RPA-based calculations for ν-nucleus scattering

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Outline

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

- Rapid review of 2009 -->2013 Results

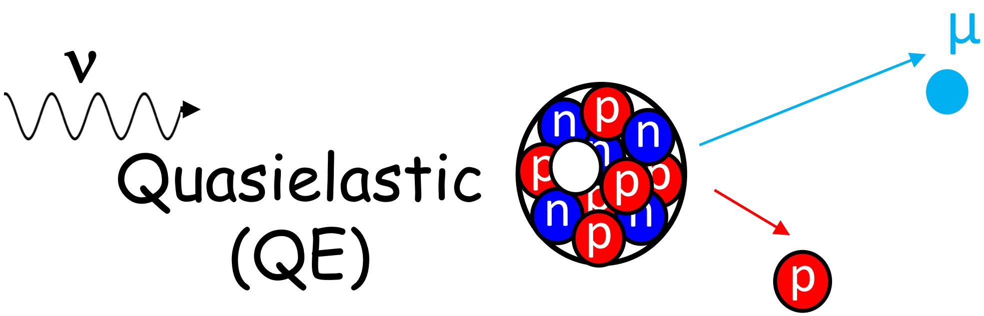
- Presentation of our 2014 and 2015 Results
  - combining ν and antiν CCQE cross sections
  - 1 pion production
  - inclusive cross sections

Phys. Rev. C 80 065501 (2009)
Phys. Rev. C 81 045502 (2010)
Phys. Rev. C 84 055502 (2011)
Phys. Rev. D 85 093012 (2012)
Phys. Rev. D 87 013009 (2013)
Phys. Rev. C 87 065501 (2013)
Phys. Rev. C 90 025501 (2014)
Phys. Rev. C 91 035501 (2015)

Our theoretical model

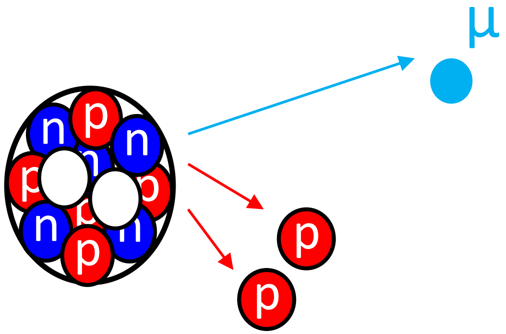
Neutrino - nucleus interaction @ E$_\nu$ ~ O (1 GeV)

[MiniBooNE, T2K energies]

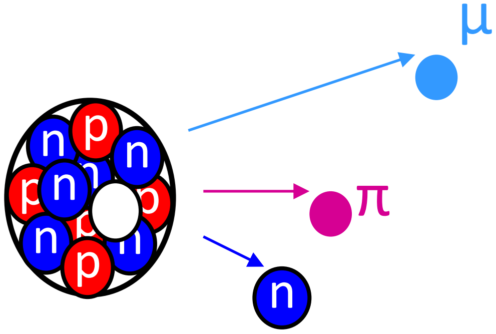


Quasielastic (QE)

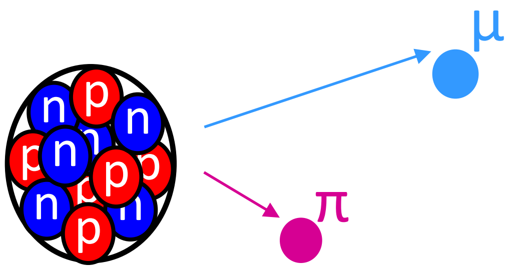
Two Nucleons knock-out (2p-2h)



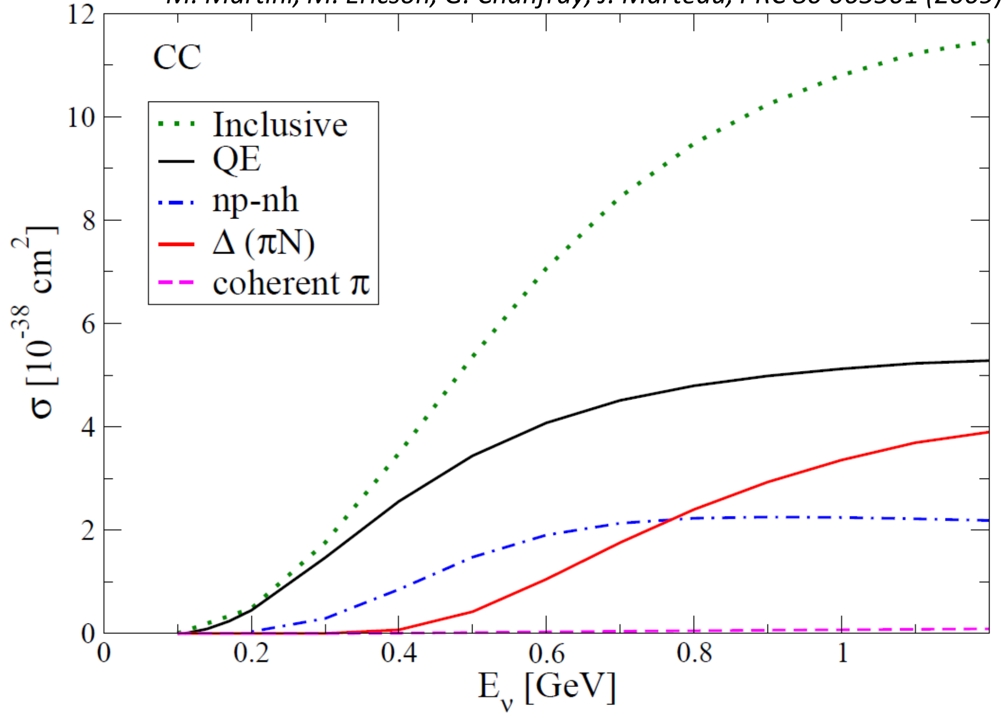
Incoherent π production



Coherent π production

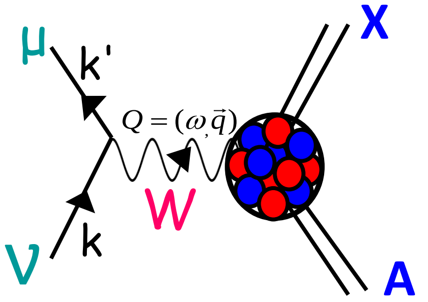


M. Martini, M. Ericson, G. Chanfray, J. Marteau, PRC 80 065501 (2009)



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

Neutrino-nucleus cross section



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

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

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:

$$\frac{\partial^2\sigma}{\partial\Omega\ \partial\epsilon'} = \sigma_0 \left[\underbrace{L_{00}R_{00} + L_{0z}R_{0z} + L_{zz}R_{zz}}_{\text{Longitudinal}} + \underbrace{L_{xx}R_{xx}}_{\text{Transverse}} \pm \underbrace{L_{xy}R_{xy}}_{\text{Transverse V-A interference}} \right]$$

A simplified expression (useful for illustration):

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

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

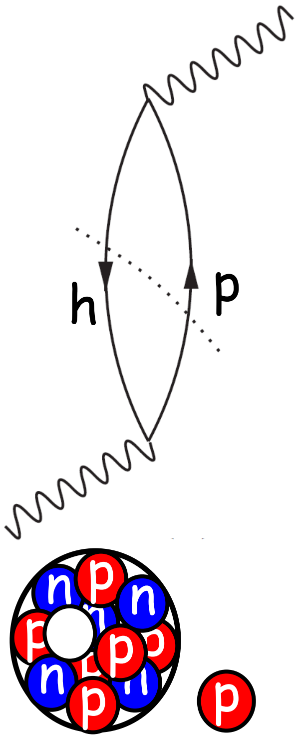
Nuclear dynamics → Nuclear Response Functions R(q,ω):

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

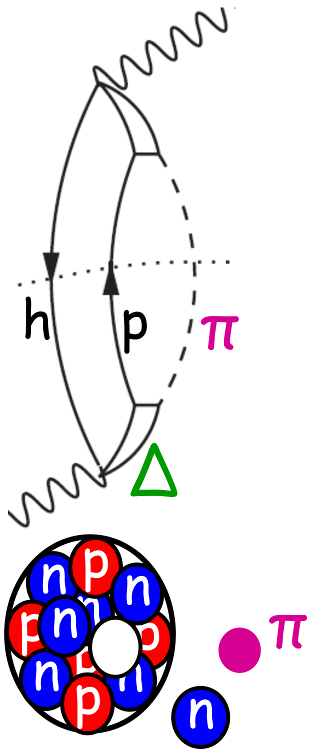
Nuclear Response Functions

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

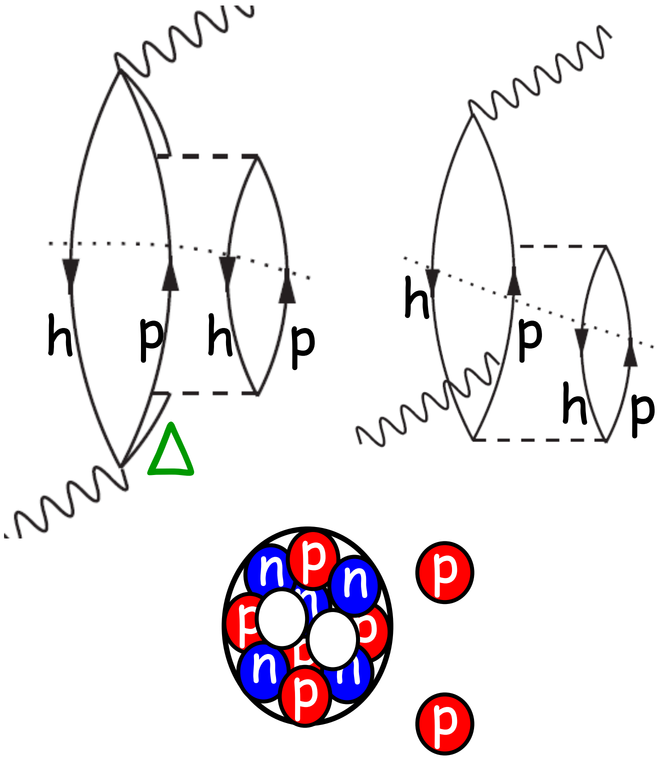
1p-1h
QE



1p-1h
1π production



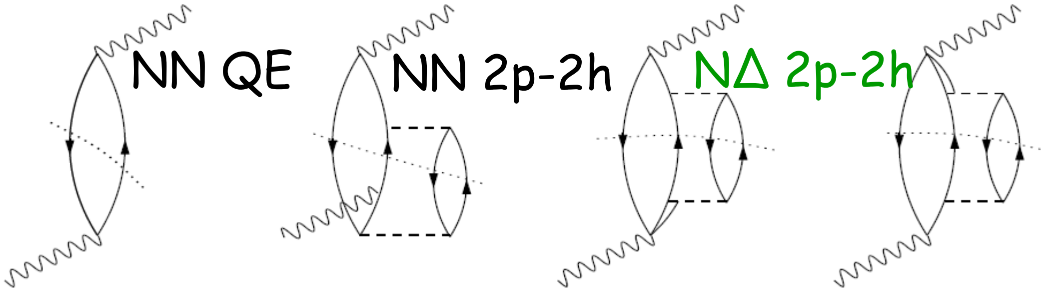
2p-2h:
two examples

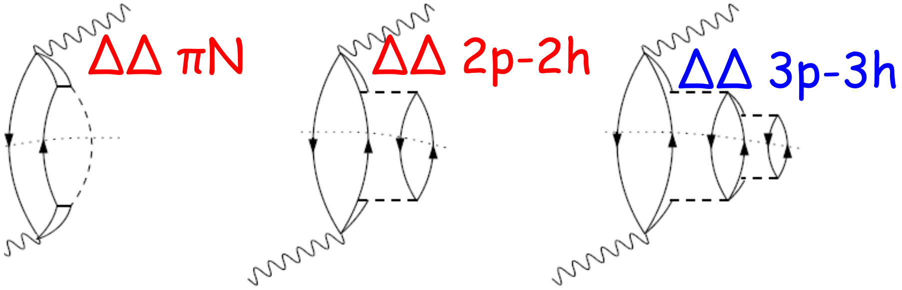


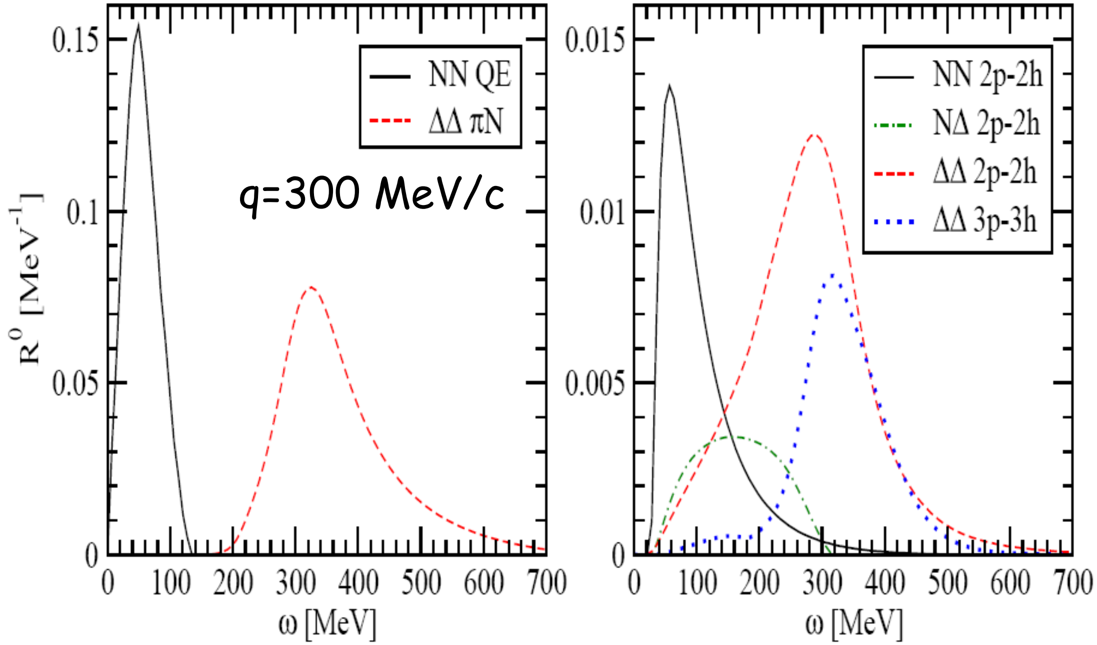
Bare nuclear responses

Several partial components
(final state channels)

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

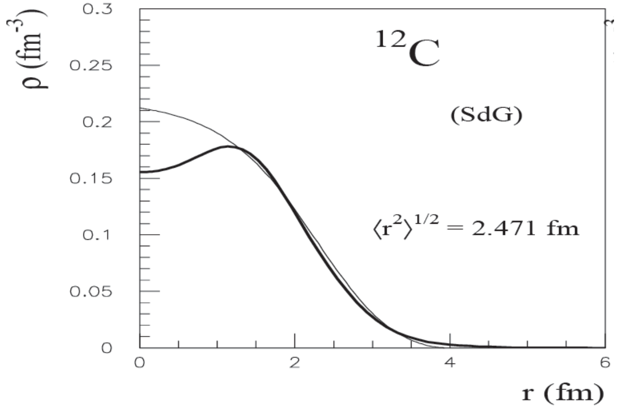






Semi-classical approximation

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



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

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

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

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

N, Δ

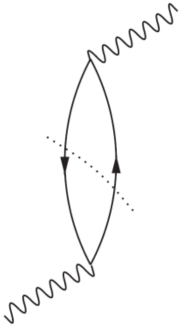
$$R^{0PP'}_{(k)xy}(\omega, q) = -\frac{\mathcal{V}}{\pi} \sum_J \frac{2J+1}{4\pi} \mathrm{Im}[\Pi^{0(J)}_{(k)xy_{PP'}}(\omega, q, q)]$$

QE,2p-2h,...

Longit., Transv.

Bare polarization propagators

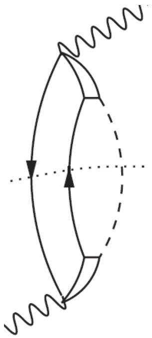
Quasielastic



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

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

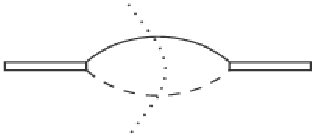
Delta in the medium

Mass

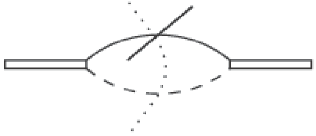
$$\tilde{M}_\Delta = M_\Delta + 40(MeV)\frac{\rho}{\rho_0}$$

Width

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

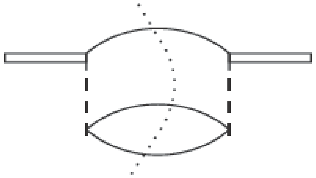


Δ→π N

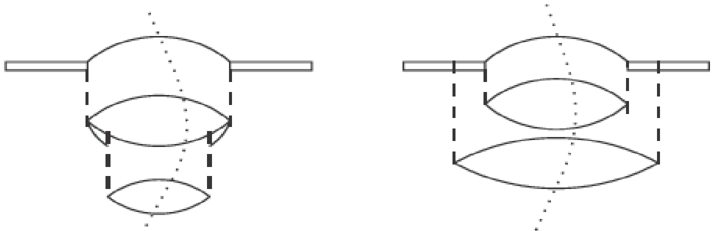


Pauli correction (F_P)

Pion distortion (C_Q)



2p-2h



3p-3h

Self energy

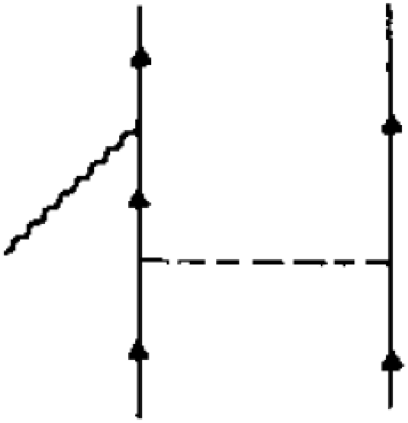
$$\mathrm{Im}(\Sigma_\Delta(\omega)) = -\left[C_Q(\frac{\rho}{\rho_0})^\alpha + C_{2p2h}(\frac{\rho}{\rho_0})^\beta + C_{3p3h}(\frac{\rho}{\rho_0})^\gamma\right]$$

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

2p-2h sector

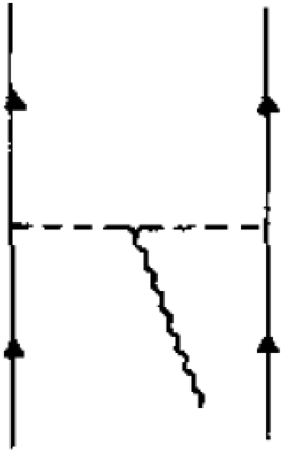
Some diagrams for 2 body currents

Nucleon-Nucleon correlations

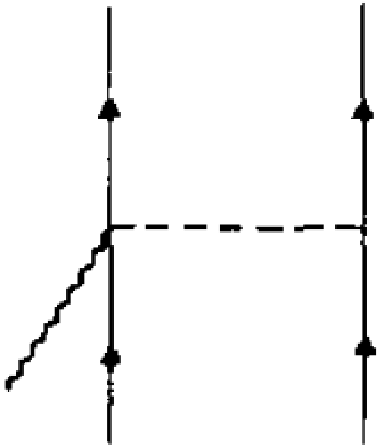


J^{corr}

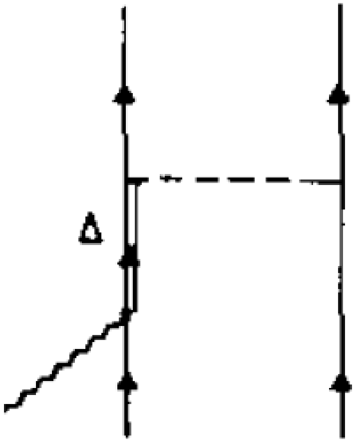
Meson Exchange Currents (MEC)



Pion in flight



Contact

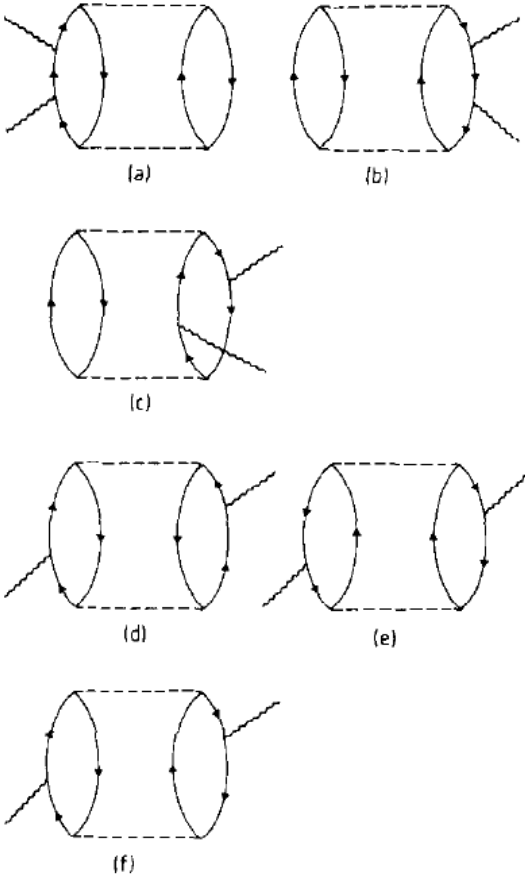


Delta

J^{MEC}

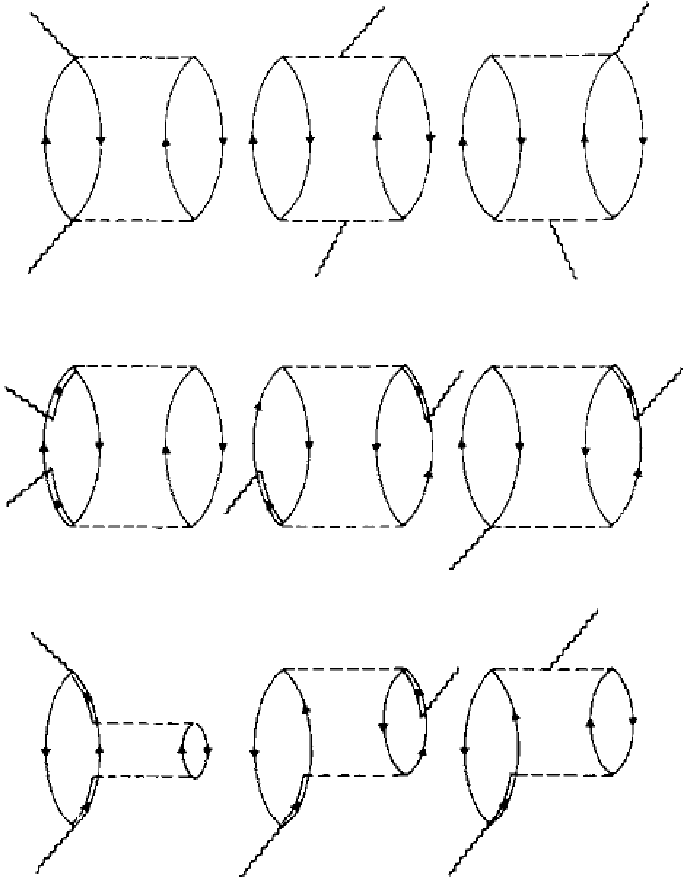
Some diagrams for 2p-2h responses

NN correlations



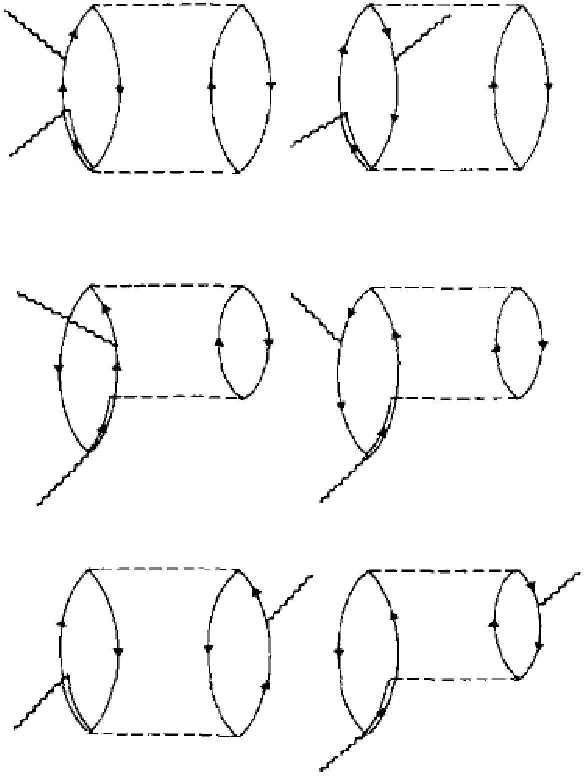
16 diagrams

MEC



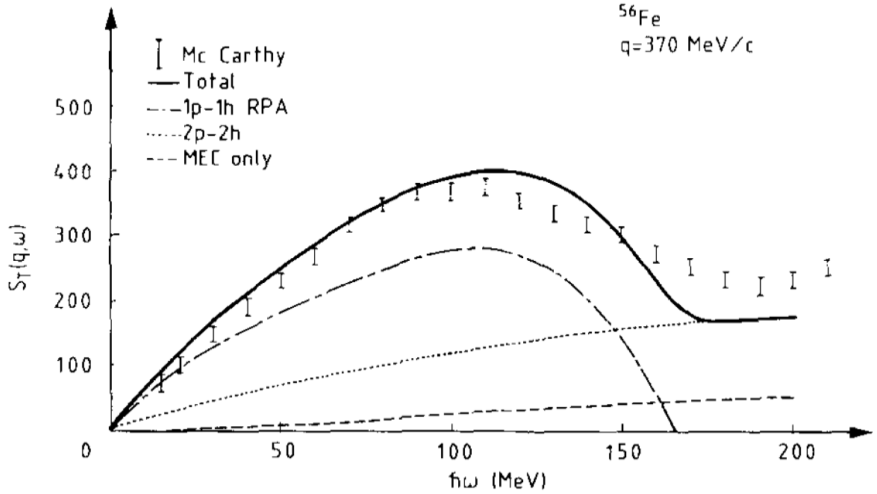
49 diagrams

NN correlation-MEC Interference (or NΔ)



56 diagrams

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

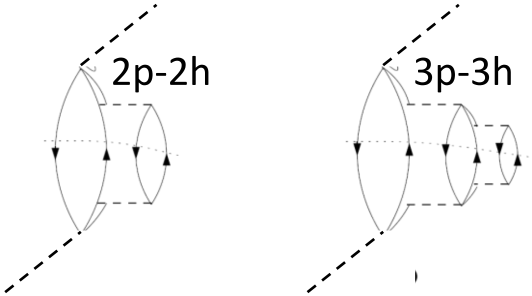
Our work

- 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

ΔΔ (MEC) contributions to np-nh in our model

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



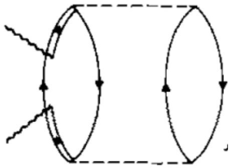
E. Oset and L. L. Salcedo, Nucl. Phys. A 468, 631 (1987):

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

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

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)

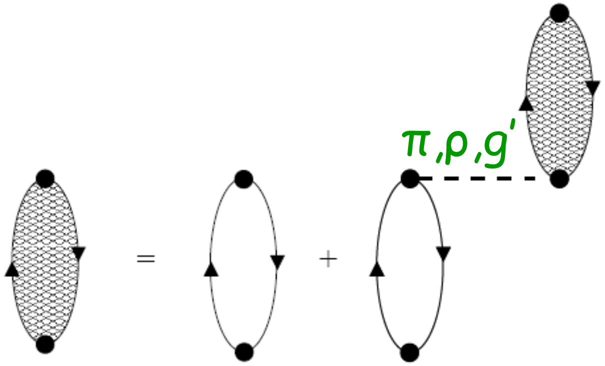
Extrapolation to other energies

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

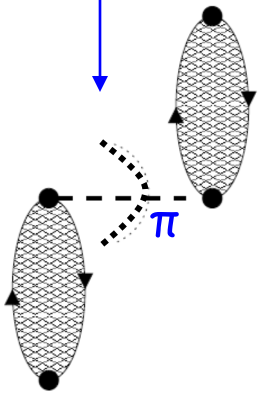
Switching on the interaction: random phase approximation

RPA

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



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

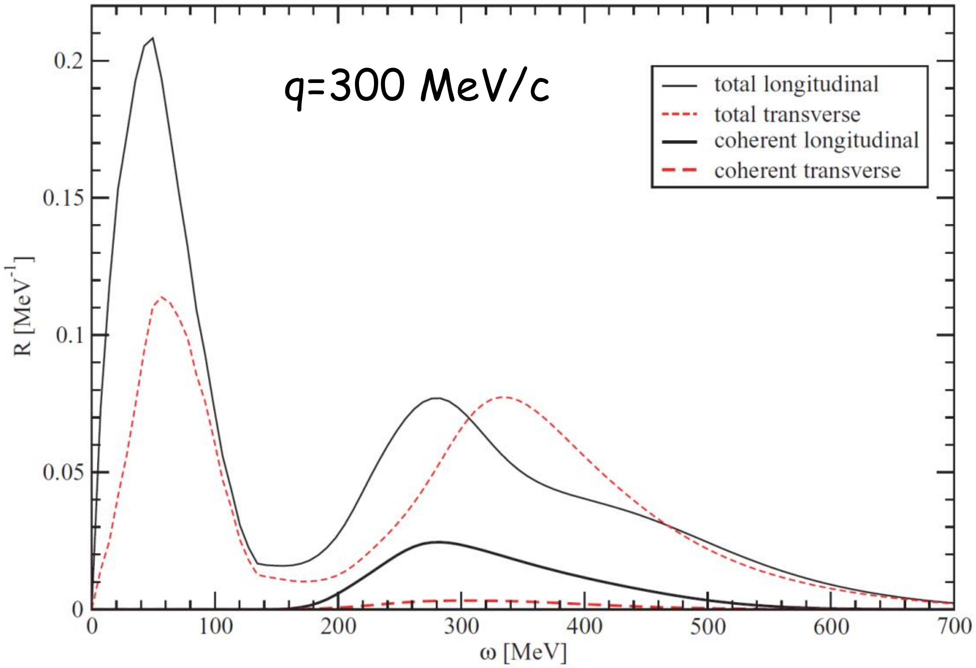


coherent π
production

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

exclusive channels:
QE, 2p-2h, Δ→πN …

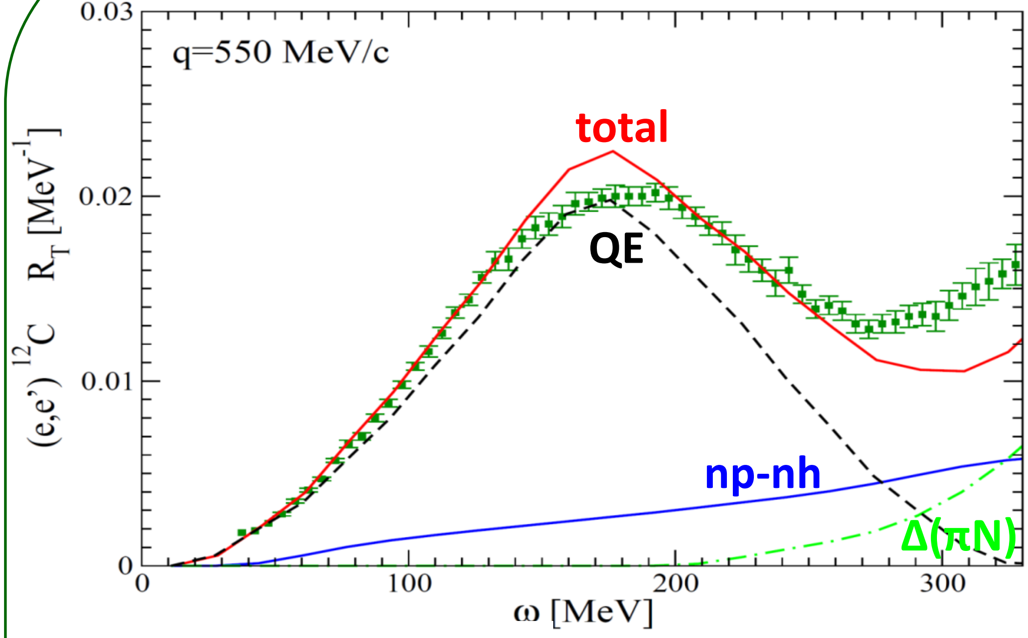
M. Martini, M. Ericson, G. Chanfray, J. Marteau, PRC 80 065501 (2009)

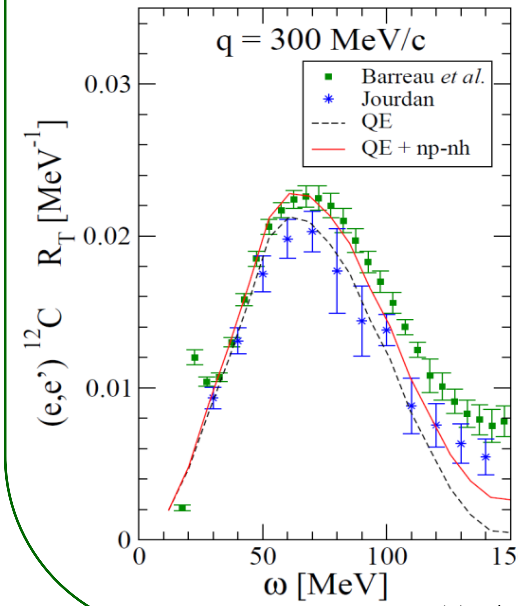


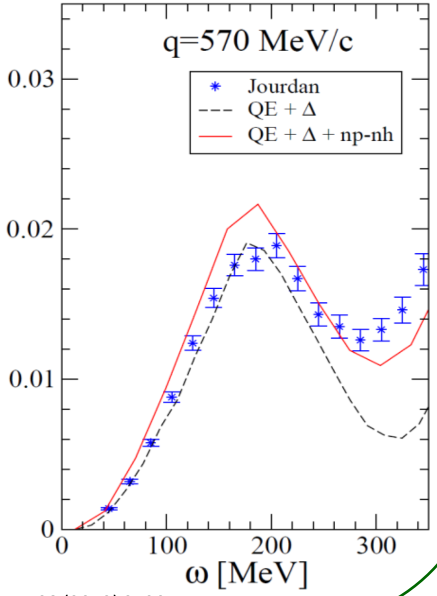
Several partial components
treated in self-consistent,
coupled and coherent way

Testing our approach in other processes

Electron scattering

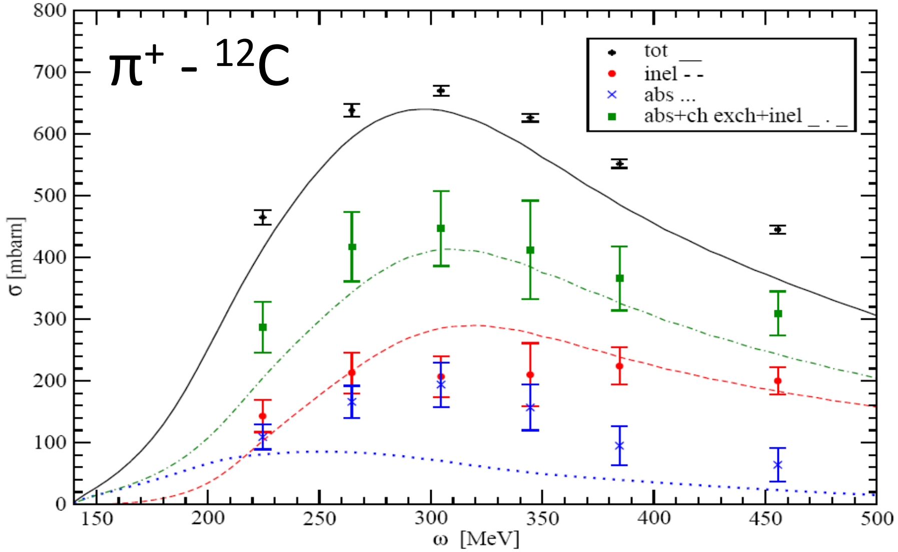


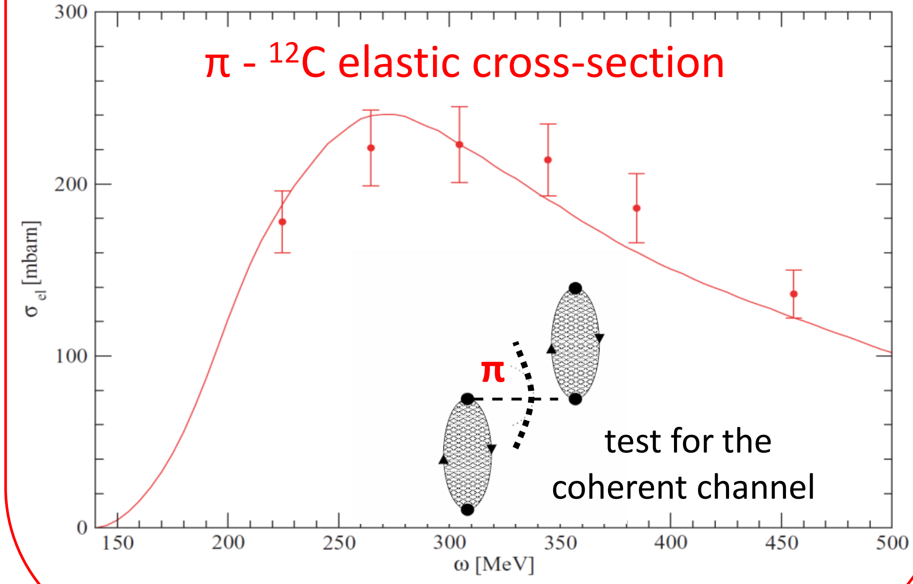




Martini, J.Phys.Conf.Ser. 408 (2013) 012041

Pion scattering




π - ^{12}C elastic cross-section

test for the coherent channel

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

Neutrino scattering - Effects of the RPA in the quasielastic channel

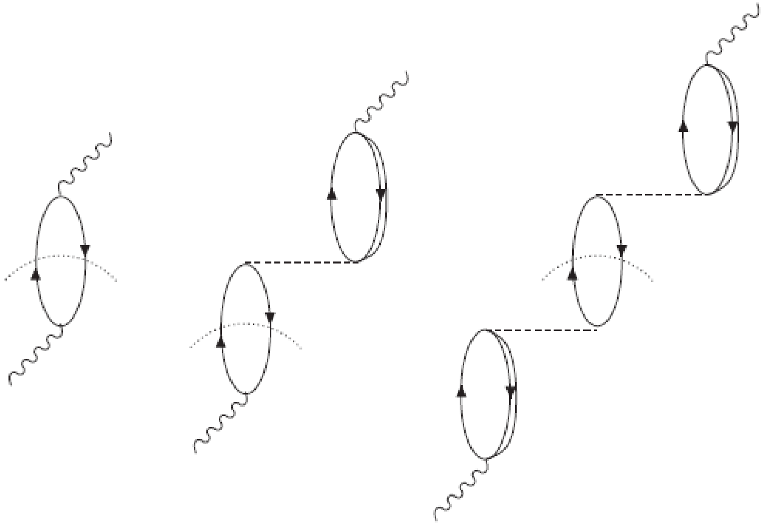
QE totally dominated by isospin spin-transverse response $R_{\sigma\tau(T)}$

RPA reduction

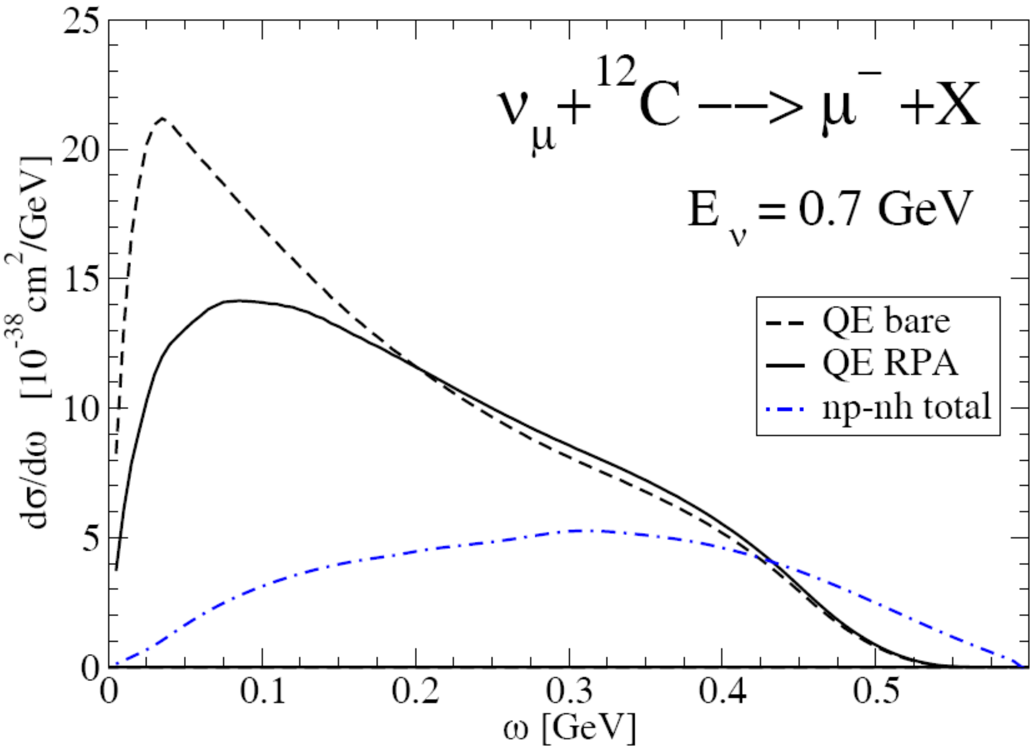
- expected from the repulsive character of p-h interaction in T channel
- mostly due to interference term $R^{N\Delta} < 0$

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

Lowest order contribution to QE

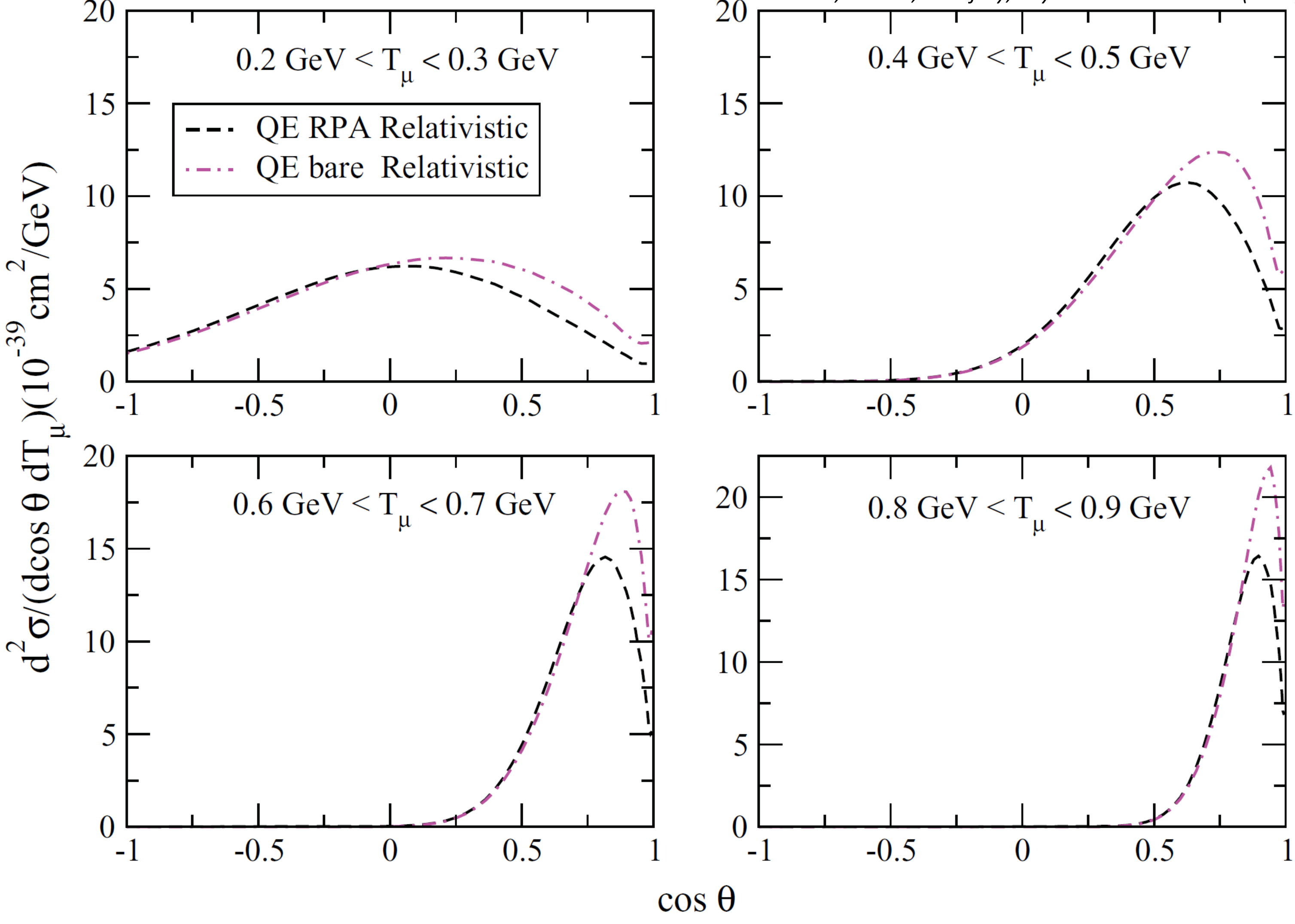


R^{NN}_{QE} $R^{N\Delta}_{QE}$ $R^{\Delta\Delta}_{QE}$



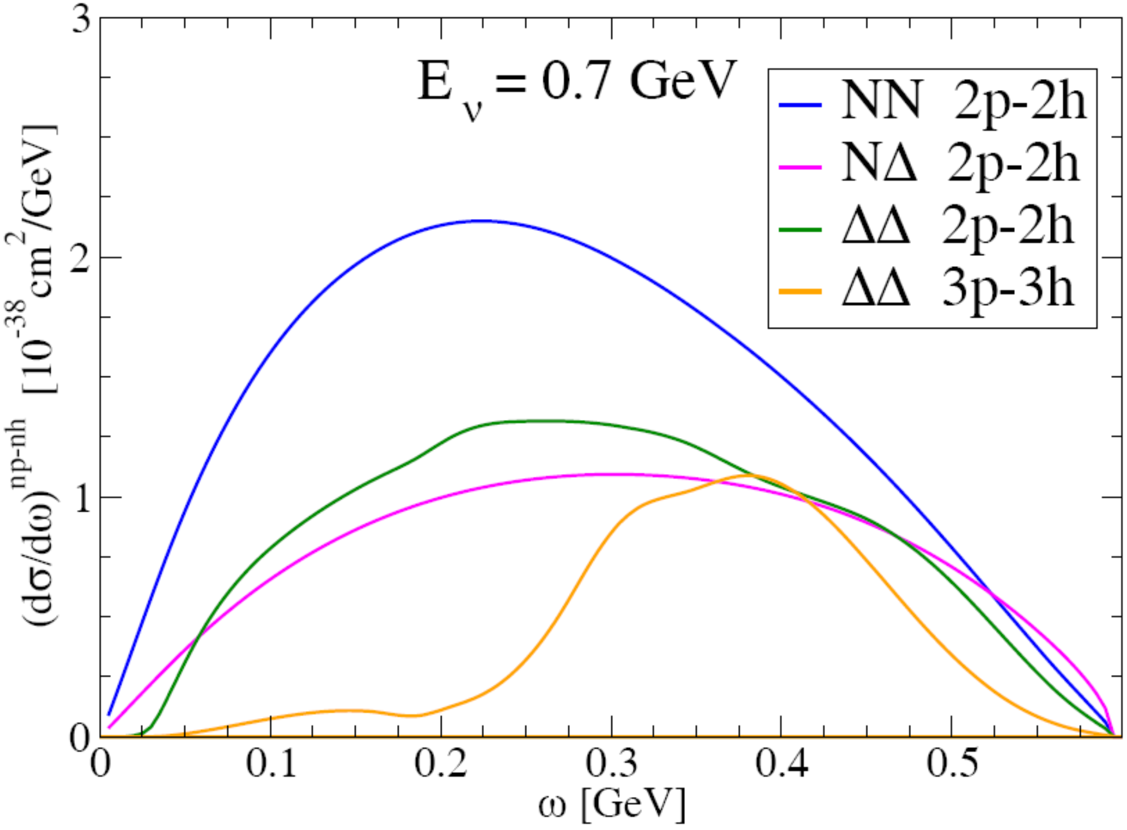
Bare *vs* RPA for MiniBooNE flux folded $d^2\sigma$ (genuine QE)

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



RPA produces a quenching and some shift towards larger angles

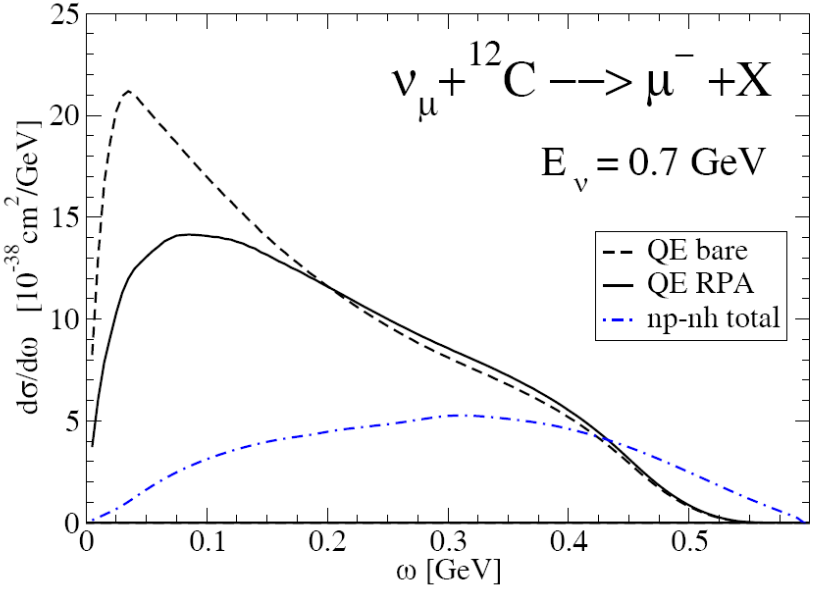
Neutrino scattering - some details on the np-nh contributions



Correlations

Interference

MEC

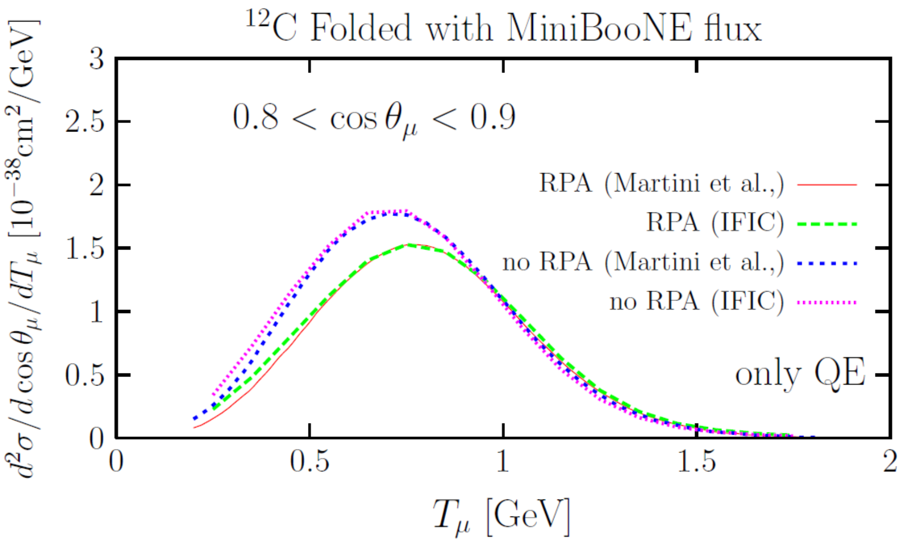


Comparison between our approach and the one of Nieves et al. (IFIC)

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

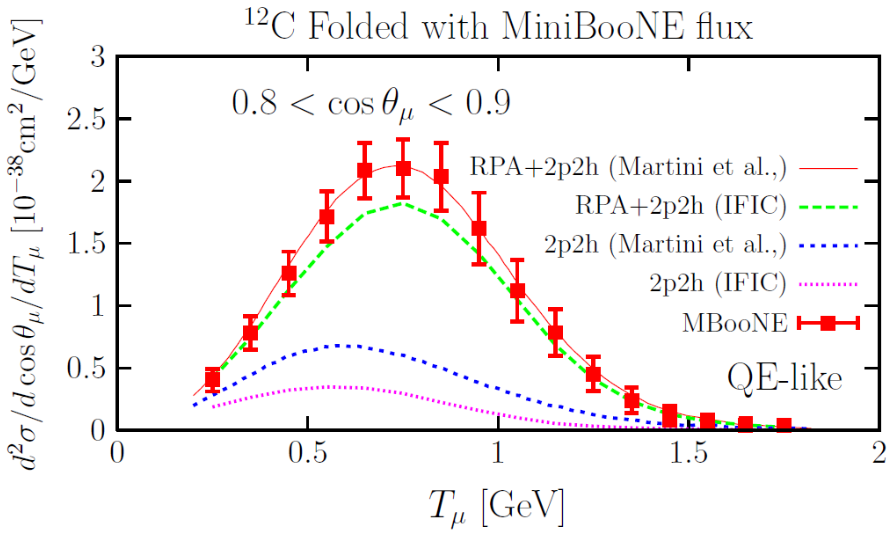
ν

Genuine QE



- Genuine QE bare and RPA very similar

QE + np-nh



- Factor ~2 for the np-nh contribution

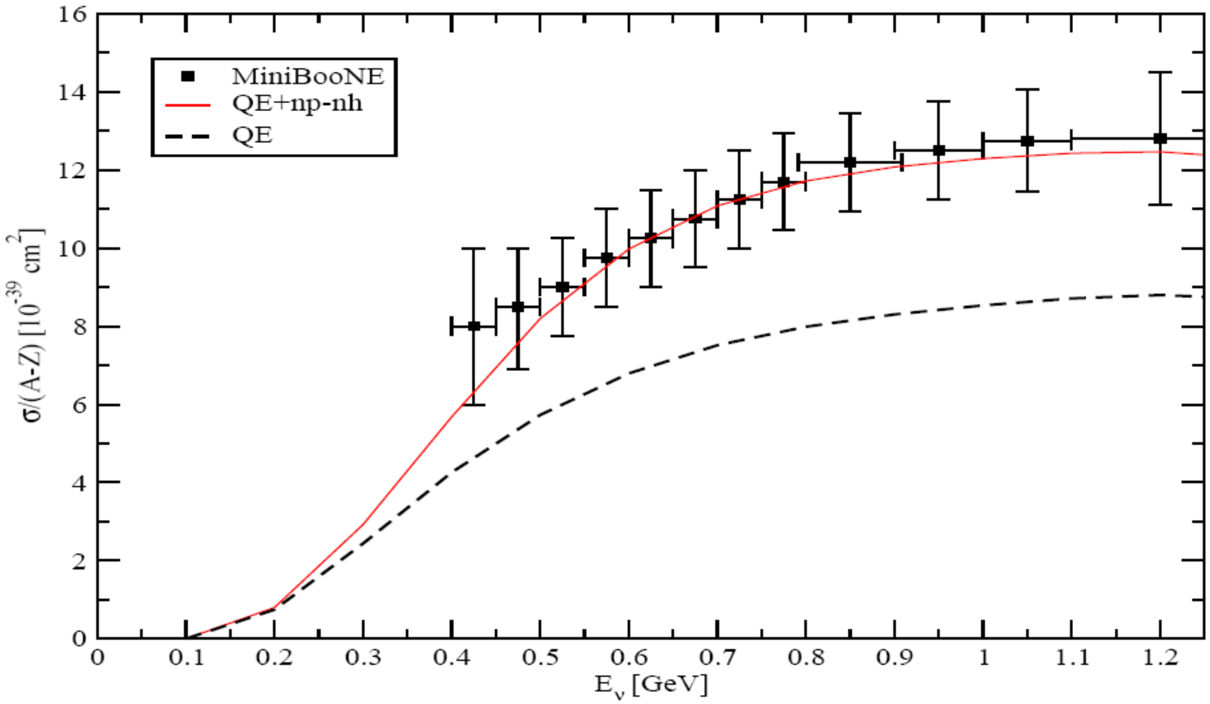
Both models compatible with MiniBooNE

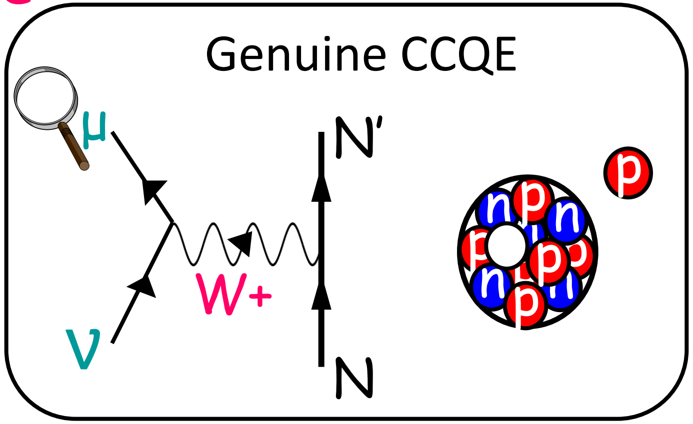
(additional normalization uncertainty of 10% in the MB data not shown here)

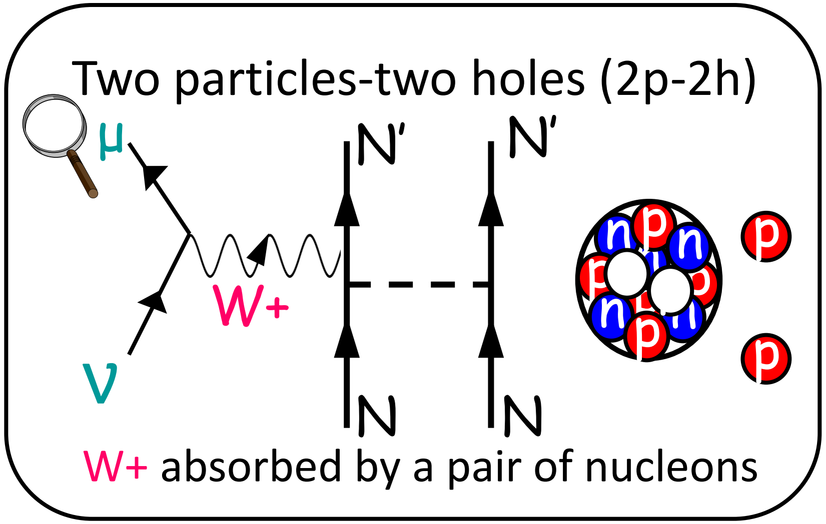
Rapid Review of our 2009 -->2013 results

First explanation of the MiniBooNE CCQE cross section and of the M_A puzzle

Inclusion of the multinucleon emission channel (np-nh)







W+ absorbed by a pair of nucleons

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

Agreement with MiniBooNE without increasing M_A

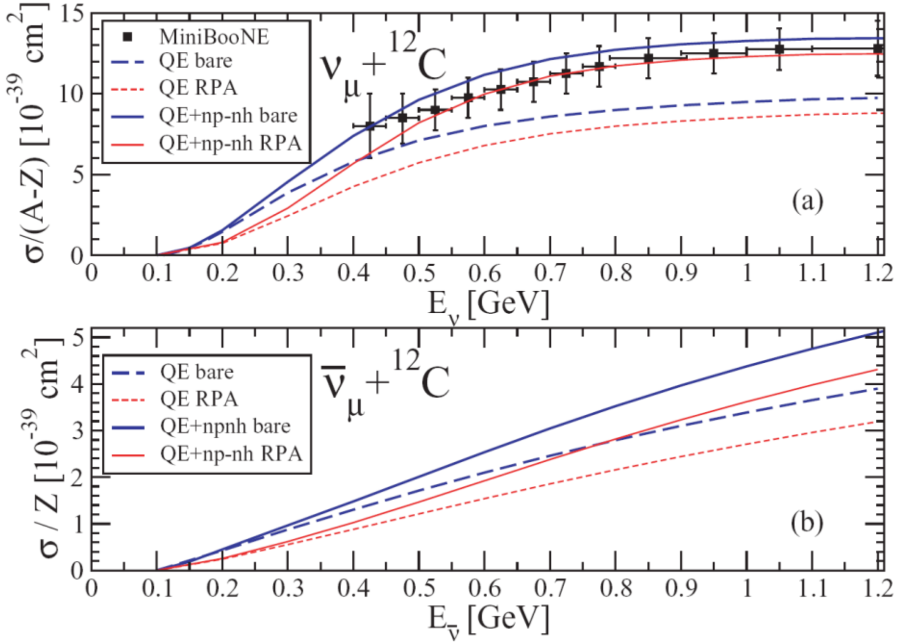
Neutrino *vs* Antineutrino interactions

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

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

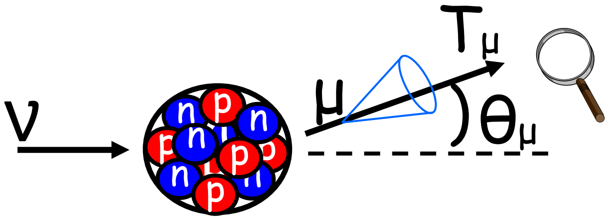
→the relative weight of the different nuclear responses is different for neutrinos and antineutrinos

→the relative role of 2p-2h contributions is different for neutrinos and antineutrinos

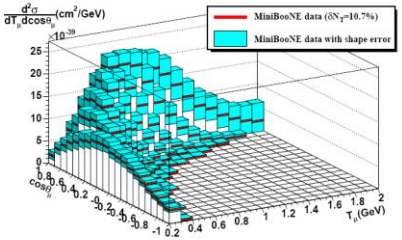


M. Martini, M. Ericson, G. Chanfray, J. Marteau, Phys. Rev. C 81 045502 (2010)

MiniBooNE CCQE-like flux-integrated double differential cross section

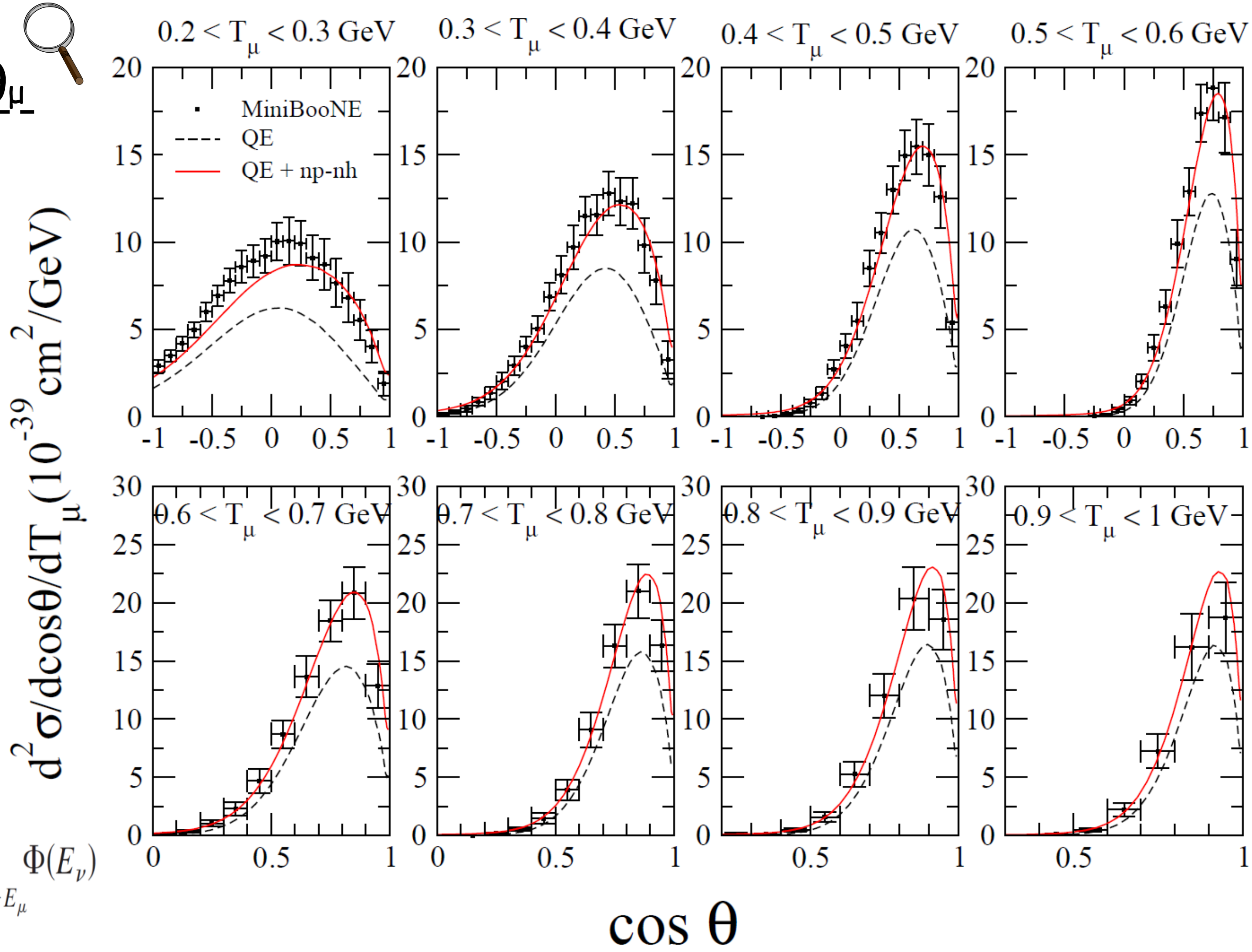


ν



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

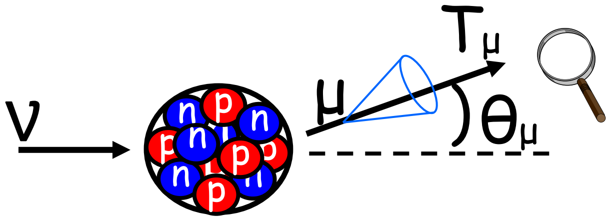
$$\frac{d^2\sigma}{dE_\mu d\cos\theta} = \int dE_\nu \left[\frac{d^2\sigma}{d\omega\, d\cos\theta}\right]_{\omega=E_\nu-E_\mu} \Phi(E_\nu)$$



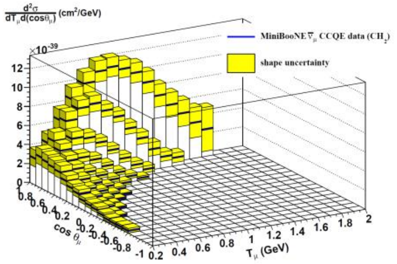
Agreement with MiniBooNE without increasing M_A once np-nh is included

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

MiniBooNE CCQE-like flux-integrated double differential cross section

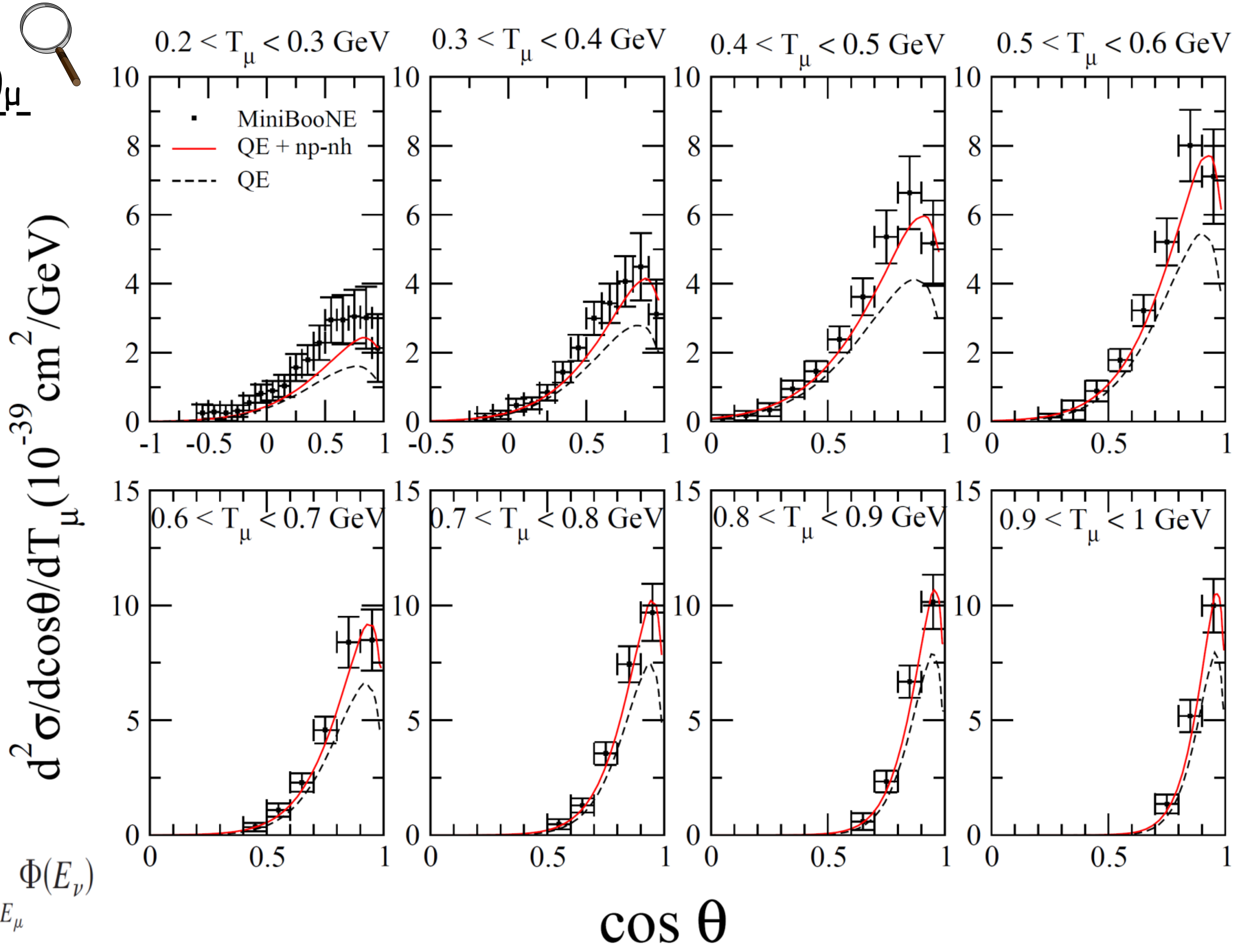


$\bar{\nu}$



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

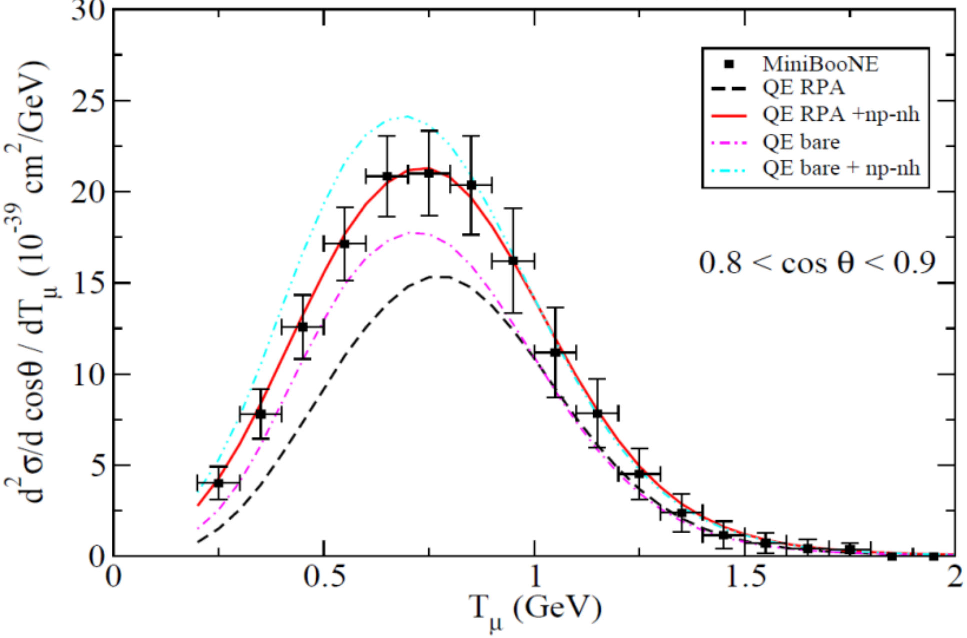
Martini, Ericson, Phys. Rev. C 87 065501 (2013)

Flux-integrated CCQE double differential X section versus T_μ

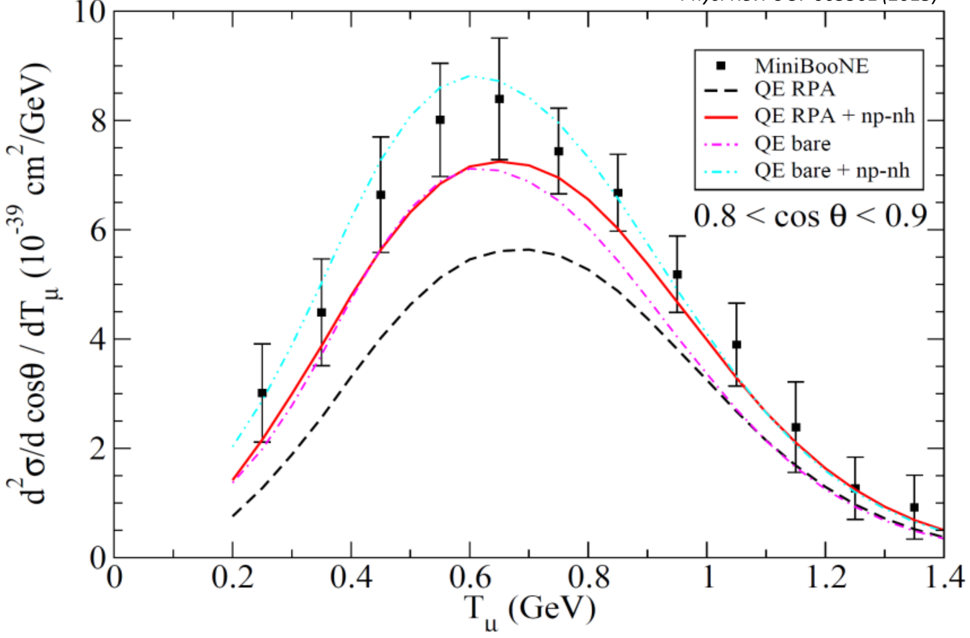
ν

$\bar{\nu}$

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

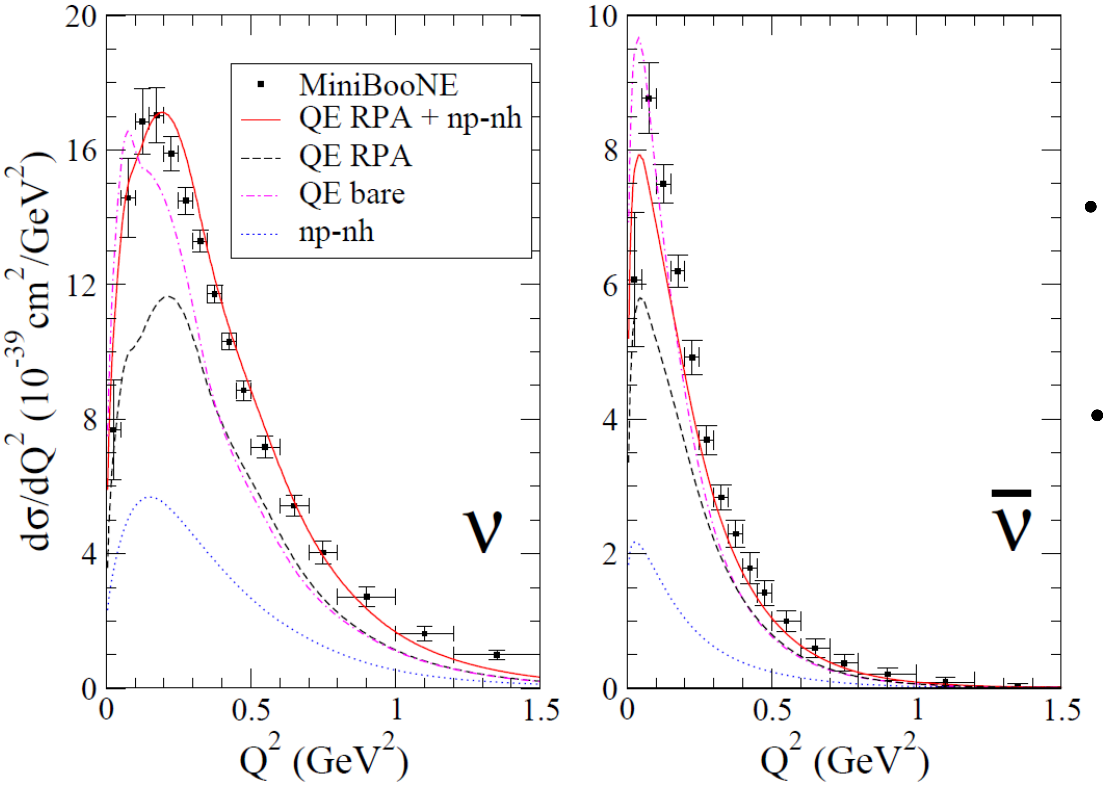


Martini, Ericson,
Phys. Rev. C 87 065501 (2013)



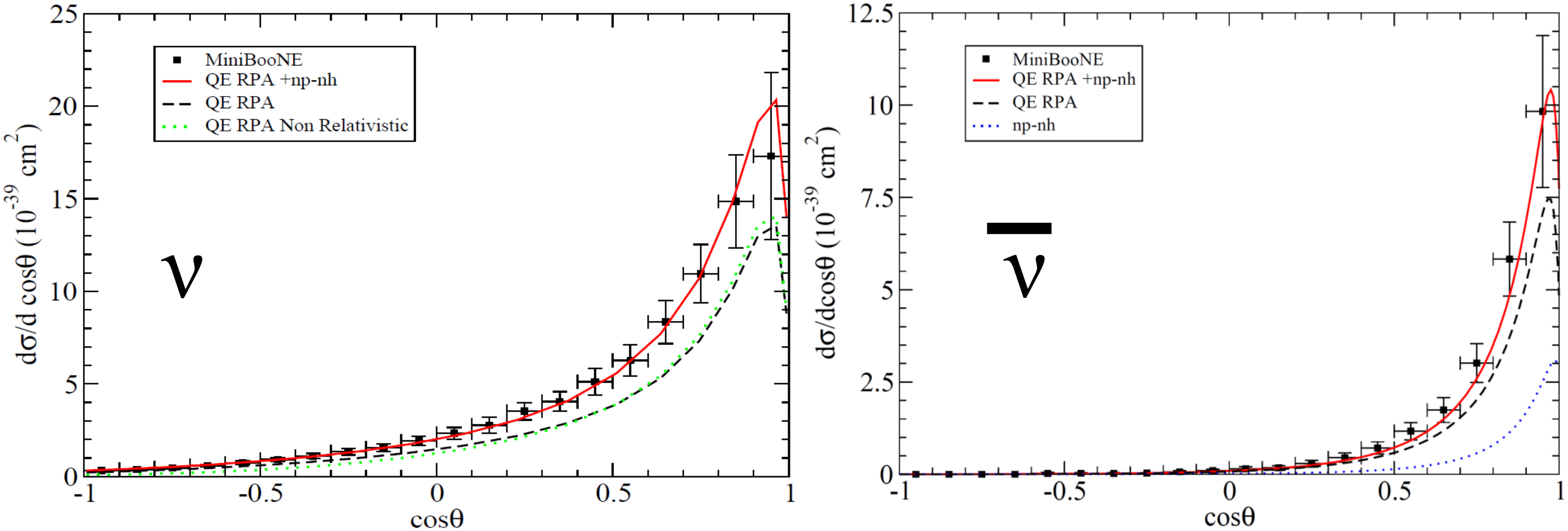
Delicate balance between
RPA quenching and np-nh enhancement

CC Q^2 distribution



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

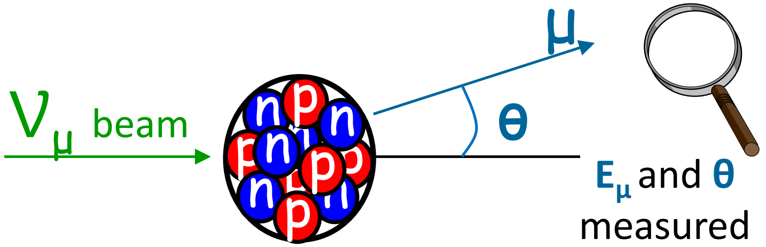
dσ/dcosθ



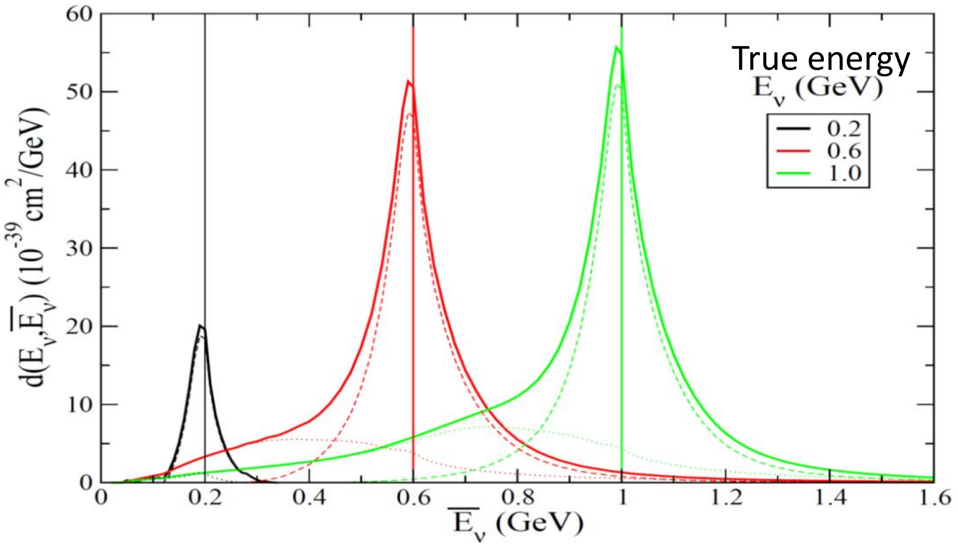
Antineutrino cross section falls more rapidly than the neutrino one

Neutrino energy reconstruction and neutrino oscillations

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

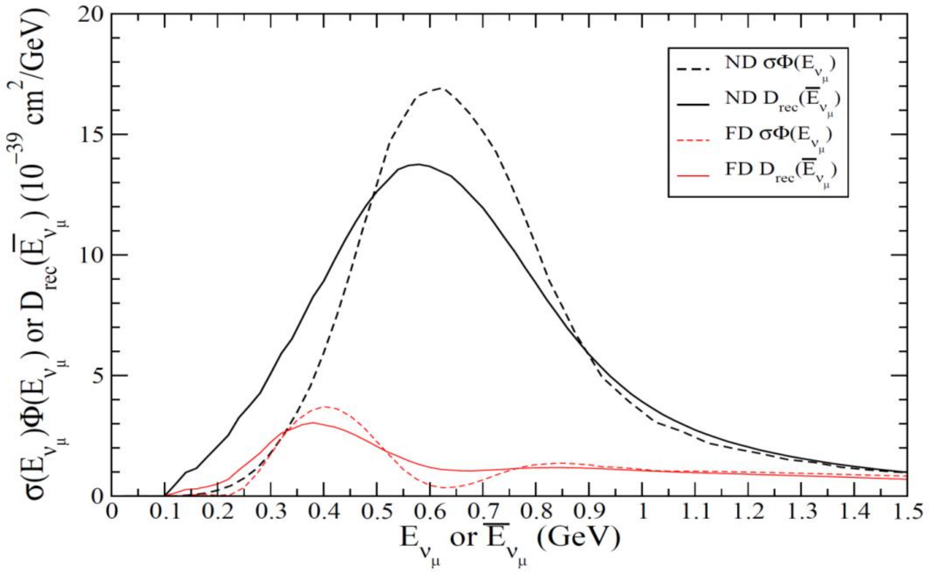


ν energy distribution



- 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

Similar analysis for $\nu_\mu \rightarrow \nu_e$
of MiniBooNE and T2K

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

2014 and 2015 Results

I) 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

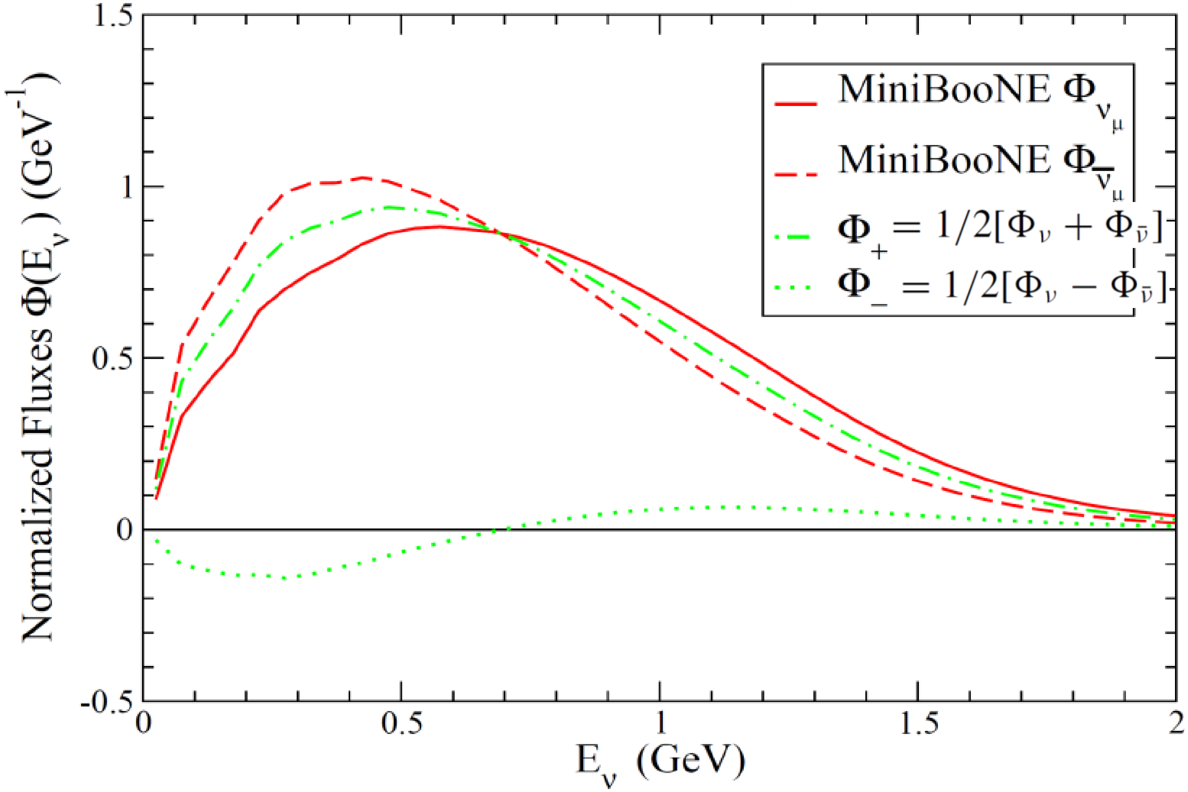
$$d\sigma \sim d\sigma_L + d\sigma_T \pm d\sigma_{VA}$$

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

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

Problem: flux dependence of dσ

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

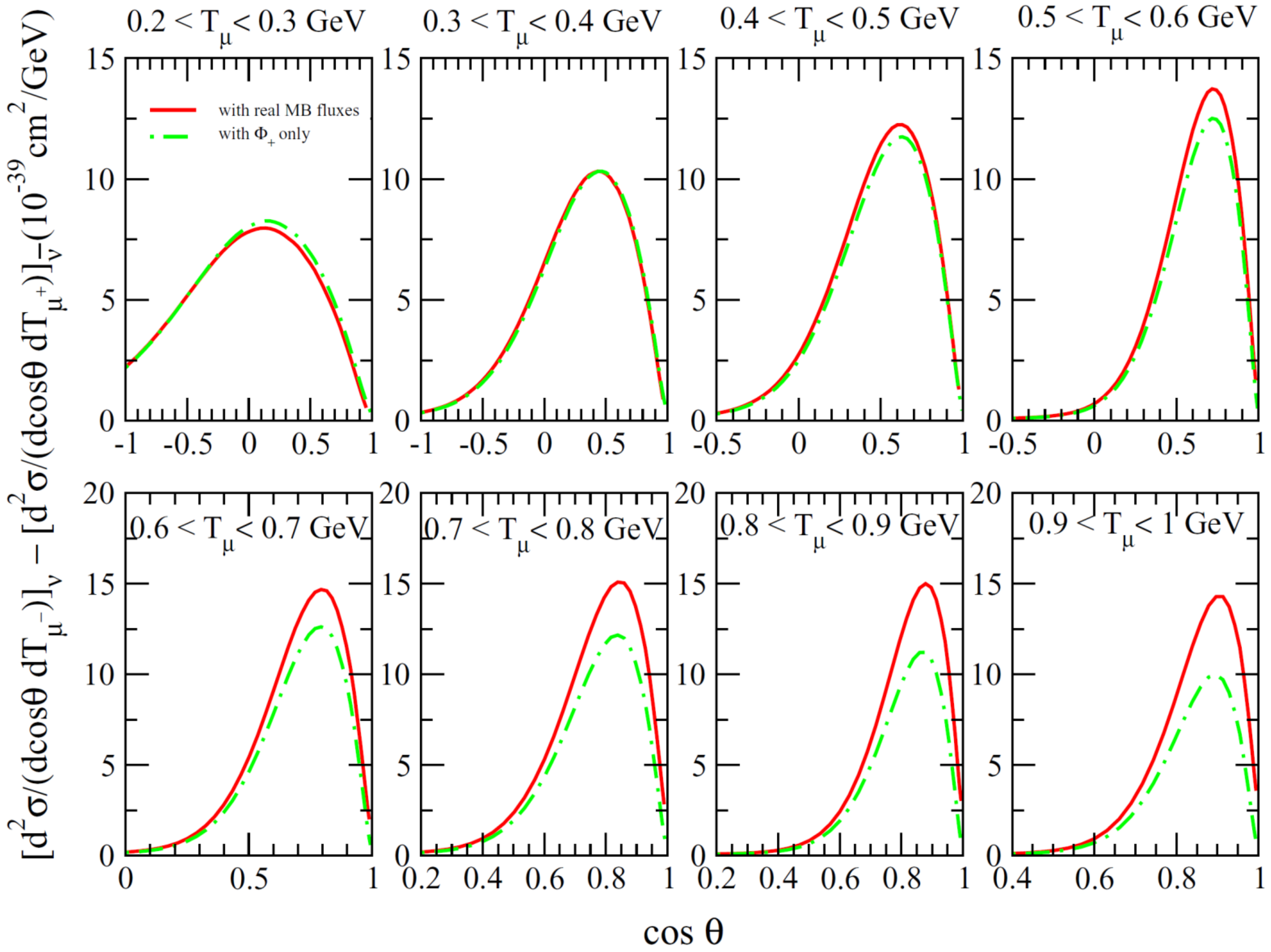


$$\begin{matrix} sum(\cos\theta,\omega) \\ dif(\cos\theta,\omega) \end{matrix} = \frac{d^2\sigma_\nu}{d\cos\theta\, d\omega} \pm \frac{d^2\sigma_{\bar{\nu}}}{d\cos\theta\, d\omega}$$

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

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

CCQE-like

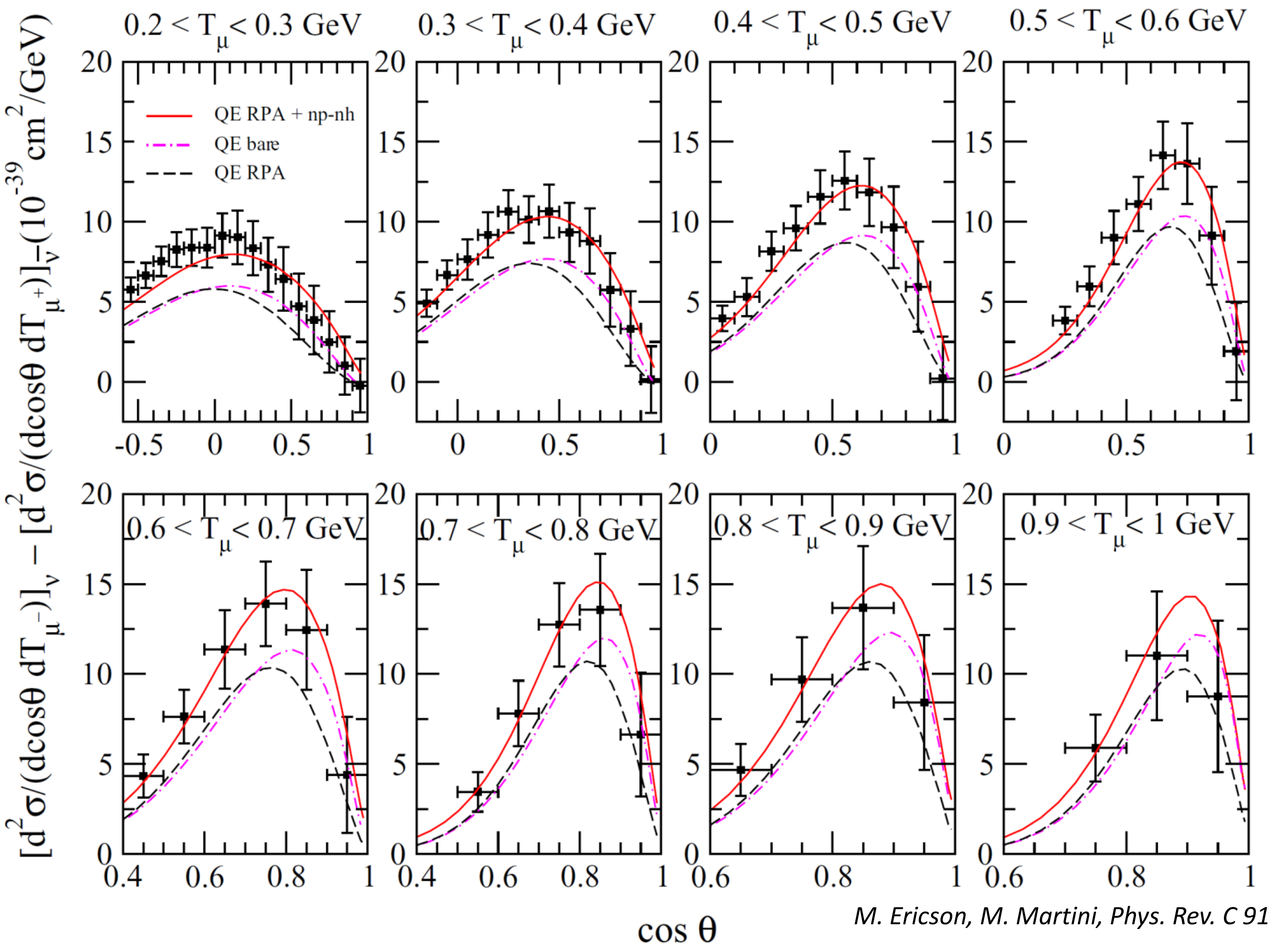


The mean flux (Φ_+) contribution is dominant in the ν antiν difference

$\Longrightarrow$ 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

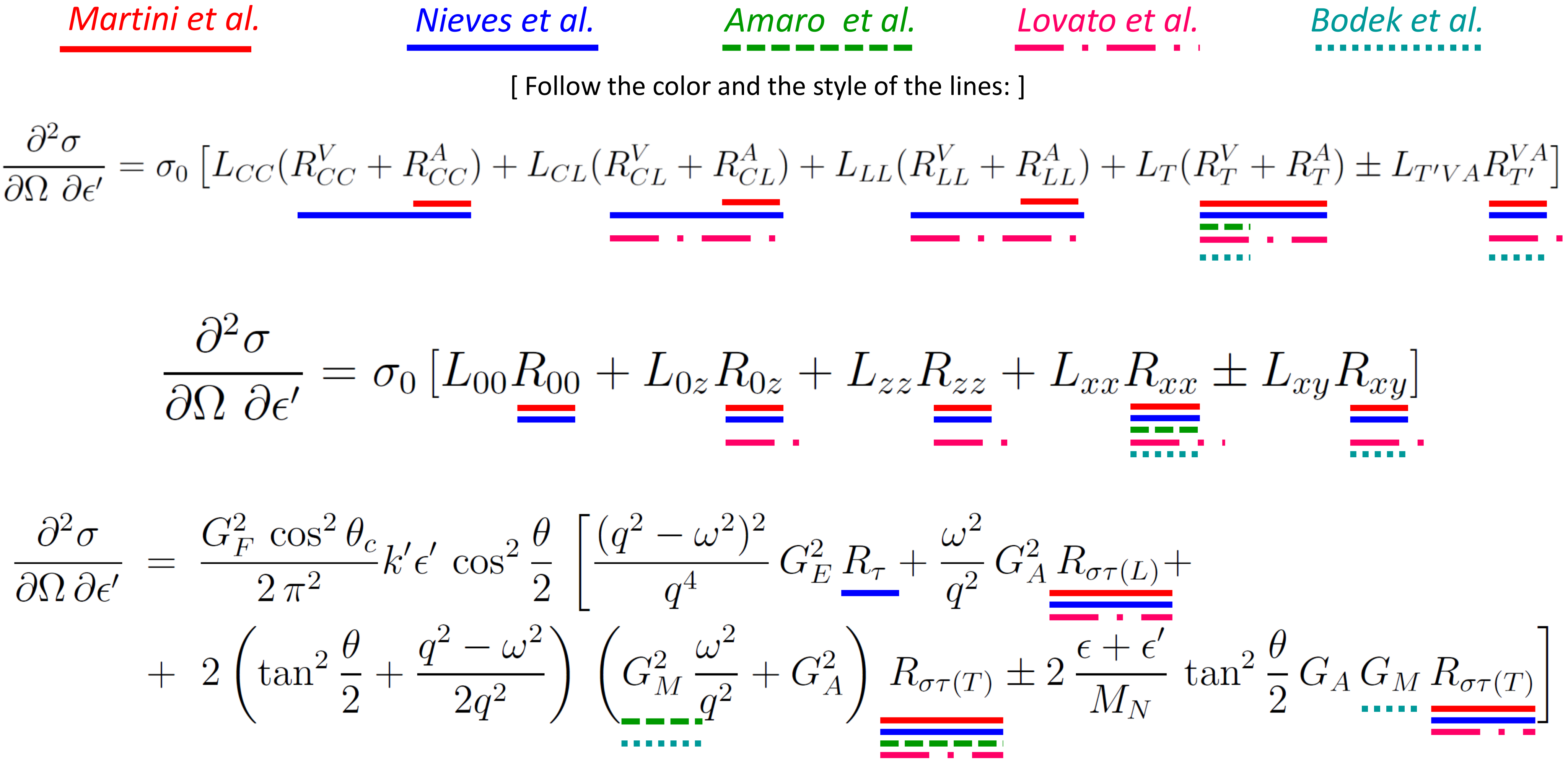


M. Ericson, M. Martini, Phys. Rev. C 91 035501 (2015)

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

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

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:]

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

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

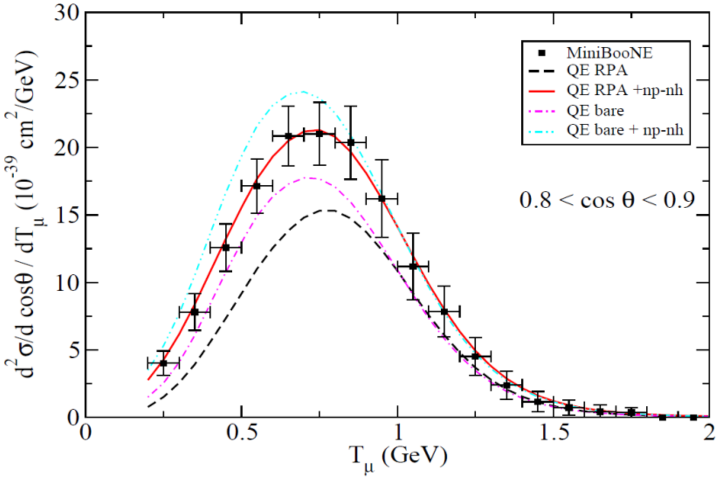
$$\frac{\partial^2\sigma}{\partial\Omega\,\partial\epsilon'} = \frac{G_F^2\,\cos^2\theta_c}{2\,\pi^2}k'\epsilon'\,\cos^2\frac{\theta}{2}\Bigg[\frac{(q^2-\omega^2)^2}{q^4}G_E^2\,R_\tau + \frac{\omega^2}{q^2}G_A^2\,R_{\sigma\tau(L)} + 2\left(\tan^2\frac{\theta}{2}+\frac{q^2-\omega^2}{2q^2}\right)\left(G_M^2\frac{\omega^2}{q^2}+G_A^2\right)R_{\sigma\tau(T)}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

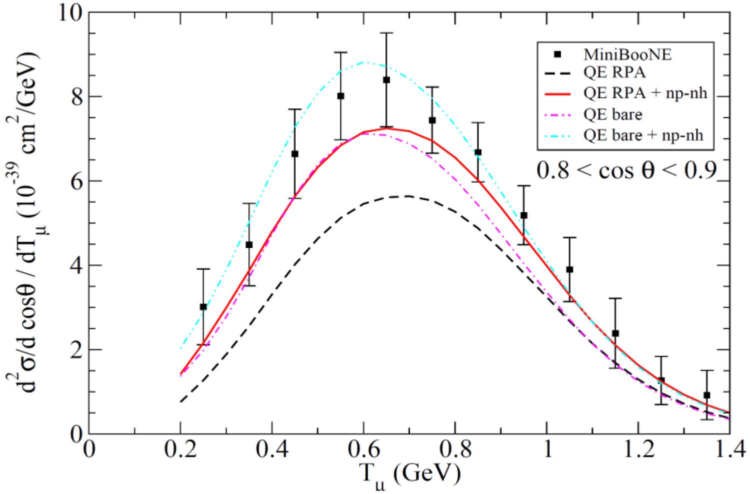
Relative role of 2p-2h for neutrinos and antineutrinos is different due to the **interference term**

ν

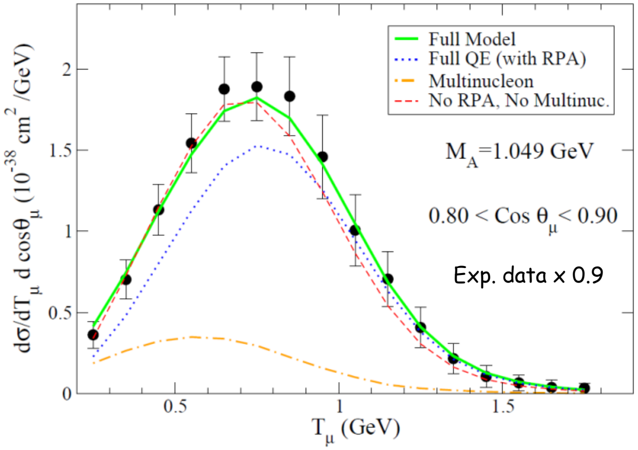
$\overline{\nu}$

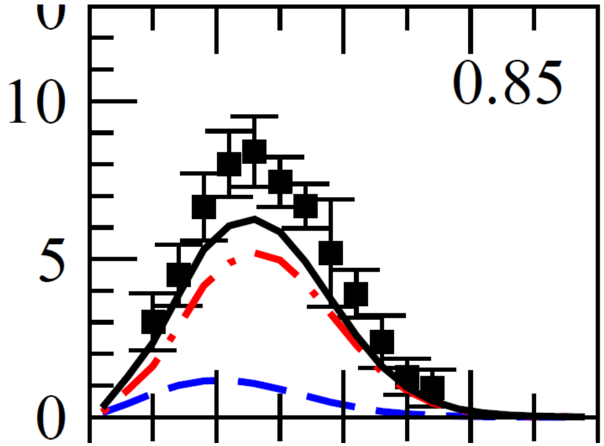
Martini et al.





Nieves et al.

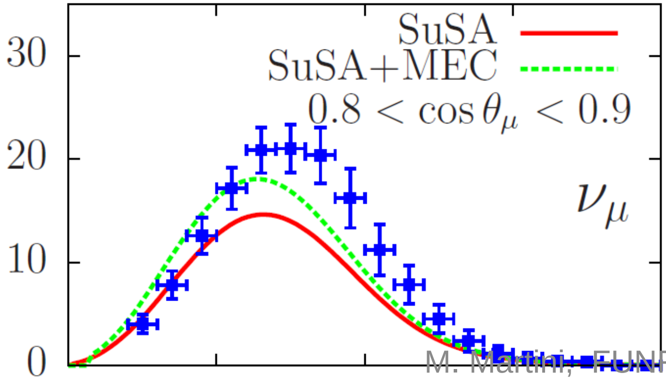


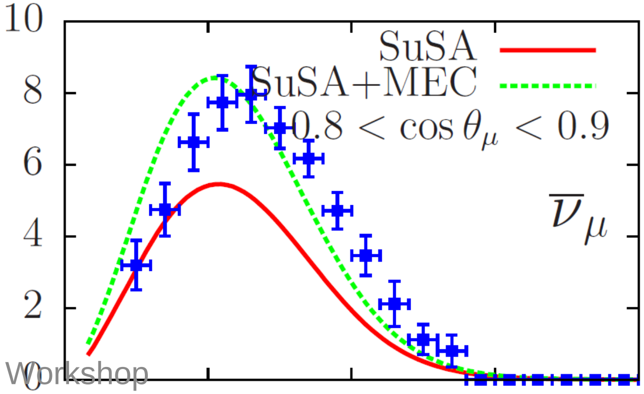


black: QE RPA+2p2h

red: QE RPA

Amaro et al.

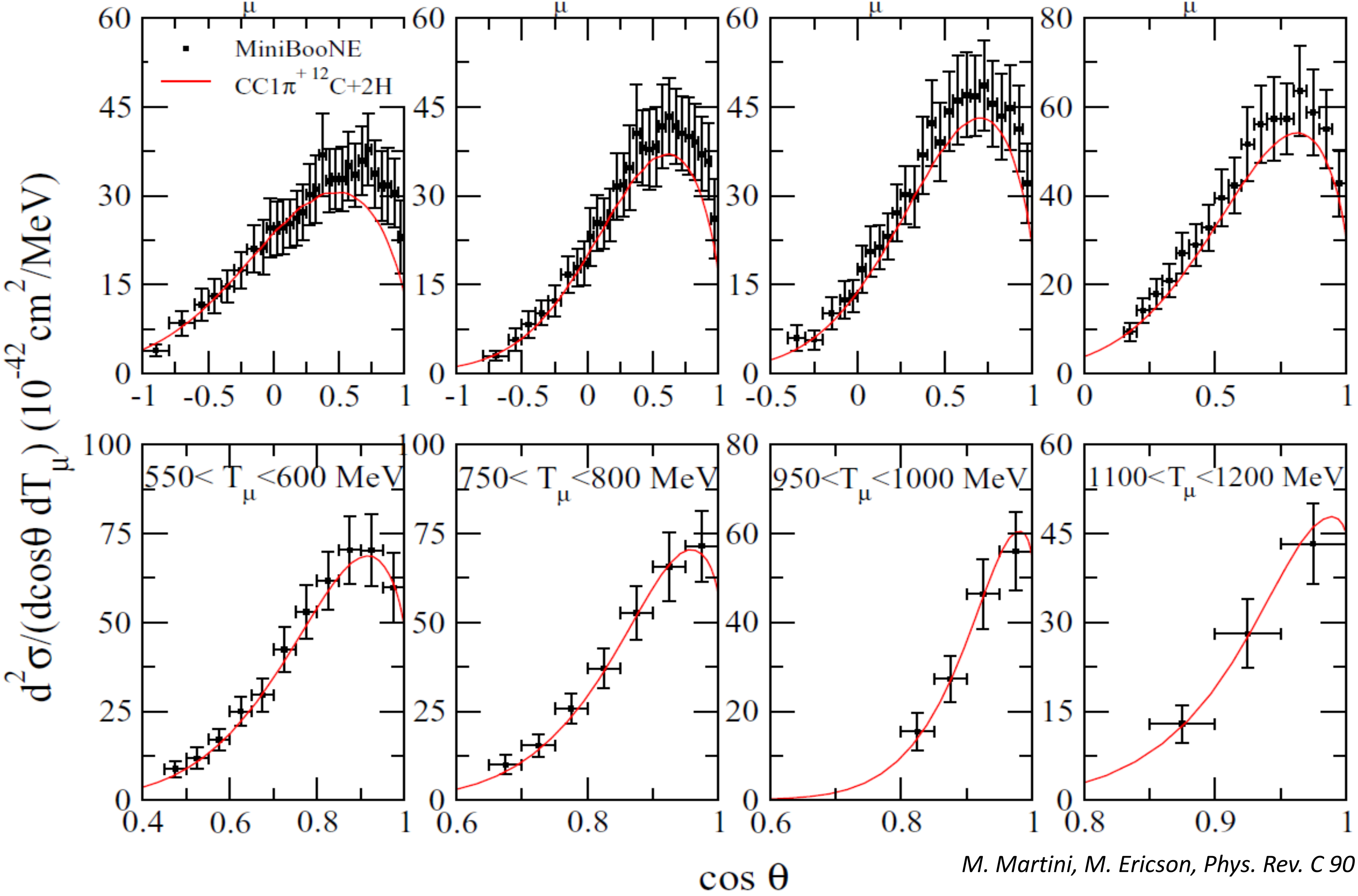




II) CC1π+ production

MiniBooNE flux-integrated CC1π+ double differential cross section

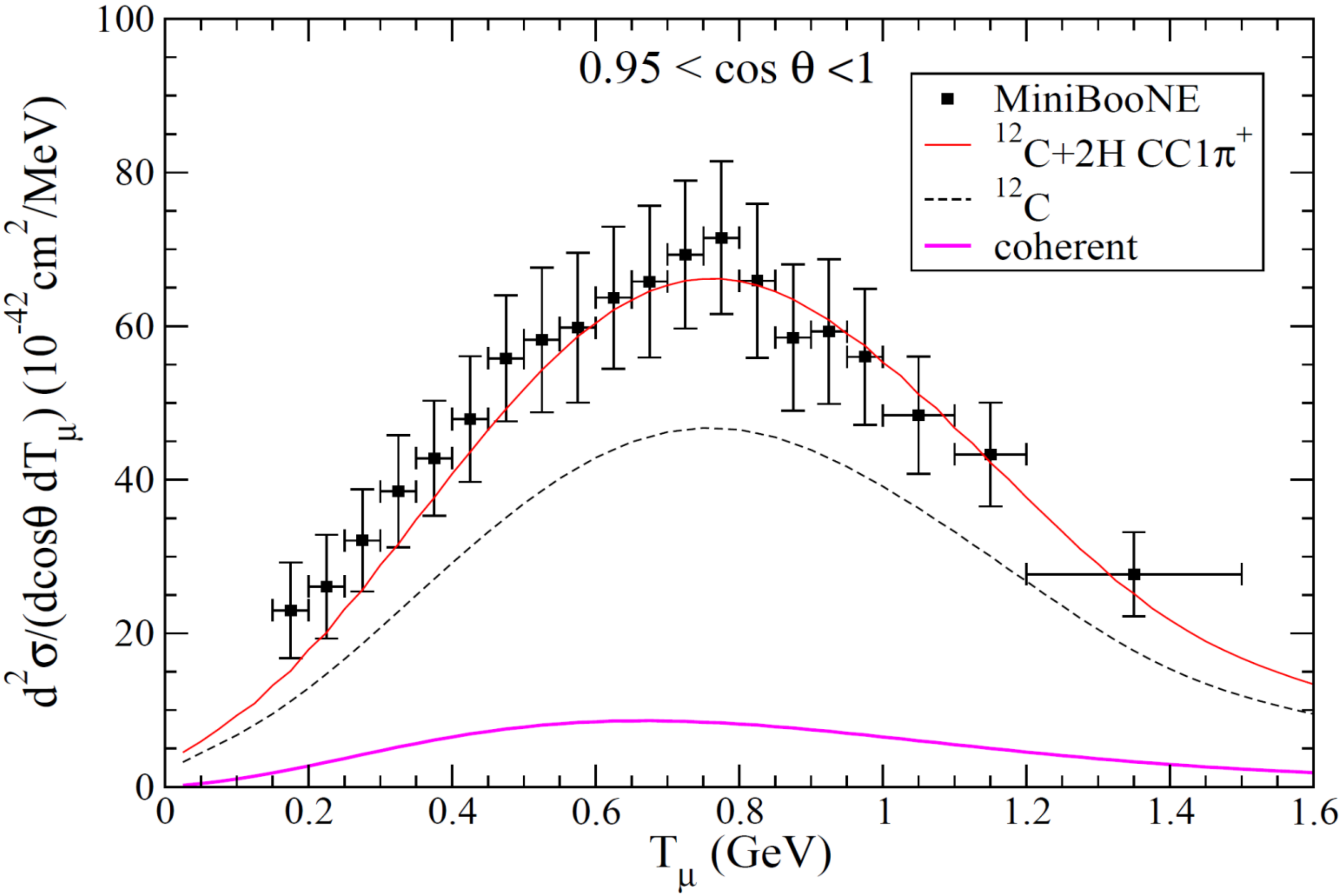
MiniBooNE Phys. Rev. D 83 052007 (2011)



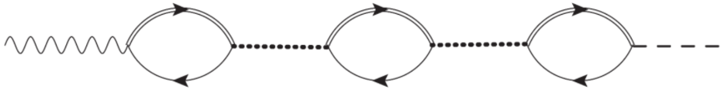
M. Martini, M. Ericson, Phys. Rev. C 90 025501 (2014)

- The general agreement between our evaluation and the data is good.
- Our model does not incorporate the final state interaction for the emitted π on its way out the nucleus

CC1π+ double differential cross section in the forward direction



The coherent contribution is significant although not dominant.
This contribution is interesting due to its relation to a high energy collective state of the nucleus, the **pion branch**, a coherent mixture of Delta-hole states and pions.



It is only in the forward direction that the spin longitudinal response which is sensitive to the pion branch, can dominate the cross section *[Delorme and Ericson, PLB 156, 263 (1985)].*

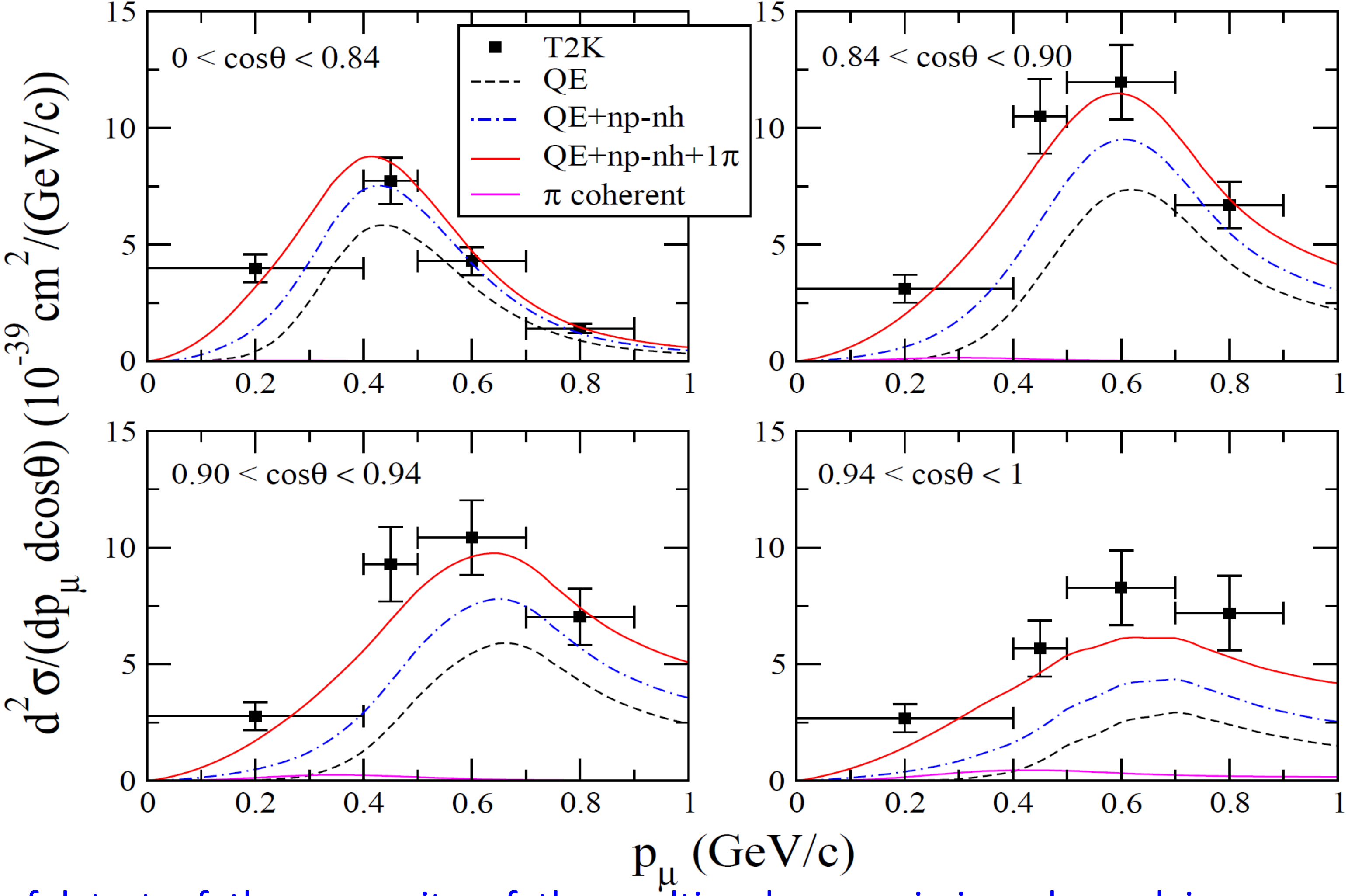
III) CC Inclusive

T2K flux-integrated inclusive double differential cross section on carbon

The inclusive cross section is less affected by background subtraction with respect to exclusive ones

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

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

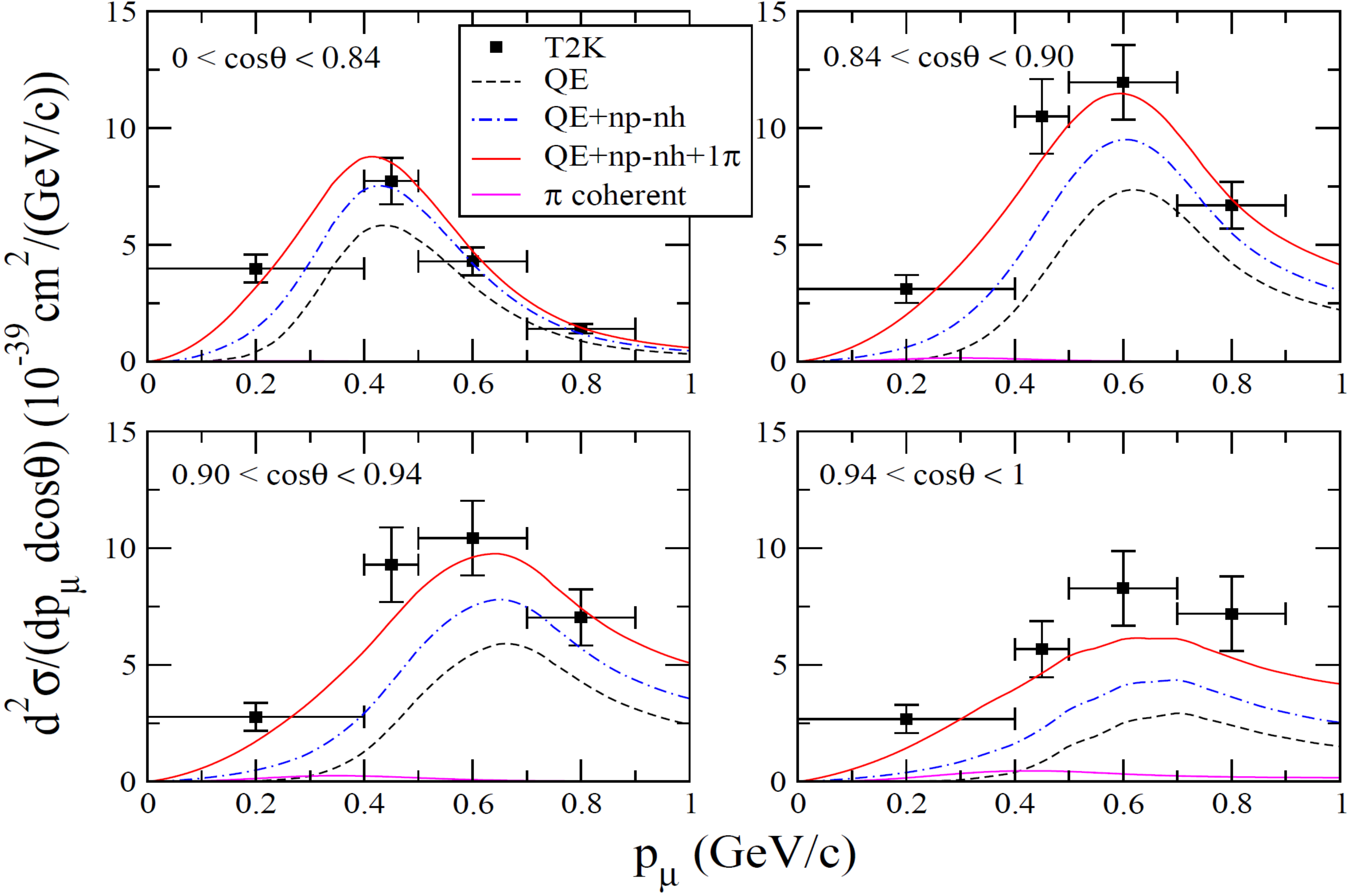


First successful test of the necessity of the multinucleon emission channel in an experiment with another neutrino flux with respect to the one of MiniBooNE.

T2K flux-integrated inclusive double differential cross section on carbon

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

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

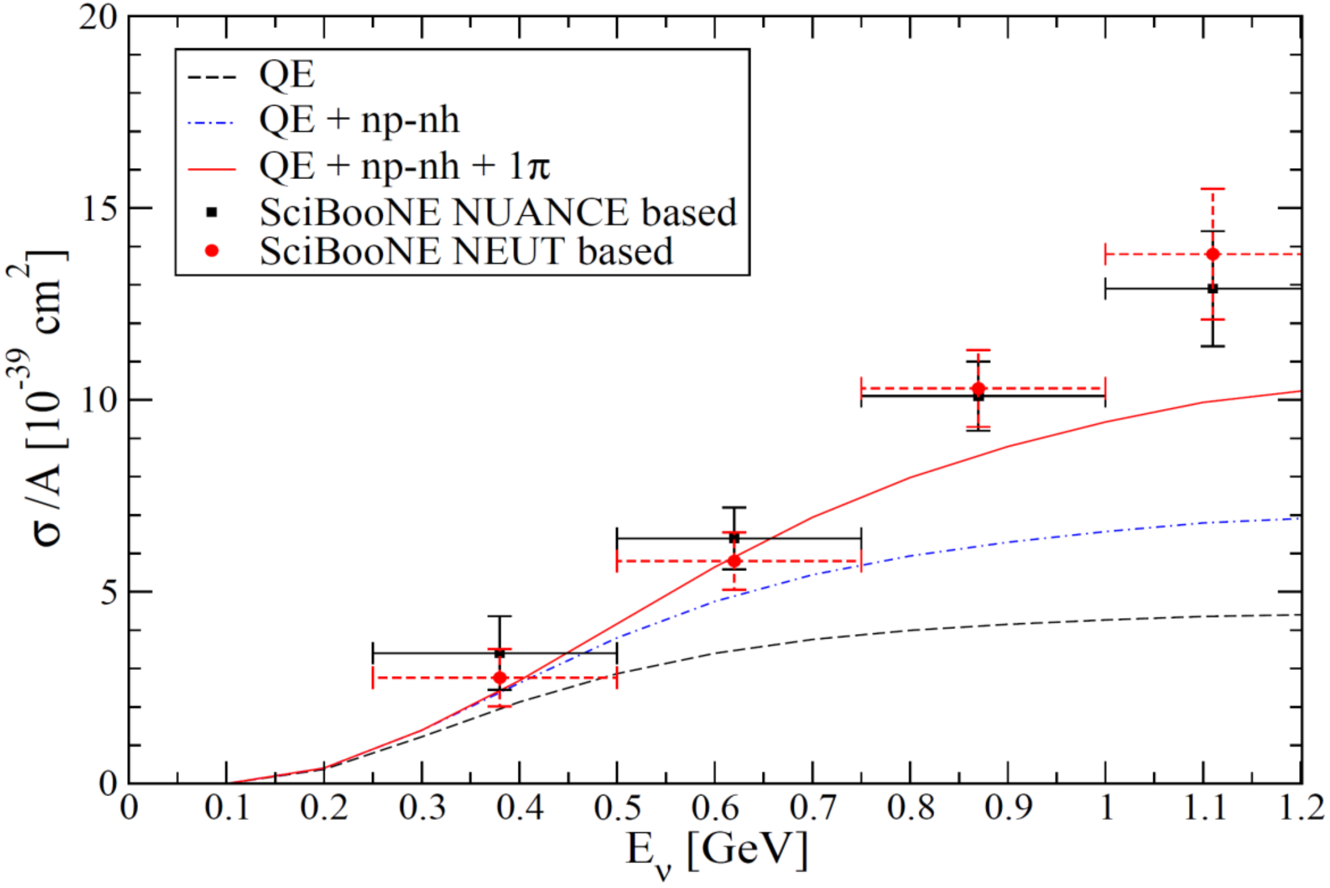


Even with the inclusion of the np-nh excitations, some undervaluation of the T2K data seems to show up in the **forward direction**. It could be due to some contributions not included in our description, such as excitations of **low-lying giant resonances**.

Inclusive CC total cross section on Carbon

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

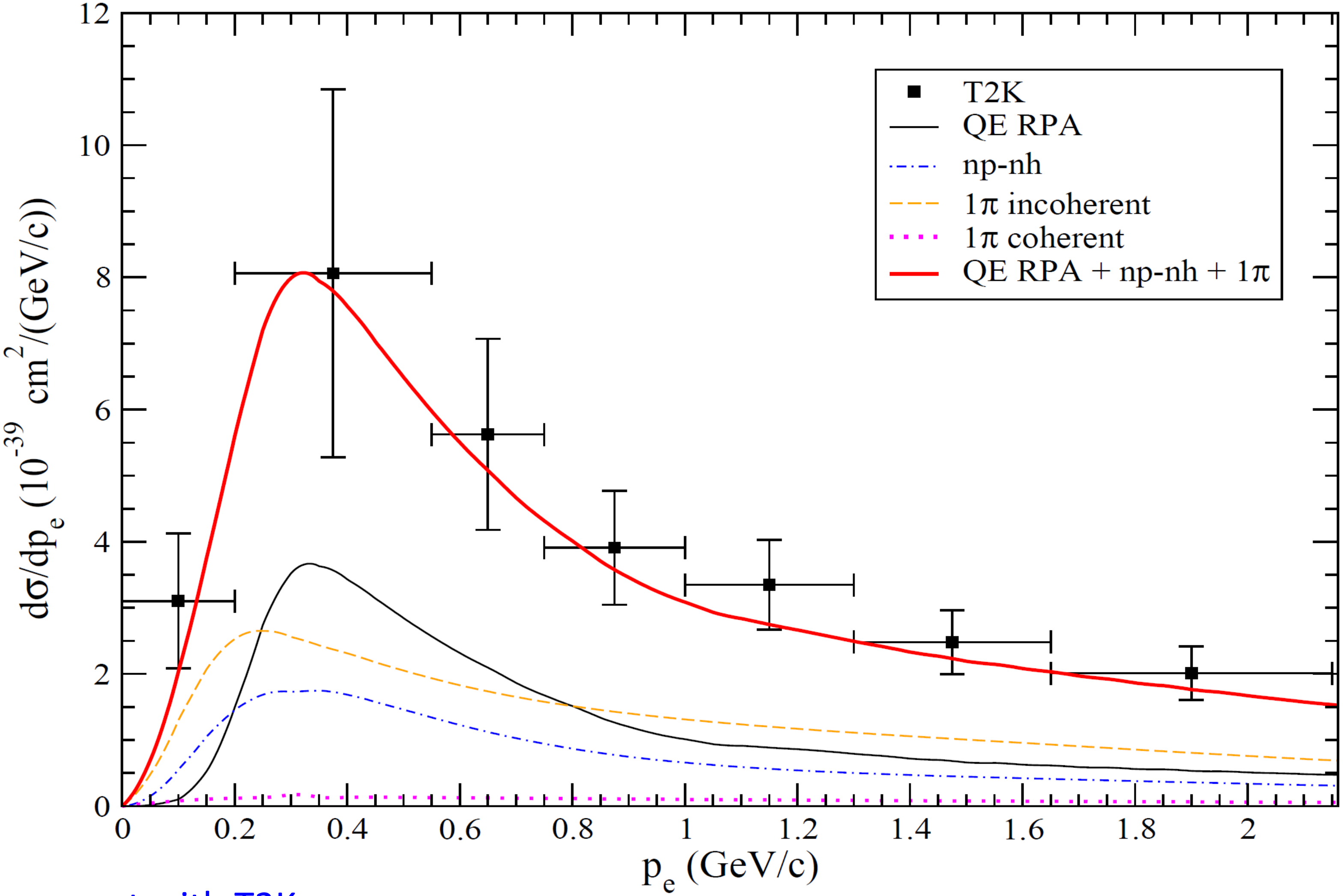
M. Martini, M. Ericson,
Phys. Rev. C 90 025501 (2014)



Our prediction gives a good fit of the data up to $E_\nu \simeq$ 1 GeV but underestimates the cross section above this value.
The natural interpretation is the existence of other channels which open up at high energies.
A likely candidate for the missing channel is the multipion production, in particular the **two pion production** one.

ν_e T2K flux-integrated inclusive differential cross section on carbon

T2K: *PRL 113, 241803 (2014)*



- Good agreement with T2K
- This agreement needs the presence of np-nh which even dominates the genuine QE for small p_e

to be submitted

Summary and conclusions

- Nuclear responses treated in RPA
  - -Quasielastic
  - -Pion production
  - **-Multinucleon emission** (np-nh excitations)

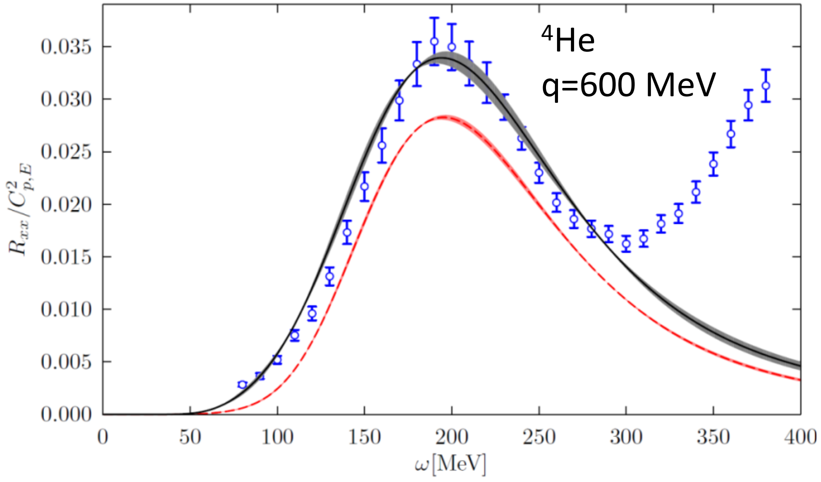
- Our model is in good agreement with the available neutrino experimental data in the different channels: QE-like, 1π production, inclusive

- Agreement with 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

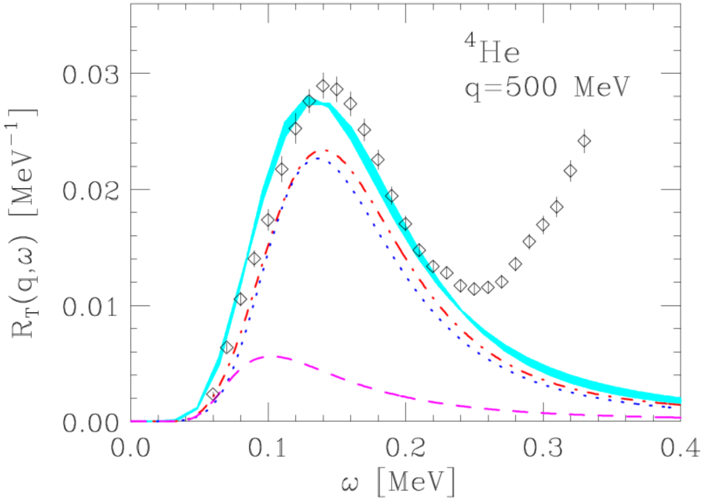
Spares

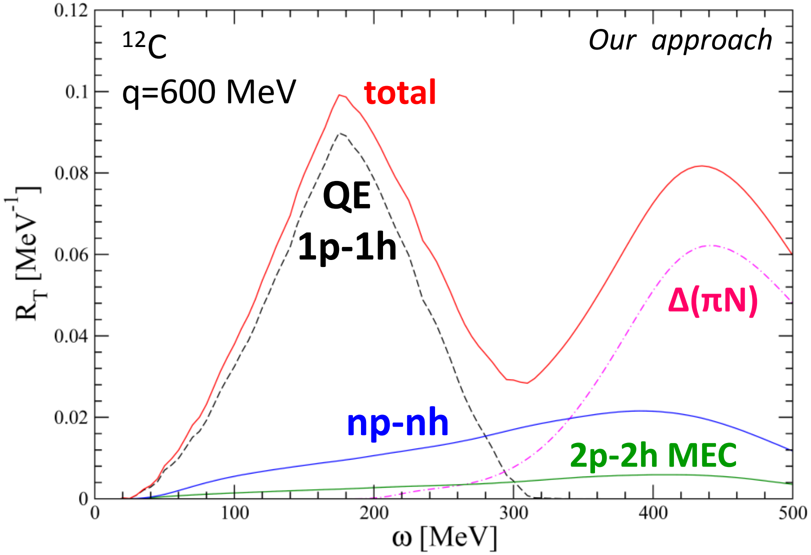
Electromagnetic transverse responses: some figures for discussion

Lovato et al.arXiv 1501.01981

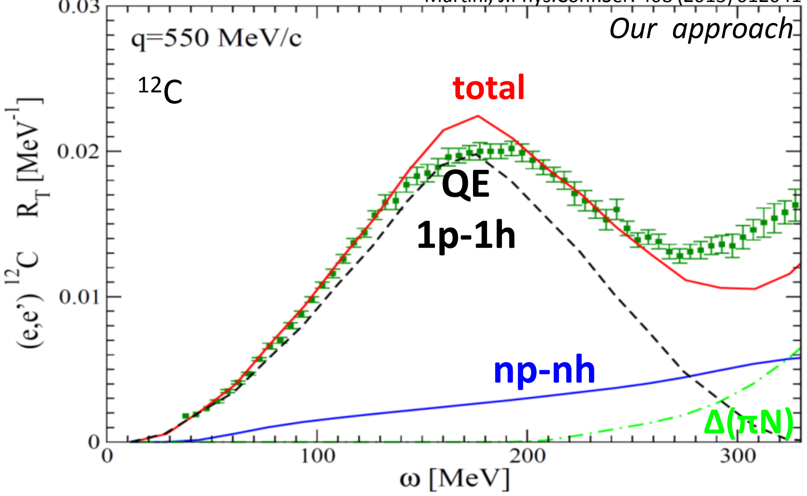


Benhar et al.arXiv 1502.00887



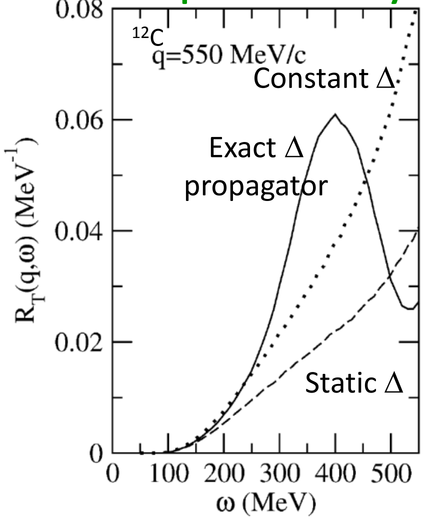


Martini, J.Phys.Conf.Ser. 408 (2013) 012041



De Pace et al. NPA741, 249 (2004)

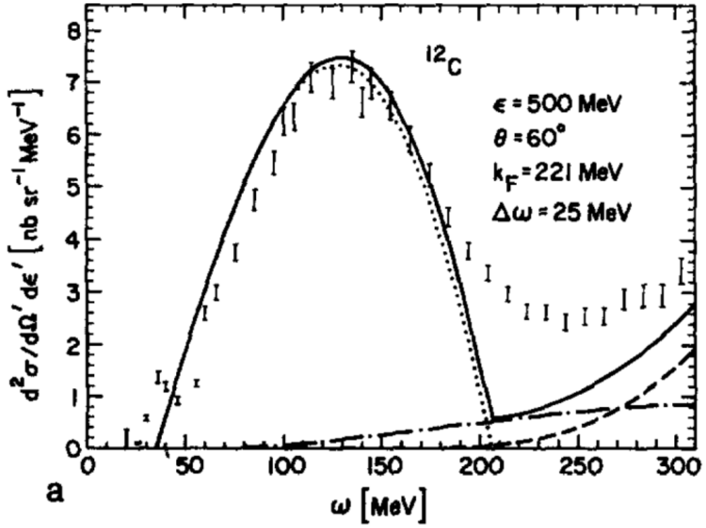
2p-2h MEC only



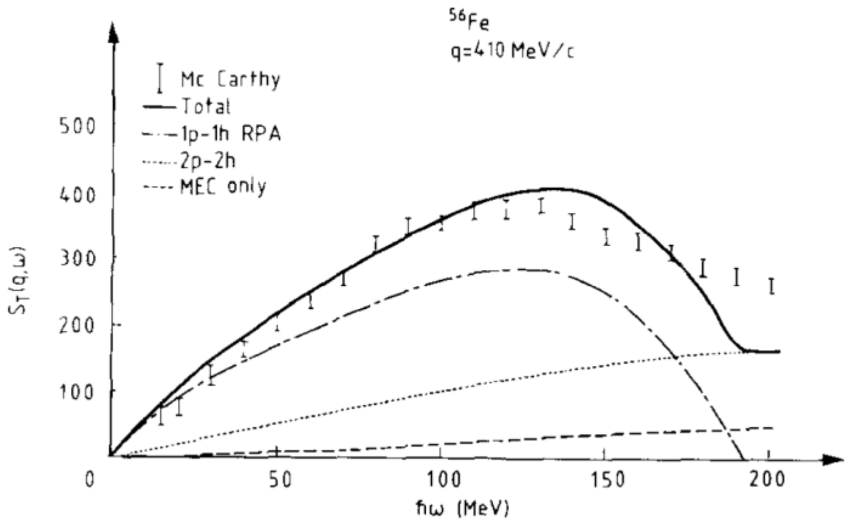
- Why the 2-body current contribution didn’t increase with ω in the case of Lovato et al. at difference with respect to many other calculations (see also next slide)?
- As shown by De Pace et al. the increase with ω appears also if one considers static or constant Δ propagator

Electromagnetic transverse responses: different theoretical calculations

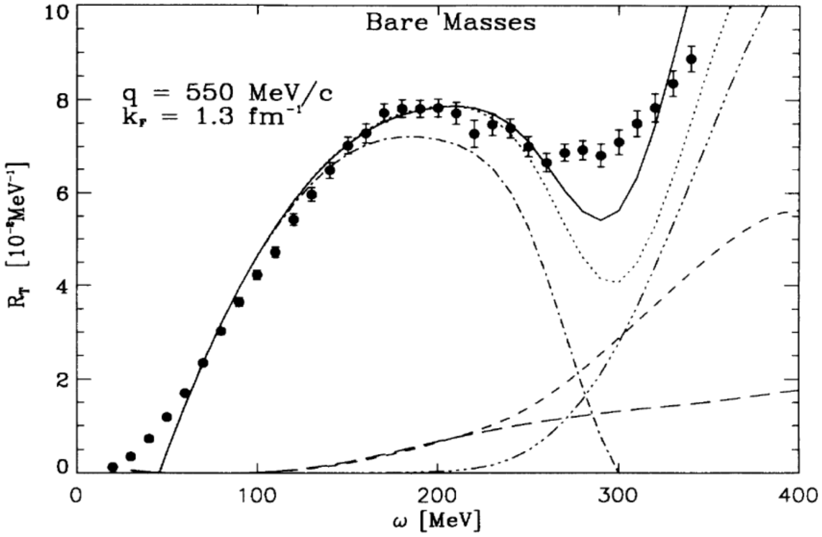
Van Orden, Donnelly, Ann. Phys. 131, 451 (1981)



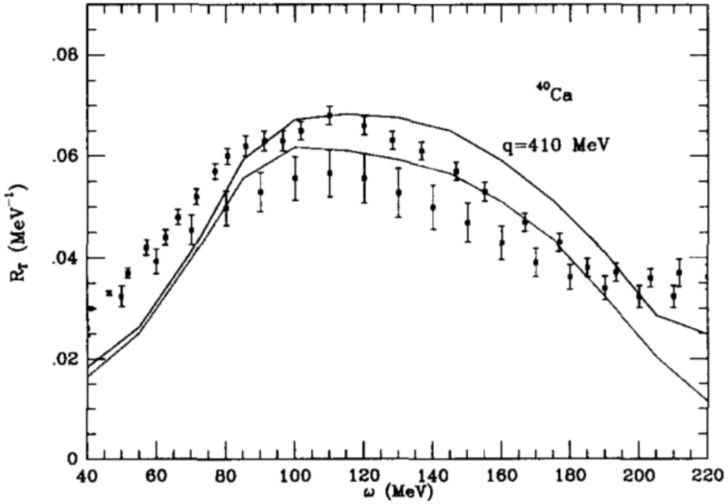
Alberico, Ericson, Molinari, Ann. Phys. 154, 356 (1984)



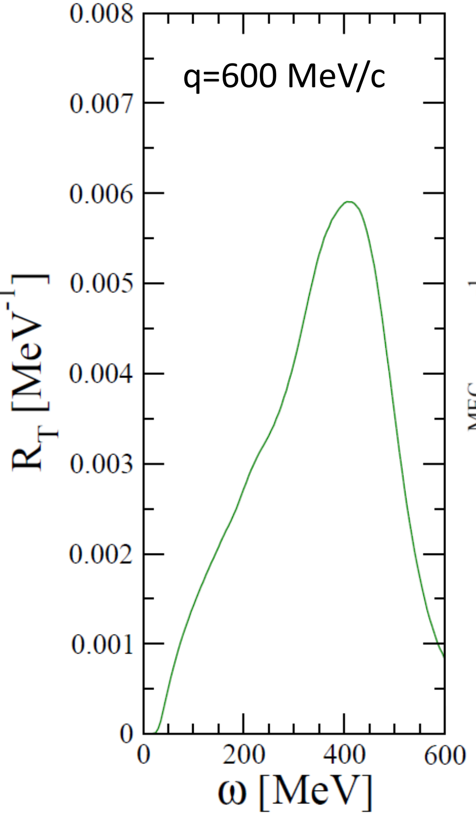
Dekker, Brussaard, Tjon, Phys. Rev. C 49 ,2650 (1994)



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

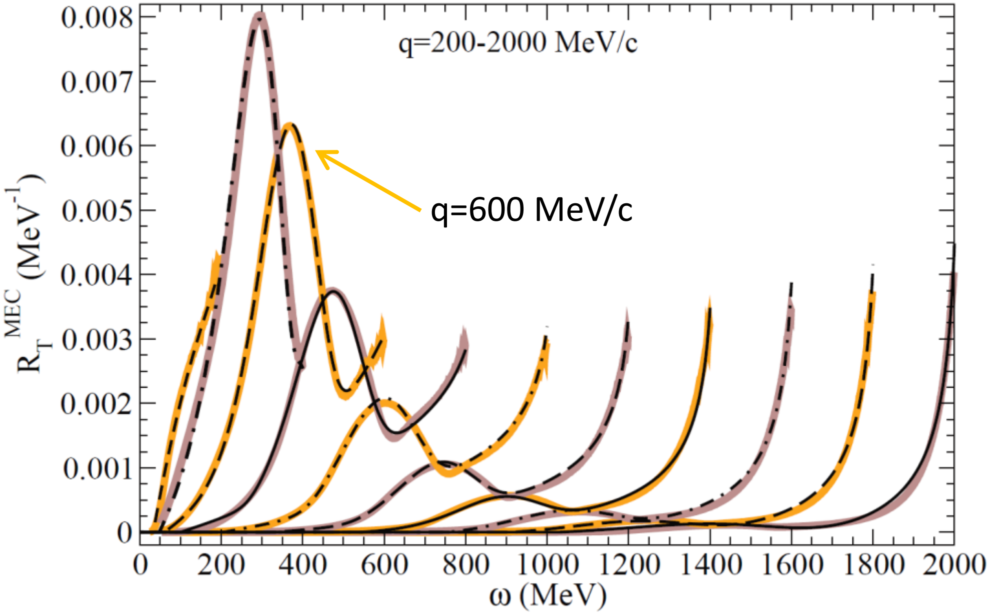


2p-2h MEC contribution to the electromagnetic transverse response

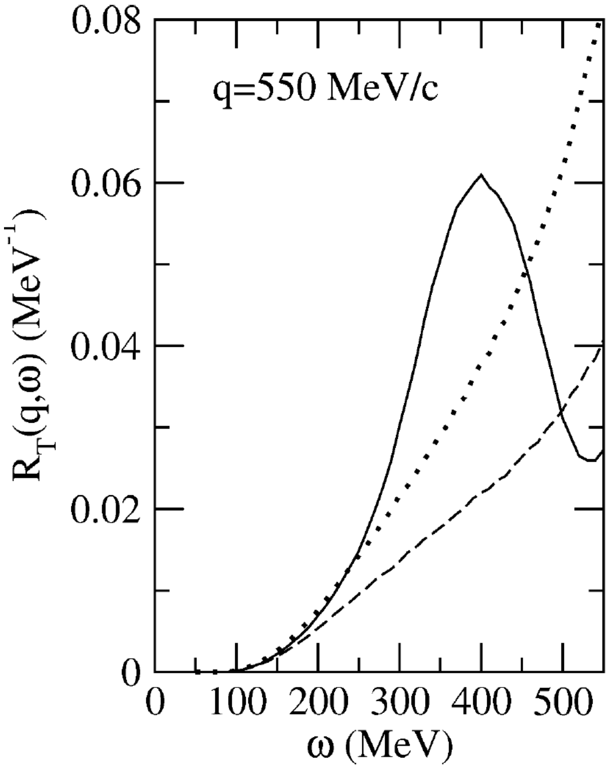


2p-2h MEC only

Our approach



Megias et al. Phys.Rev. D91, 073004 (2015)



De Pace et al. NPA741, 249 (2004)

Our evaluation is compatible with the one of Megias et al. which is a parameterization of the De Pace et al. results

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

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

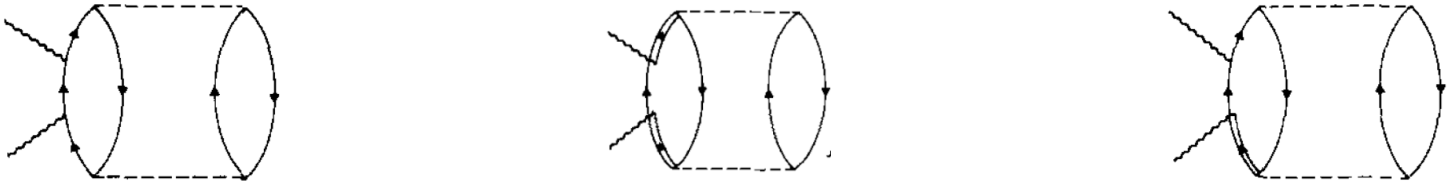
Hence different approximations by different groups:

- 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

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)

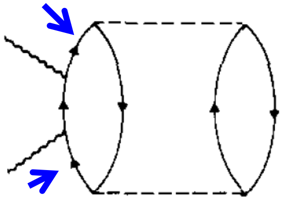
fully relativistic calculation (just of MEC !):

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

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

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

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*)

Analogies and differences of 2p-2h

π,g'

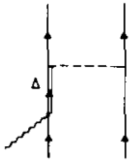
π,ρ,g'

π

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



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.

[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.

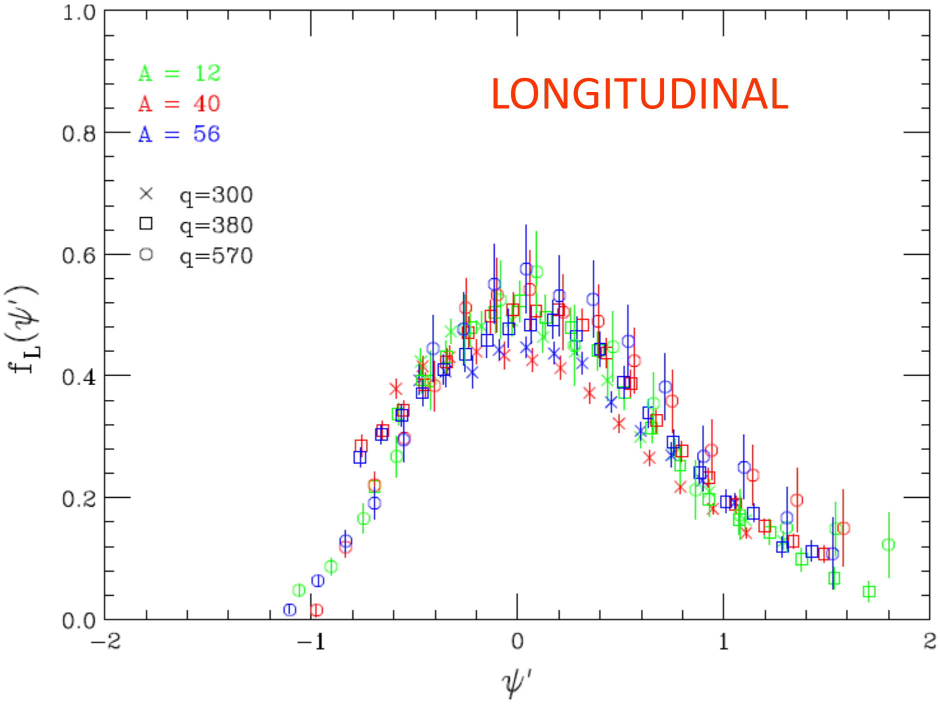
In the approach of **Lovato et al.**, who work in a correlated basis, the effects of NN correlations **are included in the 1 body contribution**.
For this reason Lovato et al. refer to the "NN correlation – MEC interference" as "one nucleon – two nucleon currents interference"

Neutrino scattering

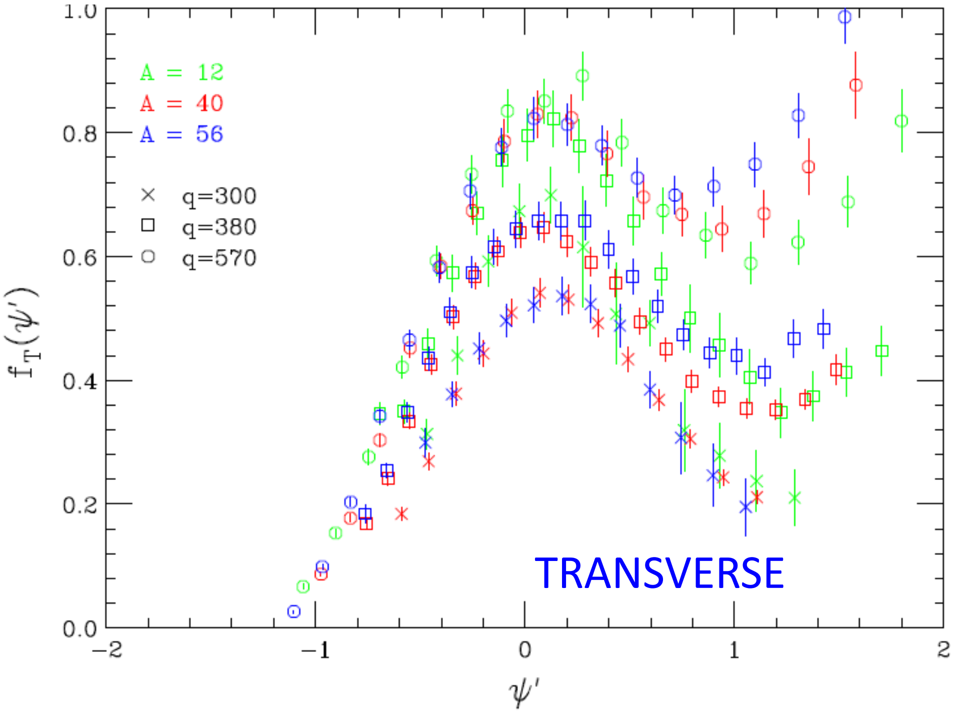
$$\frac{\partial^2\sigma}{\partial\Omega\,\partial\epsilon'} = \frac{G_F^2\,\cos^2\theta_c}{2\,\pi^2}k'\epsilon'\,\cos^2\frac{\theta}{2}\left[\frac{(q^2-\omega^2)^2}{q^4}G_E^2\,R_\tau + \frac{\omega^2}{q^2}G_A^2\,R_{\sigma\tau(L)} + 2\left(\tan^2\frac{\theta}{2}+\frac{q^2-\omega^2}{2q^2}\right)\left(G_M^2\frac{\omega^2}{q^2}+G_A^2\right)R_{\sigma\tau(T)}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

Electron scattering

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



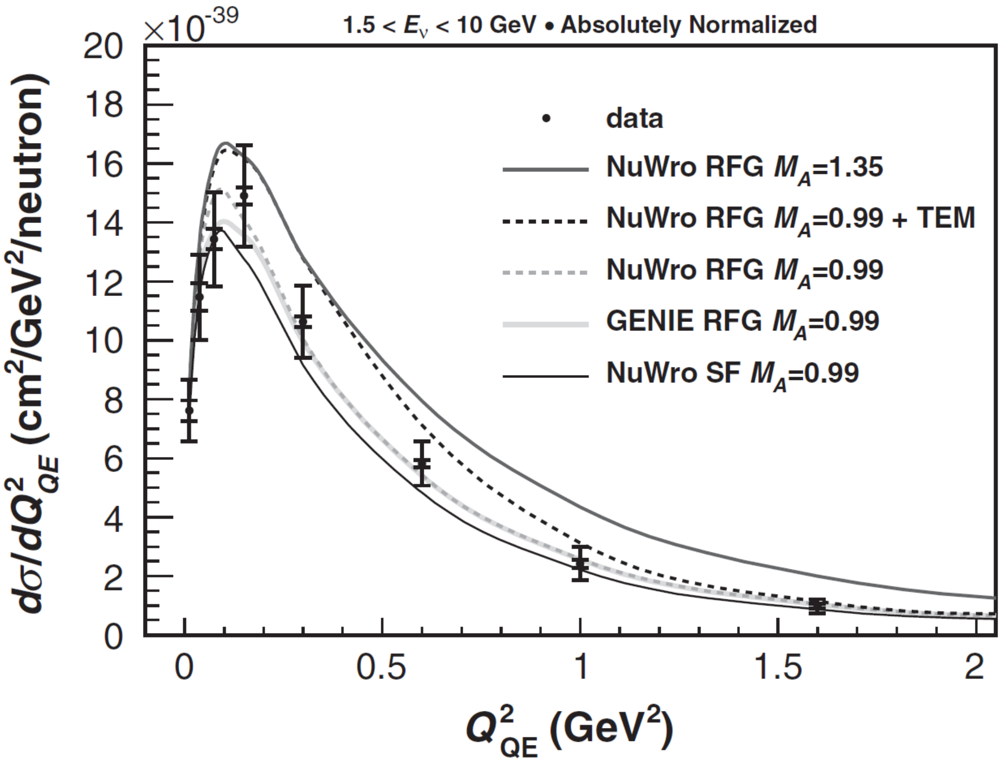
Donnelly et al. PRC 60 '99,…



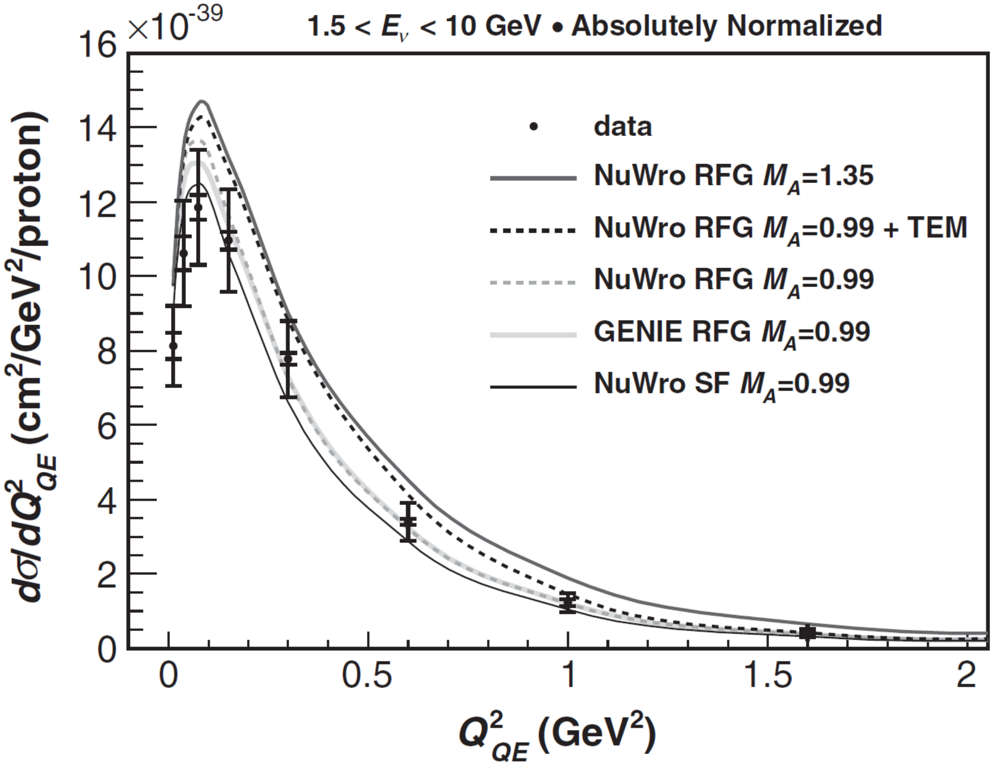
MINERνA ($E_\nu \sim$ 3.5 GeV) CCQE Q^2 distribution

ν

$\overline{\nu}$



PRL 111 022502 (2013)

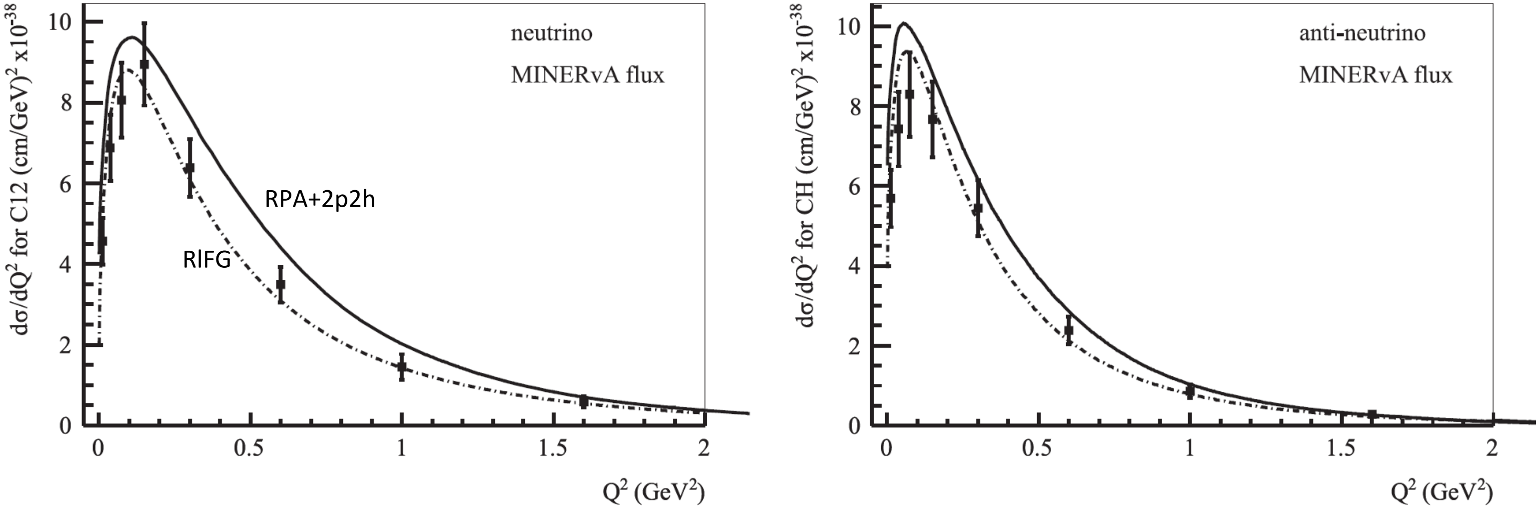


PRL 111 022501 (2013)

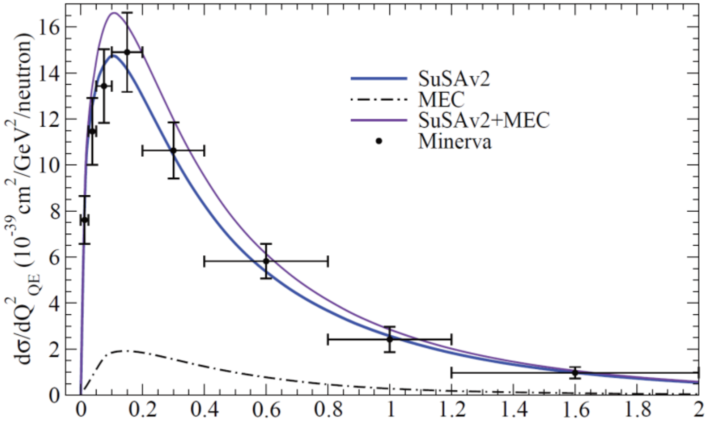
ν

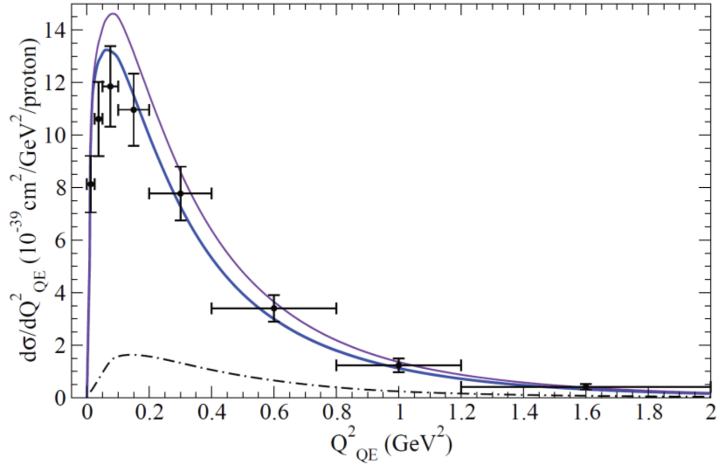
$\bar{\nu}$

Gran, Nieves et al.
PRD 88 (2013)

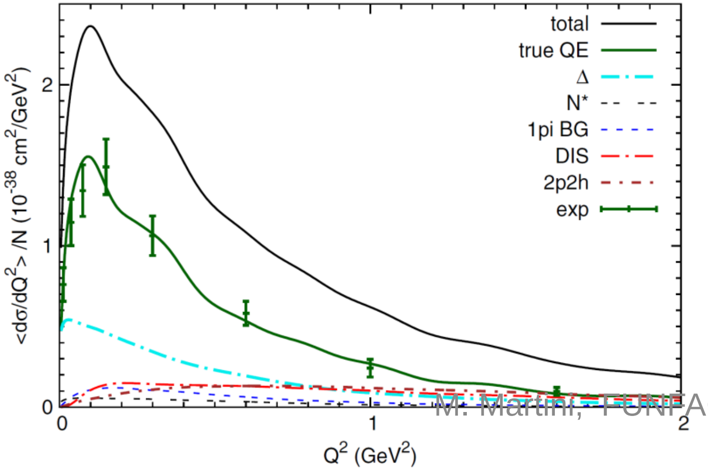


Megias, Amaro et al.
arXiv 1412.1822





Mosel et al.
PRD 89 (2014)



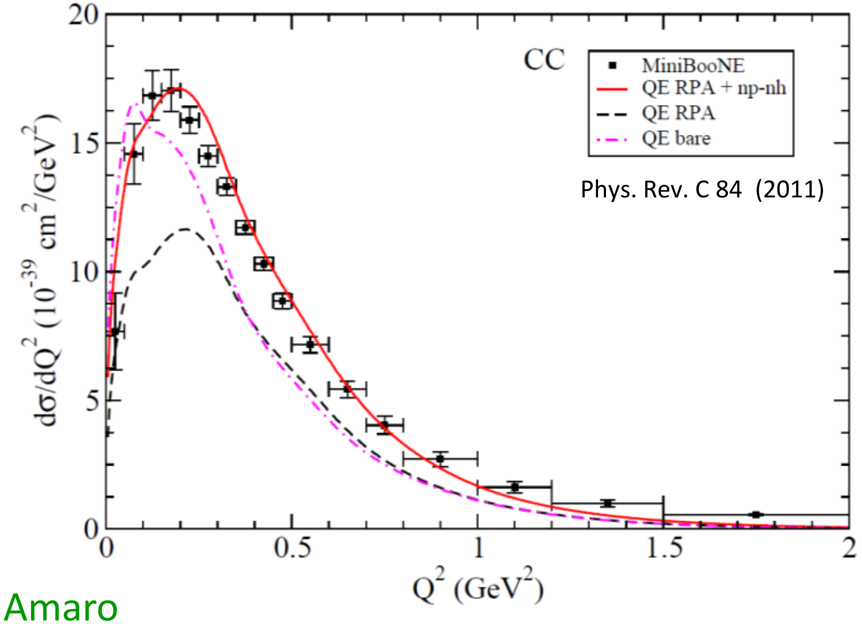
- **MINERνA Q^2 distributions can be reproduced also without the inclusion of np-nh**
- **This is not the case of the MiniBooNE Q^2 distributions**
- Mosel et al: “The sensitivity to details of the treatment of np-nh contributions is smaller than the uncertainties introduced by the Q^2 reconstruction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

ν

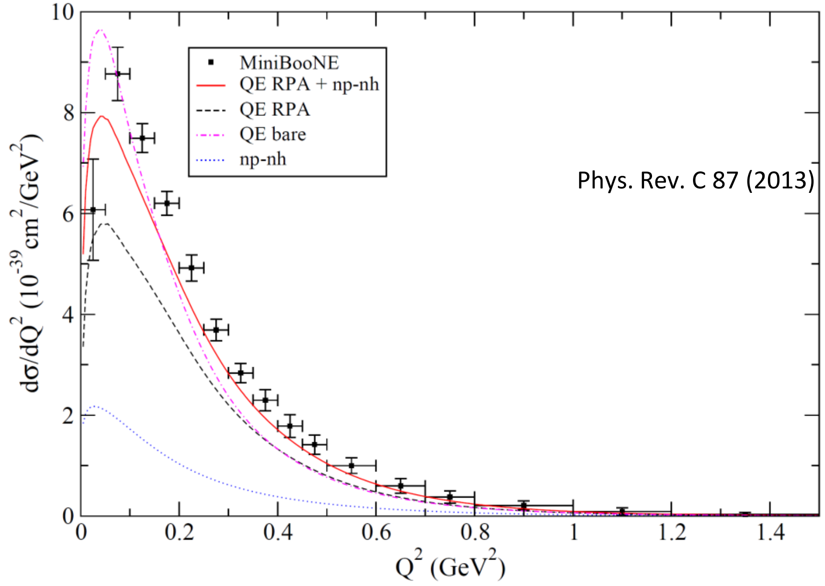
Coming back to MiniBooNE CCQE: the Q^2 distributions

$\overline{\nu}$

Martini et al.

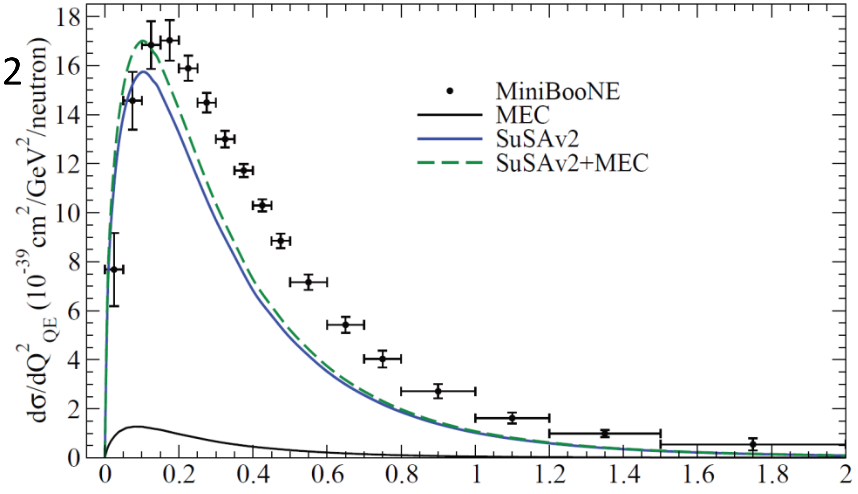


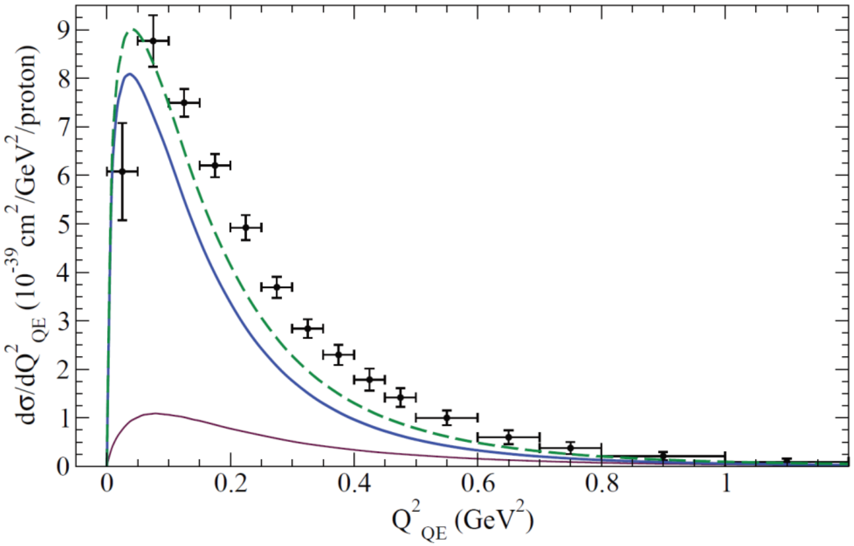
Phys. Rev. C 84 (2011)



Phys. Rev. C 87 (2013)

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

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

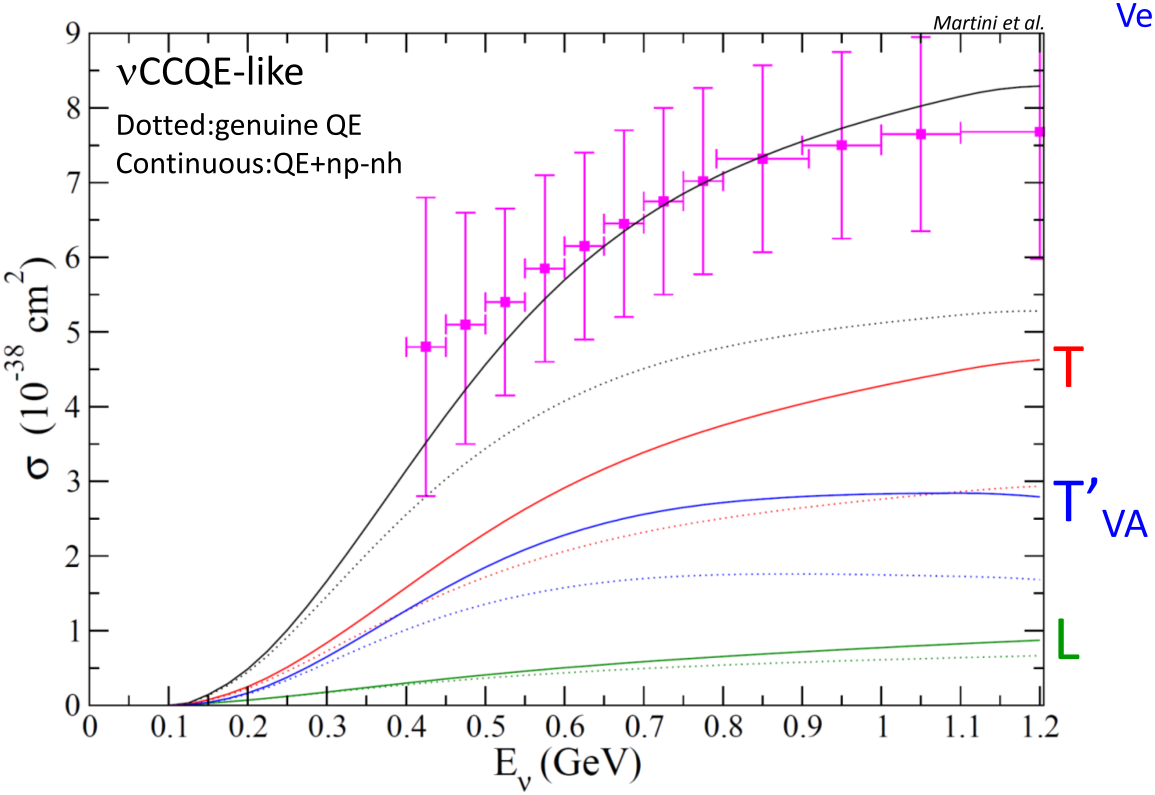
The notation of Lovato et al:

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

Longitudinal

Transverse

Transverse
Vector-Axial interference



A third simplified expression (useful for illustration)

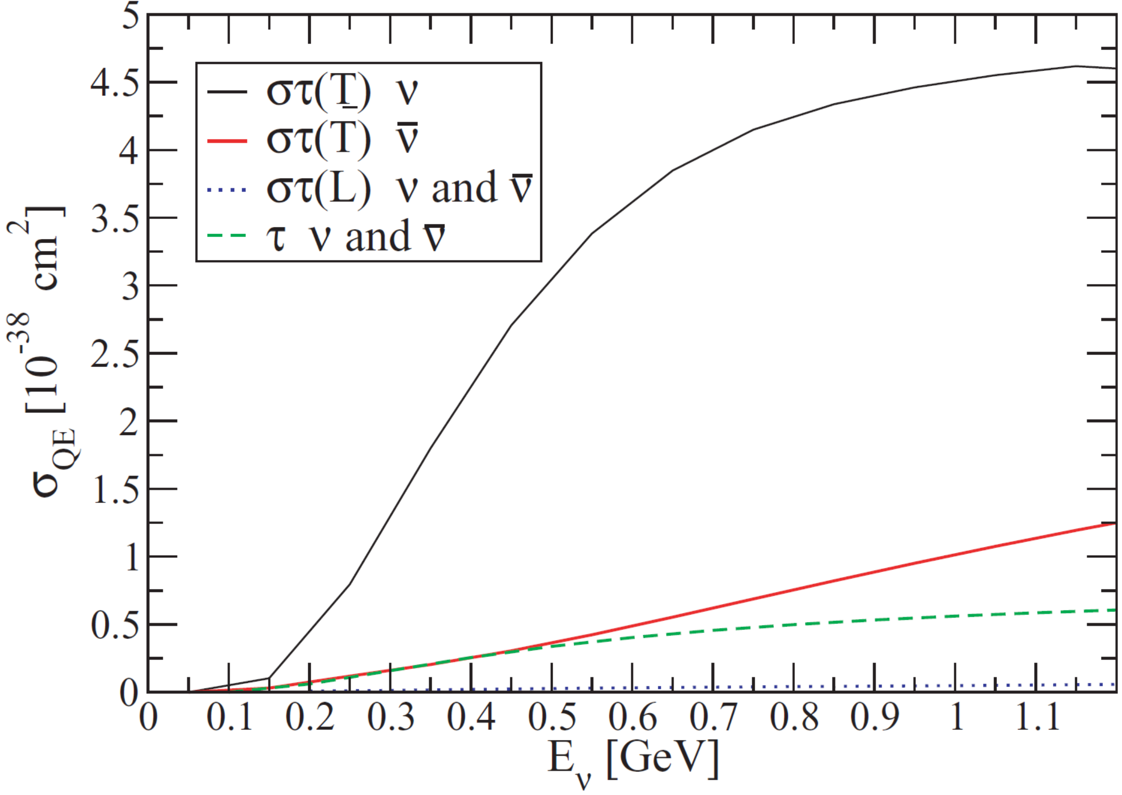
Resp. Functions: Charge R_τ (τ), Isospin Spin-Longitudinal $R_{\sigma\tau(L)}$(τ $\sigma\cdot$q), Isospin Spin Transverse $R_{\sigma\tau(T)}$ (τ σxq)

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

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

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

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



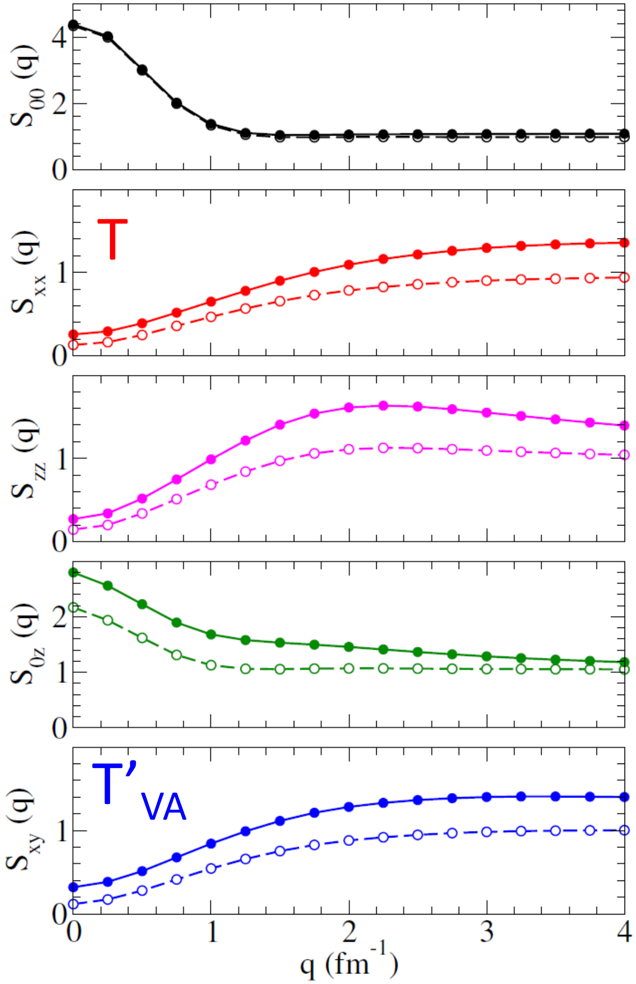
The relative weight of the 3 different nuclear responses (**R_τ** , **$R_{\sigma\tau(L)}$** , **$R_{\sigma\tau(T)}$**) is different for neutrinos and antineutrinos due to the Vector-Axial interference term

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

Sum rules of NC

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

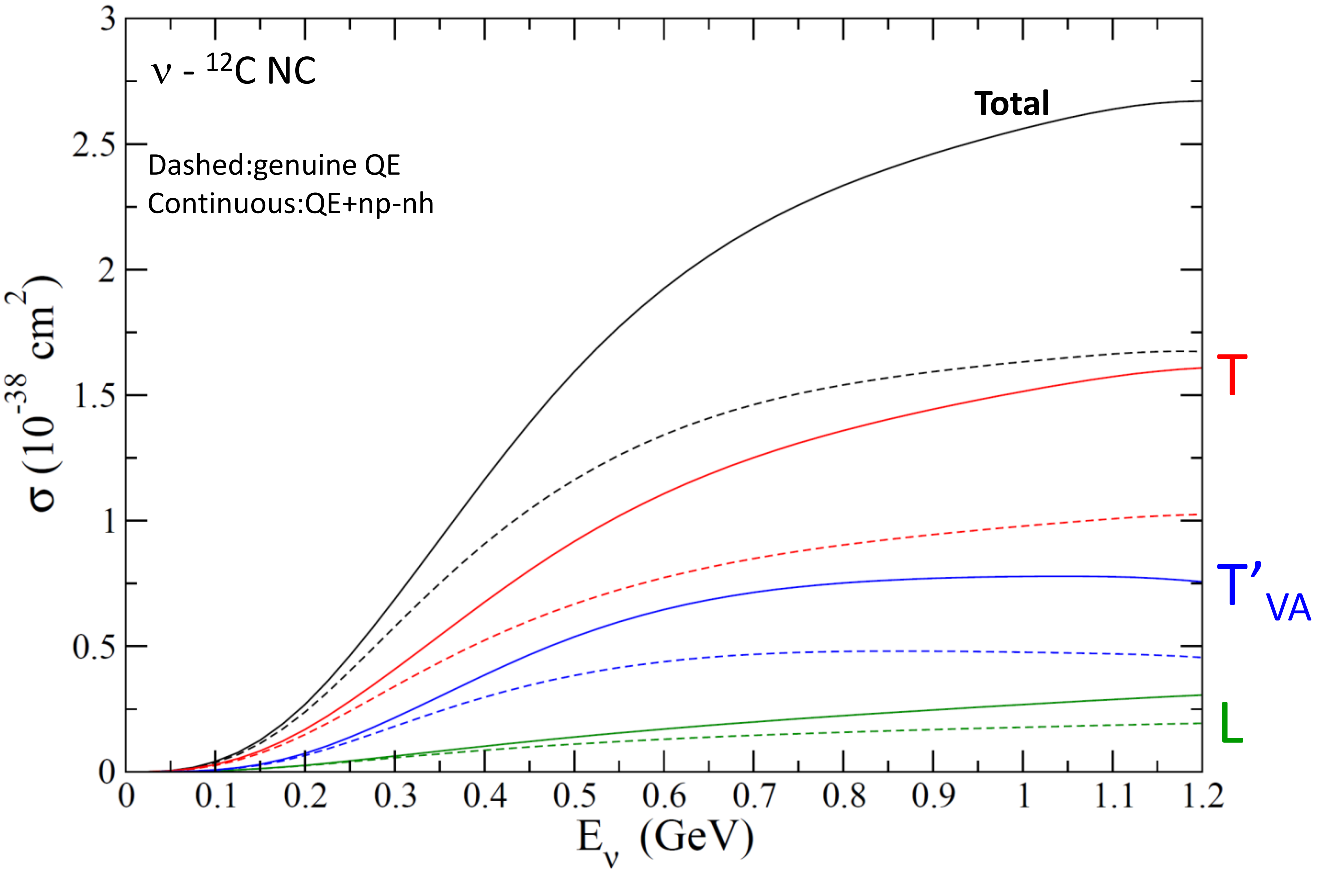
Lovato et al. PRL 112 182502 (2014)



Cross section

$$\frac{\partial^2\sigma}{\partial\Omega\;\partial\epsilon'}=\sigma_0\left[\underbrace{L_{00}R_{00}+L_{0z}R_{0z}+L_{zz}R_{zz}}_{\text{Longitudinal}}+\underbrace{L_{xx}R_{xx}}_{\text{Transverse}}\pm\underbrace{L_{xy}R_{xy}}_{\text{Transverse VA Interf.}}\right]$$

Martini et al.

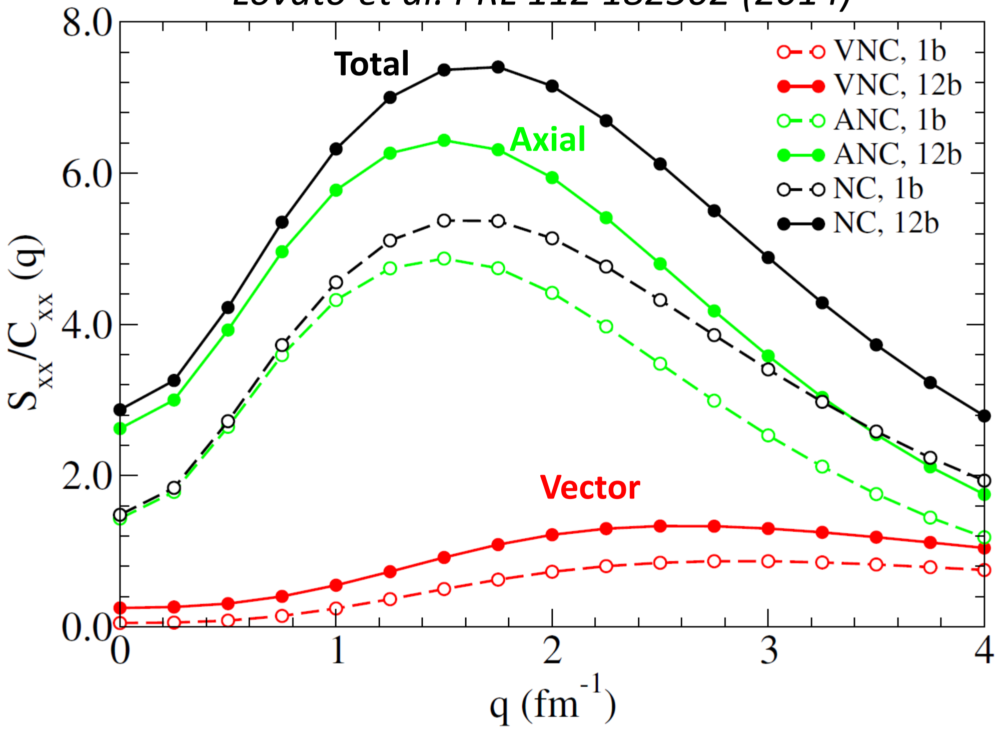


In both approaches 2p-2h are important in **all components** (but the charge)

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

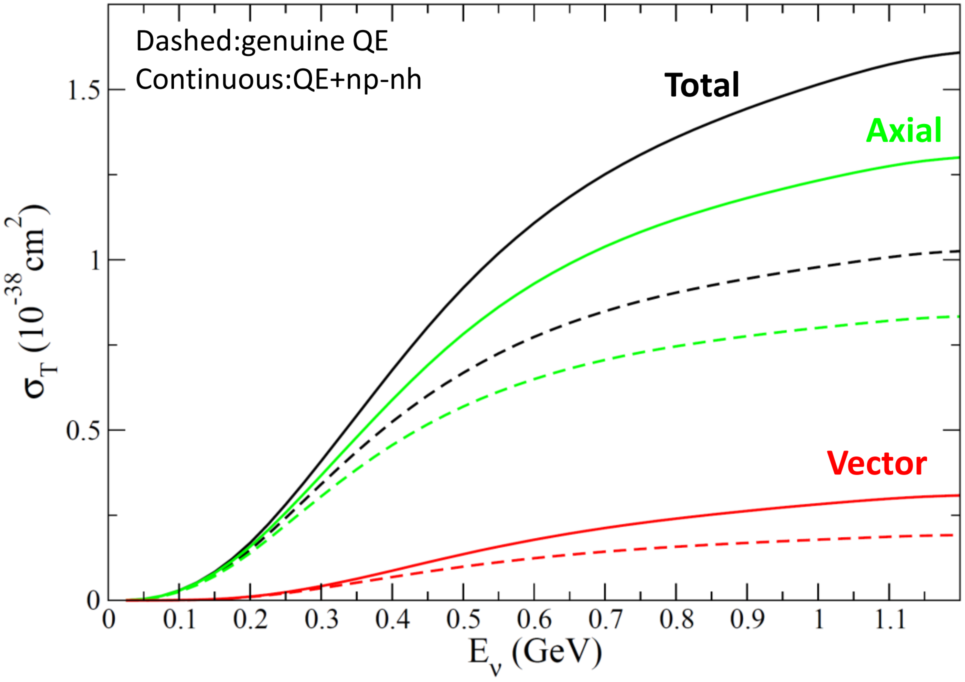
Sum rule of the Transverse response multiplied by the form factors

Lovato et al. PRL 112 182502 (2014)



Transverse contribution to the NC cross section

Martini et al.



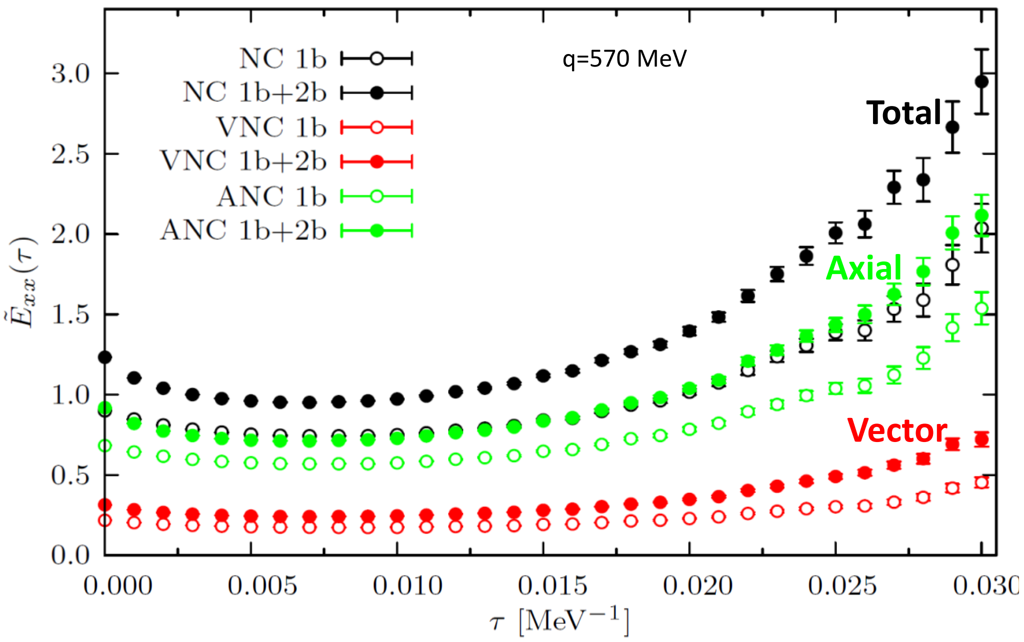
In both approaches, similar behavior:

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

Some instructive comparison of two different quantities (II bis)

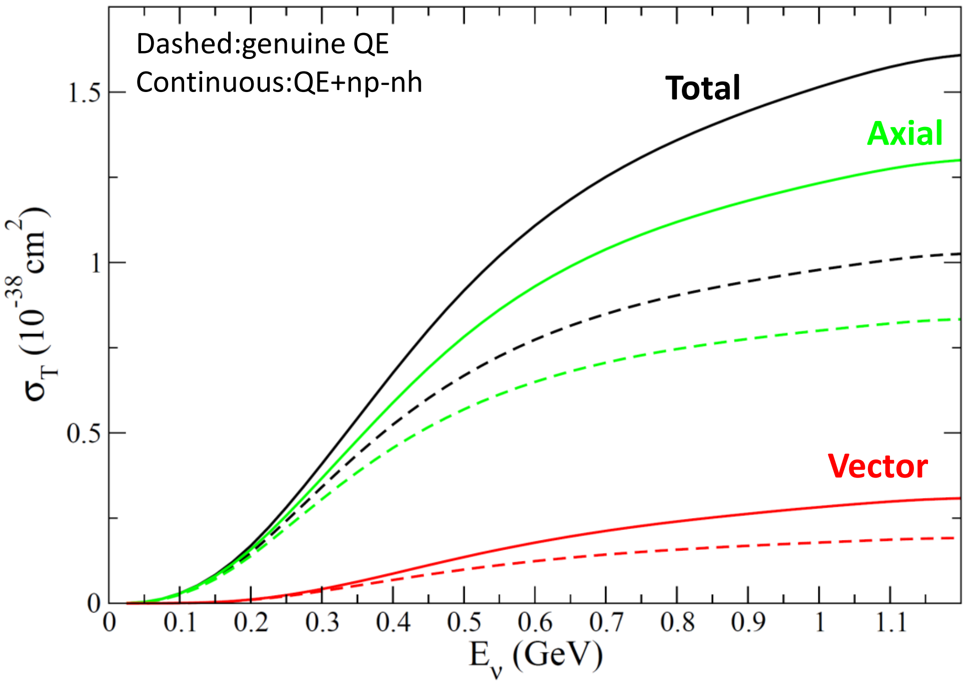
Euclidean NC transverse response

Lovato et al. arXiv 1501.01981(2015)



Transverse contribution to the NC cross section

Martini et al.



In both approaches, similar behavior:

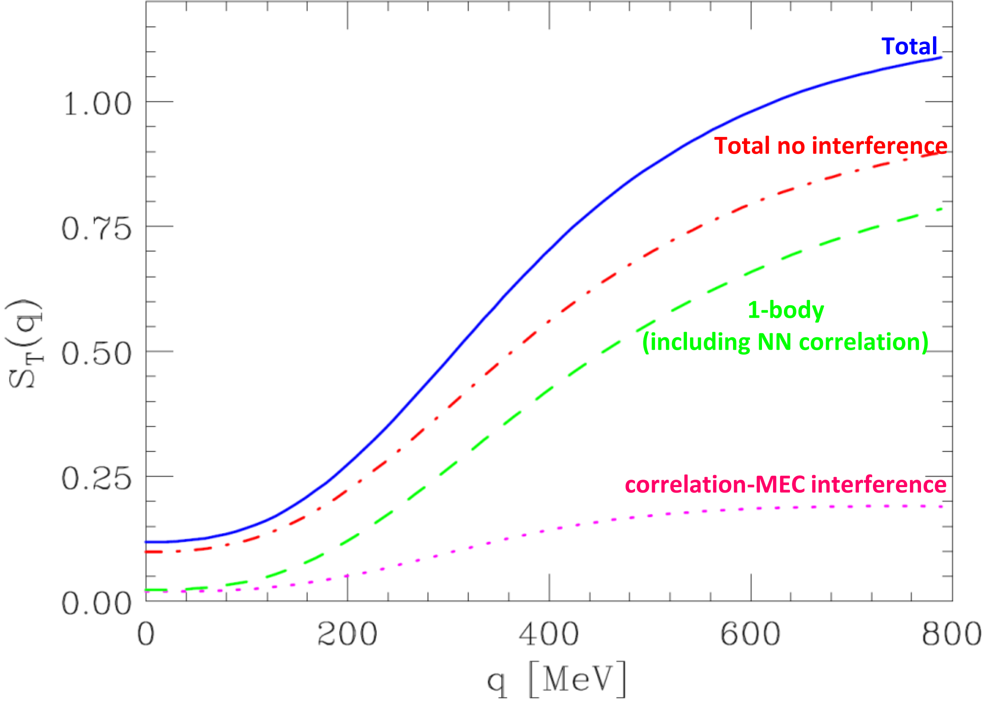
2p-2h important also in the **Axial part** of the transverse contribution

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

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

Sum rule of the transverse response

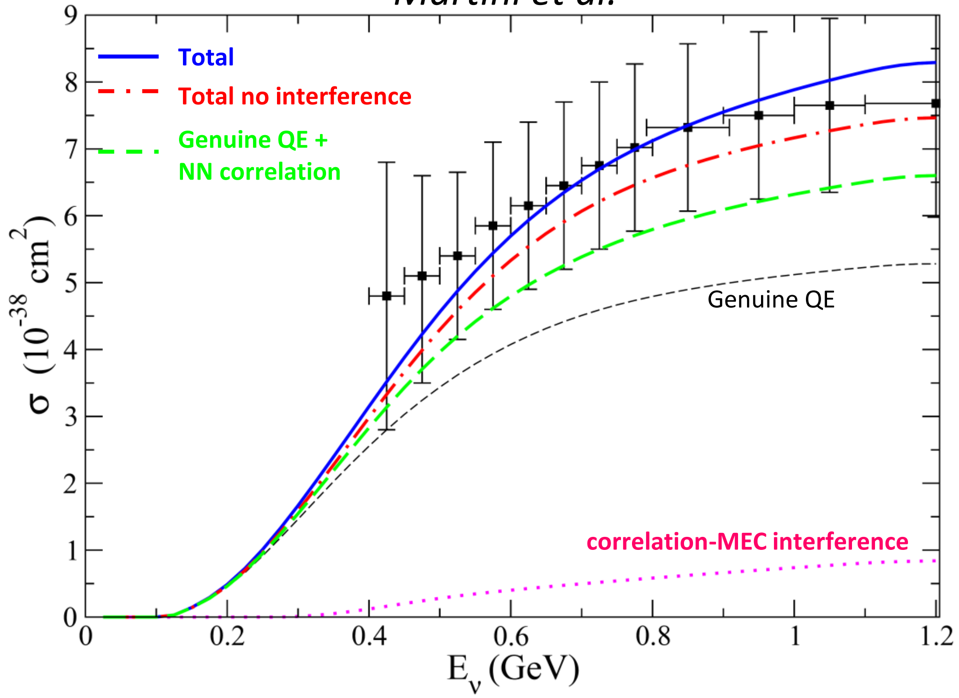
Benhar, Lovato, Rocco, arXiv :1312.1210



- 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"

The VA interference term in an *ab-initio* microscopic approach

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

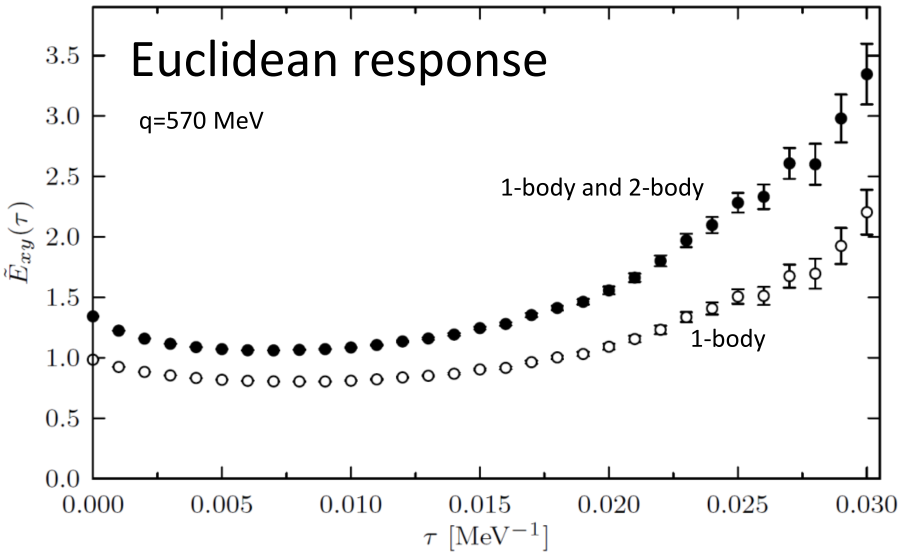
Neutral weak current two-body contributions to sum rules and Euclidean responses in ^{12}C

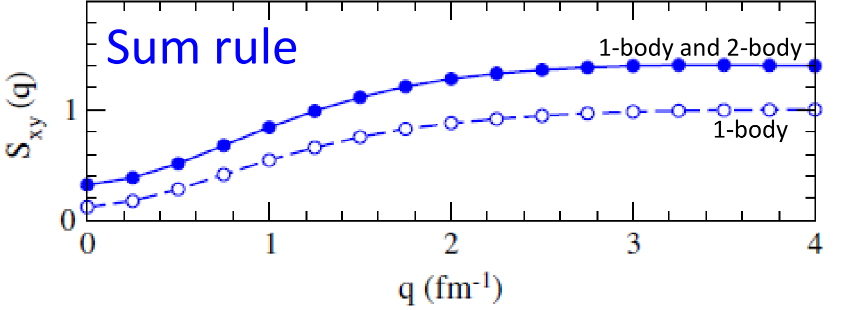
$$E_{\alpha\beta}(q,\tau) = C_{\alpha\beta}(q) \int_{\omega_{\rm th}}^{\infty} d\omega\, e^{-\tau\omega} R_{\alpha\beta}(q,\omega)$$

arXiv 1501.01981(2015)

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

Phys. Rev. Lett. 112 182502 (2014)





important 2p-2h contributions in the **VA interference** term

Some comments on this theoretical approach

Advantages:

- Include full realistic interactions fit to NN data with simultaneous two-body currents
- State of the art description of nuclear ground state and correlations

Disadvantages:

- Non relativistic currents
- No pion or Δ production
- Computing very demanding

Limitation: an evaluation of ^{12}C responses and ν cross sections is beyond the present computational capabilities.

But the results obtained with this approach offer a benchmark for phenomenological methods

MEC

Direct

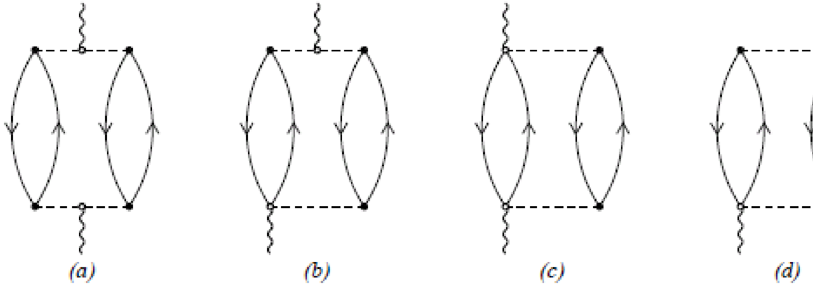


FIG. 2: The direct pionic contributions to the MEC 2p-2h response function.

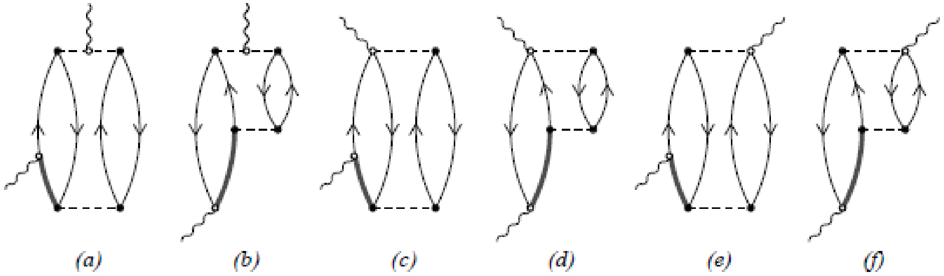


FIG. 3: The direct pionic/Δ interference contributions to the MEC 2p-2h response function.

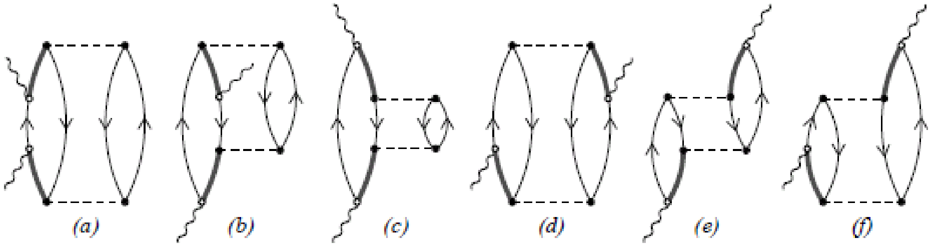


FIG. 4: The direct Δ contributions to the MEC 2p-2h response function.

Exchange

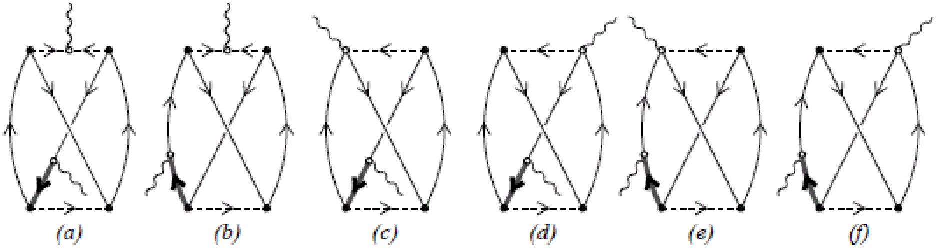


FIG. 5: The exchange pionic/Δ interference contributions to the MEC 2p-2h response function.

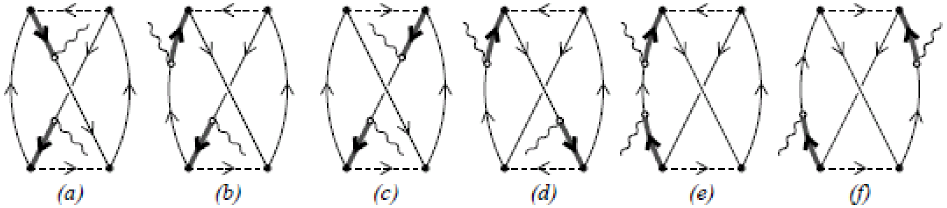


FIG. 6: The exchange Δ contributions to the MEC 2p-2h response function.

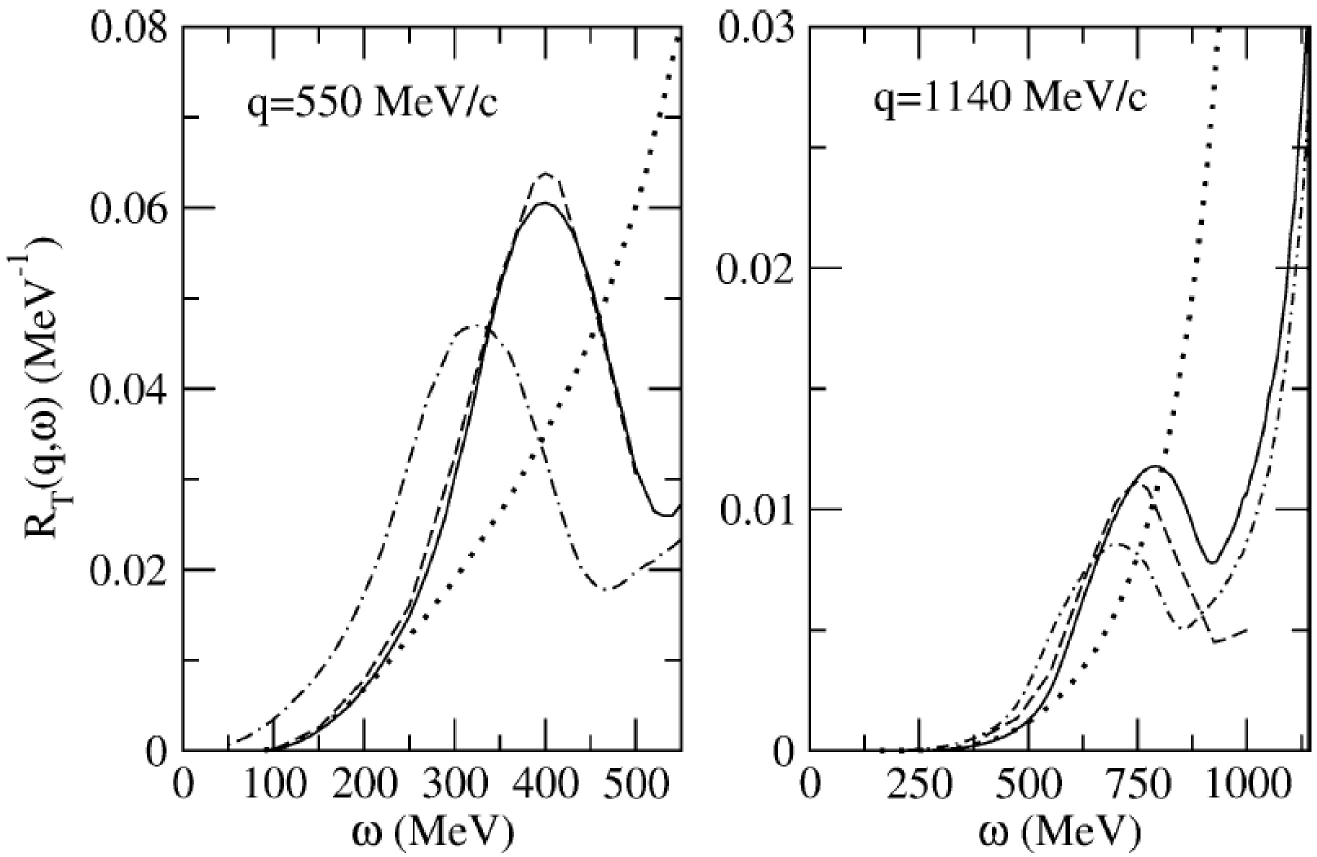


Fig. 8. The relativistic transverse response function $R_T(q,\omega)$ at $q = 550$ MeV/c and $q = 1140$ MeV/c calculated with $\bar{\epsilon}_2 = 70$ MeV (solid) and with $\bar{\epsilon}_2 = 0$ (dot-dashed). Only the direct contribution is shown. The non-relativistic results are also displayed in order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

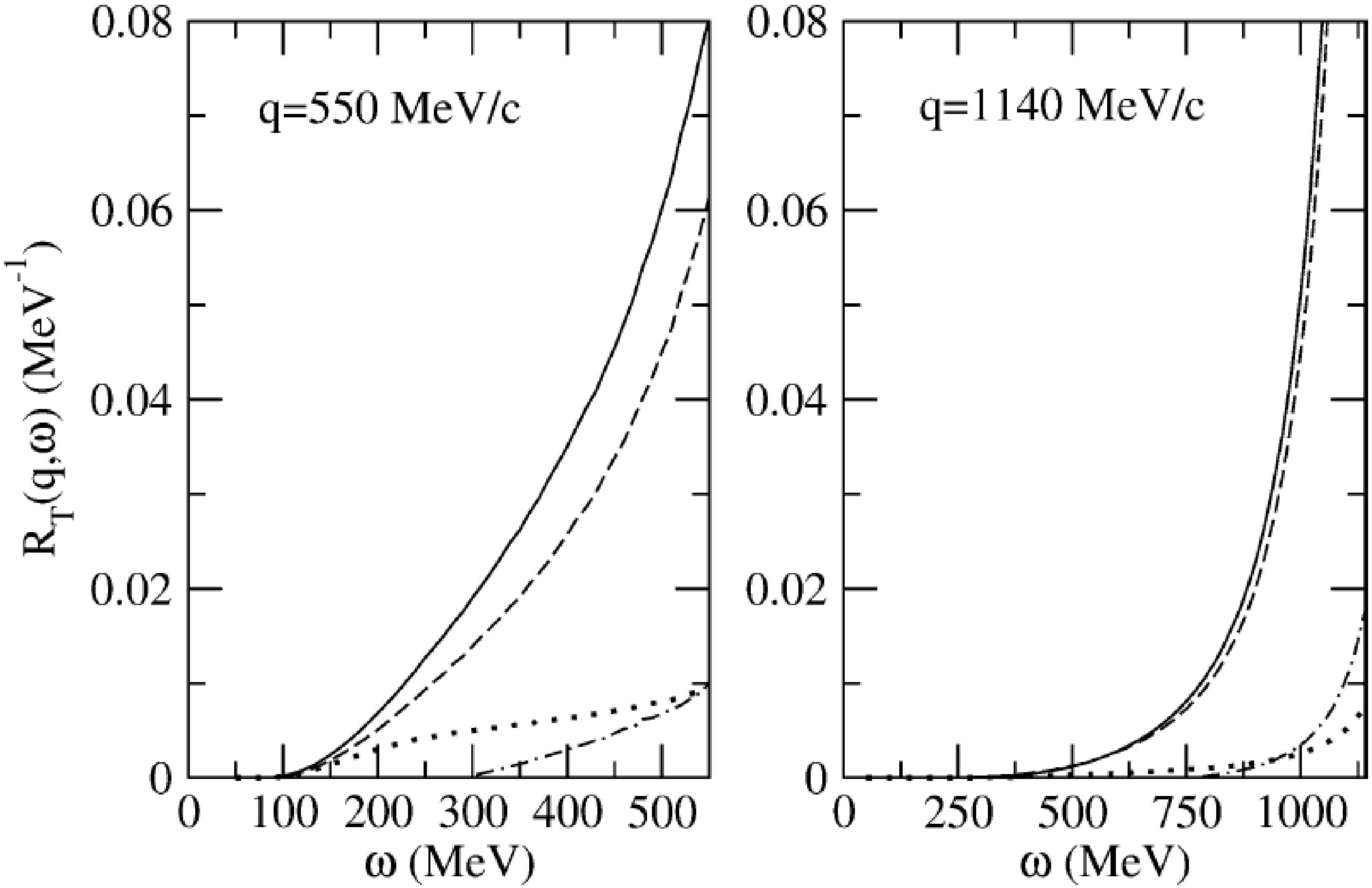


Fig. 9. Separate contributions to the transverse response function $R_T(q,\omega)$ in the non-relativistic limit at $q = 550$ MeV$/c$ and $q = 1140$ MeV$/c$: pionic (dotted), pionic–Δ interference (dash-dotted), Δ (dashed) and total (solid); $k_F = 1.3$ fm^{-1}. The exchange contribution is disregarded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

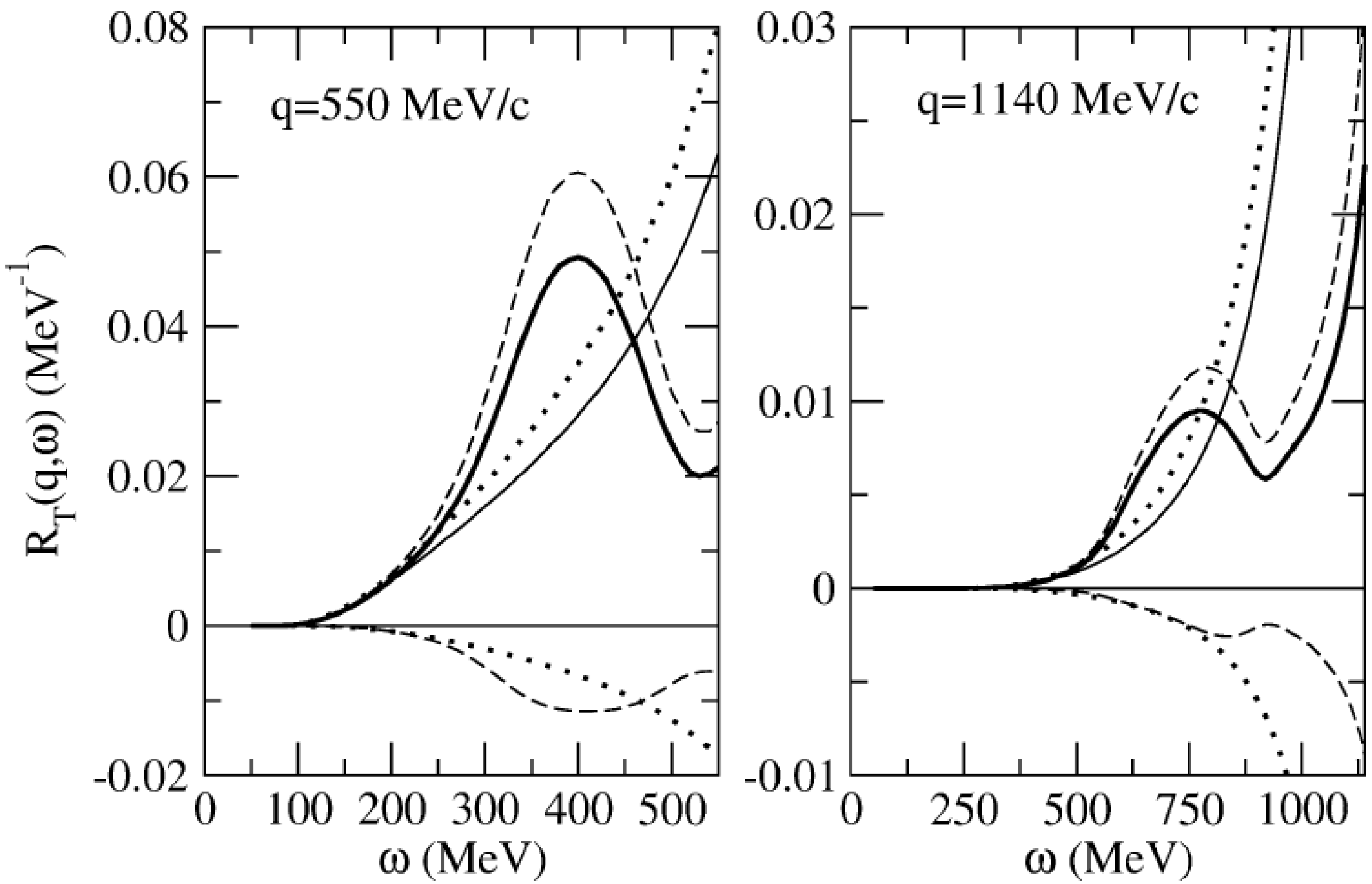
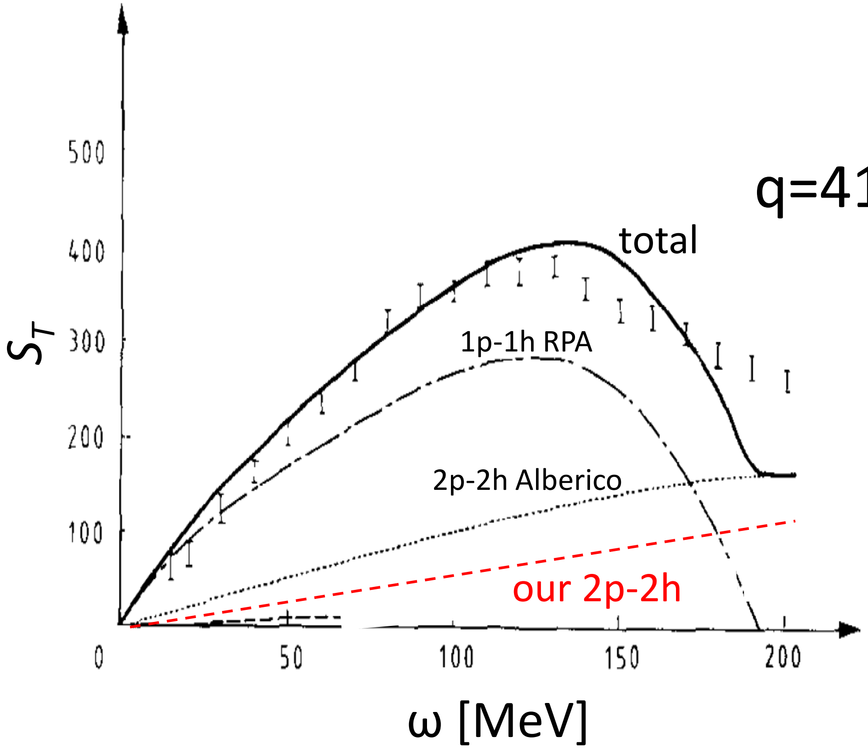


Fig. 12. The transverse response function $R_T(q, \omega)$ at $q = 550$ MeV$/c$ and $q = 1140$ MeV$/c$ including the exchange contributions: non-relativistic direct (positive dotted), non-relativistic exchange (negative dotted), non-relativistic total (light solid), relativistic direct (positive dashed),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

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

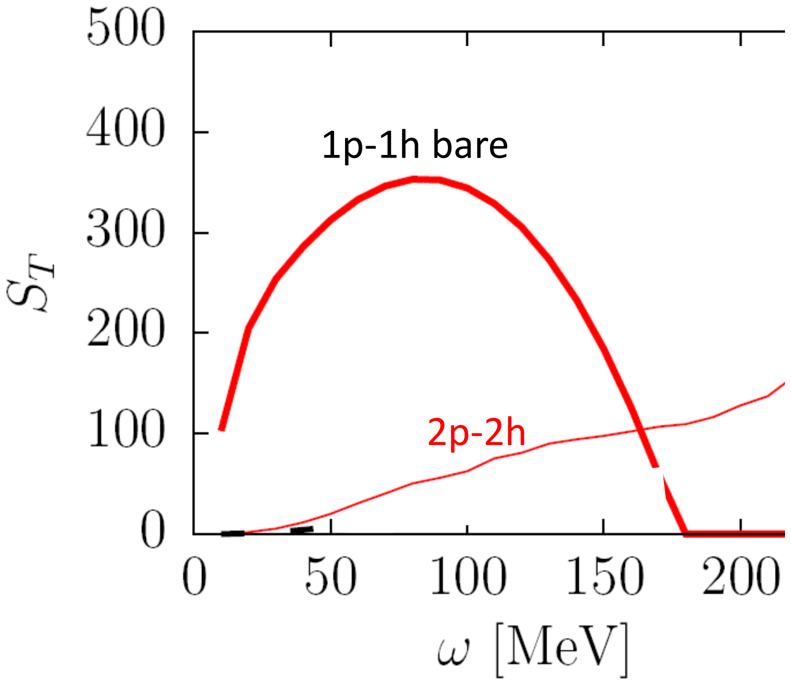
Alberico et al. Ann. Phys. 154, 356 (1984)



^{56}Fe

q=410 MeV/c

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



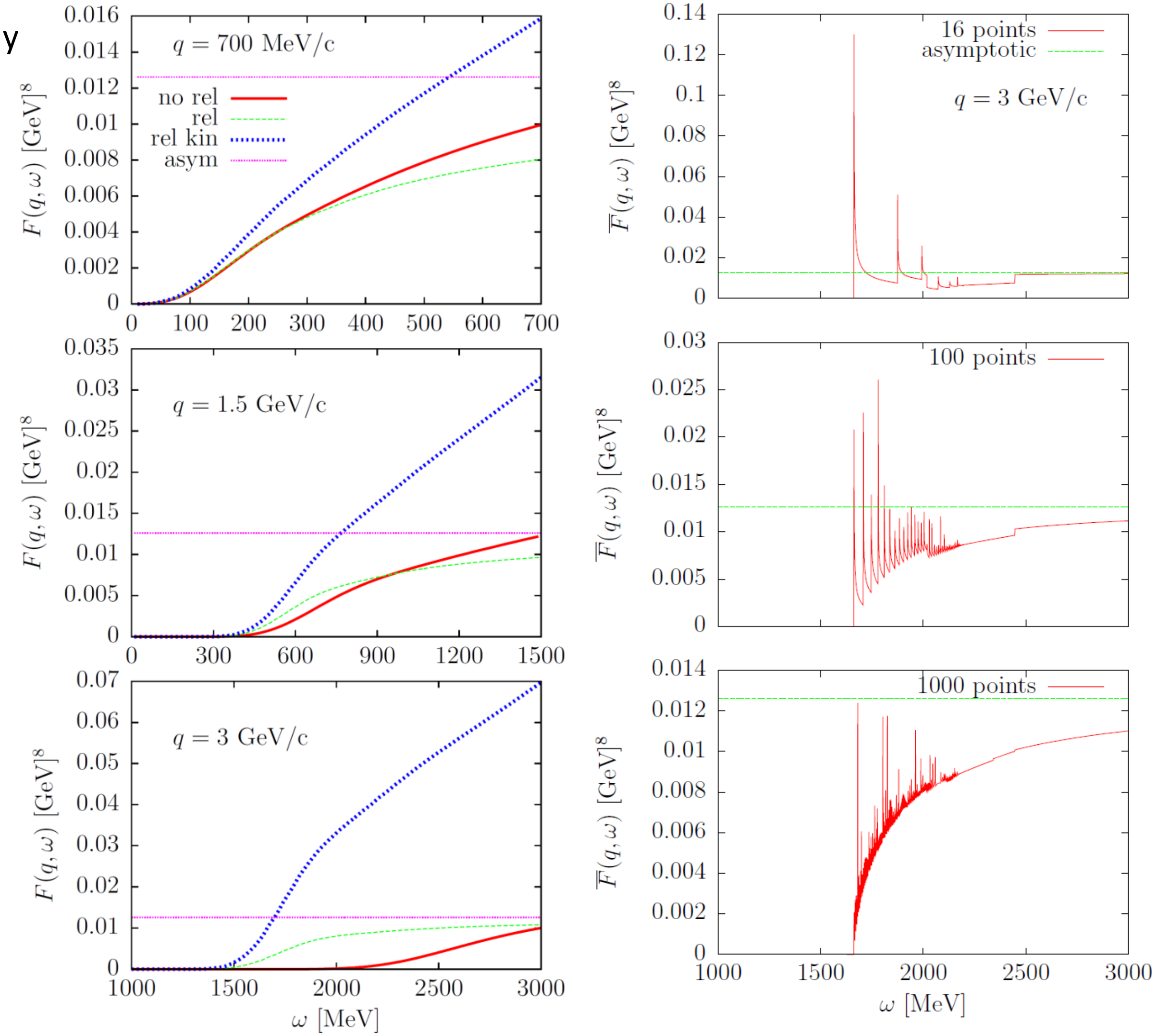
Our parameterization is quite close to the results of Amaro et al.

2p-2h phase space integral

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

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

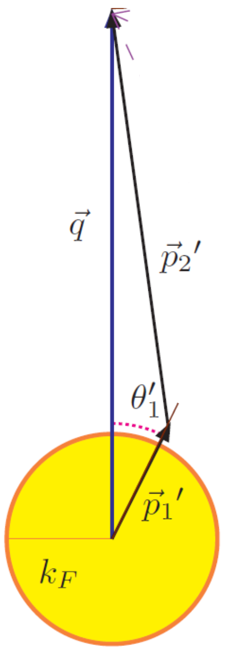
Ruiz Simo, Albertus, Amaro, Barbaro, Caballero, Donnelly
Phys. Rev. D 90 033012 (2014)
Phys. Rev. D 90 053010 (2014)



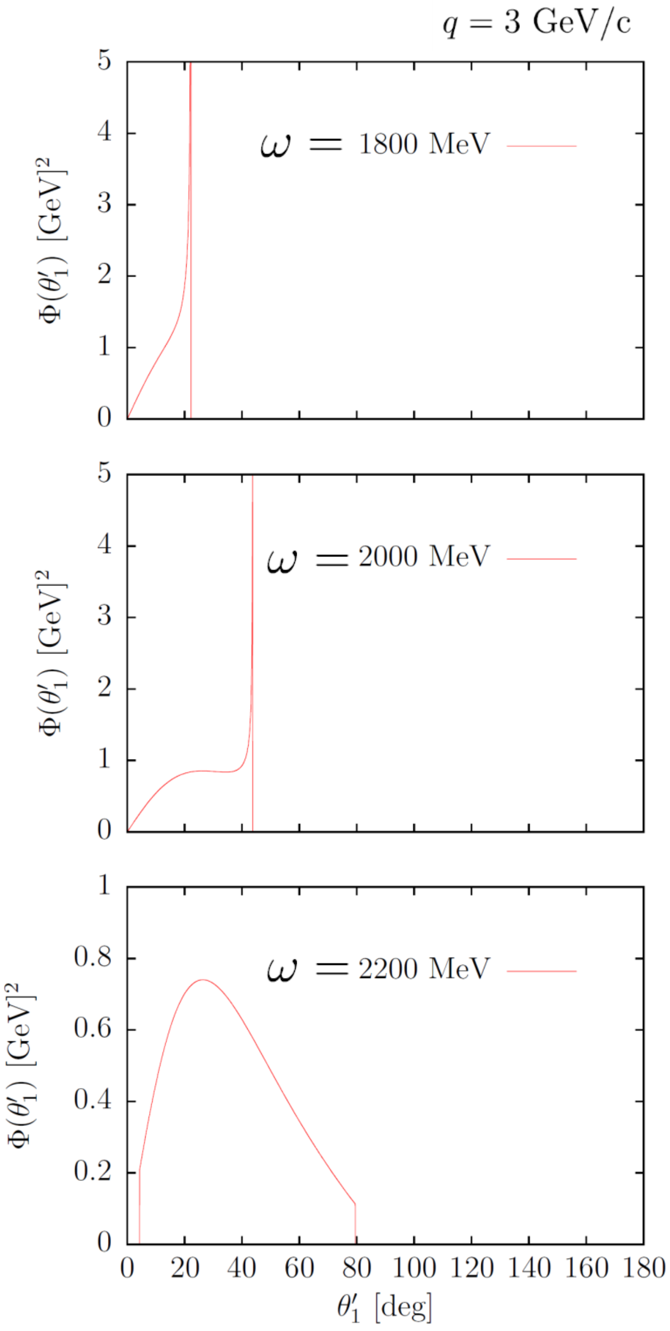
Angular distribution of ejected nucleons

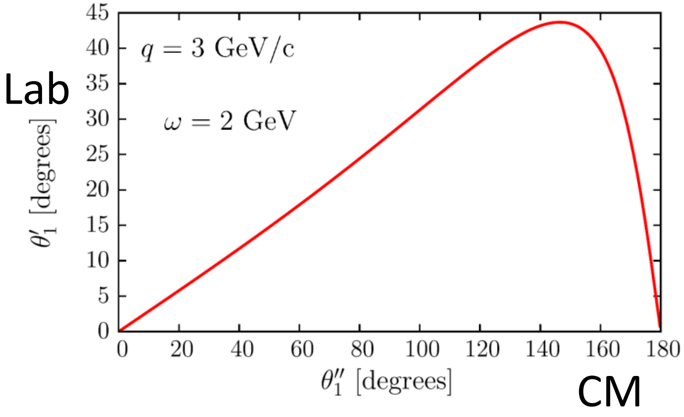
$$\overline{F}(\omega,q) = \left(\frac{4}{3}\pi k_F^3\right)^2 2\pi \int_0^{\pi} d\theta'_1\,\Phi(\theta'_1)$$

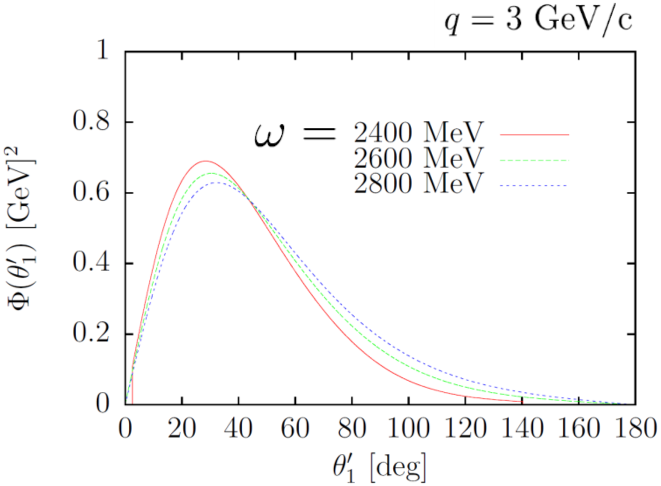
$$\begin{aligned}\Phi(\theta'_1) &= \sin\theta'_1 \int {p'_1}^2 dp'_1 \delta(E_1+E_2+\omega-E'_1-E'_2)\\ &\quad\times\Theta(p'_1,p'_2,h_1,h_2)\frac{m_N^4}{E_1E_2E'_1E'_2}\\ &= \sum_{\alpha=\pm}\left.\frac{m_N^4 \sin\theta'_1 {p'_1}^2\Theta(p'_1,p'_2,h_1,h_2)}{E_1E_2E'_1E'_2\left|\frac{p'_1}{E'_1}-\frac{\mathbf{p}'_2\cdot\hat{\mathbf{p}}'_1}{E'_2}\right|}\right|_{p'_1={p'_1}^{(\alpha)}}\end{aligned}$$



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







Single nucleon weak CC current

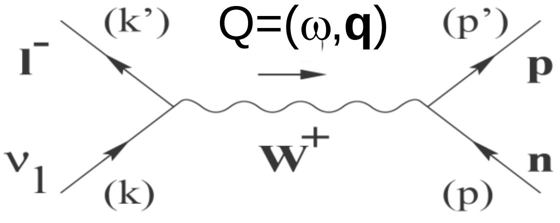
$$j^\mu = j^\mu_V - j^\mu_A$$

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

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

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

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



Some two-body currents

Electromagnetic

- Seagull or contact:

$$j_{\mathrm{s}}^{\mu}(\mathbf{p}_1',\mathbf{p}_2',\mathbf{p}_1,\mathbf{p}_2)=\frac{f^2}{m_\pi^2}\,\mathrm{i}\epsilon_{3ab}\overline{u}(\mathbf{p}_1')\tau_a\gamma_5\not{K}_1u(\mathbf{p}_1)\frac{F_1^{\mathrm{V}}}{K_1^2-m_\pi^2}\,\overline{u}(\mathbf{p}_2')\tau_b\gamma_5\gamma^\mu u(\mathbf{p}_2)+(1\leftrightarrow 2)\;.$$

- Pion-in-flight:

$$j_{\mathrm{p}}^{\mu}(\mathbf{p}_1',\mathbf{p}_2',\mathbf{p}_1,\mathbf{p}_2)=\frac{f^2}{m_\pi^2}\,\mathrm{i}\epsilon_{3ab}\frac{F_\pi(K_1-K_2)^\mu}{(K_1^2-m_\pi^2)(K_2^2-m_\pi^2)}\,\overline{u}(\mathbf{p}_1')\tau_a\gamma_5\not{K}_1u(\mathbf{p}_1)\overline{u}(\mathbf{p}_2')\tau_b\gamma_5\not{K}_2u(\mathbf{p}_2)\;.$$

- Correlation:

$$j_{\mathrm{cor}}^{\mu}(\mathbf{p}_1',\mathbf{p}_2',\mathbf{p}_1,\mathbf{p}_2)=\frac{f^2}{m_\pi^2}\,\overline{u}(\mathbf{p}_1')\tau_a\gamma_5\not{K}_1u(\mathbf{p}_1)\frac{1}{K_1^2-m_\pi^2}\overline{u}(\mathbf{p}_2')[\tau_a\gamma_5\not{K}_1S_{\mathrm{F}}(P_2+Q)\Gamma^\mu(Q)$$

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

Weak

- CC Seagull

$$j_s^\mu(\mathbf{p}_1',\mathbf{p}_2',\mathbf{h}_1,\mathbf{h}_2)=$$

$$\tau_0\otimes\tau_{+1}-\tau_{+1}\otimes\tau_0\;\frac{f}{m_\pi}\frac{1}{\sqrt{2}f_\pi}\overline{u}(\mathbf{p}_1')\gamma_5\;\not{K}_1u(\mathbf{h}_1)\;\frac{\overline{u}(\mathbf{p}_2')\left[g_AF_1^V(Q^2)\gamma_5\gamma^\mu+F_\rho(K_2^2)\gamma^\mu\right]u(\mathbf{h}_2)}{K_1^2-m_\pi^2}$$

$$-(1\leftrightarrow 2)$$

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)

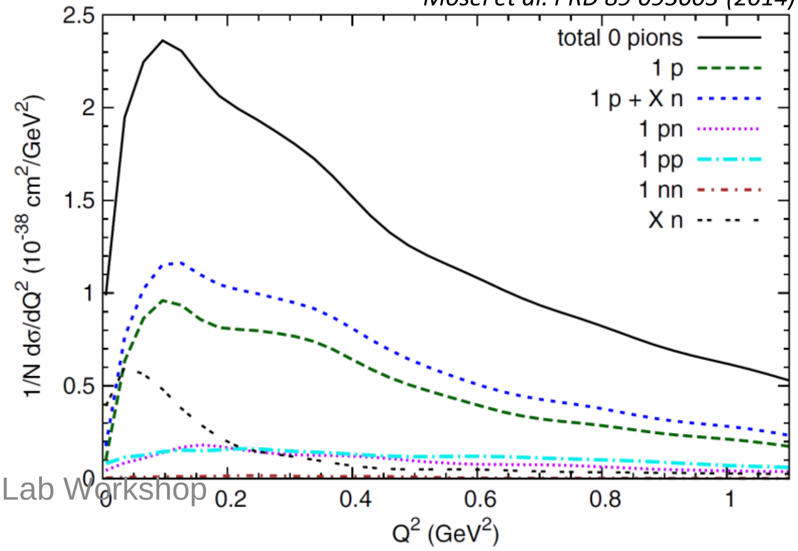
"The present study suggests that two nucleon currents generate a significant enhancement of the single-nucleon neutral weak current response, even at quasi-elastic kinematics. This enhancement is driven by strongly correlated np pairs in nuclei."

MINER νA PRL 111 022501 (2013)

The MINERνA vertex energy on antineutrino mode "might be explained if the dominant multibody process is $\overline{\nu}_\mu$ (np) $\rightarrow \mu^+$ nn since MINERνA 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)

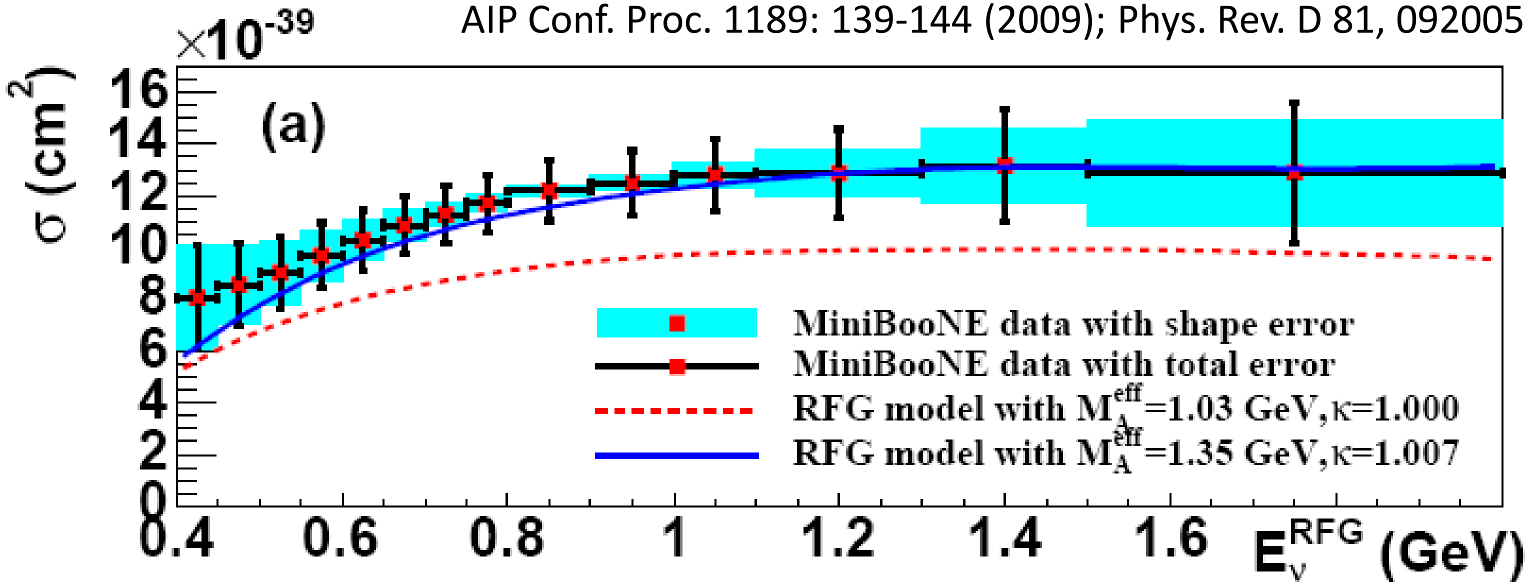
"The channels with a pp or a pn pair are very similar, quite flat, and suppressed and thus of minor importance. Interesting, however, is the pileup of strength seen in the Xn channel at small $Q^2 \approx 0.1$ GeV^2. This is entirely due to fsi."



Mosel et al. PRD 89 093003 (2014)

MiniBooNE CC Quasielastic cross section on Carbon and the M_A puzzle

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



Comparison with a prediction based on RFG 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

p.s. Relativistic Fermi Gas: Nucleus as ensemble of non interacting fermions (nucleons)

puzzle??

Form Factors

Standard dipole parameterization

Vector

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

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

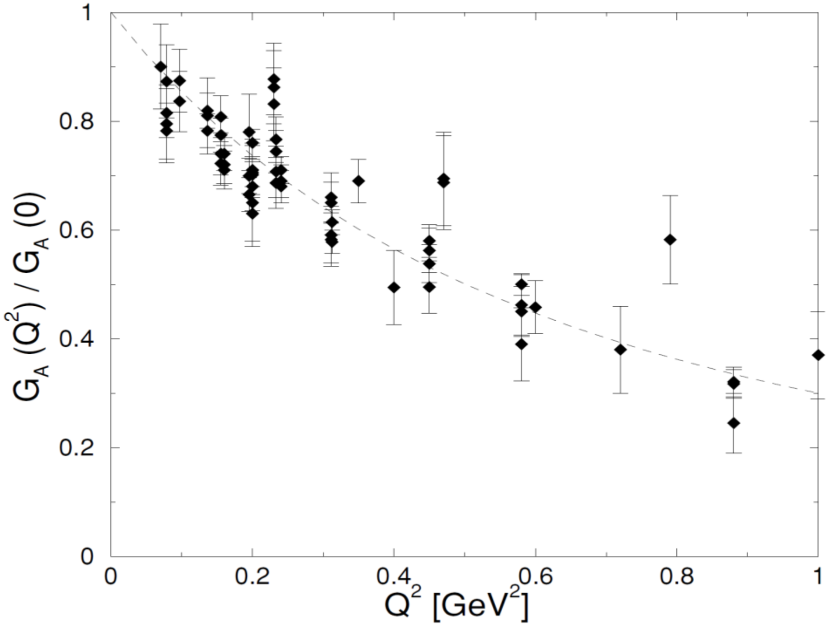
$$M_V = 0.84\,\mathrm{GeV}/c^2$$

Axial

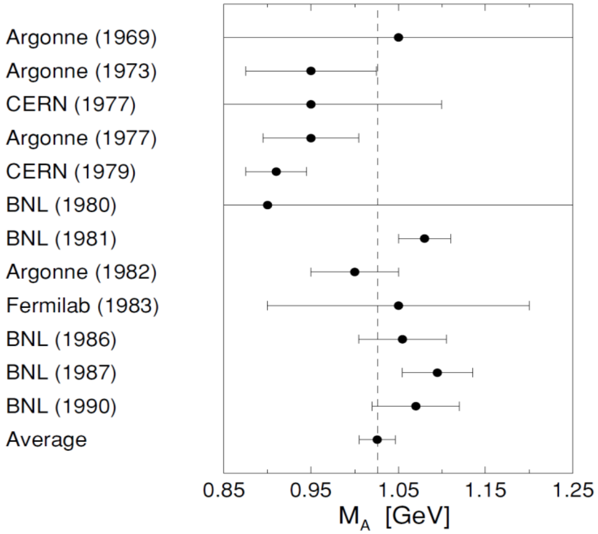
$$G_A(Q^2) = g_A(1 + Q^2 / M_A^2)^{-2}$$

$g_A = 1.26$ from neutron β decay

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



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



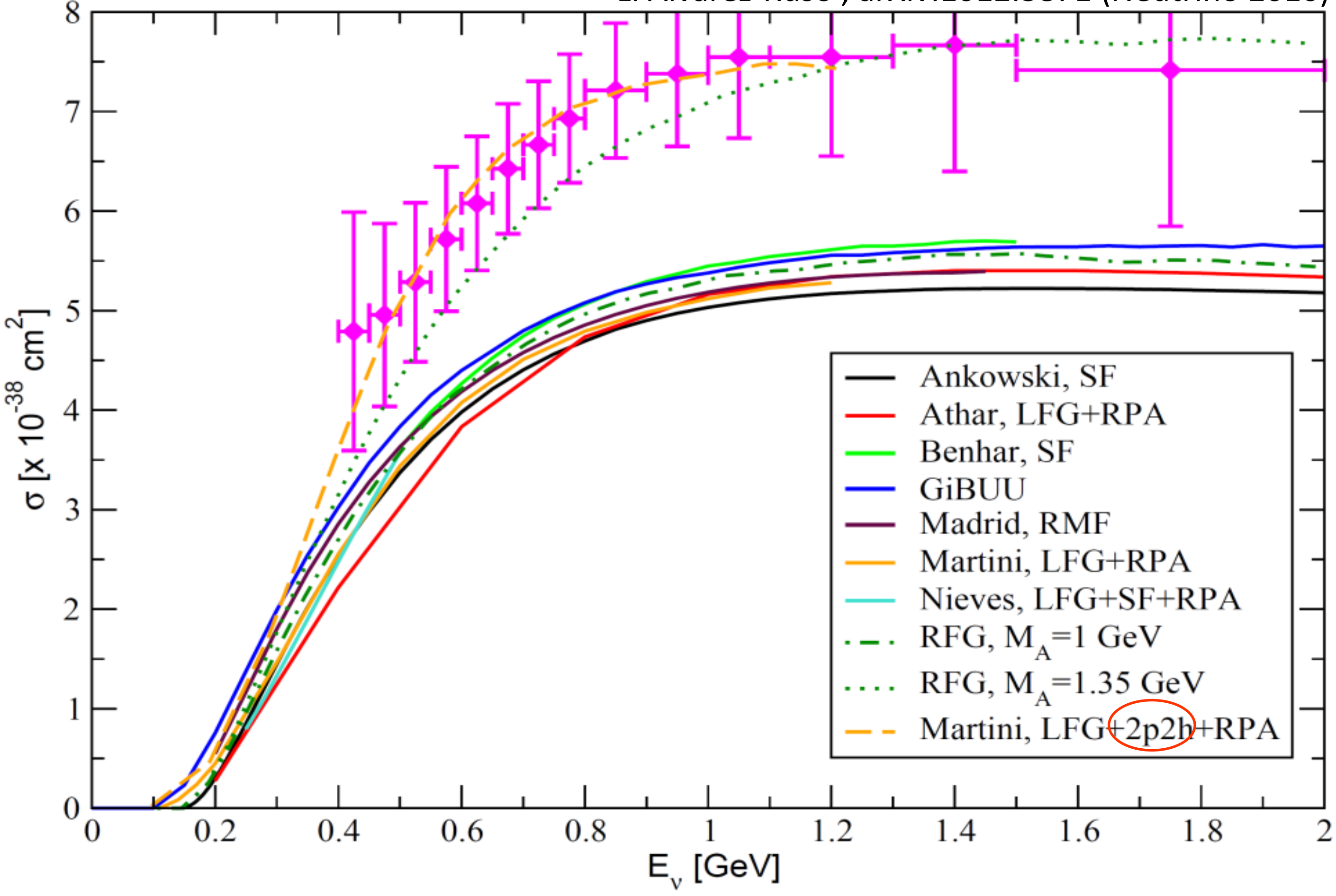
from ν-deuterium CCQE

and

from π electroproduction

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

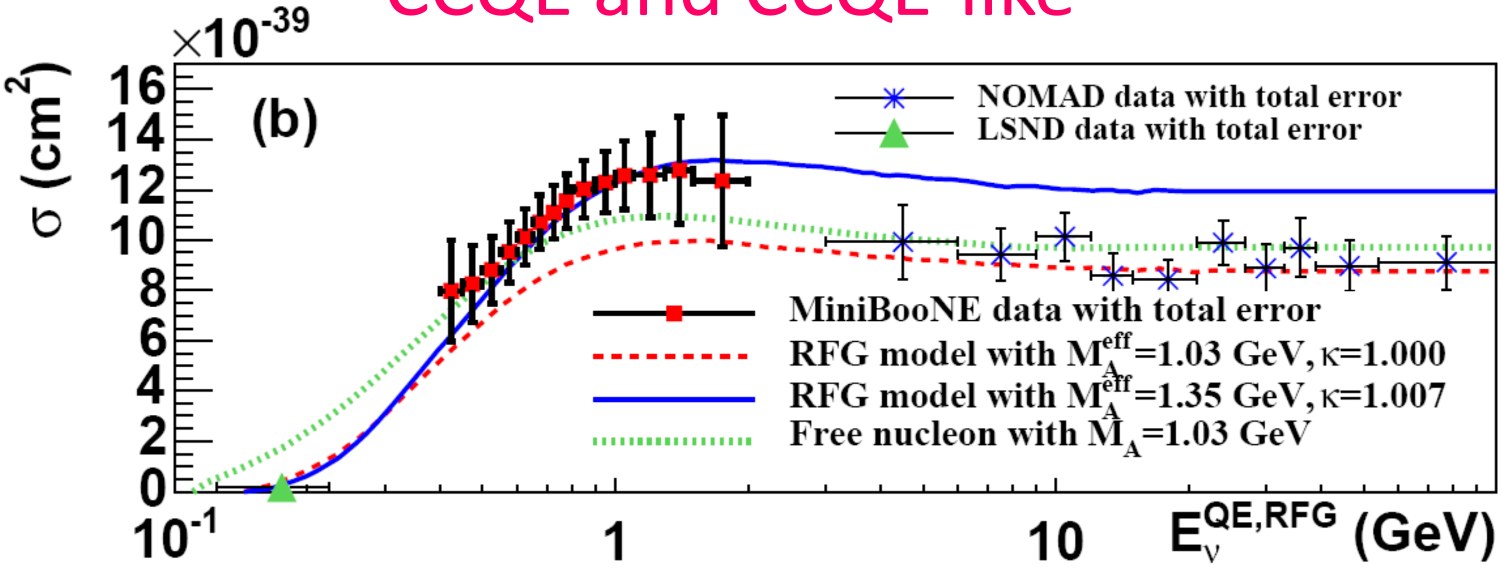
RMF: Relativistic Mean Field

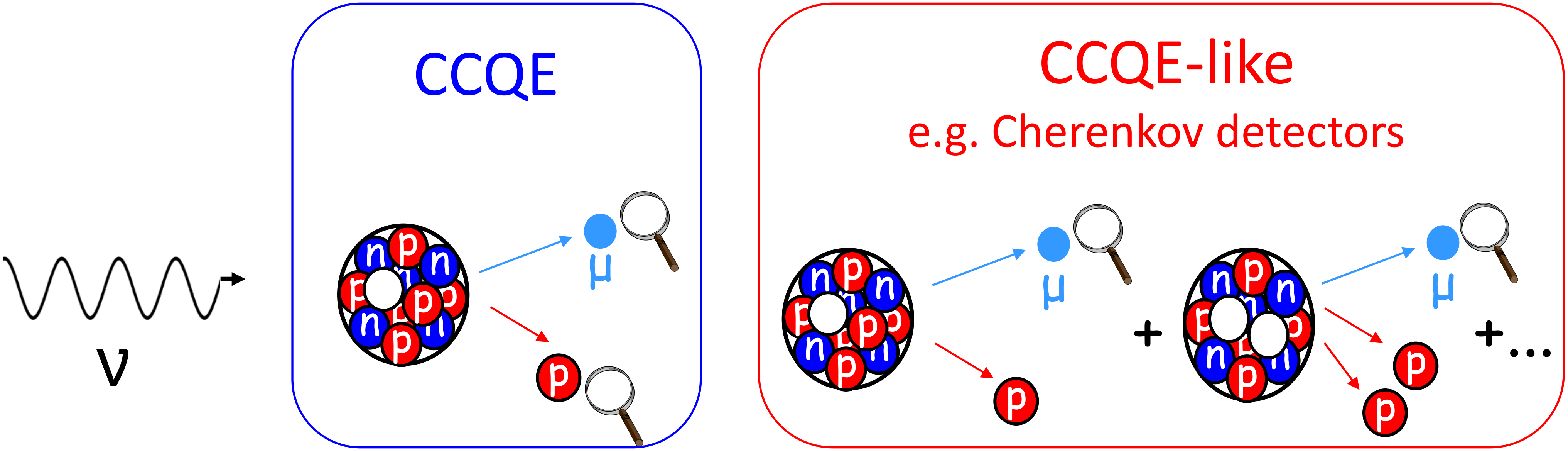
GiBUU: Transport Equation

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

puzzle??

CCQE and CCQE-like



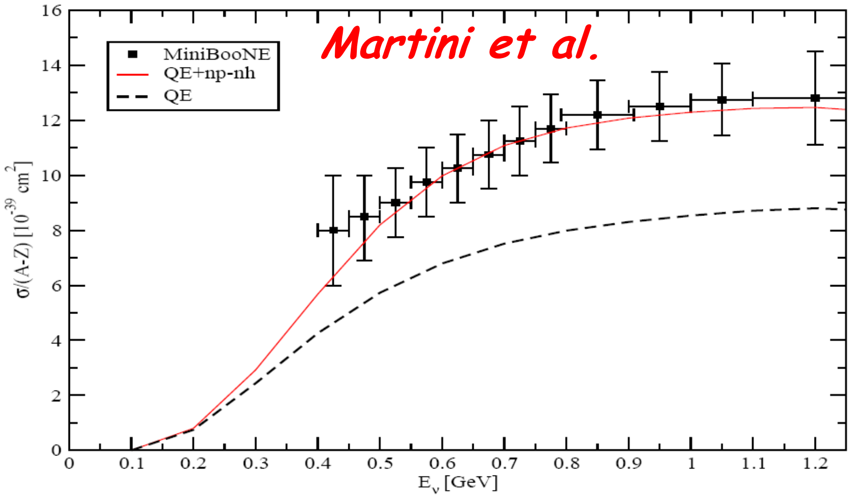


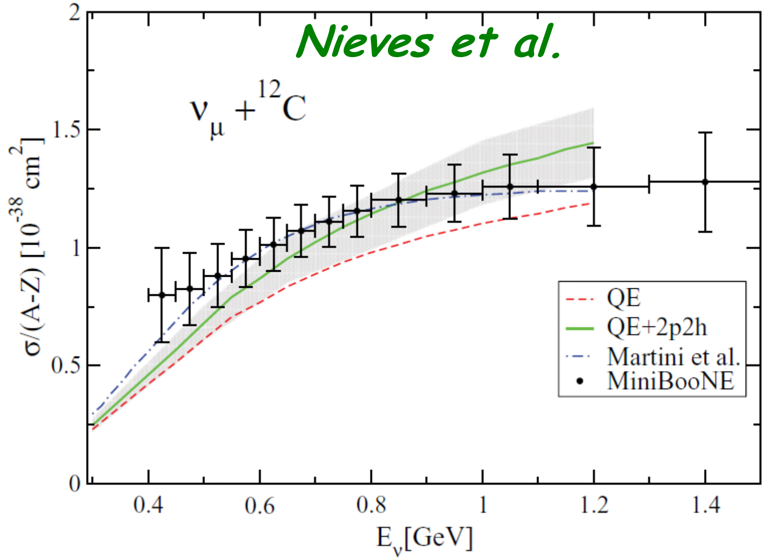
CCQE

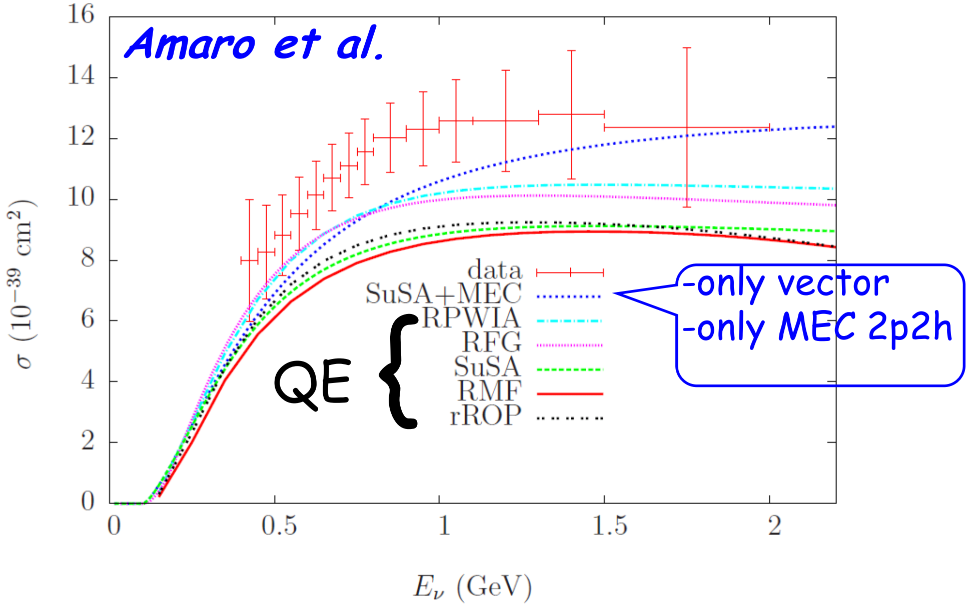
CCQE-like

e.g. Cherenkov detectors

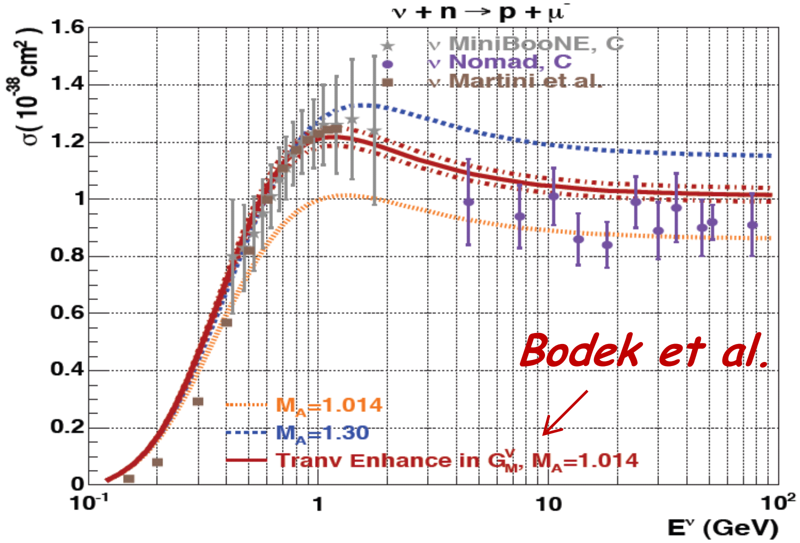
Total CCQE and comparison with flux unfolded MB







-only vector
-only MEC 2p2h



N.B. The experimental unfolding is model dependent

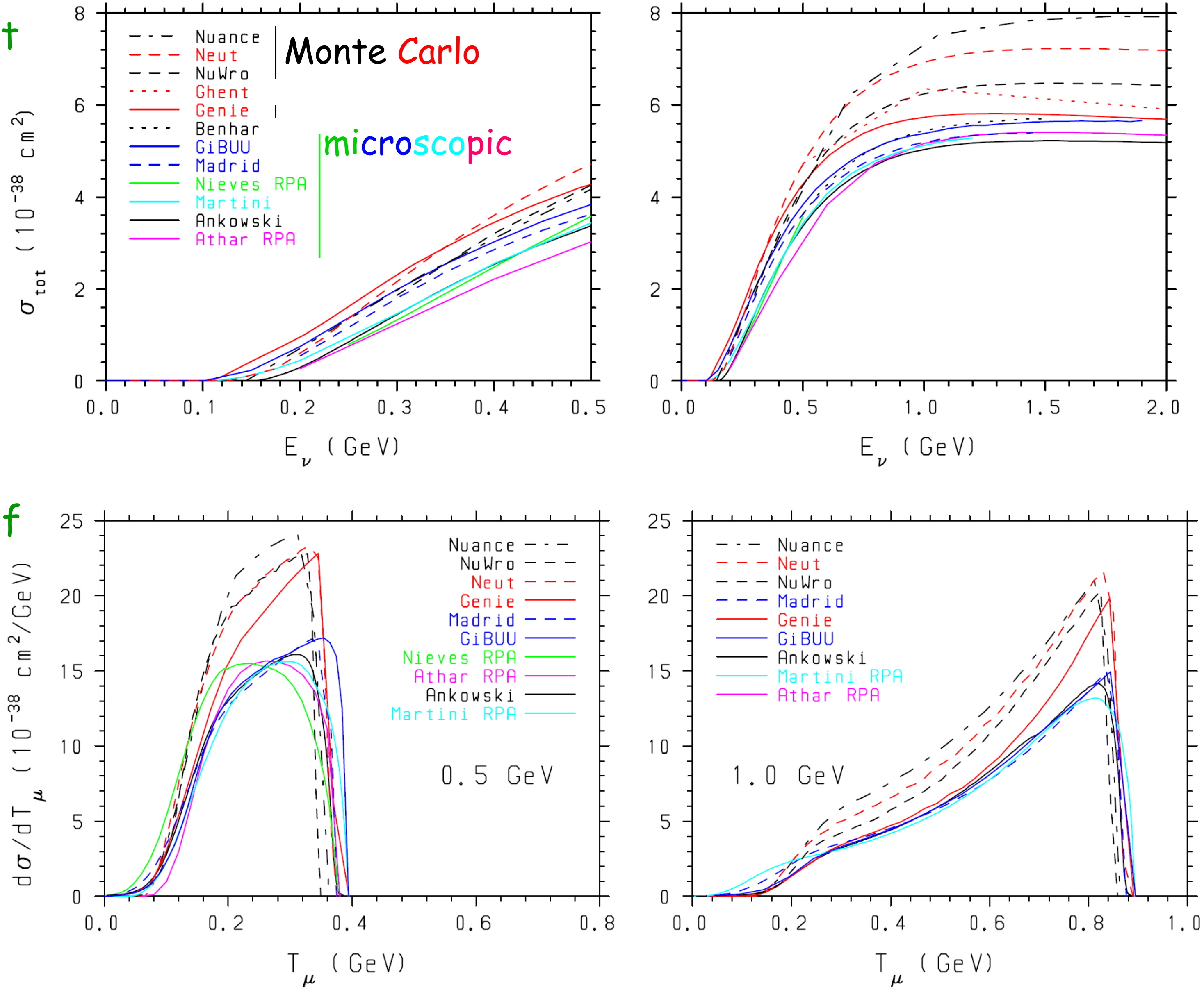
Comparison of Models of Neutrino-Nucleus Interactions

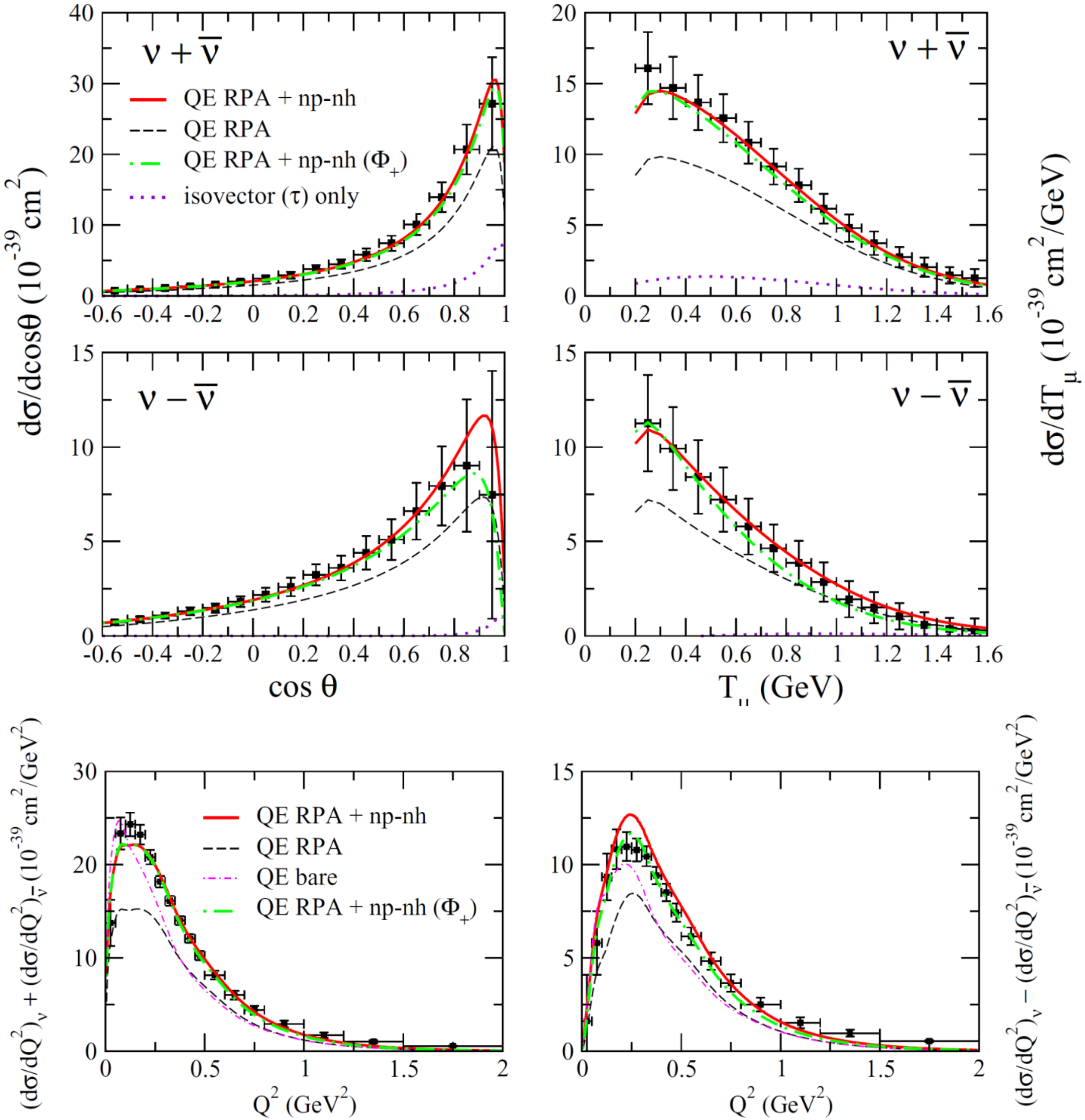
S. Boyd*, S. Dytman†, E. Hernández**, J. Sobczyk‡ and R. Tacik§

QE tot

QE diff

NUINT09

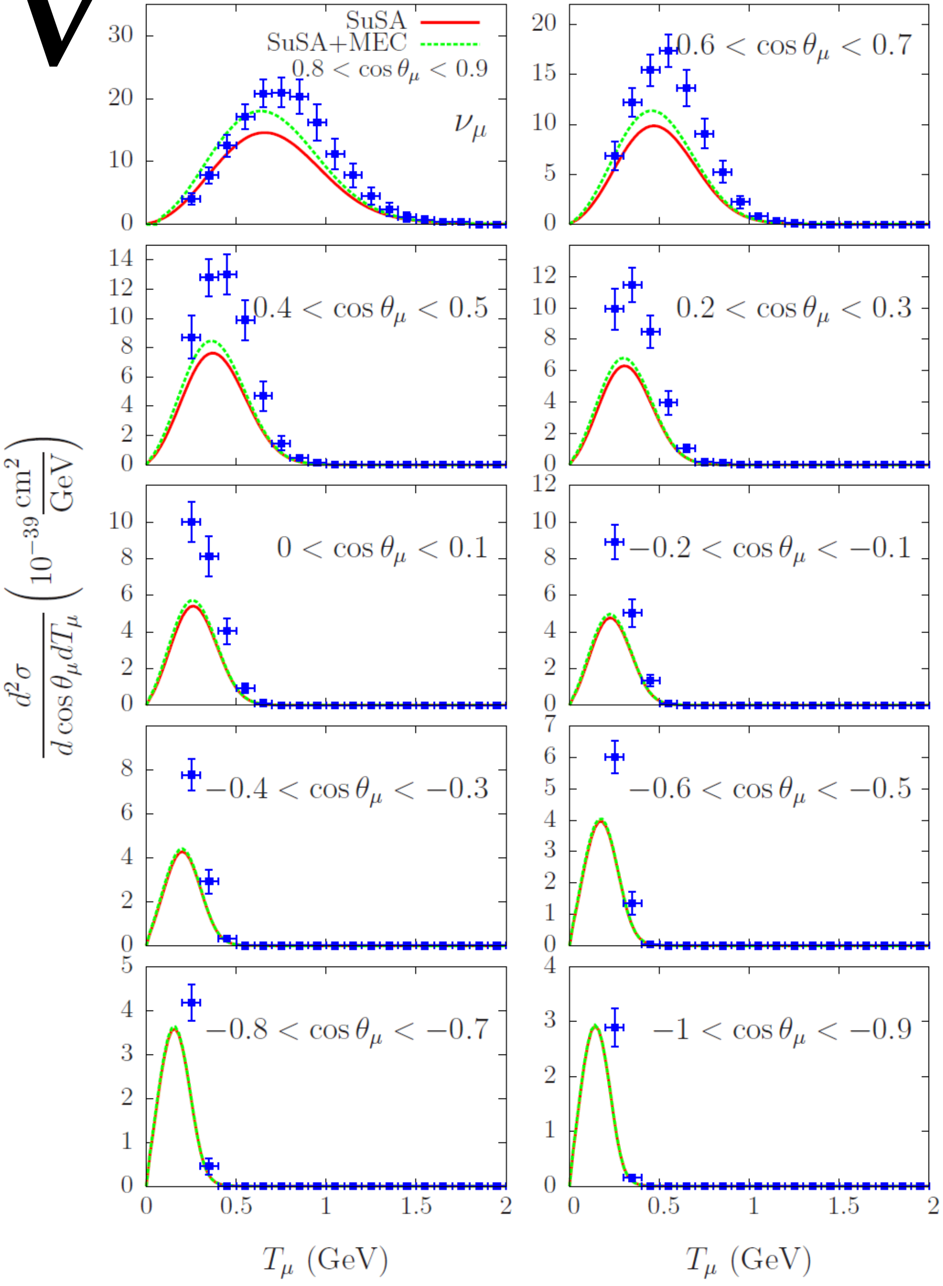




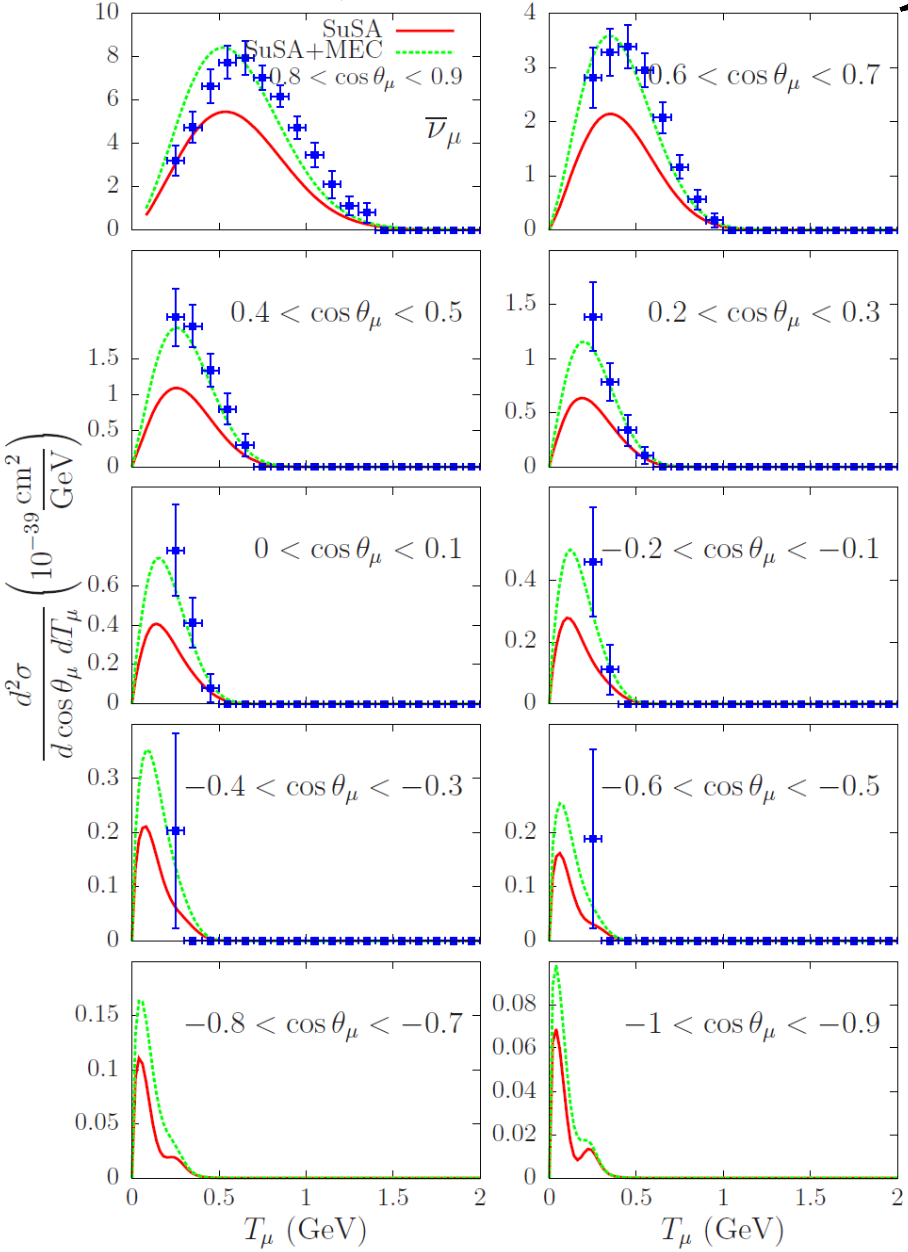
M. Ericson, M. Martini, Phys. Rev. C 91 035501 (2015)

Amaro et al.

ν Phys. Lett. B 696 151-155 (2011)



Phys. Rev. Lett. 108 152501 (2012) $\overline{\nu}$

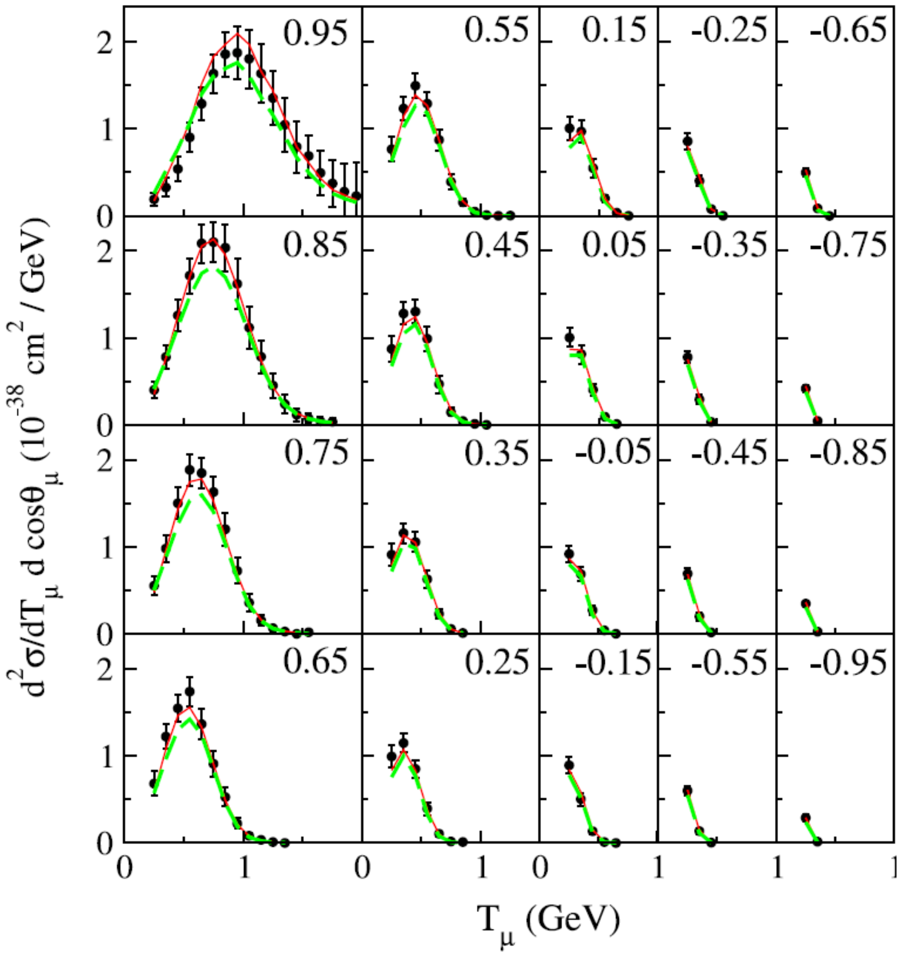


ν

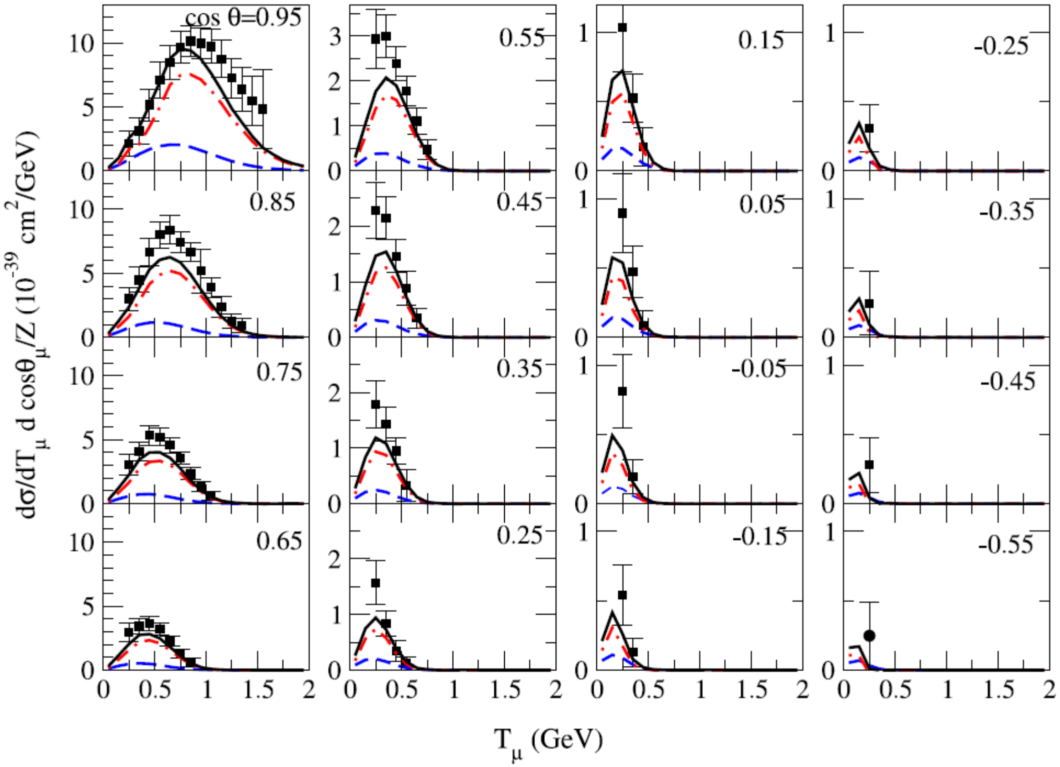
Nieves et al.

$\bar{\nu}$

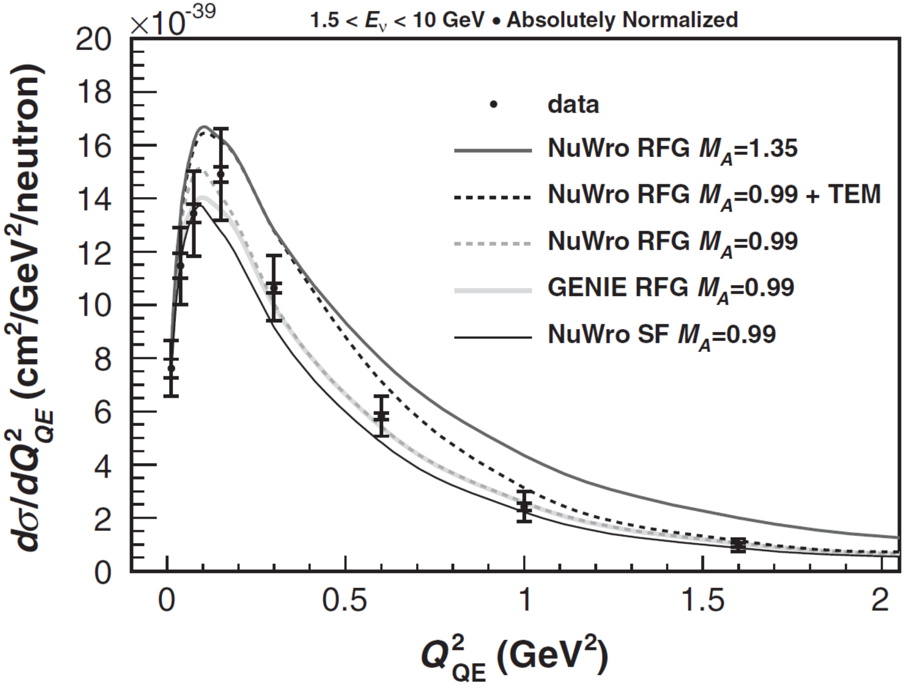
Phys. Lett. B 707 72-75 (2012)



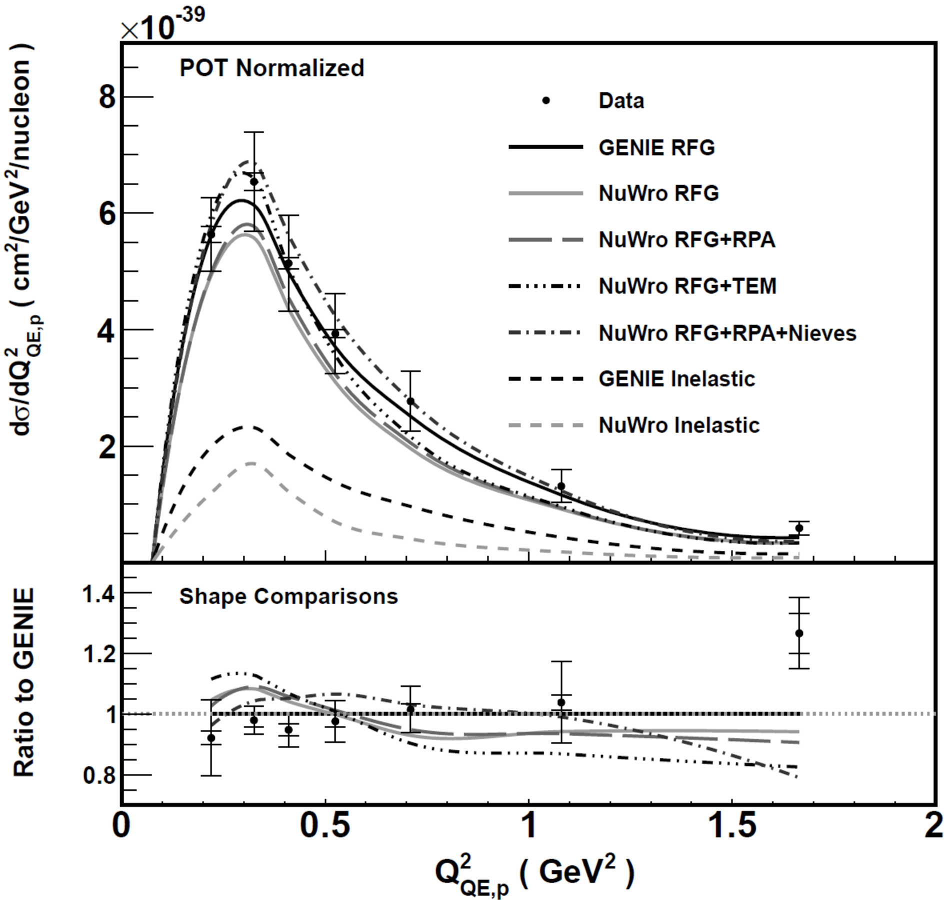
Phys. Lett. B 721 90-93 (2013)



MINERνA Q^2 distributions



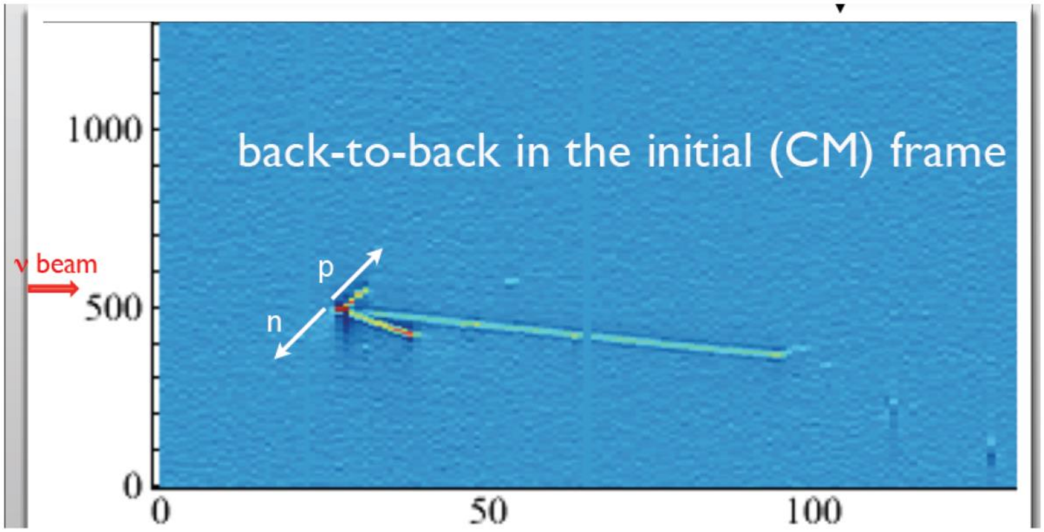
PRL 111 022502 (2013)



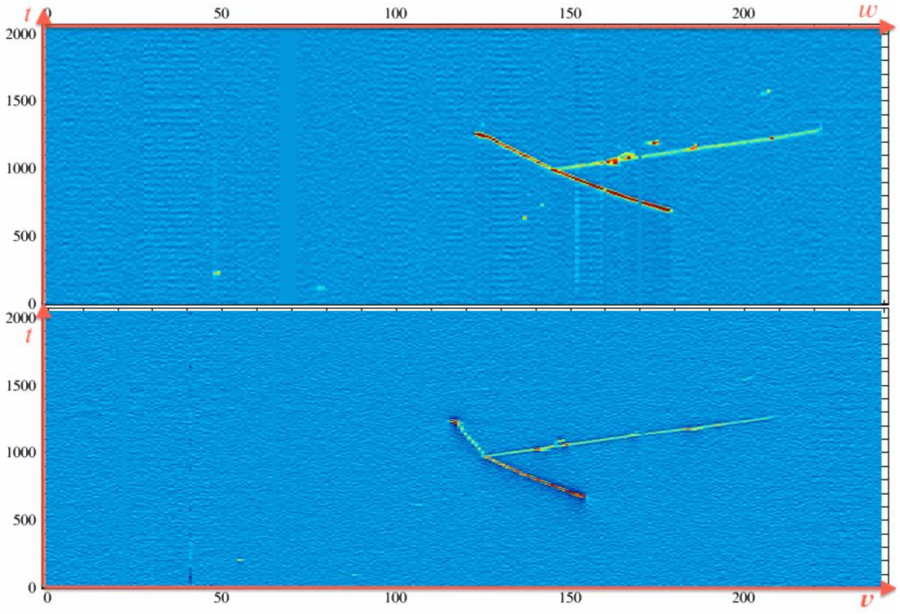
arXiv:1409.4497

ArgoNeut

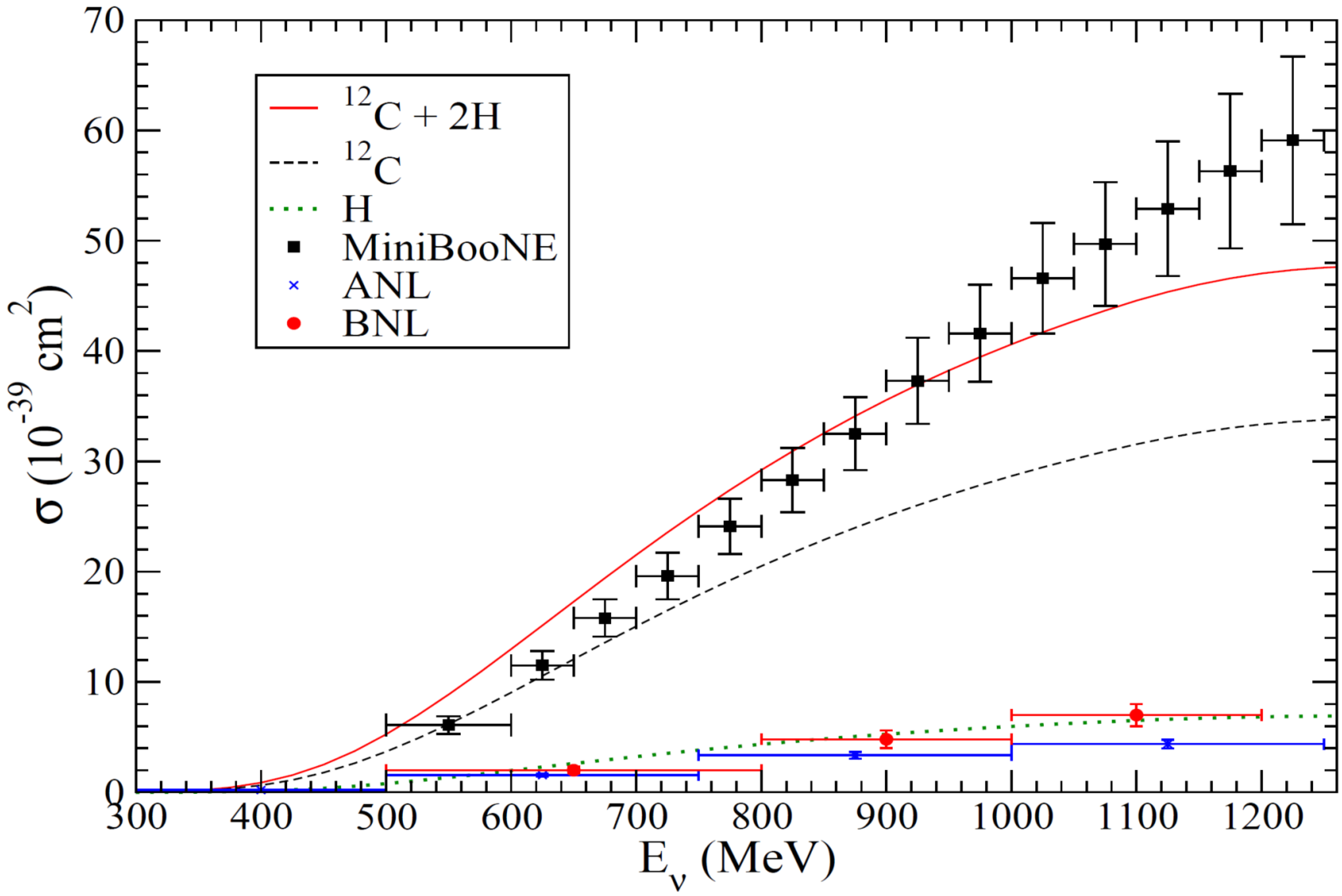
arXiv:1501.01983



Phys.Rev. D90 (2014) 1, 012008

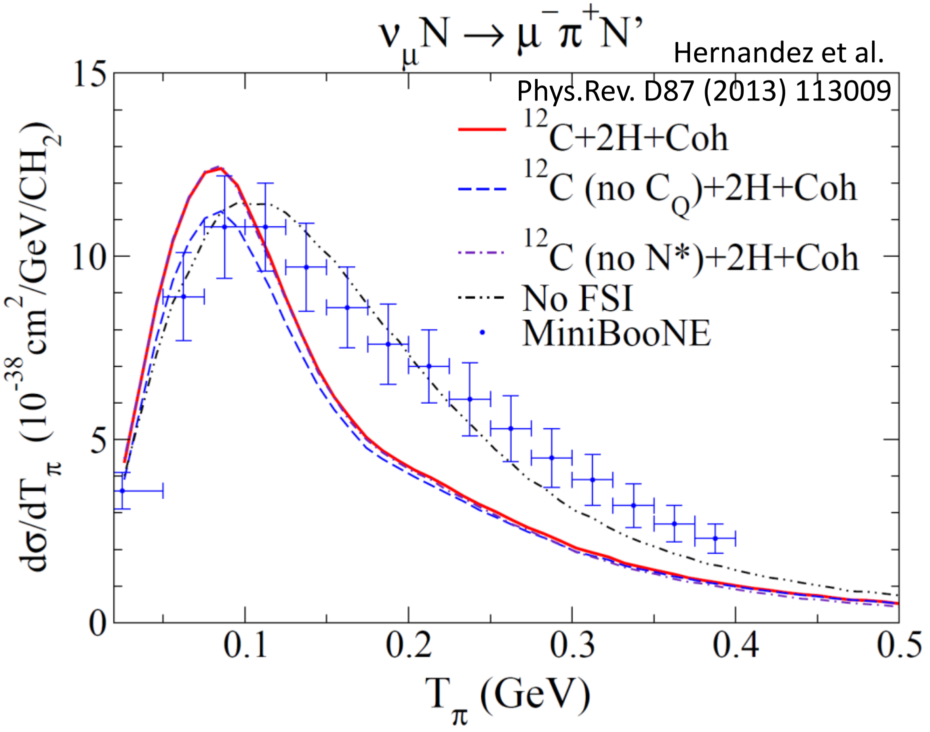


CC1π+ cross section versus the neutrino energy



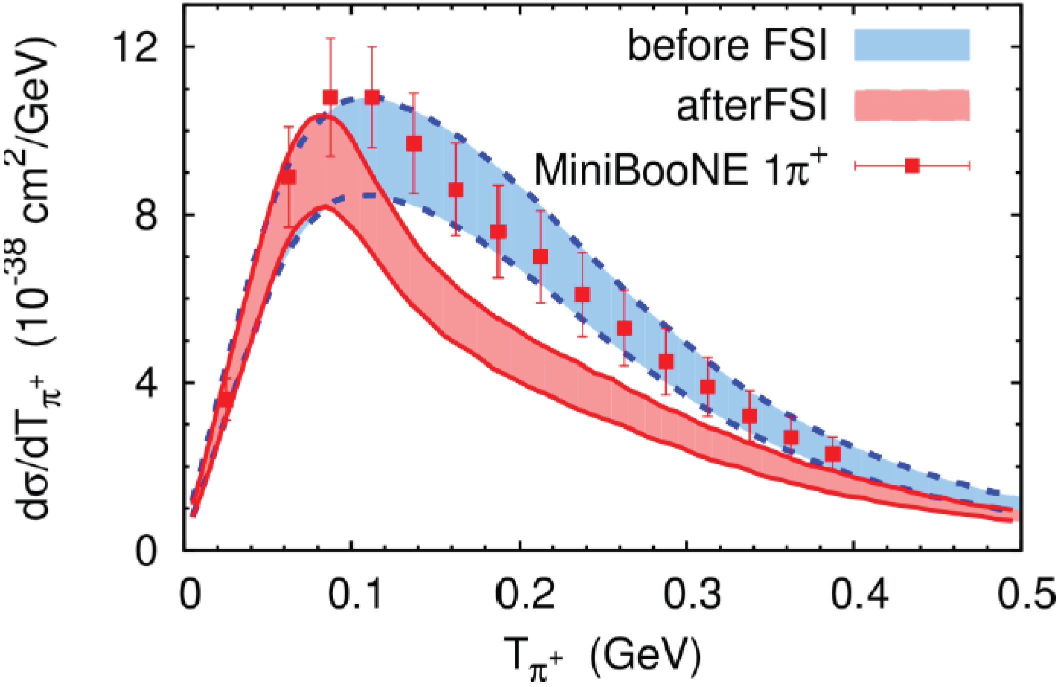
Undervaluation of our theory with respect to the data above an energy $E_\nu \simeq$ 1 GeV, as for the inclusive cross section.
Misidentification of two pion production process, with only one pion detected?
We remind that no correction has been applied for the reconstruction of the neutrino energy.

MiniBooNE CC1π+ production: theory versus experiment



Hernandez et al. Phys.Rev. D87 (2013) 113009

Lalakulich, Mosel , Phys.Rev. C 87 (2013) 014602



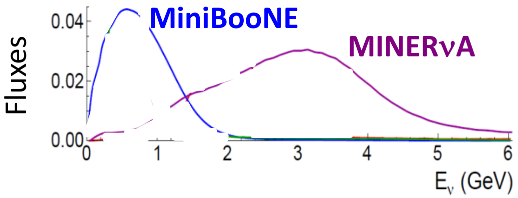
Valencia

GiBUU

controversy

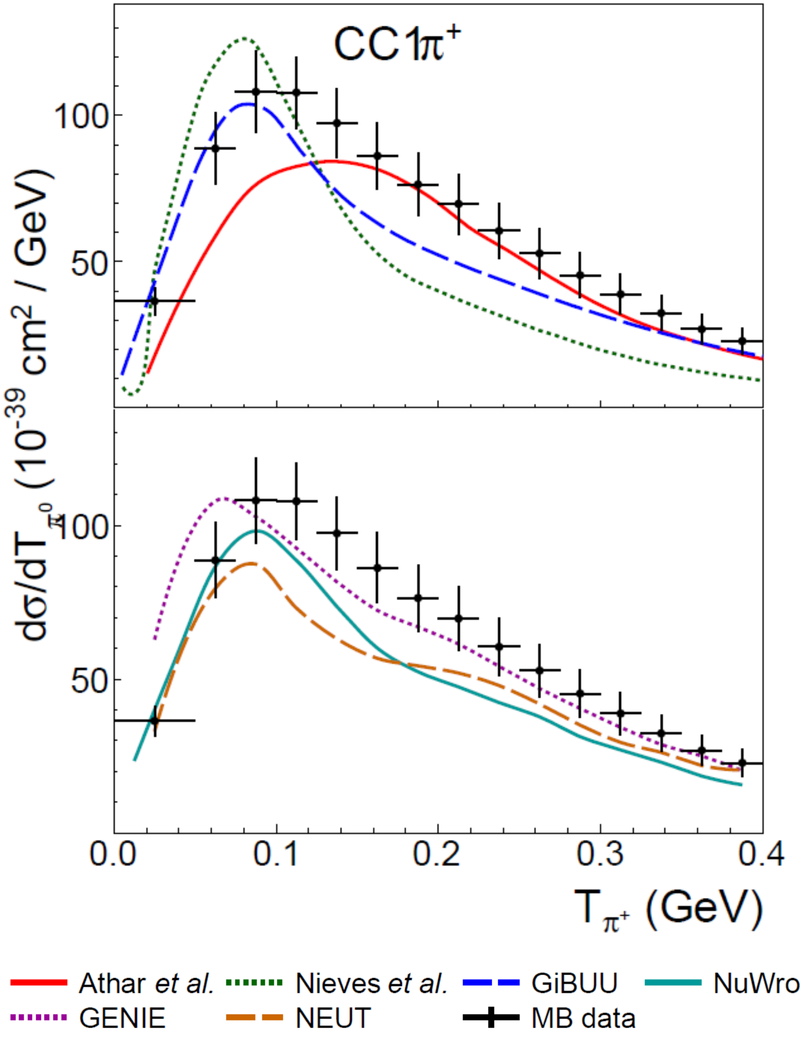
- Best theories (with Δ medium effects and pion rescattering) do not agree with pion KE spectrum
- MiniBooNE data *(PRD 83 052007 (2011))* prefer calculations with no Final State Interaction for the pion

MiniBooNE *vs* MINERνA CC1π+ production



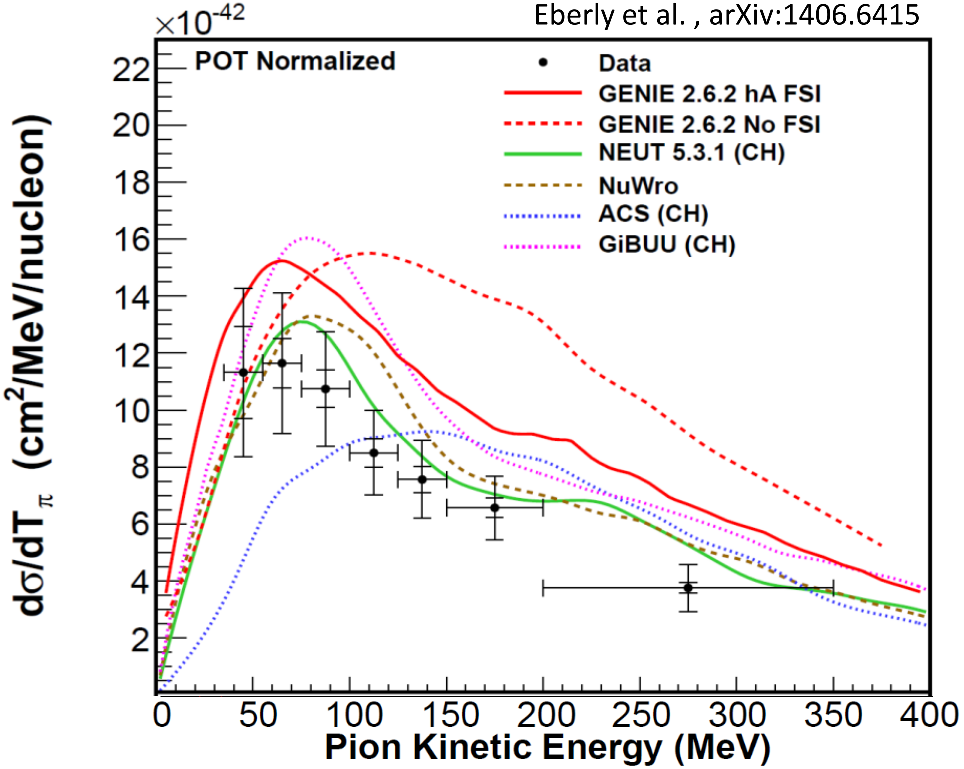
MiniBooNE

Rodrigues, arXiv:1402.4709



MINERνA

Eberly et al. , arXiv:1406.6415

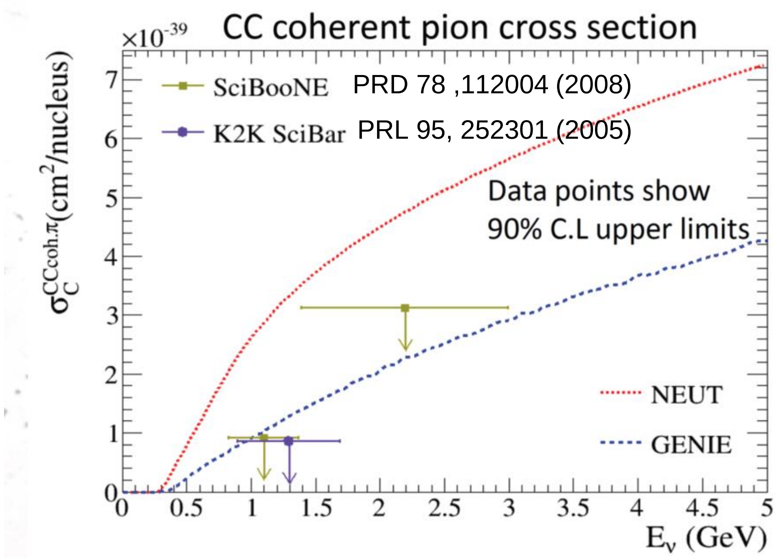


Some tension

Coherent π production

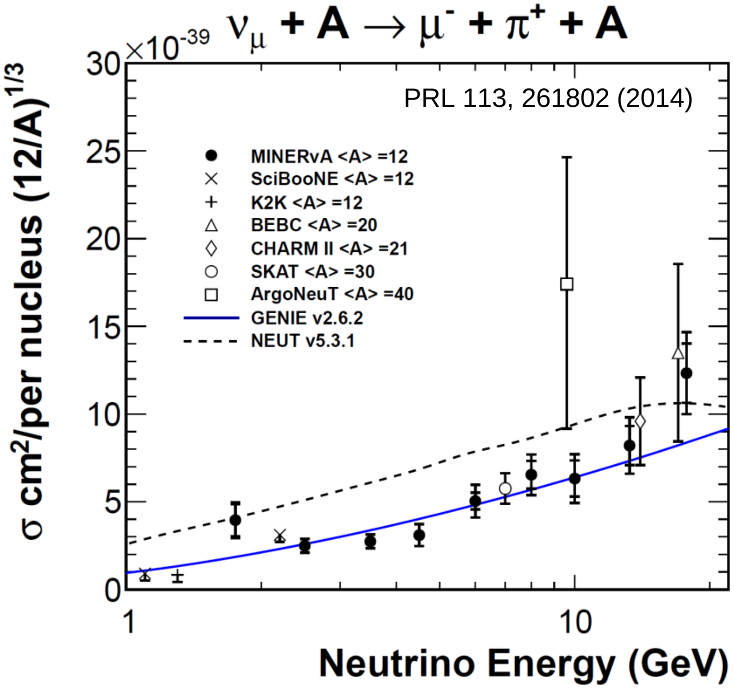
K2K and SciBooNE did not observe coherent π^+ production at neutrino energies ~1GeV

Recently MINERνA and ArgoNeut see evidence for CC coherent pion production



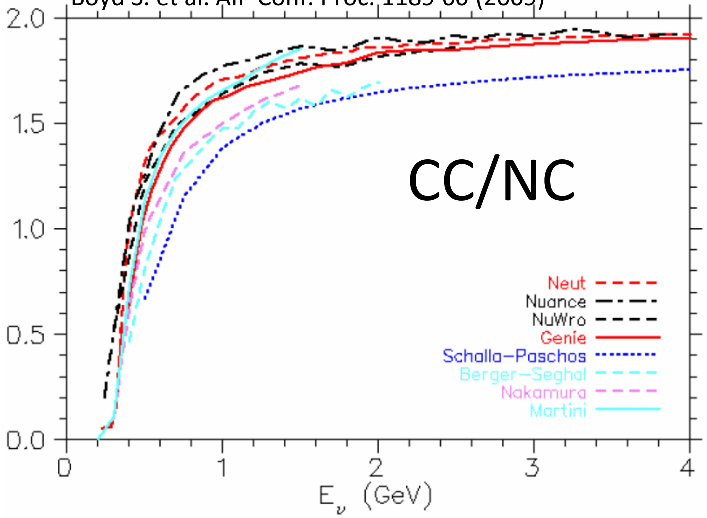
PRD 78 ,112004 (2008)

PRL 95, 252301 (2005)



PRL 113, 261802 (2014)

Boyd S. et al. AIP Conf. Proc. 1189 60 (2009)



Coherent puzzle at $E_\nu \sim 1$ GeV

Theoretical models:

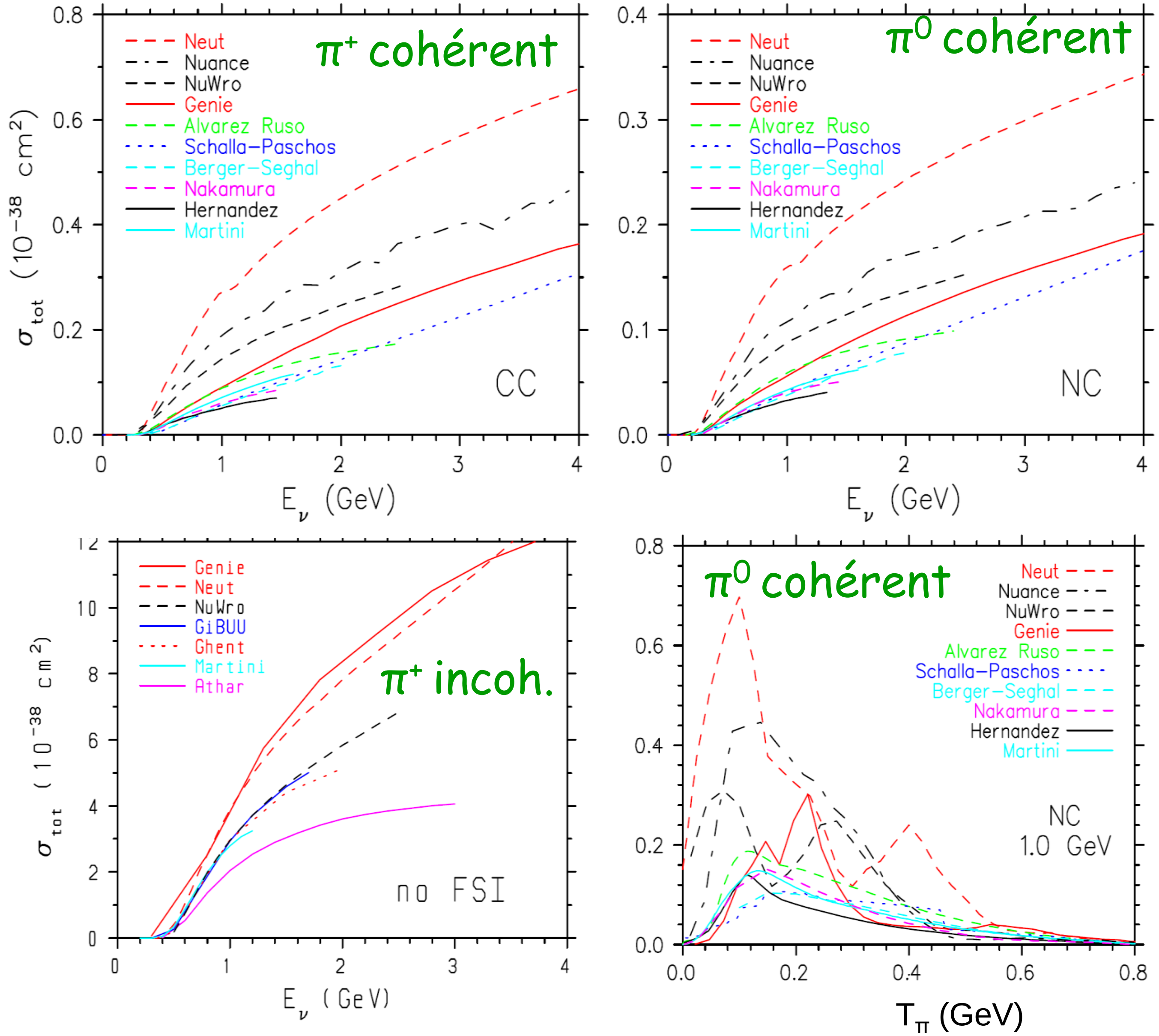
$$\frac{\pi+ \text{ coh. CC}}{\pi0 \text{ coh. NC}} = 1.5 \sim 2$$

SciBooNE:

$$\frac{\pi+ \text{ coh. CC}}{\pi0 \text{ coh. NC}} = 0.14^{+0.30}_{-0.28}$$

Kurimoto et al, PRD 81 (2010)

NUINT09



Monte Carlo

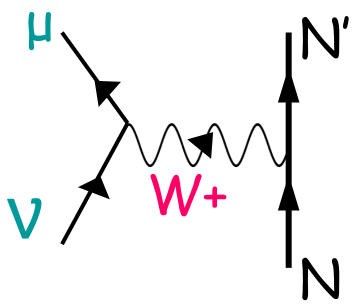
QE: Fermi Gas

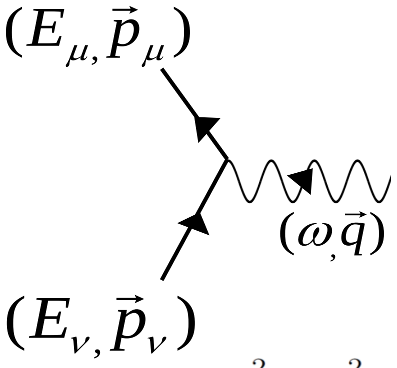
π prod:Rein-Sehgal

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

MC larger than microscopic models

QE Scattering with free nucleon at rest: two-body kinematics





$$\omega = E_\nu - E_\mu$$

$$q^2 = E_\nu^2 + p_\mu^2 - 2E_\nu p_\mu \cos\theta$$

$$q^2 - \omega^2 = 4(E_\mu + \omega)E_\mu \sin^2\frac{\theta}{2} - m_\mu^2 + 2(E_\mu + \omega)(E_\mu - p_\mu)\cos\theta$$

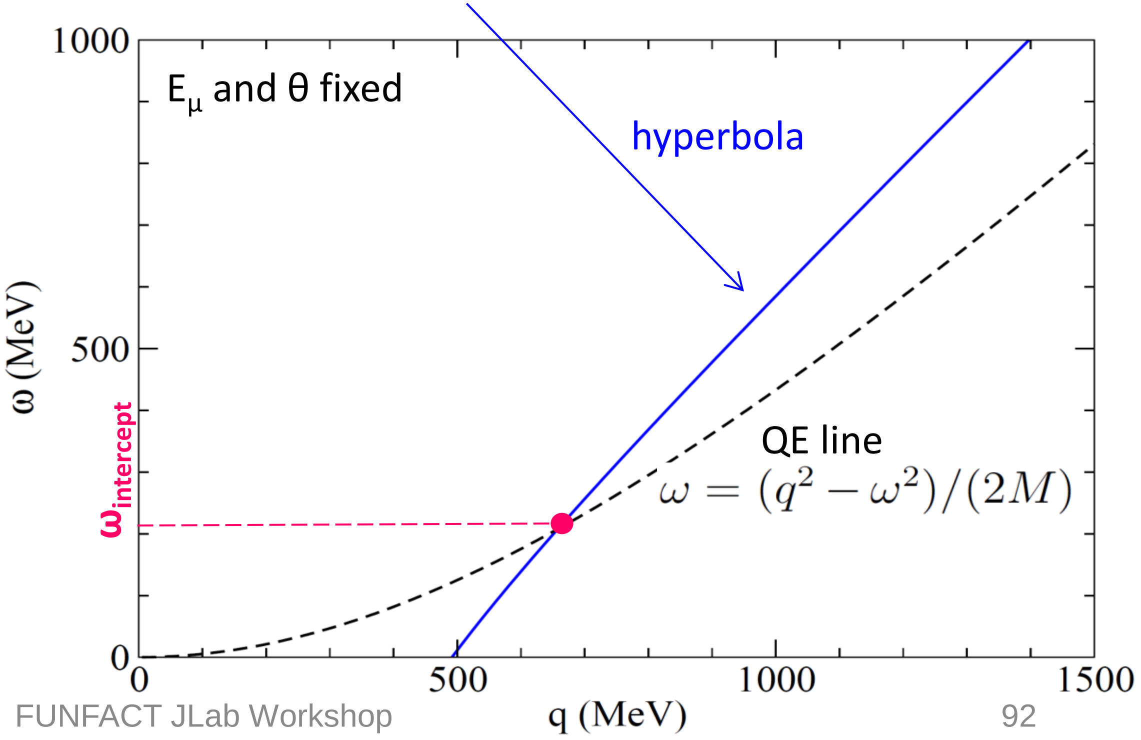
The nuclear response function is proportional to the delta distribution

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

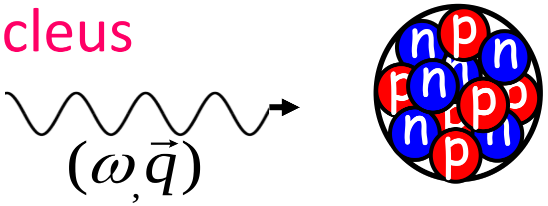
The intercept of the **hyperbola** with the **QE line** fixes the possible ω and q values for given E_μ and θ.

Hence the neutrino energy is determined

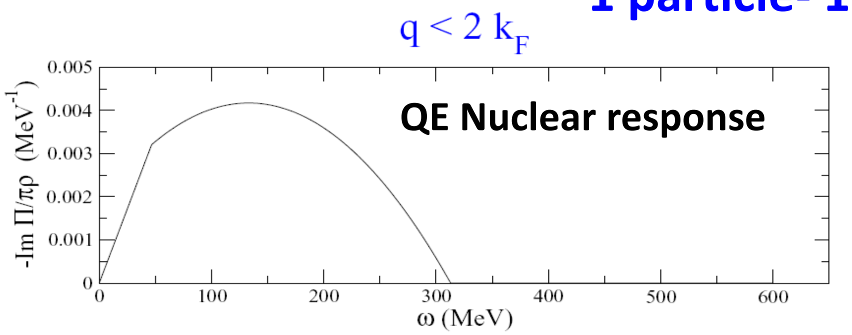
$$\boxed{E_\nu \;=\; E_\mu + \omega_{\text{intercept}}}$$



QE Scattering with nucleons inside the nucleus



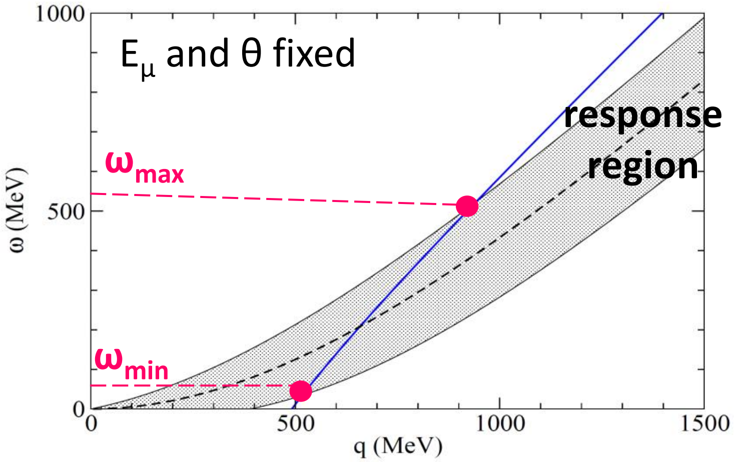
1 particle- 1 hole (p-h) excitation



Fermi motion spreads δ distribution (**Fermi Gas**)

Pauli blocking cuts part of the
low momentum nuclear response

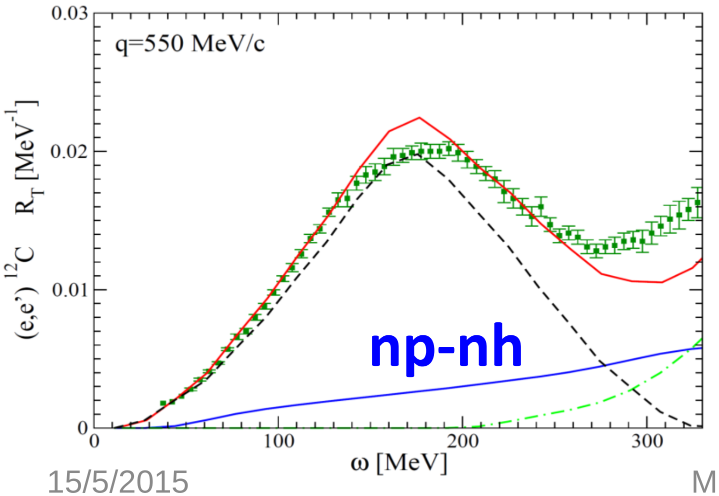
RPA collective effects



Broadening of the neutrino energy

$$\boxed{E_\nu = E_\mu + (\omega_{\min} \le \omega \le \omega_{\max})}$$

np-nh excitations



- np-nh creates a high energy tail above the QE peak
- np-nh enlarges the region of response to the whole (ω,q) plane

no reason to fulfill the QE relation for Ev reconstruction

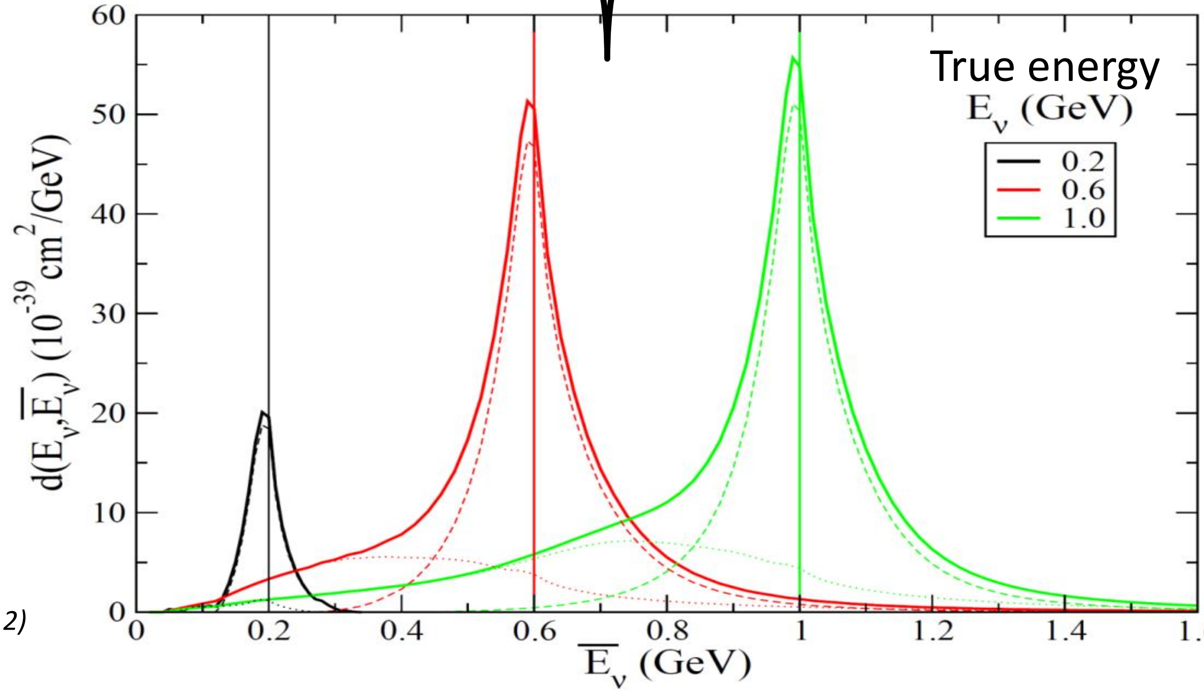
From true neutrino energy to reconstructed neutrino energy

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

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)

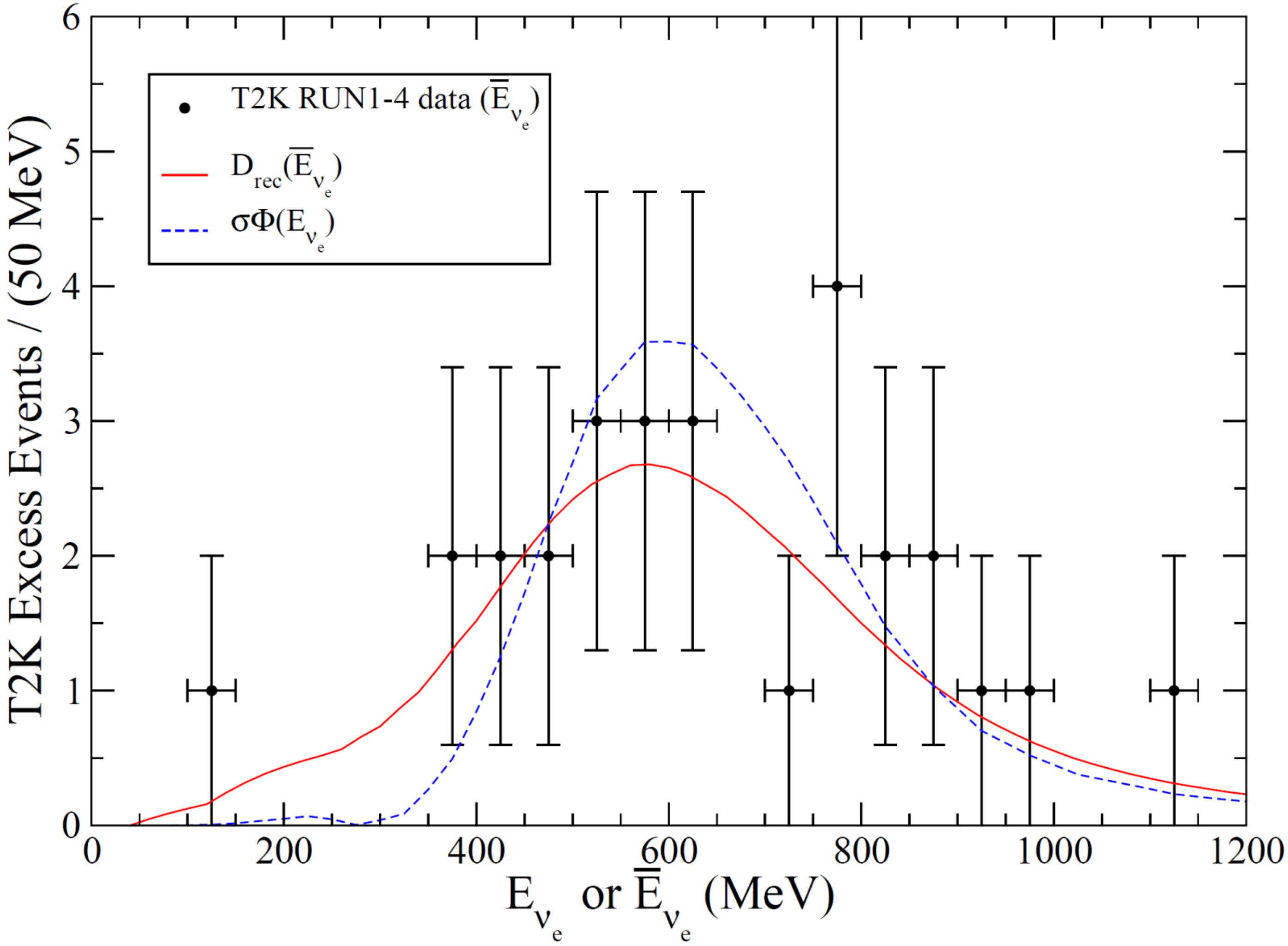


- Distributions not symmetrical around Eν
- Crucial role of np-nh: low energy tail

$\nu_\mu \to \nu_e$ T2K

PRL 107 (2011), PRD 88 (2013), PRL 112 (2014)

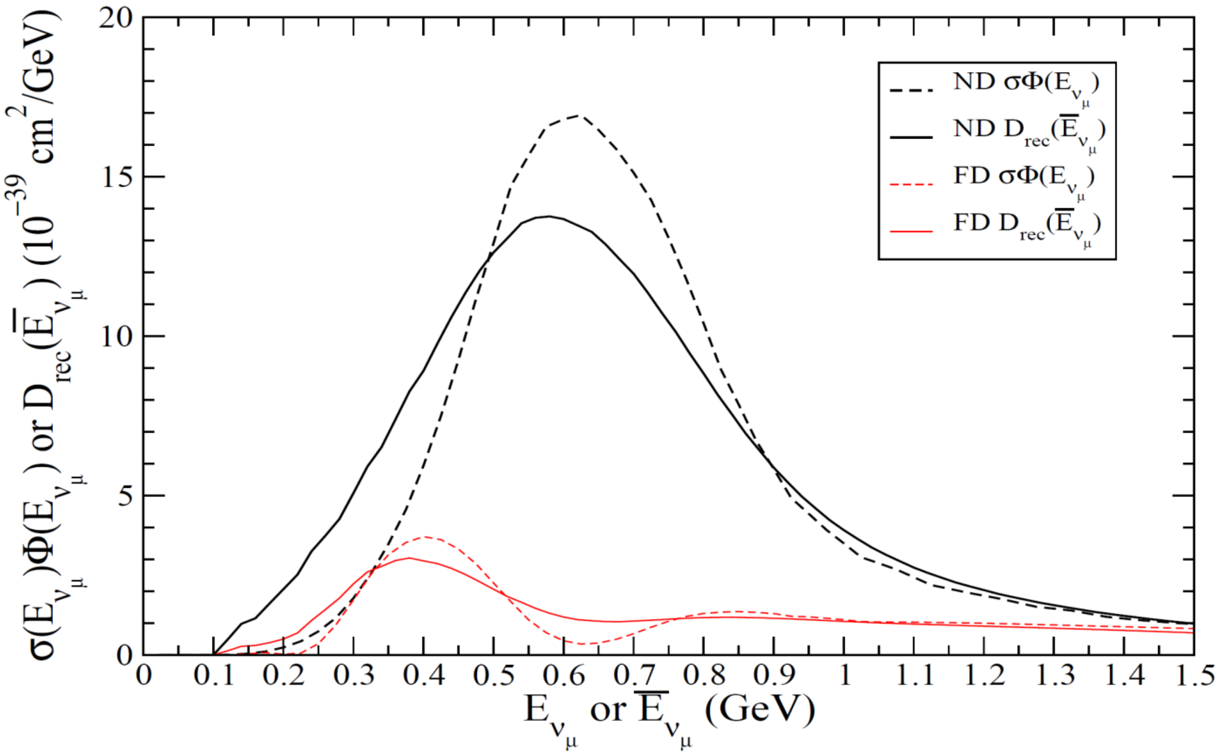
2013: 28 events

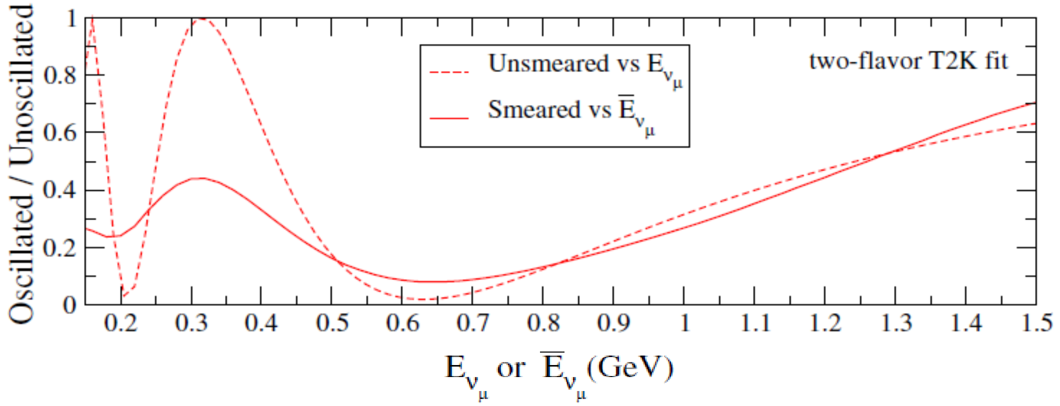


The reconstruction correction tends to make events leak outside the high flux region, especially towards the low energy side

νμ disappearance T2K

PRD85 (2012); PRL 111 (2013)





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

Similar results in: O. Lalakulich, U. Mosel, K. Gallmeister, PRC 86 054606 (2012)

After reconstruction:

- Near Detector:
  clear low energy enhancement
- Far Detector:
  low energy tail and
  the middle hole is largely filled

Effects largely due to np-nh

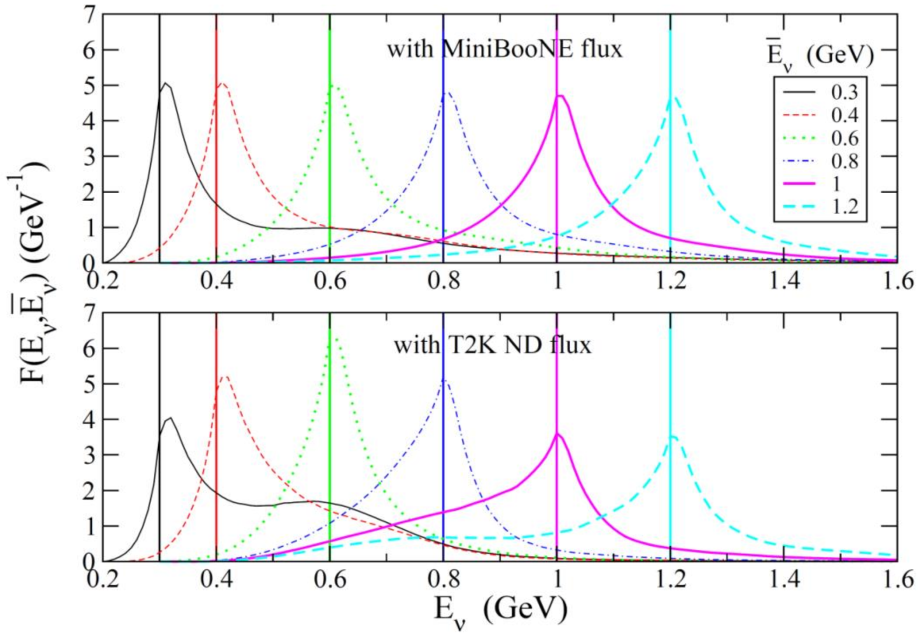
Recent T2K experimental analysis :

arXiv: 1502.01550

"For the present exposure, the effect can be ignored, but future analyses will need to incorporate multi-nucleon effects in their model of neutrino-nucleus interactions."

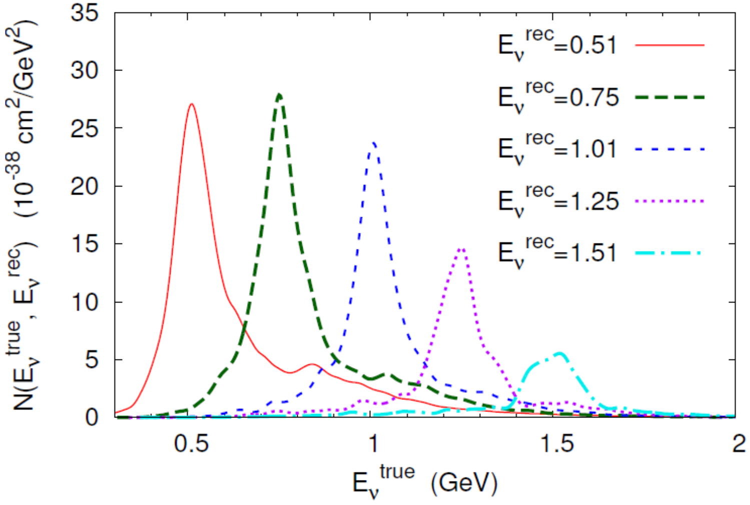
Distributions in terms of true E_ν for fixed values of reconstructed E_ν

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

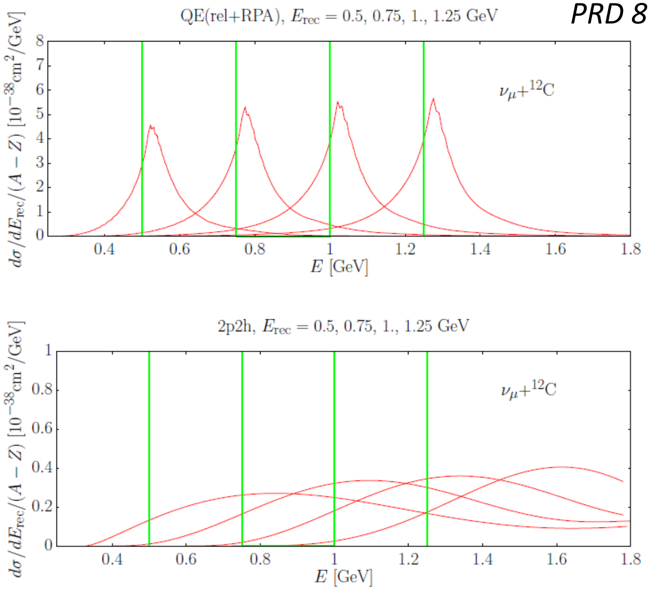


- The distributions are not symmetrical around Ēν.
- The asymmetry favors higher energies at low Ēν and smaller energies for large Ēν.
- Crucial role of neutrino flux.

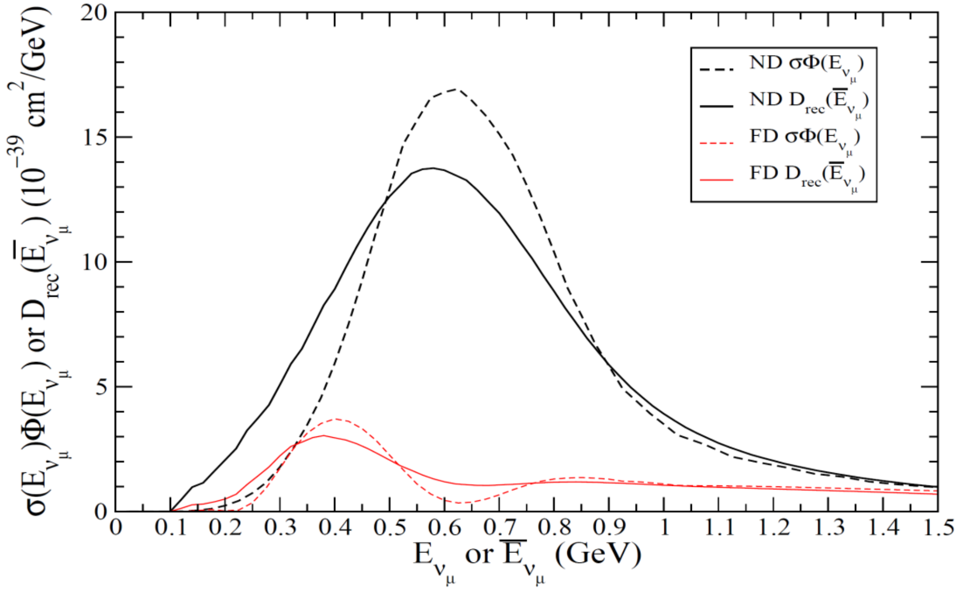
O. Lalakulich, U. Mosel, K. Gallmeister PRC 86 054606 (2012)

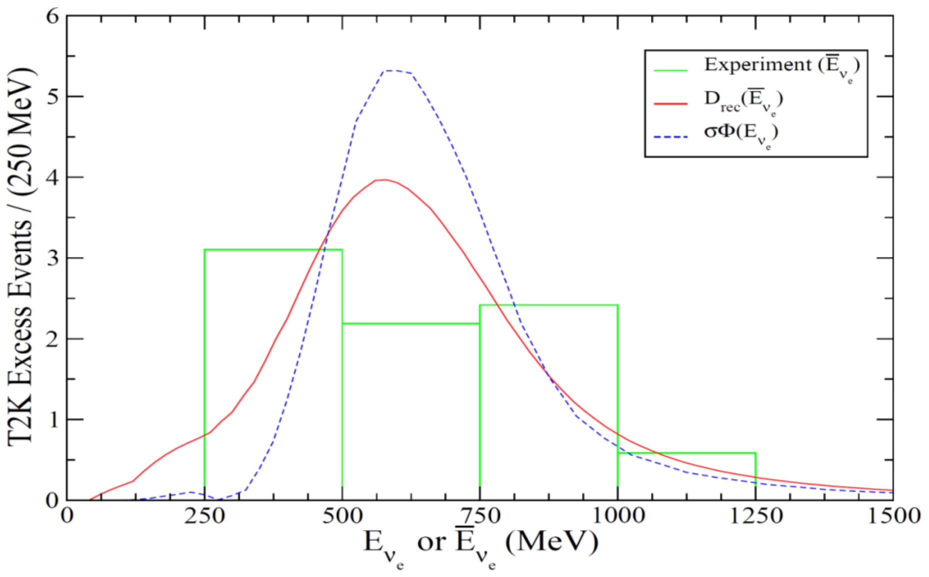


J. Nieves, F. Sanchez, I. Ruiz Simo, M.J. Vicente Vacas PRD 85 113008 (2012)

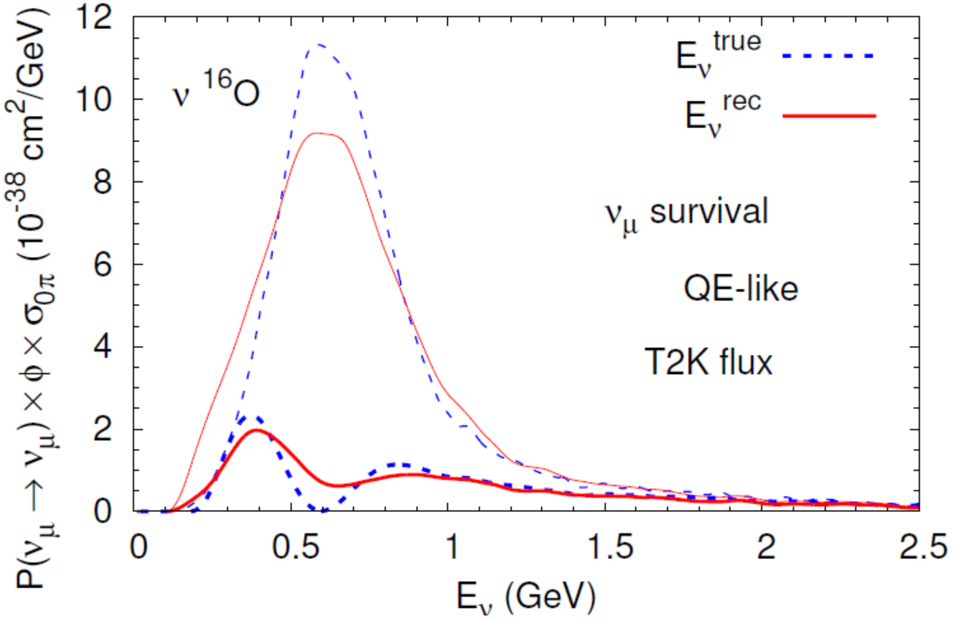


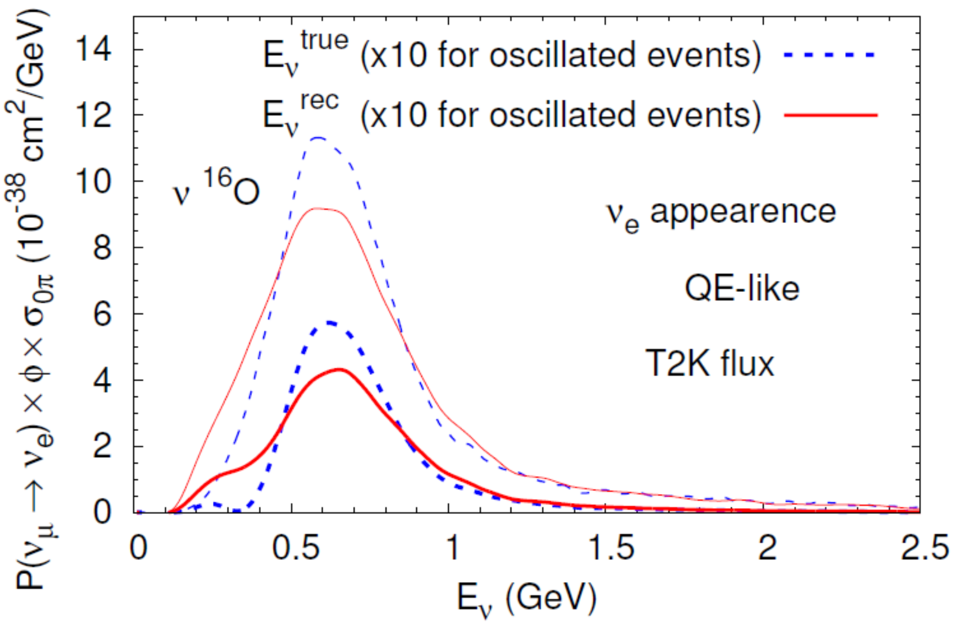
M. Martini, M. Ericson, G. Chanfray, PRD 87 013009 (2013)





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





T2K experimental analysis

arXiv: 1502.01550

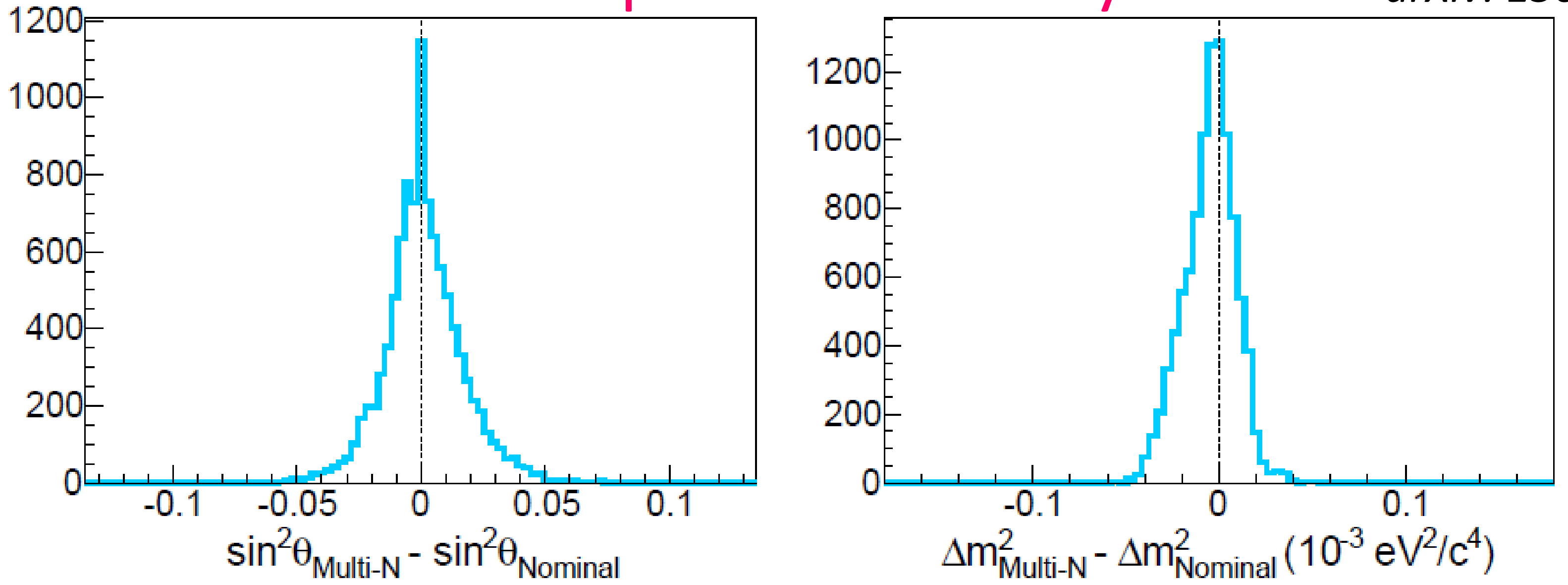
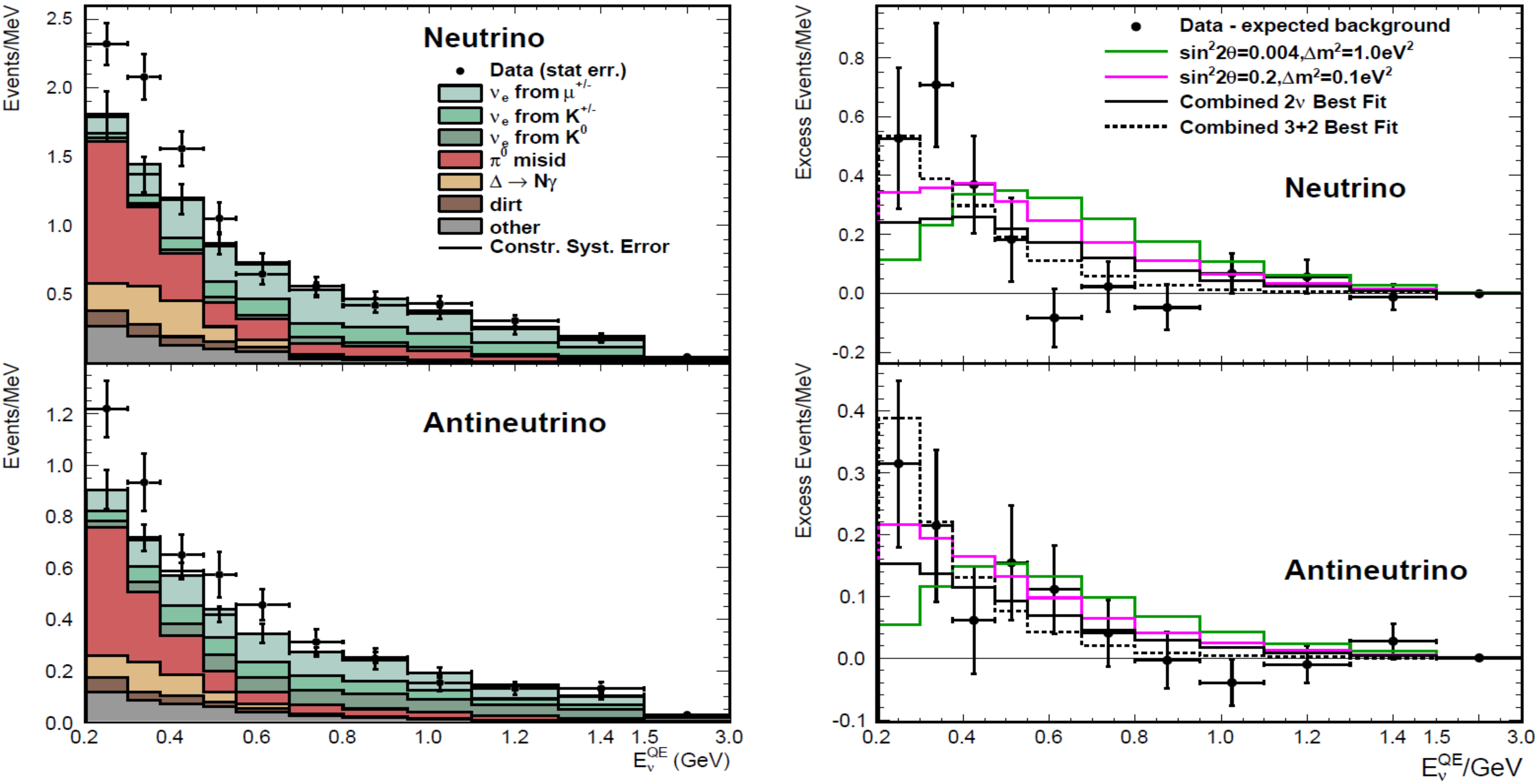


FIG. 30: Difference in the point estimates of $\sin^2\theta_{23}$ (left) and $|\Delta m^2|$(right) between pairs of toy MC datasets with and without including multi-nucleon effects.

The overall bias for both is negligible, compared to the precision obtained for the parameters. However, the additional variation in $\sin^2\theta_{23}$ is about 3%, comparable to the size of other systematic uncertainties. The bias was evaluated at $\sin^2\theta_{23} = 0.45$ to avoid the the physical boundary at maximal disappearance which could reduce the size of the apparent bias. For the present exposure, the effect can be ignored, but future analyses will need to incorporate multi-nucleon effects in their model of neutrino-nucleus interactions.

$\nu_\mu \longrightarrow \nu_e$ MiniBooNE

PRL 98 (2007), PRL 102 (2009), PRL 105 (2010), PRL 110 (2013)

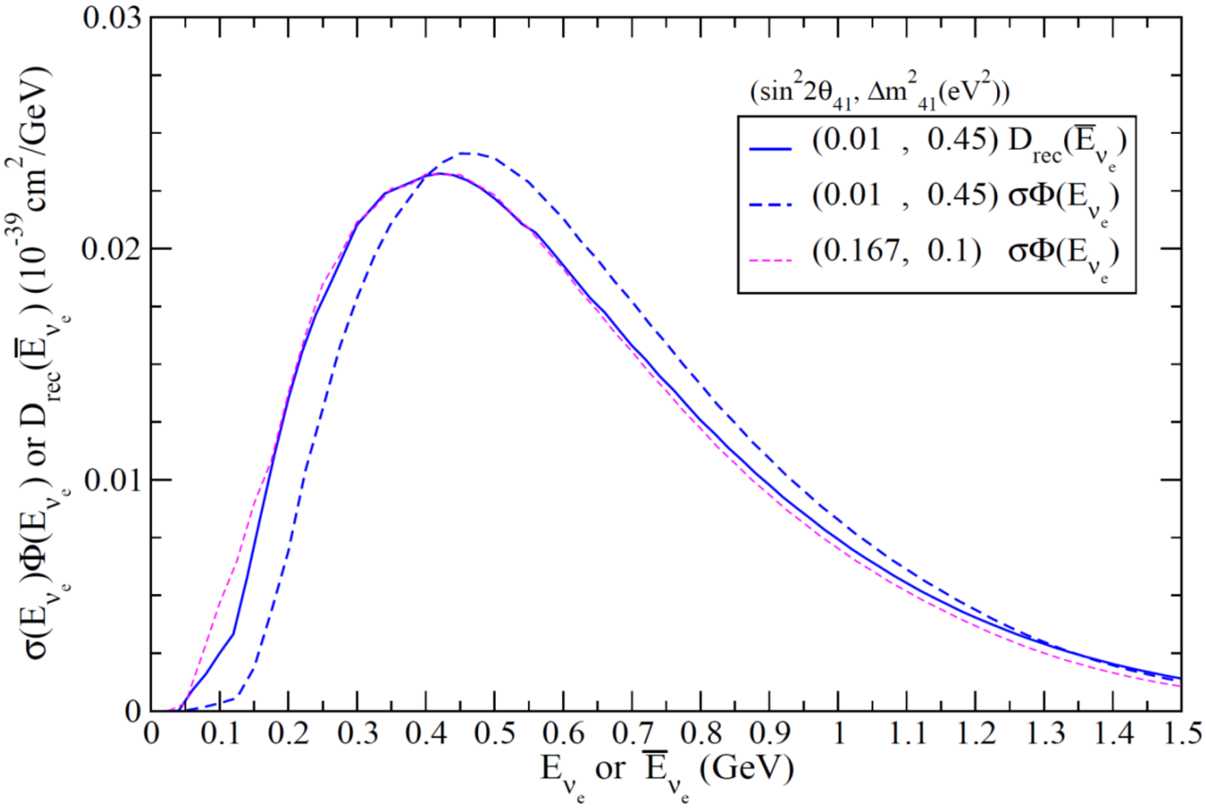


MiniBooNE Anomaly: Excess of events at low energies

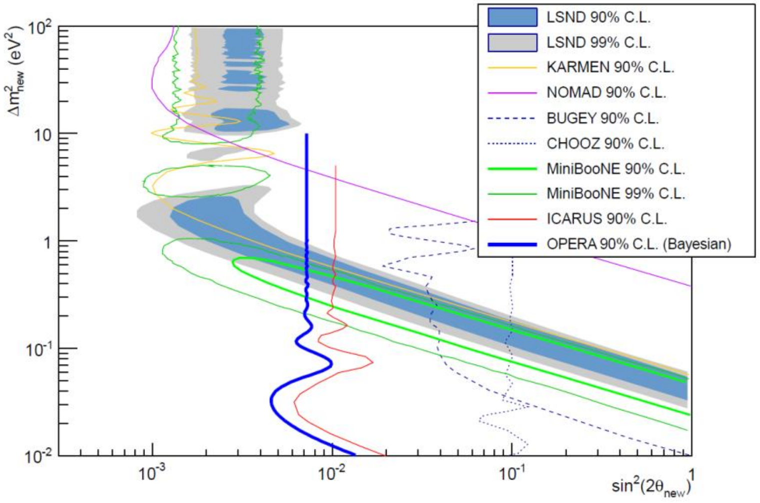
Sterile neutrino??

Taking into account the energy reconstruction correction

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



OPERA, JHEP 1307 (2013) 004, Addendum-ibid. 1307 (2013) 085



A large mass value allows the same quality of fit of data than is obtained in the unsmeared case with a much smaller mass.

The energy reconstruction leads to an increase of the oscillation mass parameters

⇨ **Gain for the compatibility with the existing constraints**

νμ —> νe MiniBooNE

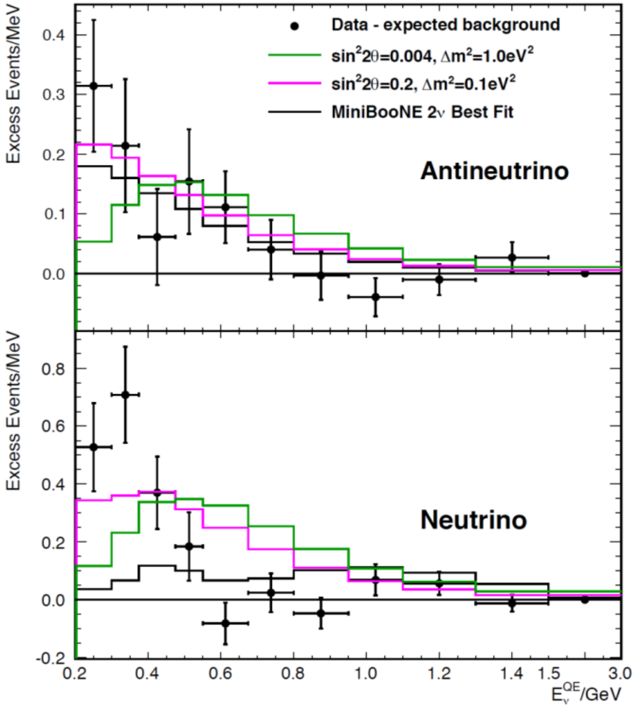


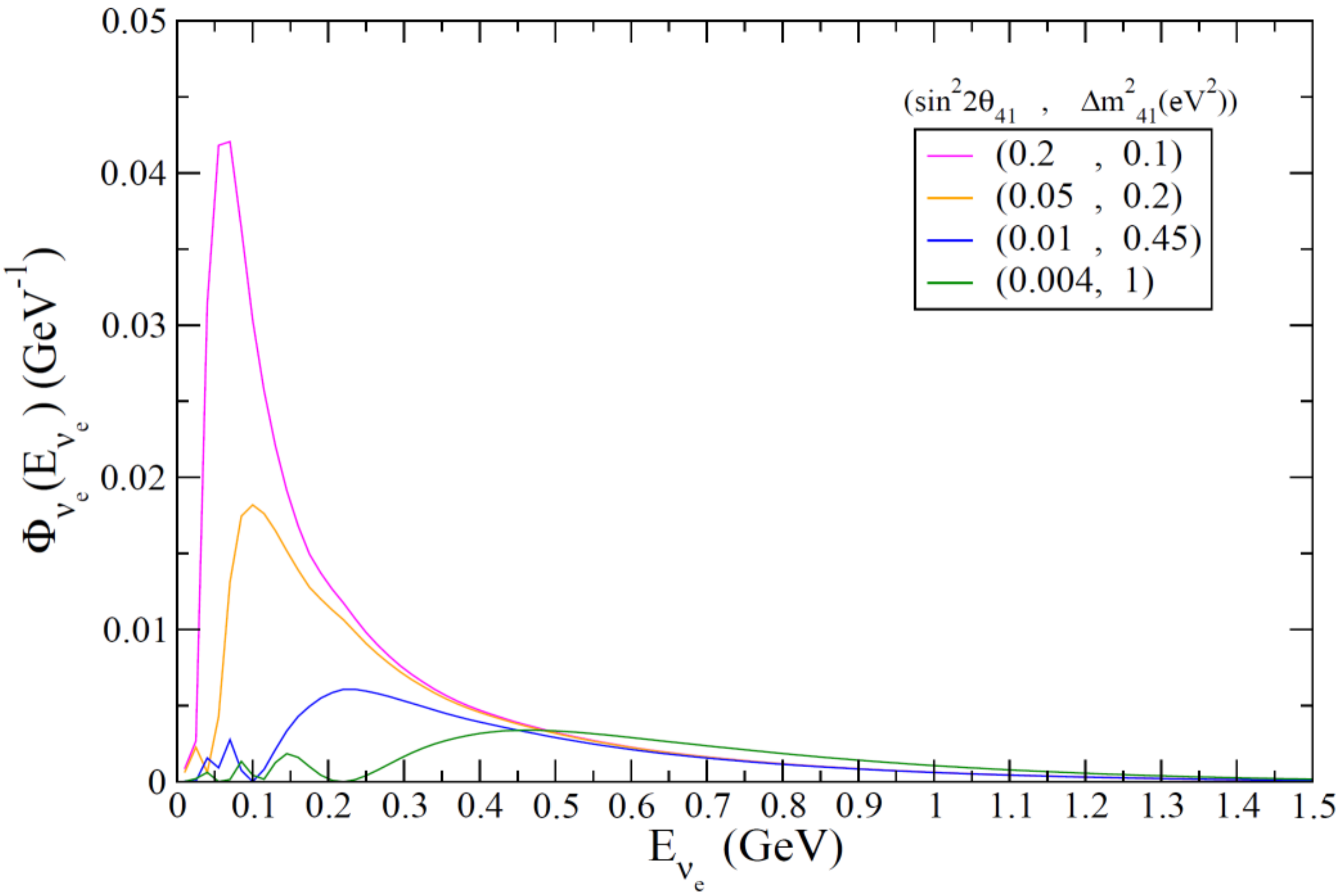
TABLE II: χ^2 *values from oscillation fits to the antineutrino-mode data for different prediction models. The best fit* $(\Delta m^2, \sin^2 2\theta)$ *values are* (0.043 eV^2, 0.88), (0.059 eV^2, 0.64), *and* (0.177 eV^2, 0.070) *for the nominal, Martini, and disappearance models, respectively. The test point* χ^2 *values in the third column are for* $\Delta m^2 = 0.5$ eV^2 *and* $\sin^2 2\theta = 0.01$. *The effective dof values are approximately 6.9 for best fits and 8.9 for the test points.*

	χ^2 values	
Prediction Model	Best Fit	Test Pt.
Nominal $\bar{\nu}$−mode Result	5.0	6.2
Martini *et al.* [25] Model	5.5	6.5
Model With Disapp. (see text)	5.4	6.7

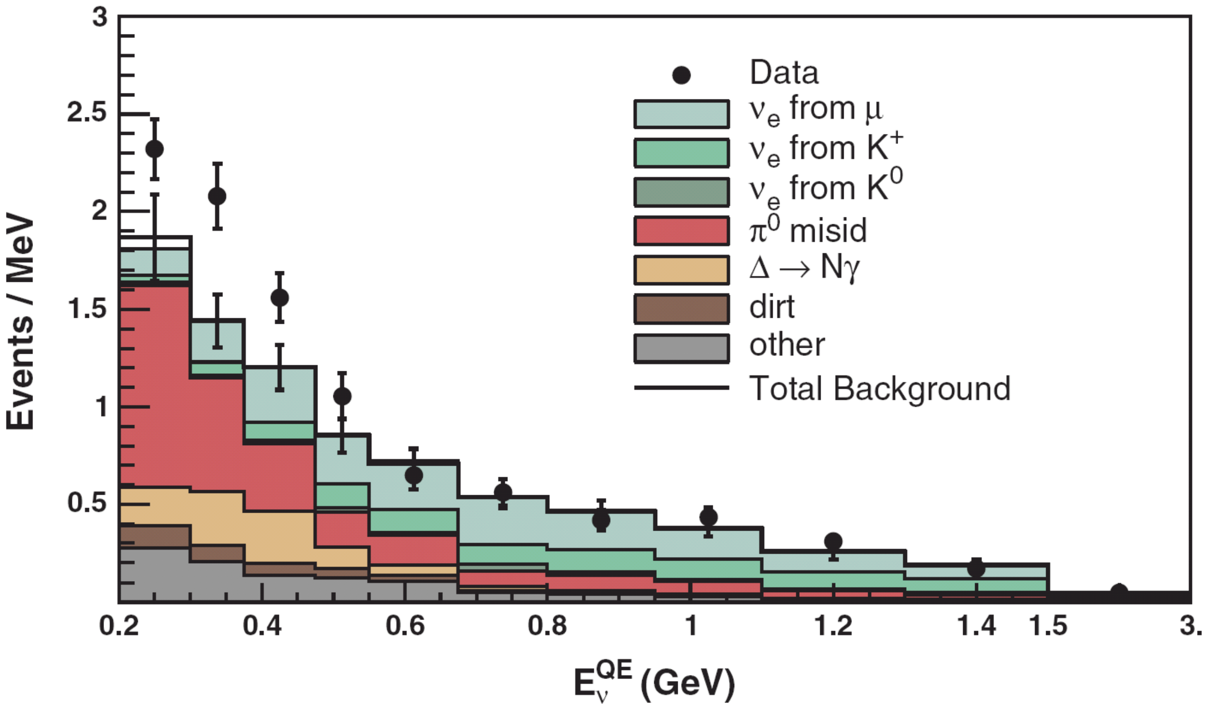
Phys.Rev.Lett. 110 (2013) 161801

Oscillations induced by sterile neutrino; 3+1 hypothesis

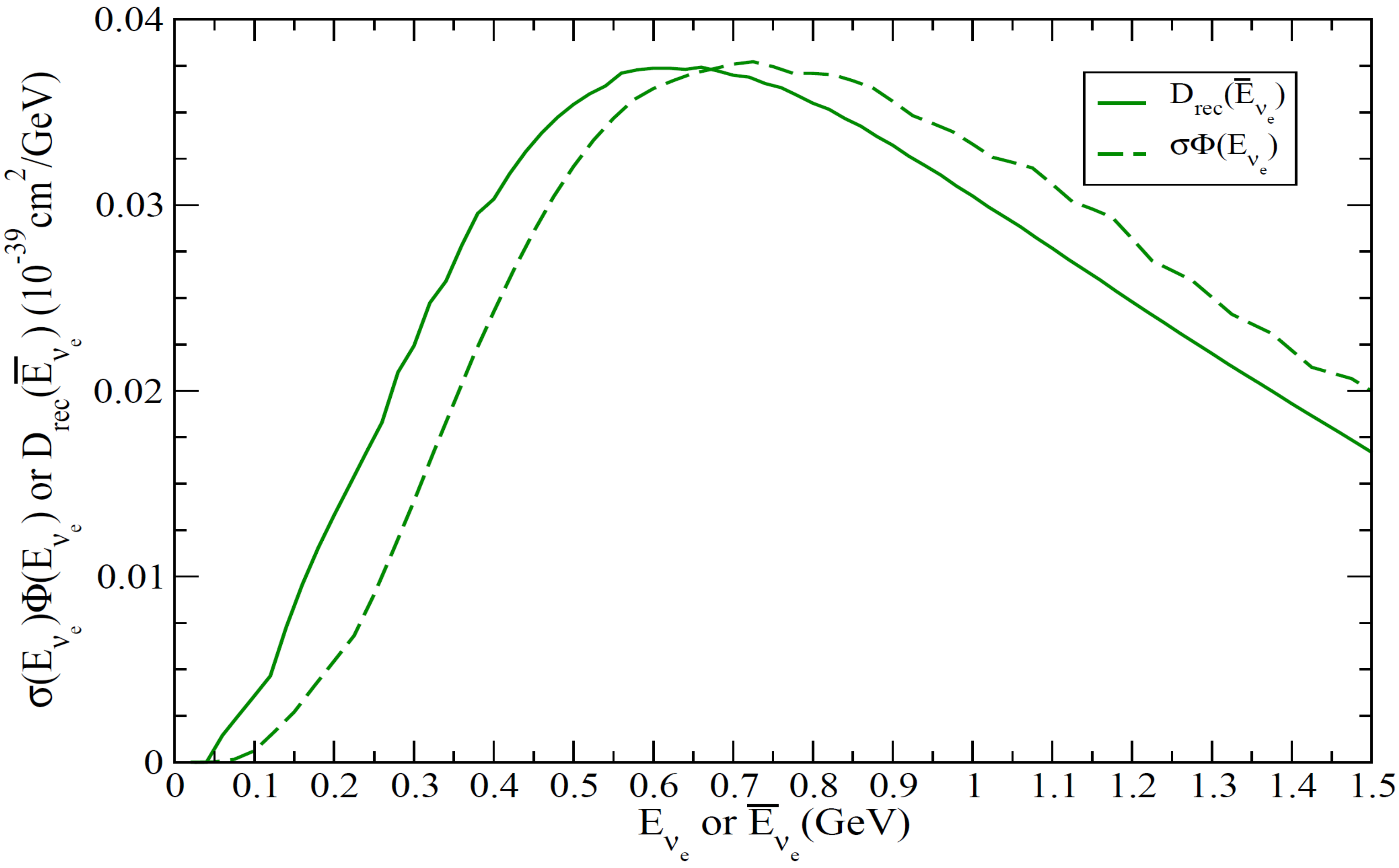
$$\Phi_{\nu_e}(E_{\nu_e}) = \Phi_{\nu_\mu}(E_{\nu_\mu})\sin^2(2\theta_{41})\sin^2\left(\frac{\Delta m_{41}^2 L}{4E_\nu}\right)$$



ν_e background
and
effective cross sections

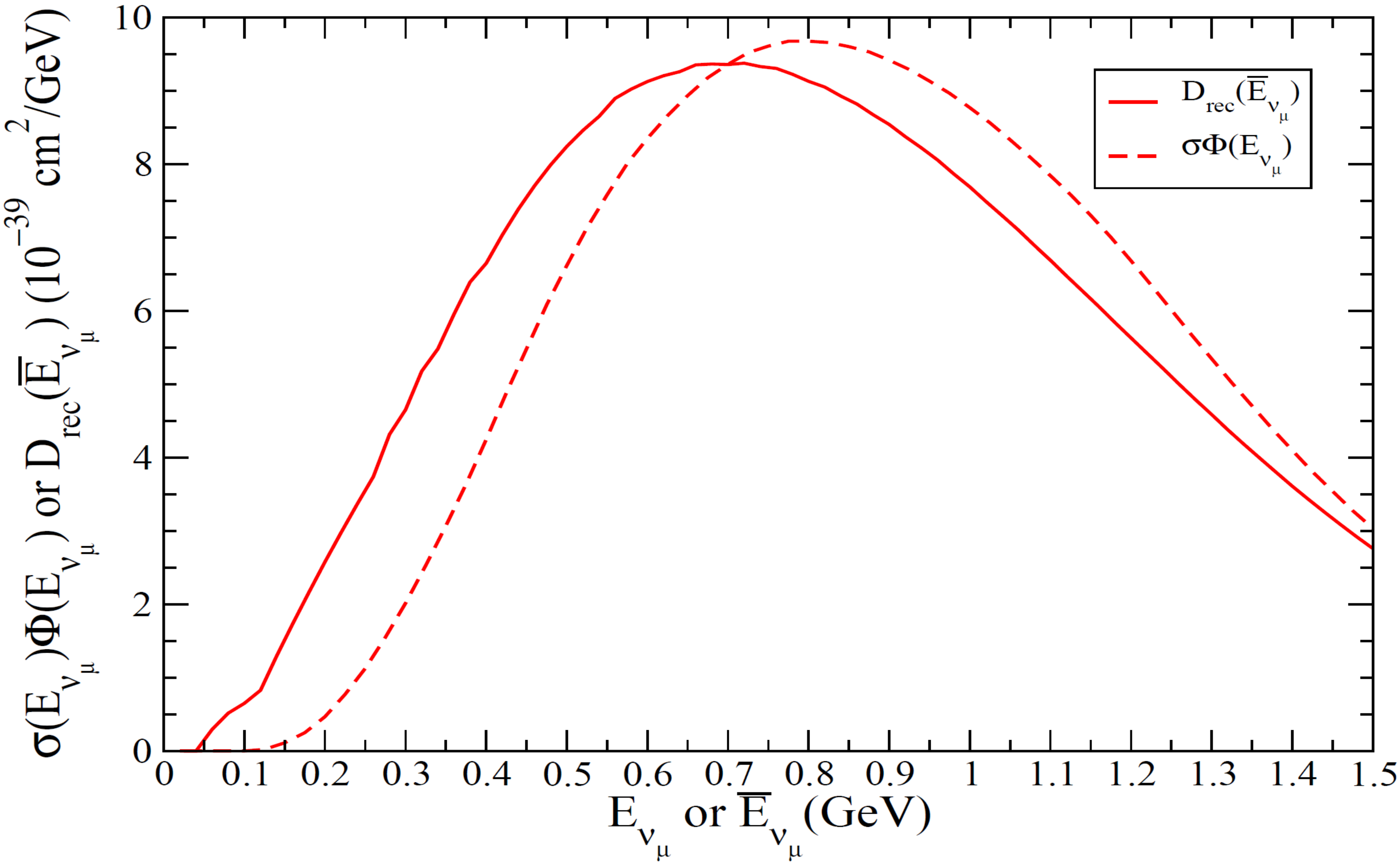


MiniBooNE electron events distribution for νe background



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

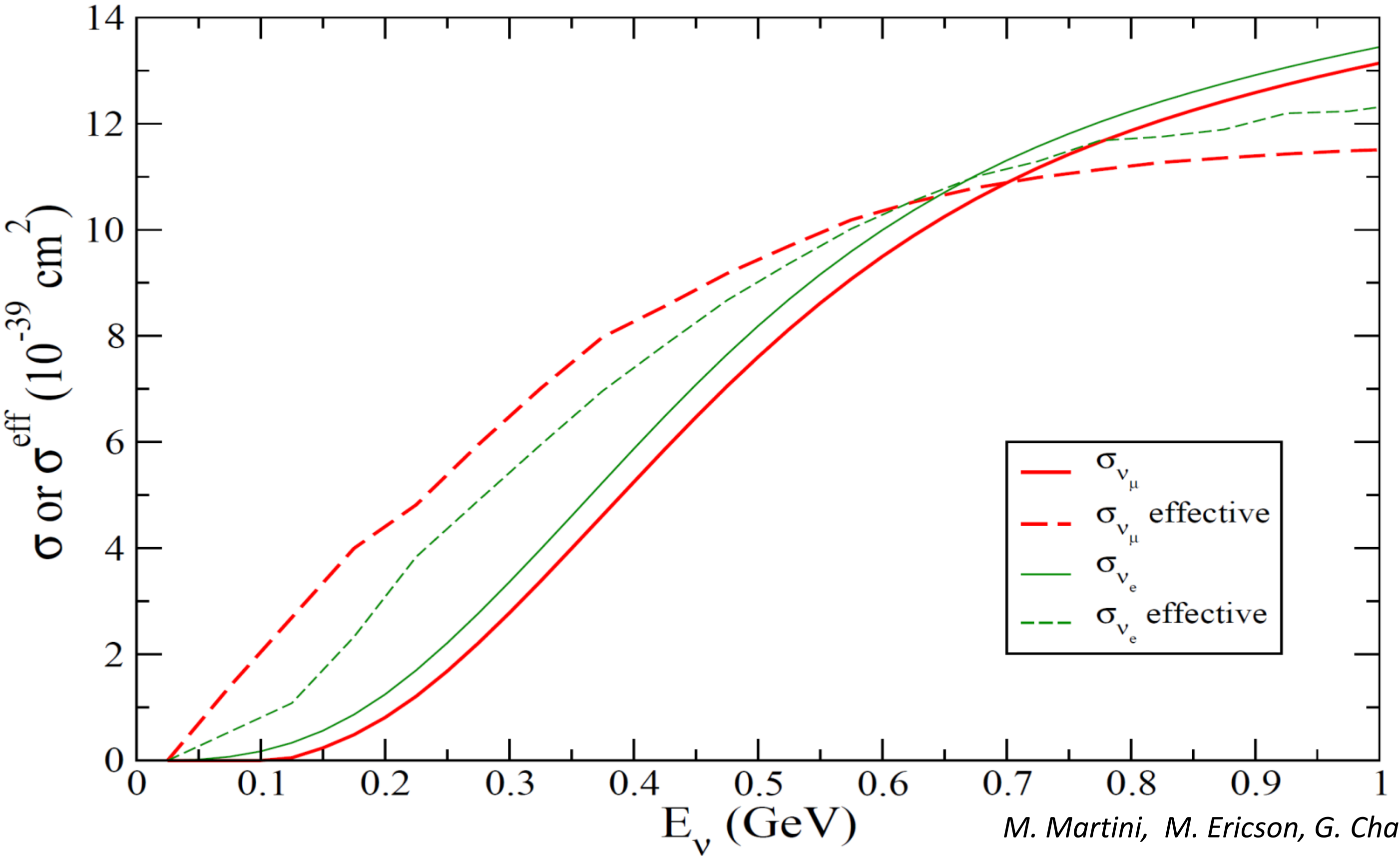
MiniBooNE muon events distribution



Real and effective cross sections for ν_μ and ν_e

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

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

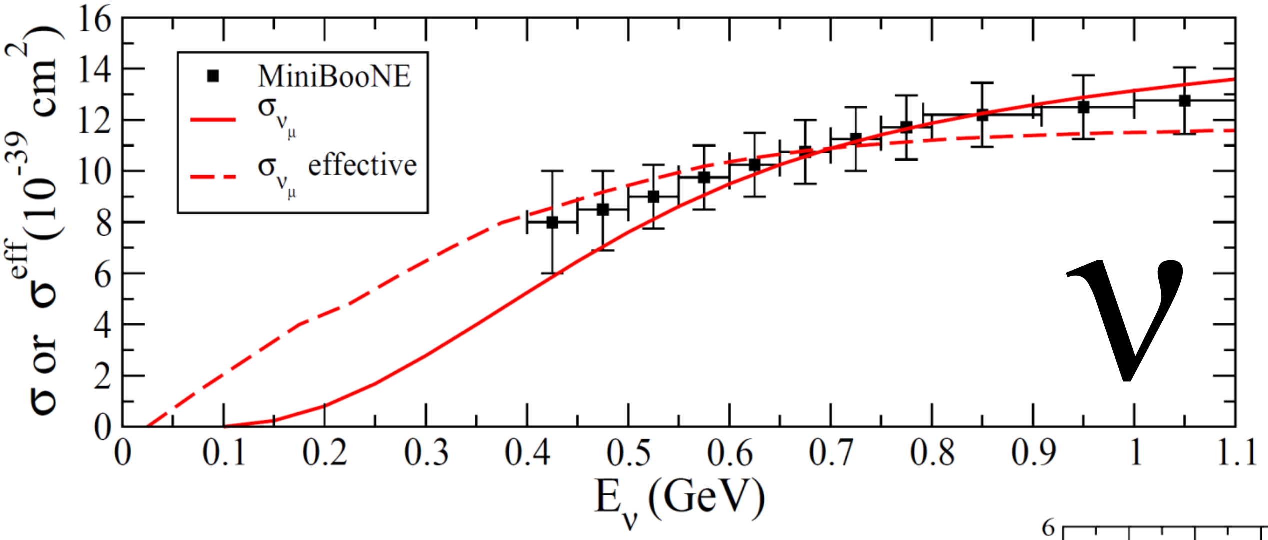


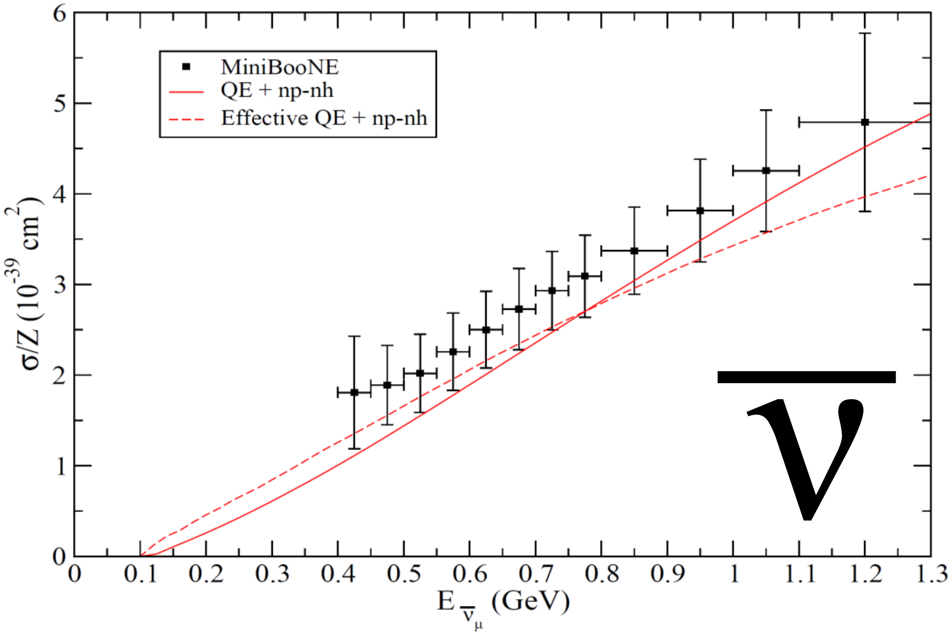
M. Martini, M. Ericson, G. Chanfray, PRD 87 013009 (2013)

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

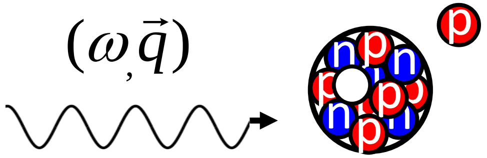
(here we used ν_μ and ν_e MiniBooNE fluxes)

Real and effective cross sections for μ





Genuine Quasielastic Scattering



Nucleon-Nucleon interaction switched off

Nucleons respond individually

Nucleon at rest:

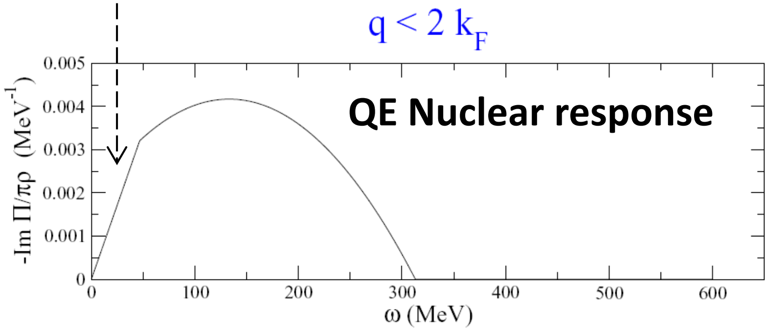
$$R\alpha\ \delta\left(\omega-\left(\sqrt{q^{2}+M^{2}}-M\right)\right)$$

Nucleon inside the nucleus:

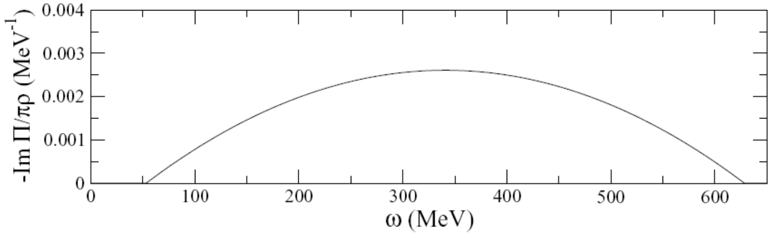
Fermi motion spreads δ distribution (Fermi Gas)

Pauli blocking cuts part of the low momentum Resp.

$q < 2\ k_F$



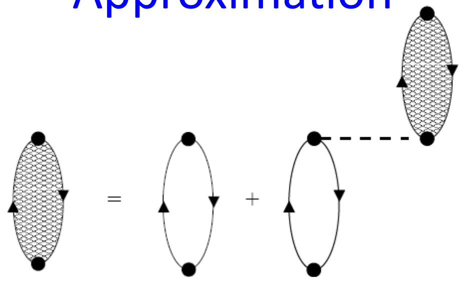
$q > 2\ k_F$



Nucleon-Nucleon interaction switched on

The nuclear response becomes collective

Random Phase Approximation

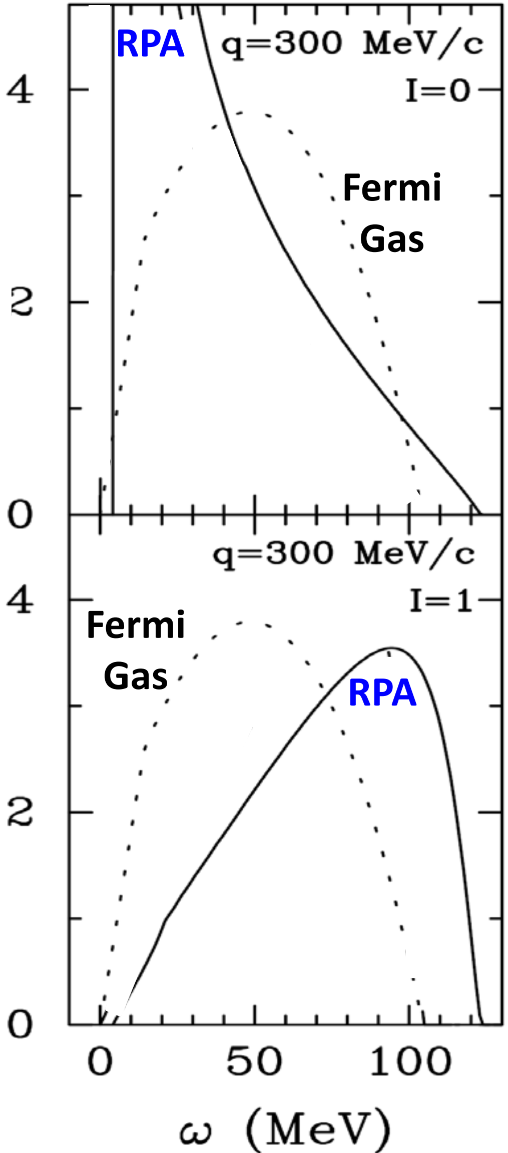


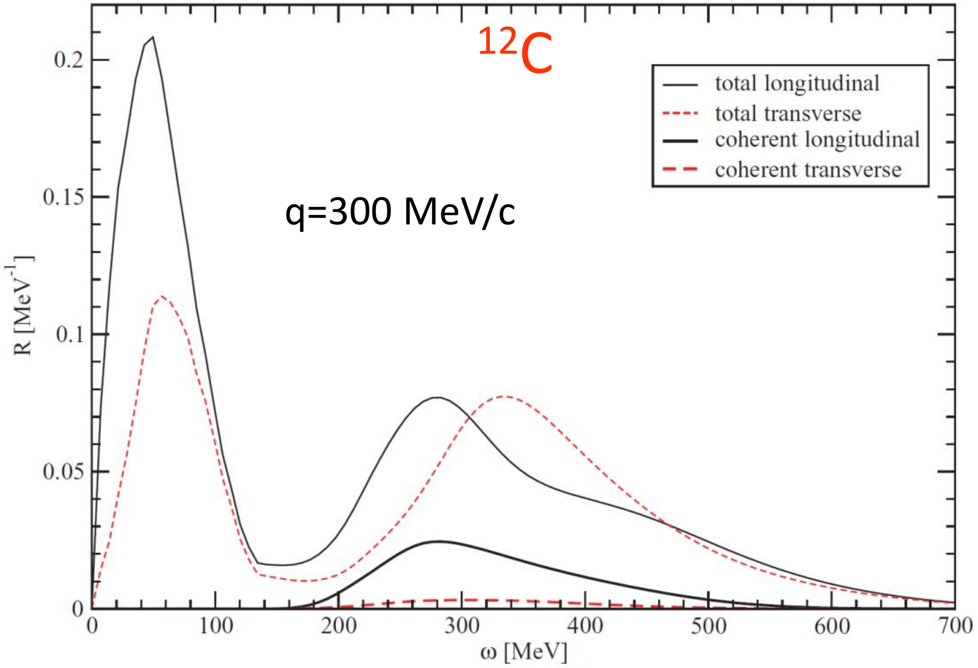
$$\Pi = \Pi^{0} + \Pi^{0}\, V\, \Pi$$

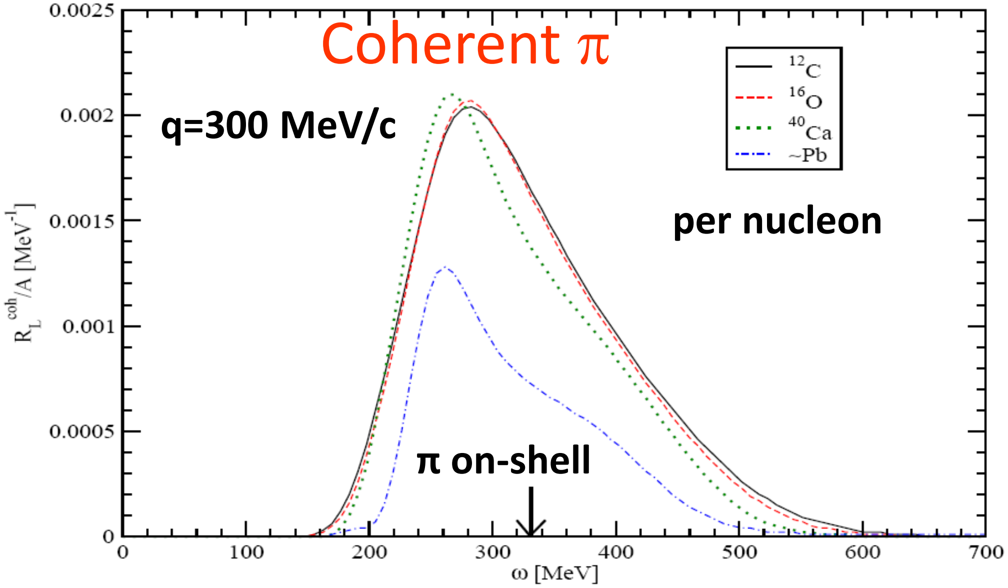
*Force acting on one nucleon is transmitted by the interaction

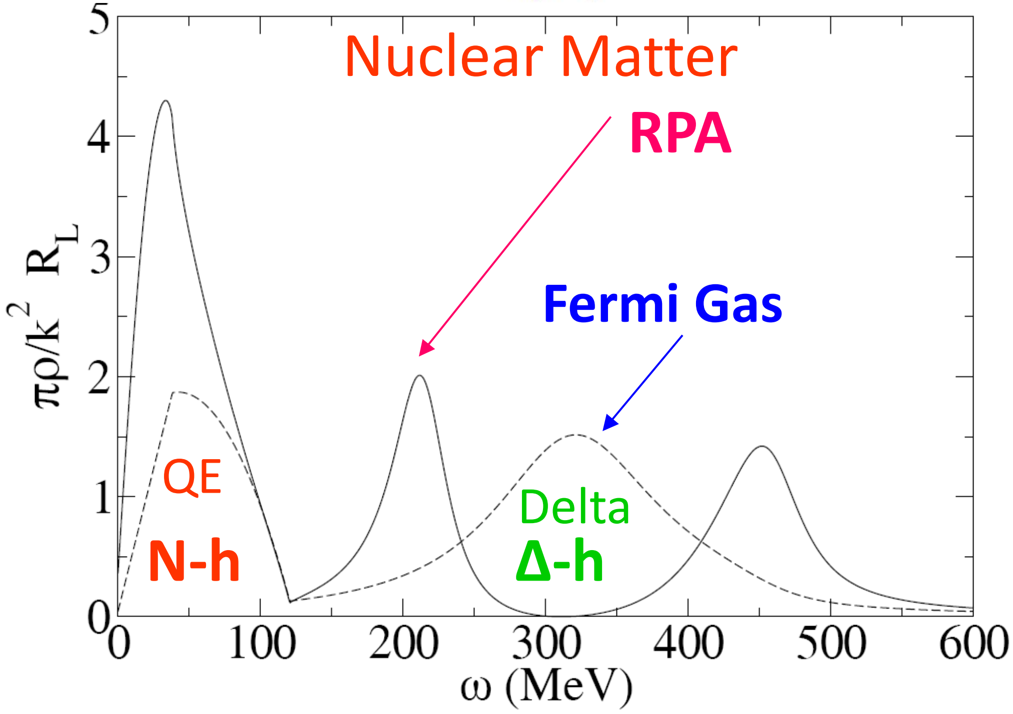
*Shift of the peak with respect to Fermi Gas, decrease, increase,…

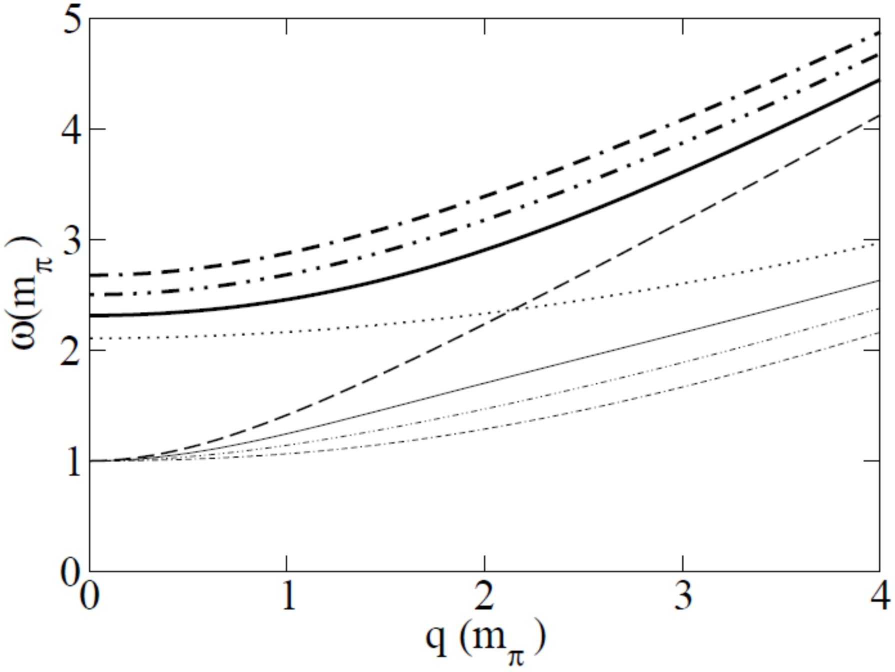
Alberico, Ericson, Molinari, Nucl. Phys. A 379, 429 (1982)




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


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





Details: p-h effective interaction

$$\begin{aligned} V_{NN} &= (f' + V_\pi + V_\rho + V_{g'})\, \boldsymbol{\tau}_1 . \boldsymbol{\tau}_2 \\ V_{N\Delta} &= (V_\pi + V_\rho + V_{g'})\, \boldsymbol{\tau}_1 . \boldsymbol{T}^\dagger_2 \\ V_{\Delta N} &= (V_\pi + V_\rho + V_{g'})\, \boldsymbol{T}_1 . \boldsymbol{\tau}_2 \\ V_{\Delta\Delta} &= (V_\pi + V_\rho + V_{g'})\, \boldsymbol{T}_1 . \boldsymbol{T}^\dagger_2 . \end{aligned}$$

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

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

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

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

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

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

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

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

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