Inclusion of multi-nucleon effects in RPA-based calculations for ν-nucleus scattering

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In collaboration with:

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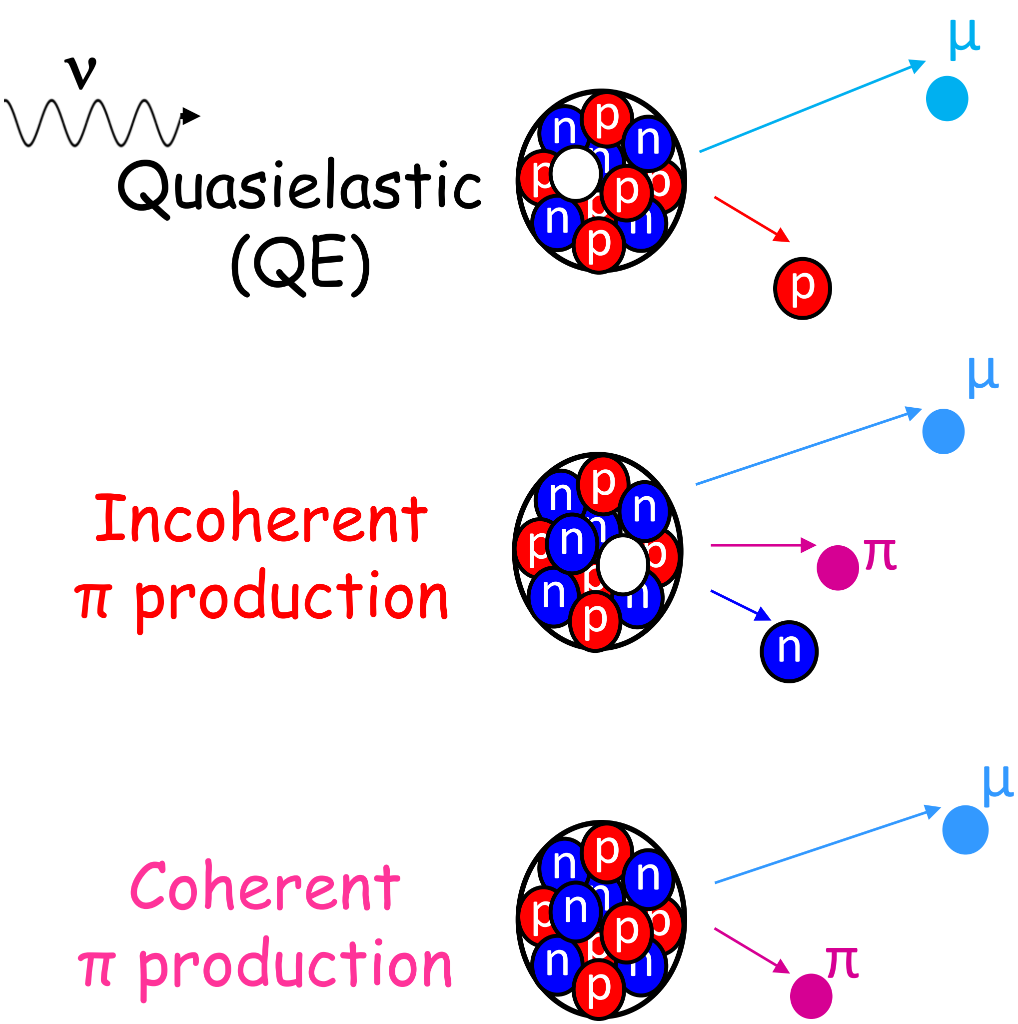
Outline

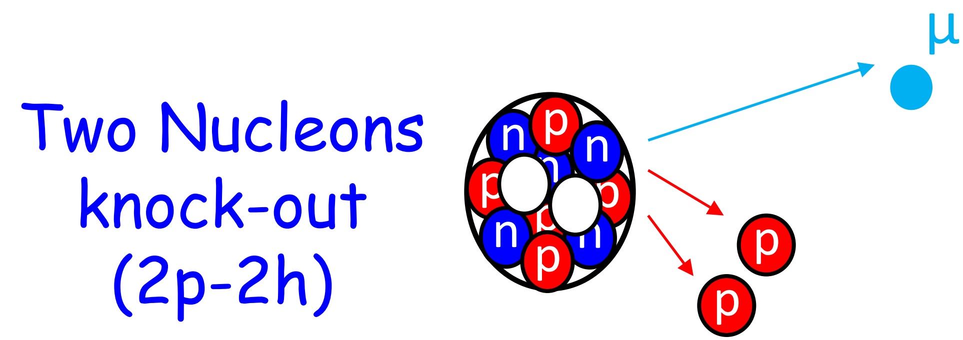
- Review of the main results obtained with our model and comparison with experimental data

- Description of our theoretical approach
  - nuclear response functions in RPA
  - np-nh excitations

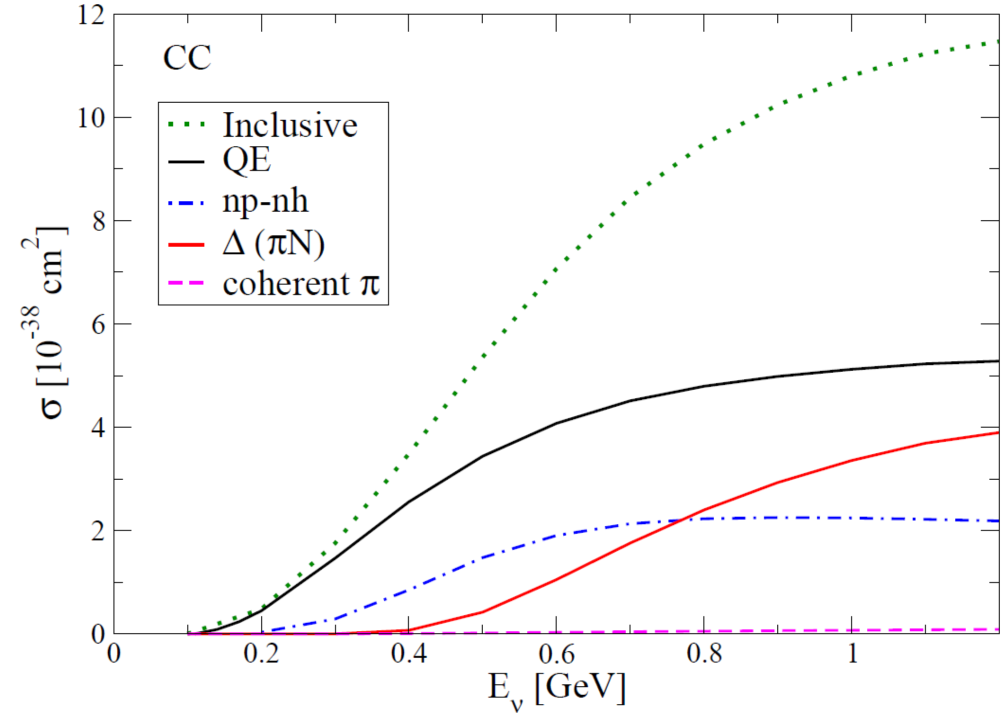
- Comparison among theoretical models

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





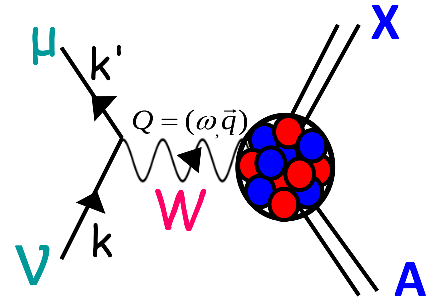
M. Martini, M. Ericson, G. Chanfray, J. Marteau, PRC 80 065501 (2009)



Unified description of all these channels in our approach

Neutrino-nucleus cross section

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



$$d\sigma \propto L_{\mu\nu} W^{\mu\nu}$$

$$L_{\mu\nu} = k_\mu k'_\nu + k'_\mu k_\nu - g_{\mu\nu} k\cdot k' \pm i\varepsilon_{\mu\nu\kappa\lambda} k^\kappa k'^\lambda$$

Leptonic tensor

$$W^{\mu\nu} = \sum_f \langle\Psi_f|J^\mu(Q)|\Psi_i\rangle^* \langle\Psi_f|J^\nu(Q)|\Psi_i\rangle \delta(E_i+\omega-E_f)$$

Hadronic tensor

The cross section in terms of the response functions R(q,ω):

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

Nuclear response functions R(q,ω):

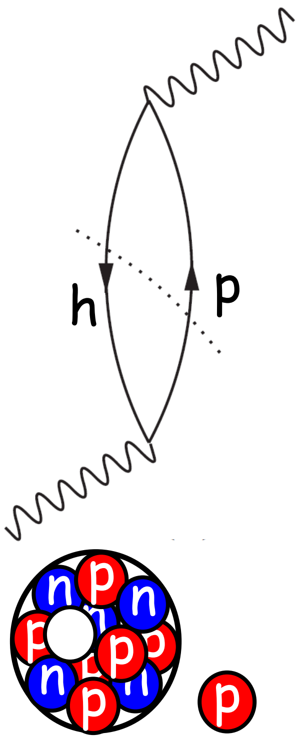
$$R_\alpha^{PP'} = \sum_n \langle n|\sum_{j=1}^{A} O_\alpha^P(j) e^{i\boldsymbol{q}\cdot\boldsymbol{x}_j}|0\rangle \langle n|\sum_{k=1}^{A} O_\alpha^{P'}(k) e^{i\boldsymbol{q}\cdot\boldsymbol{x}_k}|0\rangle^* \delta(\omega - E_n + E_0)$$

Isovector R_τ	Isospin Spin-Longitudinal $R_{\sigma\tau(L)}$	Isospin Spin-Transverse $R_{\sigma\tau(T)}$
$O_\alpha^N(j) = \tau_j^\pm$	$(\boldsymbol{\sigma}_j\cdot\hat{q})\,\tau_j^\pm$	$(\boldsymbol{\sigma}_j\times\hat{q})^i\,\tau_j^\pm$

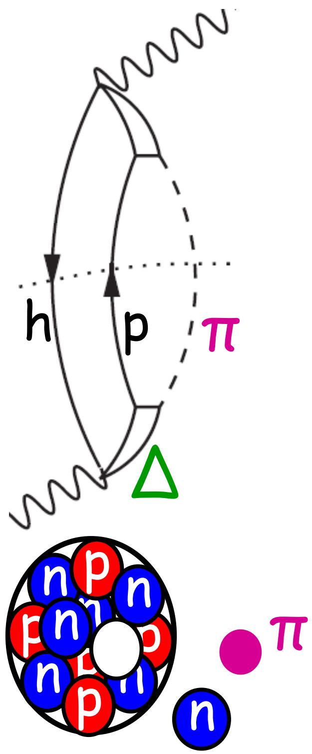
Nuclear Response Functions

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

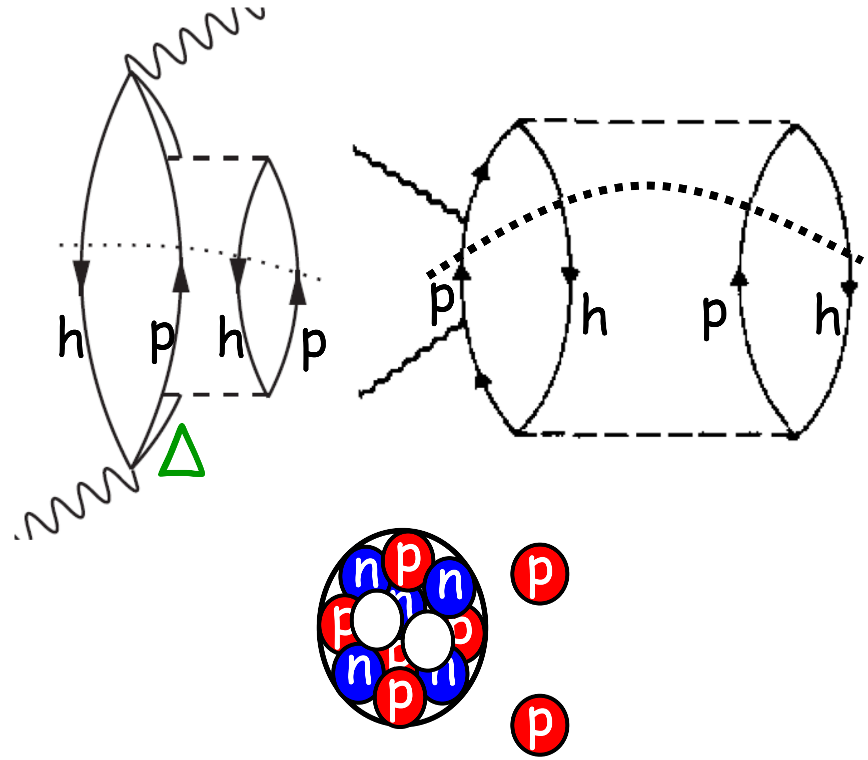
1p-1h
QE



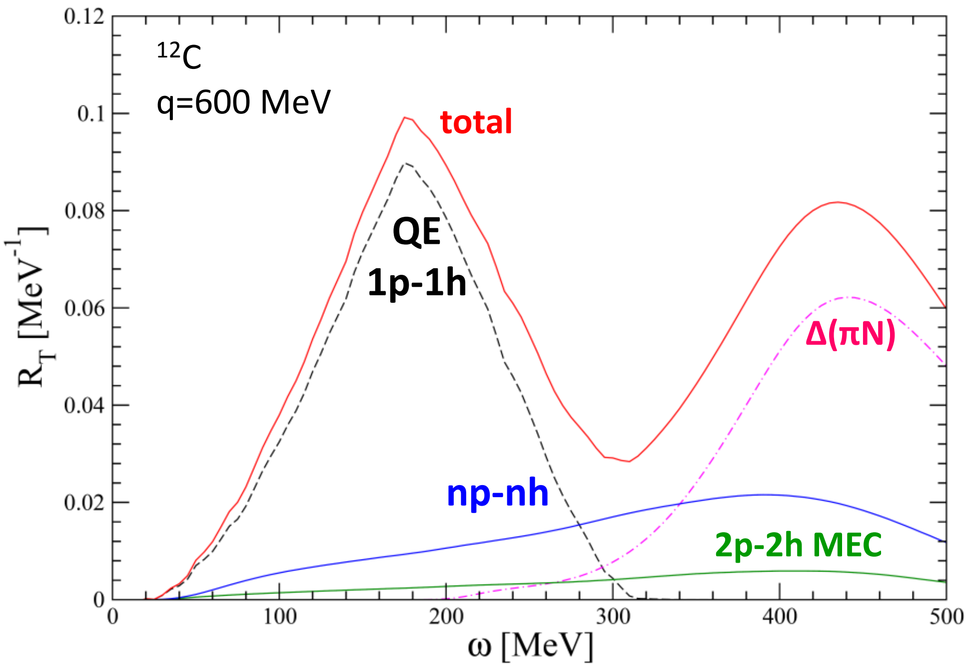
1p-1h
1π production



2p-2h:
two examples



An example of nuclear response: Isospin Spin Transverse $R_{\sigma\tau(T)}$



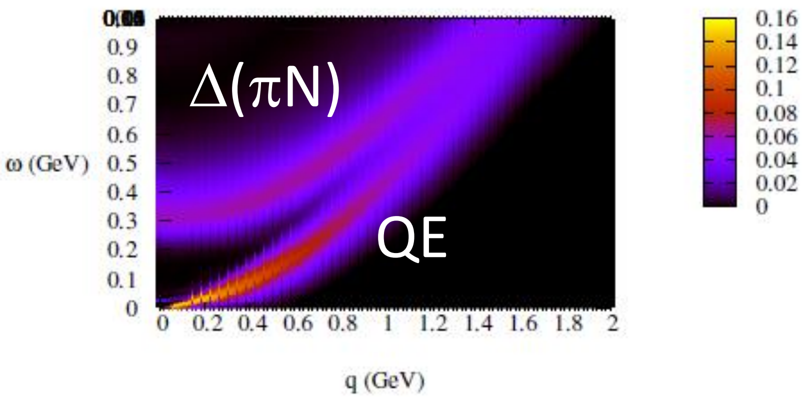
QE peak:

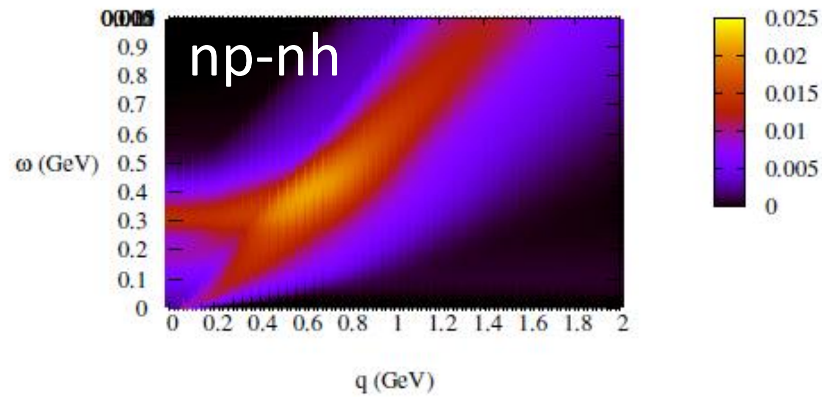
$$\omega = \sqrt{\mathbf{q}^2 + M_N^2} - M_N = \frac{Q^2}{2M_N} = \frac{\mathbf{q}^2 - \omega^2}{2M_N}$$

Δ peak:

$$\omega = \sqrt{\mathbf{q}^2 + M_\Delta^2} - M_N = \frac{Q^2}{2M_N} + \frac{M_\Delta^2 - M_N^2}{2M_N}$$

np-nh excitations fill the DIP region



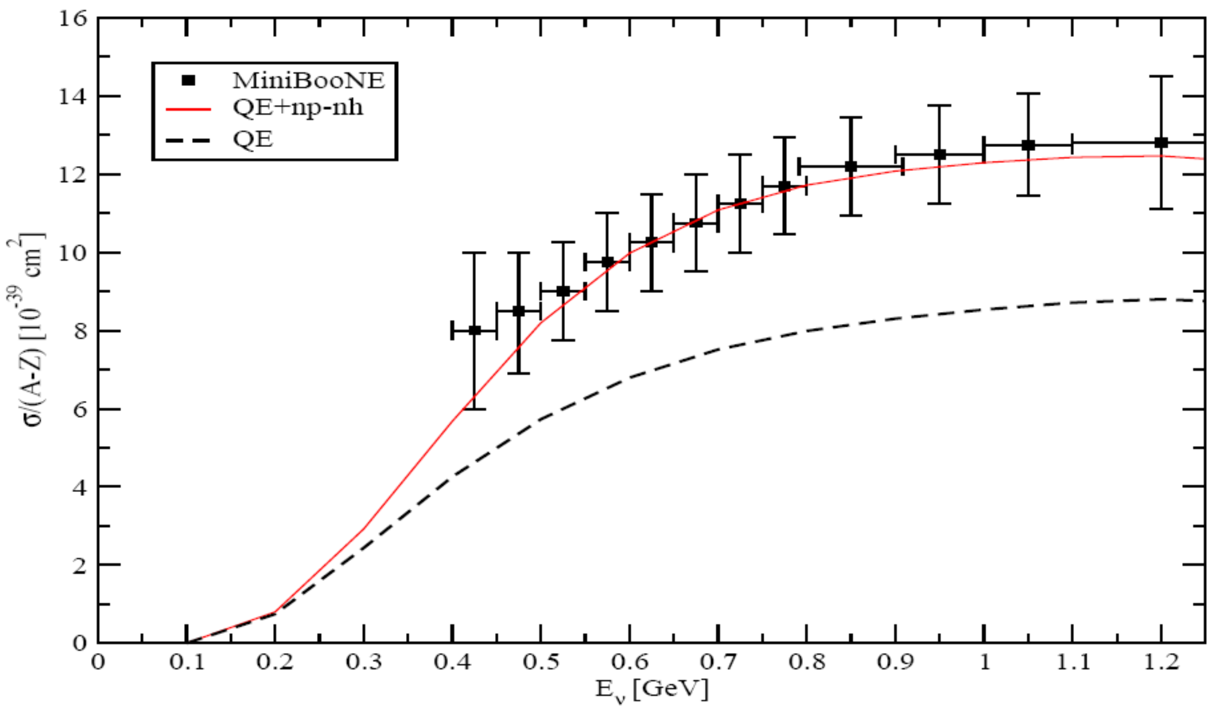


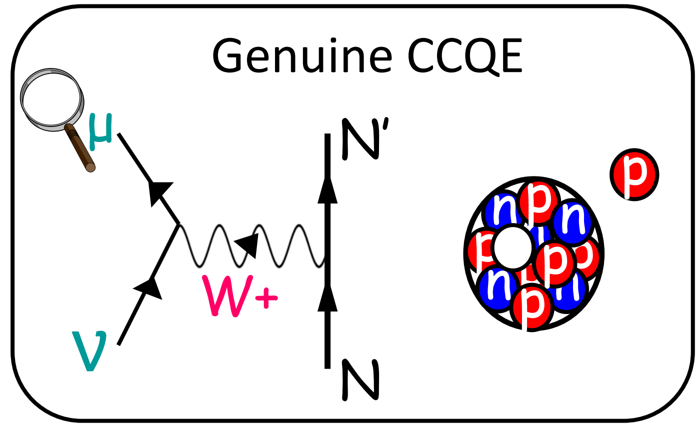
np-nh enlarges the region of response to the whole (ω,q) plane

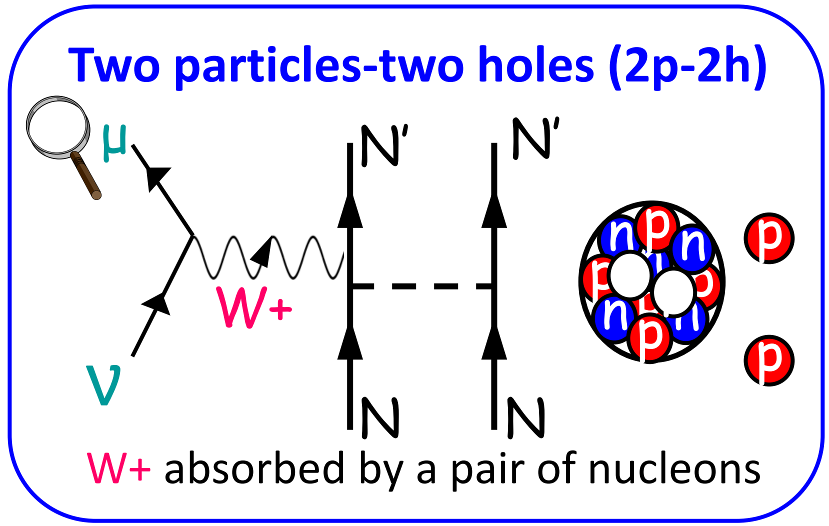
Rapid Review of our results related to np-nh excitations

First explanation of the MiniBooNE CCQE-like cross section measurement

Inclusion of the multinucleon emission channel
(np-nh=2p-2h+3p-3h)







CCQE-like = Genuine CCQE + np-nh

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

Agreement with MiniBooNE without increasing M_A

Neutrino *vs* Antineutrino interactions

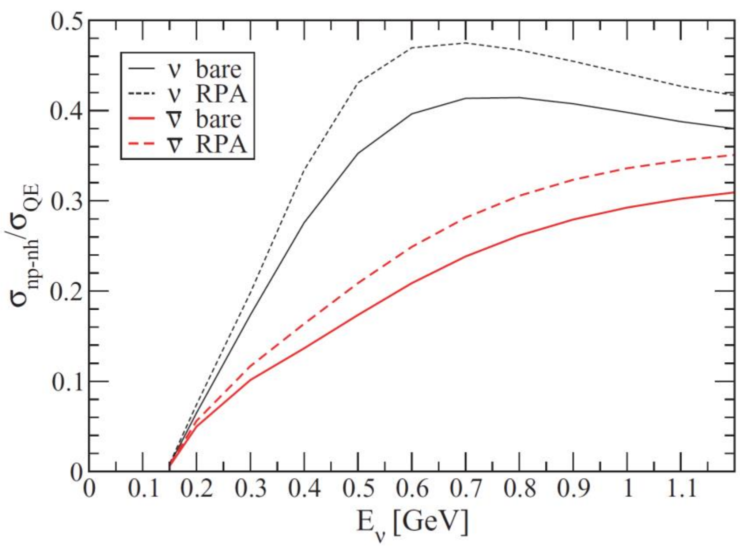
$$\frac{\partial^2\sigma}{\partial\Omega\,\partial\epsilon'} = \frac{G_F^2\,\cos^2\theta_c}{2\,\pi^2} k'\epsilon'\,\cos^2\frac{\theta}{2}\left[\frac{(q^2-\omega^2)^2}{q^4}G_E^2\,R_\tau + \frac{\omega^2}{q^2}G_A^2\,R_{\sigma\tau(L)} + \right.$$
$$\left. + \; 2\left(\tan^2\frac{\theta}{2} + \frac{q^2-\omega^2}{2q^2}\right)\left(G_M^2\frac{\omega^2}{q^2}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

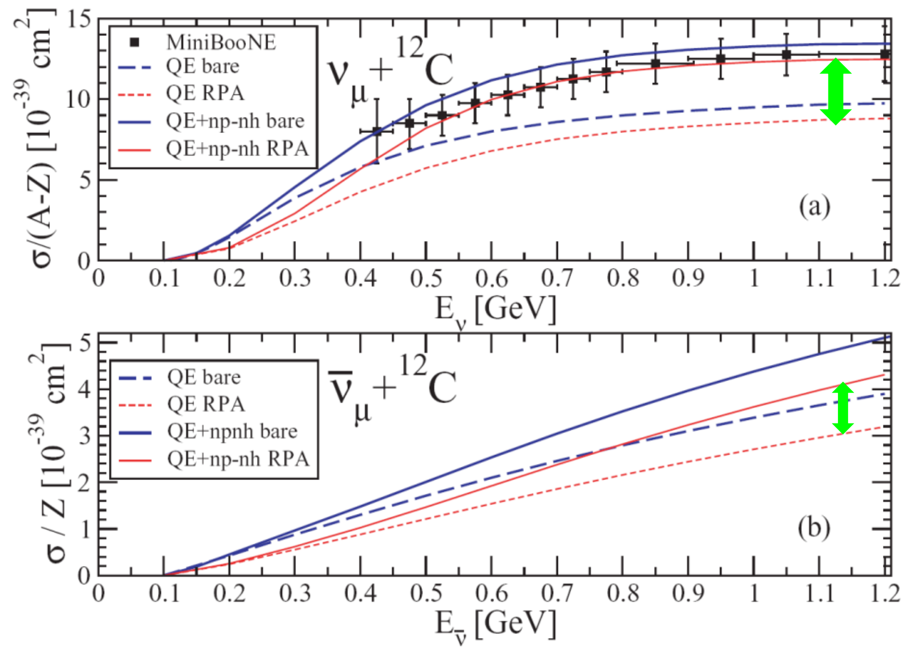
Vector-Axial interference

The ν and anti ν interactions differ by the sign of the V-A interference term

→the relative weight of the different nuclear responses is different for neutrinos and antineutrinos

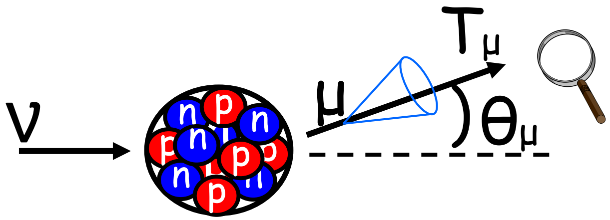
→the relative role of np-nh contributions is different for neutrinos and antineutrinos



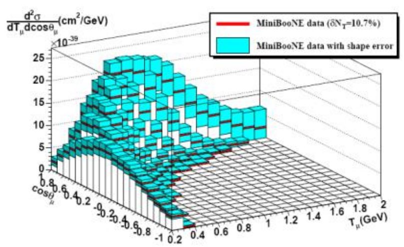


M. Martini, M. Ericson, G. Chanfray, J. Marteau, Phys. Rev. C 81 045502 (2010)

MiniBooNE CCQE-like flux-integrated double differential cross section

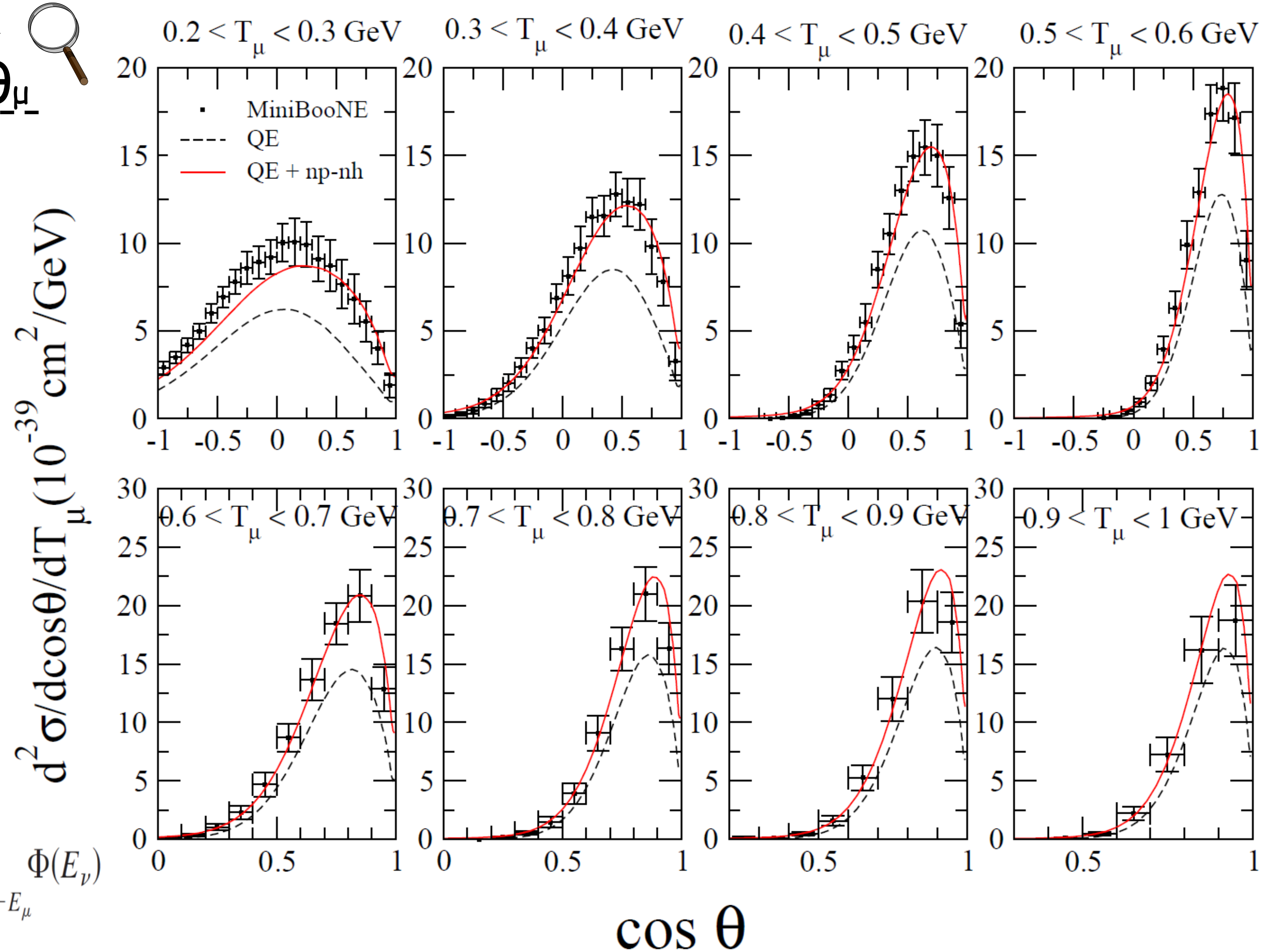


ν



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

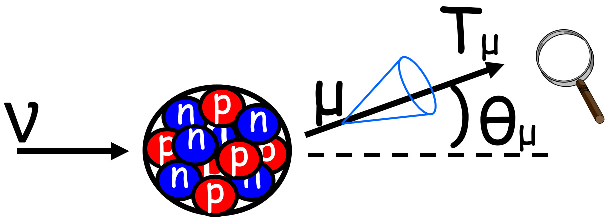
$$\frac{d^2\sigma}{dE_\mu d\cos\theta} = \int dE_\nu \left[\frac{d^2\sigma}{d\omega d\cos\theta}\right]_{\omega=E_\nu-E_\mu} \Phi(E_\nu)$$



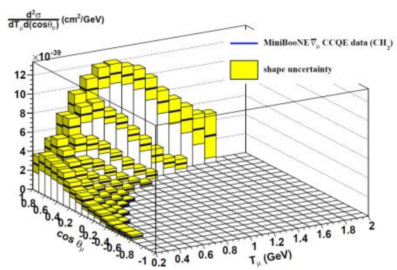
Agreement with MiniBooNE without increasing M_A once np-nh is included

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

MiniBooNE CCQE-like flux-integrated double differential cross section

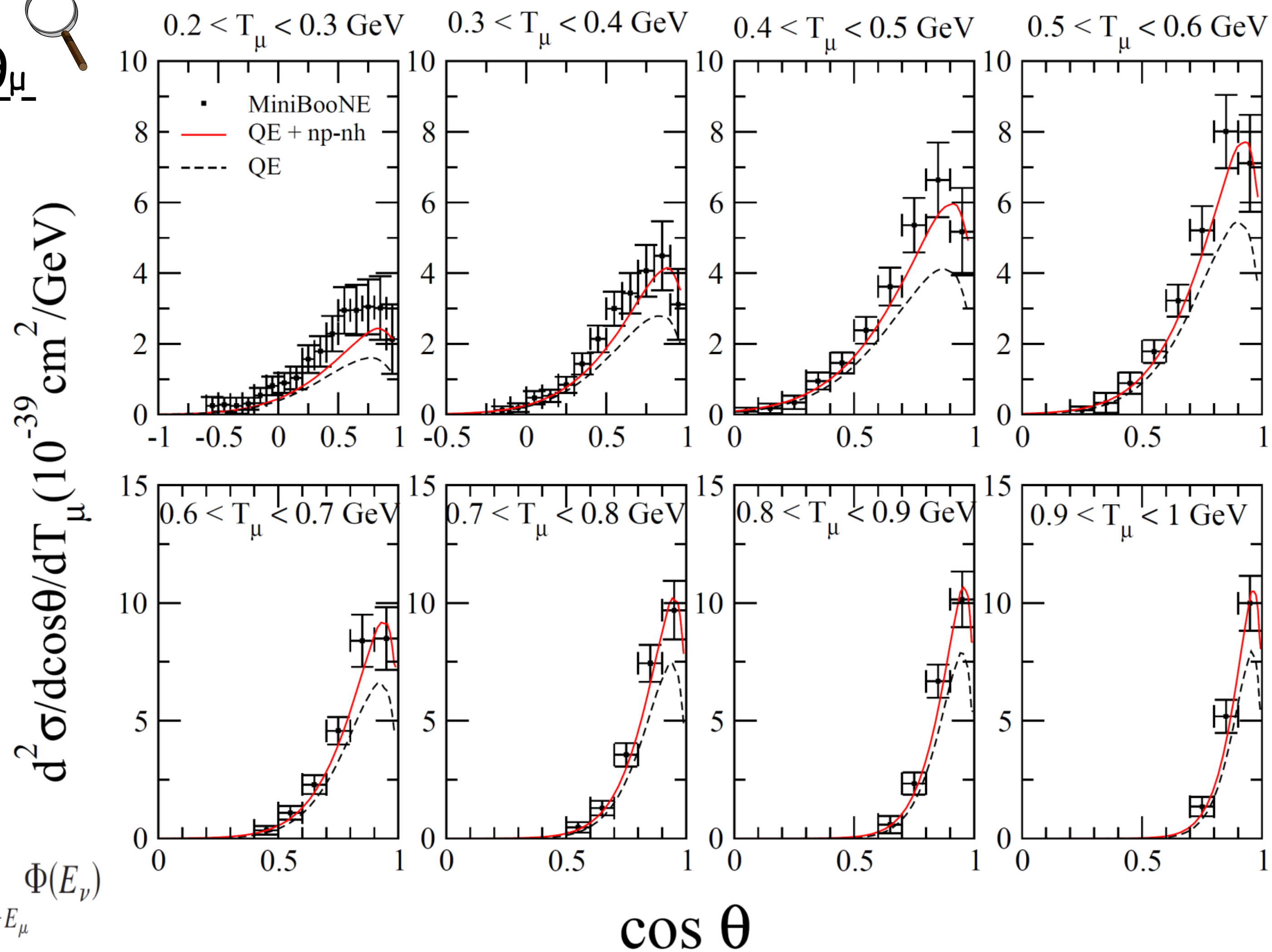


$\bar{\nu}$



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

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

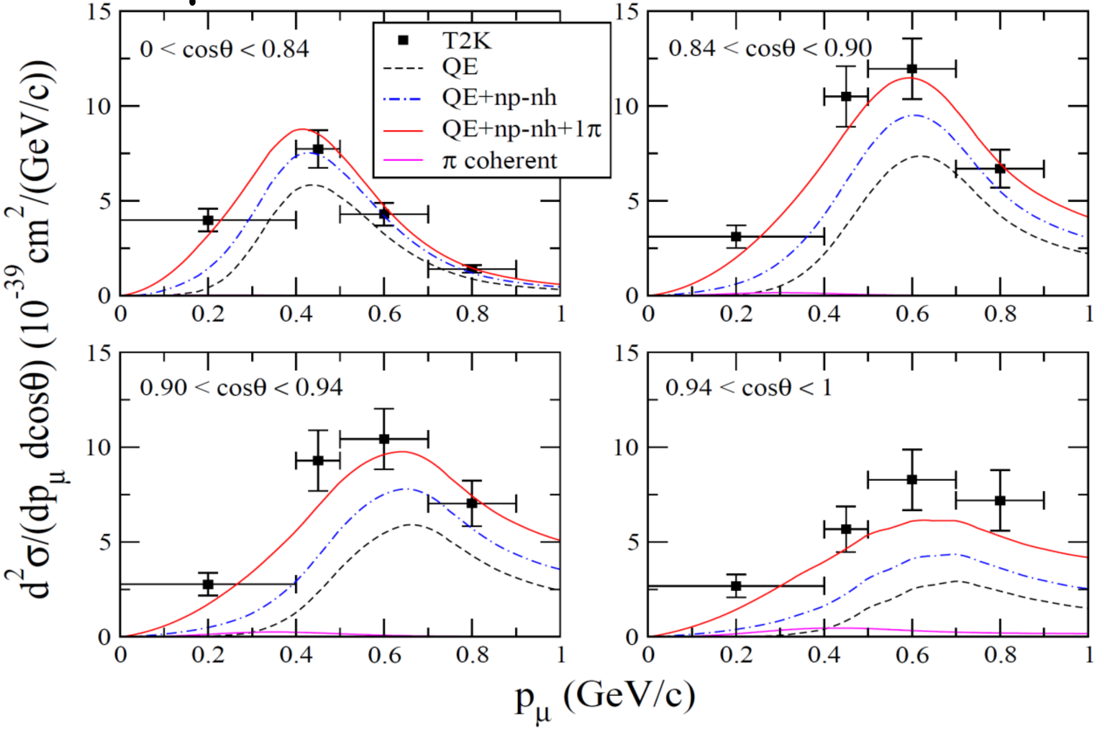


Agreement with MiniBooNE without increasing M_A once np-nh is included

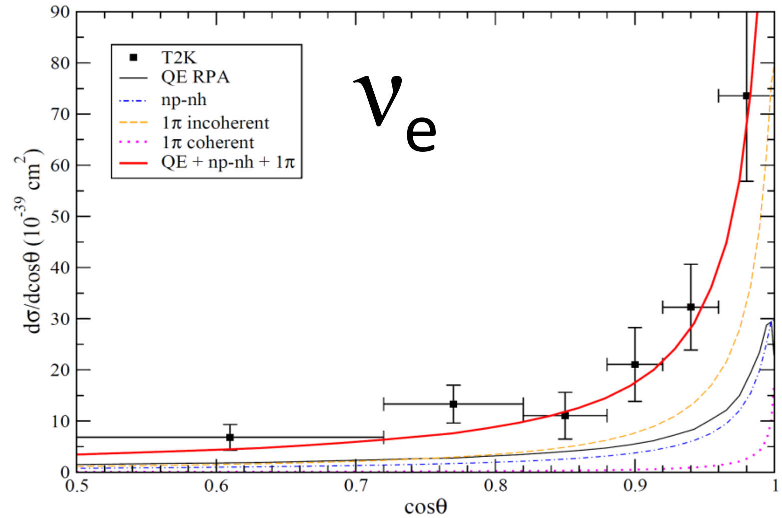
Martini, Ericson, Phys. Rev. C 87 065501 (2013)

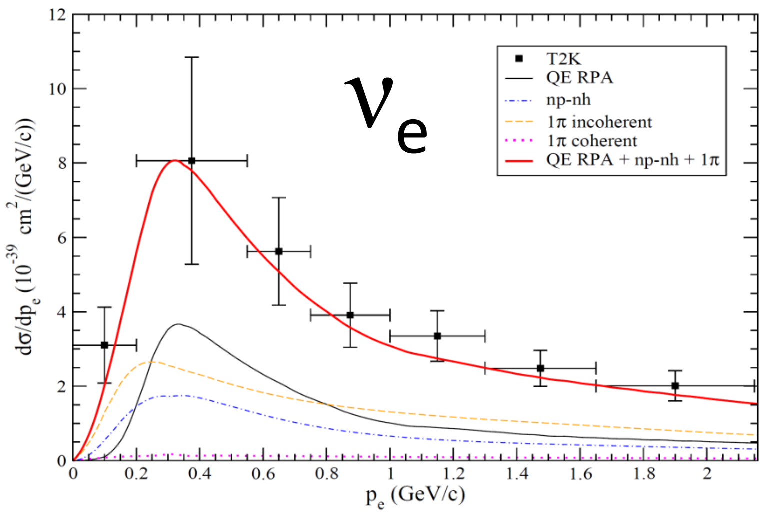
T2K flux-integrated inclusive differential cross sections on carbon

ν_μ *M. Martini, M. Ericson Phys. Rev. C 90 025501 (2014)*



Martini et al., arXiv: 1602.00230 (2016)

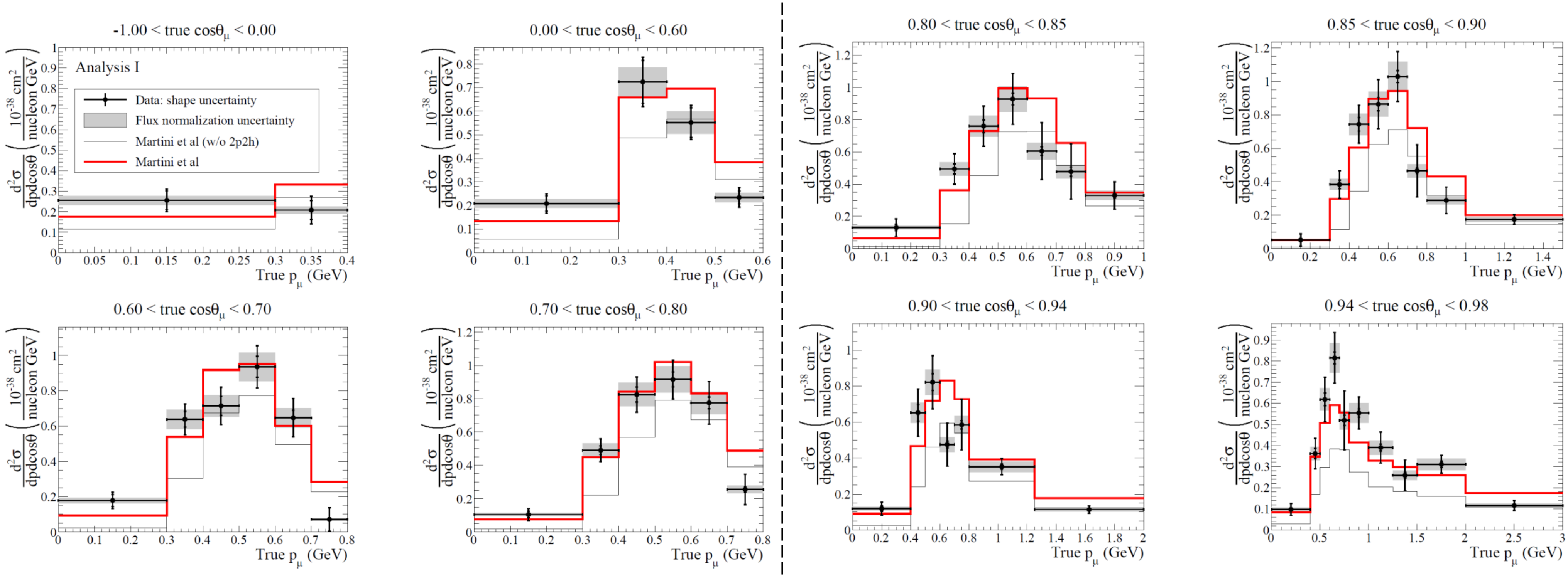




Necessity of the multinucleon emission channel
in experiments with other neutrino fluxes with respect to the ones of MiniBooNE.

ν_μ T2K flux-integrated **CC0π** measurement *vs* our RPA approach **without (grey line)** and **with (red line) np-nh**

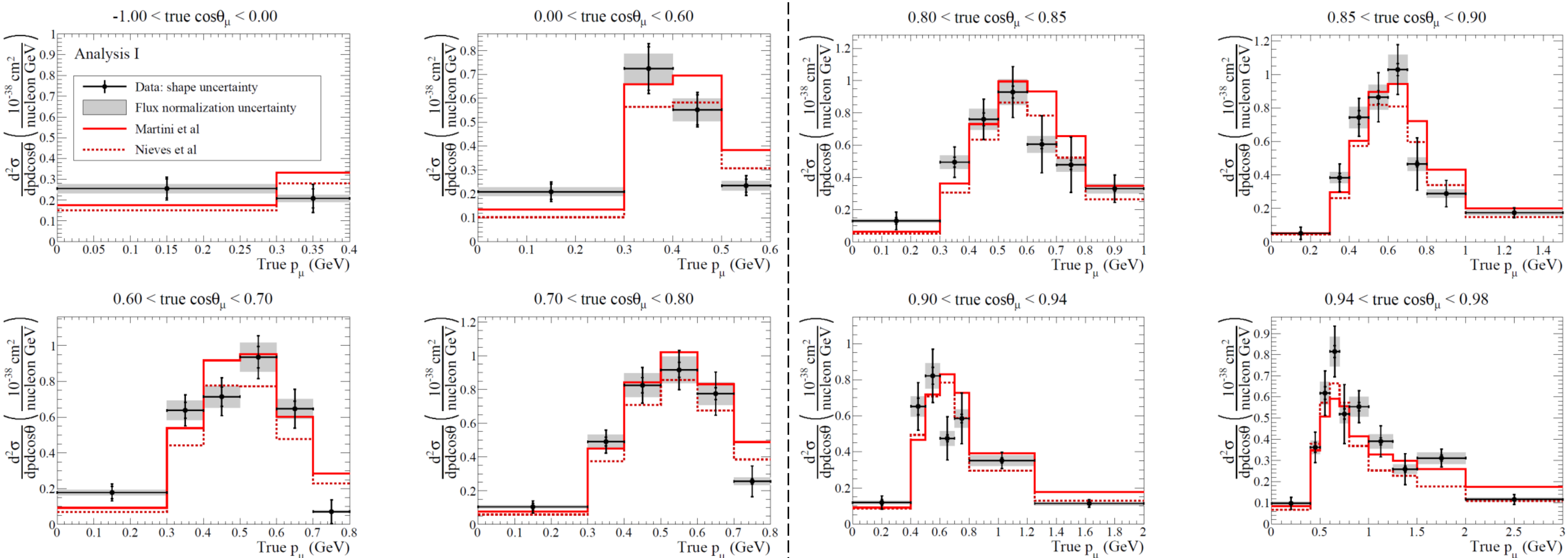
T2K collaboration: Abe et al. arXiv: 1602.03652 (PRD 2016)



Better agreement including np-nh

ν_μ T2K flux-integrated **CC0π** measurement *vs* **CCQE+np-nh** calculations

T2K collaboration: Abe et al. 1602.03652 (PRD 2016)



Martini et al.

Nieves et al.

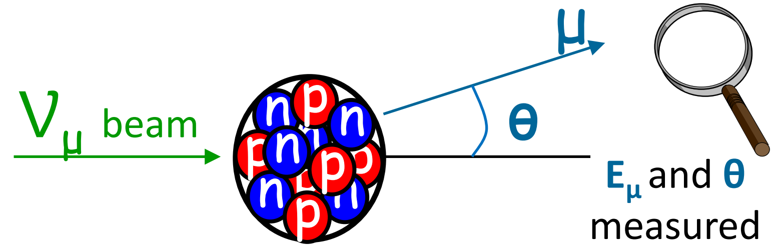
The two theoretical models are compatible with data

Neutrino energy reconstruction and neutrino oscillations

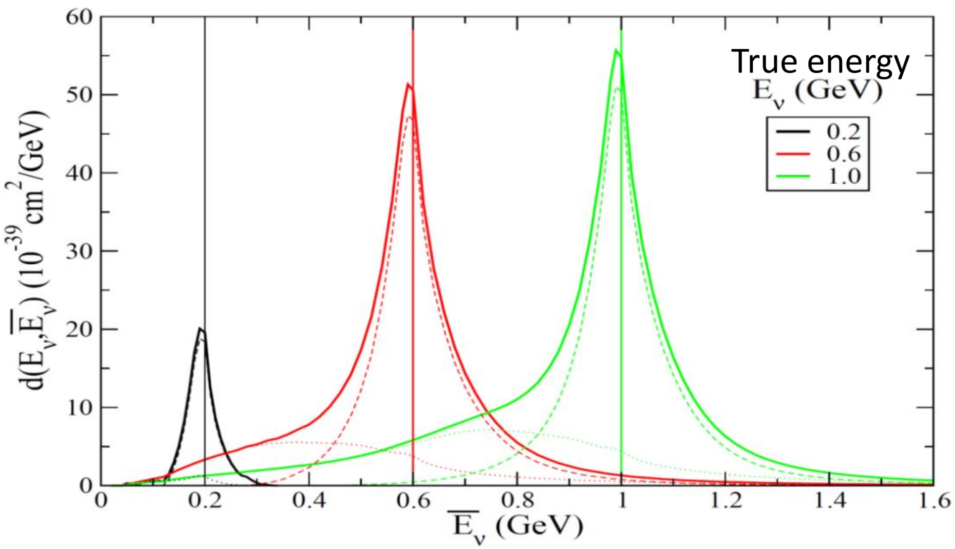
Reconstructed ν energy
(via two-body kinematics)

$\nu_\mu\, n \to \mu^- p$

$$\overline{E_\nu} = \frac{E_\mu - m_\mu^2/(2M)}{1 - (E_\mu - P_\mu \cos\theta)/M}$$

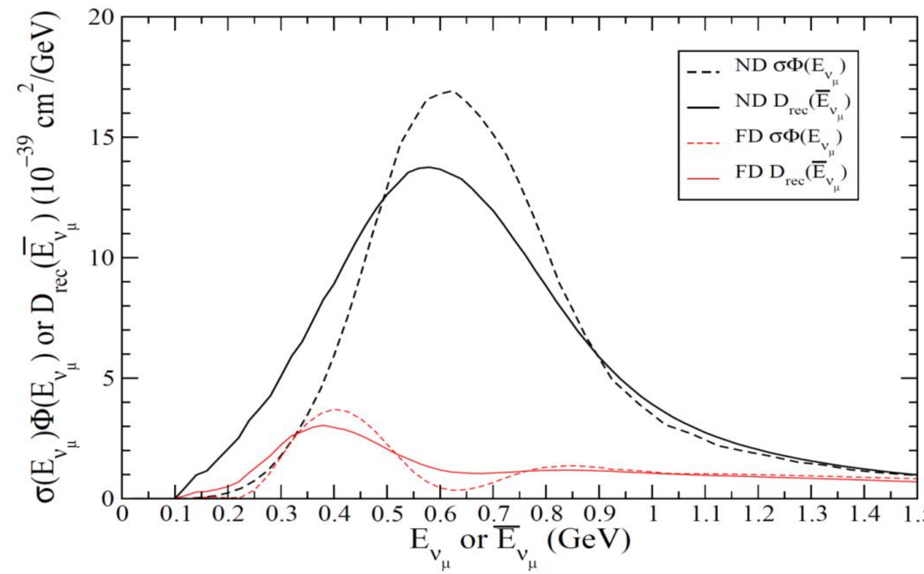


ν energy distribution



- Distributions not symmetrical around Ev
- Crucial role of np-nh: low energy tail

νμ disappearance T2K



- Low energy enhancement
- Far Detector: middle hole largely filled

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

Neutrino energy reconstruction and neutrino oscillation analysis are affected by np-nh

Recent quantitative analysis on the role of np-nh in the $\nu_\mu \to \nu_e$ MiniBooNE low-energy anomaly

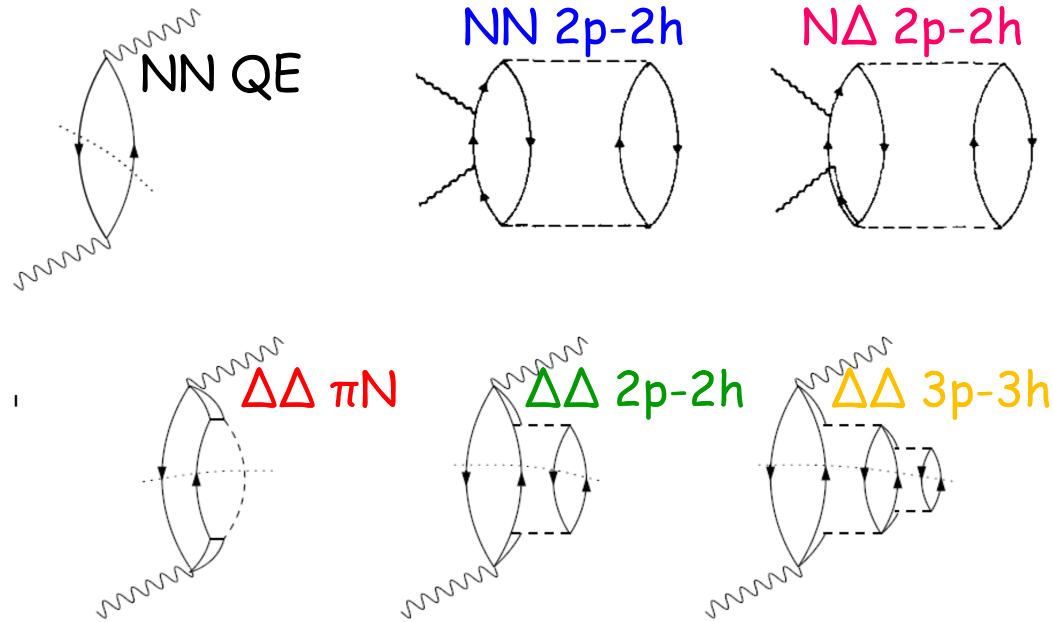
M. Ericson, M. V. Garzelli, C. Giunti, M. Martini, arXiv: 1602.01390 (PRD 2016)

Our theoretical model

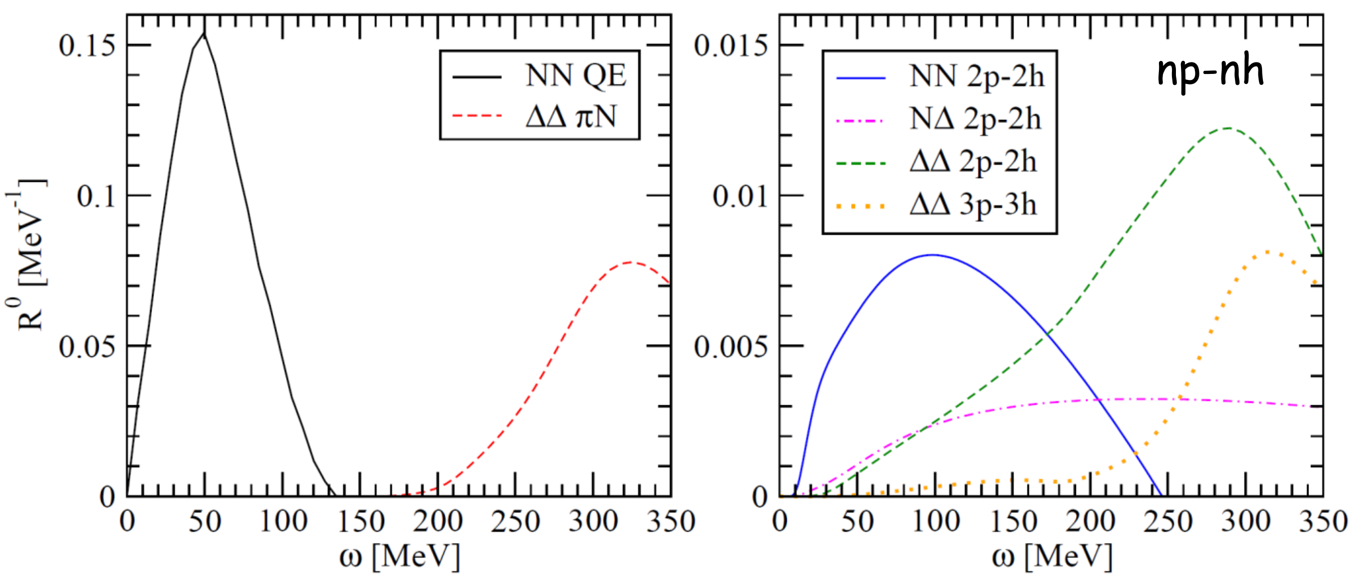
Bare nuclear responses

Several partial components
(final state channels)

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

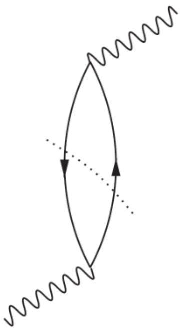


q=300 MeV/c



Bare polarization propagators

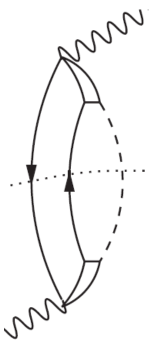
Quasielastic



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

Nucleon-hole

Pion production



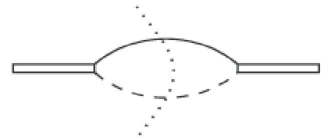
$$\Pi_{\Delta-h}(q) = \frac{32\tilde{M}_\Delta}{9}\int \frac{d^3k}{(2\pi)^3}\theta(k_F-k)\left[\frac{1}{s-\tilde{M}_\Delta^2+i\tilde{M}_\Delta\widetilde{\Gamma}_\Delta} - \frac{1}{u-\tilde{M}_\Delta^2}\right]$$

Delta-hole

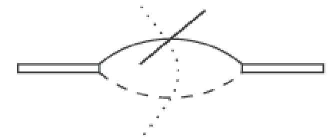
Delta in the medium

Mass

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



$\Delta \to \pi$ N

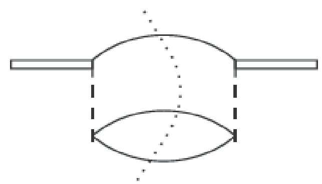


Pauli correction (F_P)

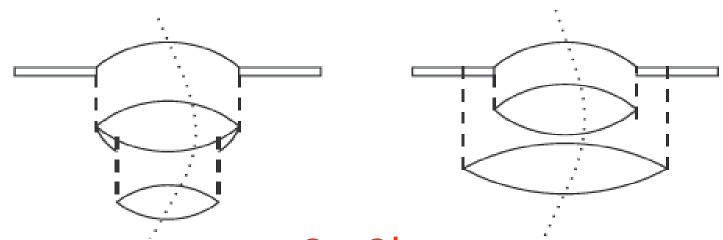
Pion distortion (C_Q)

Width

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



2p-2h



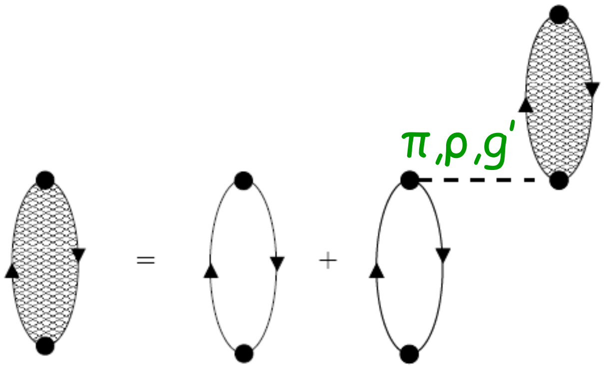
3p-3h

Self energy

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

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

Switching on the interaction: random phase approximation (RPA)



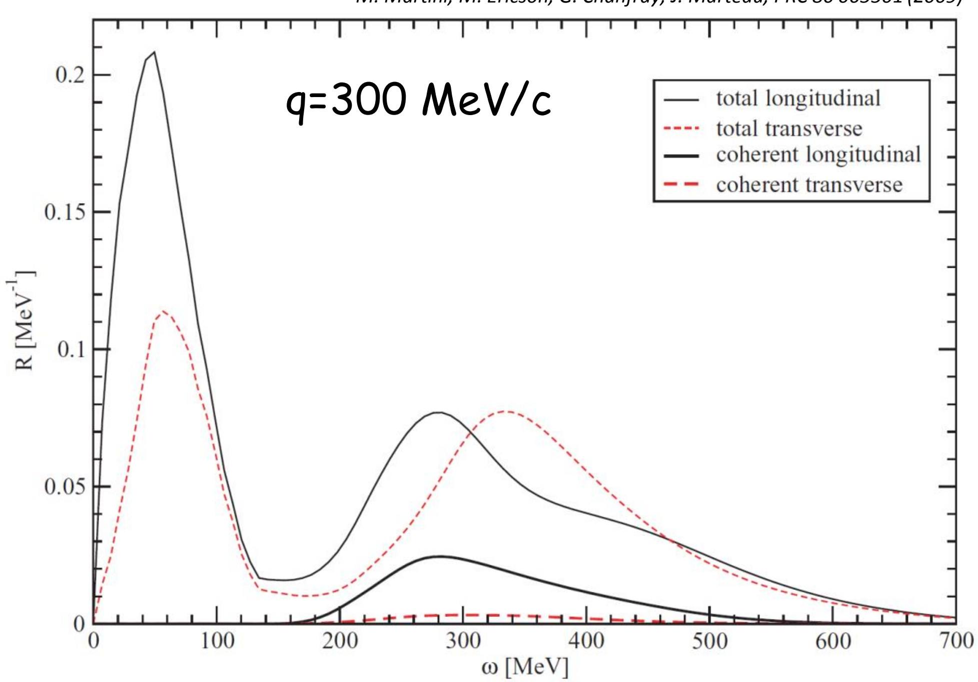
RPA

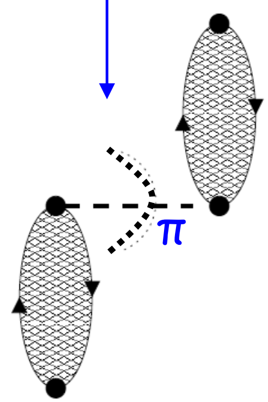
- External force acting on one nucleon is transmitted to the neighbors via the interaction
- The nuclear response becomes collective
- Long-range nucleon-nucleon correlations are included in RPA

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

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

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





coherent π production

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

exclusive channels:

QE, 2p-2h, Δ→πN …

Neutrino scattering - Effects of the RPA in the genuine quasielastic channel

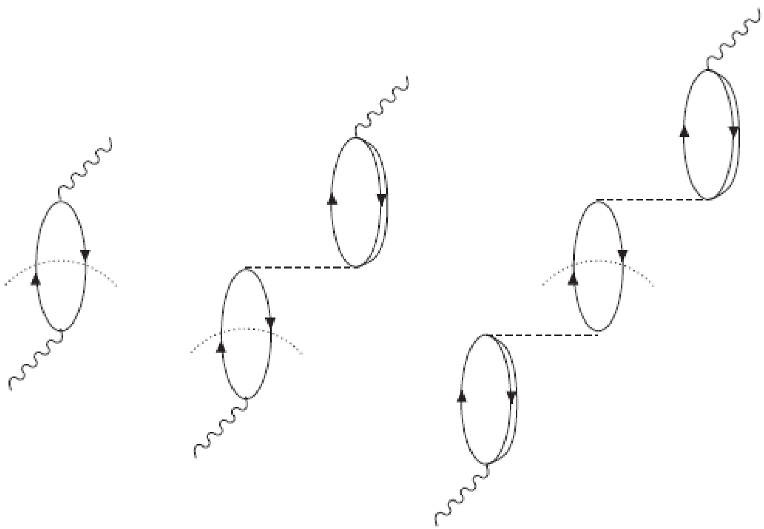
QE totally dominated by isospin spin-transverse response $R_{\sigma\tau(T)}$

RPA reduction

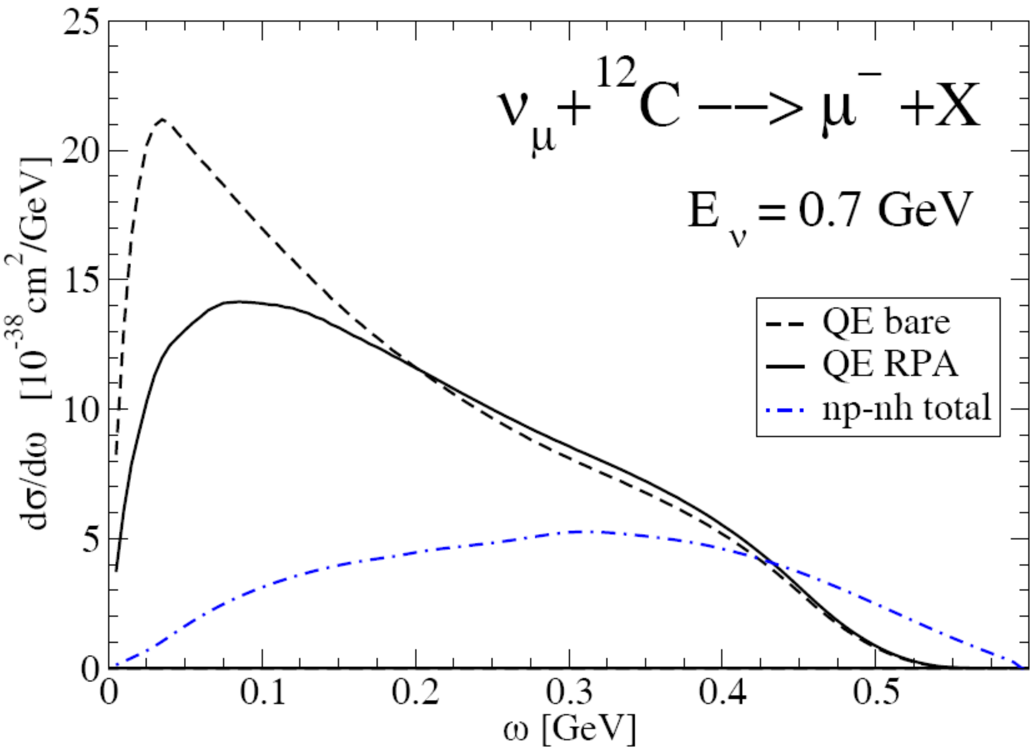
- expected from the repulsive character of p-h interaction in T channel
- mostly due to interference term $R^{N\Delta} < 0$

(Lorentz-Lorenz or Ericson-Ericson effect *[M.Ericson, T. Ericson, Ann. Phys. 36, 323 (1966)]*)

Lowest order contribution to QE:

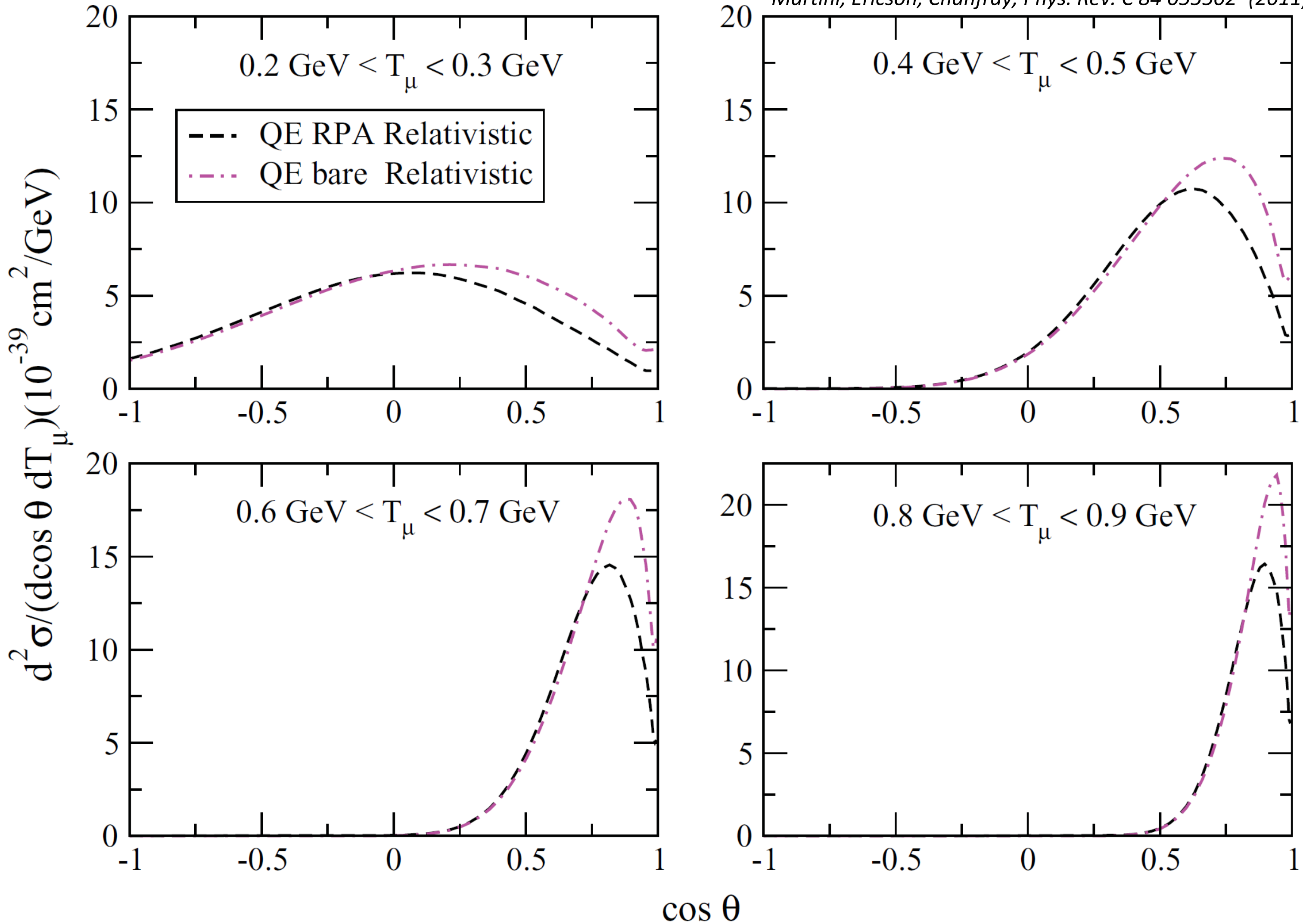


R^{NN}_{QE} $R^{N\Delta}_{QE}$ $R^{\Delta\Delta}_{QE}$



Bare *vs* RPA for MiniBooNE flux integrated $d^2\sigma$ (genuine QE)

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

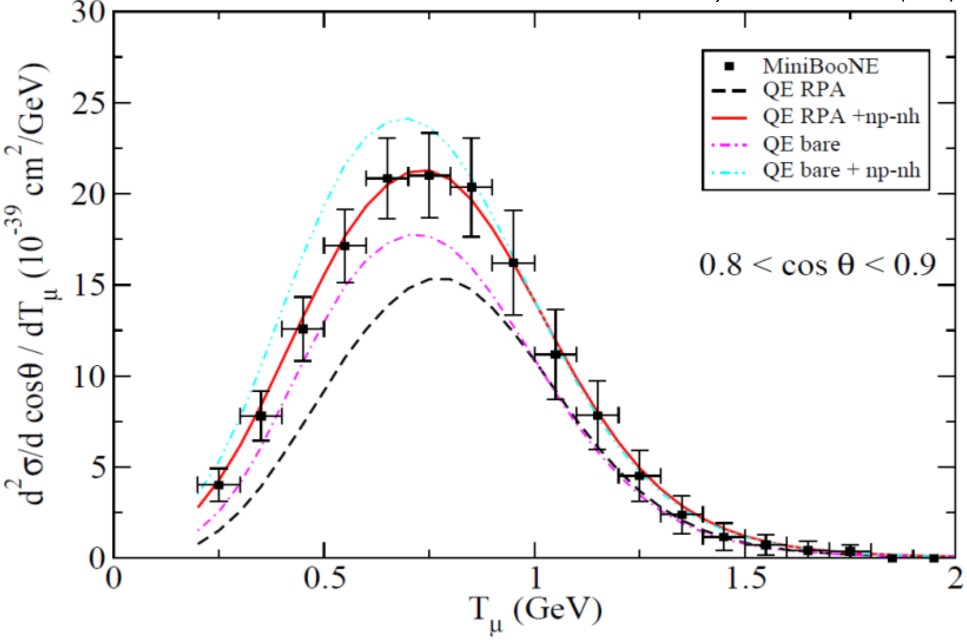


RPA produces a quenching and some shift towards larger angles

MiniBooNE flux-integrated $d^2\sigma$ CCQE-like

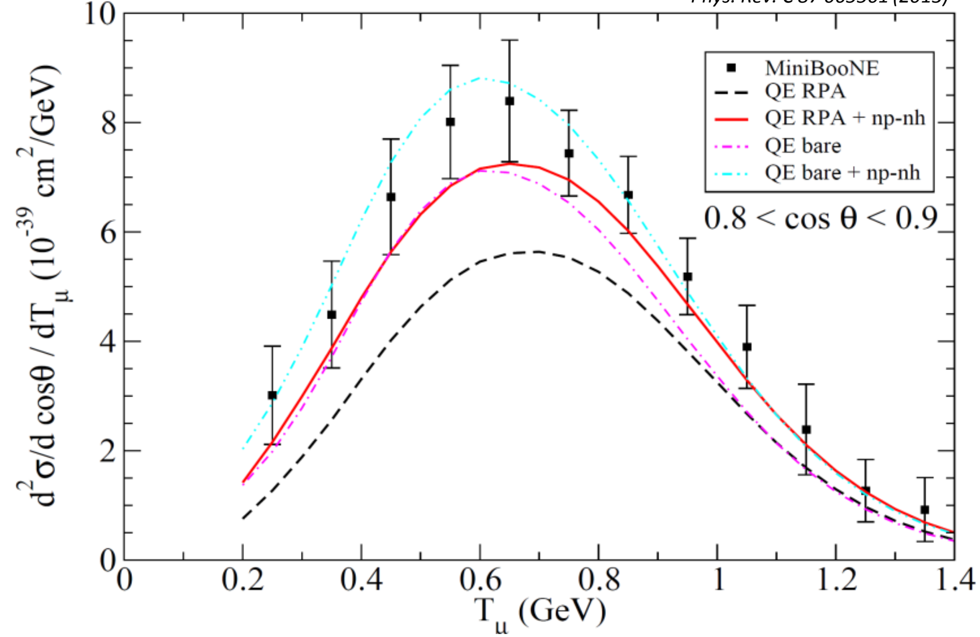
ν

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



$\bar{\nu}$

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

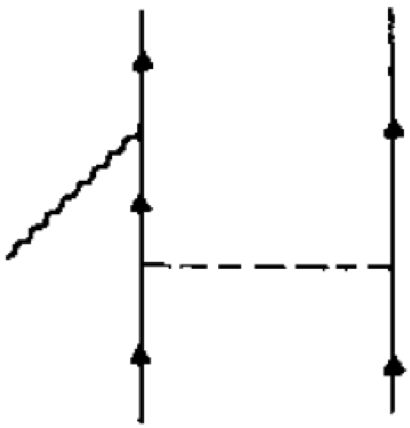


The final result is a delicate balance between
RPA quenching and **np-nh enhancement**

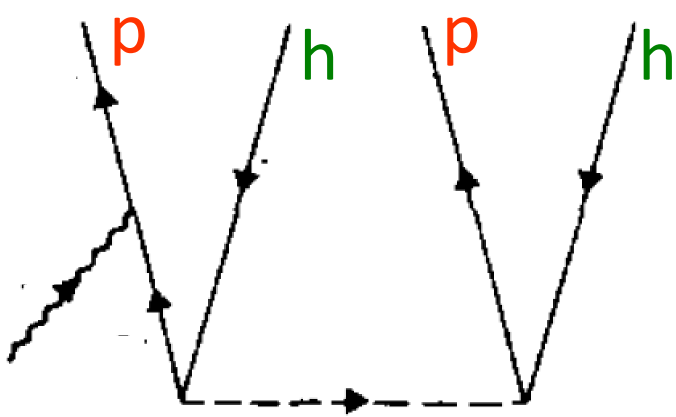
Two particle-two hole sector (2p-2h)

Three equivalent representations of the same process

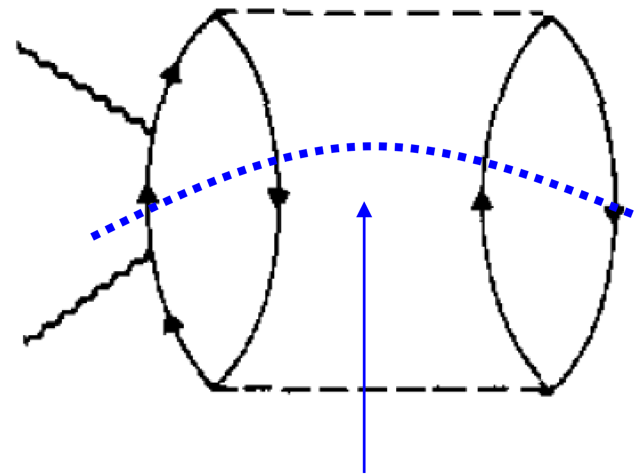
2 body current



2p-2h matrix element



2p-2h response



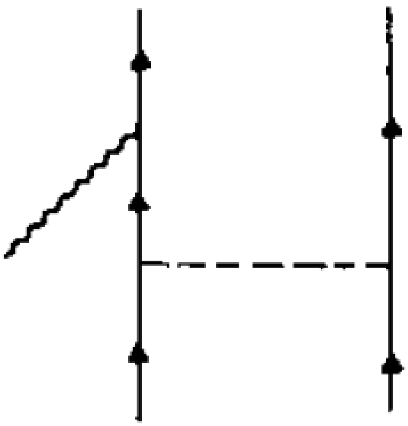
Cut
(optical theorem)

Final state: two particles-two holes

Some diagrams for 2 body currents

Nucleon-Nucleon correlations

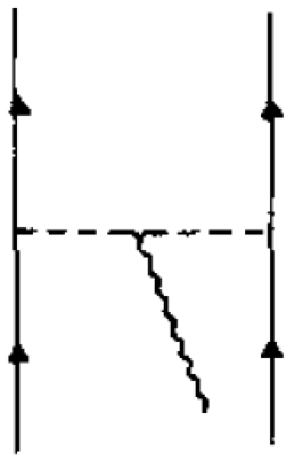
$J^{NN\text{-}corr}$



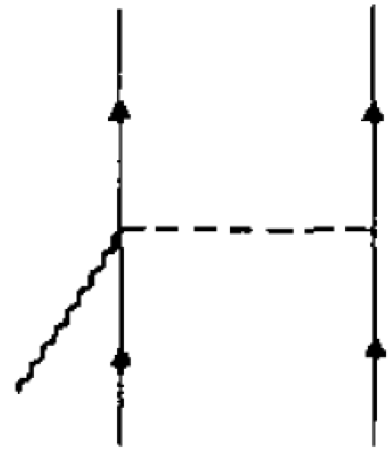
An additional two-body current to be included in the framework of independent particle models

Meson Exchange Currents (MEC)

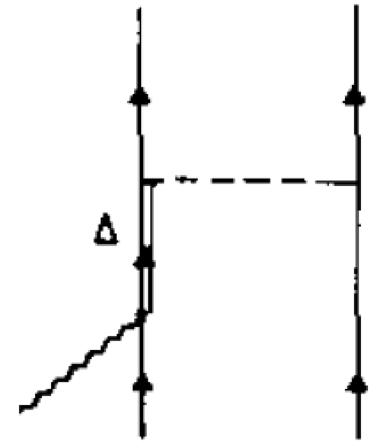
J^{MEC}



Pion in flight



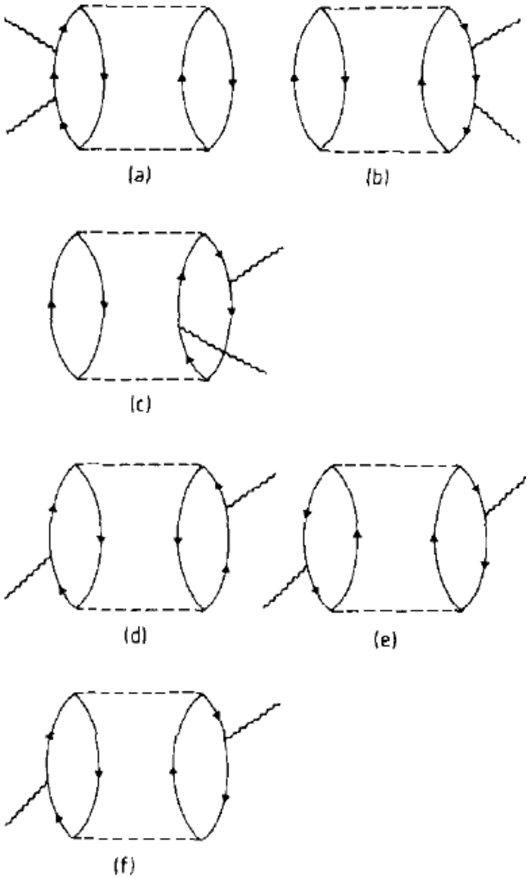
Contact



Delta

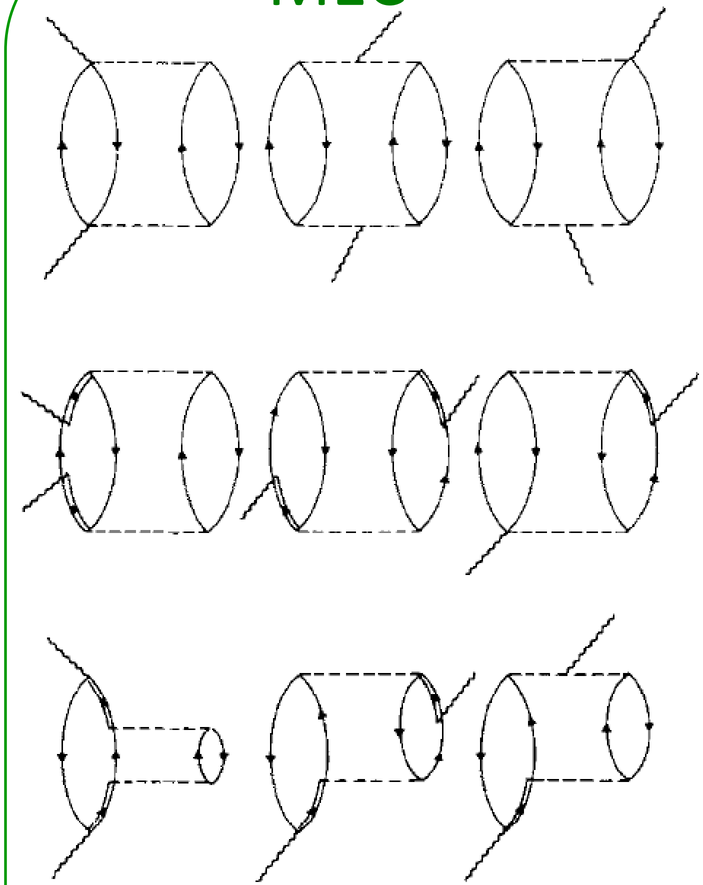
Some diagrams for 2p-2h responses

NN correlations



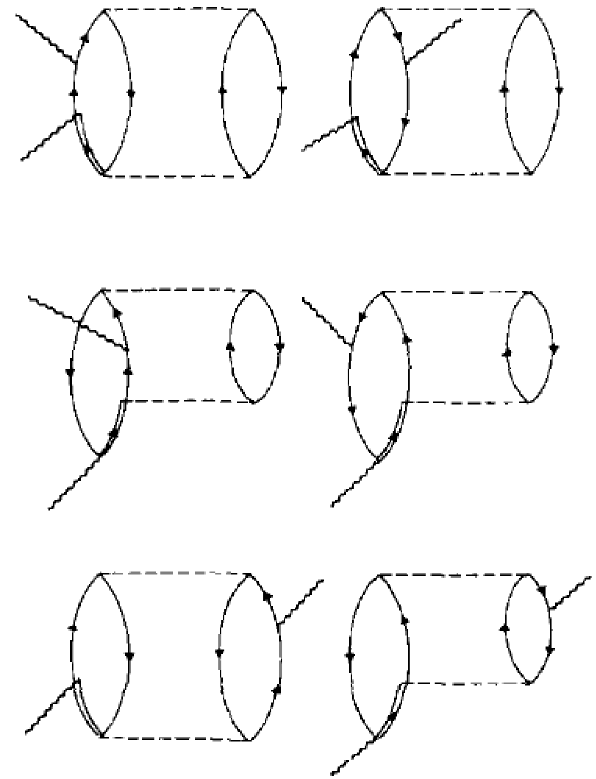
16 diagrams

MEC



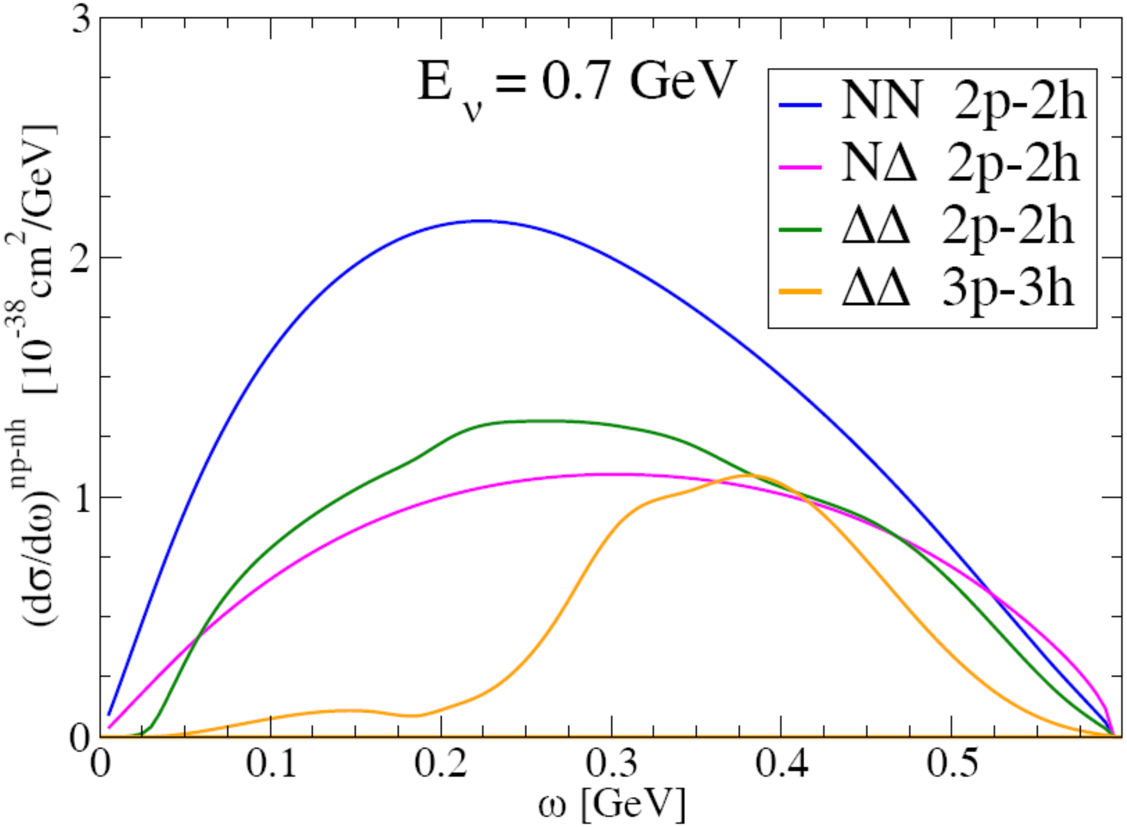
49 diagrams

NN correlation-MEC Interference (or NΔ)

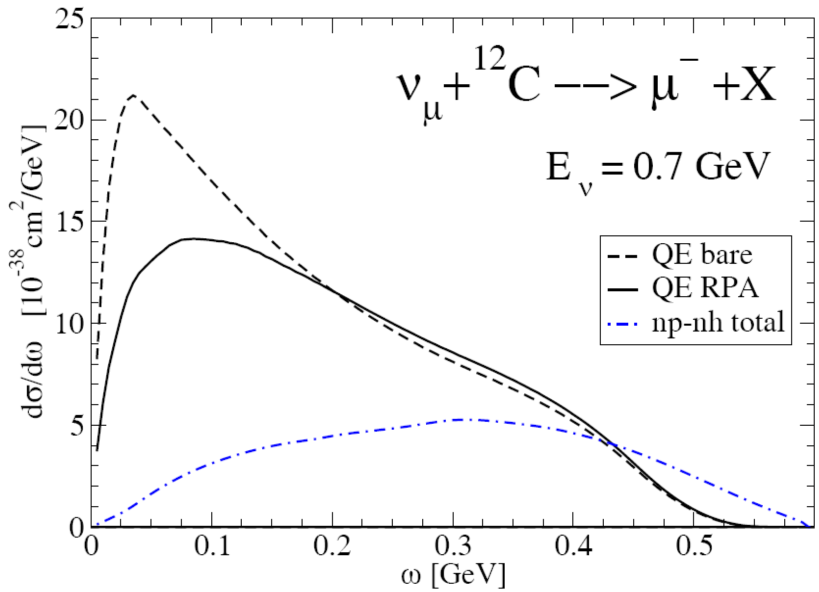


56 diagrams

Separation of np-nh contributions in the neutrino cross section



Correlations
Interference
MEC



Neutrino-nucleus cross section and 2p-2h contributions

$$\mathrm{d}\sigma \propto L_{\mu\nu} W^{\mu\nu}$$

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

If one keeps only the leading terms in the development of the hadronic current in (p/M), the cross section can be expressed in terms of three nuclear responses:

Isovector (or charge) R_τ (τ); Isospin Spin-Longitudinal $R_{\sigma\tau(L)}$($\tau\ \sigma \cdot q$); Isospin Spin Transverse $R_{\sigma\tau(T)}$($\tau\ \sigma \times q$)

[See for example O' Connell, Donnelly and Walecka, PRC 6 (1972)]

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

Where 2p-2h enter in our approach?

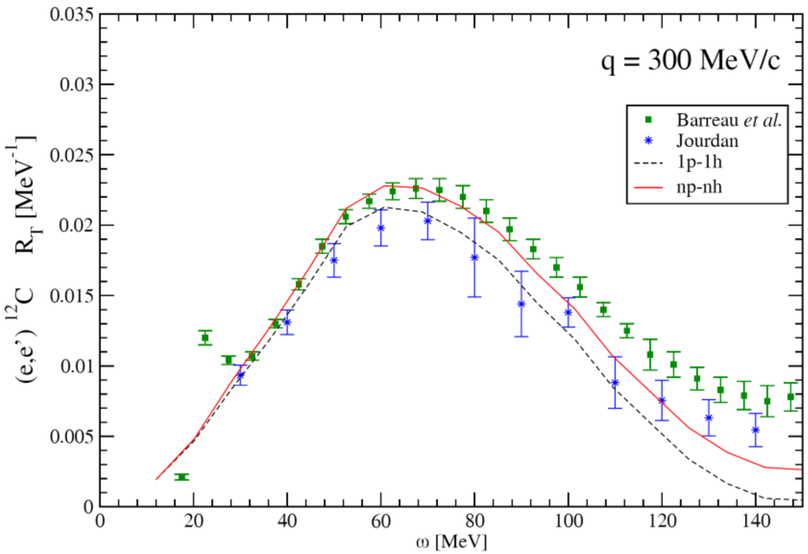
The 2p-2h term affects the spin-isospin ($\sigma\tau$) responses (terms in G_M, G_A)

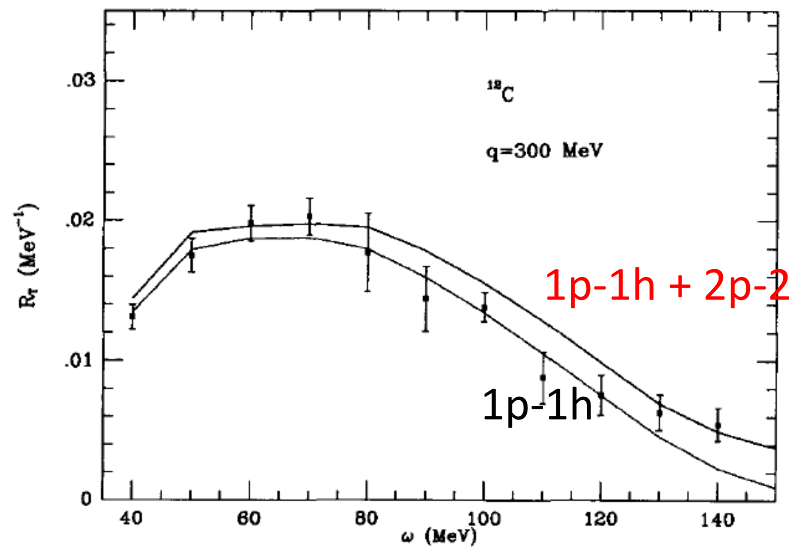
2p-2h enter in **all components** (vector and axial) but the charge

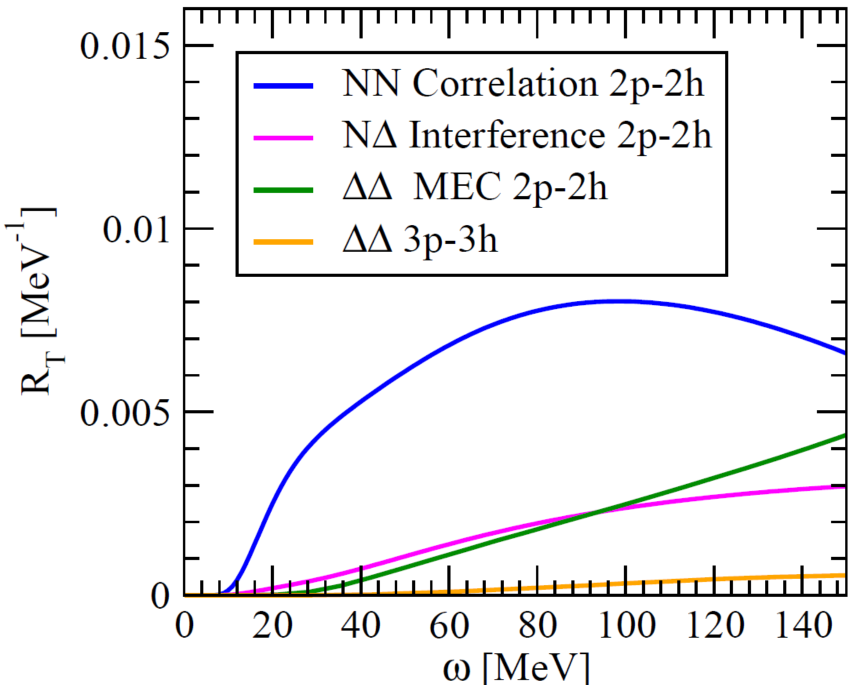
Test of R_T in ^{12}C: comparison with (e,e') data and with calculations of Gil et al.

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

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



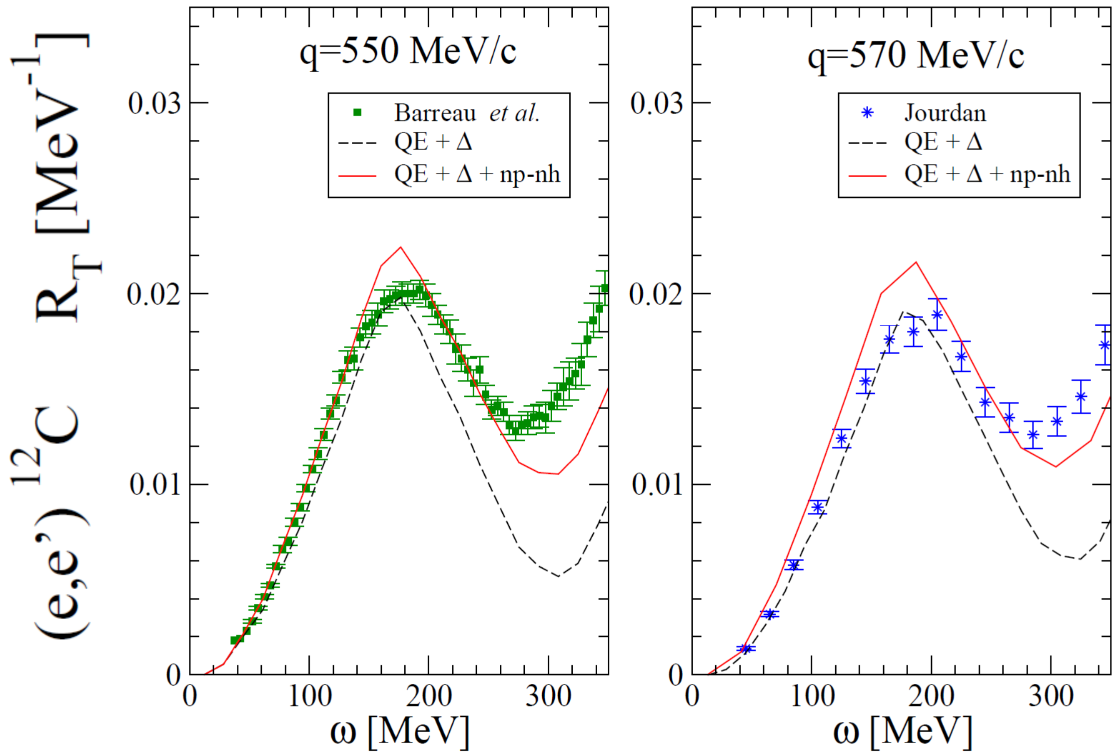


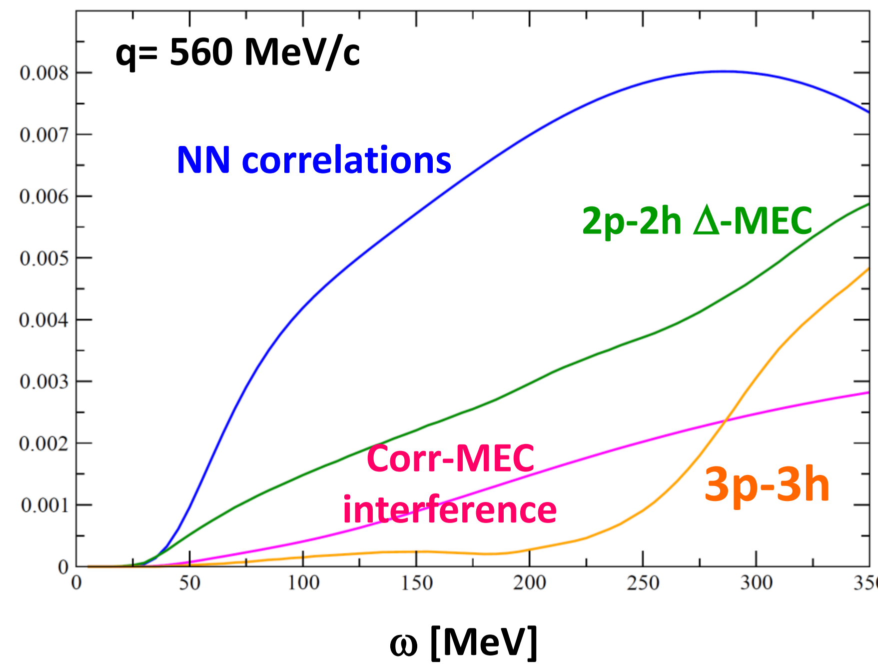


- Two evaluations of 2p-2h: same order of magnitude
- Agreement with data
- At q=300 MeV/c 2p-2h dominated by NN correlations

Our results vs (e,e') experiment for other q values

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

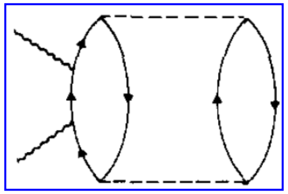


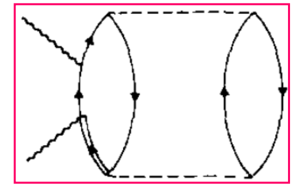


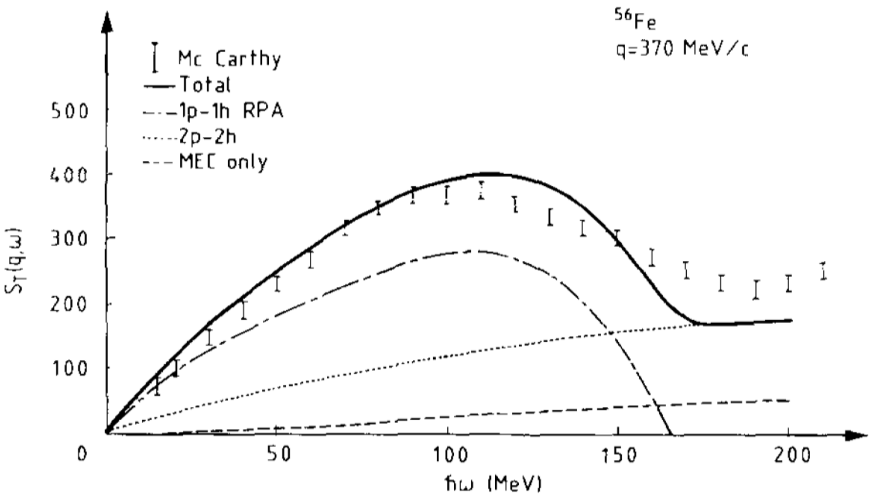
The data in the DIP region are never overestimated

In the DIP region all np-nh components are important

NN correlations and NΔ interference (correlation-MEC interference) contributions in our approach







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

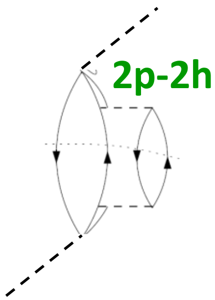
Our work

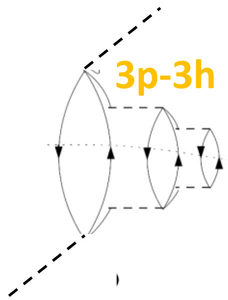
• Parameterization of these contributions in terms of $x = \frac{q^2 - \omega^2}{2M_N\omega}$ ⟶ Extrapolation to cover neutrino region

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

Δ-MEC contributions to np-nh in our model

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





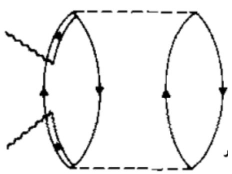
E. Oset and L. L. Salcedo, Nucl. Phys. A 468, 631 (1987):

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

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

Nieves et al. use the same model for these contributions

•Not reducible to a modification of the Delta width



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

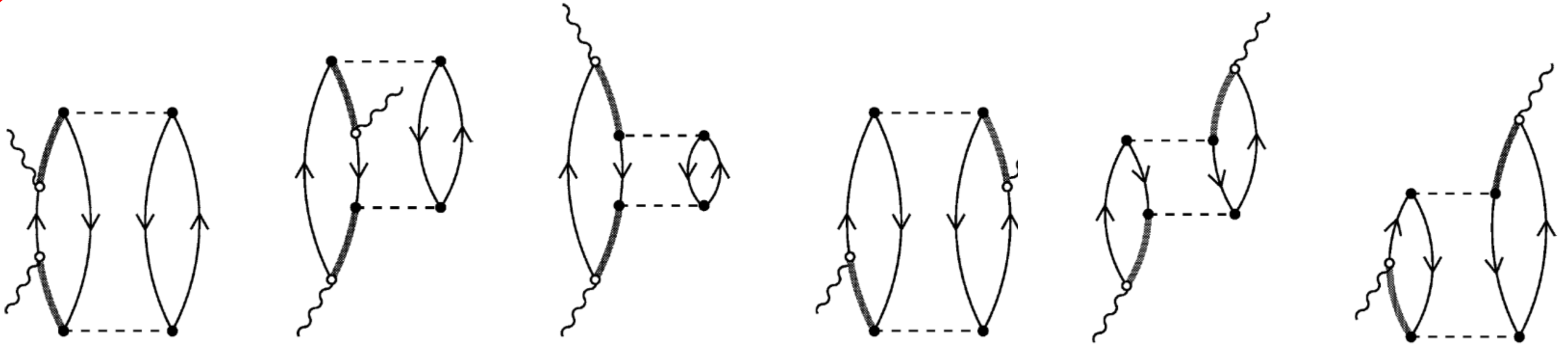
Shimizu, Faessler, Nucl. Phys. A 333,495 (1980)

Extrapolation to other energies (Delorme and Guichon)

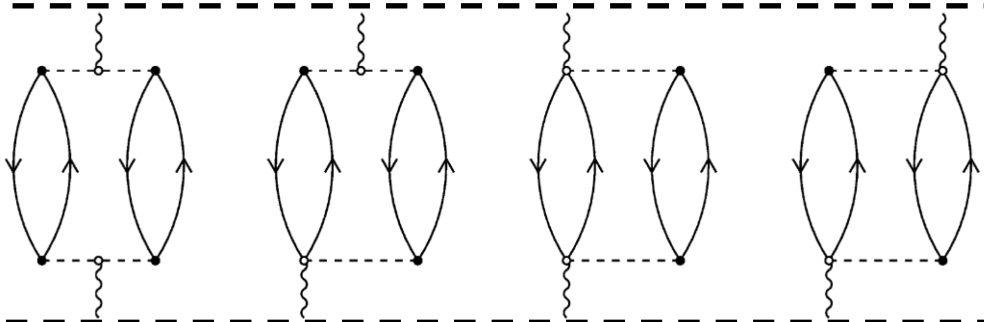
$$Im(\Pi^0_{\Delta\Delta}) \quad = \quad -4\pi\rho^2 \frac{(2M_N + m_\pi)^2}{(2M_N+\omega)^2} C_3\,\Phi_3(\omega) \left[\frac{1}{(\omega + M_\Delta - M_N)^2}\right]$$

- We include only the Δ MEC contributions (no pion in flight, no contact)
- This approximation is good (see next slides): the Δ MEC are the dominant ones

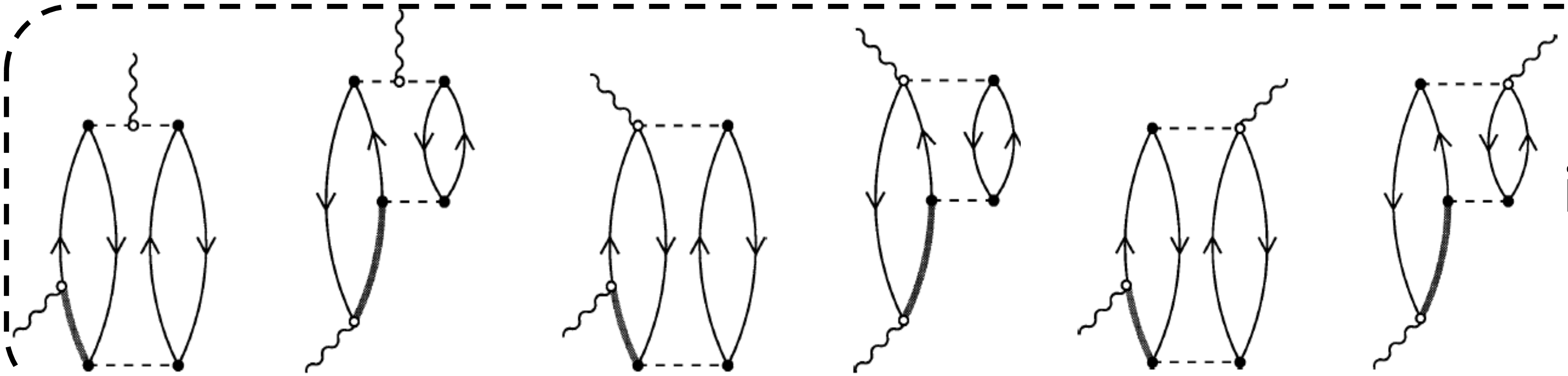
MEC contributions



Δ-MEC considered



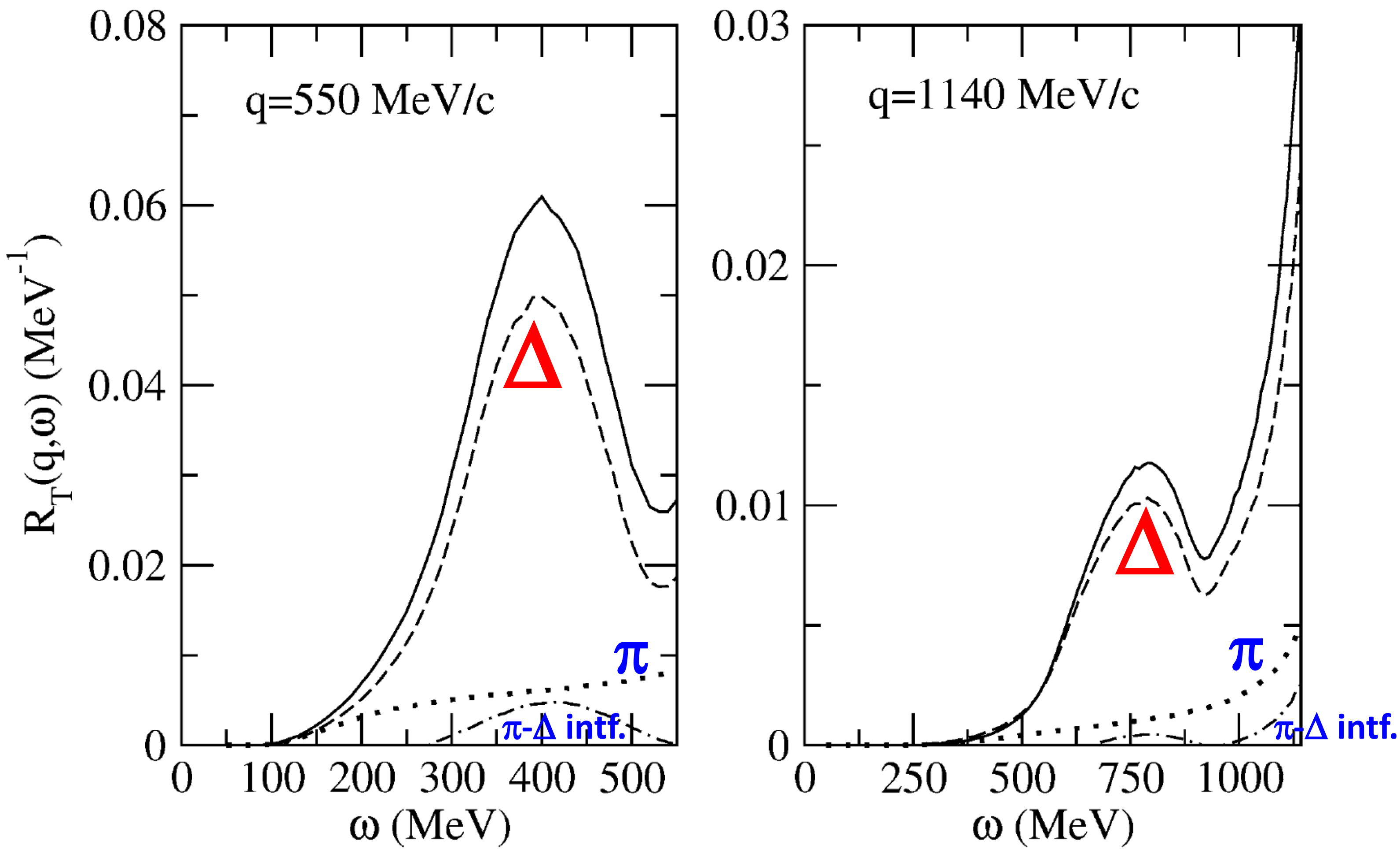
Pionic: neglected



π-Δ interference neglected

Separate MEC contributions to R_T

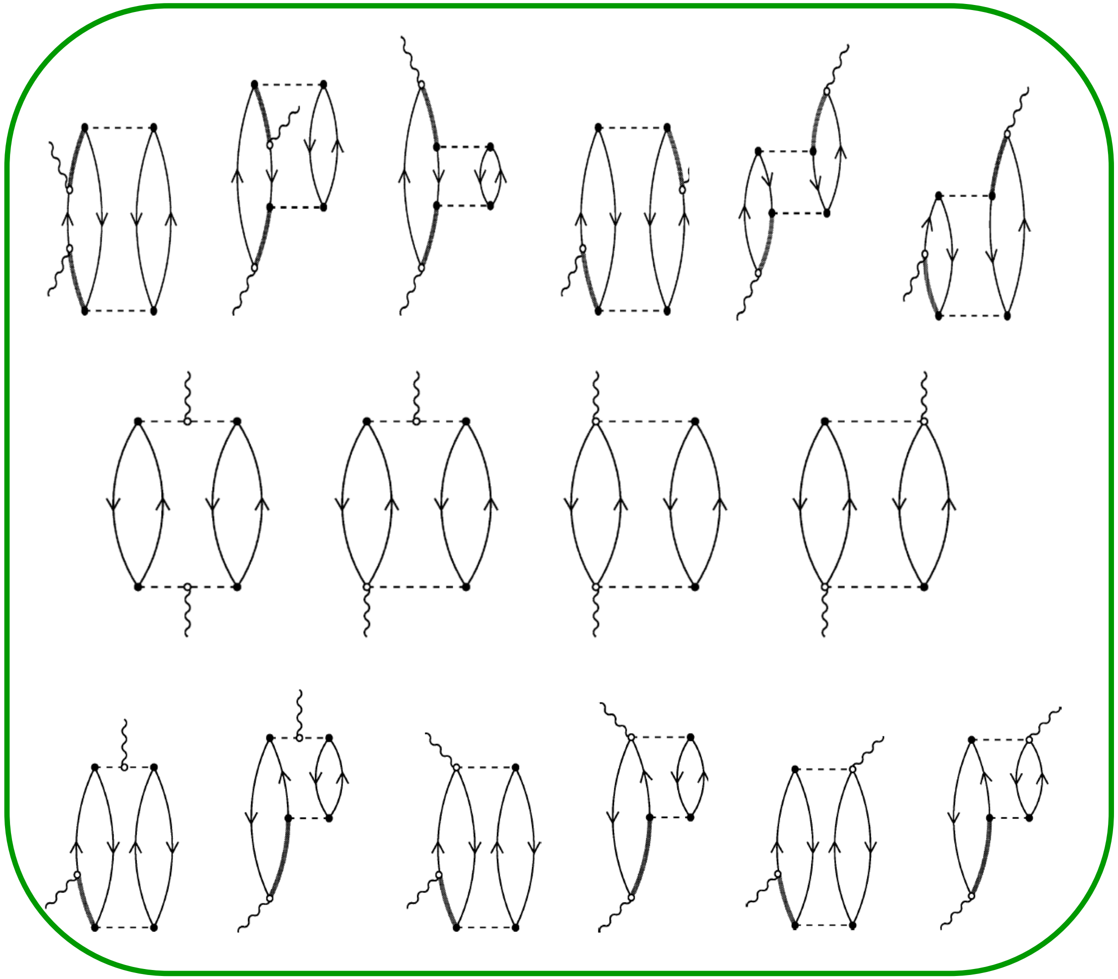
De Pace, Nardi, Alberico, Donnelly, Molinari, Nucl. Phys. A741, 249 (2004)



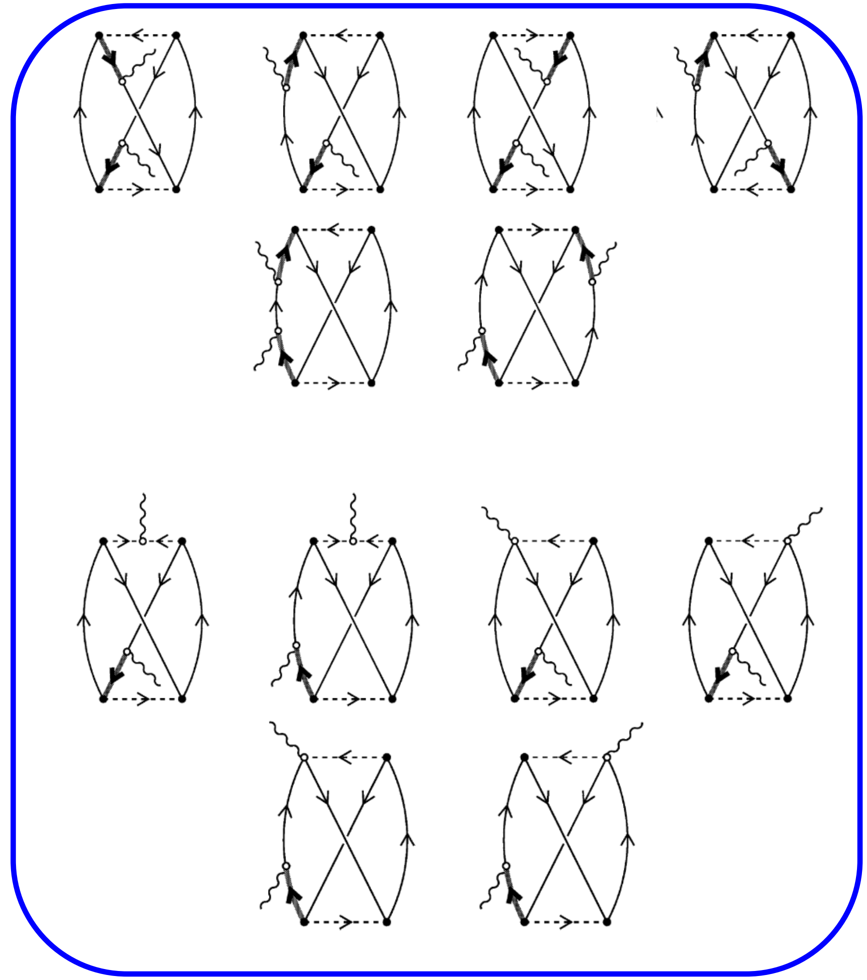
Δ-MEC contribution dominates

Direct and exchange MEC contributions

Direct



Exchange



Fully relativistic MEC calculation of De Pace et al:

3000 direct terms

More than **100 000** exchange terms

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

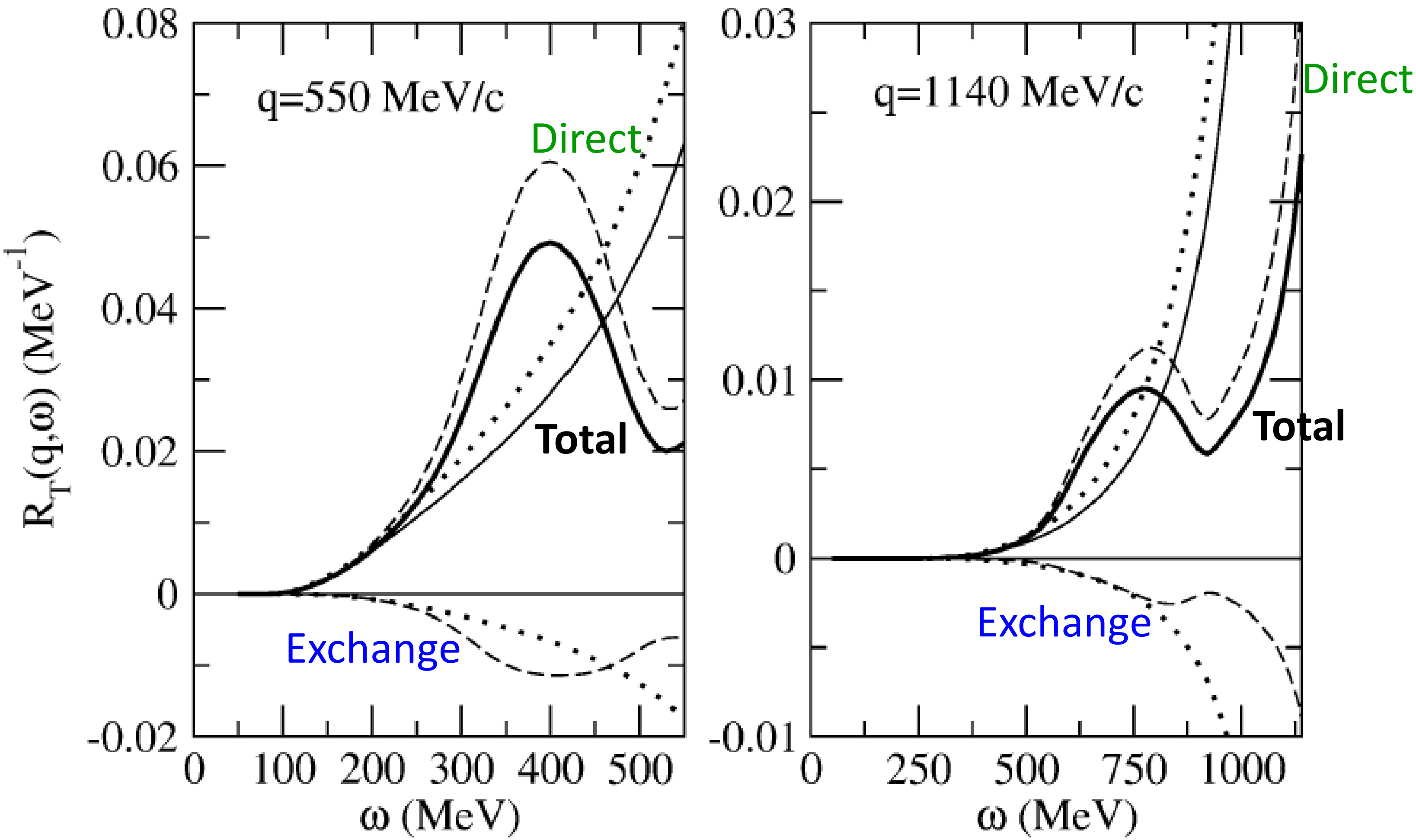
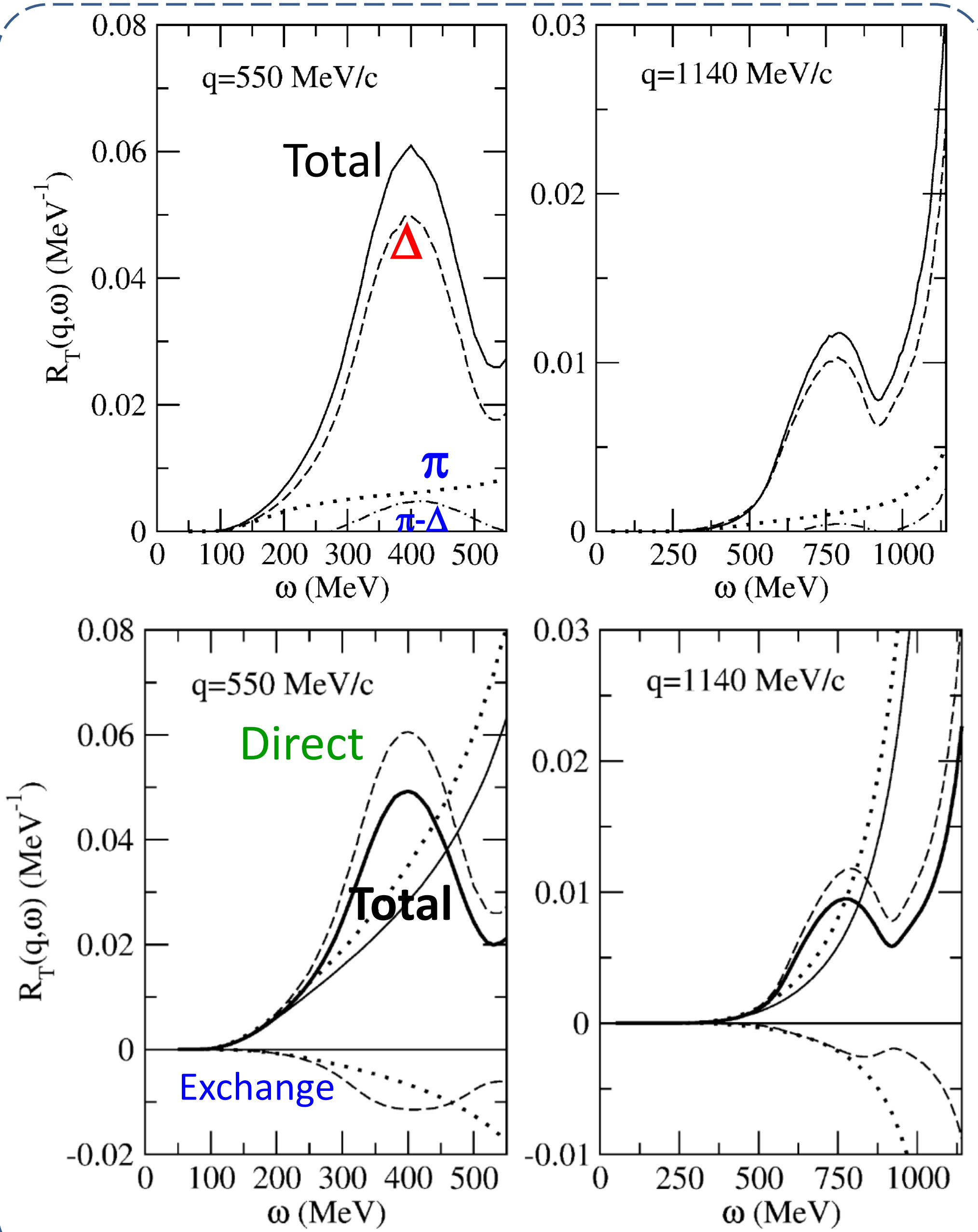


Fig. 12. The transverse response function $R_T(q,\omega)$ at $q = 550$ MeV/c and $q = 1140$ MeV/c including the exchange contributions: non-relativistic direct (positive dotted), non-relativistic exchange (negative dotted), non-relativistic total (light solid), relativistic direct (positive dashed), relativistic exchange (negative dashed) and relativistic total (heavy solid). In all instances $\bar{\epsilon}_2 = 70$ MeV and $k_F = 1.3$ fm^{-1}.



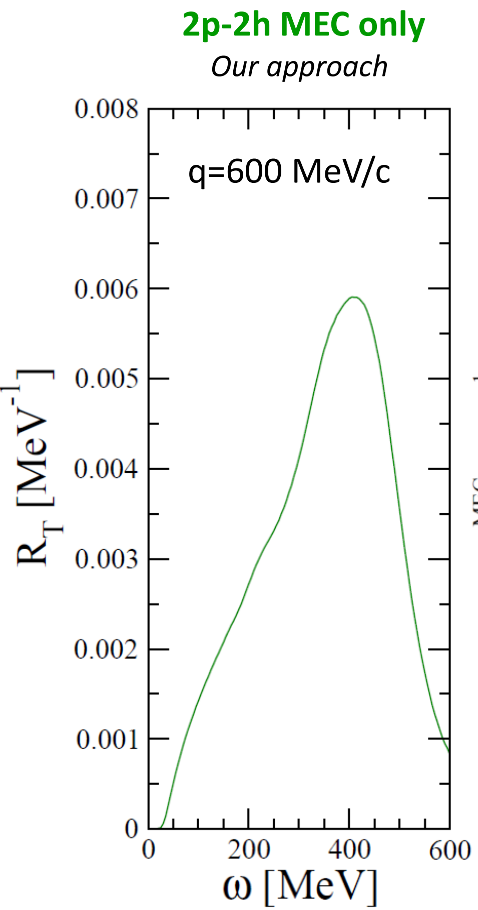
MEC summary

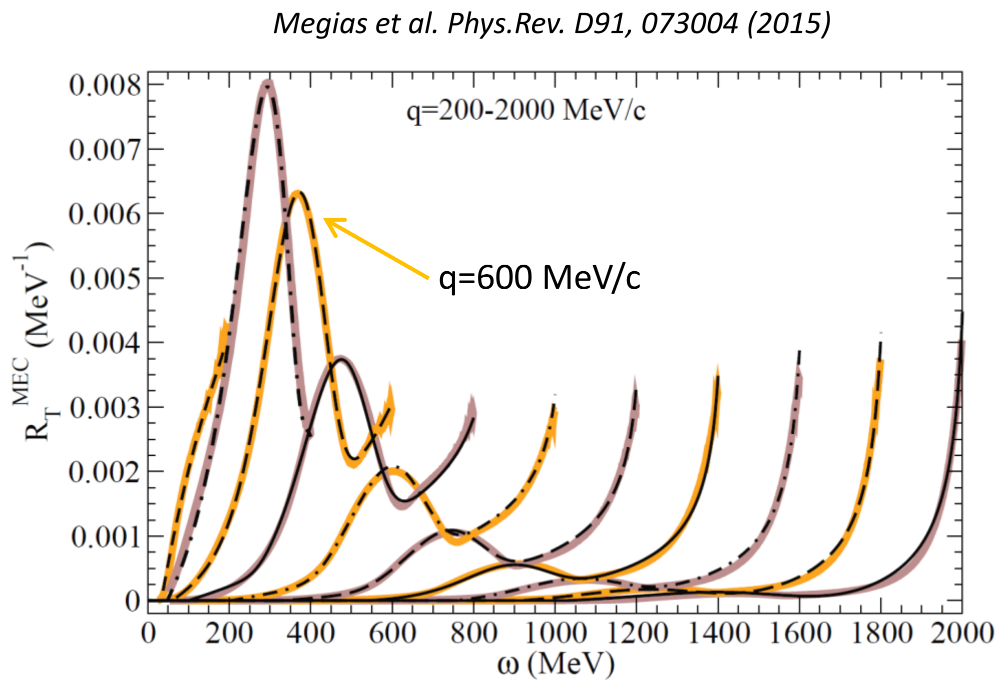
- In our approach we retain only Δ MEC direct contributions
- We discard π and π-Δ interference contributions as well as exchange contributions. These contributions not only are smaller than the Δ-direct ones but in some sense they cancel each other

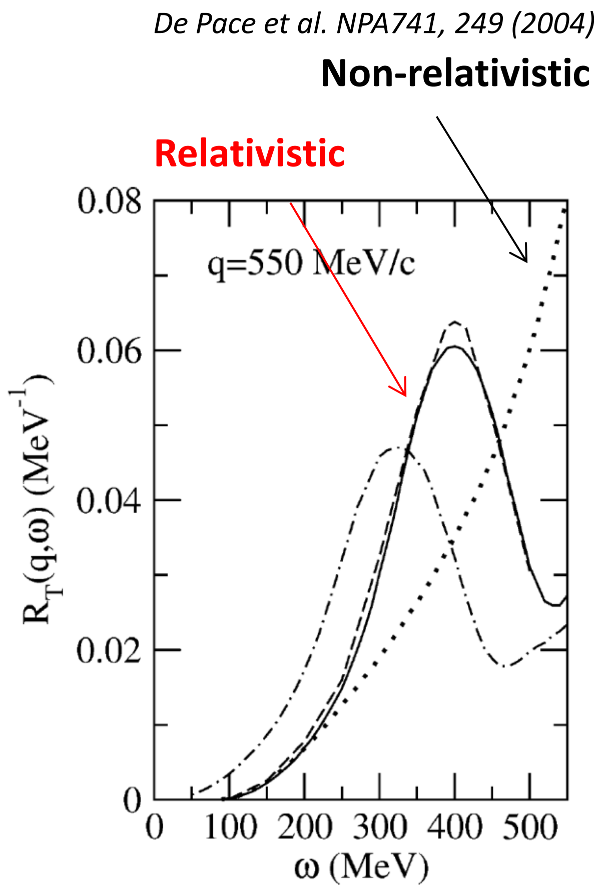
N.B. The main reason to discard from the MEC the contact and the pion in flight contributions is that they are peculiar to the external probe.
We want a "universal" spin-isospin 2p-2h response to use in different processes,
like in Alberico et al. AoP. 154 (1984)

$$R_{\sigma\tau}^{2p\text{-}2h} = R_{\sigma\tau}^{NN\ corr} + R_{\sigma\tau}^{\Delta\ MEC} + R_{\sigma\tau}^{N\Delta\ Intf.}$$

2p-2h MEC contribution to R_T: our results versus other results







- Our evaluation is compatible with the one of Megias et al. which is a parameterization of the De Pace et al. results
- We have the peaked behavior, typical of relativistic calculations, which is absent in the non-relativistic calculation

Main difficulties in the 2p-2h sector

$$W^{\mu\nu}_{2p-2h}(\mathbf{q},\omega) = \frac{V}{(2\pi)^9}\int d^3p'_1 d^3p'_2 d^3h_1 d^3h_2 \frac{m_N^4}{E_1E_2E'_1E'_2}\theta(p'_2-k_F)\theta(p'_1-k_F)\theta(k_F-h_1)\theta(k_F-h_2)$$
$$\langle 0|J^\mu|\mathbf{h}_1\mathbf{h}_2\mathbf{p}'_1\mathbf{p}'_2\rangle\langle \mathbf{h}_1\mathbf{h}_2\mathbf{p}'_1\mathbf{p}'_2|J^\nu|0\rangle\delta(E'_1+E'_2-E_1-E_2-\omega)\delta(\mathbf{p}'_1+\mathbf{p}'_2-\mathbf{h}_1-\mathbf{h}_2-\mathbf{q})$$

- 7-dimensional integrals $\int d^3h_1 d^3h_2\ d\theta'_1$ of thousands of terms
- Huge number of diagrams and terms

  e.g. 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 (angular distribution; NN correlations contributions)
- Calculations for all the kinematics compatible with the experimental neutrino flux

Computing very demanding

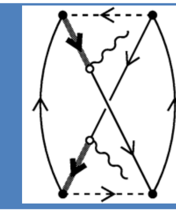
Hence different approximations by different groups:

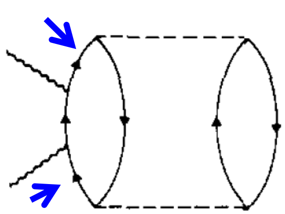
- choice of subset of diagrams and terms;
- different prescriptions to regularize the divergences;
- reduce the dimension of the integrals (7D --> 2D if non relativistic; 7D -->1D if $h_1 = h_2 = 0$)

$\Rightarrow$ Different final results

Comparison among models

Different approximations for the 2p-2h calculations

Approach	Vector	Axial	NN correlations	MEC	NN-MEC interference	Relativistic	
Martini et al.	Yes	Yes	**π,g'**	Yes (Only Δ MEC)	Yes	Some ingredients	No
Nieves et al.	Yes	Yes	**π,ρ,g'**	Yes	Yes	Approximations in the WNNπ vertex	No
Amaro et al. Megias et al.	Yes	Preliminary	**π** or already in Superscaling function	Yes	No	Fully Relativistic	Yes



$$(p_0 - E_{\mathbf{p}} + i\epsilon)^{-2}$$

- Divergences in NN correlations, prescriptions:

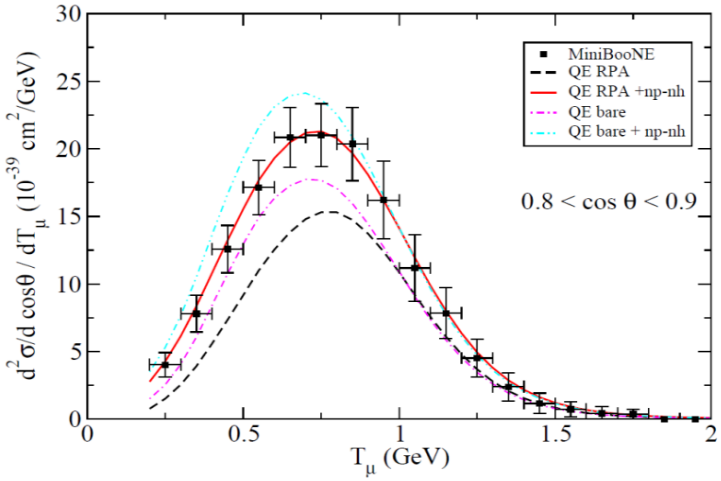
-nucleon propagator only off the mass shell (*Alberico et al. Ann. Phys. 1984*)

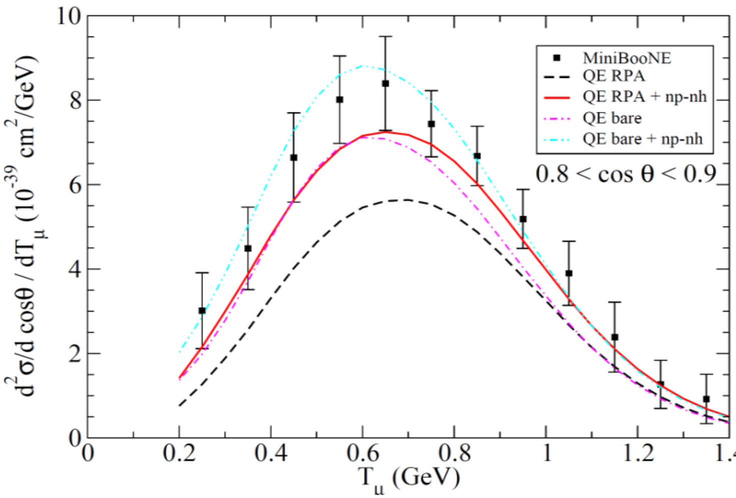
-kinematical constraints + nucleon self energy in the medium (*Nieves et al PRC 83*)

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

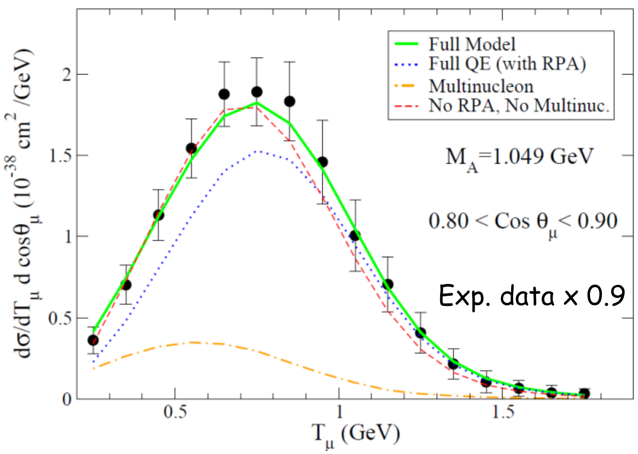
ν $\bar{\nu}$

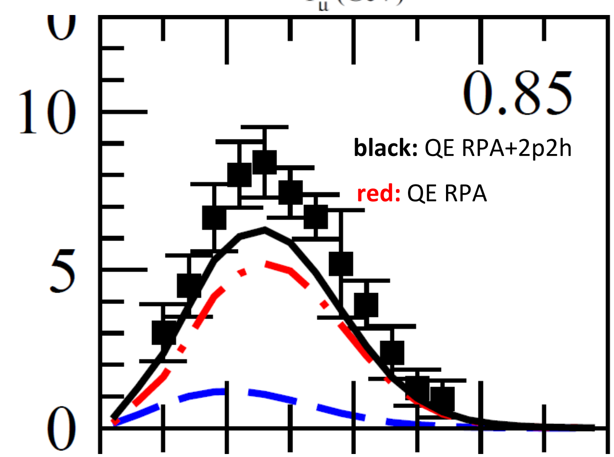
Martini et al.



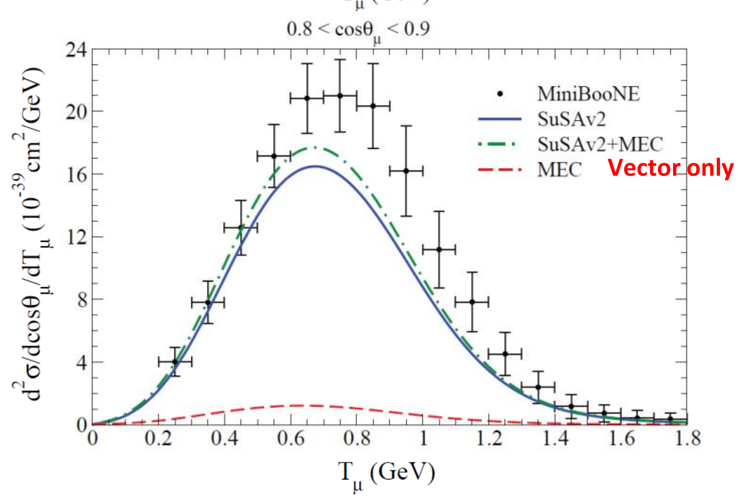


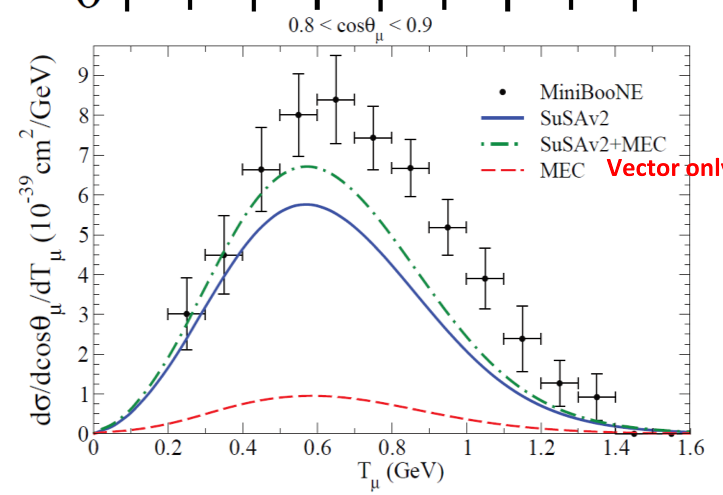
Nieves et al.





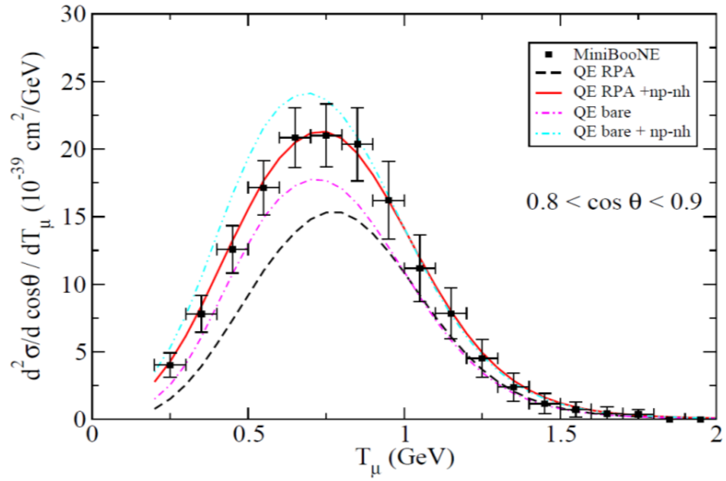
Amaro et al.

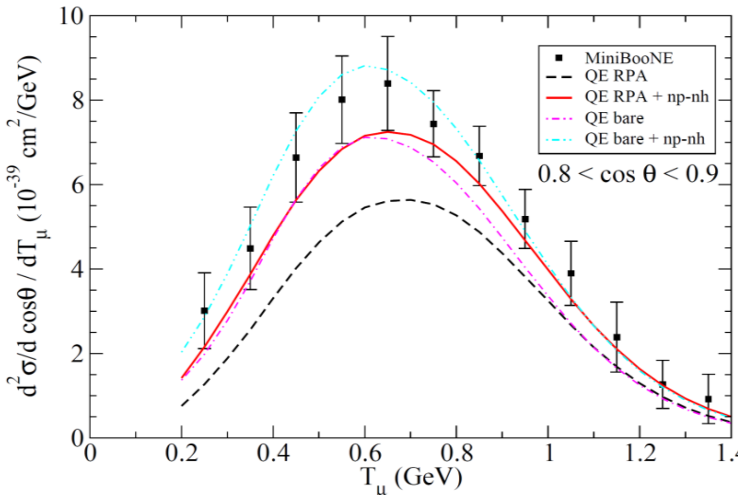




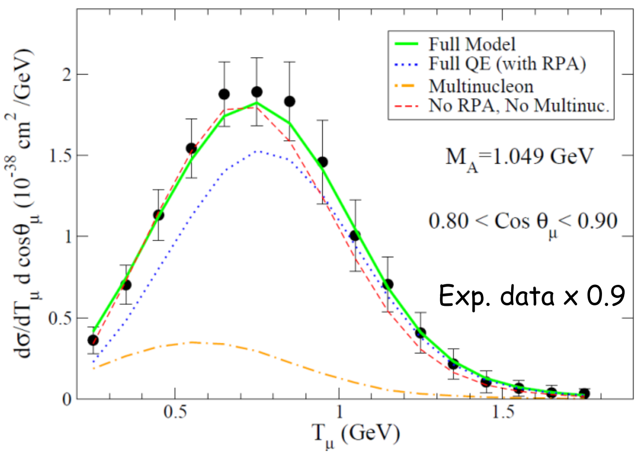
ν $\bar{\nu}$

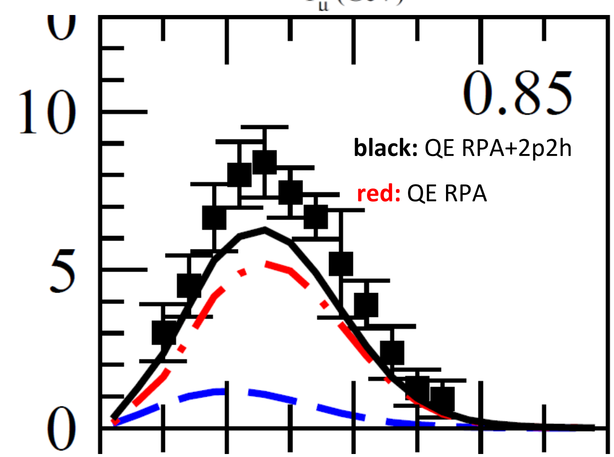
Martini et al.





Nieves et al.

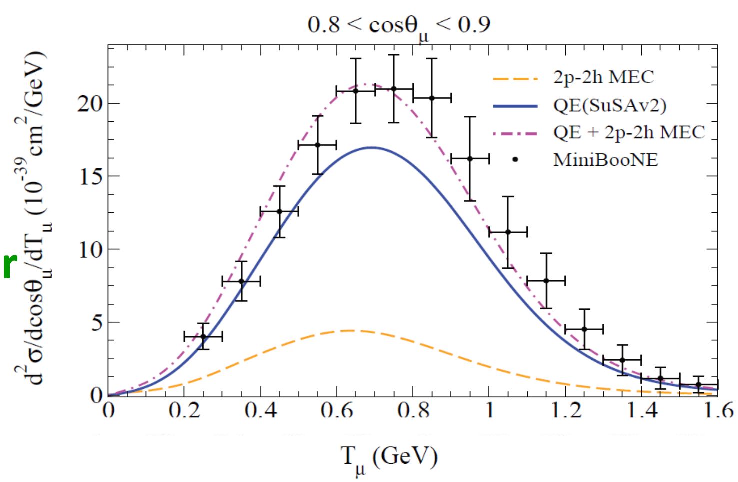


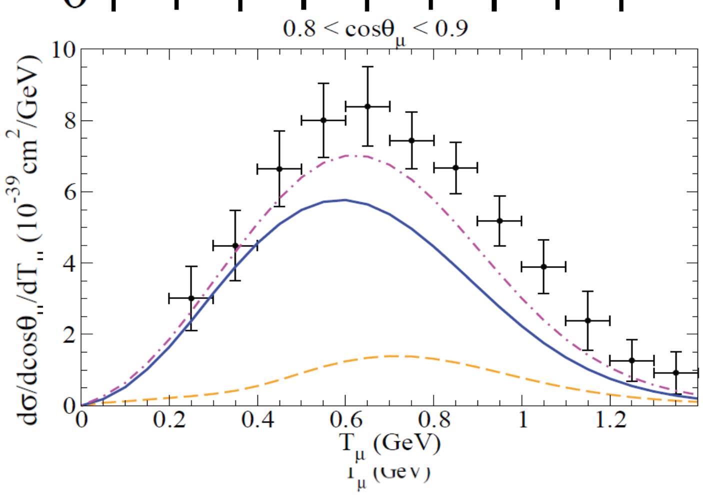


NEW, preliminary:

Inclusion of MEC also in the axial sector

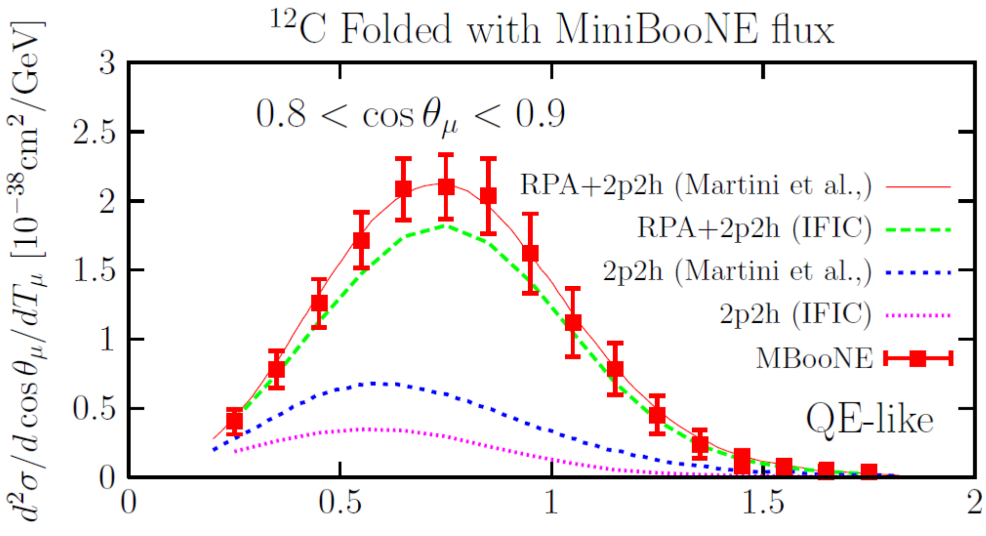
Megias talk NuFact 2015



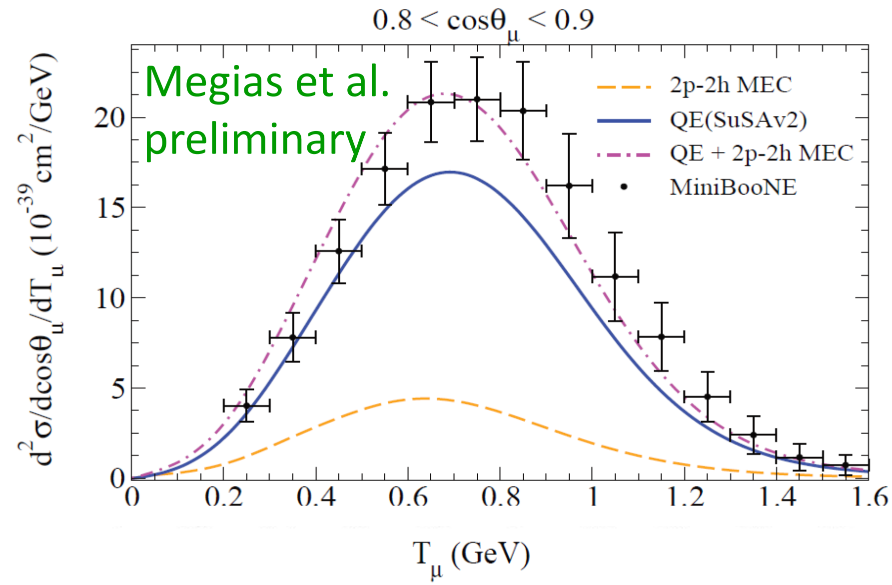


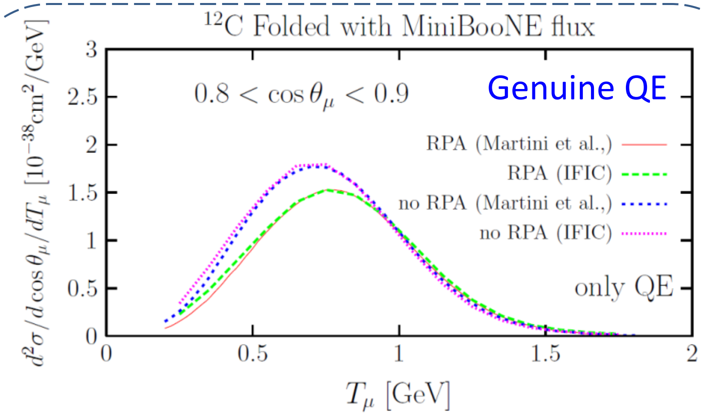
ν

Comparison between the three theoretical approaches



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





p.s. genuine QE bare and RPA very similar in Martini et al. and Nieves et al approaches

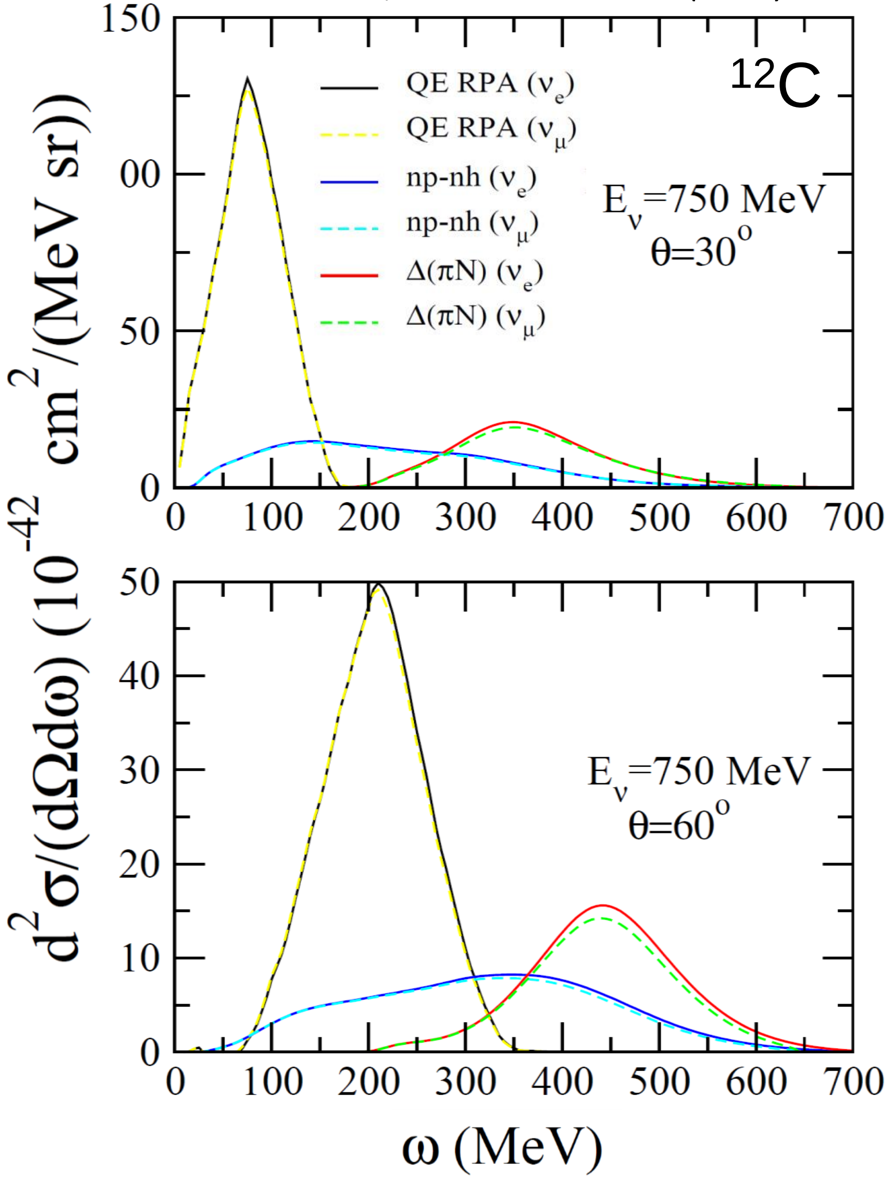
2p2h Nieves et al. < 2p2h Megias et al. < 2p2h Martini et al.

Remind about the Megias et al. approach:

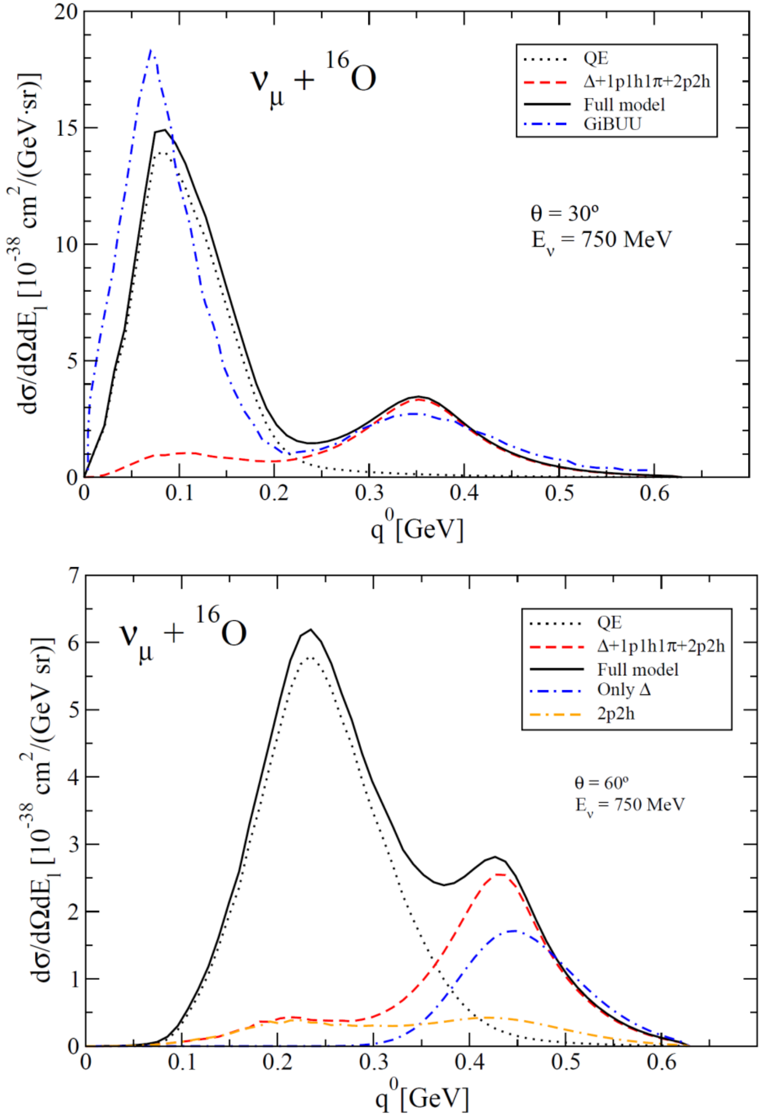
- NN correlations are already included in the QE SuSAv2
- NN correlation/MEC interference not included

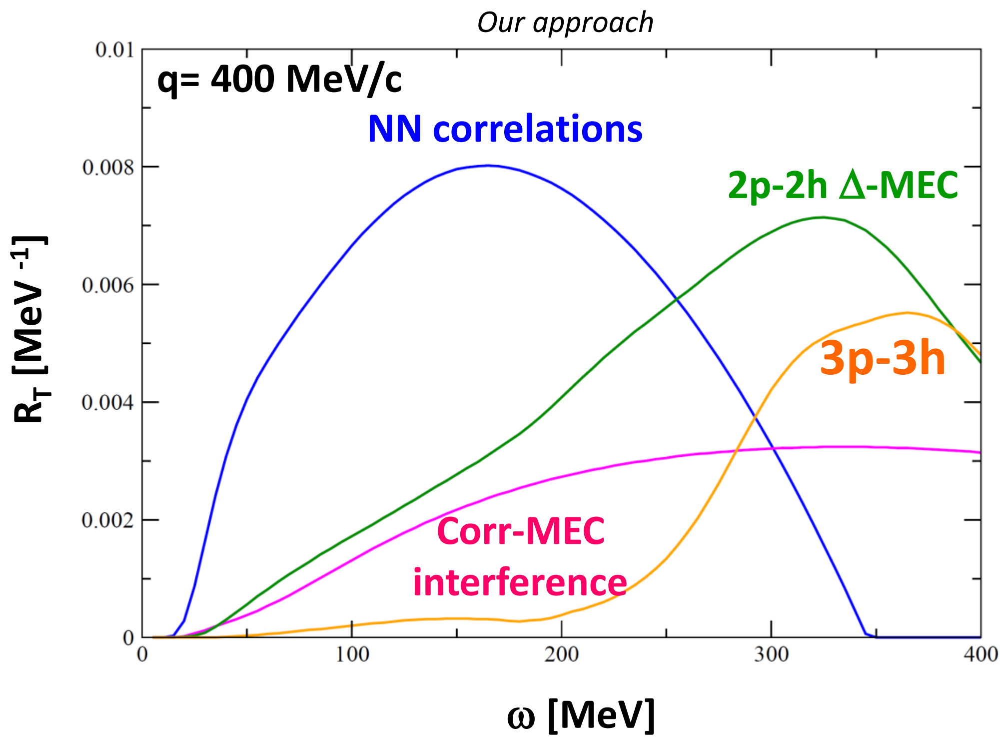
One example of comparison at fixed neutrino energy

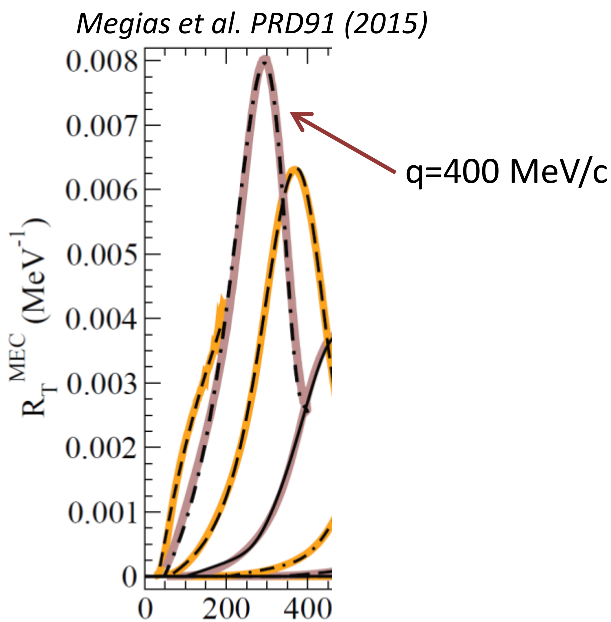
Martini et al., arXiv: 1602.00230 (2016)



Nieves et al. Phys. Rev. C 83 045501 (2011)







- The **MEC** contributions in the 3 approaches seem to be compatible among them:
  - Δ-MEC is dominant
  - our approach seems to be in agreement with the one of Megias, Amaro, De Pace et al.
  - our approach for the **ΔMEC 2p-2h** and **3p-3h** is supposed to be in agreement with the one of Nieves et al. since both are deduced from the Oset and Salcedo paper

- Major differences in **NN correlations** and **NN correlation – MEC interference** ?

What about our approximation to take the same transverse response for the Vector, the Axial and the VA interference?

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

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

- From the non-relativistic reduction of the hadronic current
- Same approximation discussed in O' Connell, Donnelly and Walecka, PRC 6 719 (1972) in order to relate the neutrino cross sections to the electron scattering responses

For the 2p-2h NN correlation contribution:

$$R_T^{A\;\text{NN corr}} \cong R_T^{V\;\text{NN corr}} = R_{\sigma\tau(T)}^{\text{NN corr}}$$

$$R_{T'}^{VA\;\text{NN corr}} \cong R_T^{V\;\text{NN corr}} = R_{\sigma\tau(T)}^{\text{NN corr}}$$

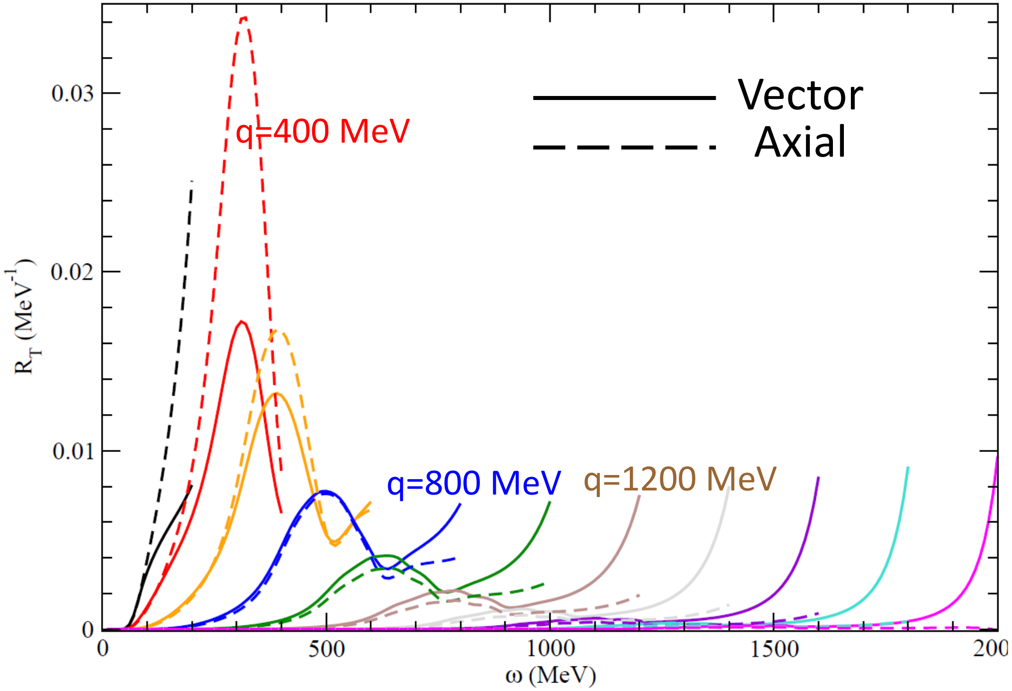
Same philosophy as the Superscaling and Spectral function approaches

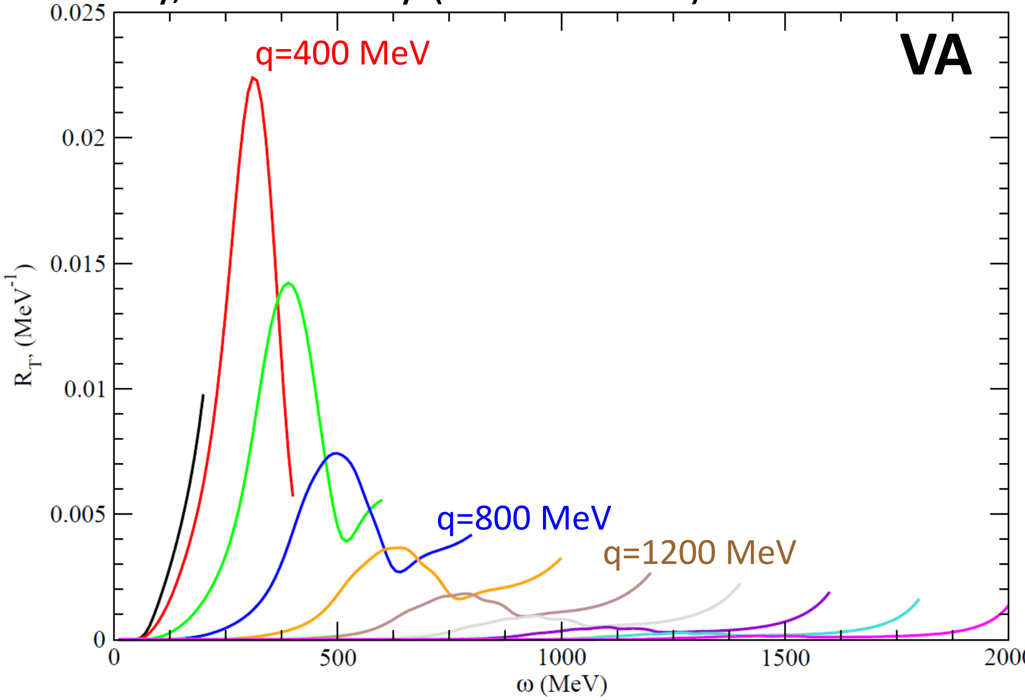
And for the 2p-2h MEC contributions?

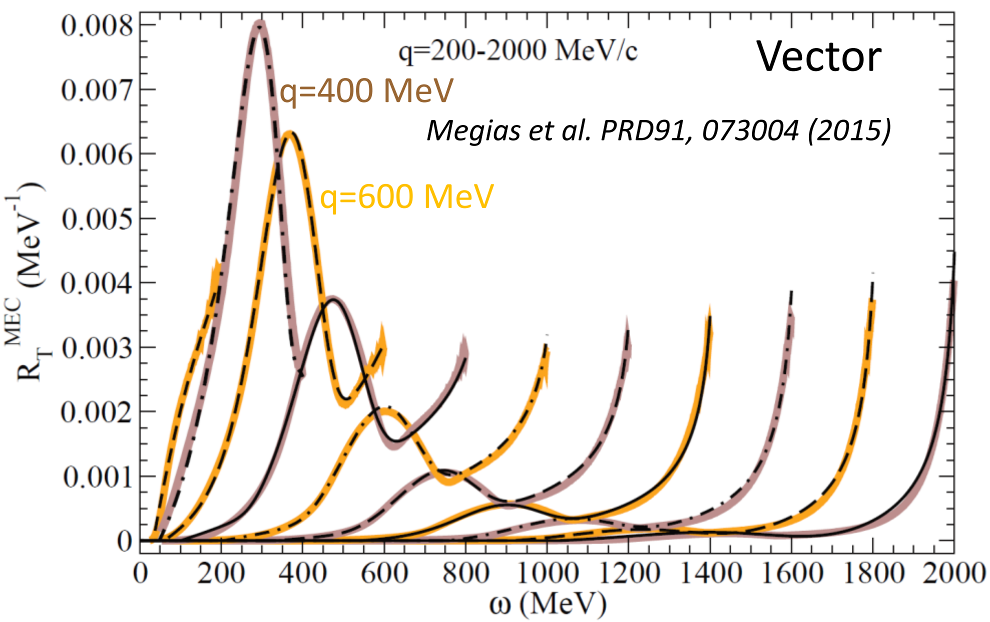
To be discussed in this workshop (see next slides)…

Transverse Vector, Axial and the VA interference MEC contributions

Megias, Amaro, Barbaro, Caballero, Donnelly, Preliminary (NuFact 2015)



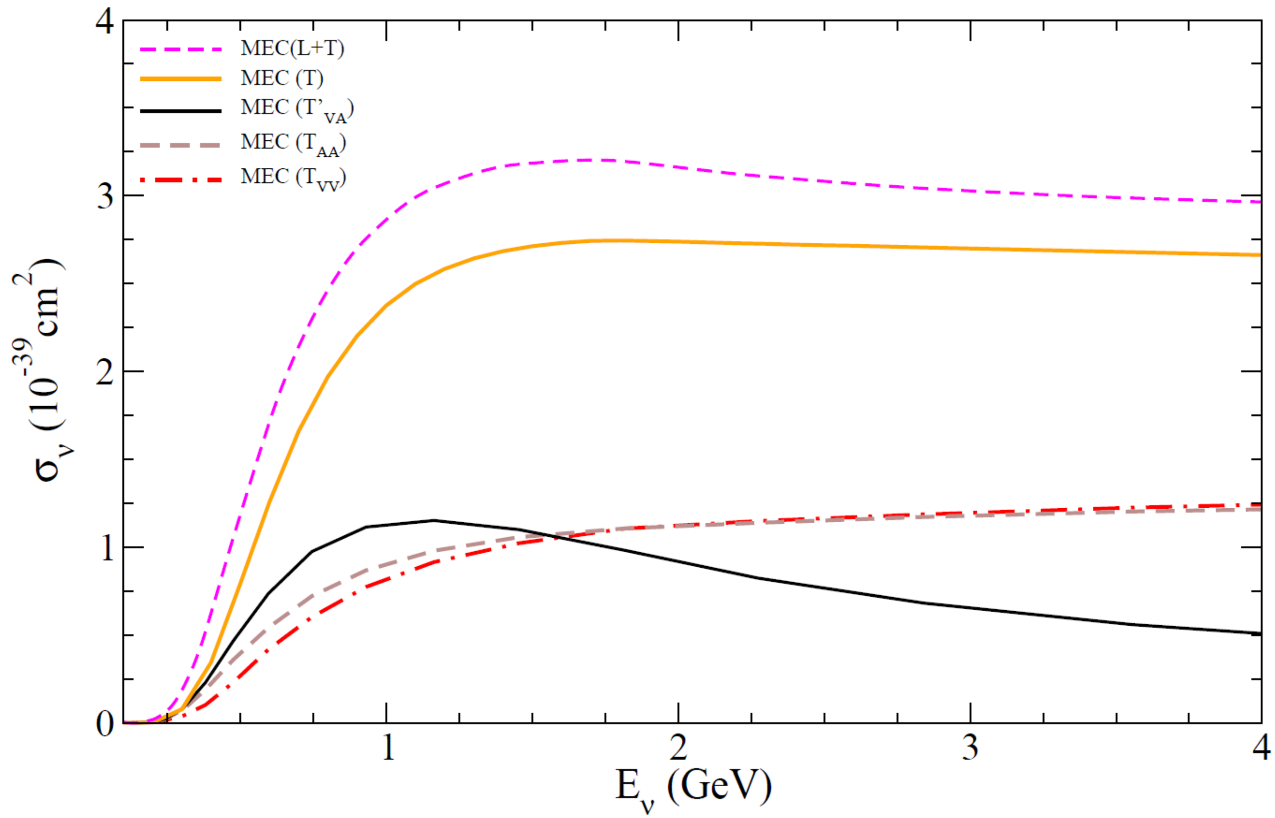




Probably the different Form Factors and kinematical factors are already included in the upper figures of the comparison of Vector, Axial and VA terms

Transverse Vector, Axial and the VA interference MEC contributions

Megias, Amaro, Barbaro, Caballero, Donnelly, Preliminary (NuFact 2015)



$$R_{T'}^{VA\ MEC} \cong R_T^{A\ MEC} \cong R_T^{V\ MEC} = R_{\sigma\tau(T)}^{MEC}$$

- This approximation looks robust up to $E_\nu \sim 2$ GeV

Major differences in the cross sections calculated by the different models unlikely due to the differences in V and A contributions treatment

Major differences in NN correlations and NN correlation – MEC interference ?

Summary

- Our model including np-nh is in agreement with CCQE-like, CC0π and CC inclusive data for the flux integrated differential cross sections with 4 different neutrino fluxes:
  - MiniBooNE ν_μ
  - MiniBooNE antiν_μ
  - T2K ν_μ
  - T2K ν_e

- Differences between theoretical approaches in the np-nh treatment
  - The MEC contributions in the 3 approaches seem to be compatible among them
  - Major differences in the results for the cross sections unlikely due to the differences in V and A contributions treatment
  - Major differences in NN correlations and NN correlation – MEC interference treatment?

…to be discussed in this workshop

Spares

Neutrino-nucleus cross section

Two equivalent expressions:

The notation for example of Amaro et al:

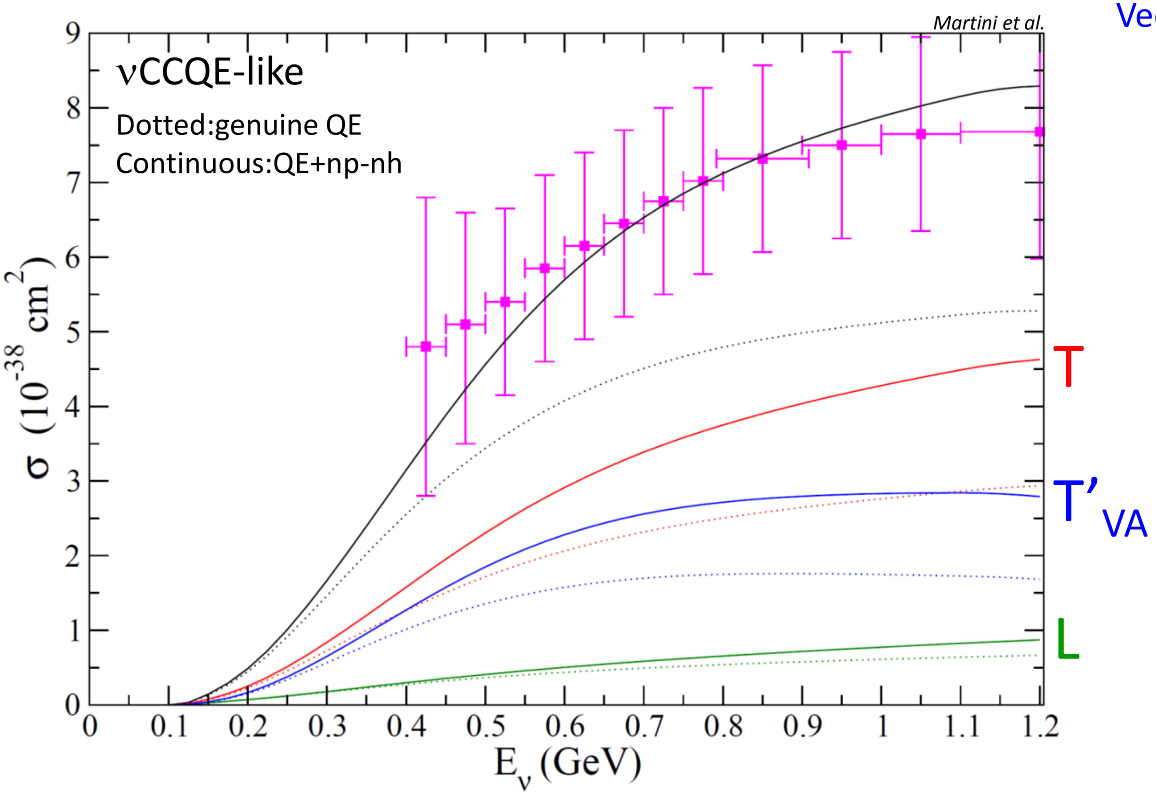
$$\frac{\partial^2\sigma}{\partial\Omega\ \partial\epsilon'} = \sigma_0 \left[L_{CC}(R^V_{CC} + R^A_{CC}) + L_{CL}(R^V_{CL} + R^A_{CL}) + L_{LL}(R^V_{LL} + R^A_{LL}) + L_T(R^V_T + R^A_T) \pm L_{T'VA} R^{VA}_{T'}\right]$$

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



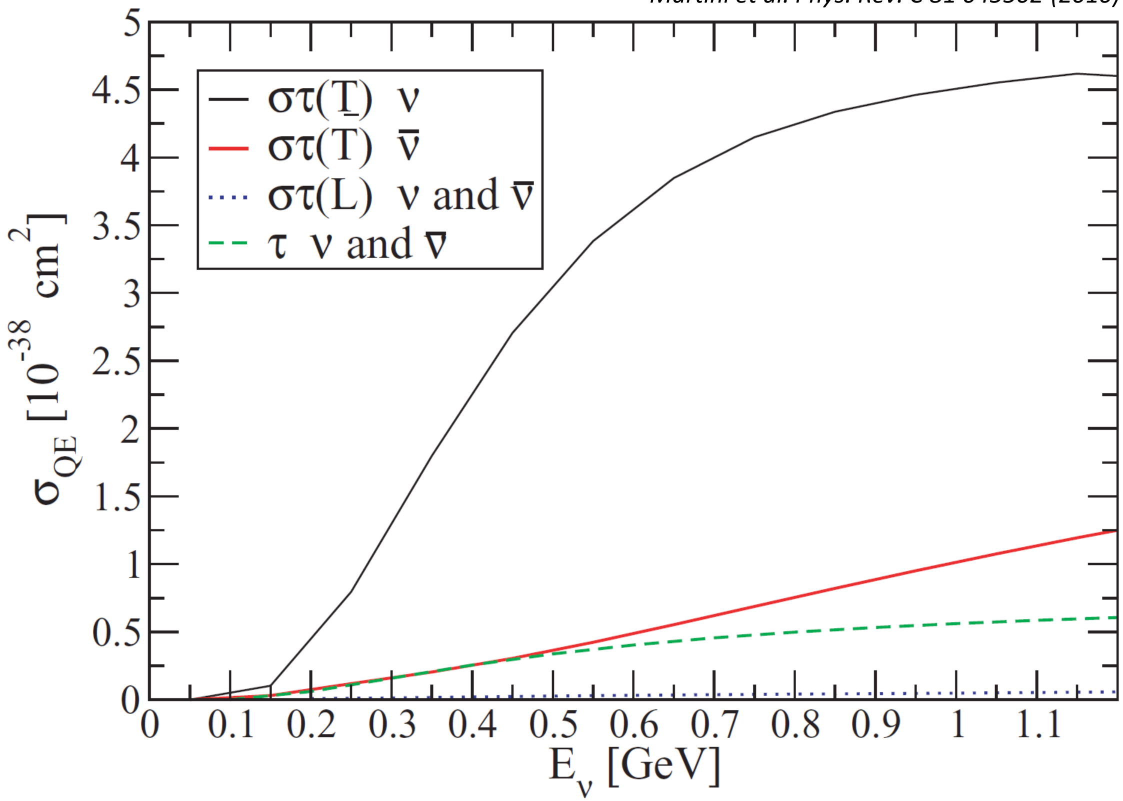
A third simplified expression (useful for illustration)

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

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

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

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

O' Connell, Donnelly and Walecka, PRC 6 719 (1972)

Electron scattering

$$\frac{d\sigma_{ee'}}{d\Omega} = 4\pi\left[\frac{\alpha \cos\frac{1}{2}\theta}{2E_0 \sin^2(\frac{1}{2}\theta)}\right]^2 \left\{\left[\frac{q_\lambda^{\,2}}{\kappa^2} F_L^{\,2}(\kappa,\omega)\right] + \left[\frac{q_\lambda^{\,2}}{2\kappa^2} + \tan^2(\tfrac{1}{2}\theta)\right] F_T^{\,2}(\kappa,\omega)\right\}$$

Neutrino scattering

$$\left(\frac{d\sigma_\nu}{d\vec{q}^2}\right)^{\text{ERL}}_{\substack{\nu\\ \bar{\nu}}} \simeq 2G^2\left(\frac{\epsilon}{\nu}\right) 2(T+1)\cos^2(\tfrac{1}{2}\theta)\left(\left[\frac{q_\lambda^{\,2}}{\kappa^2}\right]^2 F_L^{\,2}(\kappa,\omega) + \left\{\left[\frac{q_\lambda^{\,2}}{2\kappa^2} + \tan^2(\tfrac{1}{2}\theta)\right]\left[1+\left(\frac{2M_N}{\kappa\mu^V}F_A\right)^2\right]\right.\right.$$
$$\left.\left. \mp \tan(\tfrac{1}{2}\theta)\left[\frac{q_\lambda^{\,2}}{\kappa^2} + \tan^2(\tfrac{1}{2}\theta)\right]^{1/2} \frac{4M_N}{\kappa\mu^V} F_A\right\} F_T^{\,2}(\kappa,\omega)\right)$$

Same Response for V, A and VA terms

$$\frac{1}{2J_i+1}\sum_{J=1}^{\infty}\left(|\langle J_f \| \hat{\mathcal{T}}_J^{\text{el}} \| J_i\rangle|^2 + |\langle J_f \| \hat{\mathcal{T}}_J^{\text{mag}} \| J_i\rangle|^2\right) \simeq \left[1+\left(\frac{2M_N F_A}{\kappa\mu^V}\right)^2\right] F_T^{\,2}$$

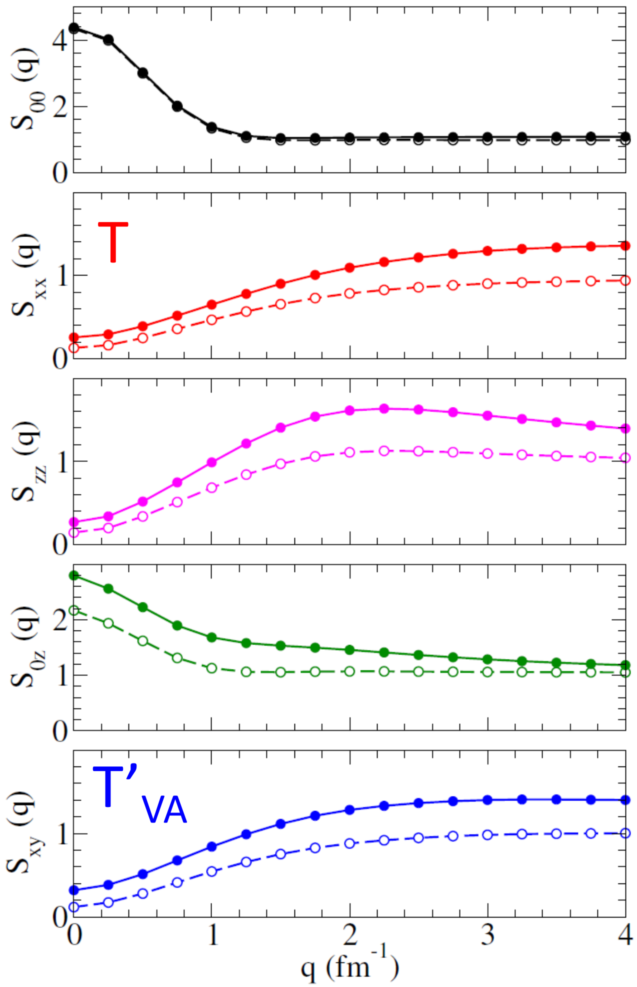
$$\frac{1}{2J_i+1}\sum_{J=1}^{\infty} \text{Re}\langle J_f \| \hat{\mathcal{T}}_J^{\text{mag}} \| J_i\rangle\langle J_f \| \hat{\mathcal{T}}_J^{\text{el}} \| J_i\rangle^* \simeq \frac{2M_N F_A}{\kappa\mu^V} F_T^{\,2}$$

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)

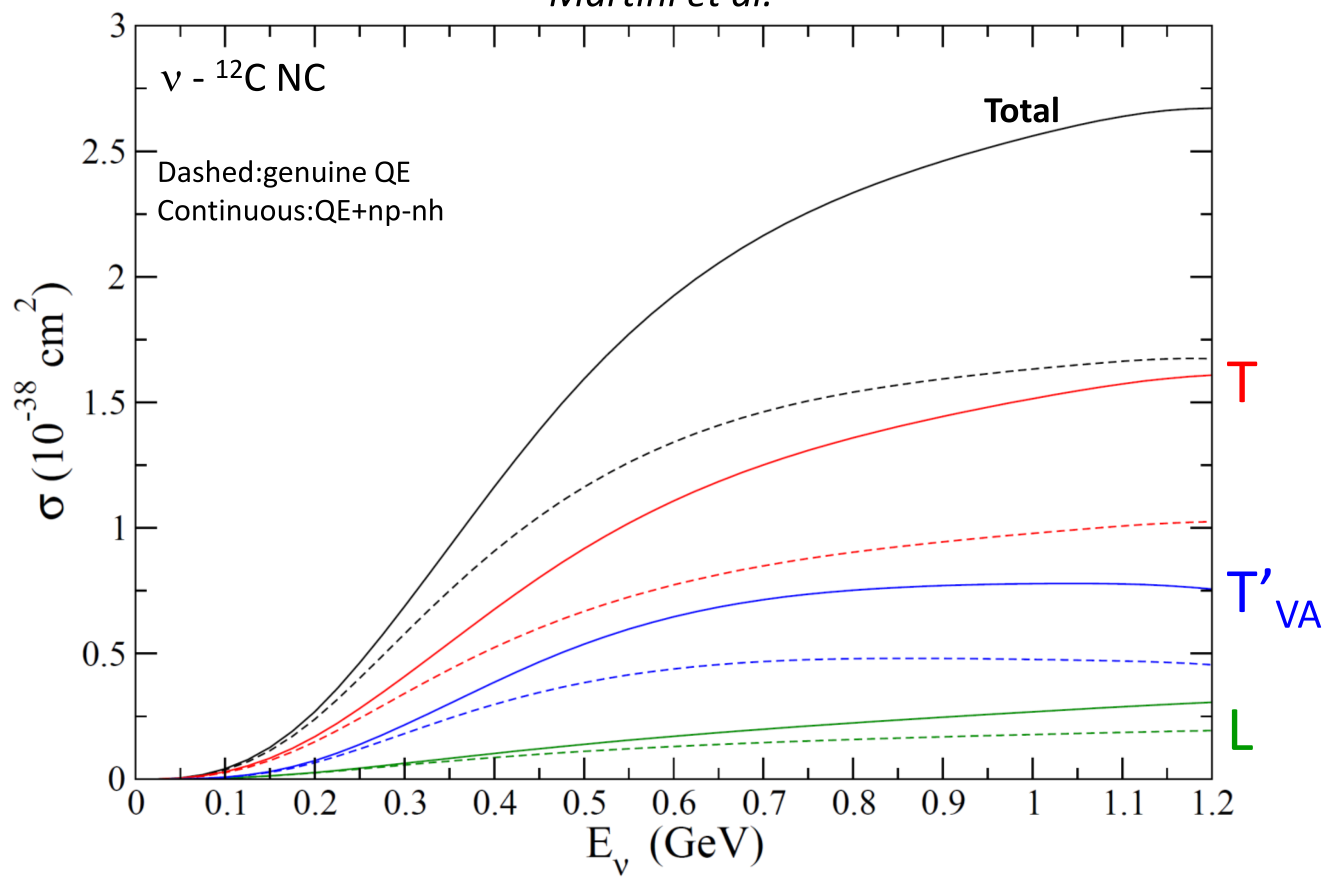


Cross section

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

Longitudinal — Transverse — Transverse VA Interf.

Martini et al.

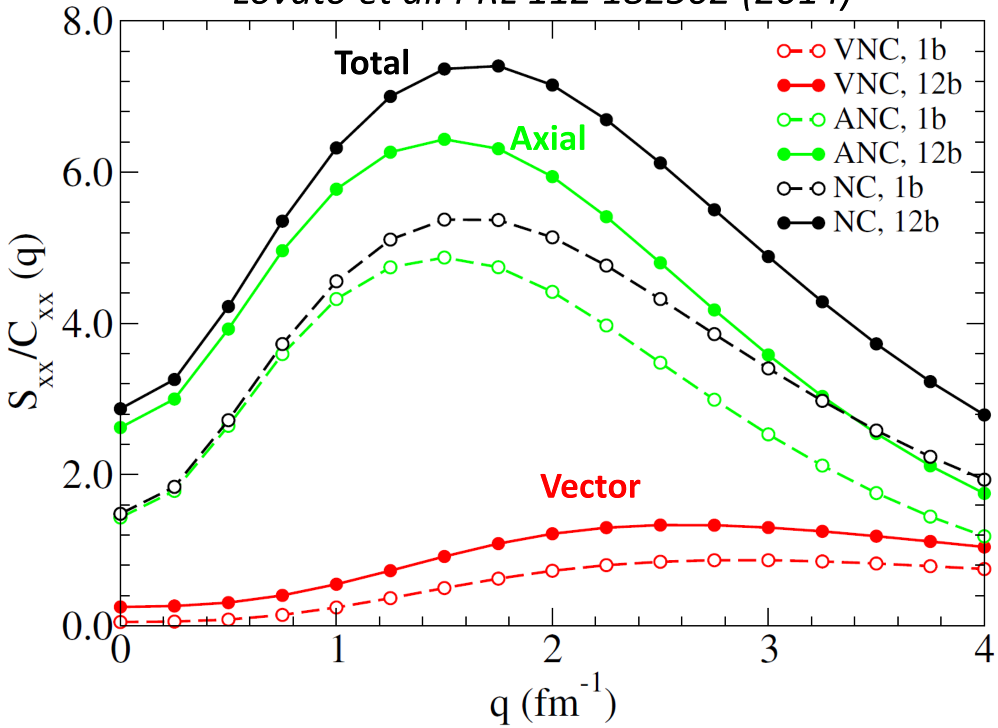


In both approaches 2p-2h are important in **all components** (but the charge)

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

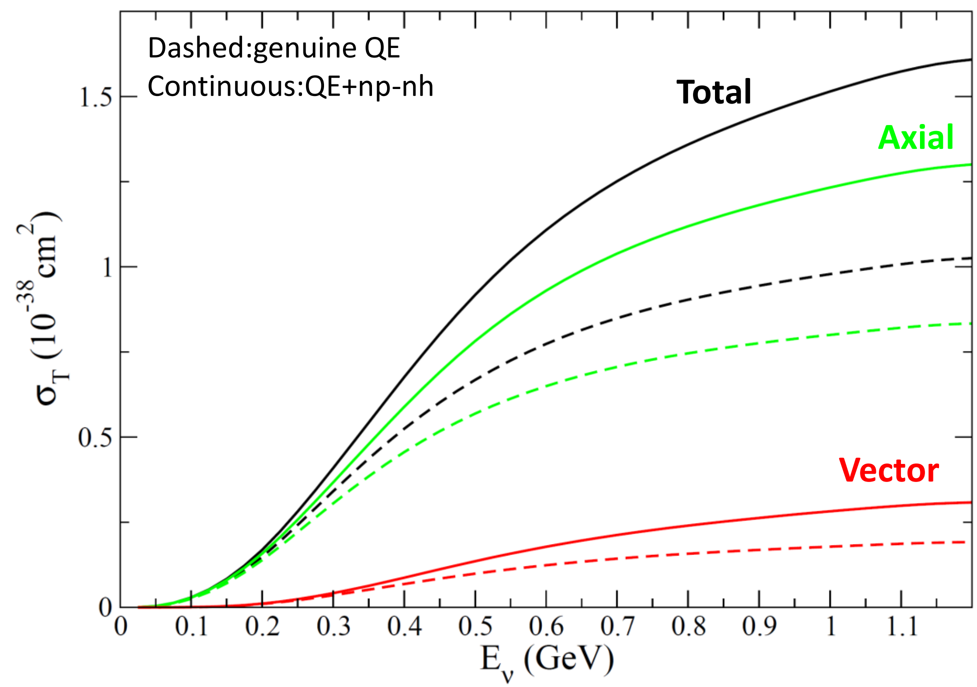
Sum rule of the Transverse response multiplied by the form factors

Lovato et al. PRL 112 182502 (2014)



Transverse contribution to the NC cross section

Martini et al.



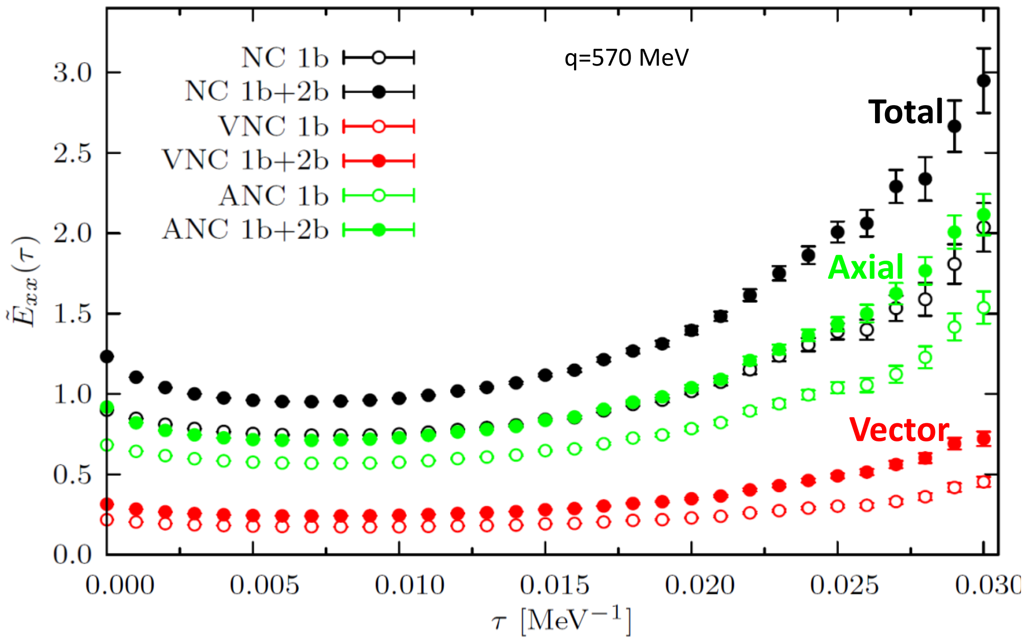
In both approaches, similar behavior:

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

Some instructive comparison of two different quantities (II bis)

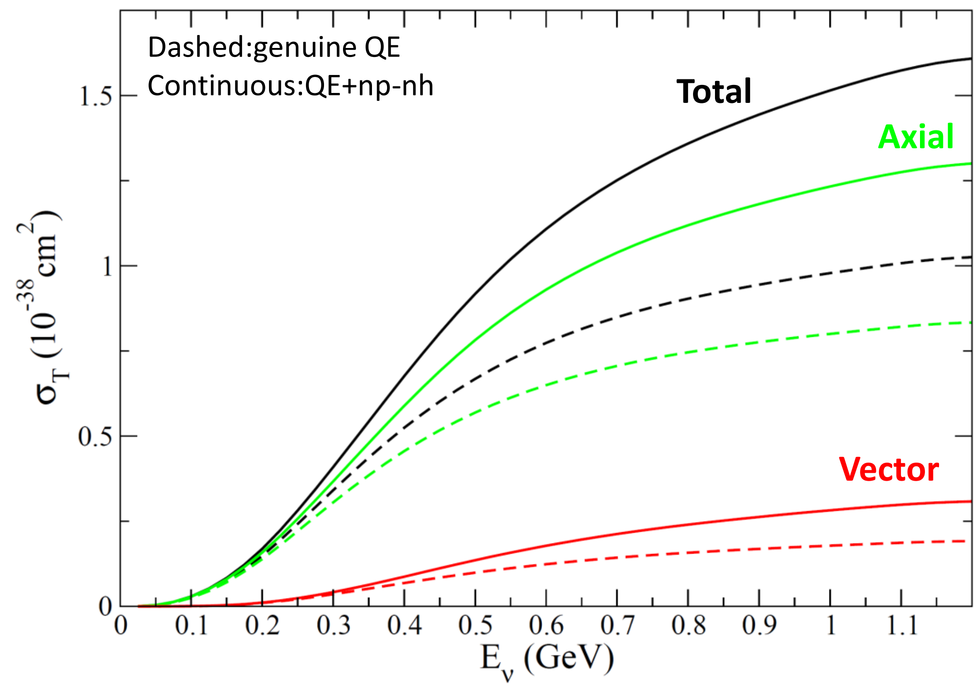
Euclidean NC transverse response

Lovato et al. arXiv 1501.01981(2015)



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

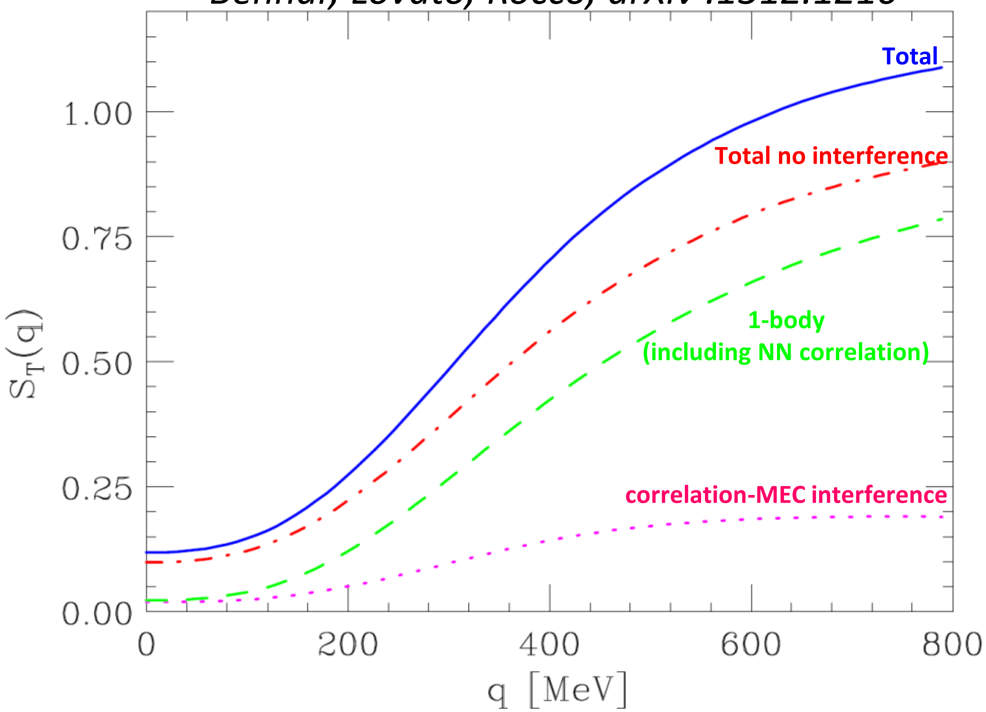
R_V+R_A
↑

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

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

Sum rule of the transverse response

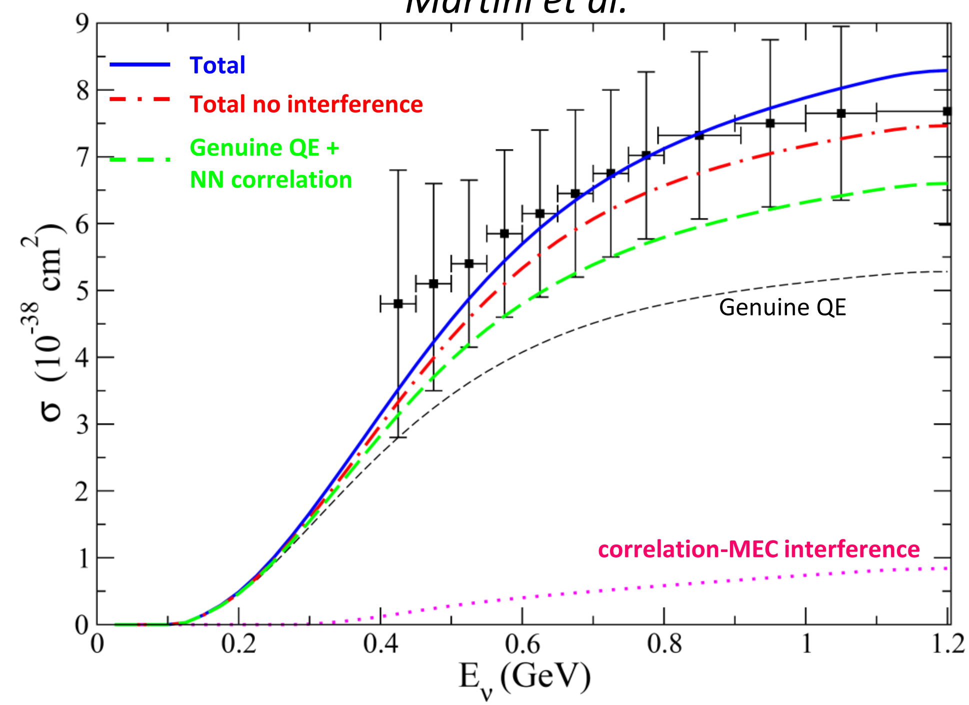
Benhar, Lovato, Rocco, arXiv :1312.1210



- 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"

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

Martini et al. *Nieves et al.* *Amaro et al. (only vector MEC)* *Lovato et al.* *Bodek et al.*

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

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

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

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

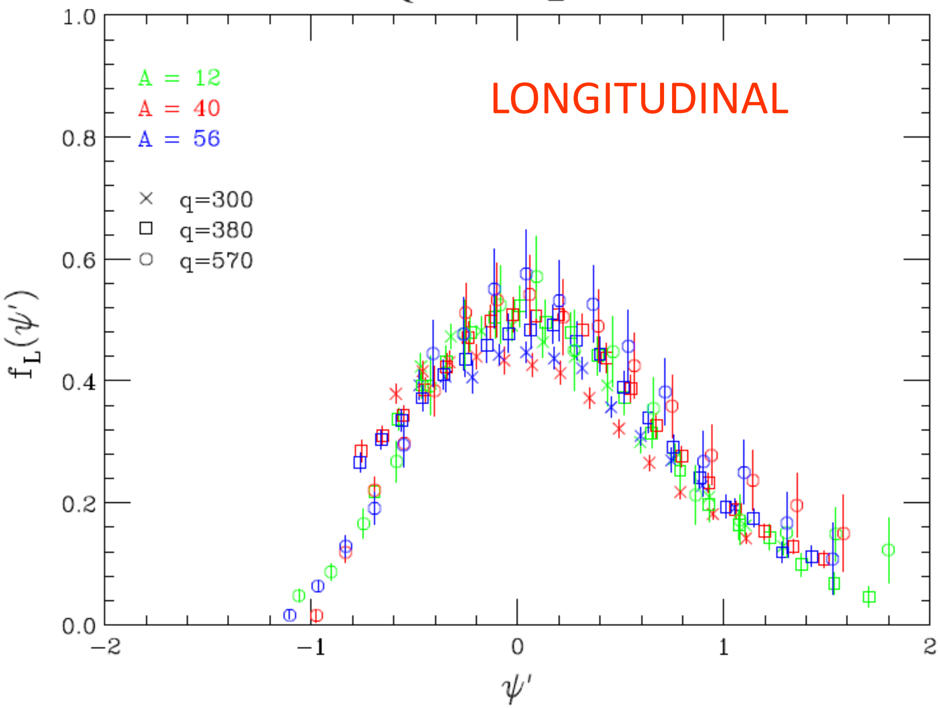
Relative role of 2p-2h for neutrinos and antineutrinos is different due to the **interference term**

Neutrino scattering

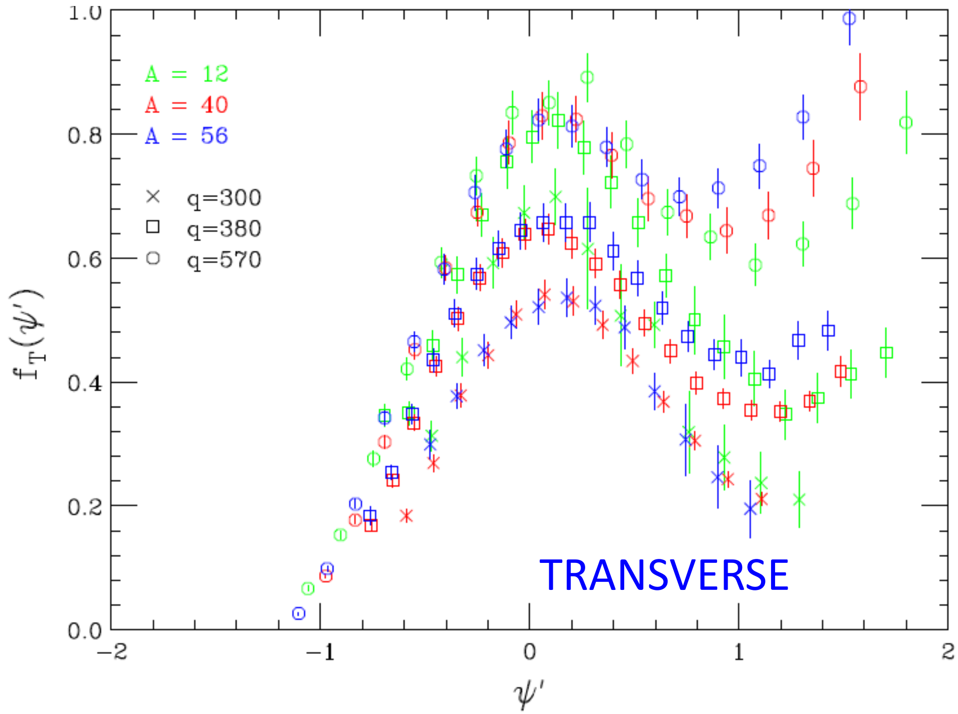
$$\frac{\partial^2\sigma}{\partial\Omega\,\partial\epsilon'} = \frac{G_F^2\cos^2\theta_c}{2\pi^2}k'\epsilon'\cos^2\frac{\theta}{2}\left[\frac{(q^2-\omega^2)^2}{q^4}G_E^2 R_\tau + \frac{\omega^2}{q^2}G_A^2 R_{\sigma\tau(L)} + 2\left(\tan^2\frac{\theta}{2}+\frac{q^2-\omega^2}{2q^2}\right)\left(G_M^2\frac{\omega^2}{q^2}+G_A^2\right)R_{\sigma\tau(T)}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

Electron scattering

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



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



Megias, Amaro, Barbaro, Caballero, Donnelly

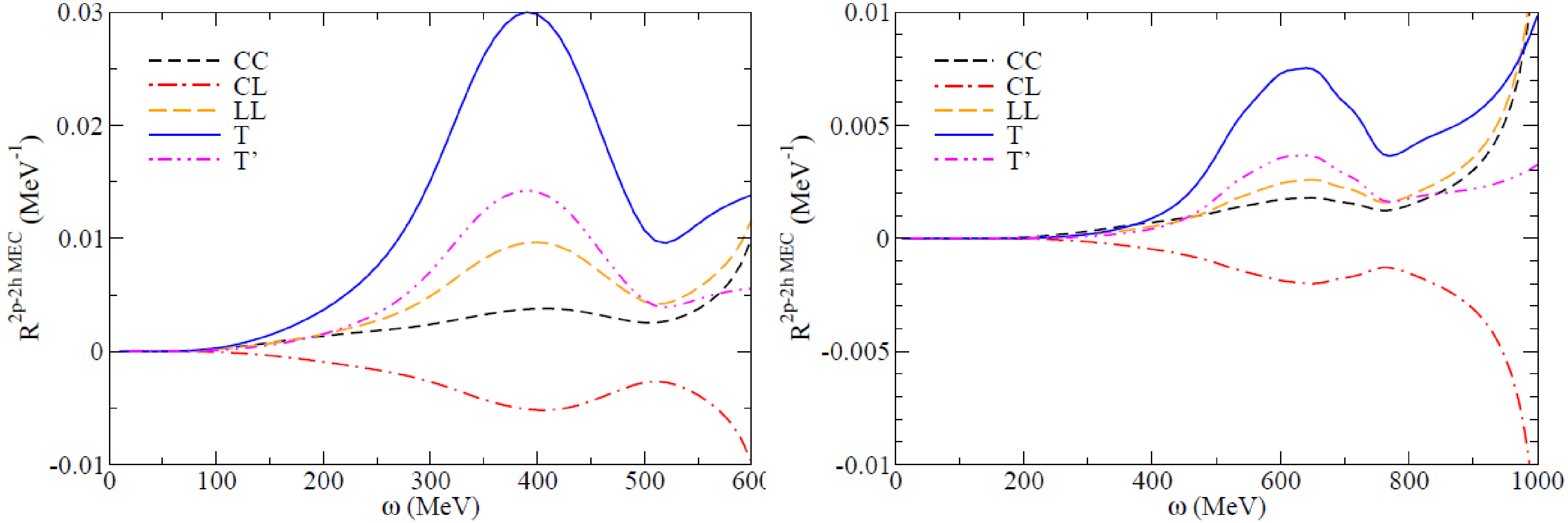


FIG. 1: (Color online) Comparison between the different components (CC, CL, LL, T and T') of the 2p-2h MEC response at different fixed values of the momentum transferred (q=600 MeV/c [left panel], q=1000 MeV/c [right panel]).

Megias, Amaro, Barbaro, Caballero, Donnelly

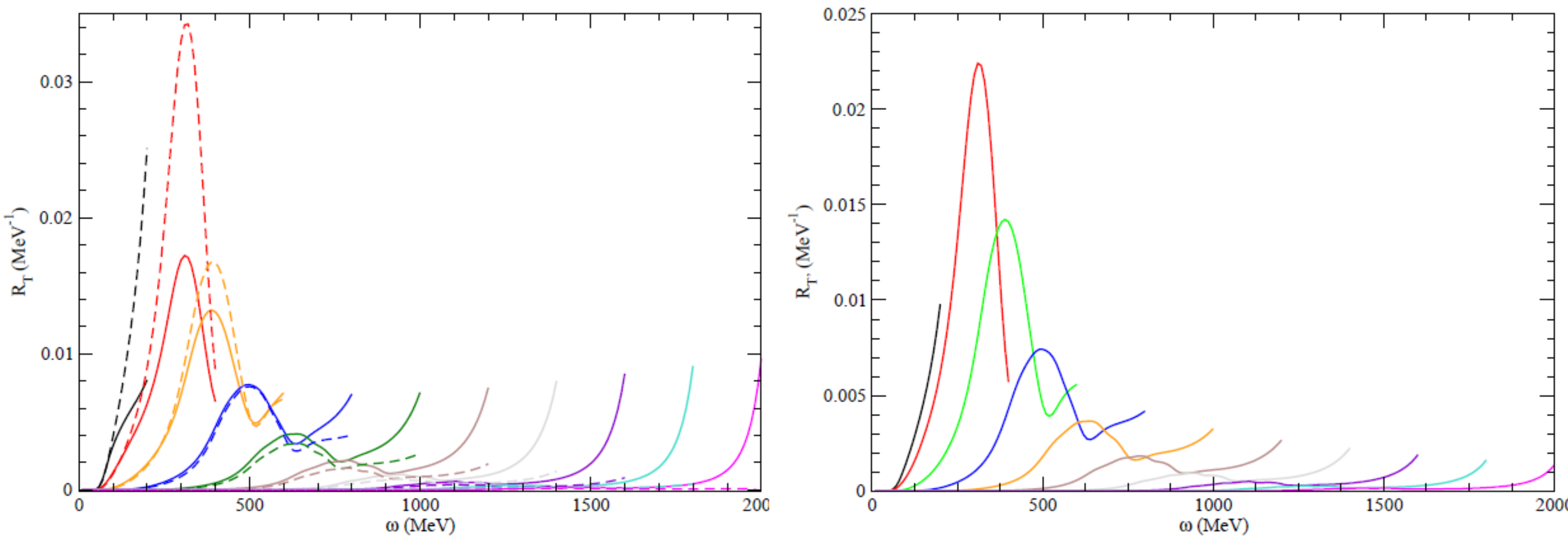


FIG. 2: (Color online) 2p-2h MEC transverse responses in terms of the energy transferred (ω) at different fixed values of the momentum transferred (q) from q=200 MeV/c to q=2000 MeV/c in steps of 200 MeV/c (from left to right). Left panel shows the vector-vector (solid lines) and axial-axial (dashed lines) responses whereas the right panel shows the interference vector-axial ones.

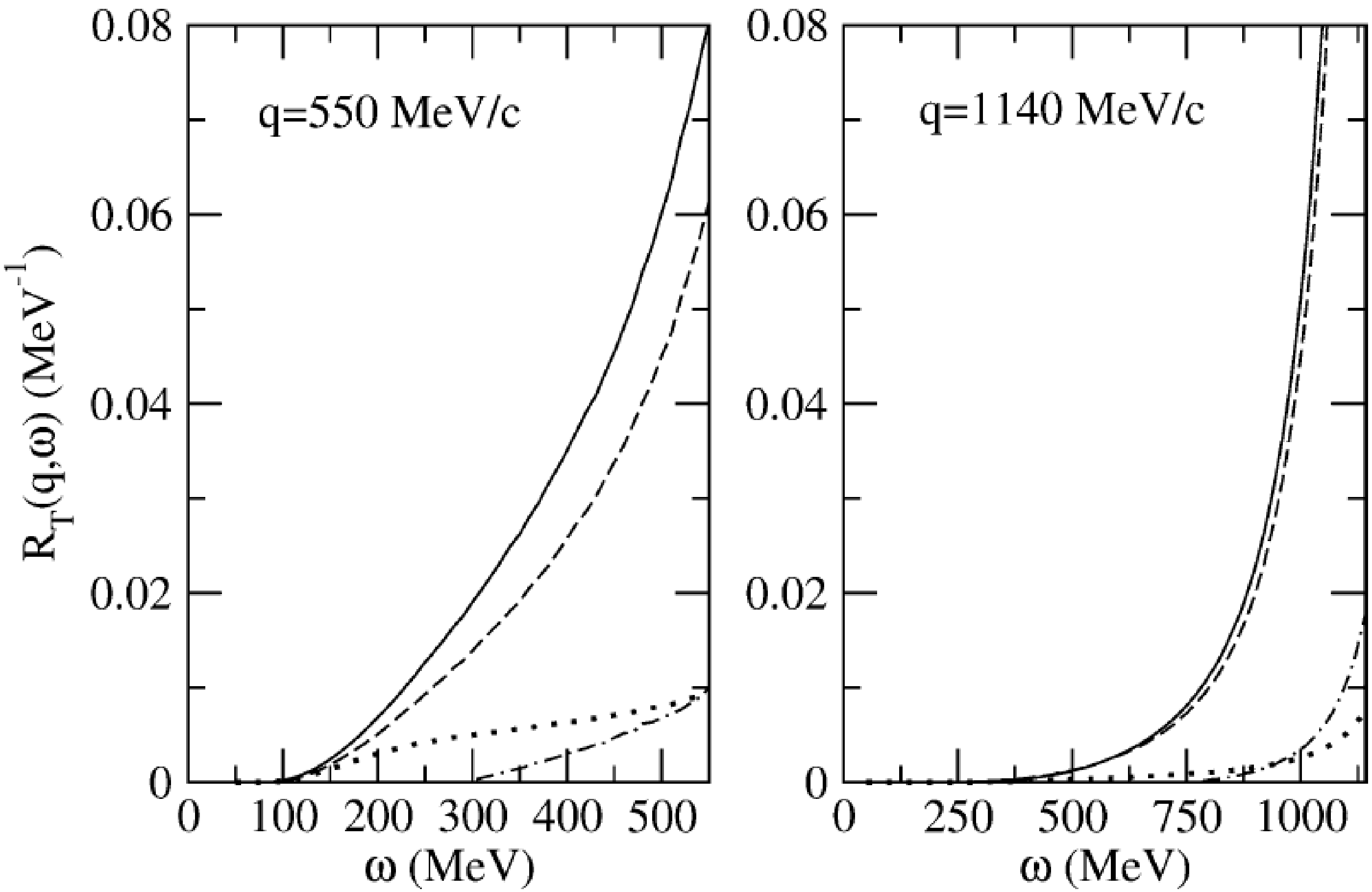


Fig. 9. Separate contributions to the transverse response function $R_T(q,\omega)$ in the non-relativistic limit at $q = 550$ MeV$/c$ and $q = 1140$ MeV$/c$: pionic (dotted), pionic–Δ interference (dash-dotted), Δ (dashed) and total (solid); $k_F = 1.3$ fm^{-1}. The exchange contribution is disregarded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

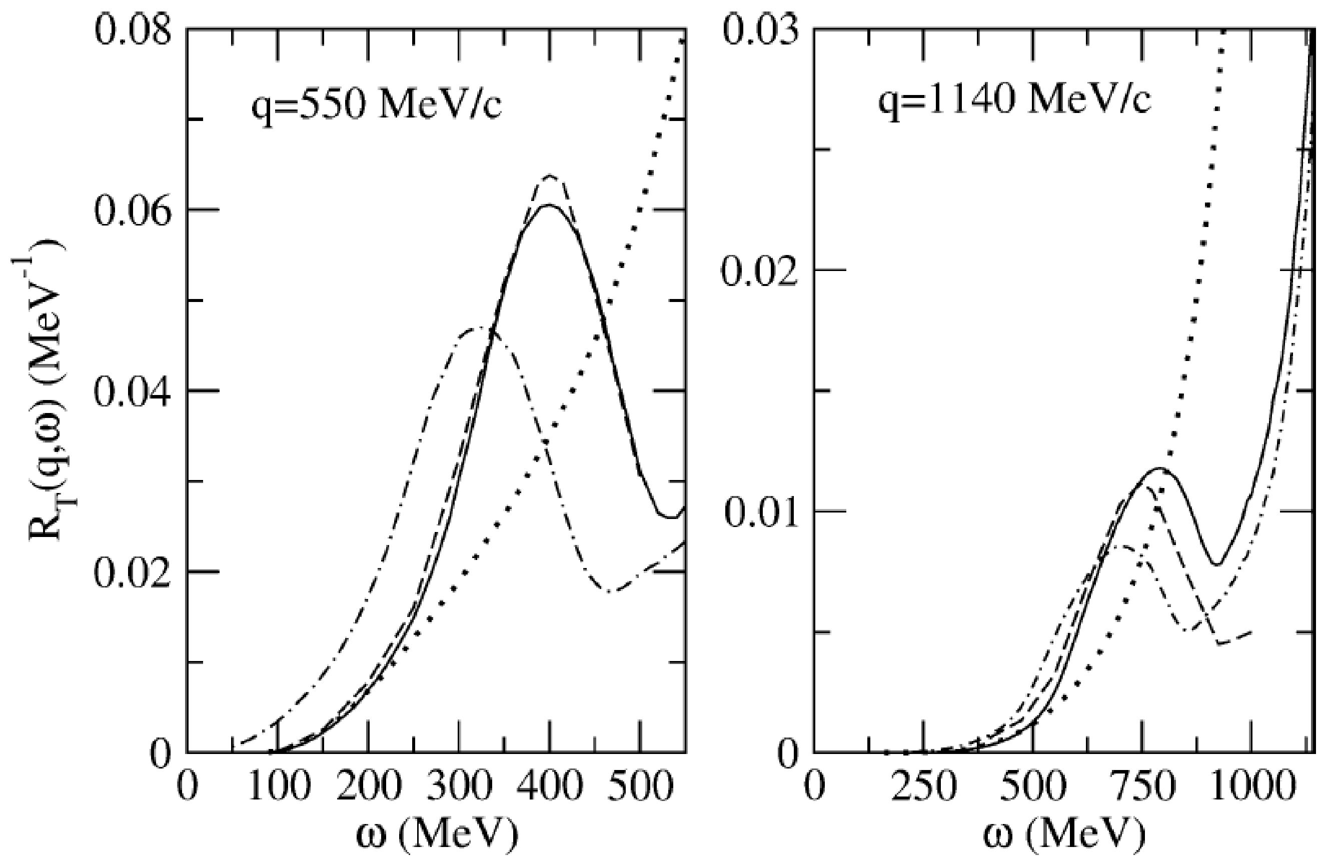
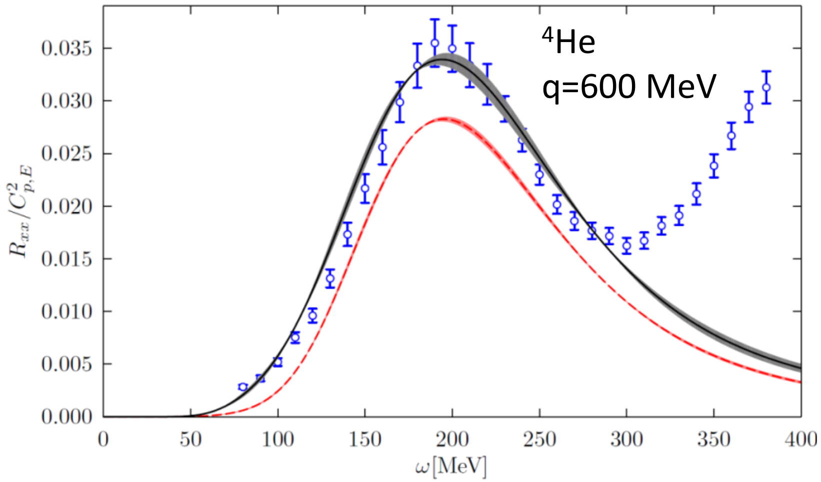


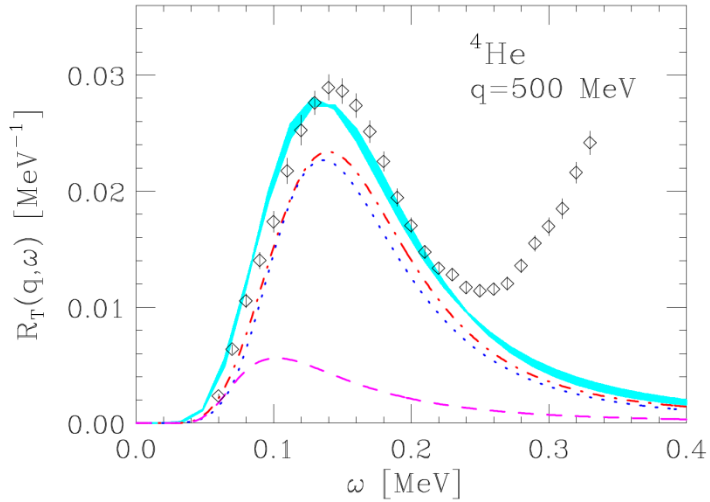
Fig. 8. The relativistic transverse response function $R_T(q,\omega)$ at $q = 550$ MeV$/c$ and $q = 1140$ MeV$/c$ calculated with $\bar{\epsilon}_2 = 70$ MeV (solid) and with $\bar{\epsilon}_2 = 0$ (dot-dashed). Only the direct contribution is shown. The non-relativistic results are also displayed in 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}.

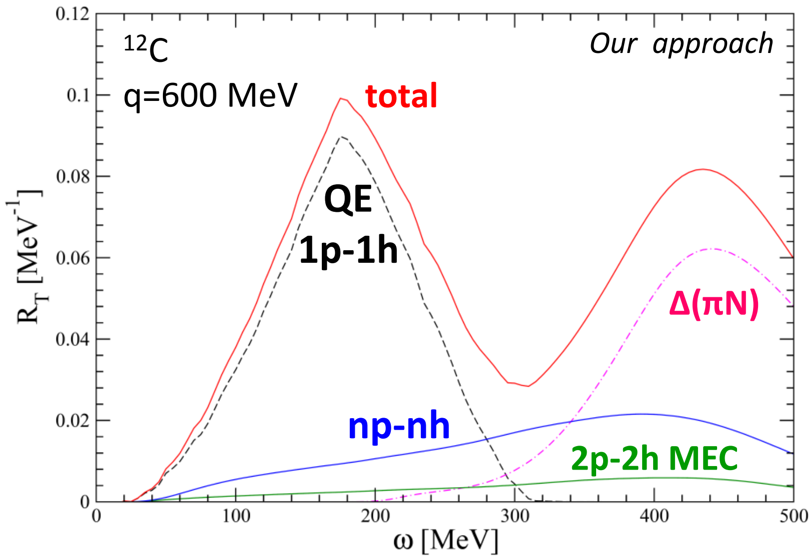
Electromagnetic transverse responses: some figures for discussion

Lovato et al.arXiv 1501.01981

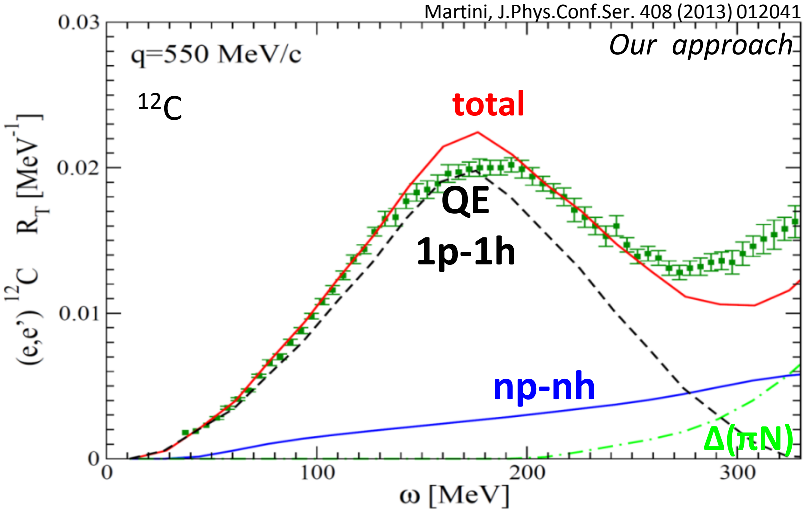


Benhar et al.arXiv 1502.00887



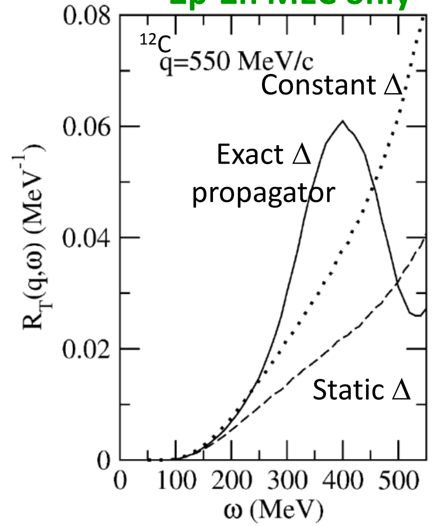


Martini, J.Phys.Conf.Ser. 408 (2013) 012041



De Pace et al. NPA741, 249 (2004)

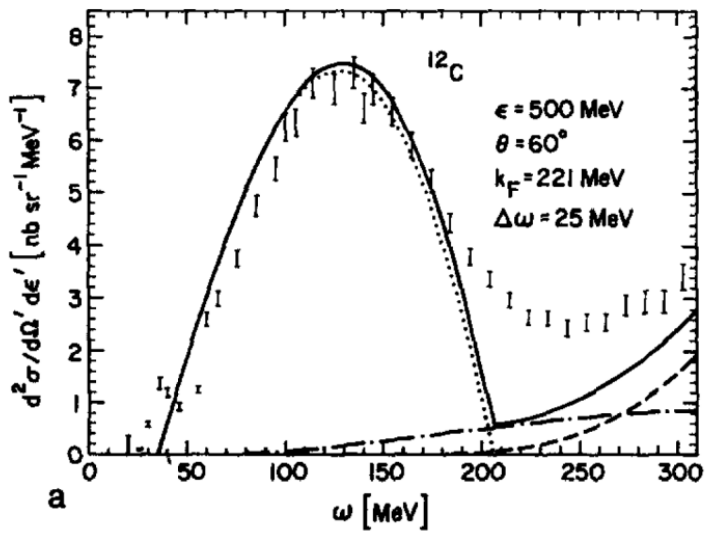
2p-2h MEC only



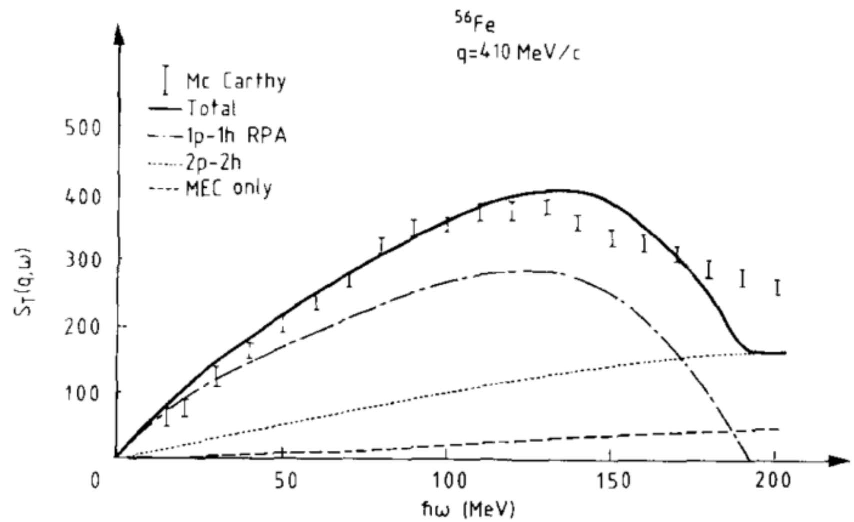
- Why the 2-body current contribution didn't increase with ω in the case of Lovato et al. at difference with respect to many other calculations (see also next slide)?
- As shown by De Pace et al. the increase with ω appears also if one considers static or constant Δ propagator

Electromagnetic transverse responses: different theoretical calculations

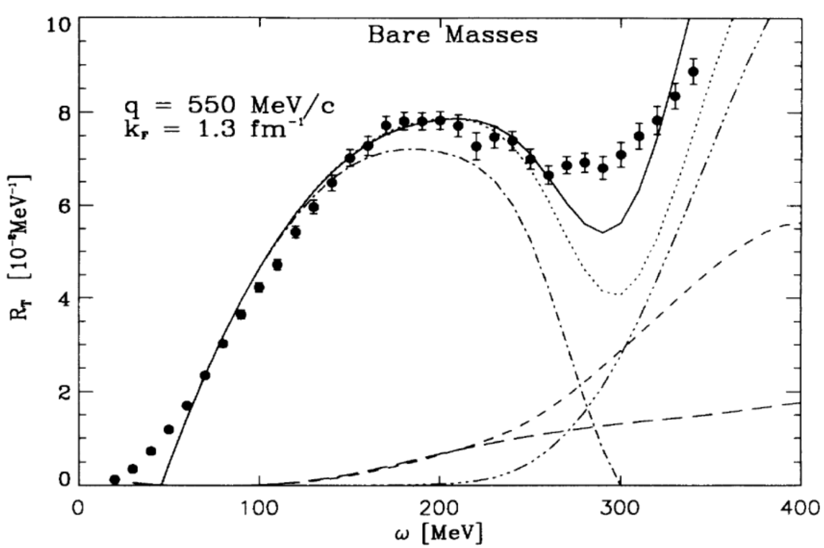
Van Orden, Donnelly, Ann. Phys. 131, 451 (1981)



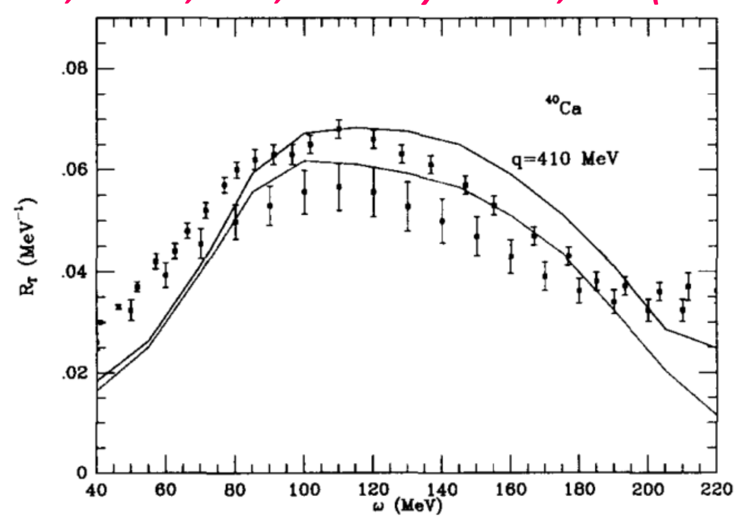
Alberico, Ericson, Molinari, Ann. Phys. 154, 356 (1984)

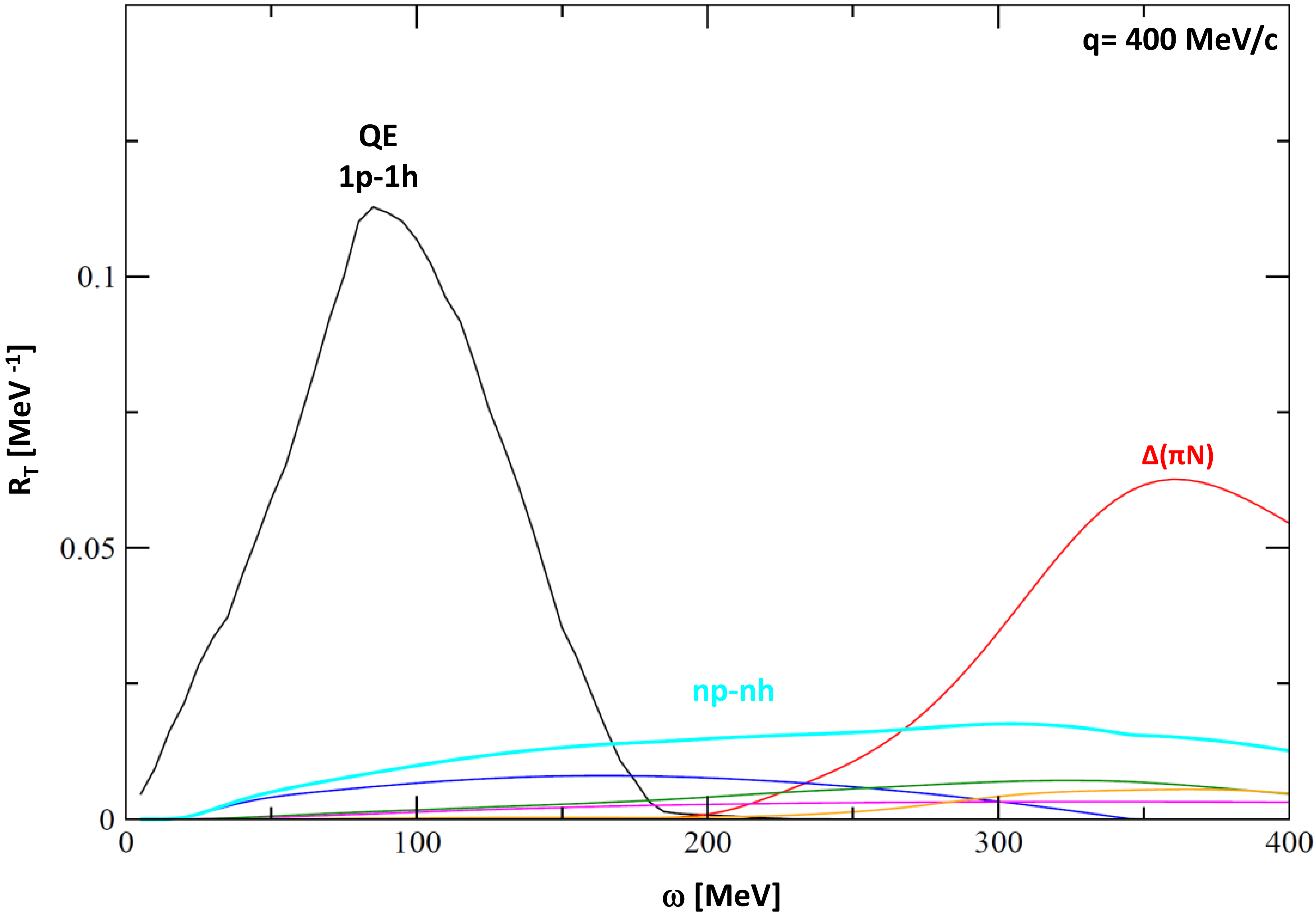


Dekker, Brussaard, Tjon, Phys. Rev. C 49 ,2650 (1994)



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

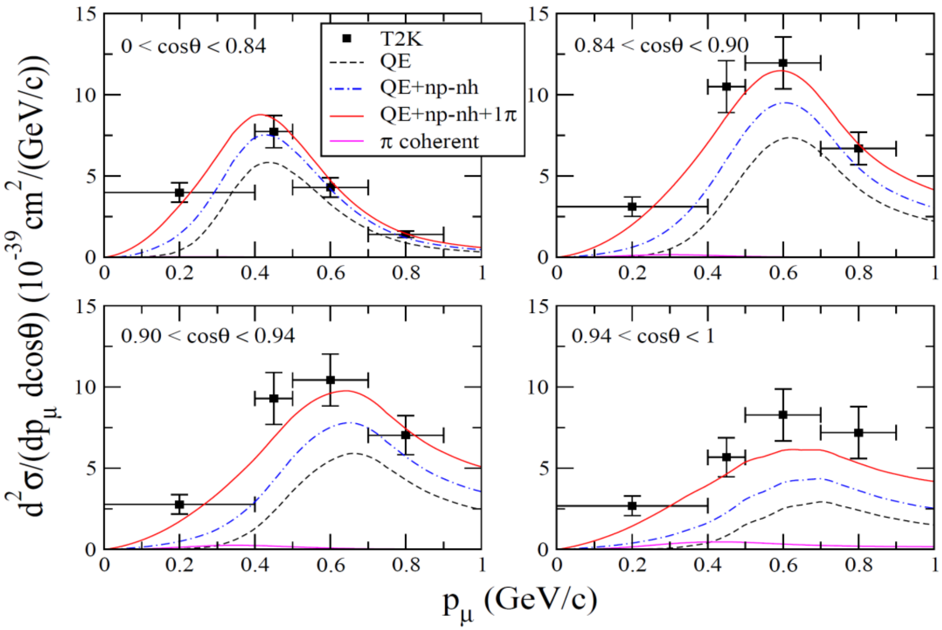




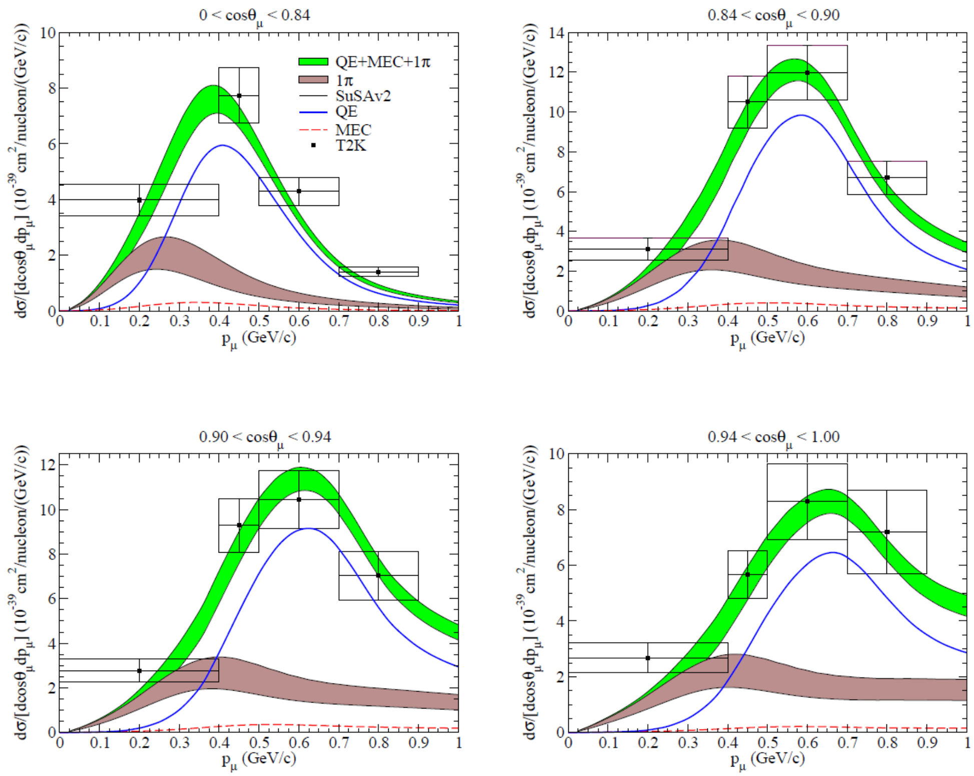
q= 400 MeV/c
QE
1p-1h
Δ(πN)
np-nh
R_T [MeV $^{-1}$]
0.1
0.05
0
0
100
200
300
400
ω [MeV]

ν_μ T2K flux-integrated **inclusive** double differential cross section on carbon

M. Martini, M. Ericson Phys. Rev. C 90 025501 (2014)



Ivanov, Megias et al. arXiv 1506.00801 (2015)



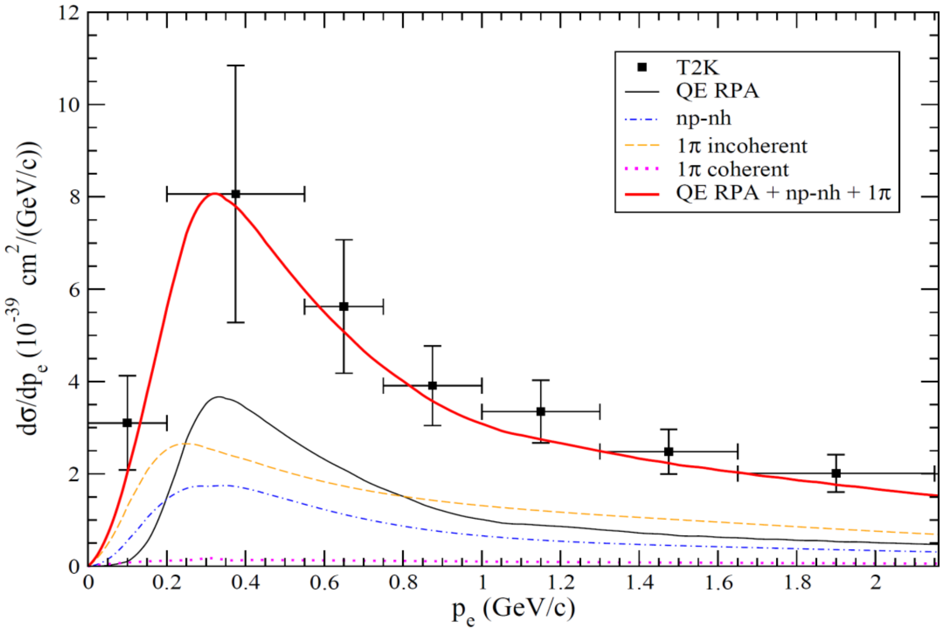
Agreement with data

With respect to Martini and Ericson:
larger genuine QE (no RPA quenching) and lower np-nh contributions (only MEC and only in the vector sector)

ν_e T2K flux-integrated inclusive differential cross section on carbon

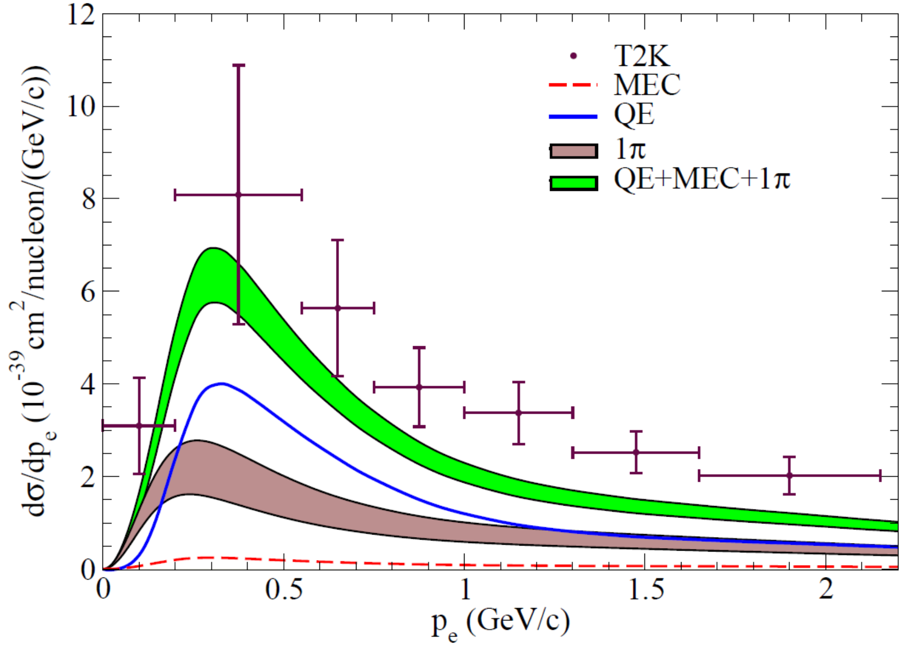
T2K: *PRL 113, 241803 (2014)*

Martini et al., arXiv: 1602.00230 (2016)

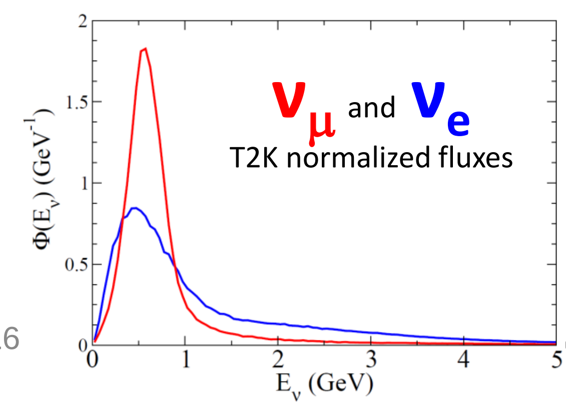


- Agreement with data (small tendency to underestimate)
- Important presence of np-nh which even dominates the genuine QE for small p_e

Ivanov, Megias et al. arXiv 1506.00801 (2015)



- Underestimation of the data
- Small np-nh contribution (only vector, only MEC)



- Important tail in the electronic neutrino flux
- In the ν_e case other reaction mechanisms such as multi-meson production and DIS expected to be most important with respect to the ν_μ case

Theoretical calculations on np-nh contributions to ν-nucleus cross sections

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 $d^2\sigma$, $d\sigma/dQ^2$
Phys. Rev. C 90 025501 (2014) inclusive ν $d^2\sigma$
Phys. Rev. C 91 035501 (2015) combining ν and antiν $d^2\sigma$, $d\sigma/dQ^2$

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, T.W. Donnelly, I. Ruiz Simo, G. Megias et al. (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
Phys. Rev. D 90 033012 (2014) 2p-2h phase space
Phys. Rev. D 90 053010 (2014) angular distribution
Phys. Rev. D 91 073004 (2015) parametrization of vector MEC

Two-body contributions to sum rules and responses in the electroweak sector

A. Lovato, S. Gandolfi, J. Carlson, S. C. Pieper, R. Schiavilla (Ab-initio many-body)

Phys. Rev. Lett. 112 182502 (2014) 12C sum rules for Neutral Current

arXiv 1501.01981 (2015) 4He and 12C responses for Neutral Current

Effective models taking into account np-nh excitations

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

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

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

$$G_{Mp}^{nuclear}(Q^2) = G_{Mp}(Q^2) \times \sqrt{1 + AQ^2 e^{-Q^2/B}}$$

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

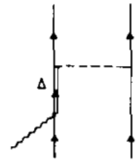
Analogies and differences of 2p-2h

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

π

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

[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

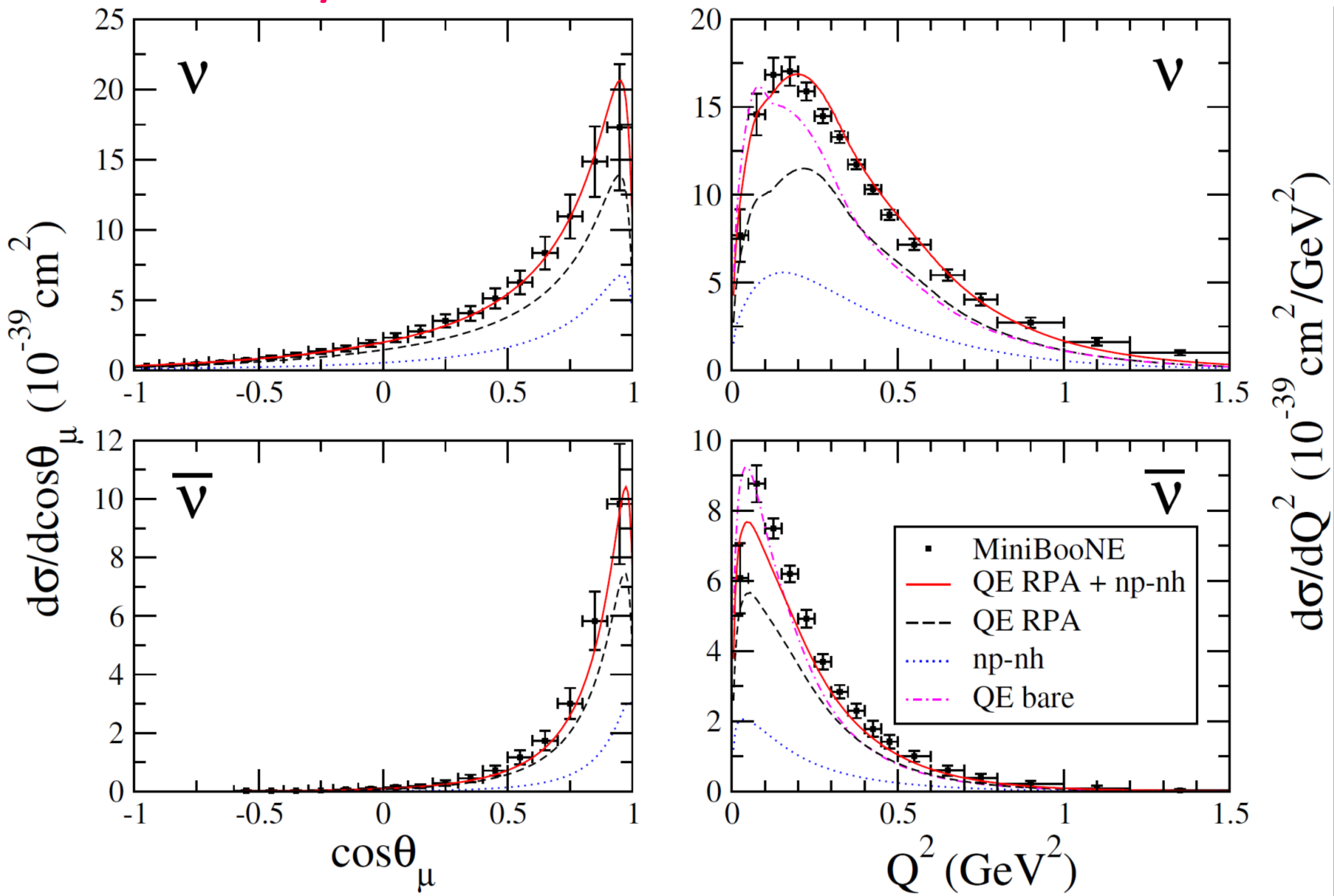
[Genuine QE (1 body contribution): GFMC with AV18 and IL7 potentials]

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”

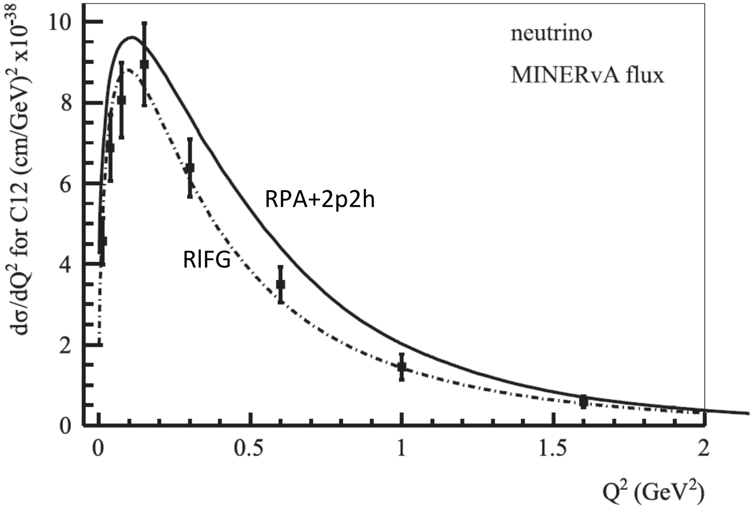
dσ/dcosθ Q^2 distributions



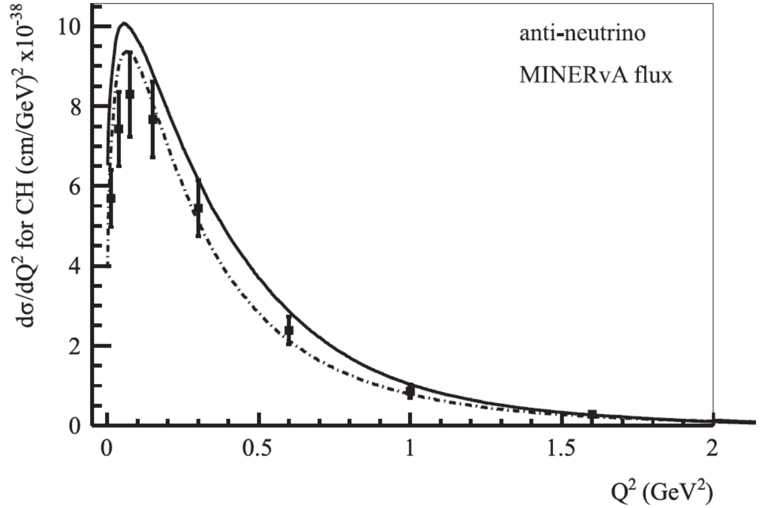
- Antineutrino cross section falls more rapidly than the neutrino one
- Antineutrino Q^2 distribution peaks at smaller Q^2 values than the neutrino one
- RPA effects disappears beyond $Q^2 \geq 0.3$ GeV^2 where the np-nh contribution is required

ν

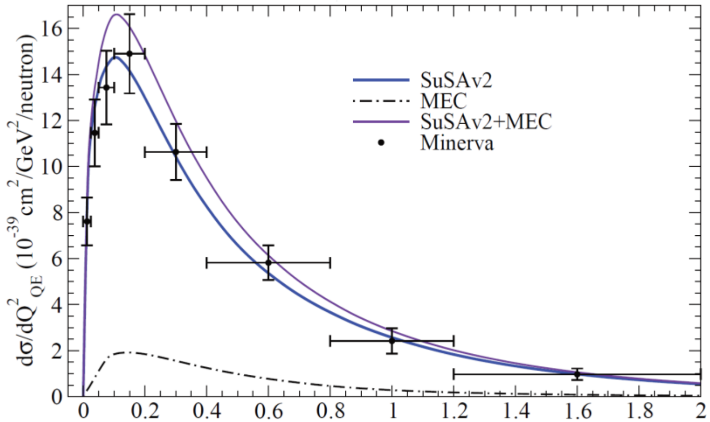
Gran, Nieves et al.
PRD 88 (2013)

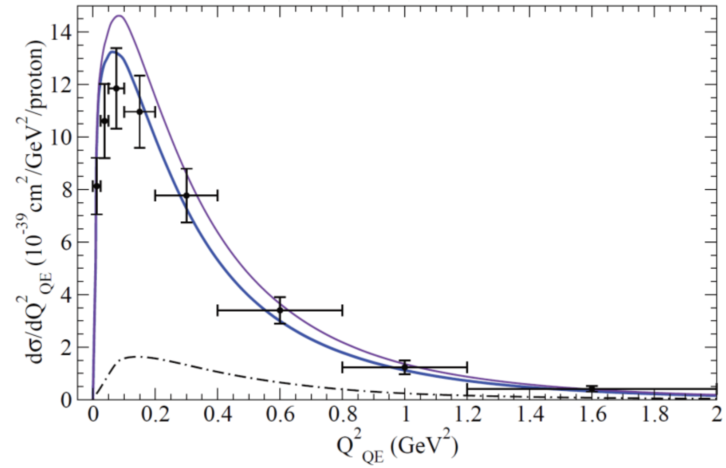


$\bar{\nu}$

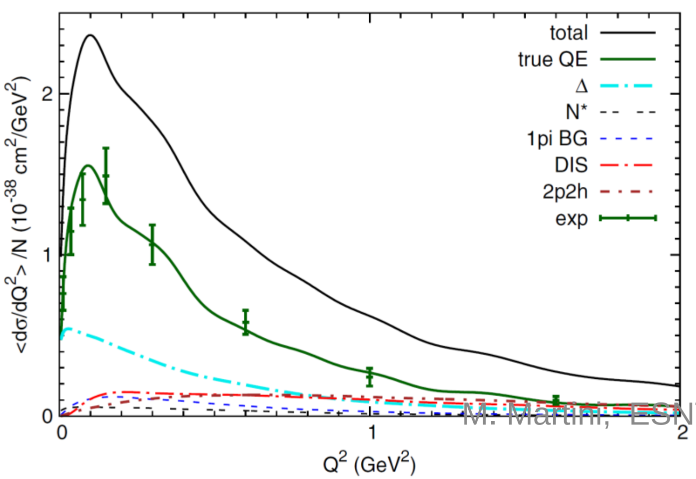


Megias, Amaro et al.
arXiv 1412.1822





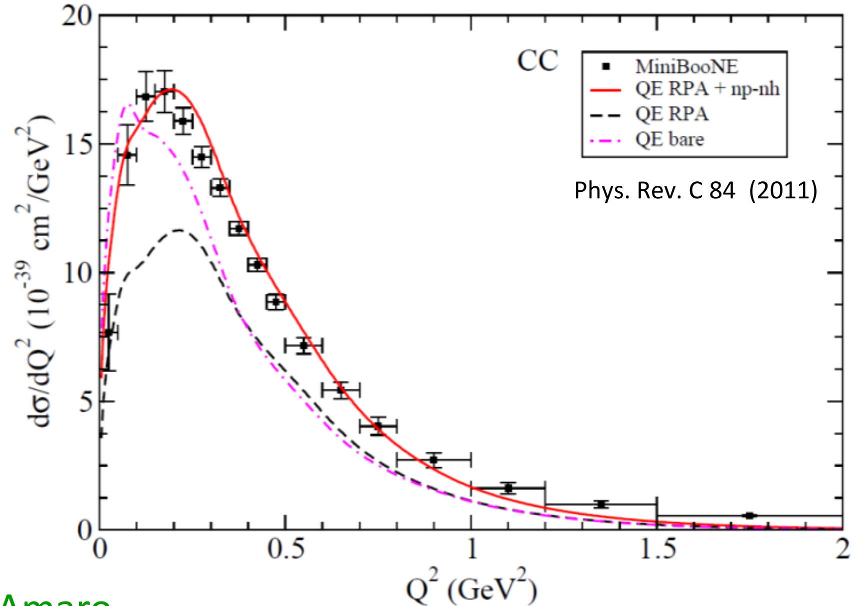
Mosel et al.
PRD 89 (2014)

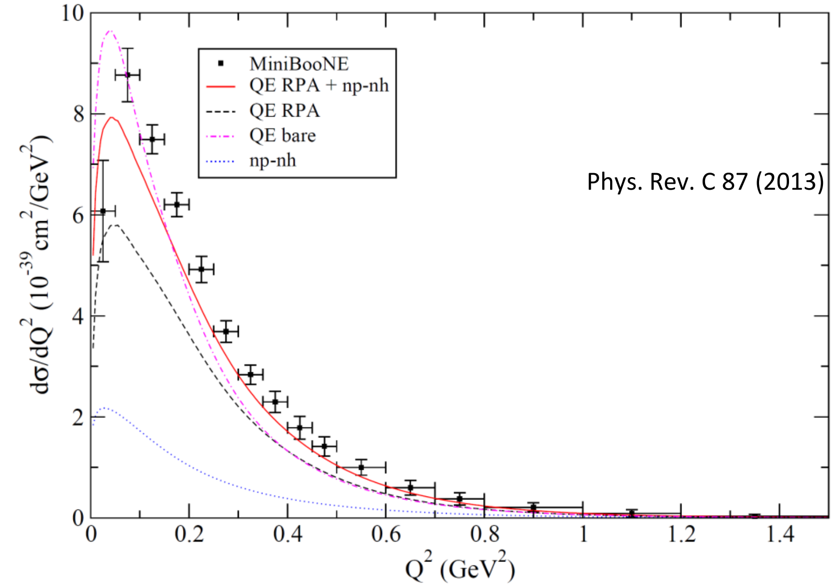


- **MINERνA Q^2 distributions can be reproduced also without the inclusion of np-nh**
- **This is not the case of the MiniBooNE Q^2 distributions**
- Mosel et al: “The sensitivity to details of the treatment of np-nh contributions is smaller than the uncertainties introduced by the Q^2 reconstruction and our insufficient knowledge of pion production”

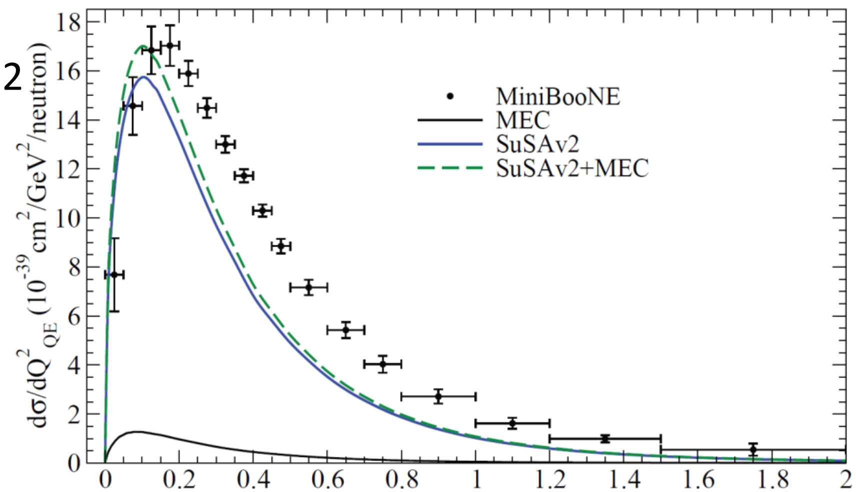
ν Coming back to MiniBooNE CCQE: the Q^2 distributions $\bar{\nu}$

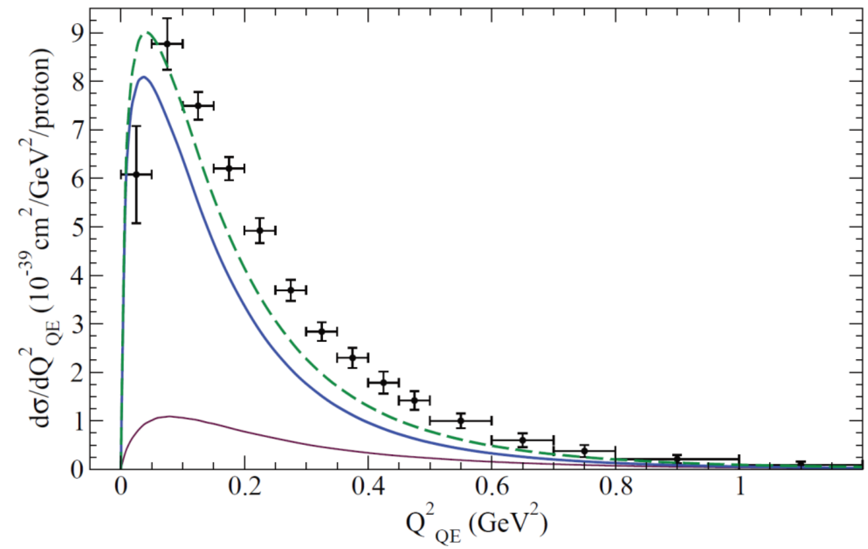
Martini et al.





Megias, Amaro et al.
1412.1822

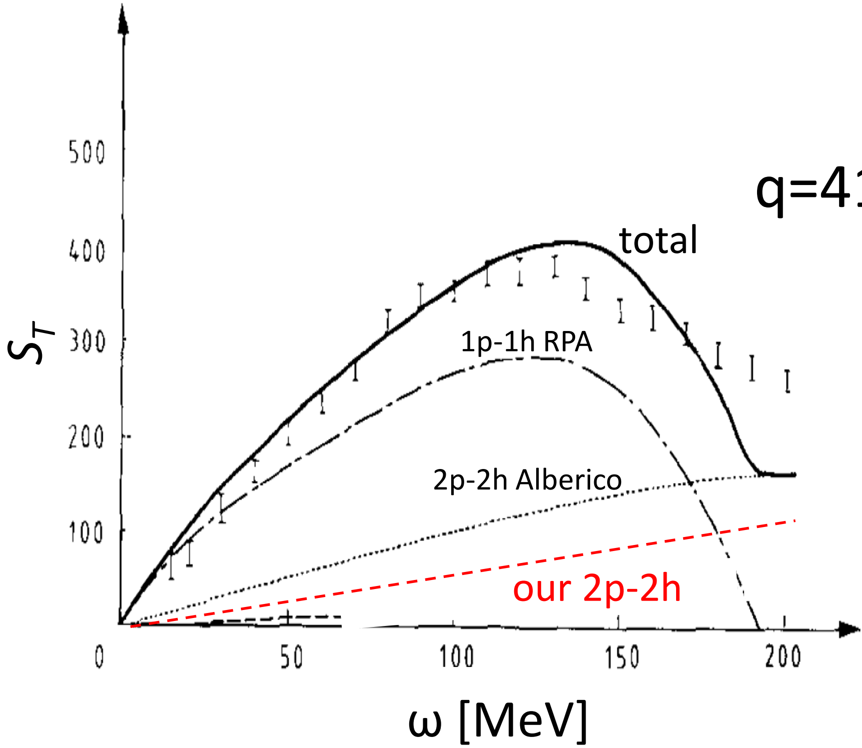




p.s. the additional normalization uncertainty in the MiniBooNE data of 10% for neutrinos and of 17.2% for antineutrinos is not shown here

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

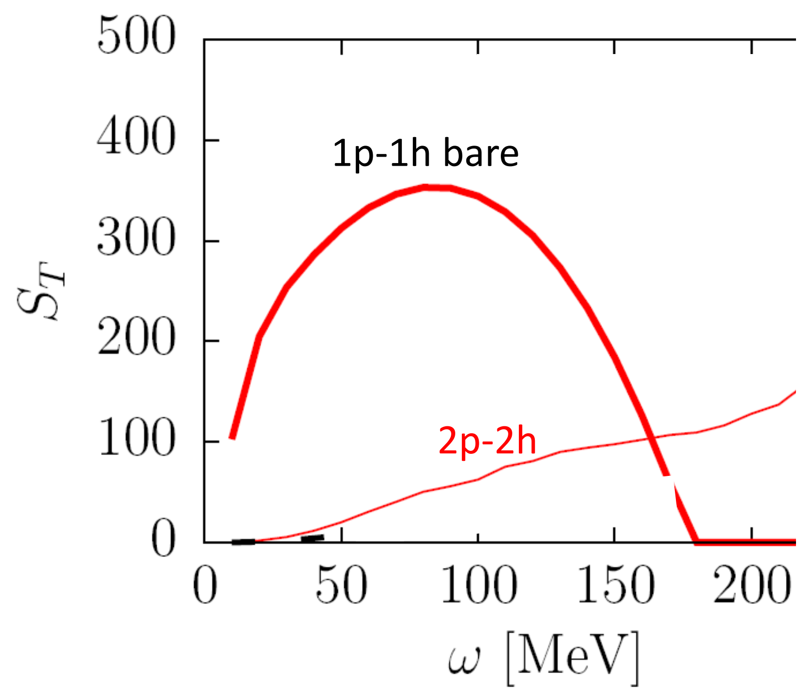
Alberico et al. Ann. Phys. 154, 356 (1984)



^{56}Fe

q=410 MeV/c

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



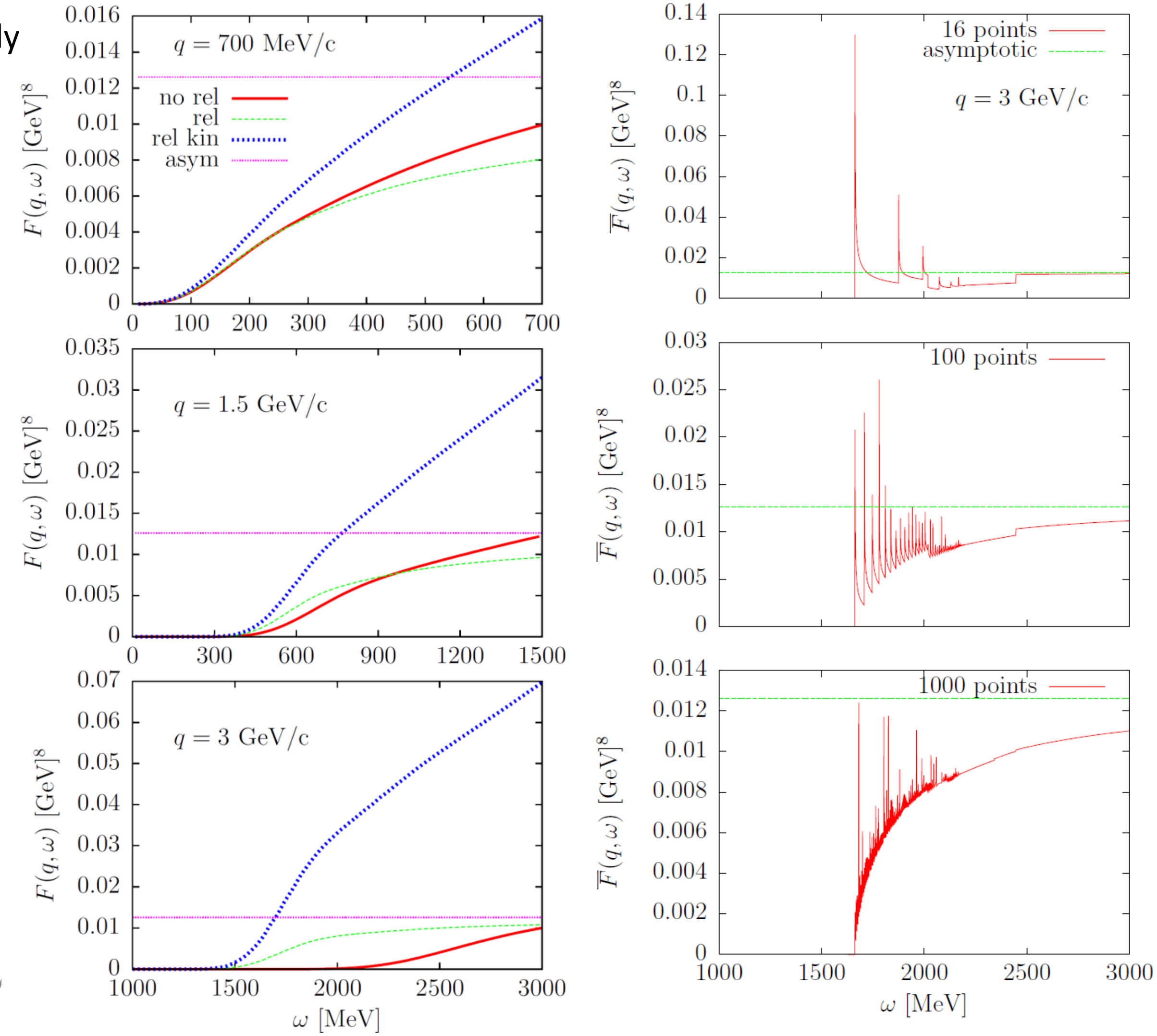
Our parameterization is quite close to the results of Amaro et al.

2p-2h phase space integral

$$F(\omega,q) \equiv \int d^3h_1\, d^3h_2\, d^3p'_1\, \frac{m_N^4}{E_1E_2E'_1E'_2}\Theta(p'_1,p'_2,h_1,h_2)\delta(E'_1+E'_2-E_1-E_2-\omega)$$

$$\overline{F}(\omega,q) = \left(\frac{4}{3}\pi k_F^3\right)^2 \int d^3p'_1\, \delta(E'_1+E'_2-\omega-2m_N)\,\Theta(p'_1,p'_2,0,0)\,\frac{m_N^2}{E'_1E'_2}$$

Ruiz Simo, Albertus, Amaro, Barbaro, Caballero, Donnelly
Phys. Rev. D 90 033012 (2014)
Phys. Rev. D 90 053010 (2014)



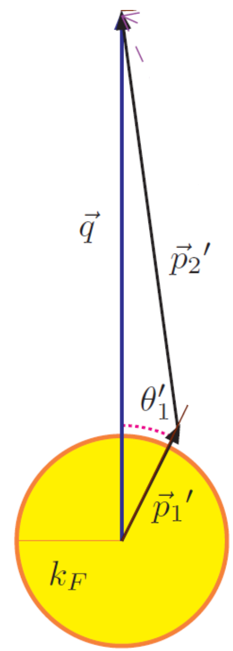
Angular distribution of ejected nucleons

$$\overline{F}(\omega,q) = \left(\frac{4}{3}\pi k_F^3\right)^2 2\pi \int_0^\pi d\theta'_1\, \Phi(\theta'_1)$$

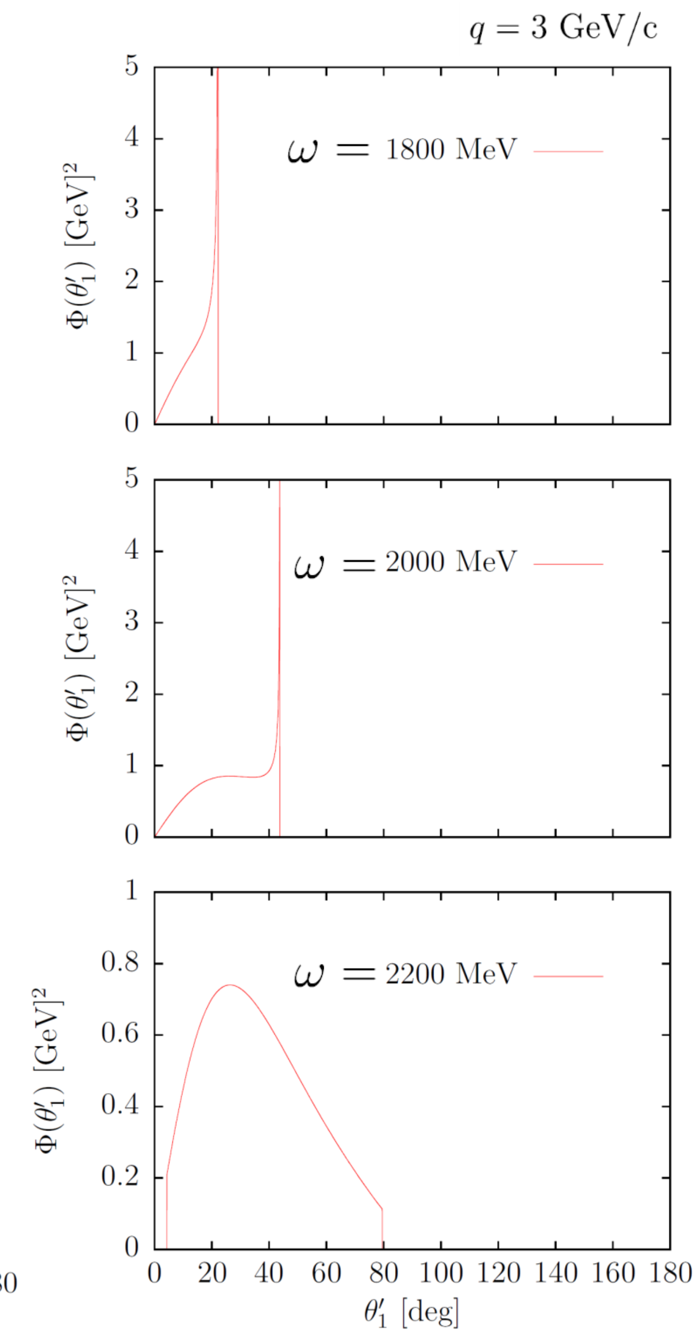
$$\Phi(\theta'_1) = \sin\theta'_1 \int p'^2_1 dp'_1 \delta(E_1 + E_2 + \omega - E'_1 - E'_2)$$

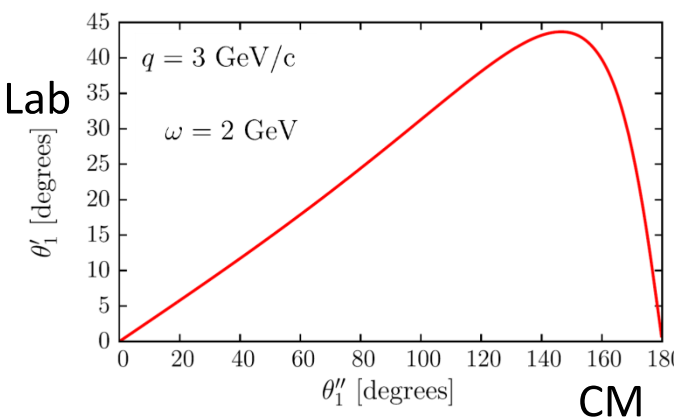
$$\times\, \Theta(p'_1, p'_2, h_1, h_2) \frac{m_N^4}{E_1 E_2 E'_1 E'_2}$$

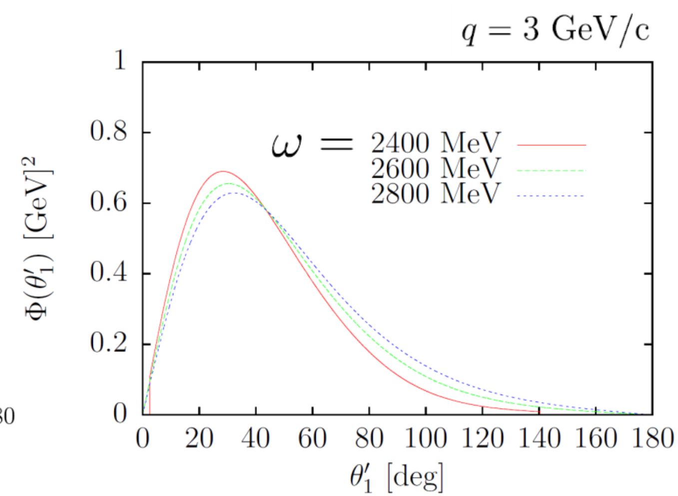
$$= \sum_{\alpha=\pm} \frac{m_N^4 \sin\theta'_1 p'^2_1 \Theta(p'_1, p'_2, h_1, h_2)}{E_1 E_2 E'_1 E'_2 \left| \frac{p'_1}{E'_1} - \frac{\mathbf{p}'_2\cdot\hat{\mathbf{p}}'_1}{E'_2} \right|}\Bigg|_{p'_1 = p'^{(\alpha)}_1}$$



Ruiz Simo, Albertus, Amaro, Barbaro, Caballero, Donnelly
Phys. Rev. D 90 033012 (2014)
Phys. Rev. D 90 053010 (2014)







Single nucleon weak CC current

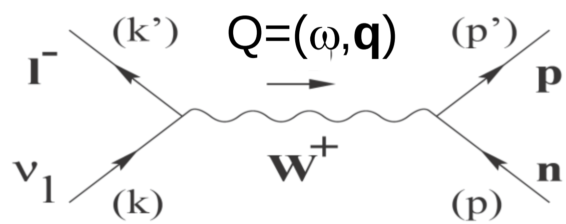
$$j^{\mu} = j_V^{\mu} - j_A^{\mu}$$

$$j_V^{\mu}(\mathbf{p}', \mathbf{p}) = \overline{u}(\mathbf{p}')\left[2F_1^V \gamma^{\mu} + i\frac{F_2^V}{m_N}\sigma^{\mu\nu}Q_{\nu}\right]u(\mathbf{p})$$

$$j_A^{\mu}(\mathbf{p}', \mathbf{p}) = \overline{u}(\mathbf{p}')\left[G_A \gamma^{\mu} + G_P \frac{Q^{\mu}}{2m_N}\right]\gamma^5 u(\mathbf{p})$$

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

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



Some two-body currents

Electromagnetic

- Seagull or contact:

$$j_{\mathrm{s}}^{\mu}(\mathbf{p}_1', \mathbf{p}_2', \mathbf{p}_1, \mathbf{p}_2) = \frac{f^2}{m_\pi^2}\, \mathrm{i}\epsilon_{3ab}\overline{u}(\mathbf{p}_1')\tau_a\gamma_5 \not{K}_1 u(\mathbf{p}_1)\frac{F_1^{\mathrm{V}}}{K_1^2 - m_\pi^2}\,\overline{u}(\mathbf{p}_2')\tau_b\gamma_5\gamma^\mu u(\mathbf{p}_2) + (1 \leftrightarrow 2)\ .$$

- Pion-in-flight:

$$j_{\mathrm{p}}^{\mu}(\mathbf{p}_1', \mathbf{p}_2', \mathbf{p}_1, \mathbf{p}_2) = \frac{f^2}{m_\pi^2}\, \mathrm{i}\epsilon_{3ab}\frac{F_\pi(K_1 - K_2)^\mu}{(K_1^2 - m_\pi^2)(K_2^2 - m_\pi^2)}\,\overline{u}(\mathbf{p}_1')\tau_a\gamma_5 \not{K}_1 u(\mathbf{p}_1)\overline{u}(\mathbf{p}_2')\tau_b\gamma_5 \not{K}_2 u(\mathbf{p}_2)\ .$$

- Correlation:

$$j_{\mathrm{cor}}^{\mu}(\mathbf{p}_1', \mathbf{p}_2', \mathbf{p}_1, \mathbf{p}_2) = \frac{f^2}{m_\pi^2}\,\overline{u}(\mathbf{p}_1')\tau_a\gamma_5 \not{K}_1 u(\mathbf{p}_1)\frac{1}{K_1^2 - m_\pi^2}\overline{u}(\mathbf{p}_2')[\tau_a\gamma_5 \not{K}_1 S_{\mathrm{F}}(P_2 + Q)\Gamma^\mu(Q)$$

$$+ \Gamma^\mu(Q) S_{\mathrm{F}}(P_2' - Q)\tau_a\gamma_5 \not{K}_1]u(\mathbf{p}_2) + (1 \leftrightarrow 2)\ .$$

Weak

- CC Seagull

$$j_s^\mu(\mathbf{p}_1', \mathbf{p}_2', \mathbf{h}_1, \mathbf{h}_2) = \tau_0 \otimes \tau_{+1} - \tau_{+1} \otimes \tau_0\ \frac{f}{m_\pi}\frac{1}{\sqrt{2} f_\pi}\overline{u}(\mathbf{p}_1')\gamma_5\ \not{K}_1 u(\mathbf{h}_1)\ \frac{\overline{u}(\mathbf{p}_2')\left[g_A F_1^V(Q^2)\gamma_5\gamma^\mu + F_\rho(K_2^2)\gamma^\mu\right] u(\mathbf{h}_2)}{K_1^2 - m_\pi^2} - (1 \leftrightarrow 2)$$

Form Factors

Standard dipole parameterization

Vector

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

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

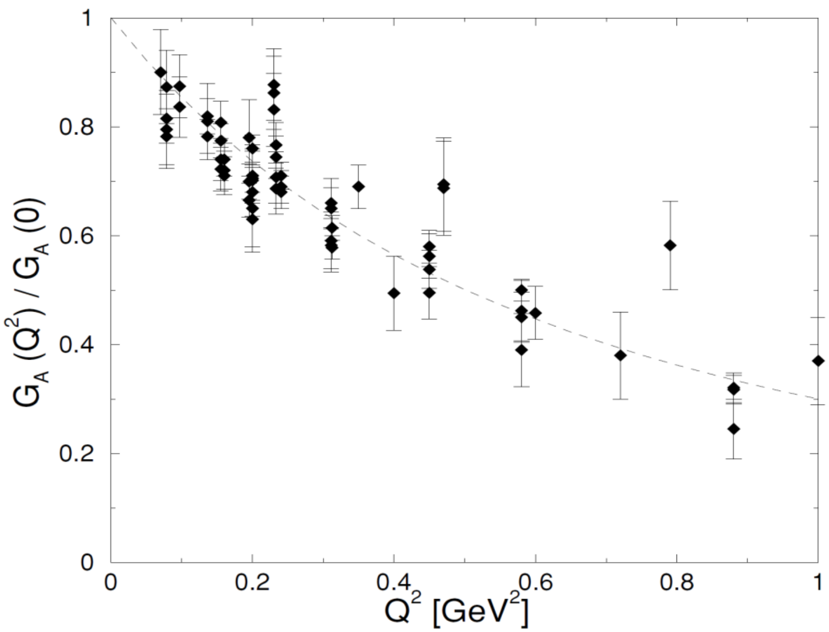
$$M_V = 0.84\,\mathrm{GeV}/c^2$$

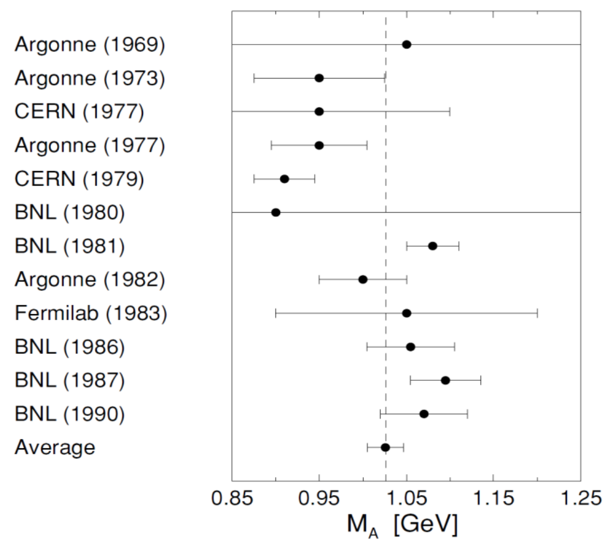
Axial

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

$g_A = 1.26$ from neutron β decay

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





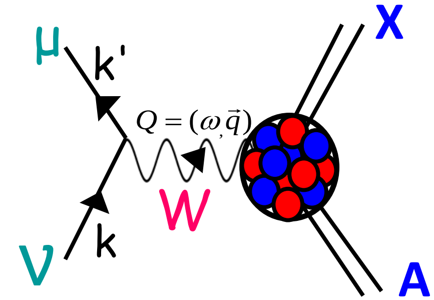
from ν-deuterium CCQE
and
from π electroproduction

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

Neutrino-nucleus cross section

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

$$d\sigma \propto L_{\mu\nu} W^{\mu\nu}$$



$$L_{\mu\nu} = k_\mu k'_\nu + k'_\mu k_\nu - g_{\mu\nu} k \cdot k' \pm i\varepsilon_{\mu\nu\kappa\lambda} k^\kappa k'^\lambda$$

Leptonic tensor

$$W^{\mu\nu} = \sum_f \langle\Psi_f|J^\mu(Q)|\Psi_i\rangle^* \langle\Psi_f|J^\nu(Q)|\Psi_i\rangle \delta(E_i+\omega-E_f)$$

Hadronic tensor

The cross section in terms of the response functions:

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

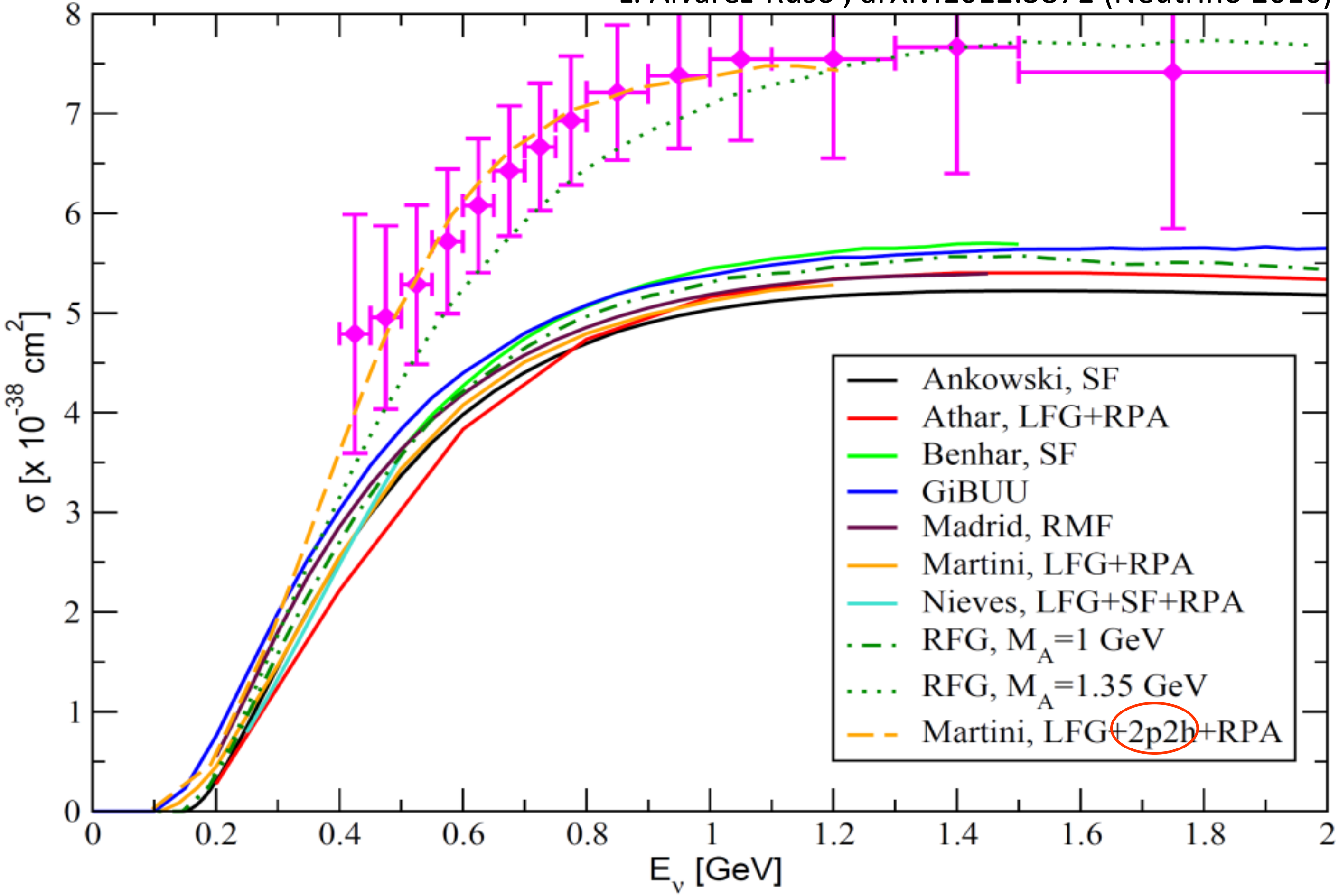
Nucleon properties → Form factors: Electric G_E, Magnetic G_M, Axial G_A

Nuclear dynamics → Nuclear Response Functions R(q,ω):

Isovector R_τ (τ); Isospin Spin-Longitudinal $R_{\sigma\tau(L)}$(τ σ•q); Isospin Spin Transverse $R_{\sigma\tau(T)}$(τ σxq)

Comparison of different theoretical models for Quasielastic

L. Alvarez-Ruso , arXiv:1012.3871 (Neutrino 2010)



SF: Spectral Function

LFG: Local Fermi Gas

RPA: Random Phase Approximation

RMF: Relativistic Mean Field

GiBUU: Transport Equation

Comparison of models and Monte Carlo:
Boyd, Dytman, Hernandez, Sobczyk, Tacik ,
AIP Conf.Proc. 1189 (2009) 60-73

puzzle??

From true neutrino energy to reconstructed neutrino energy

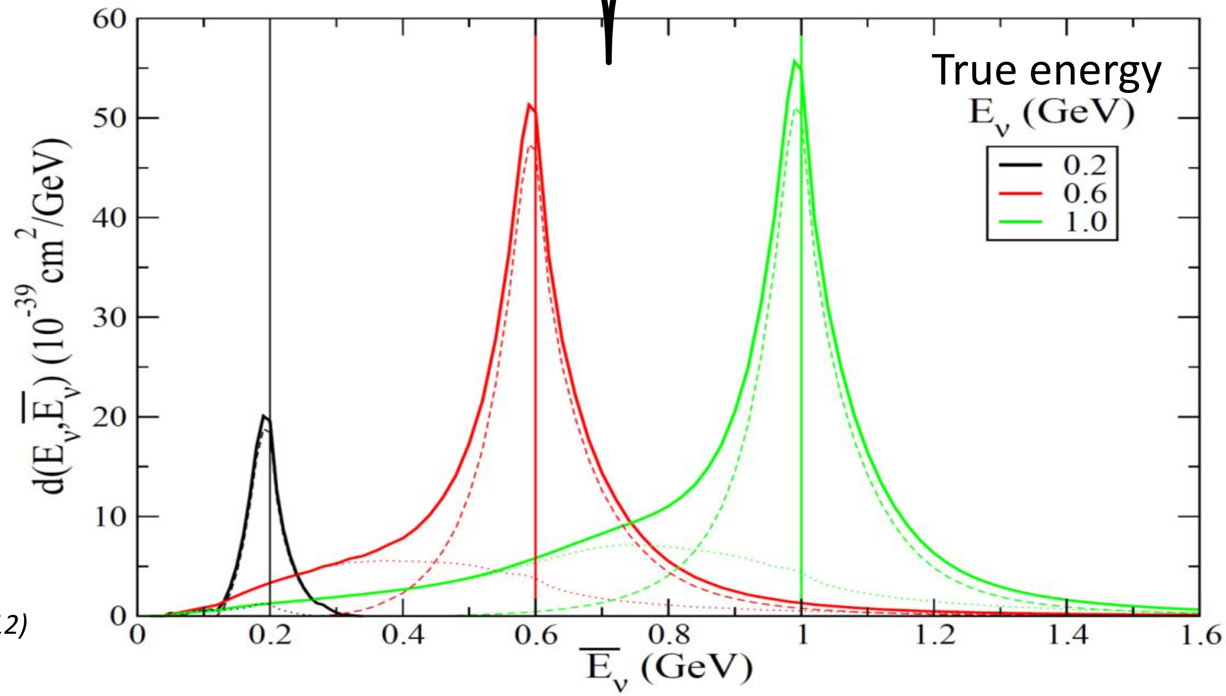
Probability energy distribution $(E_\nu, \bar{E}_\nu)$

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

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

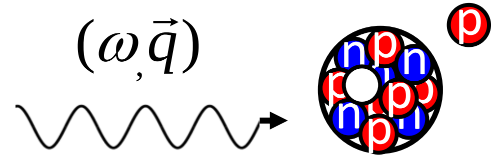
M. Martini, M. Ericson, G. Chanfray
- Phys. Rev. D 85 093012 (2012)
- Phys. Rev. D 87 013009 (2013)

Similar results in:
- Nieves, Sanchez, Simo, Vicente Vacas PRD 85 113008 (2012)
- Lalakulich, Mosel, Gallmeister, PRC 86 054606 (2012)



- Distributions not symmetrical around Eν
- Crucial role of np-nh: low energy tail

Genuine Quasielastic Scattering



Nucleon-Nucleon interaction switched off

Nucleons respond individually

Nucleon at rest:

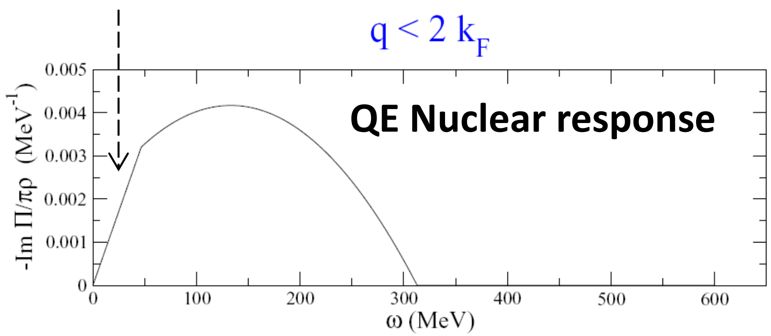
$$R\alpha\ \delta\left(\omega-\left(\sqrt{q^2+M^2}-M\right)\right)$$

Nucleon inside the nucleus:

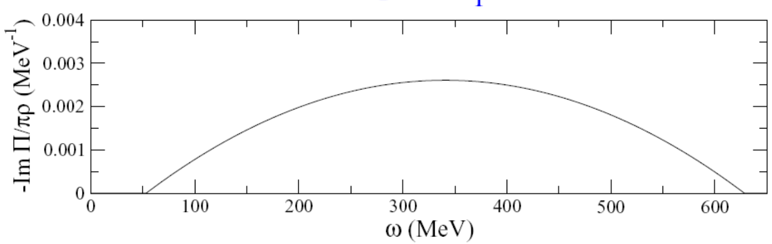
Fermi motion spreads δ distribution (Fermi Gas)

Pauli blocking cuts part of the low momentum Resp.

$q < 2\ k_F$



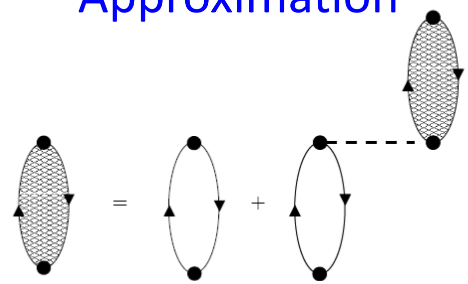
$q > 2\ k_F$



Nucleon-Nucleon interaction switched on

The nuclear response becomes collective

Random Phase Approximation

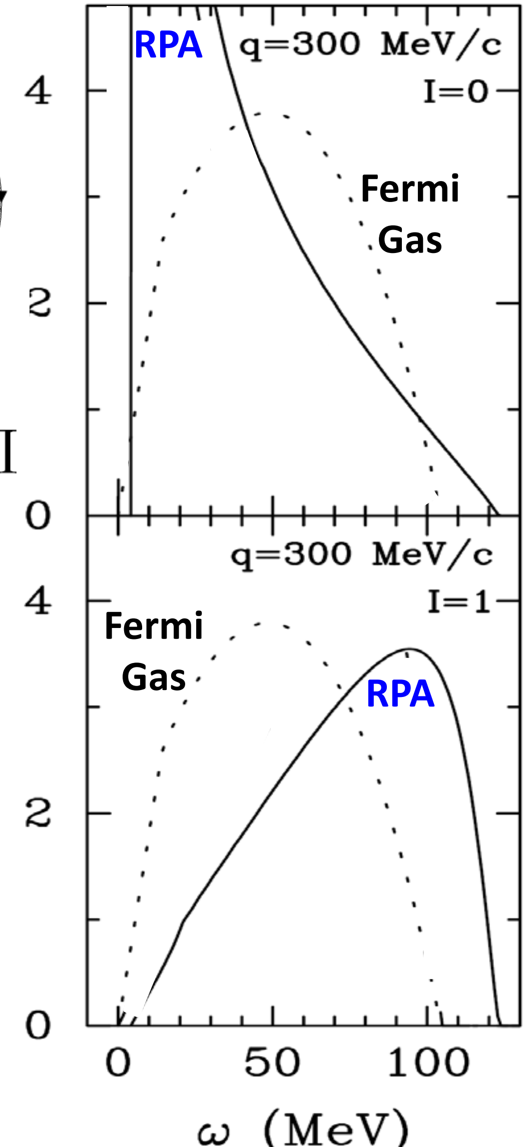


$$\Pi = \Pi^0 + \Pi^0 V \Pi$$

*Force acting on one nucleon is transmitted by the interaction

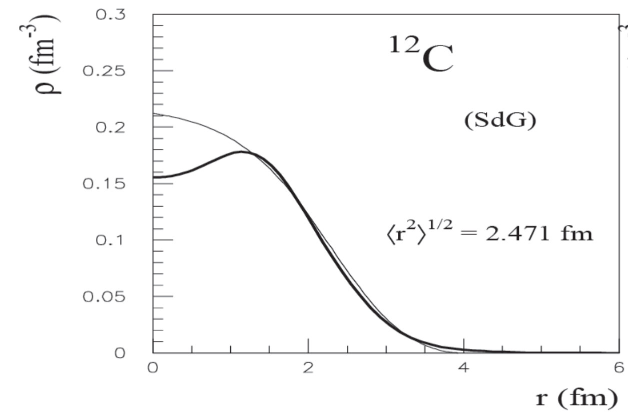
*Shift of the peak with respect to Fermi Gas, decrease, increase,…

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



Semi-classical approximation

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



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

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

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

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

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.

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

Details: RPA resolution

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

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

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

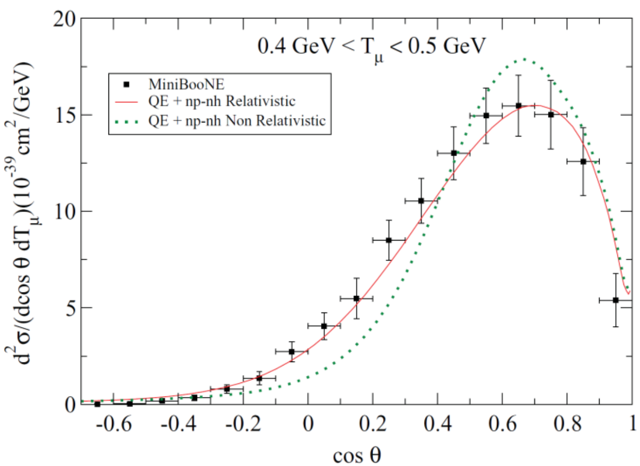
$$\left(\begin{array}{cc|cc} \Pi^{0ll_{NN}} & \Pi^0_{lt_{NN}} & \Pi^0_{ll_{N\Delta}} & \Pi^0_{lt_{N\Delta}} \\ \Pi^0_{tl_{NN}} & \Pi^0_{tt_{NN}} & \Pi^0_{tl_{N\Delta}} & \Pi^0_{tt_{N\Delta}} \\ \hline \Pi^0_{ll_{\Delta N}} & \Pi^0_{lt_{\Delta N}} & \Pi^0_{ll_{\Delta\Delta}} & \Pi^0_{lt_{\Delta\Delta}}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

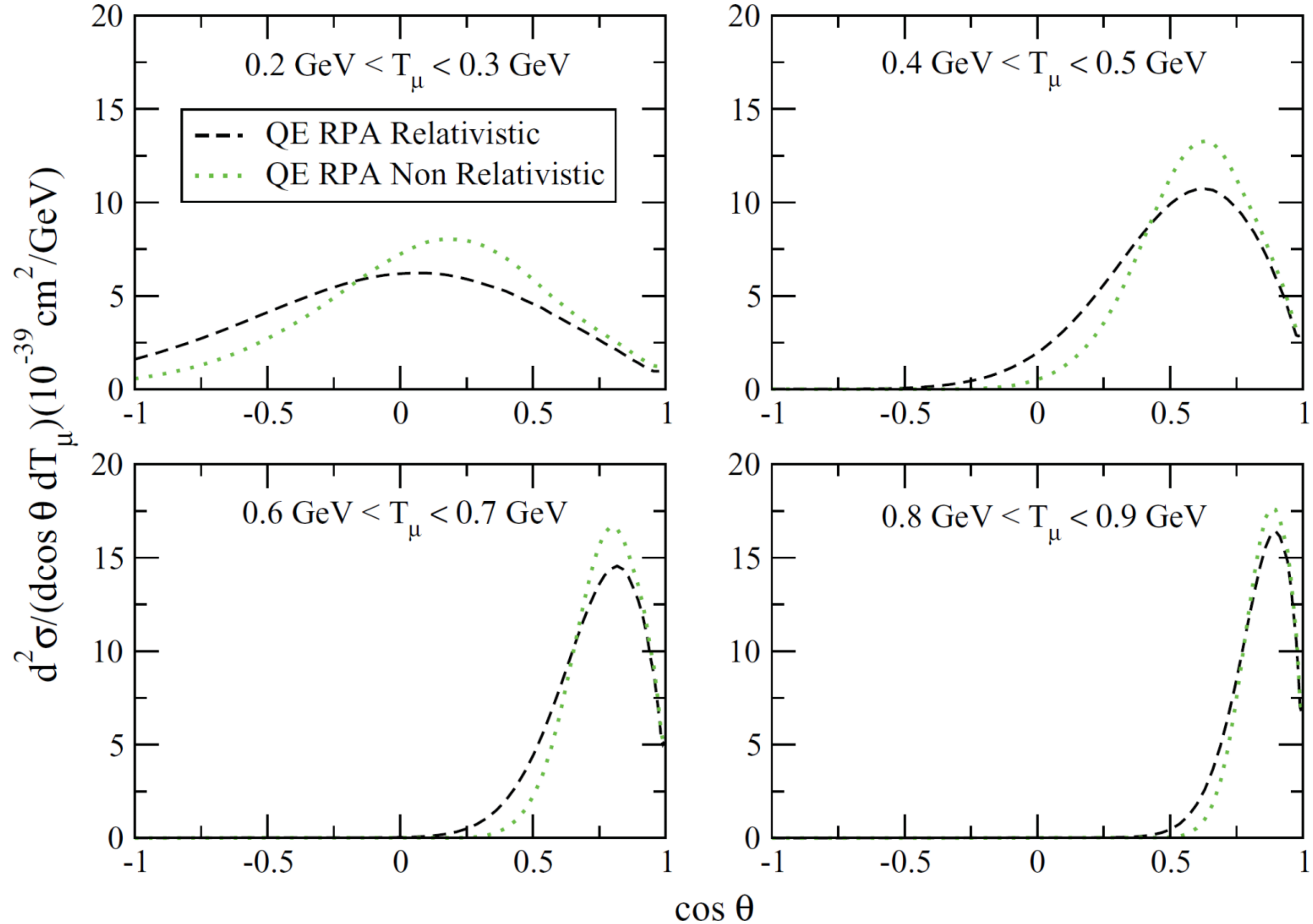
Relativistic corrections

$$\omega \to \omega(1 + \frac{\omega}{2M_N})$$

$$\Pi \to (1 + \frac{\omega}{M_N})\,\Pi$$

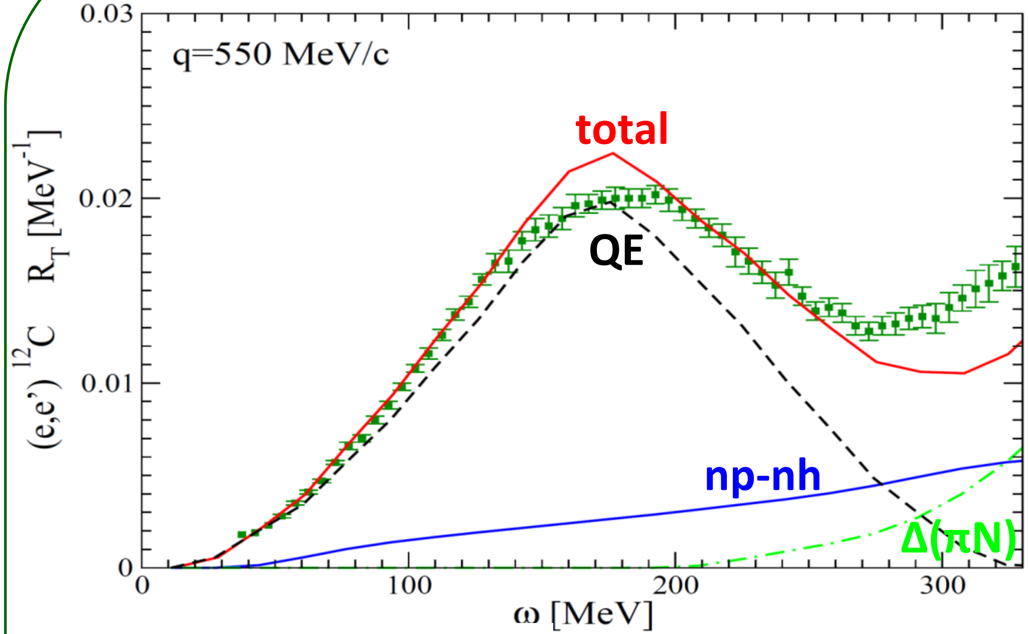
Martini, Ericson, Chanfray, Phys. Rev. C 84 055502 (2011)

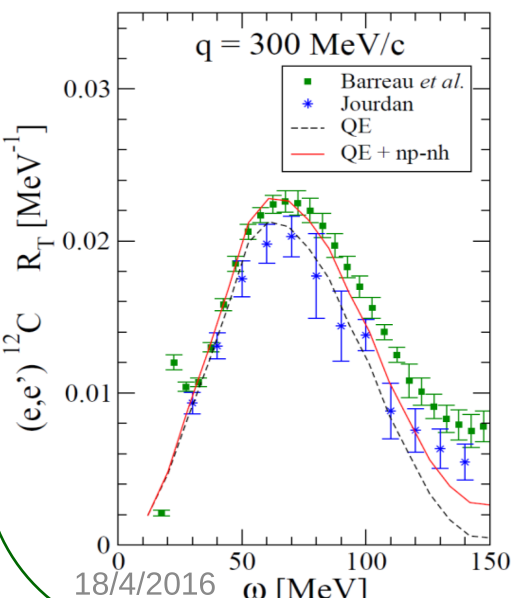


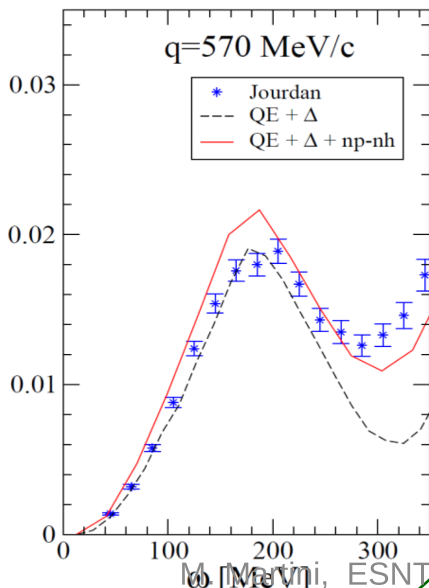


Testing our approach in other processes

Electron scattering

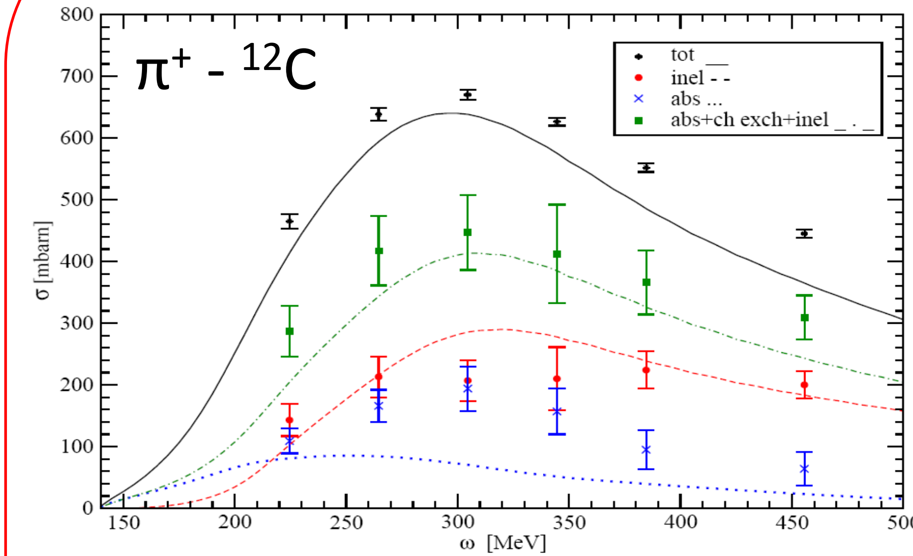


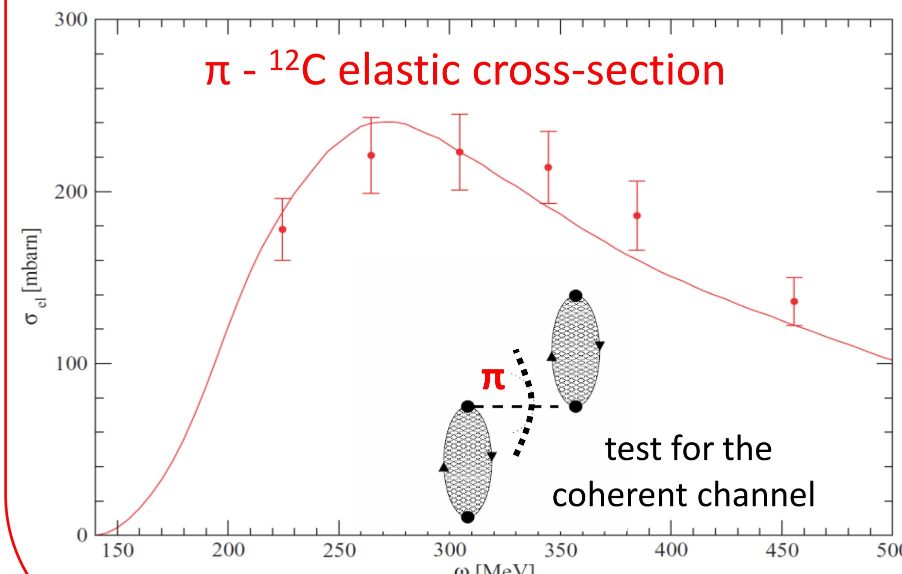




Martini, J.Phys.Conf.Ser. 408 (2013) 012041

Pion scattering





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

Combining ν and $\bar{\nu}$ CCQE-like cross sections

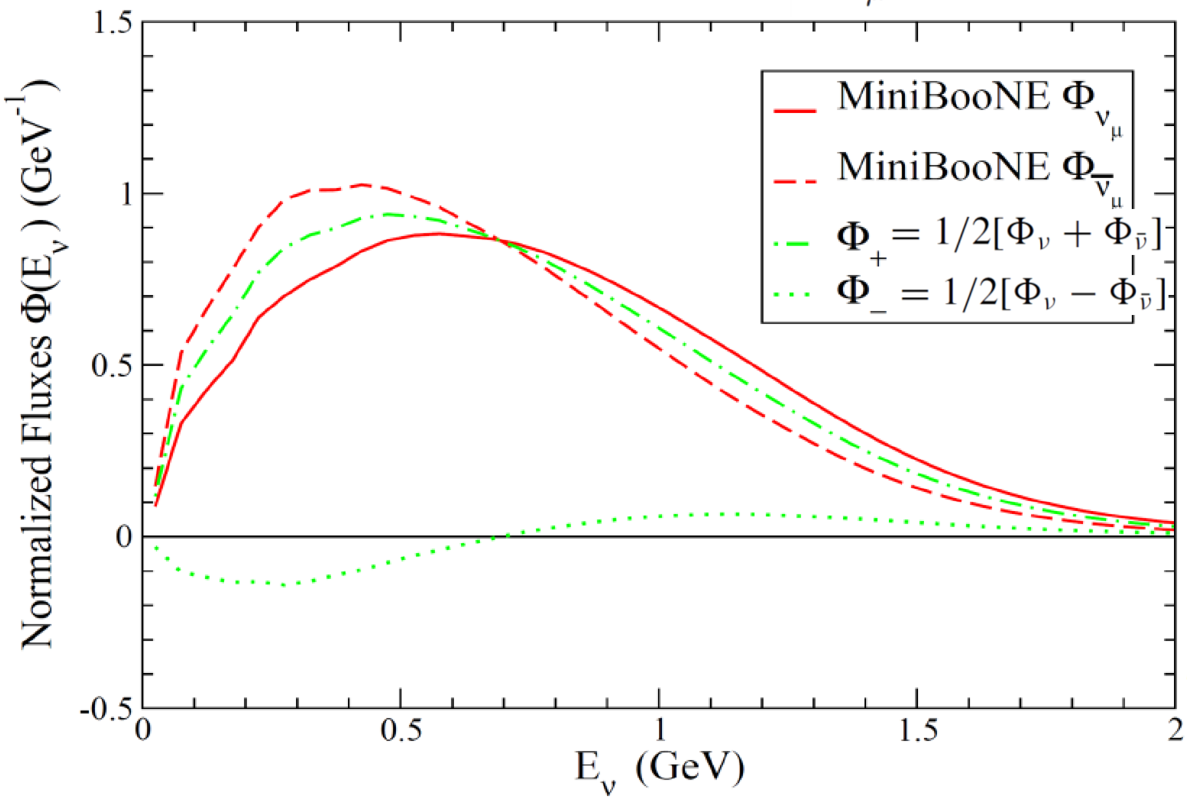
M. Ericson, M. Martini, Phys. Rev. C 91 035501 (2015)

Difference of ν and antiν cross sections and the VA interference term

$$d\sigma \sim d\sigma_L + d\sigma_T \pm d\sigma_{VA} \qquad d\sigma_\nu - d\sigma_{\bar\nu} \overset{?}{\leftrightarrow} 2d\sigma_{VA}$$

Difference gives only the VA term for identical ν and antiν flux

Problem: flux dependence of dσ $\quad \dfrac{d^2\sigma}{dE_\mu d\cos\theta} = \int dE_\nu \left[\dfrac{d^2\sigma}{d\omega d\cos\theta}\right]_{\omega=E_\nu-E_\mu} \Phi(E_\nu)$

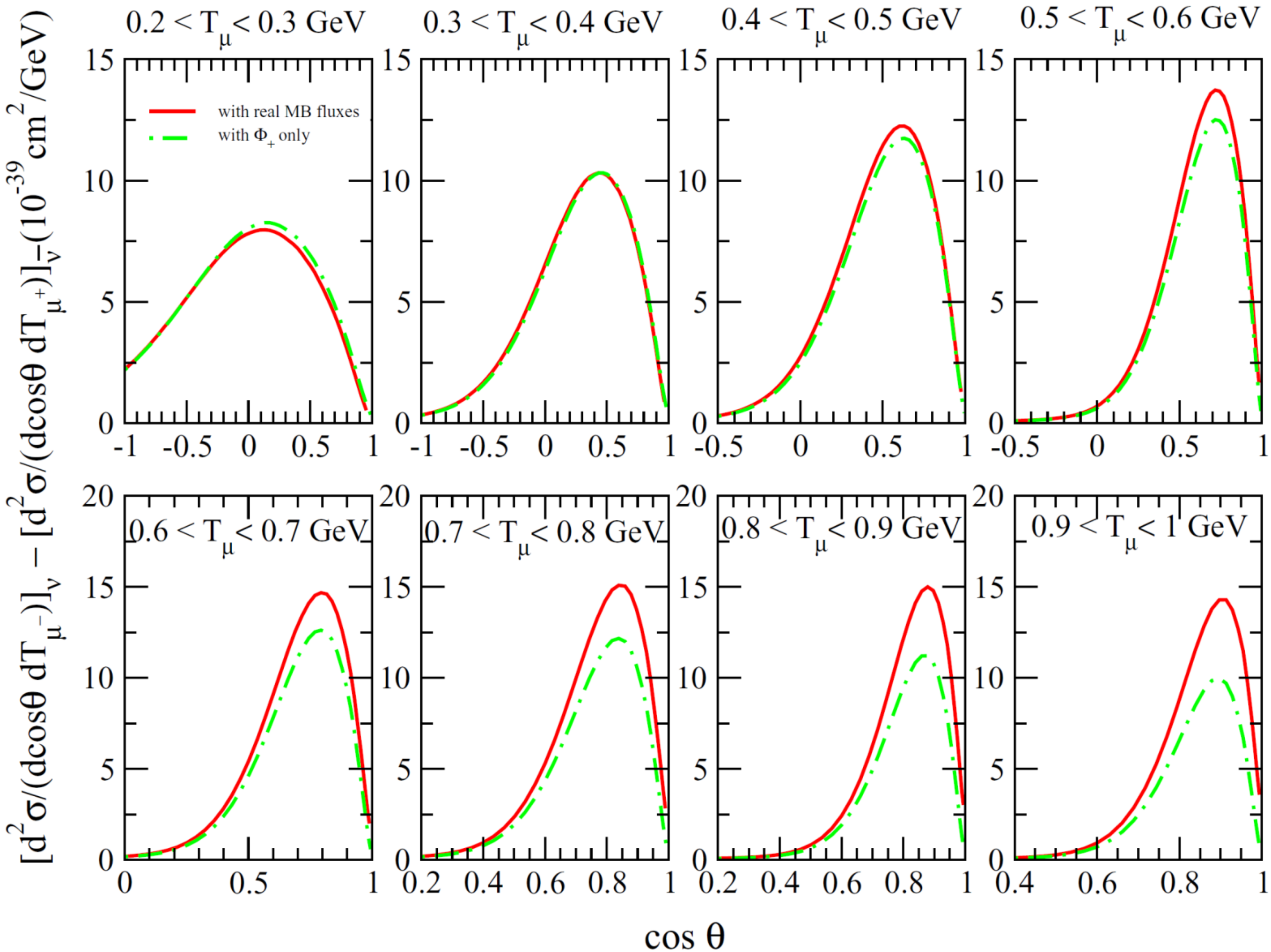


$$\begin{matrix} sum(\cos\theta,\omega) \\ dif(\cos\theta,\omega) \end{matrix} = \frac{d^2\sigma_\nu}{d\cos\theta d\omega} \pm \frac{d^2\sigma_{\bar\nu}}{d\cos\theta d\omega}$$

$$\frac{d^2\sigma_\nu}{d\cos\theta dE_\mu} - \frac{d^2\sigma_{\bar\nu}}{d\cos\theta dE_\mu} = \int dE_\nu \left[sum(\cos\theta,\omega)|_{\omega=E_\nu-E_\mu}\Phi_-(E_\nu) + dif(\cos\theta,\omega)|_{\omega=E_\nu-E_\mu}\Phi_+(E_\nu)\right]$$

Difference of ν and antiν $d^2\sigma$ considering the real and mean MiniBooNE fluxes

CCQE-like

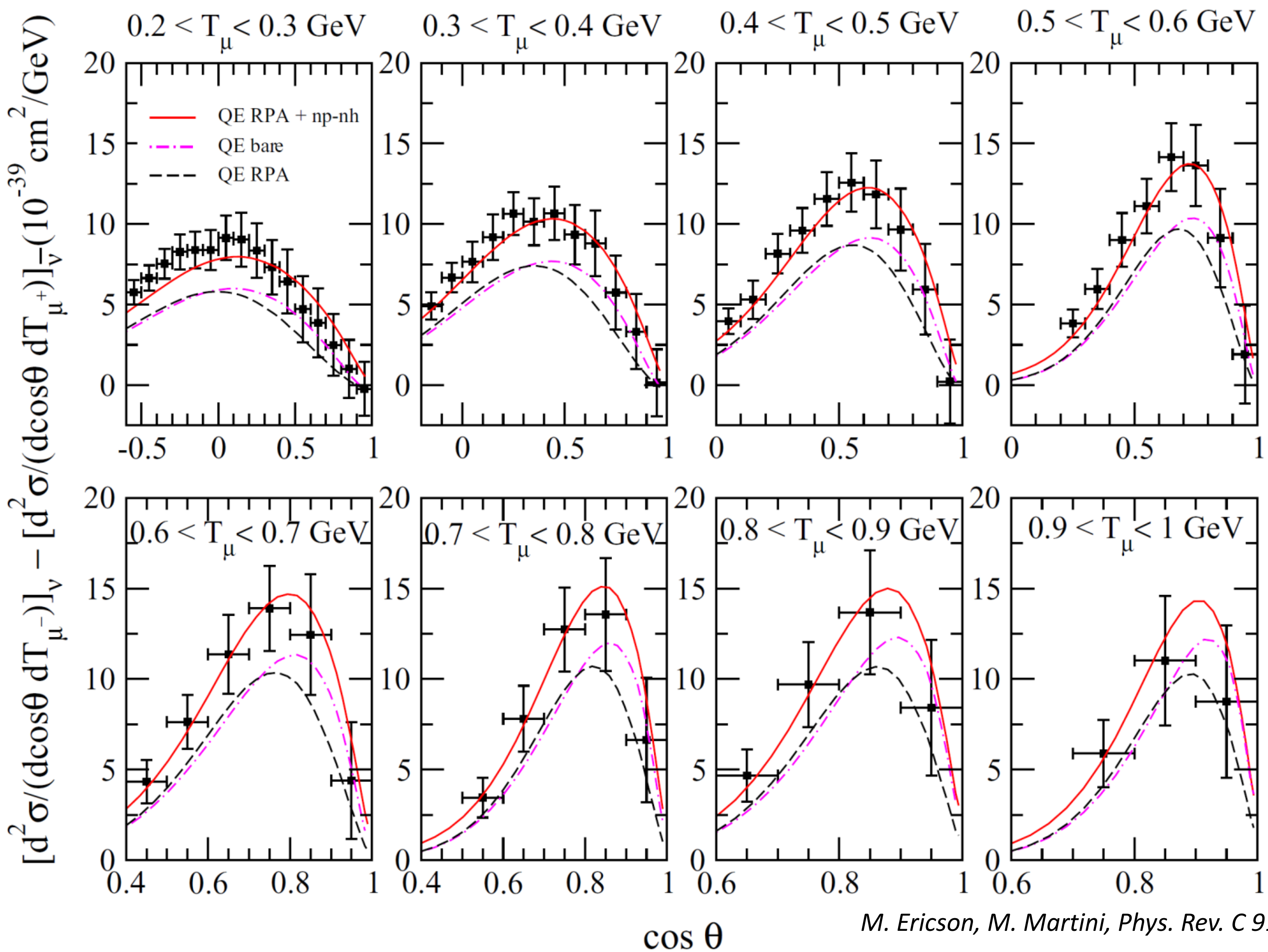


The mean flux (Φ_+) contribution is dominant in the ν antiν difference

⟹ The VA interference term is experimentally accessible in MiniBooNE data

Difference of ν and antiν $d^2\sigma$: our calculations *vs* MiniBooNE data

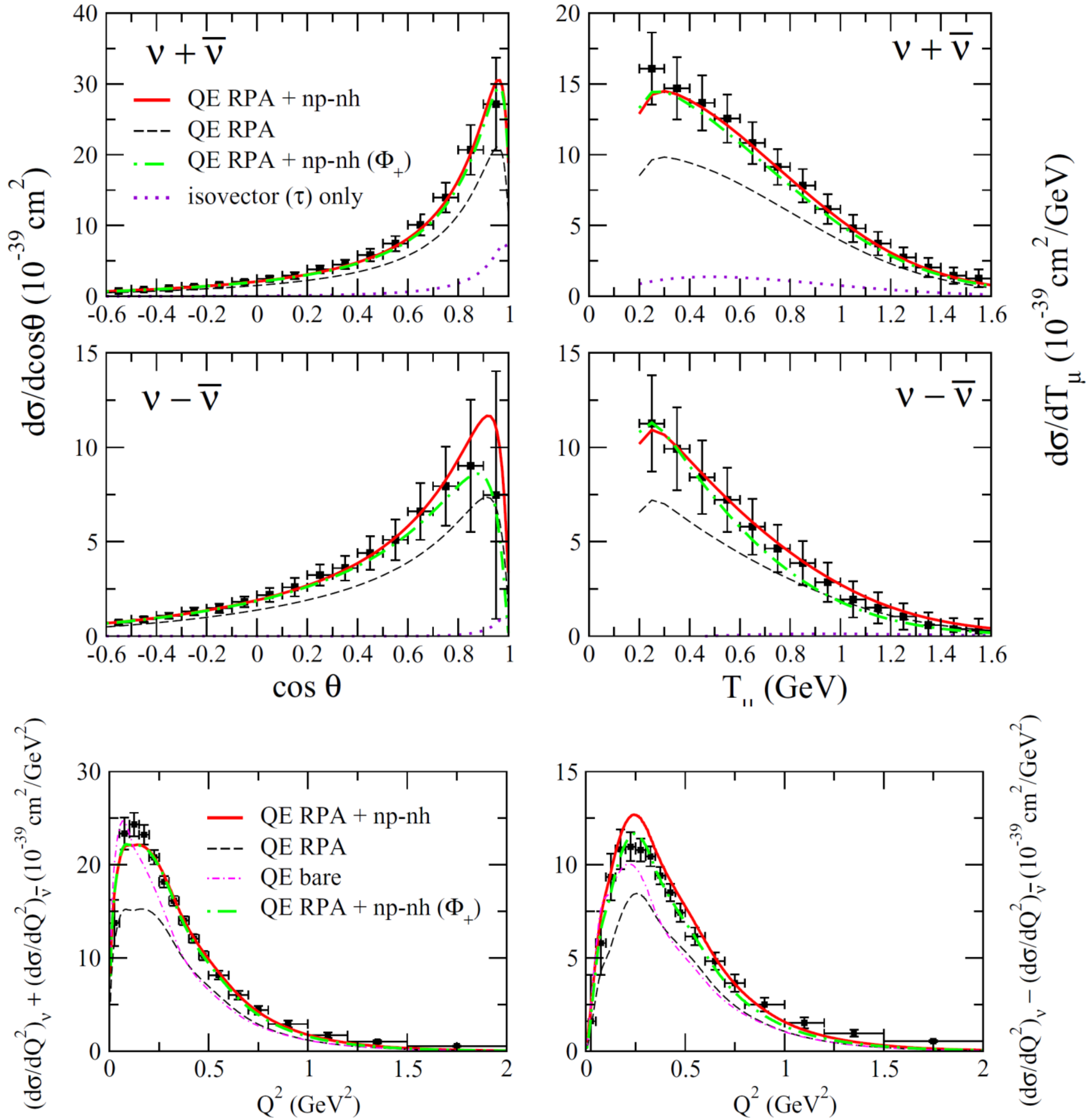
CCQE-like



M. Ericson, M. Martini, Phys. Rev. C 91 035501 (2015)

Need for the multinucleon component to reproduce the difference of ν and antiν MiniBooNE $d^2\sigma$

$\Longrightarrow$ **Need** for the **multinucleon** component in the **VA interference**



M. Ericson, M. Martini, Phys. Rev. C 91 035501 (2015)

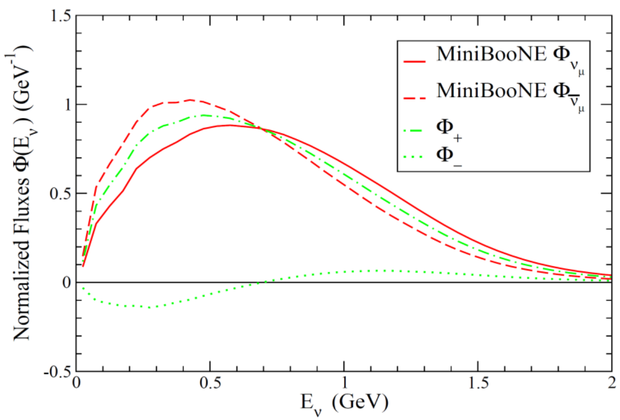
Difference of ν and antiν cross sections and the VA interference term

$$d\sigma \sim d\sigma_L + d\sigma_T \pm d\sigma_{VA}$$

$$d\sigma_{\nu} - d\sigma_{\bar{\nu}} \overset{?}{\leftrightarrow} 2 d\sigma_{VA}$$

Difference gives only the VA term for identical ν and antiν flux

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



We introduce the **mean flux**

$$\Phi_+ = 1/2[\Phi_\nu + \Phi_{\bar{\nu}}]$$

We calculate the difference using **real** and **mean** MiniBooNE fluxes results

The mean flux contribution is dominant in the ν antiν difference

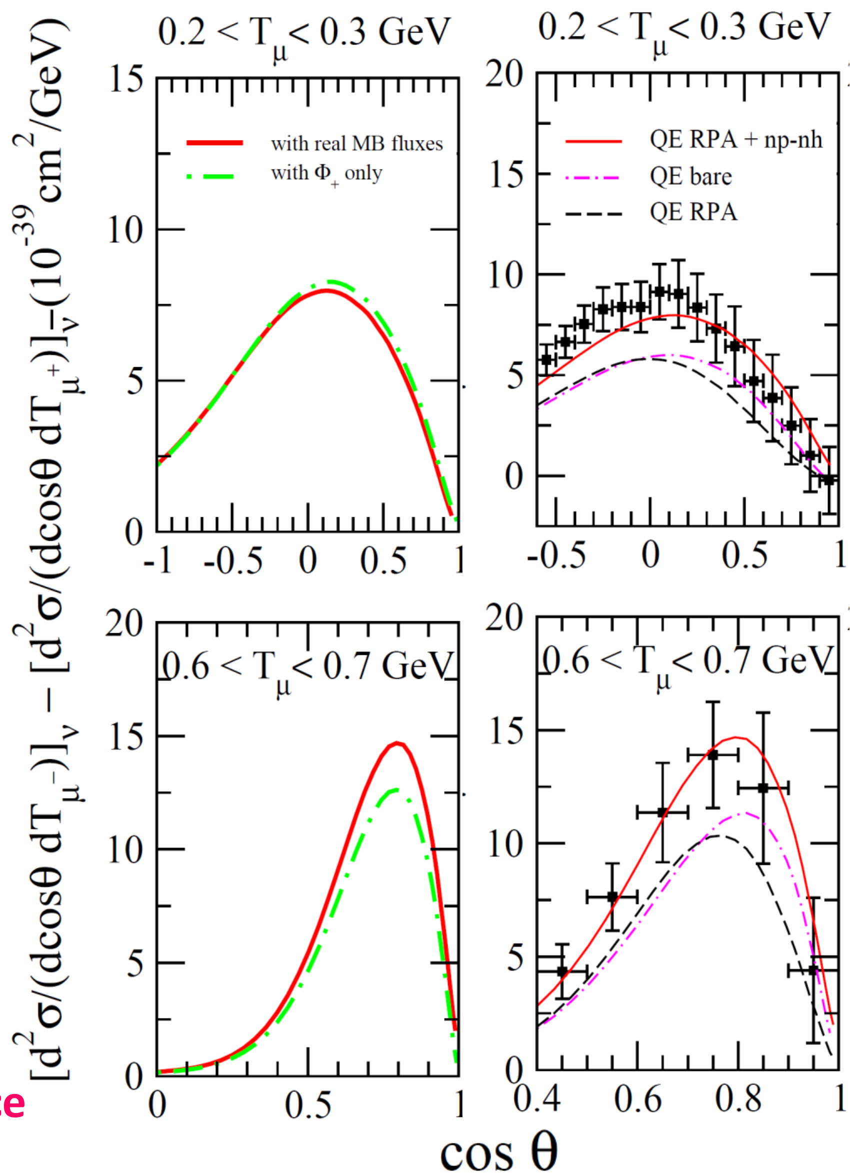
⇓

The VA interference term is experimentally accessible in MiniBooNE data

⇓

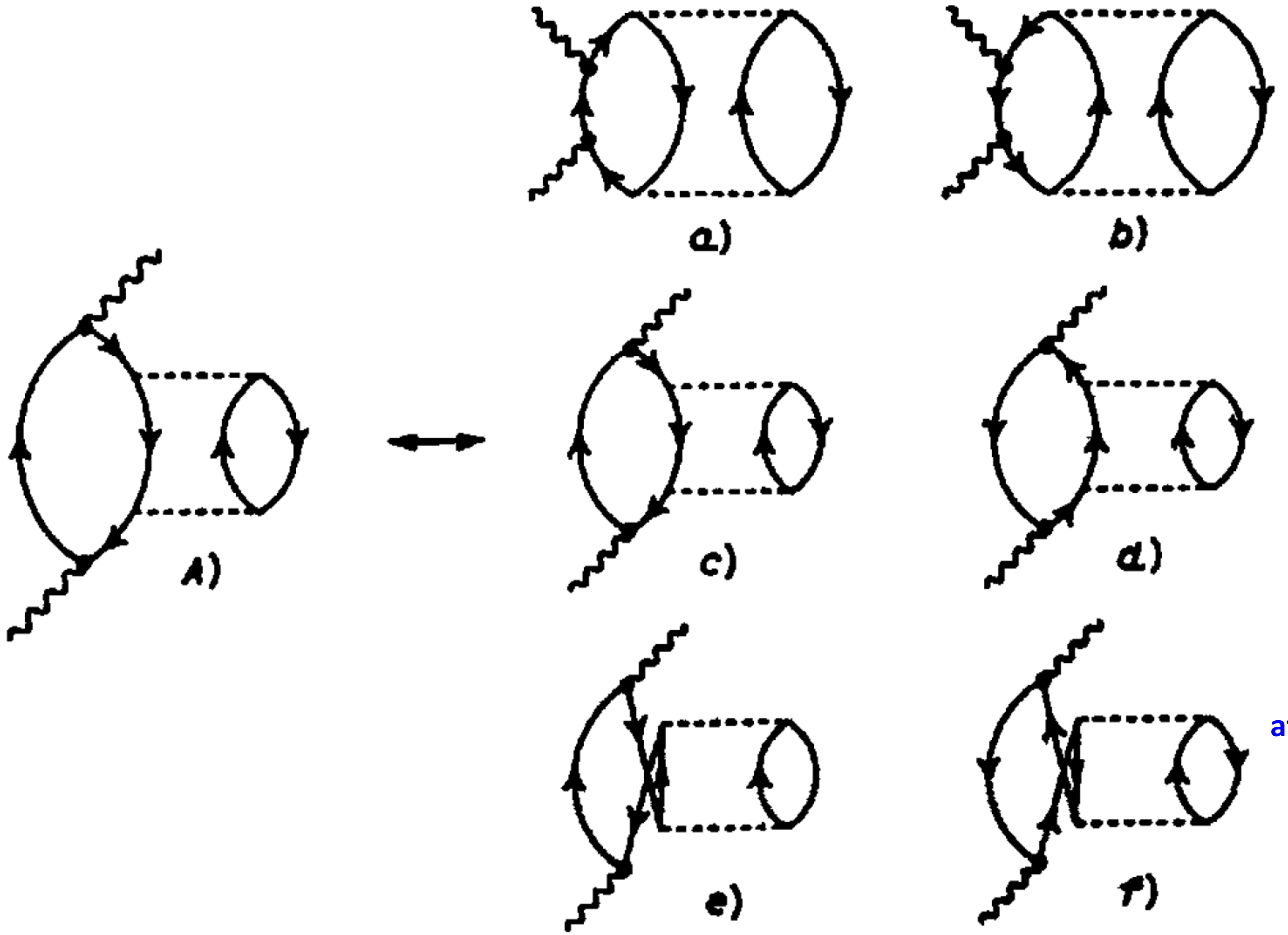
Need for the **multinucleon** component in the **VA interference**

It would be interesting to repeat similar analysis with other ν and antiν beams (T2K, NuMI)



M. Ericson, M. Martini Phys. Rev. C 91 035501 (2015)

W. M. ALBERICO, A. DE PACE, A. DRAGO and A. MOLINARI



NN correlations

2p-2h only

Second order self energy

2p-2h and 1p-1h

How the self-energy is affected by the correlations in the medium

1p-1h only