np-nh excitations in ν-nucleus scattering: a theoretical overview

Marco Martini

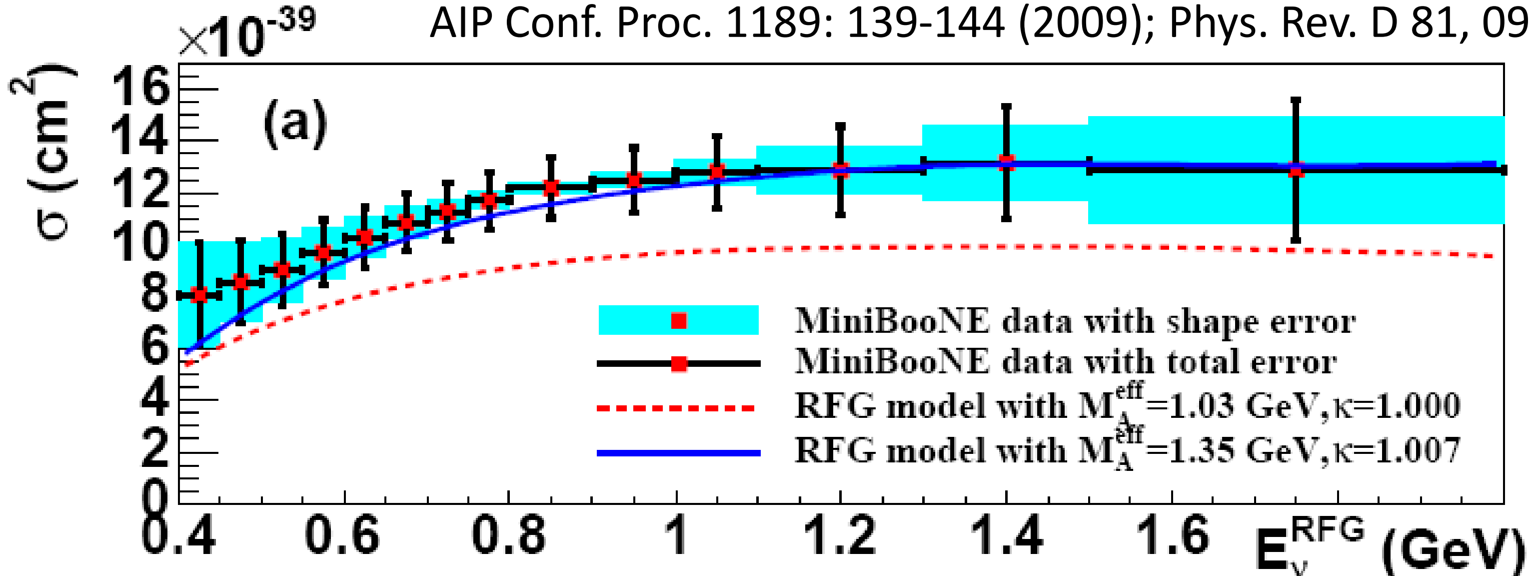
Outline

- MiniBooNE QE-like cross section and np-nh excitations
- Review of different theoretical models: comparison among them and with data
- np-nh excitations in connection with other experiments: SciBooNE, T2K, MINERνA

np-nh excitations and MiniBooNE data

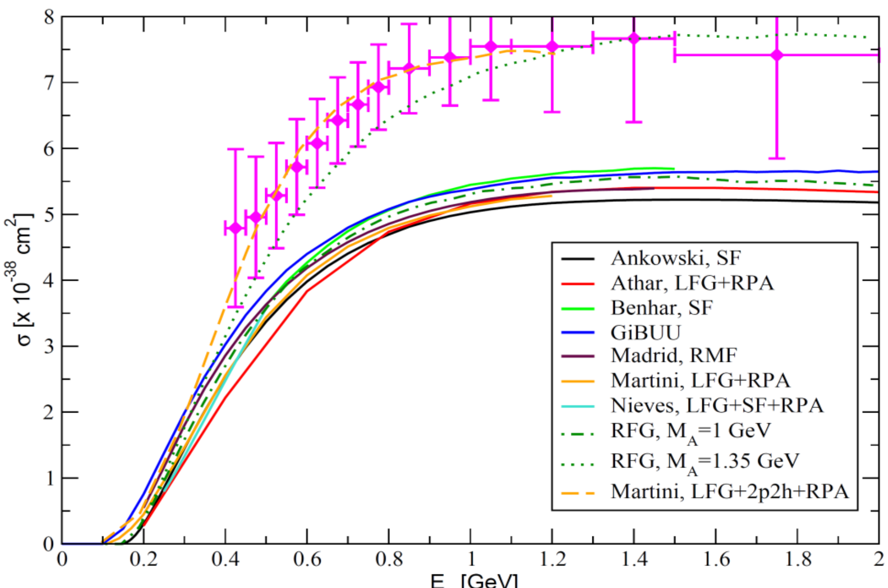
MiniBooNE CC Quasielastic neutrino cross section on Carbon

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



Comparison with predictions using M_A=1.03 GeV (standard value) reveals a discrepancy

In the Relativistic Fermi Gas (RFG) model an axial mass of 1.35 GeV is needed to account for data



L. Alvarez-Ruso

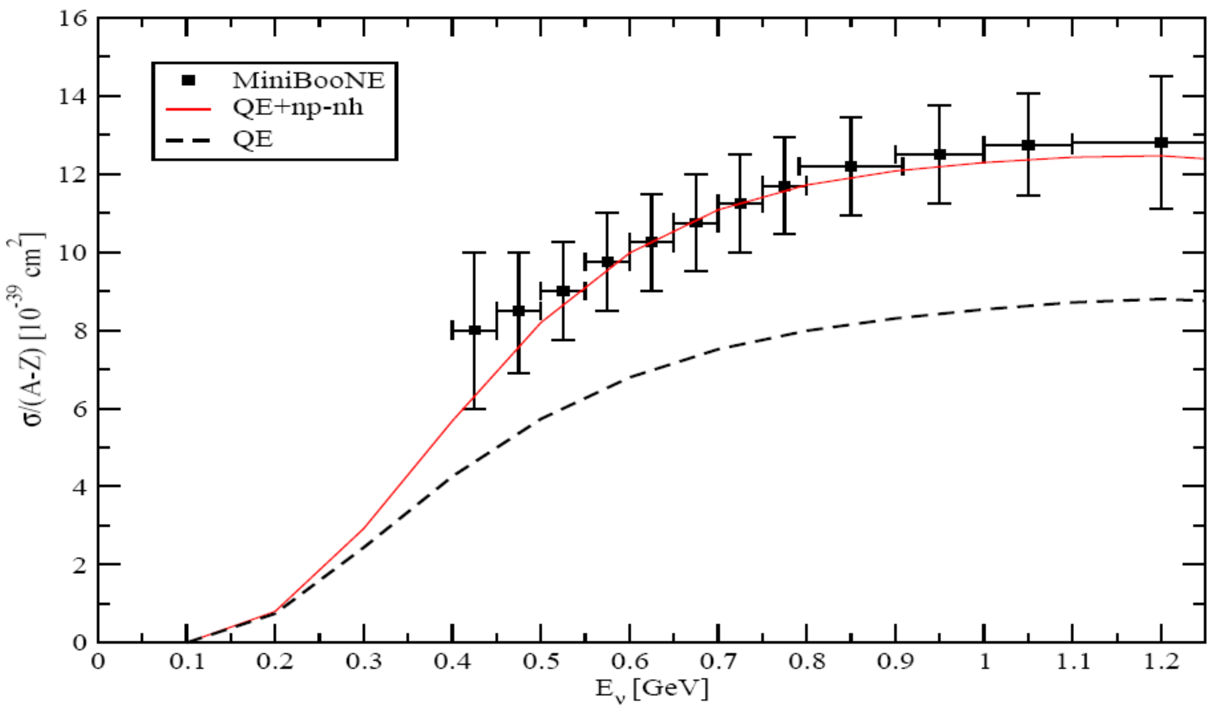
arXiv:1012.3871

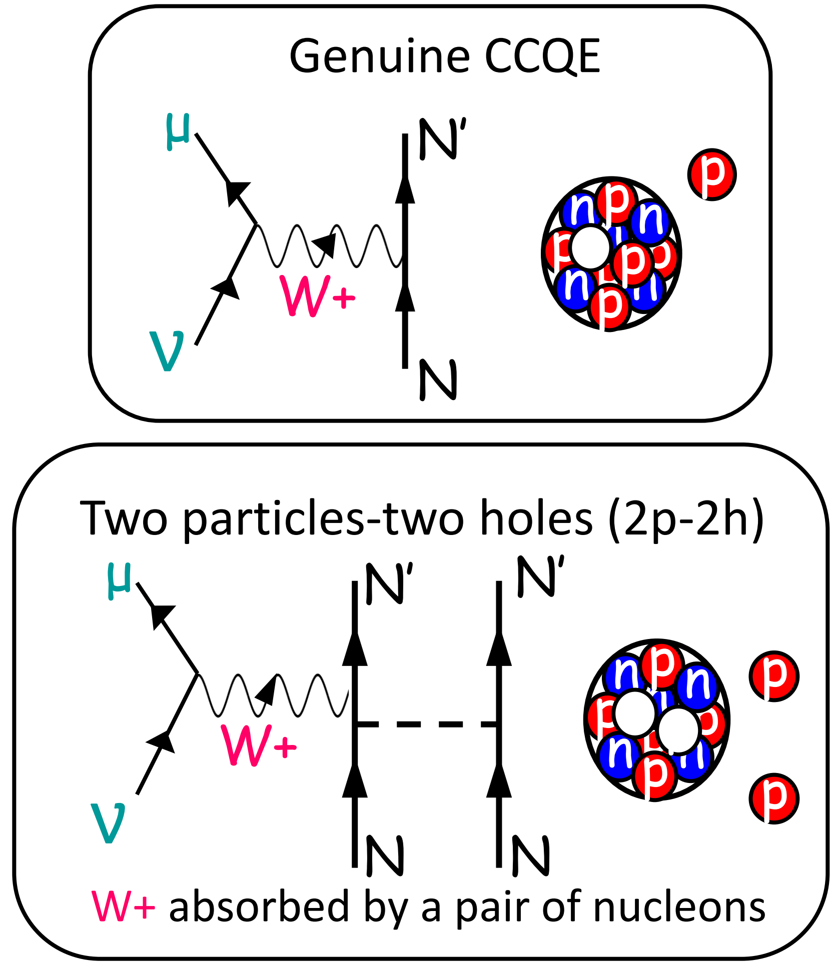
(Neutrino 2010)

puzzle??

An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)



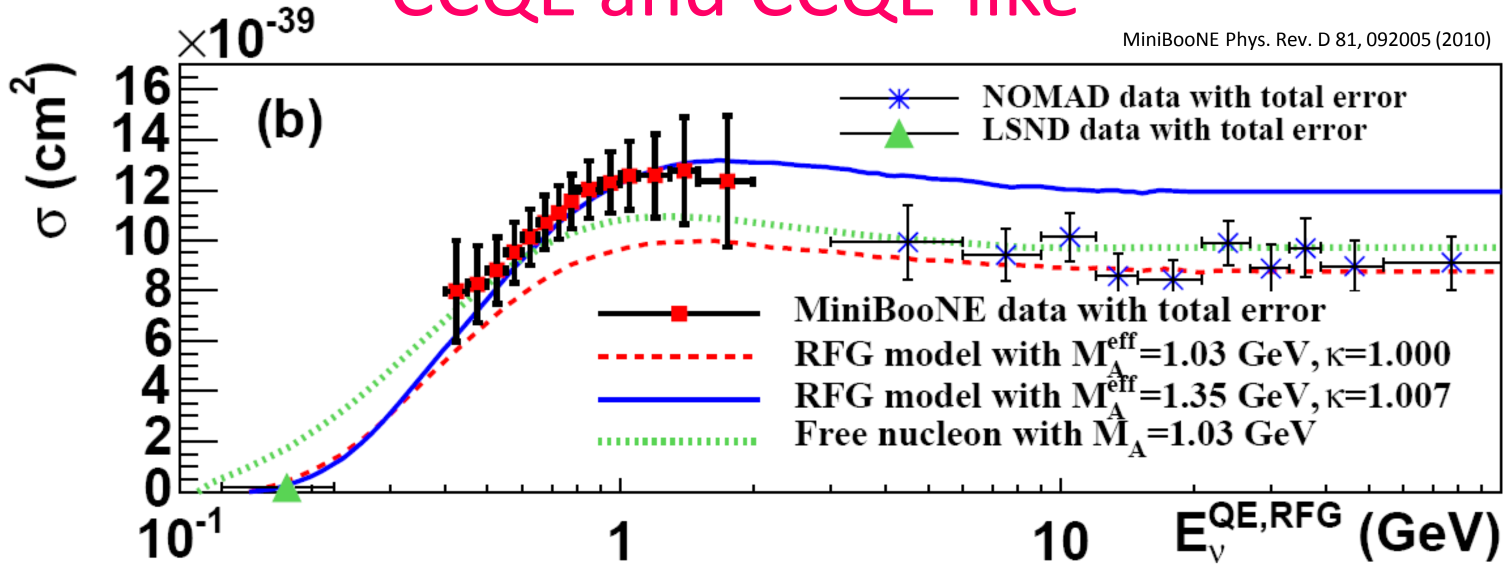


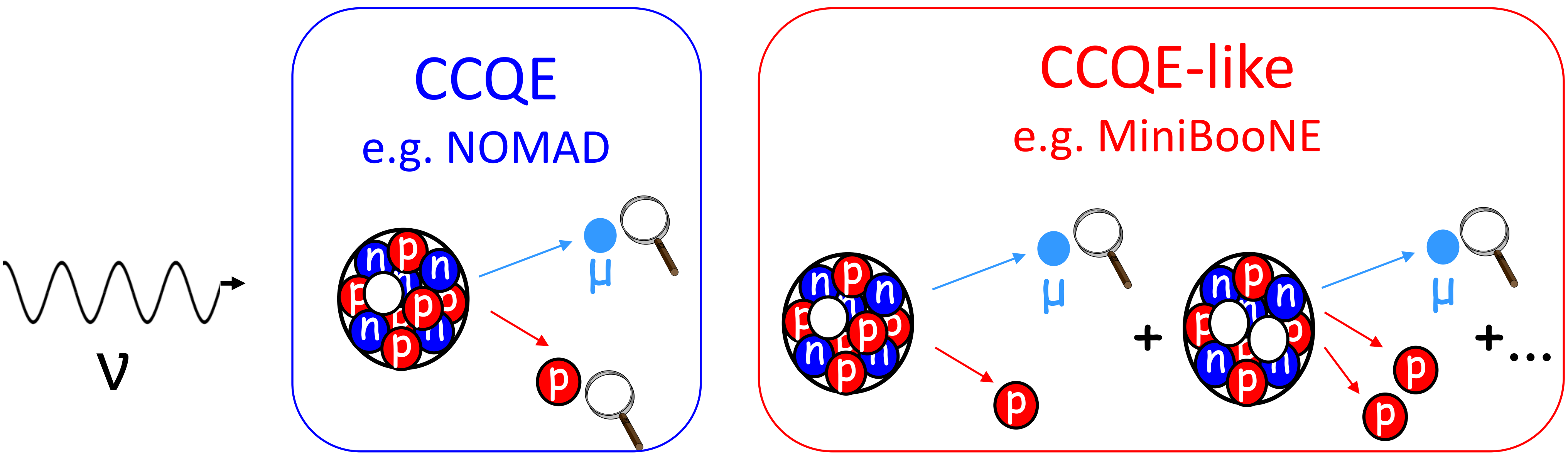
M. Martini, M. Ericson, G. Chanfray, J. Marteau Phys. Rev. C 80 065501 (2009)

Agreement with MiniBooNE without increasing M_A

CCQE and CCQE-like

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

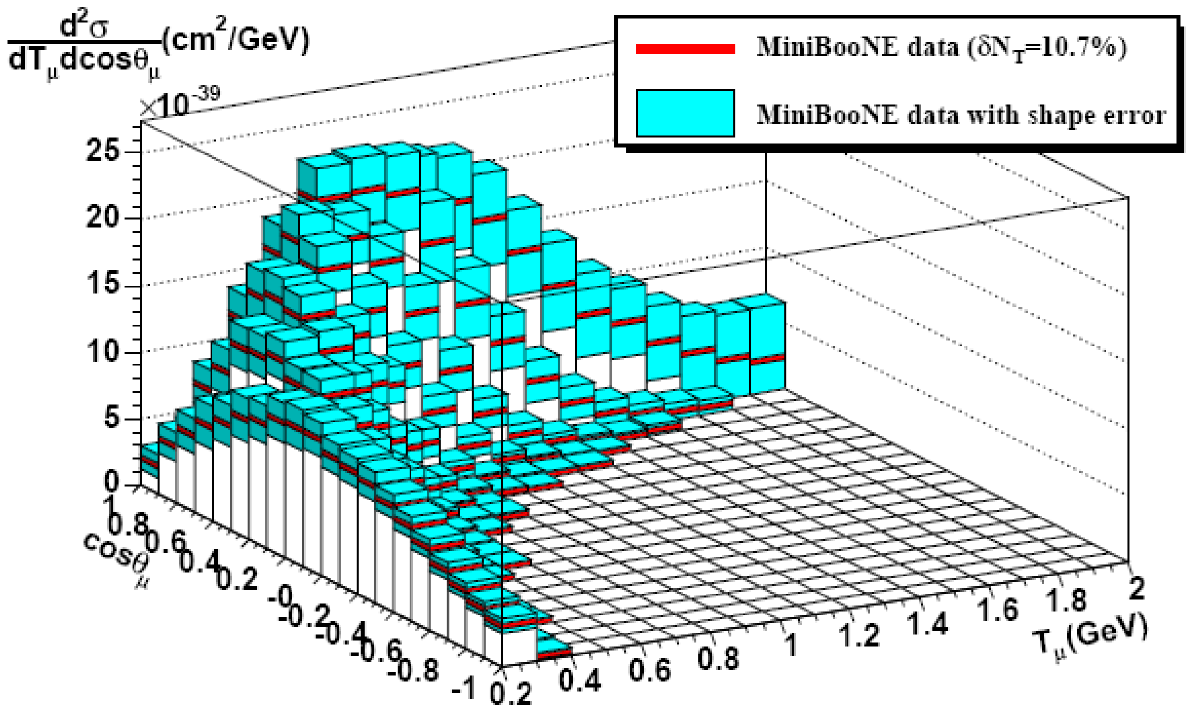


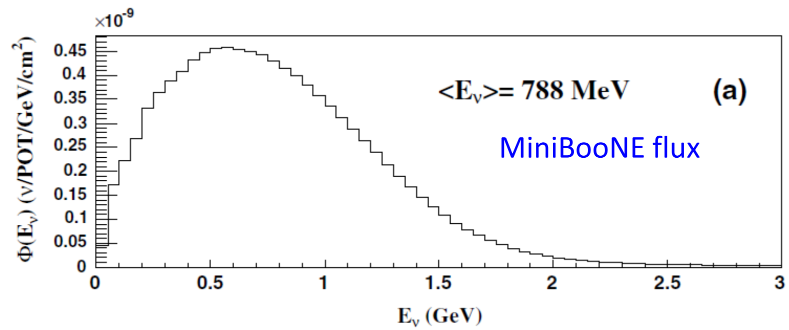


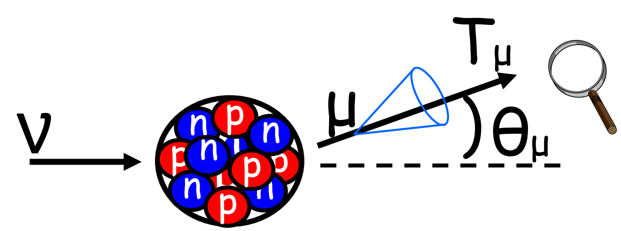
Cherenkov detectors measure CCQE-like which includes np-nh contributions

MiniBooNE CCQE-like flux-integrated double diff. cross section

$$\frac{d^2\sigma}{dE_\mu d\cos\theta} = \int dE_\nu \left[\frac{d^2\sigma}{d\omega d\cos\theta}\right]_{\omega=E_\nu-E_\mu} \Phi(E_\nu)$$



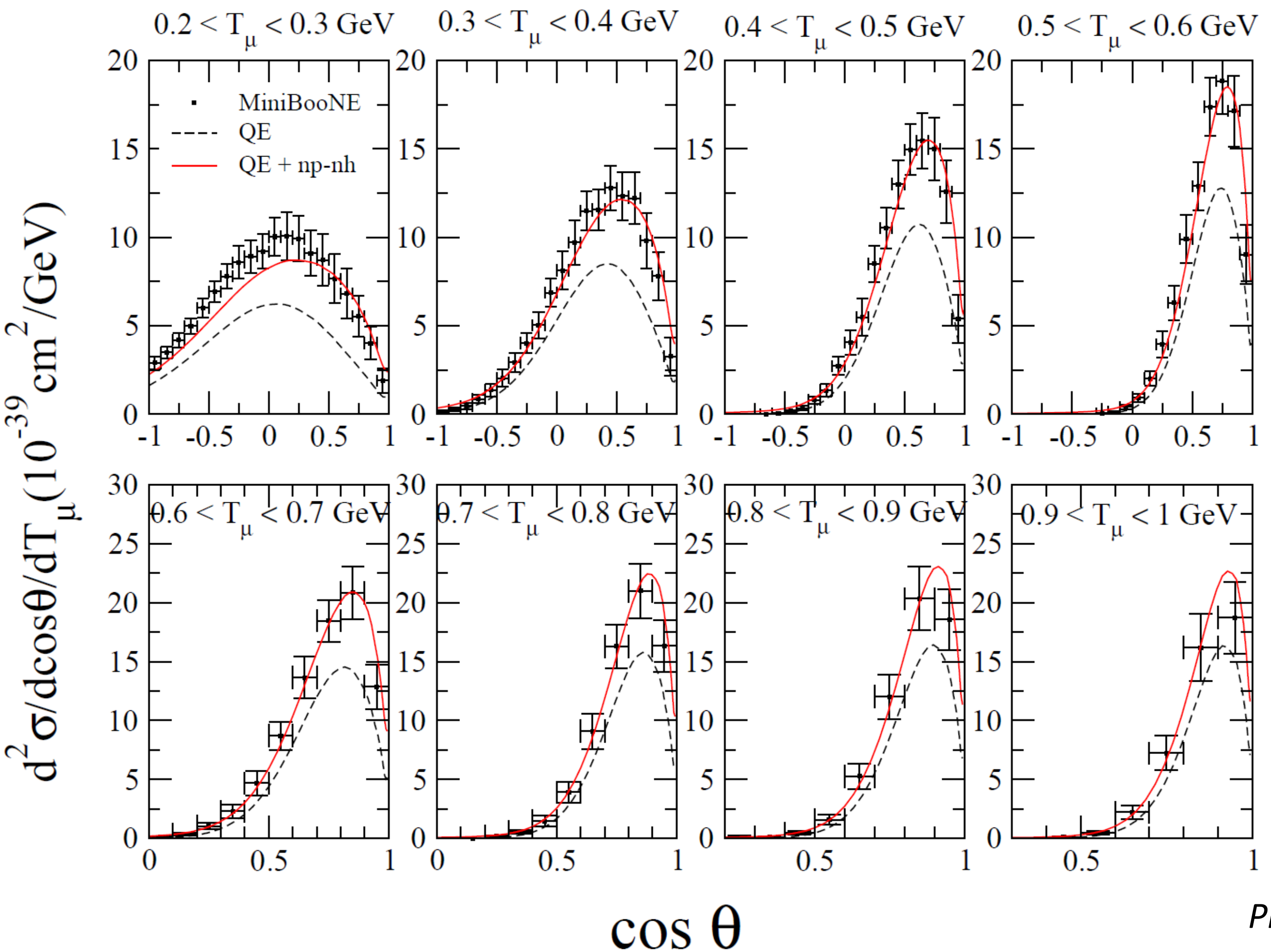




Function of two measured variables

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

Flux-integrated double differential cross section



red: including np-nh

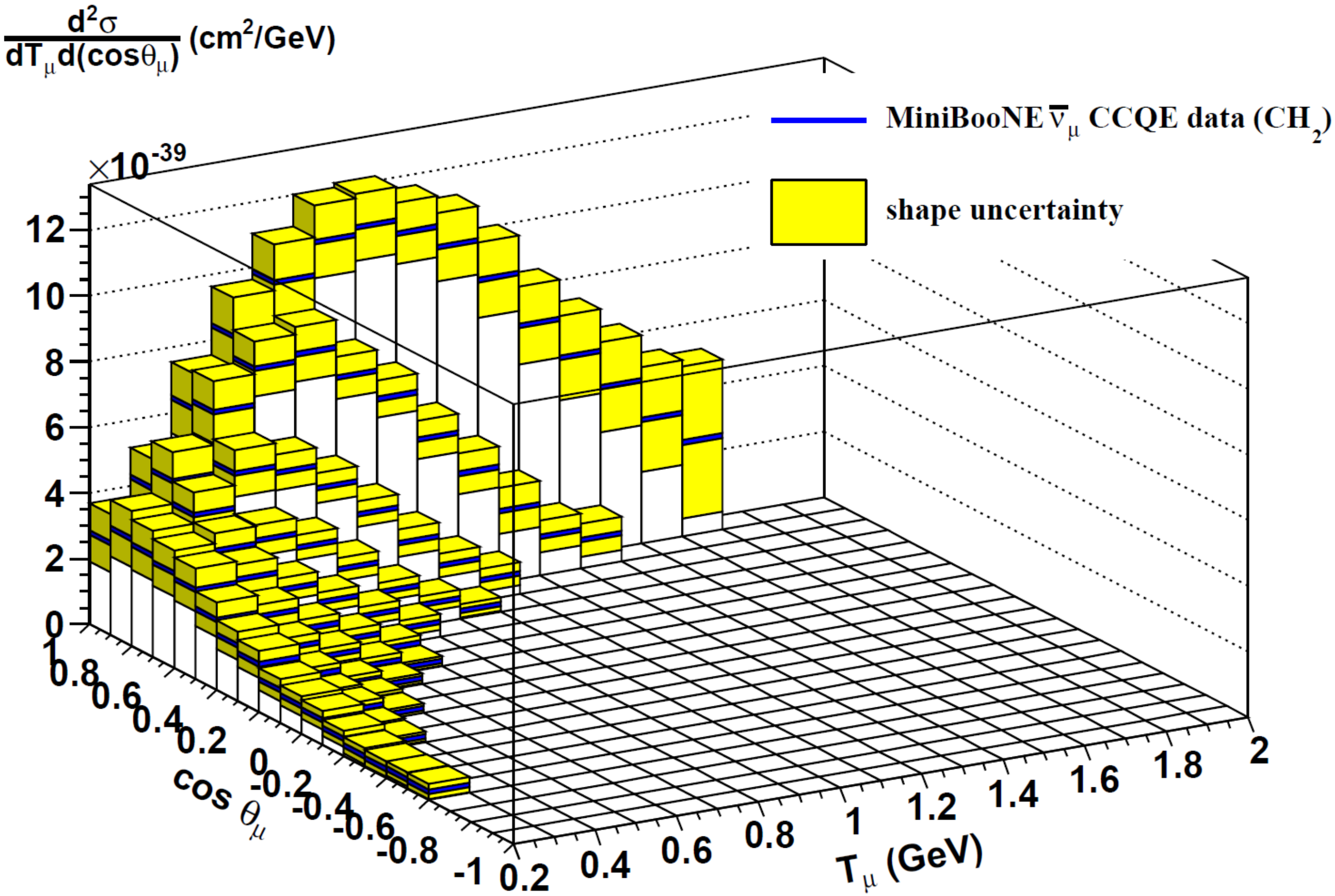
black: genuine QE

Martini, Ericson, Chanfray, Phys. Rev. C 84 055502 (2011)

Agreement with MiniBooNE without increasing M_A once np-nh is included

Similar conclusions in *Nieves et al. PLB 707, 72 (2012)*

Antineutrino MiniBooNE CCQE-like $d^2\sigma$

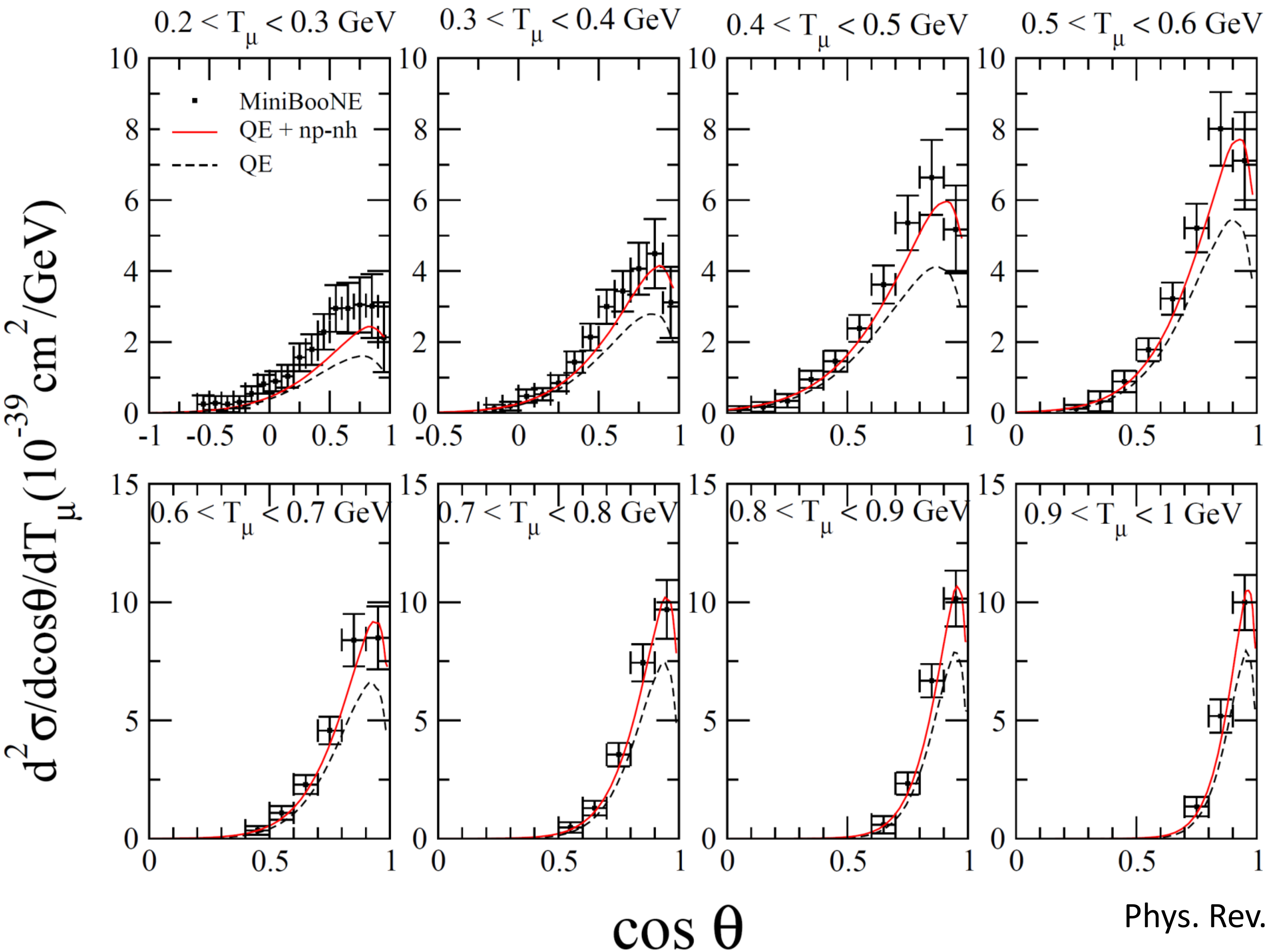


MiniBooNE, Phys. Rev. D 88 (2013) 032001

CH_2 and Carbon

$\overline{\nu}$

Flux-integrated double differential cross section



red: including np-nh

black: genuine QE

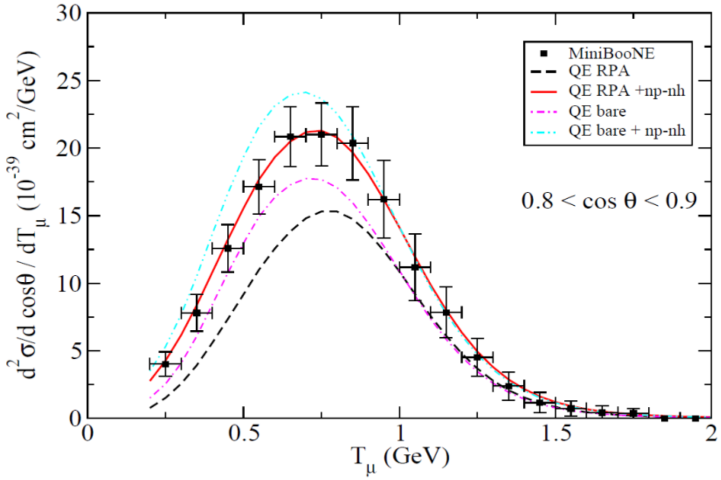
Martini, Ericson,
Phys. Rev. C 87 065501 (2013)

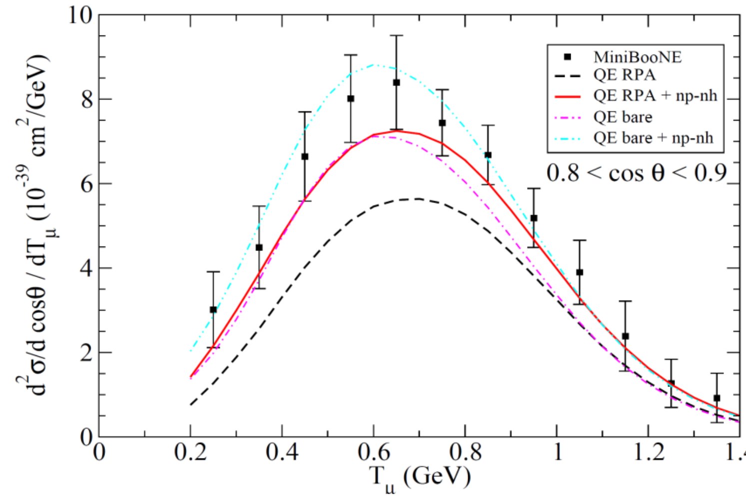
Agreement with MiniBooNE without increasing M_A once np-nh is included

Similar conclusions in *Nieves et al. PLB 721, 90 (2013)*

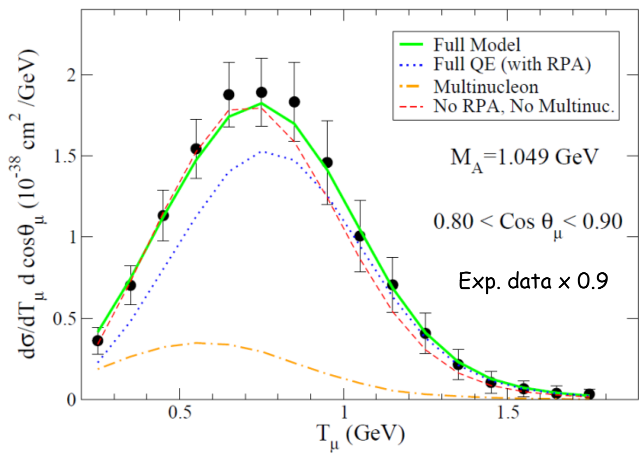
ν $\overline{\nu}$

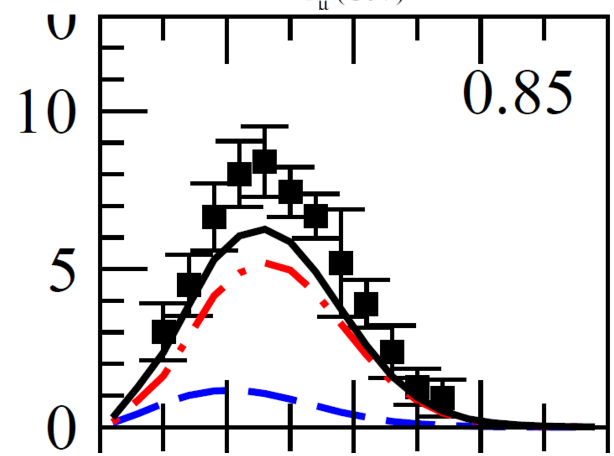
Martini et al.





Nieves et al.

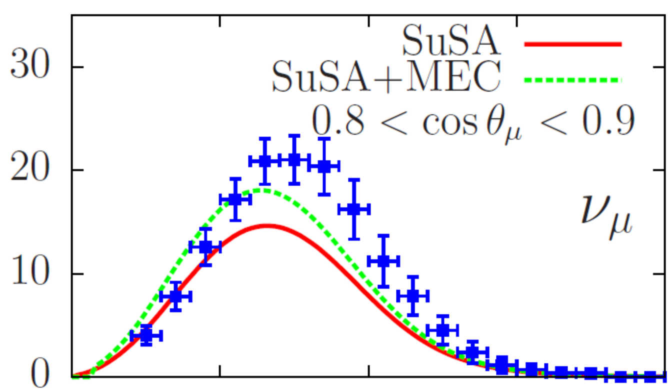


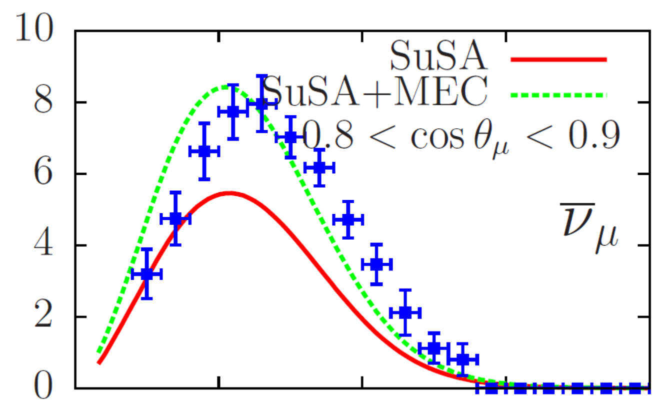


black: QE RPA+2p2h

red: QE RPA

Amaro et al.





Theoretical studies on np-nh excitations in ν QE-like

M. Martini, M. Ericson, G. Chanfray, J. Marteau (Lyon, IPNL)

Phys. Rev. C 80 065501 (2009) ν σtotal
Phys. Rev. C 81 045502 (2010) ν vs antiν (σtotal)
Phys. Rev. C 84 055502 (2011) ν $d^2\sigma$, $d\sigma/dQ^2$
Phys. Rev. D 85 093012 (2012) impact of np-nh on ν energy reconstruction
Phys. Rev. D 87 013009 (2013) impact of np-nh on ν energy reconstruction and ν oscillation
Phys. Rev. C 87 065501 (2013) antiν $d^2\sigma$, $d\sigma/dQ^2$
arXiv 1404.1490 (2014) inclusive ν $d^2\sigma$

J. Nieves, I. Ruiz Simo, M.J. Vicente Vacas, F. Sanchez, R. Gran (Valencia, IFIC)

Phys. Rev. C 83 045501 (2011) ν, antiν σtotal
Phys. Lett. B 707 72-75 (2012) ν $d^2\sigma$
Phys. Rev. D 85 113008 (2012) impact of np-nh on ν energy reconstruction
Phys. Lett. B 721 90-93 (2013) antiν $d^2\sigma$
Phys. Rev. D 88 113007 (2013) extension of np-nh up to 10 GeV

J.E. Amaro, M.B. Barbaro, J.A. Caballero, T.W. Donnelly , J.M. Udias, C. F. Williamson, I. Ruiz Simo, C. Albertus (Superscaling)

Phys. Lett. B 696 151-155 (2011) ν $d^2\sigma$
Phys. Rev. D 84 033004 (2011) ν $d^2\sigma$, σtotal
Phys. Rev. Lett. 108 152501 (2012) antiν $d^2\sigma$, σtotal
arXiv: 1405.4280 2p-2h phase space

A. Lovato, S. Gandolfi, J. Carlson, S. C. Pieper, R. Schiavilla (SNPA)

Phys. Rev. Lett. 112 182502 (2014) **ab initio** calculation of the sum rules for NC (**but not X sections**)

np-nh excitations taken into account in an effective way

O. Lalakulich, K. Gallmeister and U. Mosel (GiBUU)

Phys. Rev. C 86 014614 (2012) ν σtotal, $d^2\sigma$, $d\sigma/dQ^2$
Phys. Rev. C 86 054606 (2012) impact of np-nh on ν energy reconstruction and ν oscillation
Phys. Rev. Lett. 112 151802 (2014) energy reconstruction in LBNE
Phys. Rev. D 89 093003 (2014) reaction mechanisms at MINERvA

A. Bodek, H.S. Budd, M.E. Christy (Transverse Enhancement Model - TEM)

EPJ C 71 1726 (2011) ν and antiν σtotal, $d\sigma/dQ^2$

np – nh excitations in the Monte Carlo generators

J. Zmuda talk

Sources and References of 2p-2h

M. Martini, M. Ericson, G. Chanfray, J. Marteau

Alberico, Ericson, Molinari, Ann. Phys. 154, 356 (1984) (e,e') γ π

**Oset and Salcedo, Nucl. Phys. A 468, 631 (1987)* π γ

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

Delorme, Ericson, Phys.Lett. B156 263 (1985)

Marteau, Eur.Phys.J. A5 183-190 (1999); PhD thesis

Marteau, Delorme, Ericson, NIM A 451 76 (2000)

} ν *pioneer works*

J. Nieves, I. Ruiz Simo, M.J. Vicente Vacas et al.

Gil, Nieves, Oset, Nucl. Phys. A 627, 543 (1997) (e,e') γ

**Oset and Salcedo, Nucl. Phys. A 468, 631 (1987)* π γ

J.E. Amaro, M.B. Barbaro, J.A. Caballero, T.W. Donnelly et al.

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

Amaro, Maieron, Barbaro, Caballero, Donnelly ,Phys. Rev. C 82 044601 (2010) (e,e')

A. Lovato, S. Gandolfi, J. Carlson, S. C. Pieper, R. Schiavilla

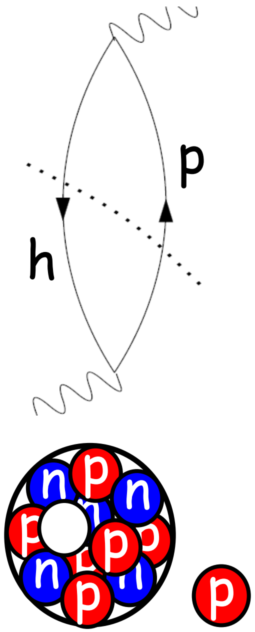
Lovato, Gandolfi, Butler, Carlson, Lusk, Pieper, Schiavilla, Phys. Rev. Lett. 111 092501 (2013) (e,e')

Shen, Marcucci, Carlson, Gandolfi, Schiavilla, Phys. Rev. C 86 035503 (2012) ν- deuteron

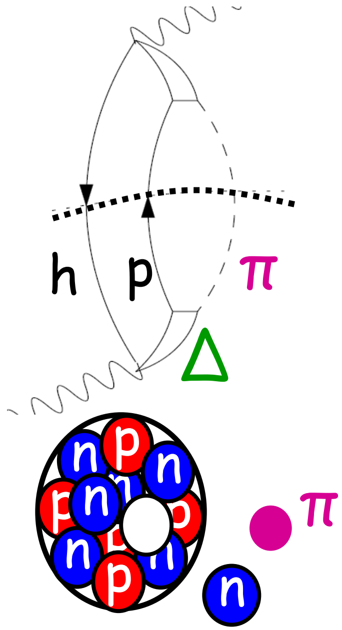
Theoretical details and comparisons

Nuclear Response Functions

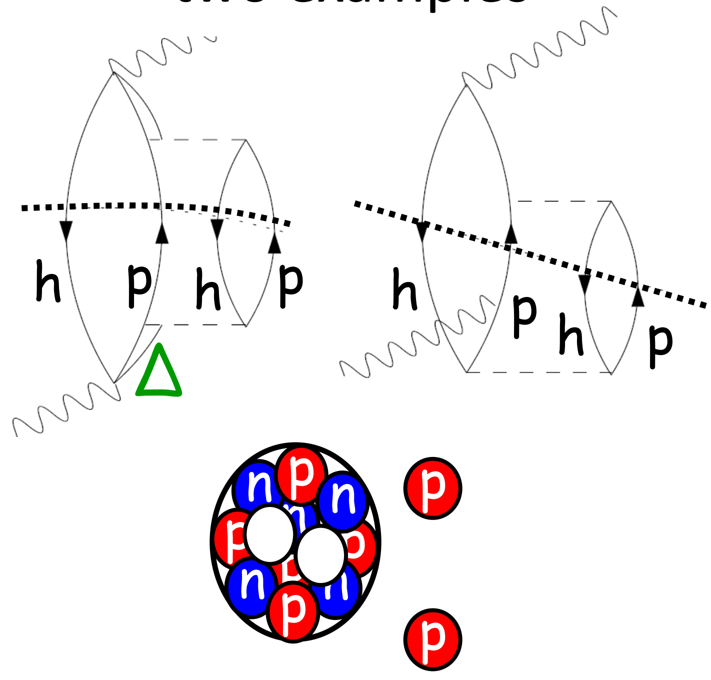
1p-1h
QE



1p-1h
1π production



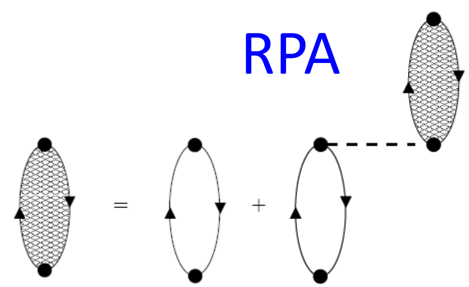
2p-2h:
two examples



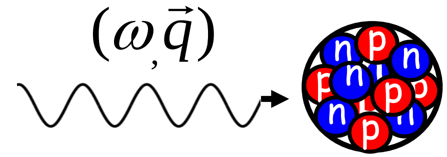
Nuclear response in Random Phase Approximation

(the approach used by Martini et al. and Nieves et al.)

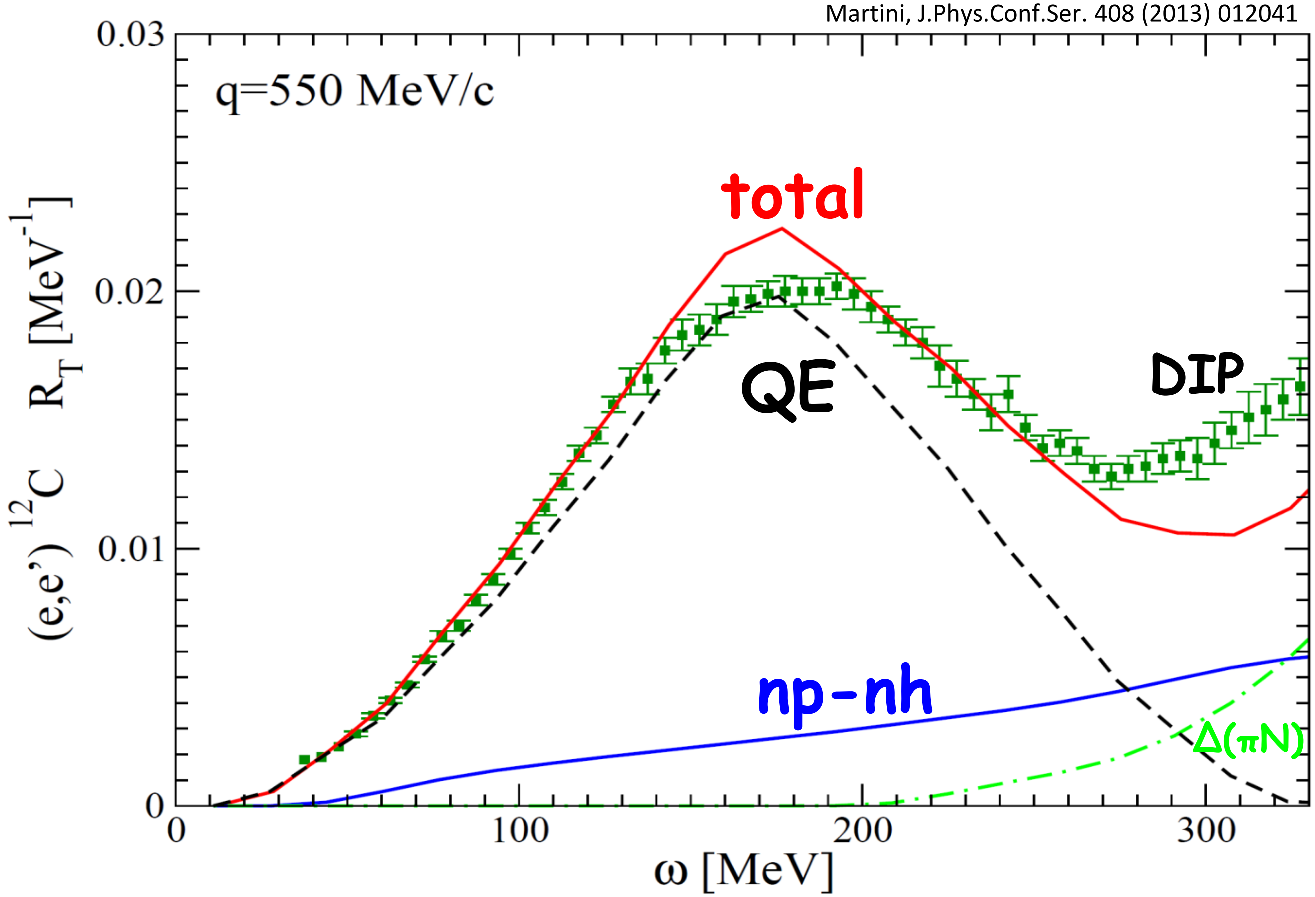
RPA



An example of nuclear response : transverse response in electron scattering



Martini, J.Phys.Conf.Ser. 408 (2013) 012041



np-nh creates a high energy tail in the nuclear response above the QE peak

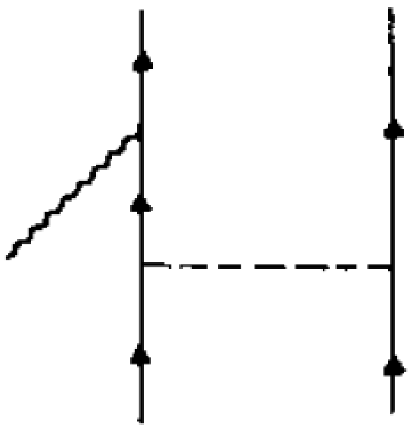
[first pointed out in: Donnelly, van Orden, de Forest, Hermans, Phys. Lett. 76 B 393 (1978) and Alberico, Ericson, Molinari, Ann. Phys. 154, 356 (1984)]

Various evaluations (Amaro et al, Martini et al, Nieves et al) of np-nh contributions to (e,e') R_T are compatible among them and with data. This test is important for ν cross section which is dominated by the transverse response .

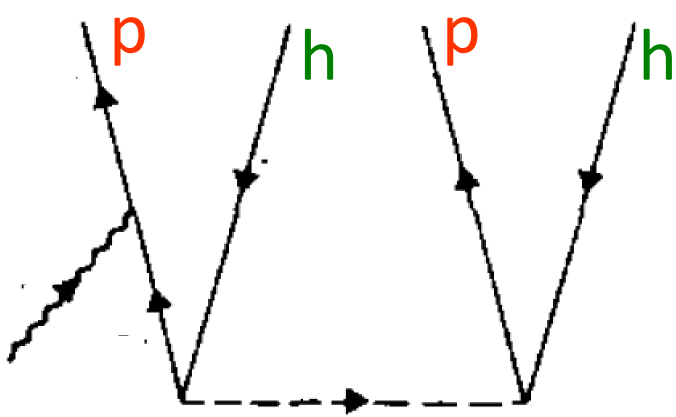
Two particle-two hole sector (2p-2h)

Three equivalent representations of the same process

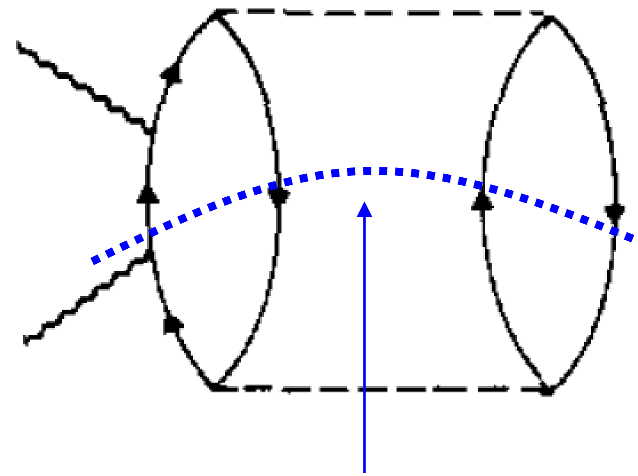
2 body current



2p-2h matrix element



2p-2h response

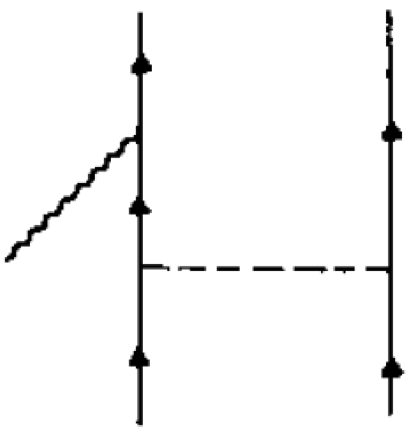


Cut
(optical theorem)

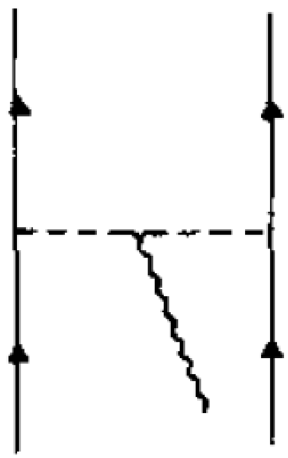
Final state: two particles-two holes

Some diagrams for 2 body currents

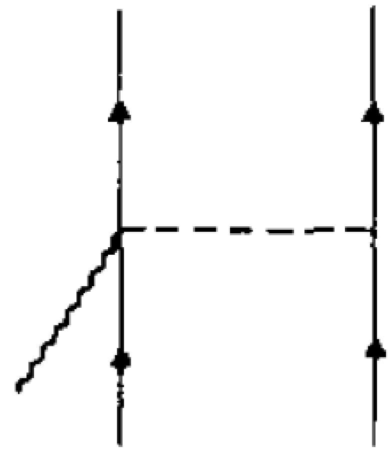
Nucleon-Nucleon correlations



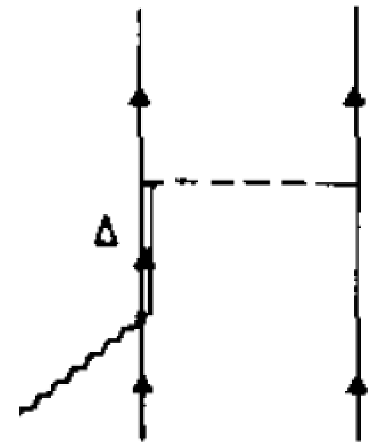
Meson Exchange Currents (MEC)



Pion in flight



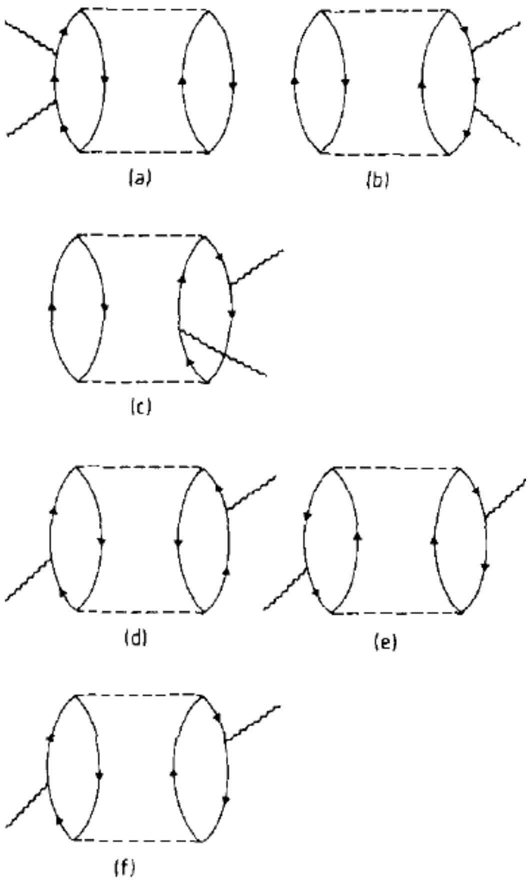
Contact



Delta

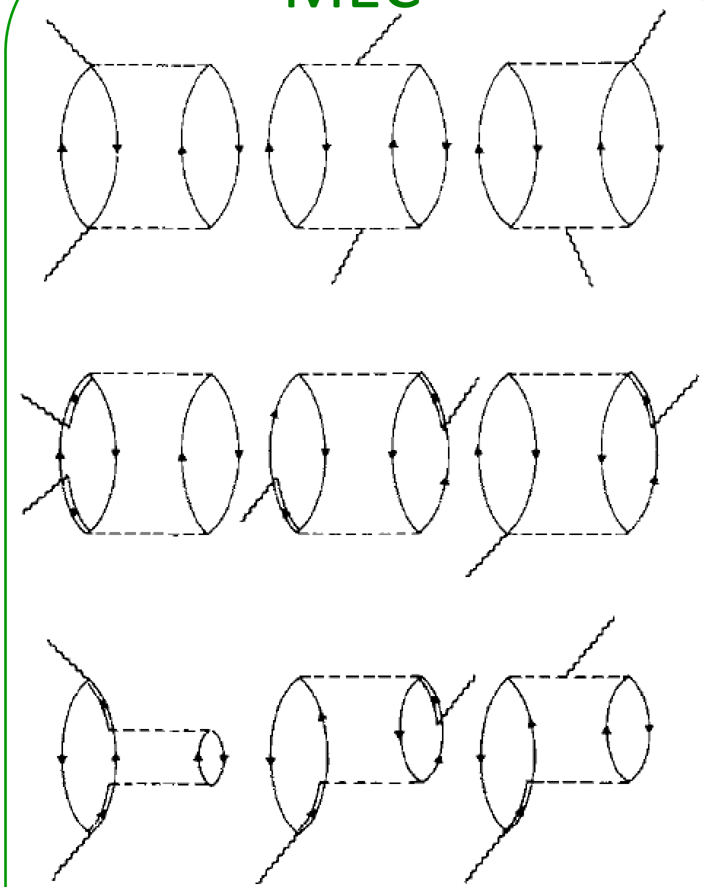
Some diagrams for 2p-2h responses

NN correlations



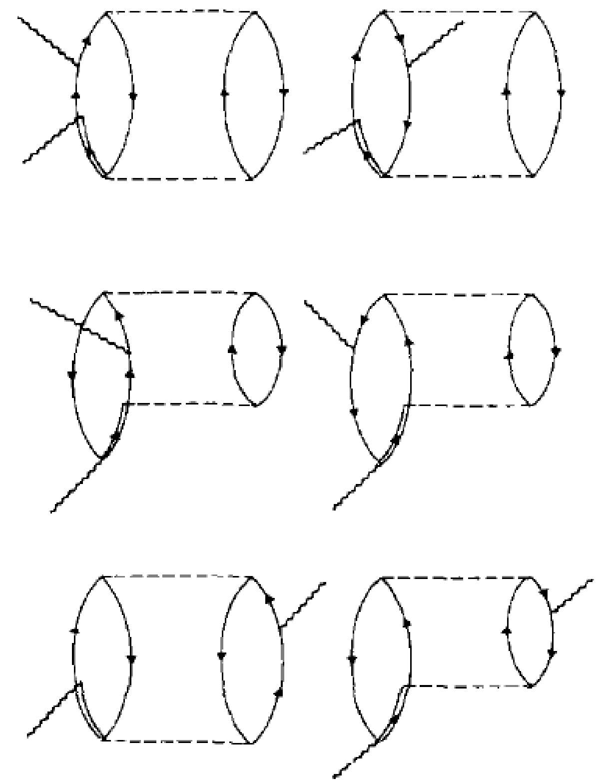
16 diagrams

MEC



49 diagrams

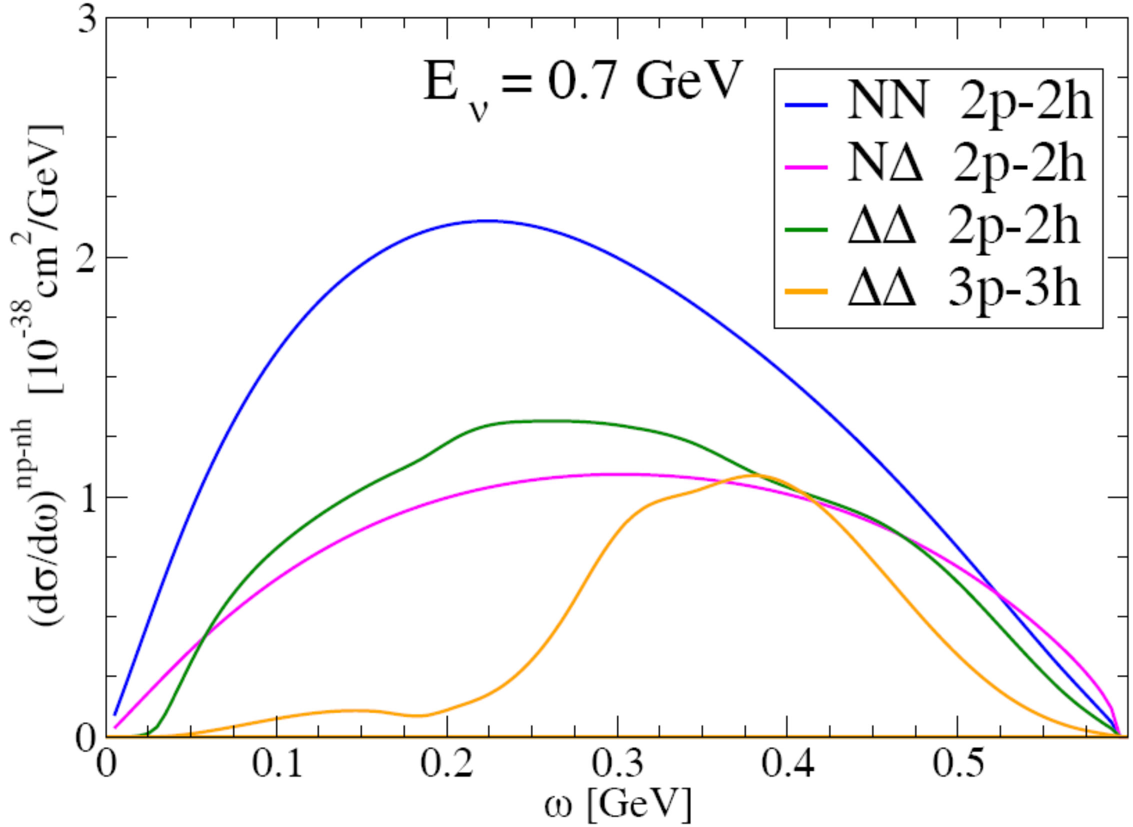
NN correlation-MEC interference



56 diagrams

Different contributions in the np-nh channel

Martini et al.

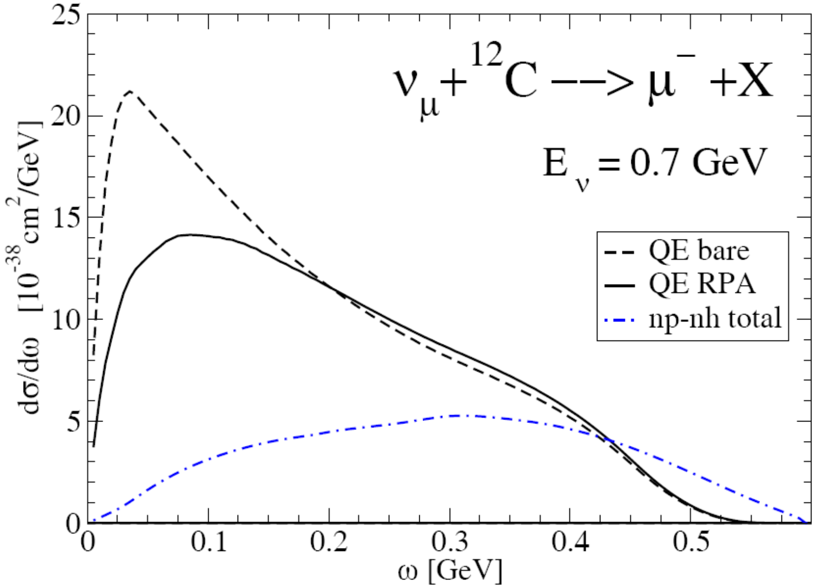


Correlations

Interference

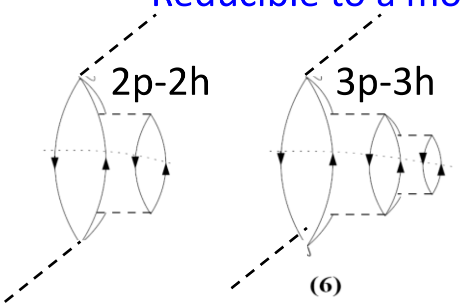
MEC

Martini et al.



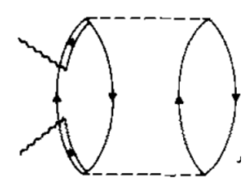
ΔΔ contributions

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



From:
E. Oset and L. L. Salcedo, NPA 468, 631 (1987)
in Martini et al, Nieves et al and also in the T2K analyses.

- Not reducible to a modification of the Δ width



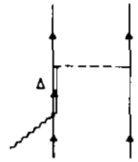
Analogies and differences of 2p-2h

π,g'

M. Martini, M. Ericson, G. Chanfray, J. Marteau

[Genuine QE (1 body contribution): LRFG+RPA]

NN correlations Δ-MEC NN correlations - MEC interference Axial and Vector



π,ρ,g'

J. Nieves, I. Ruiz Simo, M.J. Vicente Vacas et al.

[Genuine QE (1 body contribution): LRFG+SF+RPA]

NN correlations MEC NN correlations - MEC interference Axial and Vector

J.E. Amaro, M.B. Barbaro, J.A. Caballero, T.W. Donnelly et al.

π

[Genuine QE (1 body contribution): Superscaling] Only Vector

MEC

[Inclusion of NN corr. and corr.-MEC Interf. in progress (already studied for the electron scattering)] [Generalization to axial in progress]

A. Lovato, S. Gandolfi, J. Carlson, S. C. Pieper, R. Schiavilla

[Genuine QE (1 body contribution): GFMC with AV18 and IL7 potentials]

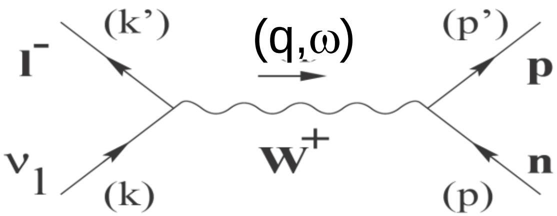
NN correlations MEC NN correlations - MEC interference Axial and Vector

N.B.

In the approach of **Lovato et al.**, who work in a correlated basis, the effects of NN correlations **are included in the 1 body contribution**.
For this reason Lovato et al. refer to the "NN correlation – MEC interference" as "one nucleon – two nucleon currents interference"

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

Neutrino-nucleus cross section



Two equivalent expressions:

The notation for example of Amaro et al:

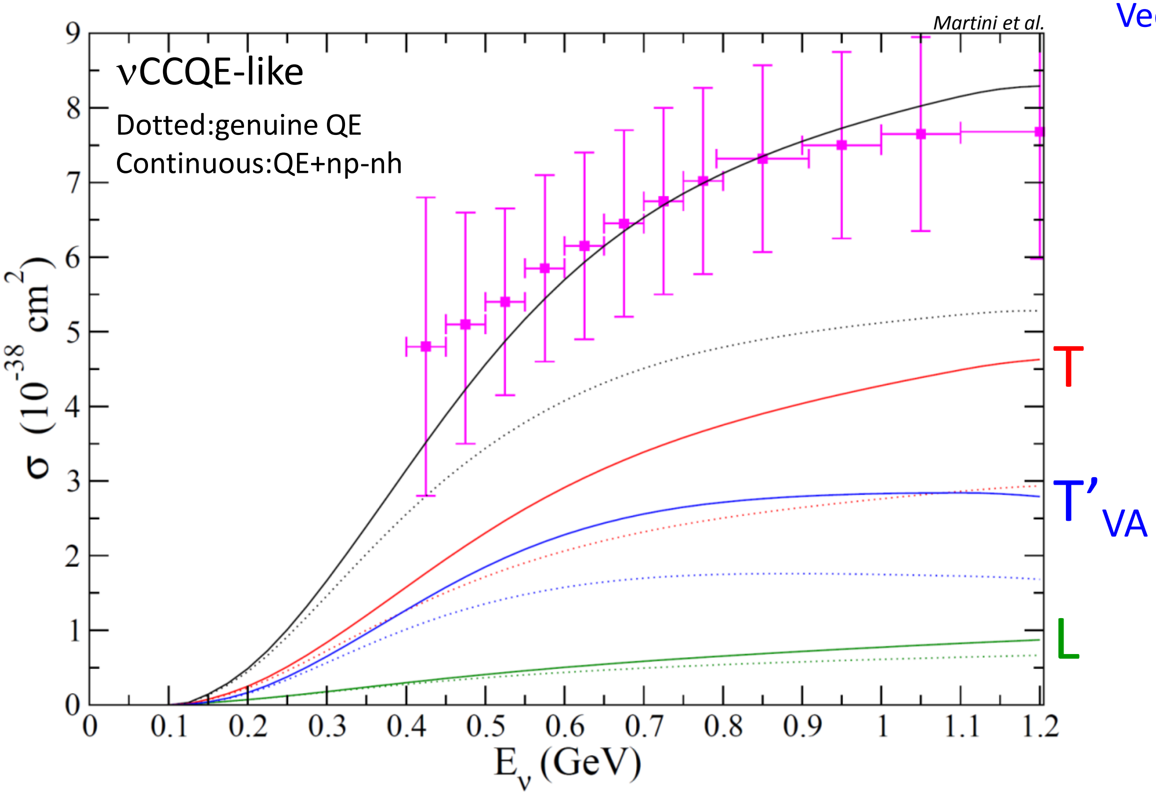
$$\frac{\partial^2\sigma}{\partial\Omega\ \partial\epsilon'} = \sigma_0 \left[L_{CC}(R^V_{CC} + R^A_{CC}) + L_{CL}(R^V_{CL} + R^A_{CL}) + L_{LL}(R^V_{LL} + R^A_{LL}) + L_T(R^V_T + R^A_T) \pm L_{T'VA} R^{VA}_{T'}\right]$$

Longitudinal | Transverse | Transverse V-A interference

The notation of Lovato et al:

$$\frac{\partial^2\sigma}{\partial\Omega\ \partial\epsilon'} = \sigma_0 \left[L_{00}R_{00} + L_{0z}R_{0z} + L_{zz}R_{zz} + L_{xx}R_{xx} \pm L_{xy}R_{xy}\right]$$

Longitudinal | Transverse | Transverse Vector-Axial interference



A third simplified expression (useful for illustration)

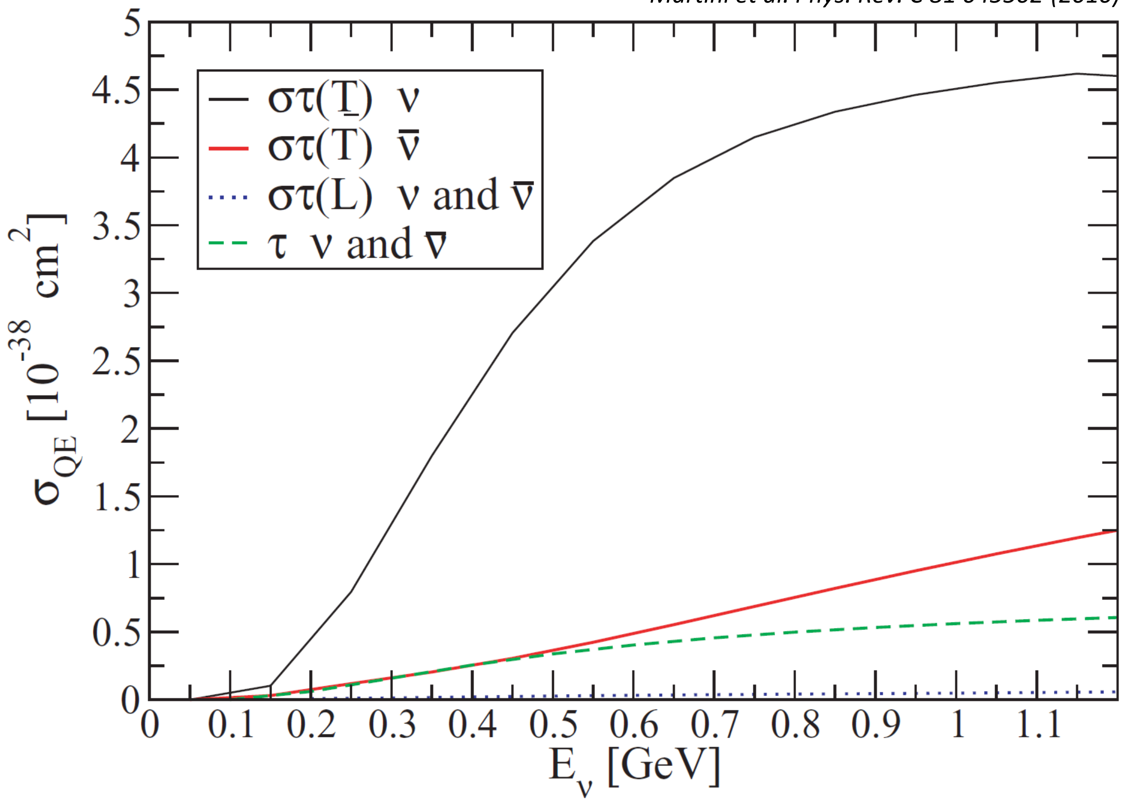
Resp. Functions: Charge R_τ (τ), Isospin Spin-Longitudinal $R_{\sigma\tau(L)}$($\tau\ \sigma\cdot q$), Isospin Spin Transverse $R_{\sigma\tau(T)}$ ($\tau\ \sigma x q$)

$$\frac{\partial^2\sigma}{\partial\Omega\,\partial\epsilon'} = \frac{G_F^2\,\cos^2\theta_c}{2\,\pi^2}k'\epsilon'\,\cos^2\frac{\theta}{2}\left[\frac{(q^2-\omega^2)^2}{q^4}G_E^2\,R_\tau + \frac{\omega^2}{q^2}G_A^2\,R_{\sigma\tau(L)} + \right.$$

$$\left. +\;2\left(\tan^2\frac{\theta}{2}+\frac{q^2-\omega^2}{2q^2}\right)\left(G_M^2\,\frac{\omega^2}{q^2}+G_A^2\right)\,R_{\sigma\tau(T)} \pm 2\,\frac{\epsilon+\epsilon'}{M_N}\,\tan^2\frac{\theta}{2}\,G_A\,G_M\,R_{\sigma\tau(T)}\right]$$

$$\begin{cases} + & (\nu) \\ - & (\bar{\nu}) \end{cases}$$

Martini et al. Phys. Rev. C 81 045502 (2010)



The relative weight of the 3 different nuclear responses (R_τ , $R_{\sigma\tau(L)}$, $R_{\sigma\tau(T)}$) is different for neutrinos and antineutrinos due to the Vector-Axial interference term

Where 2p-2h contributions enter in the different approaches

Martini et al.   *Nieves et al.*   *Amaro et al.*   *Lovato et al.*   *Bodek et al.*

[Follow the color and the style of the lines:]

$$\frac{\partial^2\sigma}{\partial\Omega\ \partial\epsilon'} = \sigma_0 \left[L_{CC}(R^V_{CC} + R^A_{CC}) + L_{CL}(R^V_{CL} + R^A_{CL}) + L_{LL}(R^V_{LL} + R^A_{LL}) + L_T(R^V_T + R^A_T) \pm L_{T'VA}R^{VA}_{T'}\right]$$

$$\frac{\partial^2\sigma}{\partial\Omega\ \partial\epsilon'} = \sigma_0 \left[L_{00}R_{00} + L_{0z}R_{0z} + L_{zz}R_{zz} + L_{xx}R_{xx} \pm L_{xy}R_{xy}\right]$$

$$\frac{\partial^2\sigma}{\partial\Omega\,\partial\epsilon'} = \frac{G_F^2\ \cos^2\theta_c}{2\,\pi^2}k'\epsilon'\ \cos^2\frac{\theta}{2}\left[\frac{(q^2-\omega^2)^2}{q^4}G_E^2\,R_\tau + \frac{\omega^2}{q^2}G_A^2\,R_{\sigma\tau(L)} + \right.$$
$$\left. + \ 2\left(\tan^2\frac{\theta}{2} + \frac{q^2-\omega^2}{2q^2}\right)\left(G_M^2\frac{\omega^2}{q^2} + G_A^2\right)R_{\sigma\tau(T)} \pm 2\,\frac{\epsilon+\epsilon'}{M_N}\ \tan^2\frac{\theta}{2}\,G_A\,G_M\,R_{\sigma\tau(T)}\right]$$

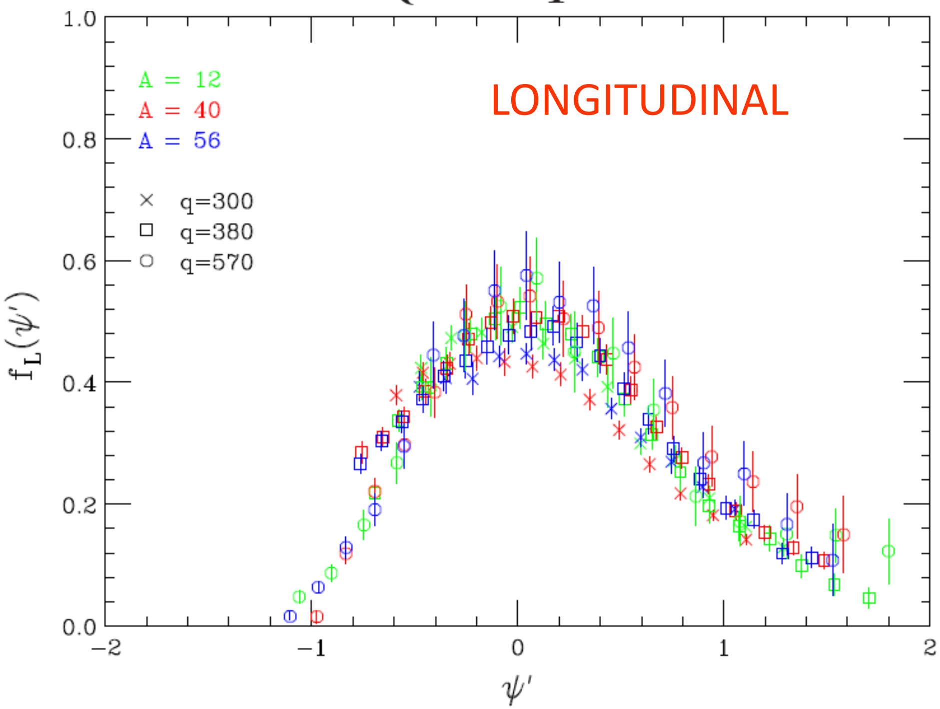
Relative role of 2p-2h for neutrinos and antineutrinos is different due to the **interference term**

Neutrino scattering

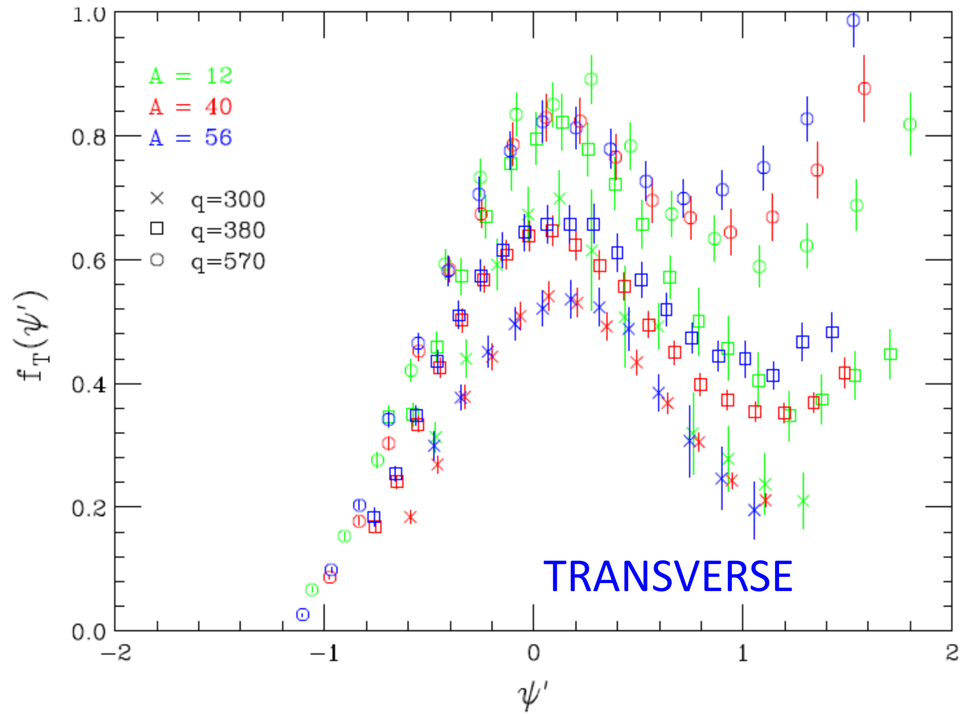
$$\frac{\partial^2\sigma}{\partial\Omega\,\partial\epsilon'} = \frac{G_F^2\,\cos^2\theta_c}{2\,\pi^2}k'\epsilon'\,\cos^2\frac{\theta}{2}\left[\frac{(q^2-\omega^2)^2}{q^4}\,G_E^2\,R_\tau + \frac{\omega^2}{q^2}\,G_A^2\,R_{\sigma\tau(L)} + 2\left(\tan^2\frac{\theta}{2}+\frac{q^2-\omega^2}{2q^2}\right)\left(G_M^2\frac{\omega^2}{q^2}+G_A^2\right)R_{\sigma\tau(T)} \pm 2\frac{\epsilon+\epsilon'}{M_N}\tan^2\frac{\theta}{2}\,G_A\,G_M\,R_{\sigma\tau(T)}\right]$$

Electron scattering

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}\theta\,\mathrm{d}\omega} = \sigma_{\mathrm{M}}\left\{\frac{(\omega^2-q^2)^2}{q^4}R_{\mathrm{L}}(\omega,q) + \left[\tan^2\left(\frac{\theta}{2}\right) - \frac{\omega^2-q^2}{2q^2}\right]\boxed{R_{\mathrm{T}}(\omega,q)}\right\}$$



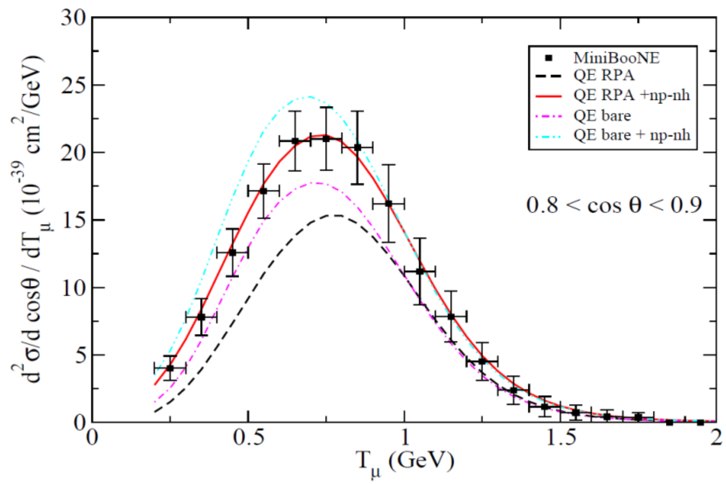
Donnelly et al. PRC 60 '99,…

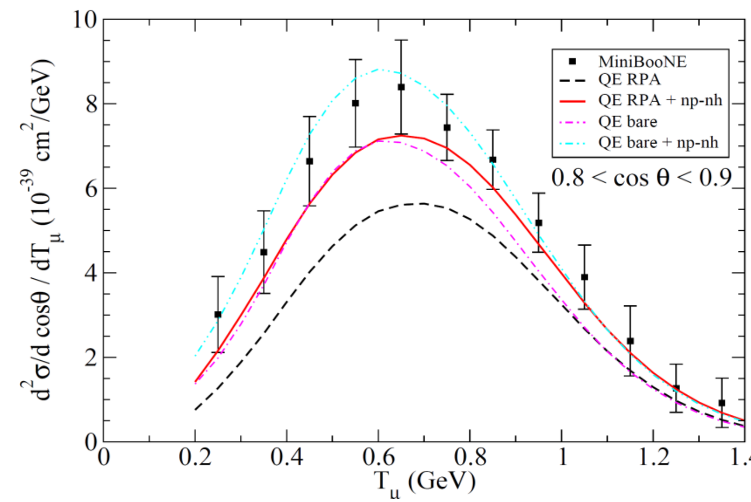


Excess in the transverse channel likely due to 2-body currents (MEC and correlations)

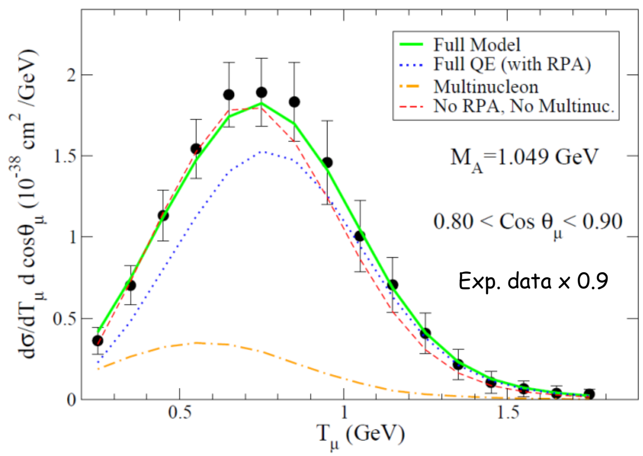
ν $\bar{\nu}$

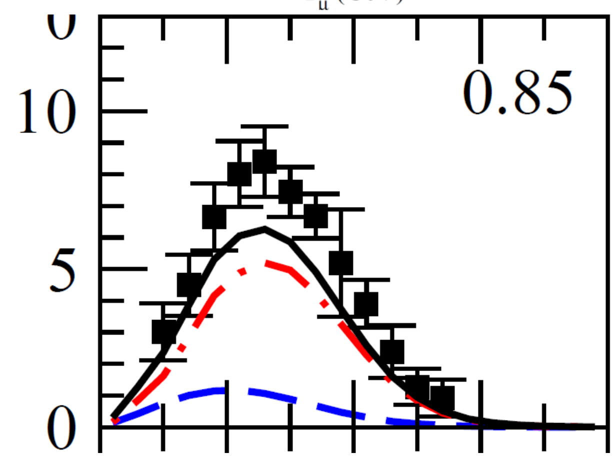
Martini et al.





Nieves et al.

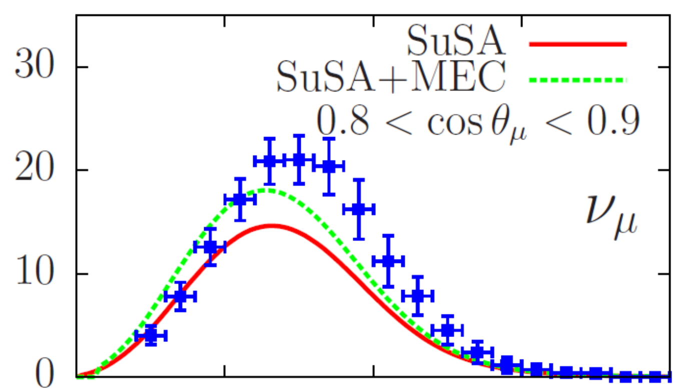


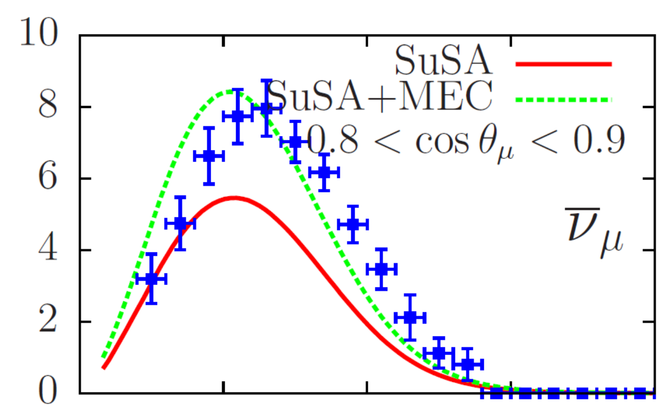


black: QE RPA+2p2h

red: QE RPA

Amaro et al.



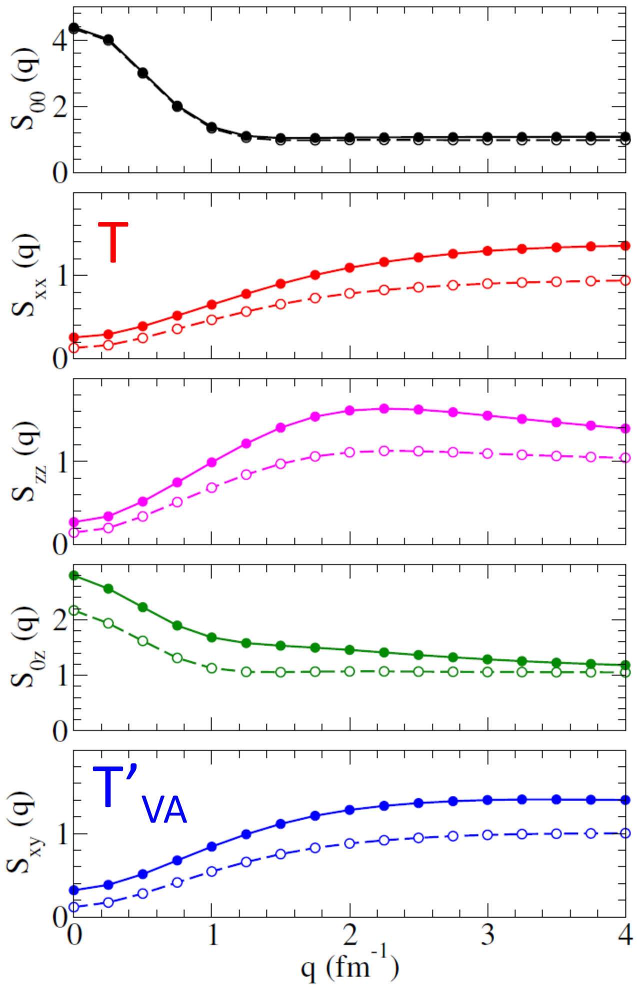


Some instructive comparisons (of two different quantities) (I)

Sum rules of NC

$$S_{\alpha\beta}(q) = C_{\alpha\beta} \int_{\omega_{el}}^{\infty} d\omega\, R_{\alpha\beta}(q,\omega)$$

Lovato et al. PRL 112 182502 (2014)

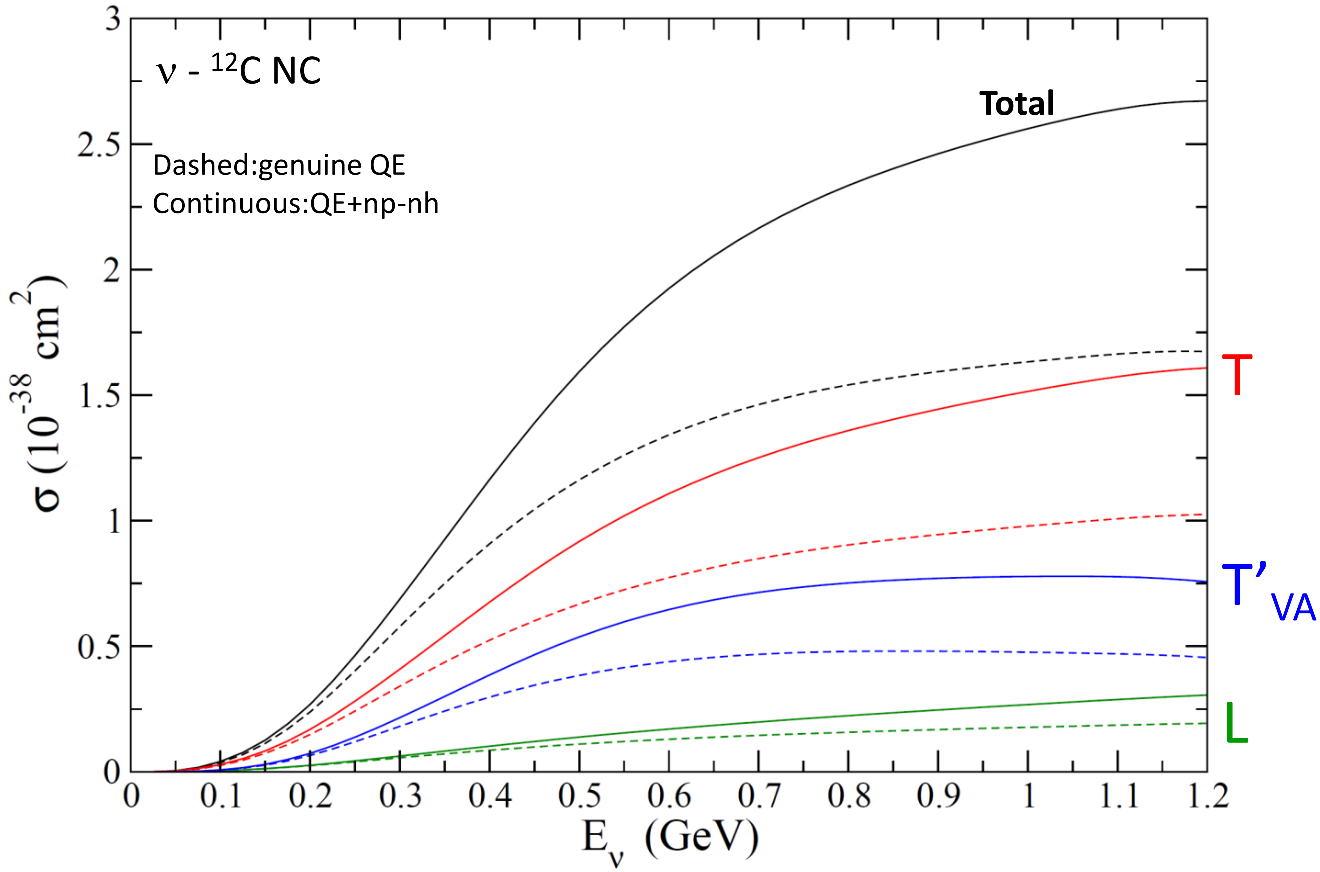


Cross section

$$\frac{\partial^2 \sigma}{\partial\Omega\, \partial\epsilon'} = \sigma_0 \left[L_{00}R_{00} + L_{0z}R_{0z} + L_{zz}R_{zz} + L_{xx}R_{xx} \pm L_{xy}R_{xy} \right]$$

Longitudinal ($L_{00}R_{00} + L_{0z}R_{0z} + L_{zz}R_{zz}$), Transverse ($L_{xx}R_{xx}$), Transverse VA Interf. ($L_{xy}R_{xy}$)

Martini et al.

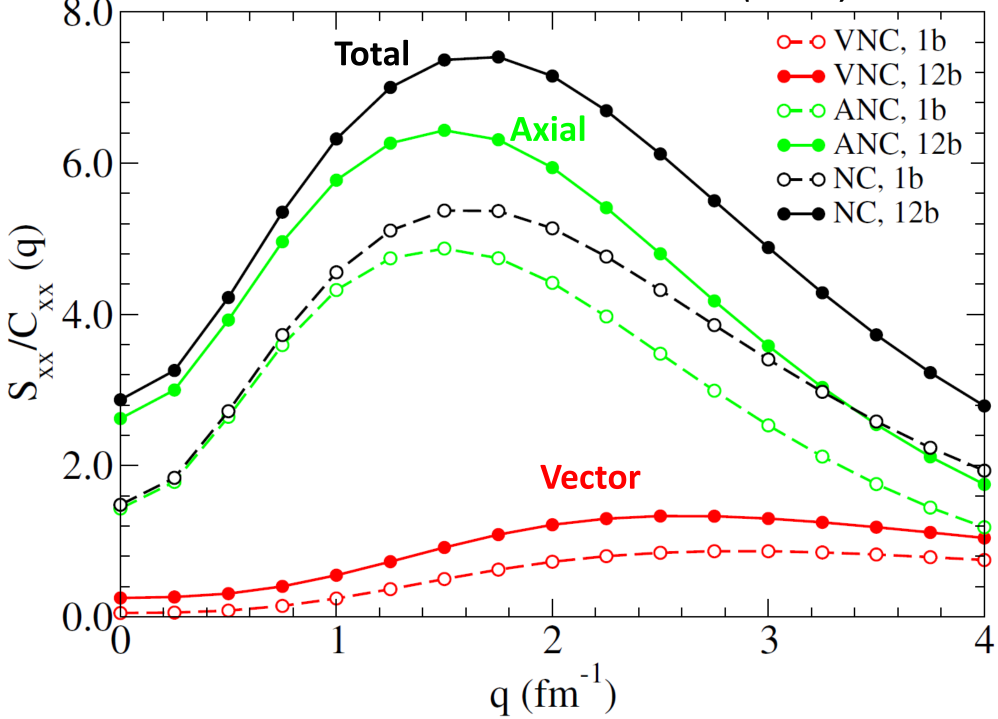


In both approaches 2p-2h are important in **all components** (but the charge)

Some instructive comparisons (of two different quantities) (II)

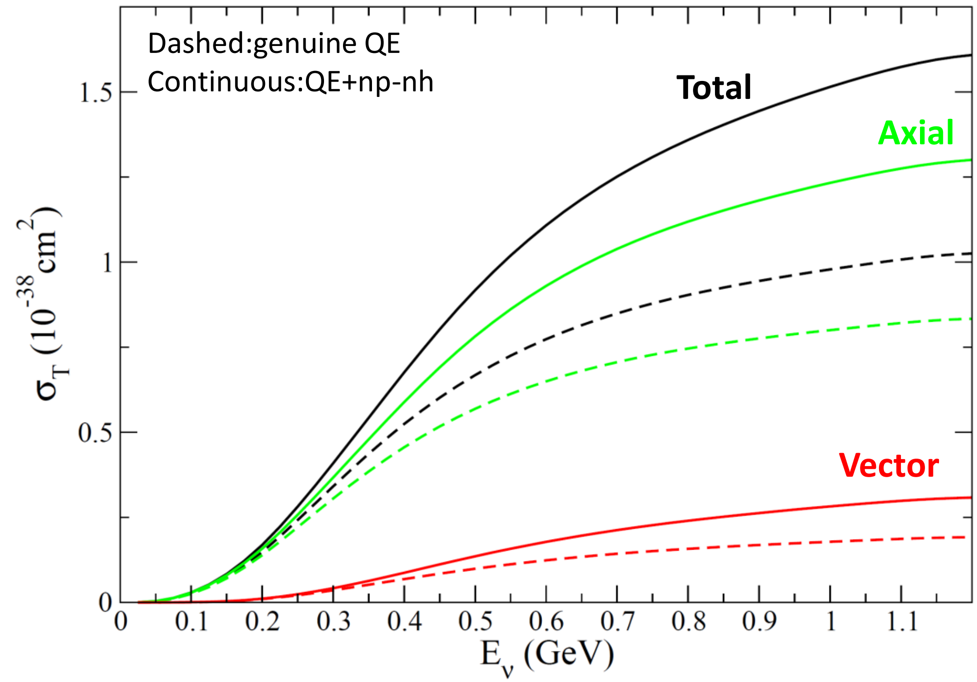
Sum rule of the Transverse response multiplied by the form factors

Lovato et al. PRL 112 182502 (2014)



Transverse contribution to the NC cross section

Martini et al.



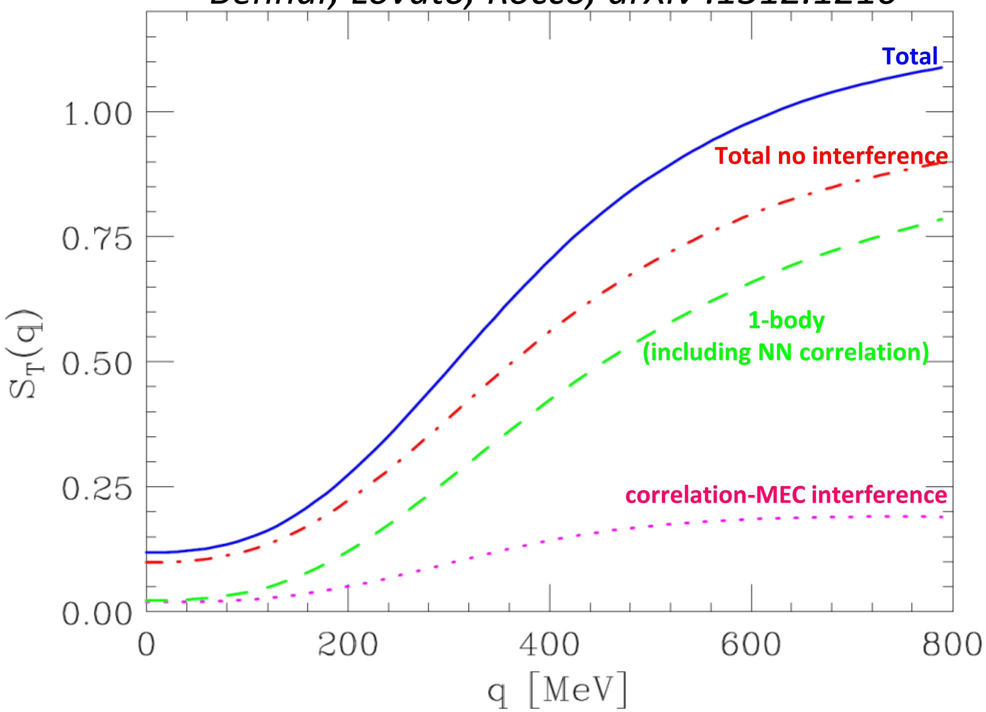
In both approaches, similar behavior:

2p-2h important also in the **Axial part** of the transverse contribution

Some instructive comparisons (of two different quantities) (III)

Sum rule of the transverse response

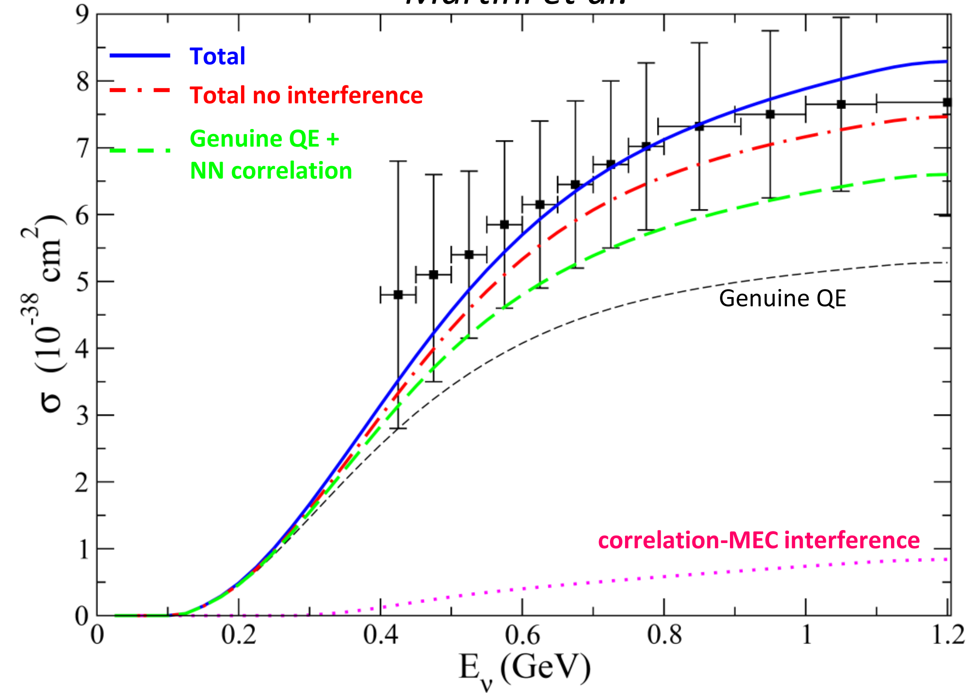
Benhar, Lovato, Rocco, arXiv :1312.1210



- Sum rule function of q
- Only Vector Transverse

Neutrino CCQE-like cross section

Martini et al.



- Cross section function of E_ν
- Total

No problem in our approach with the so called "1 nucleon – 2 nucleon currents interference"

Comments

- The contributions corresponding to the **interference** between the NN correlation current and the MEC **are included** in the approaches of Martini et al. and Nieves et al. as in the original corresponding electron scattering papers [Alberico et al. AP 1984, Gil et al. NPA 1997] (see also slides 20-22). For the moment the NN correlation contributions (and as a consequence the interference with the MEC) are not included in the approach of Amaro et al. for the neutrino scattering but have been studied for the electron scattering [Amaro et al. PRC 2010] .

- **No problem in the theoretical approaches with the so called "1 nucleon–2 nucleon currents interference**"

"1 nucleon – 2 nucleon currents interference" ⟺ (equivalent) "NN correlation – MEC interference"

- In the correlated basis approaches the effects of NN correlations are included in the 1 body contribution while in the uncorrelated basis approaches (Martini et al. Nieves et al, Amaro et al.) they are considered as part of two-body currents.

⇓

- **Caution for the Monte Carlo community**:

If the start is in a correlated basis **pay attention not to include twice the NN correlation contributions** when adding a full theoretical (Martini et al., Nieves et al, Amaro et al….) multinucleon emission calculation.

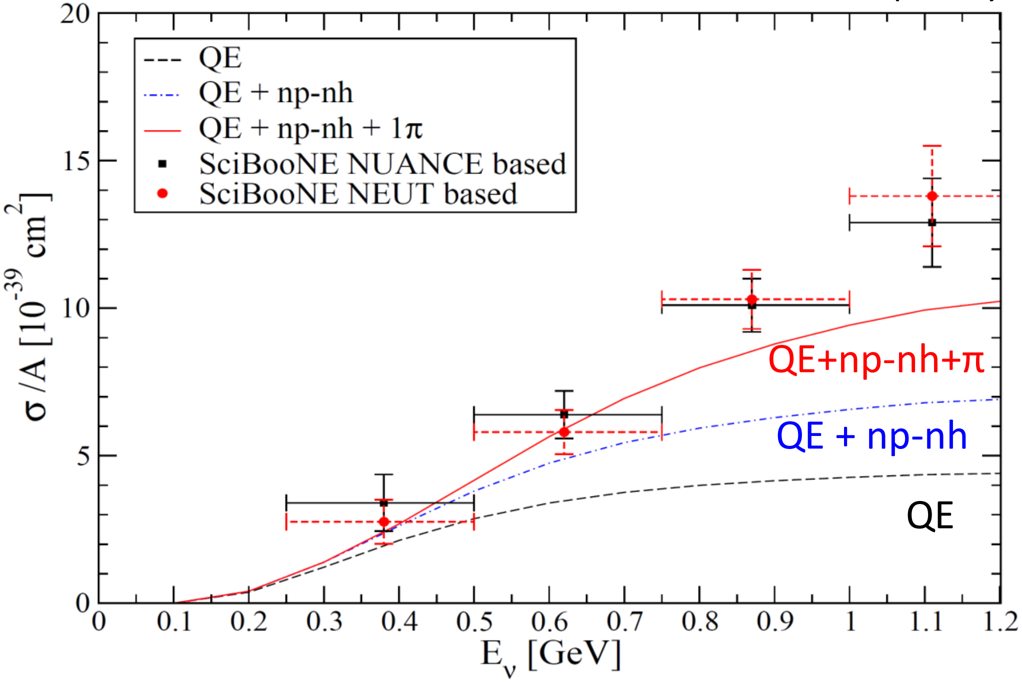
np-nh excitations in connection with other experiments

Inclusive CC total cross section on Carbon

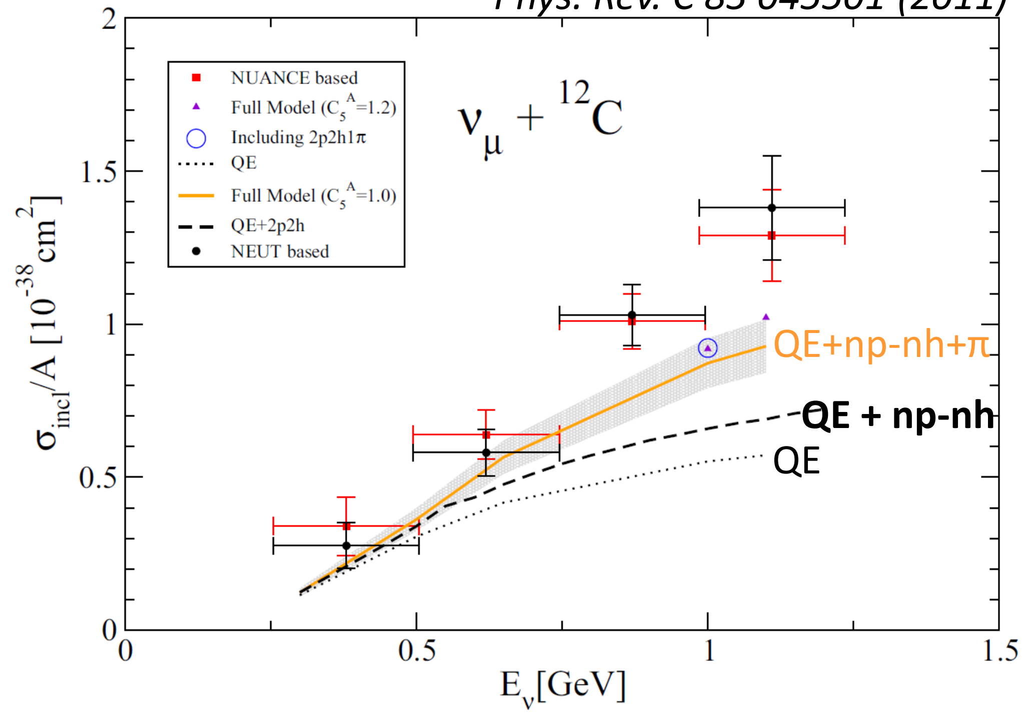
Less affected by background subtraction with respect to exclusive channels

SciBooNE, *Phys. Rev. D. 83, 012005 (2011)*

arXiv: 1404.1490 (2014)



Phys. Rev. C 83 045501 (2011)



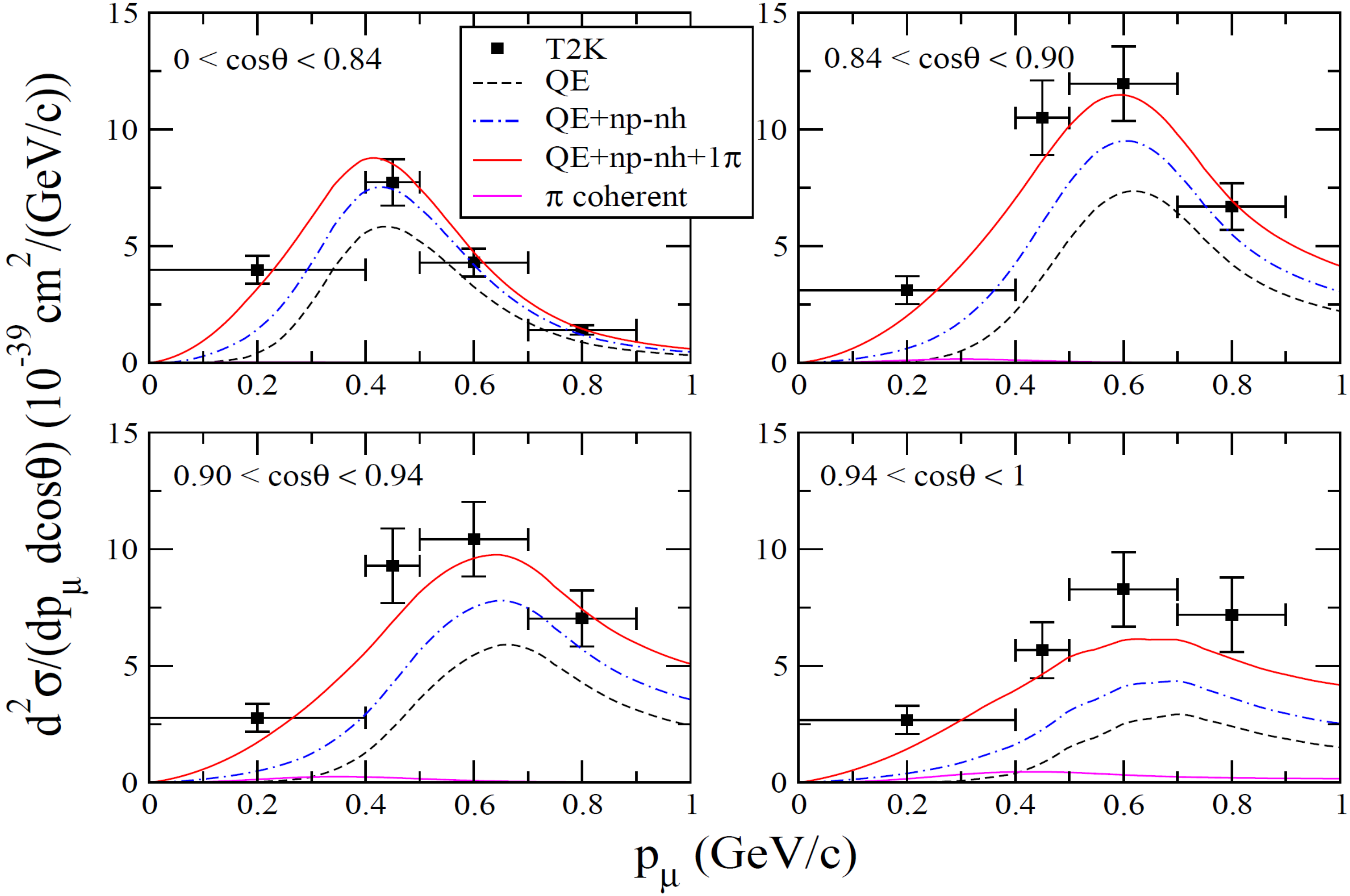
M. Martini, M. Ericson, G. Chanfray, J. Marteau

J. Nieves, I. Ruiz Simo, M.J. Vicente Vacas

T2K flux-integrated inclusive double differential cross section on carbon

T2K, *Phys. Rev. D 87, 092003 (2013)*

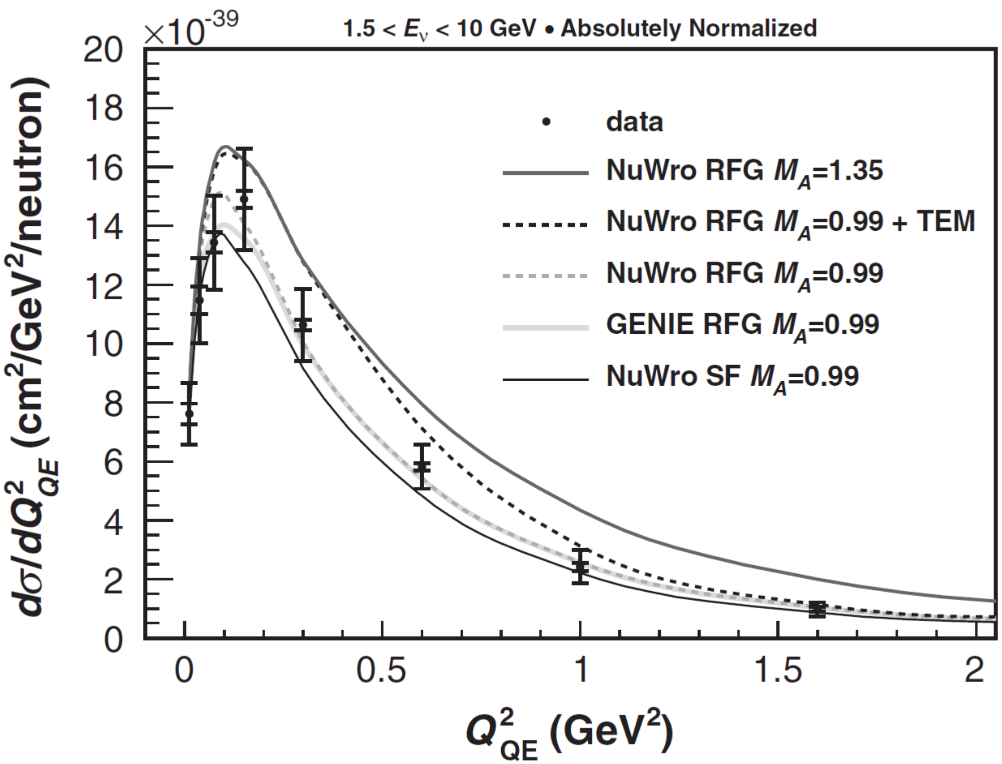
M. Martini, M. Ericson, arXiv: 1404.1490 (2014)



First successful test of the necessity of the multinucleon emission channel in an experiment with another neutrino flux with respect to the one of MiniBooNE.

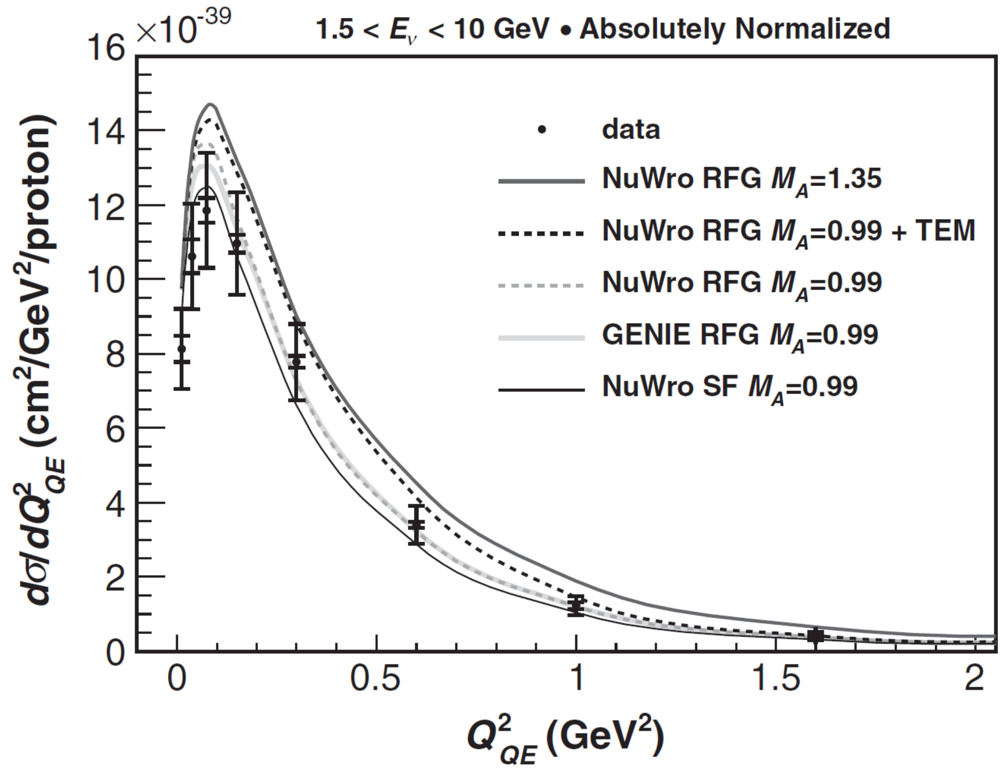
MINERνA ($E_\nu \sim$ 3.5 GeV) CCQE Q^2 distribution

ν



PRL 111 022502 (2013)

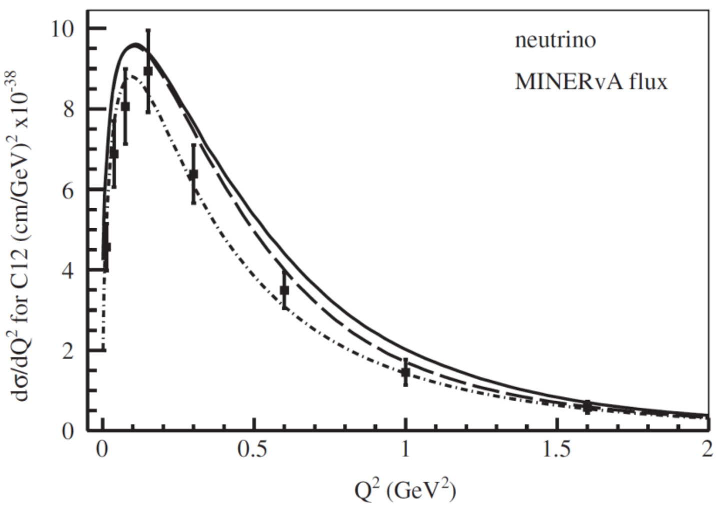
$\bar{\nu}$

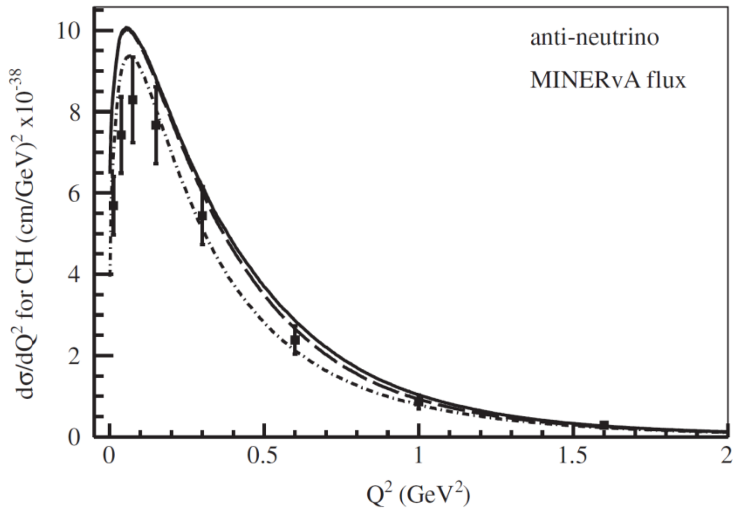


PRL 111 022501 (2013)

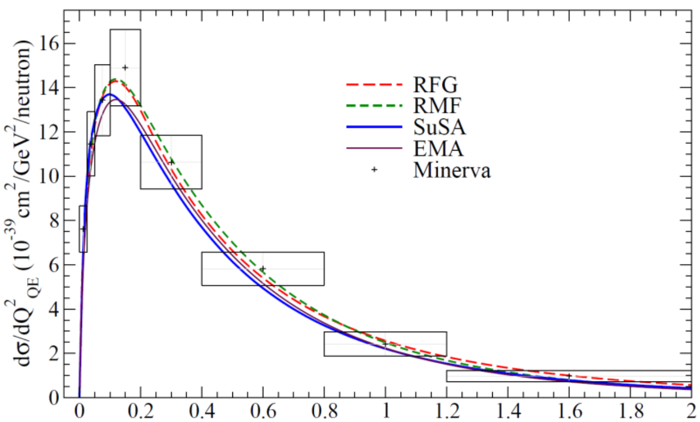
ν $\bar{\nu}$

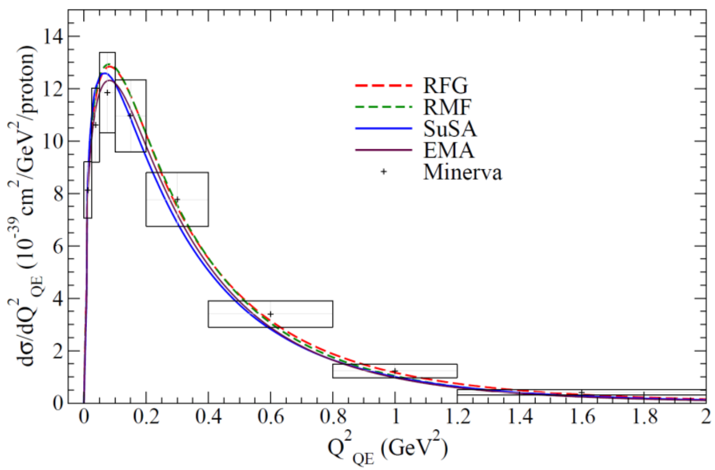
Gran,et al.
PRD 88 (2013)



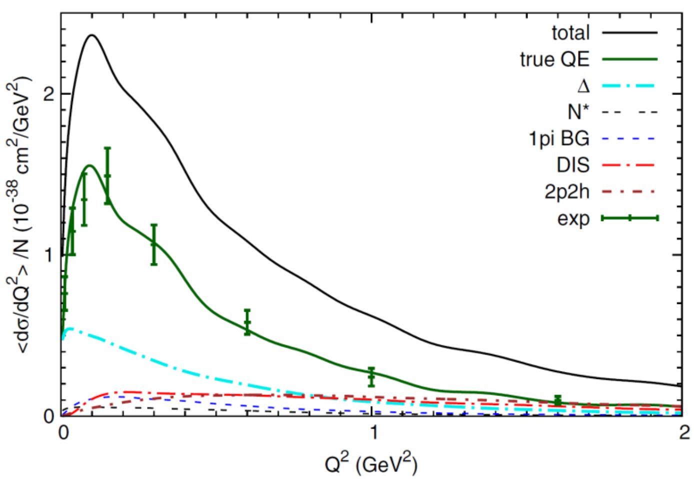


Megias et al.
PRD 89 (2014)
SuSA and other relativistic approaches without np-nh





Mosel et al.
PRD 89 (2014)



- MINERνA Q^2 distributions can be reproduced without the inclusion of np-nh
- This is not the case of the MiniBooNE Q^2 distributions
- Gran et al: The np-nh enhancement and RPA effects could be observable at MINERνA energies
- Mosel et al: The sensitivity to details of the treatment of np-nh contributions is smaller than the uncertainties introduced by the Q^2 reconstruction and our insufficient knowledge of pion production

Isospin content: correlated pairs and observables

Martini et al. PRC 80 065501 (2009)

"Also an experimental identification of the final state would be of a great importance to clarify this point. In particular the charge of the ejected nucleons will be quite significant. Because tensor correlations involve *n-p* pairs, the ejected pair is predominantly *p-p* (*n-n*) for charged current neutrino (antineutrino) reactions and *n-p* for neutral current."

Gran et al. PRD 88 11307 (2013)

"The mix of initial state for these 2p2h interactions has a complicated dependence, from 50% to 80% pn initial state for the non-Δ and Δpeaks, respectively"

Lovato et al. PRL 112 182502 (2014)

"The present study suggests that two nucleon currents generate a significant enhancement of the single-nucleon neutral weak current response, even at quasi-elastic kinematics. This enhancement is driven by strongly correlated np pairs in nuclei."

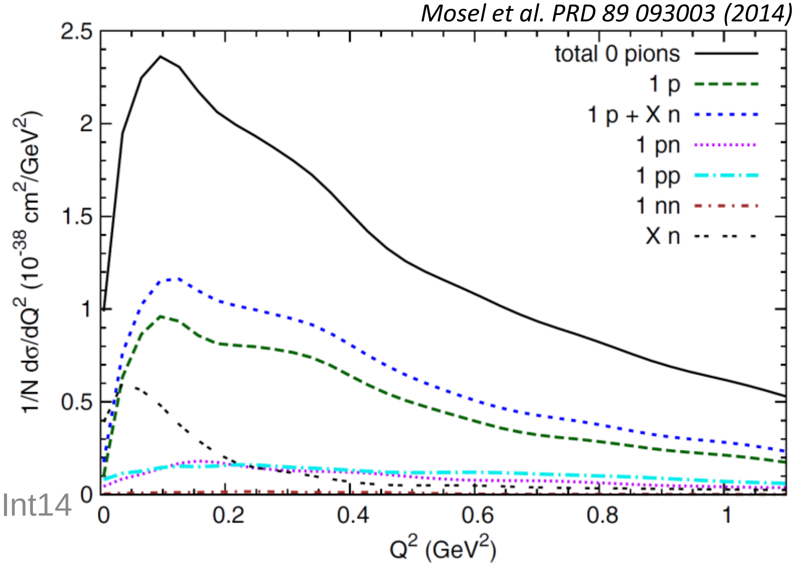
MINERνA PRL 111 022501 (2013)

The MINERνA vertex energy on antineutrino mode "might be explained if the dominant multibody process is $\bar{\nu}_\mu$ (np) $\rightarrow \mu^+$ nn since MINERvA is not very sensitive to low energy neutrons. A similar analysis on neutrino mode data is consistent with additional protons in the final state"

Mosel et al. PRD 89 093003 (2014)

"The channels with a pp or a pn pair are very similar, quite flat, and suppressed and thus of minor importance. Interesting, however, is the pileup of strength seen in the Xn channel at small $Q^2 \approx 0.1$ GeV^2. This is entirely due to fsi."

Mosel et al. PRD 89 093003 (2014)



Summary

- Several theoretical calculations agree on the crucial role of the multinucleon channel in order to explain MiniBooNE CCQE-like data
- There are some differences on the way to treat this np-nh channel which are reflected in the comparisons with neutrino and antineutrino data
- The sum rules of Lovato et al. support the cross sections results of Martini et al:
  - the two-body contributions are relevant in all components
  - there is a significant enhancement also in the transverse **axial** contribution
- No problem in the theoretical approaches with the so called “1 nucleon–2 nucleon currents interference”
- The inclusion of np-nh excitations seems to be needed in order to reproduce the SciBooNE and T2K inclusive cross sections. The role of np-nh in the MINERνA results is less evident.

Perspectives

- Extension at higher energies of the RPA-based approach of Martini et al.
- Add the axial MEC and NN correlations contributions to the SuSA approach of Amaro et al.
- Calculations of neutrino cross sections in the SNPA of Lovato et al.
- New calculations and new results are coming (see e.g. the posters of Albertus-Torres, Ruiz-Simo, Van Cuyck)

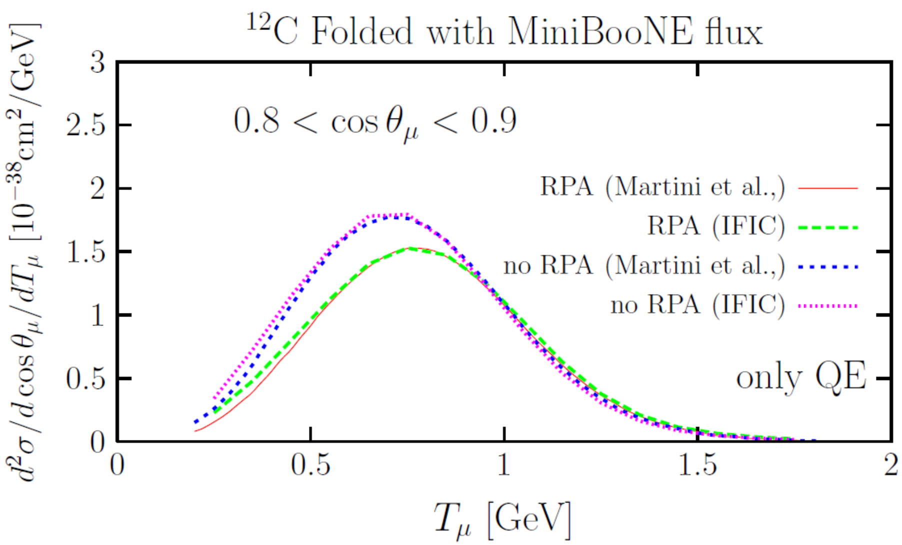
Spares

Comparison between our approach and the one of Nieves et al.

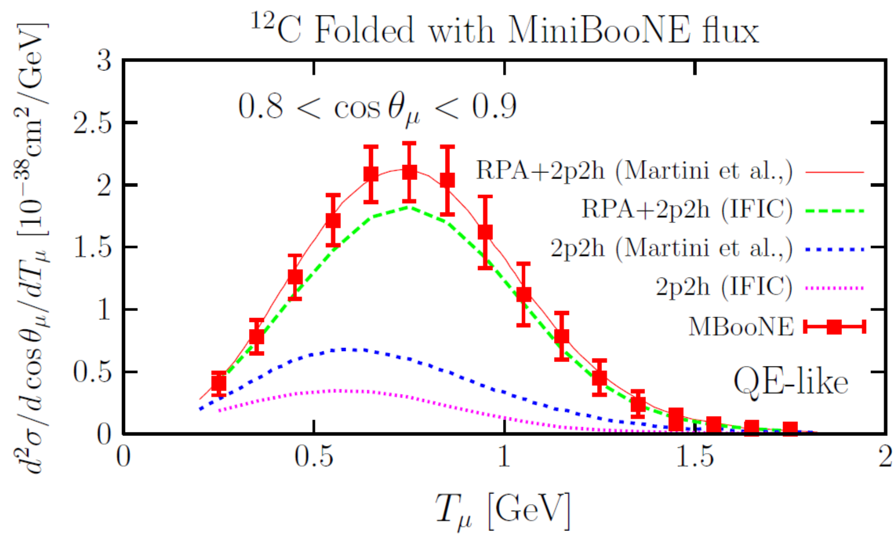
Morfin, Nieves, Sobczyk Adv.High Energy Phys. 2012 (2012) 934597

ν

Genuine QE



QE + np-nh



- Genuine QE bare and RPA very similar in Martini et al. and Nieves et al.
- Factor ~2 for the np-nh contribution

Both models compatible with MiniBooNE
(additional normalization uncertainty of 10% in the MB data not shown here)

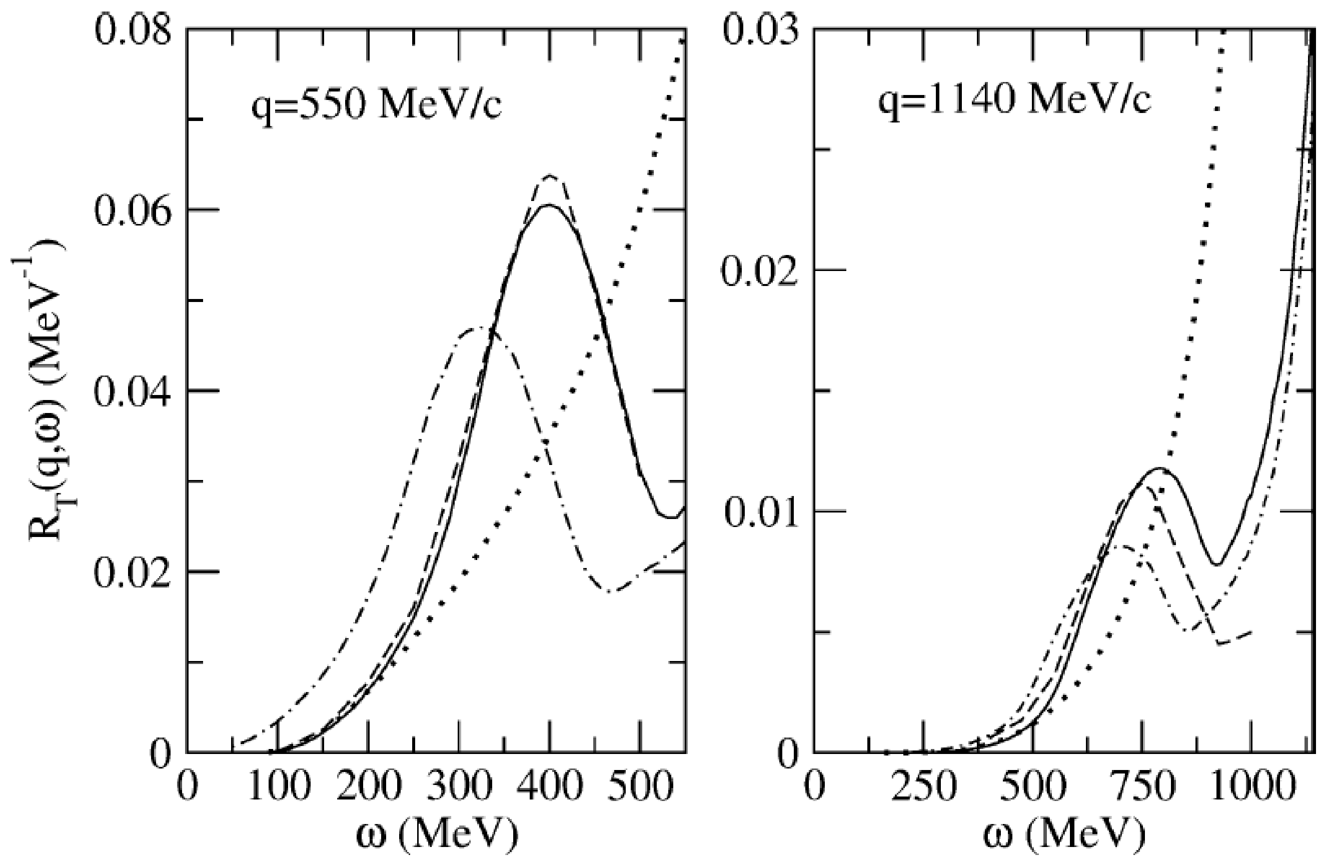


Fig. 8. The relativistic transverse response function $R_T(q,\omega)$ at $q = 550$ MeV$/c$ and $q = 1140$ MeV$/c$ calculated with $\bar{\epsilon}_2 = 70$ MeV (solid) and with $\bar{\epsilon}_2 = 0$ (dot-dashed). Only the direct contribution is shown. The non-relativistic results are also displayed in order to shed light on the role of relativity in the response (dotted). For the sake of comparison the relativistic results obtained in DBT are displayed (dashed). In all instances $k_F = 1.3$ fm^{-1}.

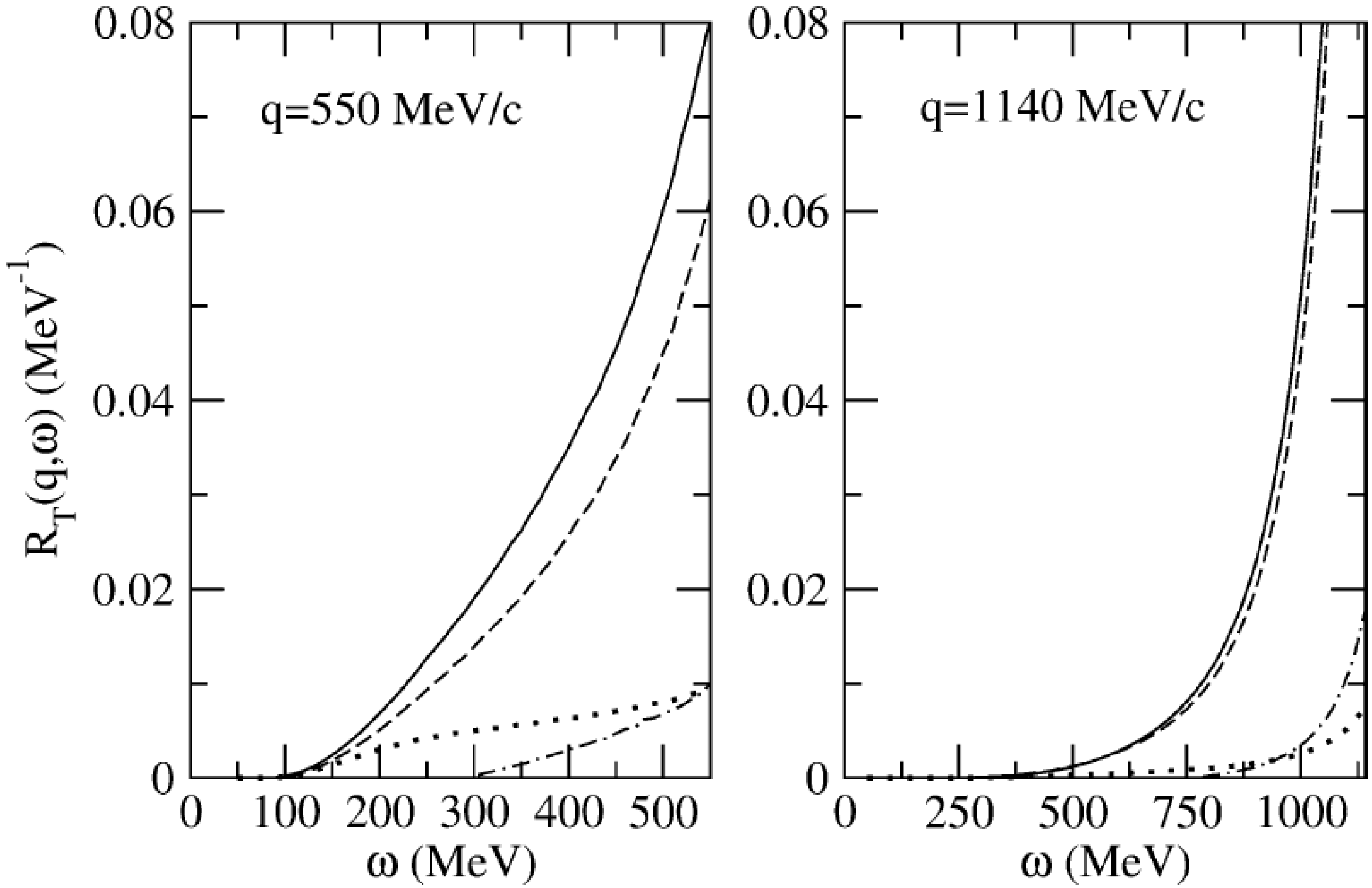


Fig. 9. Separate contributions to the transverse response function $R_T(q,\omega)$ in the non-relativistic limit at $q = 550$ MeV/c and $q = 1140$ MeV/c: pionic (dotted), pionic–Δ interference (dash-dotted), Δ (dashed) and total (solid); $k_F = 1.3$ fm^{-1}. The exchange contribution is disregarded here.

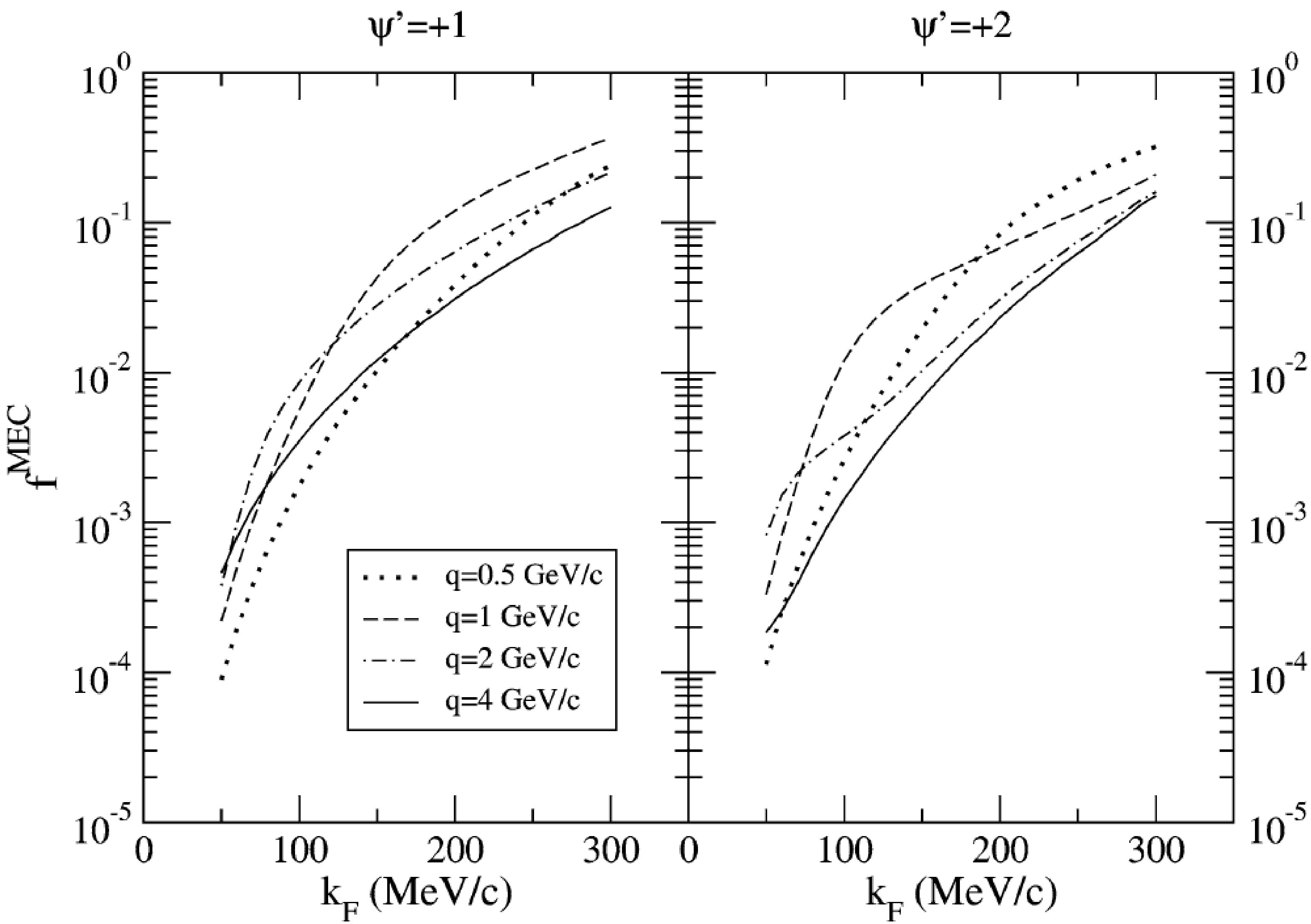


Fig. 8. As for Fig. 2, but now for the region above the QEP.

The “NN correlation – MEC interference” or “1 nucleon – 2 nucleon currents interference” in Shimizu, Faessler, Nucl. Phys. A 333,495 (1980),
(one of the Sources of the Martini, Ericson, Chanfray, Marteau approach)

Nuclear Physics **A333** (1980) 495–513 © *North-Holland Publishing Co., Amsterdam*

3.4. INTERFERENCE BETWEEN THE SINGLE NUCLEON ABSORPTION AND RESCATTERING TERMS

Here we give the results of the case when both the single nucleon absorption with the NN correlations and the rescattering terms shown in fig. 4 and fig. 5 are taken into account simultaneously. In this case, there is the interference between these two terms shown in ref. [12]).

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

(one of the Sources of the Martini, Ericson, Chanfray, Marteau approach)

4. The Nucleon–Nucleon Correlations

The MEC were revisited in the previous section in a basis of uncorrelated nucleons. Actually the protons and the neutrons in the nucleus *are* correlated, among other things, via the exchange of the same pion we have previously looked at as the main carrier of the MEC.

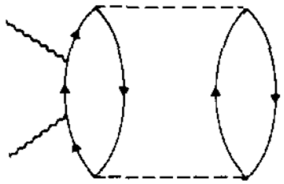
To remedy this inconsistency we take the view that accounts for *all* the diagrams where a single pion is exchanged. Accordingly, in this section we associate a current to each of the four Feynman diagrams of Fig. 5: they indeed represent the absorption

The introduction of the correlation current accounts for 16 further perturbative contributions to $S_T(q, \omega)$ which arise from the folding together of the 4 diagrams of Fig. 6: the six topologically distinct diagrams are shown in Fig. 7. In dealing with the diagrams of Fig. 7 we point out that we have kept the two nucleonic lines between the pionic and electromagnetic vertices strictly *off the mass shell* (this prescription is reflected in the θ functions which are present in formulae (5.7) to (5.13)). In so doing we neglect the contribution of self-energy insertions on nucleonic lines.

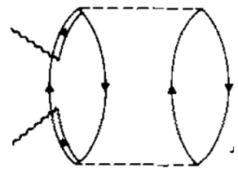
The same considerations apply also to the 56 perturbative terms corresponding to the interference between the correlation current and the MEC (see Fig. 8), which again arise from the folding together of the 7 diagrams of Fig. 3 and the 4 diagrams of Fig. 6. Thus our theory, which consistently treats the one-pion exchange at the level of currents, includes 121 perturbative diagrams altogether.

Main difficulties in the 2p-2h sector

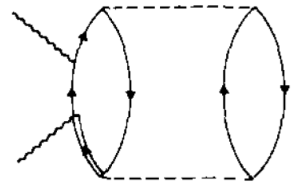
- **Huge number of diagrams and terms**



16 from NN correlations



49 from MEC



56 from interference

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

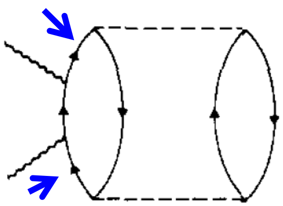
fully relativistic calculation (just of MEC !):

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

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

- **Divergences in NN correlations**

prescriptions:



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

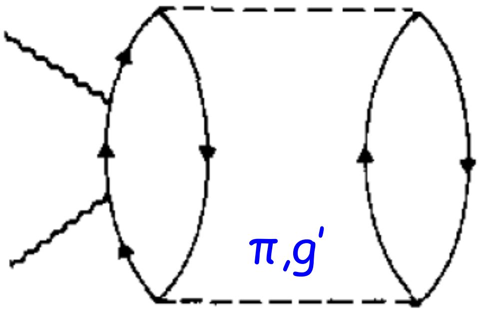
-kinematical constraints + nucleon self energy in the medium (*Nieves et al PRC 83*)

- regularization parameter taking into account the finite size of the nucleus to be fitted to data (*Amaro et al. PRC 82 044601 2010*)

Further considerations on 2p-2h

e.g.

NN correlation

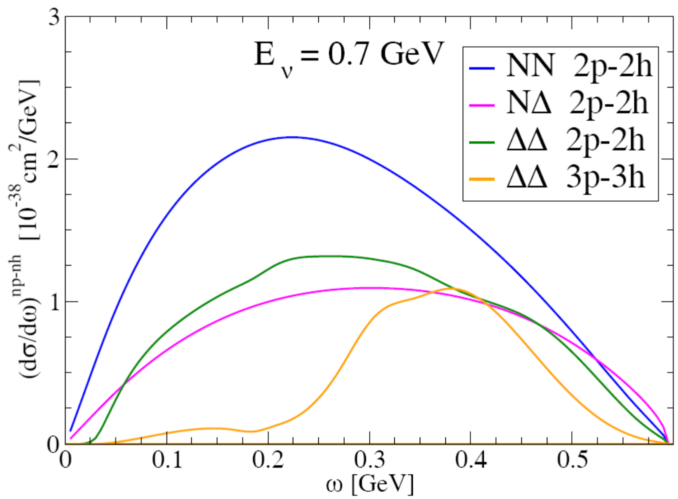


q =410 MeV/c

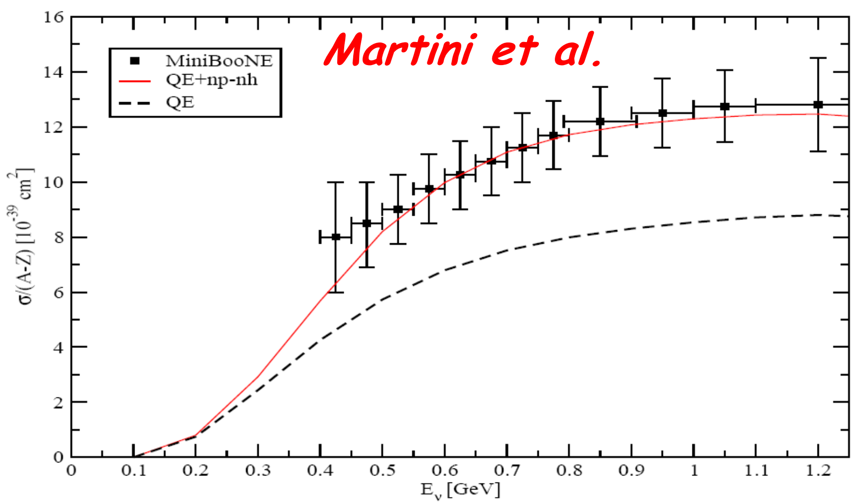
$\hbar\omega$	central βA_i^C	tensor βA_1^T
50	11.3	20.3
100	12.5	31.8
150	23.6	47.8
200	20.9	53.1
250	17.3	51.1
300	10.9	39.9

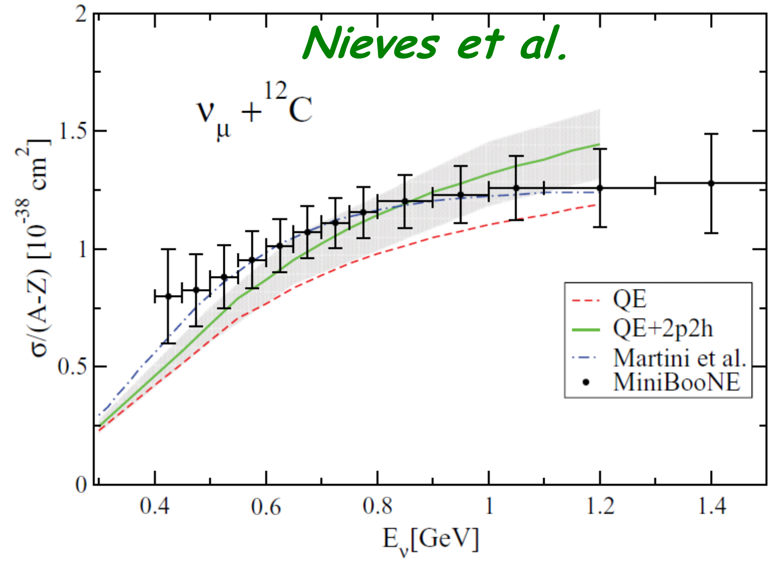
Alberico et al.
Ann. Phys. '84

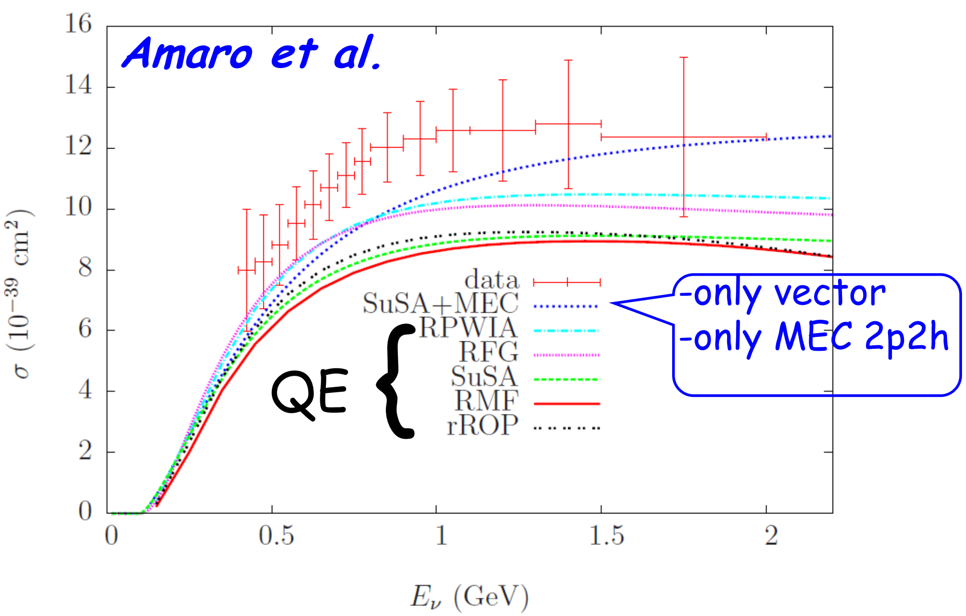
Tensor correlations are dominant in the NN correlation term but 2p-2h contributions involving Δ excitations are also very important. Tensor correlations alone are insufficient to account the overall 2p-2h effect.

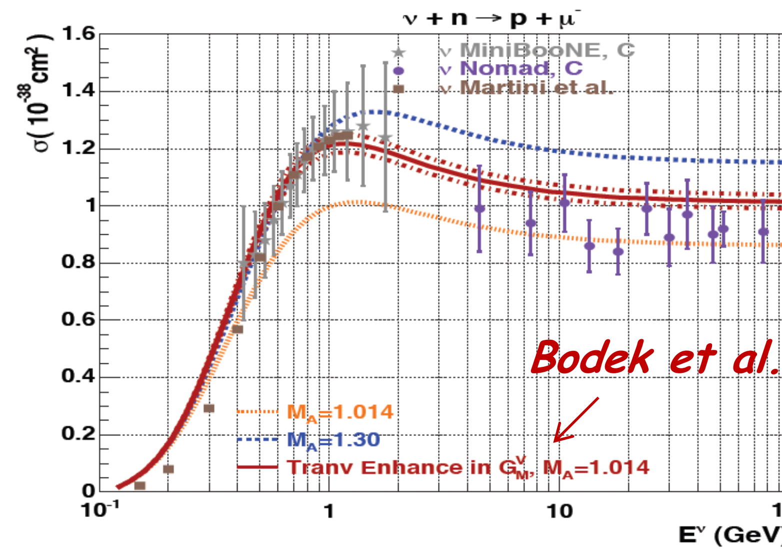


Total CCQE and comparison with flux unfolded MB



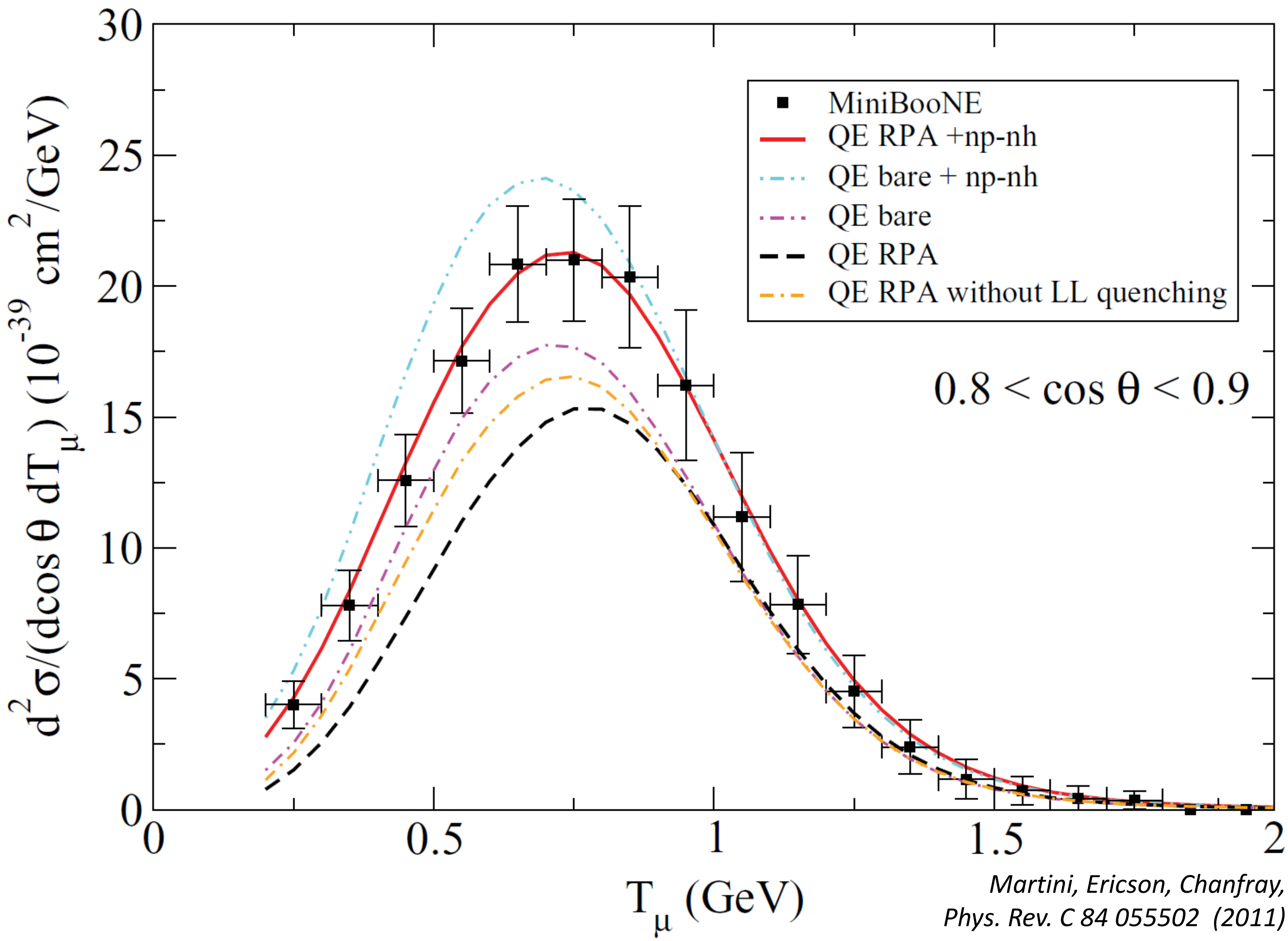






N.B. The experimental unfolding is model dependent

Flux-integrated ν CCQE double differential X section versus Tμ

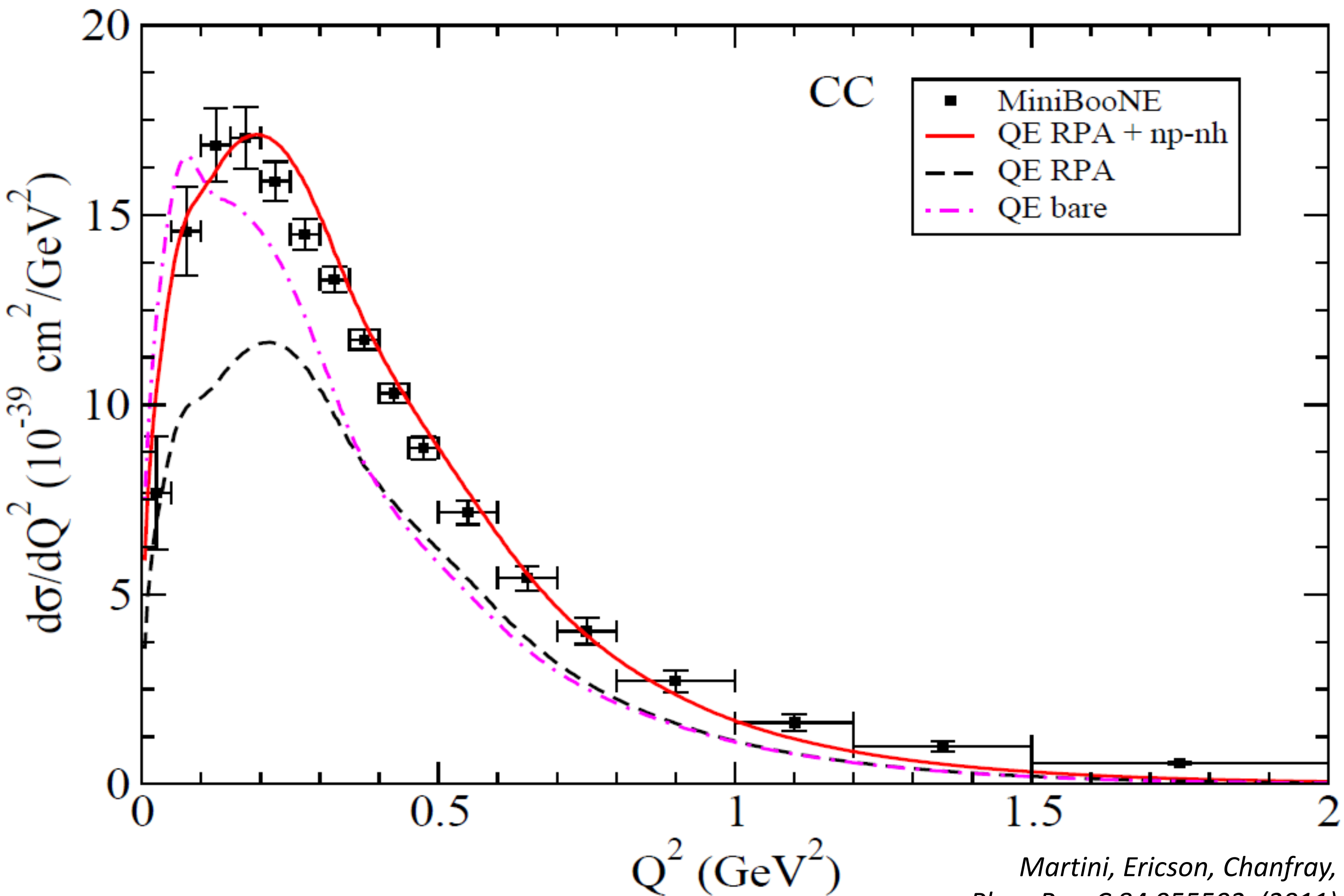


Martini, Ericson, Chanfray,
Phys. Rev. C 84 055502 (2011)

Delicate balance between
RPA quenching and np-nh enhancement but…

Charged current Q^2 distribution

Historically of interest for the determination of the axial form factor



Martini, Ericson, Chanfray, Phys. Rev. C 84 055502 (2011)

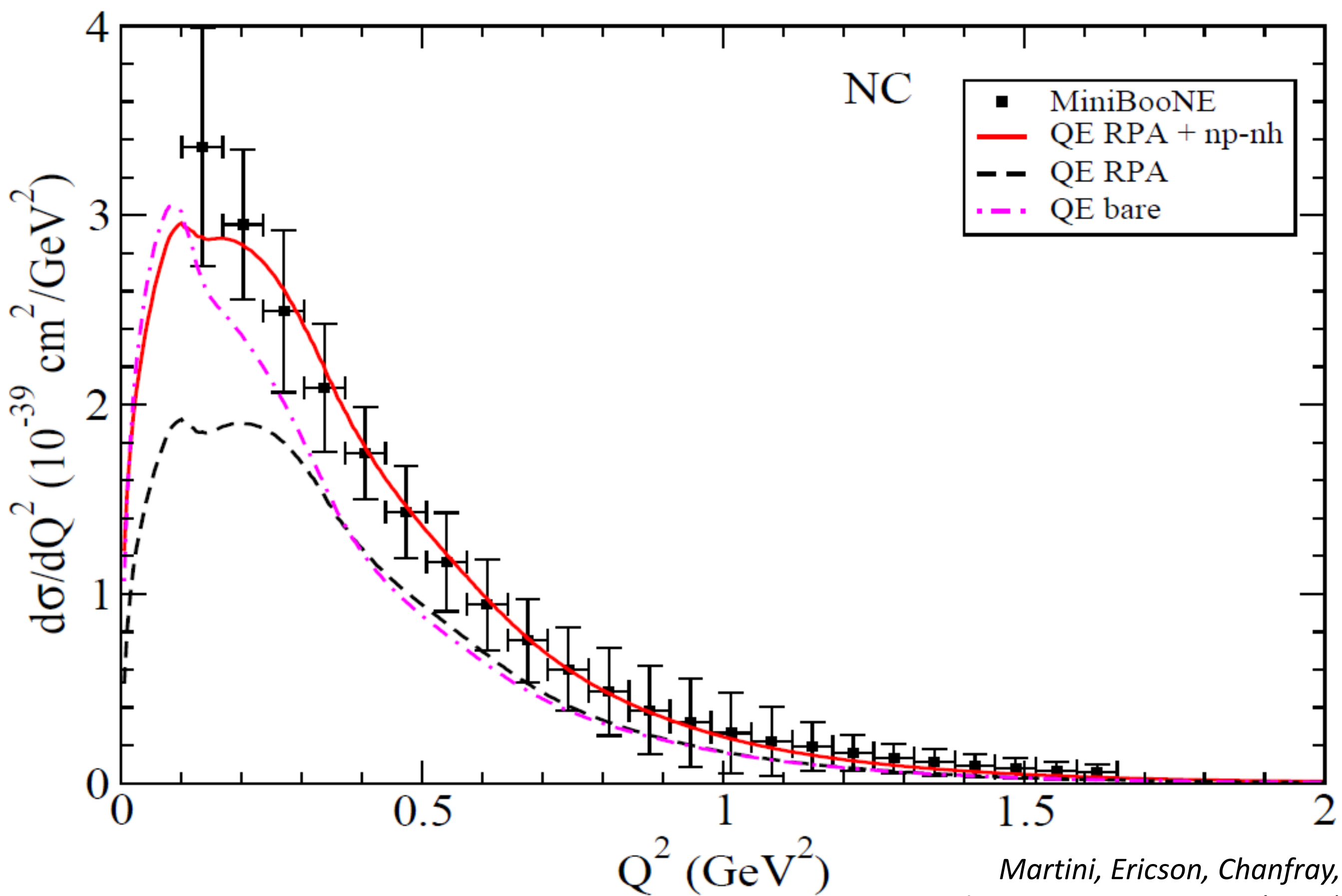
low Q^2:
opposite actions of RPA quenching and np-nh enhancement

$Q^2 > 0.2$ GeV^2:
np-nh contribution singled out

Neutral current Q^2 distribution

Exp. Data: MiniBooNE, Phys. Rev. D 82, 092005 (2010)

obtained indirectly from the energy of ejected nucleons



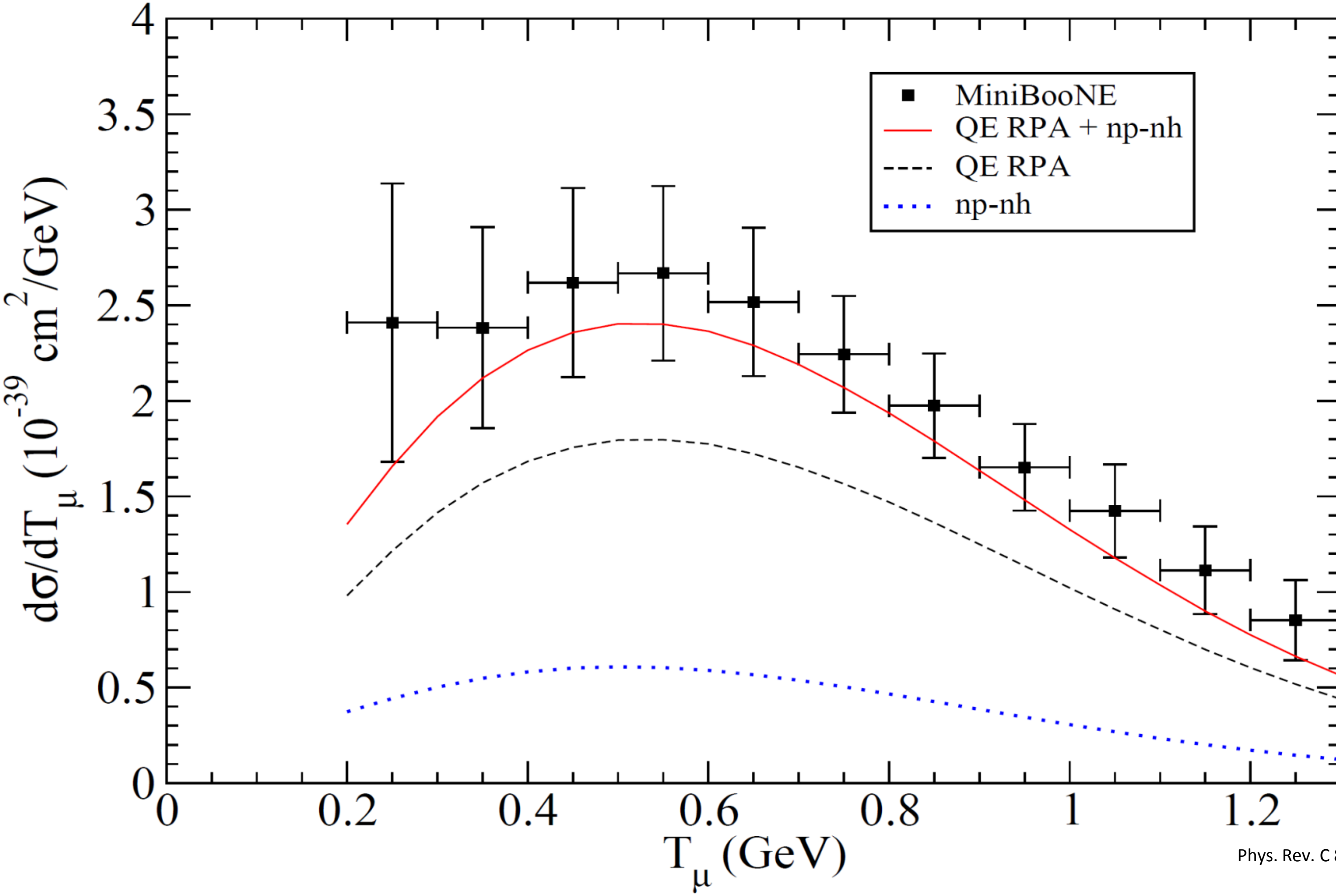
Martini, Ericson, Chanfray, Phys. Rev. C 84 055502 (2011)

is not clear how multinucleon component shows up in the data

low Q^2:
opposite actions of RPA quenching and np-nh enhancement

$Q^2 > 0.3$ GeV^2:
np-nh contribution singled out

Antineutrino dσ/dTμ

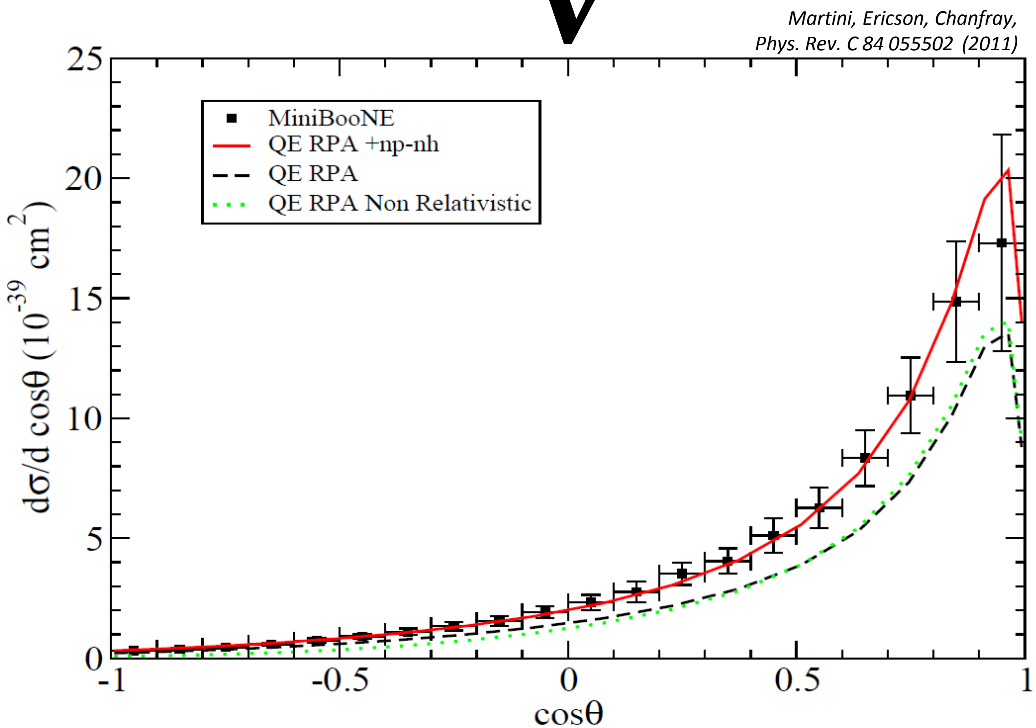


Martini, Ericson,
Phys. Rev. C 87 065501 (2013)

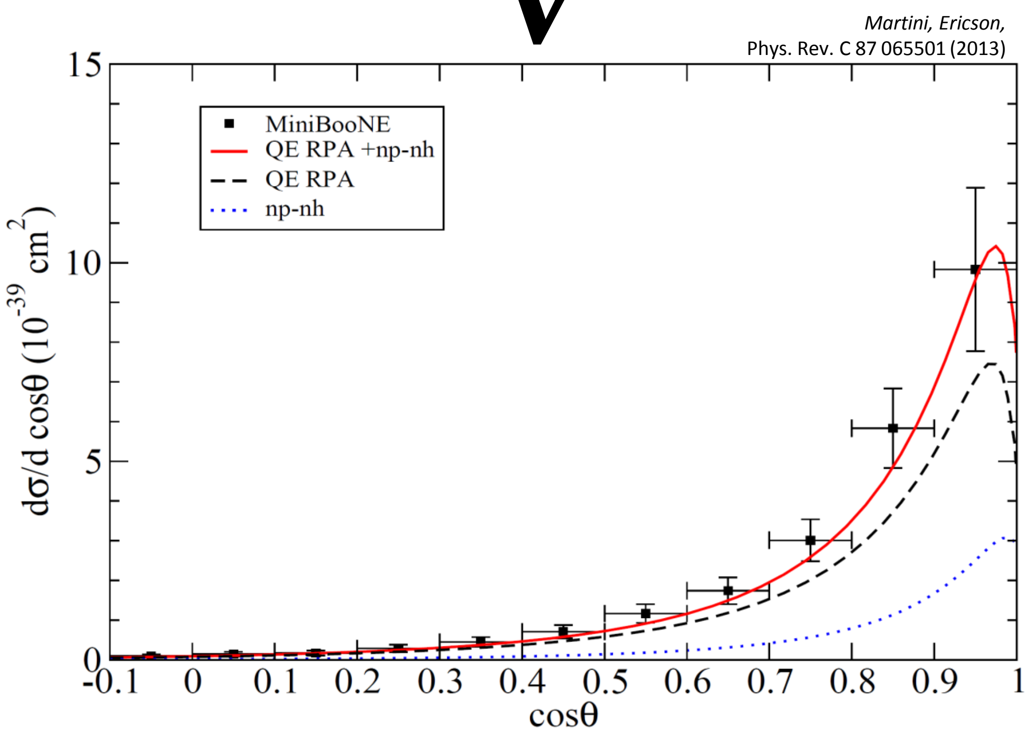
Our results are fully compatible with experimental data.
Nevertheless a small but systematic underestimation shows up.
We remind the additional normalization uncertainty of 17.2% in the MiniBooNE data not shown here.

dσ/dcosθ

ν



ν̄

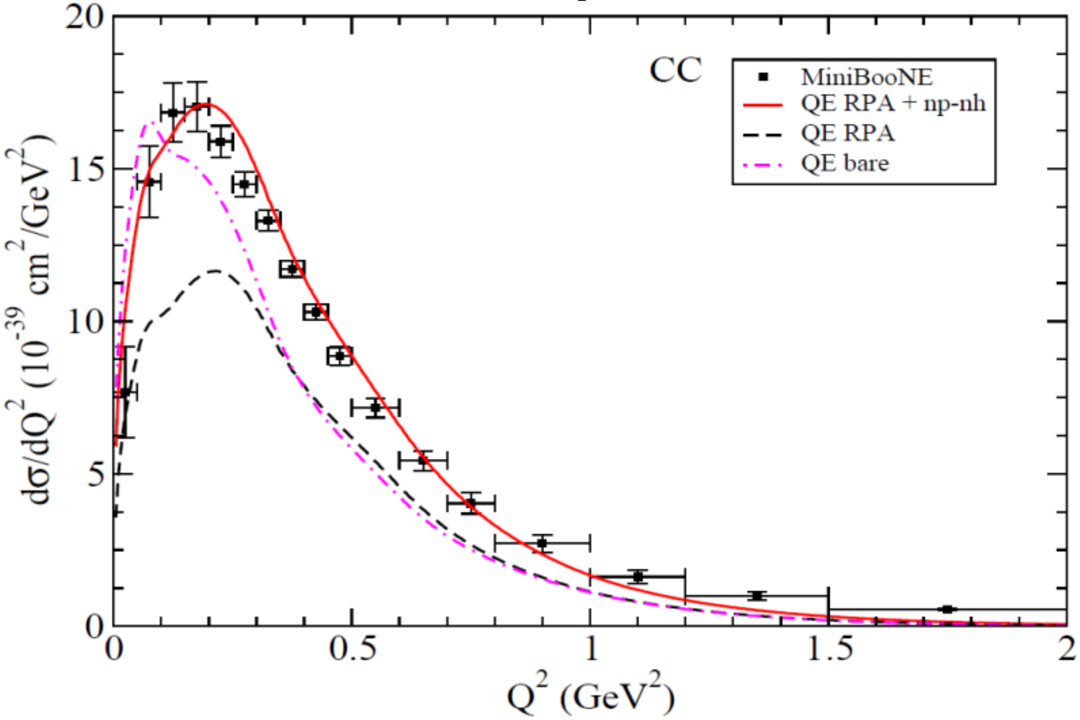


Antineutrino cross section falls more rapidly with angle than the neutrino one

CC Q^2 distribution

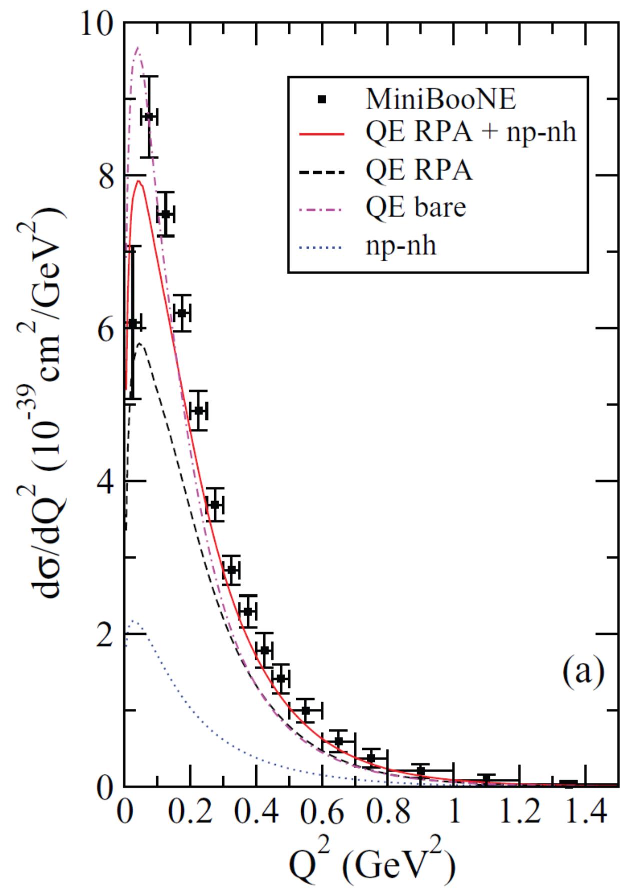
ν

Martini, Ericson, Chanfray, Phys. Rev. C 84 055502 (2011)



$\overline{\nu}$

Martini, Ericson, Phys. Rev. C 87 065501 (2013)

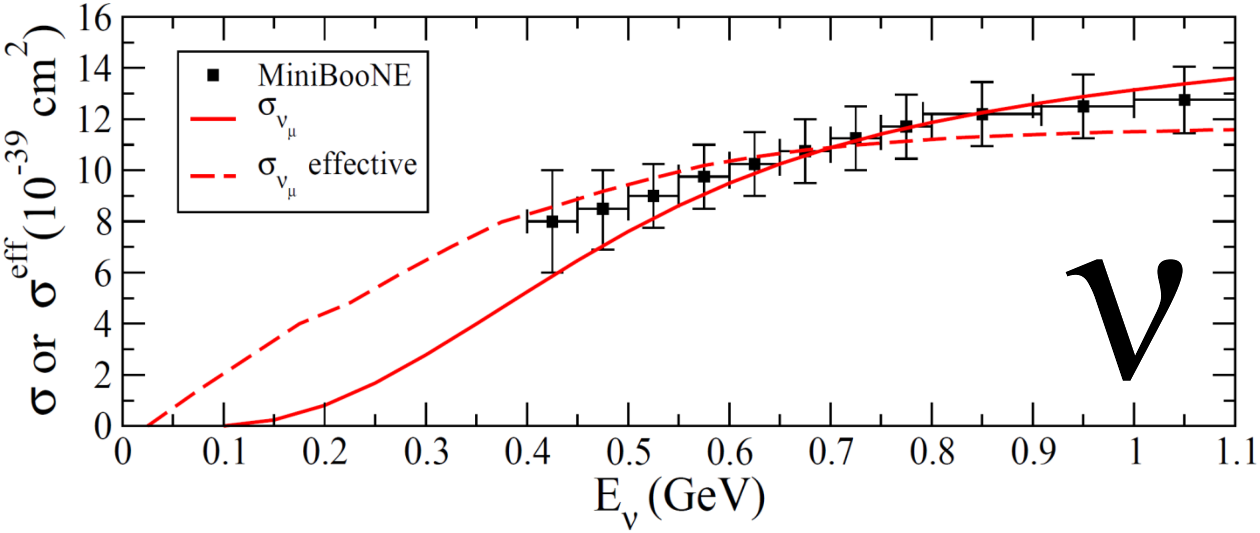


- Antineutrino Q^2 distribution peaks at smaller Q^2 values than the neutrino one
- RPA effects disappears beyond $Q^2 \geq 0.3$ GeV^2 where the np-nh singled out

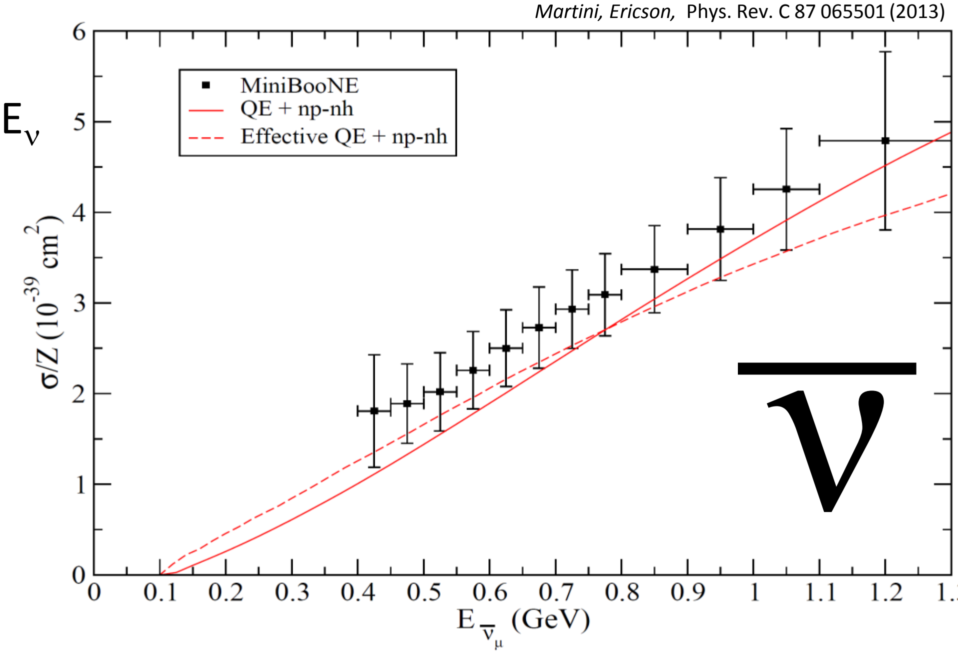
p.s. the additional normalization uncertainty in the MiniBooNE data of 10% for neutrino and of 17.2% for antineutrinos is not shown here and in the double differential cross sections

Real and effective cross sections versus E_{ν_μ}

M. Martini, M. Ericson, G. Chanfray, PRD 87 013009 (2013)



Martini, Ericson, Phys. Rev. C 87 065501 (2013)



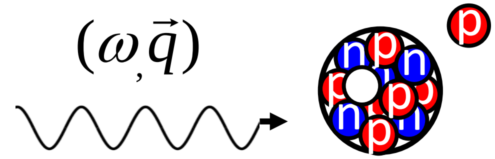
- Real: pure theoretical calculation (QE + np-nh) vs E_ν
- Effective: **taking into account the energy reconstruction corrections** as described in

  M. Martini, M. Ericson, G. Chanfray,
  PRD 85 093012 (2012); PRD 87 013009 (2013)

  - crucial role of np-nh
  - flux dependence

Our theoretical model

The nuclear response



Nucleon-Nucleon interaction switched off

Nucleons respond individually

Nucleon at rest:

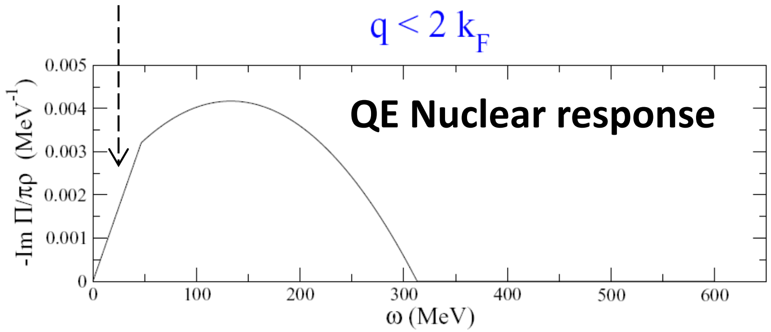
$$R \alpha\ \delta\left(\omega - \left(\sqrt{q^2 + M^2} - M\right)\right)$$

Nucleon inside the nucleus:

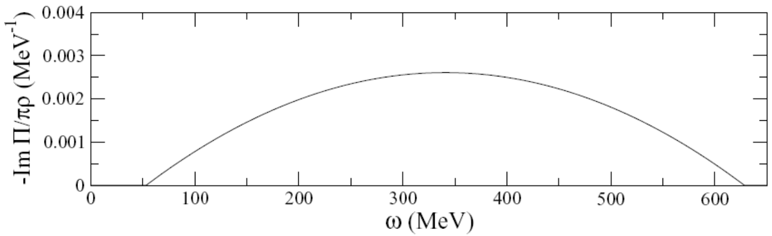
Fermi motion spreads δ distribution (Fermi Gas)

Pauli blocking cuts part of the low momentum Resp.

$q < 2\ k_F$



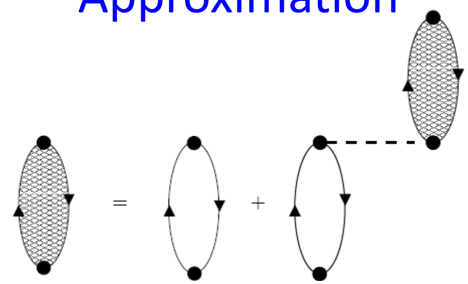
$q > 2\ k_F$



Nucleon-Nucleon interaction switched on

The nuclear response becomes collective

Random Phase Approximation

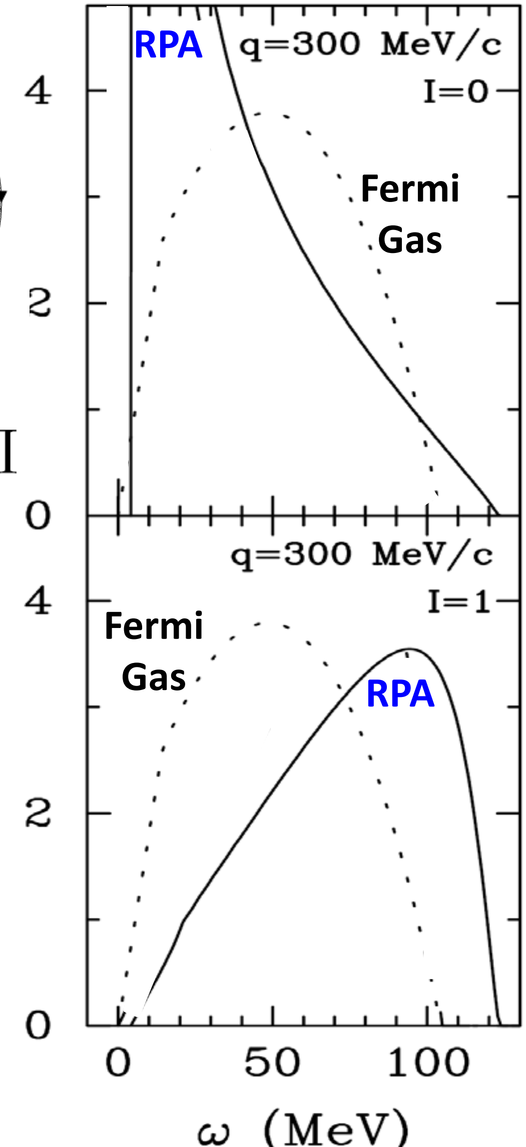


$$\Pi = \Pi^0 + \Pi^0 V \Pi$$

*Force acting on one nucleon is transmitted by the interaction

*Shift of the peak with respect to Fermi Gas, decrease, increase,...

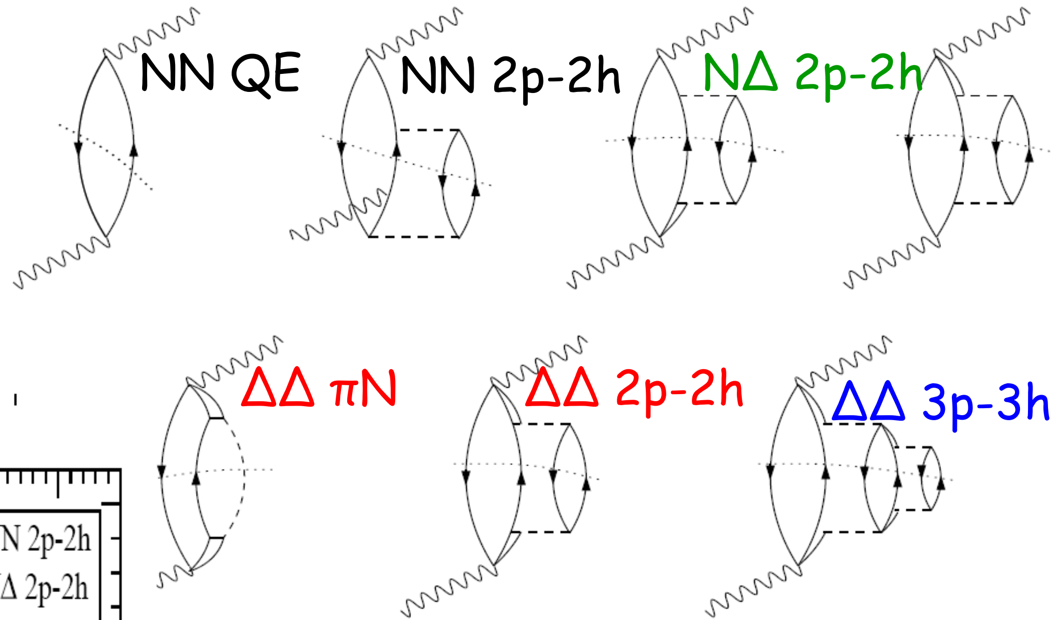
Alberico, Ericson, Molinari, Nucl. Phys. A 379, 429 (1982)

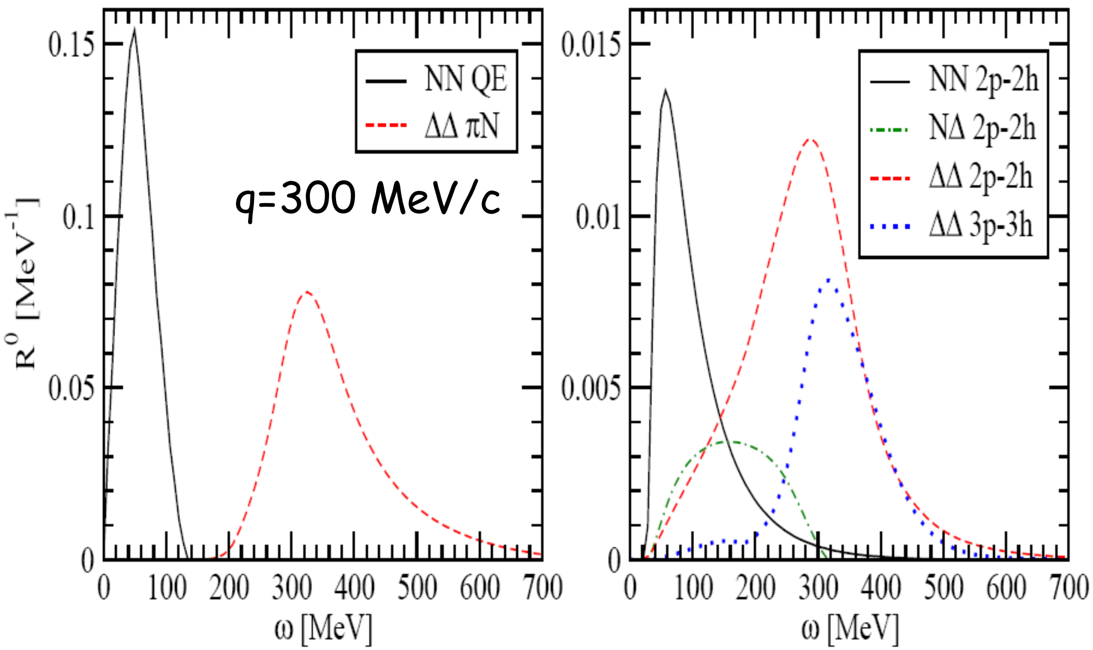


Bare nuclear responses

Several partial components
(final state channels)

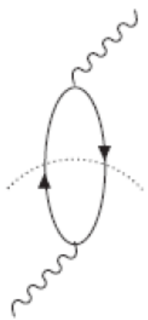
- QE (1 nucleon knock-out)
- Pion production
- Multinucleon emission





Bare polarization propagators

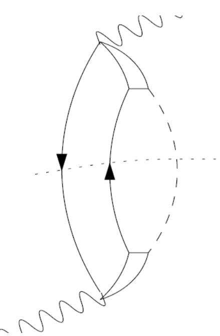
Quasielastic



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

Nucleon-hole

Pion production



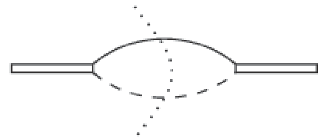
$$\Pi_{\Delta-h}(q) = \frac{32\tilde{M}_\Delta}{9}\int \frac{d^3k}{(2\pi)^3}\theta(k_F-k)\left[\frac{1}{s-\tilde{M}_\Delta^2+i\tilde{M}_\Delta\widetilde{\Gamma}_\Delta} - \frac{1}{u-\tilde{M}_\Delta^2}\right]$$

Delta-hole

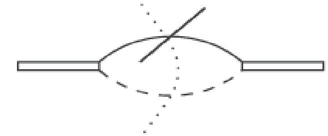
Delta in the medium

Mass

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



$\Delta \rightarrow \pi N$

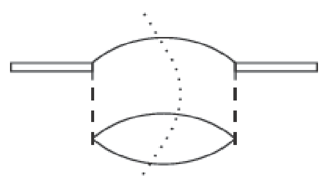


Pauli correction (F_P)

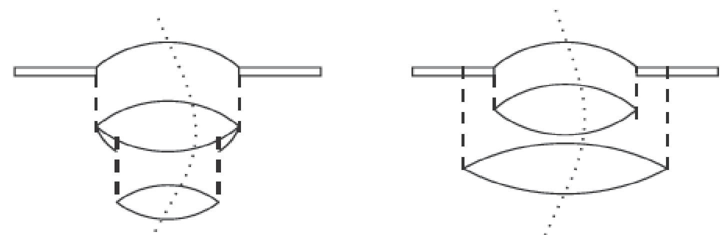
Pion distortion (C_Q)

Width

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



2p-2h



3p-3h

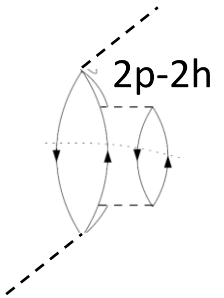
Self energy

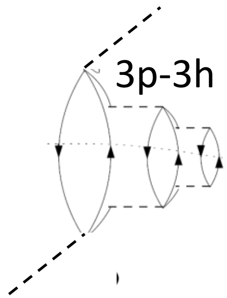
$$\text{Im}(\Sigma_\Delta(\omega)) = -\left[C_Q(\frac{\rho}{\rho_0})^\alpha + C_{2p2h}(\frac{\rho}{\rho_0})^\beta + C_{3p3h}(\frac{\rho}{\rho_0})^\gamma\right]$$

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

ΔΔ contributions to np-nh in our model

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





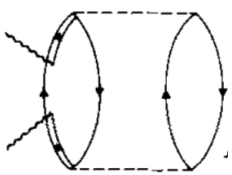
E. Oset and L. L. Salcedo, Nucl. Phys. A 468, 631 (1987):

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

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

Nieves et al. in PRC 83 (2011) and in PLB 707 (2012) use the same model for these contributions

- Not reducible to a modification of the Delta width



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

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

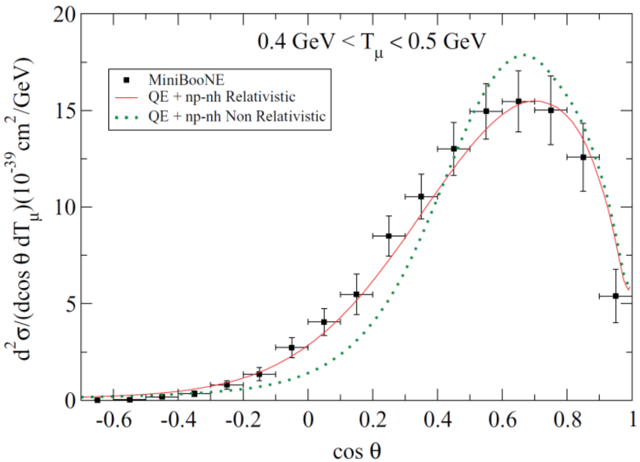
Extrapolation to other energies

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

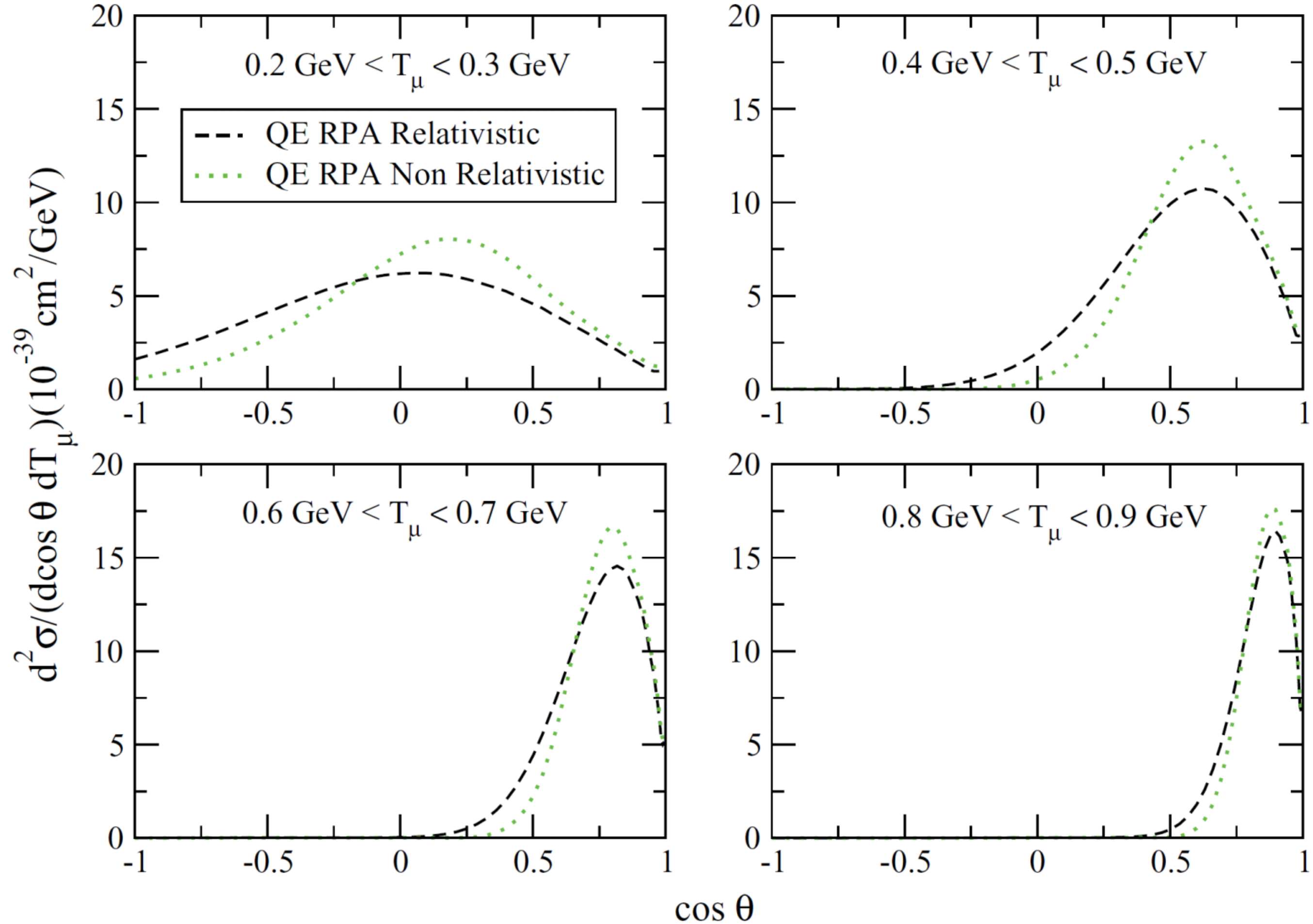
Relativistic corrections

$$\omega \rightarrow \omega\left(1 + \frac{\omega}{2M_N}\right)$$

$$\Pi \longrightarrow \left(1 + \frac{\omega}{M_N}\right)\Pi$$

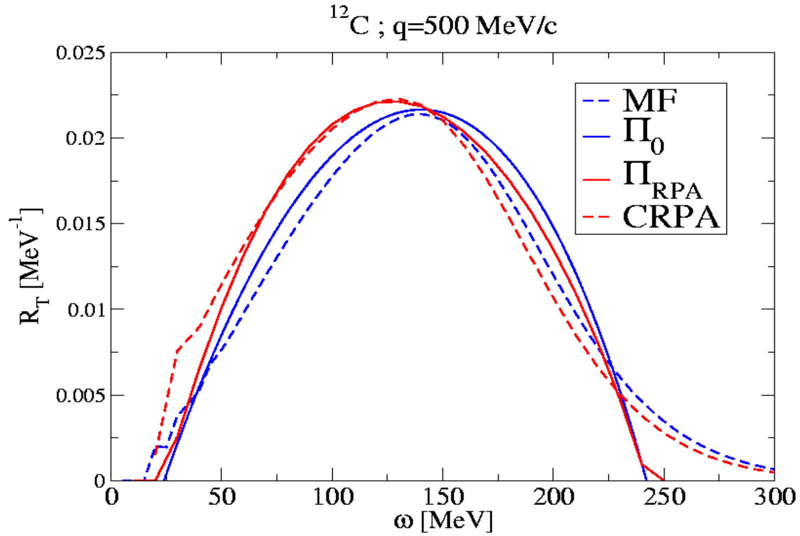


Martini, Ericson, Chanfray, Phys. Rev. C 84 055502 (2011)



From nuclear matter to finite nuclei

A comparison between a finite nucleus (Woods-Saxon + continuum RPA) and pure nuclear matter calculation shows that nuclear matter at these energies is a good approximation of the nucleus.



The agreement further improves introducing the Local density Approximation (this is the case of our model)

Local Density Approximation

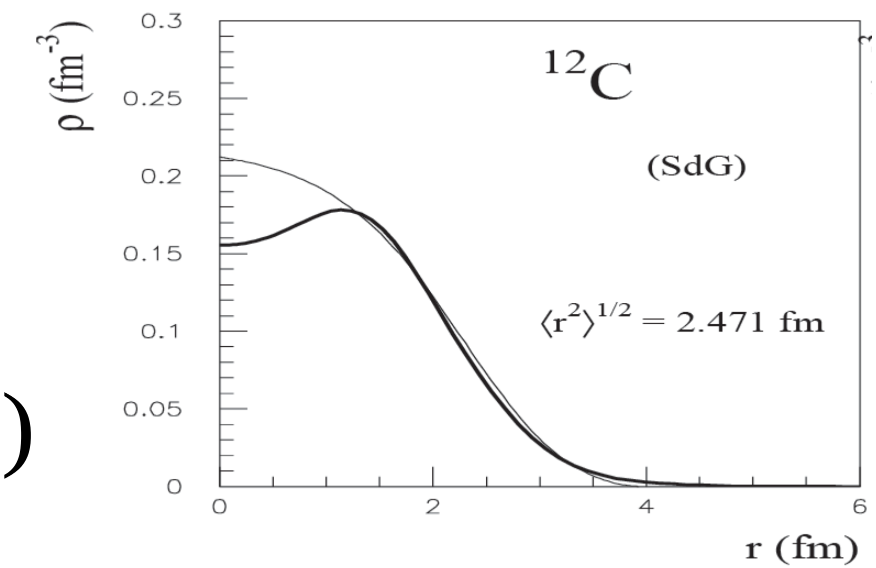
$$\rho = \frac{2k_F^3}{3\pi^2}$$

constant
in nuclear matter

$$k_F \rightarrow k_F(r)$$

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

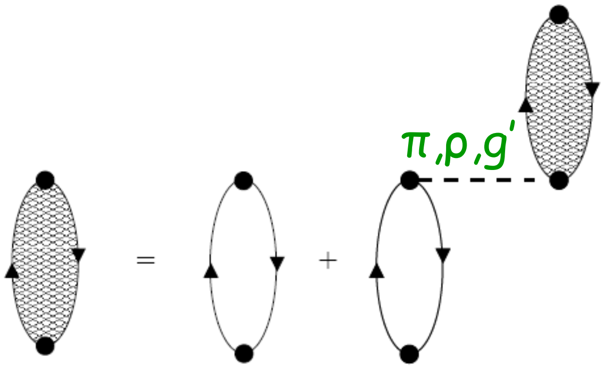
$$\Pi_{k_F}(q,\omega) \rightarrow \Pi_{k_F(r)}(q,\omega)$$



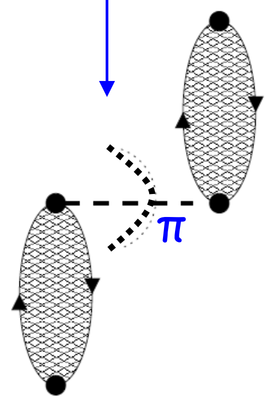
Switching on the interaction: random phase approximation

RPA

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



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

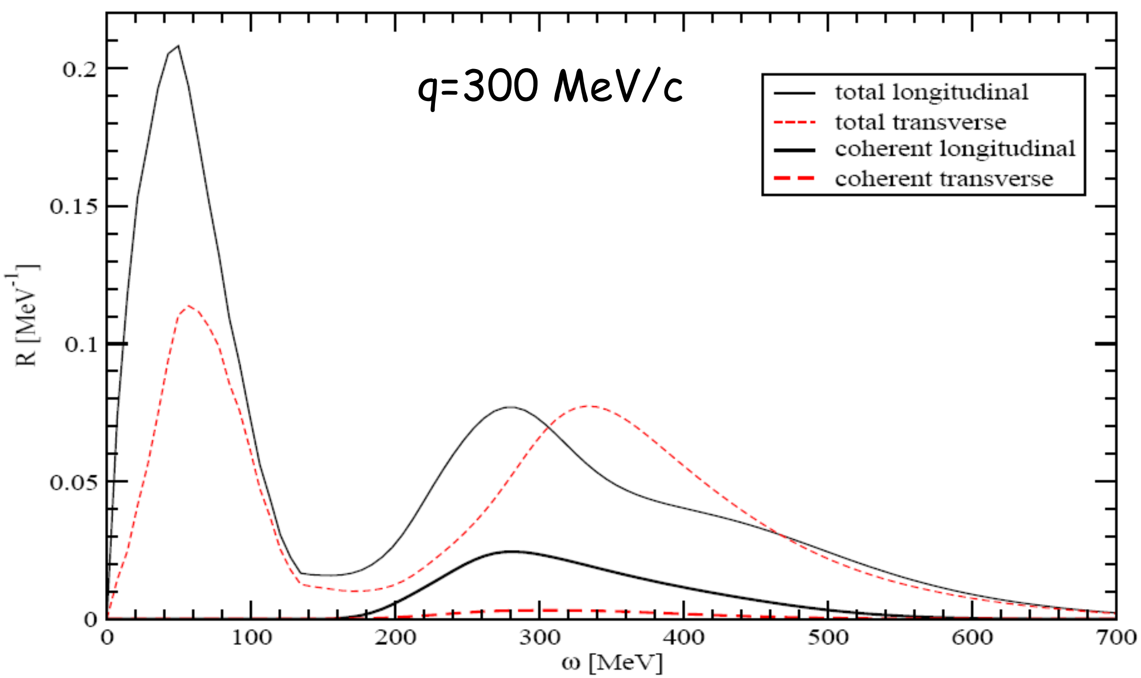


coherent π production

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

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

M. Martini, M. Ericson, G. Chanfray, J. Marteau, PRC 80 065501 (2009)



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

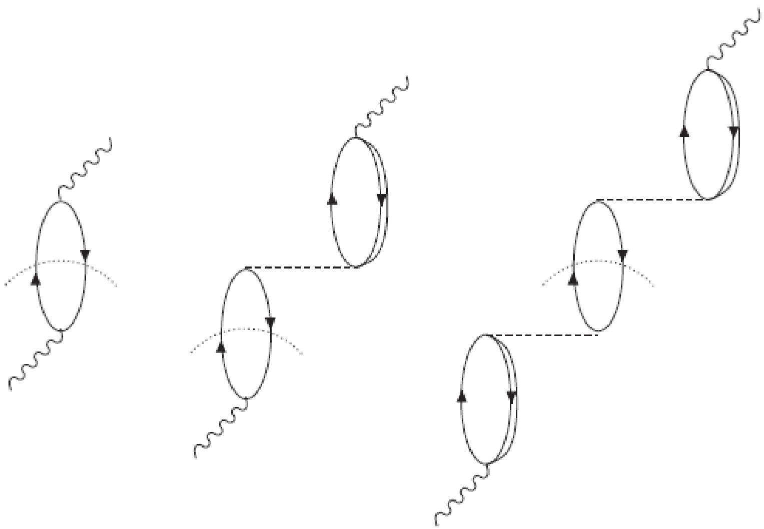
Effects of the RPA in the ν genuine quasielastic scattering

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

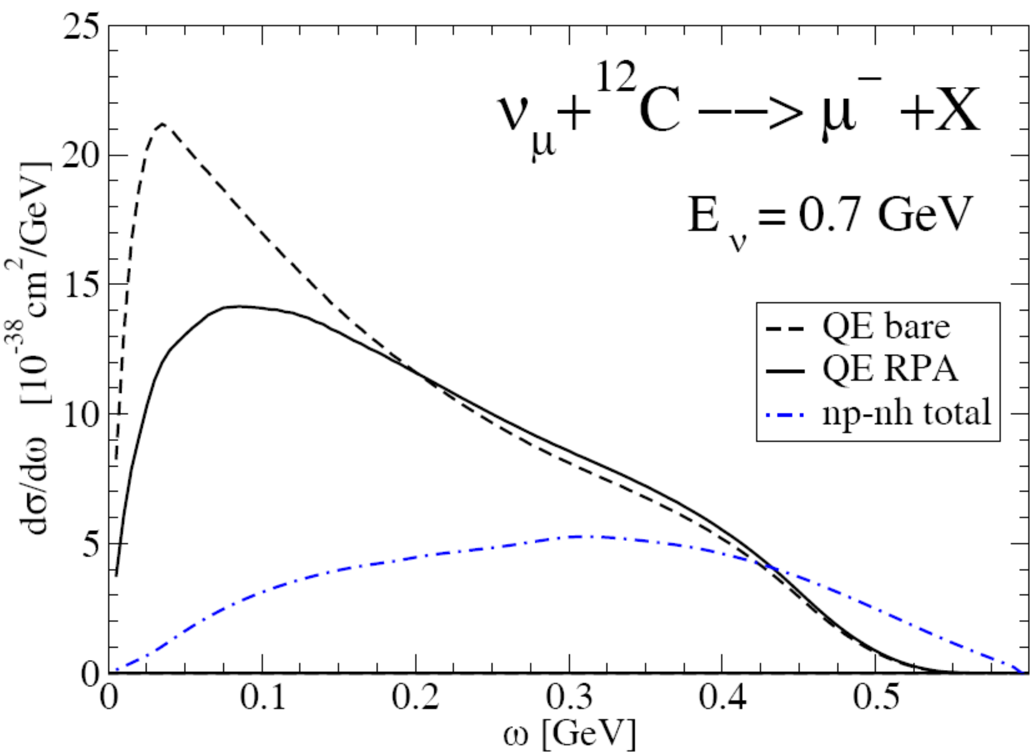
RPA reduction

- 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)

Lowest order contribution to QE



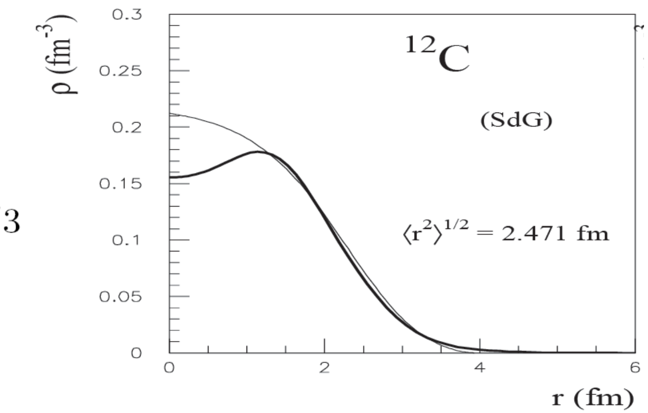
R^{NN}_{QE} $R^{N\Delta}_{QE}$ $R^{\Delta\Delta}_{QE}$



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

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

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

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

Details: p-h effective interaction

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

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

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

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

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

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

RPA

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

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

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

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

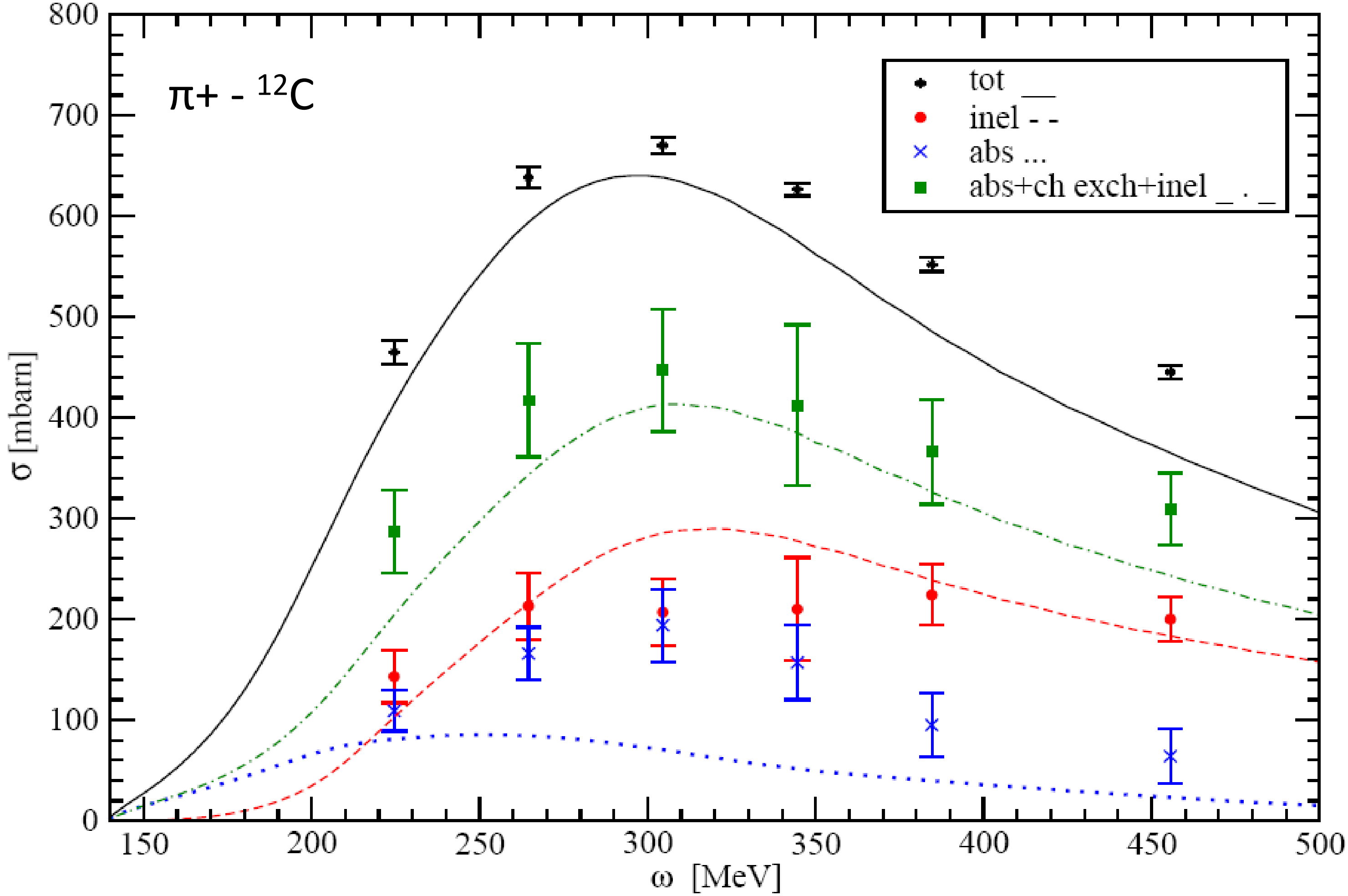
coherent

exclusive channels:
QE, 2p-2h, Δ→πN …

Testing our model: pion-nucleus cross-section

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

M. Martini, M. Ericson, G. Chanfray, J. Marteau, PRC 80 065501 (2009)

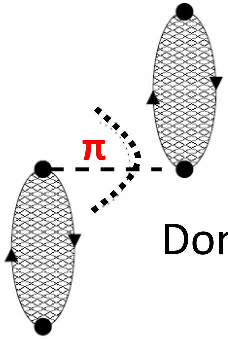


Overestimation of inelastic ch. in the delta peak region

Underestimation of absorption

Absence of π FSI

Coherent channel

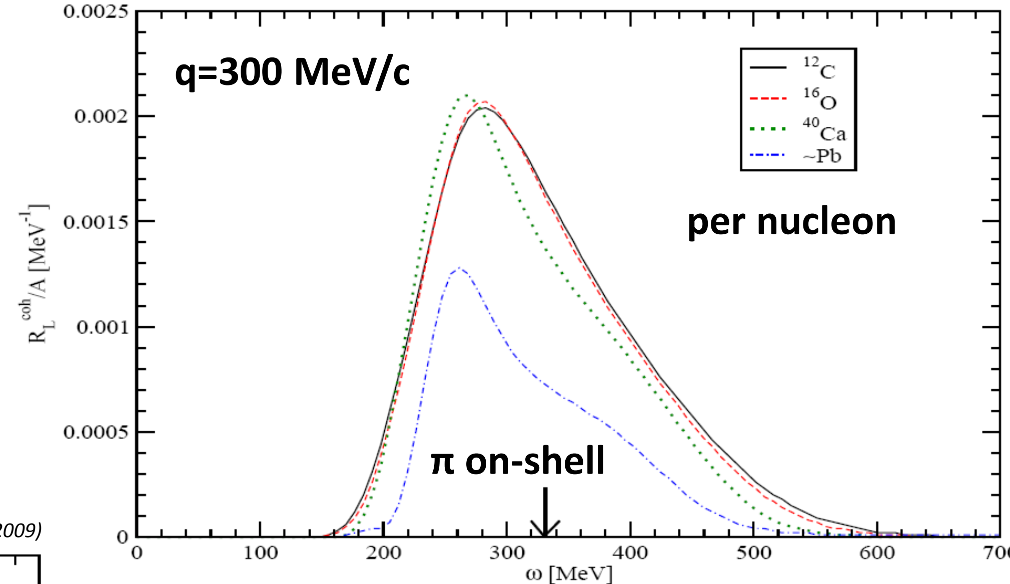


Dominated by $R_{\sigma\tau}$ longitudinal

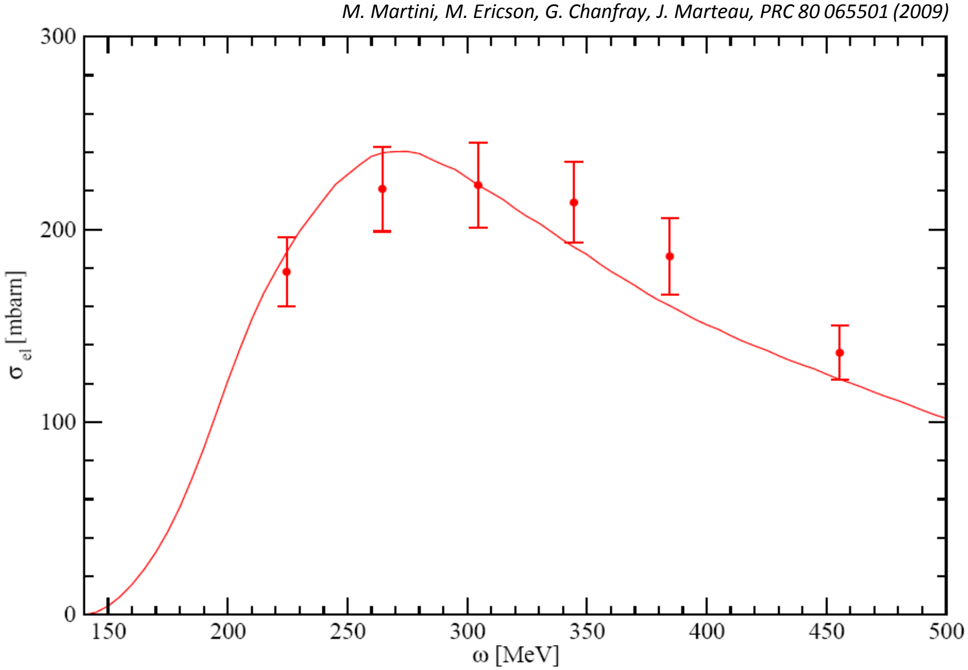
Reshaped by collective effects

Softening of the responses

M. Martini, M. Ericson, G. Chanfray, J. Marteau, PRC 80 065501 (2009)



M. Martini, M. Ericson, G. Chanfray, J. Marteau, PRC 80 065501 (2009)



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

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

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

Where 2p-2h enter in ν-nucleus cross-section?

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

isovector nuclear response

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

isospin spin-longitudinal

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

isospin spin-transverse

$$\pm\;2\,G_A\,G_M\,\frac{k+k'}{M_N}\,\tan^2\frac{\theta}{2}\,R_{\sigma\tau(T)}\Bigg]$$

interference V-A

The 2p-2h term affects the magnetic and axial responses

(terms in G_M, G_A)

(spin-isospin, στ excitation operator)

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

• Pion absorption

Two-nucleon mechanism: πNN --> NN (πN --> N strongly suppressed)

Dominated by p-n initial pairs

ν scattering

Ejected pairs will be predominantly:

p-p for ν CC

n-n for antiν CC

p-n for NC

First results of MINERνA seem to confirm this prediction (PRL 111 022501; 022502 2013)

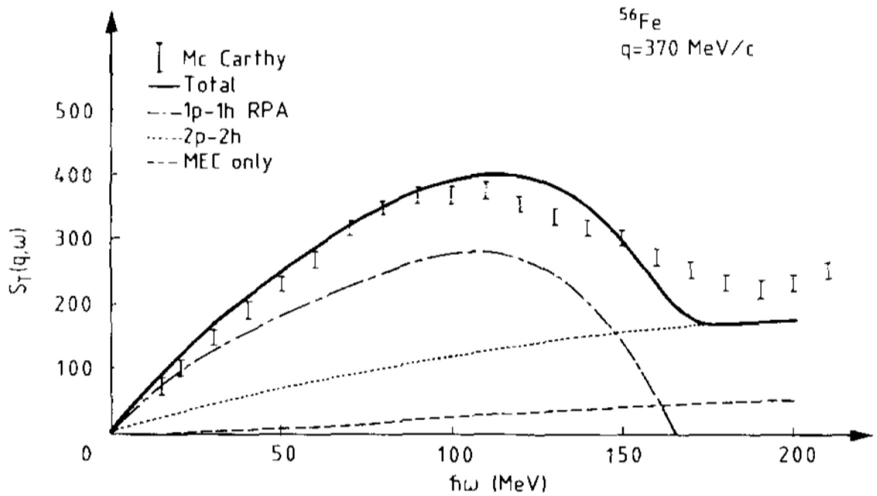
• Photon absorption

$$\sigma_\gamma^{tot} = 2\pi^2 \frac{\alpha}{\omega} \boxed{R_T(q,q)}$$

• Transverse response in electron scattering

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

NN correlations and NΔ interference contributions to 2p-2h



Starting point: a microscopic evaluation of R_T
Alberico, Ericson, Molinari, Ann. Phys. 154, 356 (1984)

Transverse magnetic response of (e,e')
for some values of q and ω,but:

^{56}Fe, instead of ^{12}C and responses available only for few q and ω values

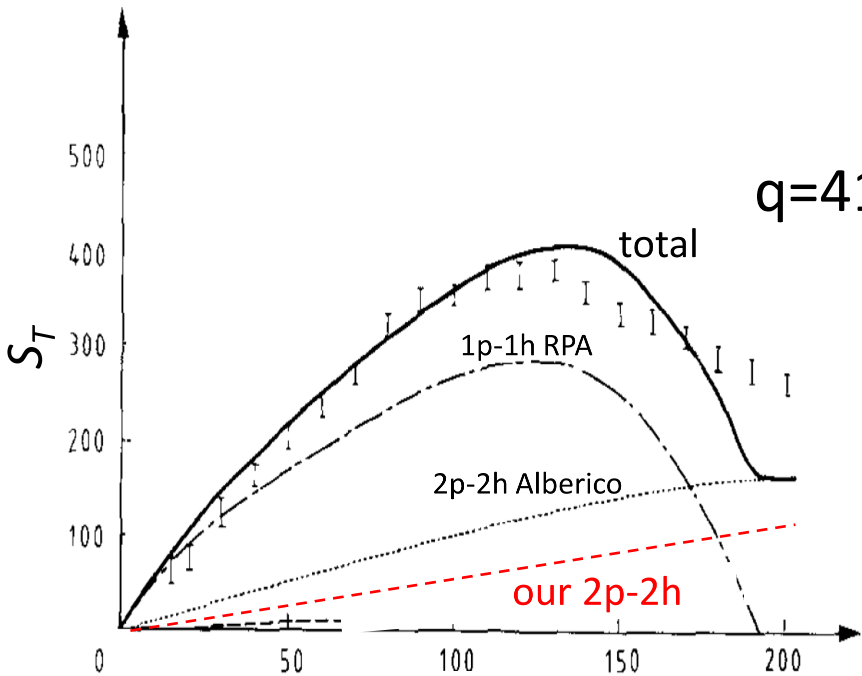
Our work

- Parameterization of these contributions in terms of $x = \frac{q^2 - \omega^2}{2 M_N \omega}$ $\longrightarrow$ Extrapolation to cover neutrino region

- Global reduction ≈ 0.5 applied to reproduce the absorptive p-wave π-A optical potential

A comparison between our parameterization of 2p-2h (PRC 2009) and the one of the PRC (2010) paper of Amaro et al. on electron scattering

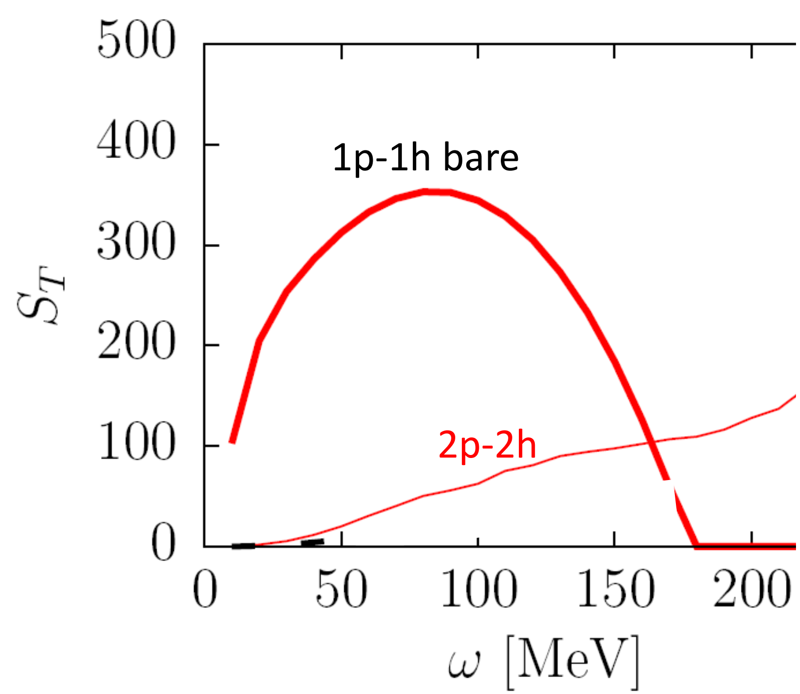
Alberico et al. Ann. Phys. 154, 356 (1984)



^{56}Fe

q=410 MeV/c

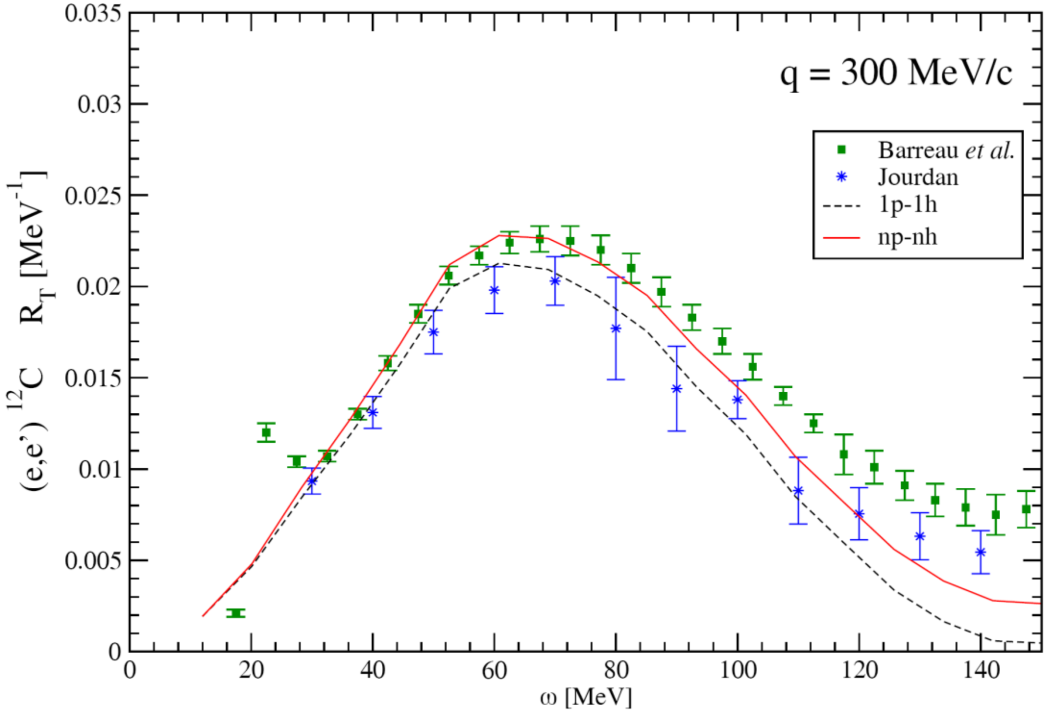
Amaro et al. PRC 82 044601 (2010)
(not yet inserted in neutrino calculations)



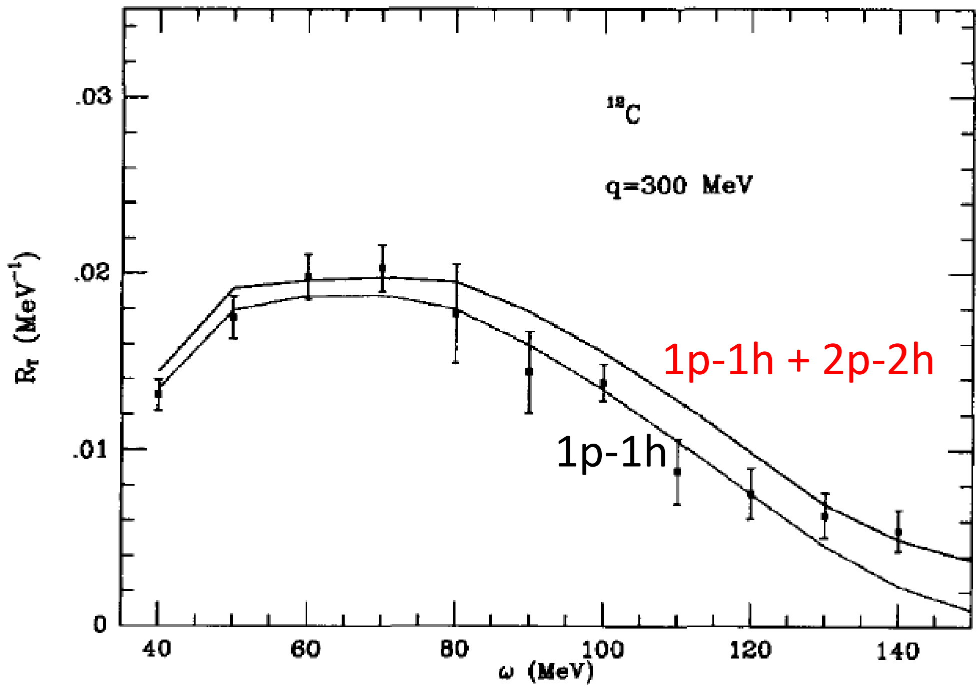
Our parameterization is quite close to the results of Amaro et al.

R_T of ^{12}C: comparison with data and with calculations of Gil, Nieves, Oset

Our calculation J.Phys.Conf.Ser. 408 (2013) 012041



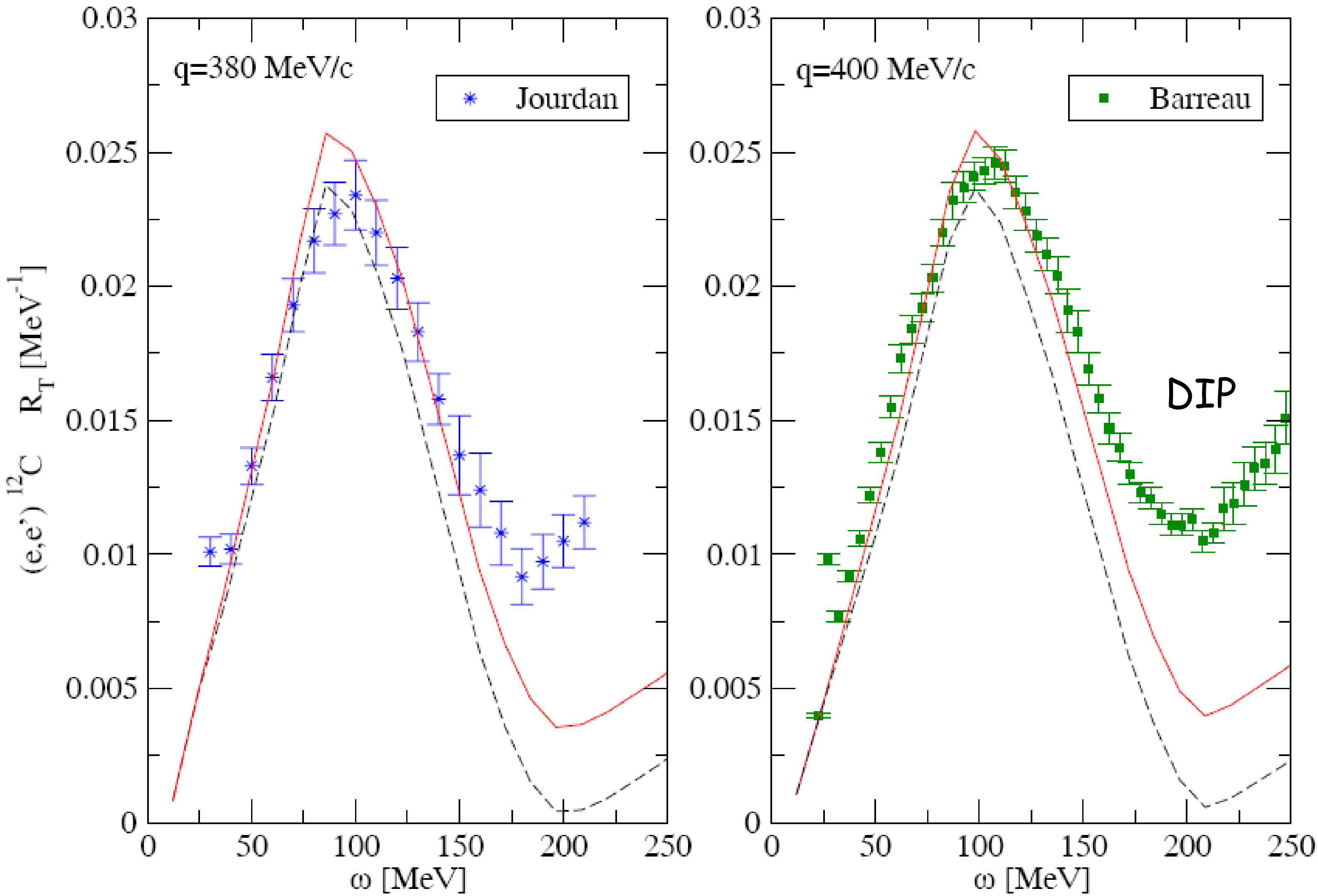
Gil, Nieves, Oset NPA 627, 543 (1997)



- Two evaluations of 2p-2h: same order of magnitude
- Agreement with data

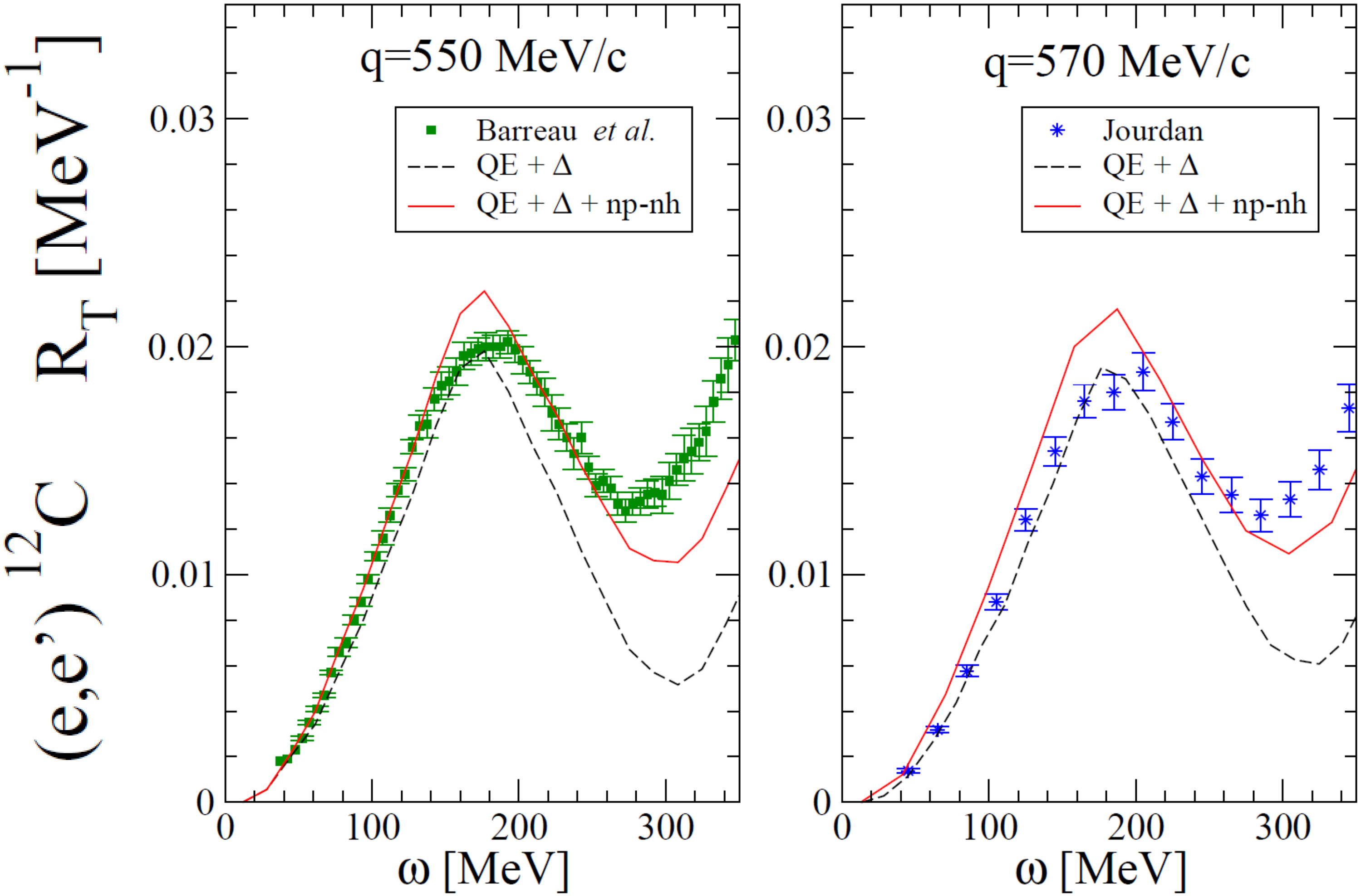
N.B. Some discrepancies in the two experimental data sets

Our results vs experiment for other q values



Our results vs experiment for other q values

M. Martini, J.Phys.Conf.Ser. 408 (2013) 012041

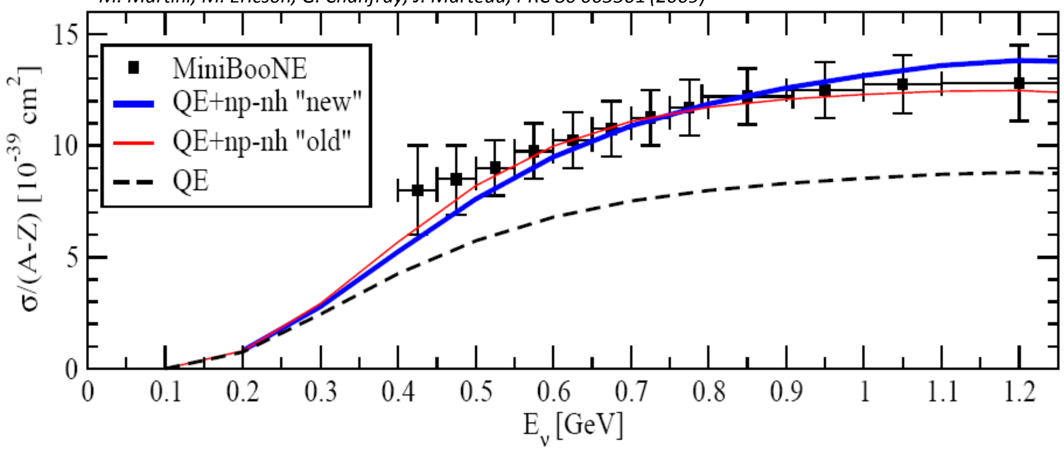


Conclusions: various evaluations of 2p-2h contributions to R_T are compatible among them and the data in the DIP region are never overestimated.

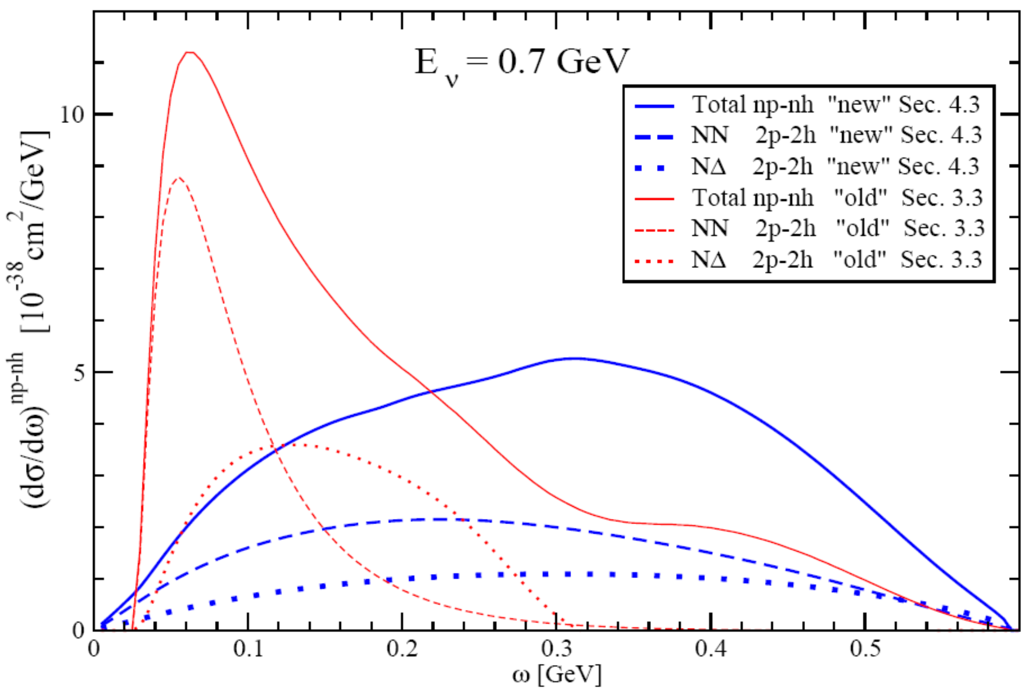
This test is important for ν cross section which is dominated by the transverse response.

In order to avoid confusion further comments on our model for the np-nh sector

M. Martini, M. Ericson, G. Chanfray, J. Marteau, PRC 80 065501 (2009)



M. Martini, M. Ericson, G. Chanfray, J. Marteau, PRC 80 065501 (2009)



In the paper
Martini, Ericson, Chanfray, Marteau, PRC 80 (2009)
we considered 2 different parameterizations of np-nh

"old" red:

Extrapolation from 2p-2h π absorption (Delorme, Guichon)
used for **total** neutrino cross section in:
Marteau, Delorme, Ericson, NIM A451 (2000) 76-80
Sometimes called "The Marteau model"
Oversimplified: no q dependence in NN and NΔ contributions only ω dependence

"new" blue:

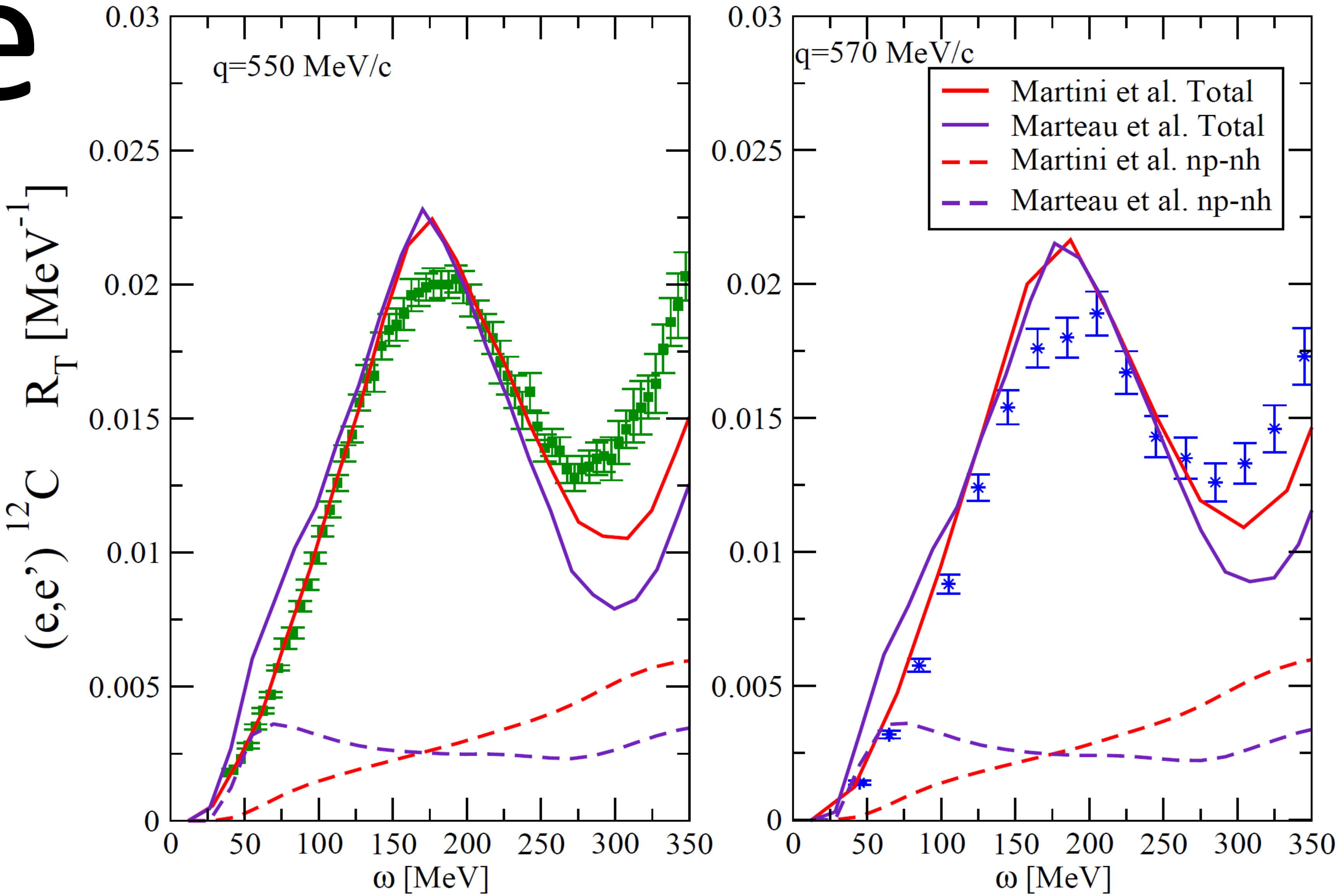
The more realistic parameterization
described previously
deduced from Alberico et al.

These two approaches give results
- very similar for the total cross section
- very different for the differential cross sections

The "New" parameterization is the only one we have considered in all our later papers

Comparison between the two approaches in electron scattering

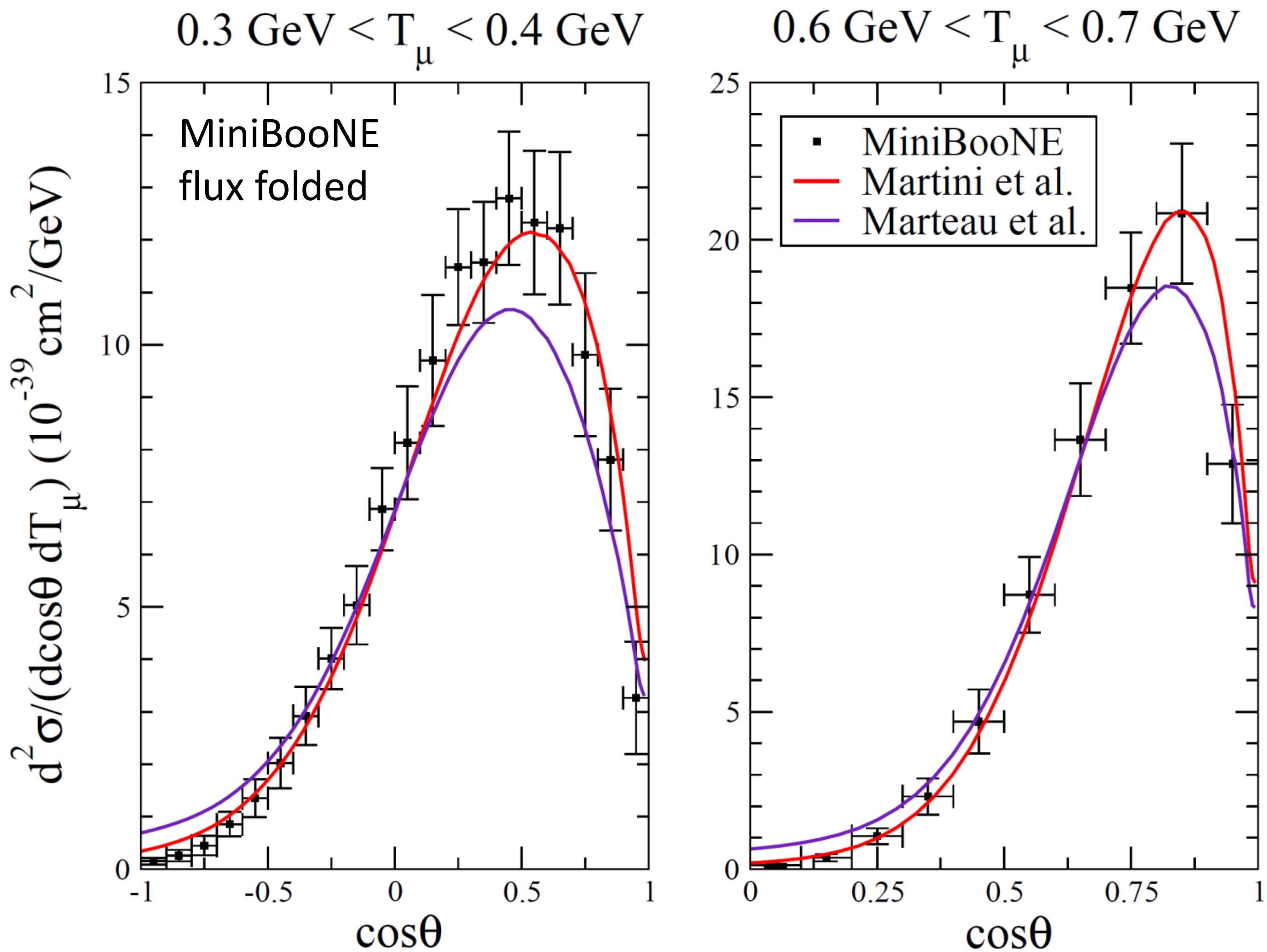
e



In the "old" model too much accumulation of strength at low ω reflecting the absence of q dependence

Comparison between the two approaches in neutrino scattering

ν



The "old" (Marteau) model does not hold for the neutrino double differential cross sections. It is obsolete. Don't use it to study neutrino energy reconstruction problems.

Form Factors

Standard dipole parameterization

Vector

$$G_E(Q^2) = G_M(Q^2)/(\mu_p - \mu_n) = (1 + Q^2/M_V^2)^{-2}$$

$$Q^2 = q^2 - \omega^2$$

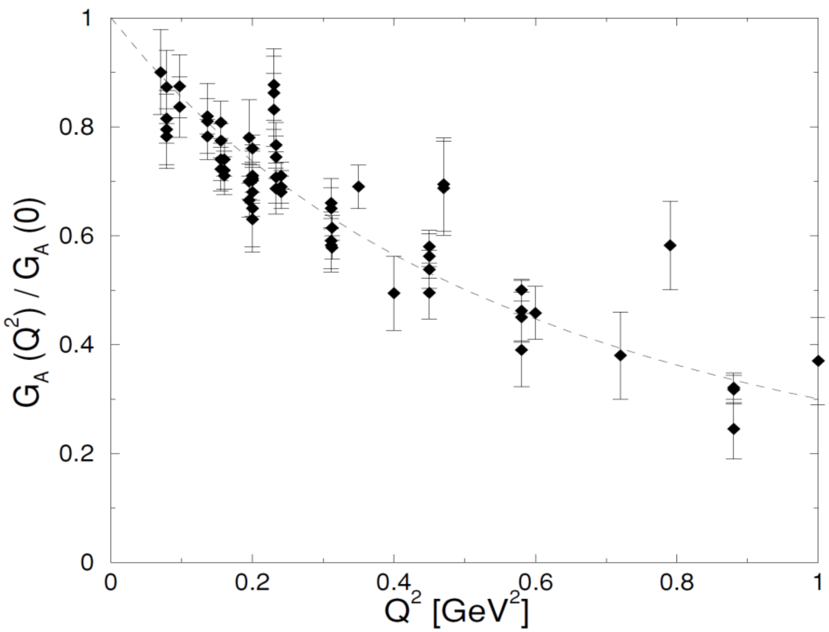
$$M_V = 0.84\,\mathrm{GeV}/c^2$$

Axial

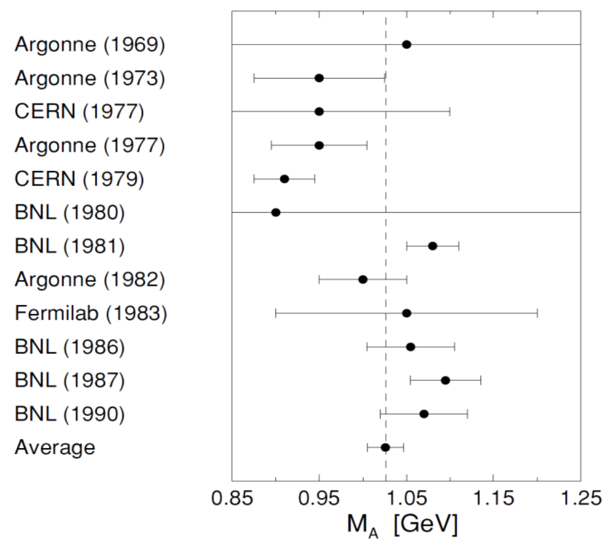
$$G_A(Q^2) = g_A(1 + Q^2/M_A^2)^{-2}$$

$g_A = 1.26$ from neutron β decay

$$M_A = (1.026 \pm 0.021)\ GeV/c^2$$



V. Bernard, J.Phys. G28 (2002) R1-R35



from ν-deuterium CCQE
and
from π electroproduction

ν PRL 111 022502 (2013)

Experience from electron quasielastic scattering on carbon suggests that multibody final states are dominated by initial-state np pairs [24,43,44]. This could lead to an expectation of final state pp pairs in neutrino quasielastic scattering and nn pairs in the analogous antineutrino channel. The vertex energy measurement, shown in Fig. 5, is sensitive to these effects. These data prefer the addition of a final state proton with less than 225 MeV kinetic energy in $25 \pm 1(\text{stat}) \pm 9(\text{syst})\%$ of the events. The corresponding result in the antineutrino mode [35], in contrast, prefers the removal of a final state proton in $10 \pm 1(\text{stat}) \pm 7(\text{syst})\%$ of the events. The systematic uncertainties for the two samples are positively correlated with a correlation coefficient of +0.7, implying that the observed difference is unlikely to be due to one of the systematic uncertainties considered. The systematic uncertainties are primarily from the detector response to protons and uncertainties in reactions in the target nucleus that absorb or create final state protons. Independent of models, elastic and inelastic nucleon reactions which might produce additional final state protons in the neutrino data should have analogous reactions in the antineutrino data, and the difference in the two results makes it unlikely that any modification of final state nucleon interactions can explain the discrepancy. Pion final state interactions (FSI), especially absorption, would produce more protons in the neutrino reaction and neutrons in the antineutrino reaction, but the associated uncertainties are included in the total systematic errors. The observed patterns in the neutrino and antineutrino channels, combined with the observation that electron quasielastic scattering with multinucleon final states in carbon produces primarily final state np pairs, suggests that an initial state of strongly correlated np pairs also may participate in the neutrino quasielastic interaction.

MINERνA

PRL 111 022501 (2013) $\bar{\nu}$

Transverse enhancement is included as a parametrization affecting the Q^2_{QE} dependence in our analysis but is thought to be due to underlying multinucleon dynamical processes [57–63]. Such processes could have an effect on the vertex and recoil energy distributions that we do not simulate. Motivated by these concerns and by discrepancies observed in our analysis of ν_μ quasielastic scattering [64], we have also studied the vertex energy to test the simulation of the number of low energy charged particles emitted in quasielastic interactions. Figure 5 shows this energy compared to the simulation. A fit which modifies the distributions to incorporate energy due to additional protons is not able to achieve better agreement. This might be explained if the dominant multibody process is $\bar{\nu}_\mu(np) \to \mu^+ nn$ [57,60,65] since MINERvA is not very sensitive to low energy neutrons. A similar analysis on neutrino mode data is consistent with additional protons in the final state [64].

ν *PRL 111 022502 (2013)*

MINERνA

PRL 111 022501 (2013) $\overline{\nu}$

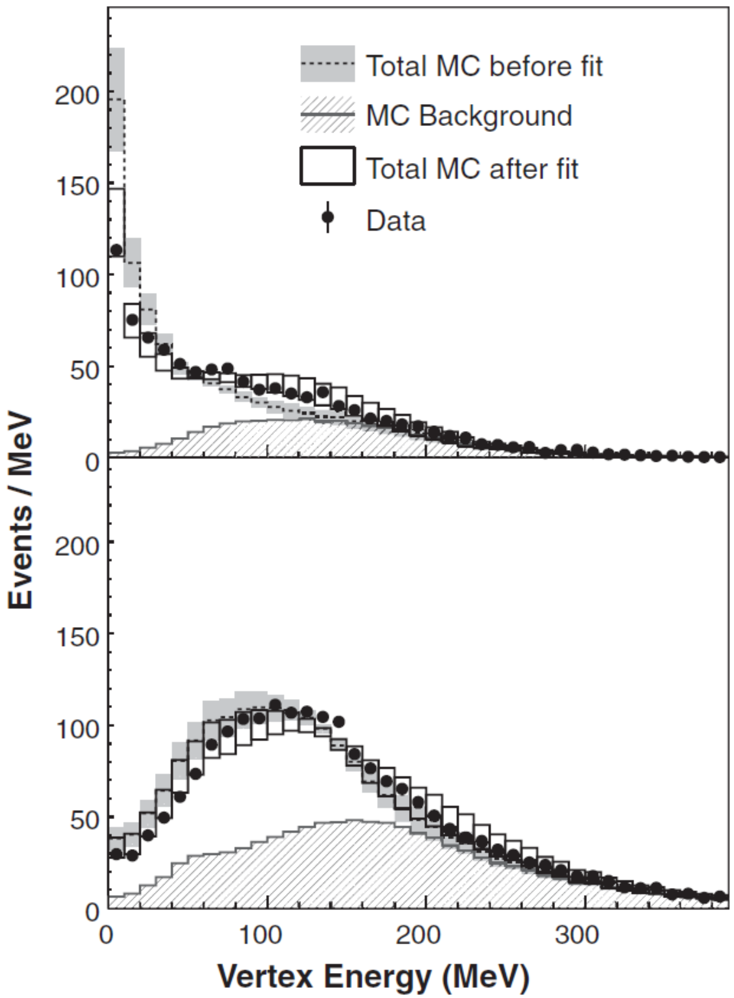


FIG. 5. Reconstructed vertex energy of events passing the selection criteria in the data (points with statistical errors) compared to the GENIE RFG model (shown with systematic errors) for $Q^2_{QE} < 0.2\ \mathrm{GeV}^2/c^2$ (top) and for $Q^2_{QE} > 0.2\ \mathrm{GeV}^2/c^2$ (bottom).

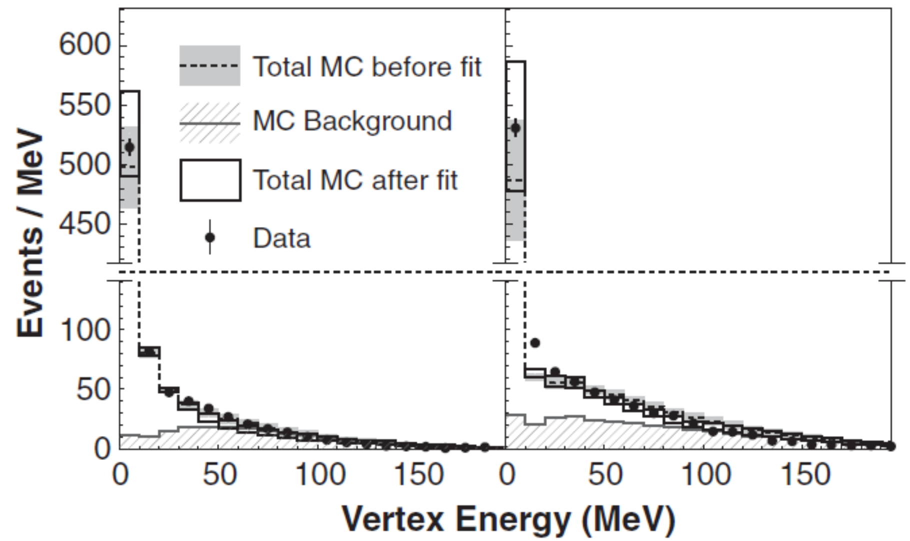


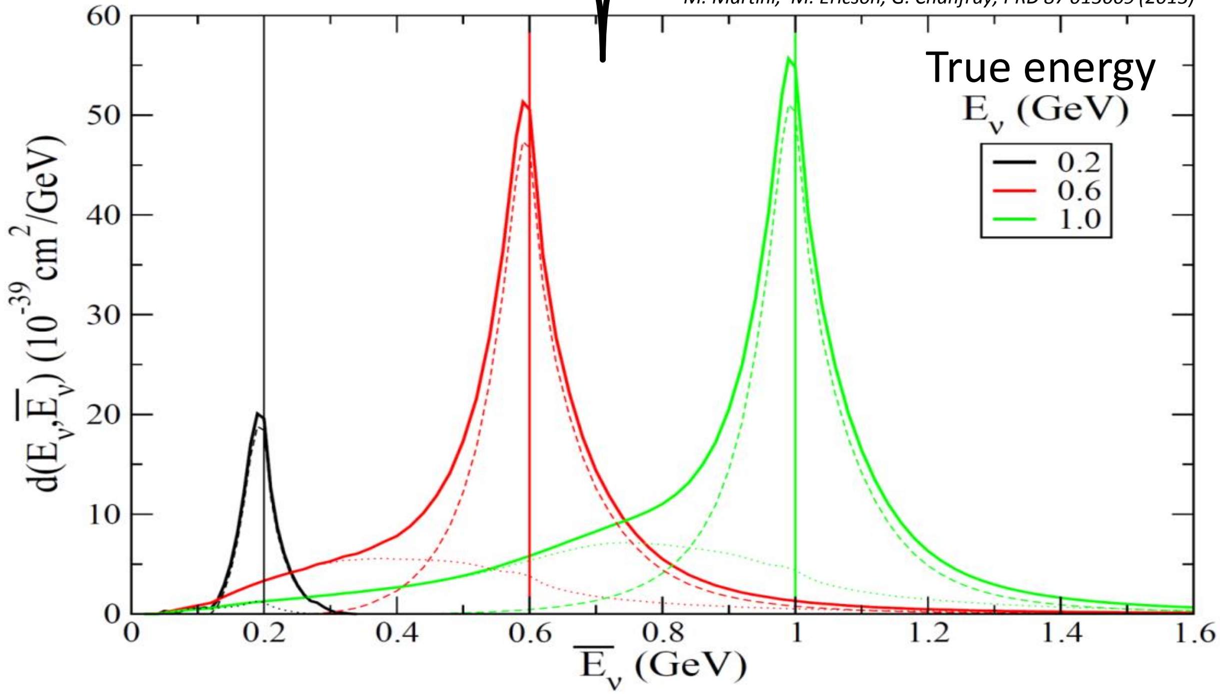
FIG. 5. Reconstructed vertex energy of events passing the selection criteria compared to the GENIE RFG model for $Q^2_{QE} < 0.2\ \mathrm{GeV}^2/c^2$ (left) and for $Q^2_{QE} > 0.2\ \mathrm{GeV}^2/c^2$ (right).

Neutrino energy reconstruction problems and neutrino oscillations

$$D_{rec}(\overline{E_\nu}) = \int dE_\nu \Phi(E_\nu) \int_{E_l^{min}}^{E_l^{max}} dE_l \frac{M E_l - m_l^2/2}{\overline{E}_\nu^2 P_l} \left[\frac{d^2\sigma}{d\omega \; d\cos\theta}\right]_{\omega=E_\nu - E_l, \; \cos\theta=\cos\theta(E_l, \overline{E_\nu})}$$

M. Martini, M. Ericson, G. Chanfray, PRD 87 013009 (2013)

The quantity $D_{rec}(\overline{E_\nu})$ corresponds to the product $\sigma(E_\nu)\Phi(E_\nu)$ but in terms of reconstructed ν energy $\overline{E_\nu}$

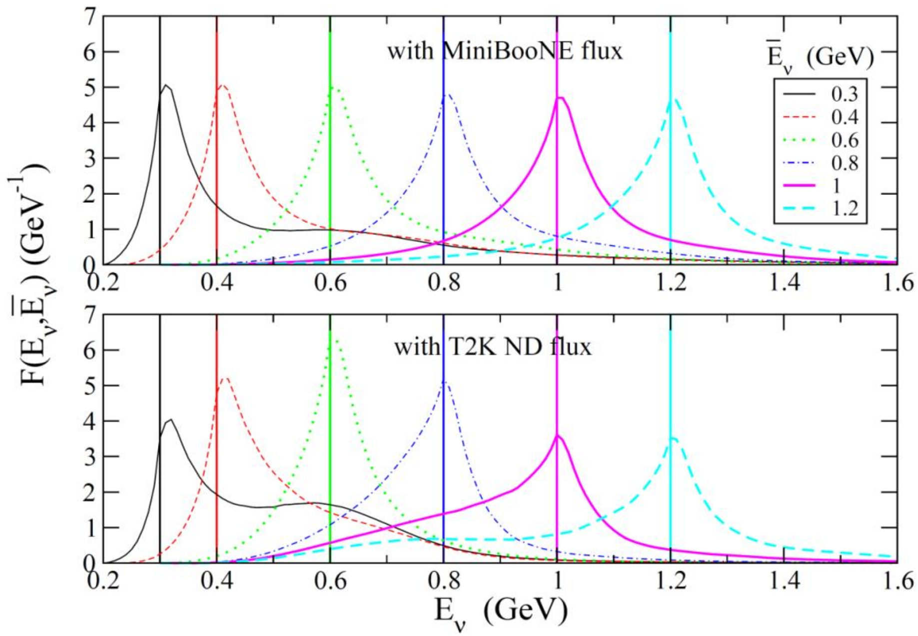


M. Martini, M. Ericson, G. Chanfray
- Phys. Rev. D 85 093012 (2012)
- Phys. Rev. D 87 013009 (2013)

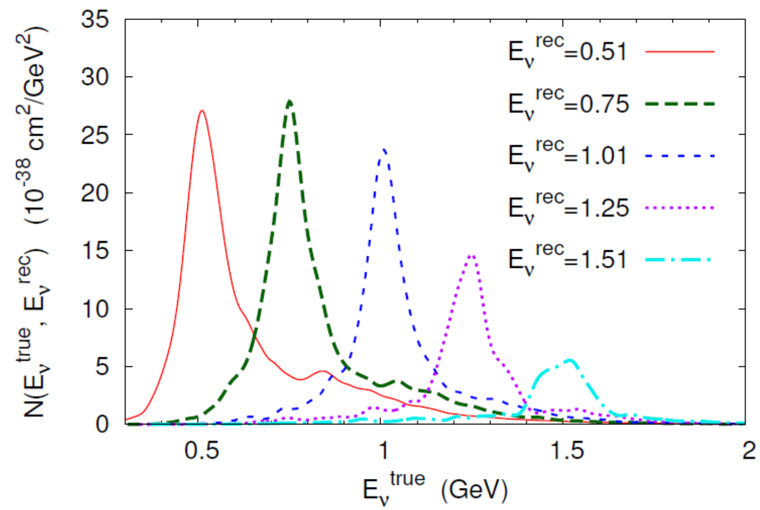
Crucial role of np-nh: low energy tail

Viceversa: distributions in terms of true E_ν for fixed values of reconstructed E_ν

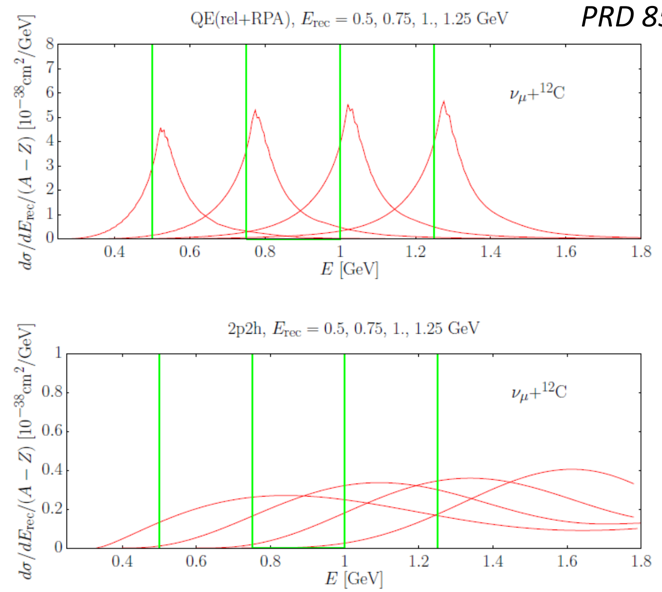
Martini, Ericson, Chanfray, PRD 85 093012 (2012)



O. Lalakulich, U. Mosel, K. Gallmeister PRC 86 054606 (2012)

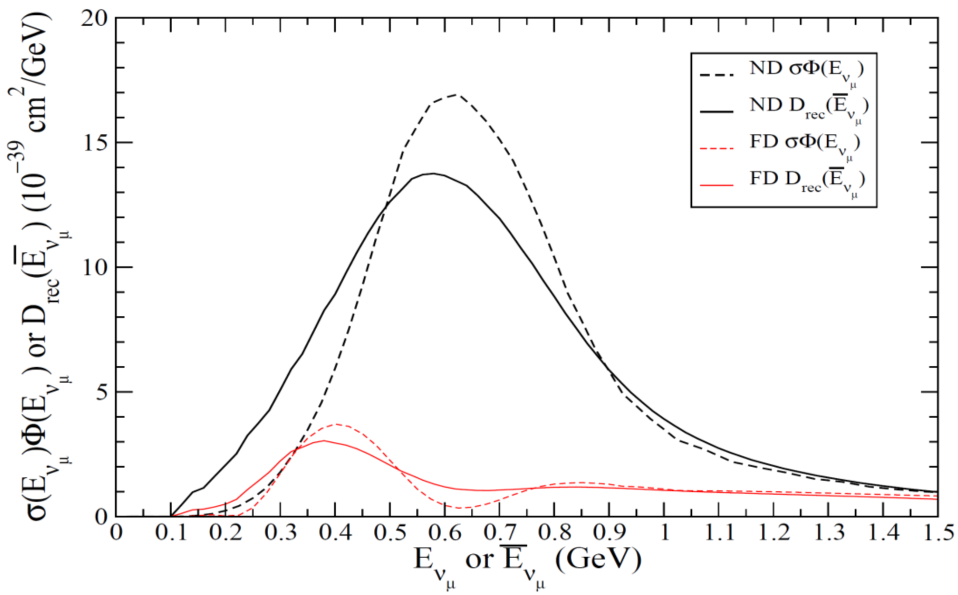


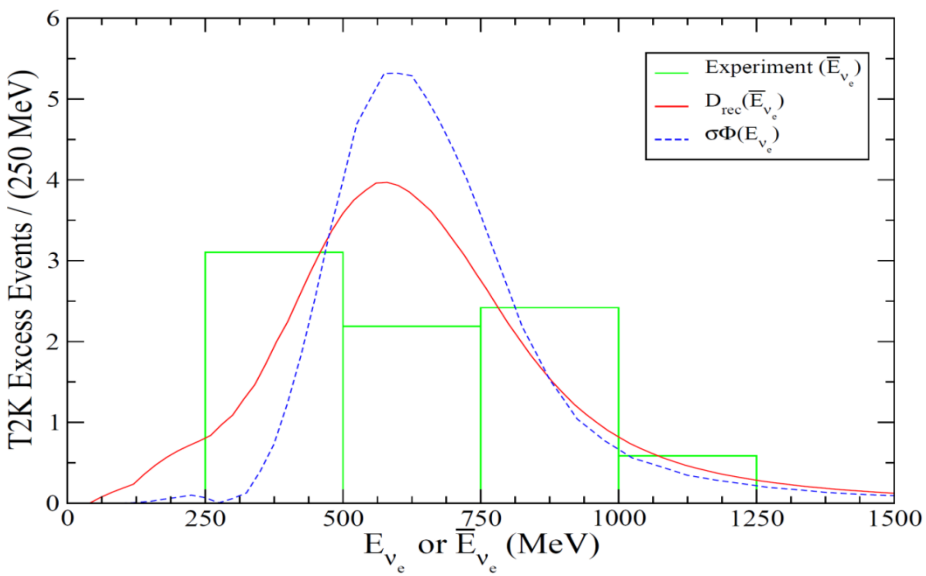
J. Nieves, F. Sanches, I. Ruiz Simo, M.J. Vicente Vacas PRD 85 113008 (2012)



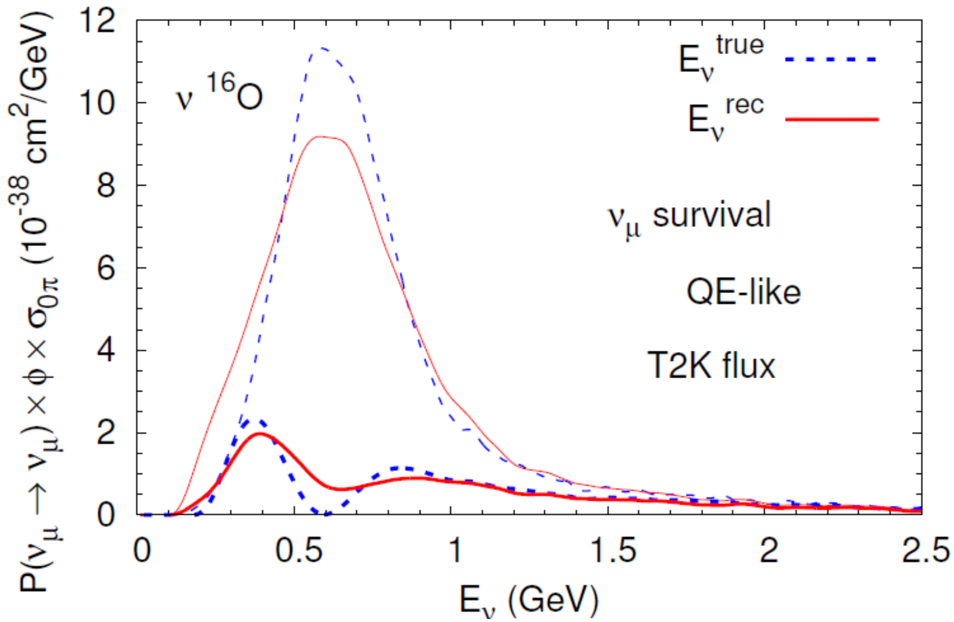
- The distributions are not symmetrical around Ēν.
- The asymmetry favors higher energies at low Ēν and smaller energies for large Ēν.
- Crucial role of neutrino flux.

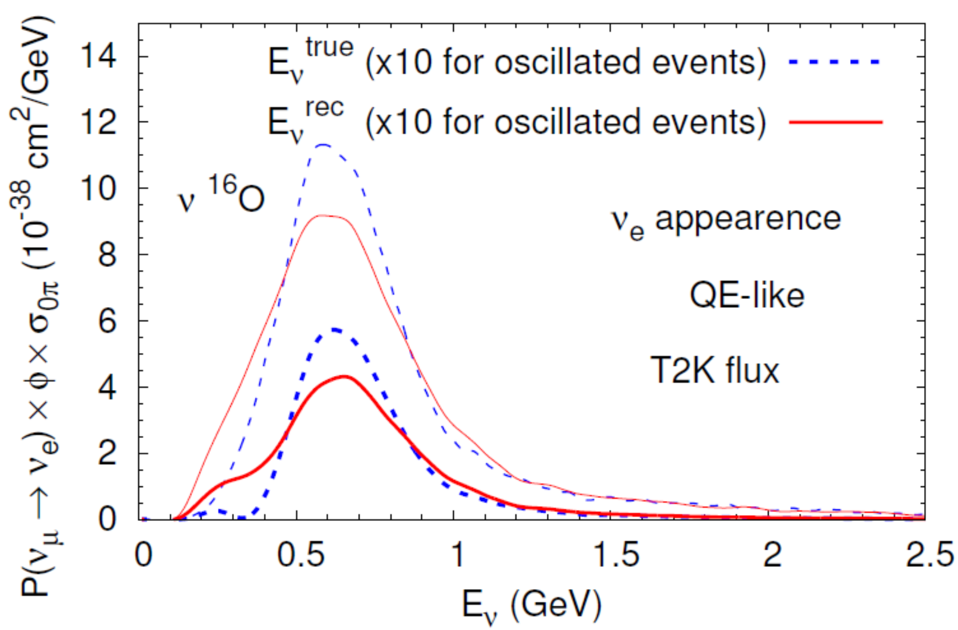
M. Martini, M. Ericson, G. Chanfray, PRD 87 013009 (2013)



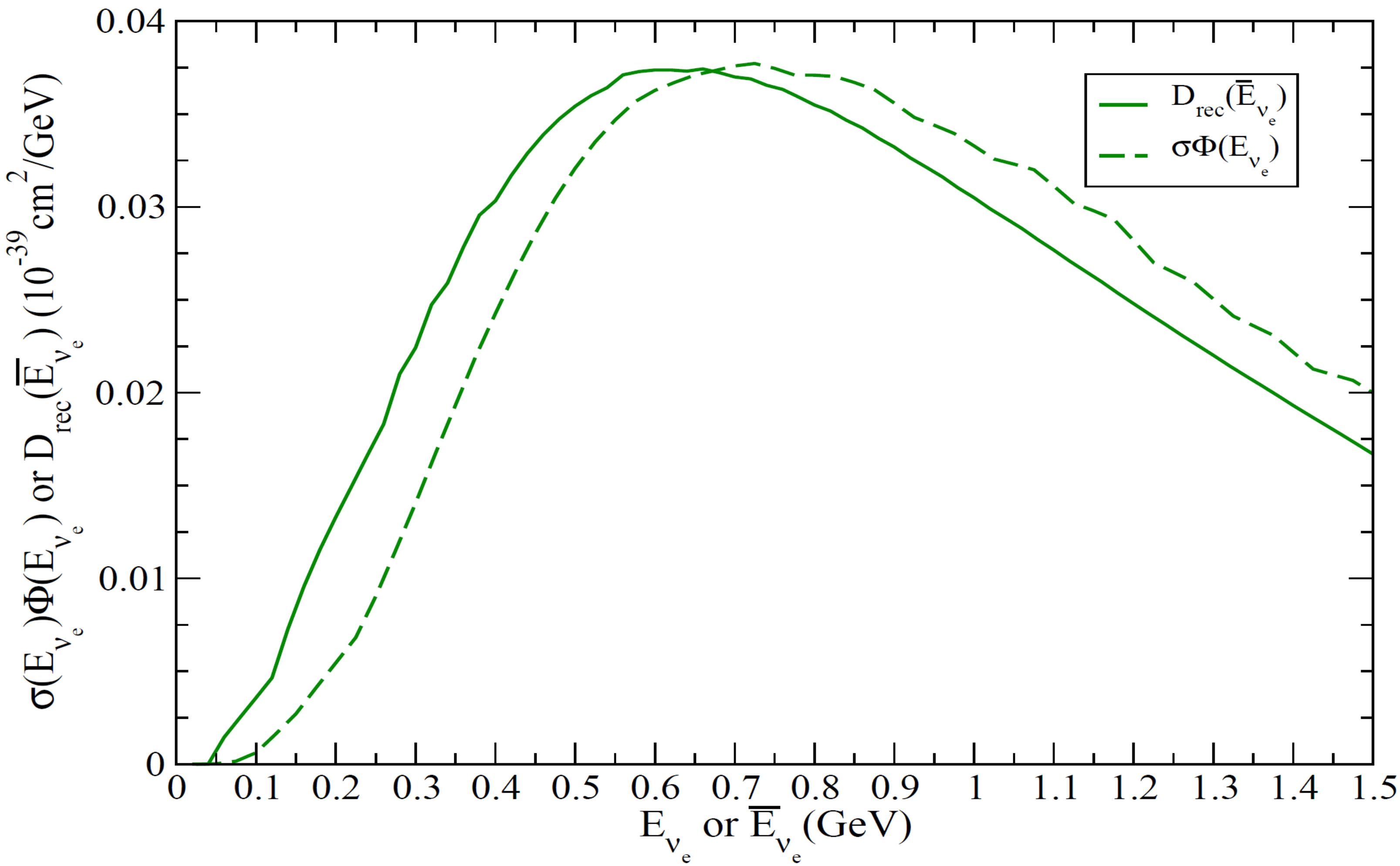


O. Lalakulich, U. Mosel, K. Gallmeister, PRC 86 054606 (2012)



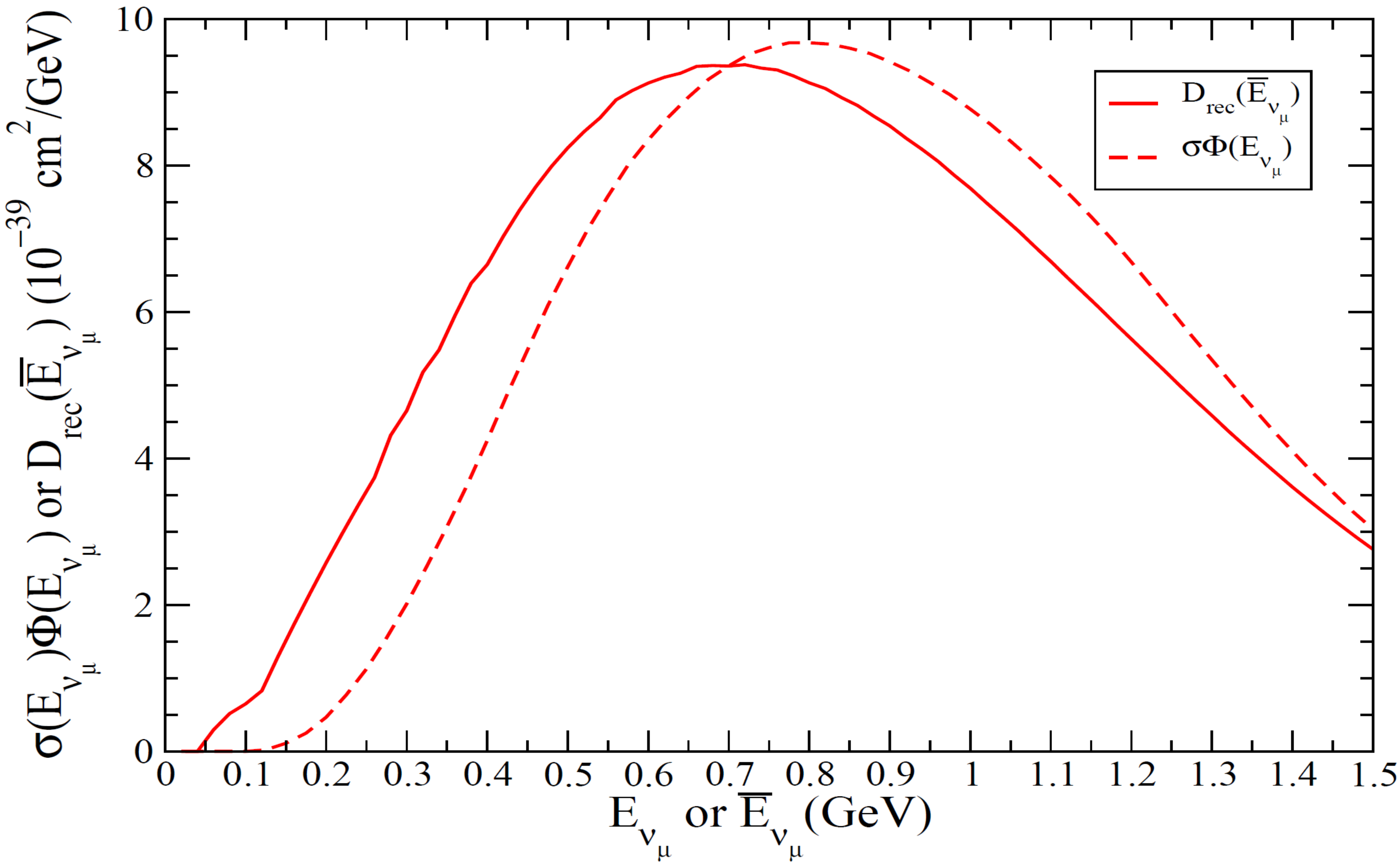


MiniBooNE electron events distribution for ν_e background



The electron event background is underestimated for low reconstructed neutrino energies E < 0.6 GeV and overestimated for larger ones

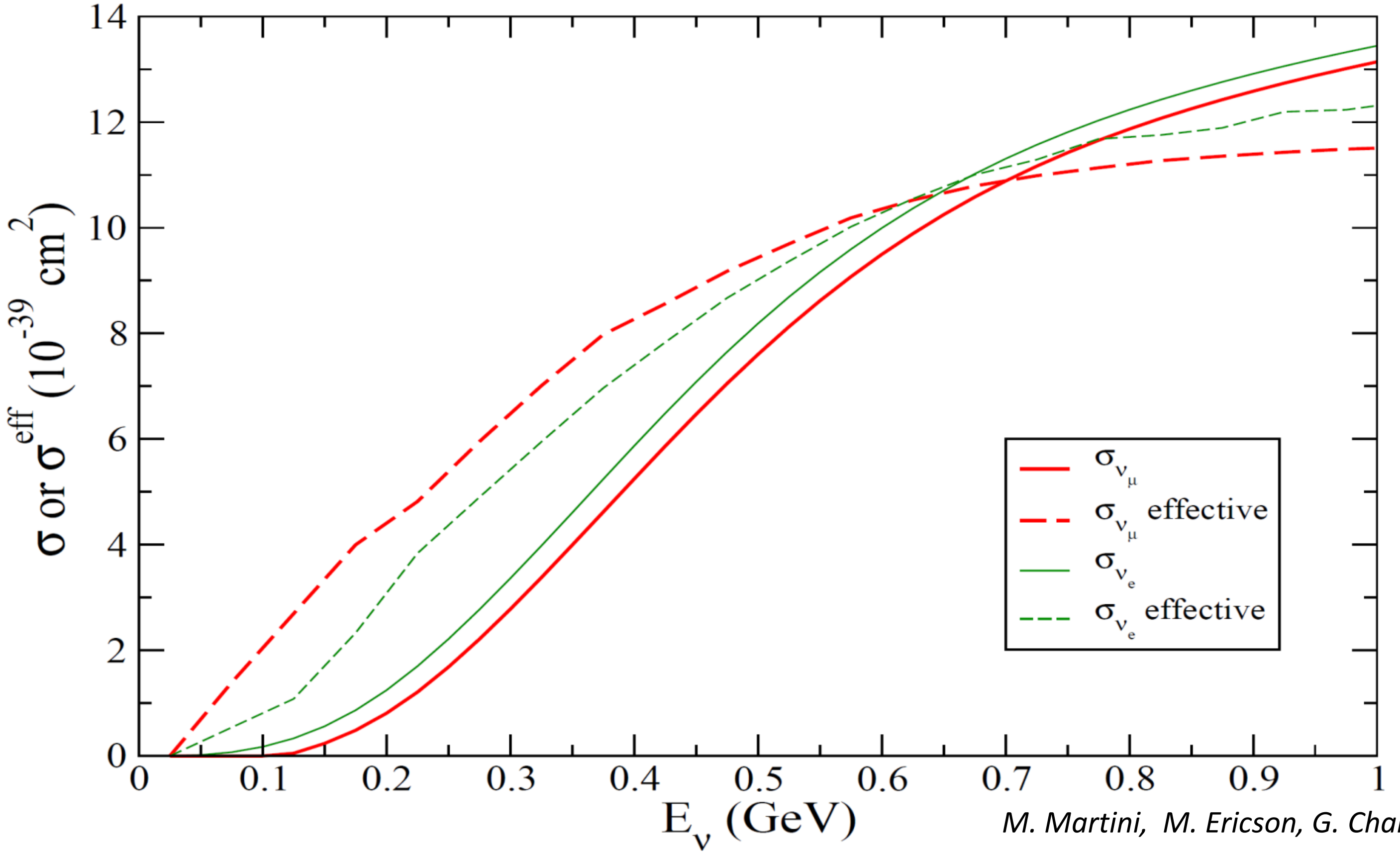
MiniBooNE muon events distribution



Real and effective cross sections for ν_μ and ν_e

Let's define the effective cross section through $D_{\text{rec}}(\bar{E}_\nu) = \sigma_\nu^{\text{eff}}(\bar{E}_\nu)\Phi(\bar{E}_\nu)$

Let's then ignore the difference between the true and reconstructed neutrino energies



M. Martini, M. Ericson, G. Chanfray, PRD 87 013009 (2013)

The effective cross section is not universal but
it depends on the particular beam energy distribution

(here we used ν_μ and ν_e MiniBooNE fluxes)