2010)



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

Including the multinucleon emission channel (np-nh)



Flux averaged:

MiniBooNE

9.4 10^{-39}cm^2 ± 11%

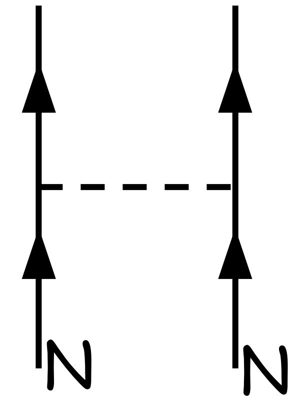
Our model
QE+np-nh (CCQE-like)
9.1 10^{-39} cm^2

Our model
genuine CCQE

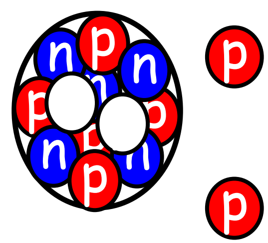
6.4 10^{-39} cm^2

M. Martini, M. Ericson, G. Chanfray, J. Marteau Phys. Rev. C 80 065501 (2009)

Agreement with MiniBooNE without increasing M_A



Two-body currents
and
Two particles-two holes excitations



Where 2p-2h enter in V-A cross-section?

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

$$+\quad G_A^2\,\frac{(M_\Delta-M_N)^2}{2\,\boldsymbol{q}^2}\,R_{\sigma\tau(L)}$$ isospin spin-longitudinal

$$+\quad\left(G_M^2\,\frac{\omega^2}{\boldsymbol{q}^2}+G_A^2\right)\left(-\frac{q_\mu^2}{\boldsymbol{q}^2}+2\tan^2\frac{\theta}{2}\right)R_{\sigma\tau(T)}$$ isospin spin-transverse

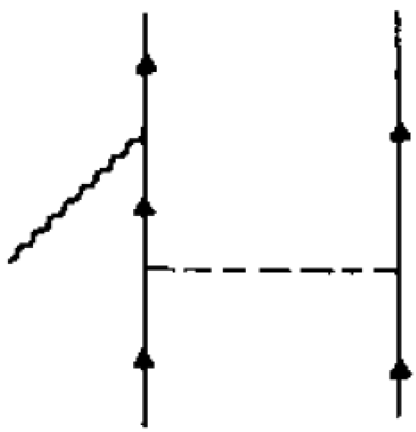
$$+\quad 2\,G_A\,G_M\,\frac{k+k'}{M_N}\,\tan^2\frac{\theta}{2}\,R_{\sigma\tau(T)}\Big]$$ interference V-A

The 2p-2h term affects the magnetic and axial responses (terms in G_A ,G_M)
(spin-isospin, $\sigma\tau$ excitation operator)

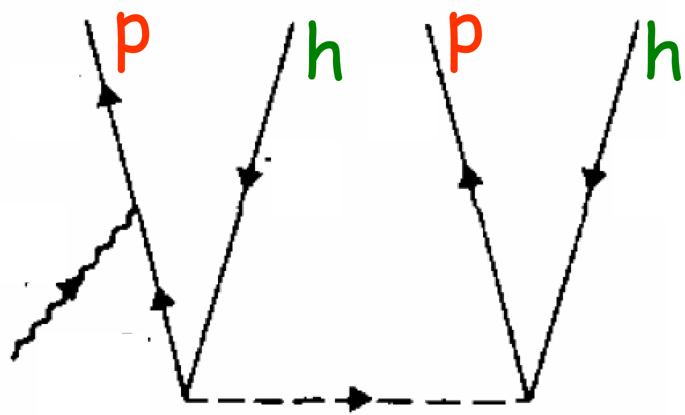
The isovector response R_τ (term in G_E) is not affected

Three equivalent representations of the same process

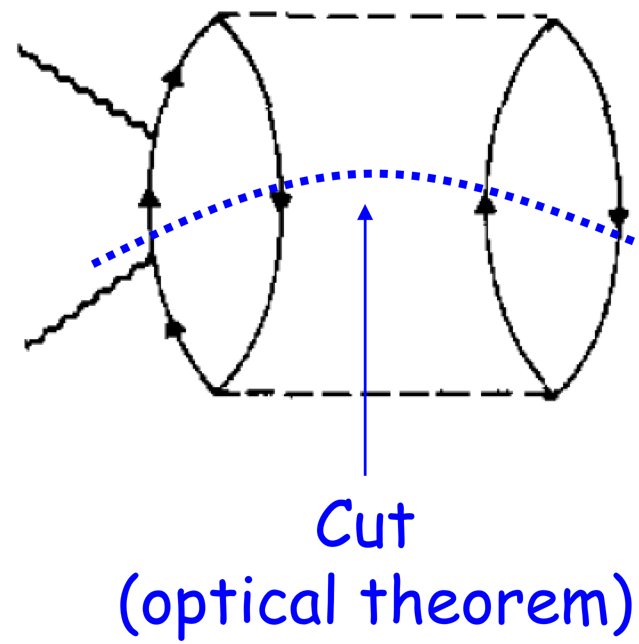
2 body current



2p-2h matrix element



2p-2h response



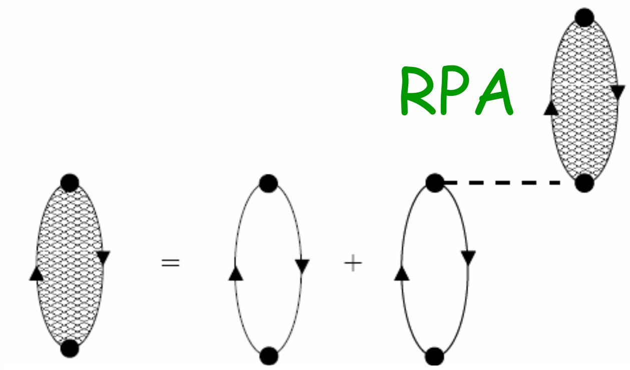
Final state: two particles-two holes

Why we prefer the response picture ?

Our model is based on RPA treatment of response functions

$$R(\omega, q) = -\frac{\mathcal{V}}{\pi}\,\mathrm{Im}[\Pi(\omega, q, q)]$$

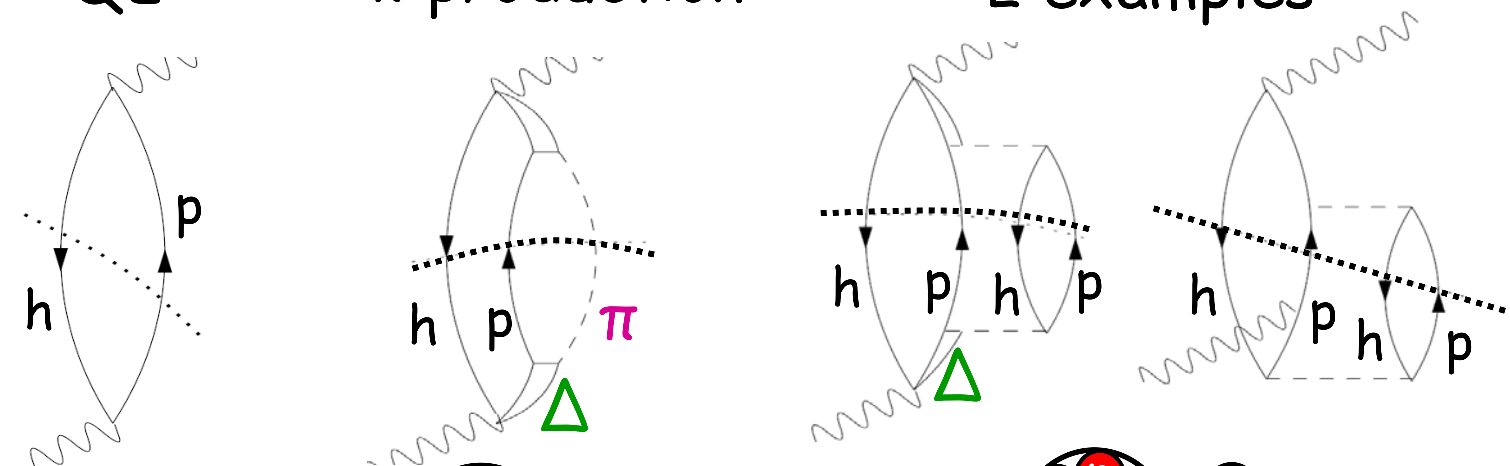
RPA

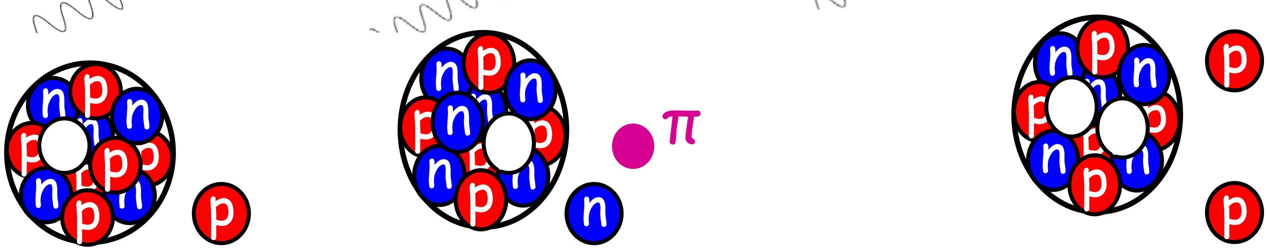


$$\Pi = \Pi^0 + \Pi^0\, V\, \Pi$$

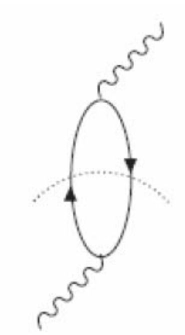
easy to separate the several channels

1p-1h QE	1p-1h π production	2p-2h: 2 examples





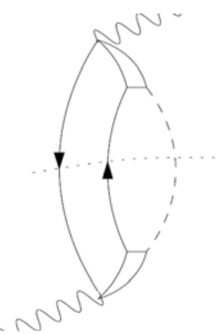
Some starting point formulas (1p-1h sector)



Particle-hole bare polarization propagator (Fermi Gas)

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

$\longrightarrow$ Quasielastic



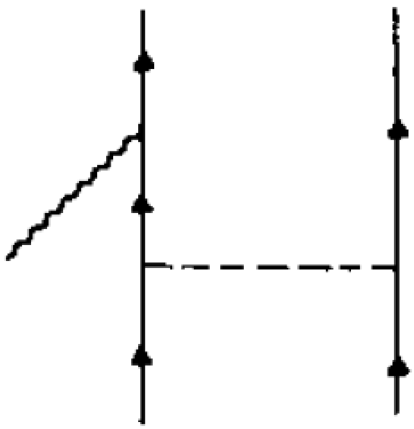
Delta-hole

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

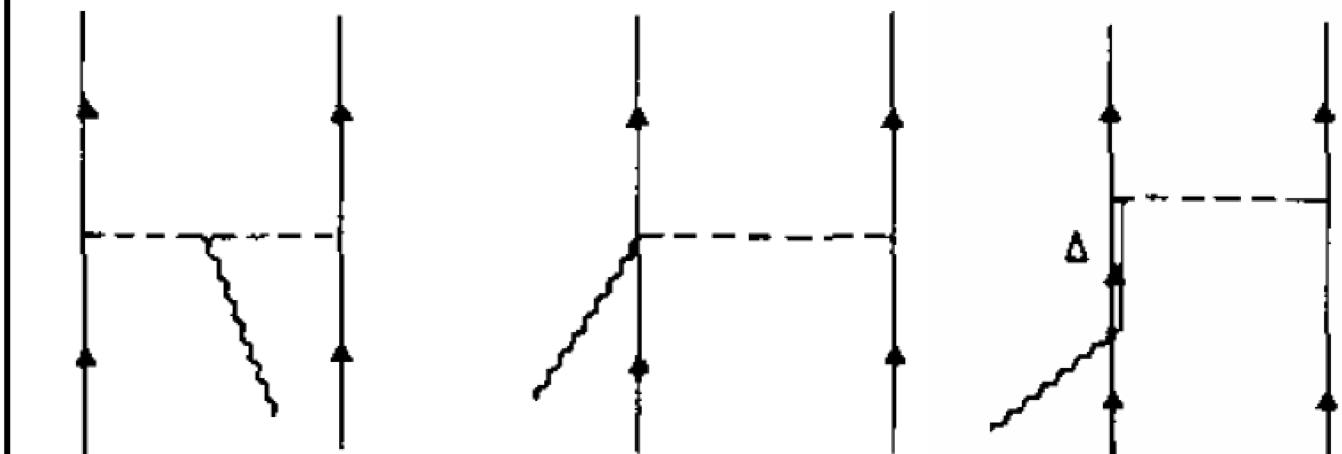
$\longrightarrow$ Pion production

Some diagrams for 2 body currents

Nucleon-Nucleon correlations



Meson Exchange Currents (MEC)



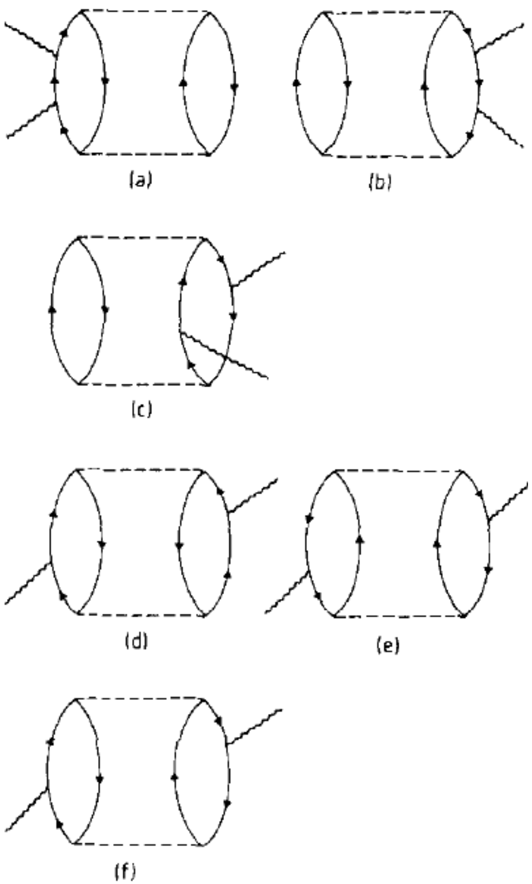
Pion in flight (only for vector)

Contact

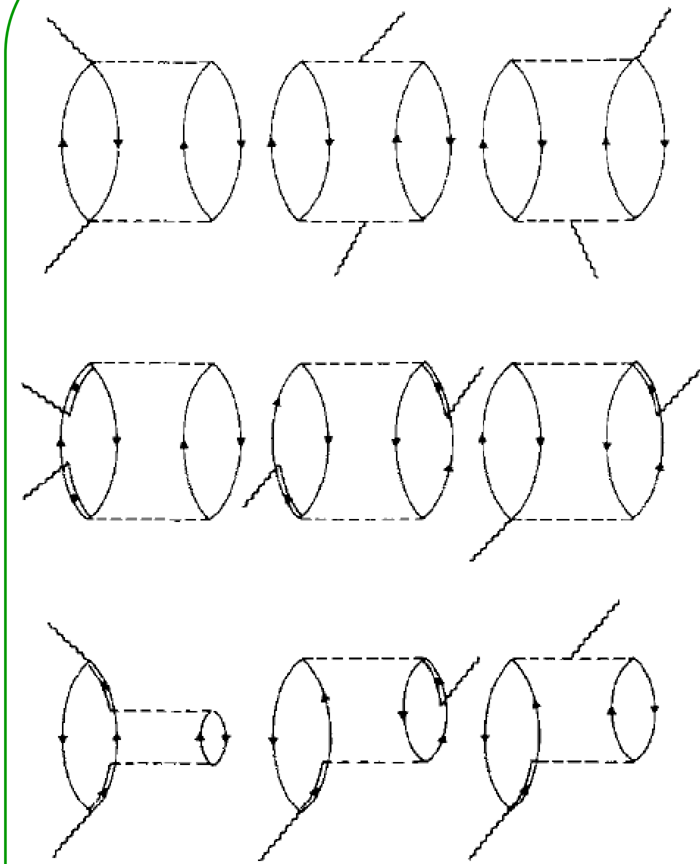
Delta

Destructive interference

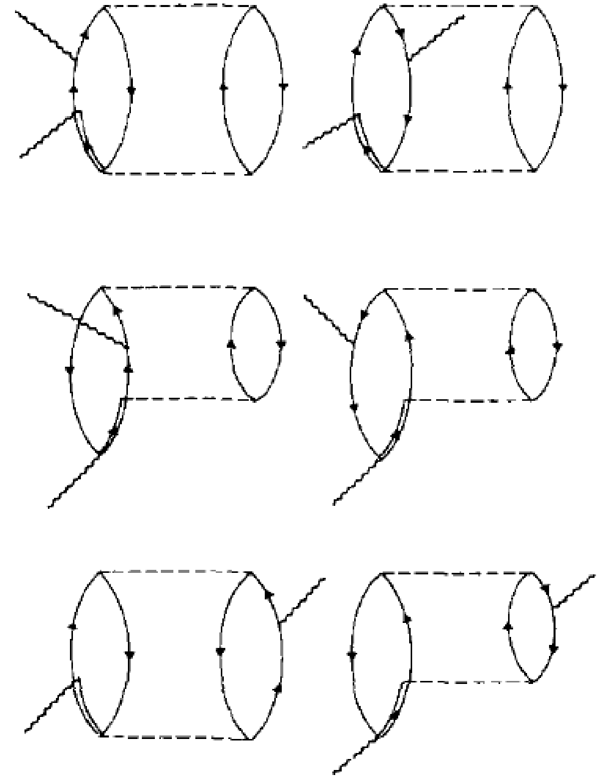
Some diagrams for 2p-2h responses



NN correlations



MEC

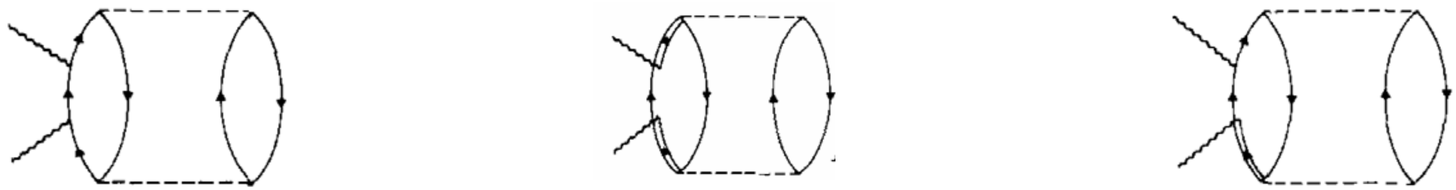


NΔ interference

Main difficulties in the 2p-2h sector

- **Huge number of diagrams**

  -non relativistic calculation



16 from NN correlations — 49 from MEC — 56 from NΔ interference

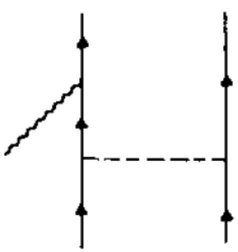
Alberico, Ericson, Molinari, Ann. Phys. 154, 356 (1984)

  - fully relativistic calculation (just of MEC !)

3000 direct terms — More than **100 000** exchange terms

De Pace, Nardi, Alberico, Donnelly, Molinari, Nucl. Phys. A741, 249 (2004)

- **Divergences in NN correlations** $(p_0 - E_{\mathbf{p}} + i\epsilon)^{-2}$



prescriptions:

-nucleon propagator only off the mass shell (*Alberico et al. Ann. Phys. 1984*)

-add nucleon self energy in the medium (*Gil et al. Nucl. Phys. A 627, 543 '97*)

-similar regularization but taking into account the finite size of the nucleus: regularization parameter to be fitted to data (*Amaro et al. 1008.0753*)

Other processes, with the same excitation operator (στ), where 2p-2h are relevant

•Pion absorption (2 body process, 1N absorption kinematically forbidden)

Absorptive part of the p-wave pion-nucleus optical potential at threshold

$$U^{\pi N}_{opt} = (4\pi/2m_\pi)\,\vec{\nabla}\cdot \mathrm{Im}C_0\ \rho^2\vec{\nabla}$$

$$\mathrm{Im}C_0 = -\frac{1}{\pi}\frac{f_\pi^2}{\mu_\pi^2}\frac{1}{\rho^2}\,\mathrm{Im}\,\Pi^{2p-2h}(q=0,\hbar\omega=m_\pi c^2)$$

experimental value $\mathrm{Im}C_0 \simeq 0.11 m_\pi^{-6}$

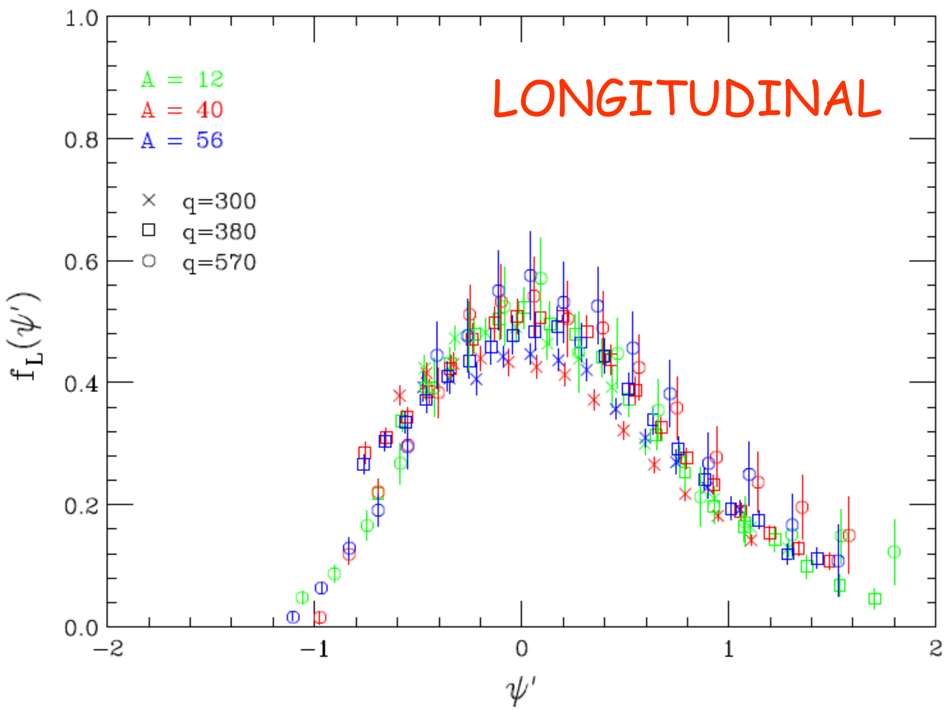
•Transverse response in electron scattering

$$\frac{d^2\sigma}{d\theta\, d\omega} = \sigma_M \left\{ \frac{(\omega^2-q^2)^2}{q^4} R_L(\omega,q) + \left[\tan^2\left(\frac{\theta}{2}\right) - \frac{\omega^2-q^2}{2q^2}\right] R_T(\omega,q) \right\}$$

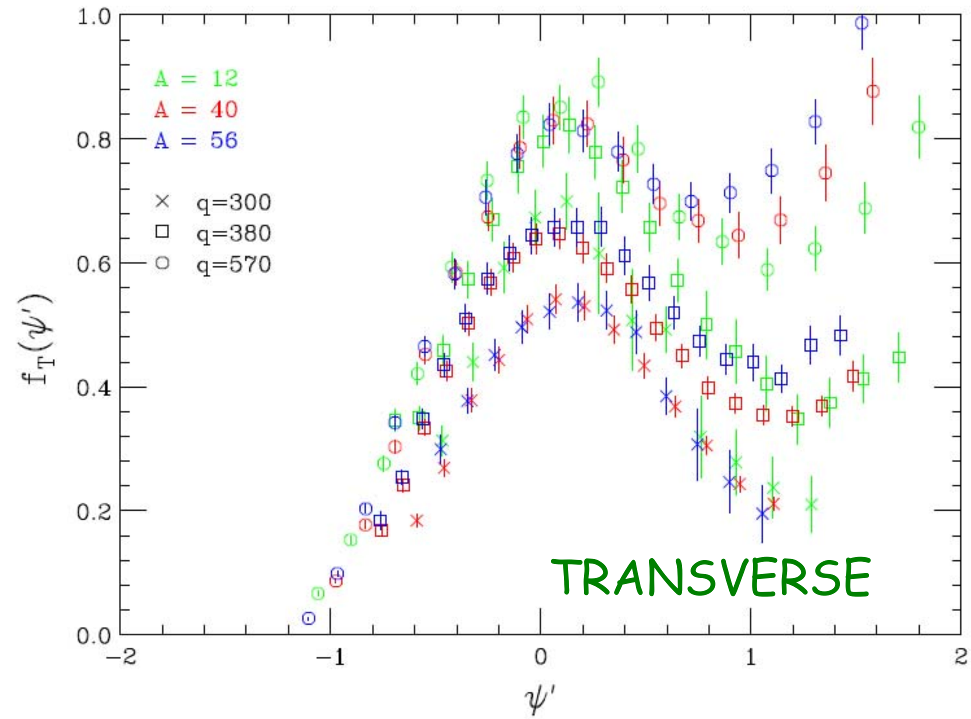
Scaling approach in electron scattering

$$f_{\mathrm{L}}(\Psi) = k_{\mathrm{F}} \frac{q^2-\omega^2}{q\,m} \frac{R_{\mathrm{L}}(\omega,q)}{Z\left(G_{\mathrm{E}}^{p}\right)^2 + N\left(G_{\mathrm{E}}^{n}\right)^2}$$

$$f_{\mathrm{T}}(\Psi) = 2\,k_{\mathrm{F}} \frac{q\,m}{q^2-\omega^2} \frac{R_{\mathrm{T}}(\omega,q)}{Z\left(G_{\mathrm{M}}^{p}\right)^2 + N\left(G_{\mathrm{M}}^{n}\right)^2}$$



Donnelly et al. PRC 60 '99,...



Superscaling: scaling with A and q

No superscaling: scaling with A, not with q

Excess in the transverse channel likely due to 2-body currents (MEC and correlations)

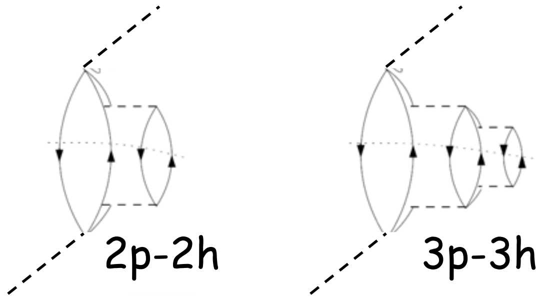
NB: the use of the longitudinal superscaling function in V scattering needs improvements!

Two different parameterizations of the multinucleon channel

a) from pion absorption
b) from electron scattering

a) 2p-2h contributions from pion absorption

- Reducible to a modification of the Delta width in the medium



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

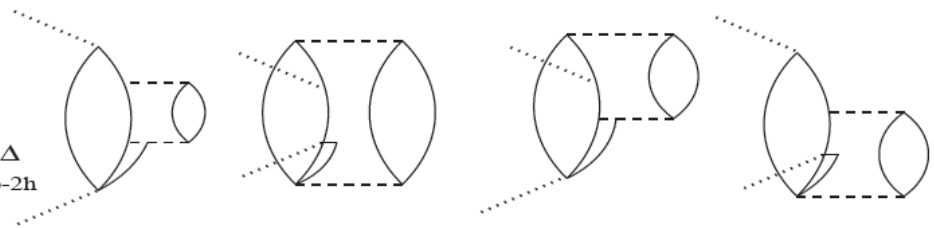
$$\widetilde{\Gamma_\Delta} = \Gamma_\Delta \; F_P - 2\mathrm{Im}(\Sigma_\Delta)$$

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

- Not reducible to a modification of the Delta width

e.g.

$\Pi^{N\Delta}_{2p\text{-}2h}$



Microscopic calculation of π absorption at threshold: **$\omega = m_\pi$**

Shimizu Faessler, Nucl. Phys. A 333,495 (1980)

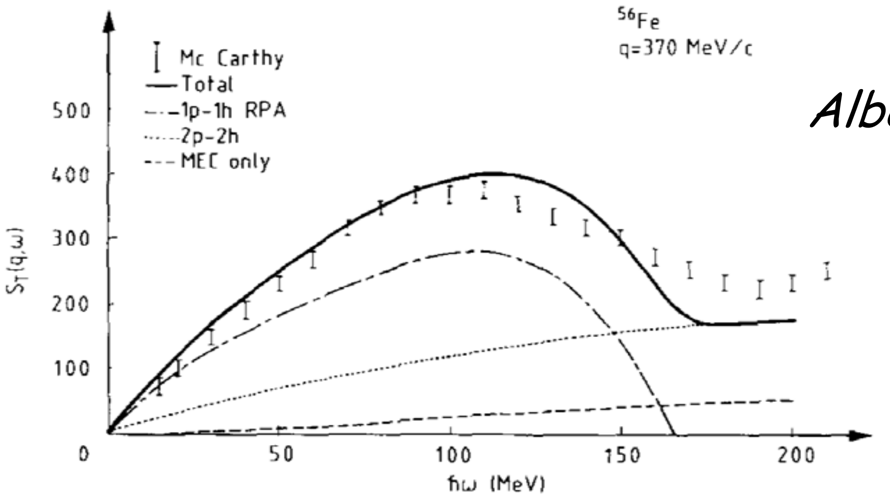
Extrapolation to other energies Delorme, Guichon, 2 proceedings (1989)

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

But no q dependence !!

b) 2p-2h contributions from R_T in electron scattering

Alternative treatment in order to have a q dependence in the 2p-2h sector



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

Transverse magnetic response of (e,e')

for some values of q and ω,but:

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

•Parameterization 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 $^{56}Fe \rightarrow {}^{12}C$

Global reduction ≈ 0.5 !!
for Carbon

A comparison between our 2009 parameterization using Alberico et al. and a recent preprint of Amaro et al.

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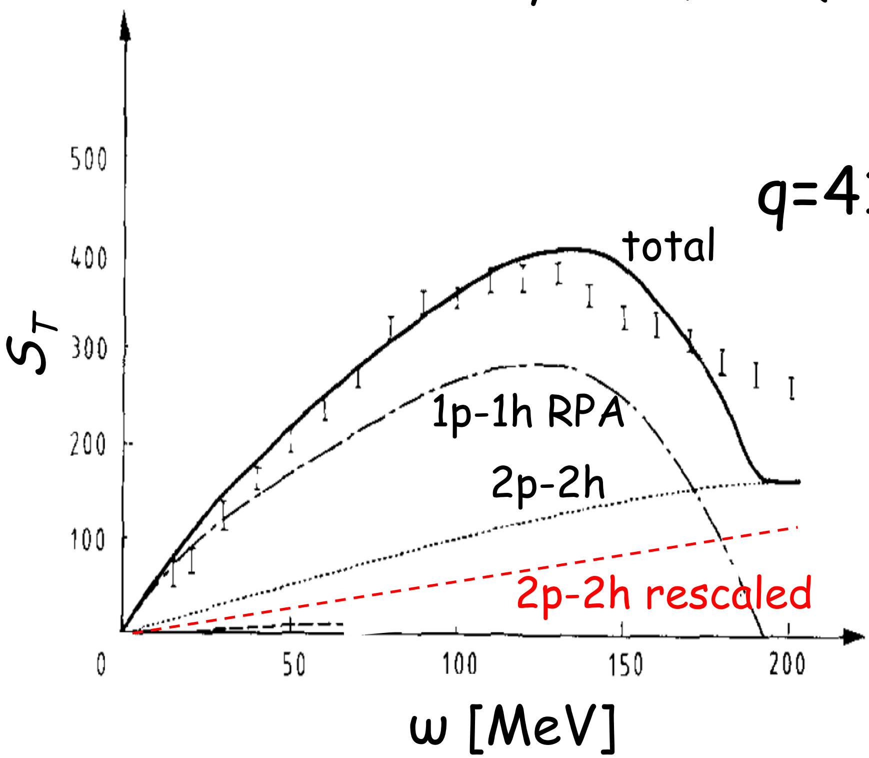
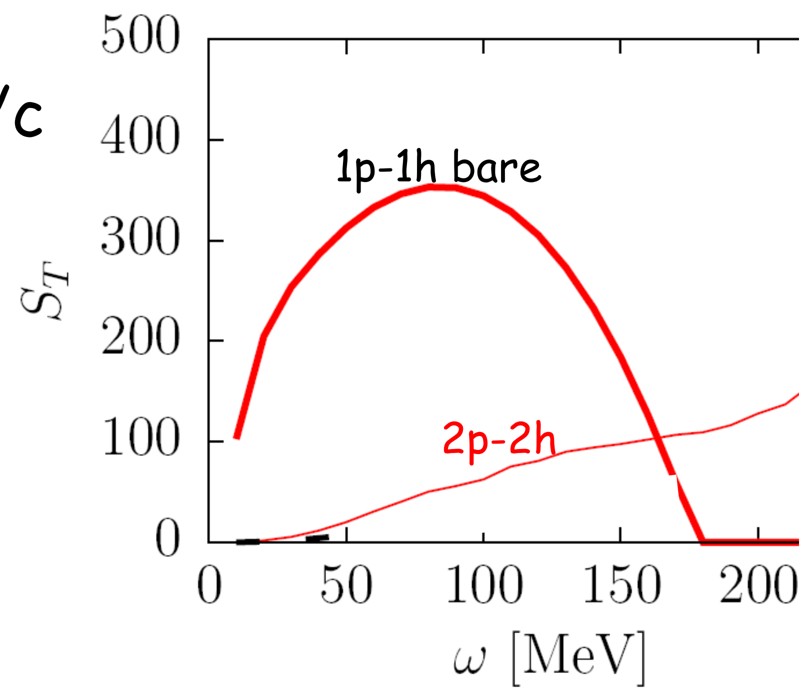
Alberico et al. Ann. Phys. 154, 356 (1984)

Amaro et al. arXiv. 1008.0753

^{56}Fe

q=410 MeV/c

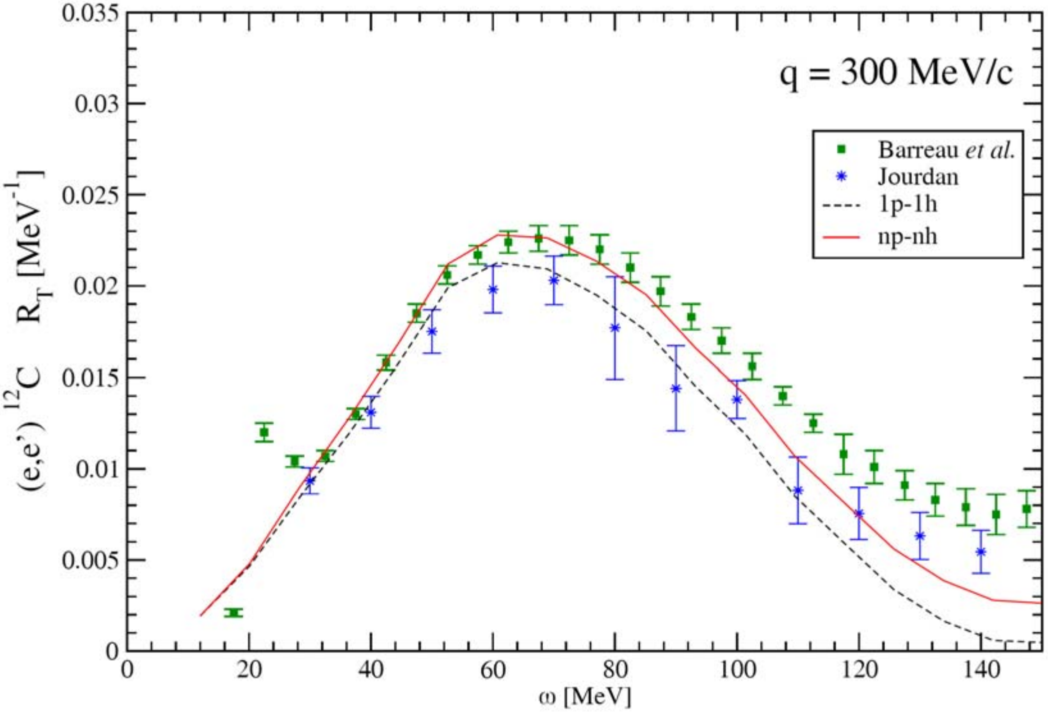




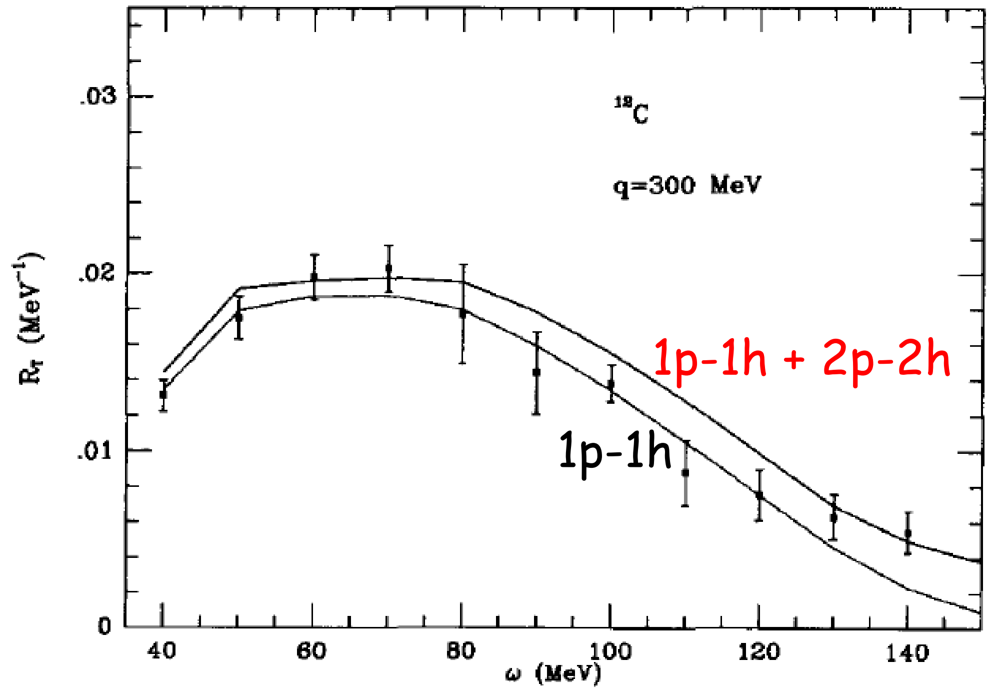
With the reduction factor 0.11/0.18=0.61 that we had applied in order to reproduce ImC_0, our parameterization is quite close to the recent results of Amaro et al. (which are ~30-40% lower than the original values of Alberico et al.)

Another test of our parameterization in electron scattering R_T of ^{12}C: comparison with data and with calculations of Gil et al.

Our calculation



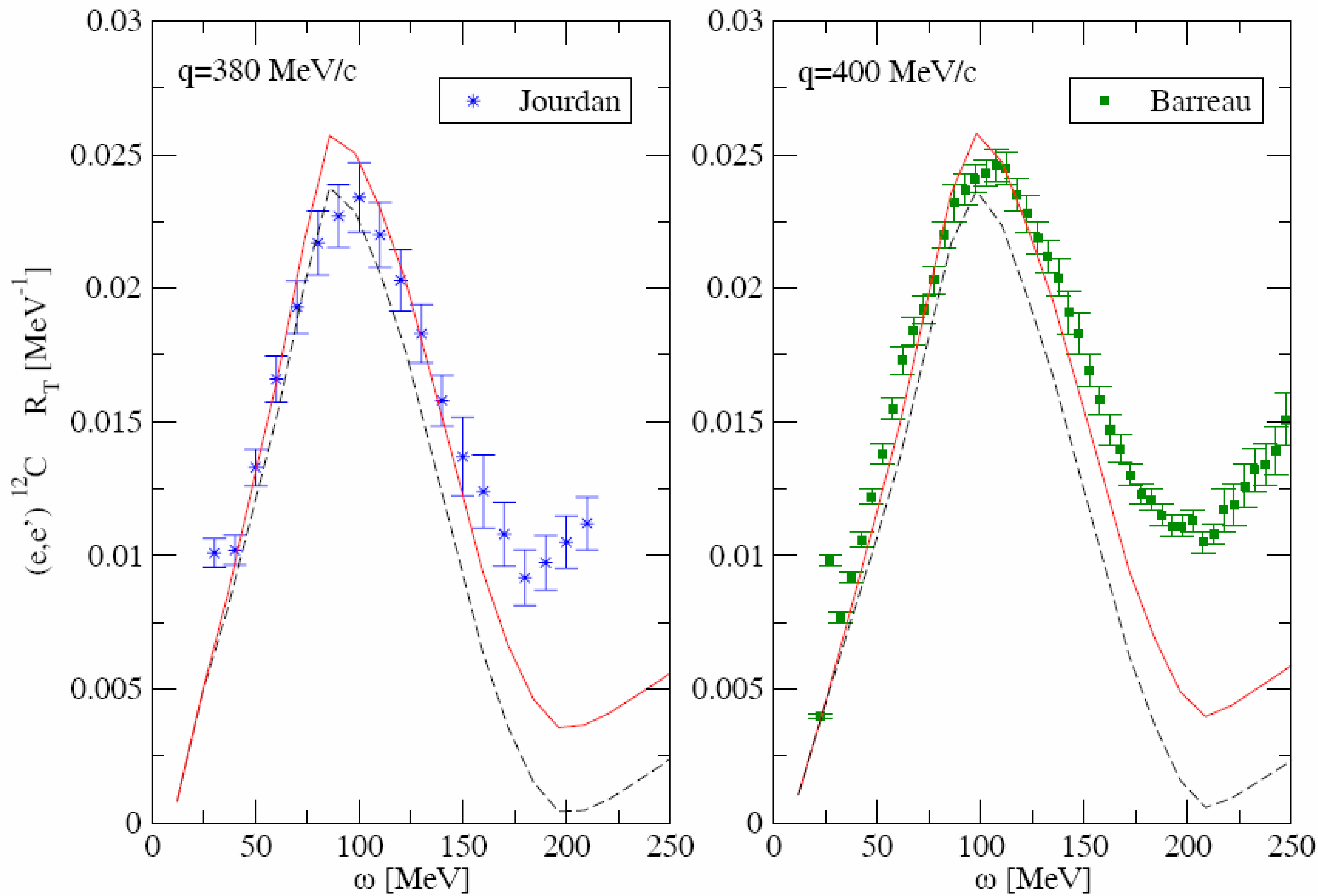
Gil, Nieves, Oset NPA'97

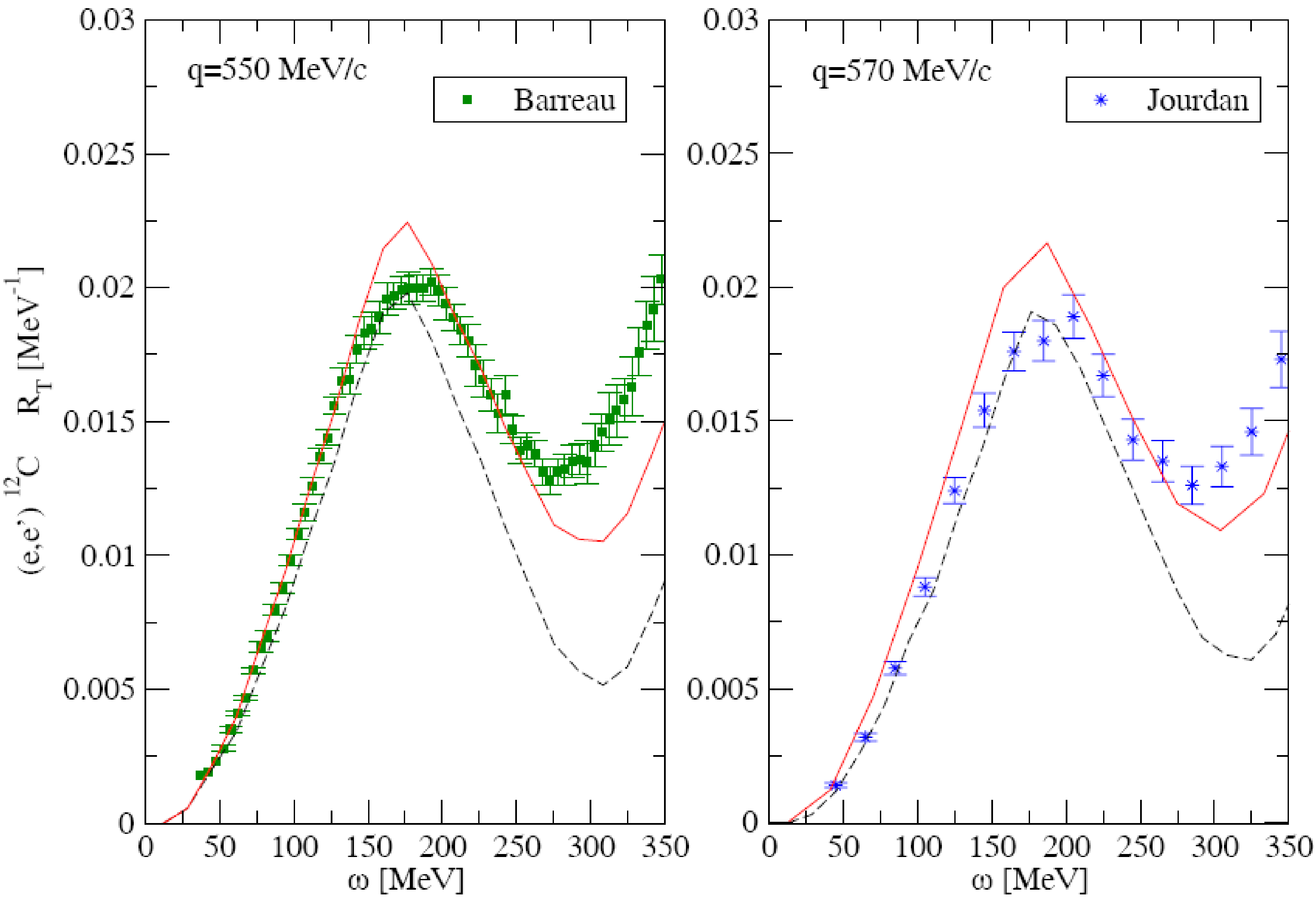


- Our evaluation: same order of magnitude as the microscopic calculation of Gil et al.

N.B. Some discrepancies in the two experimental results (new data are welcome!)

Our results vs experiment for other q values



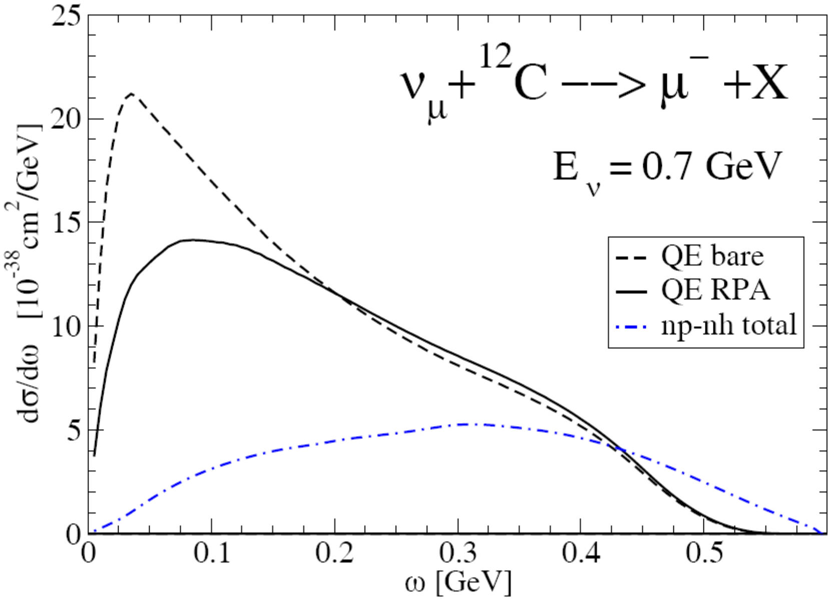


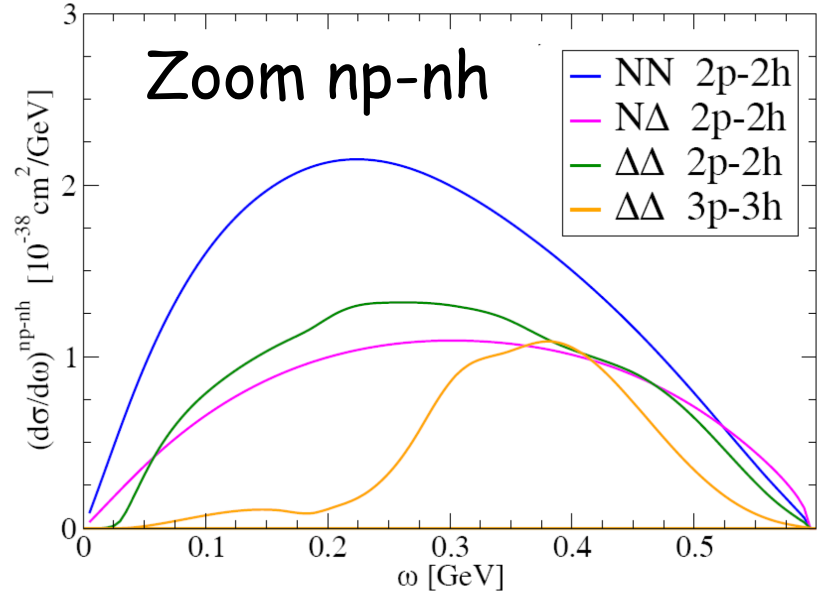
Conclusions: our evaluation of 2p-2h contributions to R_T is compatible with other microscopic evaluations and with data.

This test is important for ν cross section which is dominated by R_T

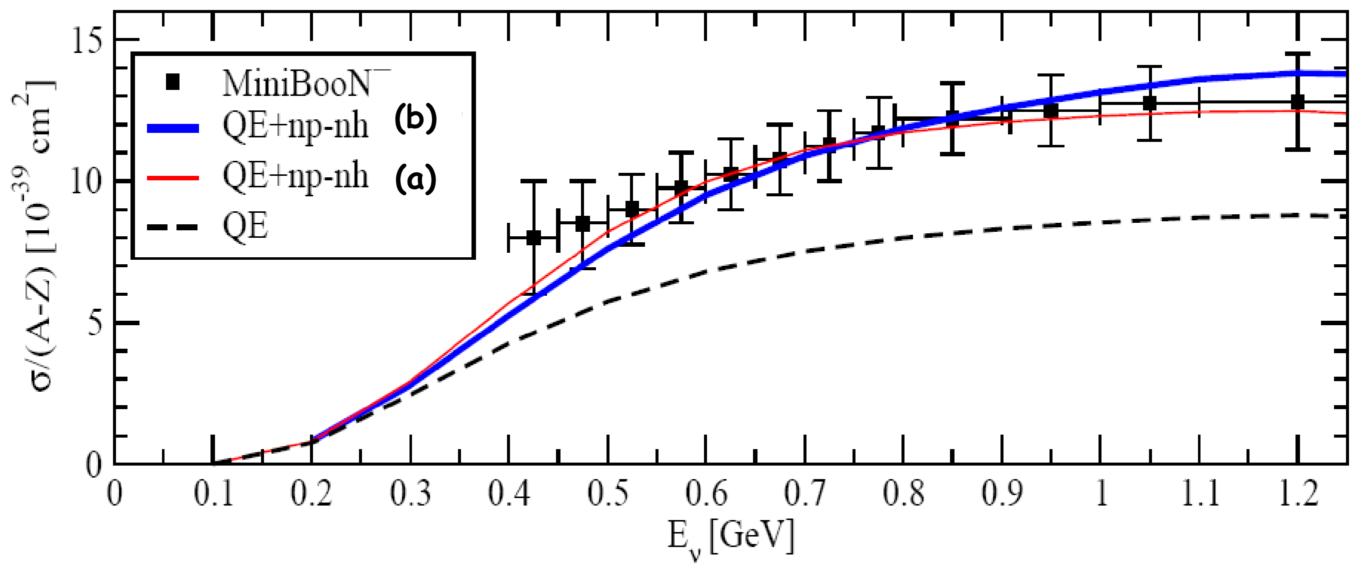
Neutrino - nucleus cross section

Differential





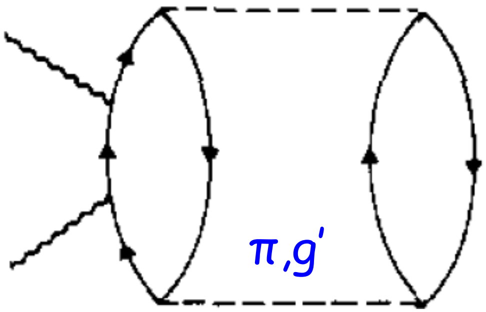
Total



Further considerations on 2p-2h

e.g.

NN correlation



q =410 MeV/c

central tensor

$\hbar\omega$	βA_i^C	βA_1^T
50	11.3	20.3
100	12.5	31.8
150	23.6	47.8
200	20.9	53.1
250	17.3	51.1
300	10.9	39.9

Alberico et al.
Ann. Phys. '84

Tensor correlations are dominant in the NN correlation term but 2p-2h contributions involving Δ excitations are also very important. Tensor correlations alone are insufficient to account the overall 2p-2h effect.

2p-2h (V,I) processes dominated, as pion absorption, by p-n initial pairs (p-p emission)

Antineutrino *vs* Neutrino-nucleus cross-section

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

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

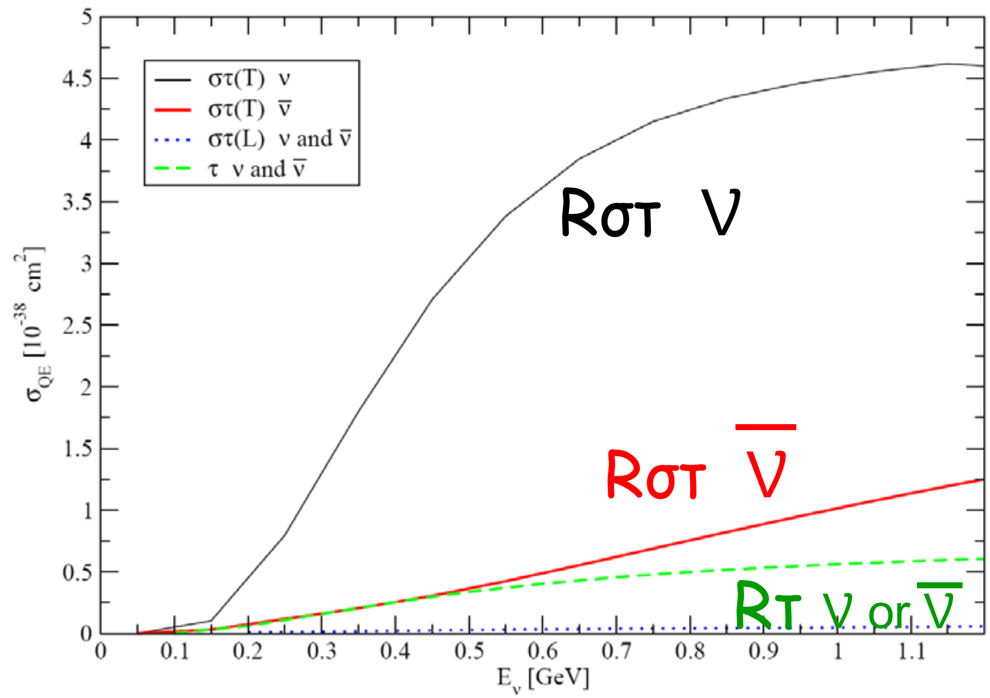
$$+\;\Big(G_M^2\,\frac{\omega^2}{\boldsymbol{q}^2} + G_A^2\Big)\Big(-\frac{q_\mu^2}{\boldsymbol{q}^2} + 2\tan^2\frac{\theta}{2}\Big)\,R_{\sigma\tau(T)}$$ isospin spin-transverse

$$\pm\;2\,G_A\,G_M\,\frac{k+k'}{M_N}\,\tan^2\frac{\theta}{2}\,R_{\sigma\tau(T)}\,\Big]$$ interference V-A $\begin{cases} + & (\nu) \\ - & (\bar{\nu}) \end{cases}$

Remind that the 2p-2h term affects the magnetic and axial responses (terms in G_A ,G_M) and not the isovector response R_τ (term in G_E)

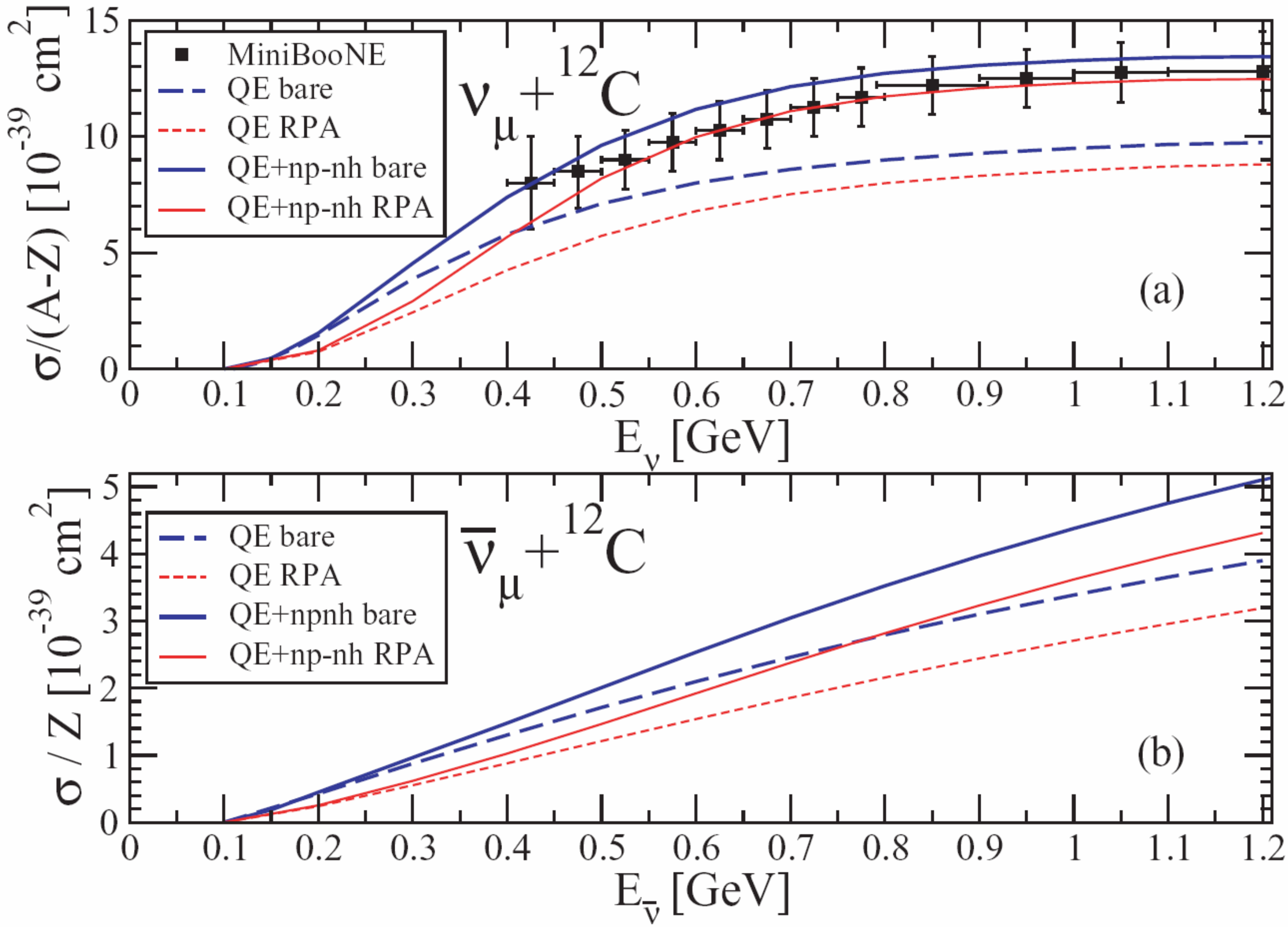
Various response contributions to the ν and $\bar{\nu}$ CCQE

The role of interference term (in $G_A G_M$) is crucial: it enhances the contribution of Rστ(T) for neutrinos.
For antineutrinos instead the destructive interference partially suppresses this contribution leaving a larger role for isovector Rτ which is insensitive to 2p-2h



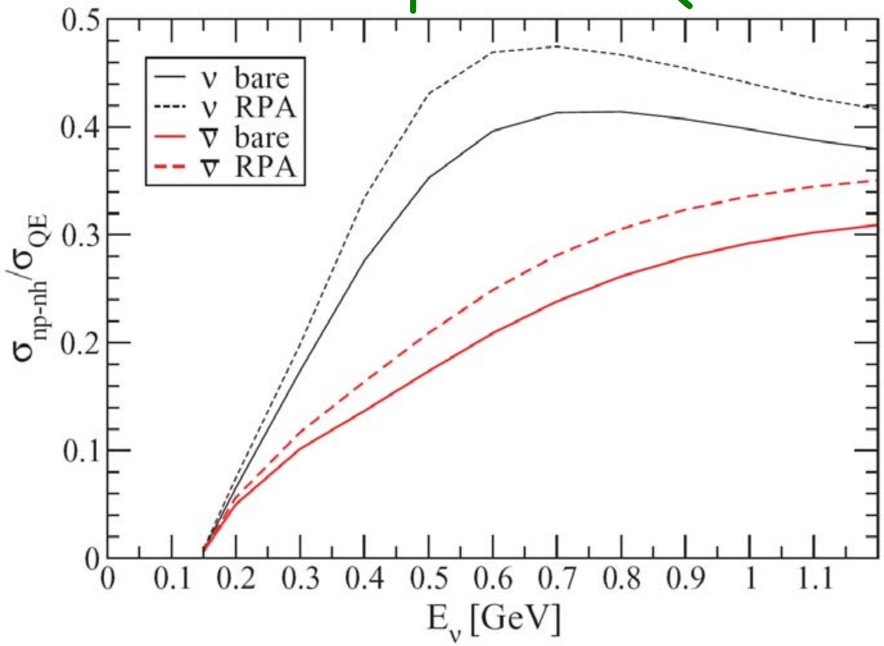
Hence the relative role of 2p-2h is smaller for antineutrinos

The relative role of the np-nh is smaller for antineutrinos



Role of multinucleon component in CCQE-like (QE+np-nh)

$\sigma_{np\text{-}nh}/\sigma_{QE}$



MiniBooNE flux integrated
CC total cross section

	Neutrino			Antineutrino		
	QE	np-nh	QE+np-nh	QE	np-nh	QE+np-nh
bare	7.46	2.77	10.23	2.09	0.52	2.61
RPA	6.40	2.73	9.13	1.60	0.47	2.07

In units of 10^{-39} cm^2

For neutrinos the fit to QE data in RFG required an appreciable increase of M_A

For antineutrinos this increase should be smaller, as the relative role of the multinucleon ejection is reduced

M. Martini, M. Ericson, G. Chanfray, J. Marteau, Phys. Rev. C 81 045502 (2010)

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Some indirect test of the multinucleon channel in neutrino scattering

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Our model takes into account all the open channels in neutrino scattering at $E_\nu \sim \mathcal{O}(1\ \mathrm{GeV})$:

- Quasielastic scattering
- Multinucleon emission
- Incoherent pion production
- Coherent pion production

Several experimental ratios of cross sections are available

Role of multinucleon channel?

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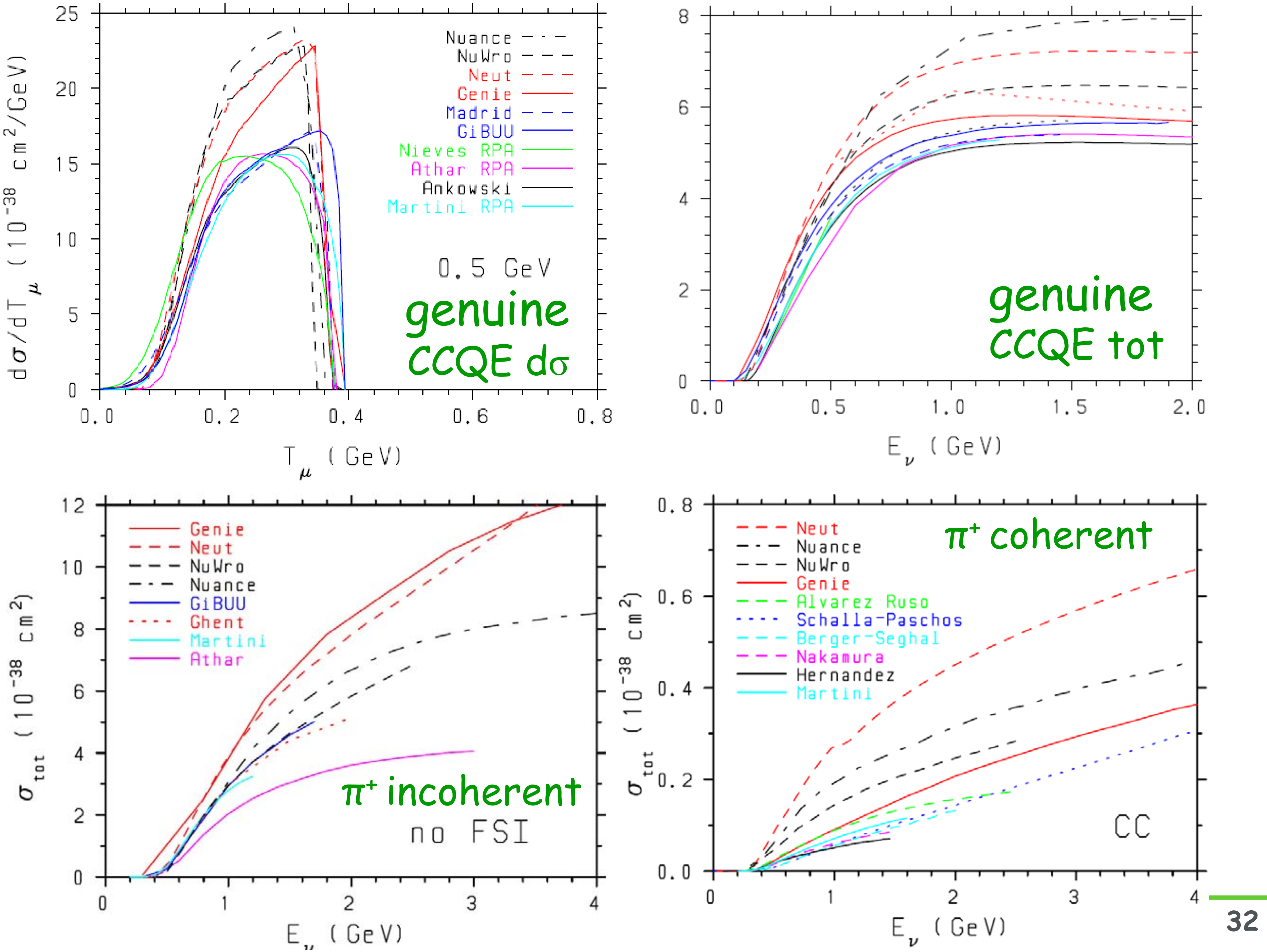
Compatibility with the other microscopic models

NUINT 2009
AIP Conf. Proc. 1189 60



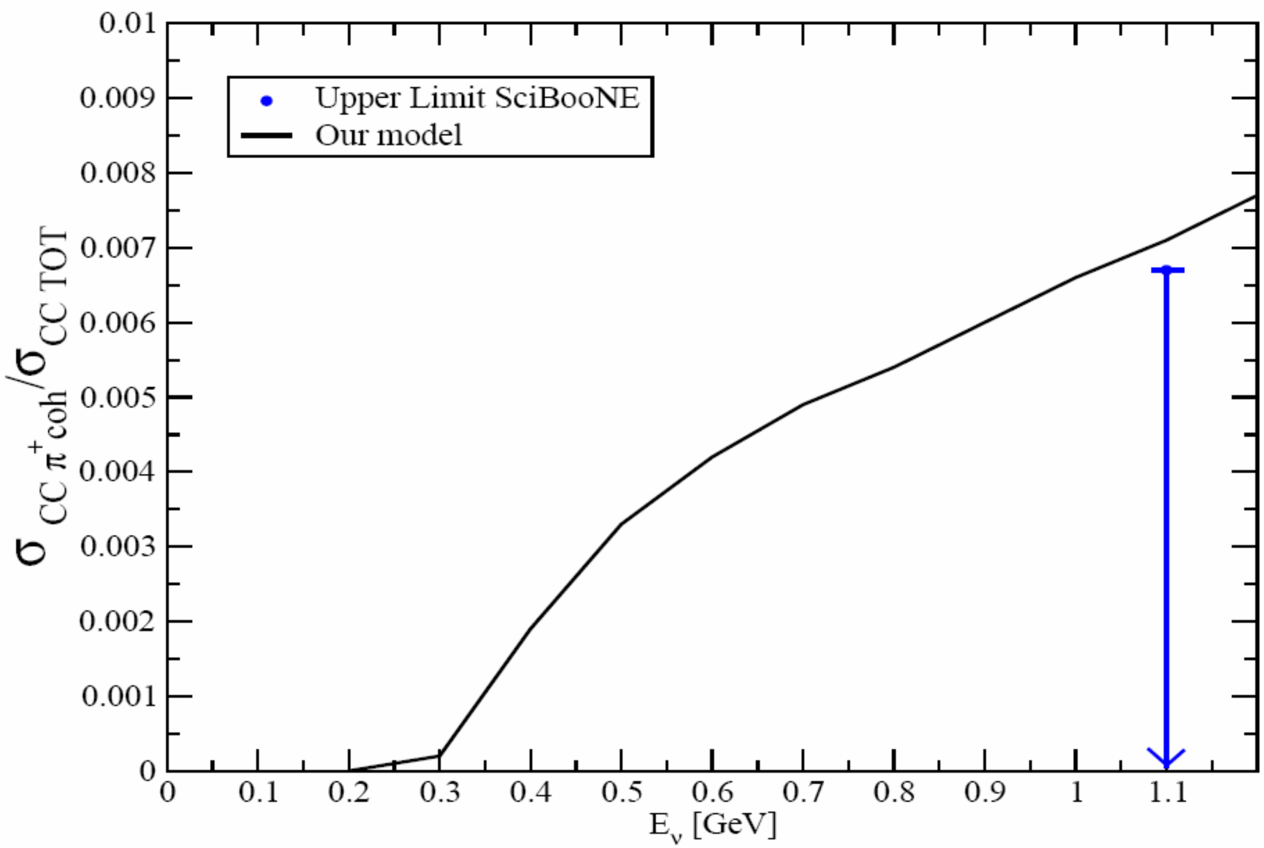
CC coherent π^+ production over CC total X section

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 **PRD 78 112004 (2008)**



Our model @

E_ν=1.1 GeV

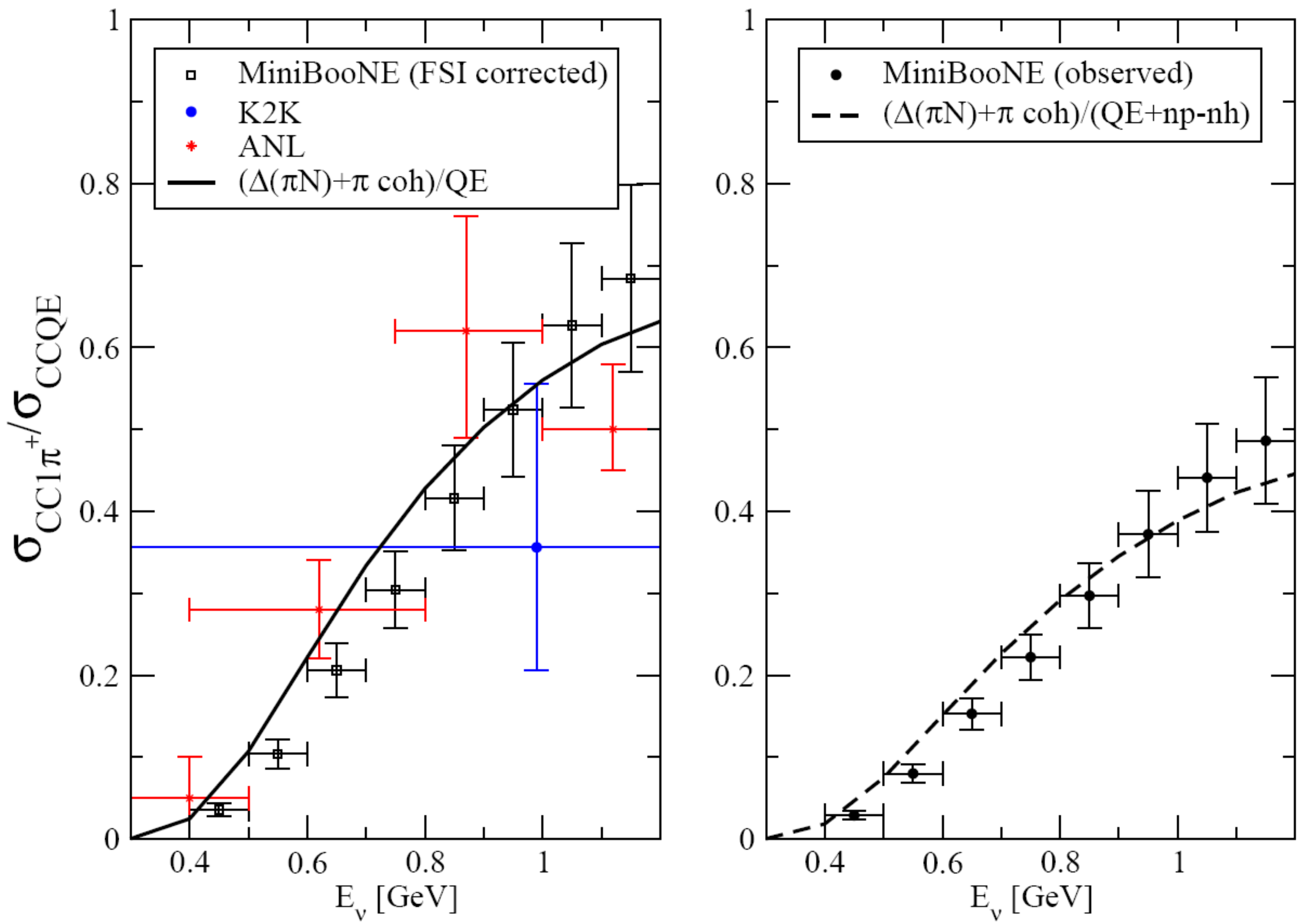
0.71 10^{-2}
Just compatible

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)

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

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 σ CC_{TOT}

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

Coherent π^0

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

SciBooNE @ E_ν = 1 GeV

Our model

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

Suppressing np-nh in σ CC_{TOT}

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

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
$\bar{\nu}$ @ 664 MeV	1.48 ± 0.05 st ± 0.23 sy	1.37

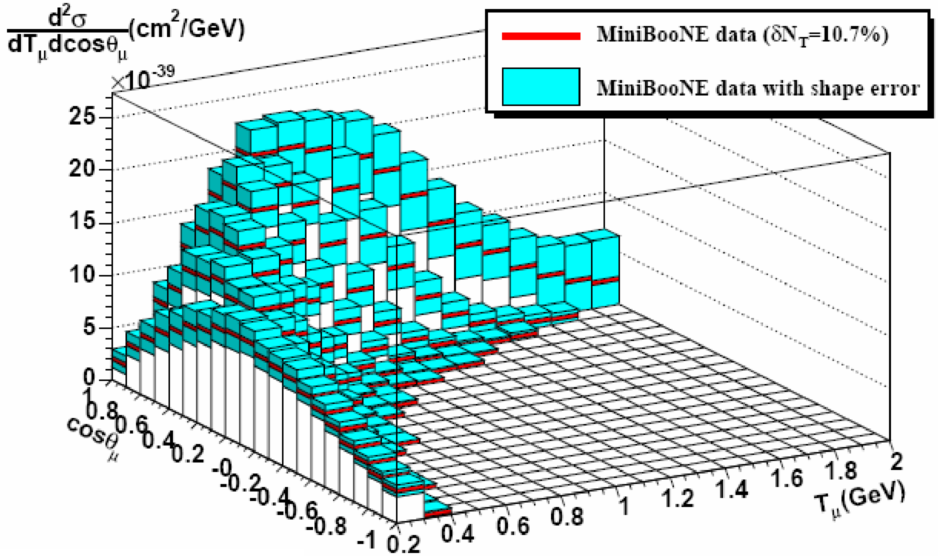
Incoherent exclusive NC $1\pi^0$

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

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

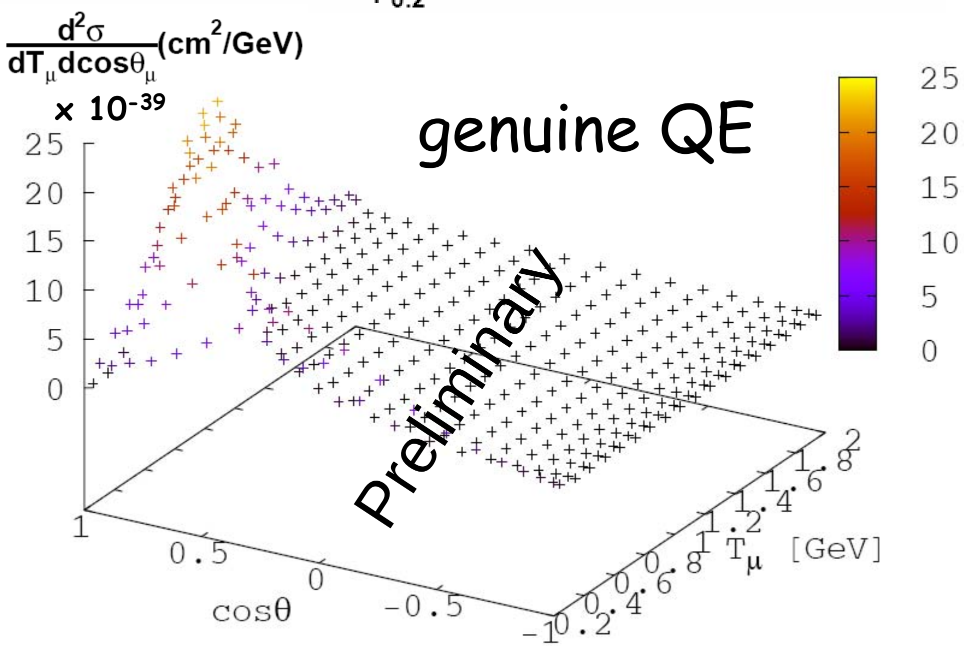
P.S. Our model: $\Delta N \rightarrow NN$ absorption process, but not absorption once π_{inco} is placed on-shell

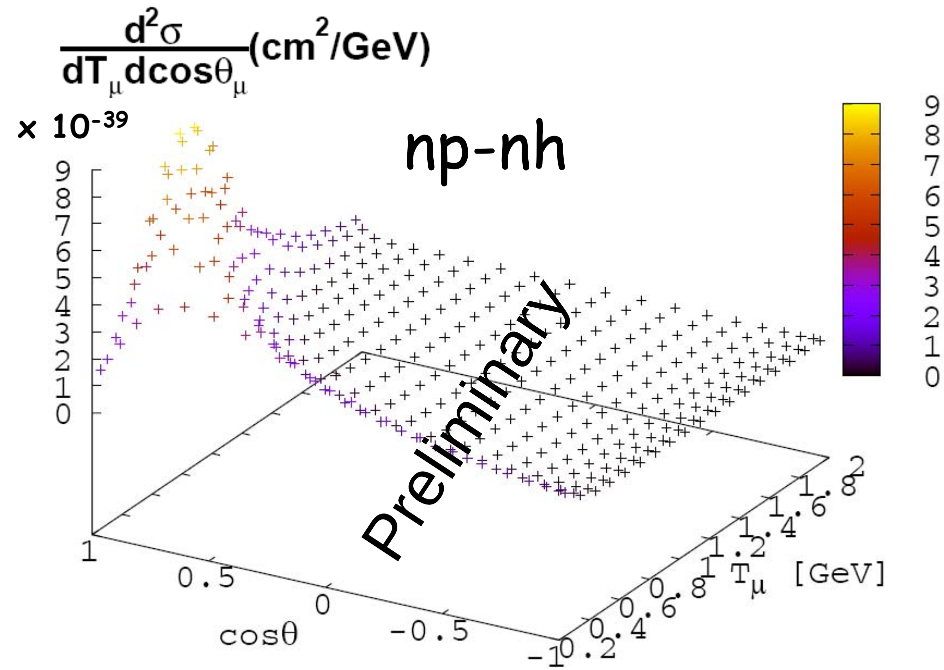
Most constraining test of our evaluation



MiniBooNE CCQE-like flux-integrated double differential X section

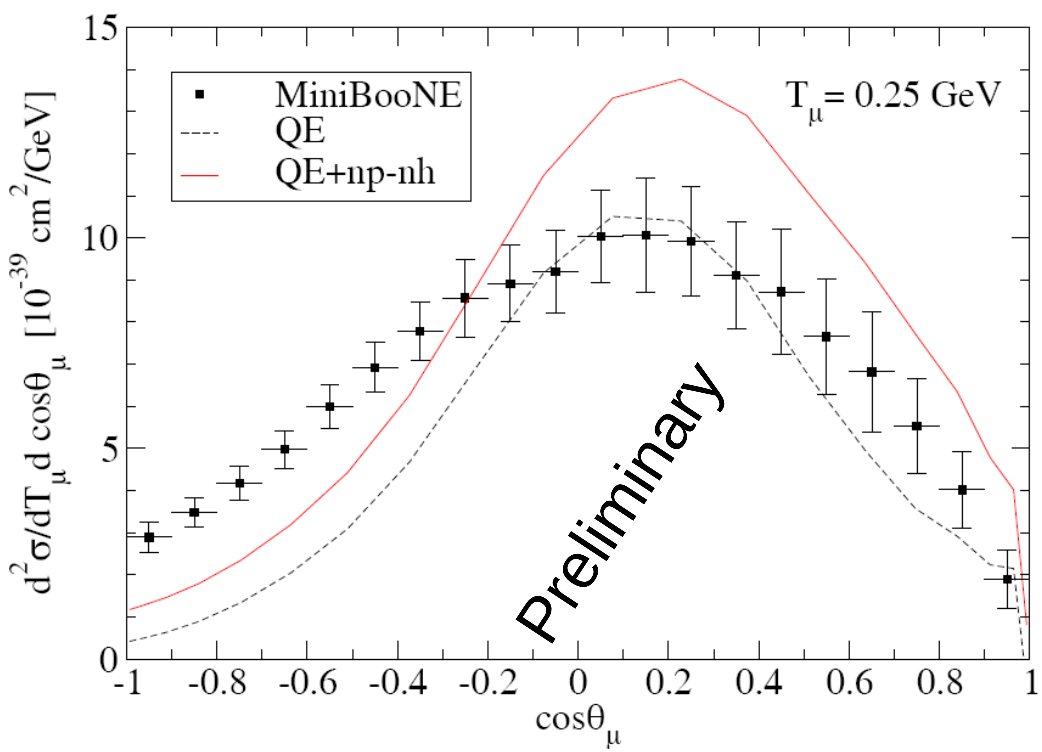
MiniBooNE,
Phys. Rev. D 81, 092005 (2010)



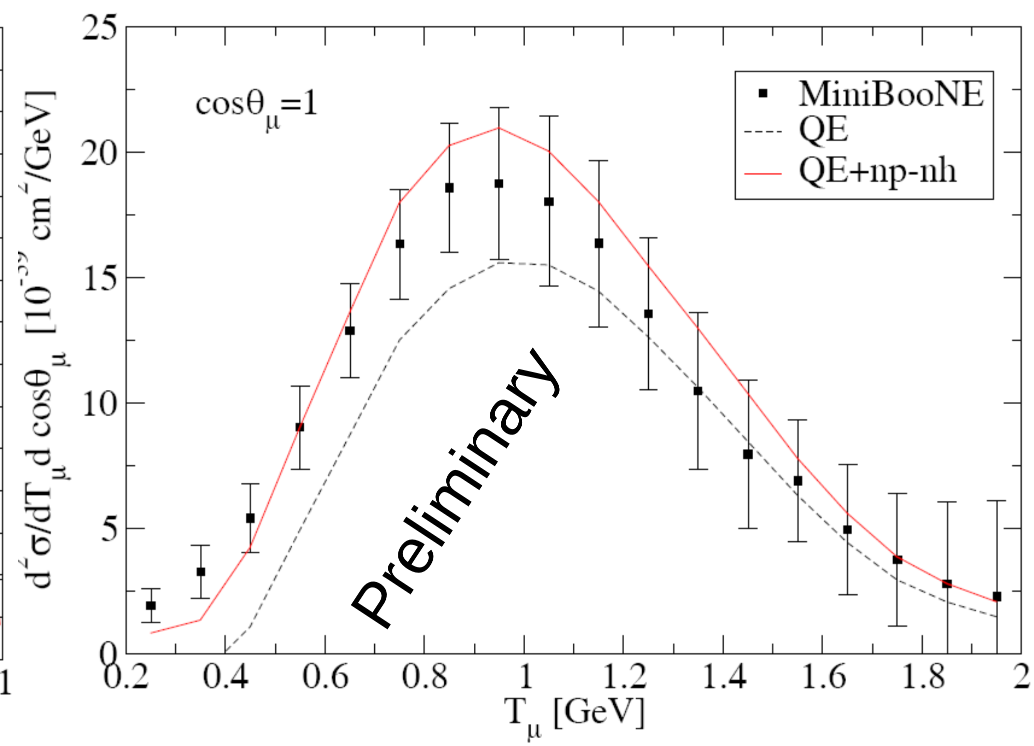


MiniBooNE CCQE flux-integrated double differential X section

Fixed muon energy



Fixed angle



N.B.
Final State Interaction not included

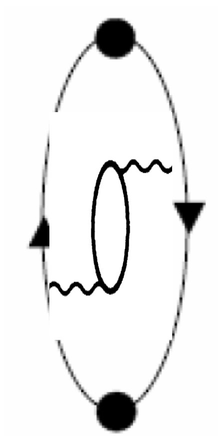
Role of nucleon final state interaction

Effects of FSI in inclusive processes:

•energy shift of the cross section

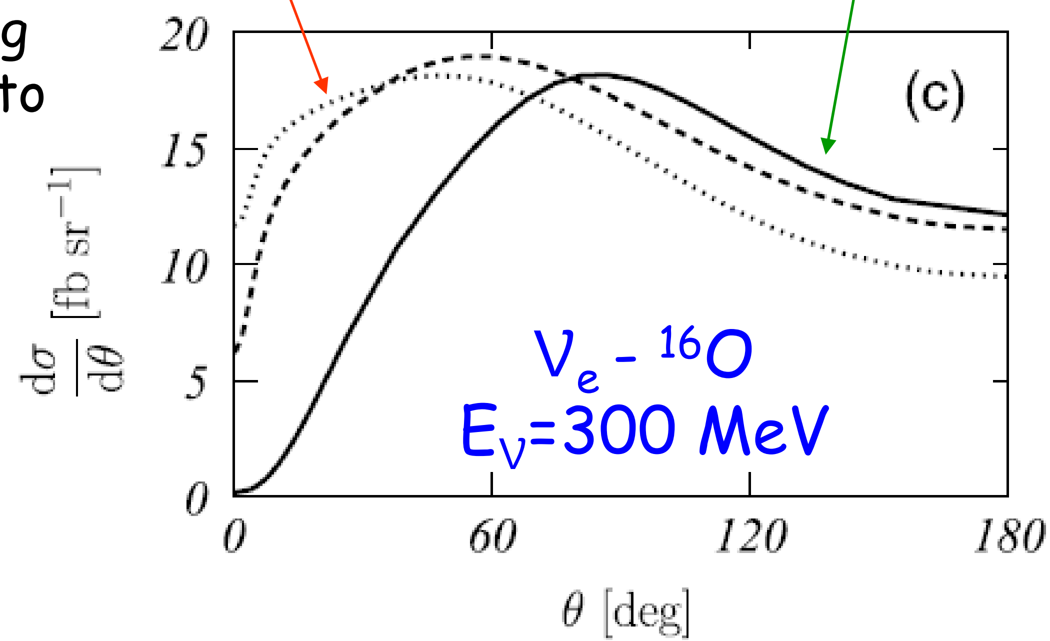
•redistribution of the strength leading to the quenching of the QE peak and to an enhancement of the tails

Example of diagrams to be included:



superscaling

CRPA+FSI:
Increase in backward direction



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

Summary and perspectives

- Multinucleon emission as a possible explanation of CCQE-like cross section measured by MiniBooNE
- Two body currents and multinucleon emission:
  - modelizations and tests from pion absorption and electron scattering
  - different weight in neutrino and antineutrino scattering: smaller increase of M_A in antineutrino mode if one use RFG
- Comparison with experiments
  - agreement with all cross section ratios measurements
  - multinucleon emission channel seems to be needed in order to reproduce data

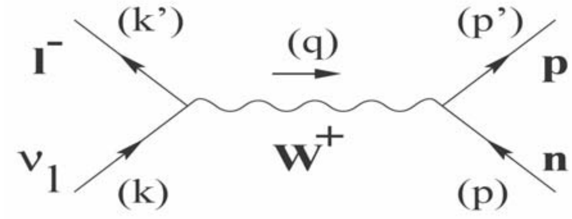
Perspectives:

- detailed study of double differential cross section
- inclusion of FSI in our model

Spares

Neutrino-nucleus cross-section

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



lepton

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

$$\langle p', s' | h^\mu | p, s \rangle = e^{iqx} \bar{u}(p', s') \left[F_1(t) \gamma^\mu + F_2(t) \sigma^{\mu\nu} \frac{i q_\nu}{2 M_N} + G_A(t) \gamma^\mu \gamma_5 + G_P(t) \gamma_5 \frac{q^\mu}{2 M_N} \right] u(p, s)$$

hadron

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

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

After non-relativistic reduction:

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

charge nuclear response

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

isospin spin-longitudinal

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

isospin spin-transverse

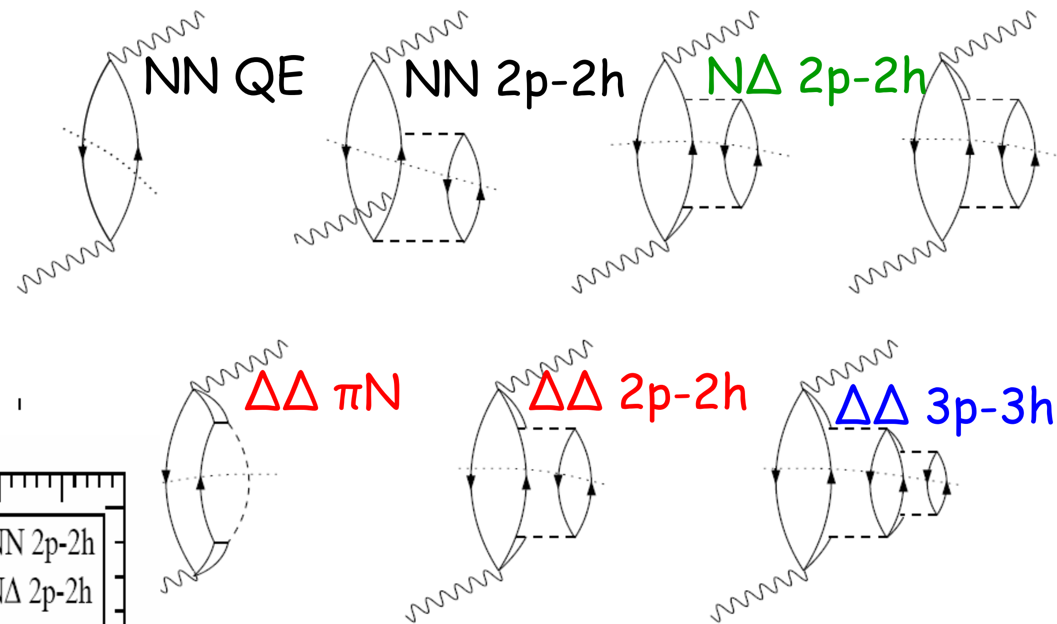
$$\left. \begin{cases} + & (\nu) \\ - & (\bar{\nu}) \end{cases} \boxed{\pm} \; 2 G_A G_M \frac{k + k'}{M_N} \tan^2 \frac{\theta}{2} \left(\boxed{R_{\sigma\tau(T)}^{NN} + 2 R_{\sigma\tau(T)}^{N\Delta} + R_{\sigma\tau(T)}^{\Delta\Delta}} \right) \right]$$

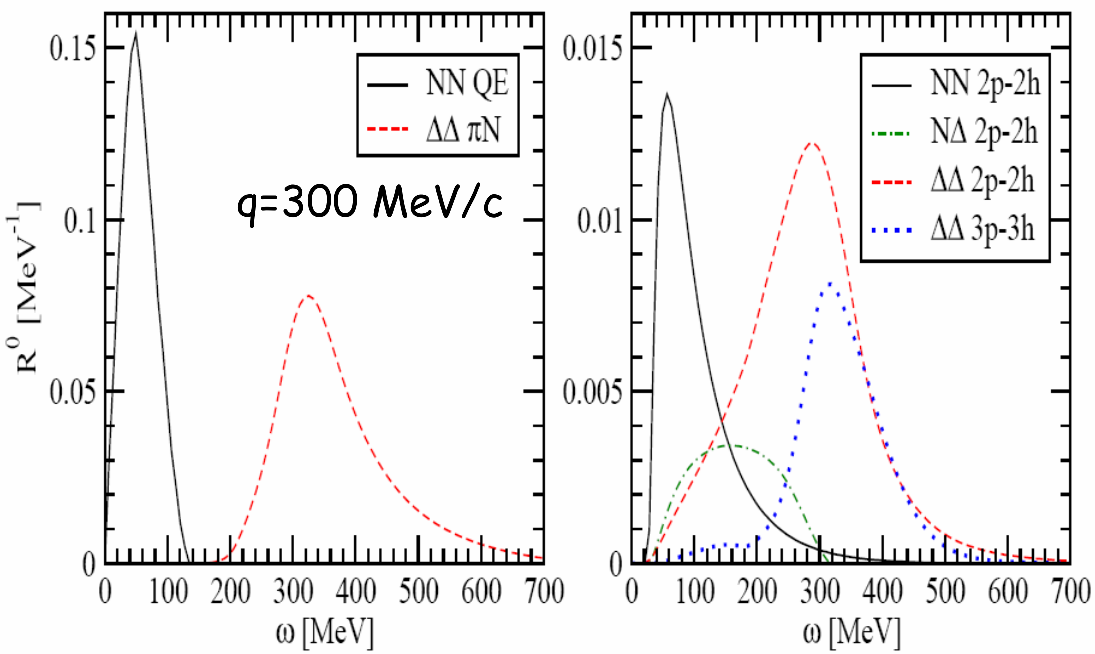
interference V-A

Bare nuclear responses

Several partial components
(final state channels)

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





Delta in the medium

Mass

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

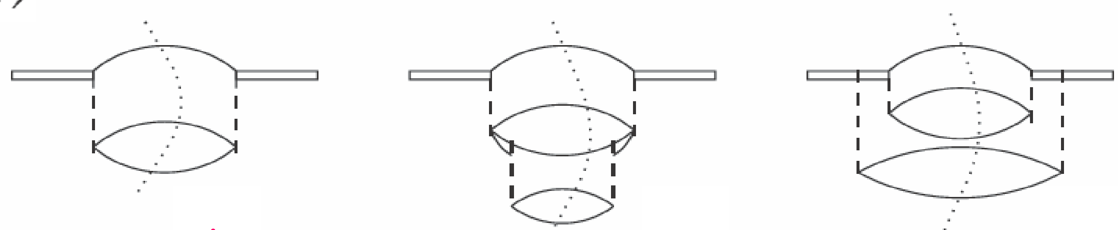
Δ→π N

Pauli correction (F_P)

Width

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

Pion distortion (C_Q)



2p-2h

3p-3h

Self energy

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

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

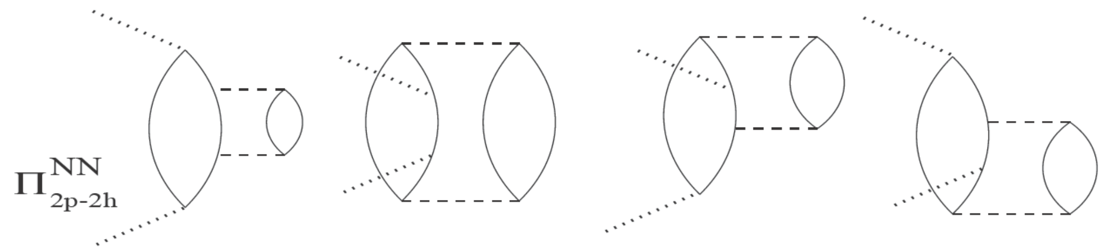
Mostly n-p pairs correlated by tensor interaction

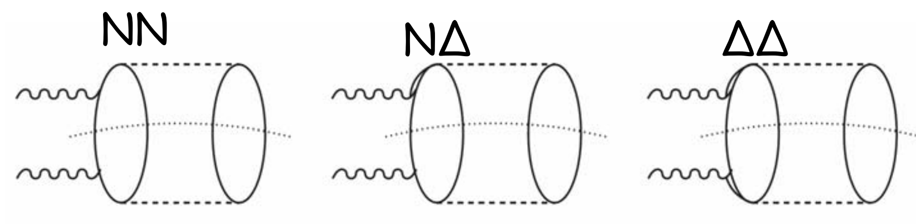
2p-2h π absorption at threshold

Shimizu Faessler, NPA 333,495 (1980)

extrapolation

Delorme, Guichon, 2 proceedings (1989)





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

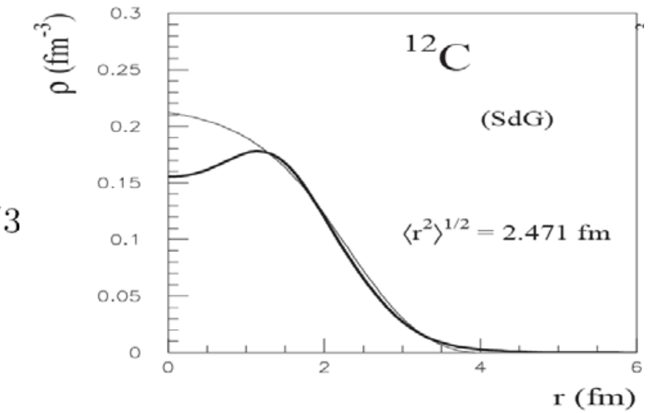
$$Im(\Pi^0_{N\Delta}) = -4\pi\rho^2 \frac{(2M_N+m_\pi)^2}{(2M_N+\omega)^2} C_2\,\Phi_2(\omega)\,\mathrm{Re}\left[\frac{1}{\omega(\omega-\tilde{M}_\Delta+M_N+i\frac{\Gamma_\Delta}{2})}+\frac{1}{\omega(\omega+\tilde{M}_\Delta-M_N)}\right]$$

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

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

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

e.g. Lindhard funct. for QE

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

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

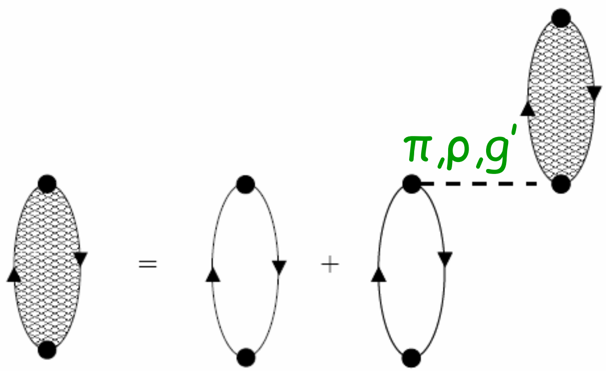
N, Δ

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

QE,2p-2h,...

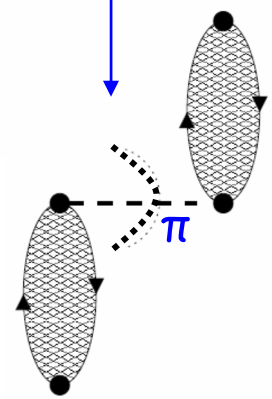
Longit., Transv., Charge

Switching on the interaction



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

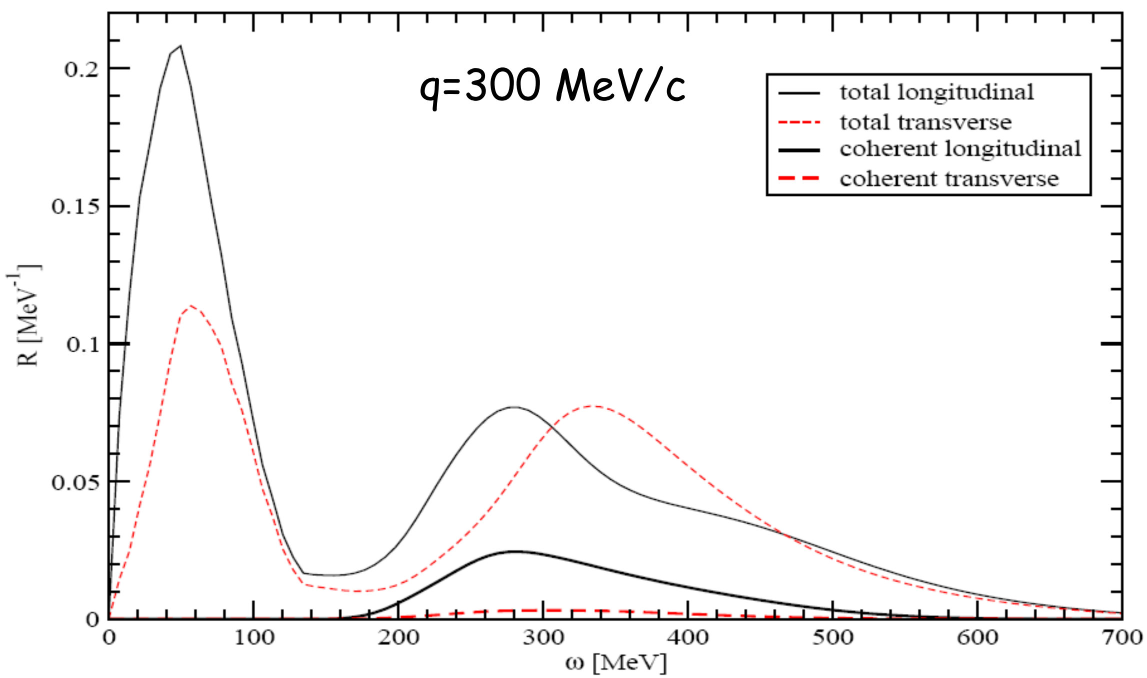
$$\mathrm{Im}\Pi = |\Pi|^2 \, \mathrm{Im}V + |1 + \Pi V|^2 \, \mathrm{Im}\Pi^0$$



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

ν-Nucleus Quasielastic scattering

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

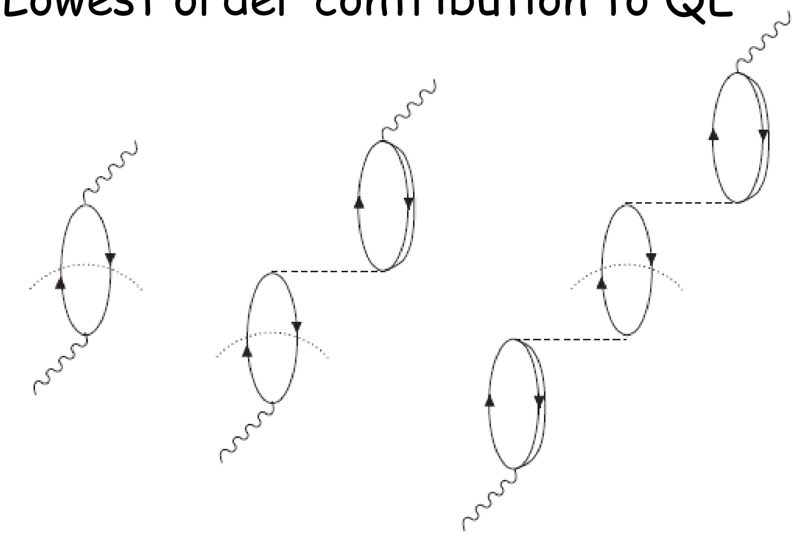
RPA reduction

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

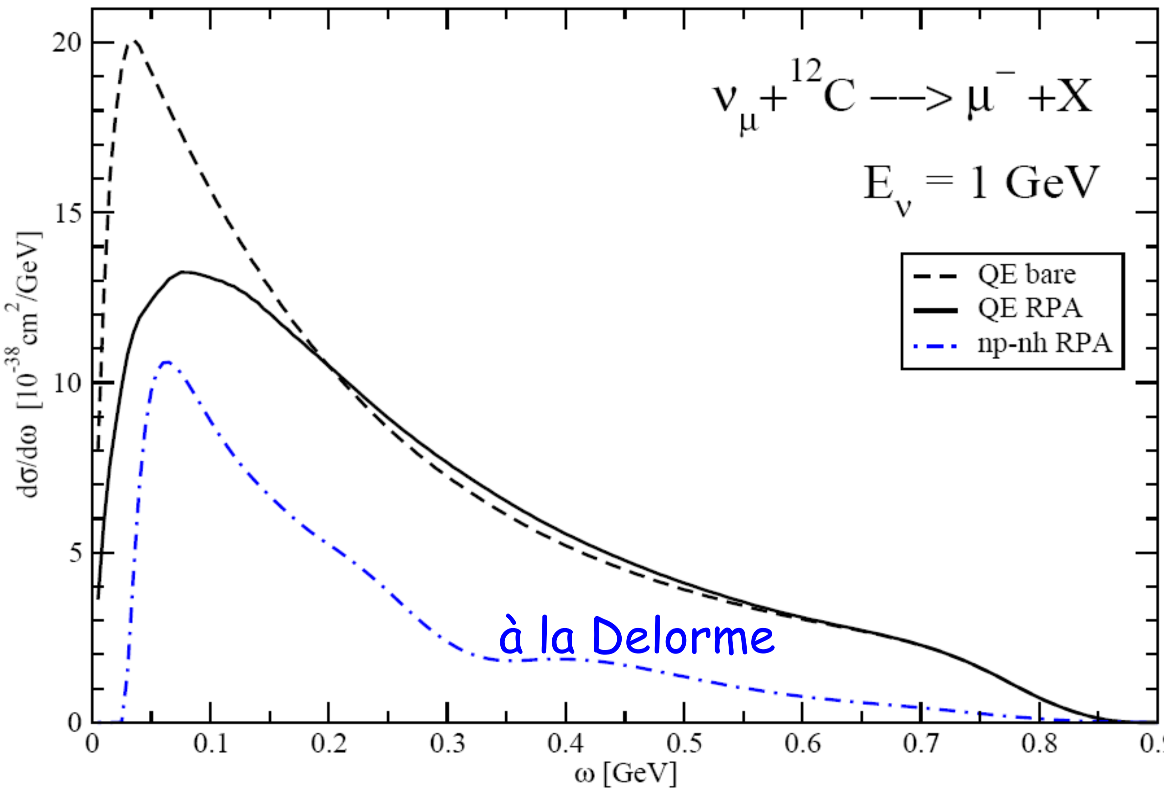
(Lorentz-Lorenz or Ericson-Ericson effect)

Test: electron-nucleus scattering

Lowest order contribution to QE



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

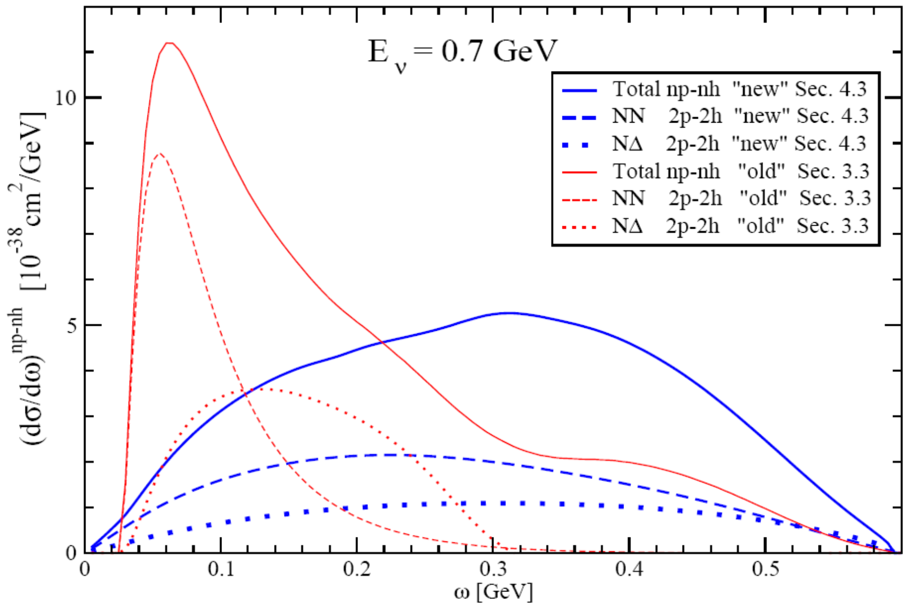


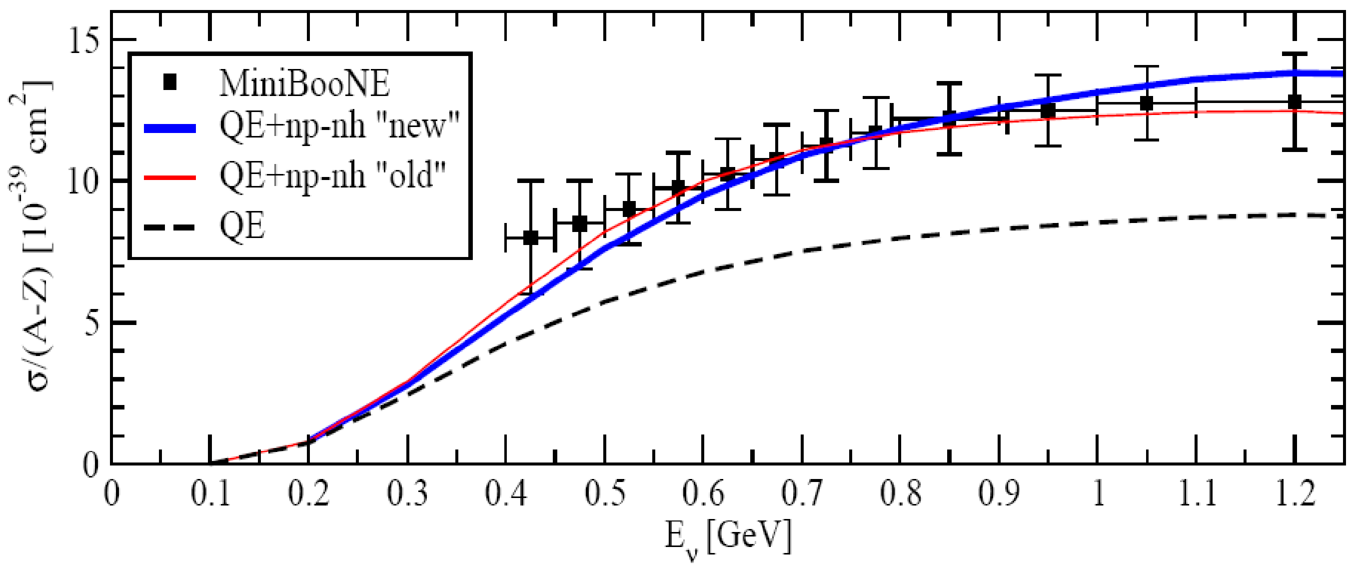
Comparison of the two 2p-2h parametrizations in ν-^{12}C scattering

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

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

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)

π production and np-nh ; nuclear mass dependence

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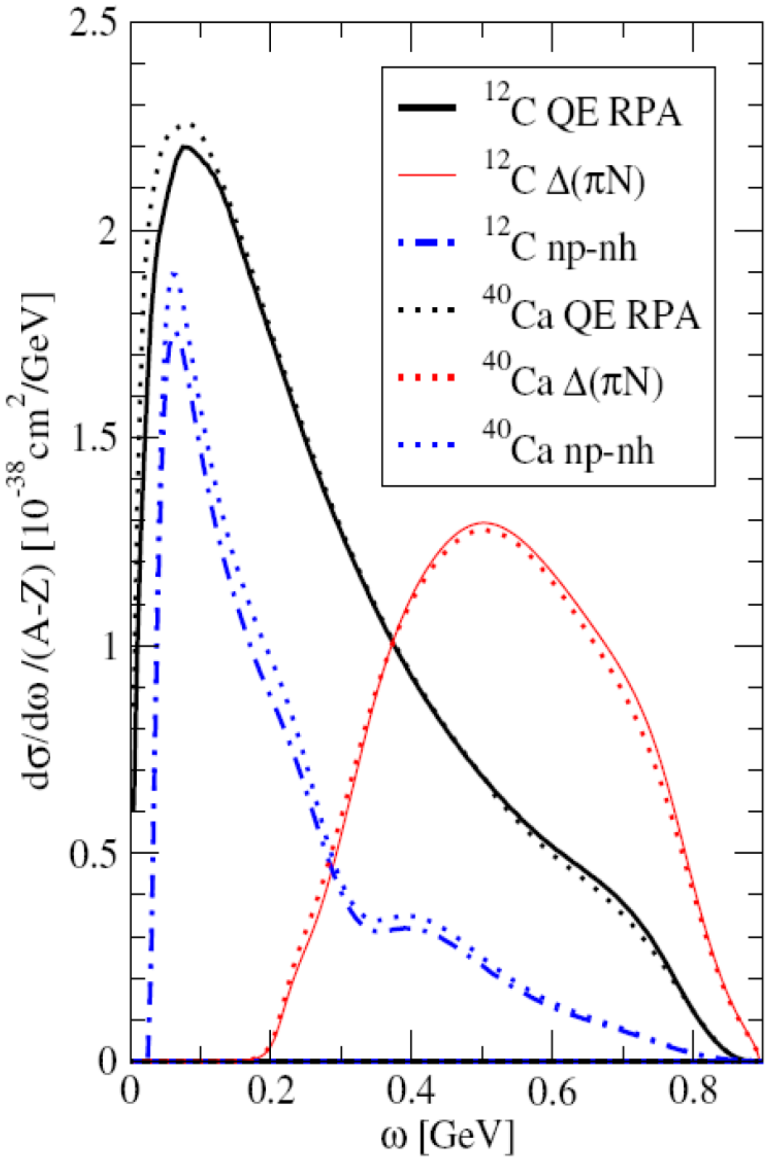
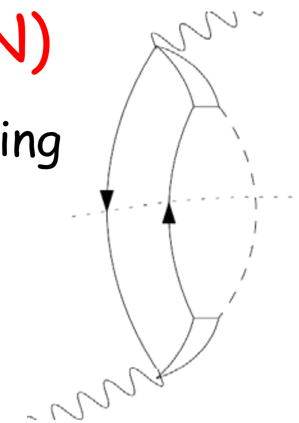


Scaling with A

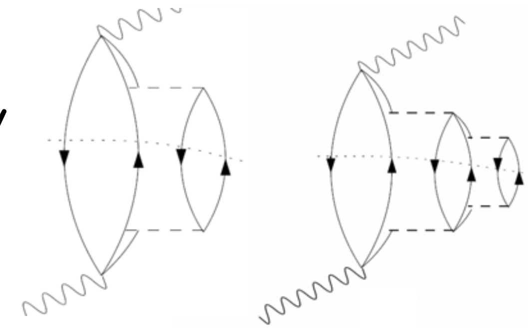
Pion production: Δ(πN)

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

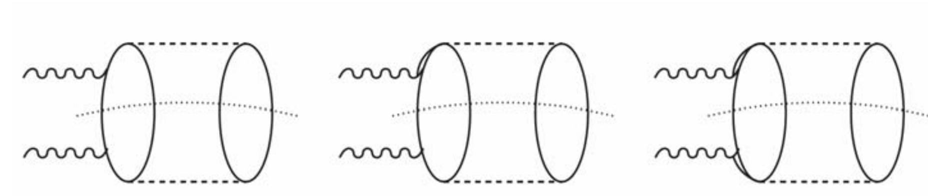


np-nh channel

- non pionic Δ decay in nuclear medium ΔN→NN

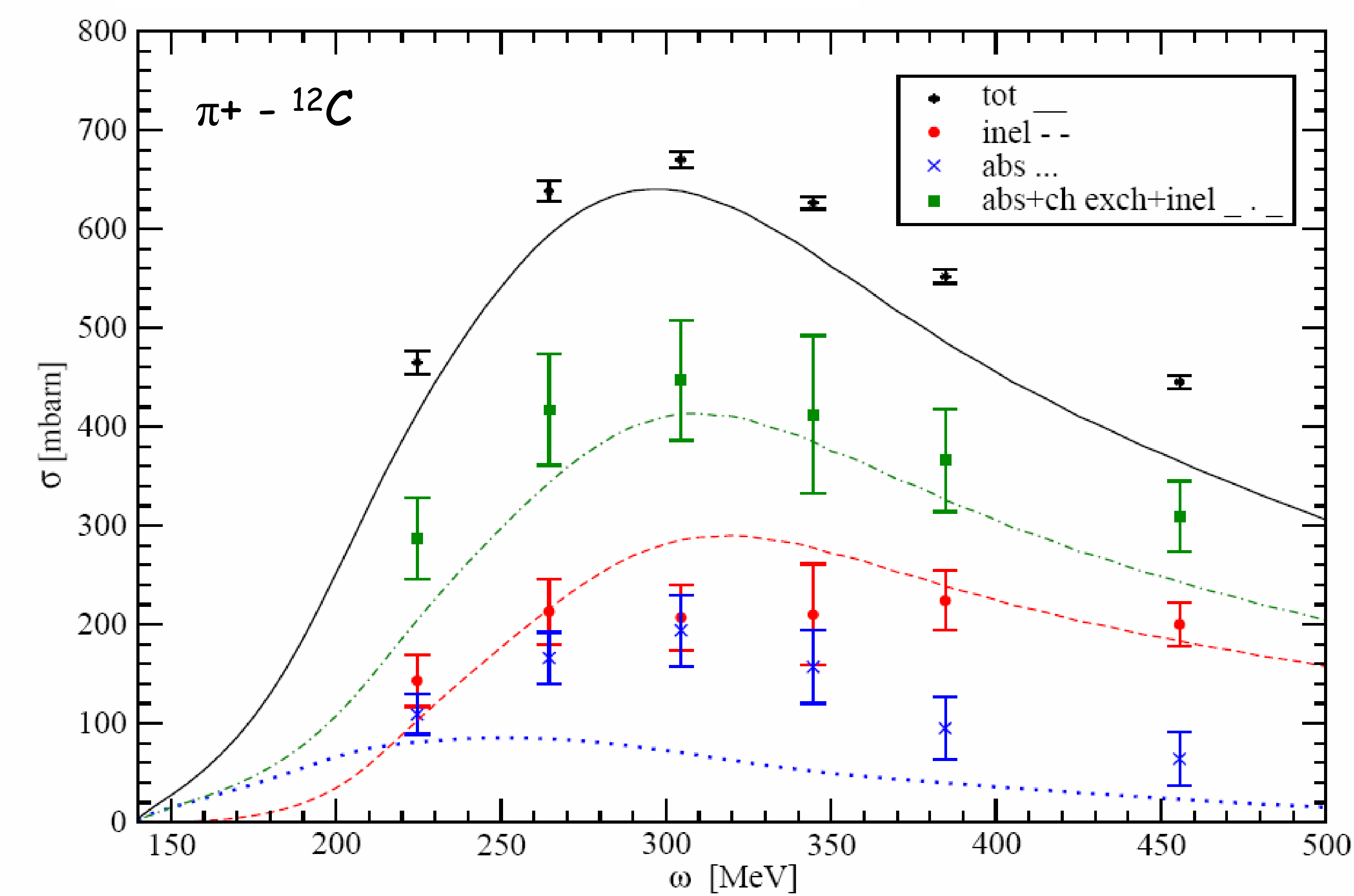


- Initial state nucleon correlation



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

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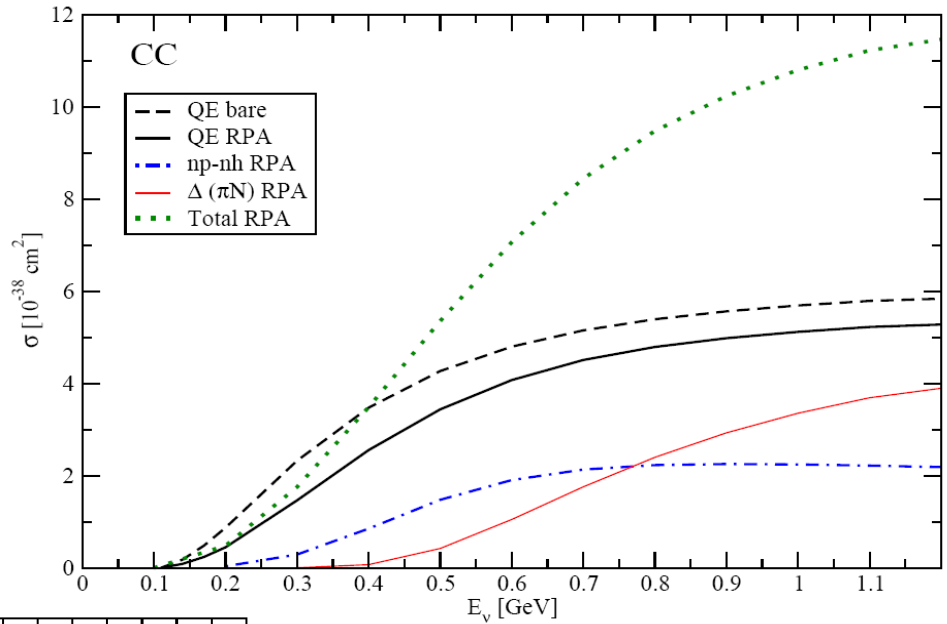
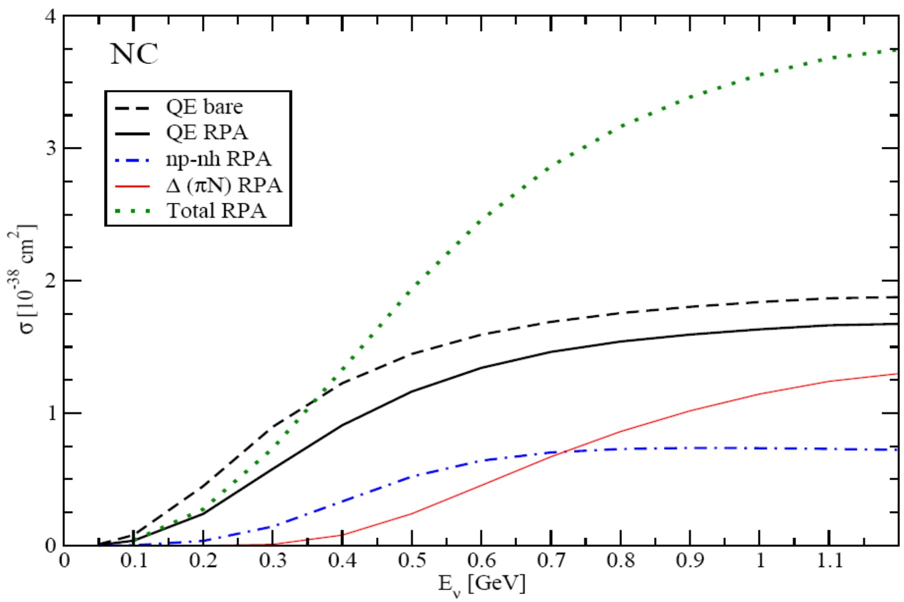
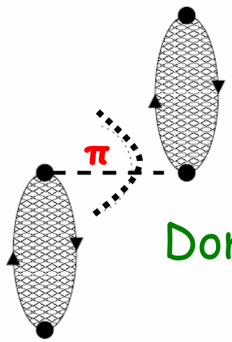
ν_μ-^{12}C Cross sections





as a function of ν energy

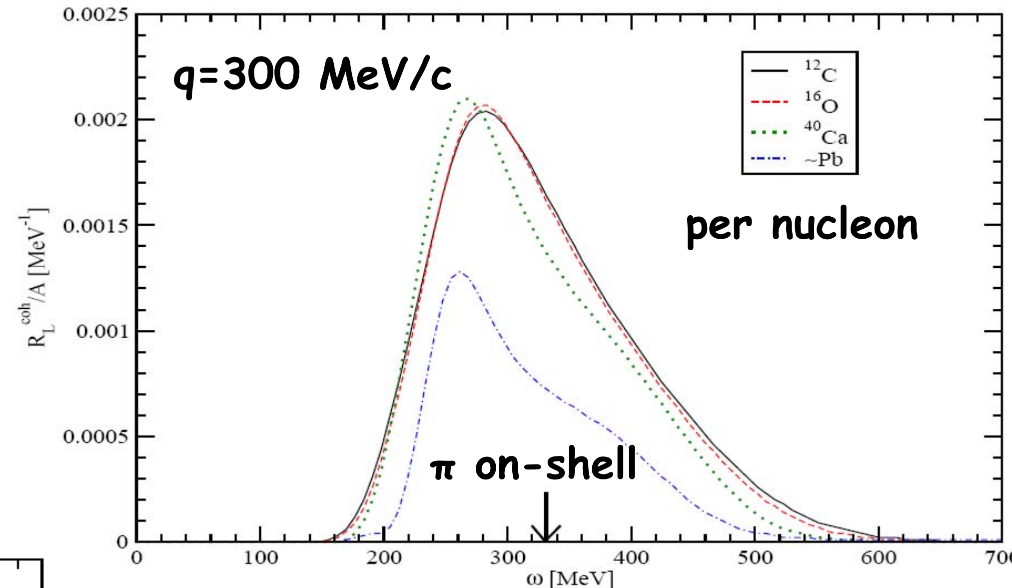
Coherent channel

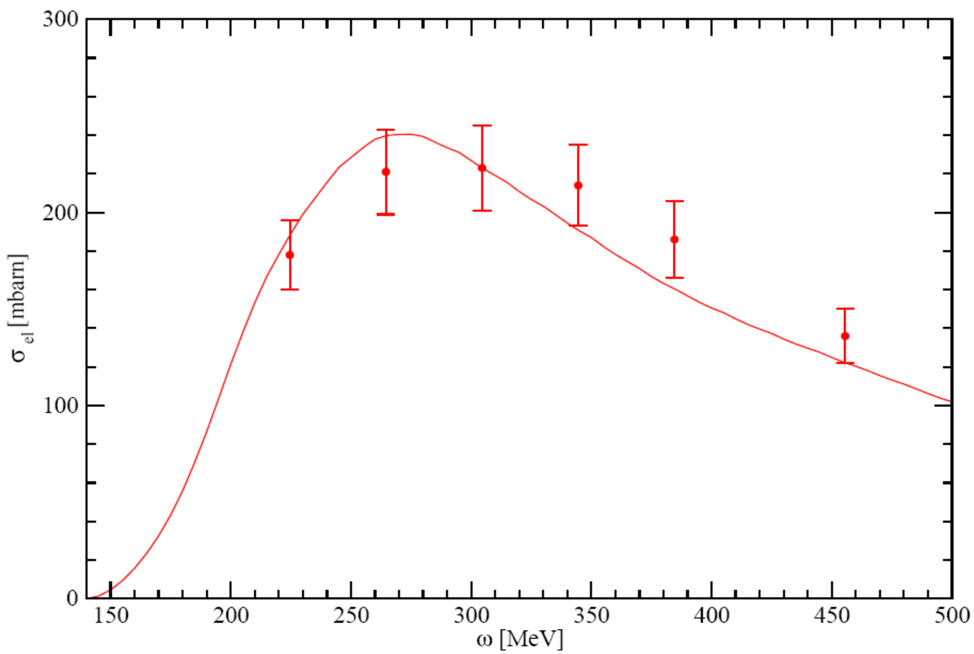


Dominated by $R_{\sigma\tau}$ longitudinal

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

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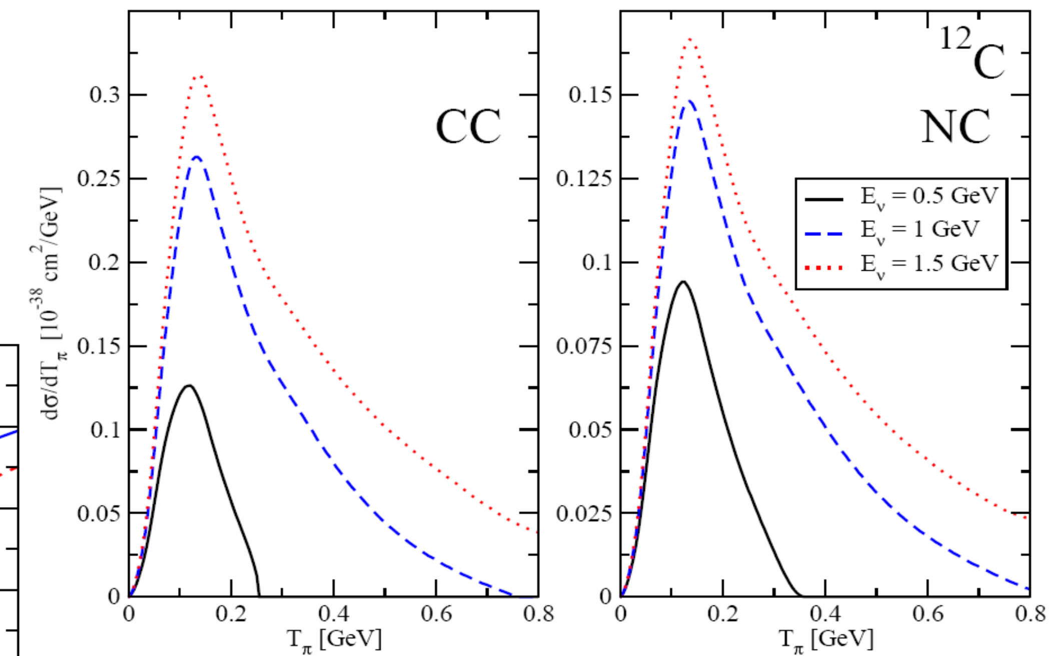
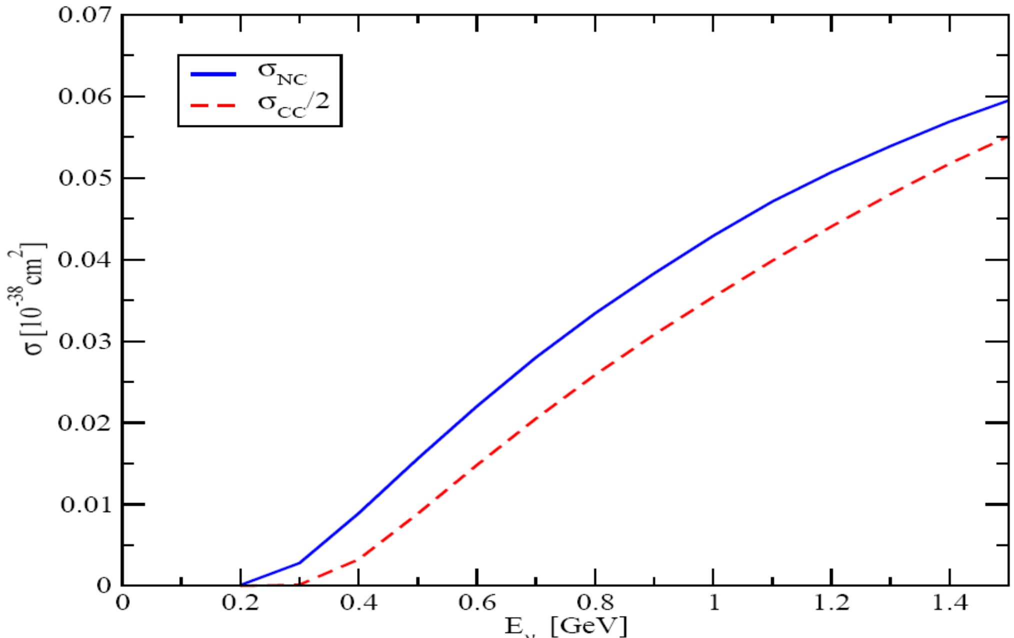
Differential cross section



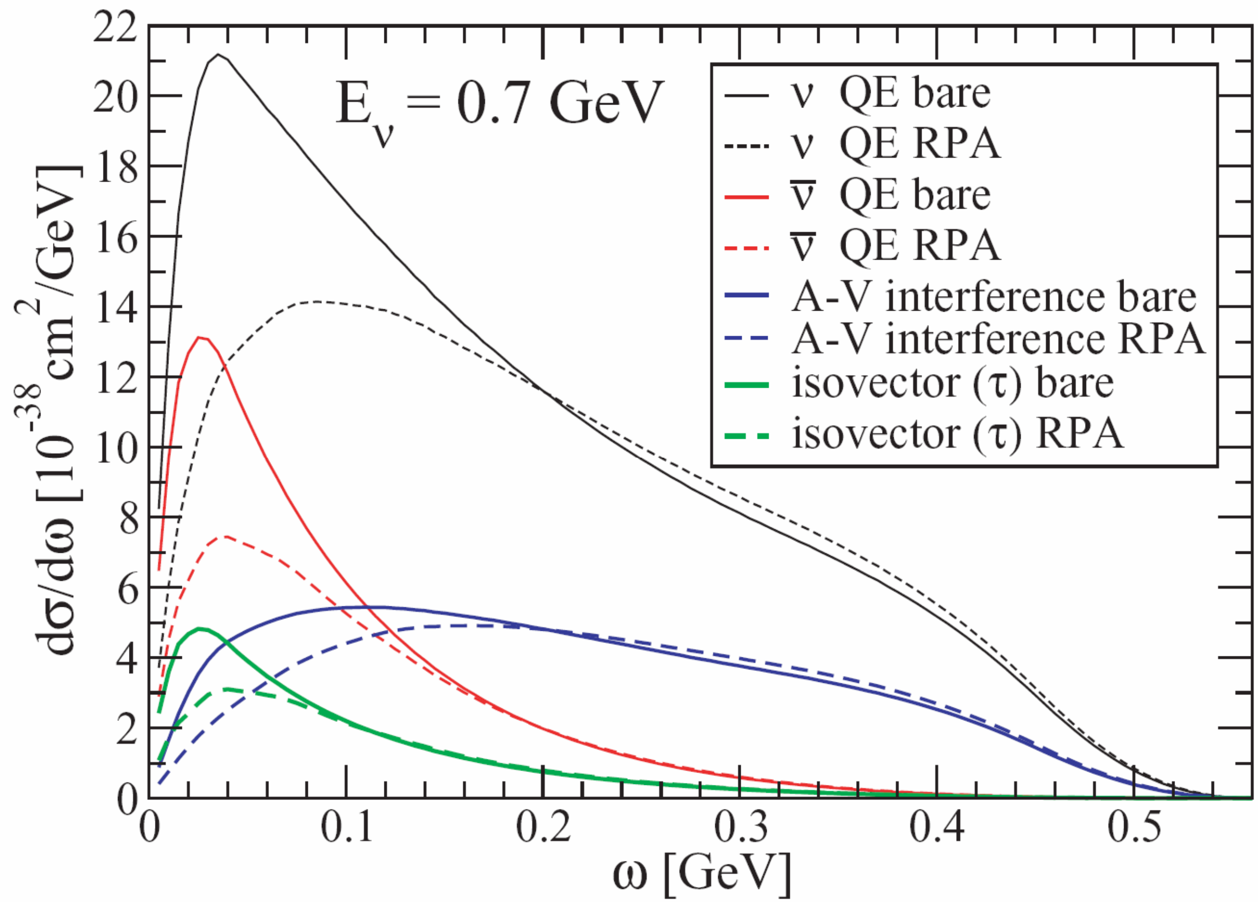
pion kinetic energy

Total cross section



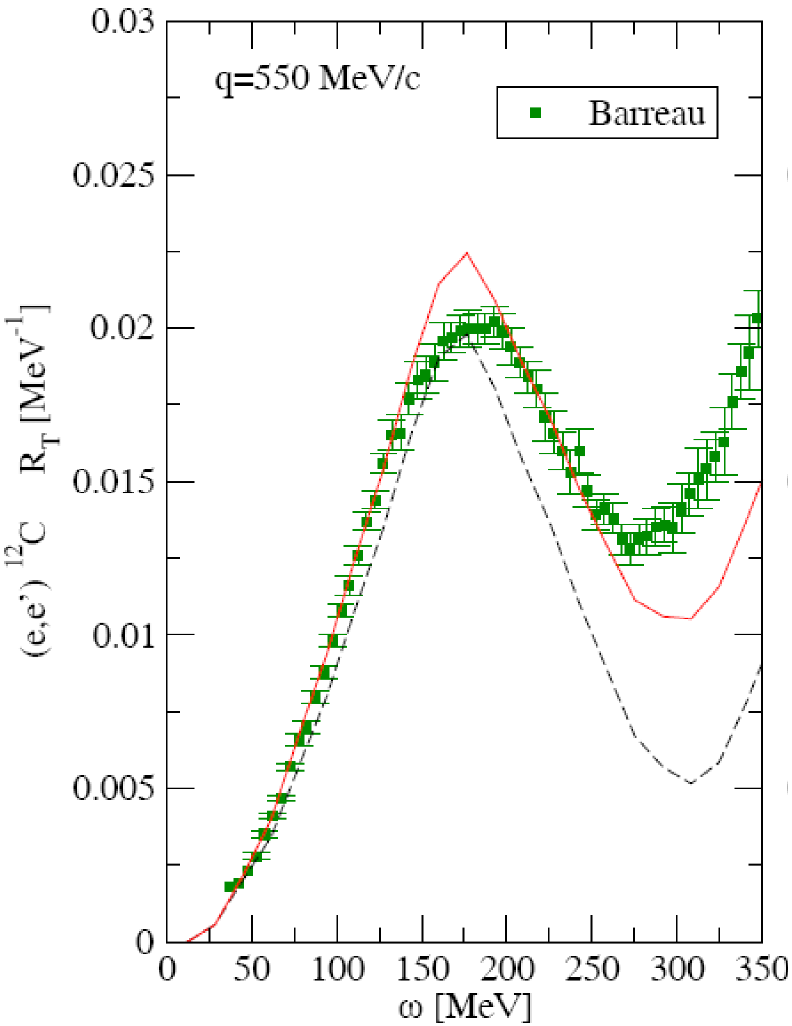
neutrino energy

Neutrino vs antineutrino differential cross section

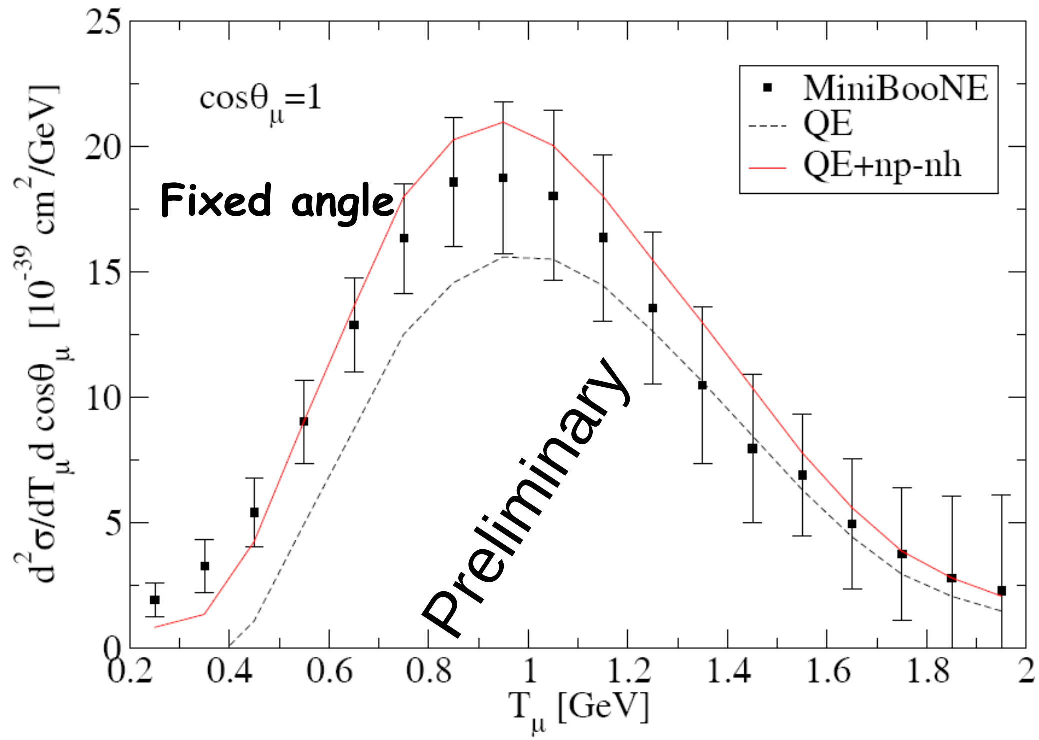


Electron scattering *vs* Neutrino scattering

(e,e') ^{12}C R_T



MiniBooNE CCQE flux-integrated double differential X section



Electron-nucleus scattering

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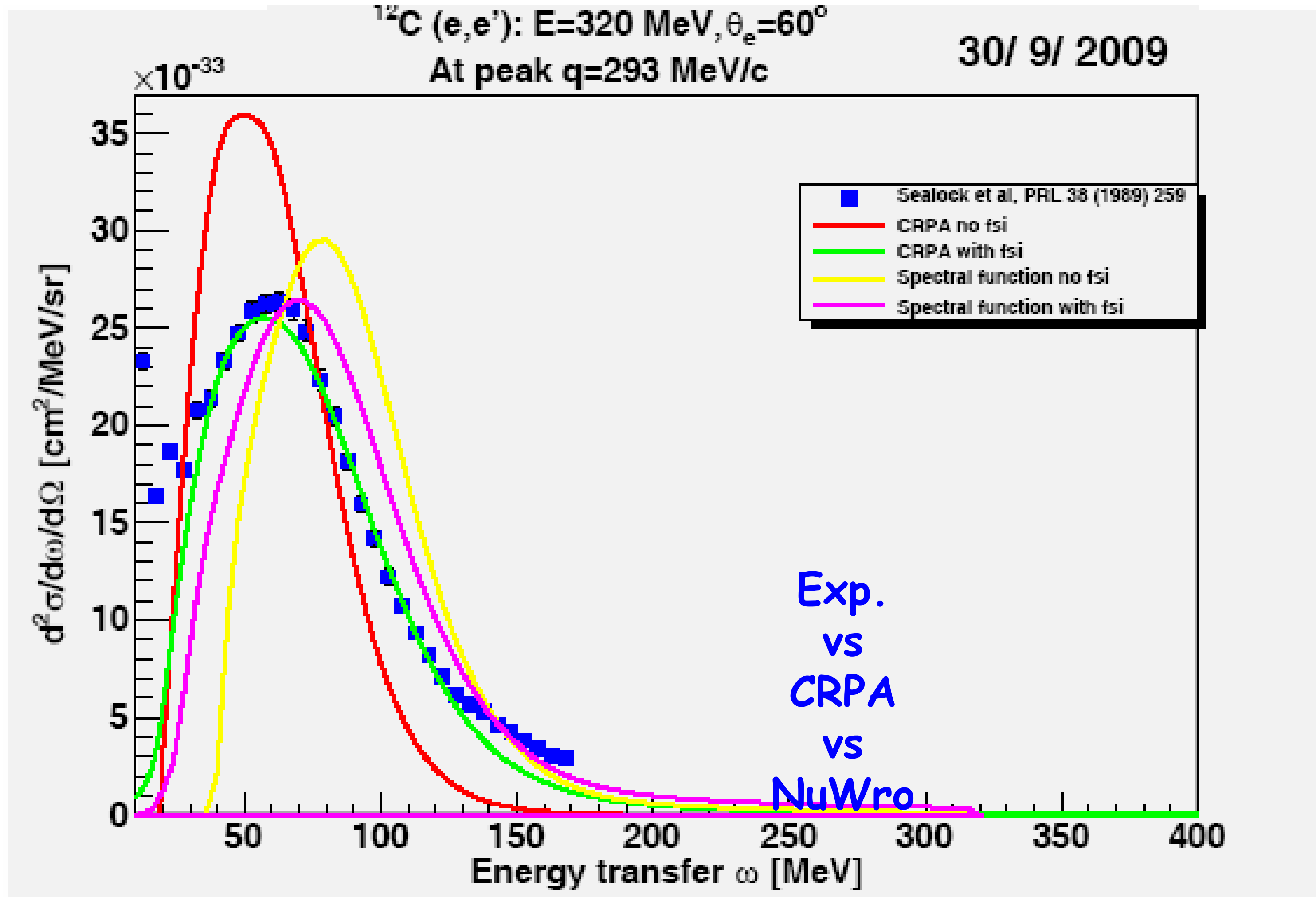
Role of FSI



CRPA+FSI M. Martini et al.Phys. Rev. C 75, 034604 (2007)

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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 $\mathrm{Im}\,B_0$ and $\mathrm{Im}\,C_0$ 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 $\mathrm{Im}\,C_0$ 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 2p-2h evaluation: Alberico et al. Ann. Phys. 154, 356 (1984)

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