

Theoretical models of neutrino-nucleus cross sections

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.

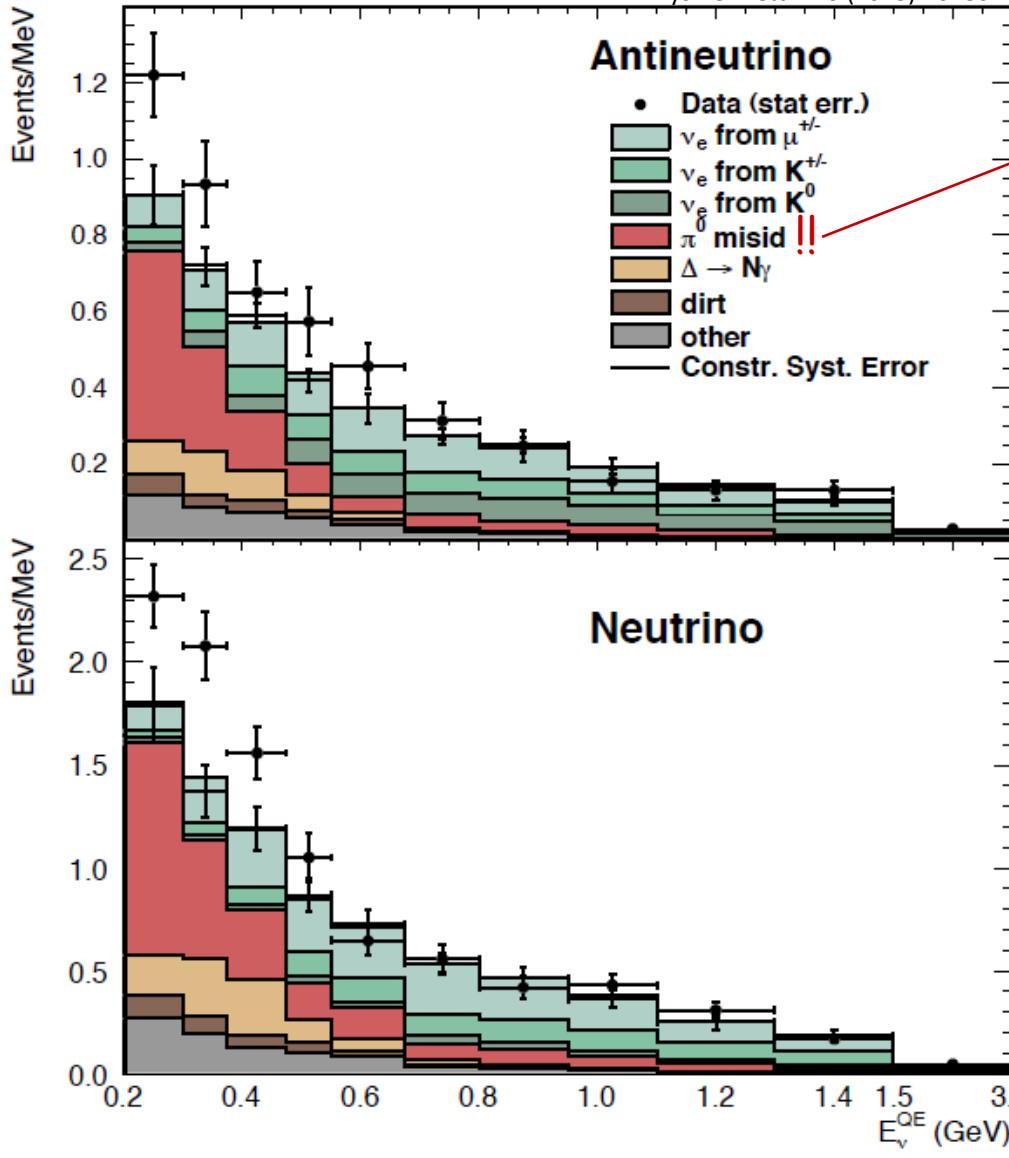
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4E_\nu} \right)$$

- Modern neutrino oscillation experiments use nuclear targets (C, O, Ar, Fe...)
- Nuclear effects play a crucial role

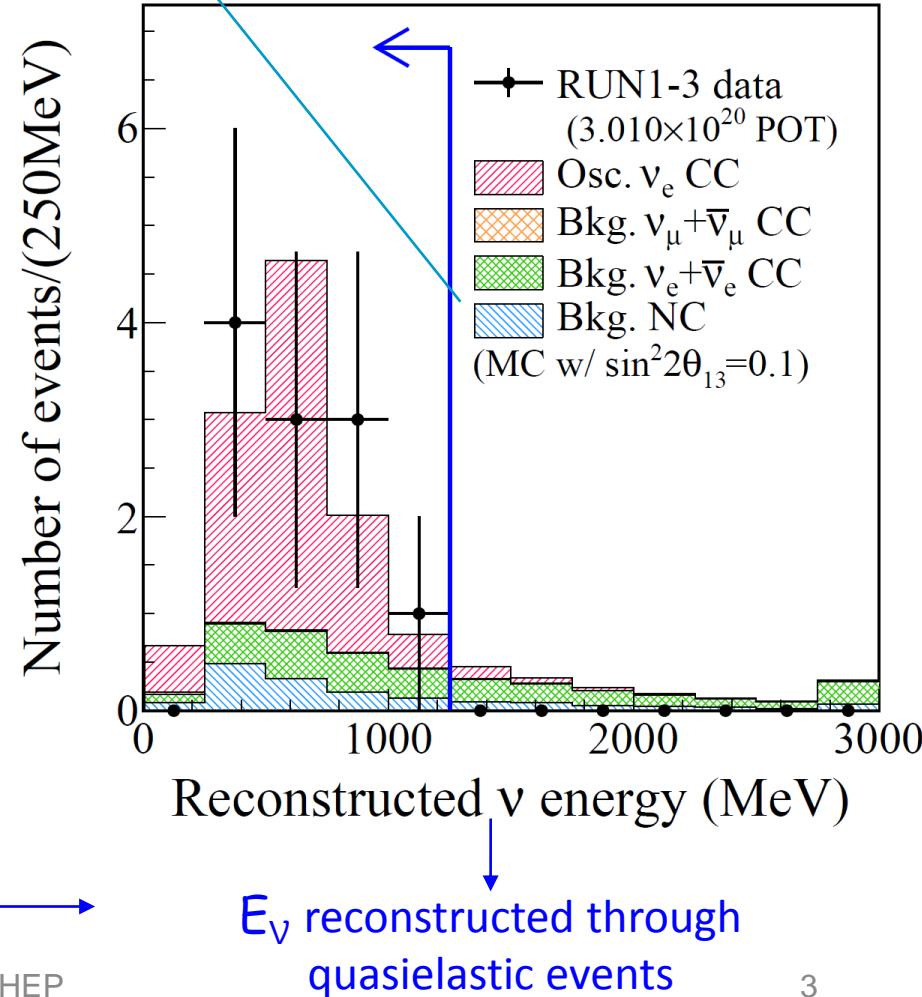
MiniBooNE

$\nu_\mu \rightarrow \nu_e$

Phys.Rev.Lett. 110 (2013) 161801

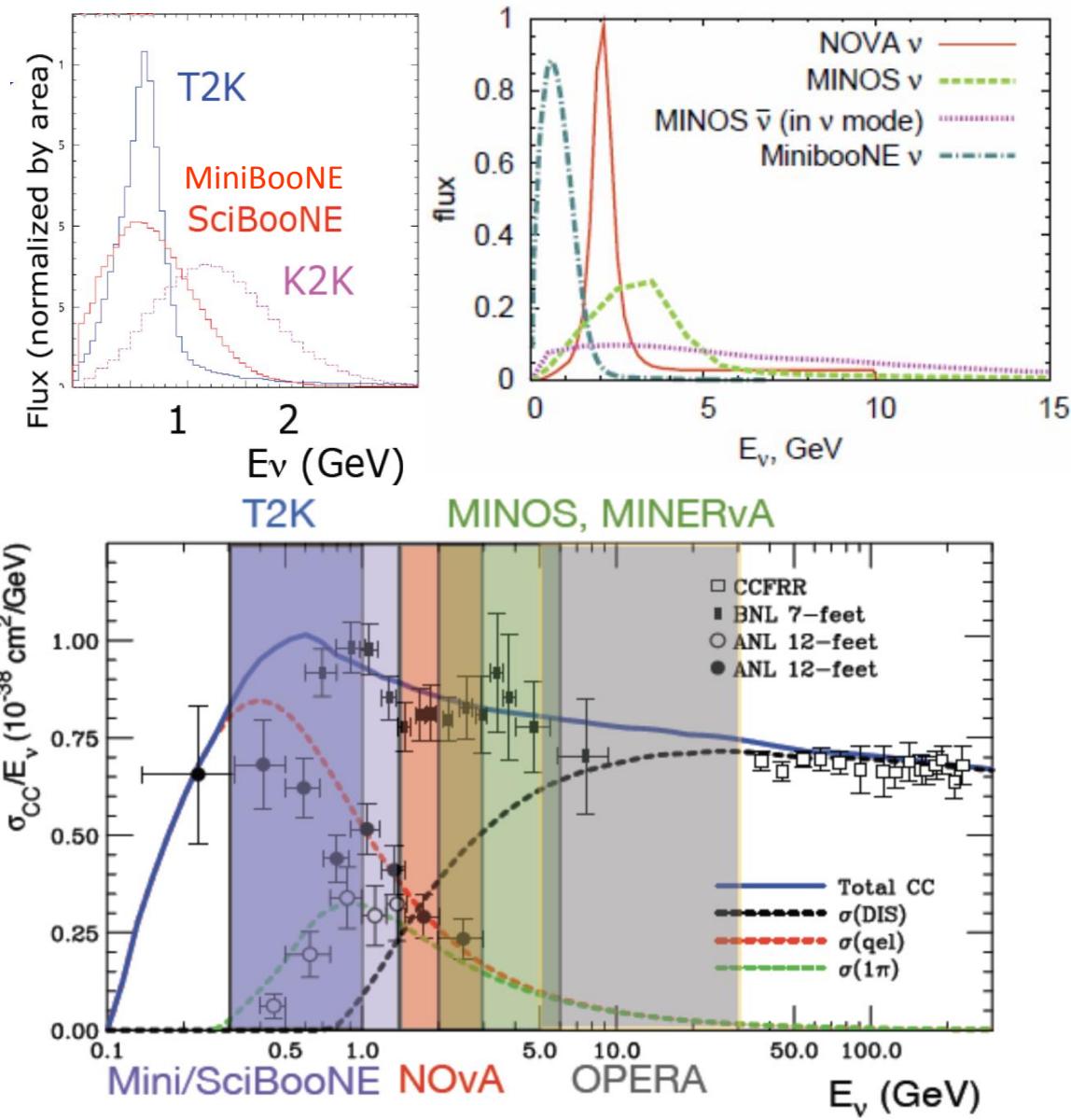


NC π^0 important background



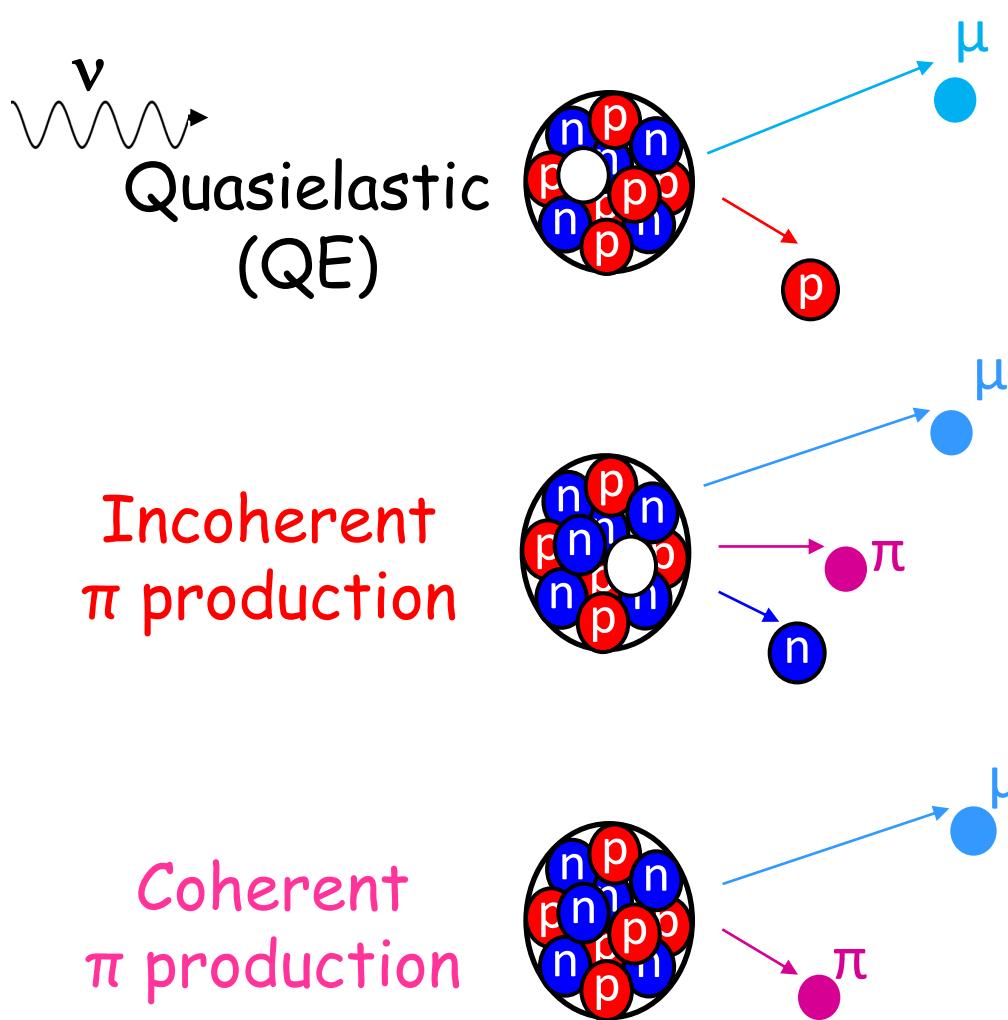
Some crucial points

- 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

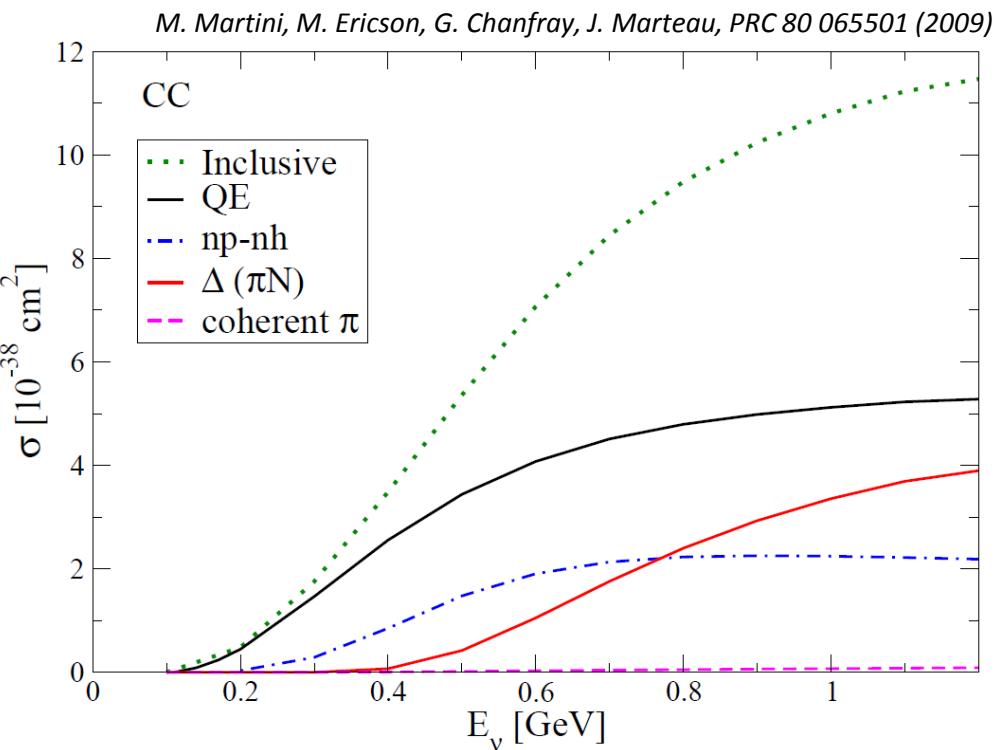


Neutrino - nucleus interaction @ $E_\nu \sim 0$ (1 GeV)

[MiniBooNE, T2K energies]

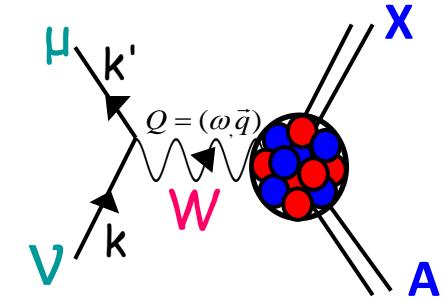


Two Nucleons
knock-out
(2p-2h)



Different processes are entangled

Neutrino-nucleus cross section



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

$$L_{\mu\nu} = k_\mu k'_\nu + k'_\mu k_\nu - g_{\mu\nu} k \cdot k' \pm i\varepsilon_{\mu\nu\kappa\lambda} k^\kappa k'^\lambda \quad W^{\mu\nu} = \sum_f \langle \Psi_f | J^\mu(Q) | \Psi_i \rangle^* \langle \Psi_f | J^\nu(Q) | \Psi_i \rangle \delta(E_i + \omega - E_f)$$

Leptonic tensor

Hadronic tensor

The cross section in terms of the response functions:

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

Longitudinal

Transverse

Transverse
V-A interference

A simplified expression (useful for illustration):

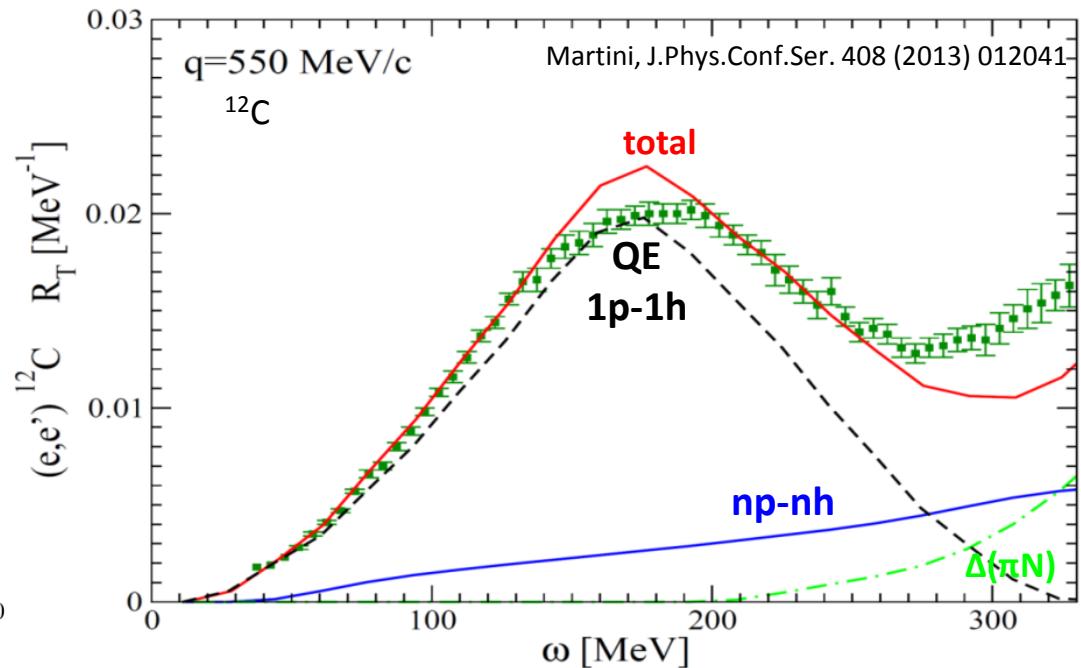
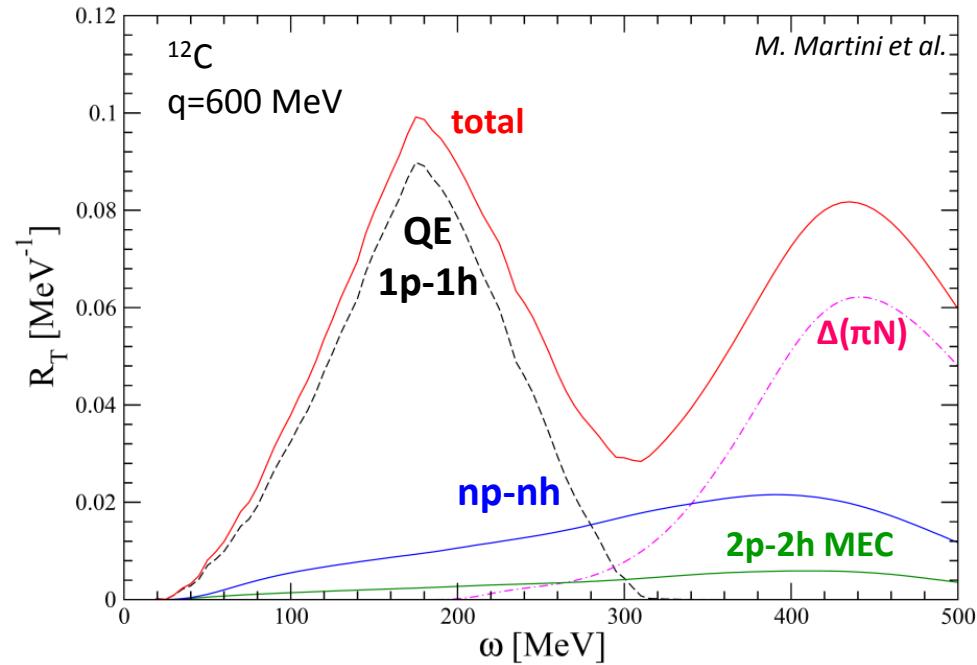
$$\begin{aligned} \frac{\partial^2 \sigma}{\partial \Omega \partial \epsilon'} &= \frac{G_F^2 \cos^2 \theta_c}{2\pi^2} k' \epsilon' \cos^2 \frac{\theta}{2} \left[\frac{(q^2 - \omega^2)^2}{q^4} G_E^2 R_\tau + \frac{\omega^2}{q^2} G_A^2 R_{\sigma\tau(L)} + \right. \\ &\quad \left. + 2 \left(\tan^2 \frac{\theta}{2}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

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

Nuclear dynamics → Nuclear Response Functions $R(q, \omega)$:

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

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



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

Form Factors

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

Standard dipole parameterization

Vector

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

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

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

Axial

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

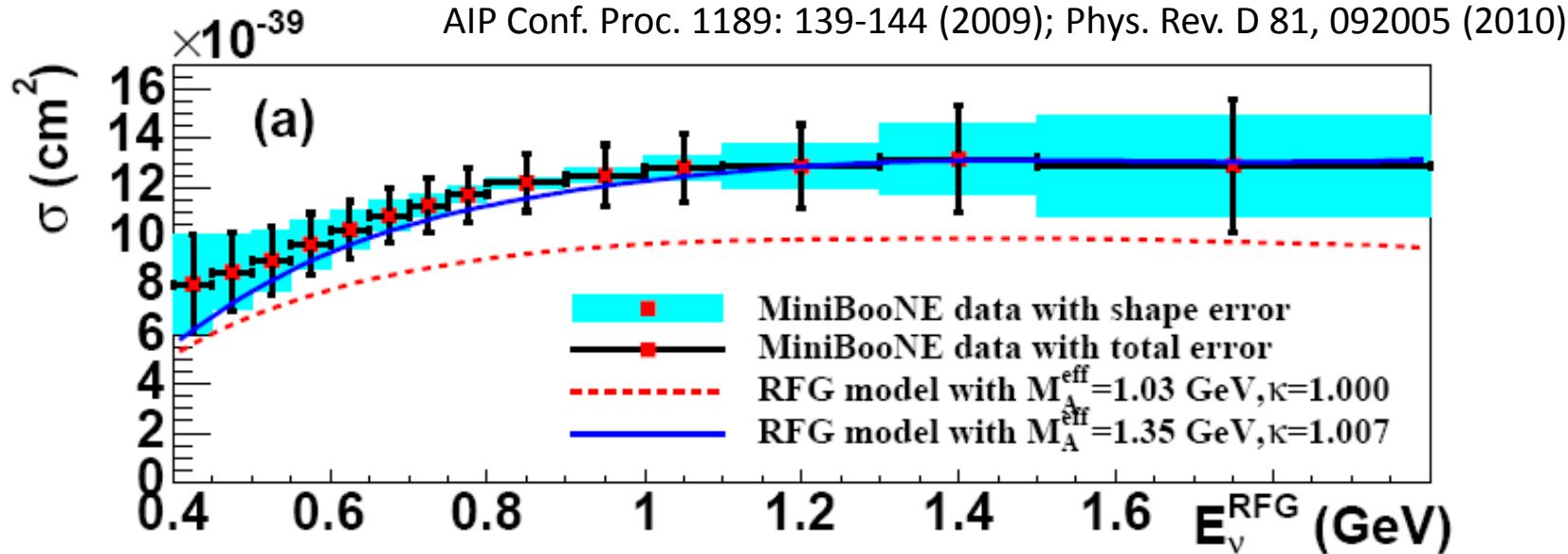
$$g_A = 1.26 \text{ from neutron } \beta \text{ decay}$$

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

from ν -deuterium CCQE and from π electroproduction

Quasielastic

MiniBooNE CC Quasielastic cross section on Carbon and the M_A puzzle



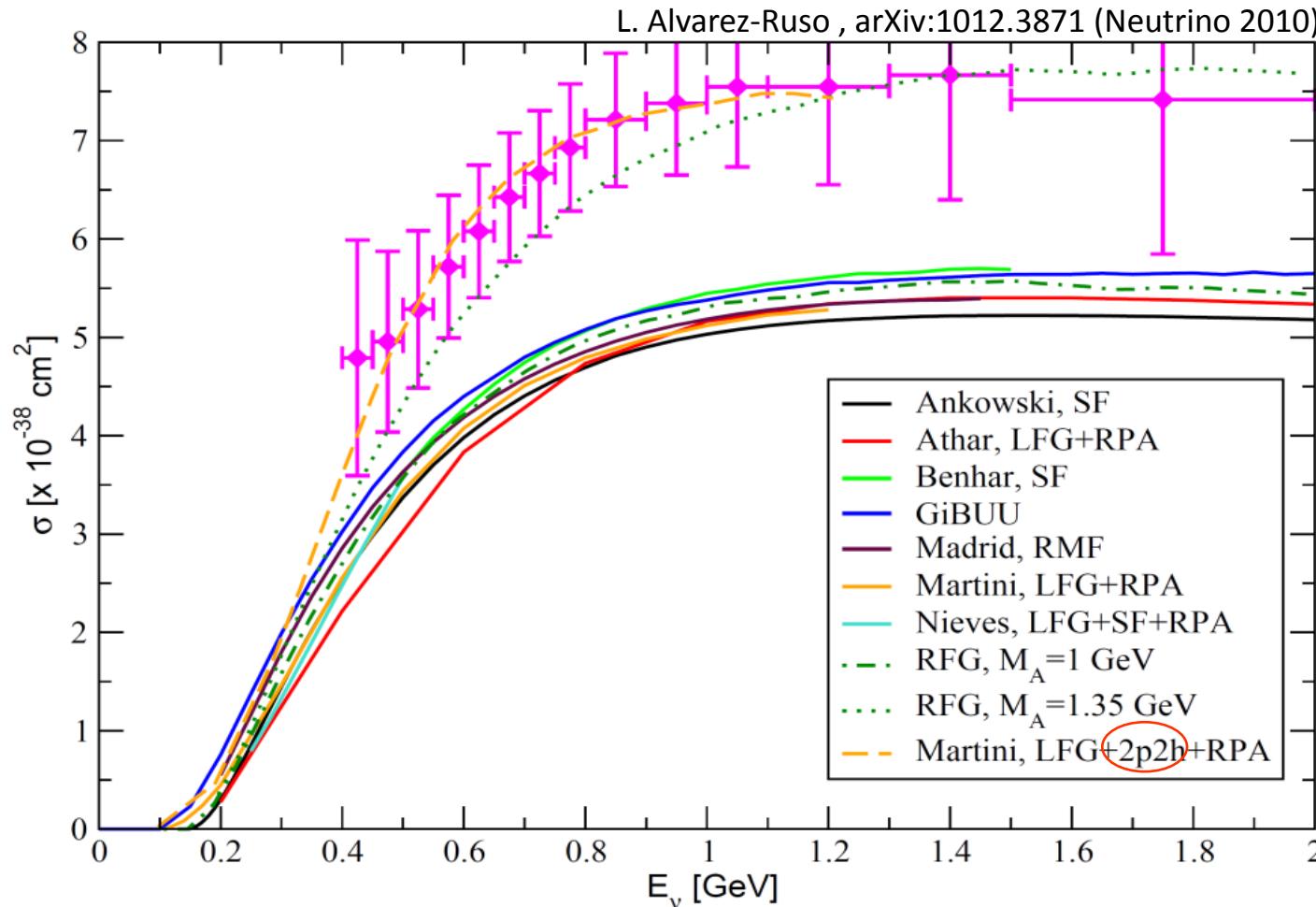
Comparison with a prediction based on RFG using $M_A = 1.03 \text{ GeV}$ (standard value) reveals a discrepancy

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



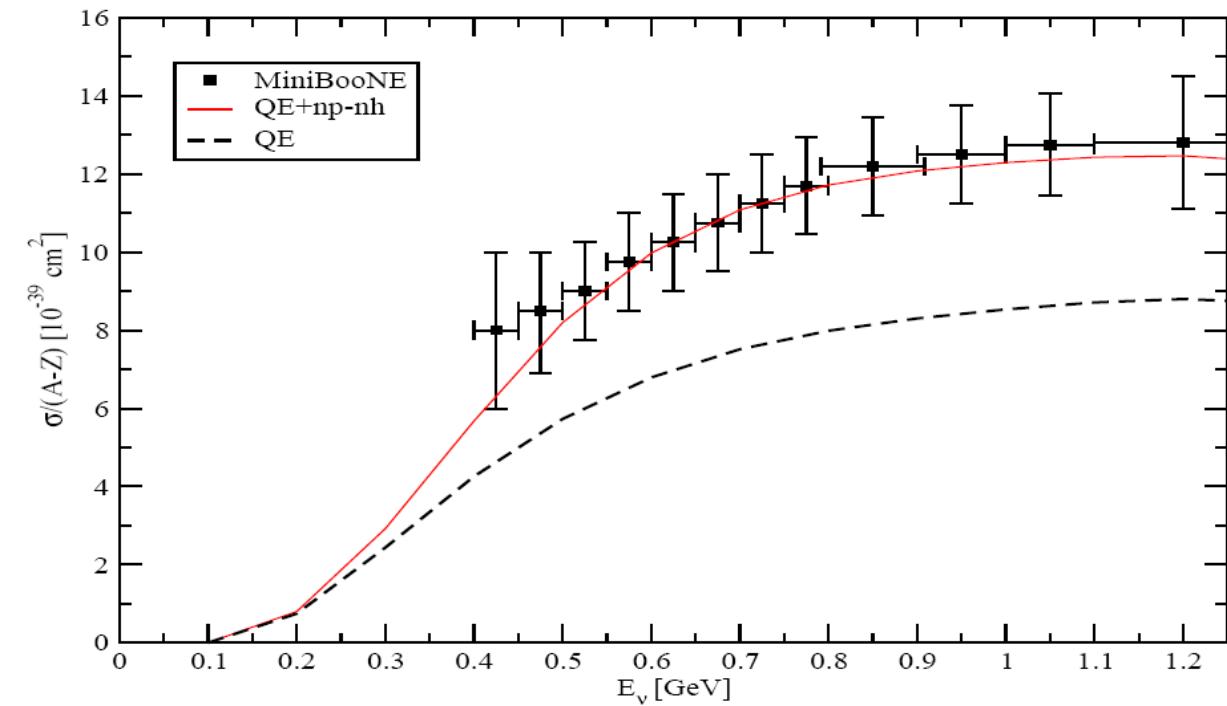
SF: Spectral Function
LFG: Local Fermi Gas
RPA: Random Phase Approximation
RMF: Relativistic Mean Field
GiBUU: Transport Equation

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

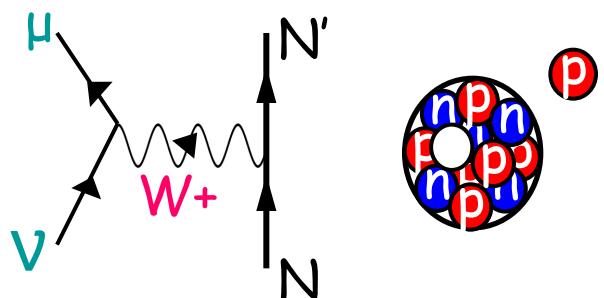
puzzle??

An explanation of this puzzle

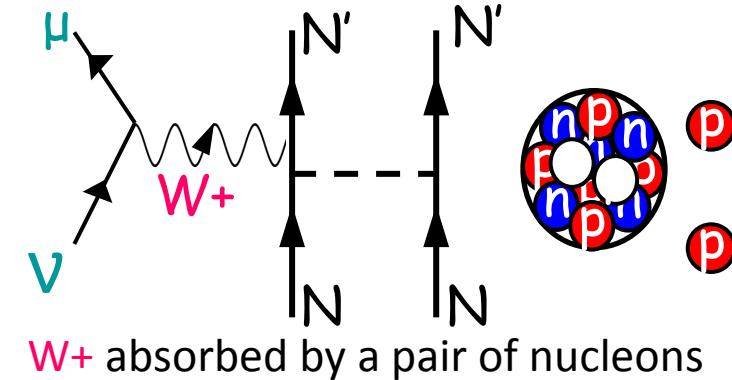
Inclusion of the multinucleon emission channel (np-nh)



Genuine CCQE



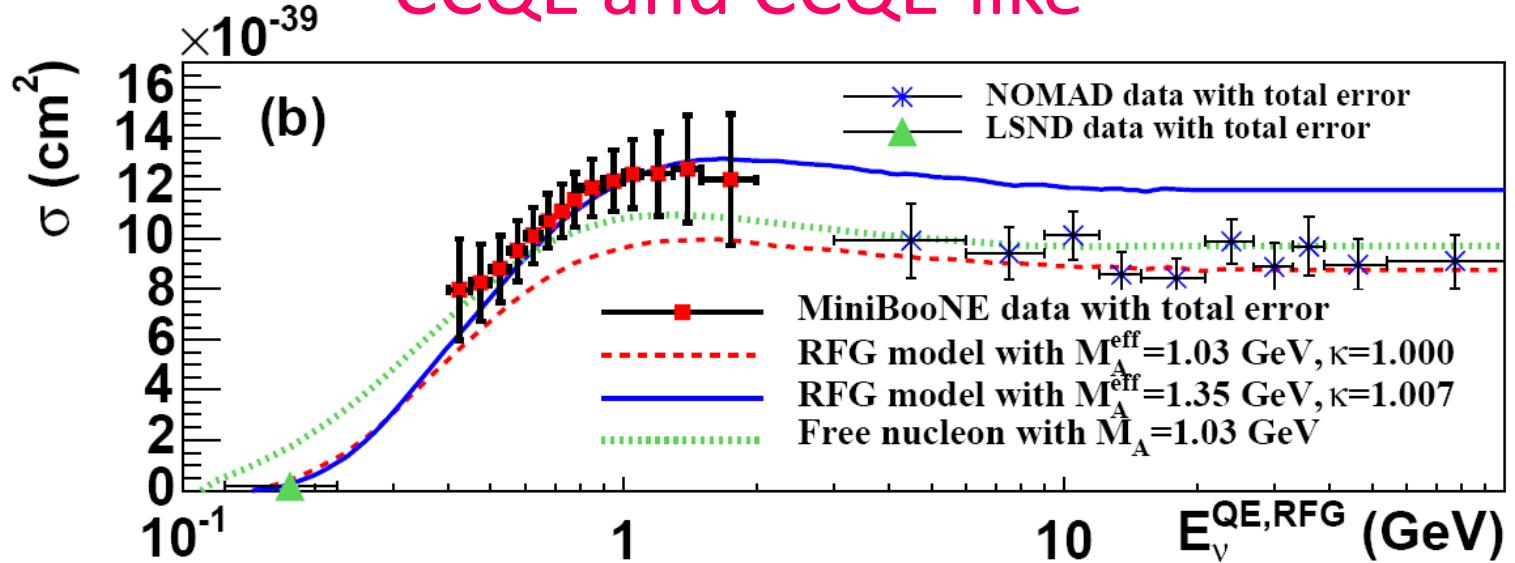
Two particles-two holes (2p-2h)



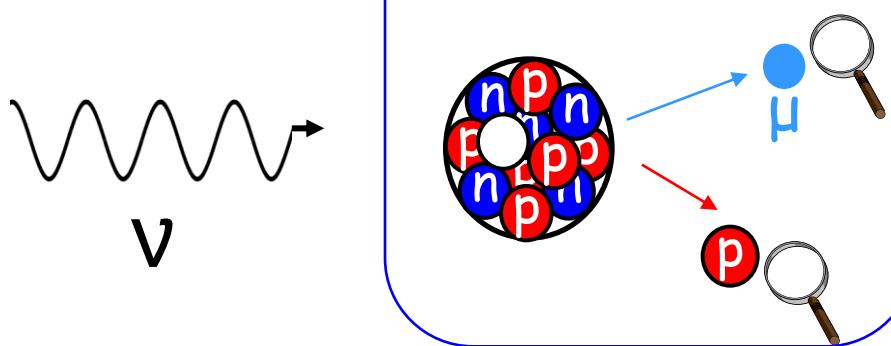
M. Martini, M. Ericson, G. Chanfray, J. Marteau Phys. Rev. C 80 065501 (2009)

Agreement with MiniBooNE without increasing M_A

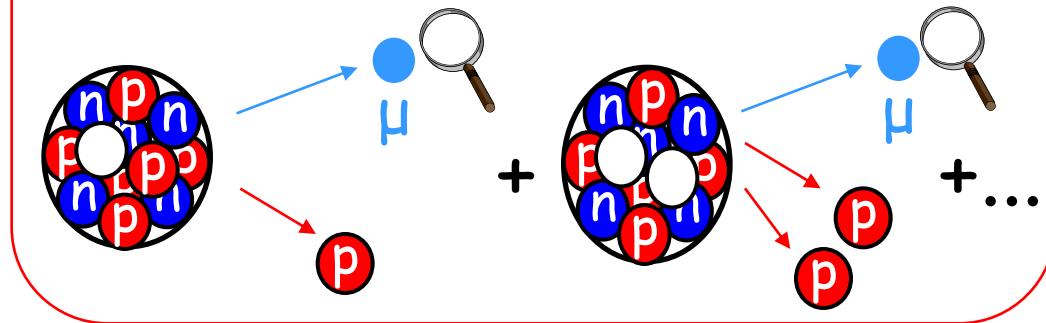
CCQE and CCQE-like



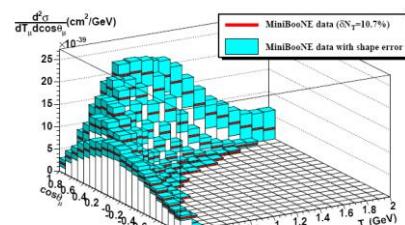
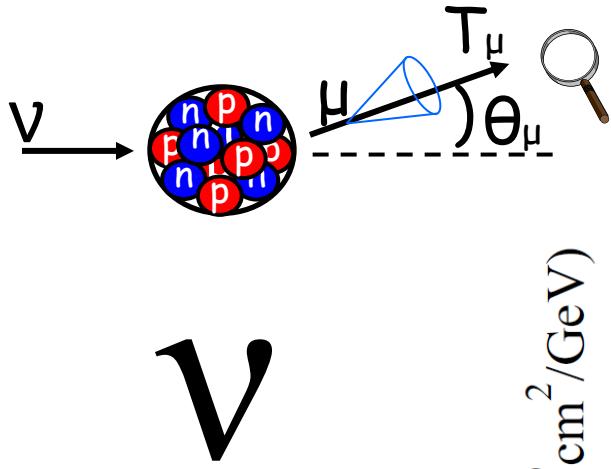
CCQE



CCQE-like
e.g. Cherenkov detectors

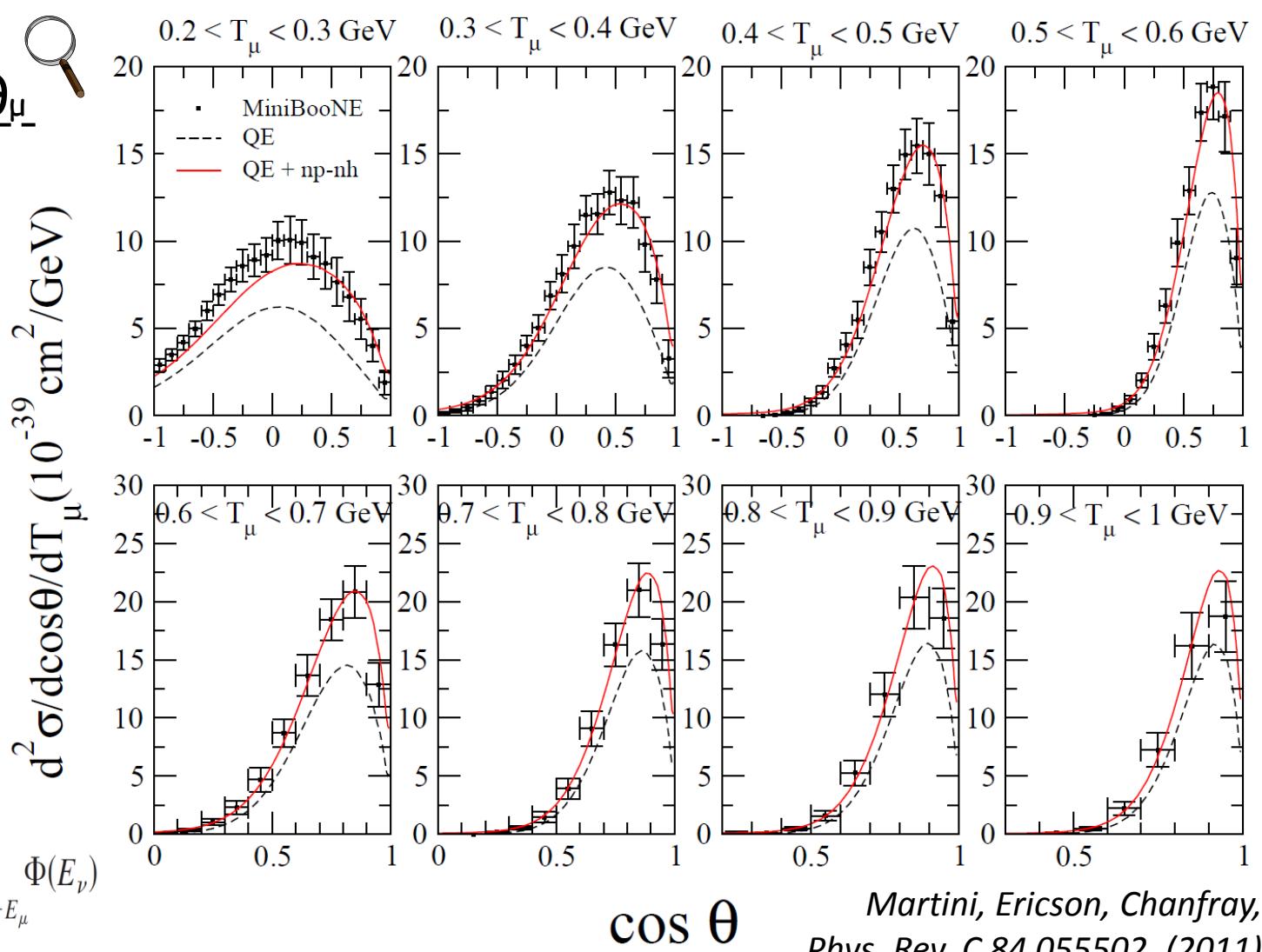


MiniBooNE CCQE-like flux-integrated double differential cross section



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

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

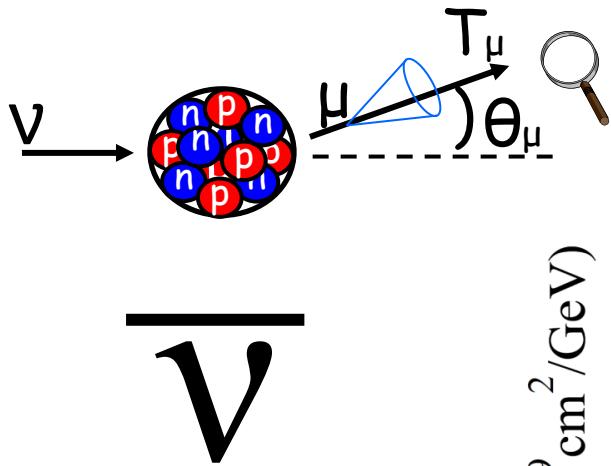


Martini, Ericson, Chanfray,
Phys. Rev. C 84 055502 (2011)

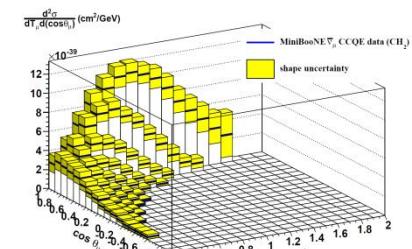
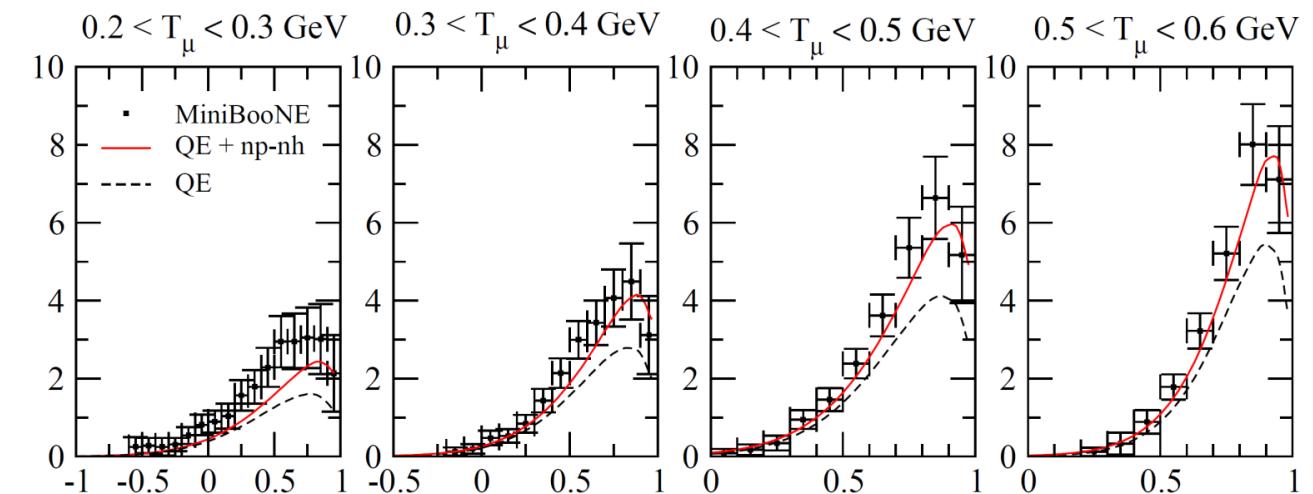
Agreement with MiniBooNE without increasing M_A once np-nh is included

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

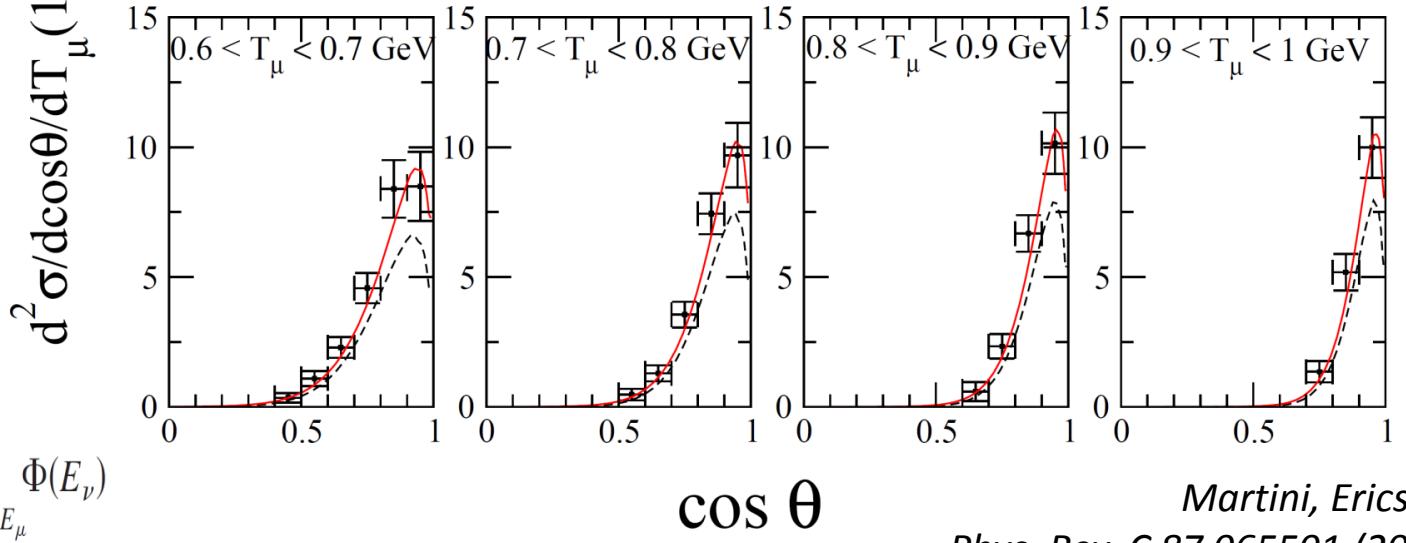
MiniBooNE CCQE-like flux-integrated double differential cross section



$$\frac{d^2\sigma}{dT_\mu d\cos\theta} (10^{-39} \text{ cm}^2/\text{GeV})$$



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



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

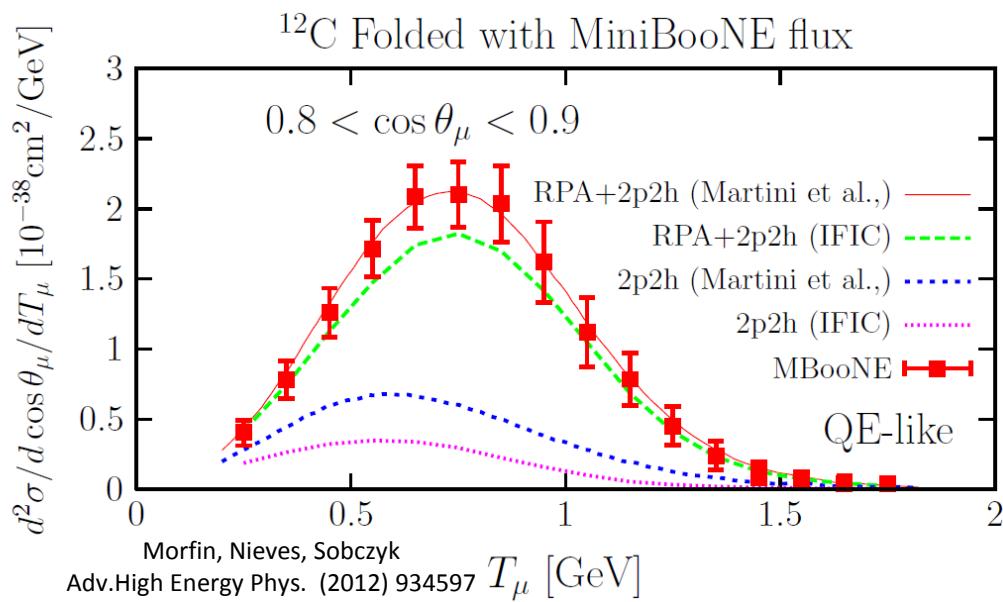
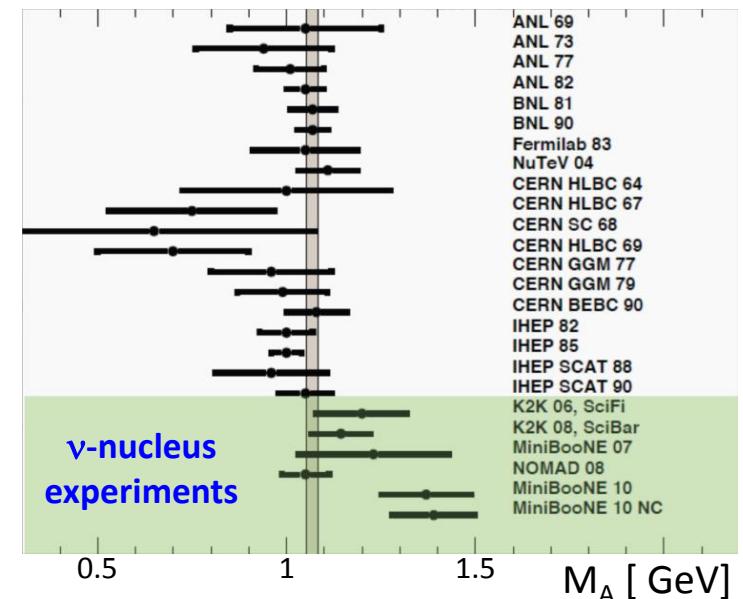
Agreement with MiniBooNE without increasing M_A once np-nh is included

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

[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 σ_{total}

Phys. Rev. C 81 045502 (2010) ν vs antiv (σ_{total})

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) antiv $d^2\sigma$, $d\sigma/dQ^2$

Phys. Rev. C 90 025501 (2014) inclusive ν $d^2\sigma$

Phys. Rev. C 91 035501 (2015) combining ν and antiv $d^2\sigma$, $d\sigma/dQ^2$

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

Phys. Rev. C 83 045501 (2011) ν , antiv σ_{total}

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) antiv $d^2\sigma$

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 $d^2\sigma$, σ_{total}

Phys. Rev. Lett. 108 152501 (2012) antiv $d^2\sigma$, σ_{total}

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

arXiv 1506.00801 (2015) inclusive ν $d^2\sigma$

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](#)

Phys. Rev. C 91 062501 (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\$](#)

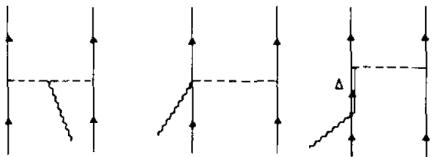
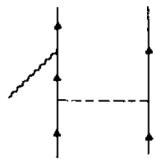
Phys. Rev. C 86 054606 (2012) [impact of np-nh on ν energy reconstruction and ν oscillation](#)

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

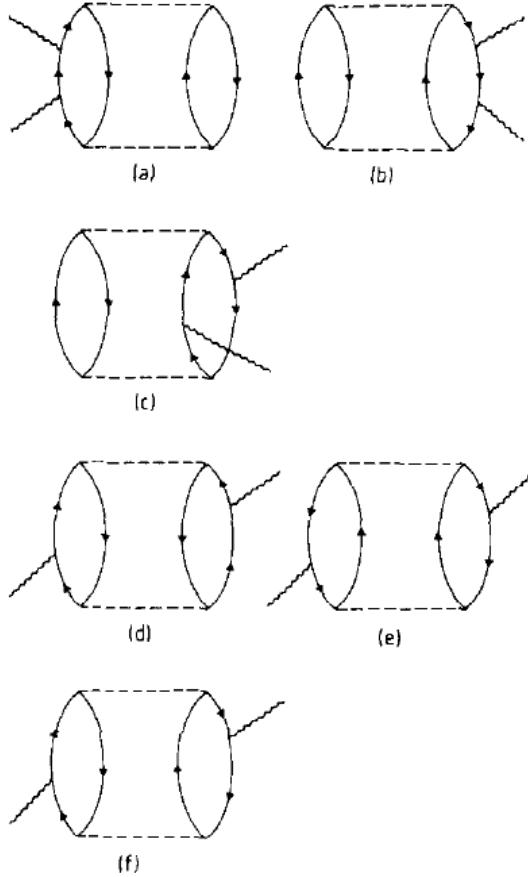
EPJ C 71 1726 (2011) [ν and antiv σtotal, \$d\sigma/dQ^2\$](#)

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

2p-2h

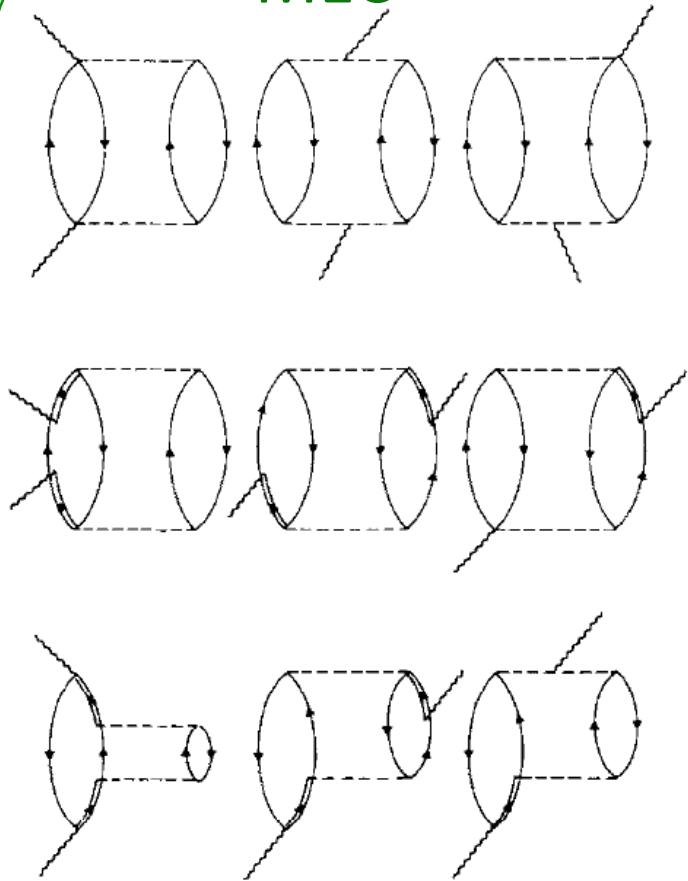


NN correlations



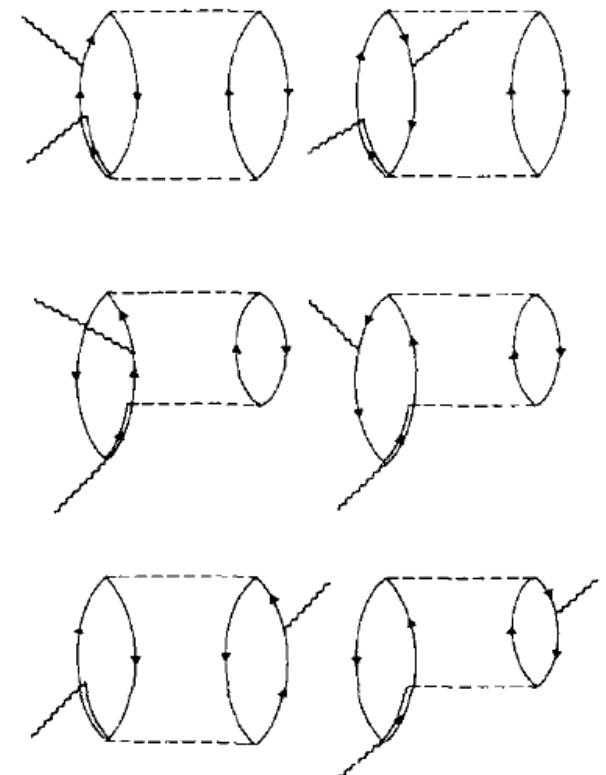
16 diagrams

MEC



49 diagrams

NN correlation-MEC interference



56 diagrams

Main difficulties in the 2p-2h sector

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

- 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:

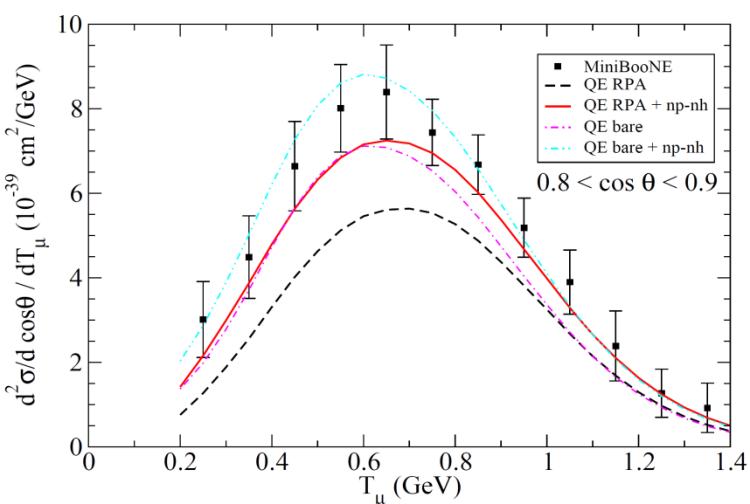
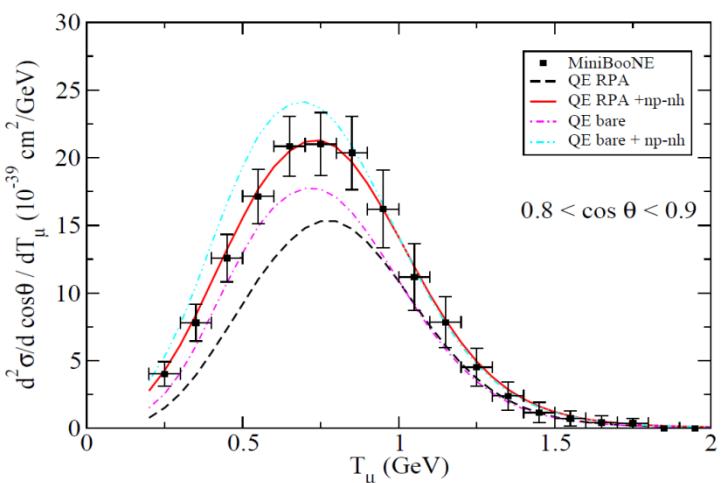
- choice of subset of diagrams and terms;
- different prescriptions to regularize the divergences;
- reduce the dimension of the integrals (7D --> 2D if non relativistic; 7D -->1D if $h_1 = h_2 = 0$)

⇒ Different final results

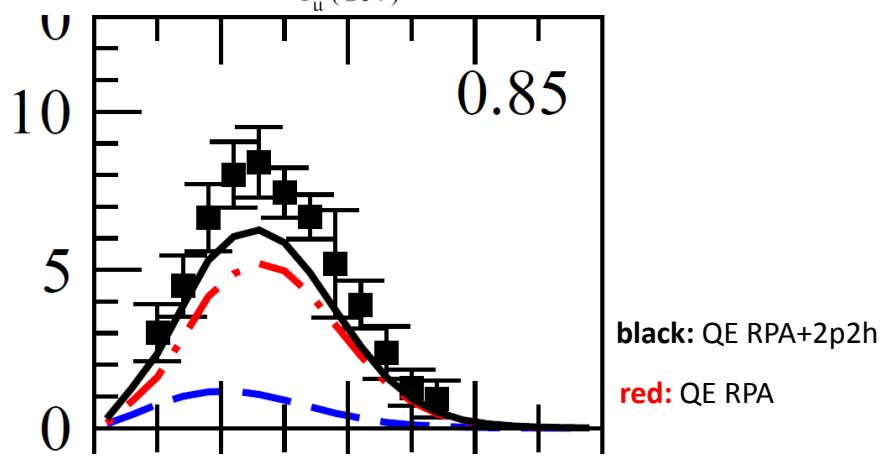
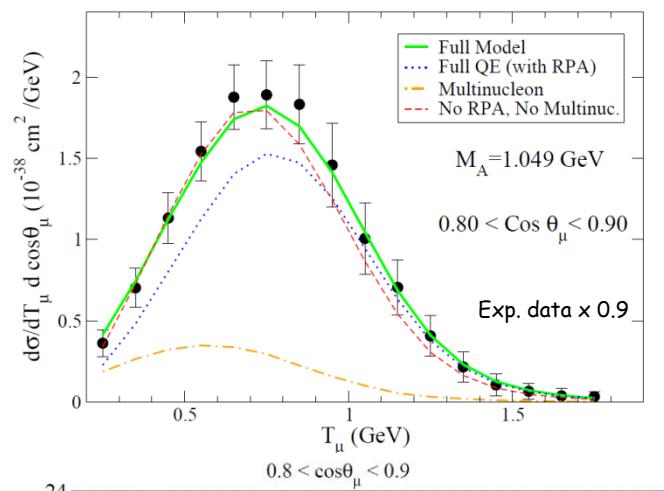
V

V

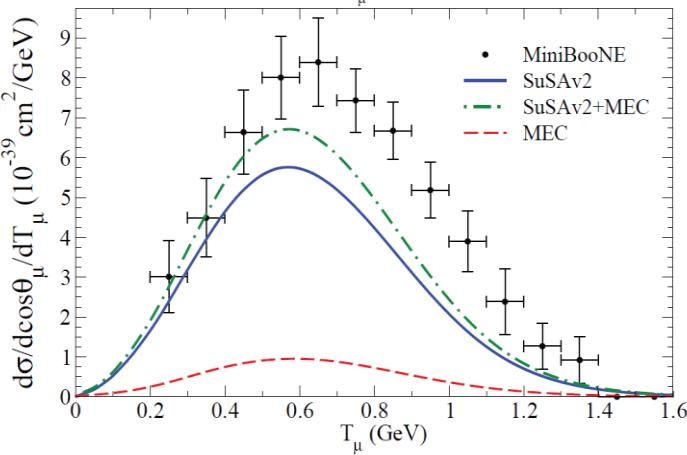
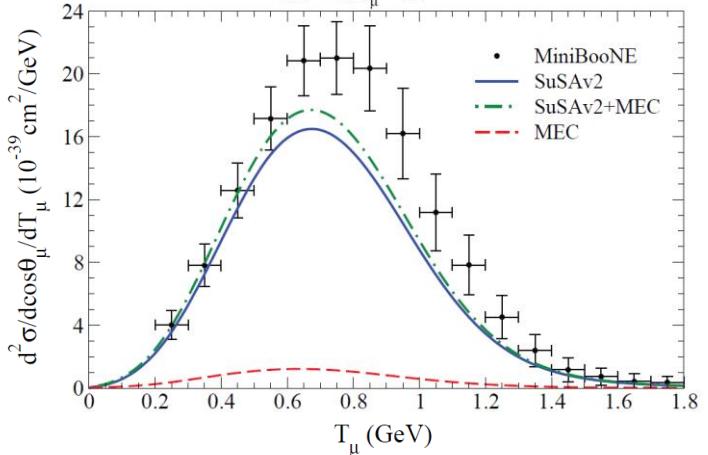
Martini et al.



Nieves et al.



Amaro et al.



Neutrino vs Antineutrino interactions and CP violation

Detection of an asymmetry between ν and $\text{anti}\nu$ oscillation rates as evidence of CP violation

$$\nu_\mu \rightarrow \nu_e \quad \text{vs} \quad \bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

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

Vector-Axial interference:

basic asymmetry from weak interaction theory

Vector-Axial interference

$$\left\{ \begin{array}{ll} + & (\nu) \\ - & (\bar{\nu}) \end{array} \right.$$

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



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:]

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

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

Recent results of an *ab-initio* microscopic approach

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

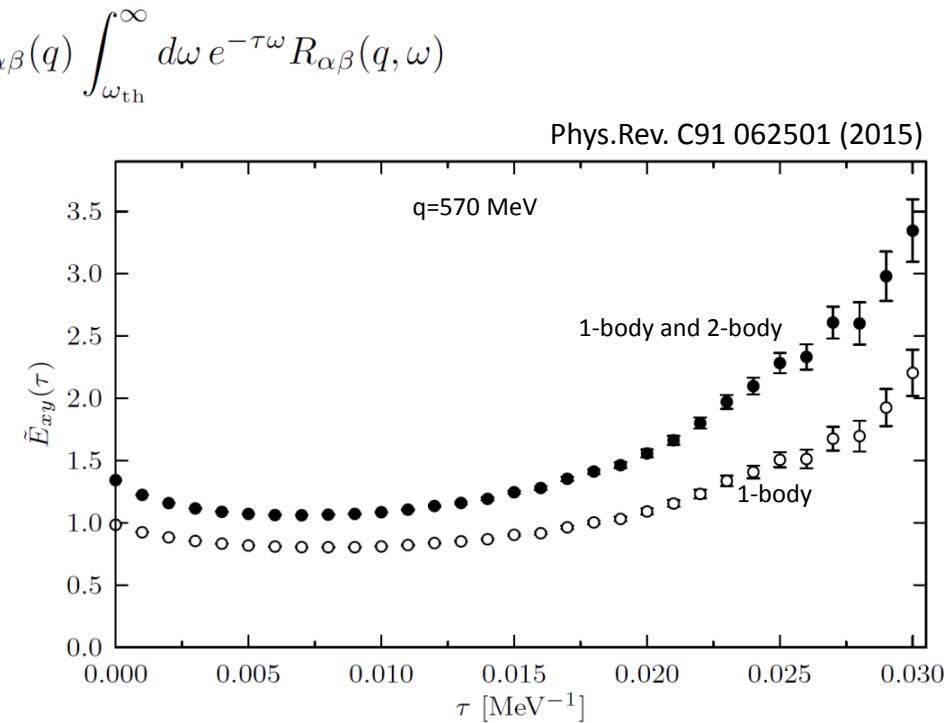
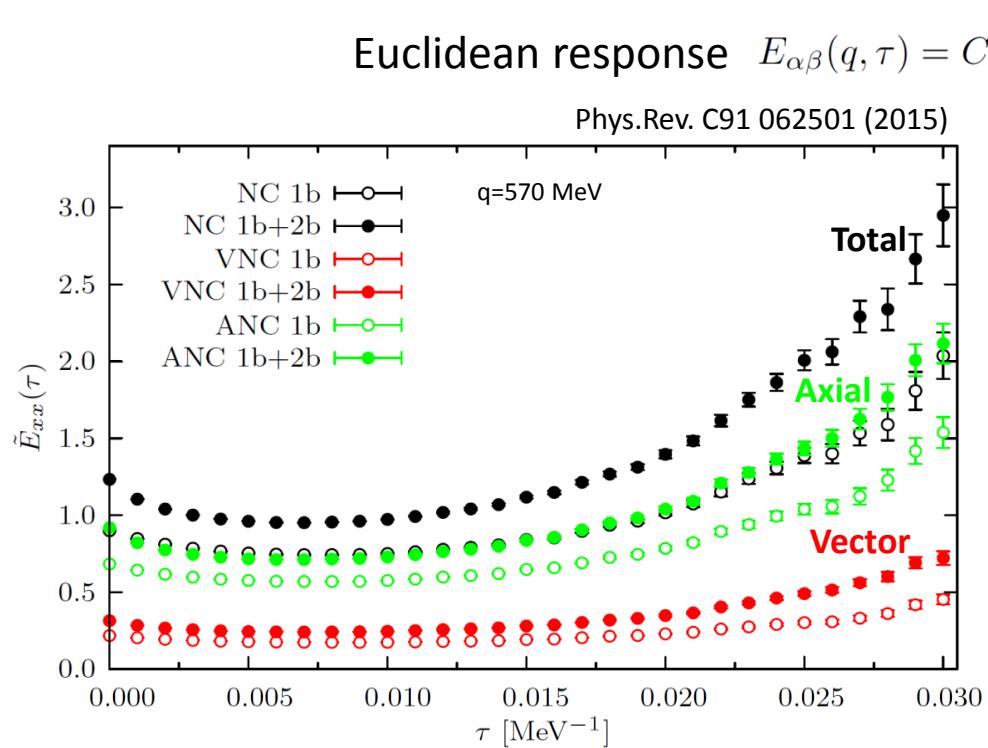
Neutral weak current two-body contributions to sum rules and Euclidean responses in ^{12}C

Phys. Rev. Lett. 112 182502 (2014)

Phys. Rev. C91 062501 (2015)

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



important 2-body contributions
also in the Axial part of the transverse response

important 2-body contributions
in the VA interference term

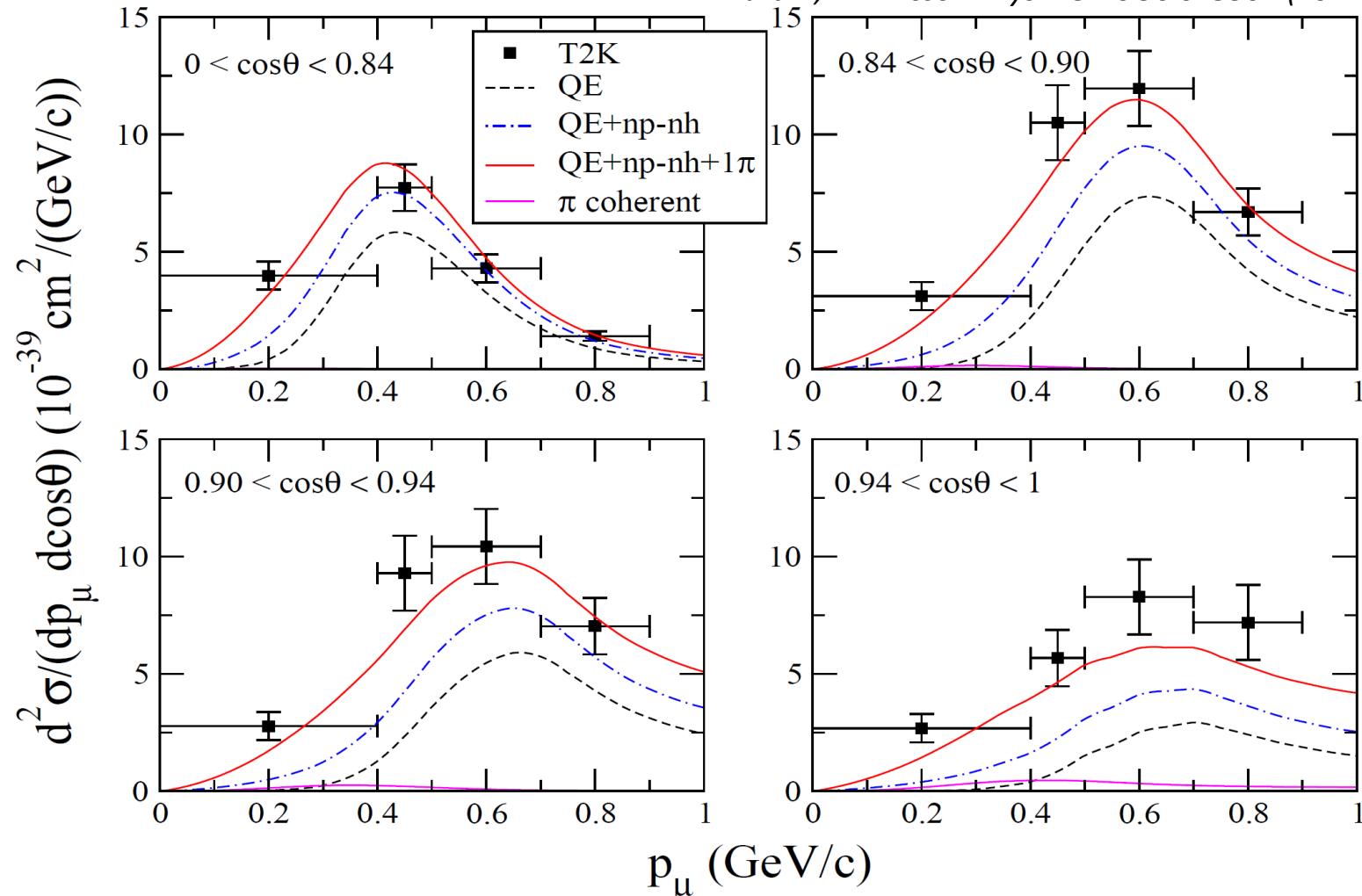
Beyond MiniBooNE QE: other channels and other experiments

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)

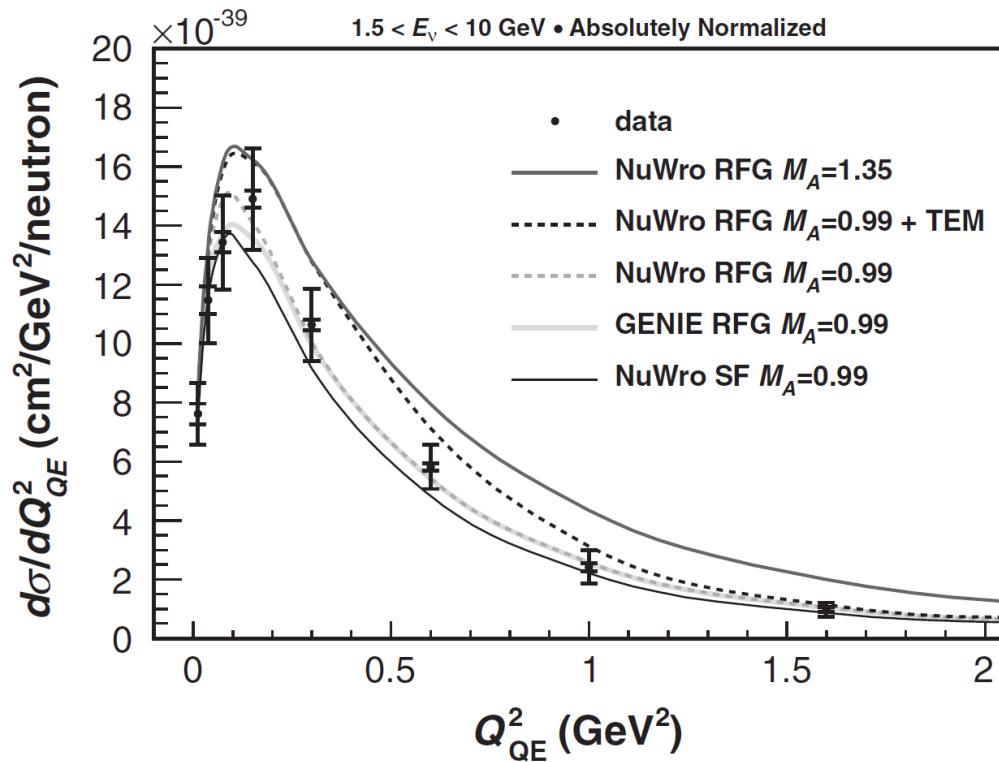


First successful test of the necessity of the multinucleon emission channel in an experiment with another neutrino flux with respect to the one of MiniBooNE.

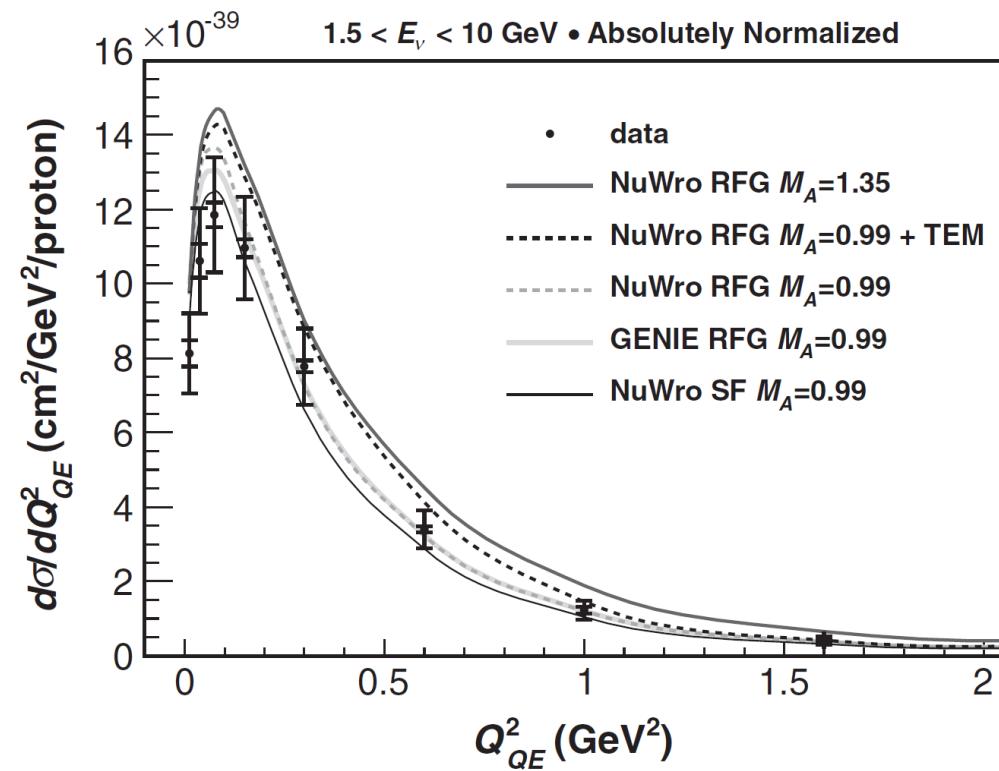
MINERvA ($E_\nu \sim 3.5$ GeV) CCQE Q^2 distribution

V

\overline{V}

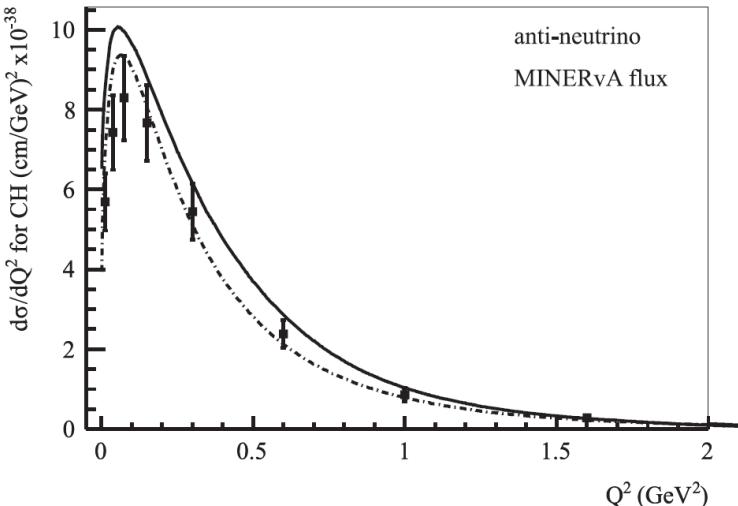
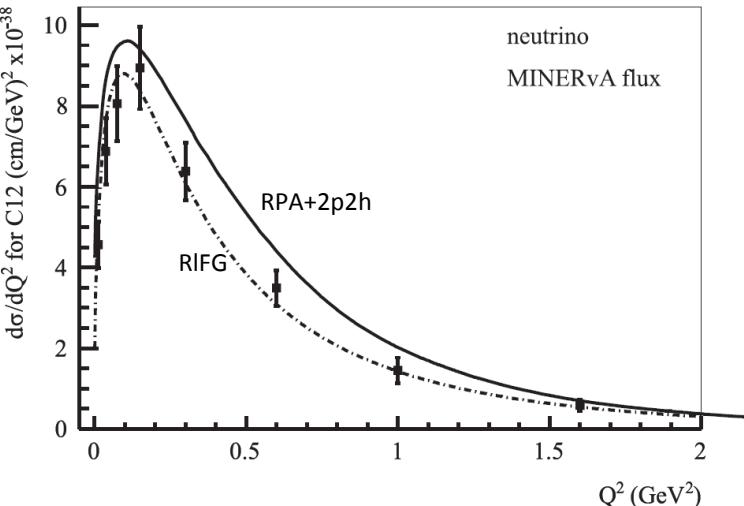


PRL 111 022502 (2013)

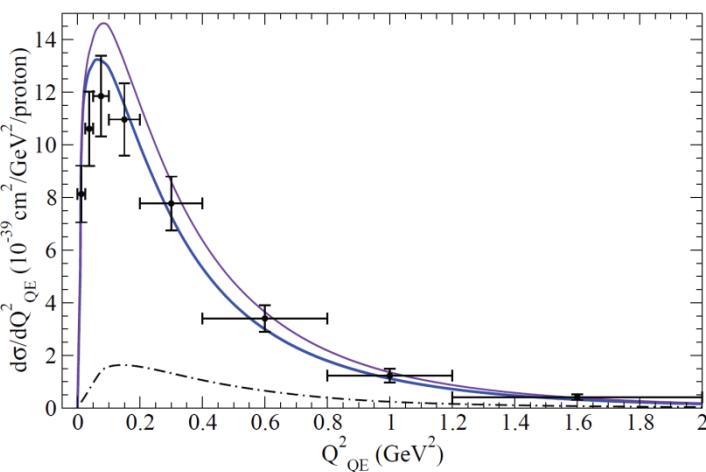
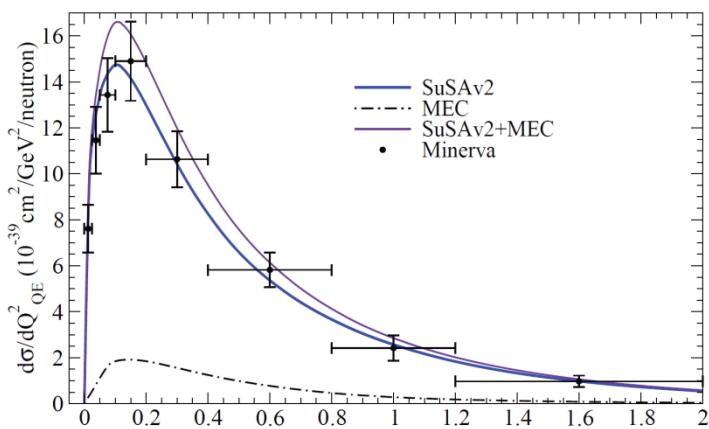


PRL 111 022501 (2013)

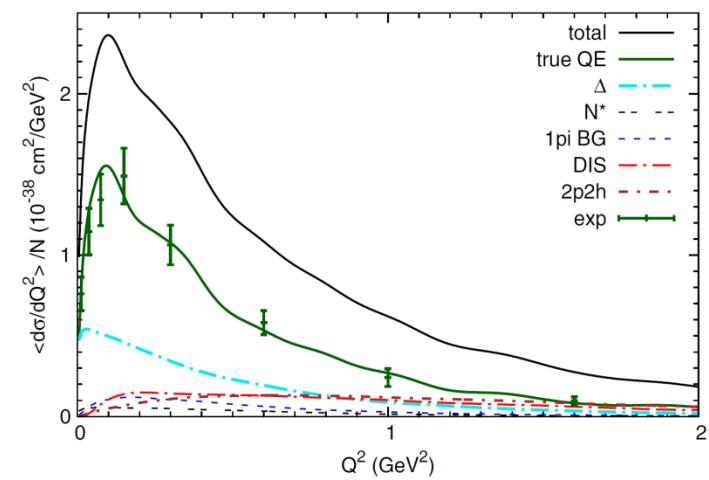
Gran, Nieves
et al.
PRD 88 (2013)



Megias, Amaro
et al.
PRD 91 (2015)



Mosel et al.
PRD 89 (2014)

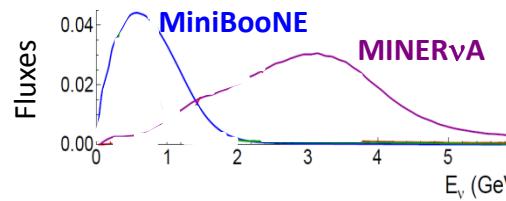
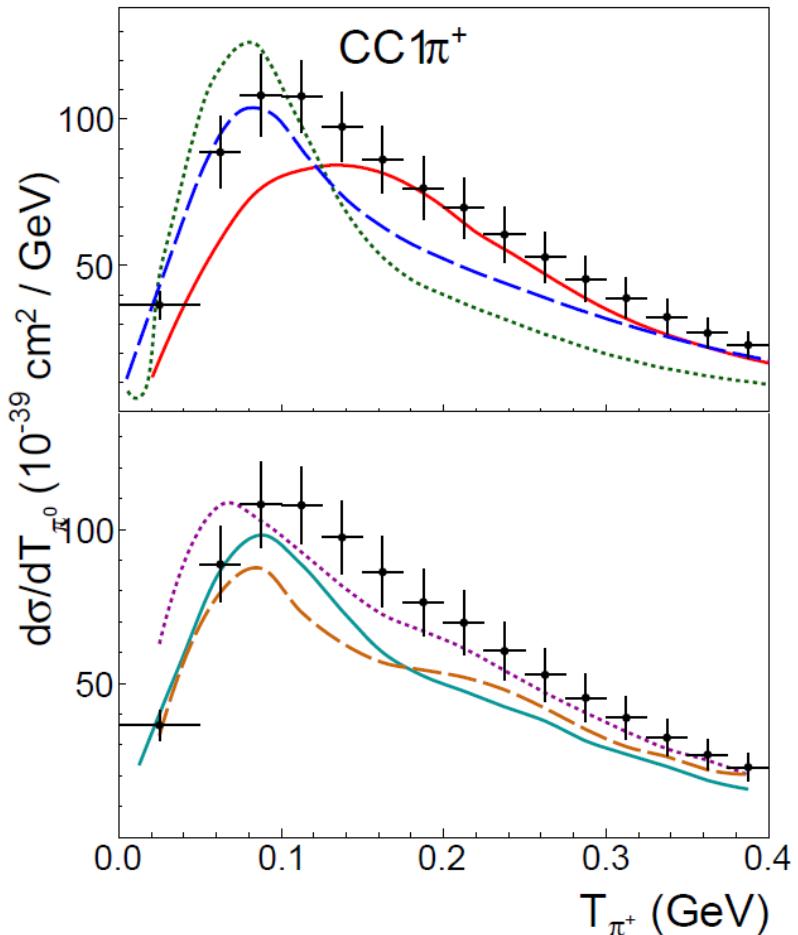


- **MINERvA CCQE Q^2 distributions can be reproduced also without the inclusion of np-nh**
- **This is not the case of the MiniBooNE Q^2 distributions**
- Mosel et al: “The sensitivity to details of the treatment of np-nh contributions is smaller than the uncertainties introduced by the Q^2 reconstruction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

MiniBooNE vs MINERvA CC1 π^+ production

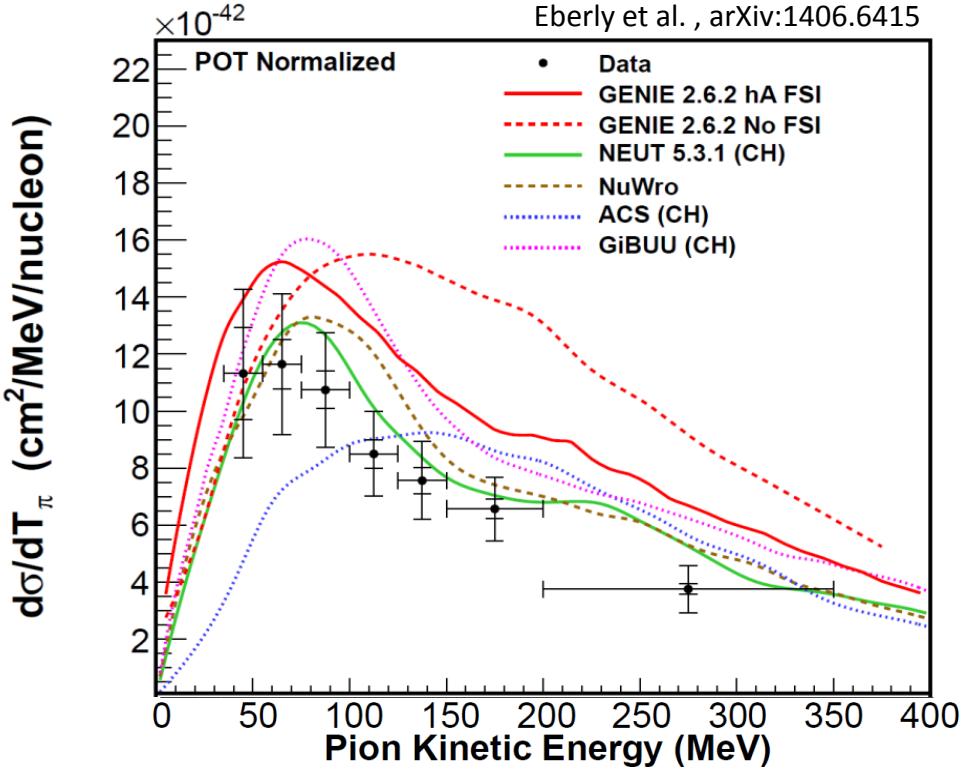
MiniBooNE

Rodrigues, arXiv:1402.4709



MINERvA

Eberly et al. , arXiv:1406.6415



Some tension

— Athar et al. ····· Nieves et al. — GiBUU — NuWro
 ····· GENIE — NEUT + MB data

23/7/2015

M. Martini, EPS - HEP

29

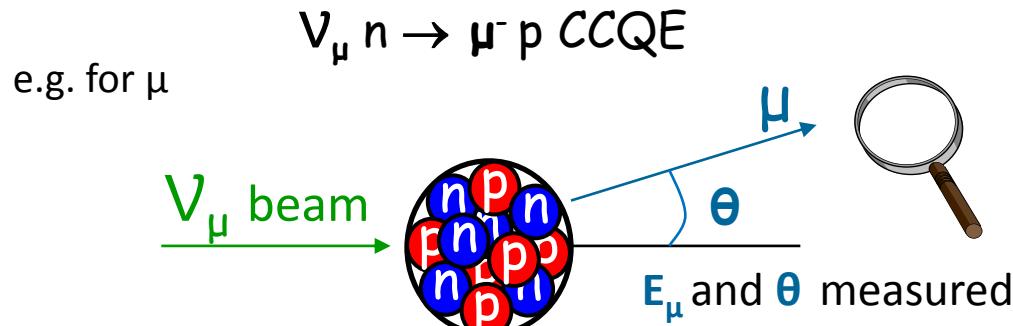
Neutrino energy reconstruction problems and neutrino oscillations

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.



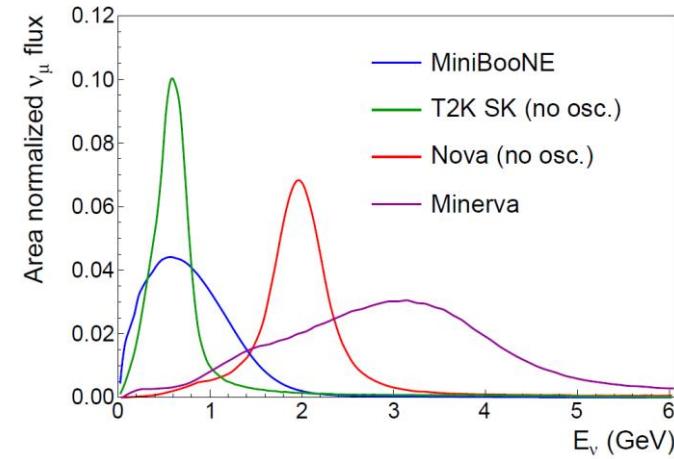
Reconstructed neutrino energy

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

via two-body
kinematics

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

reconstructed neutrino energy \overline{E}_ν $\xleftrightarrow{?} E_\nu$ true neutrino energy



From true neutrino energy to reconstructed neutrino energy

Probability energy distribution (E_ν, \bar{E}_ν)

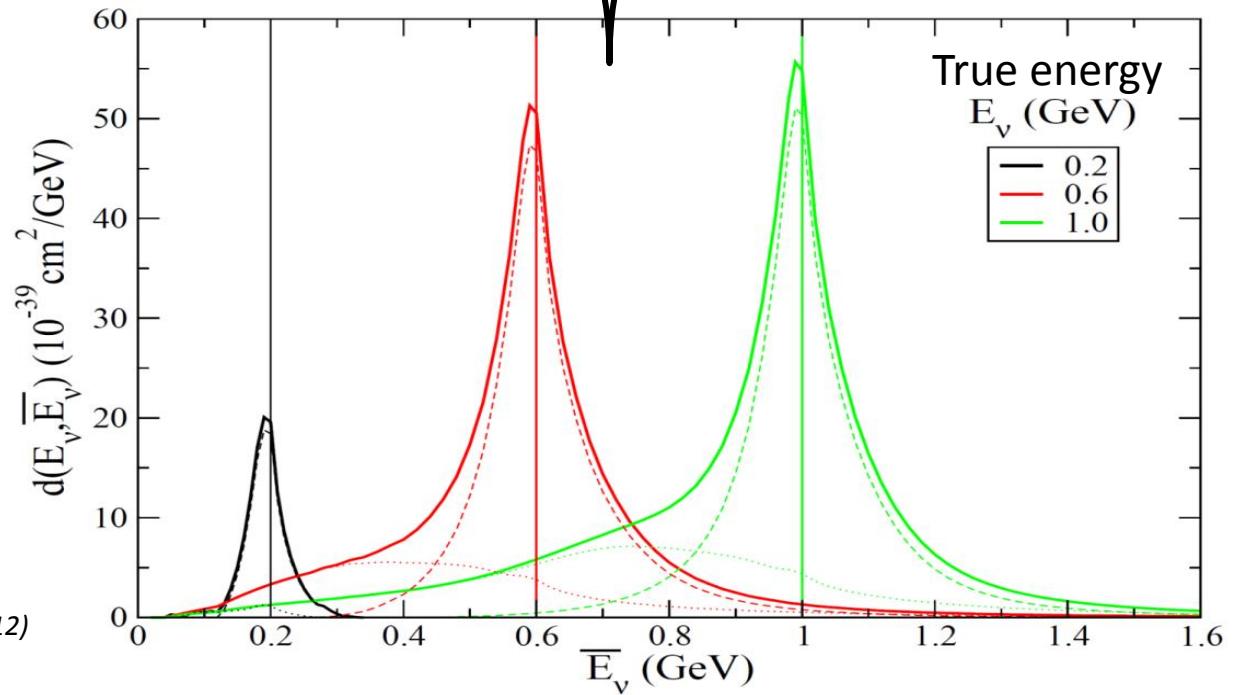
$$D_{rec}(\bar{E}_\nu) = \int dE_\nu \Phi(E_\nu) \left[\int_{E_l^{min}}^{E_l^{max}} dE_l \frac{ME_l - m_l^2/2}{\bar{E}_\nu^2 P_l} \left[\frac{d^2\sigma}{d\omega d\cos\theta} \right]_{\omega=E_\nu-E_l, \cos\theta=\cos\theta(E_l, \bar{E}_\nu)} \right]$$

The quantity $D_{rec}(\bar{E}_\nu)$ 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:

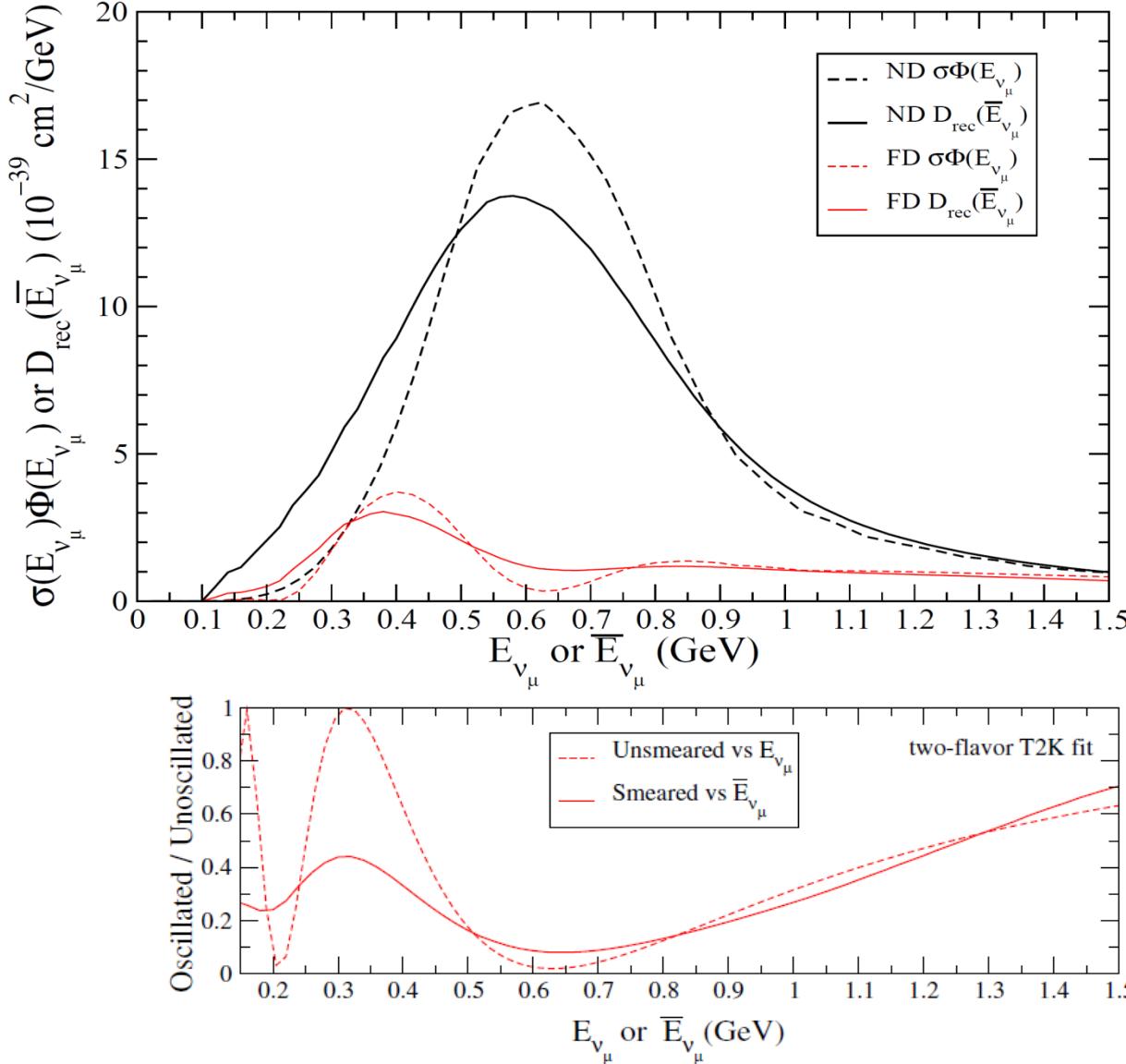
- Nieves, Sanchez, Simo, Vicente Vacas PRD 85 113008 (2012)
 - Lalakulich, Mosel, Gallmeister, PRC 86 054606 (2012)



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

ν_μ disappearance T2K

PRD85 (2012); PRL 111 (2013)



After reconstruction correction:

- 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 :

PhysRevD.91.072010 (2015)

“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.”

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

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

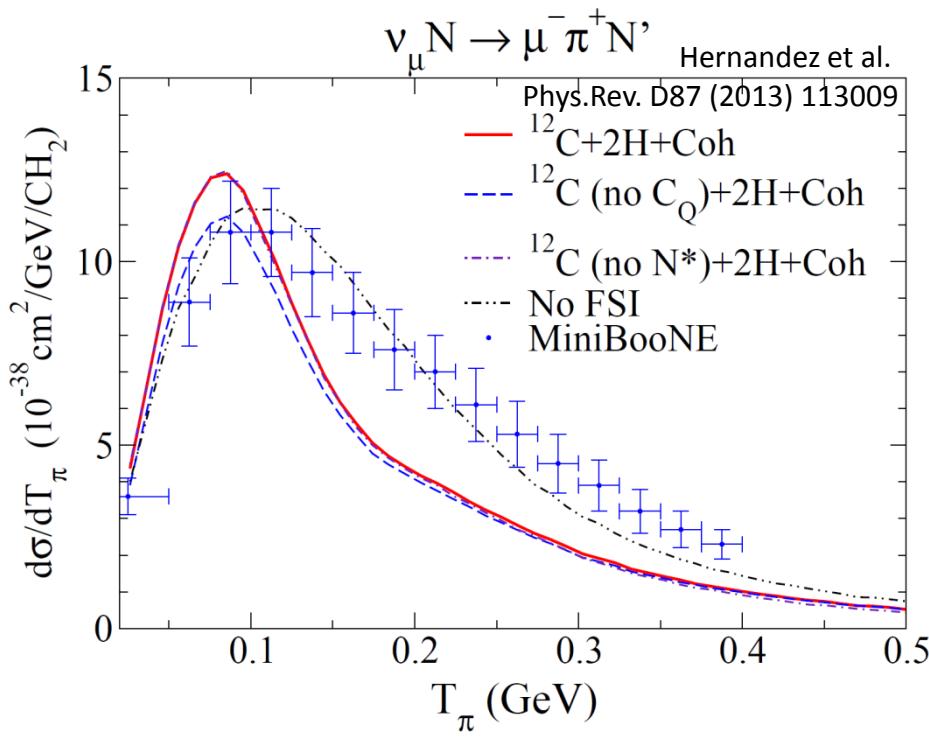
Nuclear effects in neutrino interactions

Summary

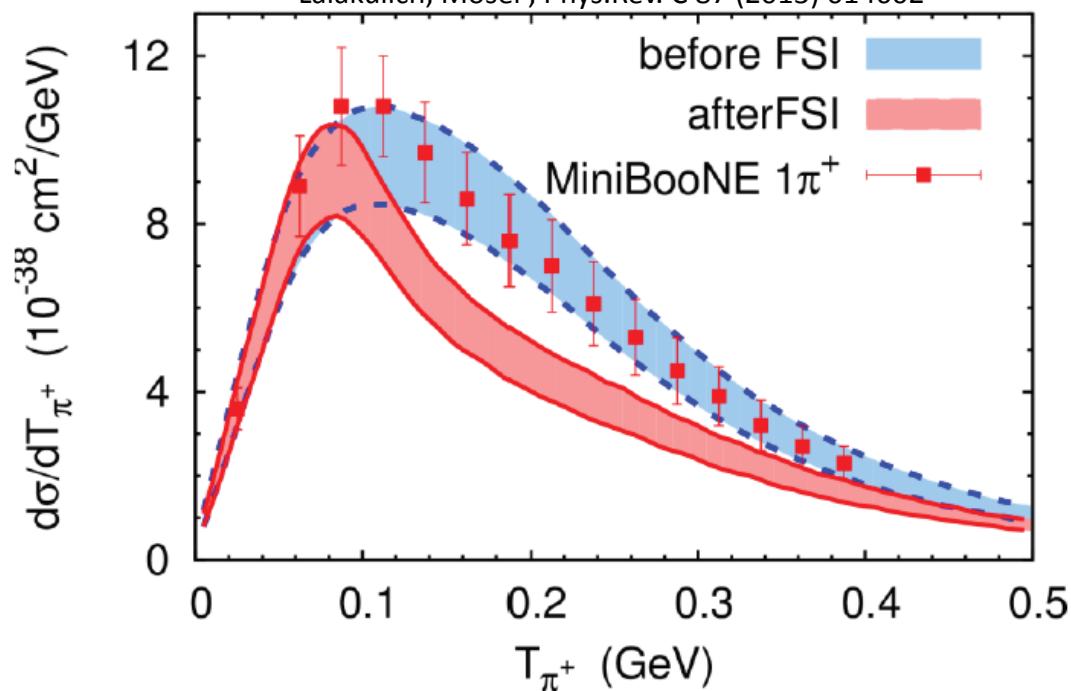
- Several theoretical calculations agree on the crucial role of the multinucleon channel (not contained in the generators) to explain MiniBooNE CCQE-like data \Rightarrow Solution of M_A puzzle
- There are some differences on the way to treat this np-nh channel which are reflected in the comparisons with the MiniBooNE neutrino and antineutrino data
- Nuclear effects generate an asymmetry between ν and anti ν 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 MINERvA results is less evident
- There are some controversies and puzzles in the 1π production channel, e.g. MiniBooNE vs MINERvA vs theory and Monte Carlo
- Neutrino energy reconstruction and neutrino oscillation analysis are affected by np-nh

Spares

MiniBooNE CC1 π^+ production: theory versus experiment



Valencia



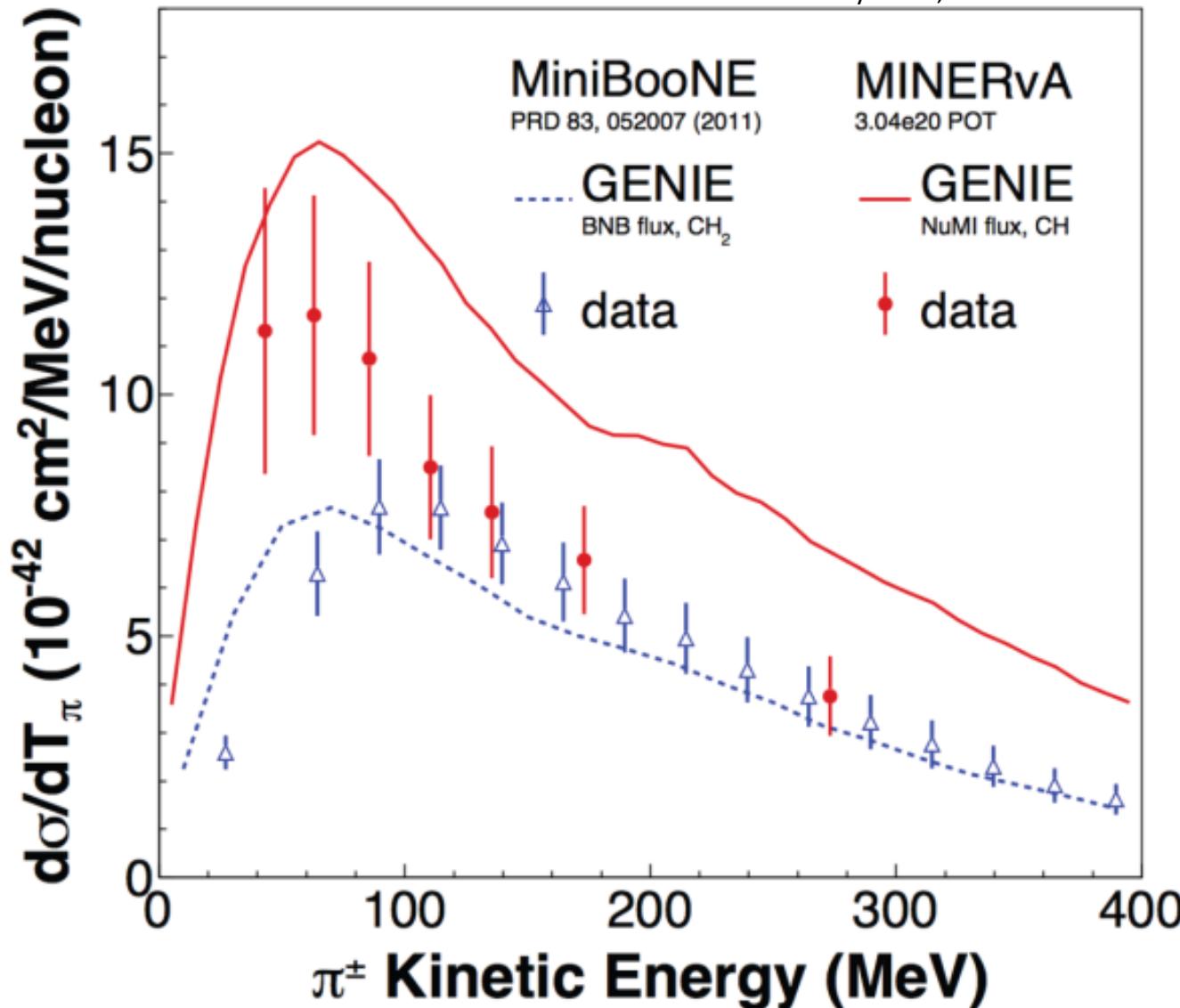
GiBUU

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

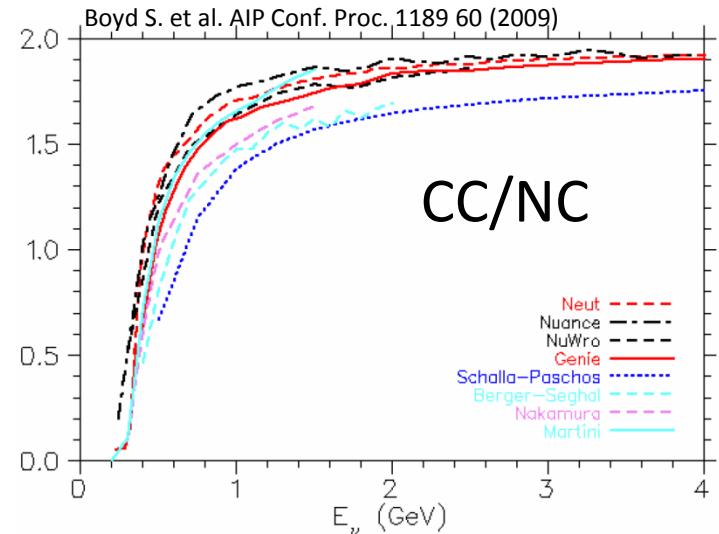
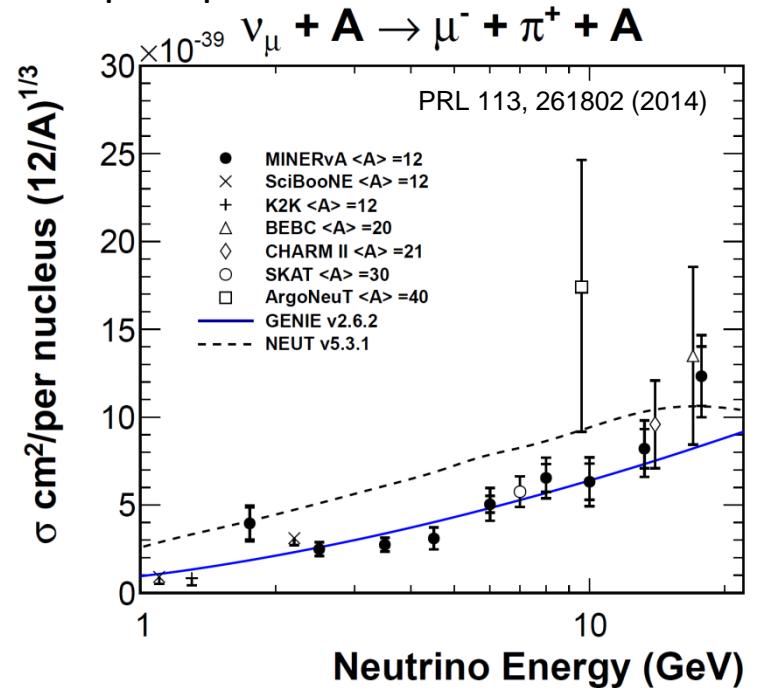
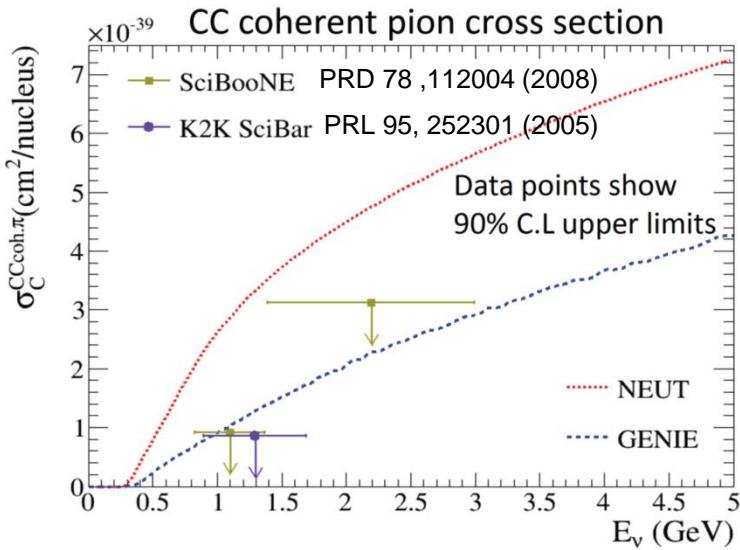
MiniBooNE vs MINERvA CC1 π^+ production

Eberly et al. , arXiv:1406.6415



Coherent π production

K2K and SciBooNE did not observe coherent π^+ production at neutrino energies $\sim 1\text{ GeV}$
 Recently MINERvA and ArgoNeut see evidence for CC coherent pion production



Coherent puzzle at $E_\nu \sim 1 \text{ GeV}$

Theoretical models:

$$\frac{\pi^+ \text{ coh. CC}}{\pi^0 \text{ coh. NC}} = 1.5 \sim 2$$

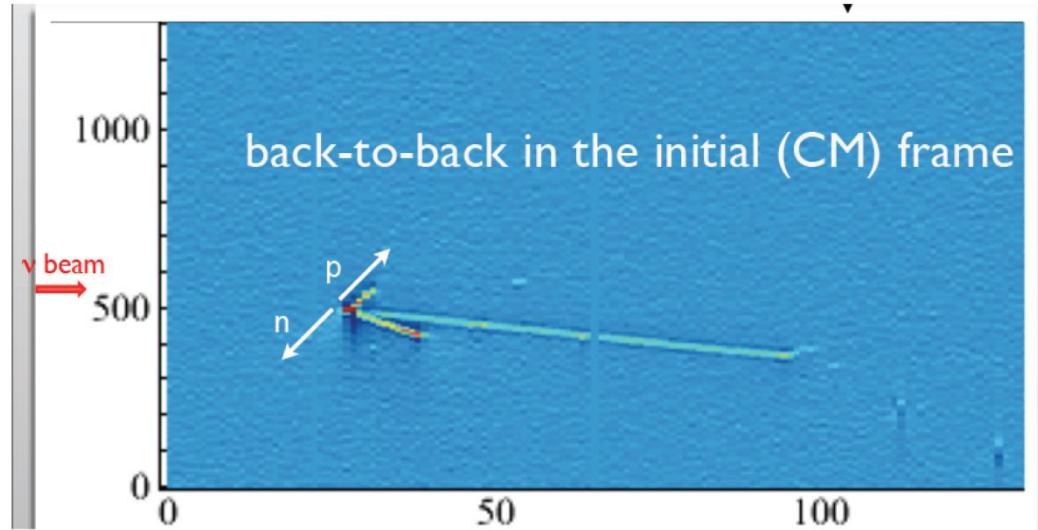
$$\frac{\pi^+ \text{ coh. CC}}{\pi^0 \text{ coh. NC}} = 0.14^{+0.30}_{-0.28}$$

SciBooNE:

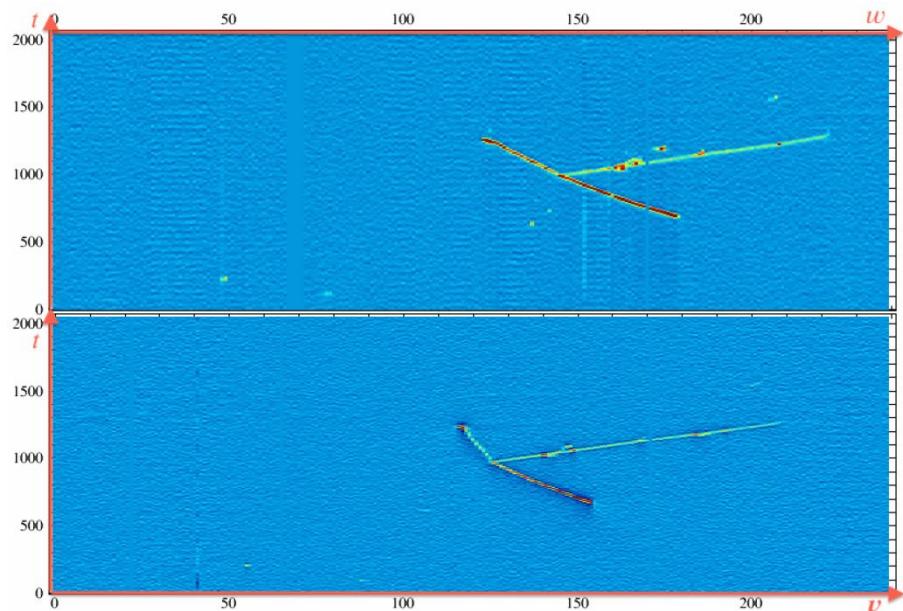
Kurimoto et al, PRD 81 (2010)

ArgoNeut

arXiv:1501.01983



Phys.Rev. D90 (2014) 1, 012008



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 Δ peaks, respectively”

Lovato et al. PRL 112 182502 (2014)

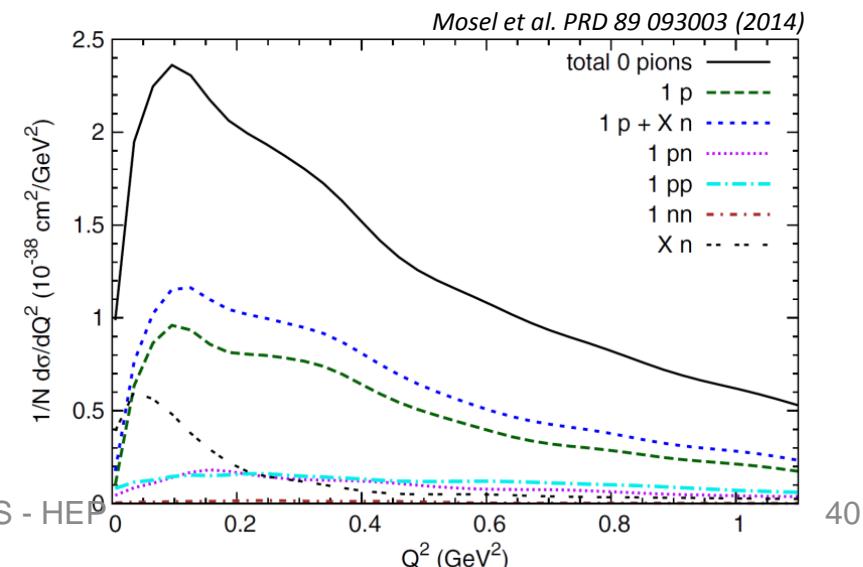
“The present study suggests that two nucleon currents generate a significant enhancement of the single-nucleon neutral weak current response, even at quasi-elastic kinematics. This enhancement is driven by strongly correlated np pairs in nuclei.”

MINERvA PRL 111 022501 (2013)

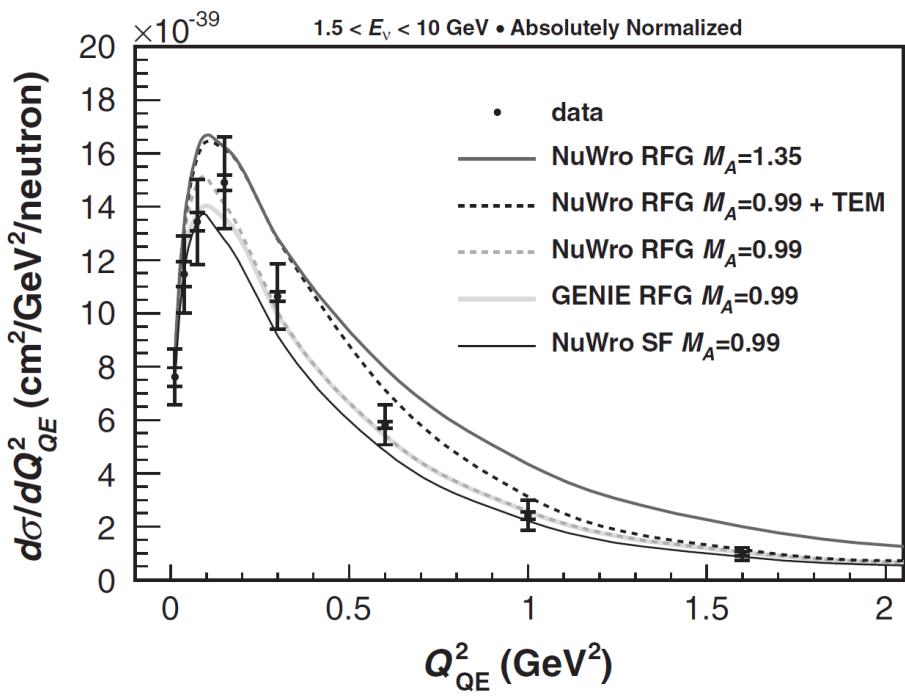
The MINERvA vertex energy on antineutrino mode “might be explained if the dominant multibody process is $\overline{\nu_\mu}(np) \rightarrow \mu^+ nn$ since MINERvA is not very sensitive to low energy neutrons. A similar analysis on neutrino mode data is consistent with additional protons in the final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

Mosel et al. PRD 89 093003 (2014)

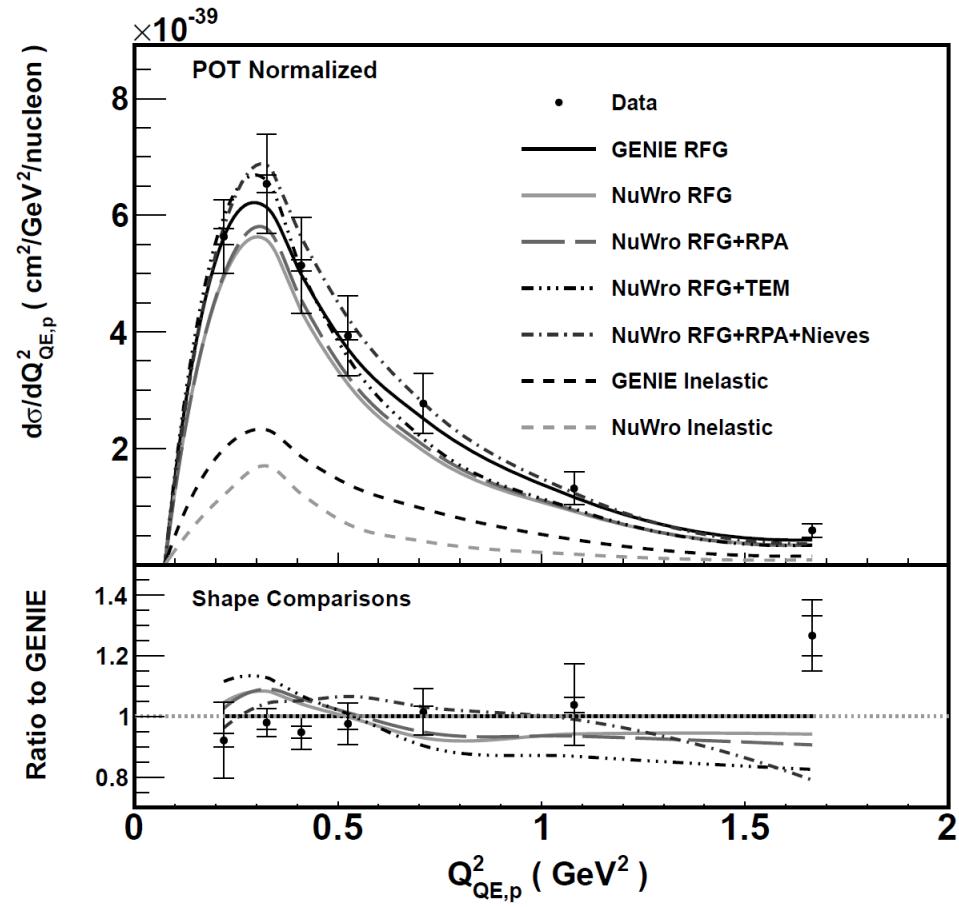
“The channels with a pp or a pn pair are very similar, quite flat, and suppressed and thus of minor importance. Interesting, however, is the pileup of strength seen in the Xn channel at small $Q^2 \approx 0.1 \text{ GeV}^2$. This is entirely due to fsi.”



MINERvA Q^2 distributions



PRL 111 022502 (2013)



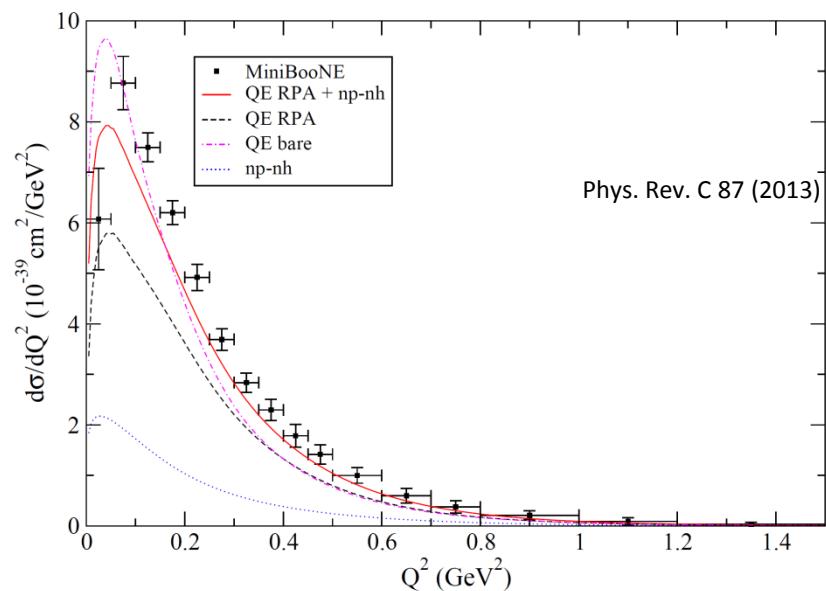
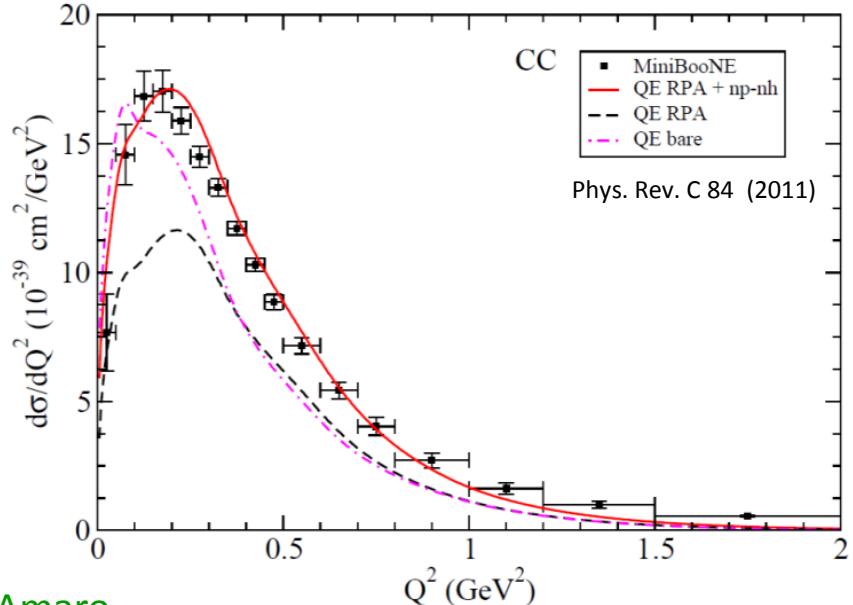
arXiv:1409.4497

MiniBooNE CCQE Q^2 distributions

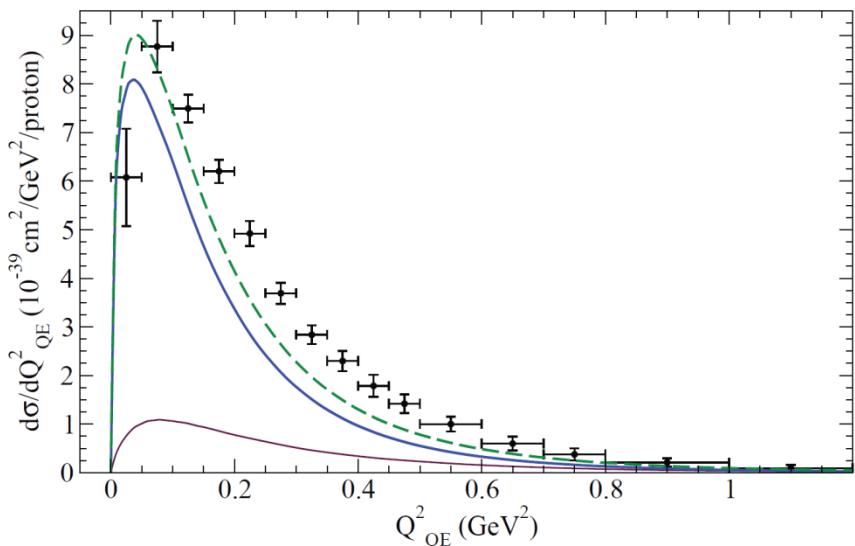
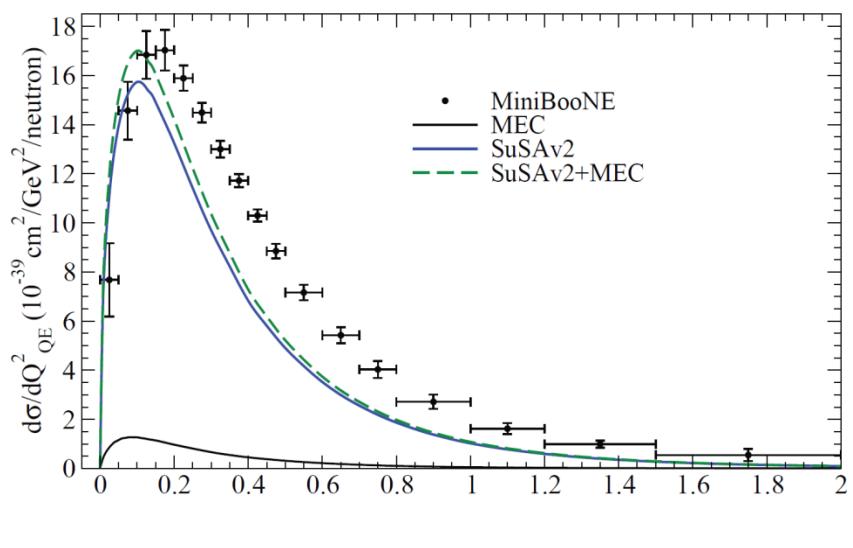
V

V

Martini
et al.

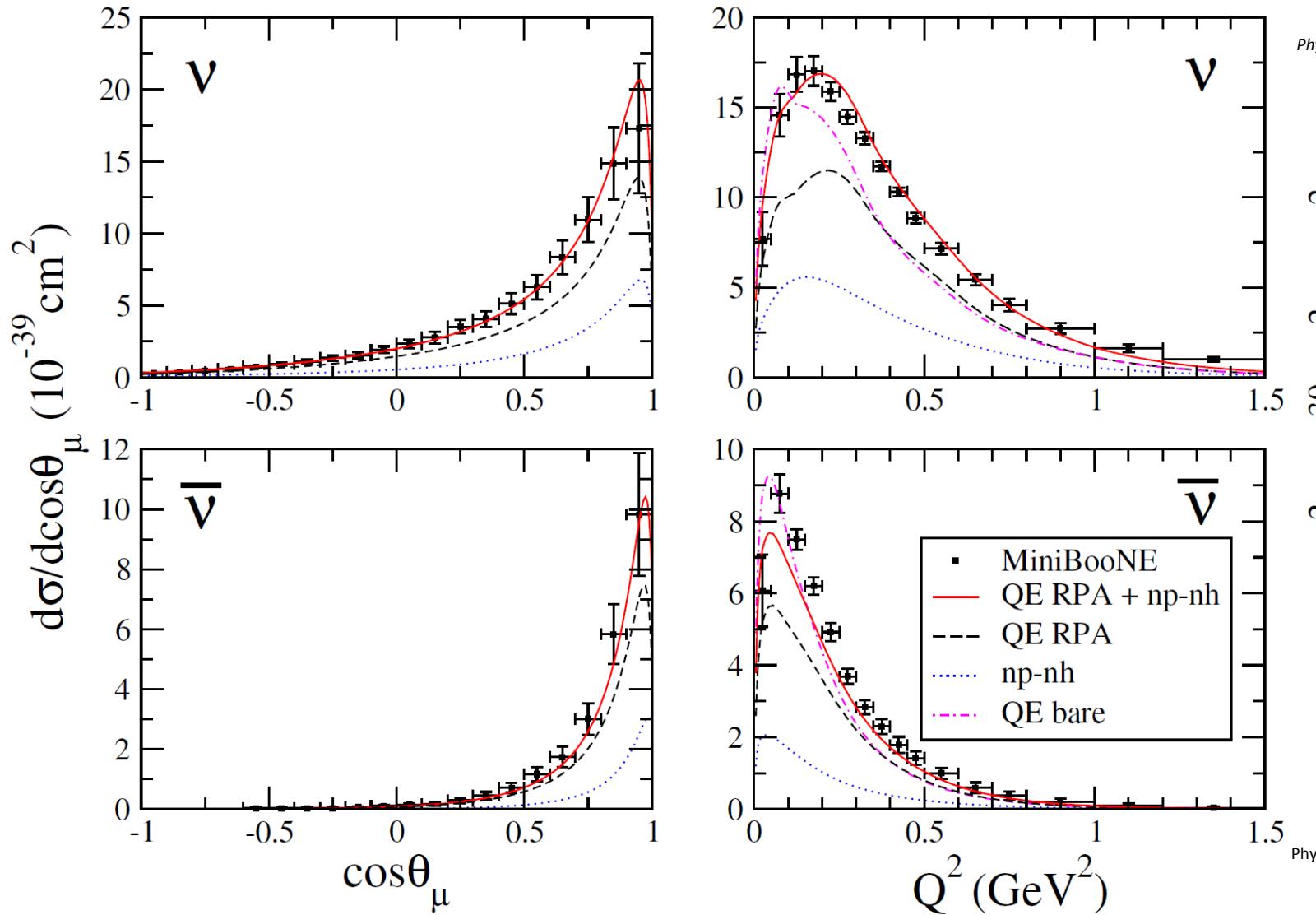


Megias, Amaro
et al.



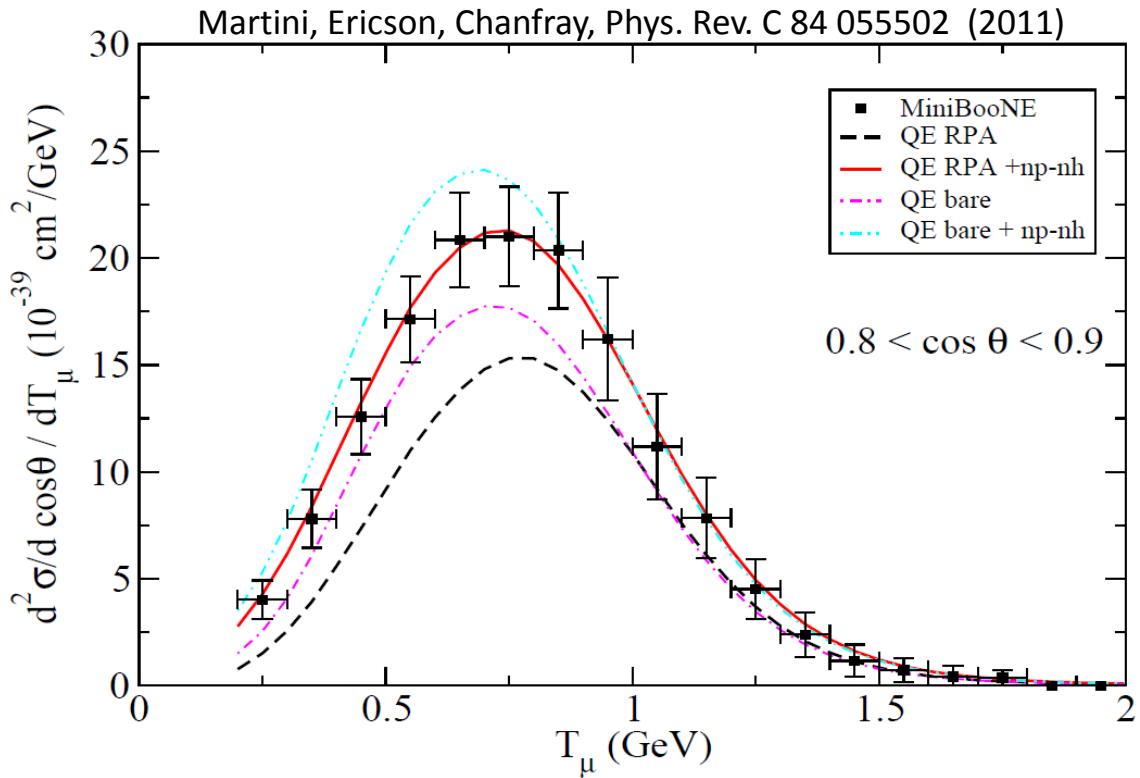
p.s. the additional normalization uncertainty in the MiniBooNE data of 10% for neutrinos and of 17.2% for antineutrinos is not shown here

MiniBooNE CCQE $d\sigma/d\cos\theta$ $d\sigma/dQ^2$



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

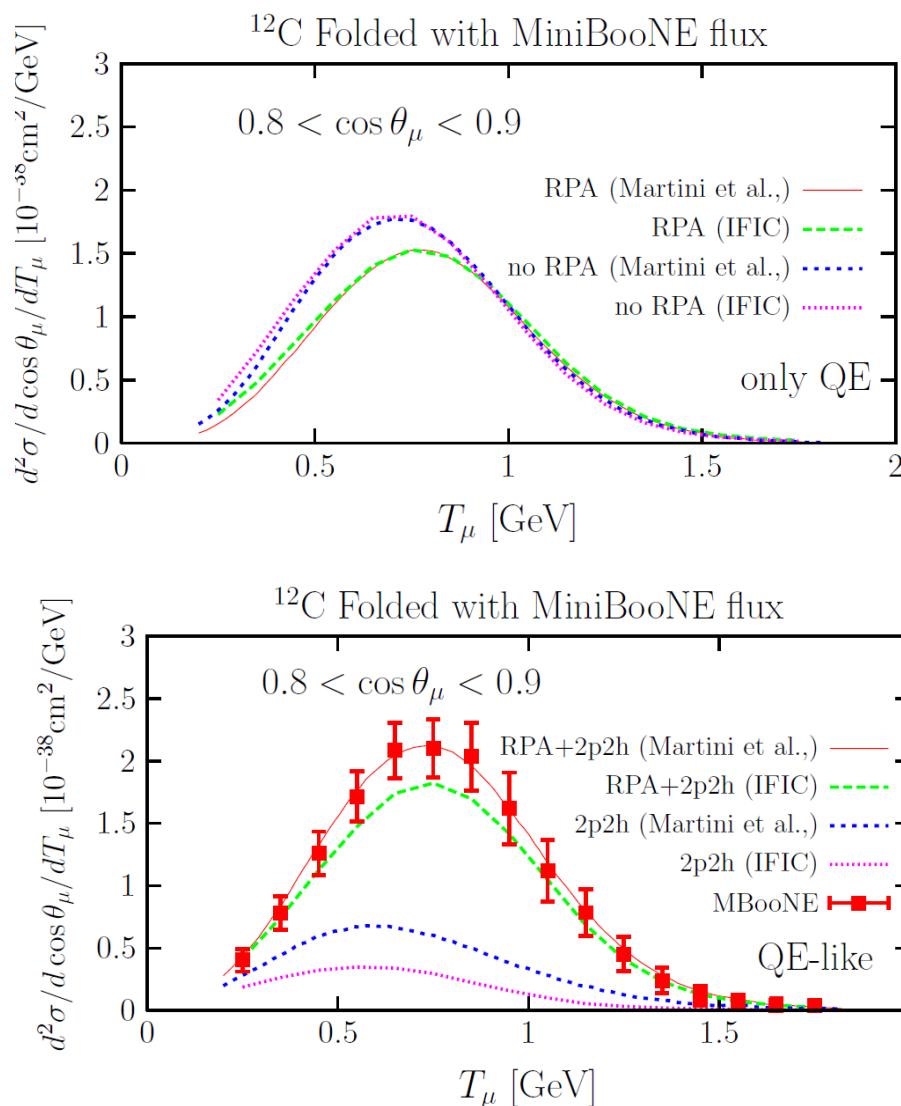
Flux-integrated v CCQE double differential X section versus T_μ



Delicate balance between

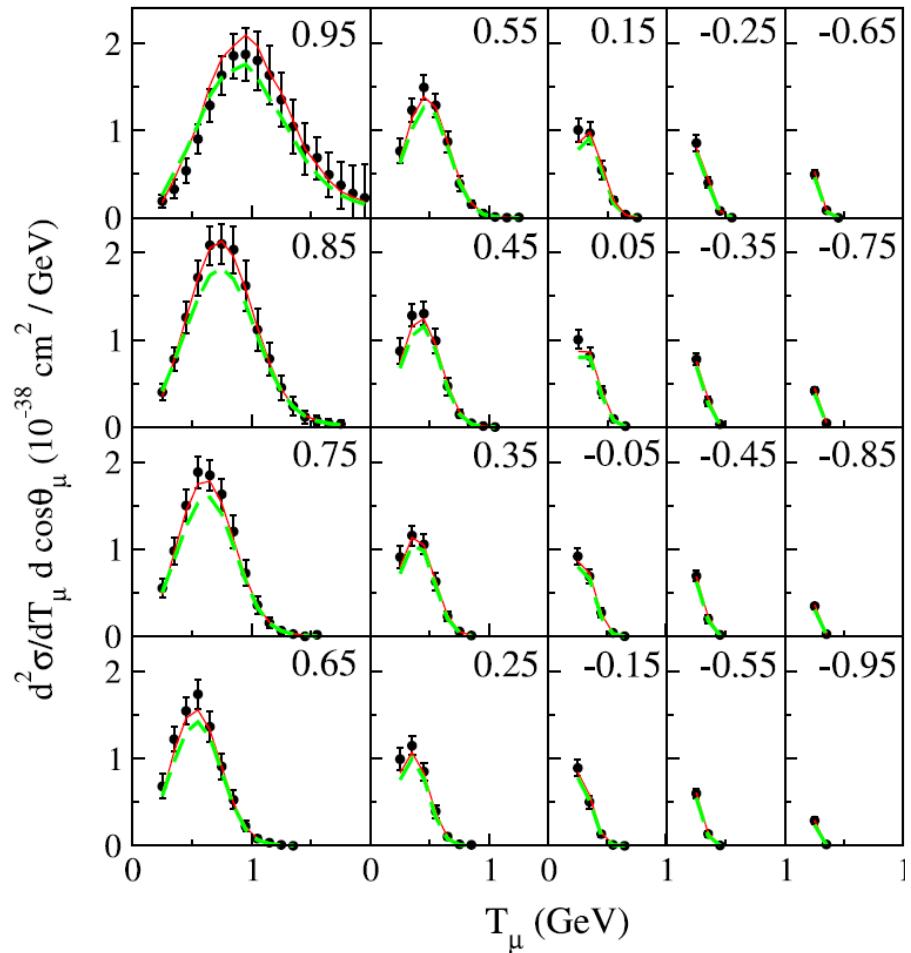
RPA quenching and np-nh enhancement

- 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)

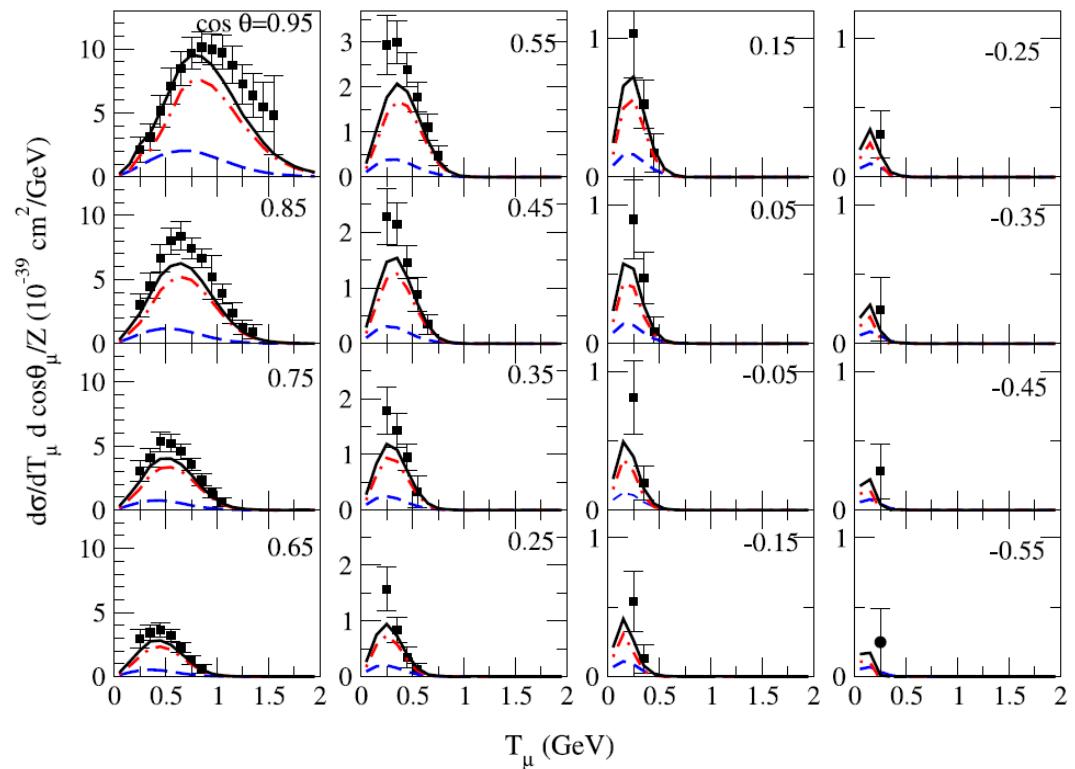


Morfin, Nieves, Sobczyk
Adv.High Energy Phys. 2012 (2012) 934597

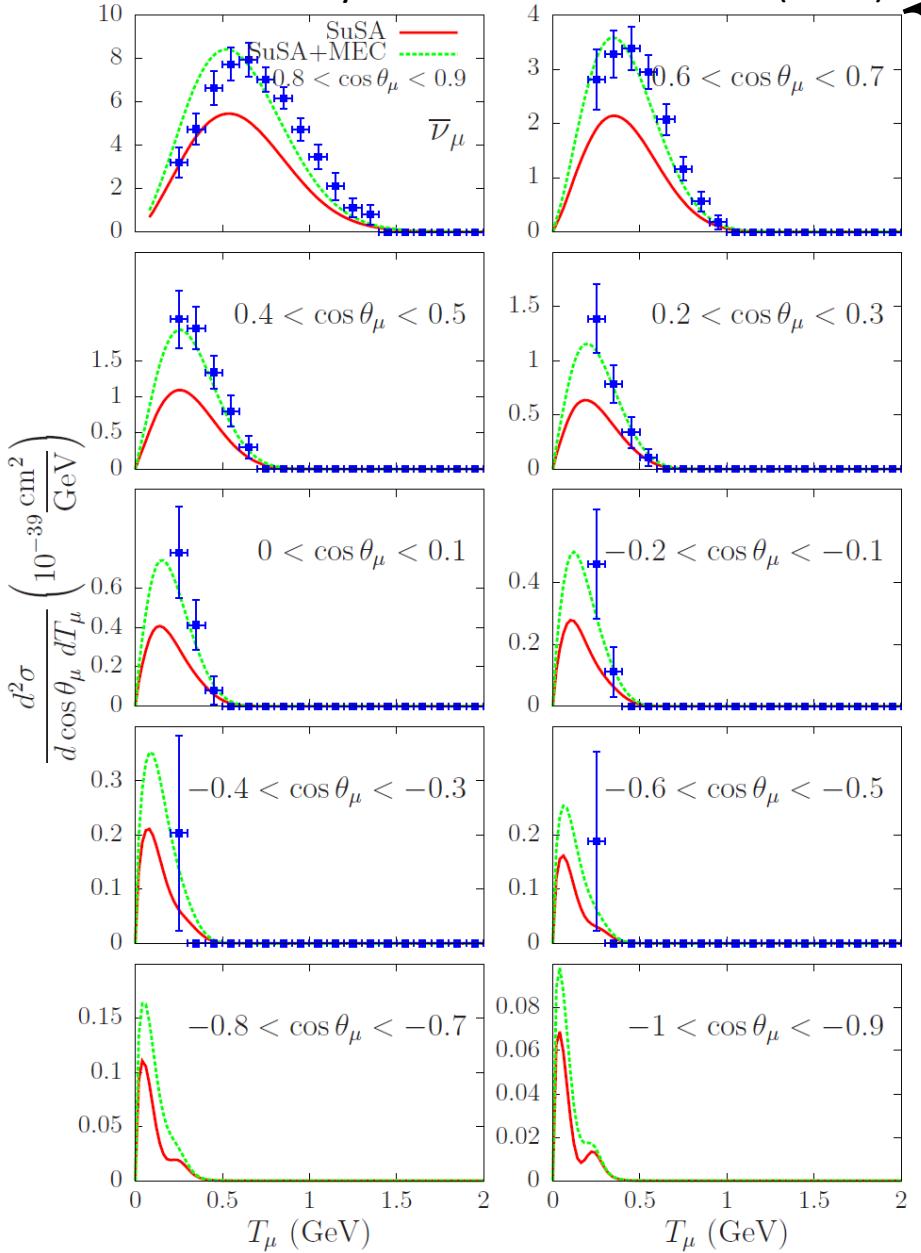
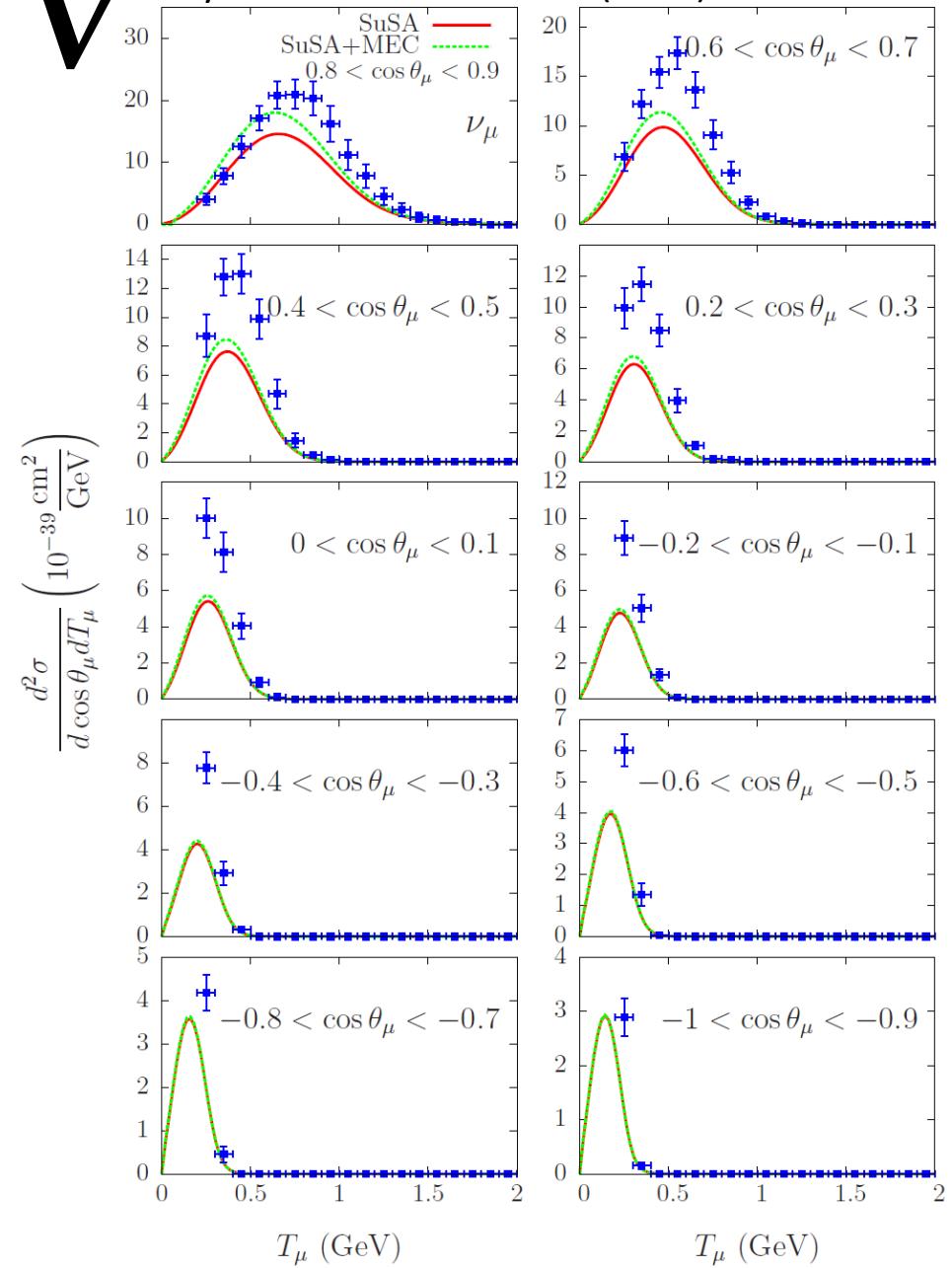
Phys. Lett. B 707 72-75 (2012)



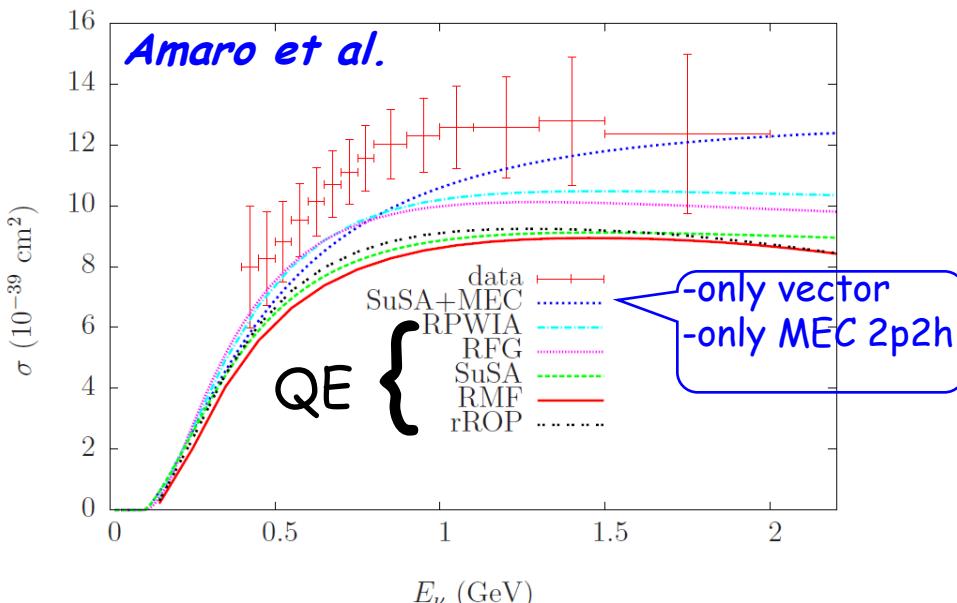
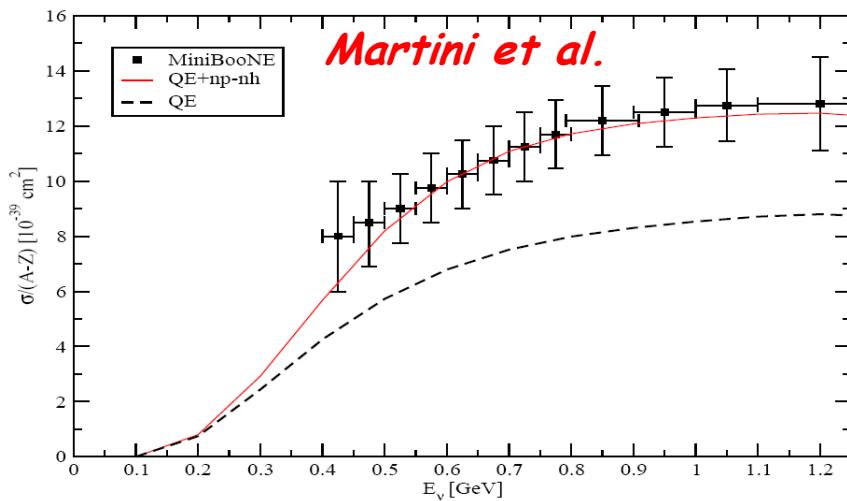
Phys. Lett. B 721 90-93 (2013)



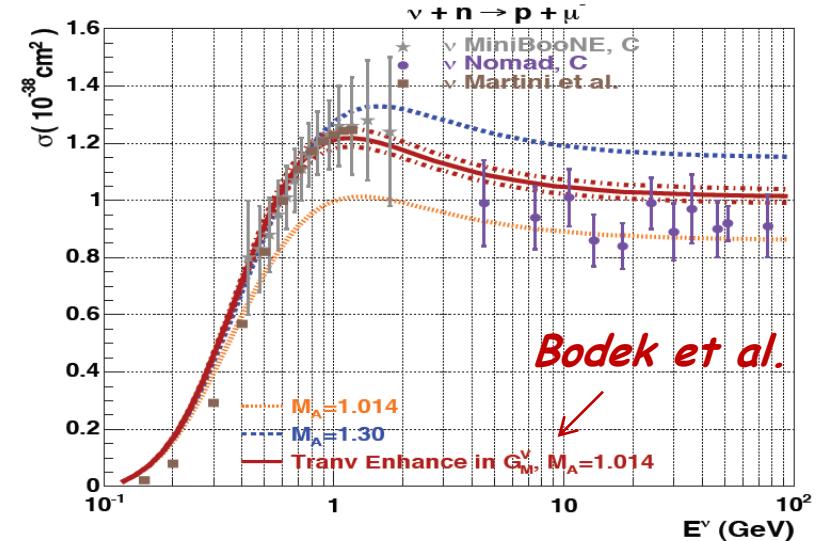
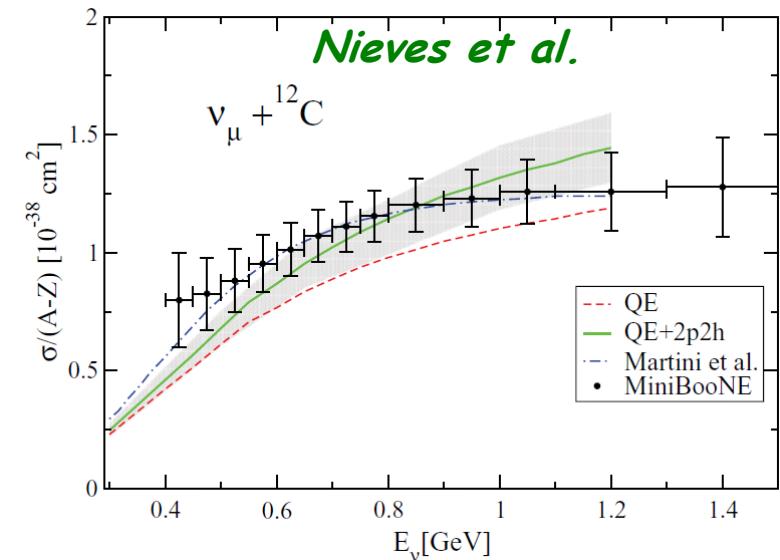
V



Total CCQE and comparison with flux unfolded MB



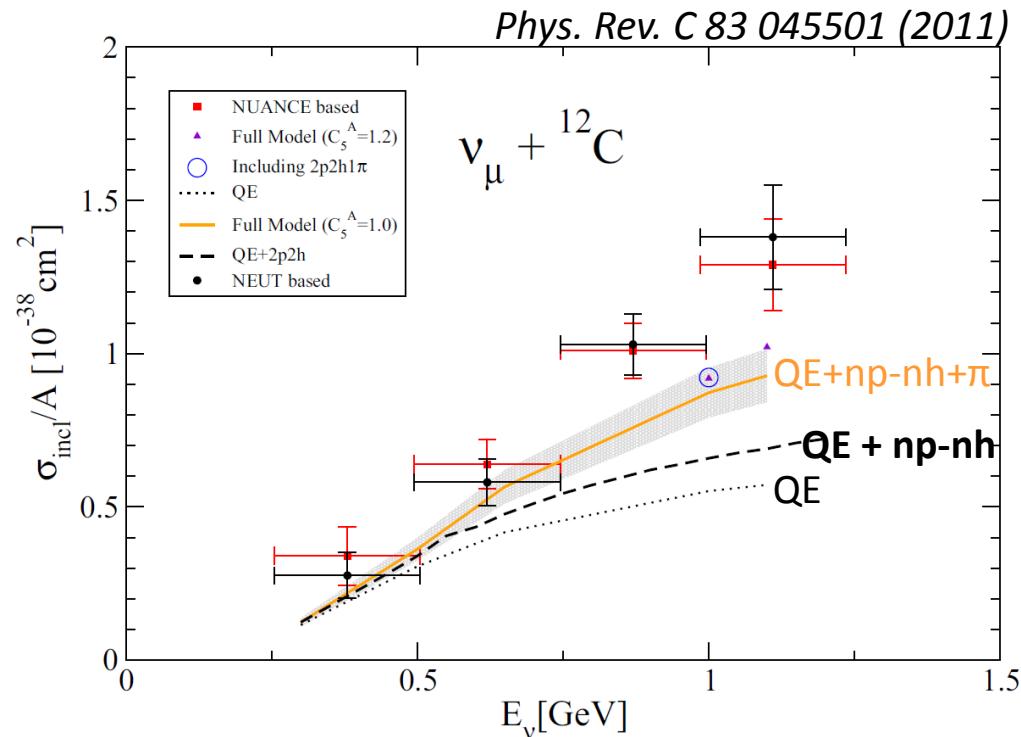
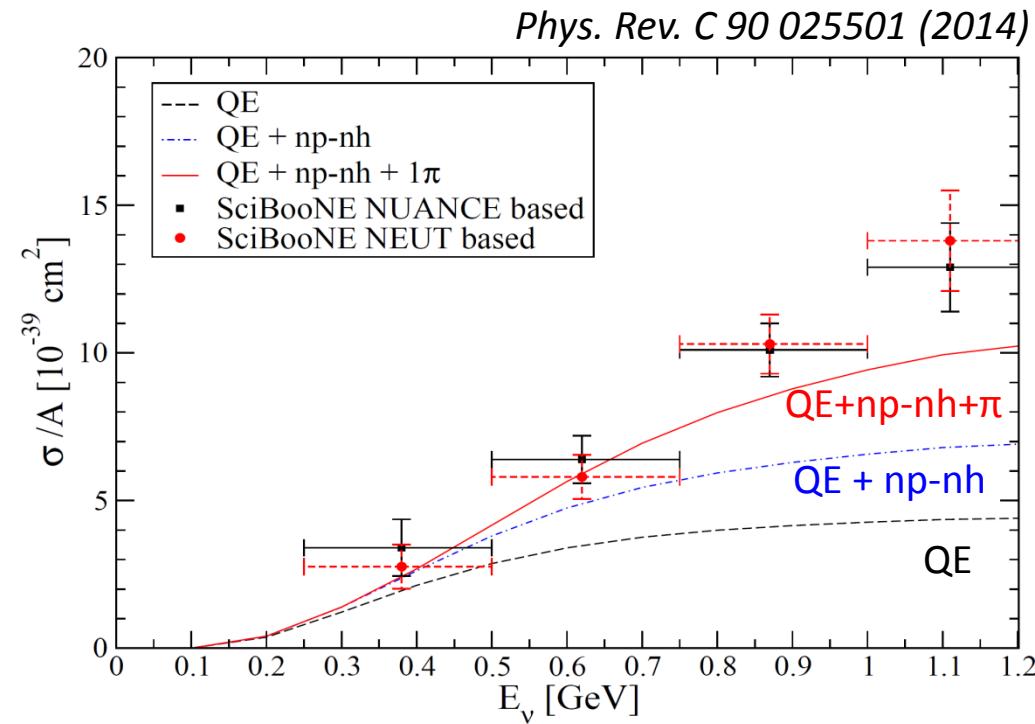
N.B. The experimental unfolding is model dependent



Inclusive CC total cross section on Carbon

Less affected by background subtraction with respect to exclusive channels

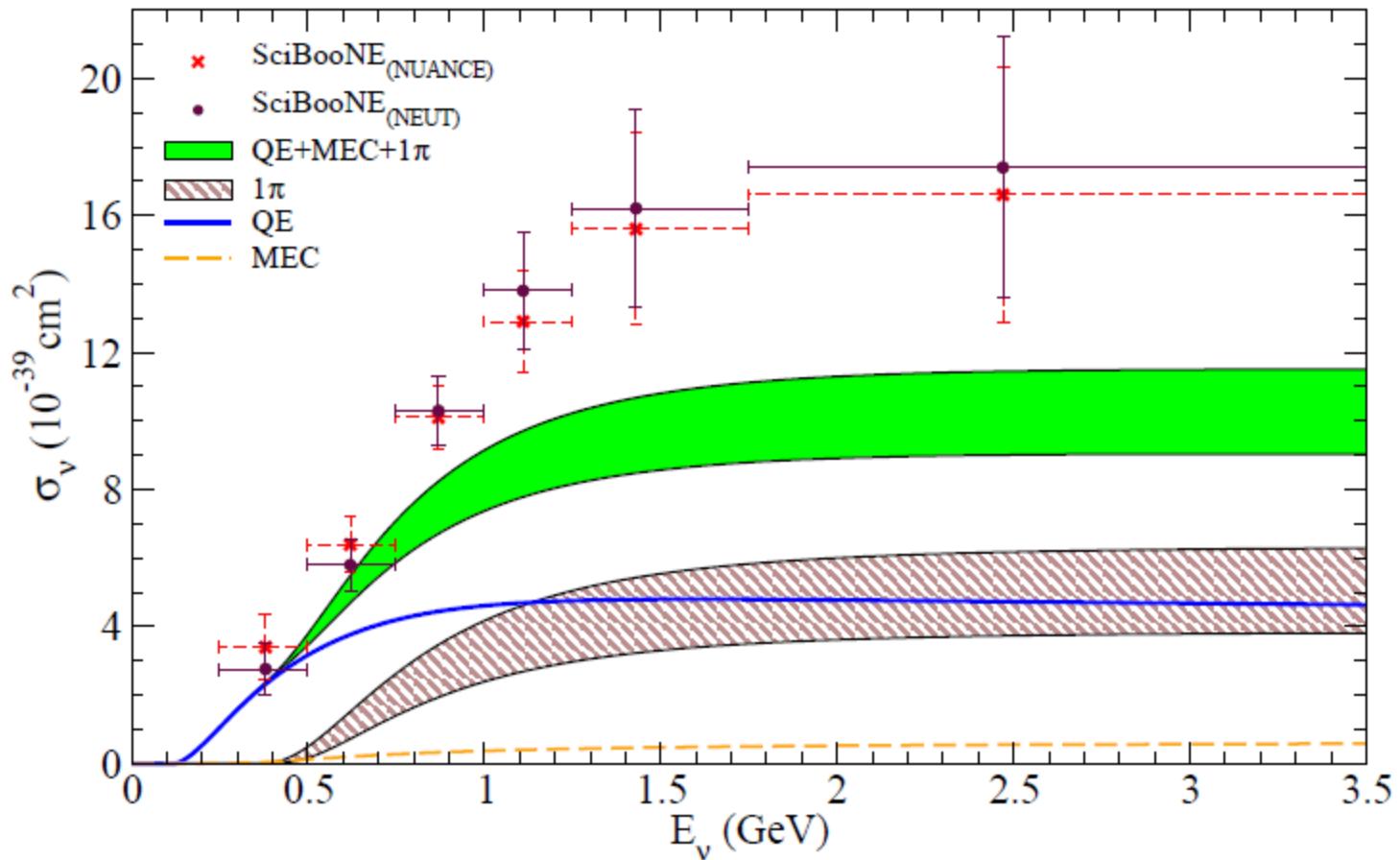
SciBooNE, *Phys. Rev. D* 83, 012005 (2011)



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

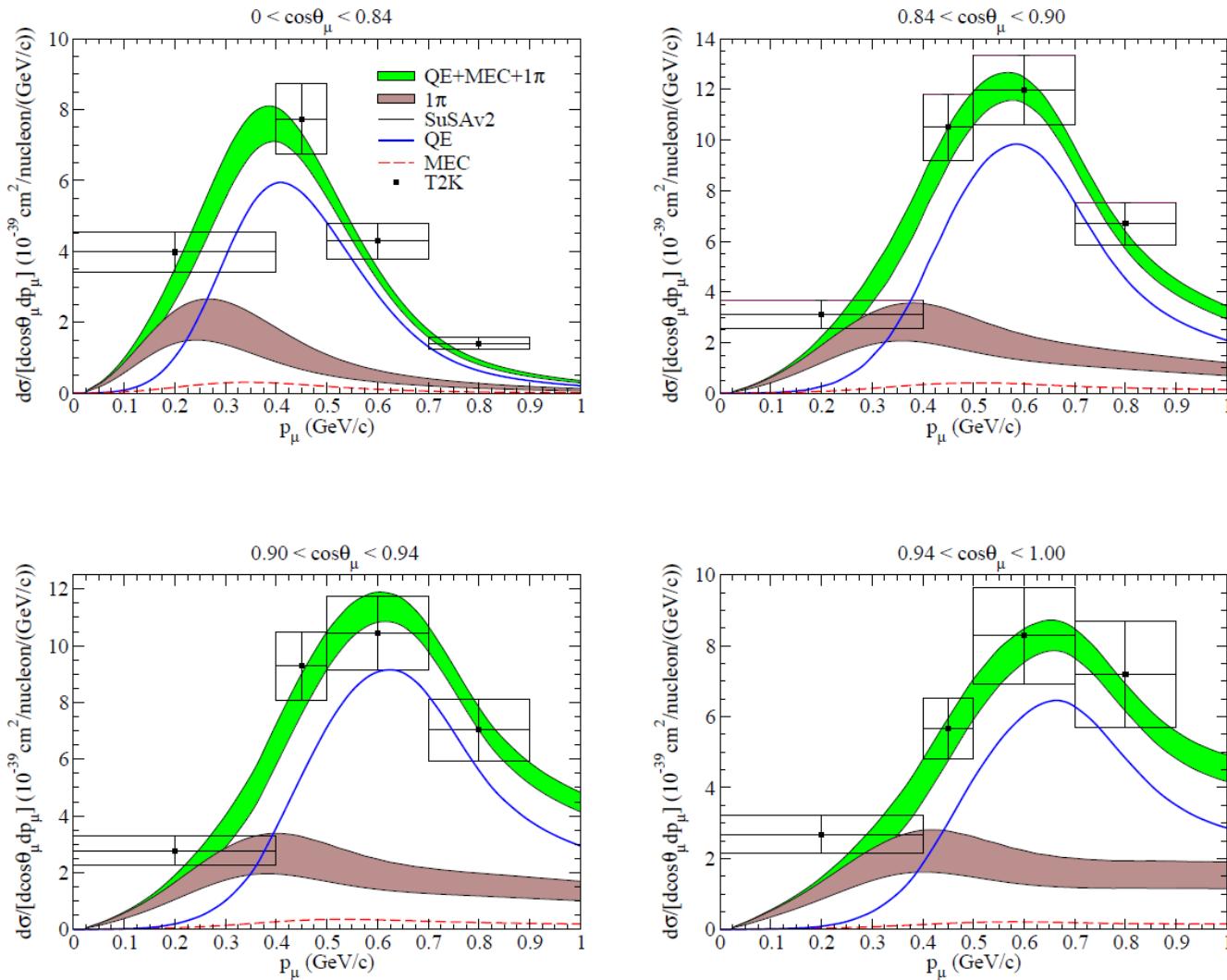
J. Nieves, I. Ruiz Simo, M.J. Vicente Vacas

Inclusive CC total cross section on Carbon



Ivanov, Megias et al. arXiv 1506.00801 (2015)

T2K flux-integrated inclusive double differential cross section on carbon

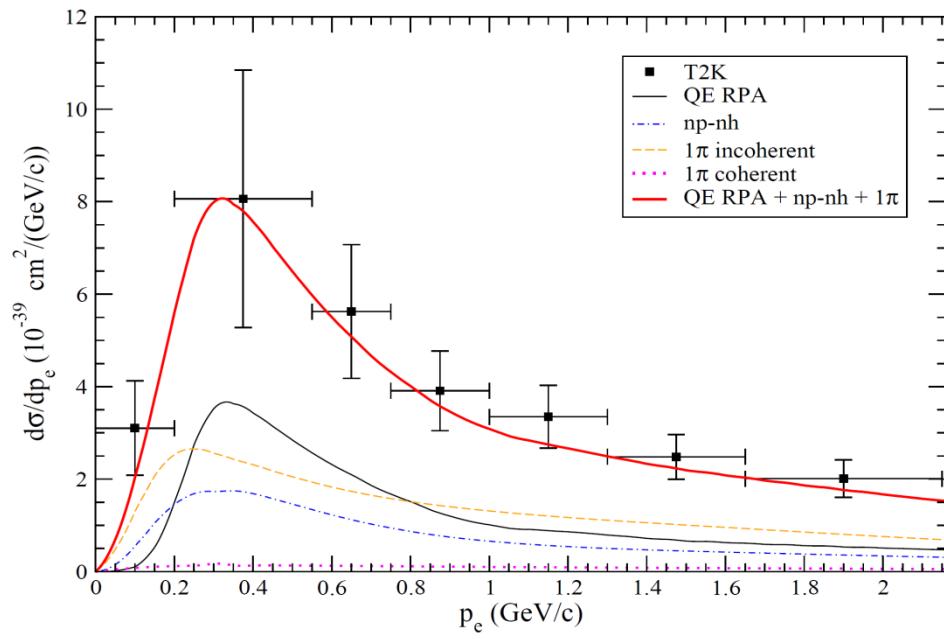


Ivanov, Megias et al. arXiv 1506.00801 (2015)

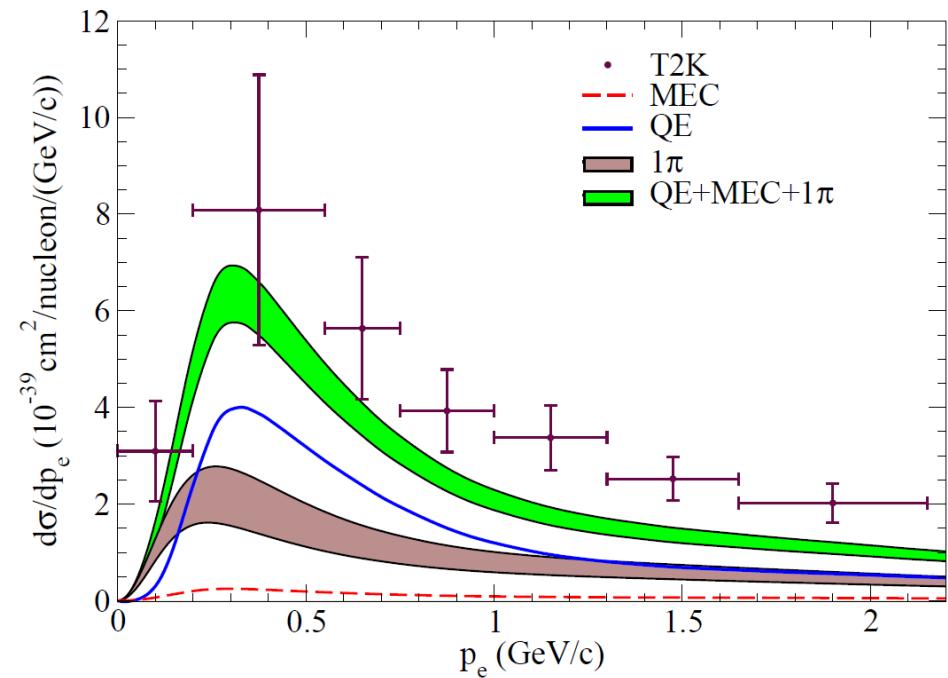
V_e T2K flux-integrated inclusive differential cross section on carbon

T2K: PRL 113,
241803 (2014)

Martini et al., to be submitted



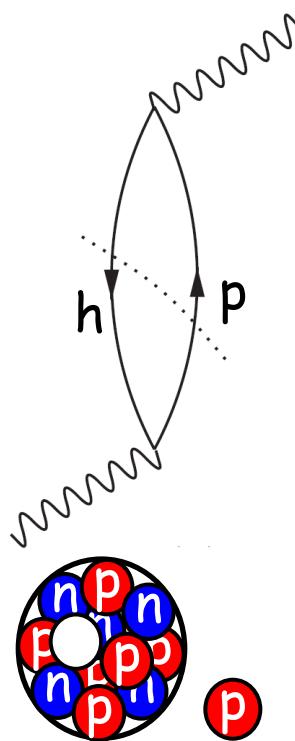
Ivanov, Megias et al. arXiv 1506.00801 (2015)



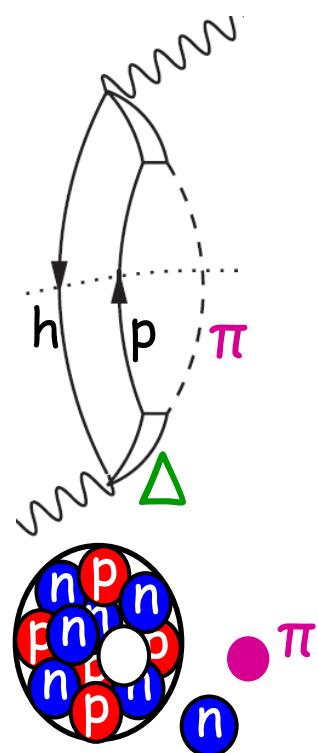
Some theoretical details

Nuclear Response Functions

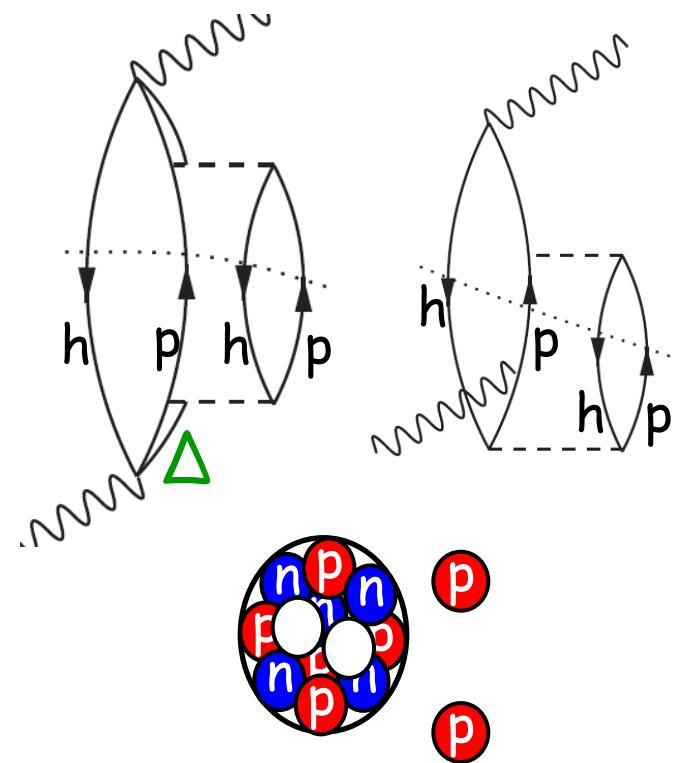
1p-1h
QE



1p-1h
1 π production



2p-2h:
two examples



Nuclear response in Random Phase Approximation

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

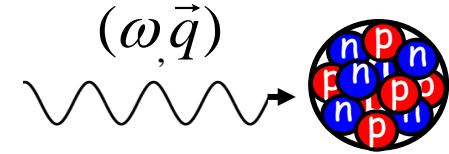
RPA

Equation for the RPA response function:

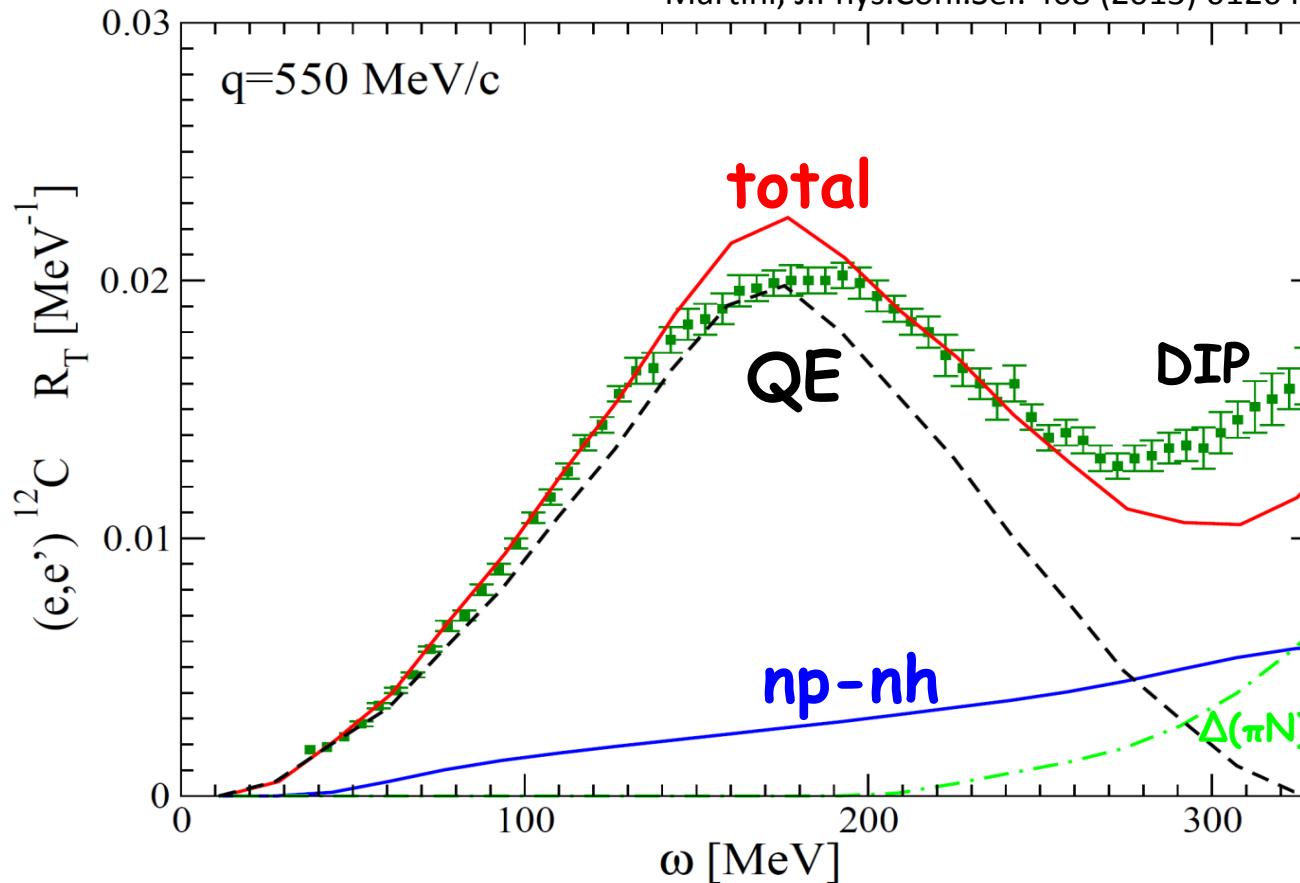
$$\text{RPA} = \text{RPA}_0 + \text{RPA}_1$$

The equation shows the RPA response function as the sum of two terms: RPA_0 and RPA_1 . RPA_0 is represented by a shaded oval with arrows indicating a collective mode. RPA_1 is represented by a dashed line connecting two shaded ovals.

An example of nuclear response : transverse response in electron scattering



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



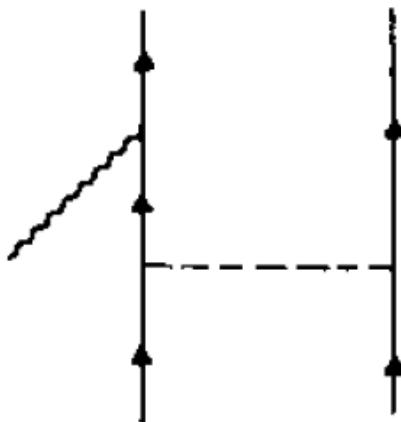
np-nh creates a high energy tail in the nuclear response above the QE peak

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

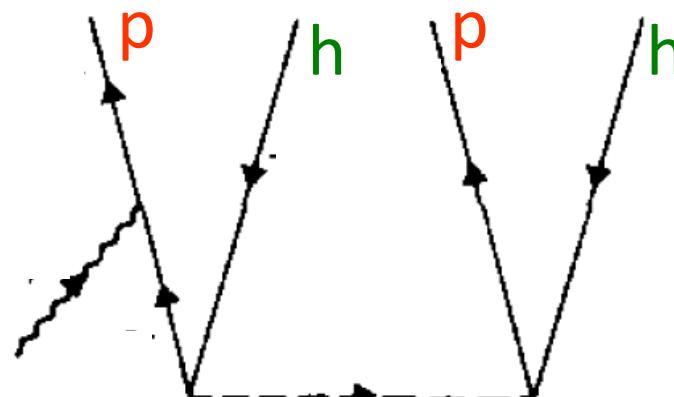
Two particle-two hole sector (2p-2h)

Three equivalent representations of the same process

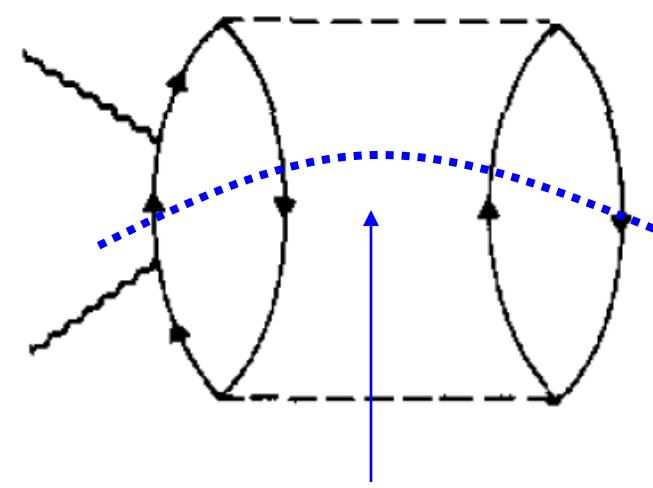
2 body current



2p-2h matrix element



2p-2h response

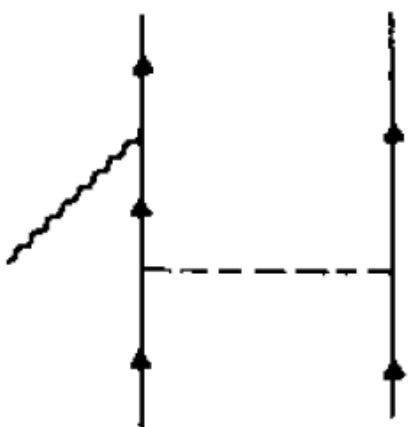


Cut
(optical theorem)

Final state: two particles-two holes

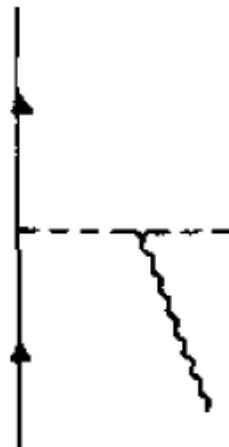
Some diagrams for 2 body currents

Nucleon-Nucleon
correlations

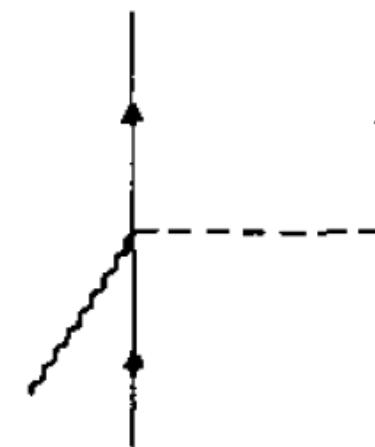


J^{corr}

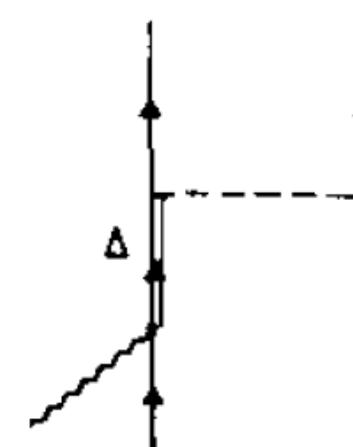
Meson Exchange Currents (MEC)



Pion in flight



Contact

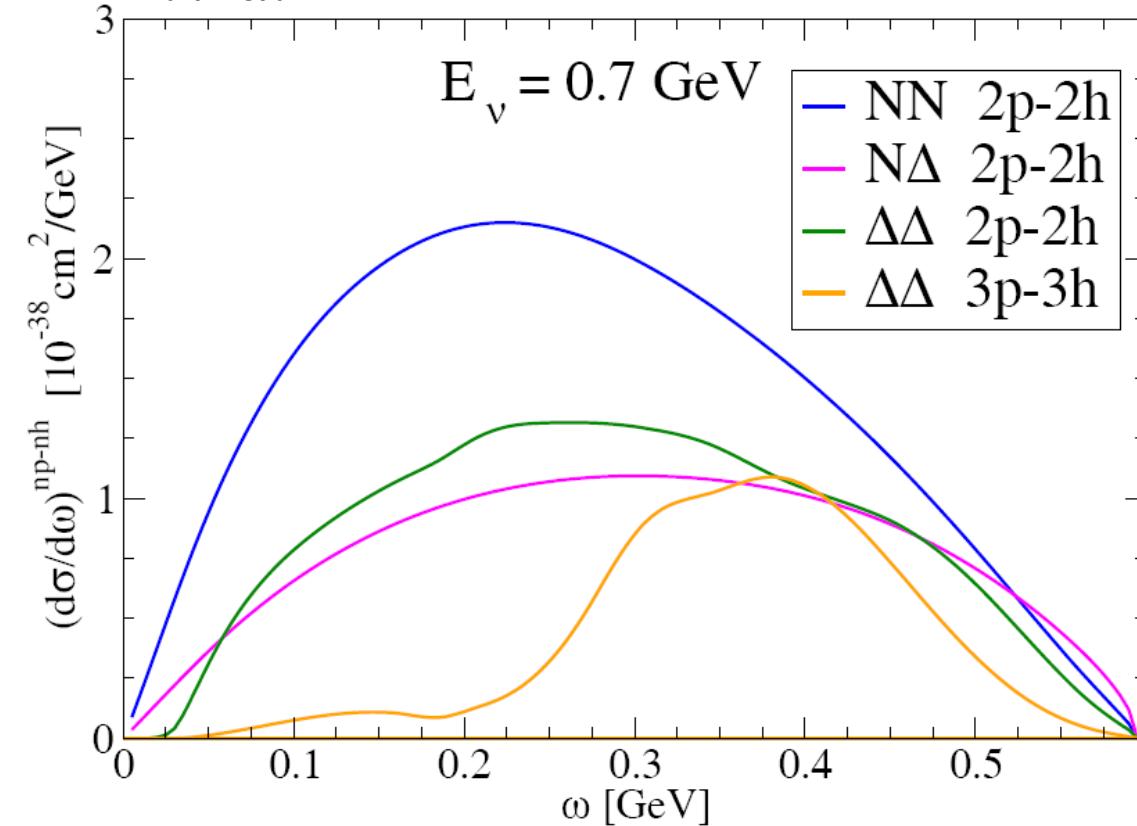


Delta

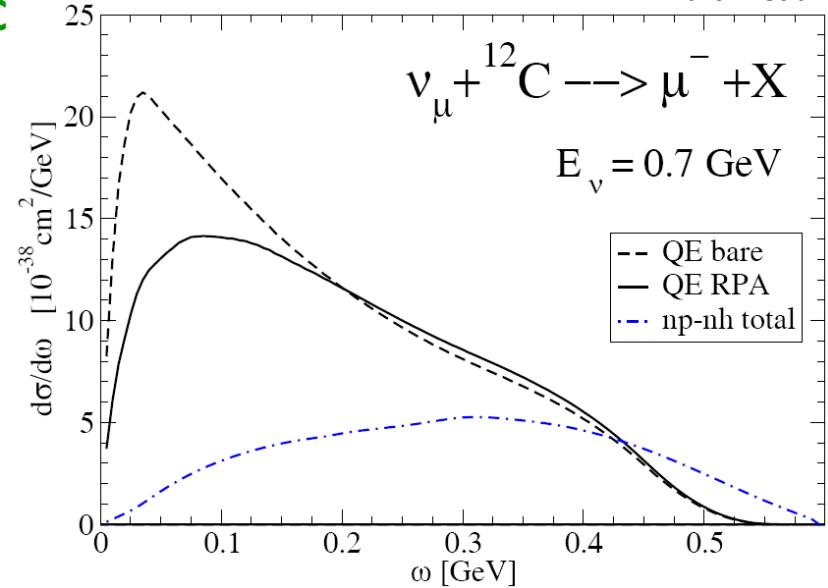
J^{MEC}

Different contributions in the np-nh channel

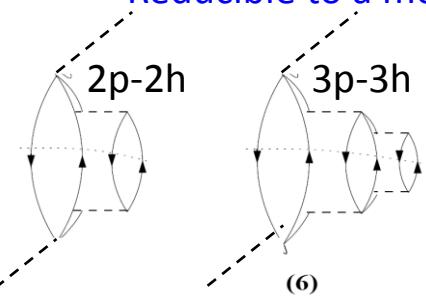
Martini et al.



Correlations
Interference
MEC



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



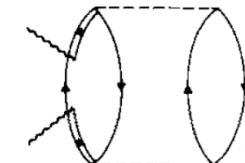
From:

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

23/7/2015

M. Martini, EPS - HEP

- Not reducible to a modification of the Δ width



57

Single nucleon weak CC current

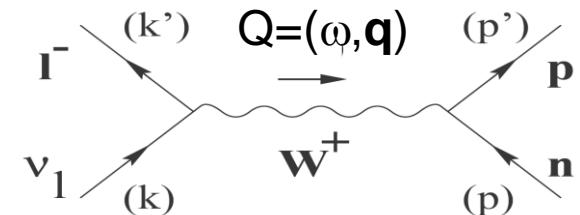
$$j^\mu = j_V^\mu - j_A^\mu$$

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

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

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

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



Some two-body currents

Electromagnetic

- Seagull or contact:

$$j_s^\mu(\mathbf{p}'_1, \mathbf{p}'_2, \mathbf{p}_1, \mathbf{p}_2) = \frac{f^2}{m_\pi^2} i\epsilon_{3ab} \bar{u}(\mathbf{p}'_1) \tau_a \gamma_5 K_1 u(\mathbf{p}_1) \frac{F_1^V}{K_1^2 - m_\pi^2} \bar{u}(\mathbf{p}'_2) \tau_b \gamma_5 \gamma^\mu u(\mathbf{p}_2) + (1 \leftrightarrow 2).$$

- Pion-in-flight:

$$j_p^\mu(\mathbf{p}'_1, \mathbf{p}'_2, \mathbf{p}_1, \mathbf{p}_2) = \frac{f^2}{m_\pi^2} i\epsilon_{3ab} \frac{F_\pi(K_1 - K_2)^\mu}{(K_1^2 - m_\pi^2)(K_2^2 - m_\pi^2)} \bar{u}(\mathbf{p}'_1) \tau_a \gamma_5 K_1 u(\mathbf{p}_1) \bar{u}(\mathbf{p}'_2) \tau_b \gamma_5 K_2 u(\mathbf{p}_2).$$

- Correlation:

$$\begin{aligned} j_{\text{cor}}^\mu(\mathbf{p}'_1, \mathbf{p}'_2, \mathbf{p}_1, \mathbf{p}_2) = & \frac{f^2}{m_\pi^2} \bar{u}(\mathbf{p}'_1) \tau_a \gamma_5 K_1 u(\mathbf{p}_1) \frac{1}{K_1^2 - m_\pi^2} \bar{u}(\mathbf{p}'_2) [\tau_a \gamma_5 K_1 S_F(P_2 + Q) \Gamma^\mu(Q) \\ & + \Gamma^\mu(Q) S_F(P'_2 - Q) \tau_a \gamma_5 K_1] u(\mathbf{p}_2) + (1 \leftrightarrow 2). \end{aligned}$$

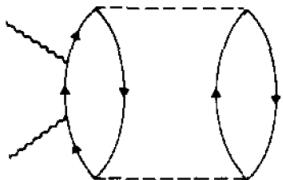
Weak

- CC Seagull

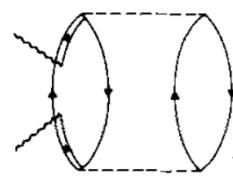
$$\begin{aligned} j_s^\mu(\mathbf{p}'_1, \mathbf{p}'_2, \mathbf{h}_1, \mathbf{h}_2) = & \tau_0 \otimes \tau_{+1} - \tau_{+1} \otimes \tau_0 \frac{f}{m_\pi} \frac{1}{\sqrt{2} f_\pi} \bar{u}(\mathbf{p}'_1) \gamma_5 K_1 u(\mathbf{h}_1) \frac{\bar{u}(\mathbf{p}'_2) [g_A F_1^V(Q^2) \gamma_5 \gamma^\mu + F_\rho(K_2^2) \gamma^\mu]}{K_1^2 - m_\pi^2} u(\mathbf{h}_2) \\ & - (1 \leftrightarrow 2) \end{aligned}$$

Main difficulties in the 2p-2h sector

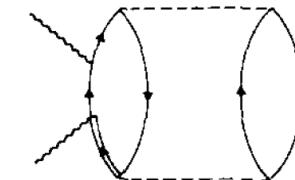
- Huge number of diagrams and terms



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

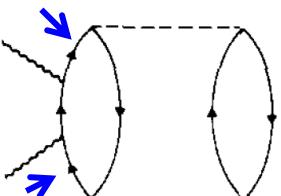
More than 100 000 exchange terms

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

- Divergences in NN correlations

$$(p_0 - E_p + i\epsilon)^{-2}$$

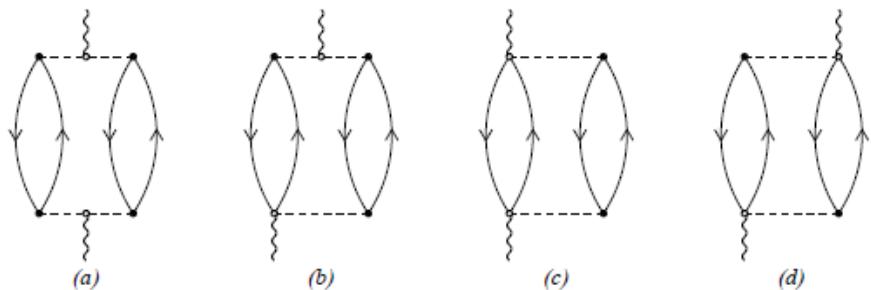
prescriptions:



- 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



Exchange

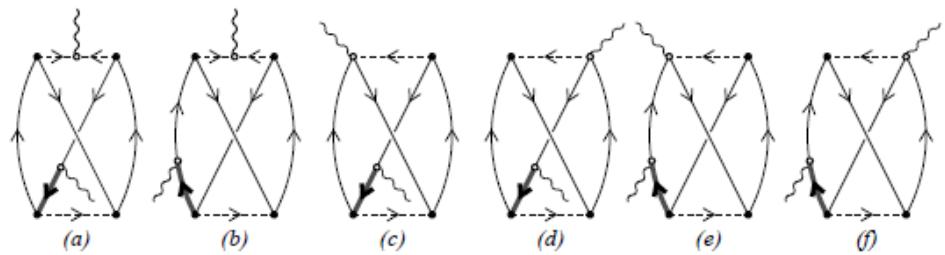


FIG. 2: The direct pionic contributions to the MEC 2p-2h response function.

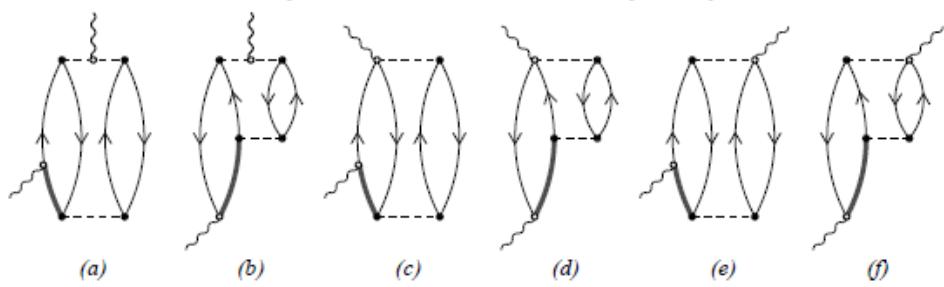


FIG. 3: The direct pionic/Δ interference contributions to the MEC 2p-2h response function.

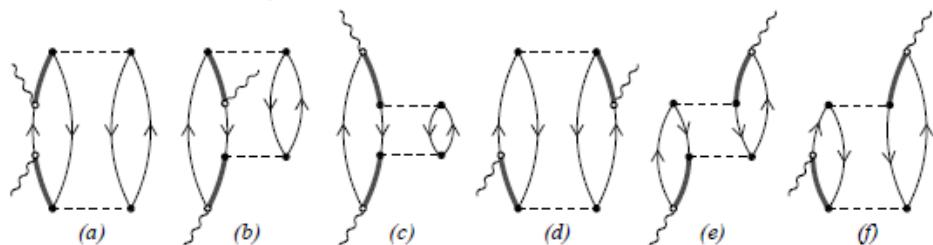


FIG. 4: The direct Δ contributions to the MEC 2p-2h response function.

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

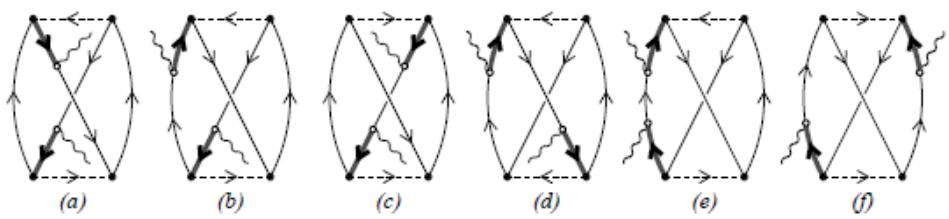


FIG. 6: The exchange Δ contributions to the MEC 2p-2h response function.

2p-2h phase space integral

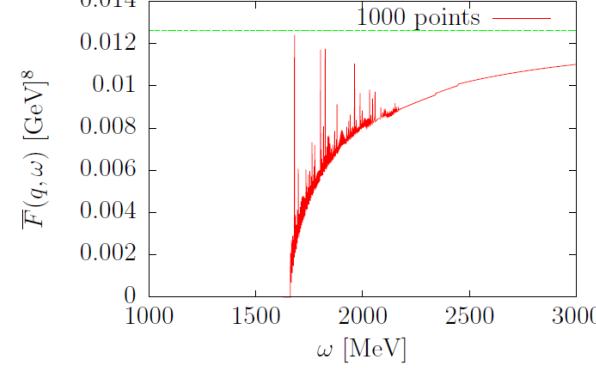
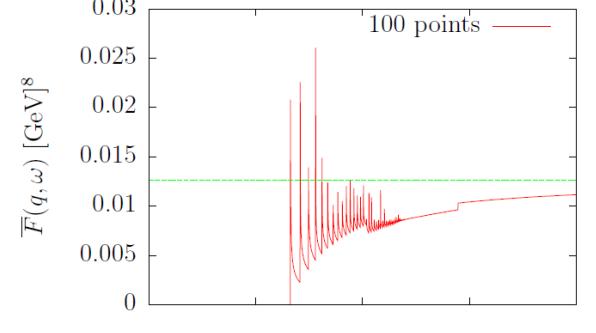
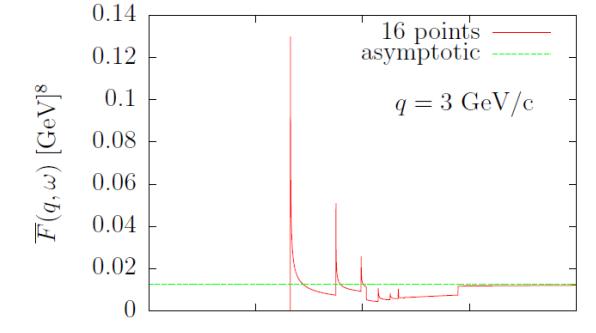
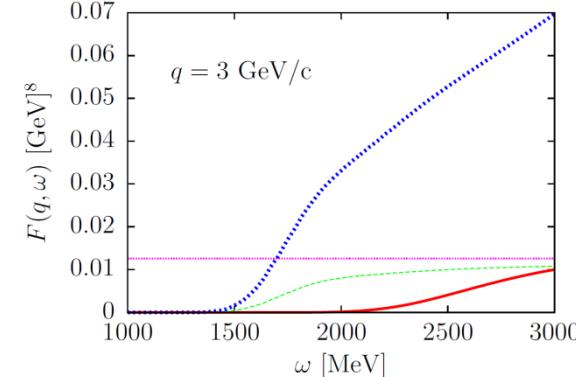
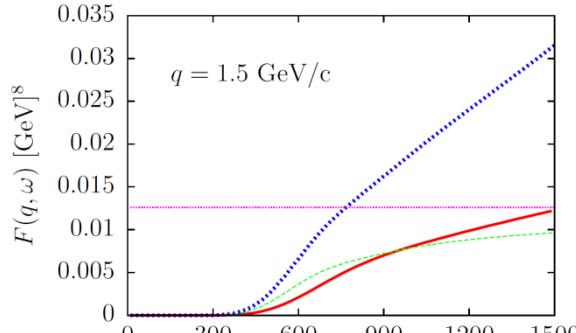
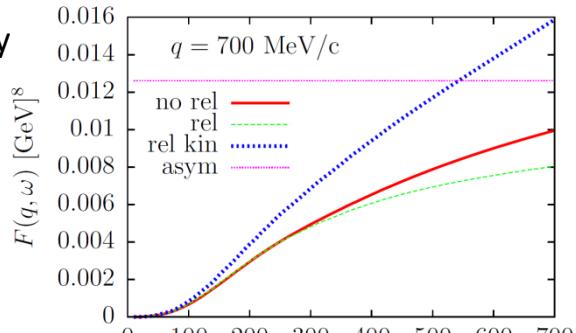
$$F(\omega, q) \equiv \int d^3 h_1 d^3 h_2 d^3 p'_1 \frac{m_N^4}{E_1 E_2 E'_1 E'_2} \Theta(p'_1, p'_2, h_1, h_2) \delta(E'_1 + E'_2 - E_1 - E_2 - \omega)$$

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

Ruiz Simo, Albertus, Amaro, Barbaro, Caballero, Donnelly

Phys. Rev. D 90 033012 (2014)

Phys. Rev. D 90 053010 (2014)

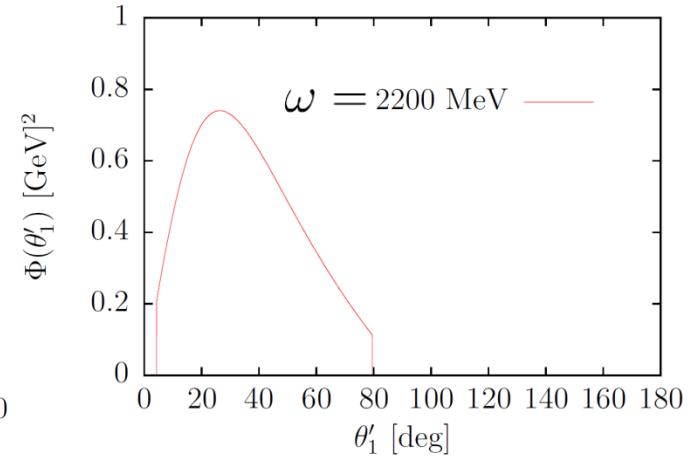
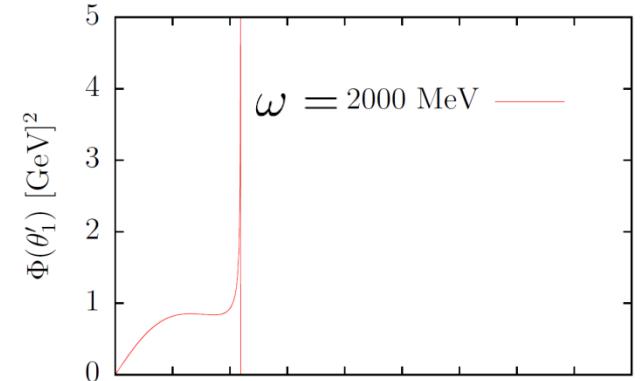
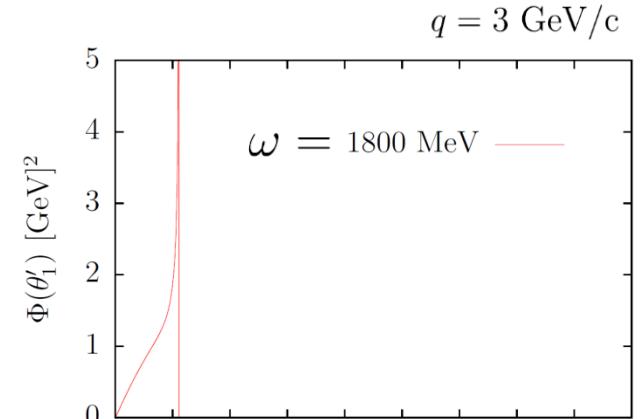
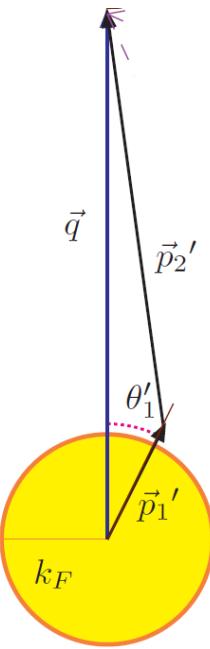


Angular distribution of ejected nucleons

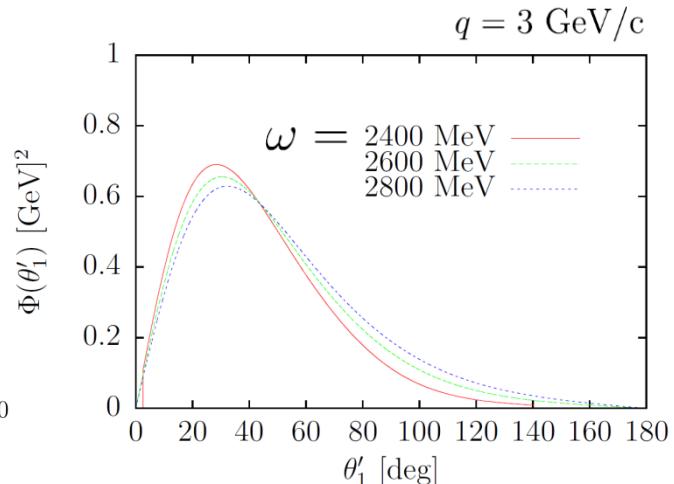
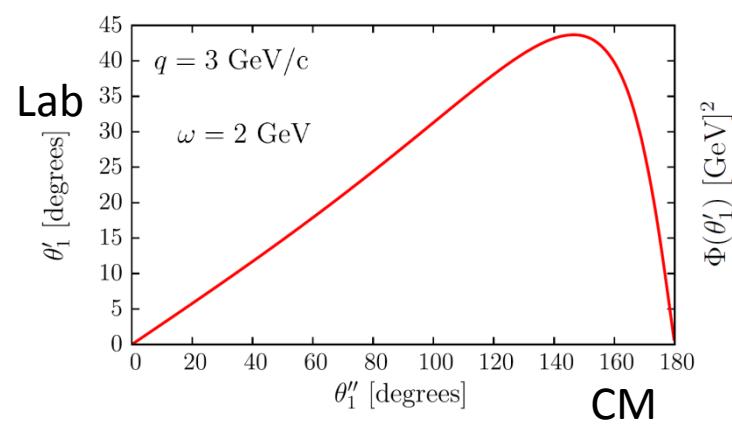
$$\bar{F}(\omega, q) = \left(\frac{4}{3} \pi k_F^3 \right)^2 2\pi \int_0^\pi d\theta'_1 \Phi(\theta'_1)$$

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

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



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

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

π, g'

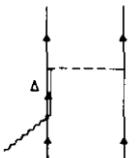
[Genuine QE (1 body contribution): LRGF+RPA]

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): LRGF+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”

Neutrino scattering

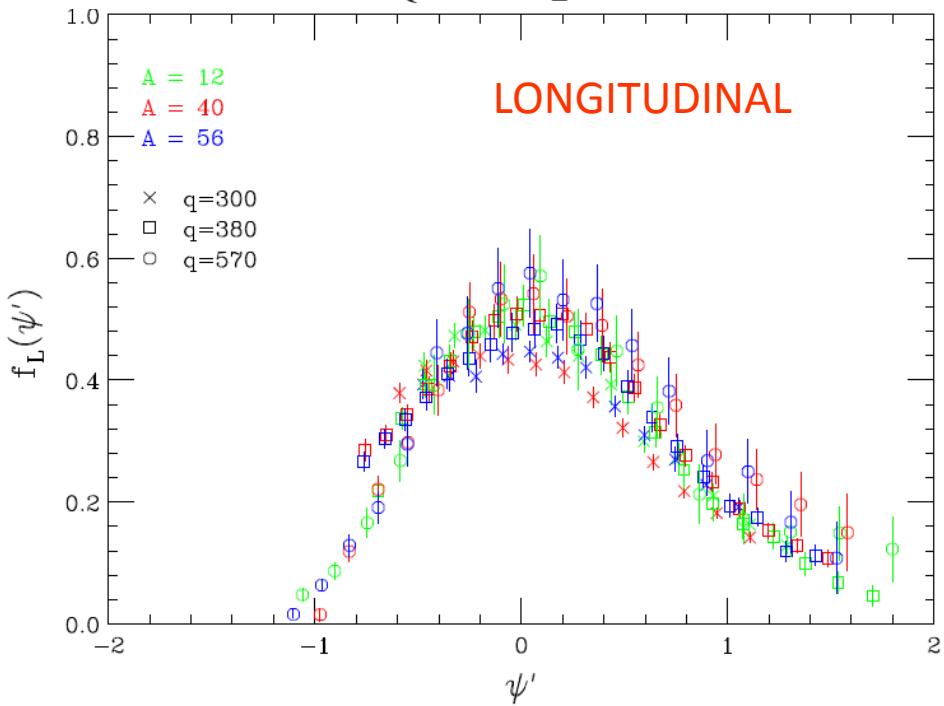
$$\frac{\partial^2 \sigma}{\partial \Omega \partial \epsilon'} = \frac{G_F^2 \cos^2 \theta_c}{2 \pi^2} k' \epsilon' \cos^2 \frac{\theta}{2} \left[\frac{(q^2 - \omega^2)^2}{q^4} G_E^2 R_\tau + \frac{\omega^2}{q^2} G_A^2 R_{\sigma\tau(L)} + \right.$$

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

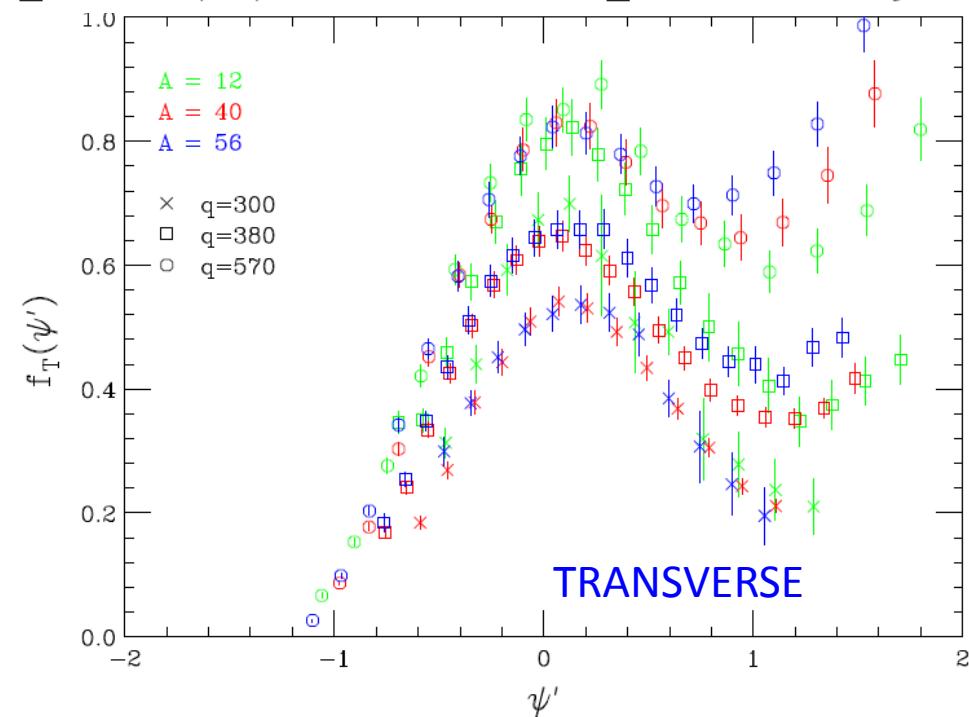
Electron scattering

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

$$+ \left[\tan^2 \left(\frac{\theta}{2} \right) - \frac{\omega^2 - q^2}{2q^2} \right] \boxed{R_T(\omega, q)}$$



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



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

Neutrino-nucleus cross section

Two equivalent expressions:

The notation for example of Amaro et al:

$$\frac{\partial^2 \sigma}{\partial \Omega \partial \epsilon'} = \sigma_0 [L_{CC}(R_{CC}^V + R_{CC}^A) + L_{CL}(R_{CL}^V + R_{CL}^A) + L_{LL}(R_{LL}^V + R_{LL}^A) + L_T(R_T^V + R_T^A) \pm L_{T'VA}R_{T'}^{VA}]$$

Longitudinal

Transverse

Transverse

V-A interference

The notation of Lovato et al:

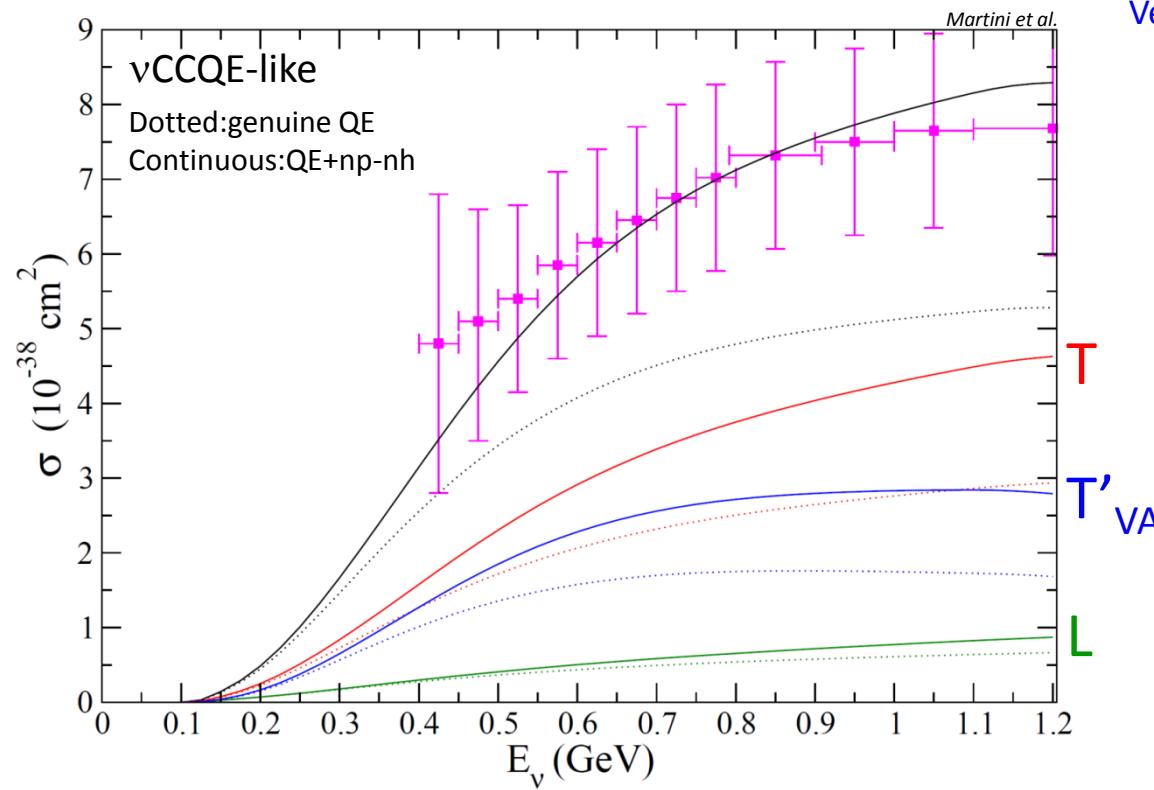
$$\frac{\partial^2 \sigma}{\partial \Omega \partial \epsilon'} = \sigma_0 [L_{00}R_{00} + L_{0z}R_{0z} + L_{zz}R_{zz} + L_{xx}R_{xx} \pm L_{xy}R_{xy}]$$

Longitudinal

Transverse

Transverse

Vector-Axial interference

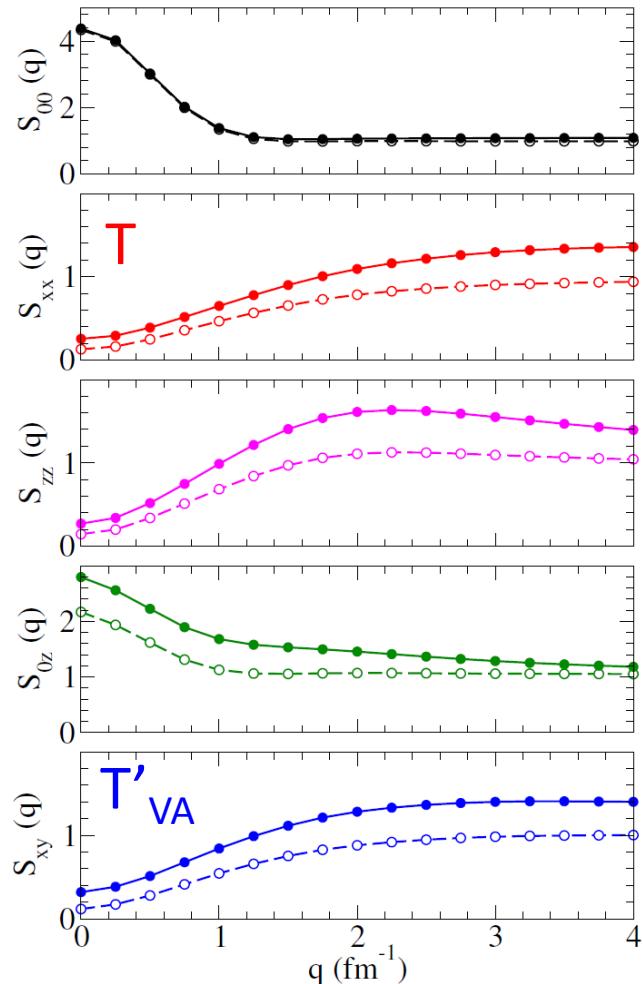


Some instructive comparisons (of two different quantities) (I)

Sum rules of NC

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

Lovato et al. PRL 112 182502 (2014)



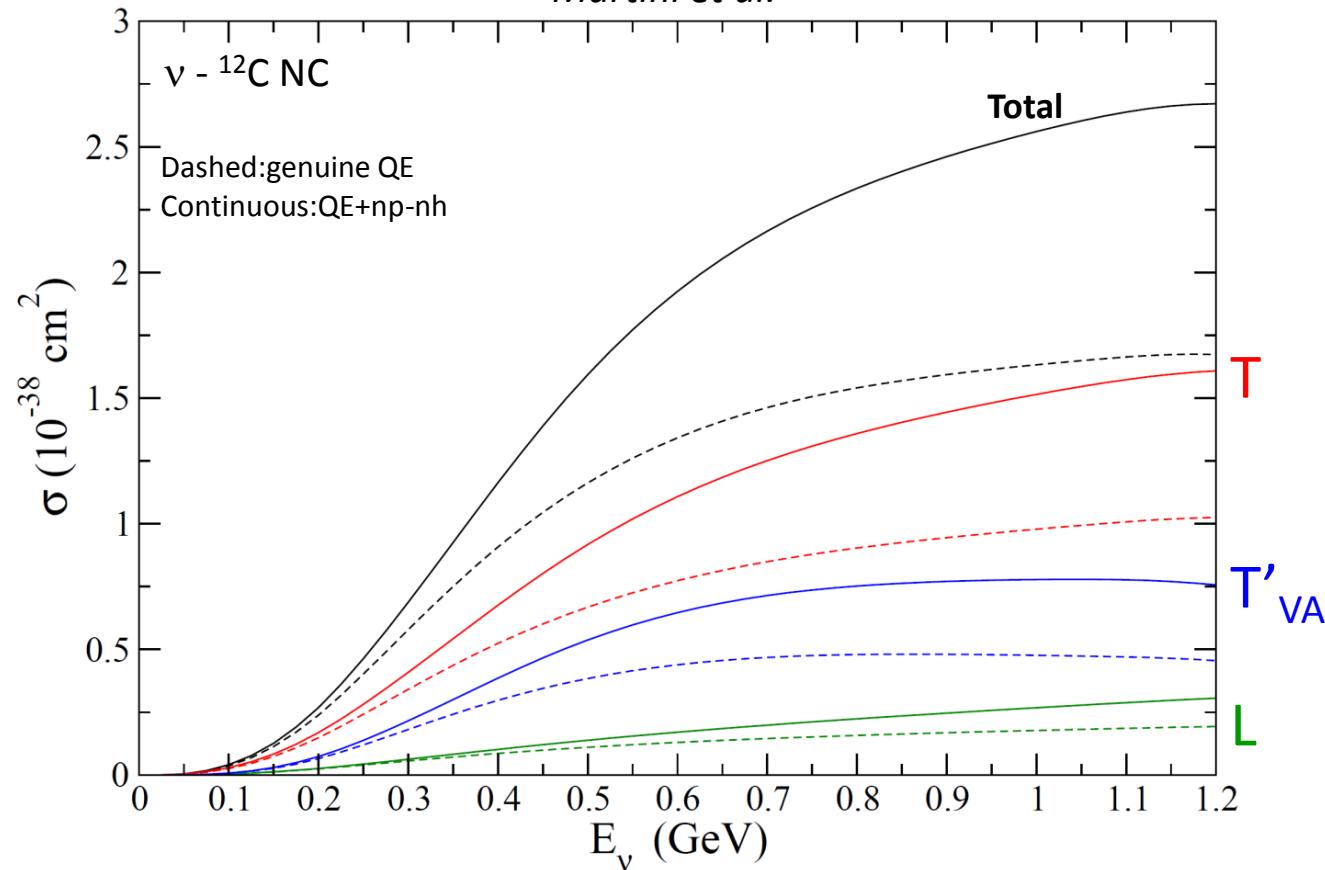
Cross section

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

Transverse Transverse
VA Interf.

Longitudinal

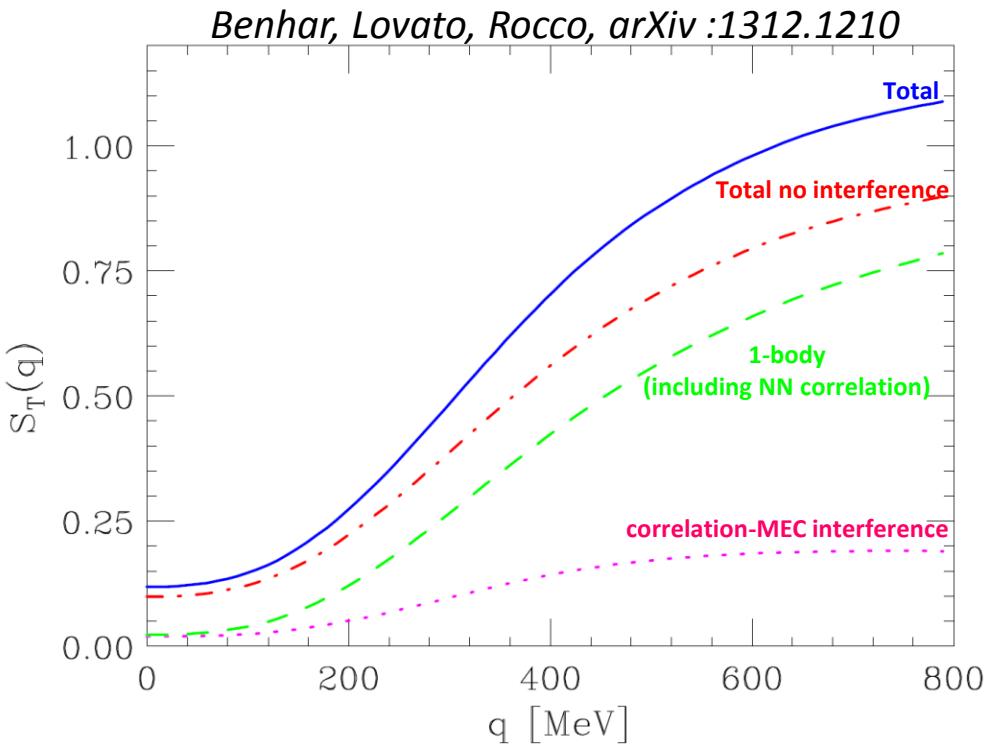
Martini et al.



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

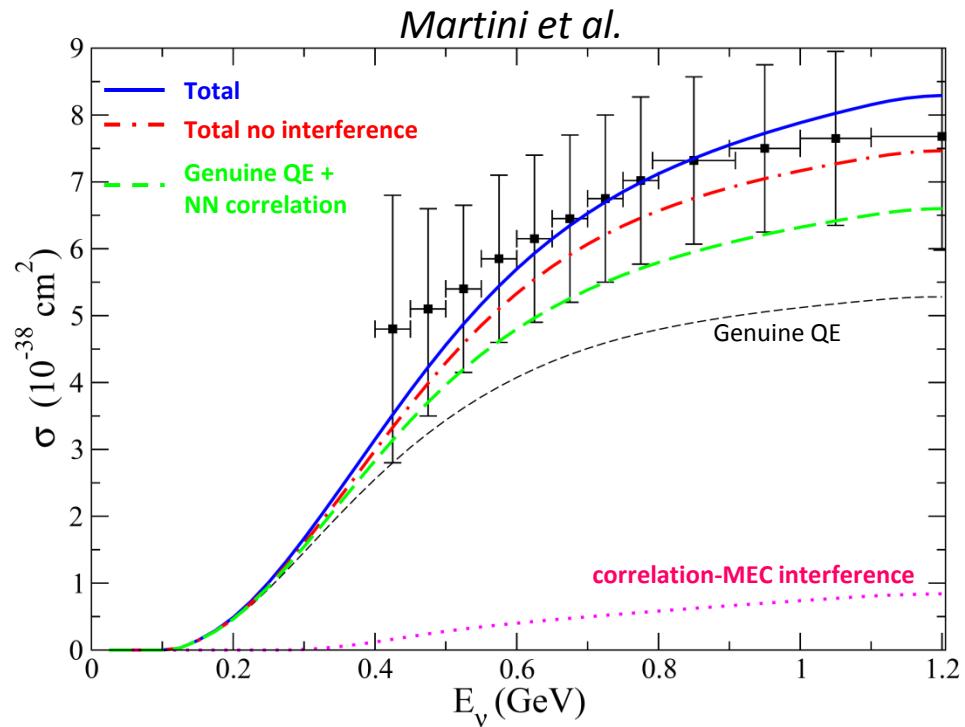
Some instructive comparisons (of two different quantities) (II)

Sum rule of the transverse response



- Sum rule function of q
- Only Vector Transverse

Neutrino CCQE-like cross section

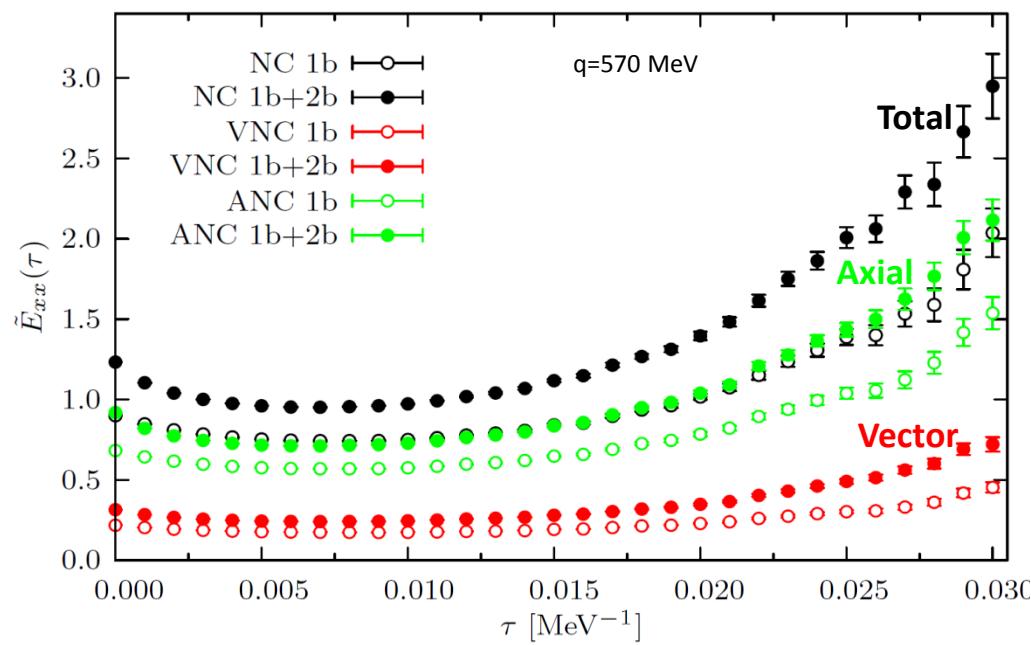


- Cross section function of E_ν
- Total

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

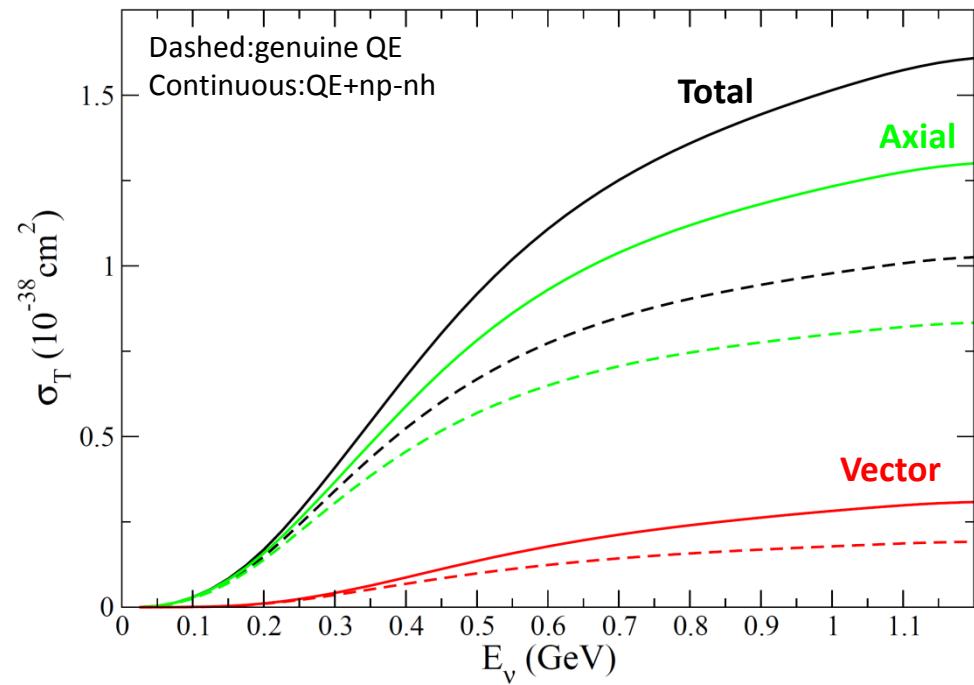
Euclidean NC transverse response

Lovato et al. Phys.Rev. C91 062501 (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

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

$\overset{\text{R}_V + \text{R}_A}{\uparrow}$

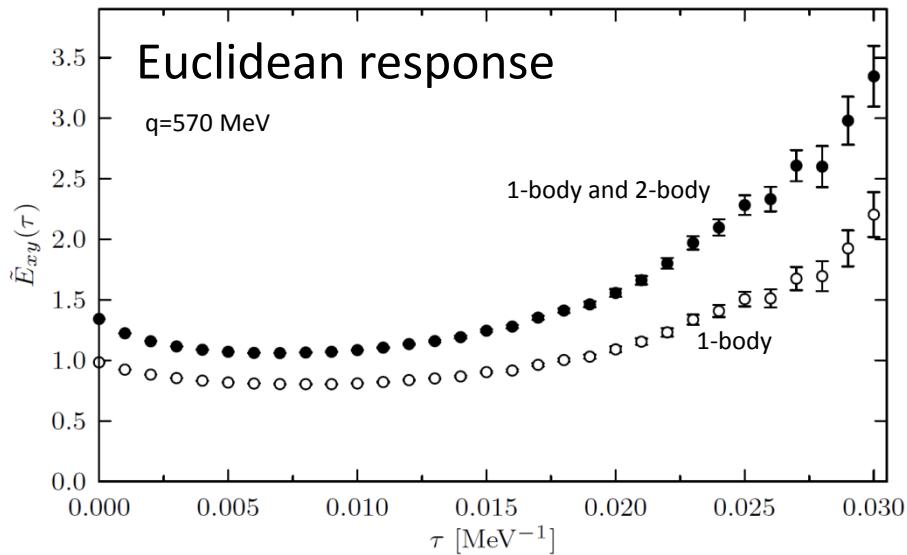
The VA interference term in an *ab-initio* microscopic approach

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

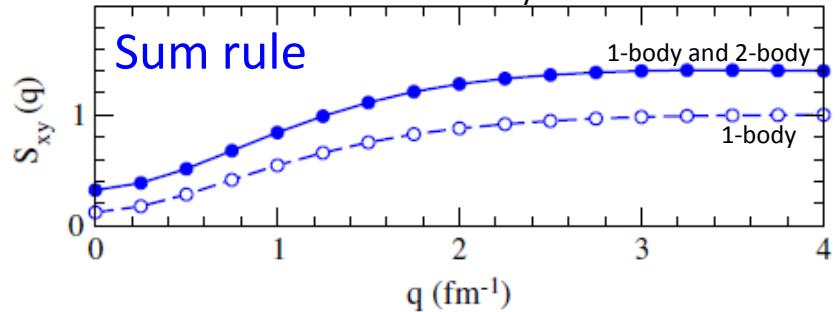
$$E_{\alpha\beta}(q, \tau) = C_{\alpha\beta}(q) \int_{\omega_{\text{th}}}^{\infty} d\omega e^{-\tau\omega} R_{\alpha\beta}(q, \omega)$$

Phys. Rev. C91 062501 (2015)



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

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

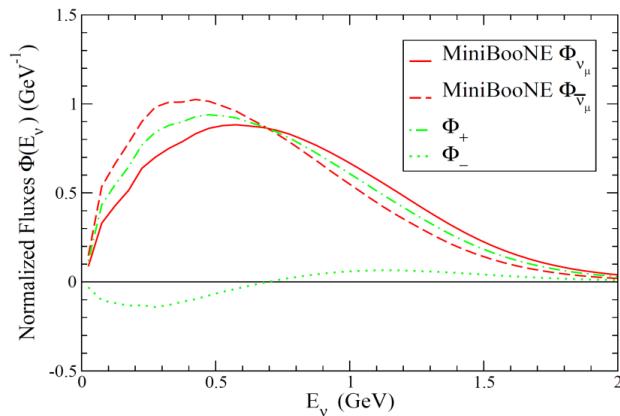
Difference of ν and antiv cross sections and the VA interference term

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

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

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

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



We introduce the **mean flux**

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

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

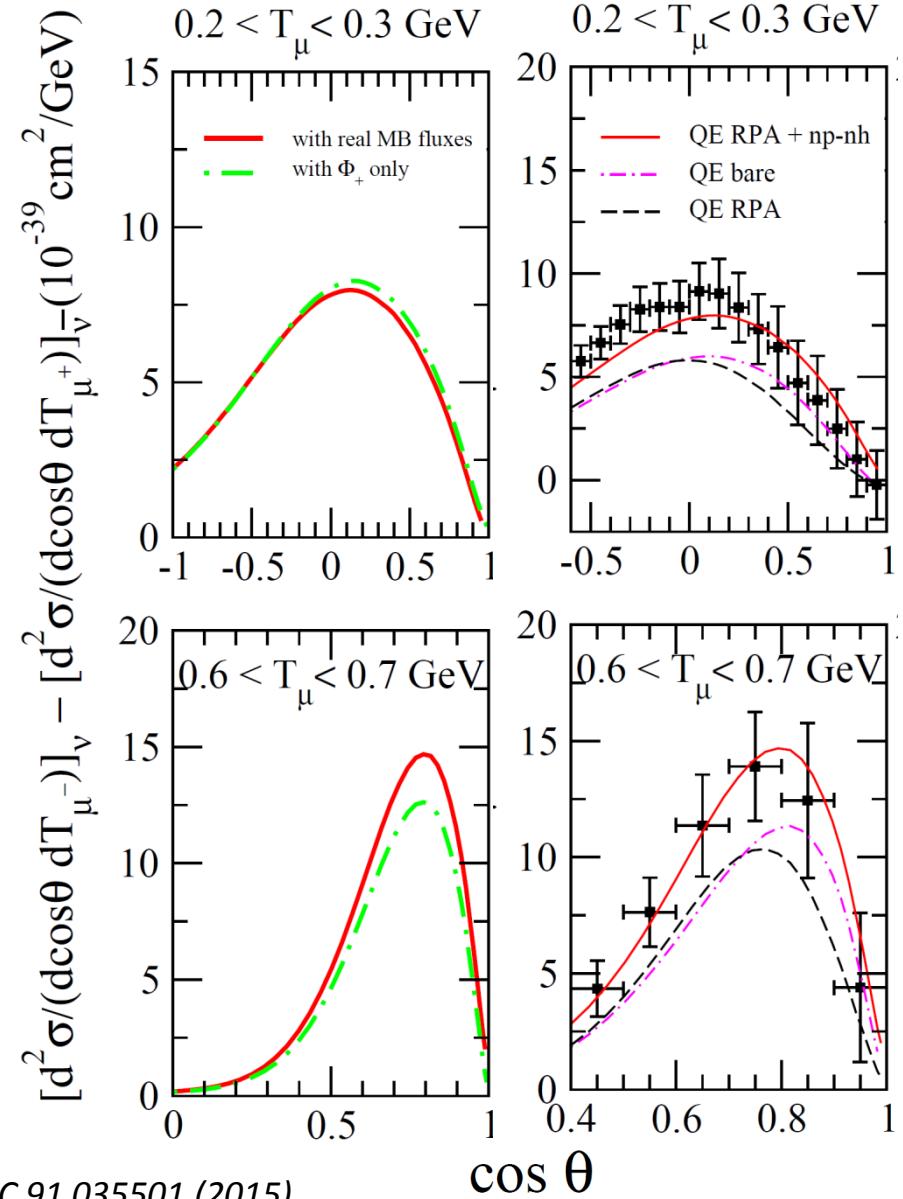
The mean flux contribution is dominant in the ν antiv difference



The VA interference term is experimentally accessible in MiniBooNE data

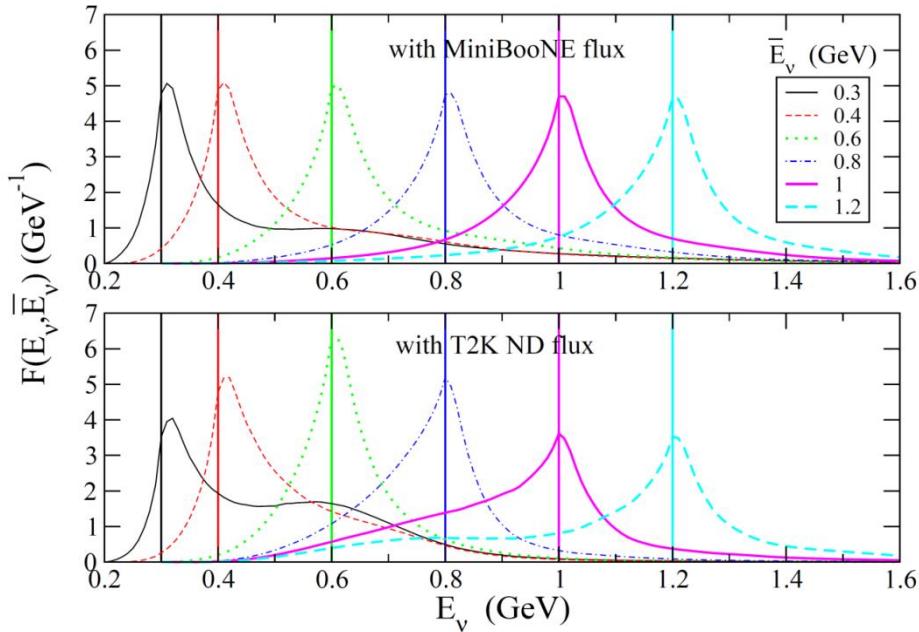


Need for the multinucleon component in the VA interference



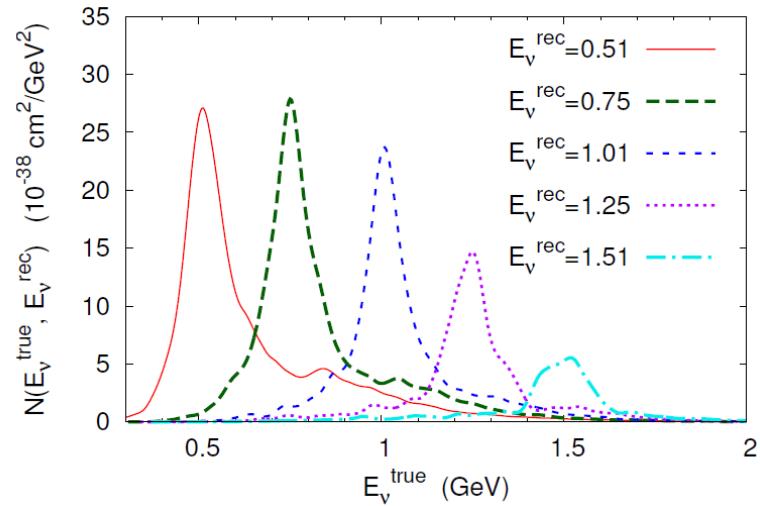
Distributions in terms of true E_ν for fixed values of reconstructed \bar{E}_ν

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

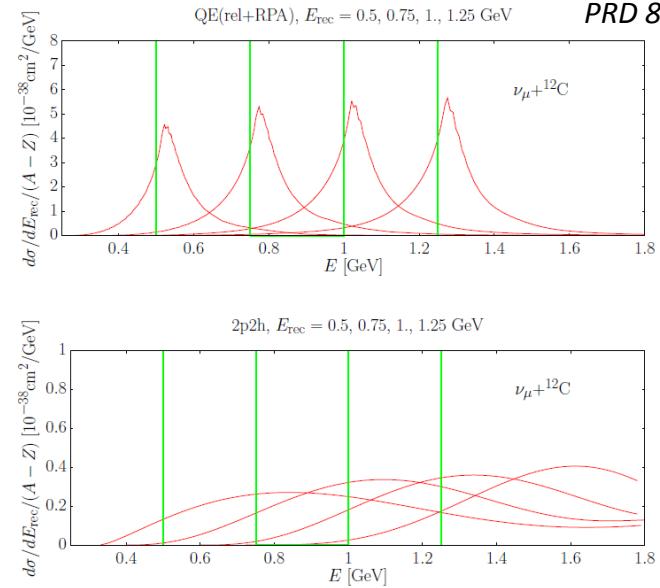


- The distributions are not symmetrical around \bar{E}_ν .
- The asymmetry favors higher energies at low \bar{E}_ν and smaller energies for large \bar{E}_ν .
- Crucial role of neutrino flux.

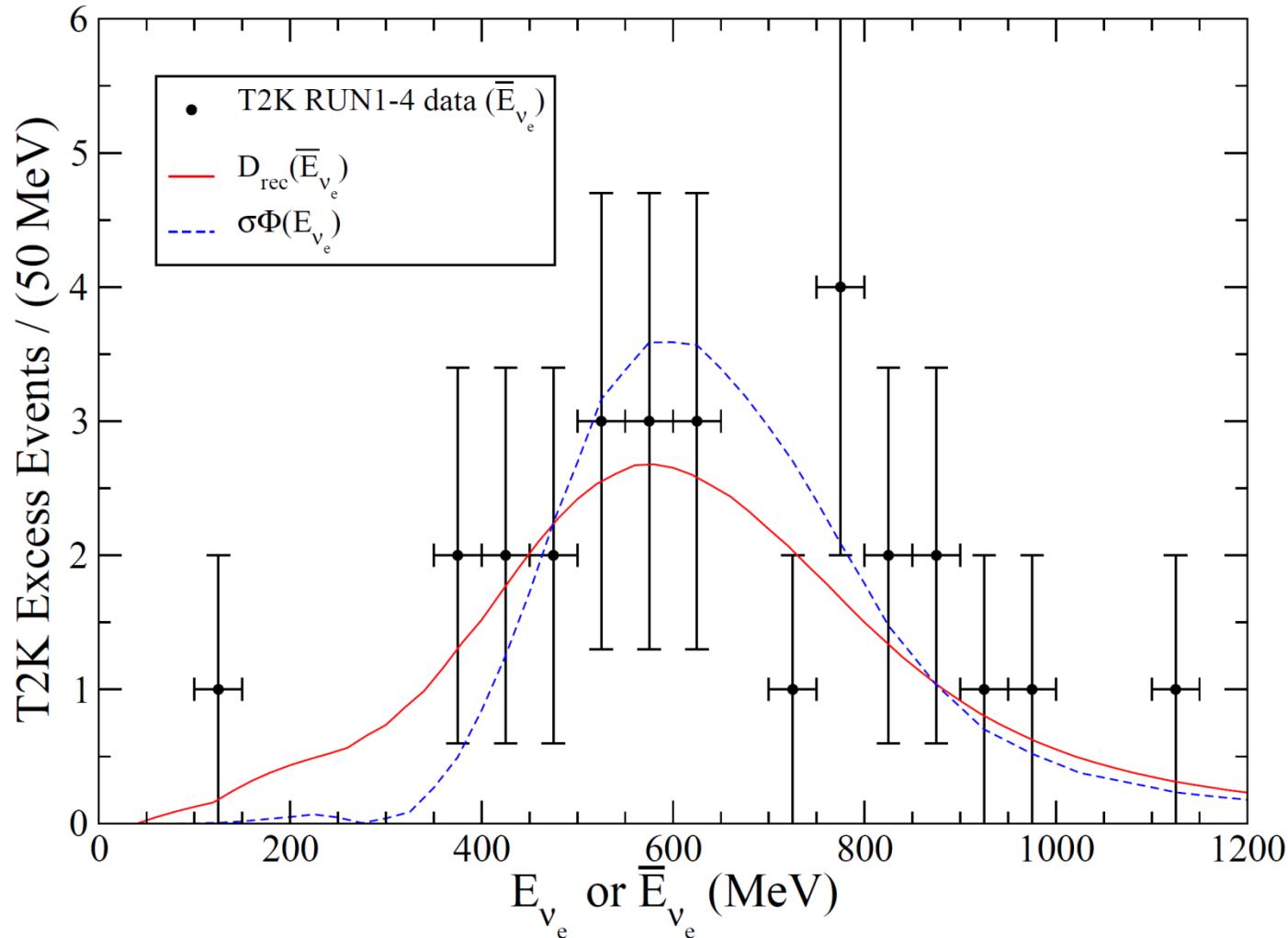
O. Lalakulich, U. Mosel, K. Gallmeister PRC 86 054606 (2012)



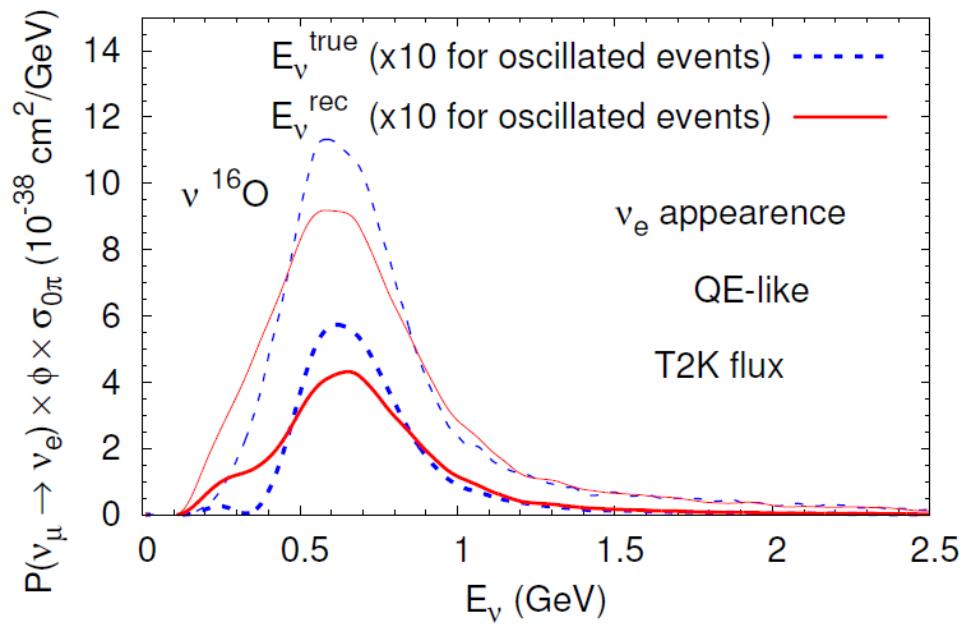
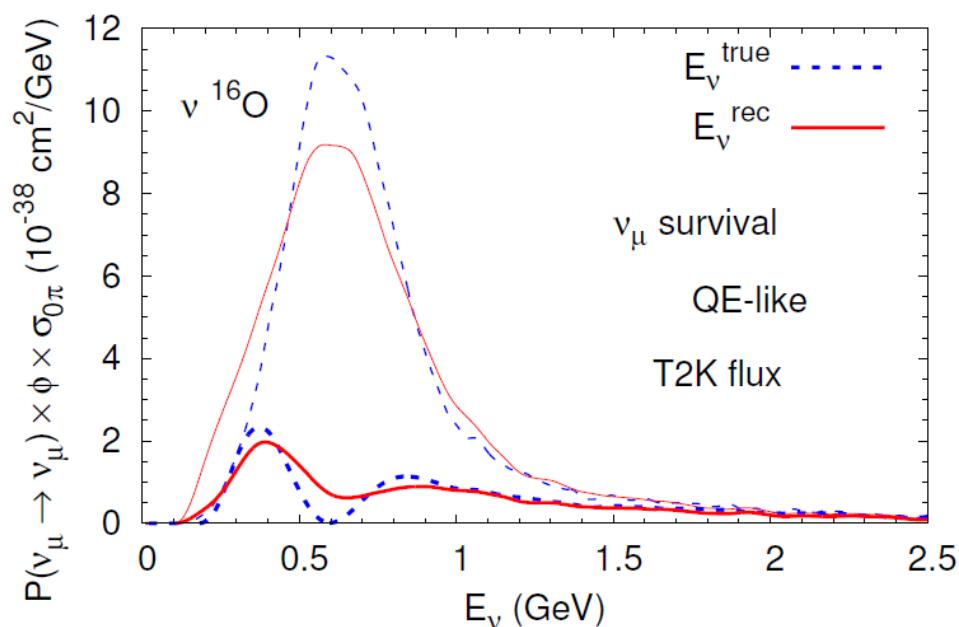
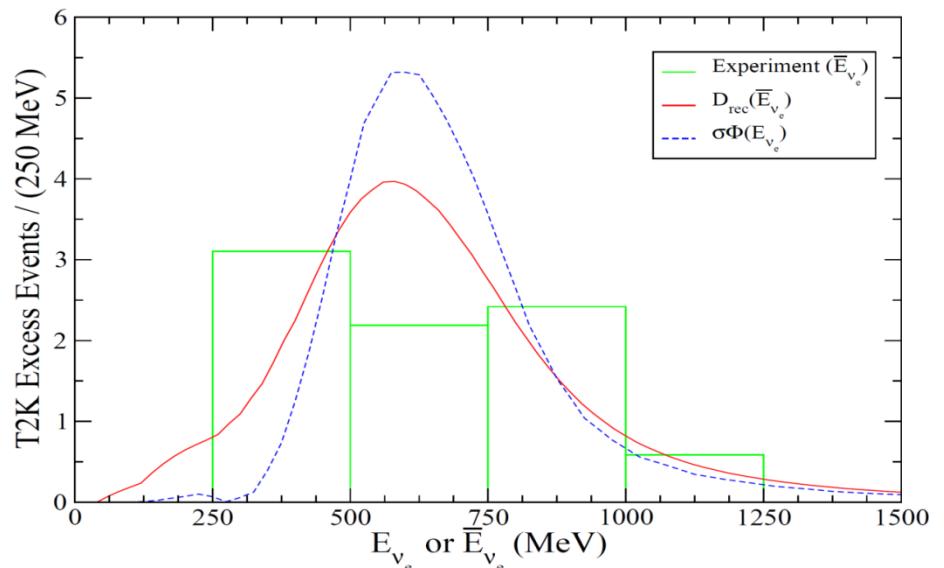
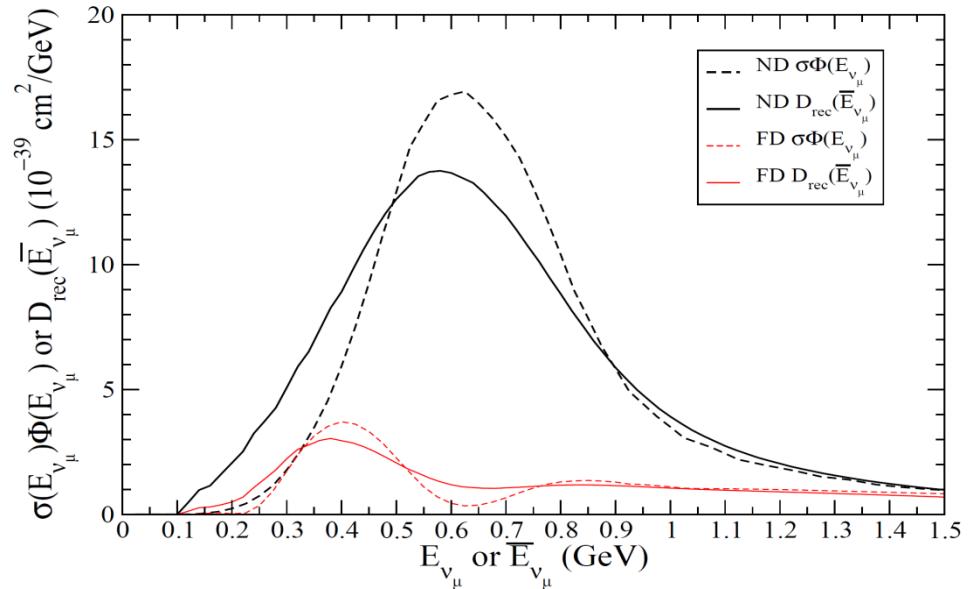
J. Nieves, F. Sanchez, I. Ruiz Simo, M.J. Vicente Vacas
QE(rel+RPA), $E_{\text{rec}} = 0.5, 0.75, 1., 1.25 \text{ GeV}$
PRD 85 113008 (2012)



2013: 28 events



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



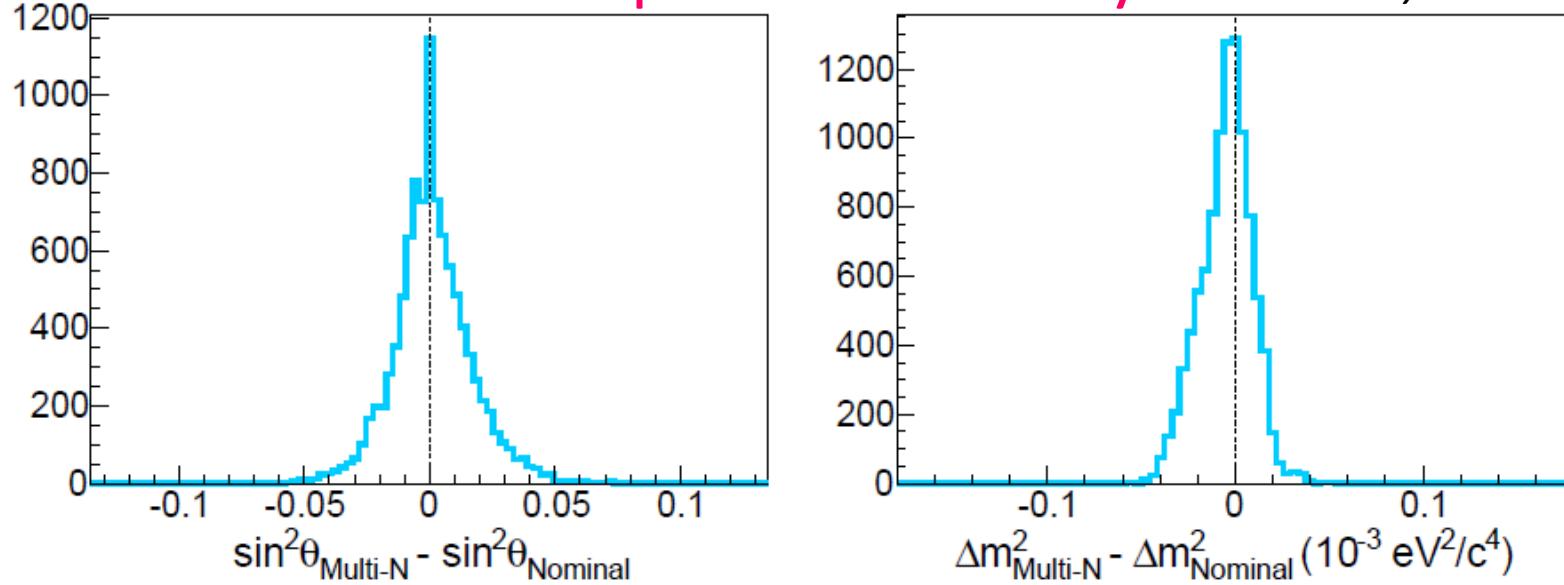
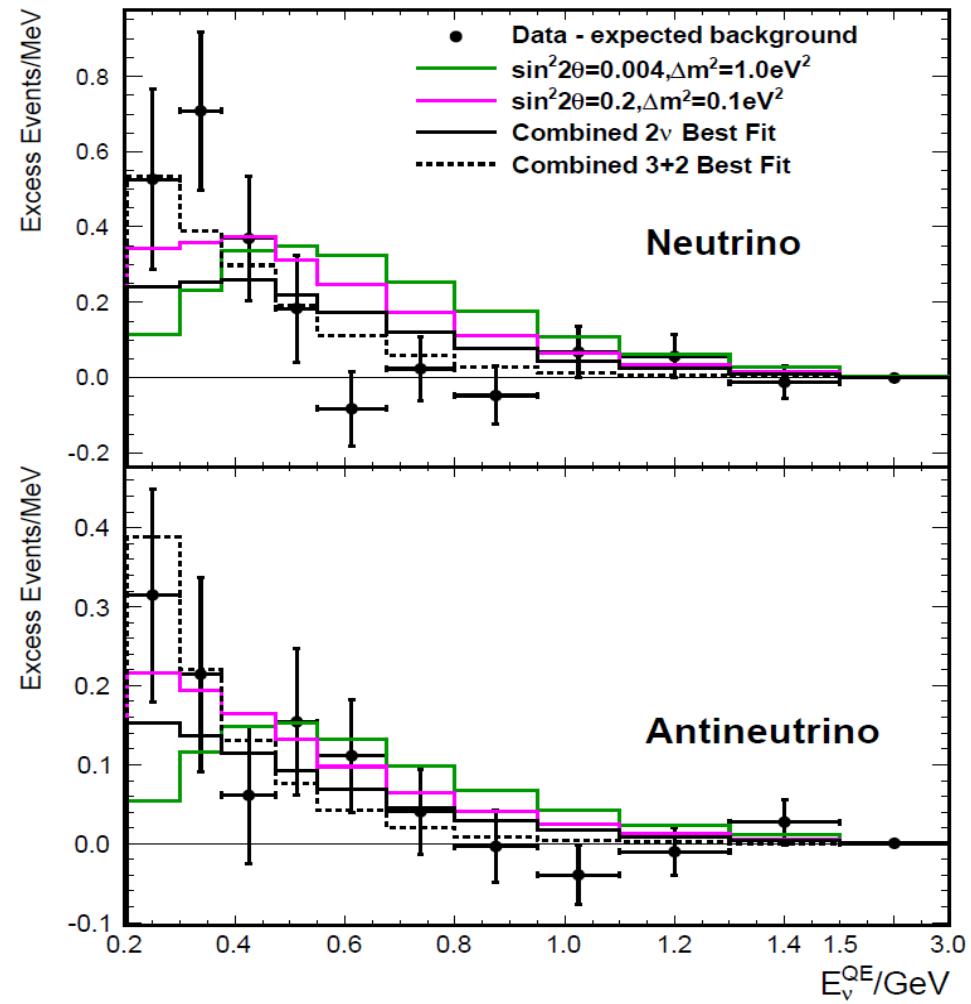
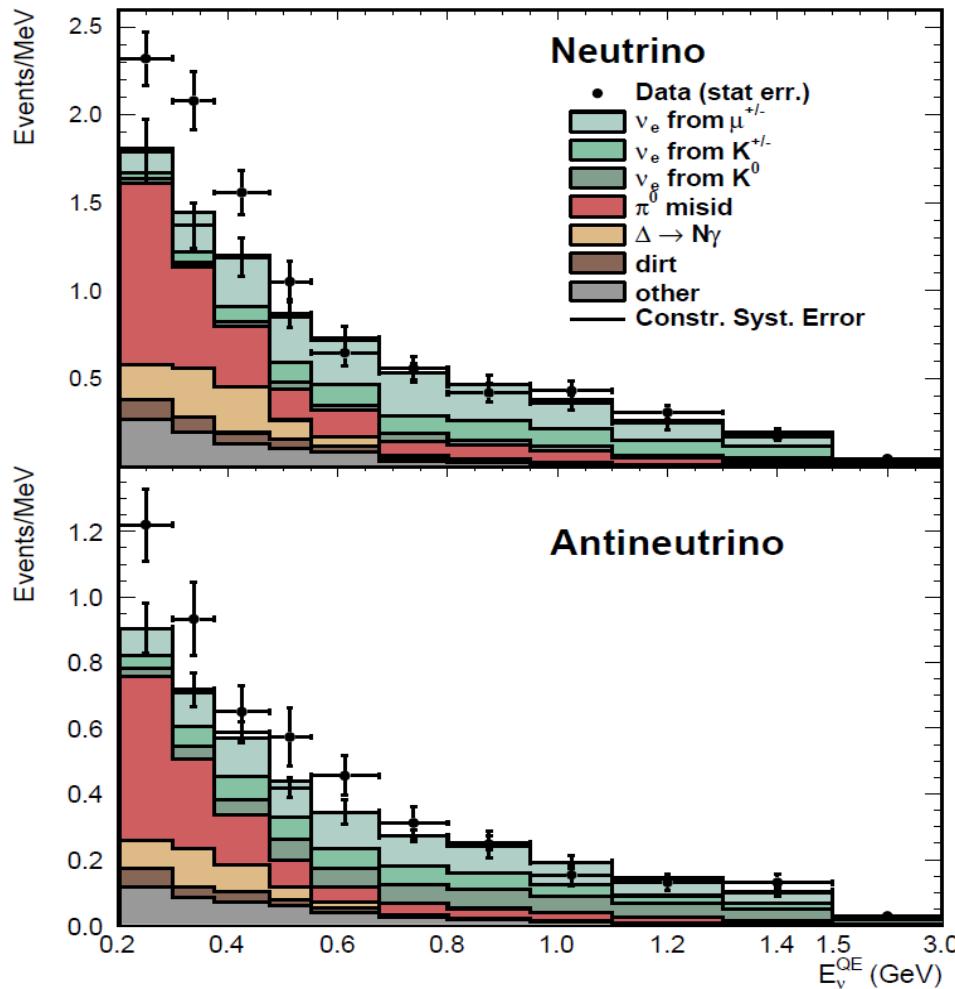


FIG. 30: Difference in the point estimates of $\sin^2\theta_{23}$ (left) and $|\Delta m^2|$ (right) between pairs of toy MC datasets with and without including multi-nucleon effects.

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 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.

$\nu_\mu \rightarrow \nu_e$ MiniBooNE

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

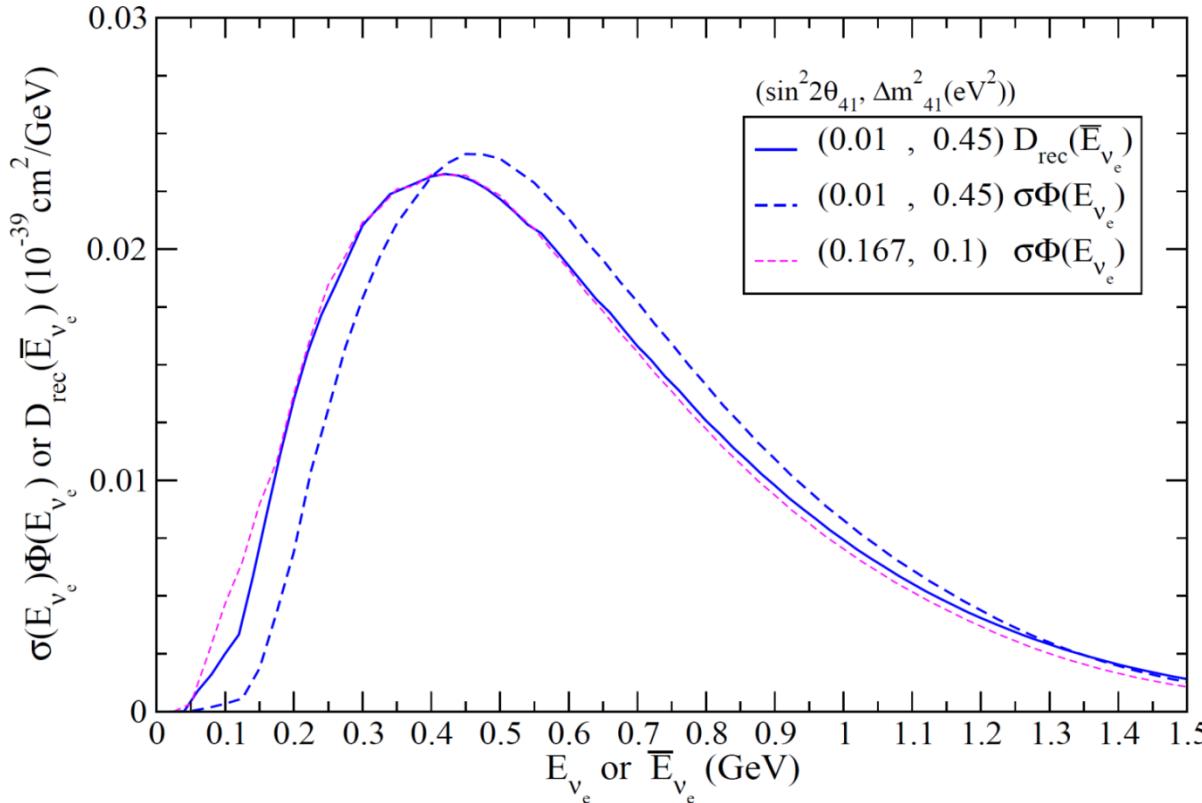


MiniBooNE Anomaly: Excess of events at low energies

Sterile neutrino??

Taking into account the energy reconstruction correction

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



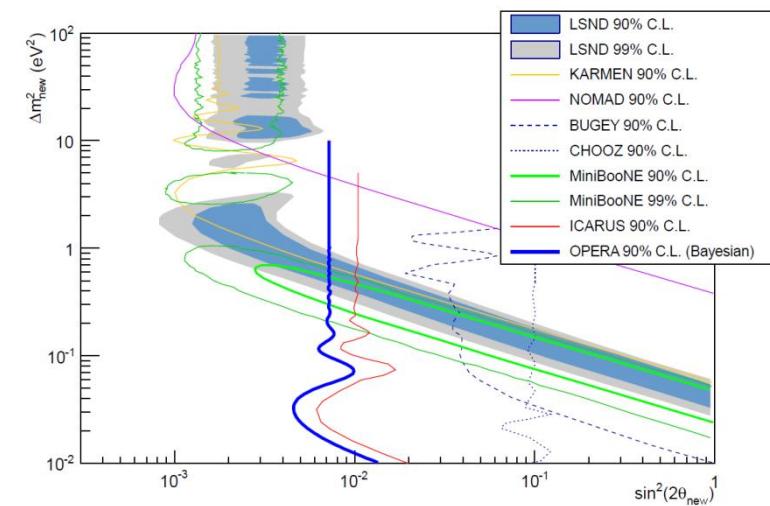
A large mass value allows the same quality of fit of data than is obtained in the unsmeared case with a much smaller mass.

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



Gain for the compatibility with the existing constraints

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



$\nu_\mu \rightarrow \nu_e$ MiniBooNE

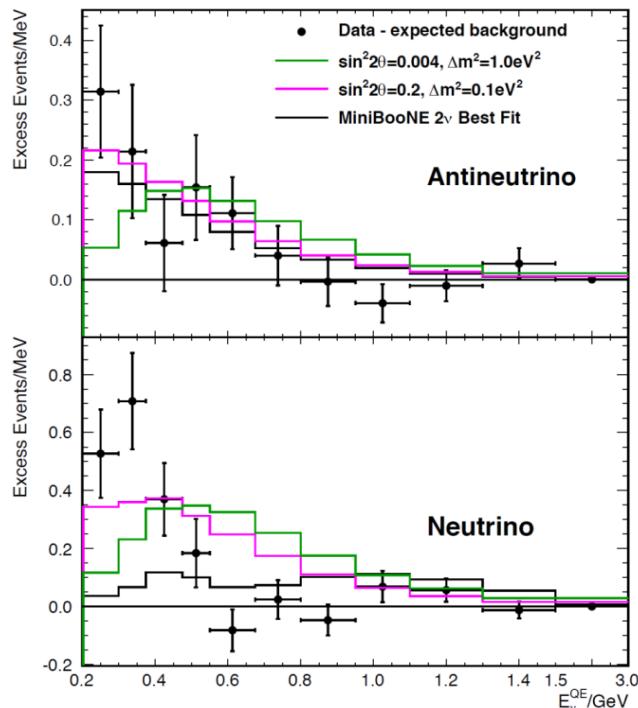


TABLE II: χ^2 values from oscillation fits to the antineutrino-mode data for different prediction models. The best fit ($\Delta m^2, \sin^2 2\theta$) values are $(0.043 \text{ eV}^2, 0.88)$, $(0.059 \text{ eV}^2, 0.64)$, and $(0.177 \text{ eV}^2, 0.070)$ for the nominal, Martini, and disappearance models,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

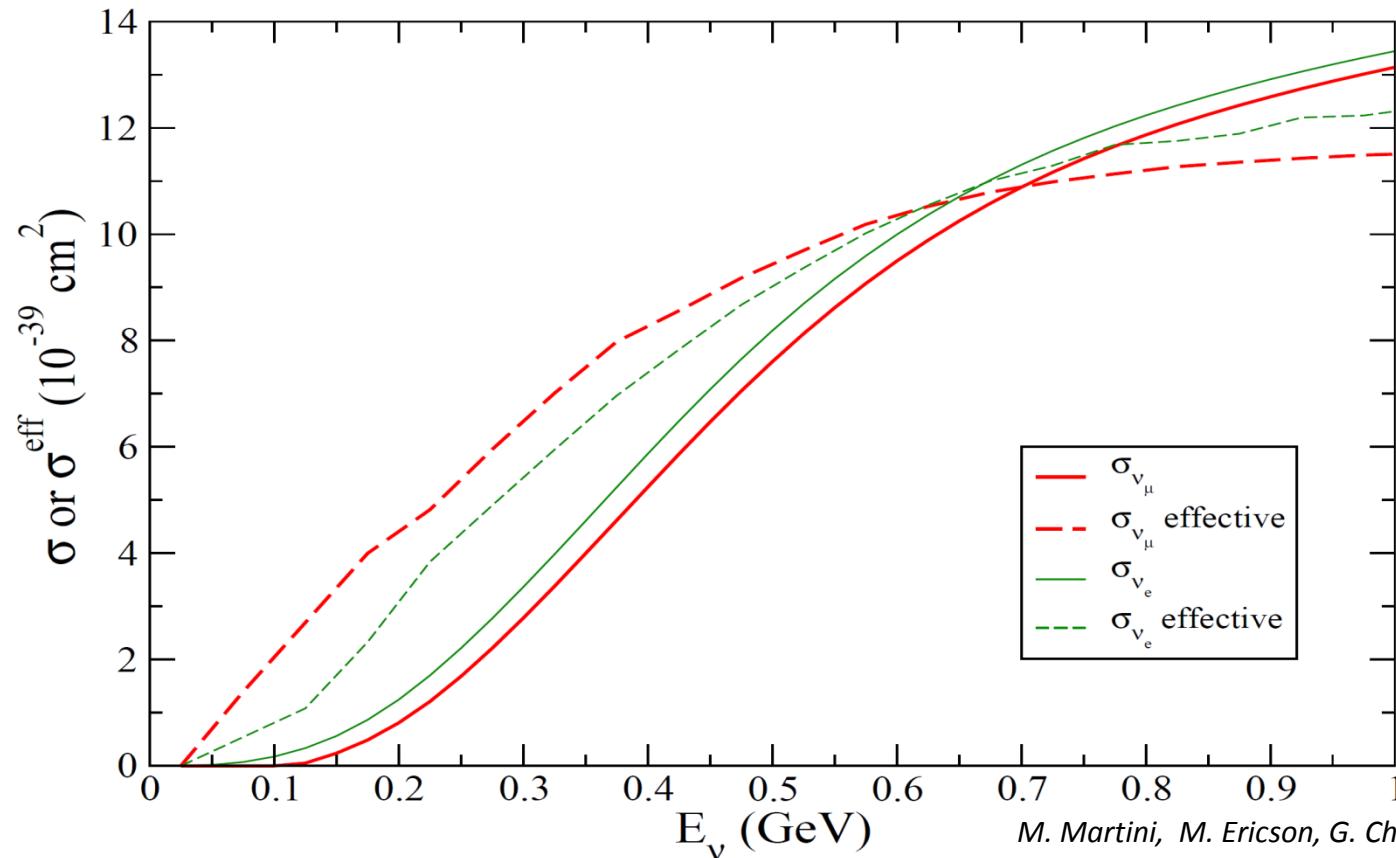
Prediction Model	χ^2 values	
	Best Fit	Test Pt.
Nominal $\bar{\nu}$ -mode Result	5.0	6.2
Martini <i>et al.</i> [25] Model	5.5	6.5
Model With Disapp. (see text)	5.4	6.7

Phys.Rev.Lett. 110 (2013) 161801

Real and effective cross sections for ν_μ and ν_e

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

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

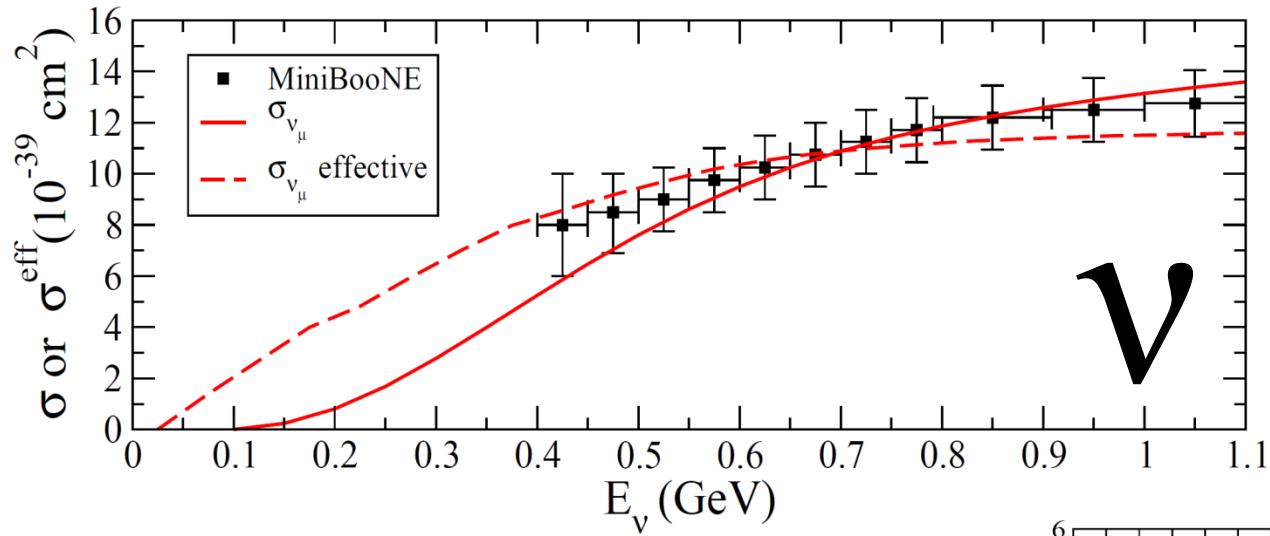


M. Martini, M. Ericson, G. Chanfray, PRD 87 013009 (2013)

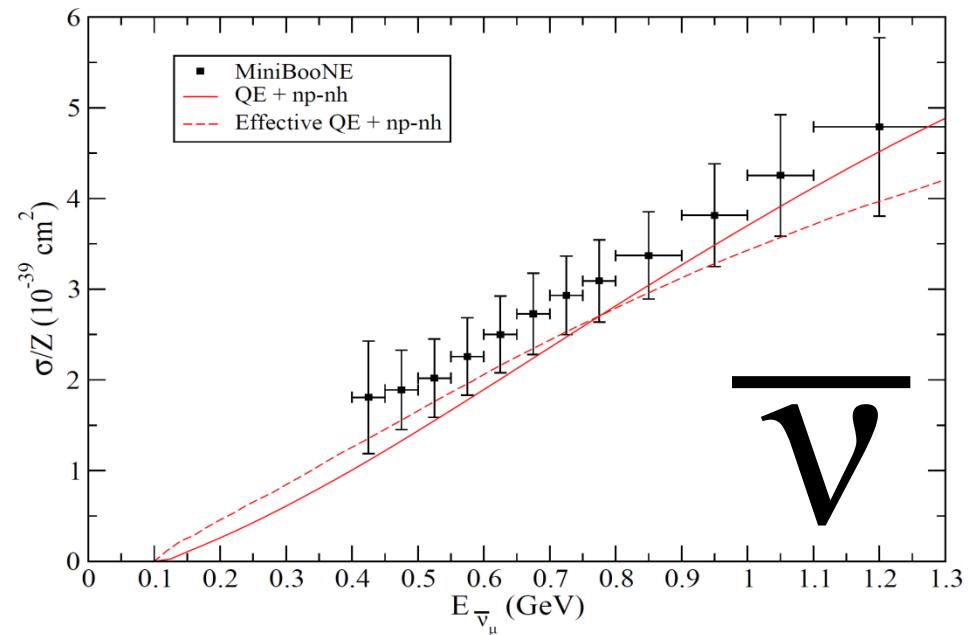
The effective cross section is not universal but
it depends on the particular beam energy distribution

(here we used ν_μ and ν_e MiniBooNE fluxes)

Real and effective cross sections for μ



V



V