# Neutrino Cross Sections: theoretical models

Marco Martini

# Neutrino - nucleus cross sections and neutrino oscillations

- Neutrino oscillation experiments require the determination of the neutrino energy which enters the expression of the oscillation probability

e.g.

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{4 \boxed{E_\nu}} \right)$$

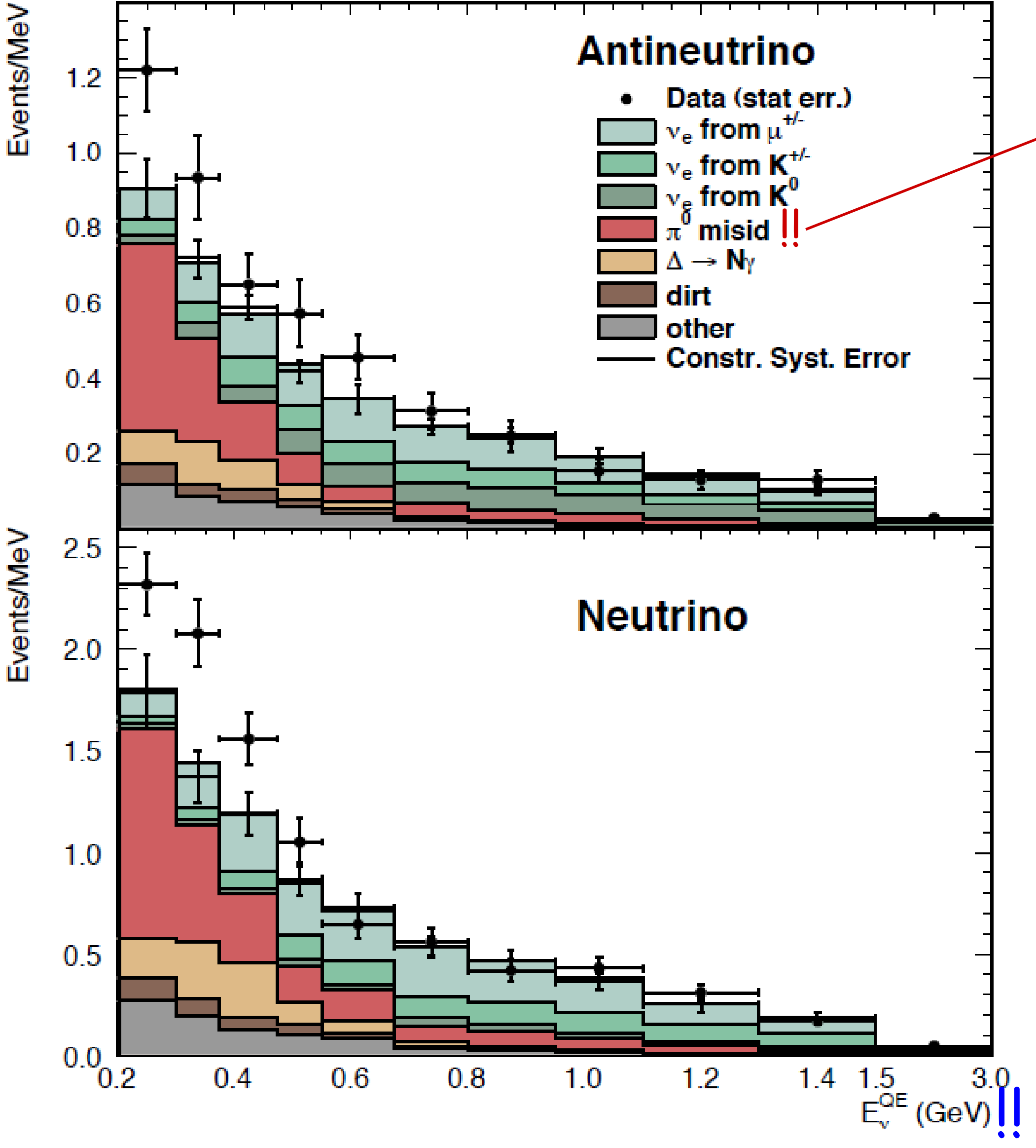
- Modern neutrino oscillation experiments use nuclear targets (C, O, Ar, Fe…)

- Nuclear effects play a crucial role

# $\nu_\mu \rightarrow \nu_e$

MiniBooNE

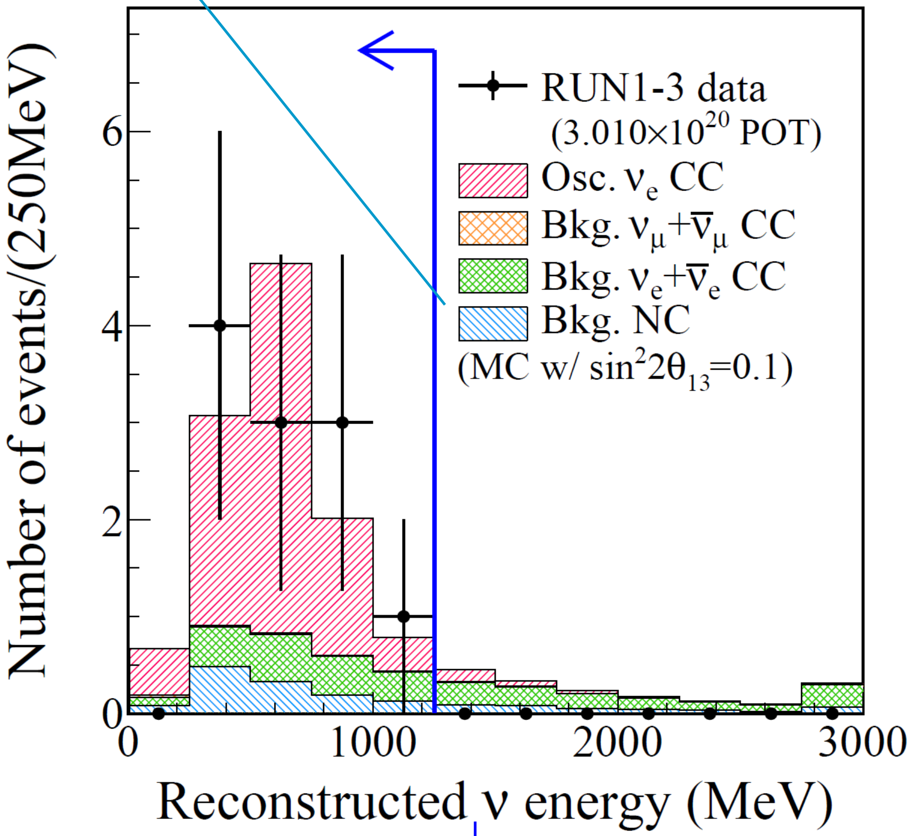
Phys.Rev.Lett. 110 (2013) 161801



NC $\pi^0$ important background

Phys.Rev. D88 (2013) 032002

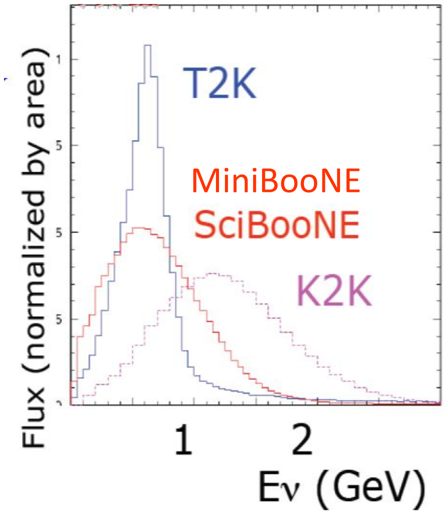
T2K

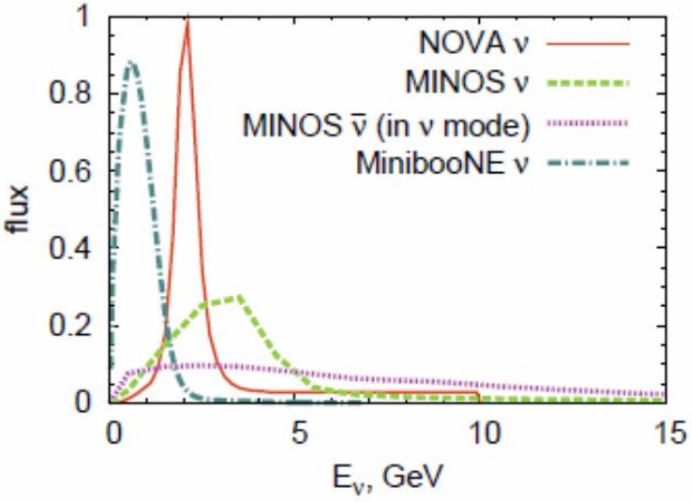


$E_\nu$ reconstructed through quasielastic events

# Some crucial points

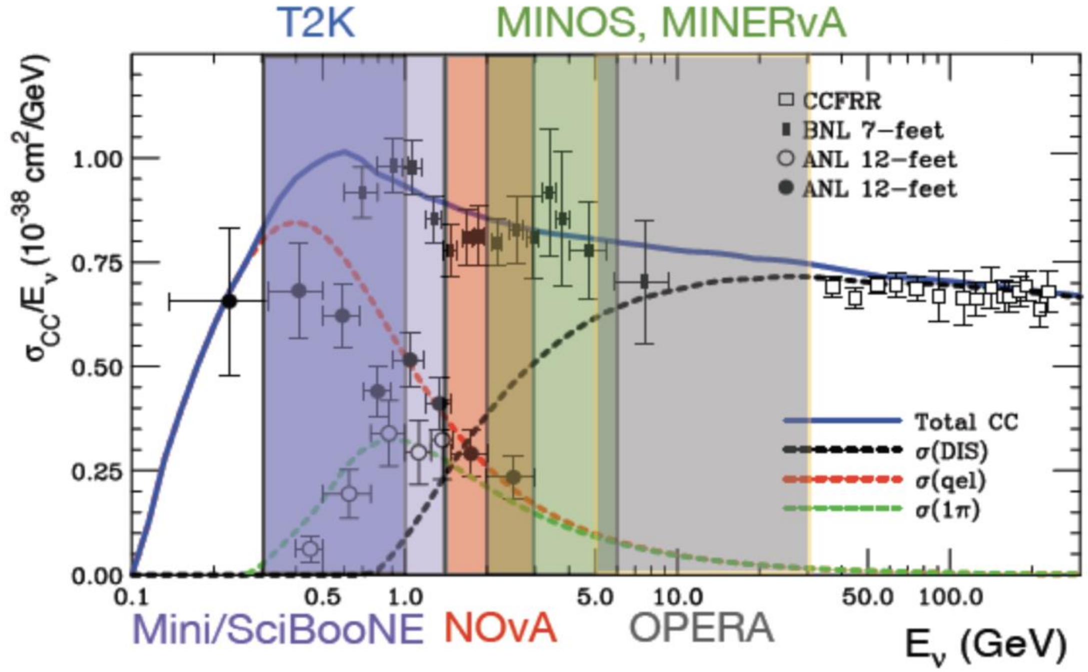
- Neutrino beams are not monochromatic
  (at difference with respect to electron beams).
  They span a wide range of energies





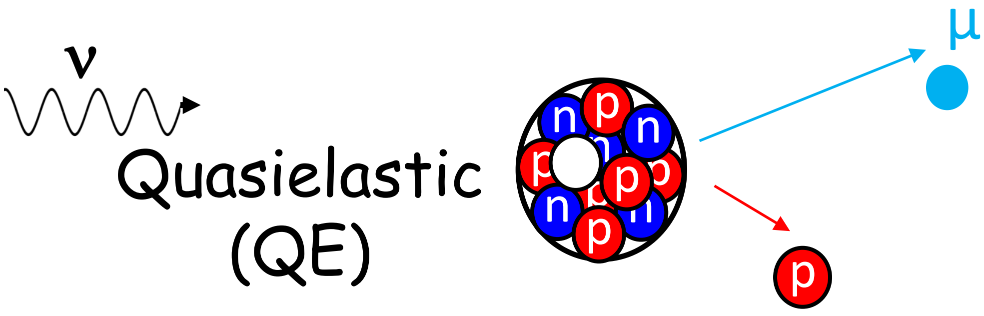
- The neutrino energy is reconstructed
  from the final states of the reaction
  (typically from CC Quasielastic events)

- Different reaction mechanisms
  contribute to the cross section
  in the modern experiments



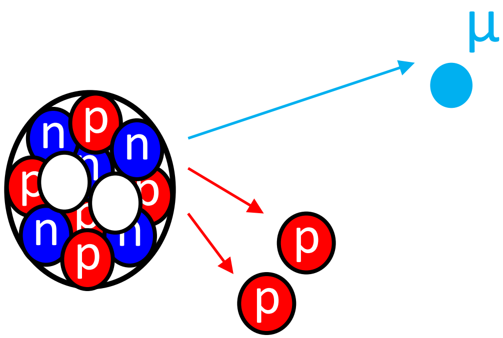
# Neutrino - nucleus interaction @ $E_\nu \sim O$ (1 GeV)

[MiniBooNE, T2K energies]

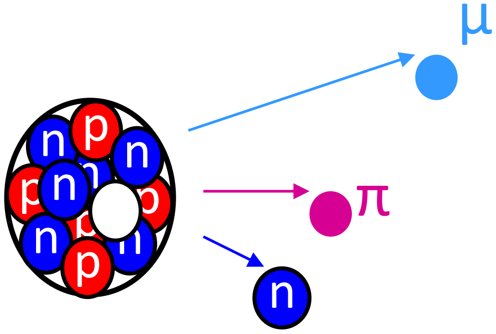


Quasielastic (QE)

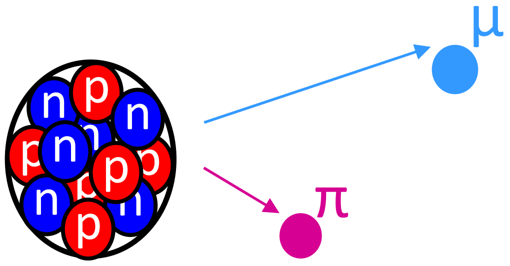
Two Nucleons knock-out (2p-2h)



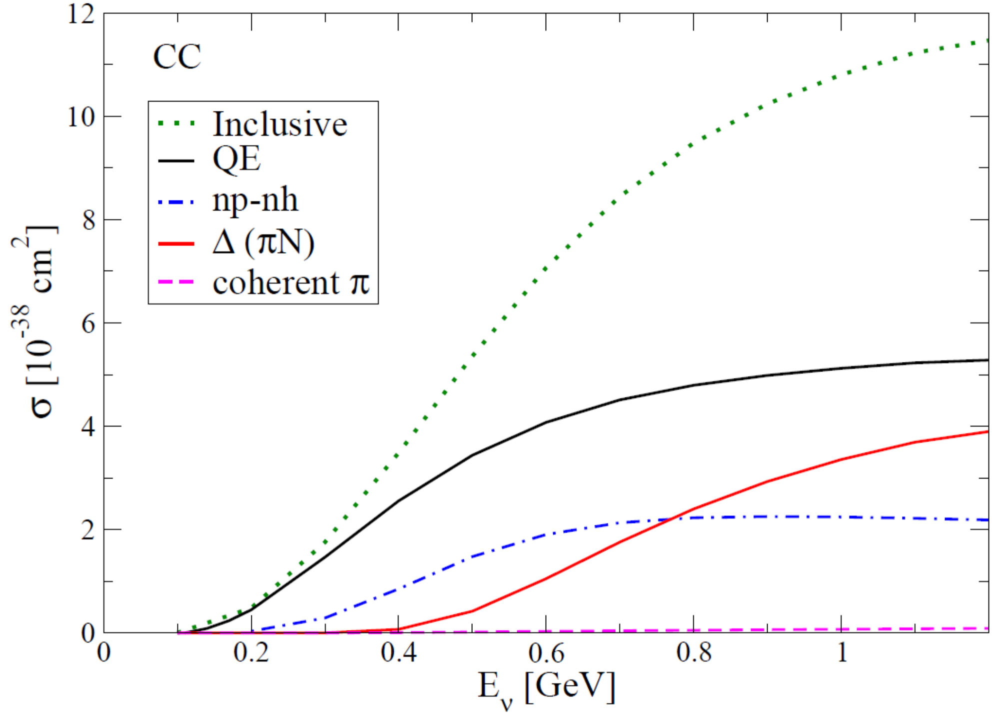
Incoherent π production



Coherent π production



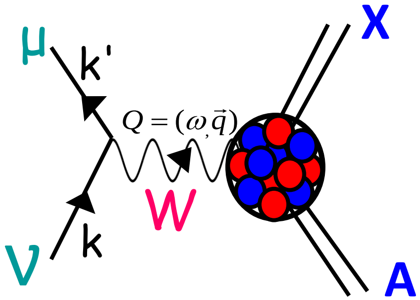
*M. Martini, M. Ericson, G. Chanfray, J. Marteau, PRC 80 065501 (2009)*



Different processes are entangled

# Neutrino-nucleus cross section

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



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

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

Leptonic tensor

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

Hadronic tensor

The cross section in terms of the response functions:

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

A simplified expression (useful for illustration):

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

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

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

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

# Form Factors

Standard dipole parameterization

**Vector**

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

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

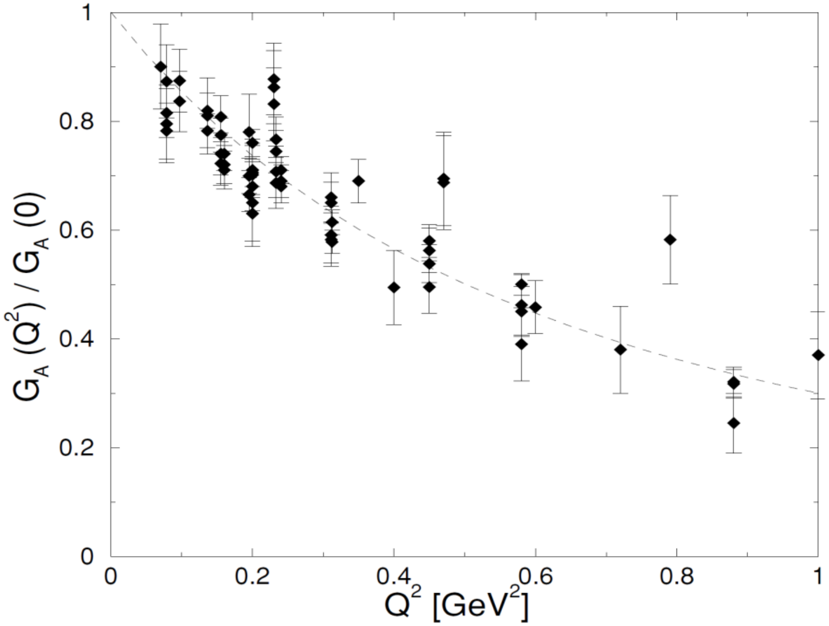
$$M_V = 0.84\,\mathrm{GeV}/c^2$$

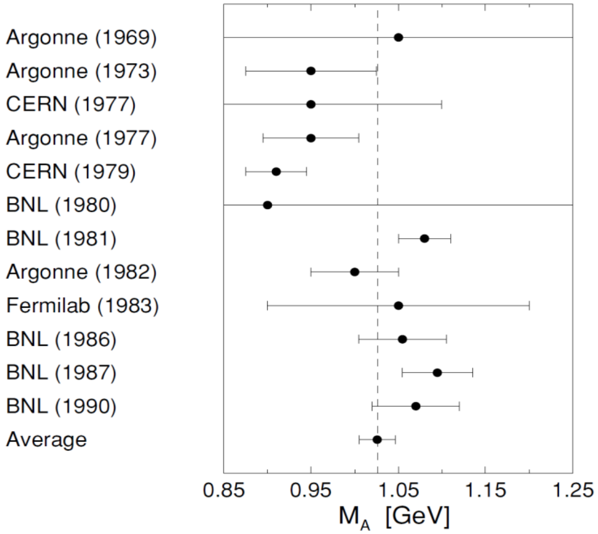
**Axial**

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

$g_A = 1.26$ from neutron β decay

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





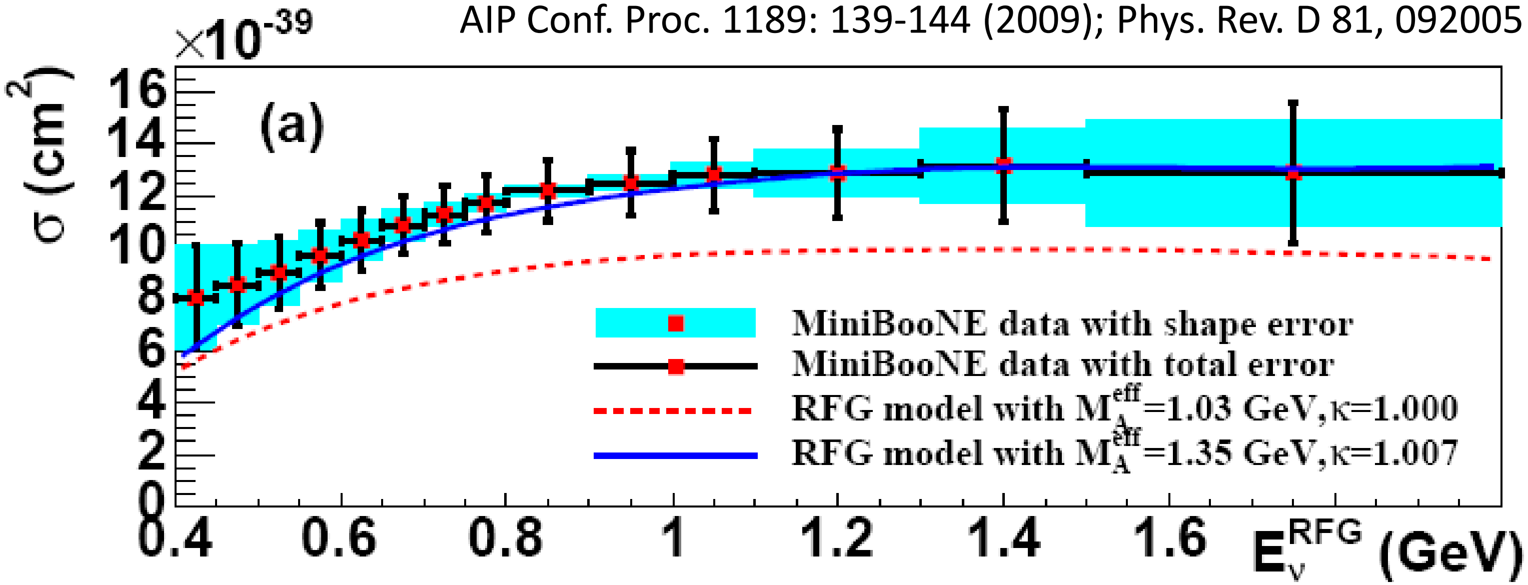
from ν-deuterium CCQE
and
from π electroproduction

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

# Quasielastic

# 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)



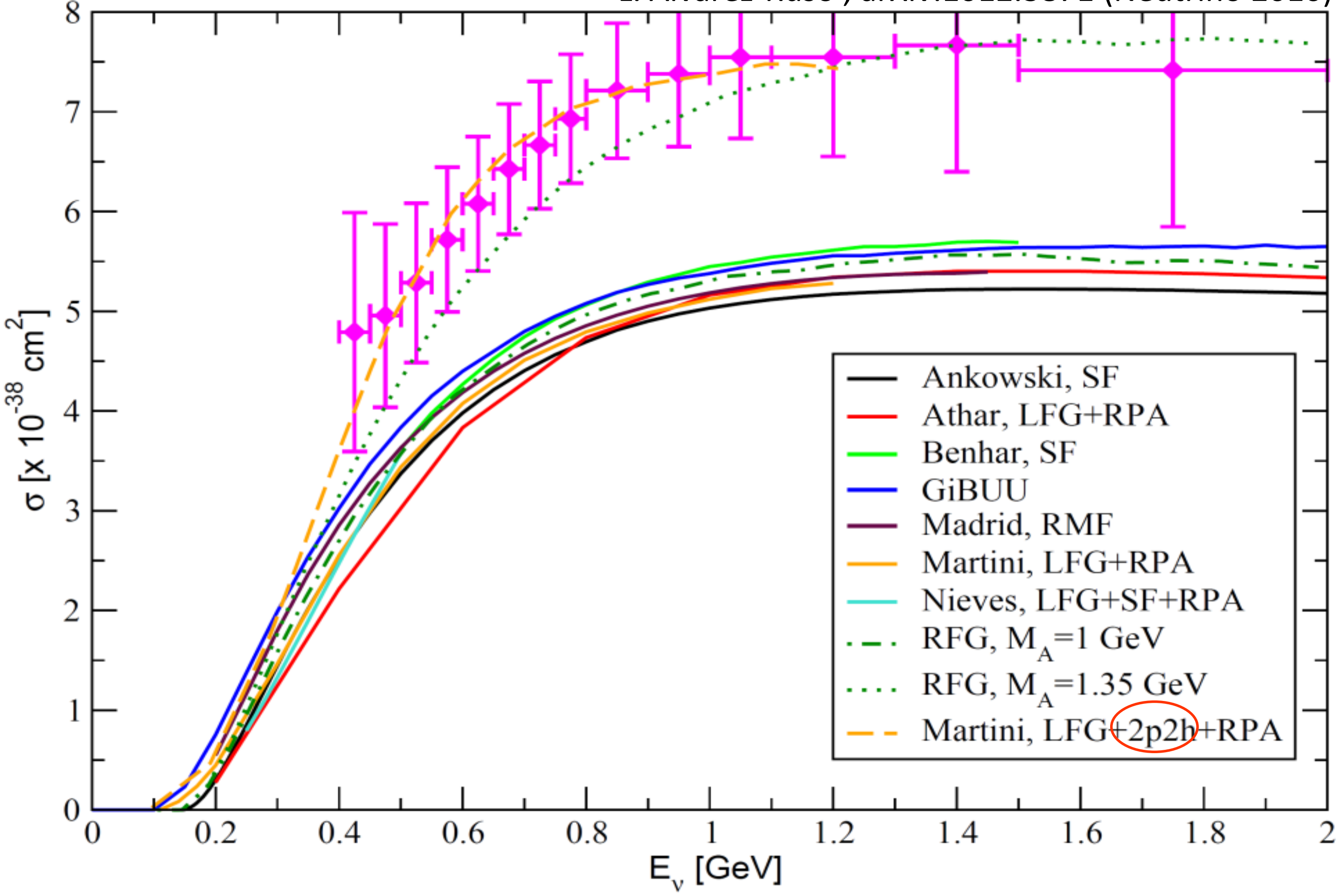
Comparison with a prediction based on RFG using $M_A$=1.03 GeV (standard value) reveals a discrepancy

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??**

# 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

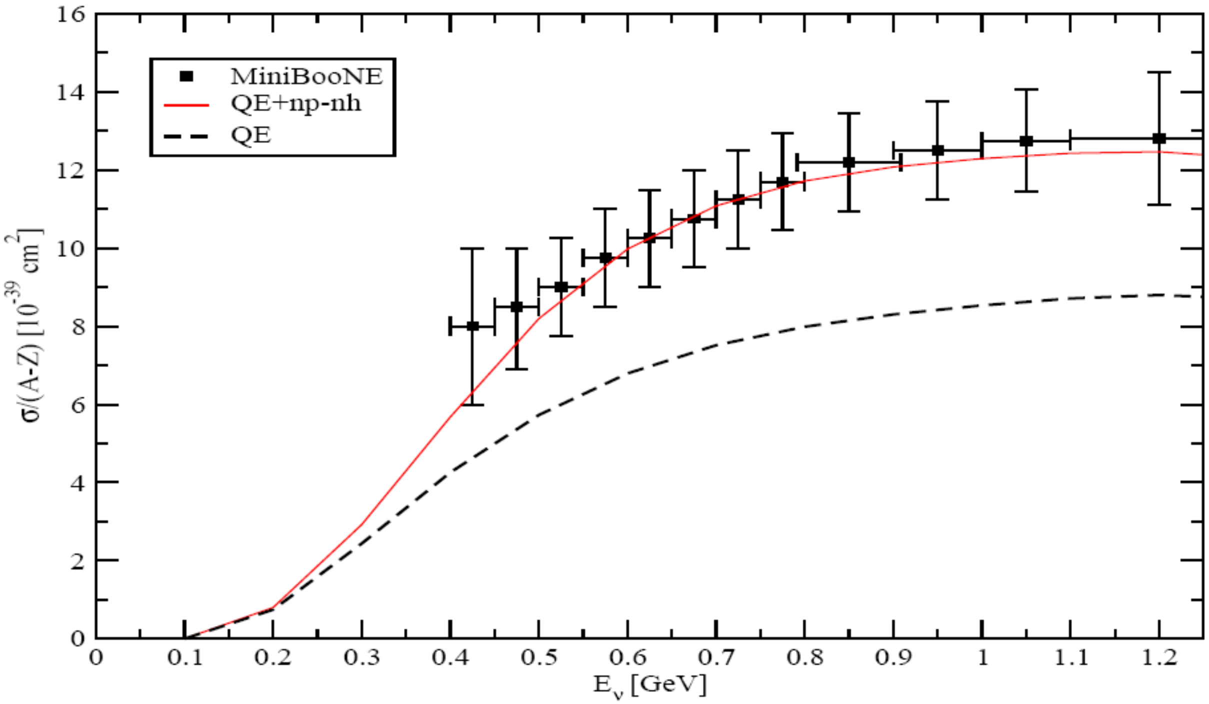
GiBUU: Transport Equation

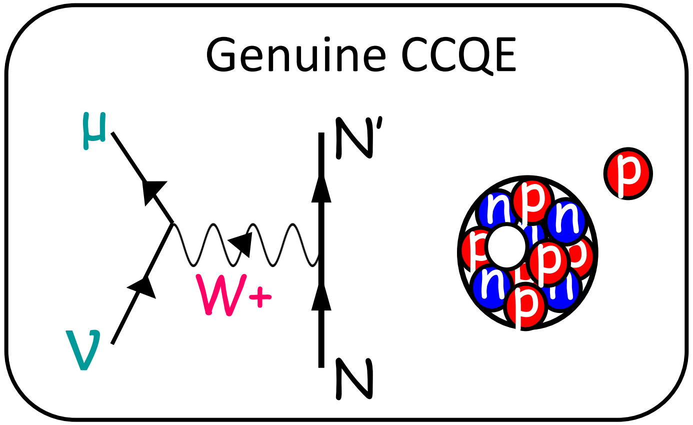
Comparison of models and Monte Carlo:
Boyd, Dytman, Hernandez, Sobczyk, Tacik ,
AIP Conf.Proc. 1189 (2009) 60-73

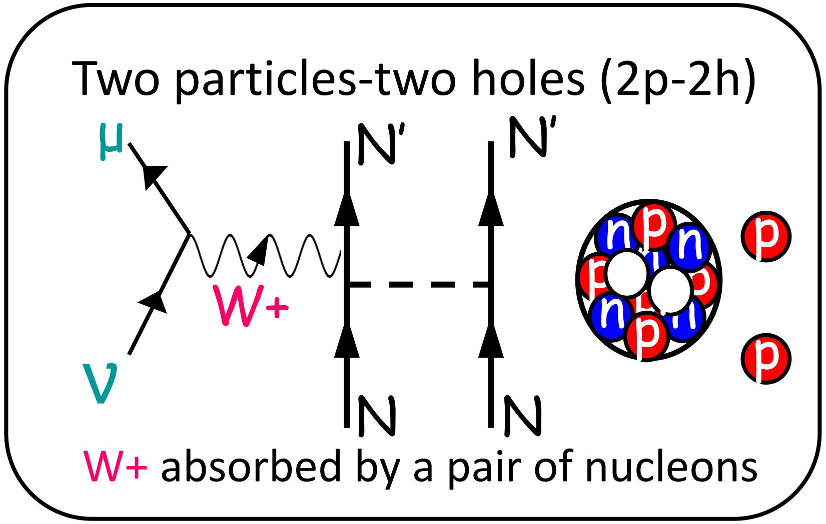
**puzzle??**

# An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)



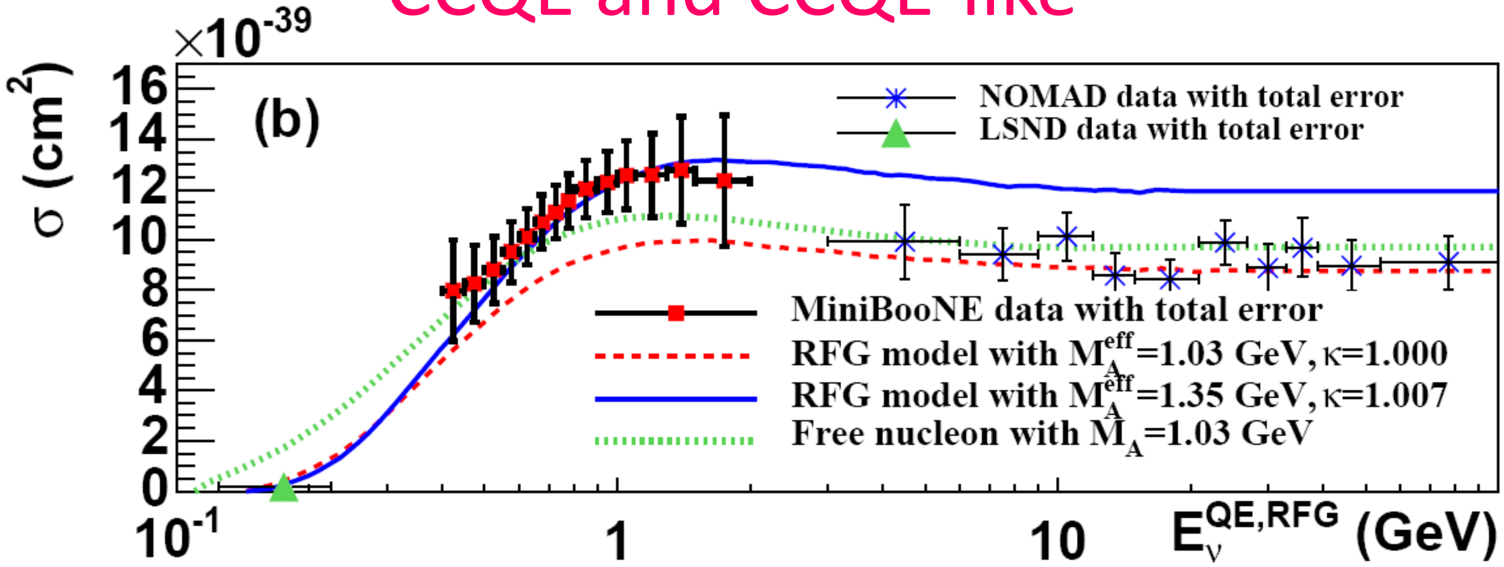


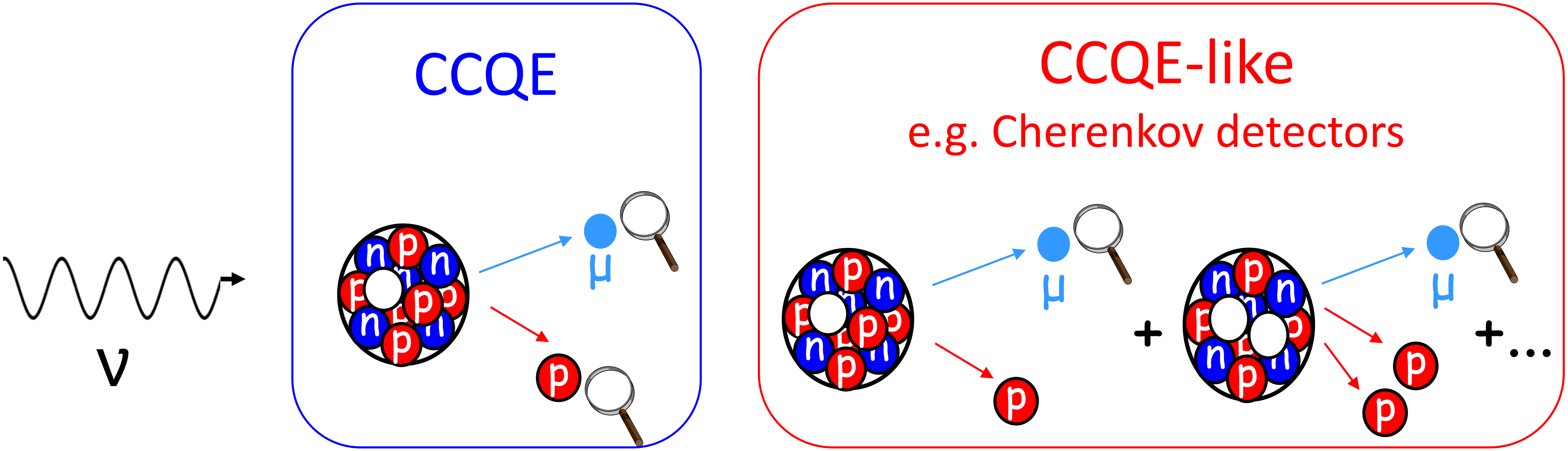


*M. Martini, M. Ericson, G. Chanfray, J. Marteau  Phys. Rev. C 80 065501 (2009)*

**Agreement with MiniBooNE without increasing $M_A$**

# CCQE and CCQE-like





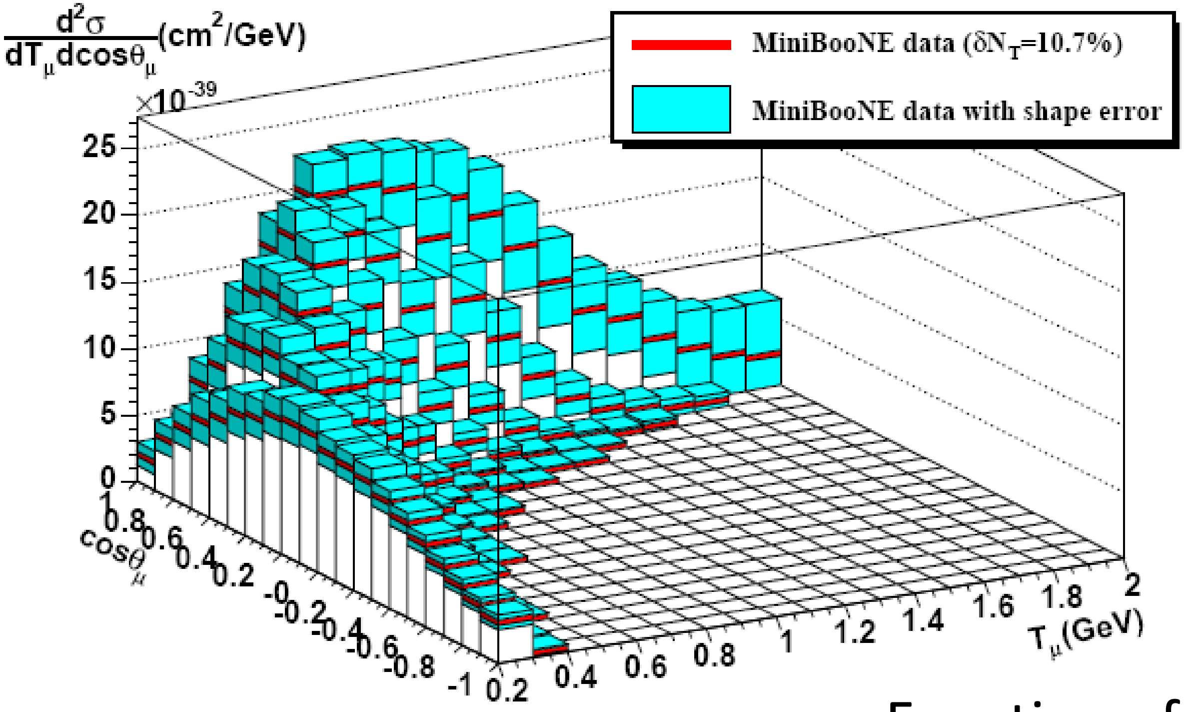
CCQE

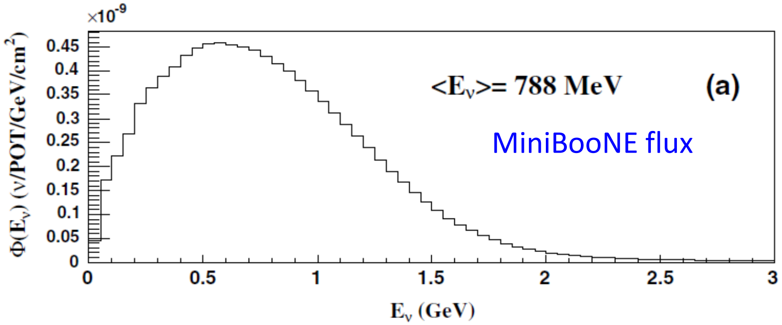
CCQE-like

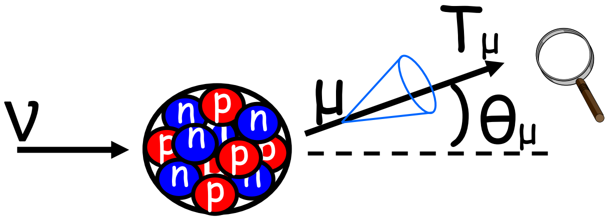
e.g. Cherenkov detectors

# MiniBooNE CCQE-like flux-integrated double differential cross section

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



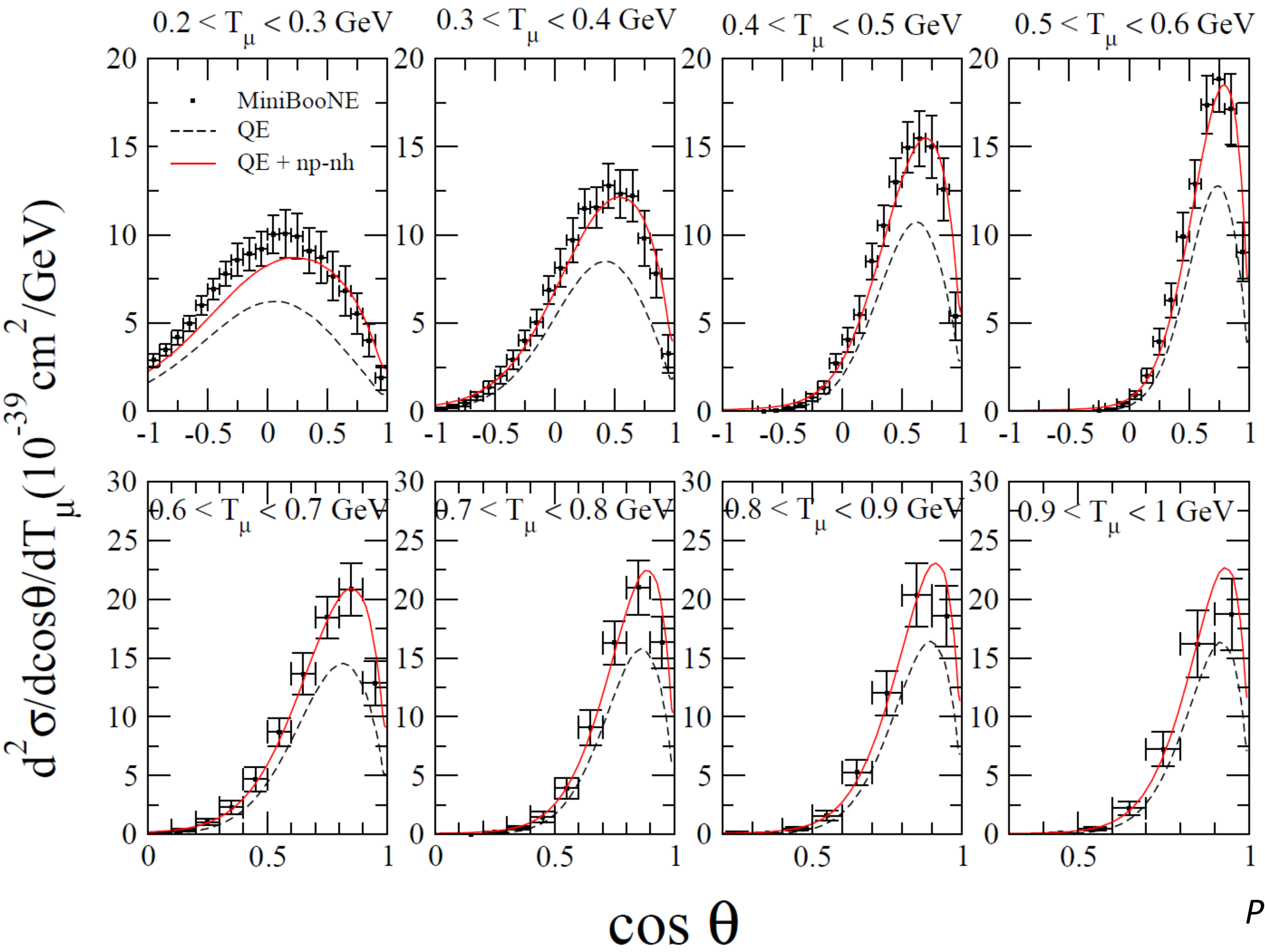




Function of two measured variables

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

# Flux-integrated double differential cross section



**red: including np-nh**

**black: genuine QE**

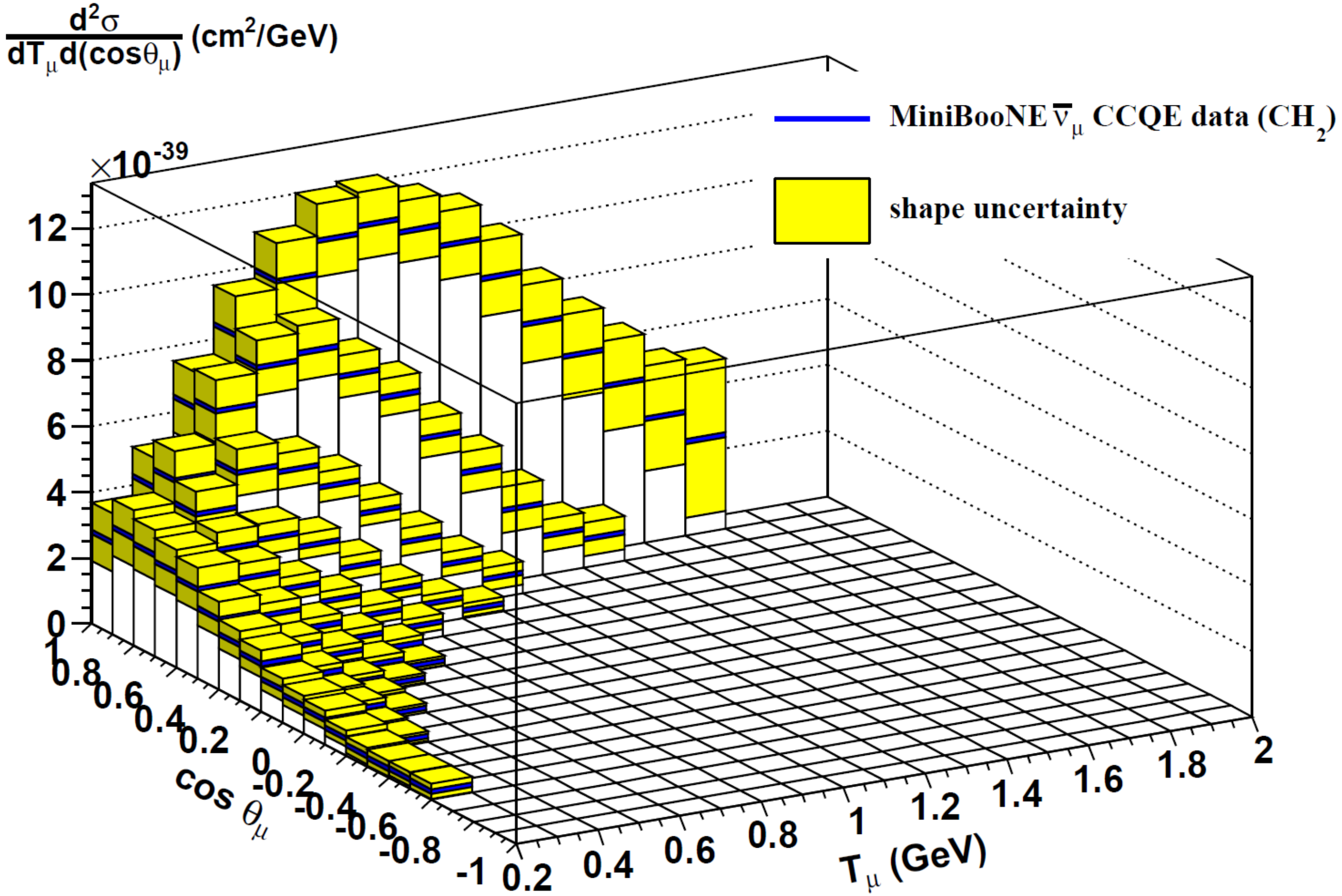
*Martini, Ericson, Chanfray,*
*Phys. Rev. C 84 055502 (2011)*

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

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

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

$\overline{\nu}$

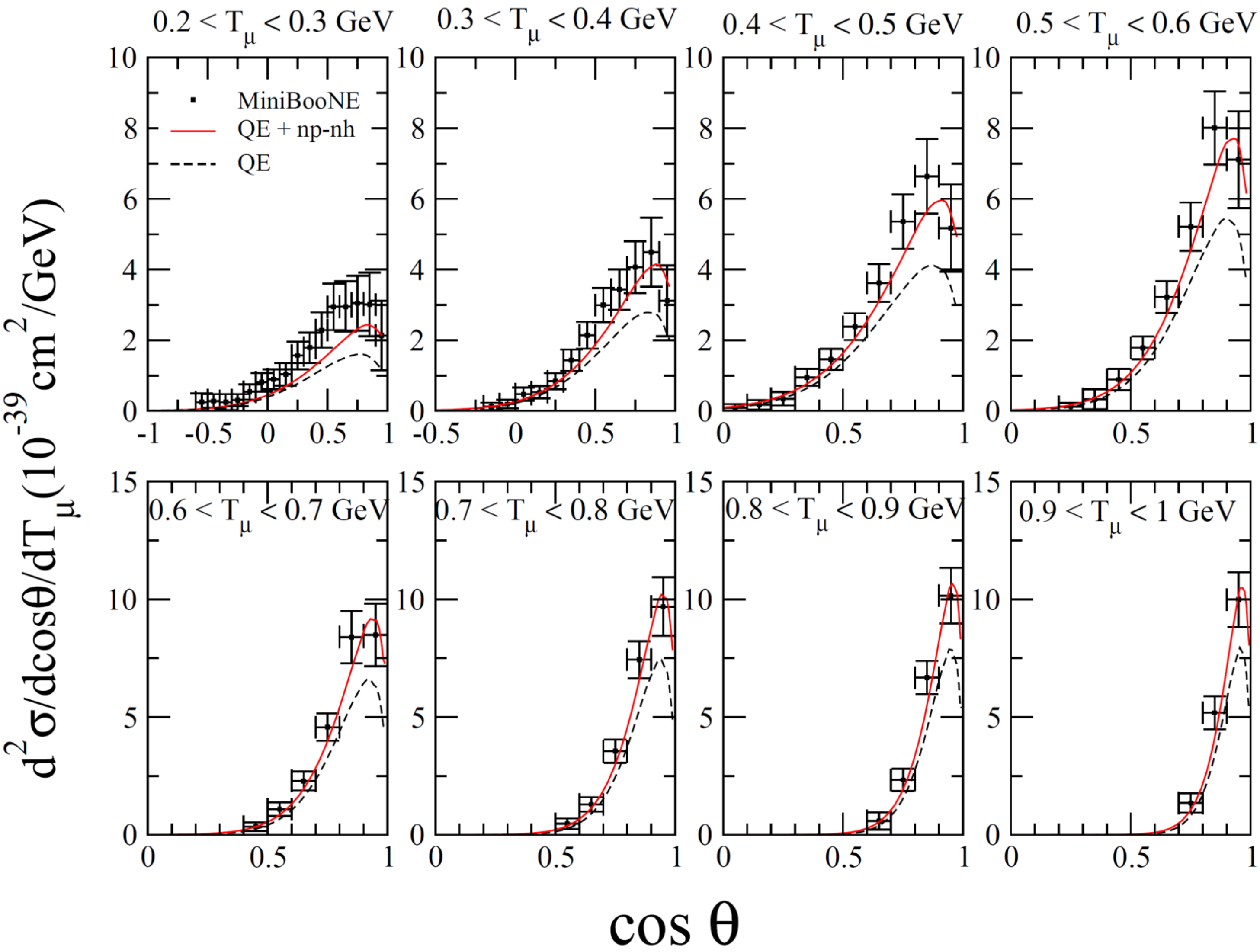


*MiniBooNE, Phys. Rev. D 88 (2013) 032001*

$CH_2$ and Carbon

# Flux integrated double differential cross section

$\overline{\nu}$



**red: including np-nh**

**black: genuine QE**

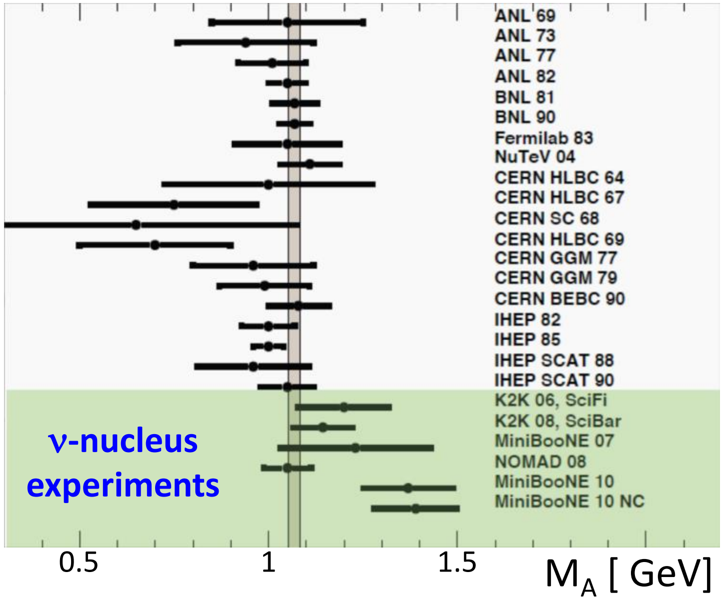
*Martini, Ericson,*
Phys. Rev. C 87 065501 (2013)

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

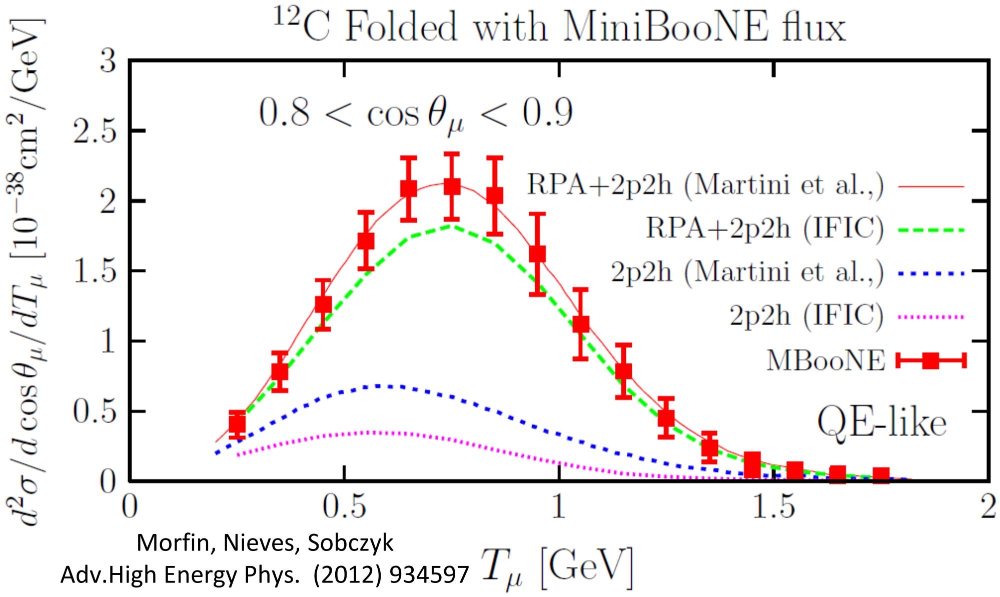
Similar conclusions in *Nieves et al. PLB 721, 90 (2013)*

# The multinucleon emission channel (or np-nh, or 2p-2h)

- A lot of interest in these last years
- Explanation of the axial mass puzzle
- It was not included in the generators used for the analyses of ν cross sections and oscillations experiments
- Today there is an effort to include this np-nh channel in several Monte Carlo



- Several theoretical calculations agree on its crucial role to explain data but there are some differences on the results obtained for this channel



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

[ In the following I will focus essentially on this channel ]

# 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
arXiv 1412.1822 (2014) 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) $\nu$ $\sigma$total, $d^2\sigma$ , $d\sigma/dQ^2$
Phys. Rev. C 86 054606 (2012) impact of np-nh on $\nu$ energy reconstruction and $\nu$ oscillation

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

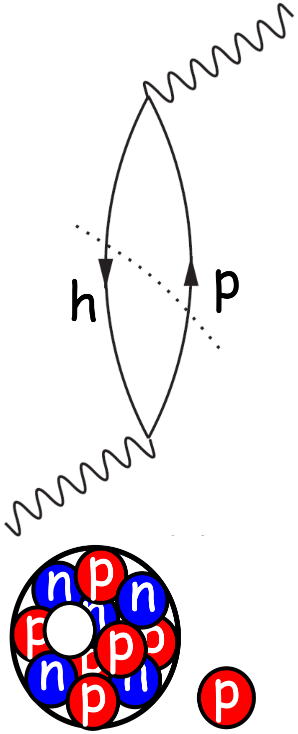
EPJ C 71 1726 (2011) $\nu$ and anti$\nu$ $\sigma$total, $d\sigma/dQ^2$

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

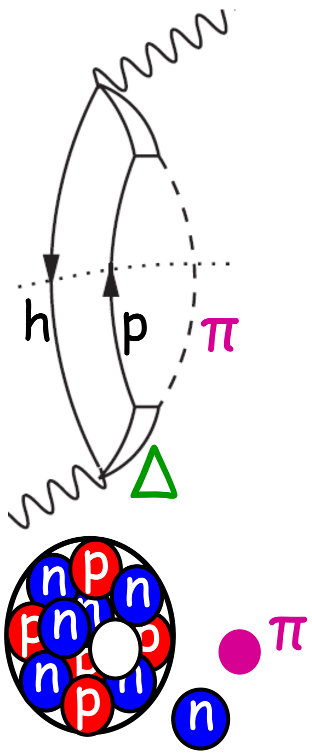
# Some theoretical details

# Nuclear Response Functions

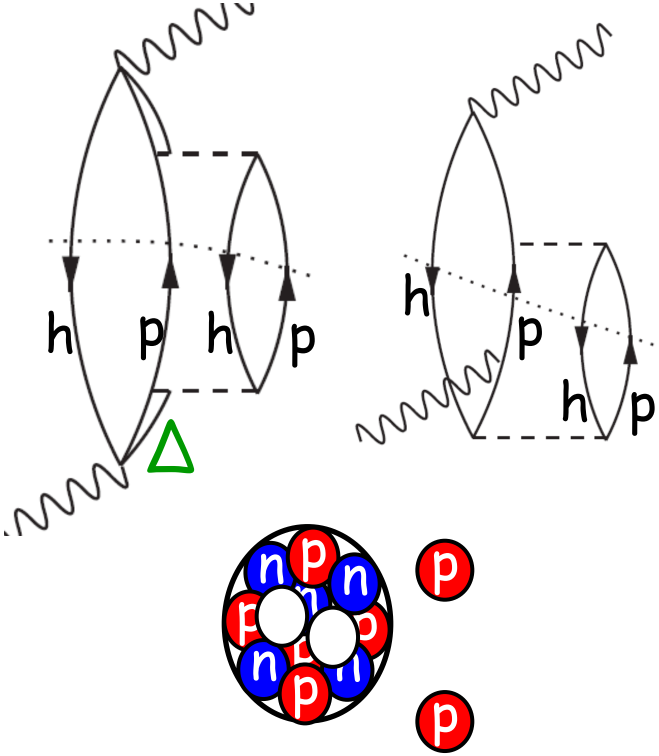
1p-1h
QE



1p-1h
1π production



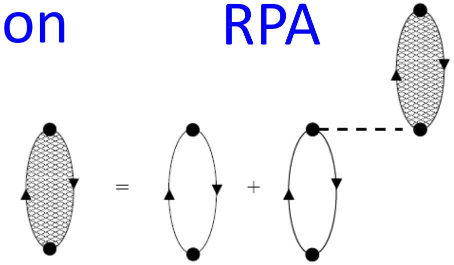
2p-2h:
two examples



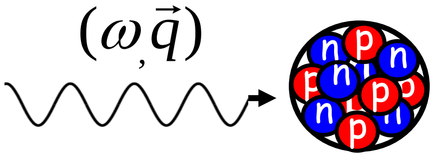
Nuclear response in Random Phase Approximation

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

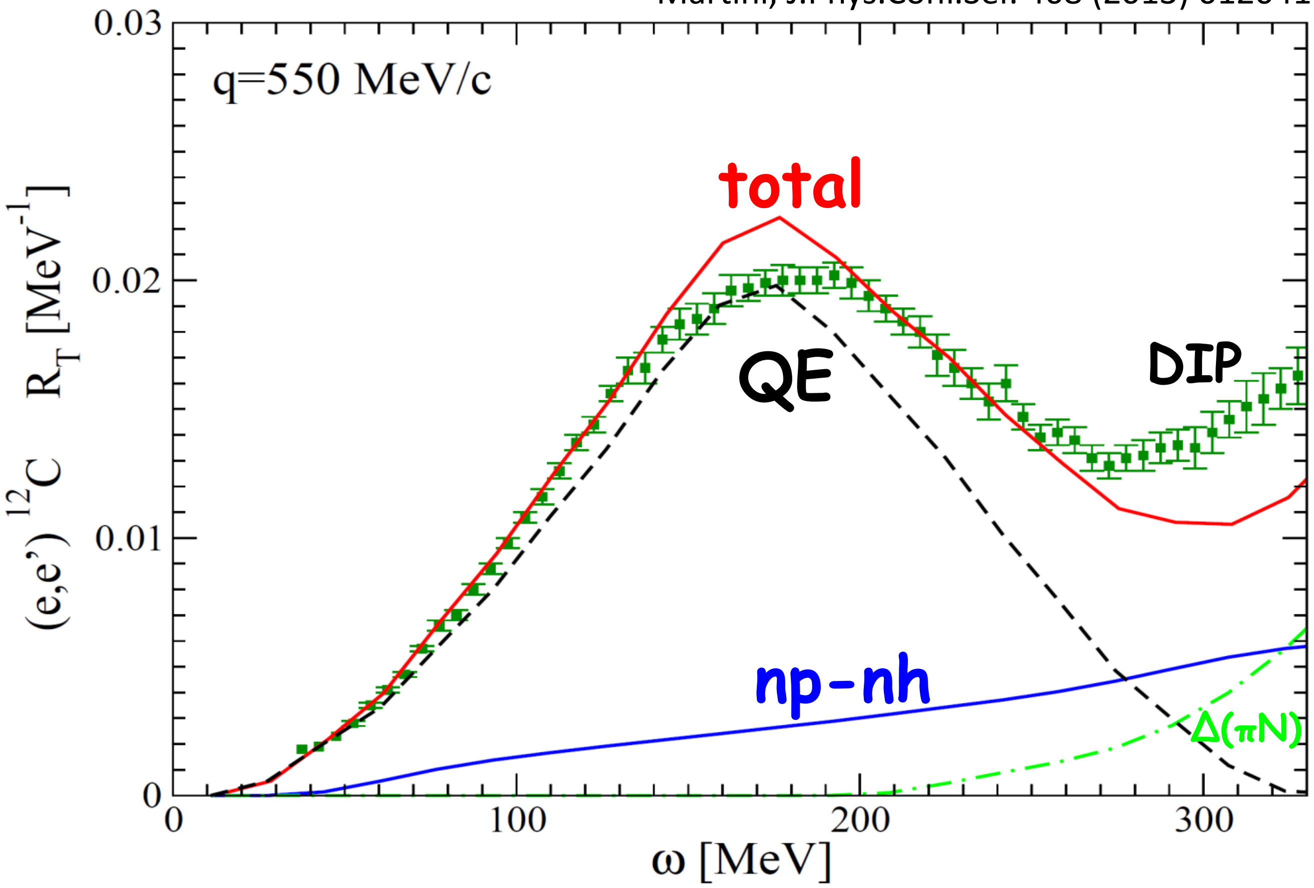
RPA



# An example of nuclear response : transverse response in electron scattering



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



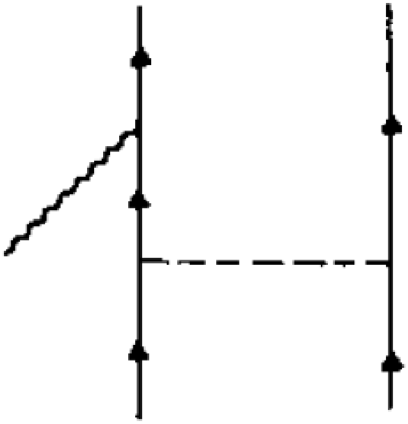
np-nh creates a high energy tail in the nuclear response above the QE peak

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

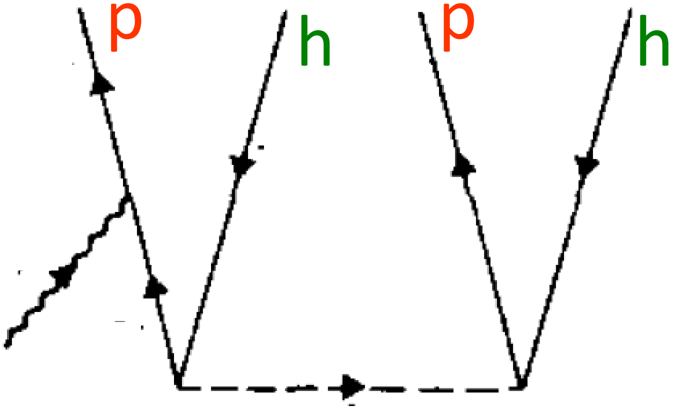
# Two particle-two hole sector (2p-2h)

## Three equivalent representations of the same process

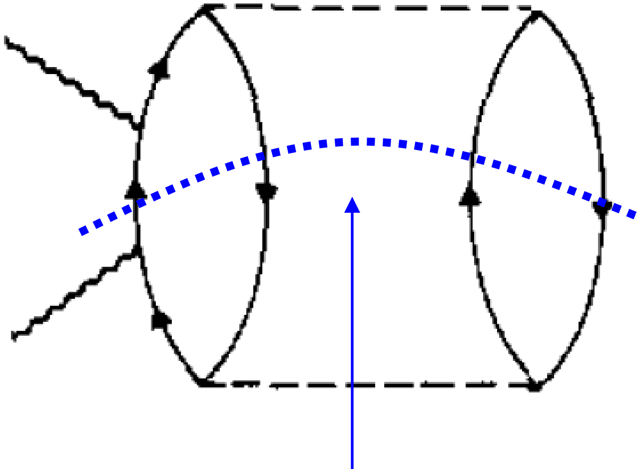
2 body current



2p-2h matrix element



2p-2h response

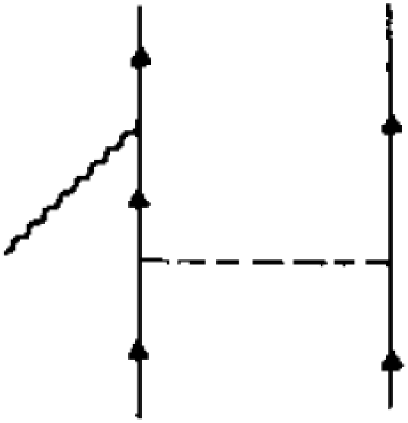


Cut
(optical theorem)

**Final state: two particles-two holes**

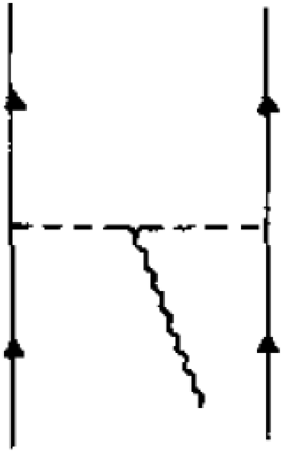
# Some diagrams for 2 body currents

## Nucleon-Nucleon correlations

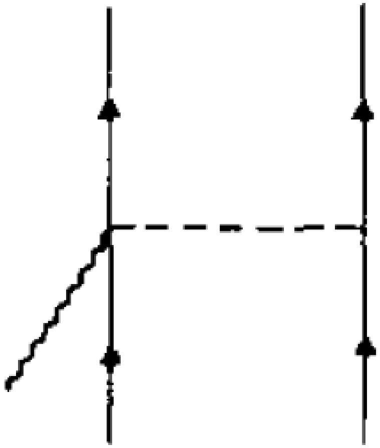


$J^{corr}$

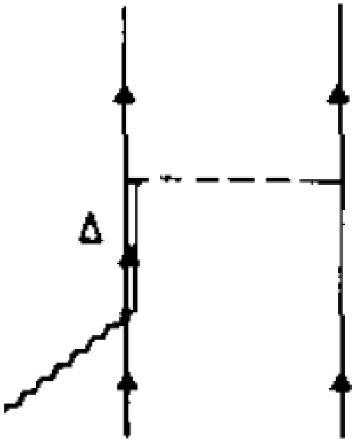
## Meson Exchange Currents (MEC)



Pion in flight



Contact

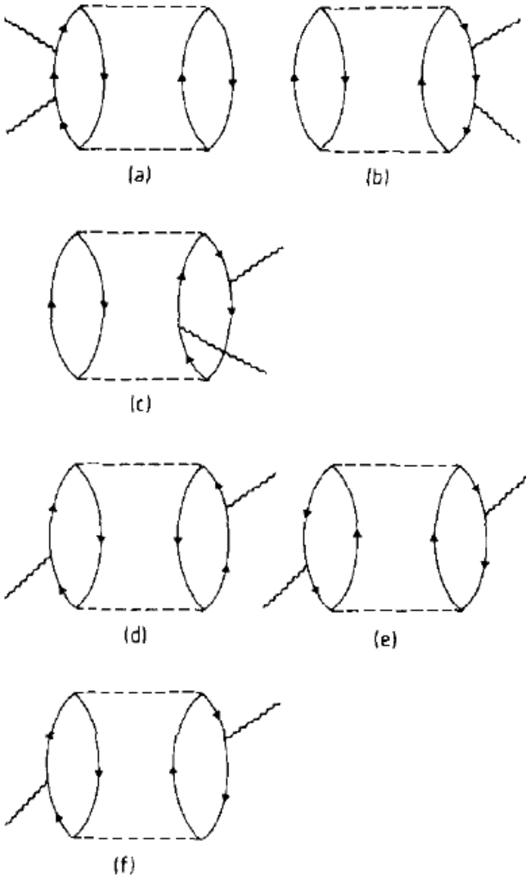


Delta

$J^{MEC}$

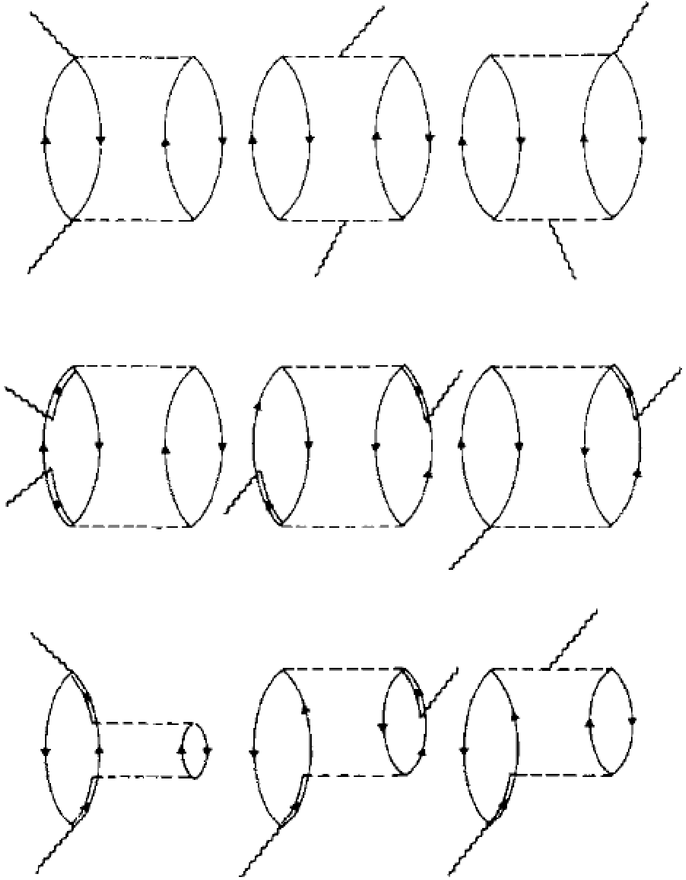
# Some diagrams for 2p-2h responses

## NN correlations



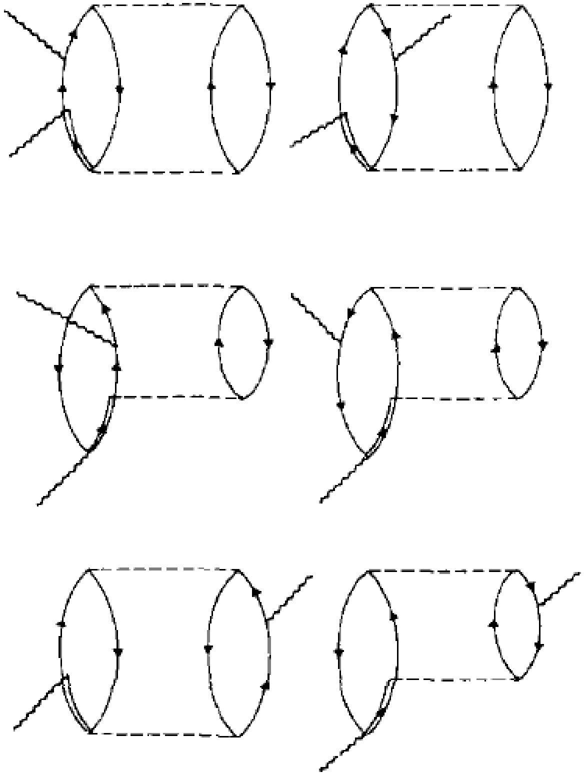
16 diagrams

## MEC



49 diagrams

## NN correlation-MEC interference



56 diagrams

# 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

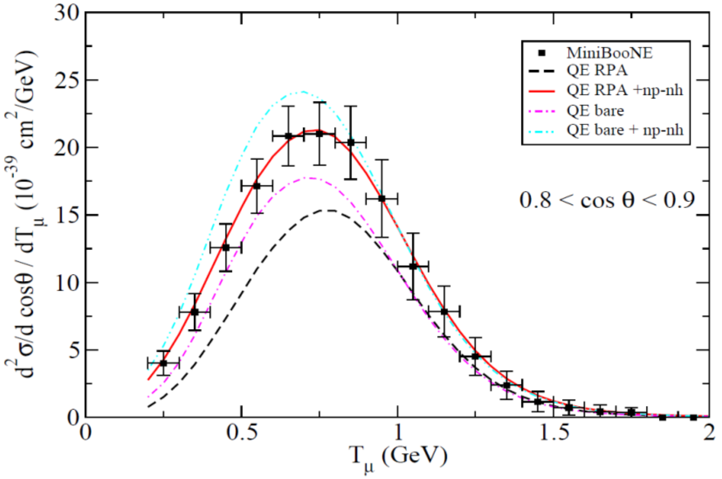
Hence different approximations by different groups:

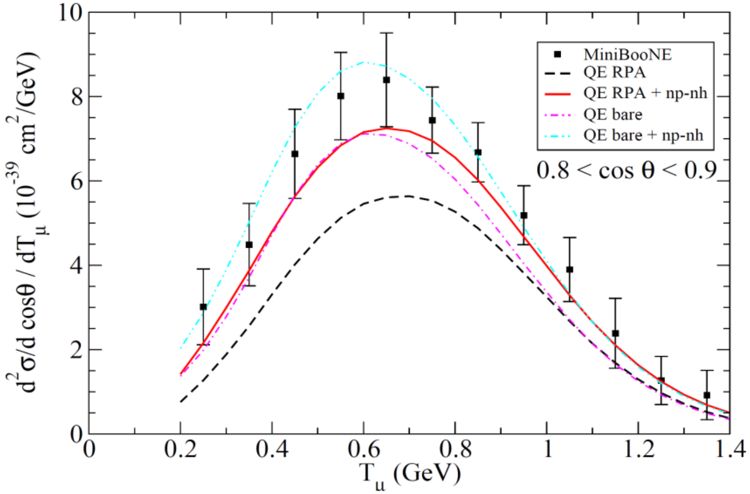
- choice of subset of diagrams and terms;
- different prescriptions to regularize the divergences;
- reduce the dimension of the integrals (7D --> 2D if non relativistic; 7D -->1D if $h_1$ = $h_2$ =0)

$\Rightarrow$ Different final results

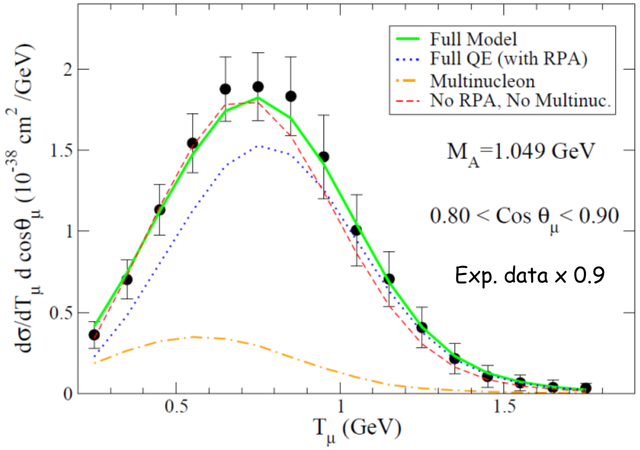
$\nu$ $\bar{\nu}$

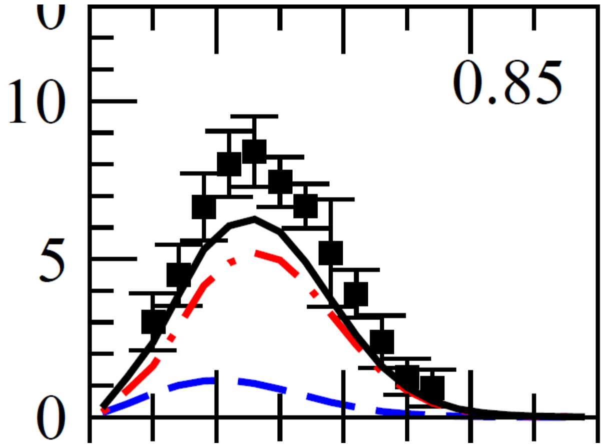
Martini et al.





Nieves et al.

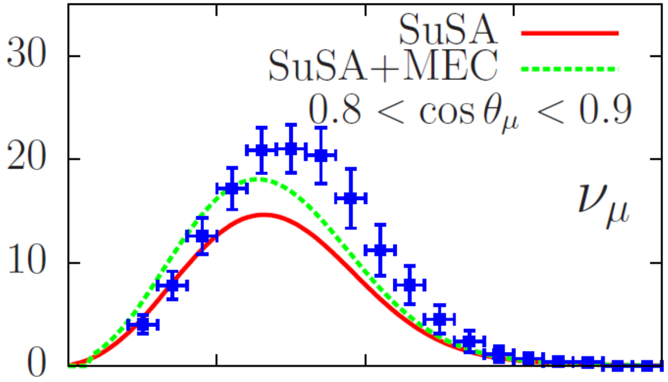


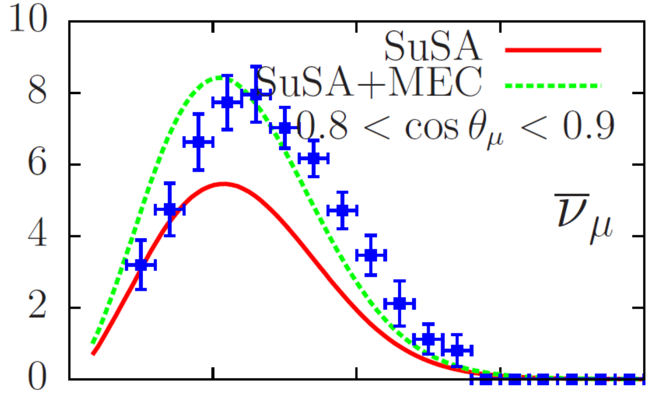


**black:** QE RPA+2p2h

**red:** QE RPA

Amaro et al.





# Neutrino *vs* Antineutrino

# Neutrino *vs* Antineutrino interactions and CP violation

Detection of an asymmetry between ν and antiν oscillation rates as evidence of CP violation

$$\nu_\mu \to \nu_e \qquad \textit{vs} \qquad \bar{\nu}_\mu \to \bar{\nu}_e$$

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

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

Vector-Axial interference:

**basic asymmetry from weak interaction theory**

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

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

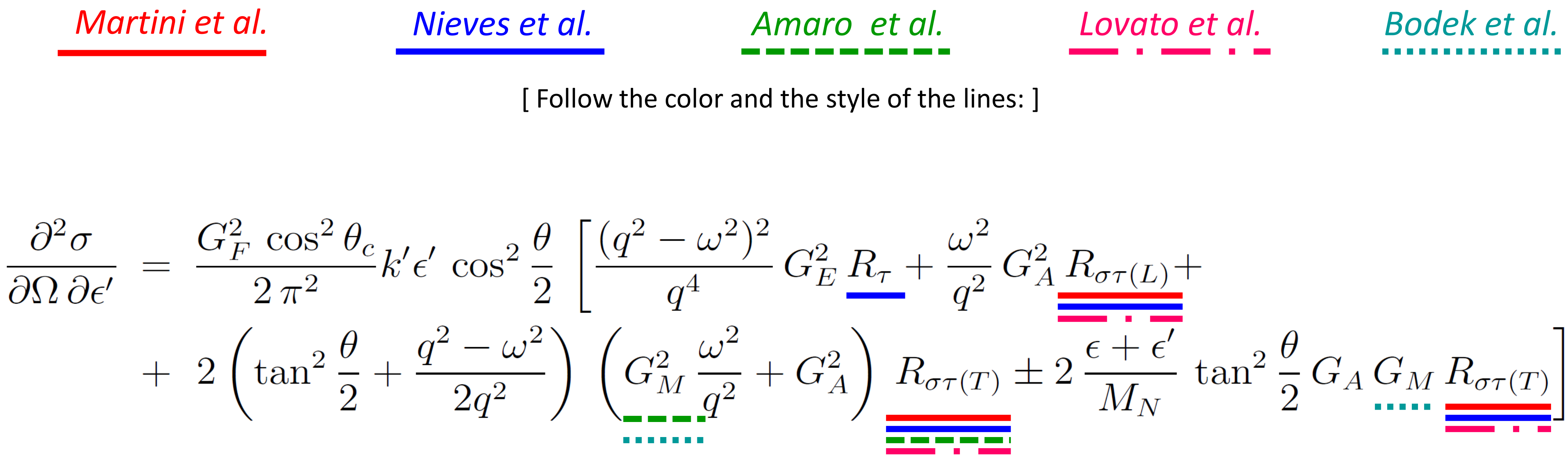
→the relative weight of the different nuclear responses is different for neutrinos and antineutrinos

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

$$\Downarrow$$

**Nuclear effects generate an asymmetry unrelated to CP violation which has to be fully mastered**

# 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: ]

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

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

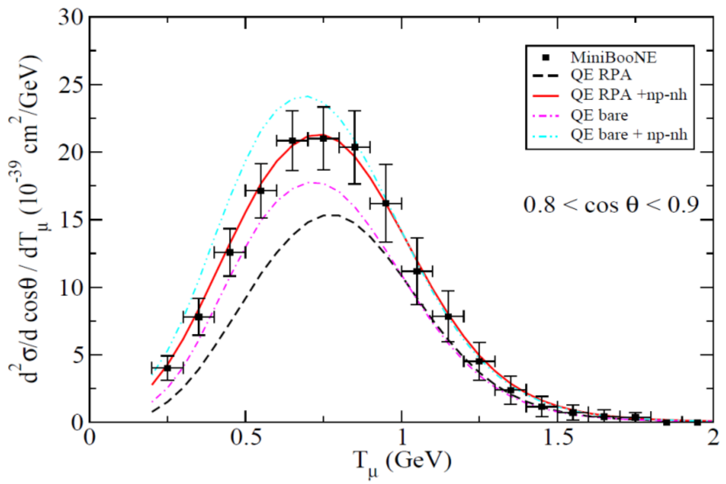
An example of difference:
in Amaro et al. there are no 2p-2h in the axial and vector-axial interference terms

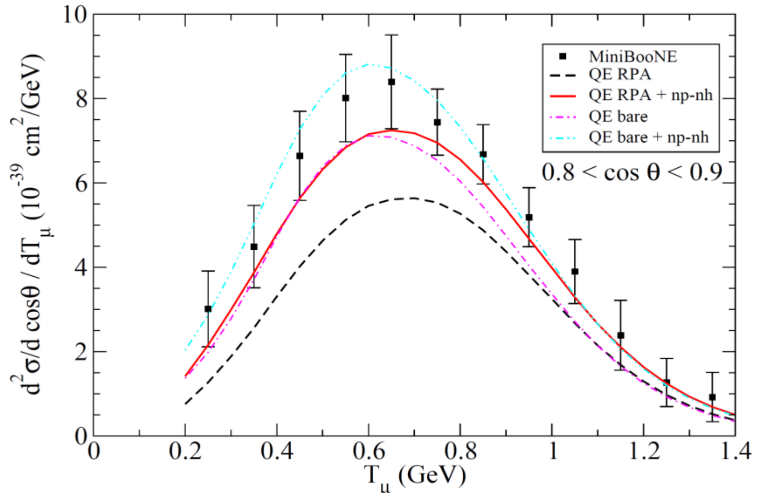
→the relative role of 2p-2h contributions for neutrinos and antineutrinos is different in the different approaches

$\nu$

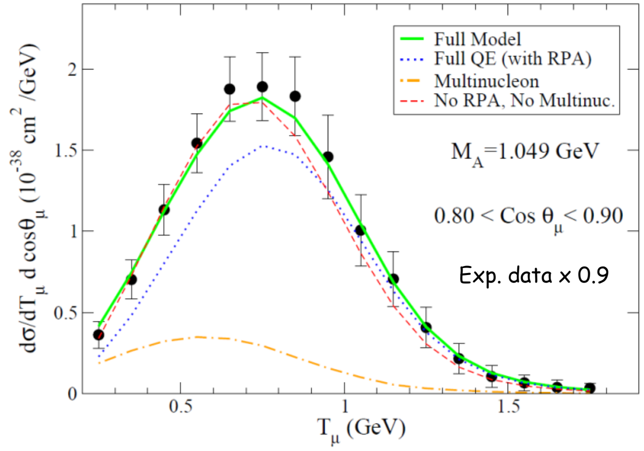
$\overline{\nu}$

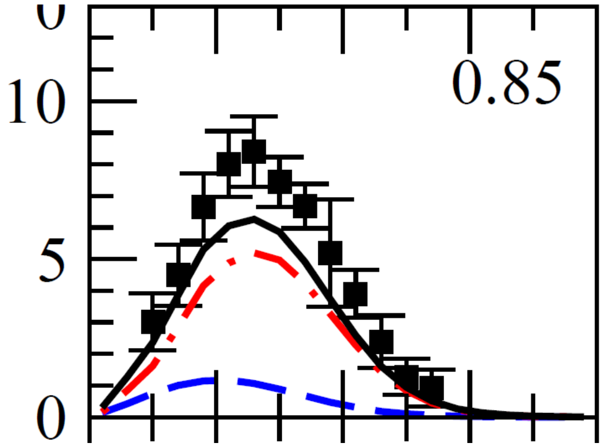
Martini et al.





Nieves et al.

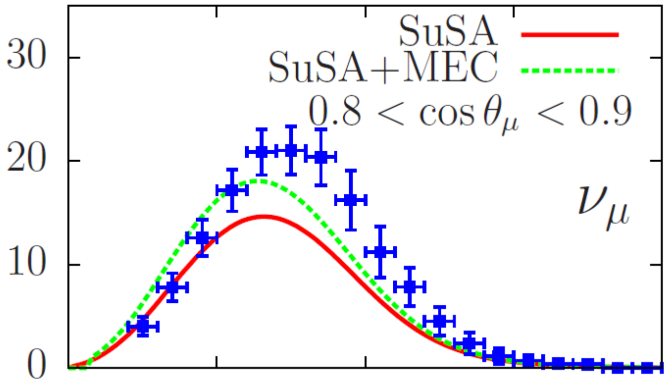


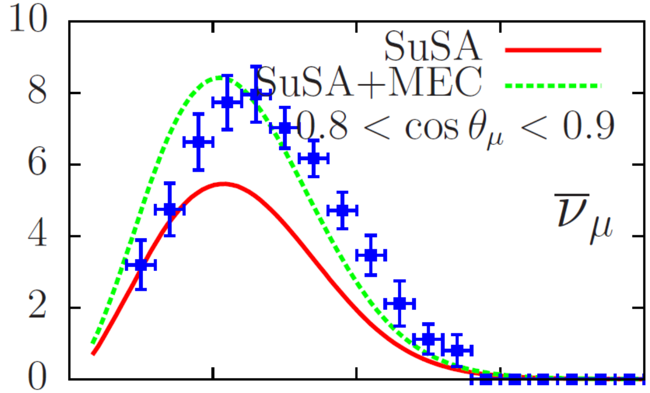


**black:** QE RPA+2p2h

**red:** QE RPA

Amaro et al.





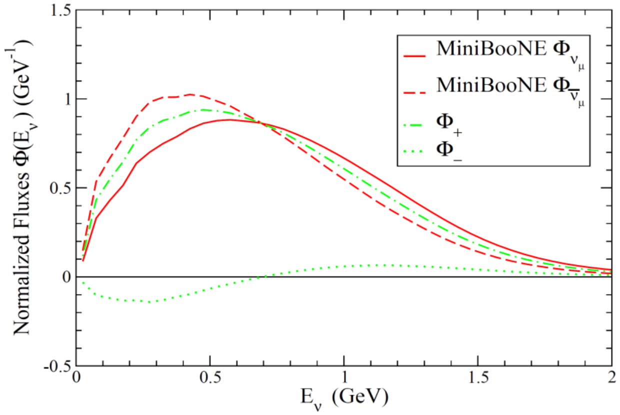
# Difference of ν and antiν cross sections and the VA interference term

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

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

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

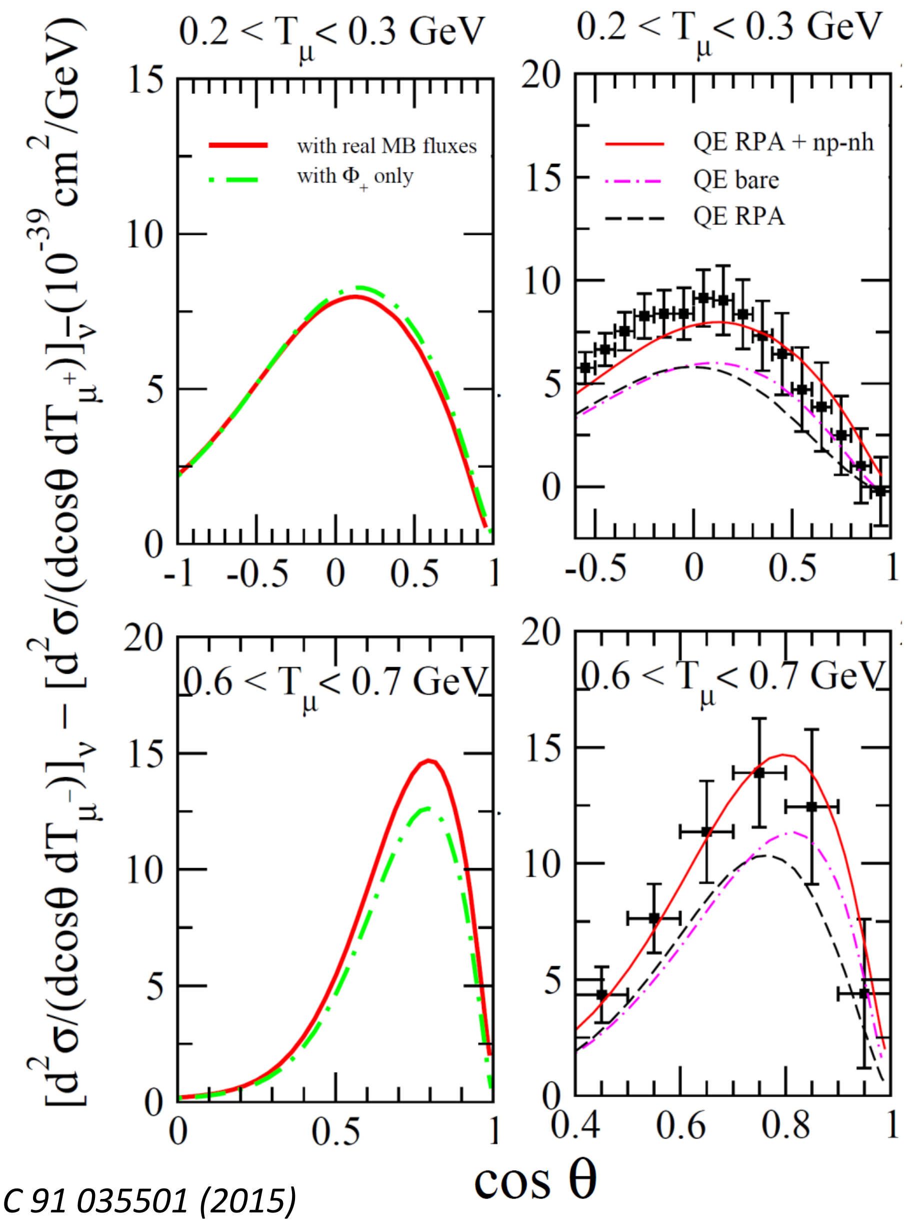
Problem: flux dependence of dσ $\frac{d^2\sigma}{dE_\mu d\cos\theta} = \int dE_\nu \left[\frac{d^2\sigma}{d\omega d\cos\theta}\right]_{\omega=E_\nu-E_\mu} \Phi(E_\nu)$



We introduce the **mean flux**

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

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



The mean flux contribution is dominant in the ν antiν difference

⇓

The VA interference term is experimentally accessible in MiniBooNE data

⇓

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

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

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

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

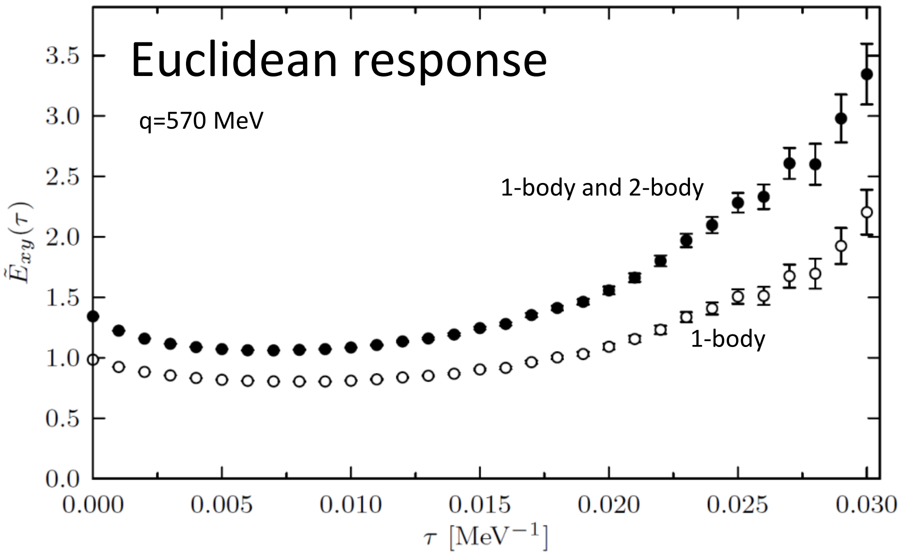
## Neutral weak current two-body contributions to sum rules and Euclidean responses in $^{12}$C

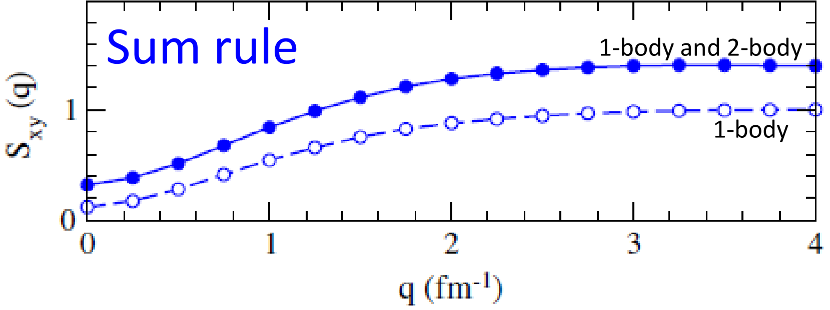
$$E_{\alpha\beta}(q,\tau) = C_{\alpha\beta}(q)\int_{\omega_{\rm th}}^{\infty} d\omega\, e^{-\tau\omega} R_{\alpha\beta}(q,\omega)$$

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 $\Delta$ production
- Computing very demanding

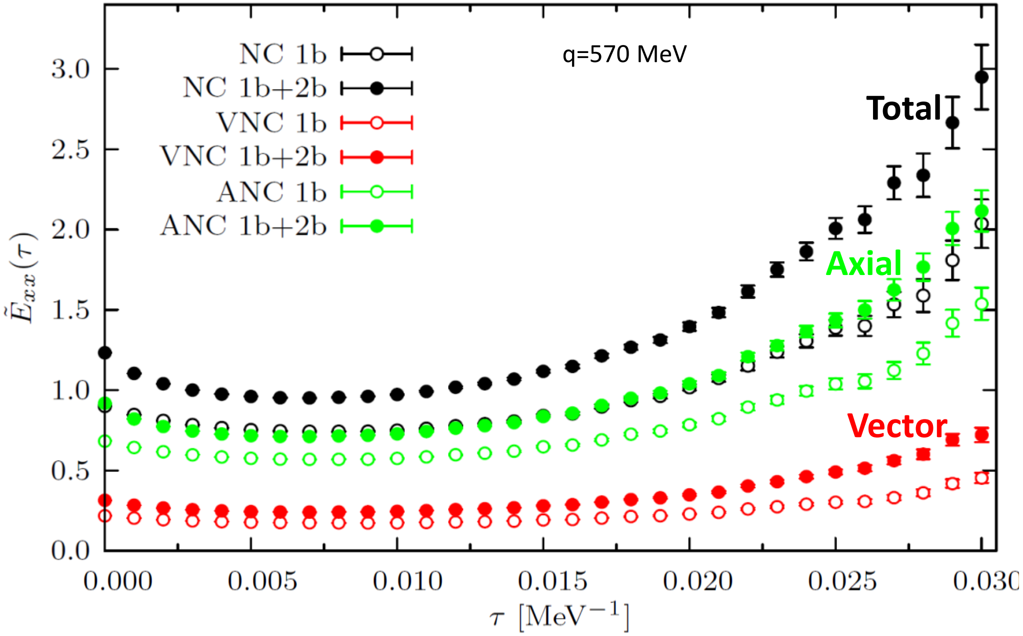
**Limitation: an evaluation of $^{12}$C responses and $\nu$ cross sections is beyond the present computational capabilities.**

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

# An instructive comparison of two different quantities

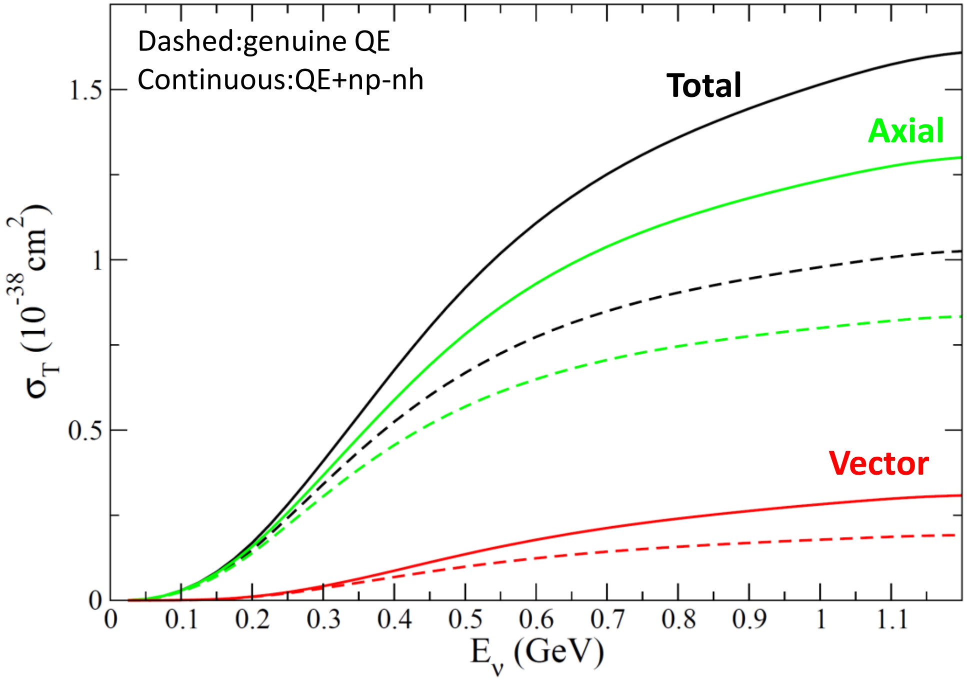
## Euclidean NC transverse response

*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

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

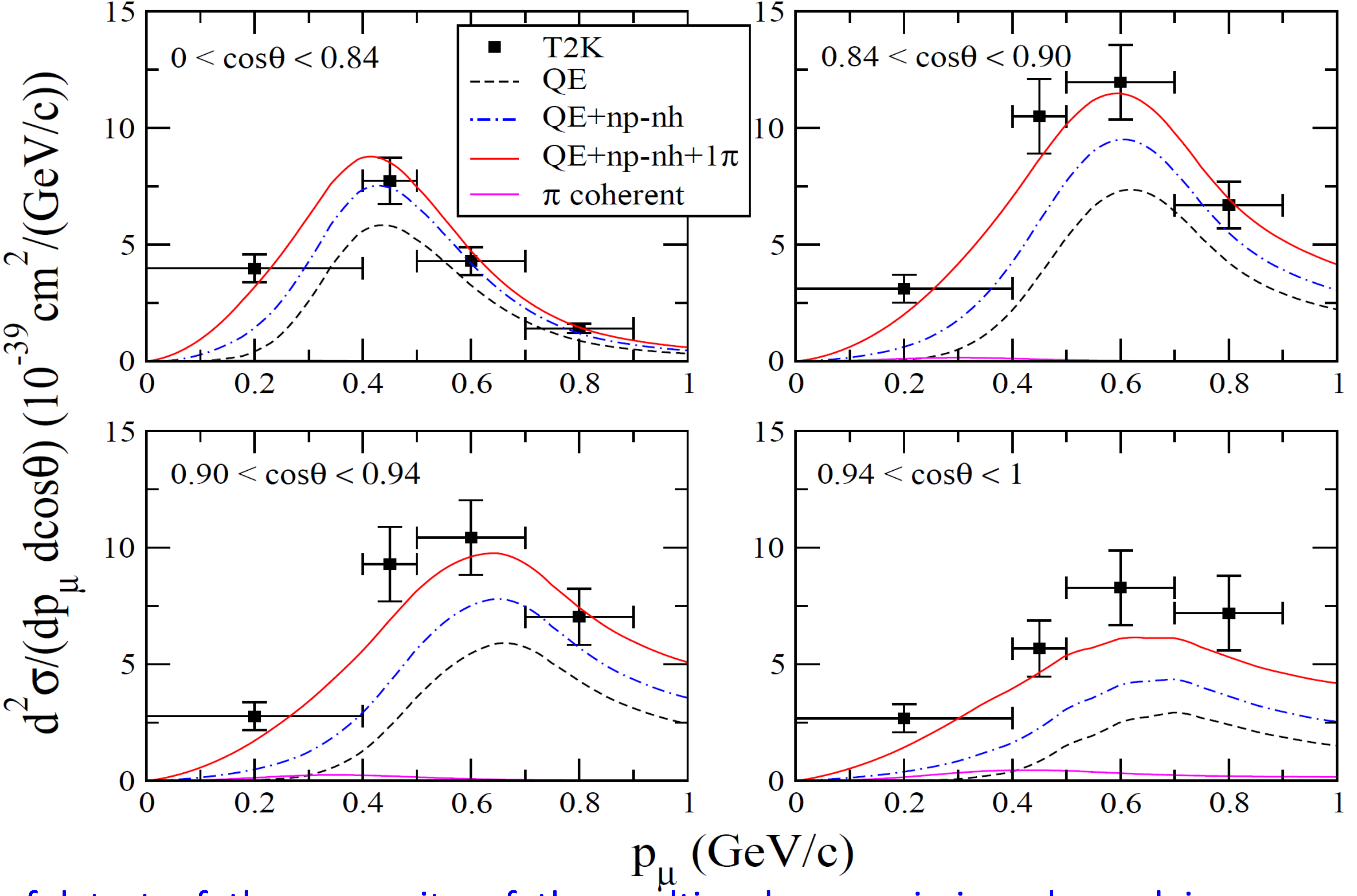
# Beyond MiniBooNE QE:
# other channels
# and
# other experiments

# 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)*

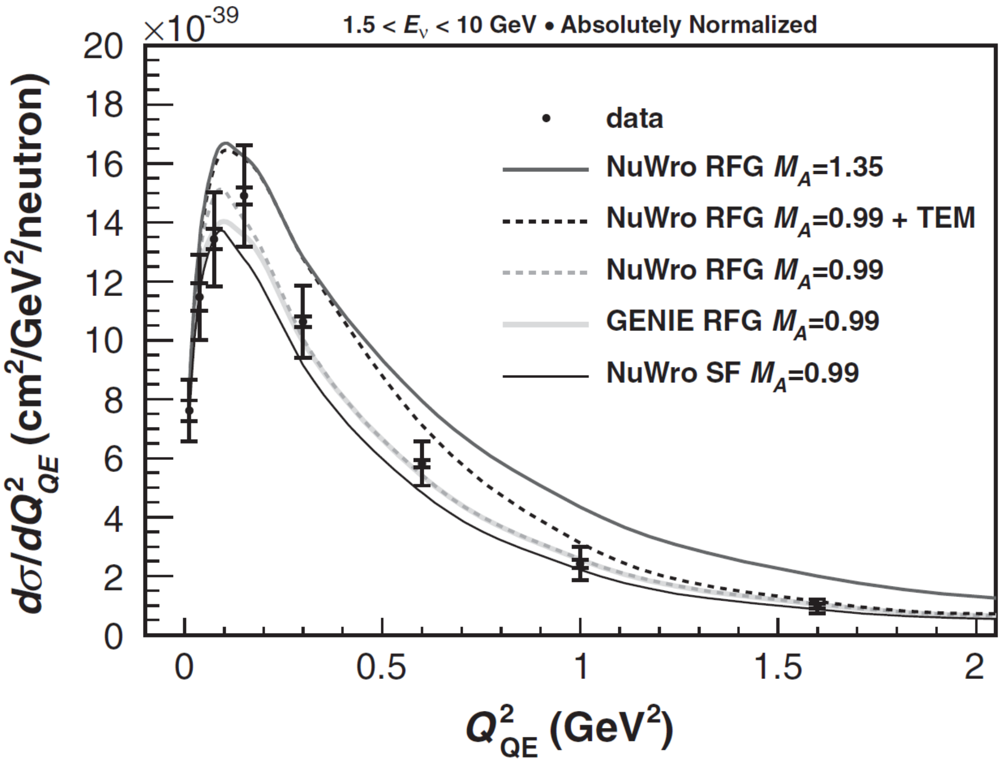


First successful test of the necessity of the multinucleon emission channel in an experiment with another neutrino flux with respect to the one of MiniBooNE.

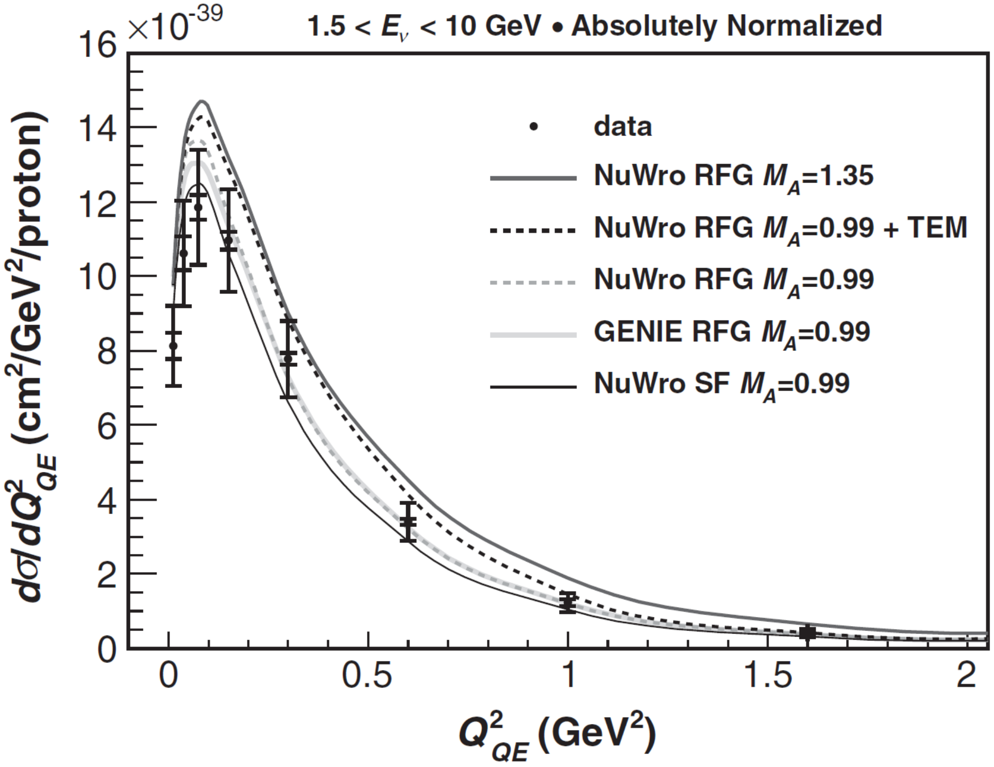
# MINERνA ($E_\nu \sim$ 3.5 GeV) CCQE $Q^2$ distribution

$\nu$

$\bar{\nu}$



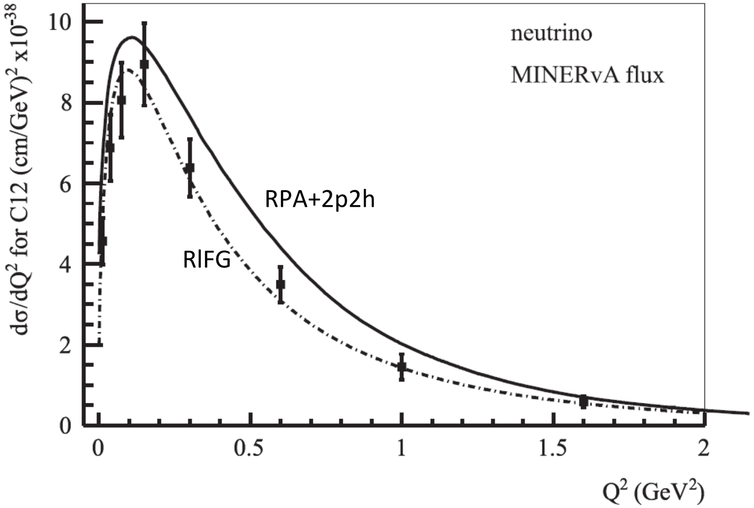
*PRL 111 022502 (2013)*

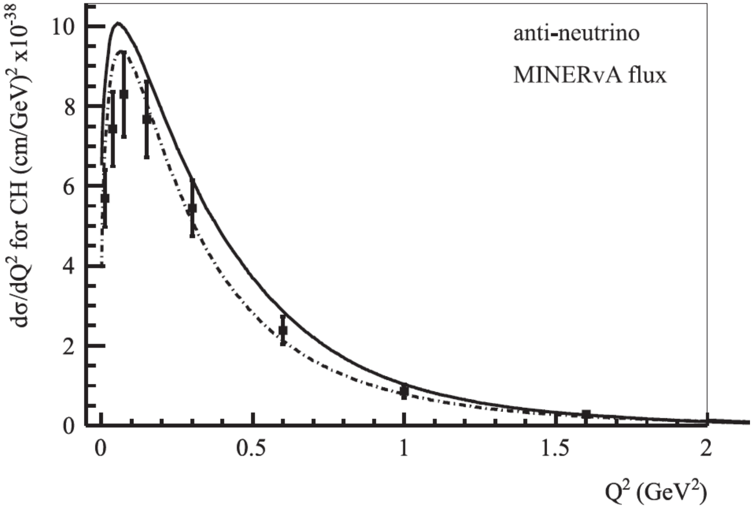


*PRL 111 022501 (2013)*

$\nu$

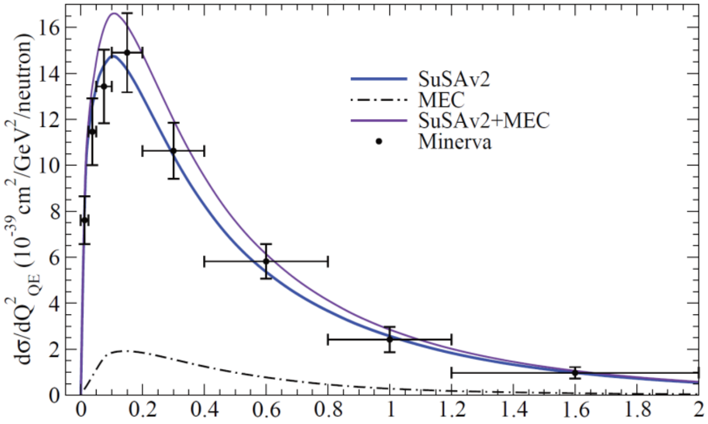
Gran, Nieves et al.
PRD 88 (2013)

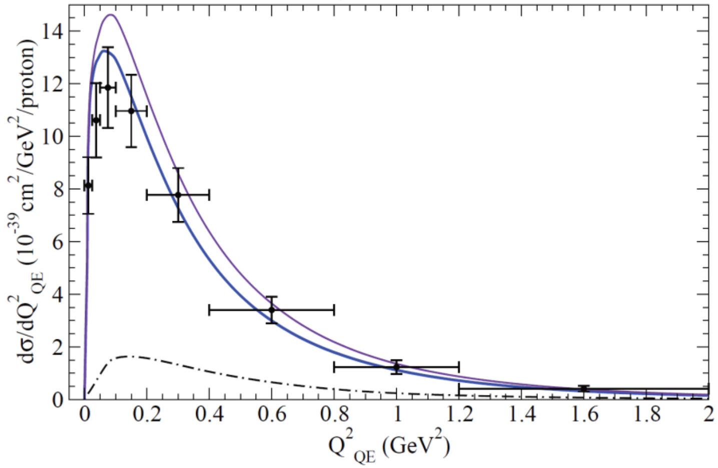




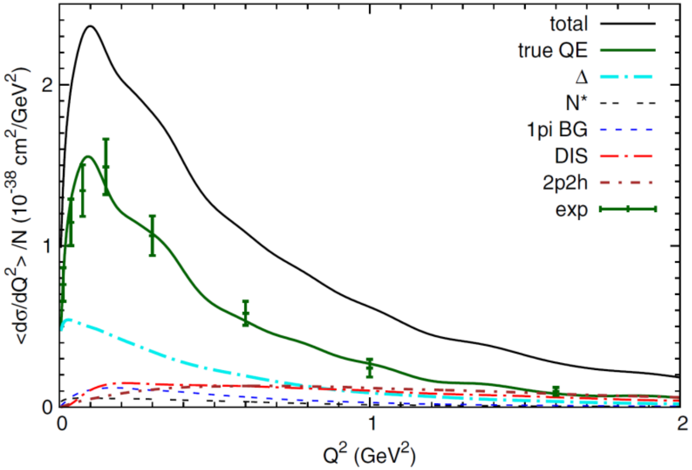
$\bar{\nu}$

Megias, Amaro et al.
arXiv 1412.1822





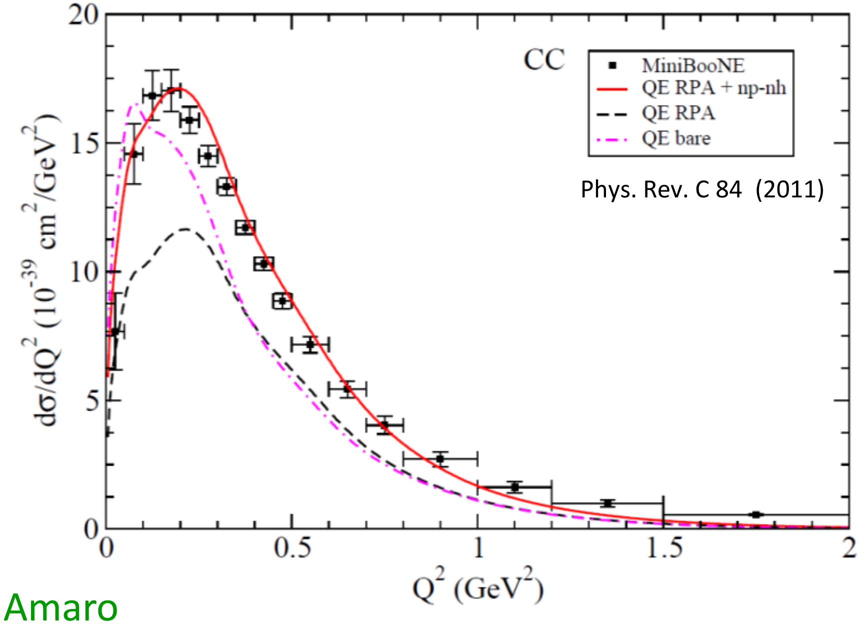
Mosel et al.
PRD 89 (2014)



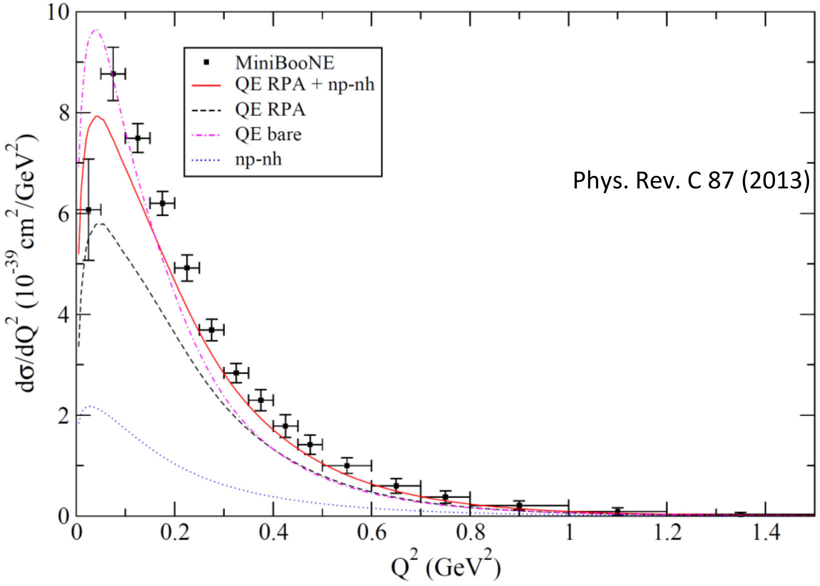
- **MINERνA $Q^2$ distributions can be reproduced also without the inclusion of np-nh**
- **This is not the case of the MiniBooNE $Q^2$ distributions**
- Mosel et al: “The sensitivity to details of the treatment of np-nh contributions is smaller than the uncertainties introduced by the $Q^2$ reconstruction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

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

Martini et al.

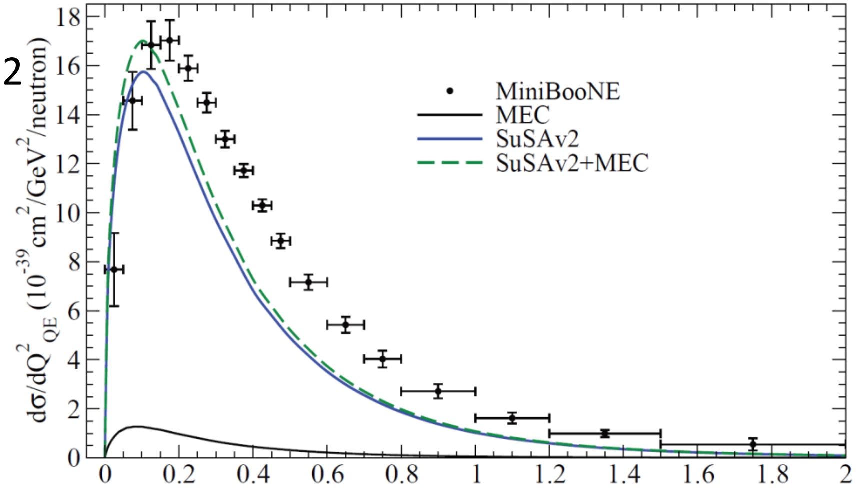


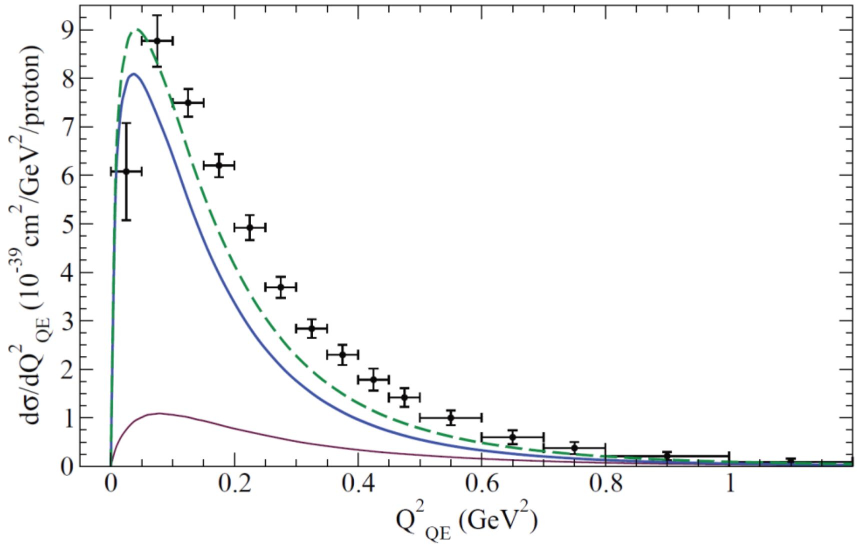
Phys. Rev. C 84 (2011)



Phys. Rev. C 87 (2013)

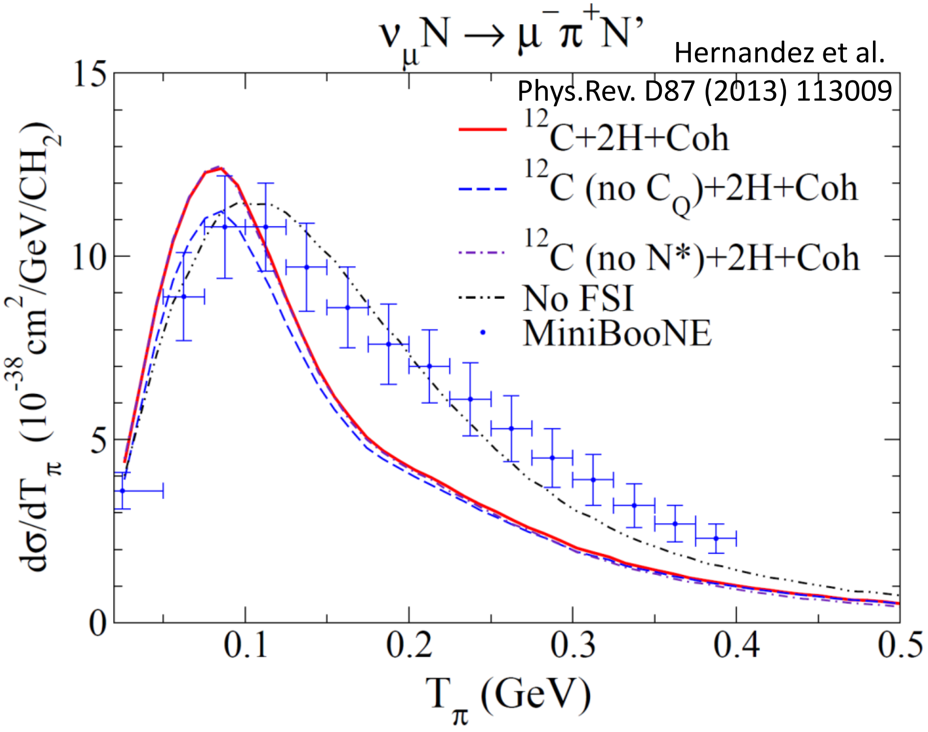
Megias, Amaro et al.
1412.1822





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

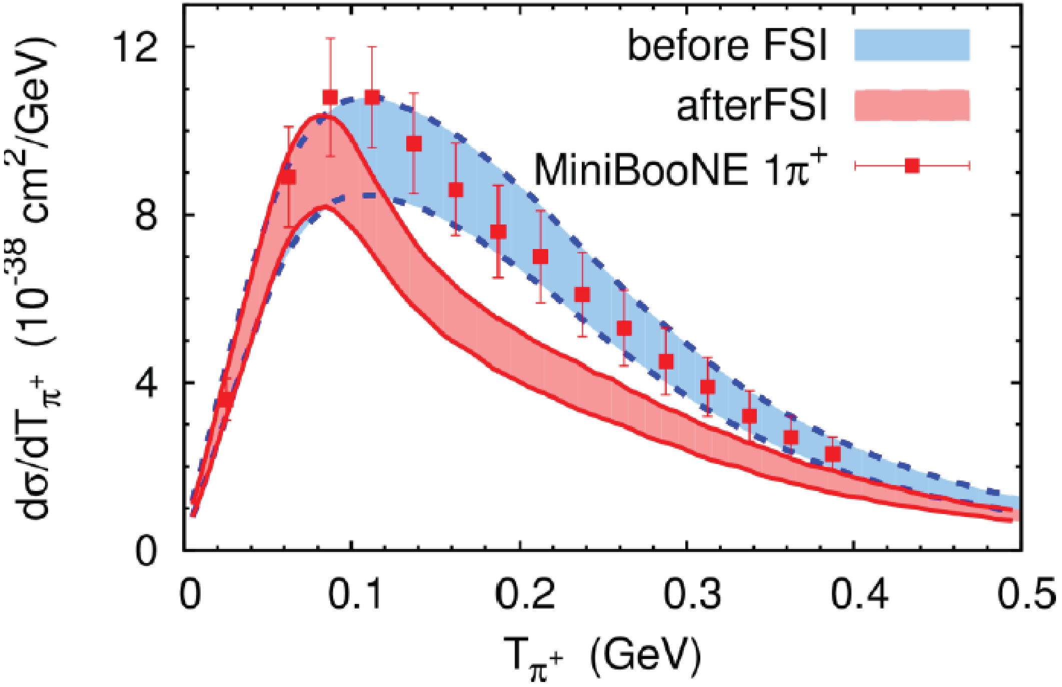
# MiniBooNE CC1π+ production: theory versus experiment



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

**Valencia**

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

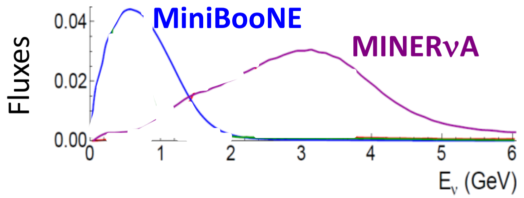


**GiBUU**

## controversy

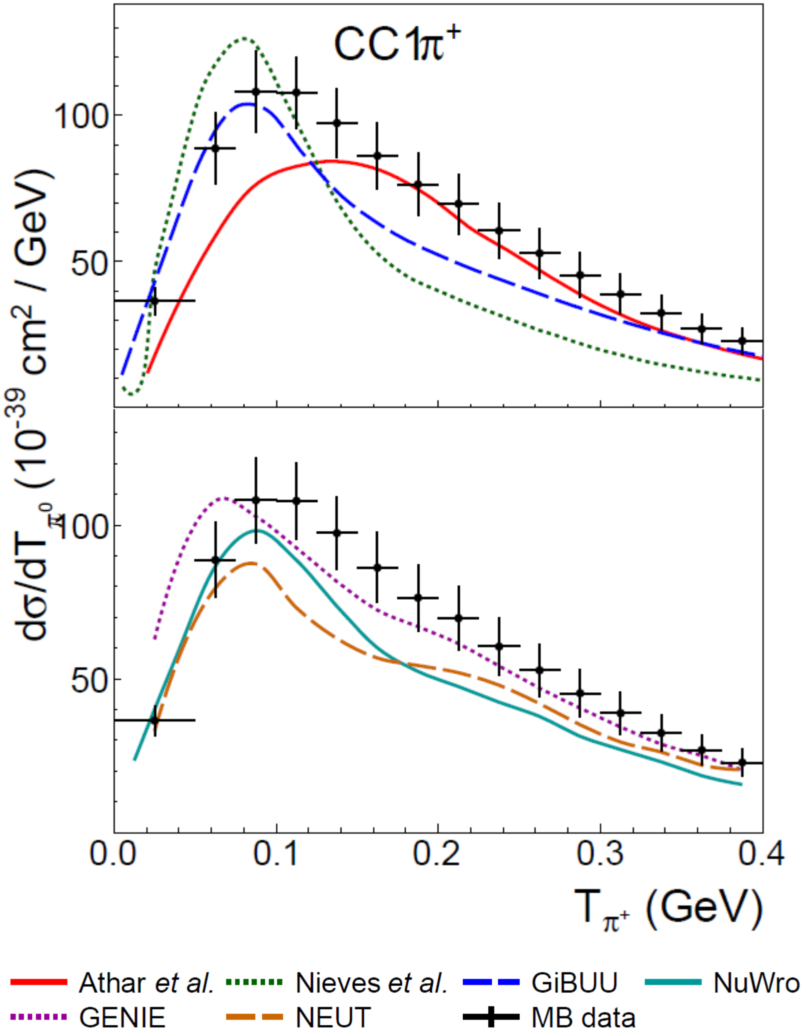
- Best theories (with Δ medium effects and pion rescattering) do not agree with pion KE spectrum
- MiniBooNE data *(PRD 83 052007 (2011))* prefer calculations with no Final State Interaction for the pion

# MiniBooNE *vs* MINERνA CC1π+ production



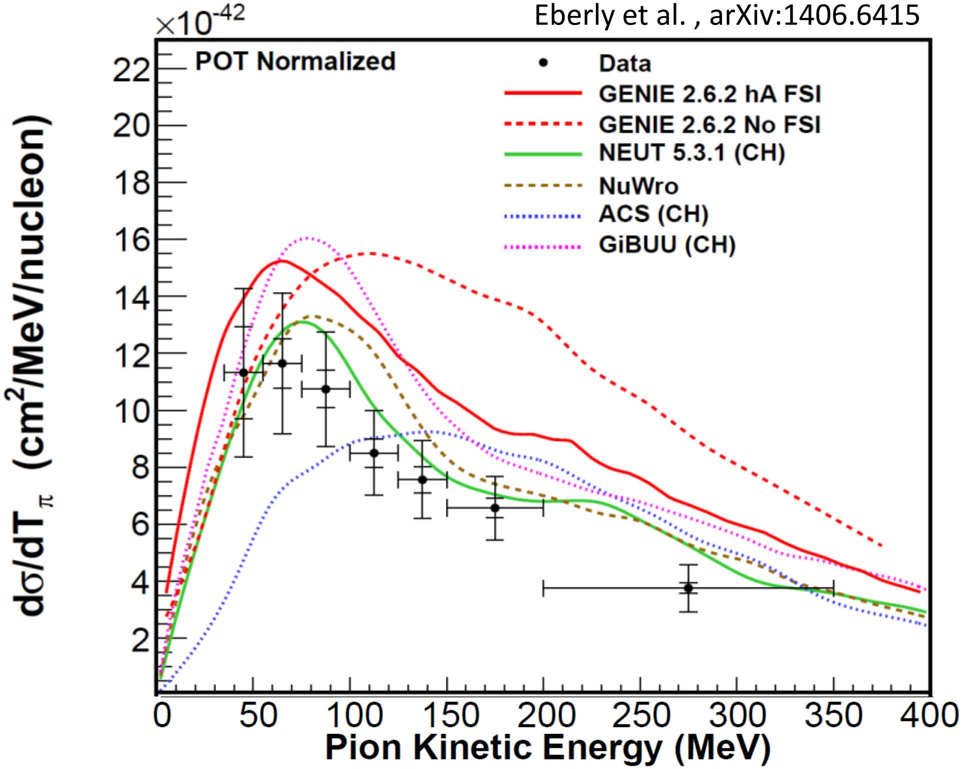
## MiniBooNE

Rodrigues, arXiv:1402.4709



## MINERνA

Eberly et al. , arXiv:1406.6415

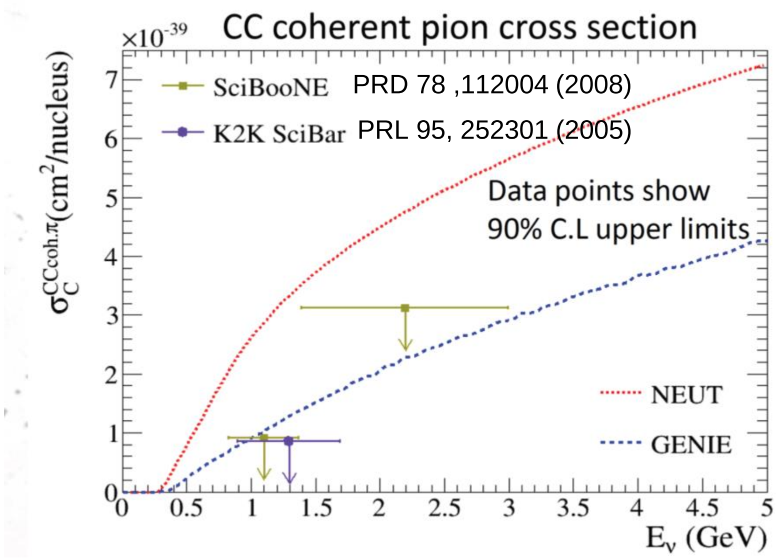


**Some tension**

# Coherent π production

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

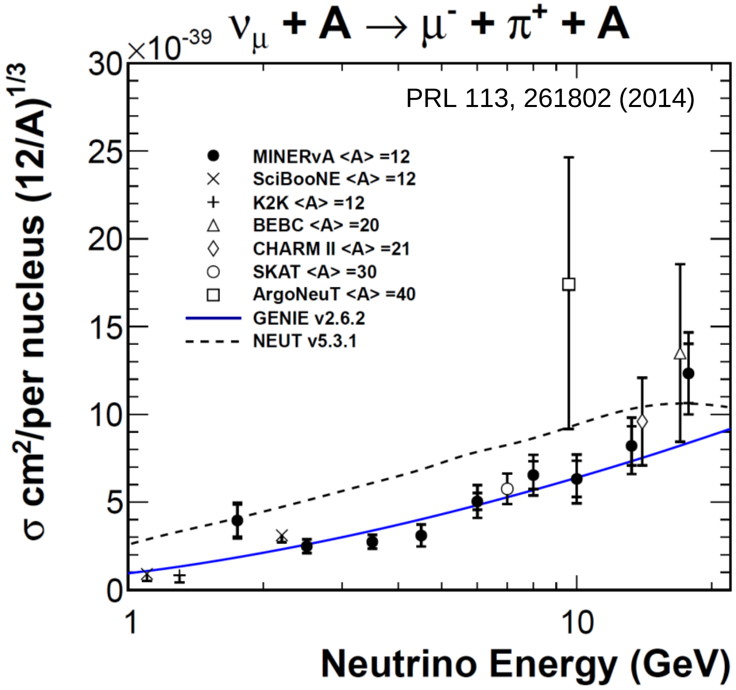
Recently MINERνA and ArgoNeut see evidence for CC coherent pion production



SciBooNE PRD 78 ,112004 (2008)

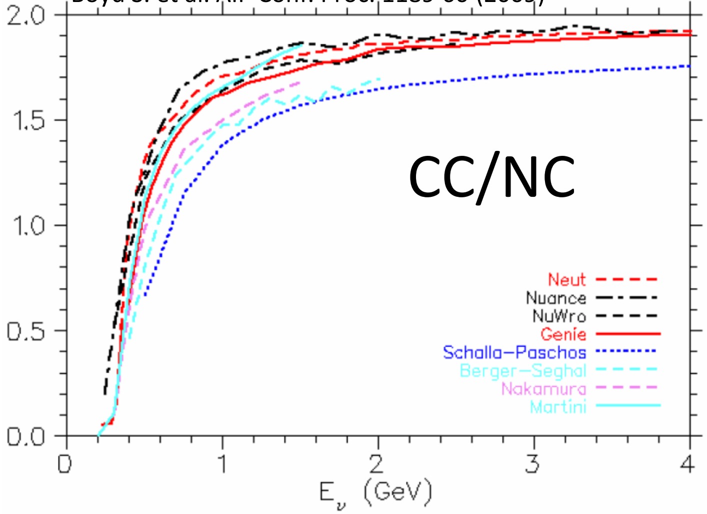
K2K SciBar PRL 95, 252301 (2005)

Data points show 90% C.L upper limits



PRL 113, 261802 (2014)

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



CC/NC

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

Theoretical models:

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

SciBooNE:

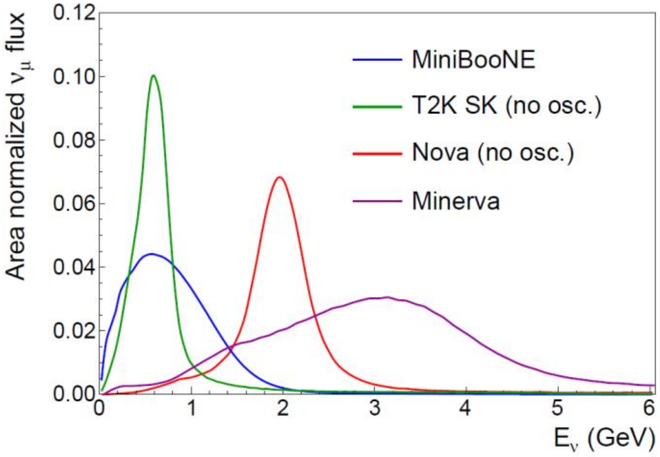
$$\frac{\pi+ \text{ coh. CC}}{\pi0 \text{ coh. NC}} = 0.14^{+0.30}_{-0.28}$$

Kurimoto et al, PRD 81 (2010)

# Neutrino energy reconstruction problems and neutrino oscillations

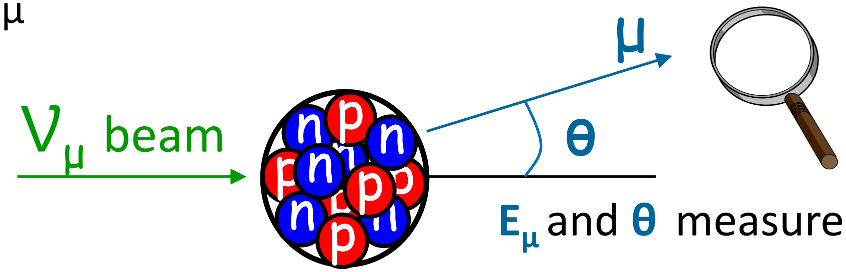
# Towards the neutrino oscillation physics

Neutrino oscillation experiments require the determination of the neutrino energy which enters the expression of the oscillation probability.
The neutrino energy is unknown. We know only broad fluxes.
The determination of the neutrino energy is done through Charged Current QuasiElastic events.



$\nu_\mu\, n \rightarrow \mu^-\, p$ CCQE

e.g. for μ



$E_\mu$ and θ measured

## Reconstructed neutrino energy

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

via two-body kinematics

$\overline{E_\nu} = E_\nu$ is exact only for CCQE with free nucleon

reconstructed neutrino energy $\overline{E_\nu} \overset{?}{\longleftrightarrow} E_\nu$ true neutrino energy

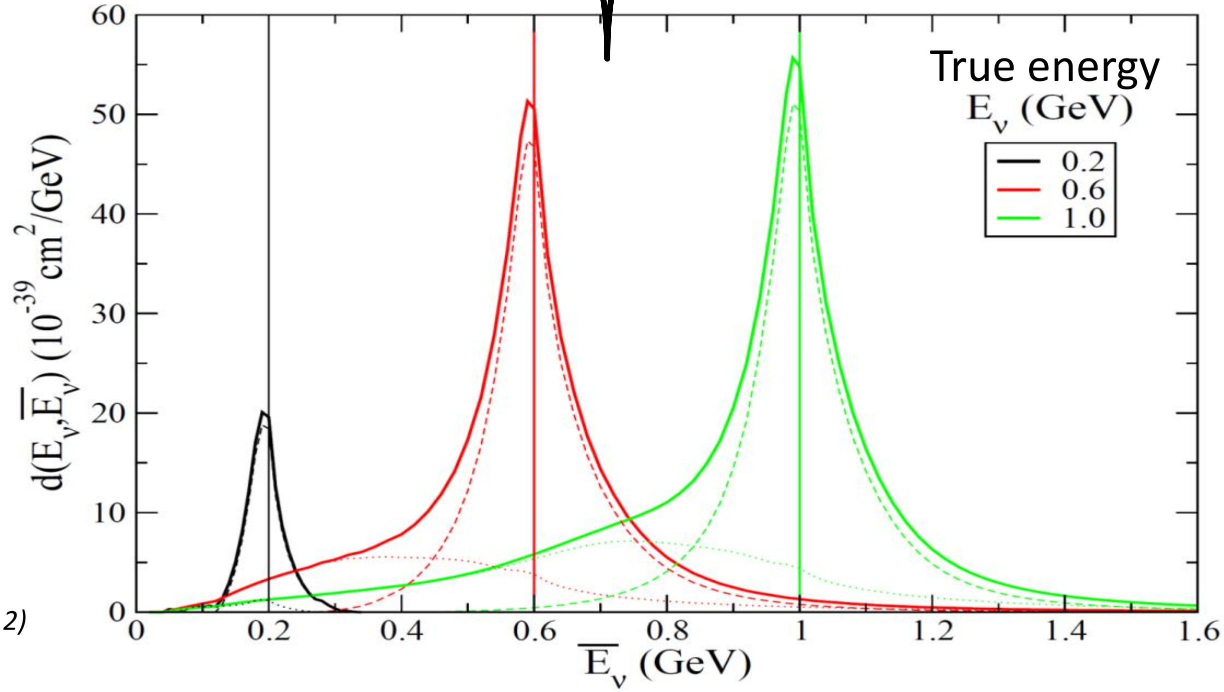
# From true neutrino energy to reconstructed neutrino energy

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

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)*

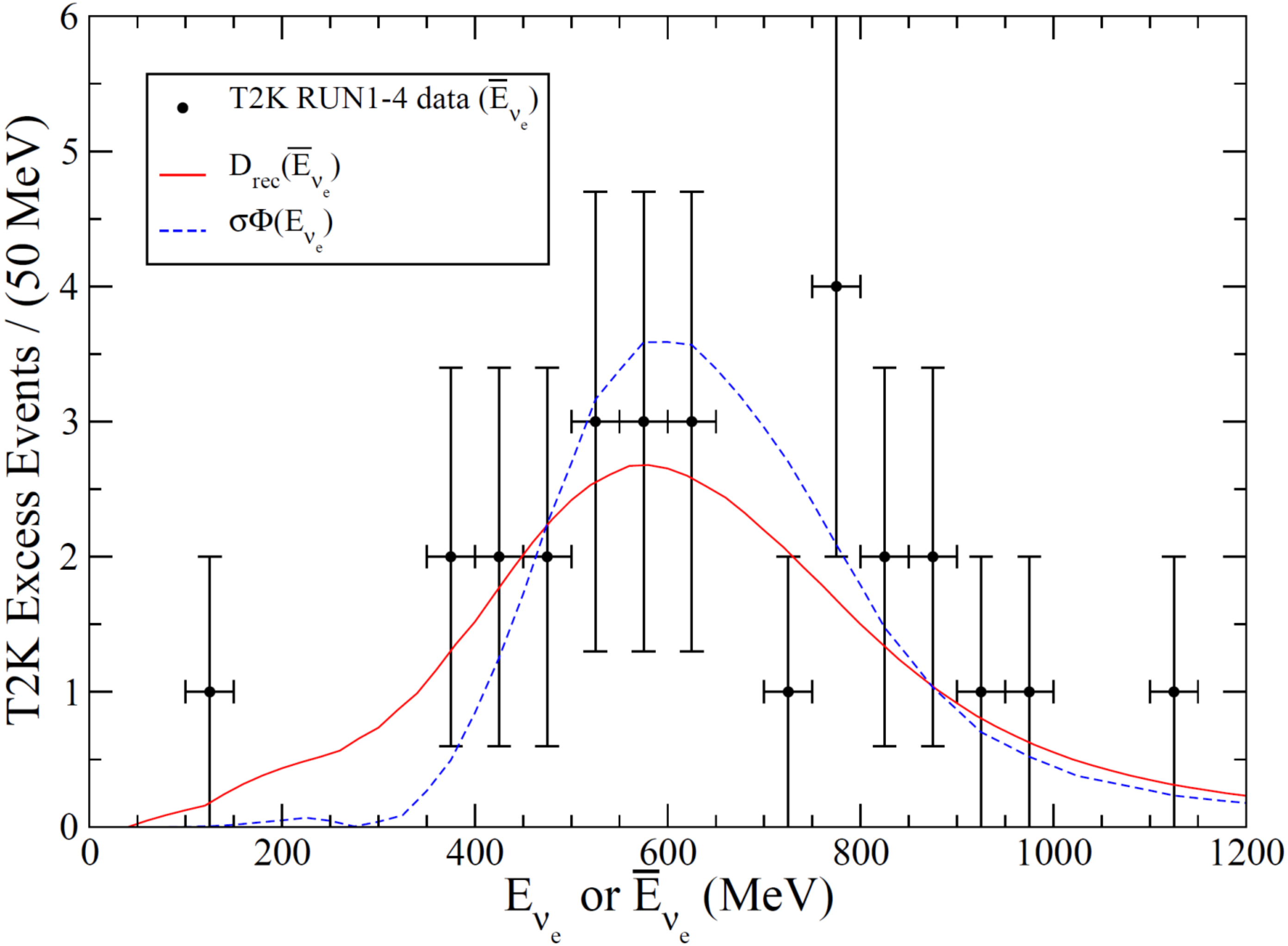


- Distributions not symmetrical around Eν
- Crucial role of np-nh: low energy tail

# $\nu_\mu \rightarrow \nu_e$ T2K

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

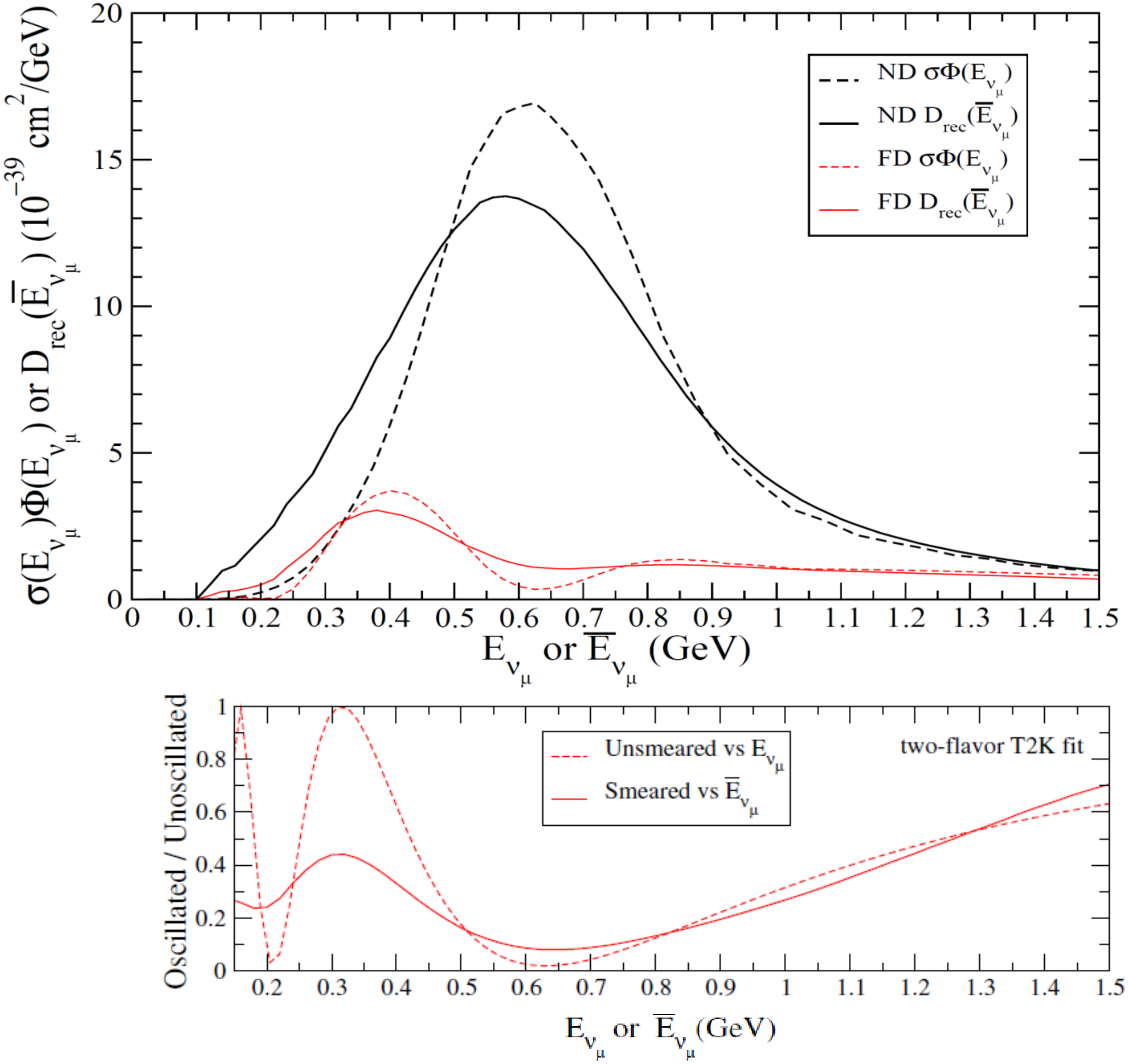
## 2013: 28 events



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

# $\nu_\mu$ 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."

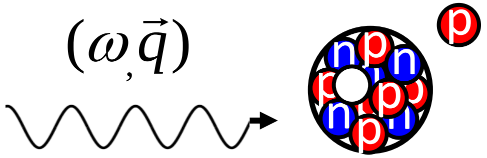
# Nuclear effects in neutrino interactions

## Summary

- Several theoretical calculations agree on the crucial role of the multinucleon channel (not contained in the generators) to explain MiniBooNE CCQE-like data $\Rightarrow$ Solution of $M_A$ puzzle
- There are some differences on the way to treat this np-nh channel which are reflected in the comparisons with the MiniBooNE neutrino and antineutrino data
- Nuclear effects generate an asymmetry between $\nu$ and anti$\nu$ interaction: important for the investigation of CP violation effects
- The inclusion of np-nh excitations seems to be needed in order to reproduce the T2K inclusive cross sections
- The role of np-nh in the MINER$\nu$A results is less evident
- There are some controversies and puzzles in the one pion production channel: MiniBooNE vs theory ; MiniBooNE vs MINER$\nu$A; SciBooNE coherent pion
- Neutrino energy reconstruction and neutrino oscillation analysis are affected by np-nh

# Spares

# Genuine Quasielastic Scattering



## Nucleon-Nucleon interaction switched off

Nucleons respond individually

**Nucleon at rest:**

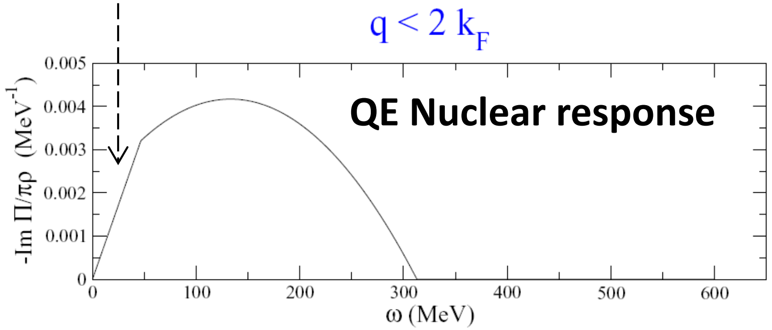
$$R \alpha \; \delta\left(\omega - \left(\sqrt{q^2 + M^2} - M\right)\right)$$

**Nucleon inside the nucleus:**

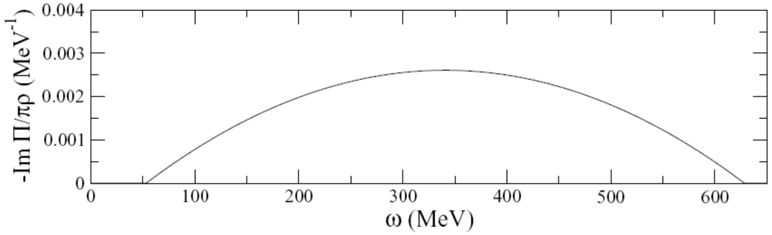
**Fermi motion** spreads δ distribution (Fermi Gas)

**Pauli blocking** cuts part of the low momentum Resp.

$q < 2\ k_F$



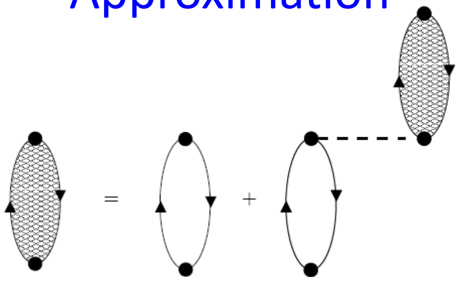
$q > 2\ k_F$



## Nucleon-Nucleon interaction switched on

The nuclear response becomes collective

Random Phase Approximation

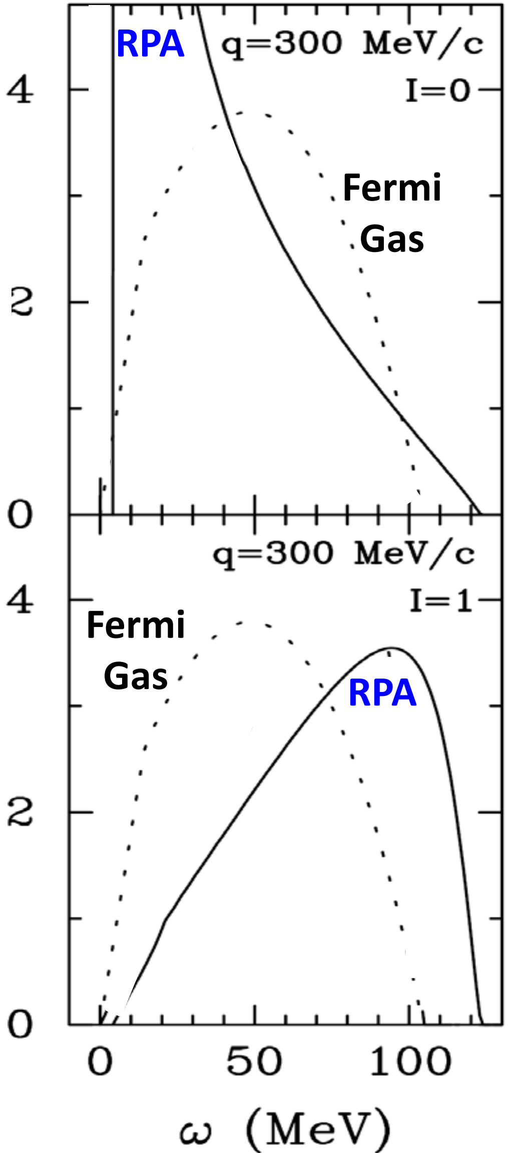


$$\Pi = \Pi^0 + \Pi^0 V \Pi$$

*Force acting on one nucleon is transmitted by the interaction

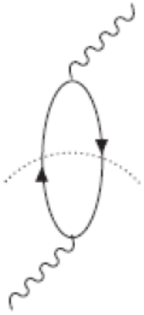
*Shift of the peak with respect to Fermi Gas, decrease, increase,…

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



# Bare polarization propagators

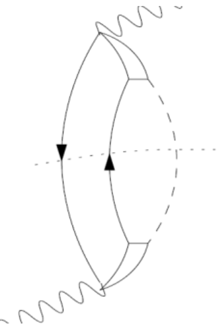
## Quasielastic



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

Nucleon-hole

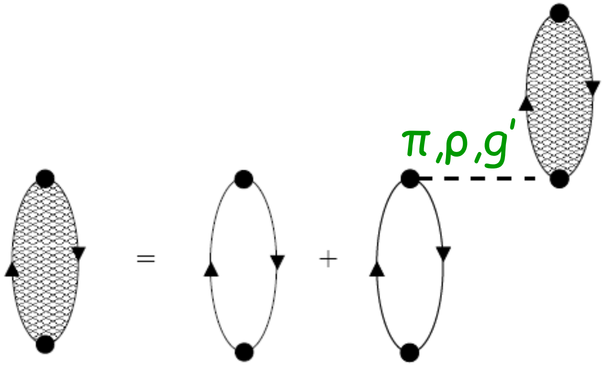
## Pion production



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

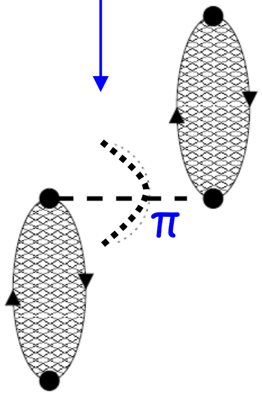
Delta-hole

# Switching on the interaction: random phase approximation



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

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

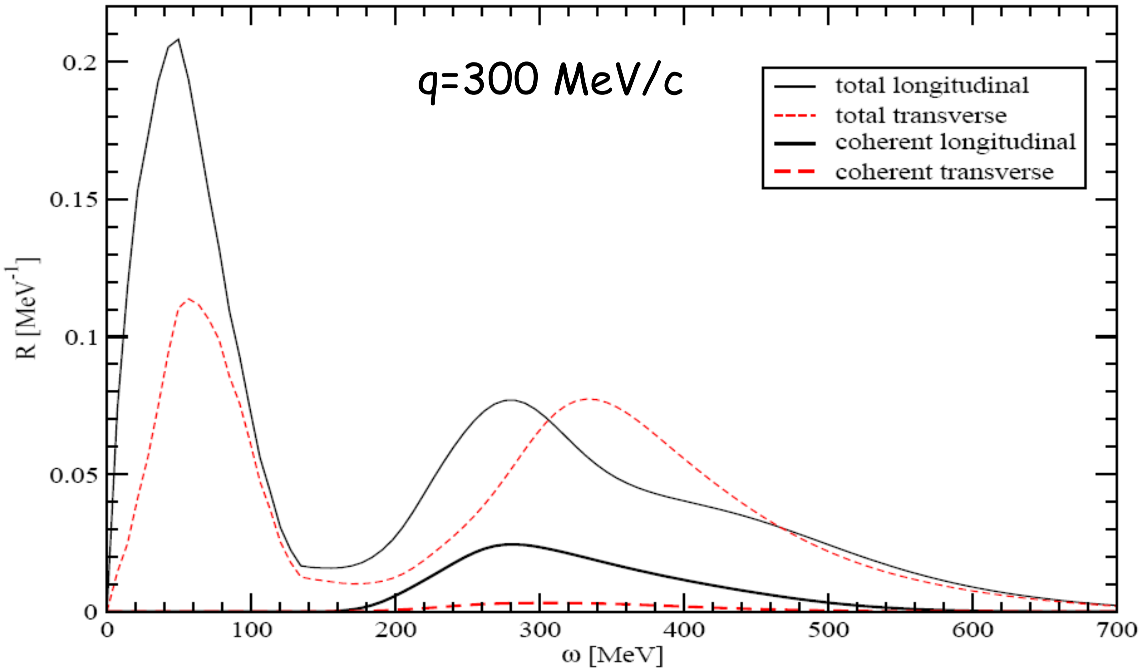


coherent π production

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

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

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



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

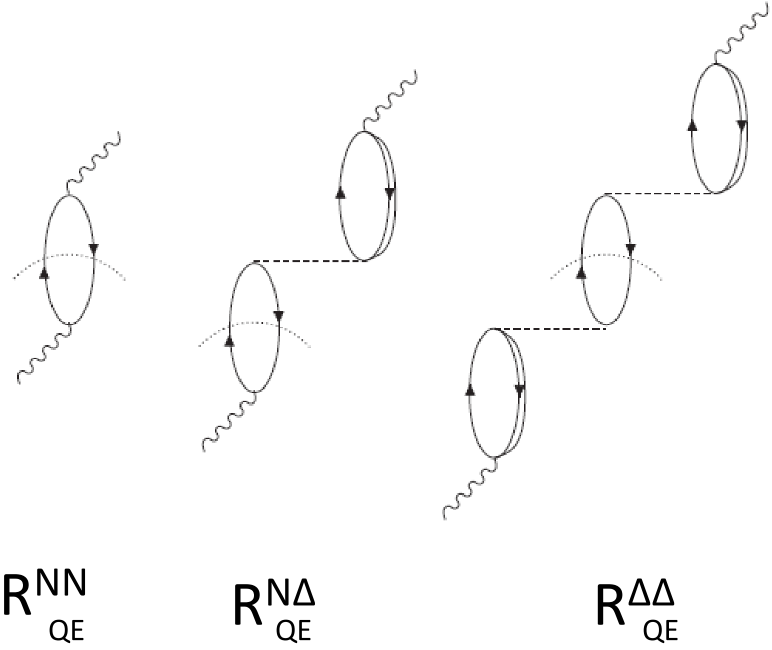
# Effects of the RPA in the ν genuine quasielastic scattering

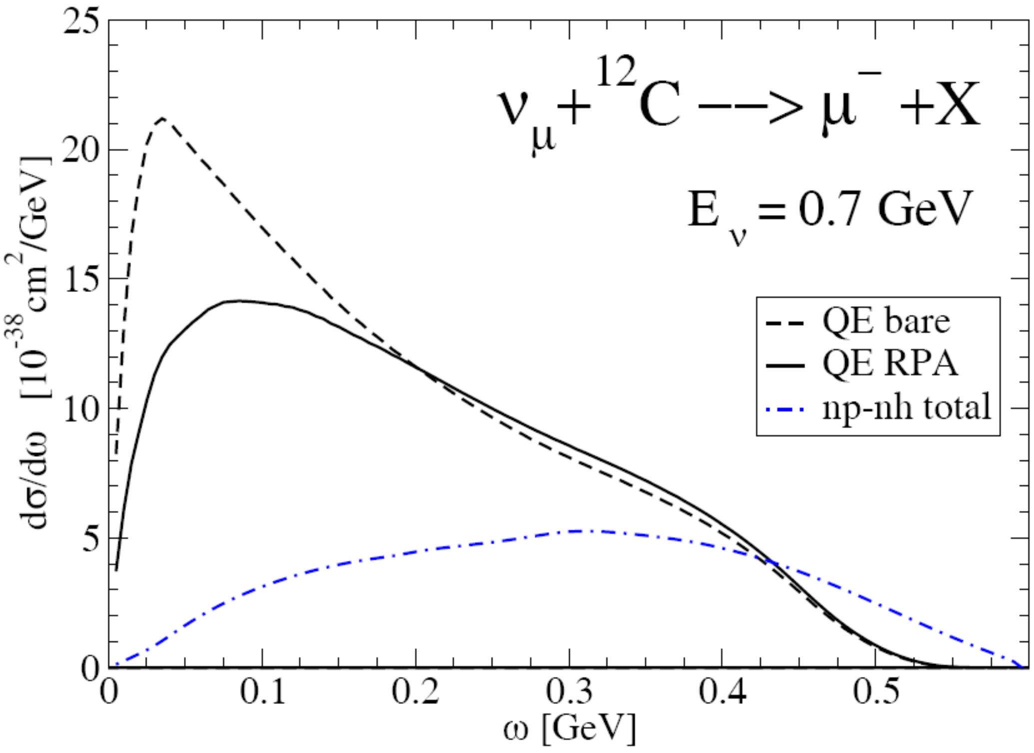
QE totally dominated by isospin spin-transverse response $R_{\sigma\tau(T)}$

RPA reduction

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

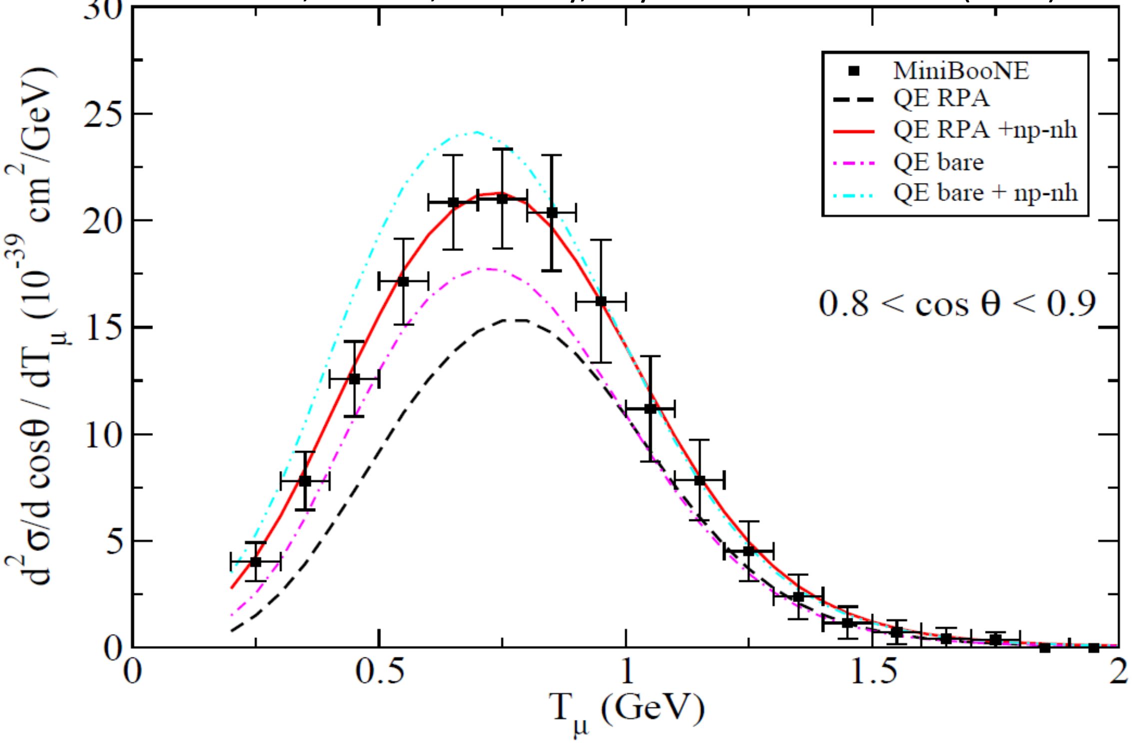
Lowest order contribution to QE

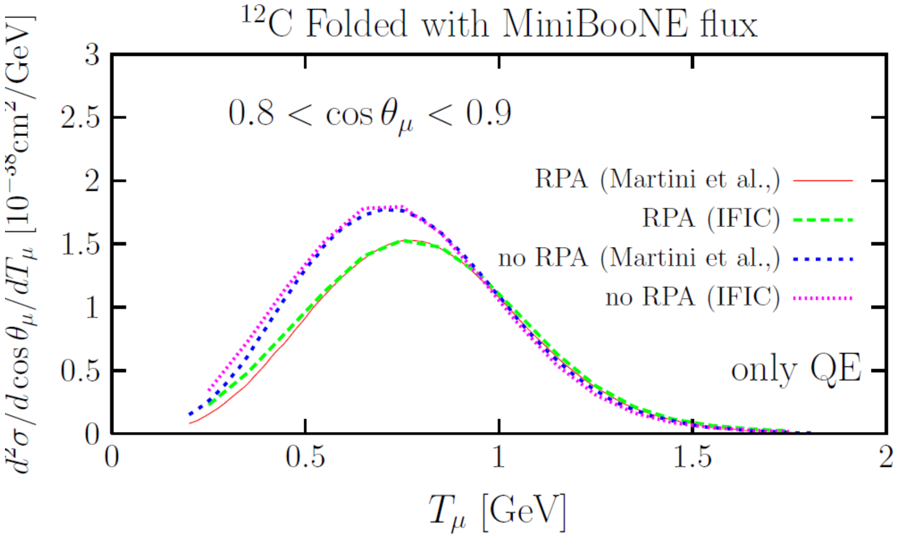


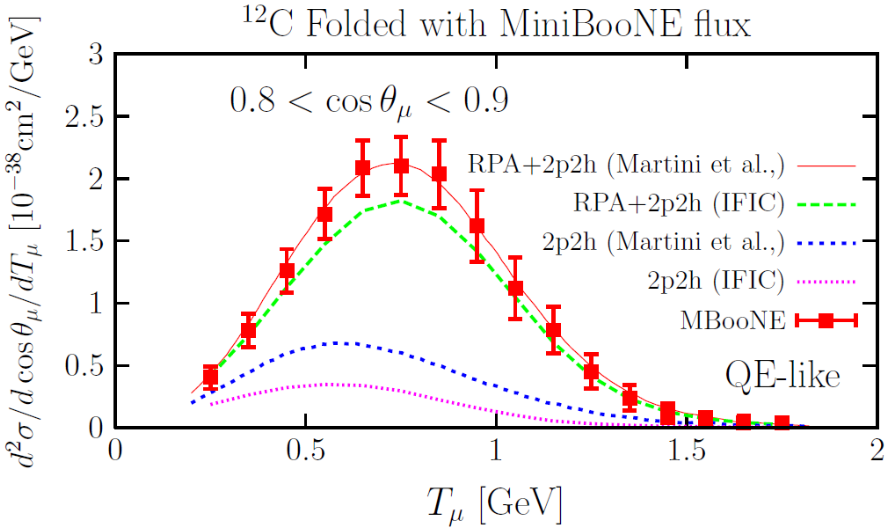


# Flux-integrated ν CCQE double differential X section versus Tμ

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







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

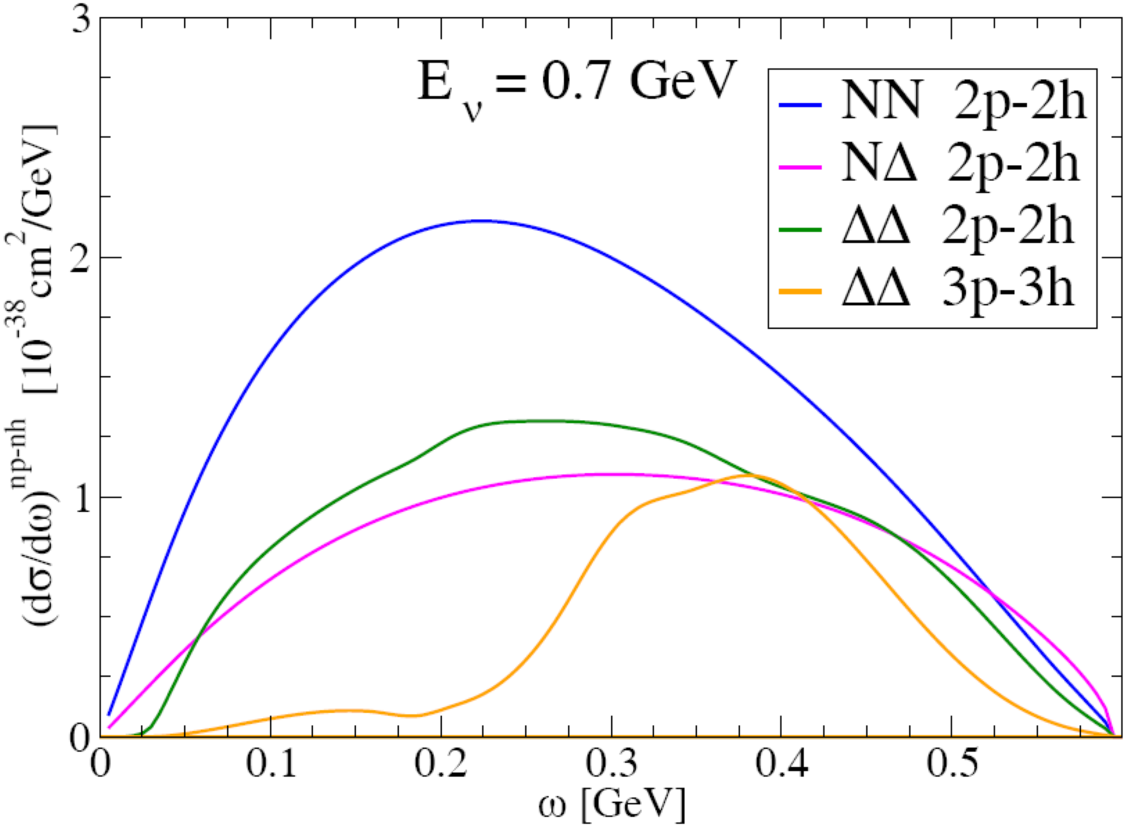
Delicate balance between
RPA quenching and np-nh enhancement

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

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

# Different contributions in the np-nh channel

Martini et al.

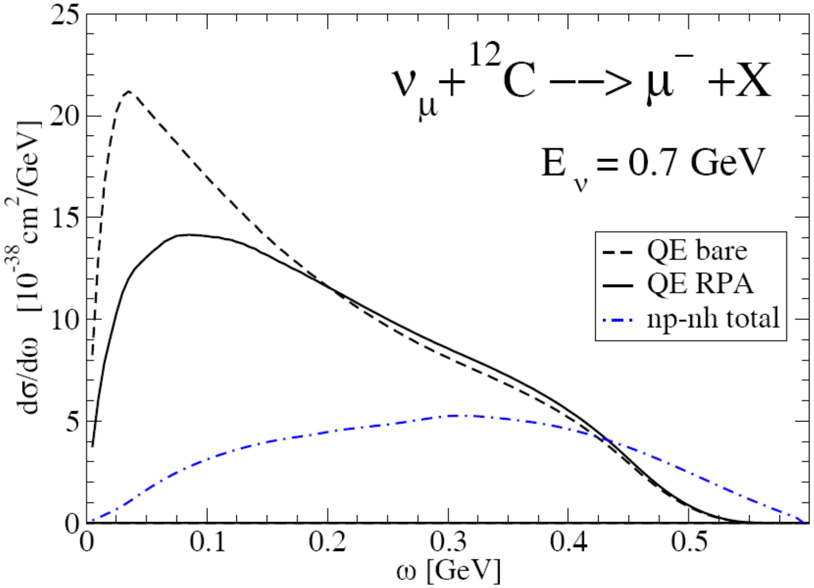


**Correlations**

**Interference**

**MEC**

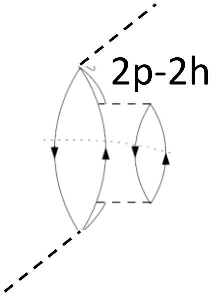
Martini et al.

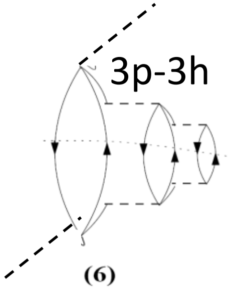


## ΔΔ contributions

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

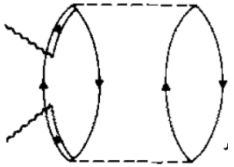
- Not reducible to a modification of the Δ width


2p-2h


3p-3h

(6)

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



# Single nucleon weak CC current

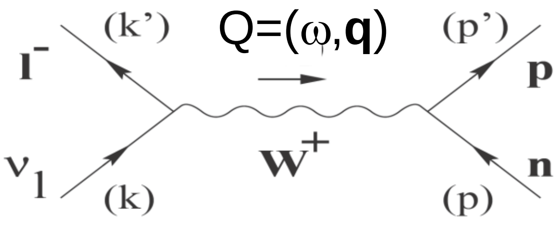
$$j^{\mu} = j_V^{\mu} - j_A^{\mu}$$

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

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

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

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



# Some two-body currents

## Electromagnetic

- Seagull or contact:

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

- Pion-in-flight:

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

- Correlation:

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

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

## Weak

- CC Seagull

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

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

$$-(1 \leftrightarrow 2)$$

# Sources and References of 2p-2h

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

*Alberico, Ericson, Molinari, Ann. Phys. 154, 356 (1984)* (e,e') $\gamma$ $\pi$

**Oset and Salcedo, Nucl. Phys. A 468, 631 (1987)* $\pi$ $\gamma$

*Shimizu, Faessler, Nucl. Phys. A 333,495 (1980)* $\pi$

*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)*

} $\nu$ *pioneer works*

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

*Gil, Nieves, Oset, Nucl. Phys. A 627, 543 (1997)* (e,e') $\gamma$

**Oset and Salcedo, Nucl. Phys. A 468, 631 (1987)* $\pi$ $\gamma$

**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') $\gamma$

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

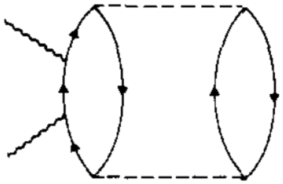
**A. Lovato, S. Gandolfi, J. Carlson, S. C. Pieper, R. Schiavilla**

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

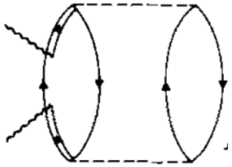
*Shen, Marcucci, Carlson, Gandolfi, Schiavilla, Phys. Rev. C 86 035503 (2012)* $\nu$- deuteron

# Main difficulties in the 2p-2h sector

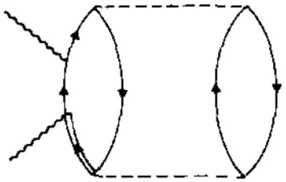
- Huge number of diagrams and terms



**16** from NN correlations



**49** from MEC



**56** from interference

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

fully relativistic calculation (just of MEC !):

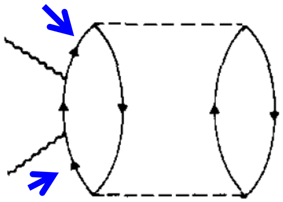
**3000** direct terms    More than **100 000** exchange terms

*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* )

# MEC

## Direct

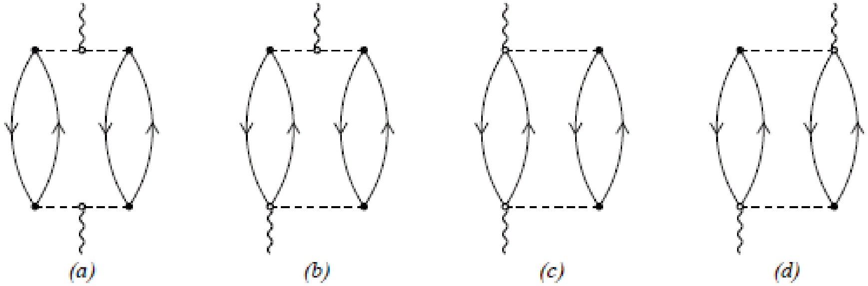


FIG. 2: The direct pionic contributions to the MEC 2p-2h response function.

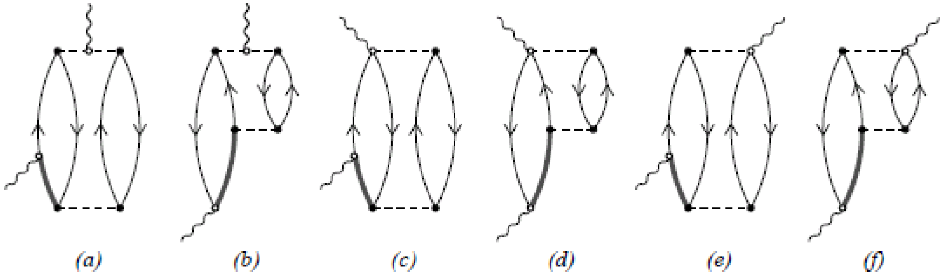


FIG. 3: The direct pionic/Δ interference contributions to the MEC 2p-2h response function.

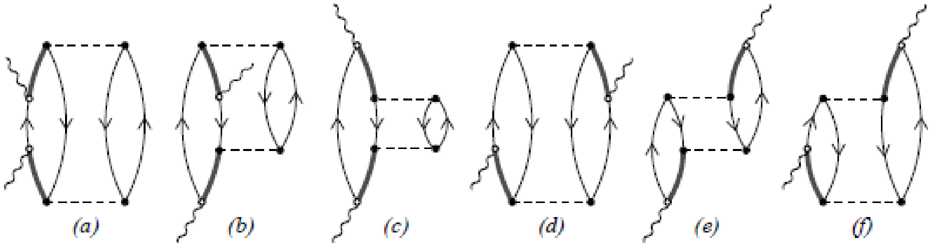


FIG. 4: The direct Δ contributions to the MEC 2p-2h response function.

## Exchange

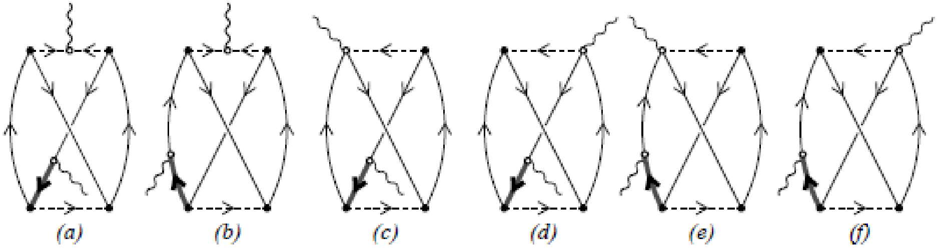


FIG. 5: The exchange pionic/Δ interference contributions to the MEC 2p-2h response function.

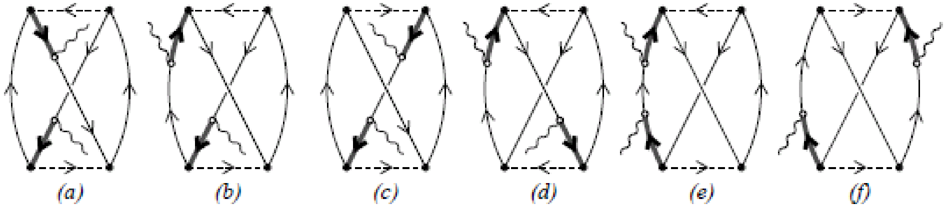


FIG. 6: The exchange Δ contributions to the MEC 2p-2h response function.

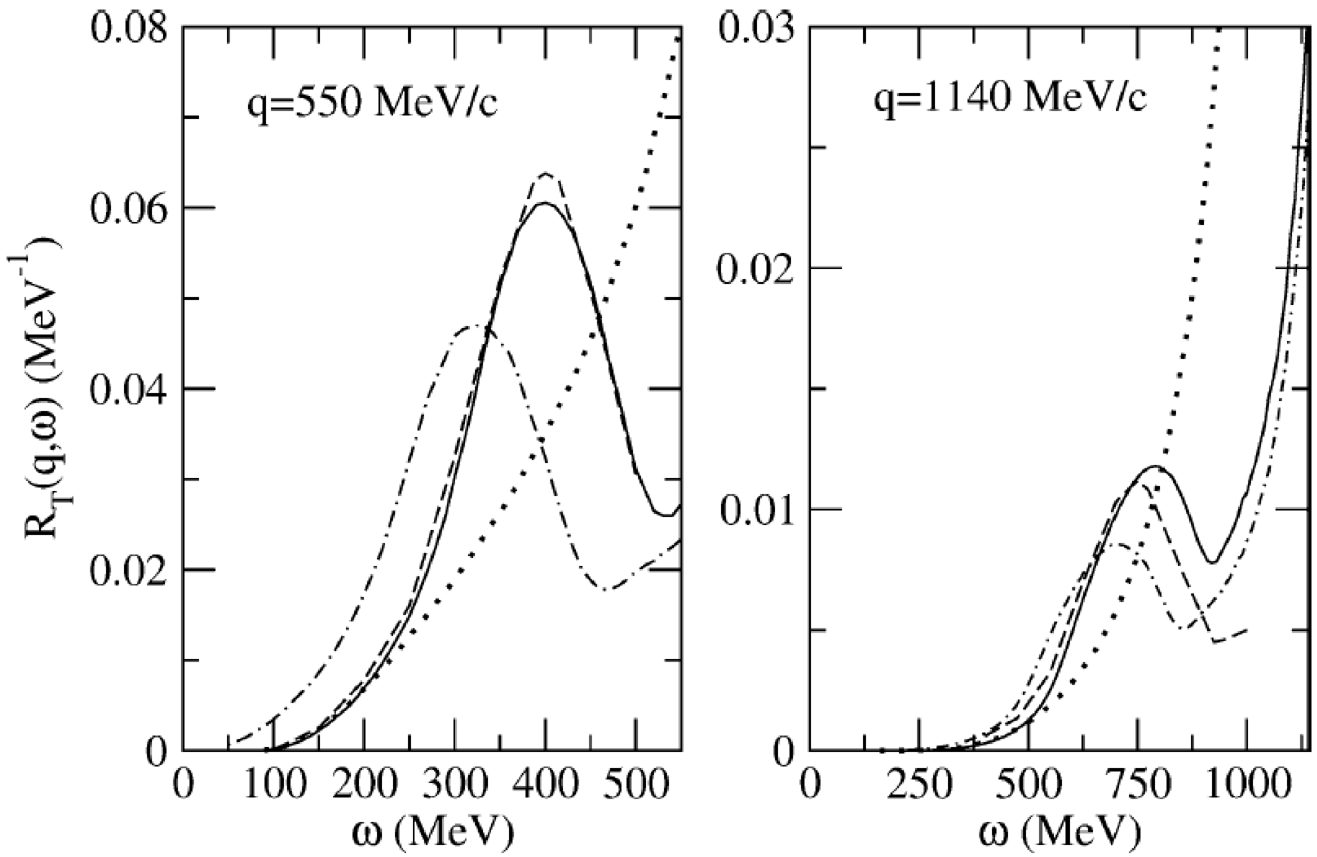


Fig. 8. The relativistic transverse response function $R_T(q,\omega)$ at $q = 550$ MeV$/c$ and $q = 1140$ MeV$/c$ calculated with $\bar{\epsilon}_2 = 70$ MeV (solid) and with $\bar{\epsilon}_2 = 0$ (dot-dashed). Only the direct contribution is shown. The non-relativistic results are also displayed in 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$^{-1}$.

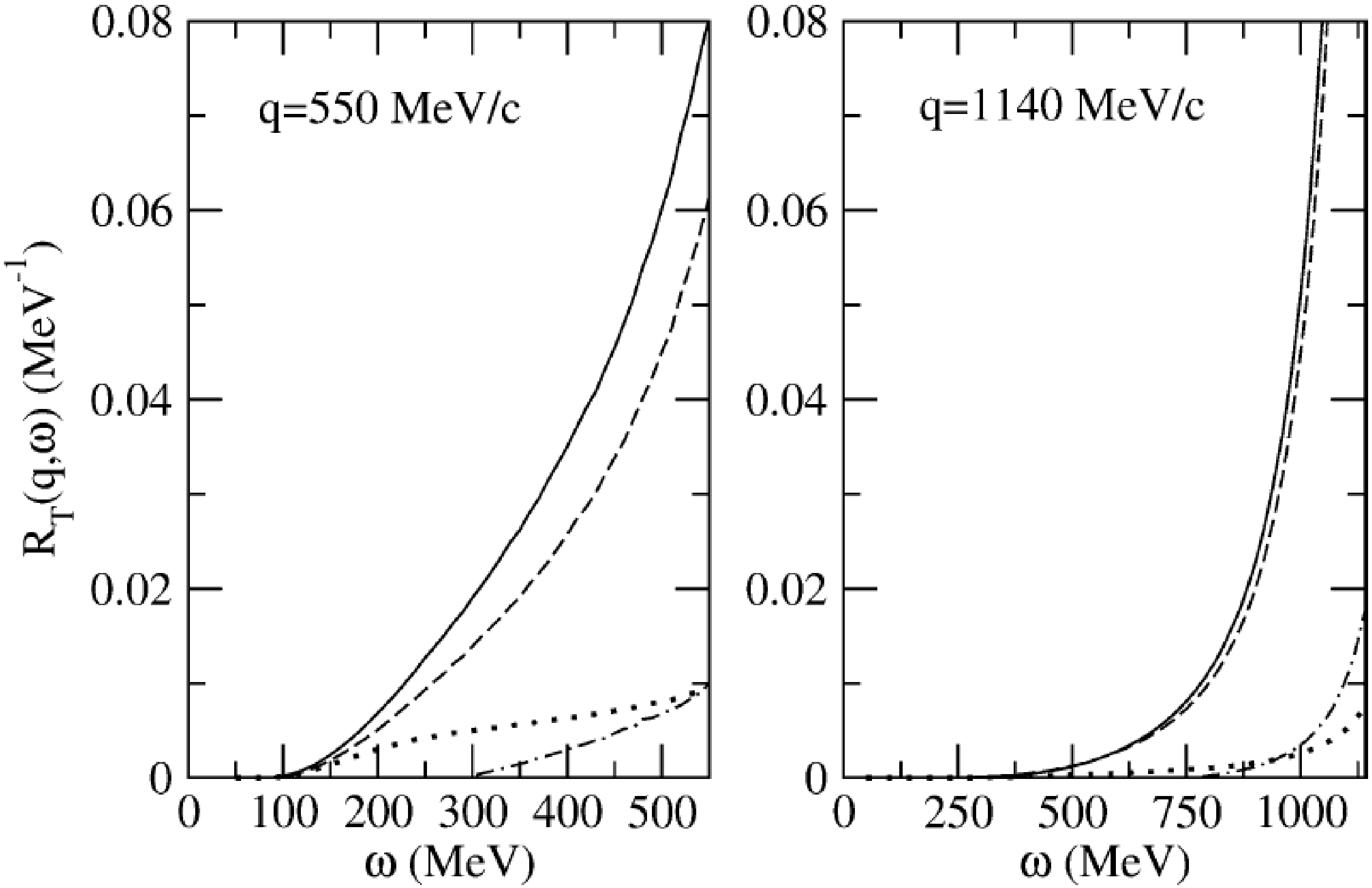


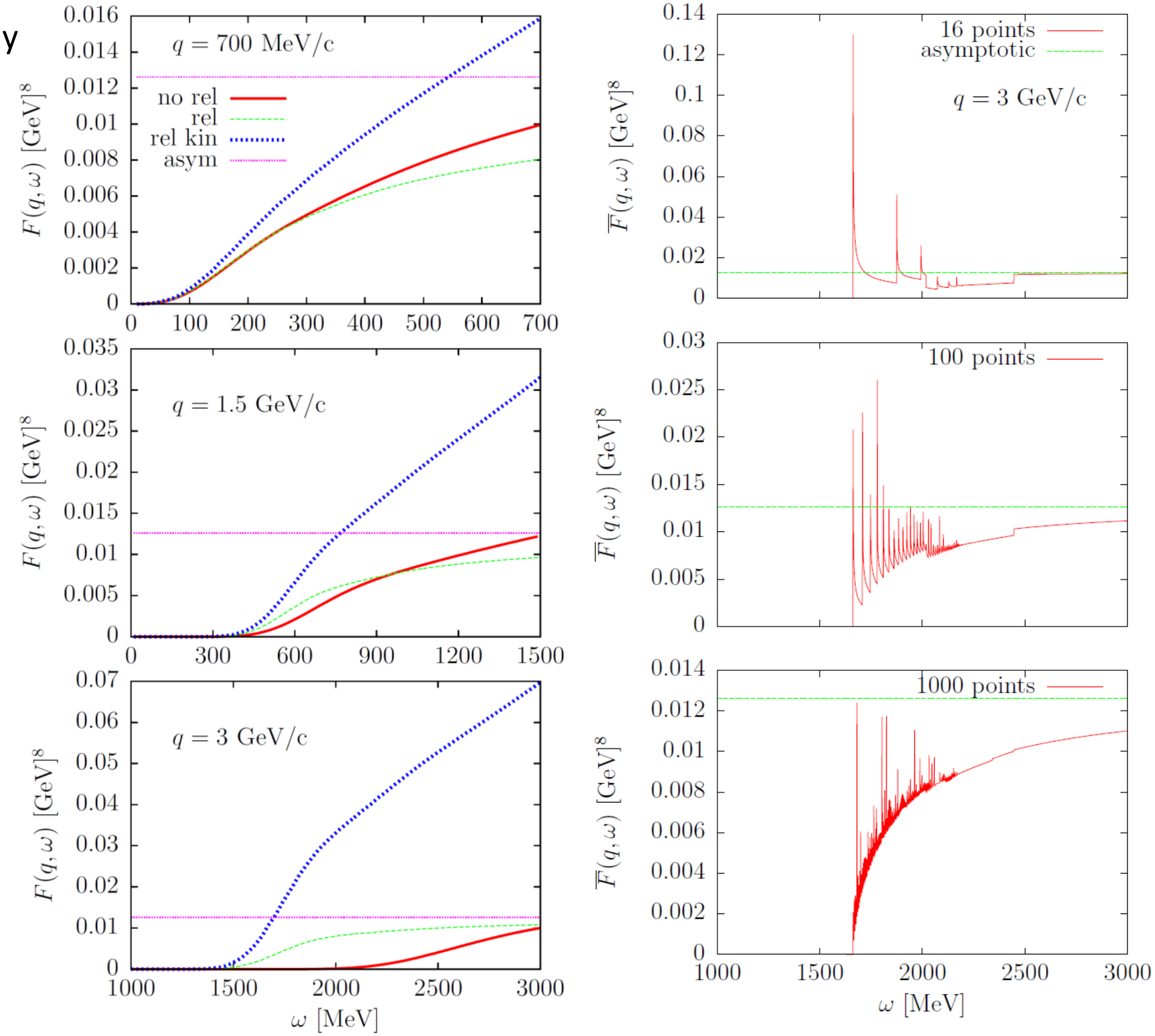
Fig. 9. Separate contributions to the transverse response function $R_T(q,\omega)$ in the non-relativistic limit at $q = 550$ MeV$/c$ and $q = 1140$ MeV$/c$: pionic (dotted), pionic–$\Delta$ interference (dash-dotted), $\Delta$ (dashed) and total (solid); $k_F = 1.3$ fm$^{-1}$. The exchange contribution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

# 2p-2h phase space integral

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

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

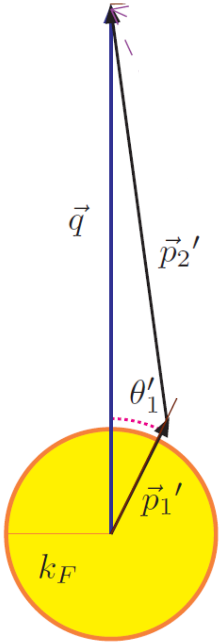
Ruiz Simo, Albertus, Amaro, Barbaro, Caballero, Donnelly
Phys. Rev. D 90 033012 (2014)
Phys. Rev. D 90 053010 (2014)



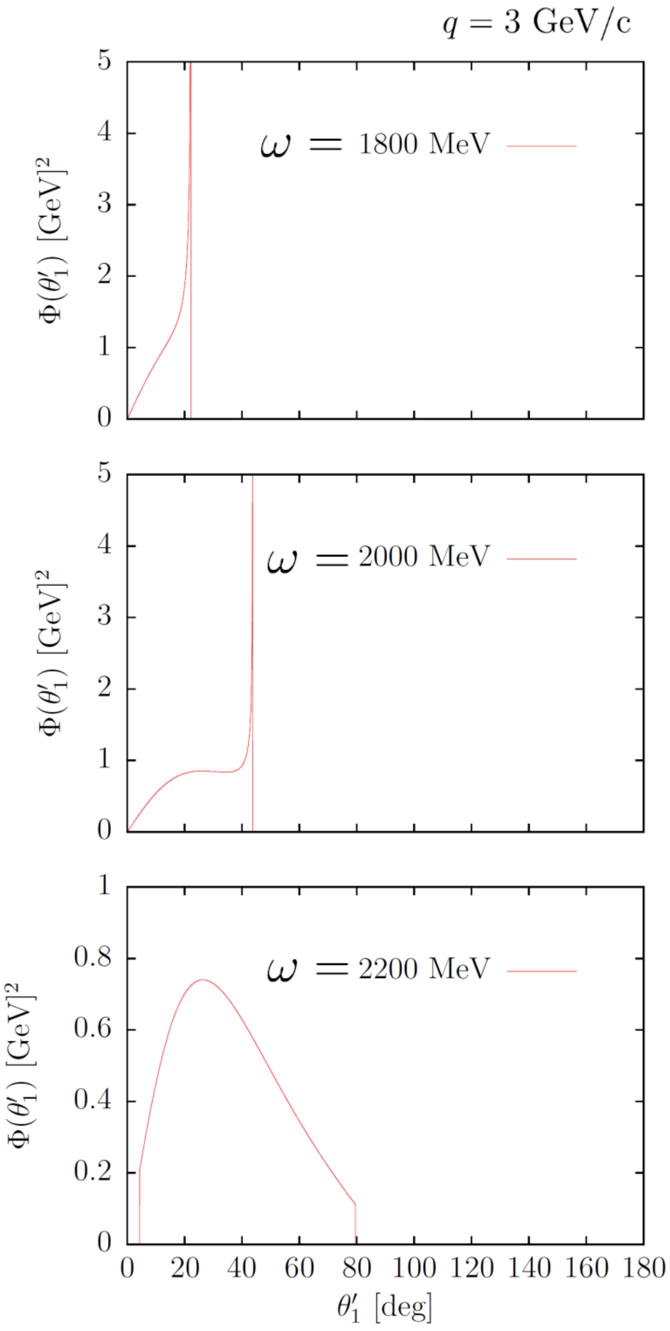
# Angular distribution of ejected nucleons

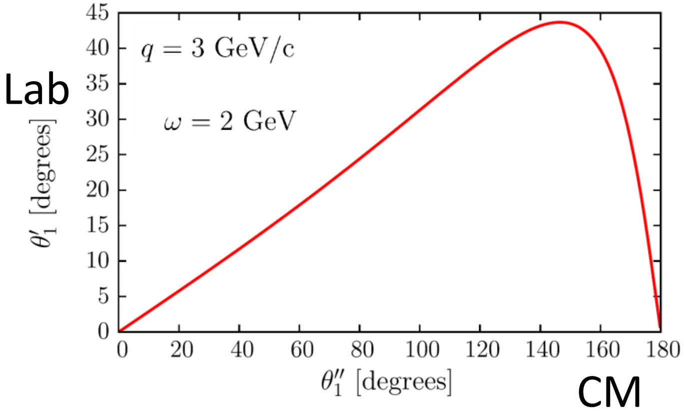
$$\overline{F}(\omega,q) = \left(\frac{4}{3}\pi k_F^3\right)^2 2\pi \int_0^\pi d\theta_1' \, \Phi(\theta_1')$$

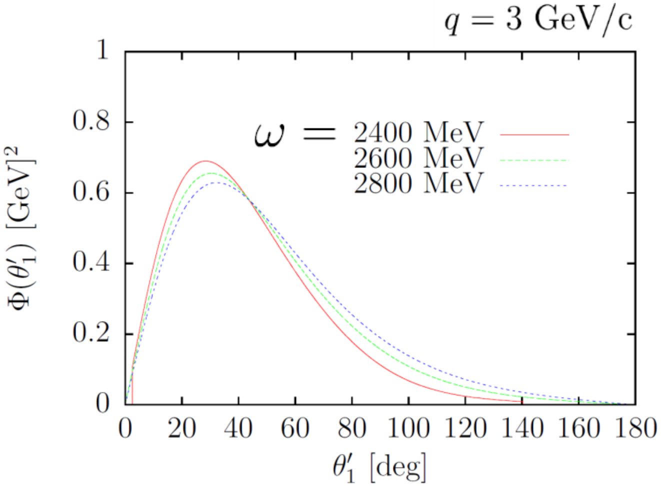
$$\begin{aligned}\Phi(\theta_1') &= \sin\theta_1' \int {p_1'}^2 dp_1' \delta(E_1 + E_2 + \omega - E_1' - E_2') \\ &\quad \times \Theta(p_1', p_2', h_1, h_2) \frac{m_N^4}{E_1 E_2 E_1' E_2'} \\ &= \sum_{\alpha=\pm} \frac{m_N^4 \sin\theta_1' {p_1'}^2 \Theta(p_1', p_2', h_1, h_2)}{E_1 E_2 E_1' E_2' \left| \frac{p_1'}{E_1'} - \frac{\mathbf{p}_2' \cdot \hat{\mathbf{p}}_1'}{E_2'} \right|} \Bigg|_{p_1' = {p_1'}^{(\alpha)}}\end{aligned}$$



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







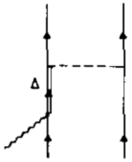
# Analogies and differences of 2p-2h

π,g’

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

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

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



π,ρ,g’

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

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

NN correlations MEC NN correlations - MEC interference Axial and Vector

π

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

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

MEC

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

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

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

NN correlations MEC NN correlations - MEC interference Axial and Vector

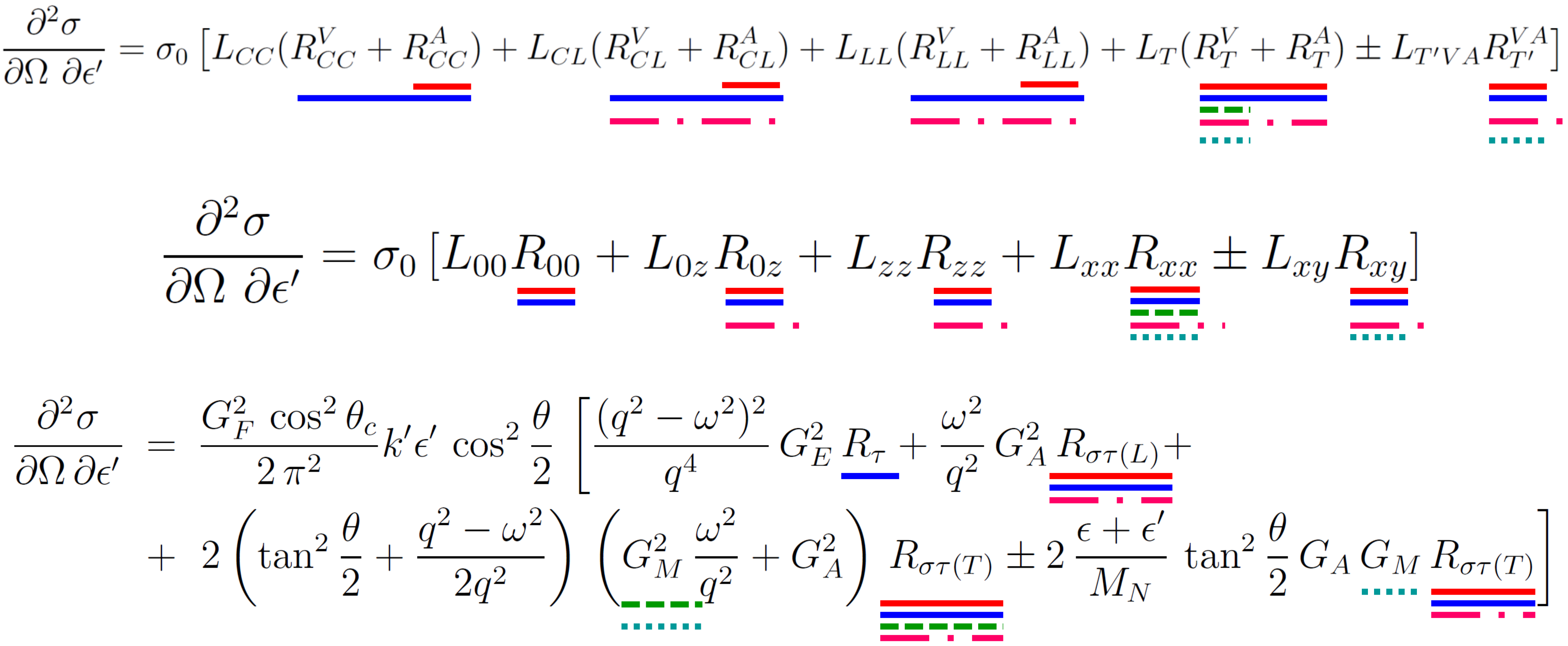
**N.B.**

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

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

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

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



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

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

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

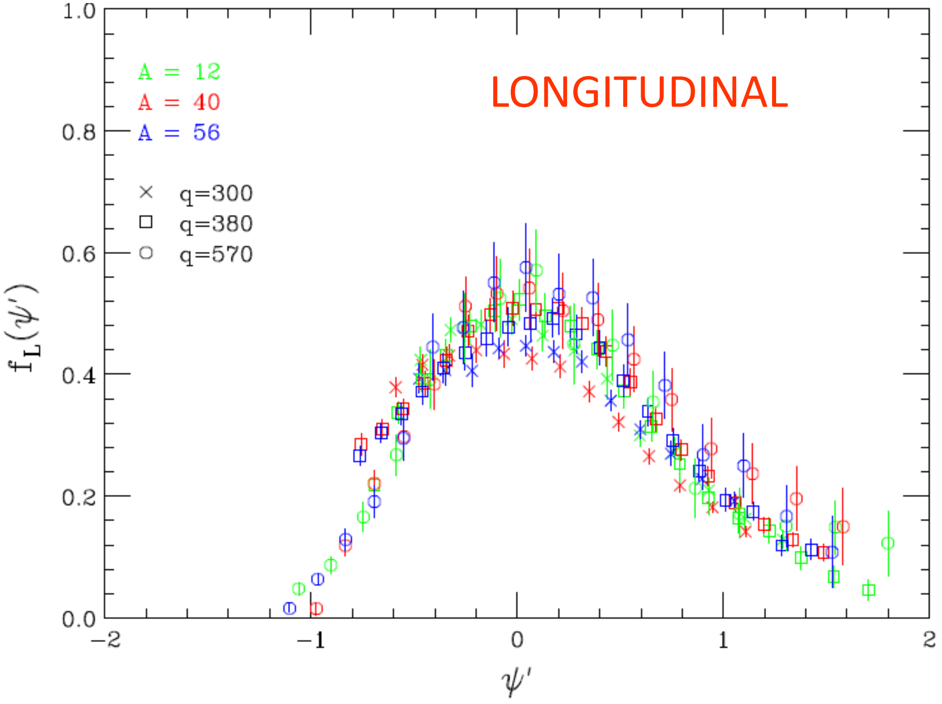
**Relative** role of 2p-2h for neutrinos and antineutrinos is different due to the **interference term**

# Neutrino scattering

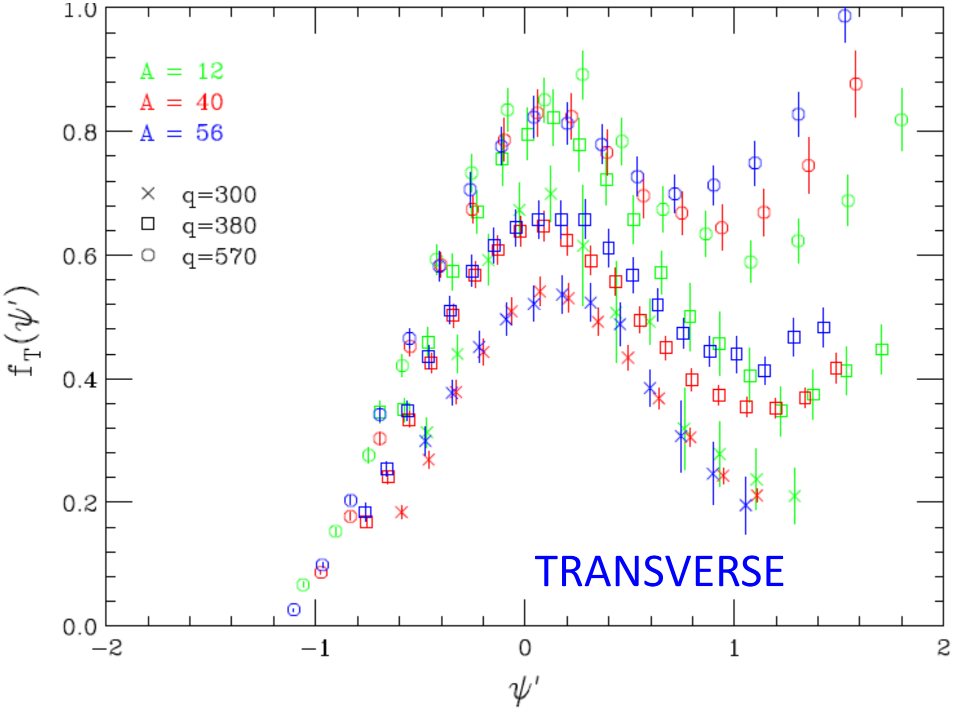
$$\frac{\partial^2\sigma}{\partial\Omega\,\partial\epsilon'} = \frac{G_F^2\,\cos^2\theta_c}{2\,\pi^2}k'\epsilon'\,\cos^2\frac{\theta}{2}\left[\frac{(q^2-\omega^2)^2}{q^4}G_E^2\,\underline{R_\tau}+\frac{\omega^2}{q^2}G_A^2\,\underline{R_{\sigma\tau(L)}}+\right.$$
$$\left. +\;2\left(\tan^2\frac{\theta}{2}+\frac{q^2-\omega^2}{2q^2}\right)\left(\underline{G_M^2}\fra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

# Electron scattering

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



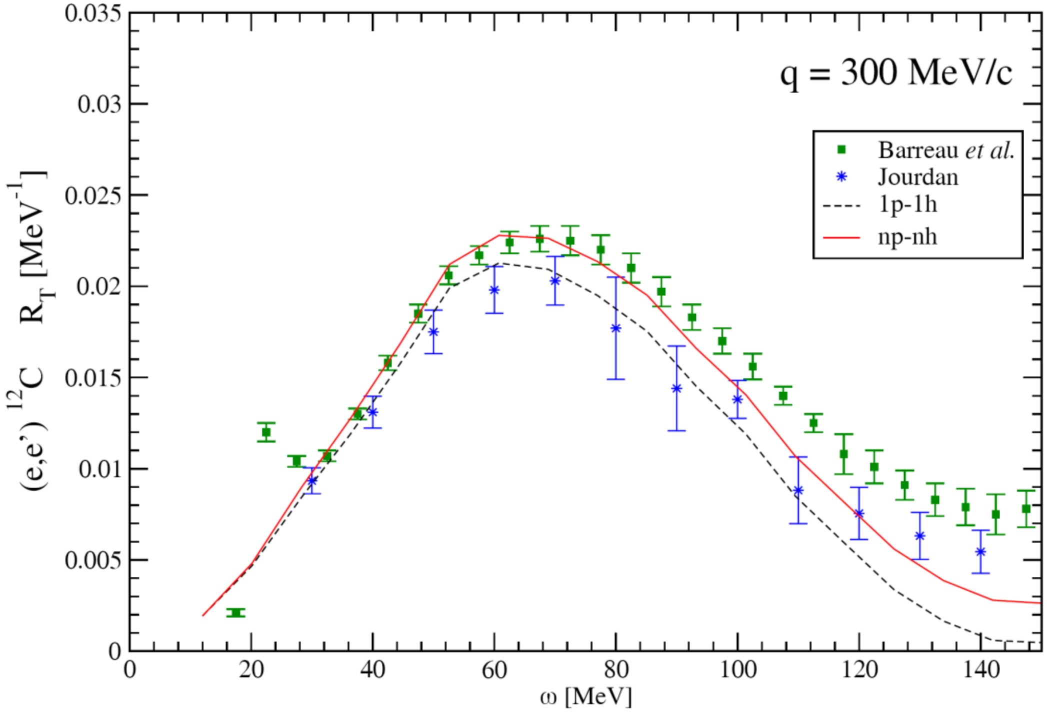
*Donnelly et al. PRC 60 '99,…*



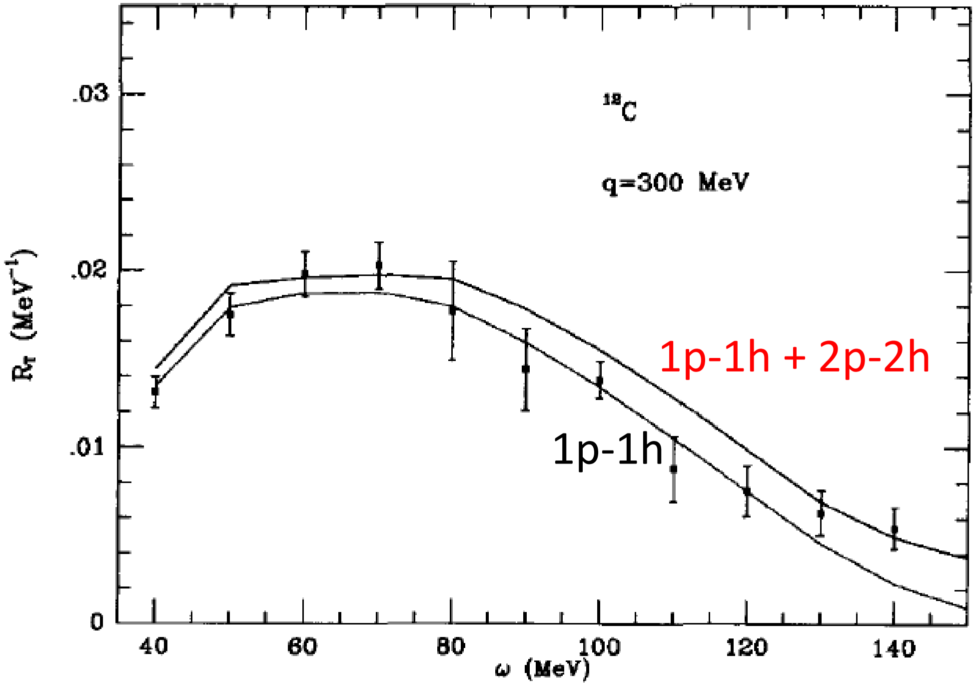
Excess in the transverse channel likely due to 2-body currents (MEC and correlations)

# $R_T$ of $^{12}$C: comparison with data and with calculations of Gil et al.

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



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



The evaluations of 2p-2h contributions to $R_T$ are compatible among them and with data.

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

# Neutrino-nucleus cross section

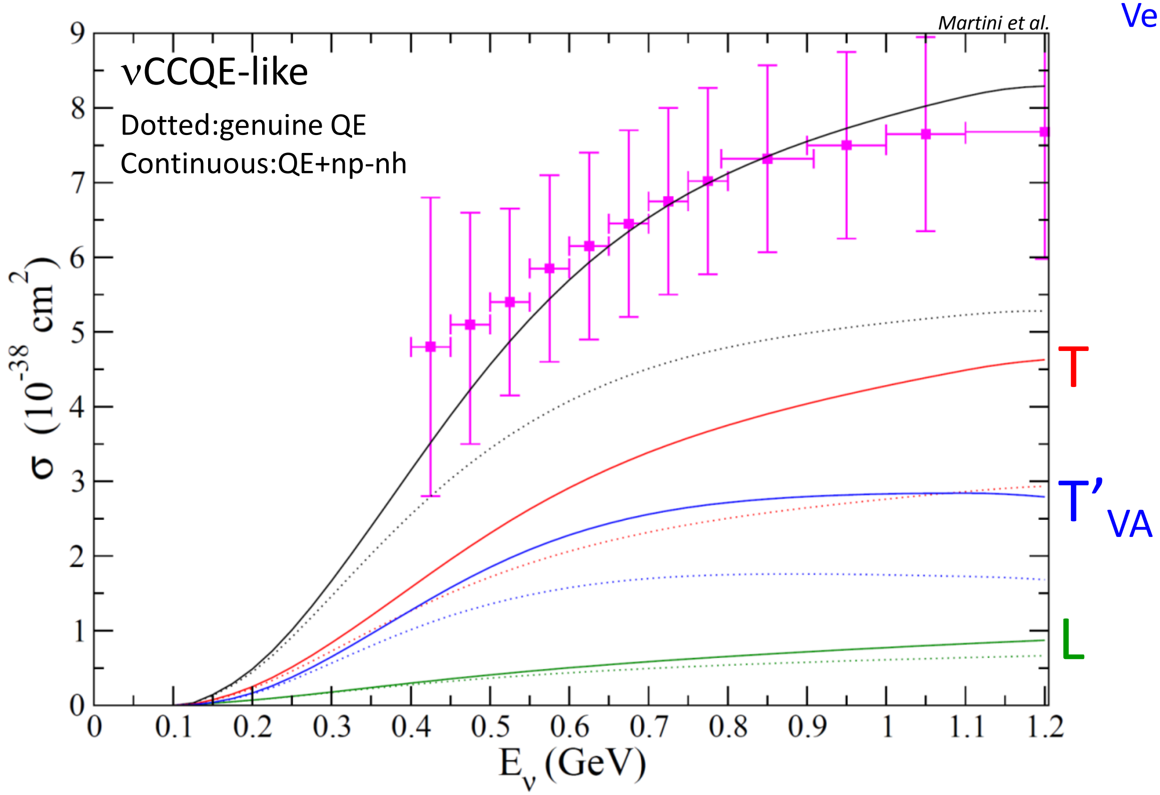
## Two equivalent expressions:

The notation for example of Amaro et al:

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

The notation of Lovato et al:

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



# A third simplified expression (useful for illustration)

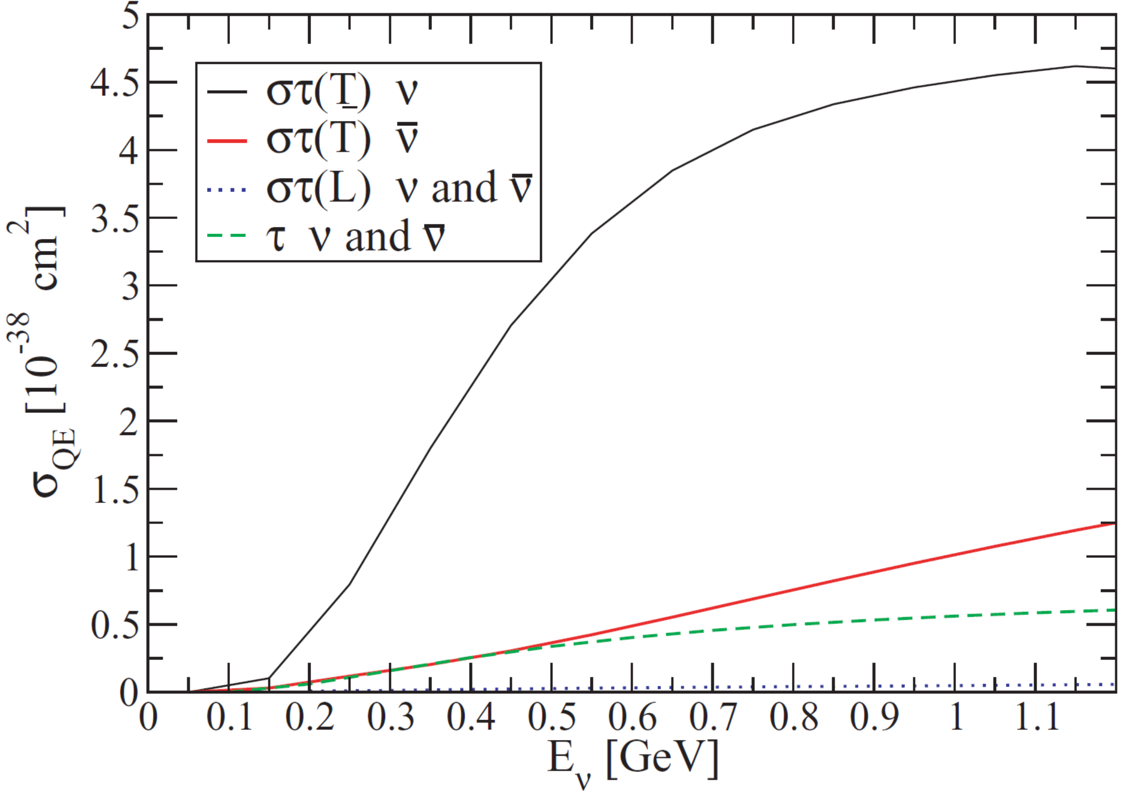
Resp. Functions: Charge $R_\tau$ ($\tau$), Isospin Spin-Longitudinal $R_{\sigma\tau(L)}$($\tau\ \sigma\bullet q$), Isospin Spin Transverse $R_{\sigma\tau(T)}$ ($\tau\ \sigma x q$)

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

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

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

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



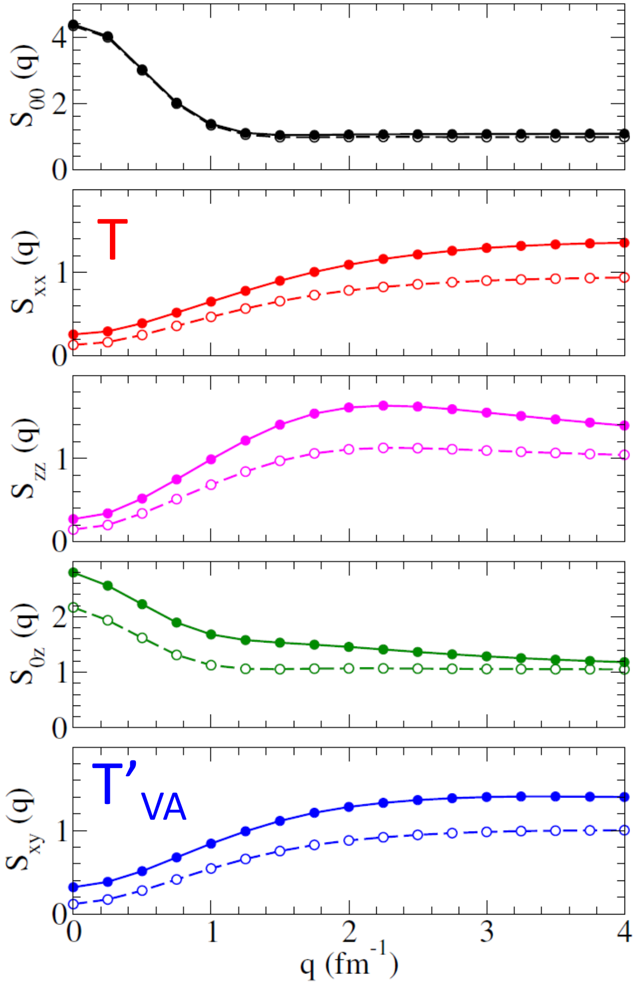
The relative weight of the 3 different nuclear responses (**$R_\tau$** , **$R_{\sigma\tau(L)}$** , **$R_{\sigma\tau(T)}$** ) is different for neutrinos and antineutrinos due to the Vector-Axial interference term

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

## Sum rules of NC

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

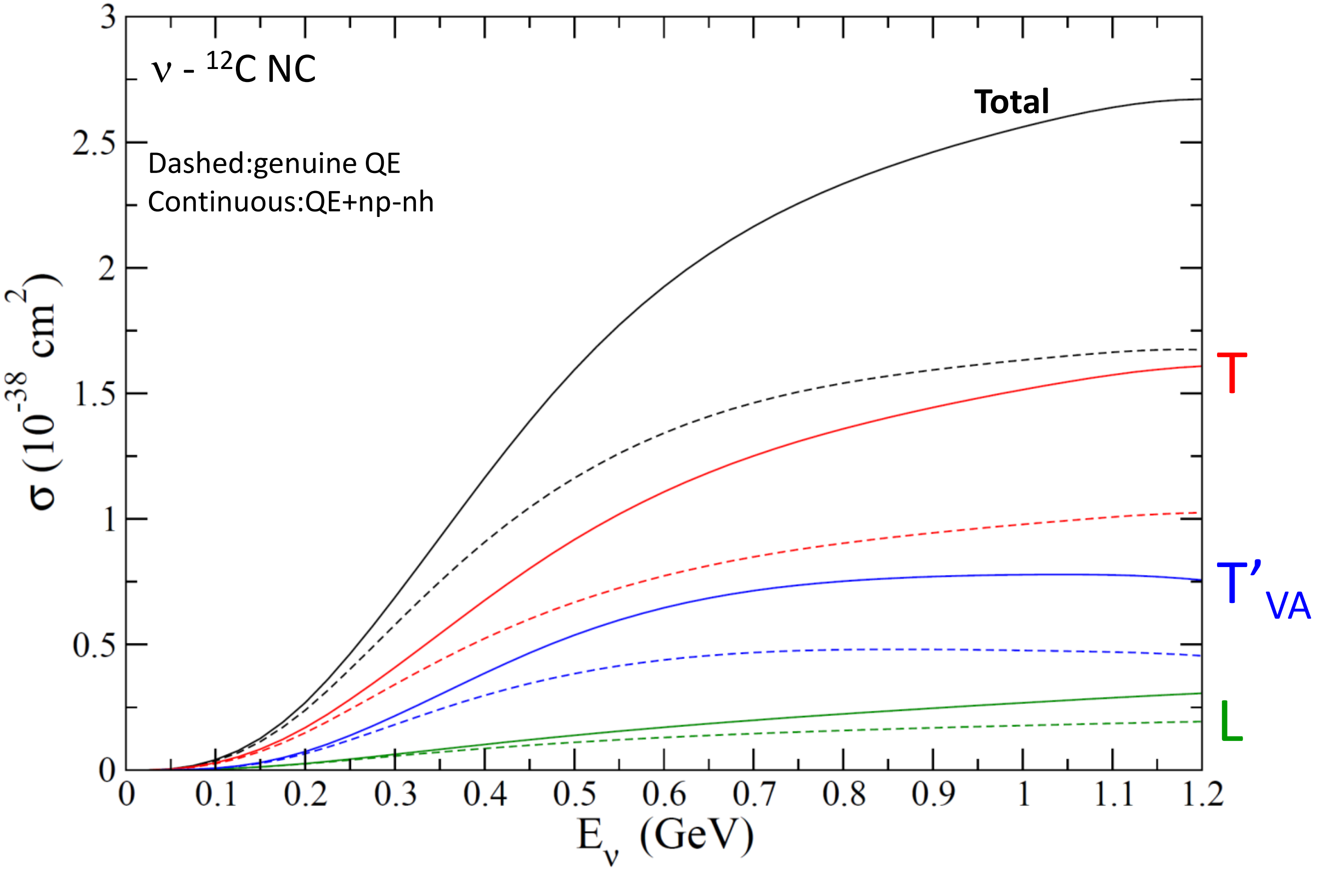
*Lovato et al. PRL 112 182502 (2014)*



## Cross section

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

*Martini et al.*

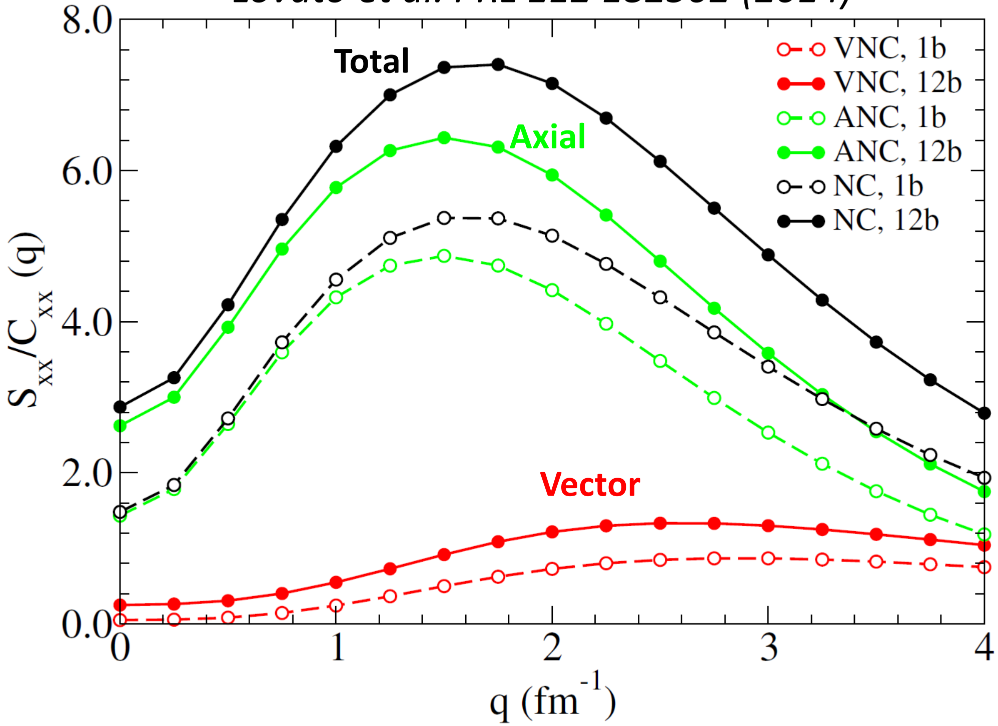


In both approaches 2p-2h are important in **all components** (but the charge)

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

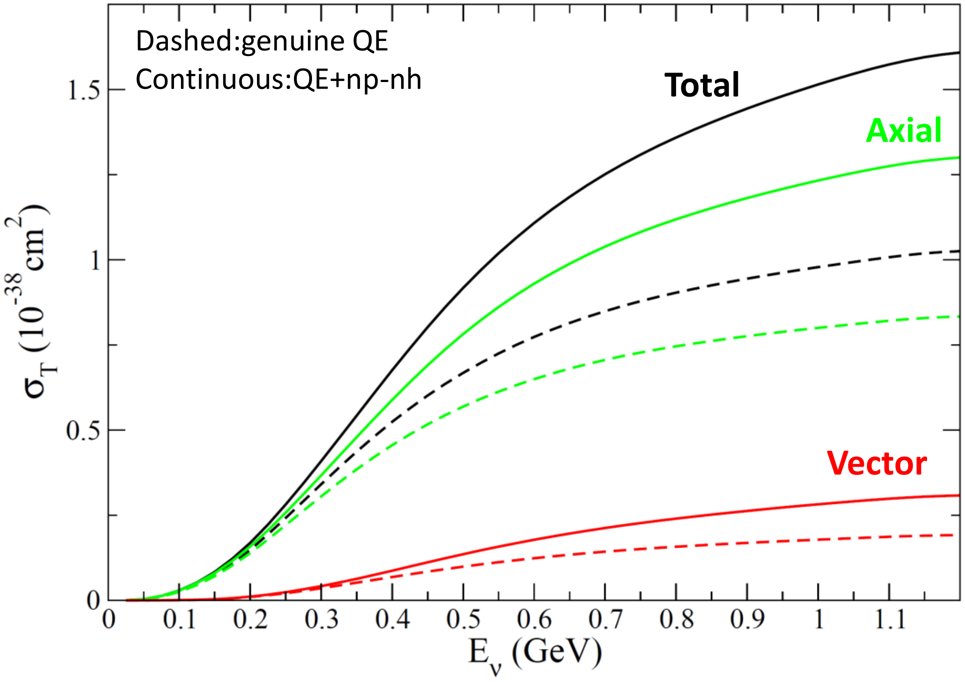
Sum rule of the Transverse response multiplied by the form factors

*Lovato et al. PRL 112 182502 (2014)*



Transverse contribution to the NC cross section

*Martini et al.*



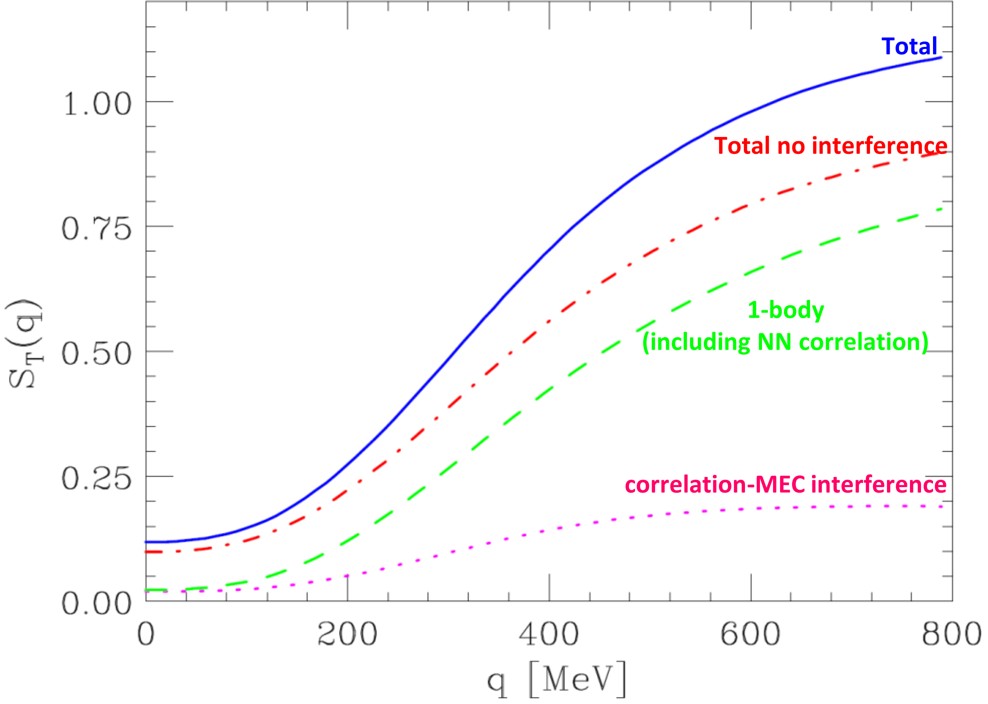
In both approaches, similar behavior:

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

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

## Sum rule of the transverse response

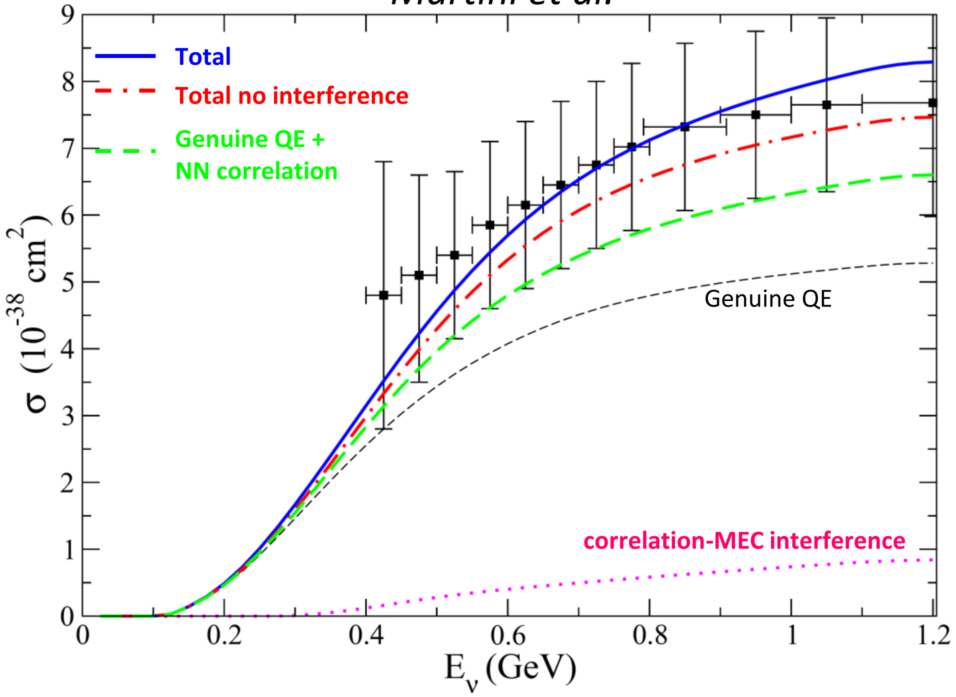
*Benhar, Lovato, Rocco, arXiv :1312.1210*



- Sum rule function of q
- Only Vector Transverse

## Neutrino CCQE-like cross section

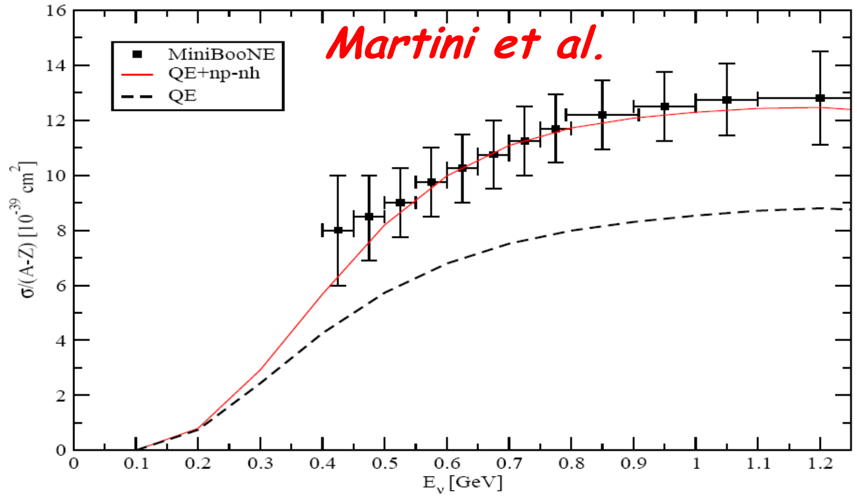
*Martini et al.*

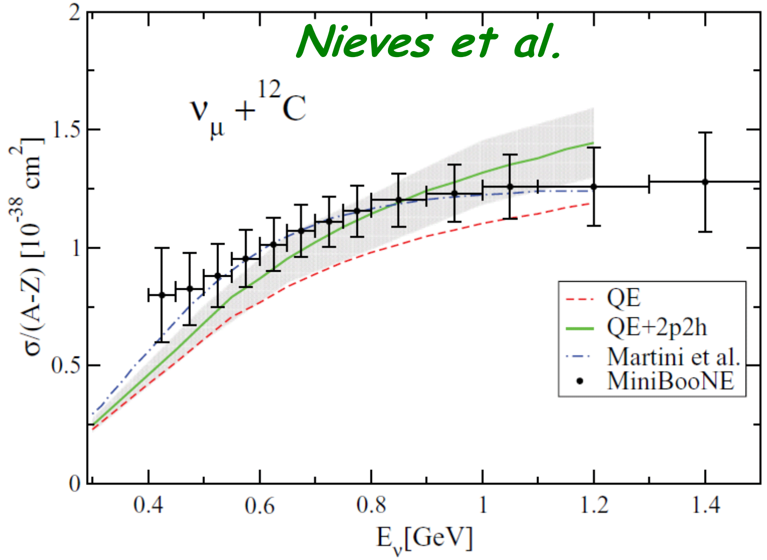


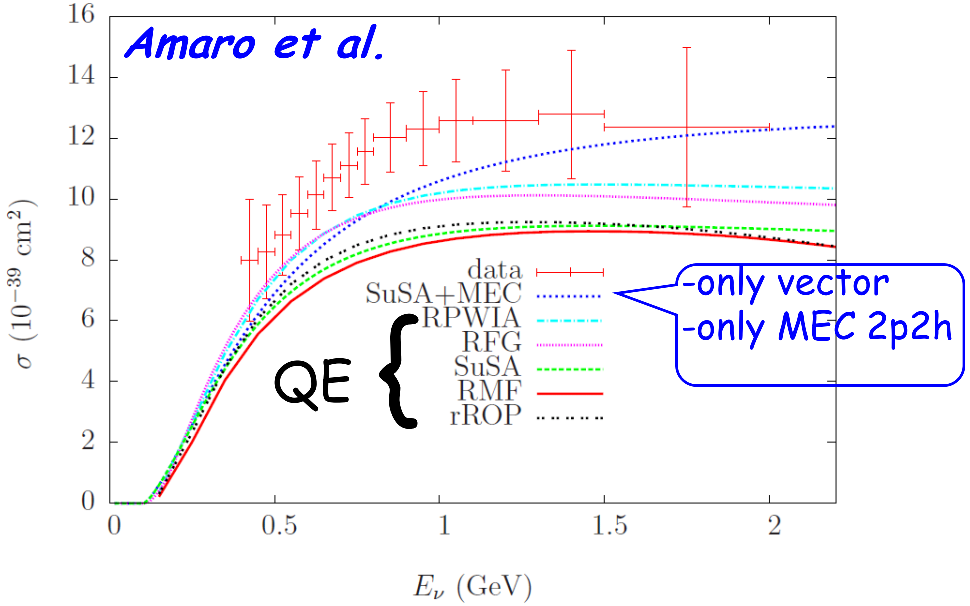
- Cross section function of $E_\nu$
- Total

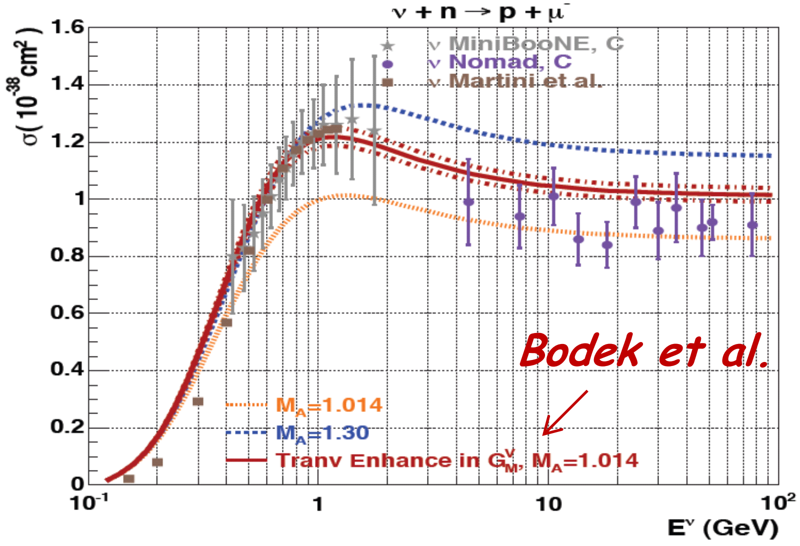
No problem in our approach with the so called "1 nucleon – 2 nucleon currents interference"

# Total CCQE and comparison with flux unfolded MB





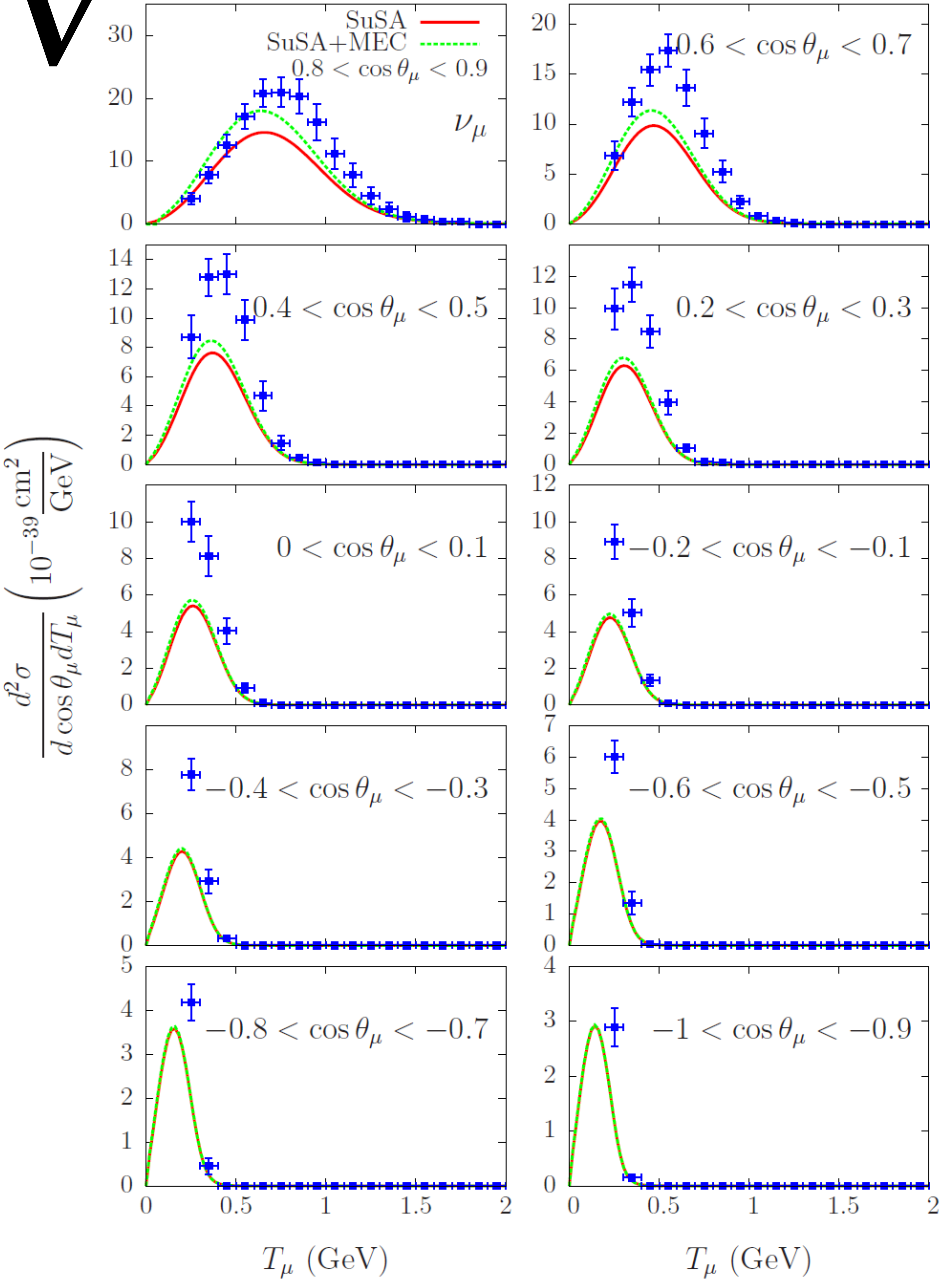




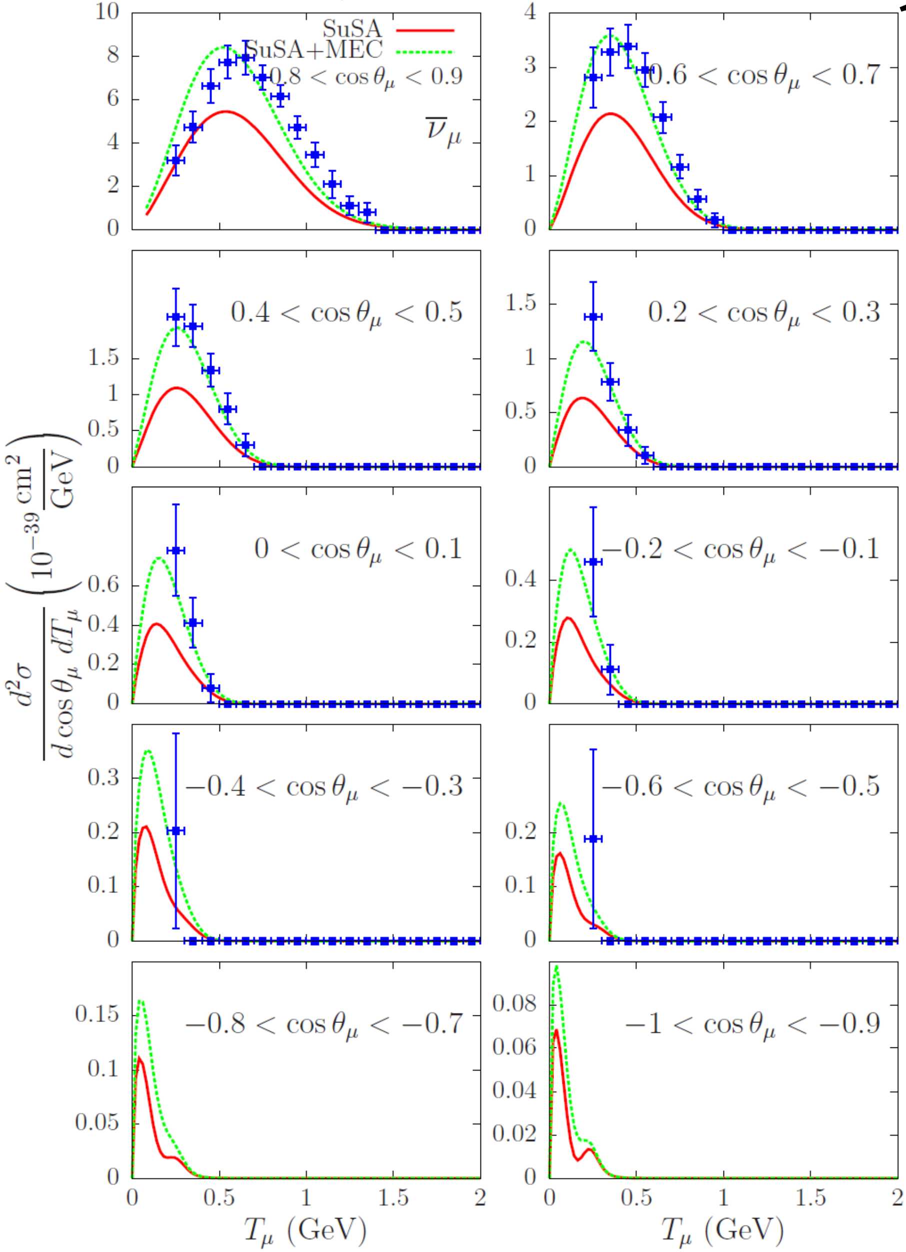
N.B. The experimental unfolding is model dependent

# Amaro et al.

$\nu$ Phys. Lett. B 696 151-155 (2011)



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

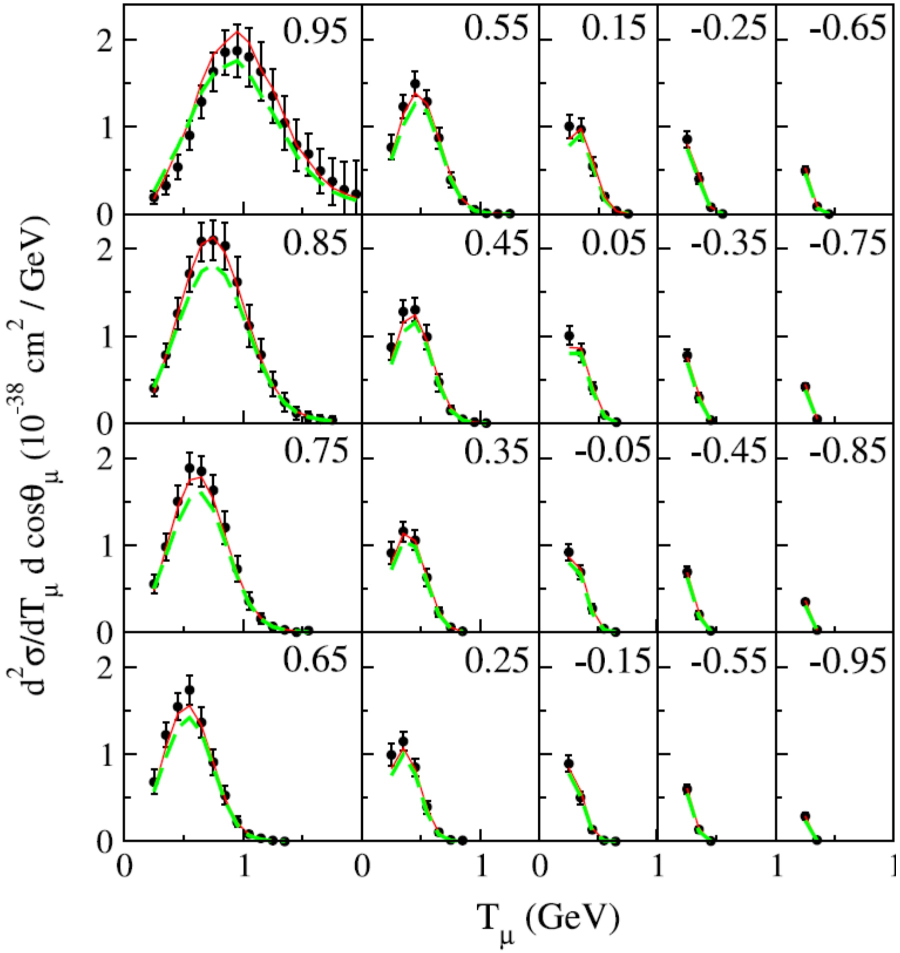


$\nu$

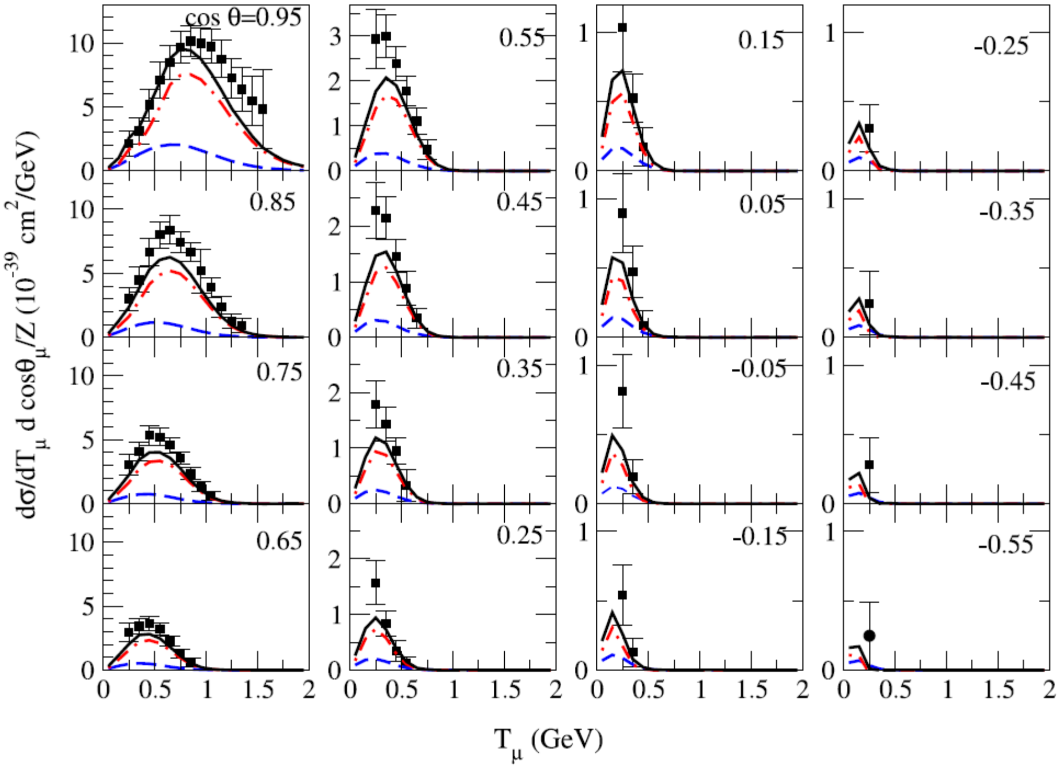
# Nieves et al.

$\bar{\nu}$

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



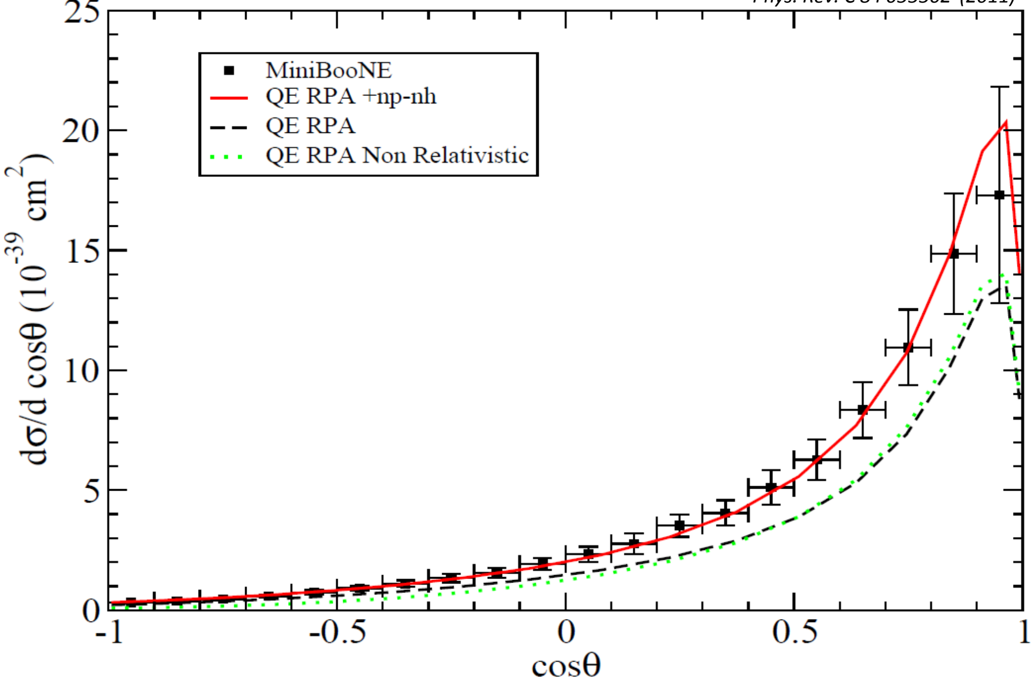
Phys. Lett. B 721 90-93 (2013)



# dσ/dcosθ

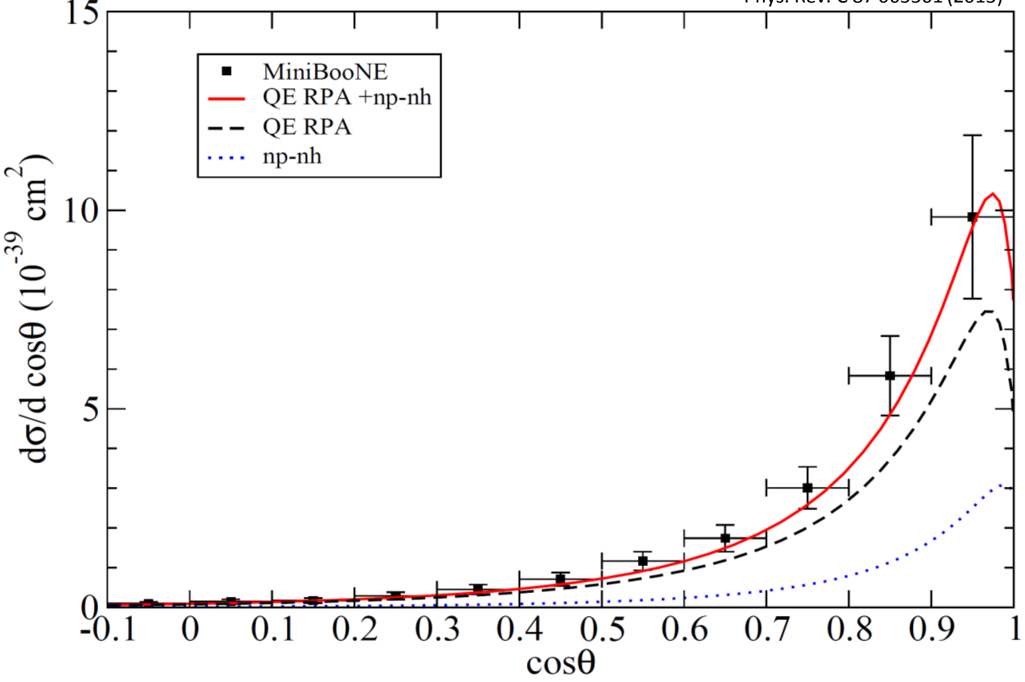
$\nu$

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

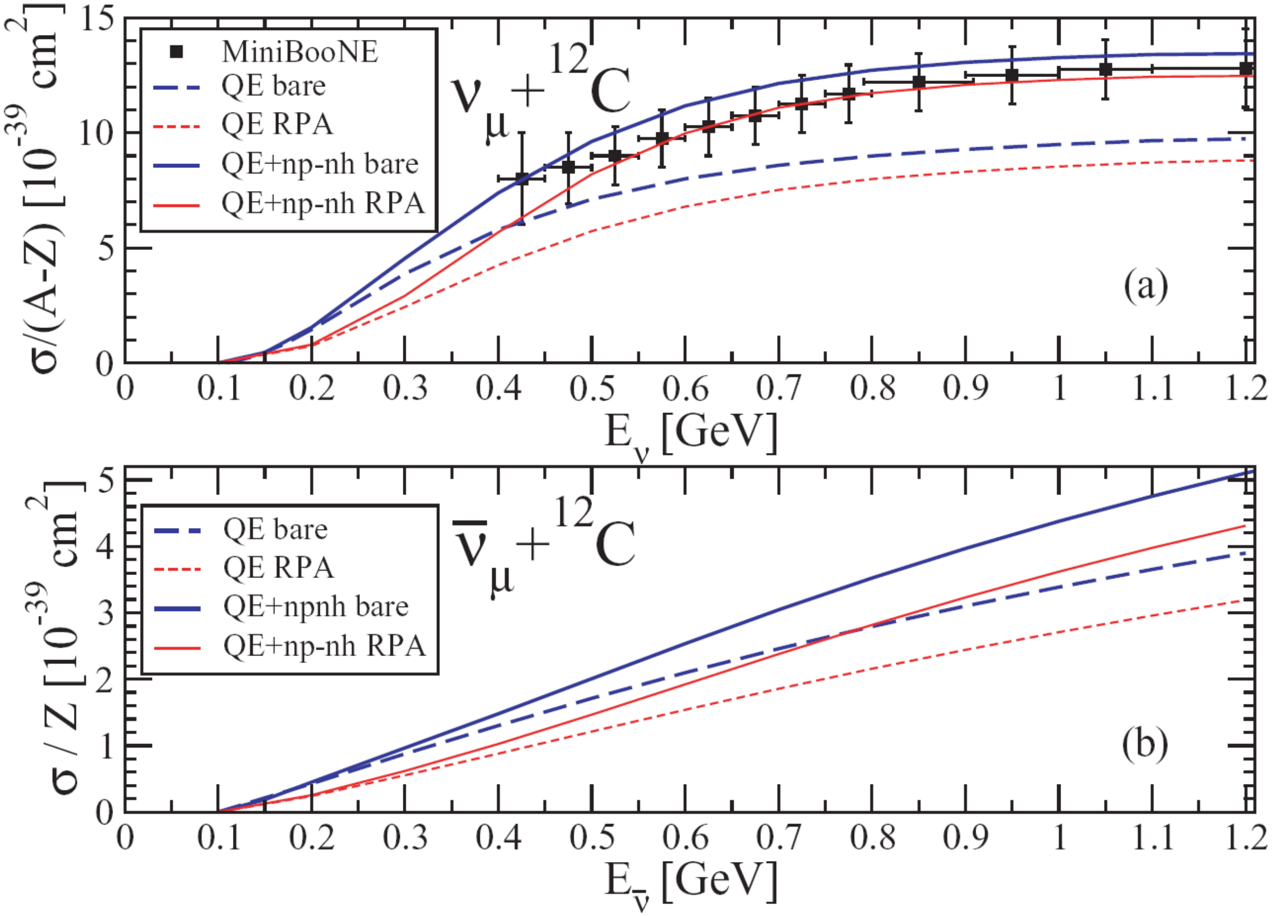


$\bar{\nu}$

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



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



**Relative** role of 2p-2h smaller for antineutrinos

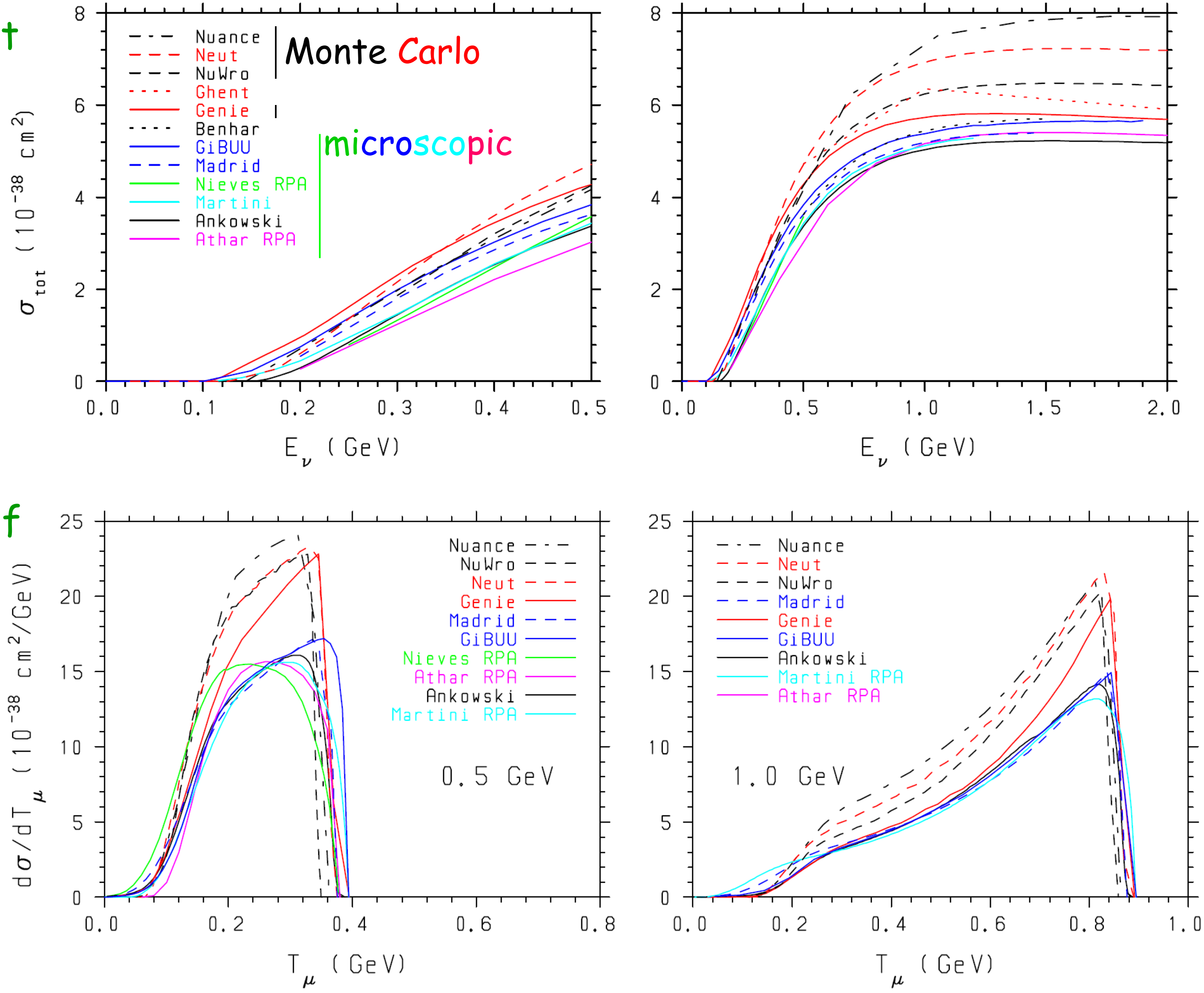
Antineutrino X section very sensitive to RPA

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

# Comparison of Models of Neutrino-Nucleus Interactions

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

QE tot



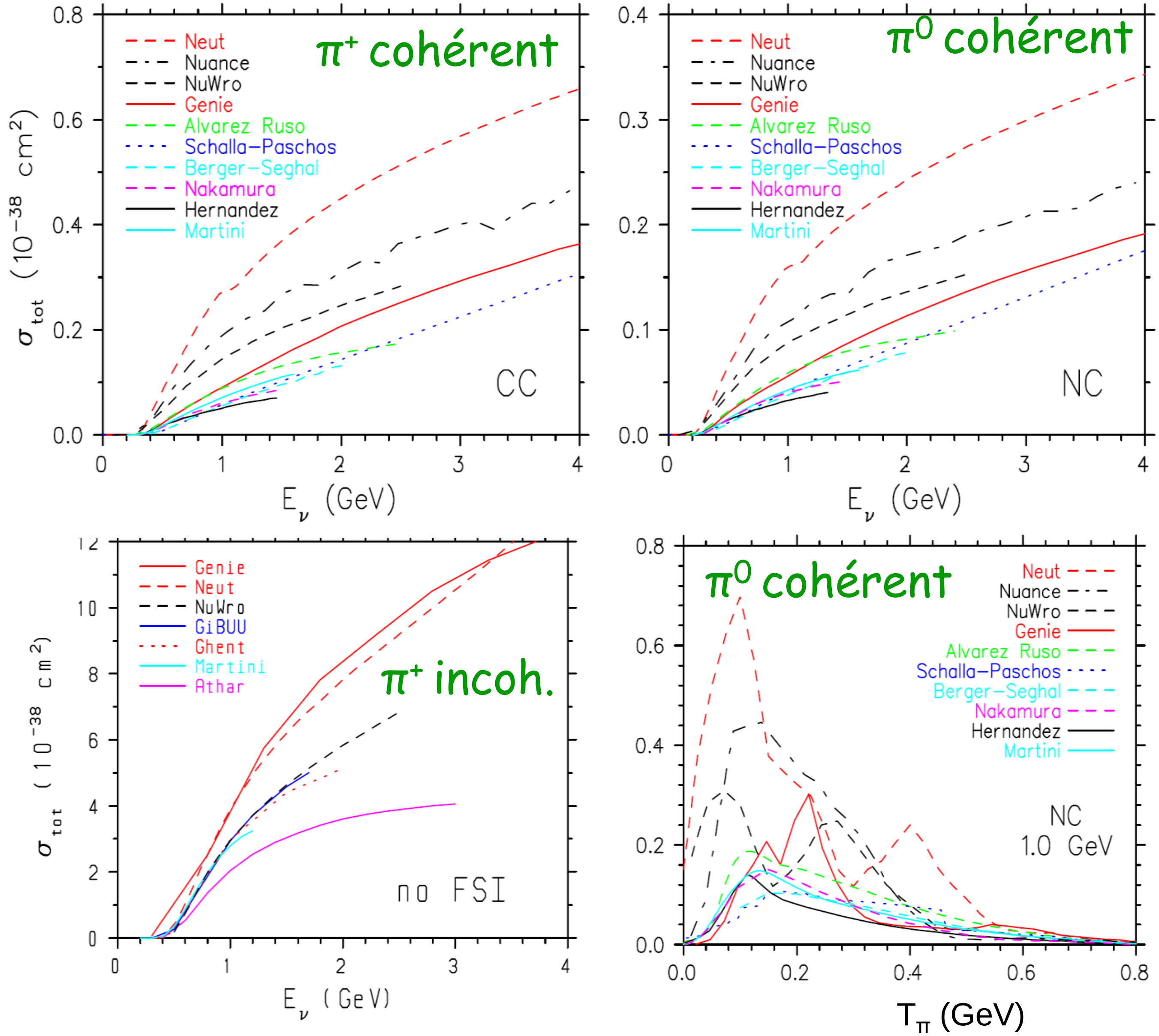
Monte Carlo

microscopic

QE diff

NUINT09

# NUINT09



## Monte Carlo

QE: Fermi Gas

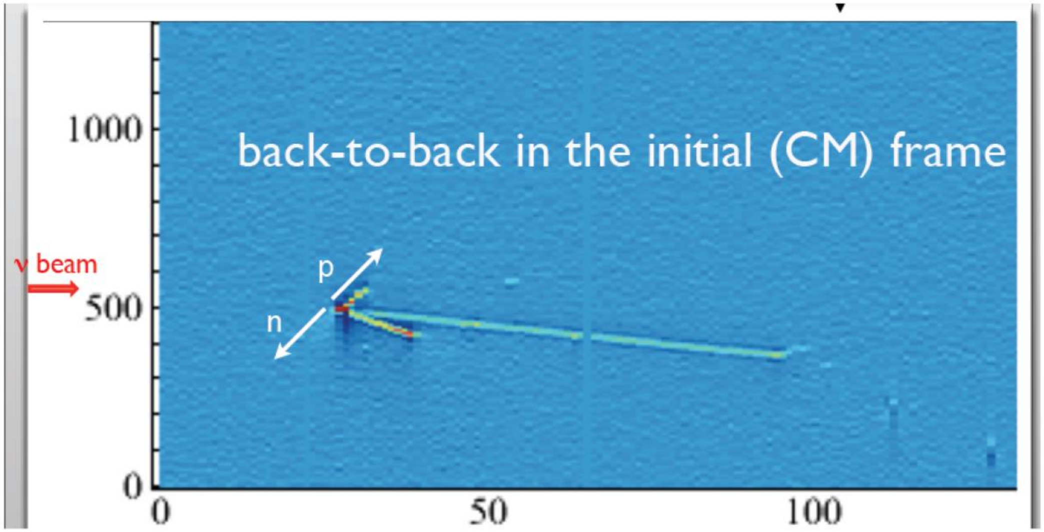
π prod:Rein-Sehgal

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

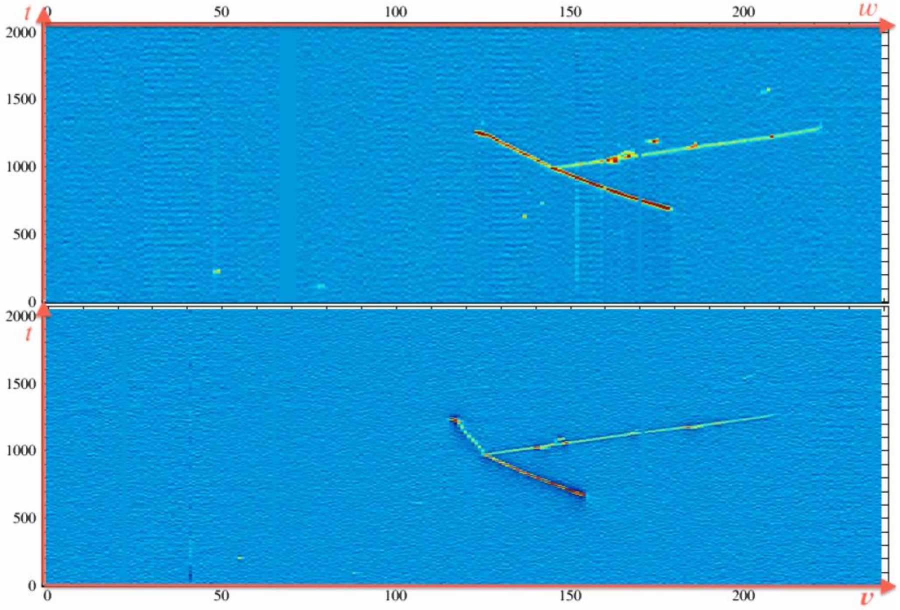
*MC larger than microscopic models*

# ArgoNeut

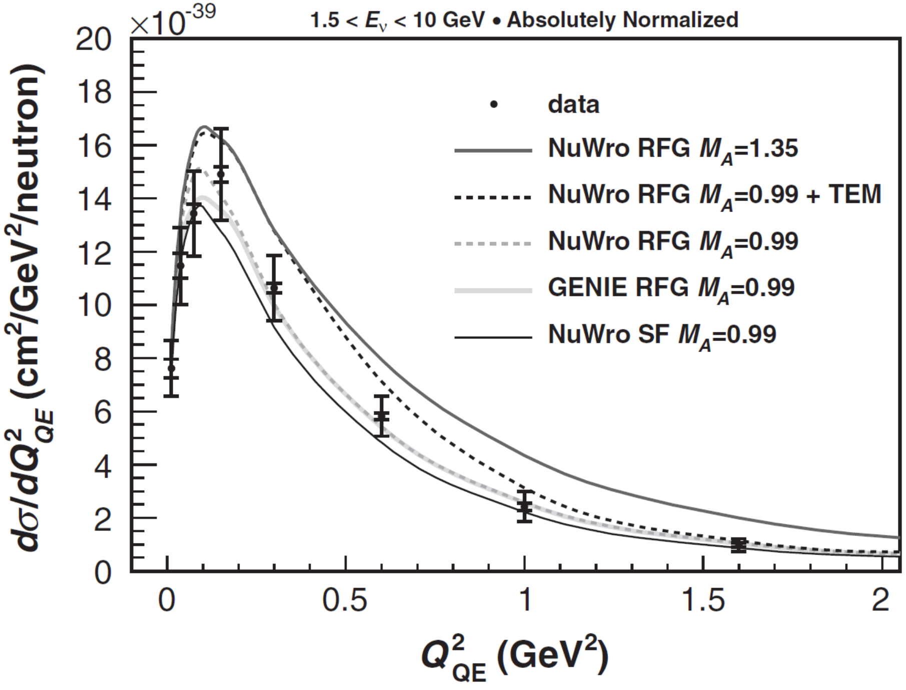
arXiv:1501.01983



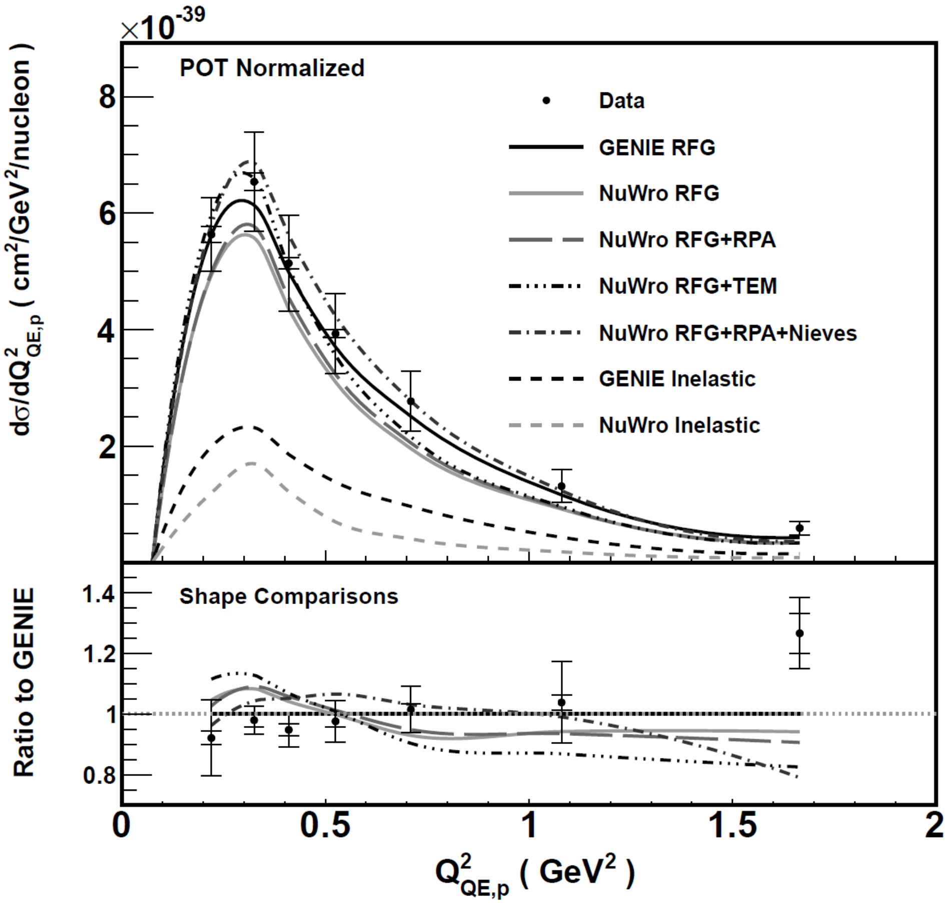
Phys.Rev. D90 (2014) 1, 012008



# MINER$\nu$A $Q^2$ distributions



*PRL 111 022502 (2013)*



*arXiv:1409.4497*

# 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-$\Delta$ and $\Delta$peaks, respectively”

*Lovato et al. PRL 112 182502 (2014)*

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

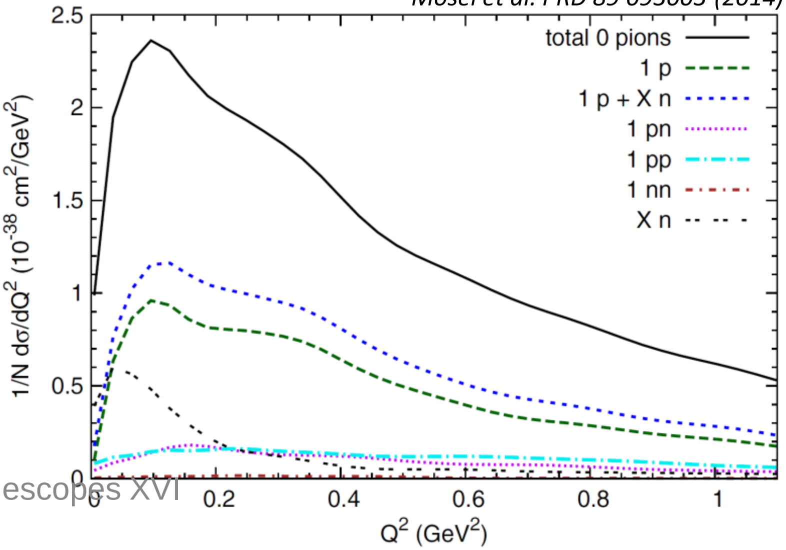
*MINERνA PRL 111 022501 (2013)*

The MINERνA vertex energy on antineutrino mode “might be explained if the dominant multibody process is $\bar{\nu}_\mu$ (np) $\to \mu^+$ 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)*

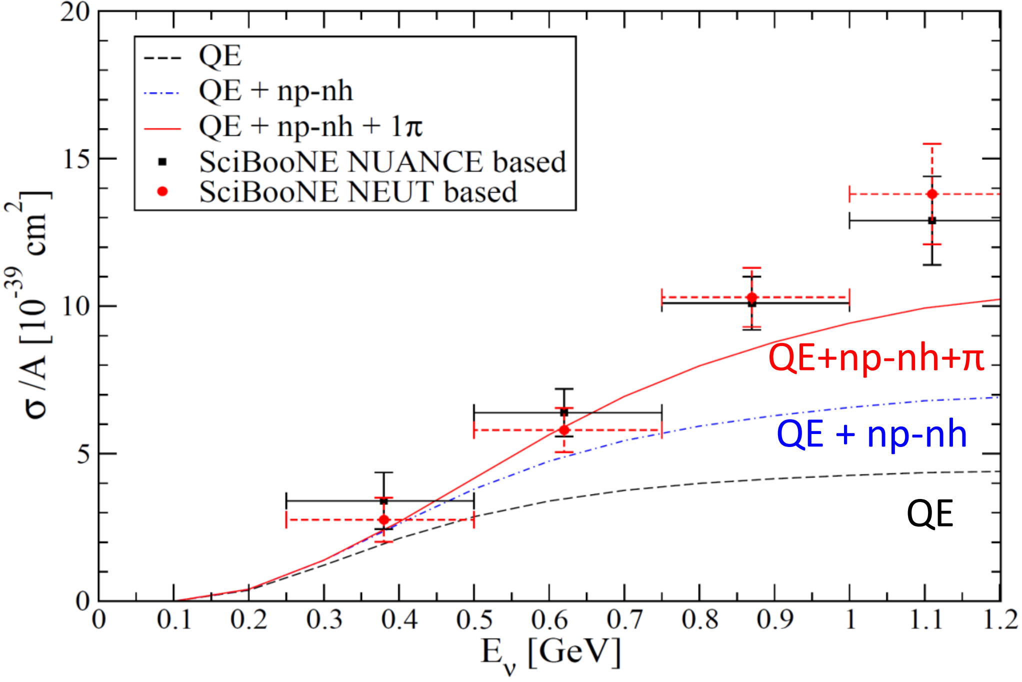


# Inclusive CC total cross section on Carbon

Less affected by background subtraction with respect to exclusive channels

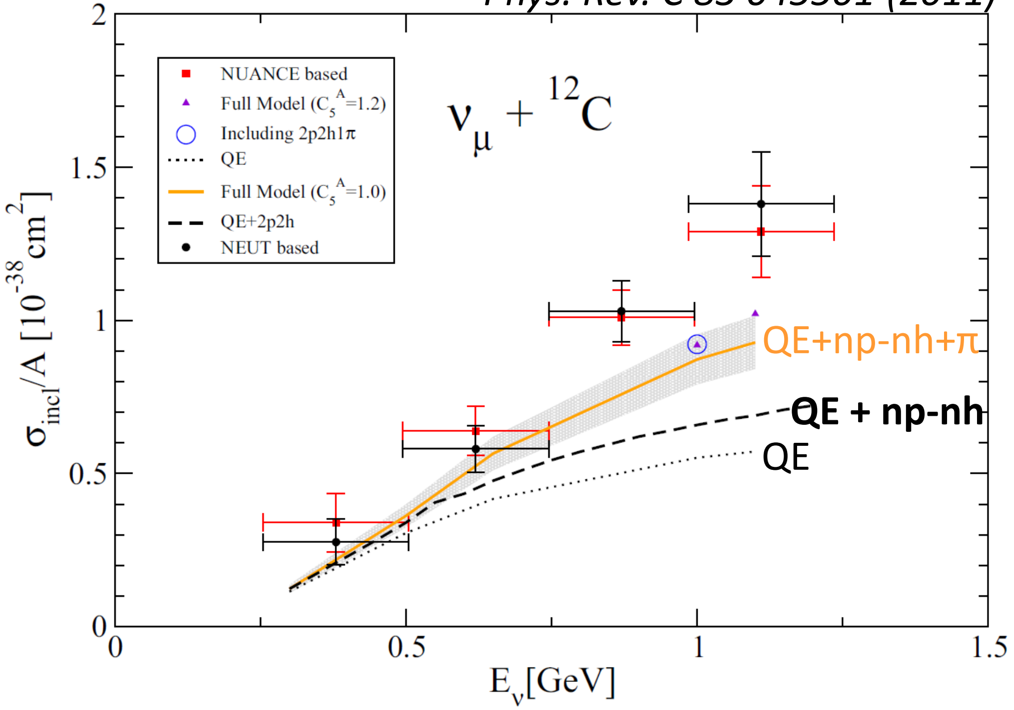
SciBooNE, *Phys. Rev. D. 83, 012005 (2011)*

*Phys. Rev. C 90 025501 (2014)*



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

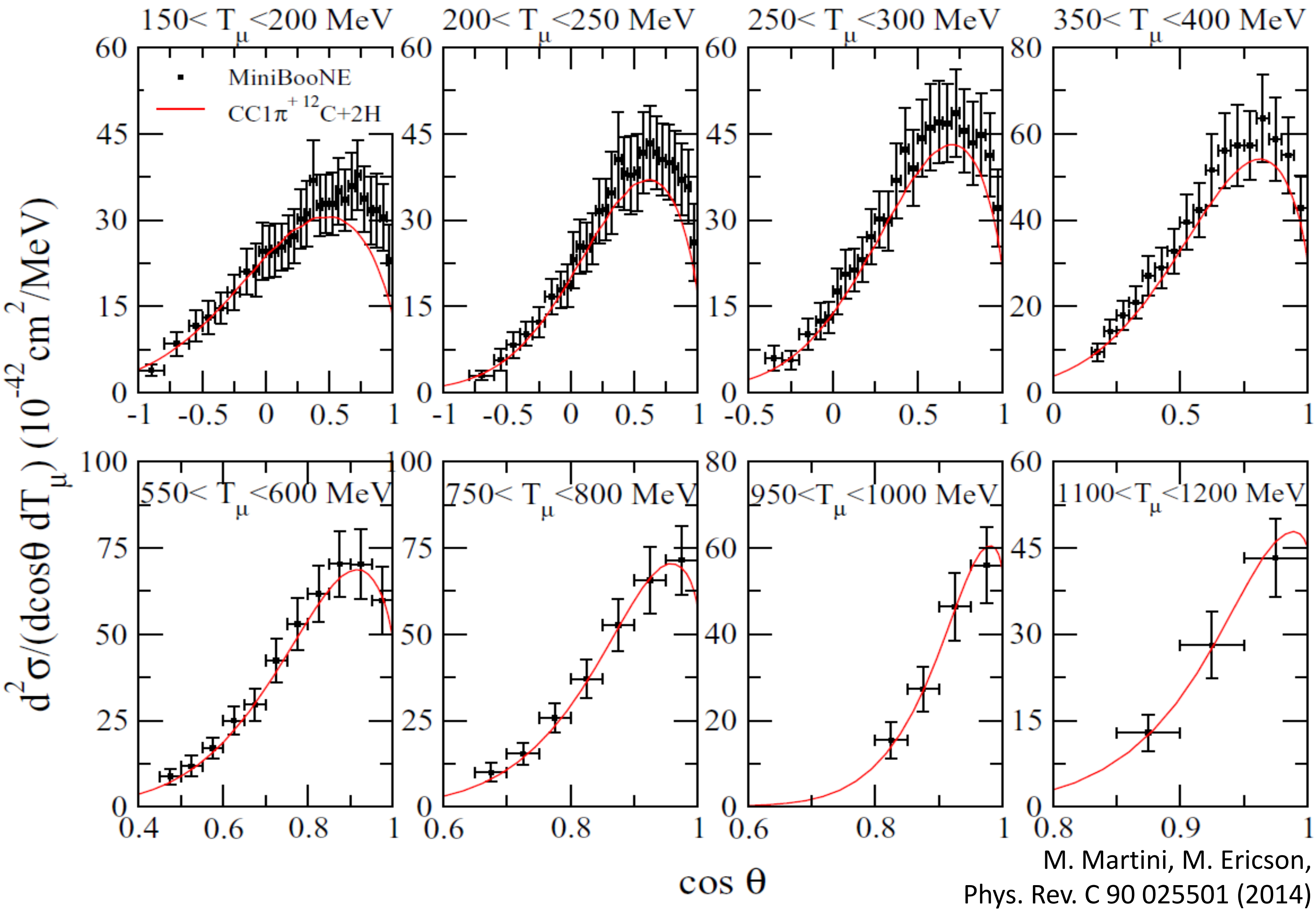
*Phys. Rev. C 83 045501 (2011)*



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

# MiniBooNE flux-integrated CC1π+ double differential cross section

MiniBooNE Phys. Rev. D 83 052007 (2011)

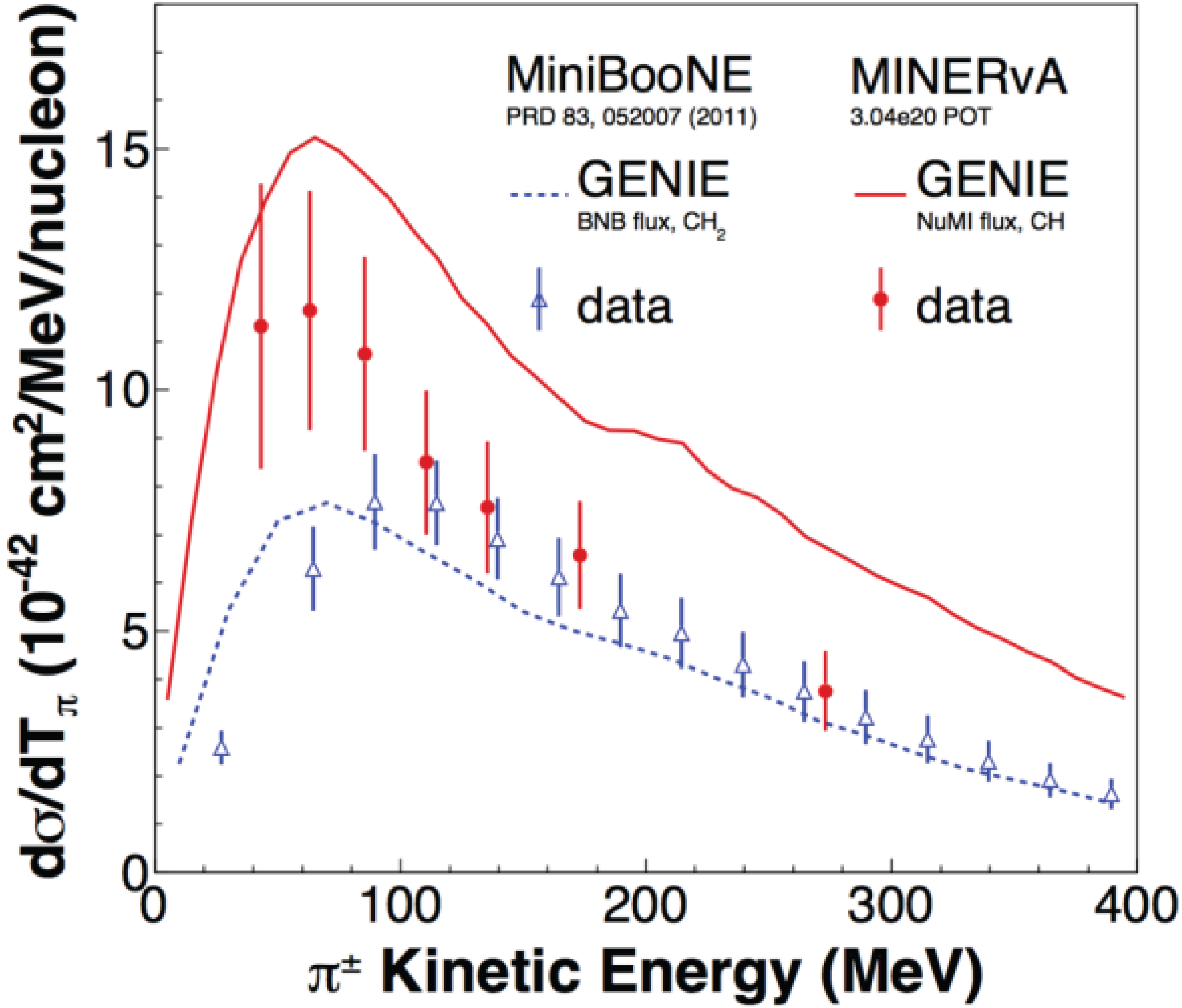


M. Martini, M. Ericson,
Phys. Rev. C 90 025501 (2014)

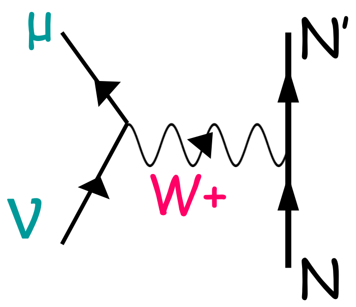
Agreement with data without Final State Interaction for the pion

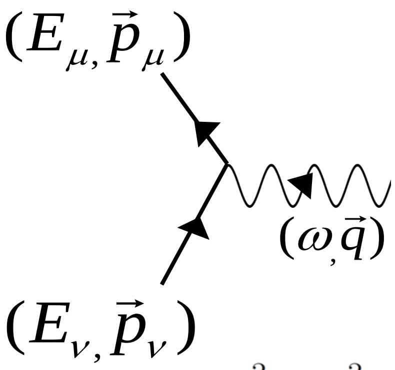
# MiniBooNE *vs* MINERνA CC1π+ production

Eberly et al. , arXiv:1406.6415



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





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

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

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

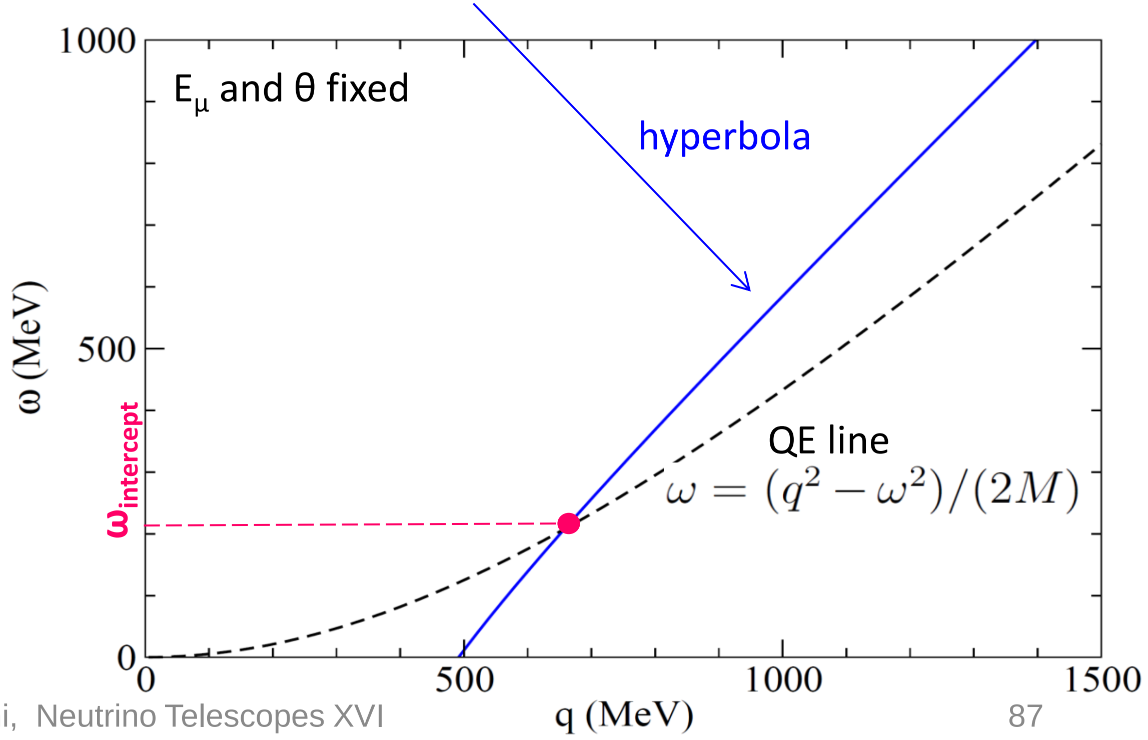
The nuclear response function is proportional to the delta distribution

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

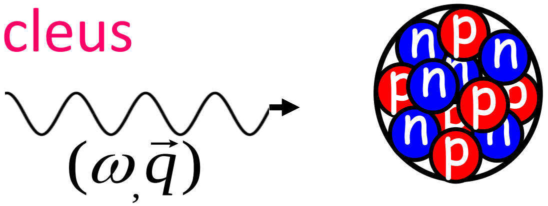
The intercept of the **hyperbola** with the **QE line** fixes the possible ω and q values for given $E_\mu$ and θ.

Hence the neutrino energy is determined

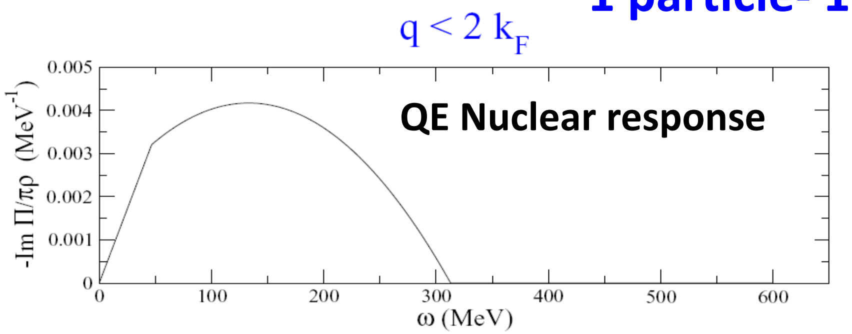
$$\boxed{E_\nu \;=\; E_\mu + \omega_{\text{intercept}}}$$



# QE Scattering with nucleons inside the nucleus



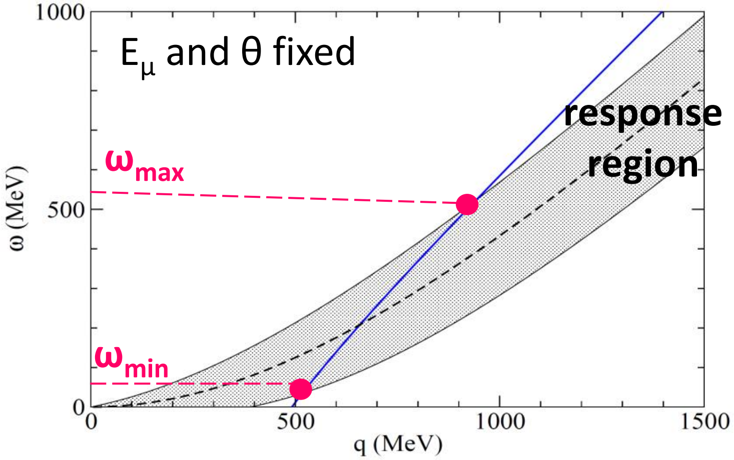
## 1 particle- 1 hole (p-h) excitation



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

**Pauli blocking** cuts part of the
low momentum nuclear response

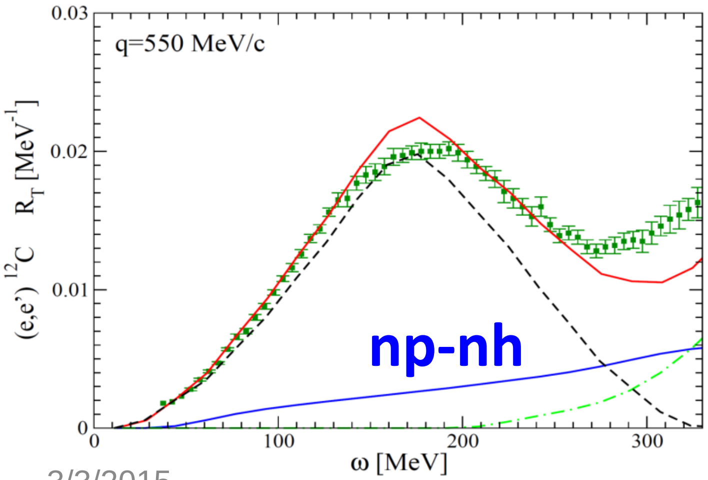
**RPA** collective effects



**Broadening of the neutrino energy**

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

## np-nh excitations

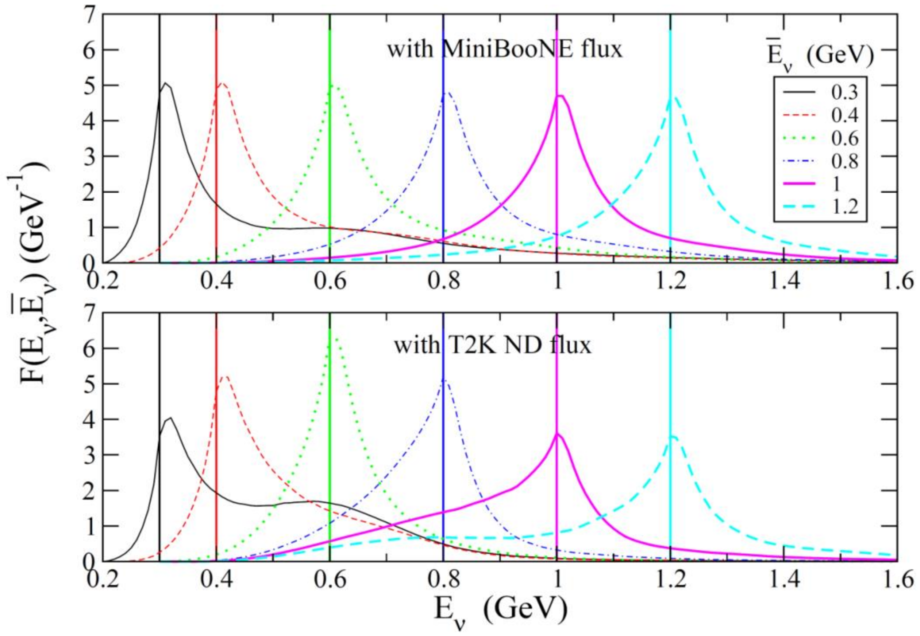


- np-nh creates a high energy tail above the QE peak
- np-nh enlarges the region of response to the whole (ω,q) plane

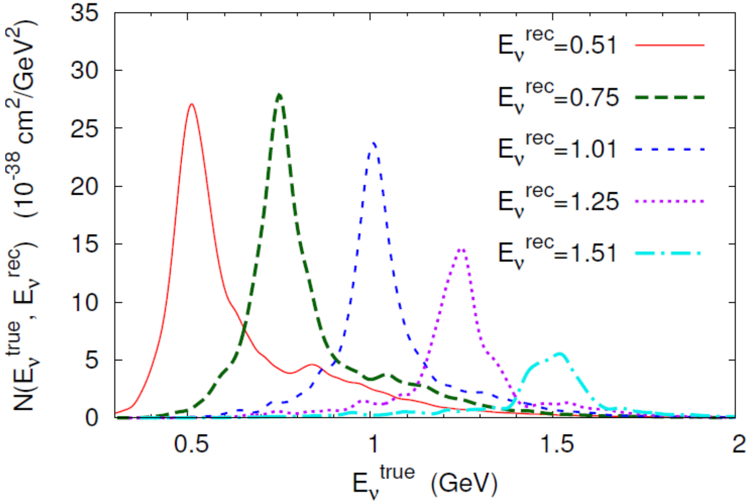
**no reason to fulfill the QE relation for Ev reconstruction**

# Distributions in terms of true $E_\nu$ for fixed values of reconstructed $E_\nu$

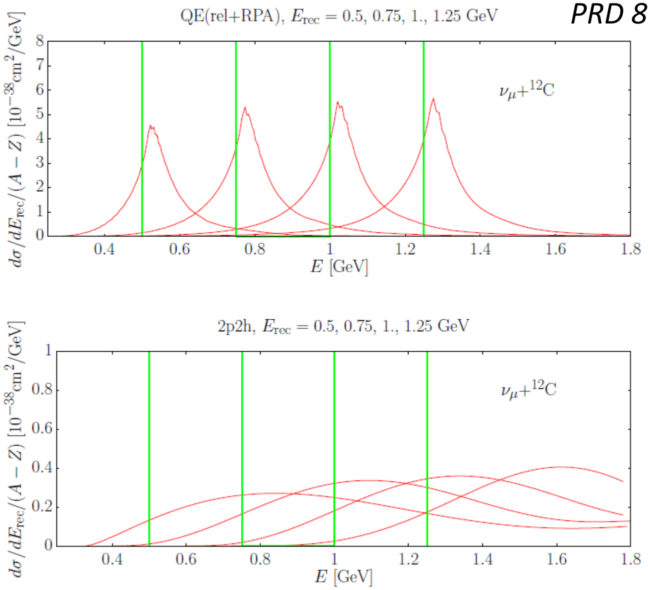
*Martini, Ericson, Chanfray, PRD 85 093012 (2012)*



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

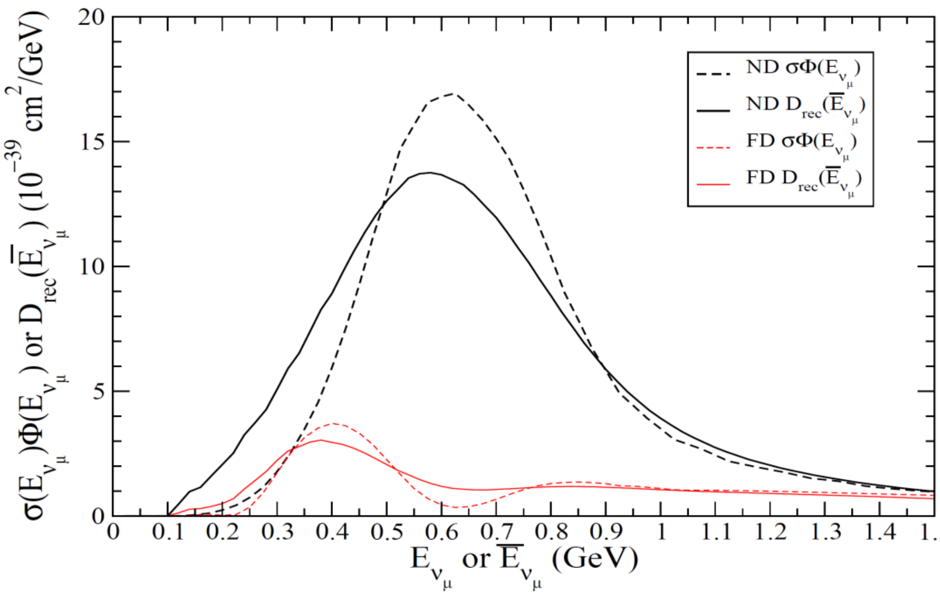


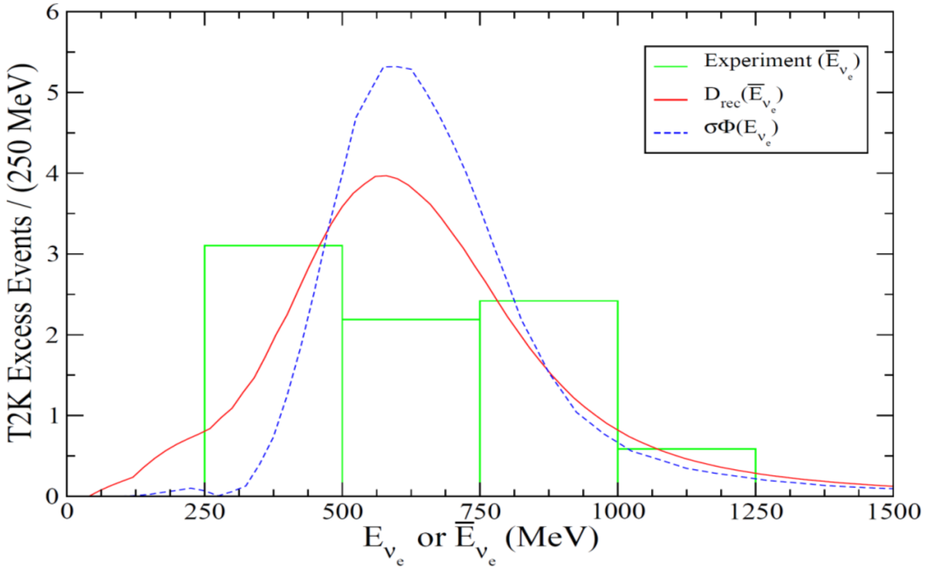
*J. Nieves, F. Sanchez, I. Ruiz Simo, M.J. Vicente Vacas*
*PRD 85 113008 (2012)*



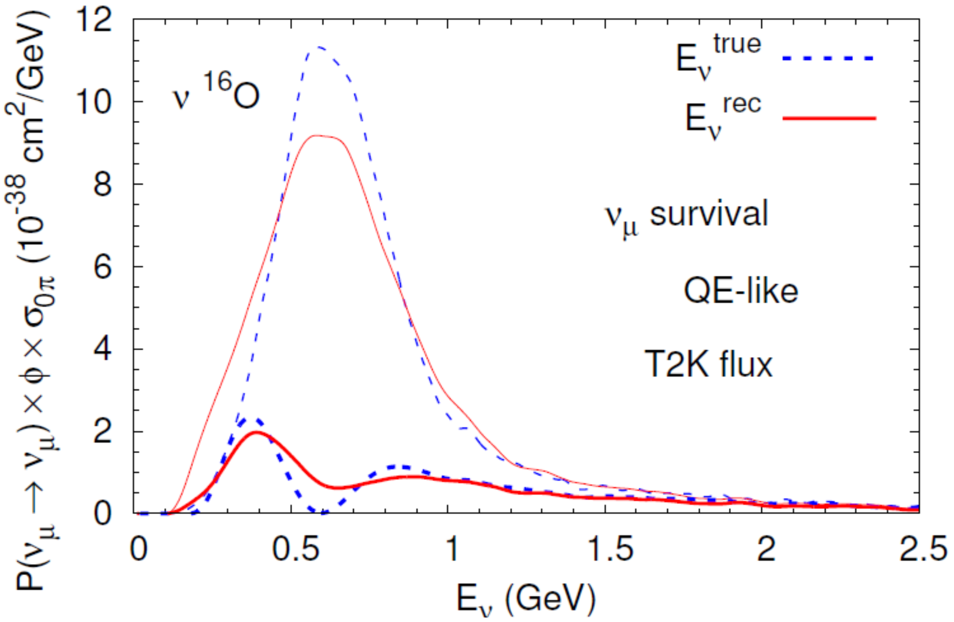
- The distributions are not symmetrical around Ēν.
- The asymmetry favors higher energies at low Ēν and smaller energies for large Ēν.
- Crucial role of neutrino flux.

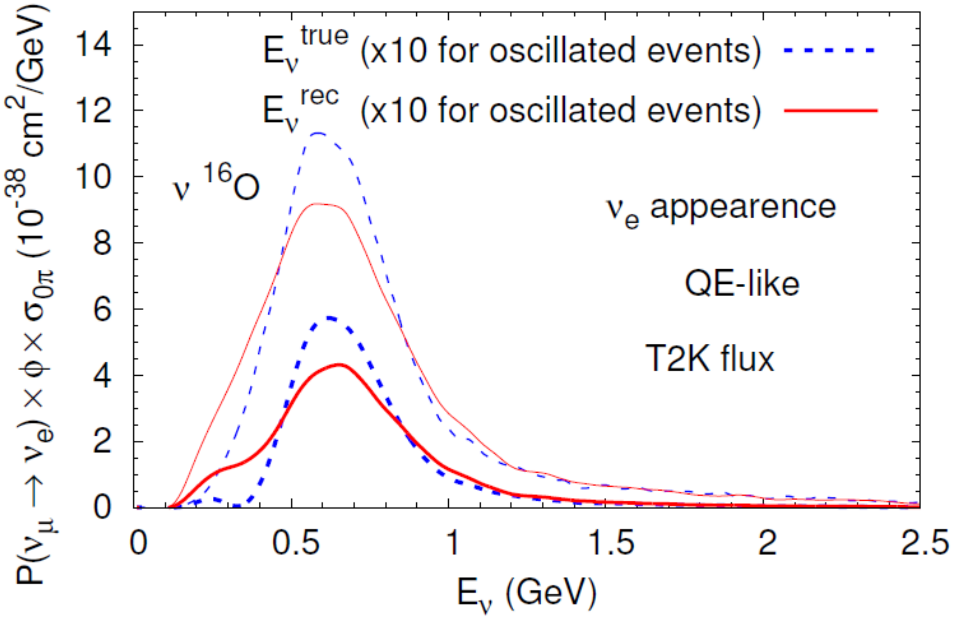
*M. Martini, M. Ericson, G. Chanfray, PRD 87 013009 (2013)*





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





# T2K experimental analysis

*arXiv: 1502.01550*

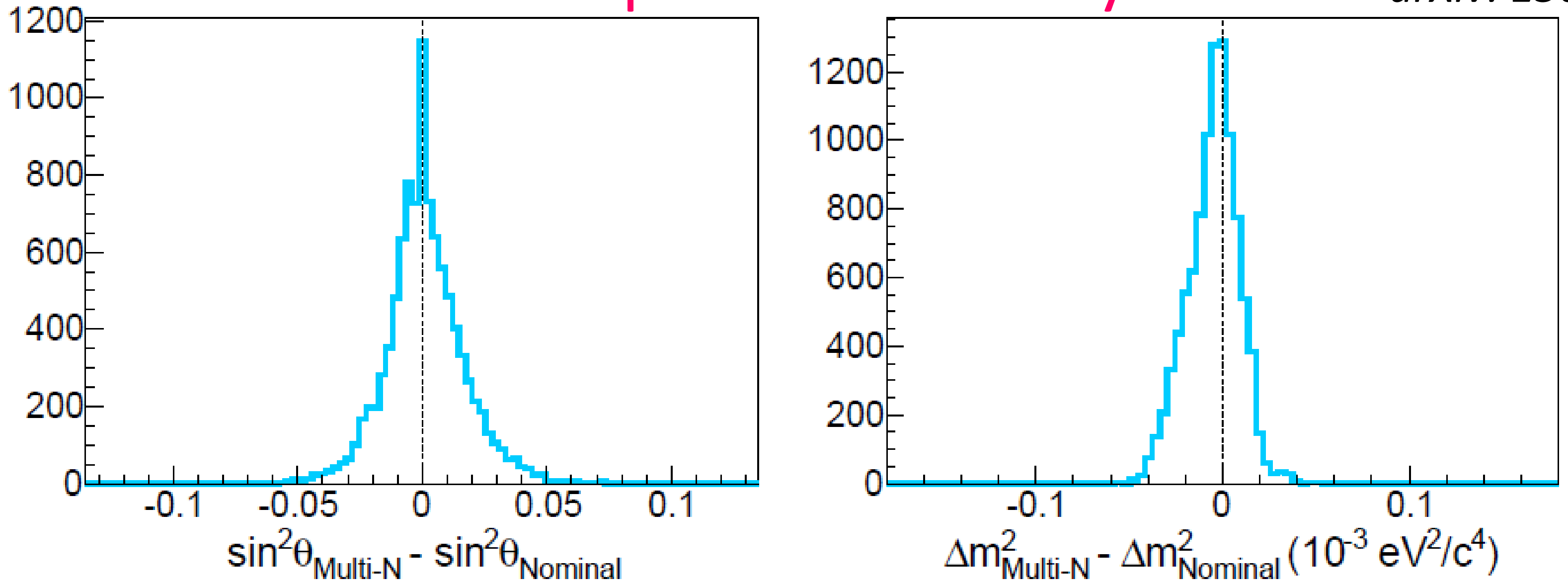
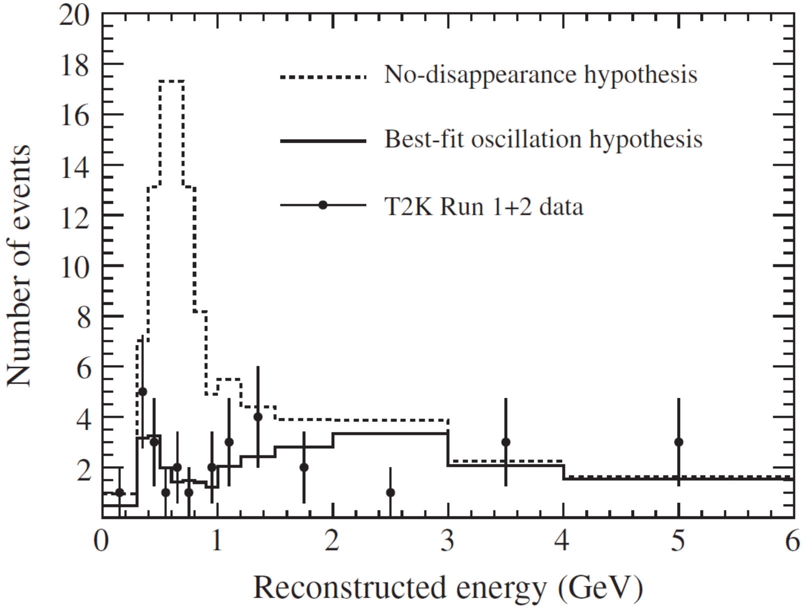


FIG. 30: Difference in the point estimates of $\sin^2\theta_{23}$ (left) and $|\Delta m^2|$(right) between pairs of toy MC datasets with and without including multi-nucleon effects.

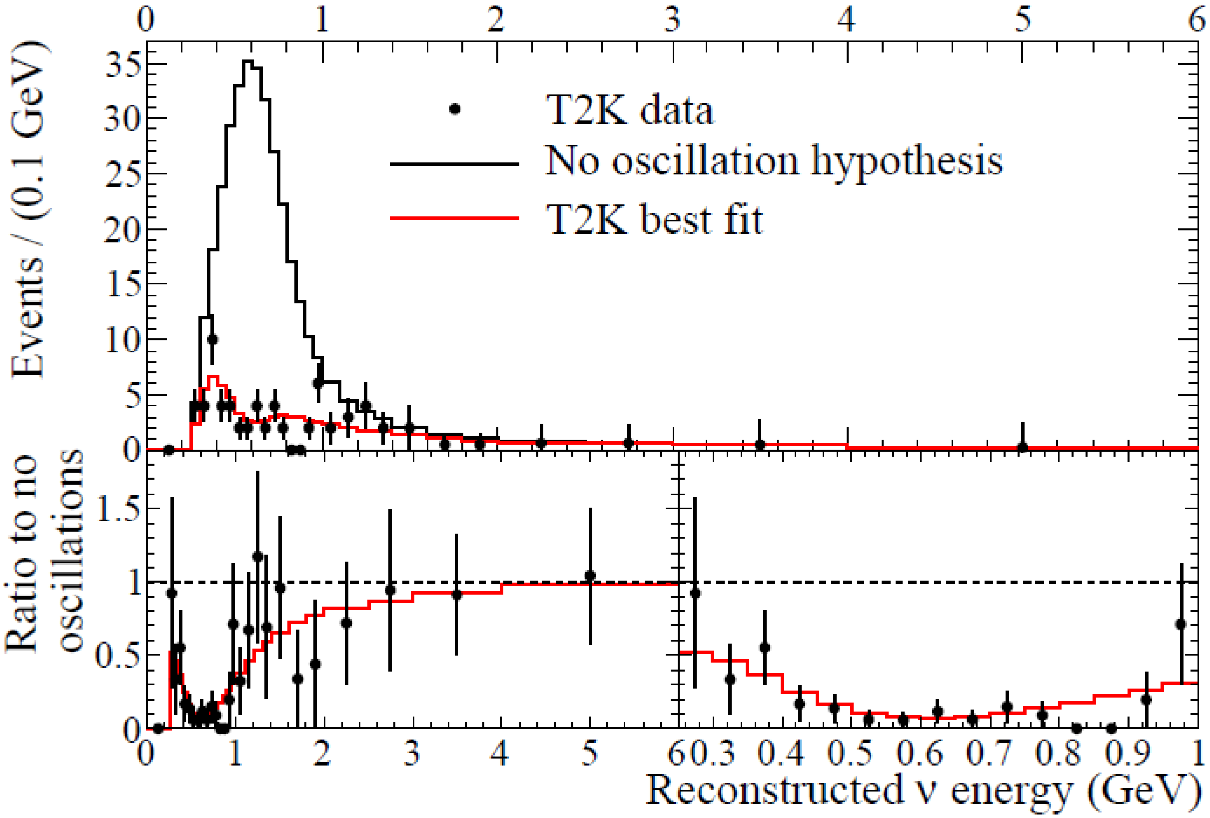
The overall bias for both is negligible, compared to the precision obtained for the parameters. However, the additional variation in $\sin^2\theta_{23}$ is about 3%, comparable to the size of other systematic uncertainties. The bias was evaluated at $\sin^2\theta_{23} = 0.45$ to avoid the the physical 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.

# T2K $\nu_\mu$ disappearance

T2K PRD 85, 031103 (2012)

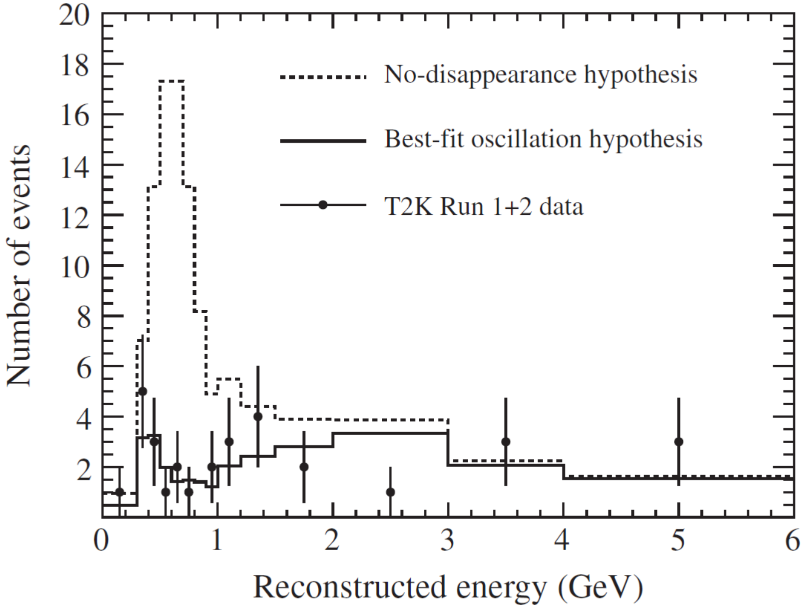


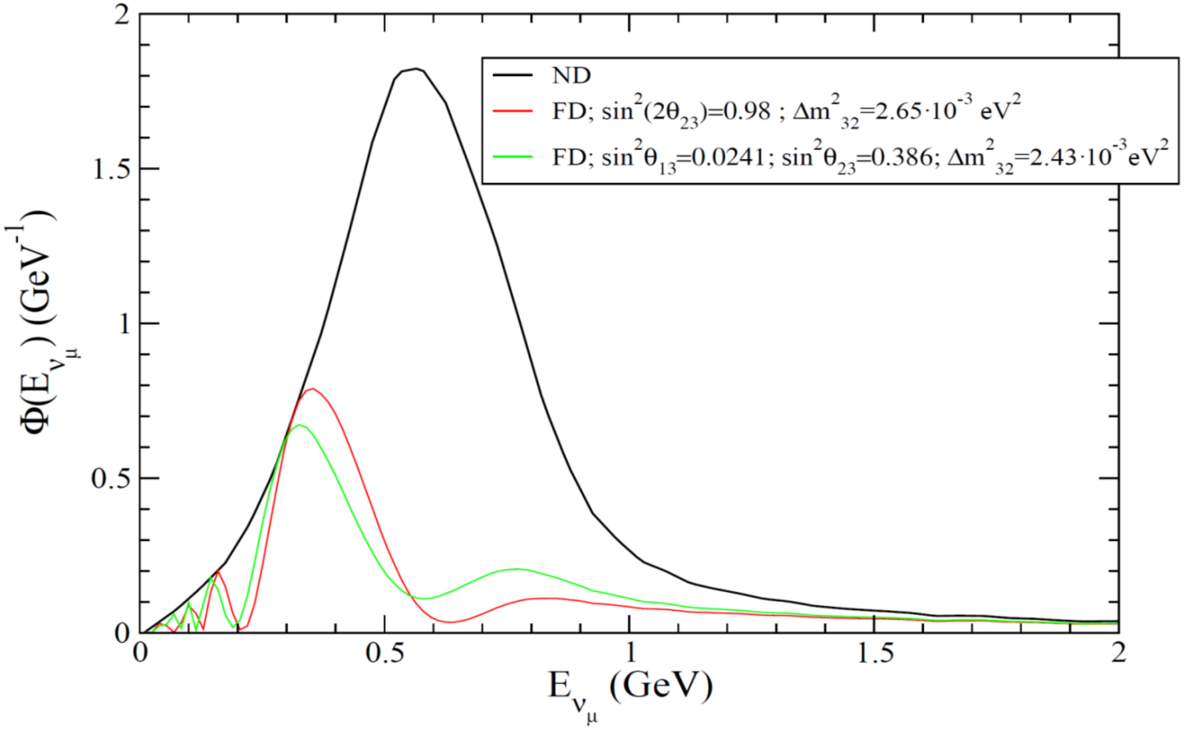
T2K arXiv 1308.0465 (2013)



# T2K $\nu_\mu$ disappearance

T2K PRD 85, 031103 (2012)

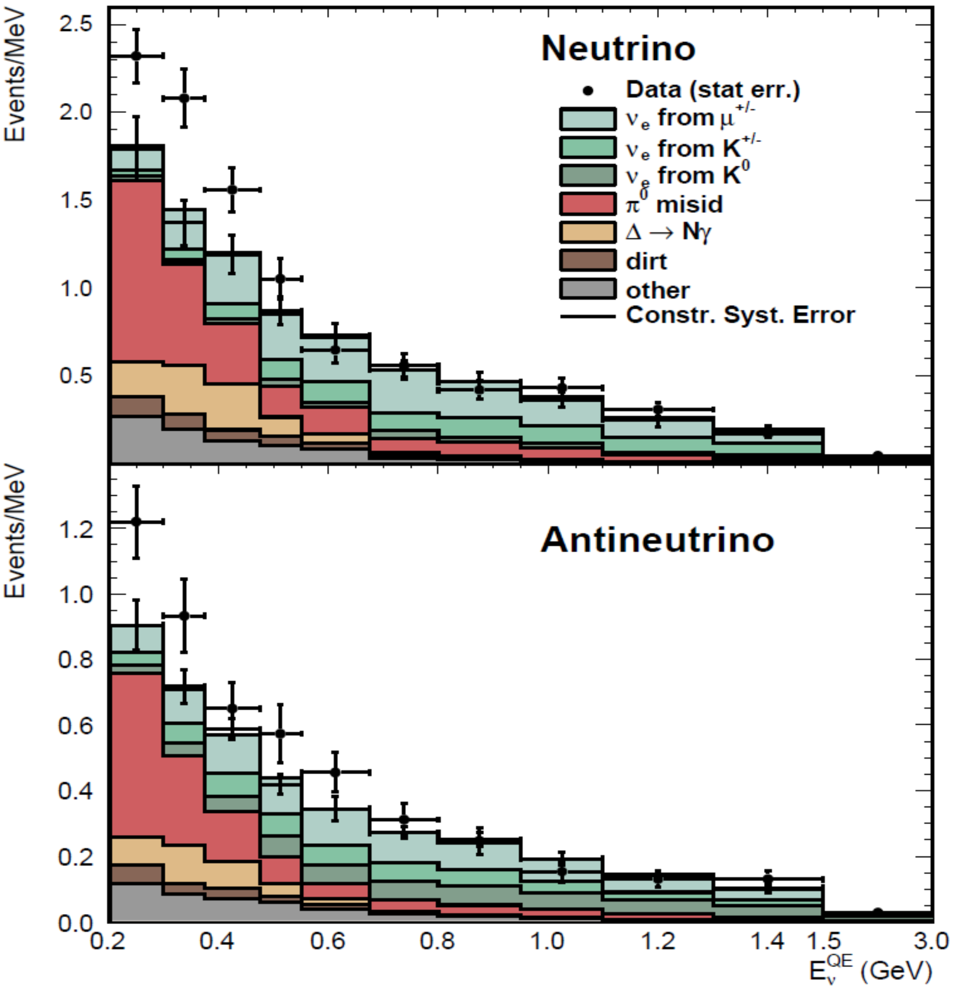


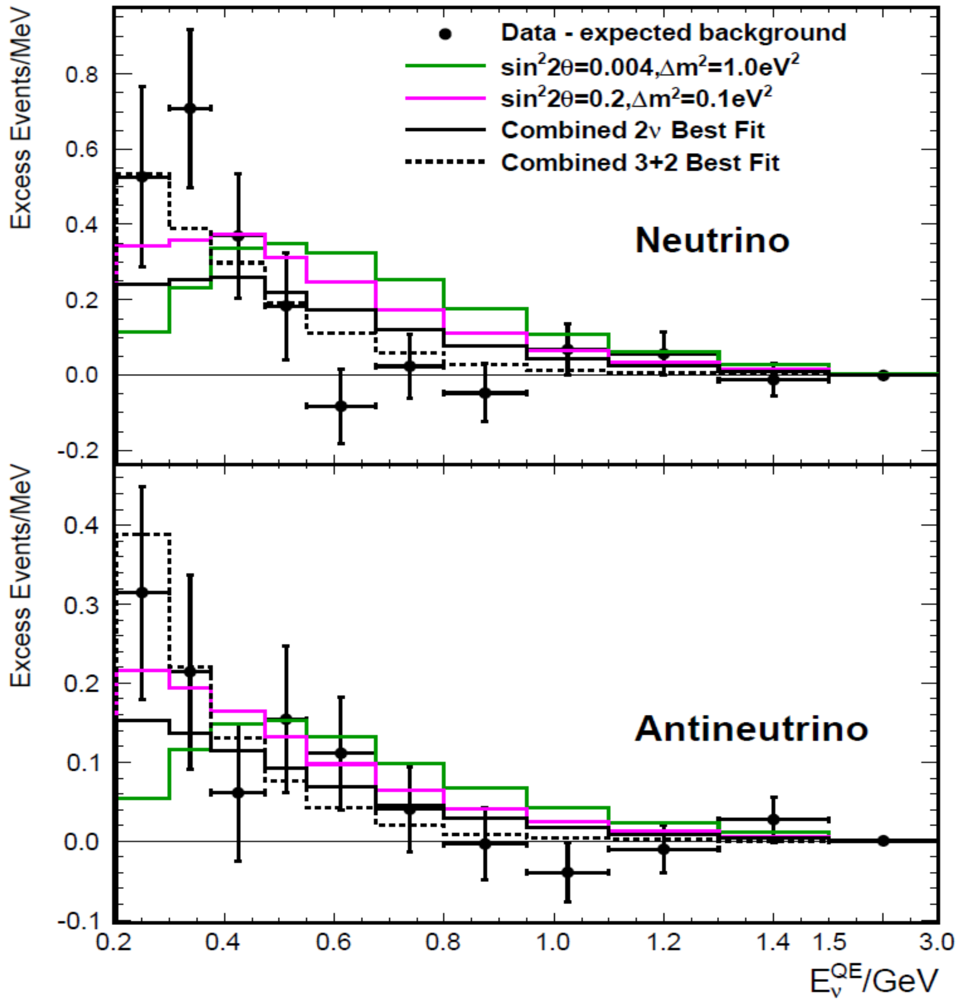


$$\Phi^{FD}_{\nu_\mu}(E_{\nu_\mu}) = \left[1 - 4\cos^2\theta_{13}\sin^2\theta_{23}(1-\cos^2\theta_{13}\sin^2\theta_{23})\sin^2\left(\frac{\Delta m^2_{32}L}{4E_{\nu_\mu}}\right)\right]\Phi^{ND}_{\nu_\mu}(E_{\nu_\mu})$$

# $\nu_\mu$ —> $\nu_e$ MiniBooNE

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



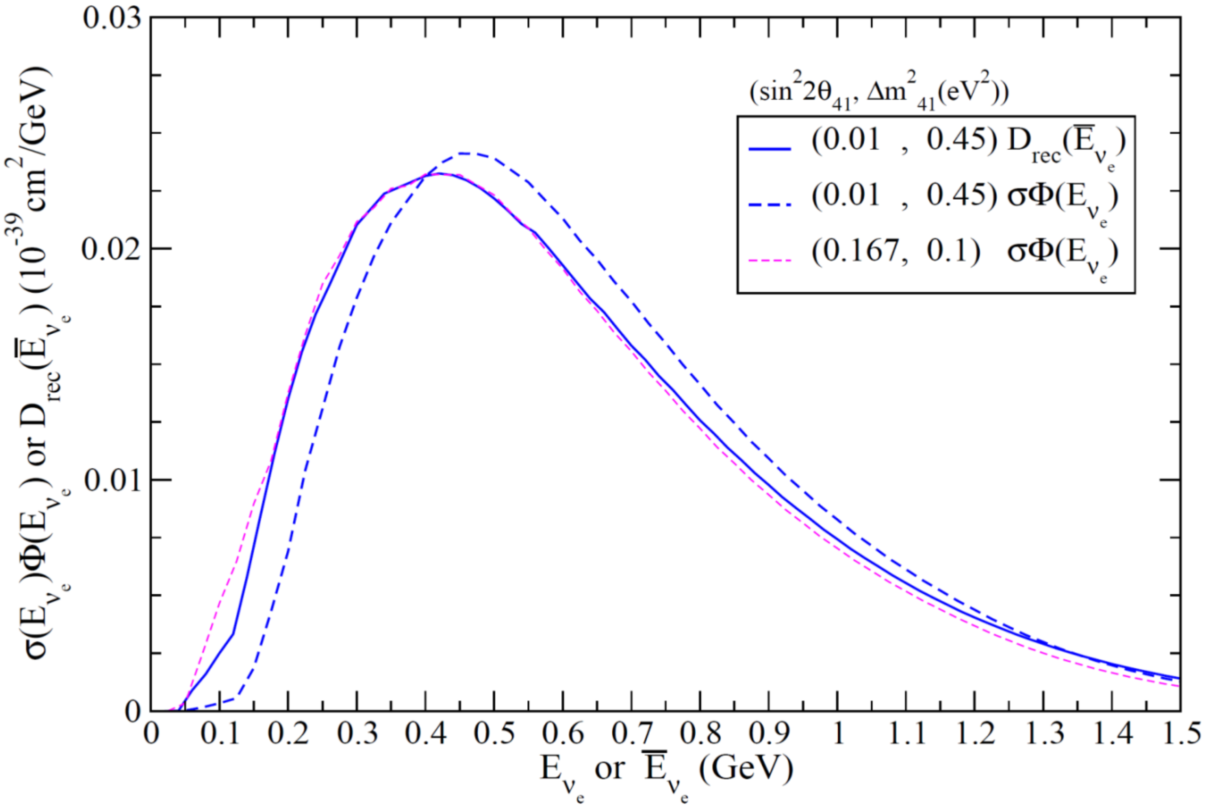


MiniBooNE Anomaly: Excess of events at low energies

Sterile neutrino??

# Taking into account the energy reconstruction correction

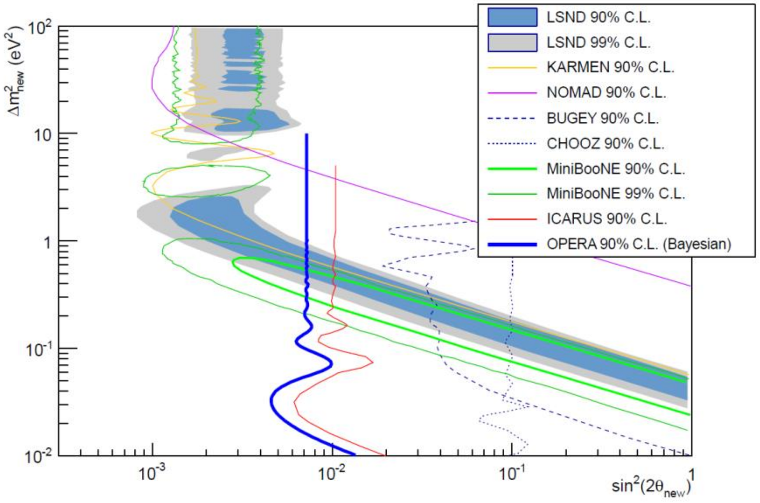
*M. Martini, M. Ericson, G. Chanfray, PRD 87 013009 (2013)*



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

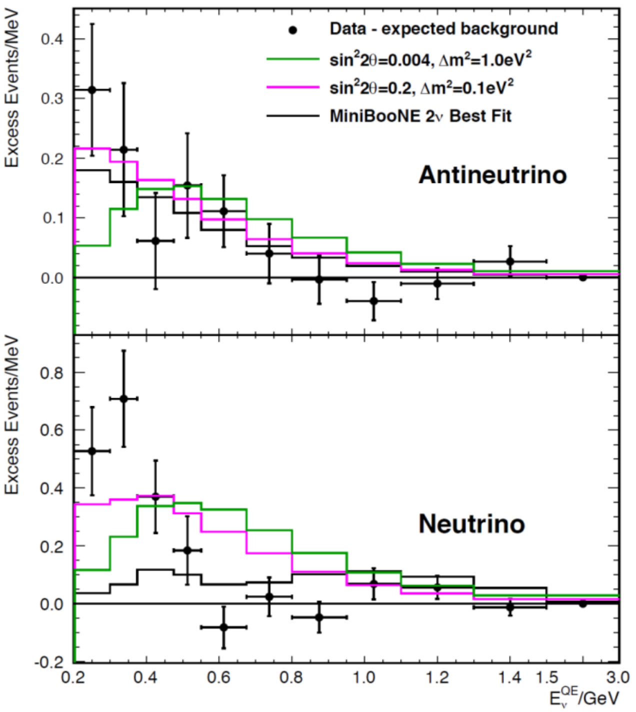
The energy reconstruction leads to an increase of the oscillation mass parameters

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



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

# $\nu_\mu \rightarrow \nu_e$ MiniBooNE



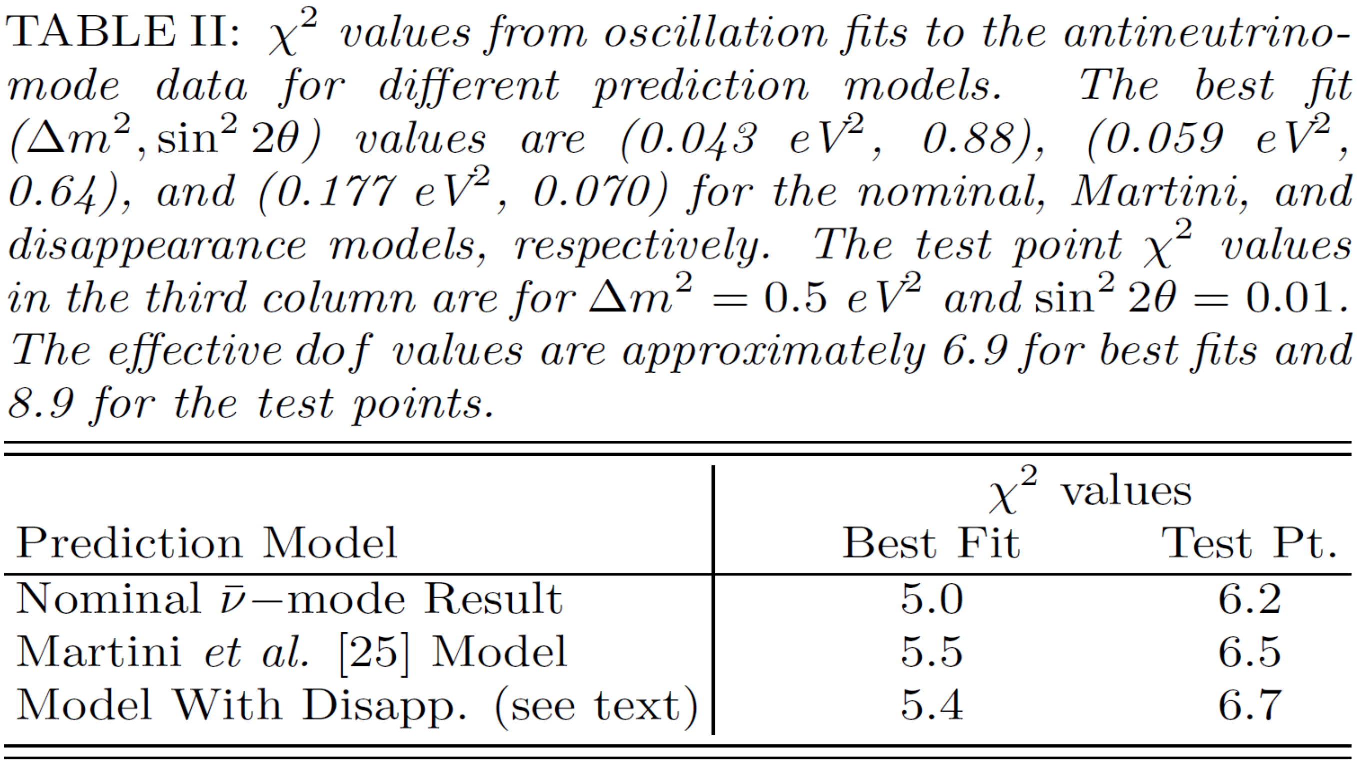


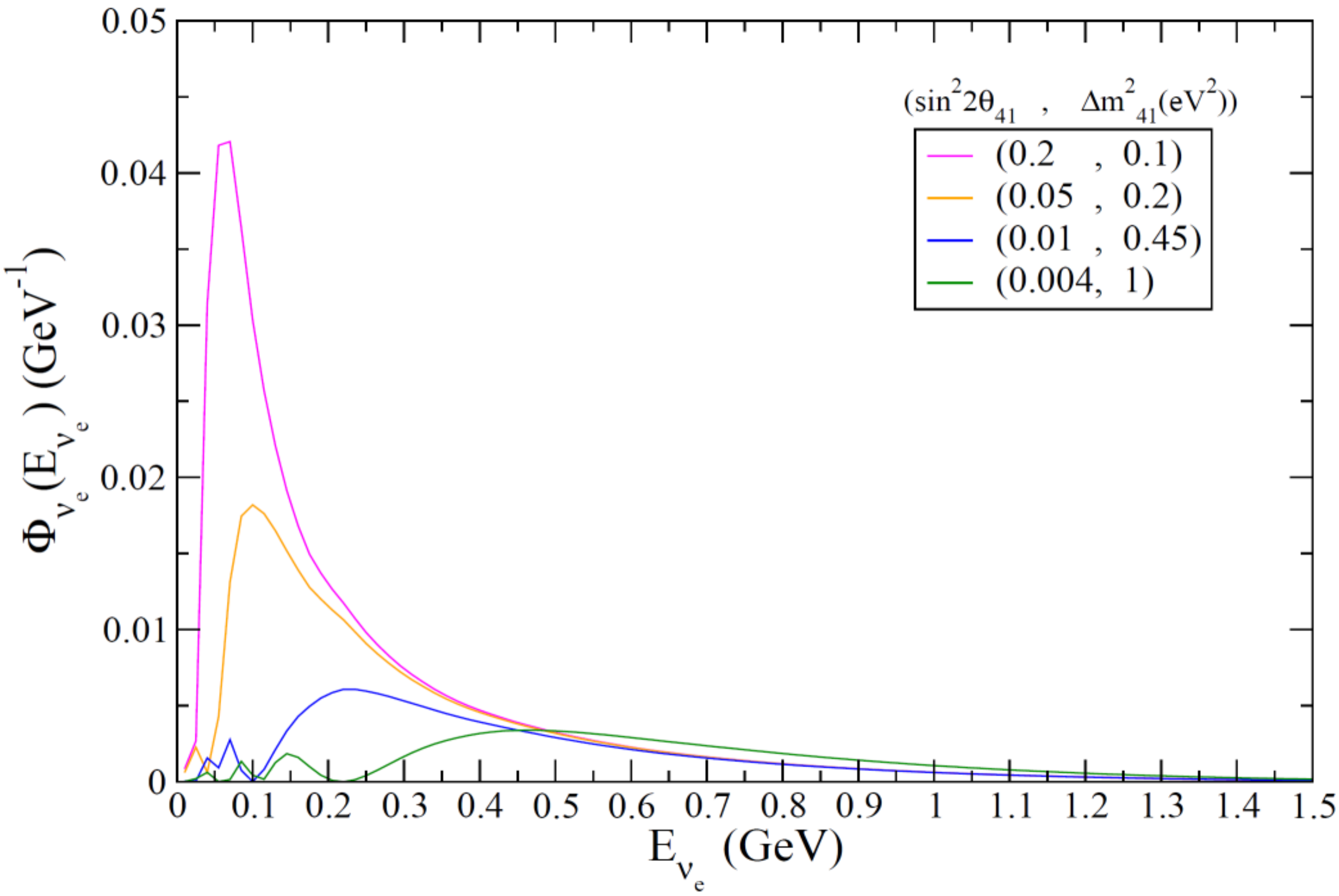
TABLE II: $\chi^2$ *values from oscillation fits to the antineutrino-mode data for different prediction models. The best fit* $(\Delta m^2, \sin^2 2\theta)$ *values are* $(0.043\ eV^2,\ 0.88)$, $(0.059\ eV^2,\ 0.64)$, *and* $(0.177\ eV^2,\ 0.070)$ *for the nominal, Martini, and disappearance models, respectively. The test point* $\chi^2$ *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.*

| | $\chi^2$ 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 |

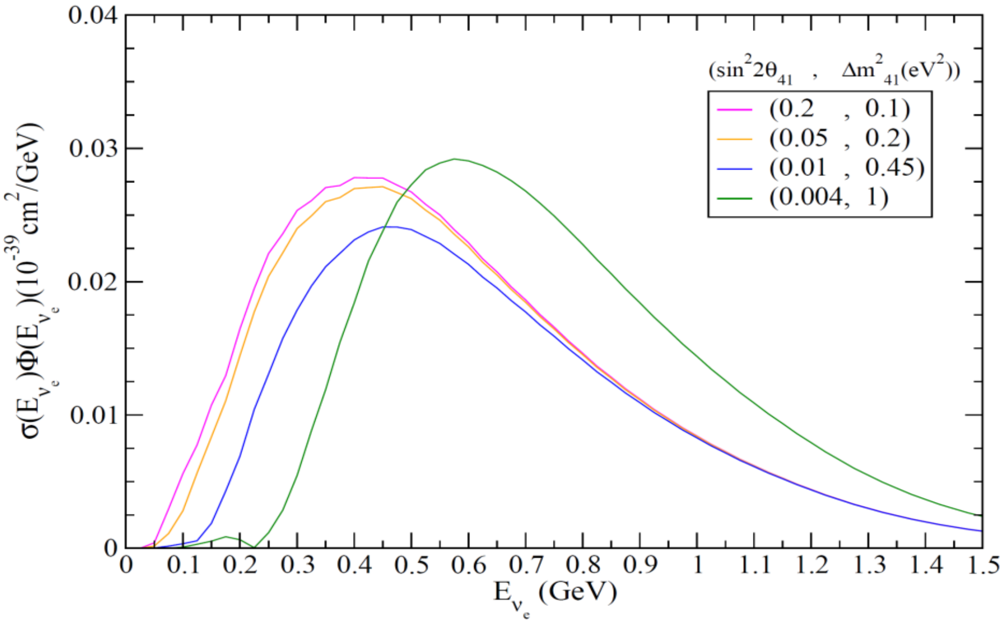
Phys.Rev.Lett. 110 (2013) 161801

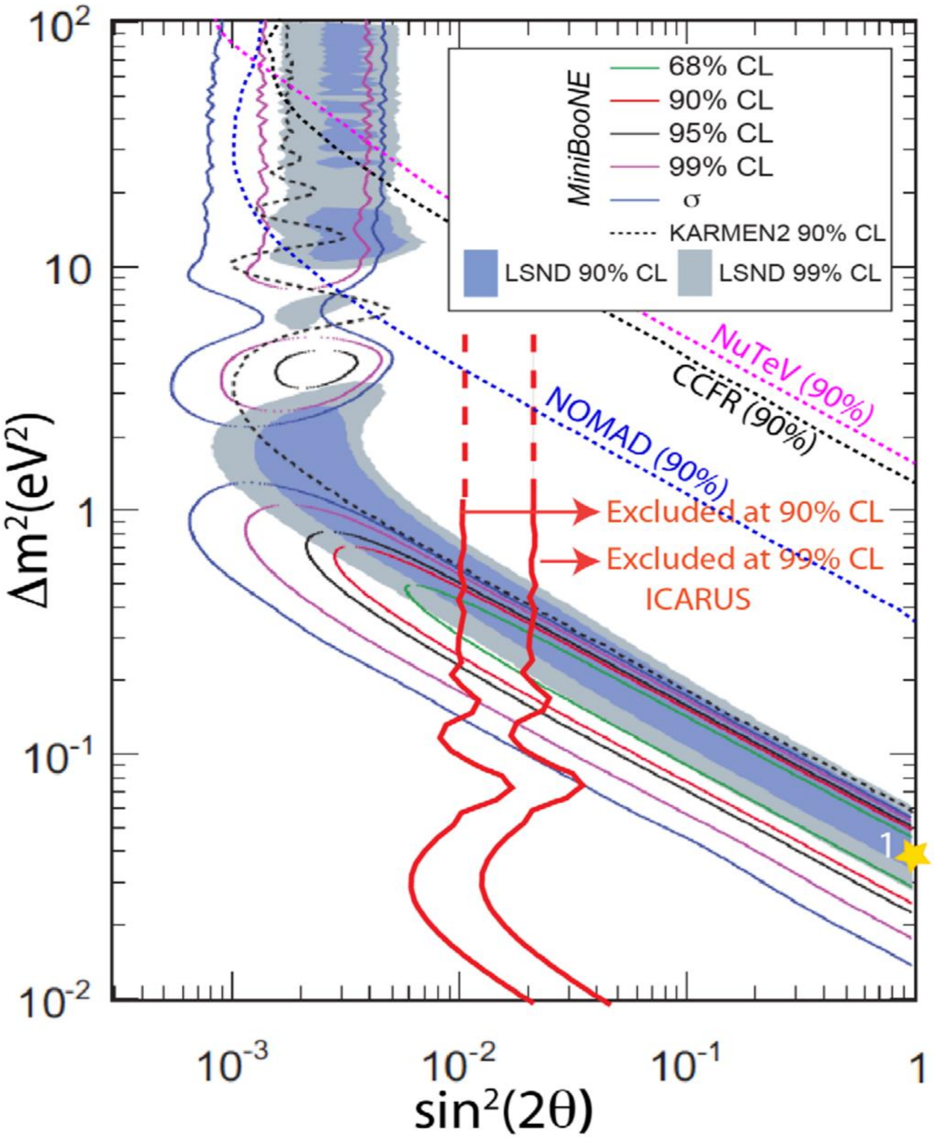
# Oscillations induced by sterile neutrino; 3+1 hypothesis

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



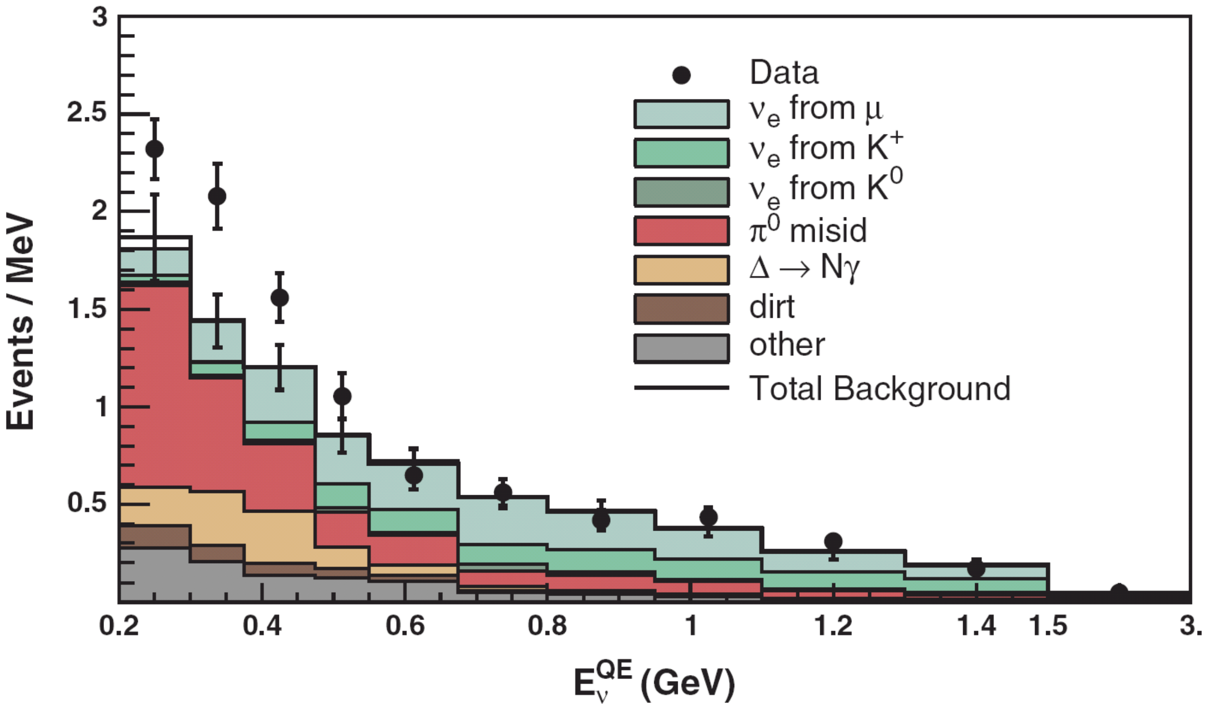
# Some considerations on the oscillation parameters



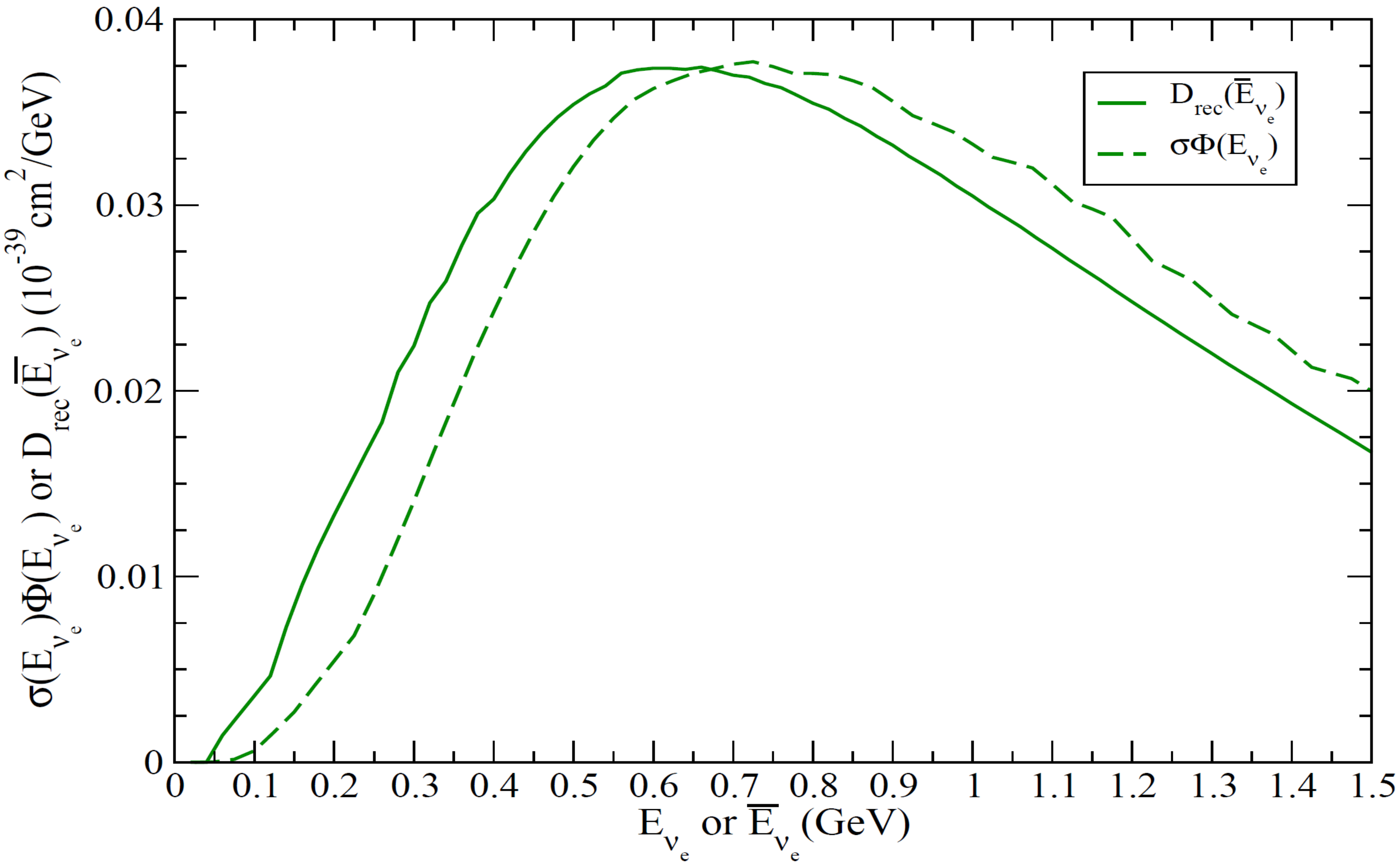


The low energy behavior of the MiniBooNE data favors small values of the mass parameter which concentrate the ν flux at low energies. But small values imply, in order to have enough events, large values of $\sin^2(2\theta)$ which are not compatible with the constraints from other sets of data.

# $\nu_e$ background
# and
# effective cross sections

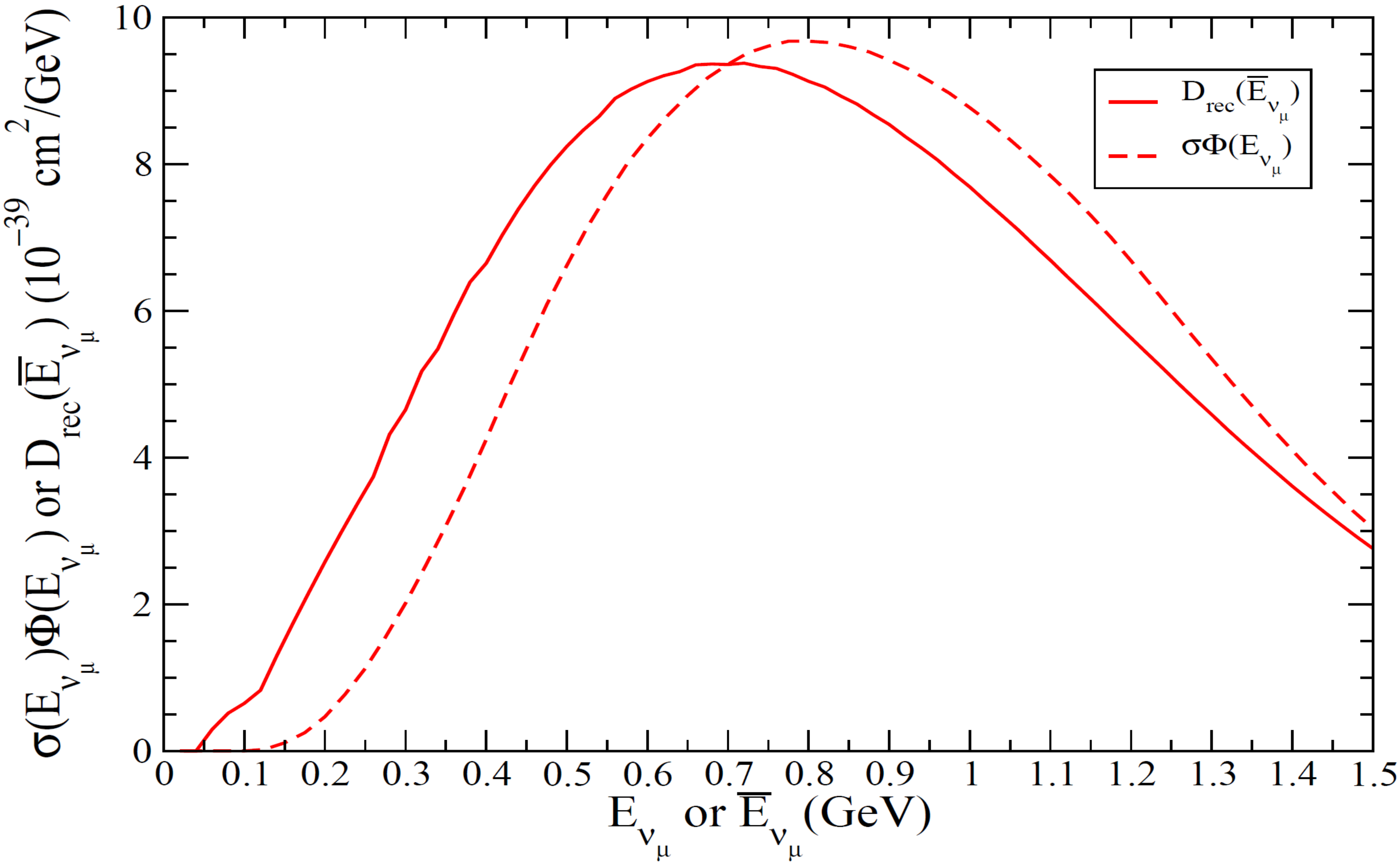


# MiniBooNE electron events distribution for νe background



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

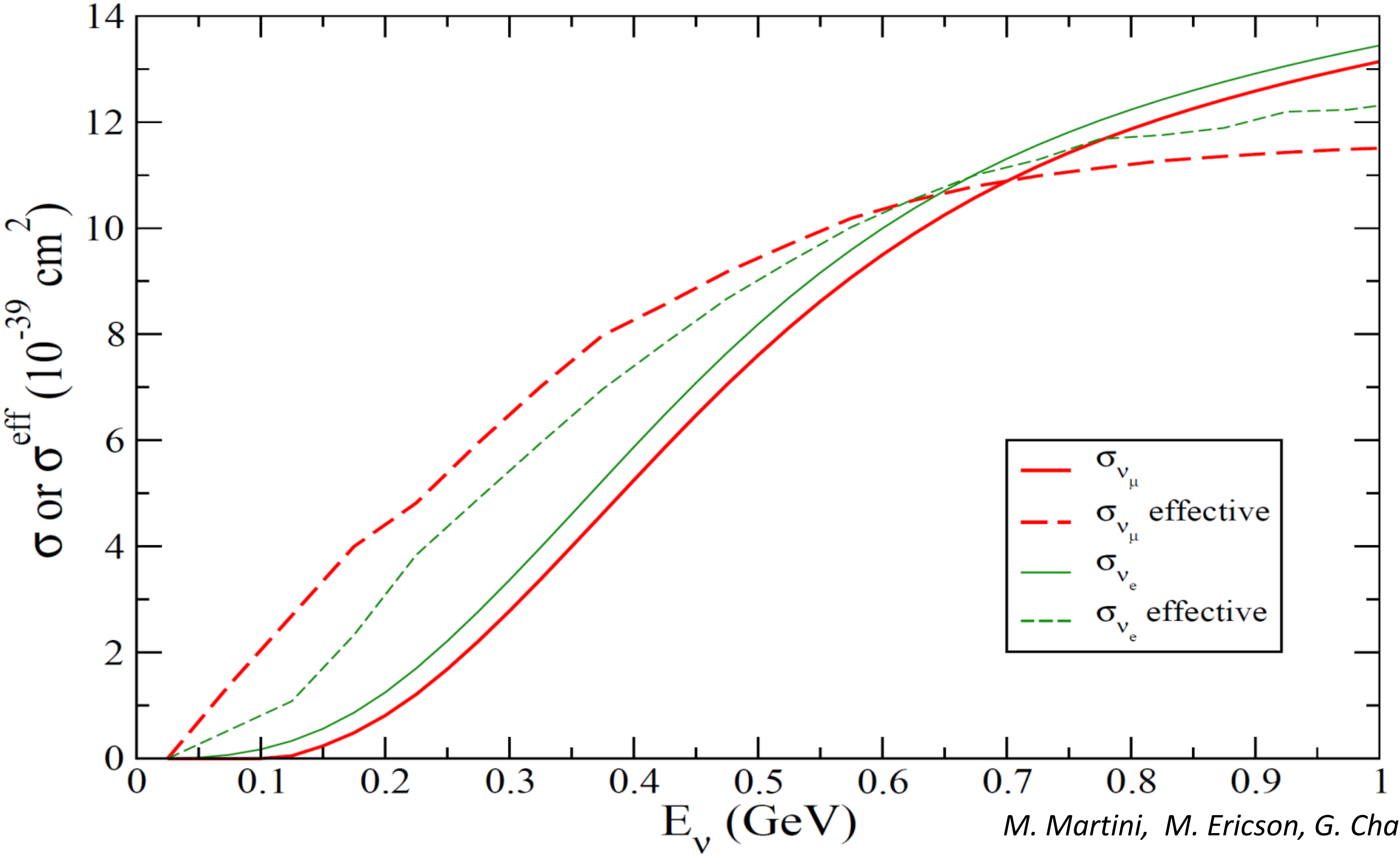
# MiniBooNE muon events distribution



# Real and effective cross sections for $\nu_\mu$ and $\nu_e$

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

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



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

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

(here we used $\nu_\mu$ and $\nu_e$ MiniBooNE fluxes)

# Real and effective cross sections for μ