Neutrino-nucleus interactions

Marco Martini
Ghent University

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.

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

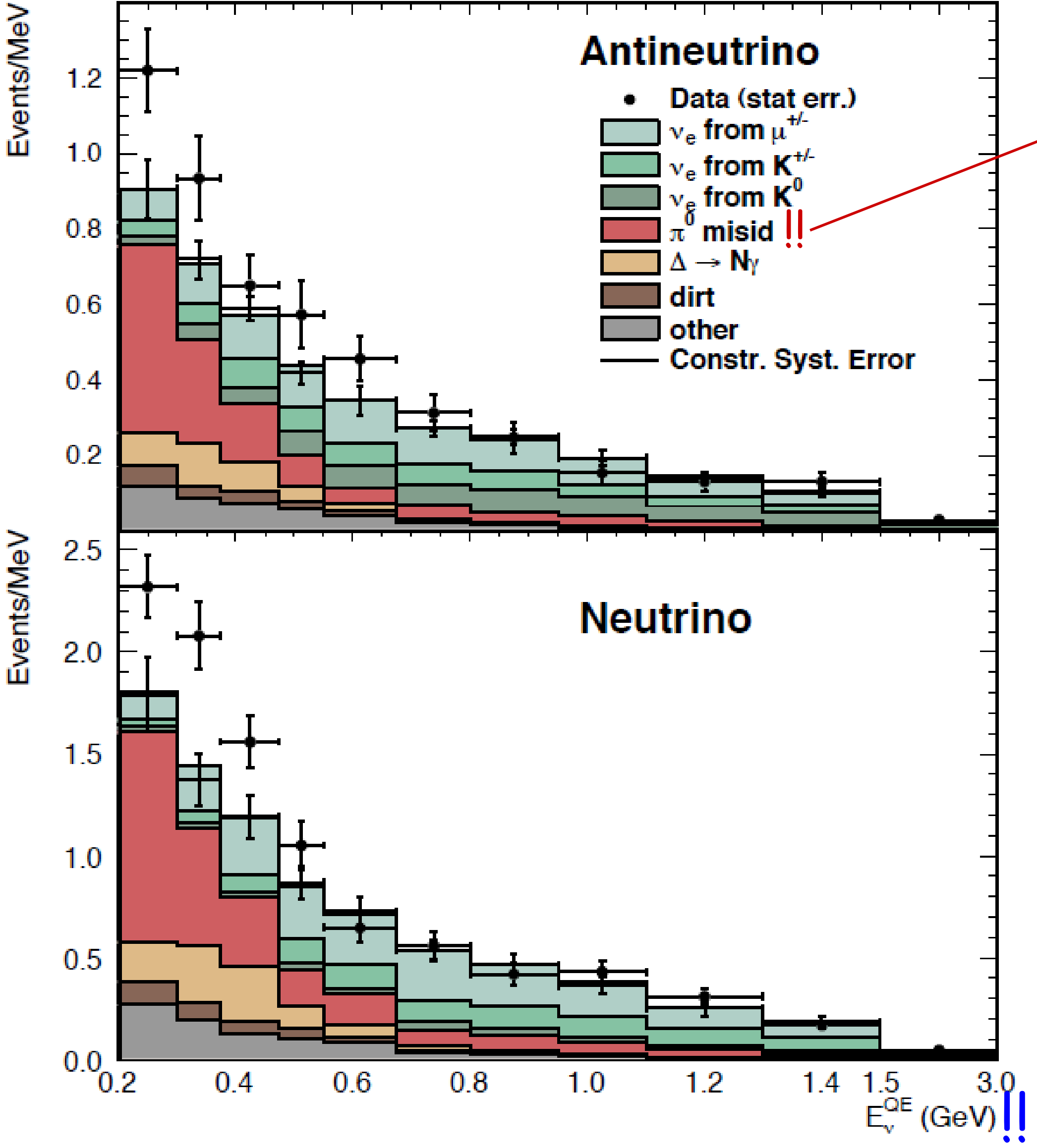
- Modern neutrino oscillation experiments use nuclear targets

- Nuclear effects play a crucial role

$\nu_\mu \longrightarrow \nu_e$

MiniBooNE

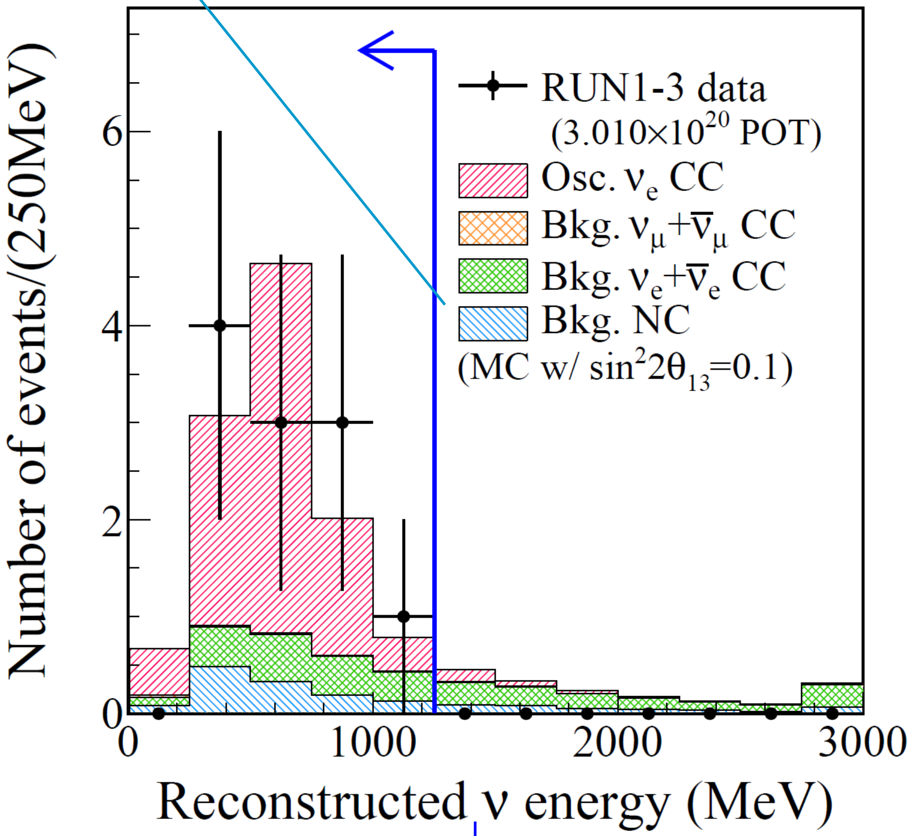
Phys.Rev.Lett. 110 (2013) 161801



NC π^0 important background

Phys.Rev. D88 (2013) 032002

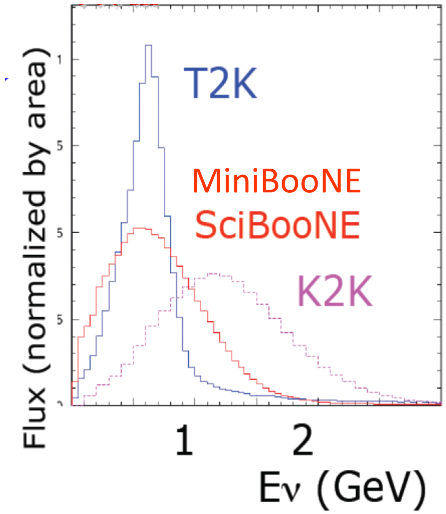
T2K

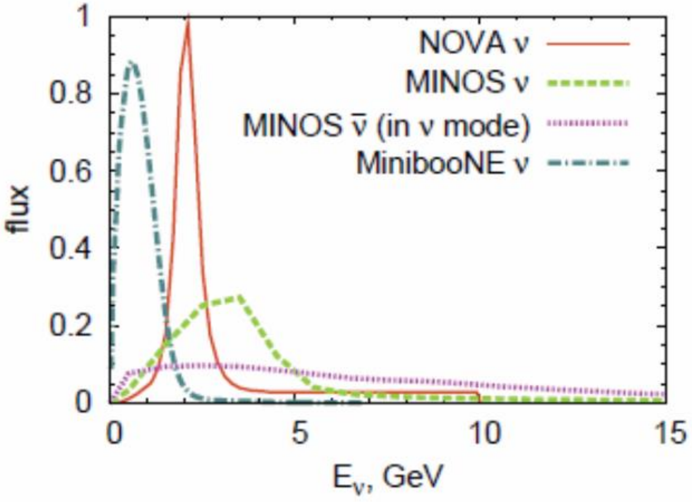


E_ν reconstructed through quasielastic events

Some crucial points

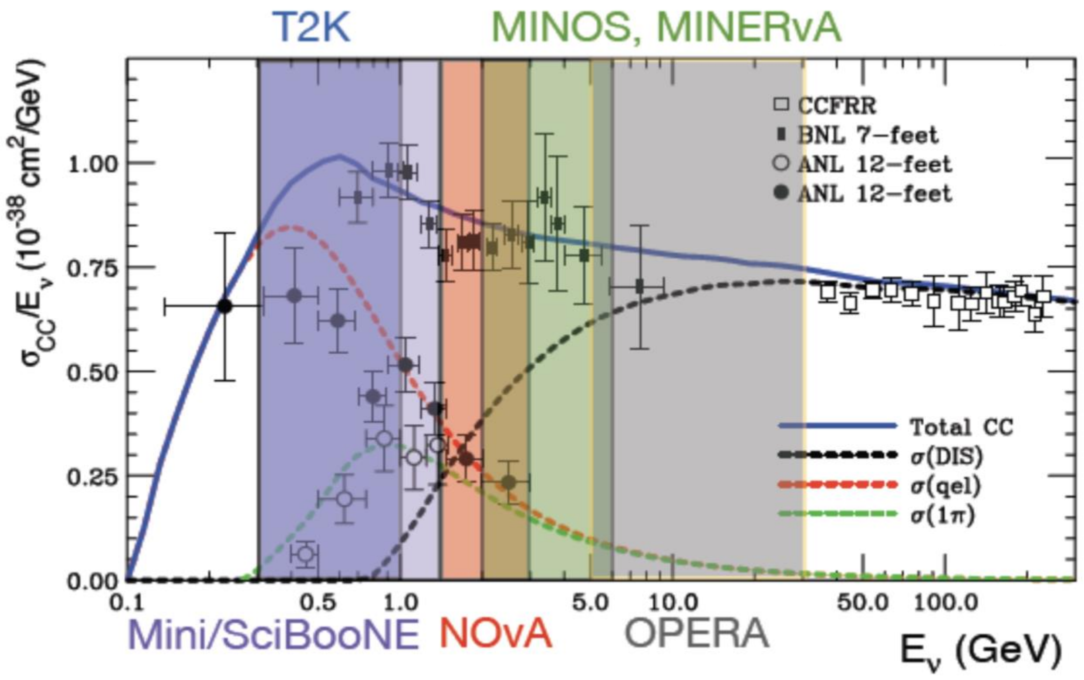
- Neutrino beams are not monochromatic
 (at difference with respect to electron beams).
 They span a wide range of energies





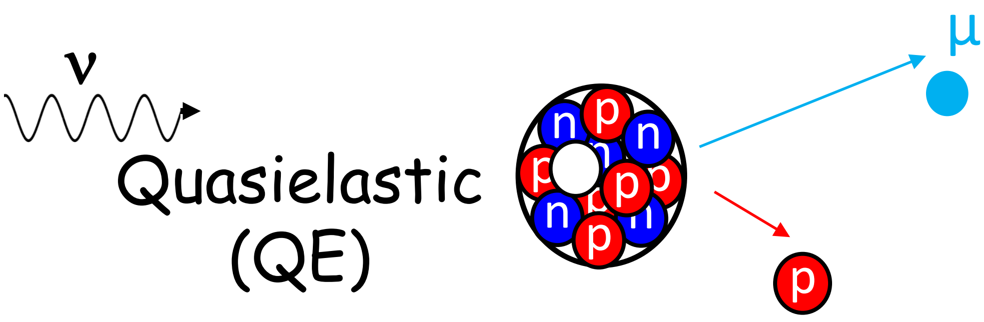
- The neutrino energy is reconstructed
 from the final states of the reaction
 (typically from CC Quasielastic events)

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



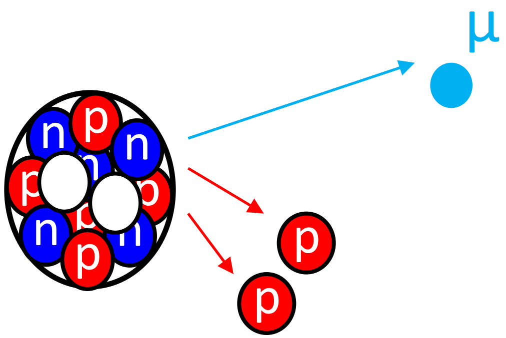
Neutrino - nucleus interaction @ $E_\nu \sim O(1\ \mathrm{GeV})$

[MiniBooNE, T2K energies]

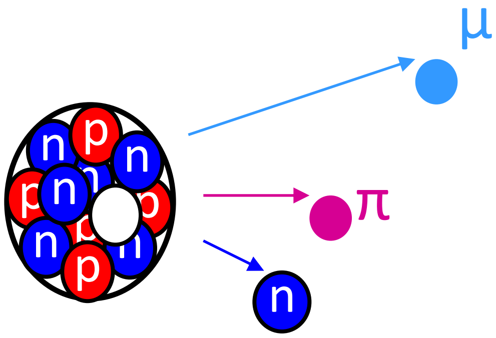


Quasielastic (QE)

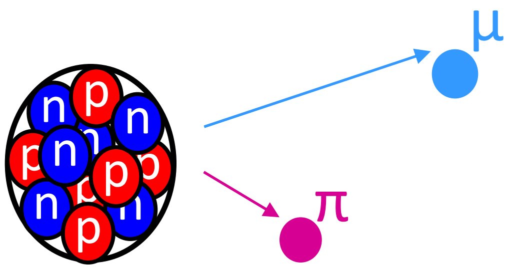
Two Nucleons knock-out (2p-2h)



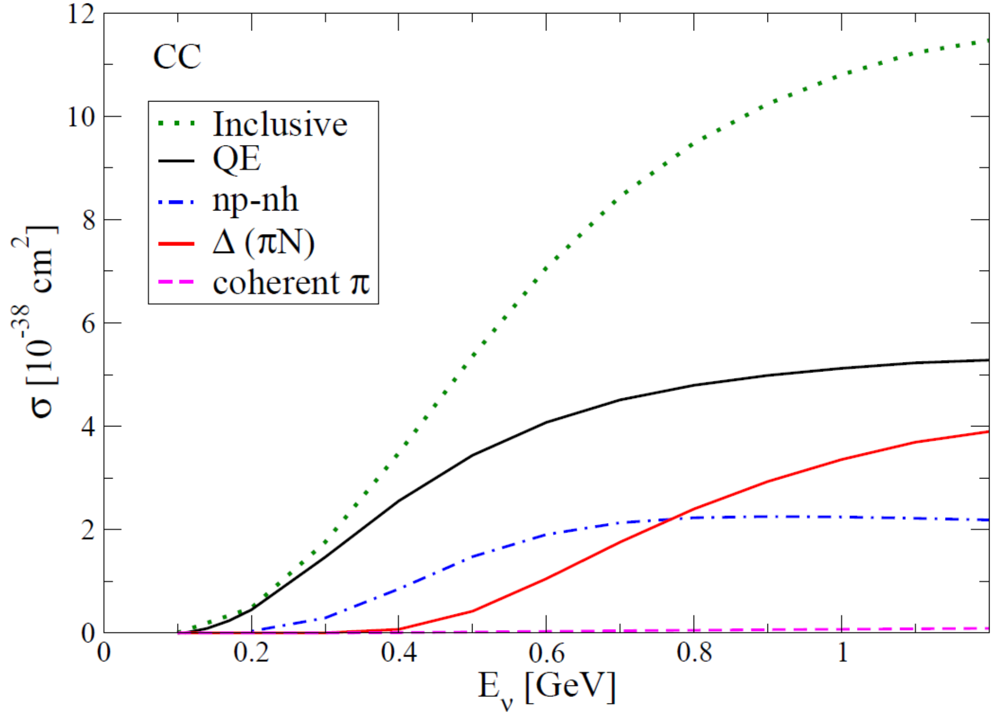
Incoherent π production



Coherent π production



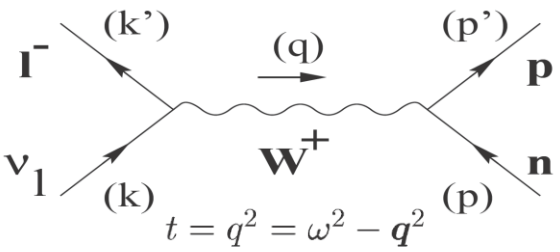
M. Martini, M. Ericson, G. Chanfray, J. Marteau, PRC 80 065501 (2009)



Different processes are entangled

Neutrino-nucleus interaction

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



lepton

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

hadron

$$\langle p', s' | h_+^\mu | p, s \rangle \;=\; e^{iqx} \bar{u}(p', s') \, [\underbrace{F_1(t)\gamma^\mu + F_2(t)\sigma^{\mu\nu}\frac{iq_\nu}{2M_N}}_{\text{Vector}} \underbrace{+ G_A(t)\gamma^\mu\gamma_5 + G_P(t)\gamma_5\frac{q^\mu}{2M_N}}_{\text{Axial}}] \, \tau_+ u(p, s)$$

Cross section:

$$\frac{\partial^2 \sigma}{\partial \Omega_{k'} \partial k'} = \frac{G_F^2 \cos^2 \theta_C \boldsymbol{k}'^2}{2\pi^2} \cos^2 \frac{\theta}{2} \Big[\underline{G_E^2} (1 - \frac{\omega^2}{\boldsymbol{q}^2})^2 \enclose{circle}{R_C} + \underline{G_A^2} \frac{(M_\Delta - M_N)^2}{\boldsymbol{q}^2} \enclose{circle}{R_L}$$

$$+ (\underline{G_M^2} \frac{\omega^2}{\boldsymbol{q}^2} + \underline{G_A^2})(1 - \frac{\omega^2}{\boldsymbol{q}^2} + 2\tan^2 \frac{\theta}{2}) \enclose{circle}{R_T} \pm \underline{G_A} \, \underline{G_M} \, 2 \frac{k + k'}{M_N} \tan^2 \frac{\theta}{2} \enclose{circle}{R_T} \Big]$$

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

Nuclear dynamics → Nuclear Response Functions:

Charge R_c (τ), Isospin Spin-Longitudinal R_L($\tau\ \sigma \cdot q$), Isospin Spin Transverse R_T ($\tau\ \sigma \times q$)

Form Factors

Standard dipole parameterization

Vector

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

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

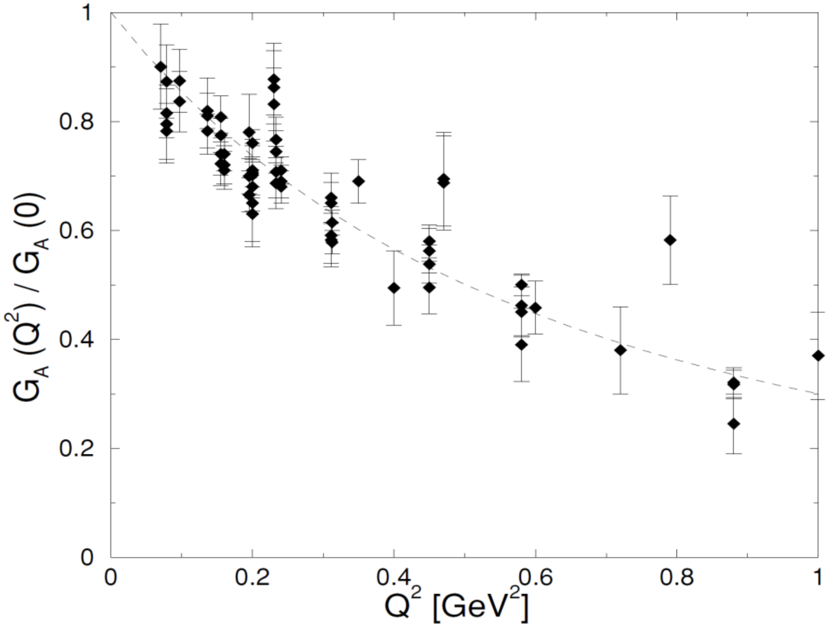
$$M_V = 0.84\,\mathrm{GeV}/c^2$$

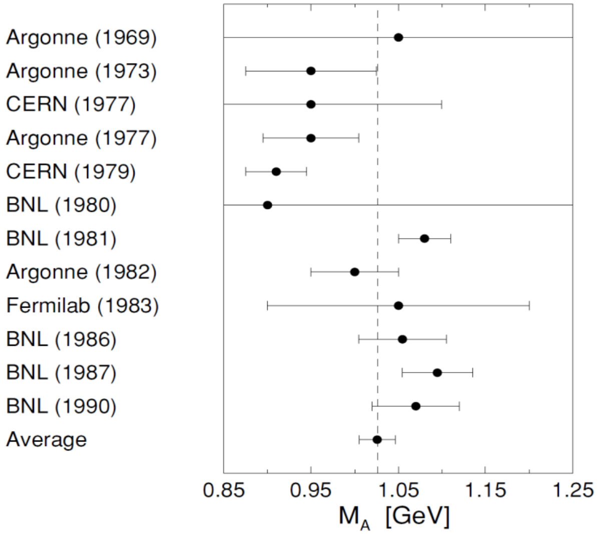
Axial

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

$g_A = 1.26$ from neutron β decay

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





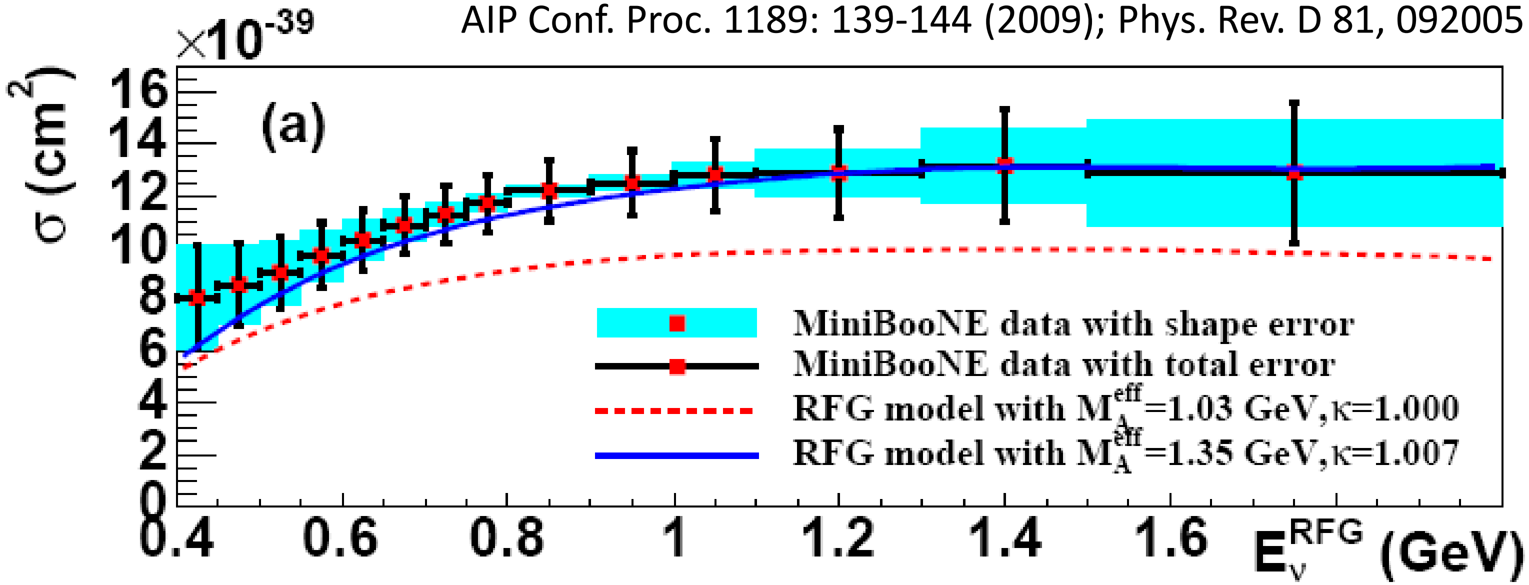
from ν-deuterium CCQE
and
from π electroproduction

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

Quasielastic

MiniBooNE CC Quasielastic neutrino cross section on Carbon

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

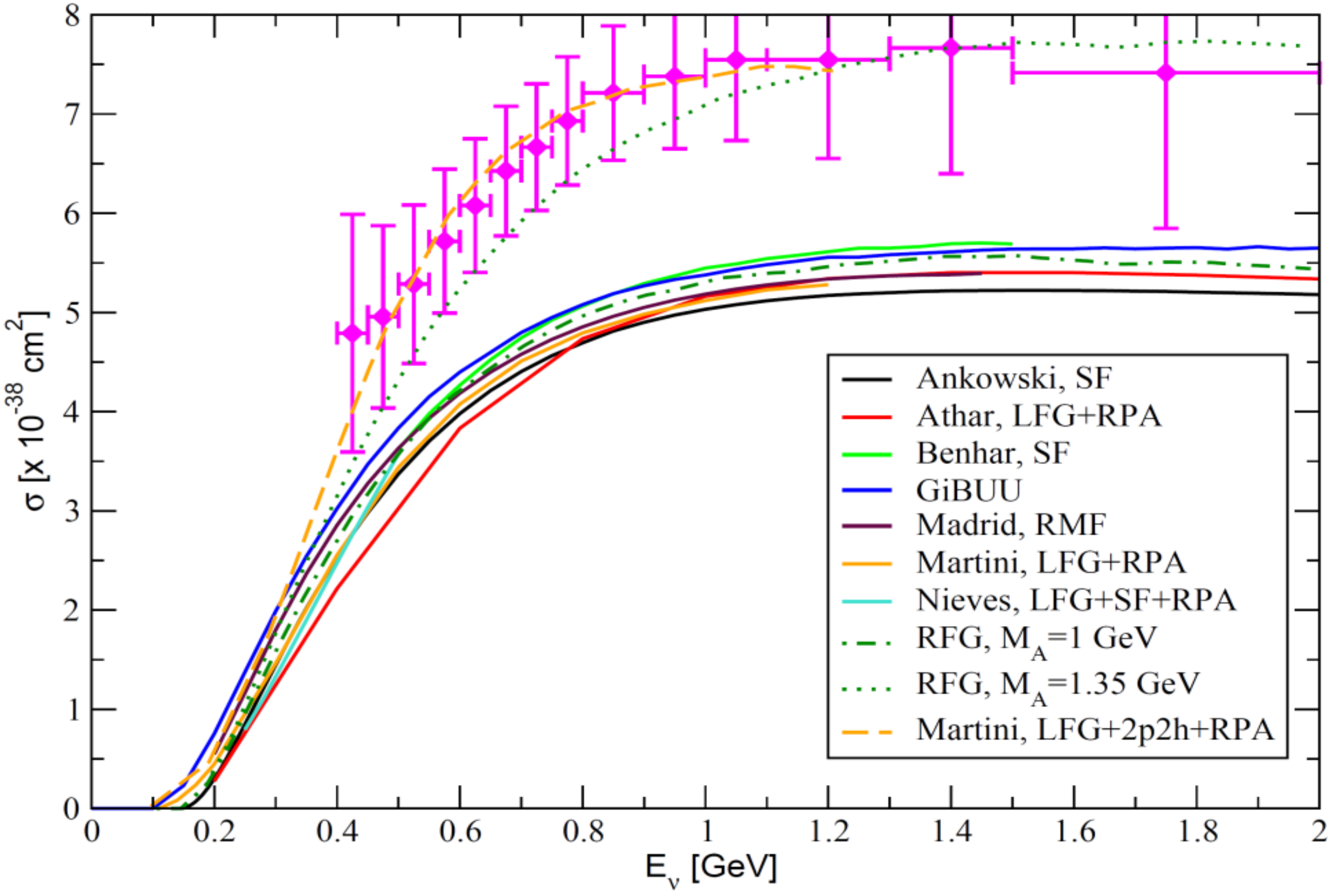
In the Relativistic Fermi Gas (RFG) model an axial mass of 1.35 GeV is needed to account for data

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

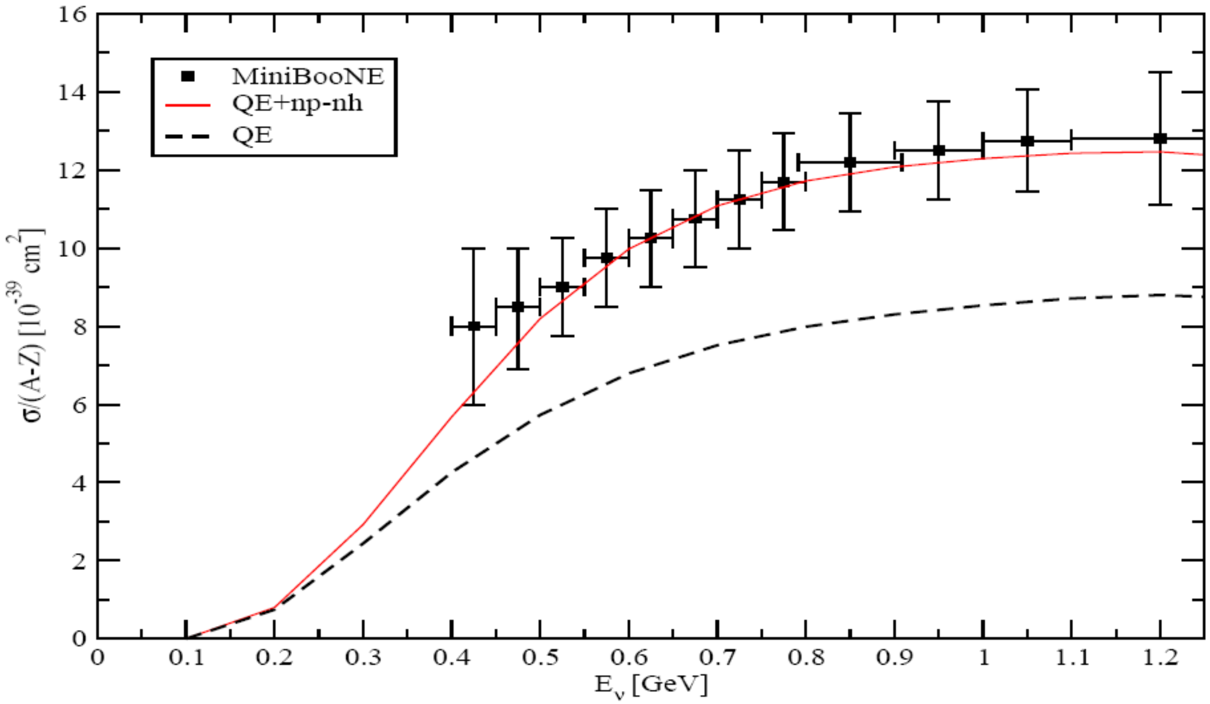
GiBUU: Transport Equation

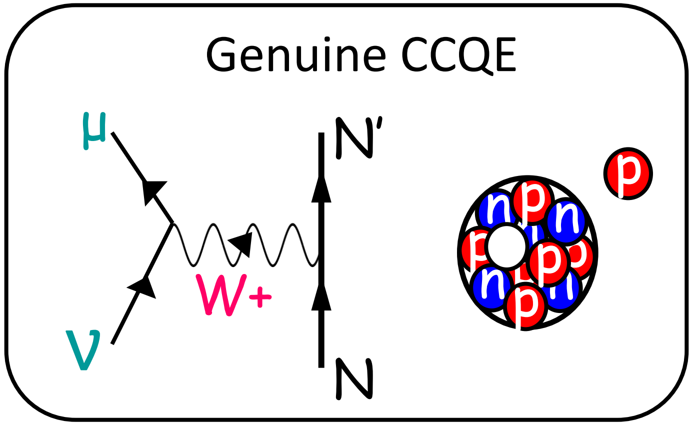
Comparison of models and Monte Carlo:
Boyd, Dytman, Hernandez, Sobczyk, Tacik ,
AIP Conf.Proc. 1189 (2009) 60-73

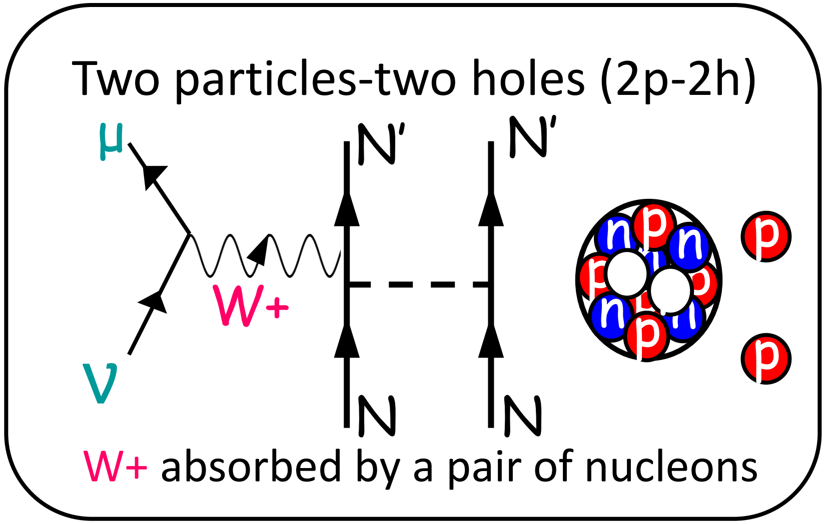
puzzle??

An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)





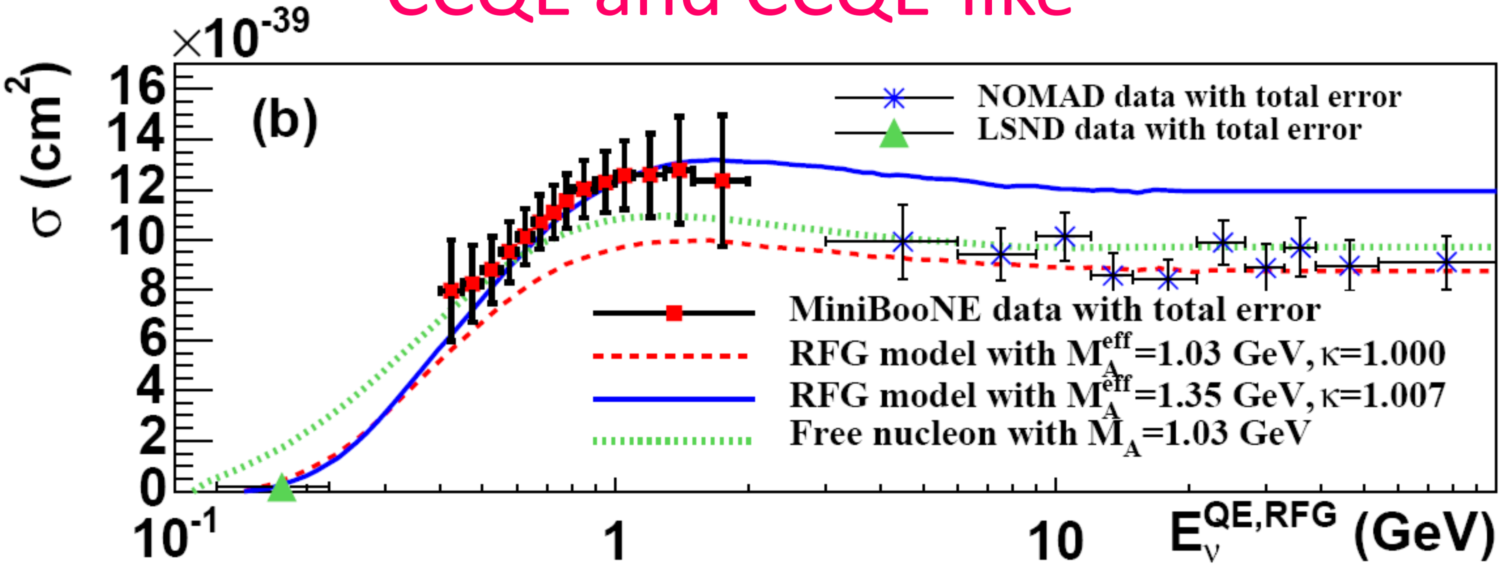


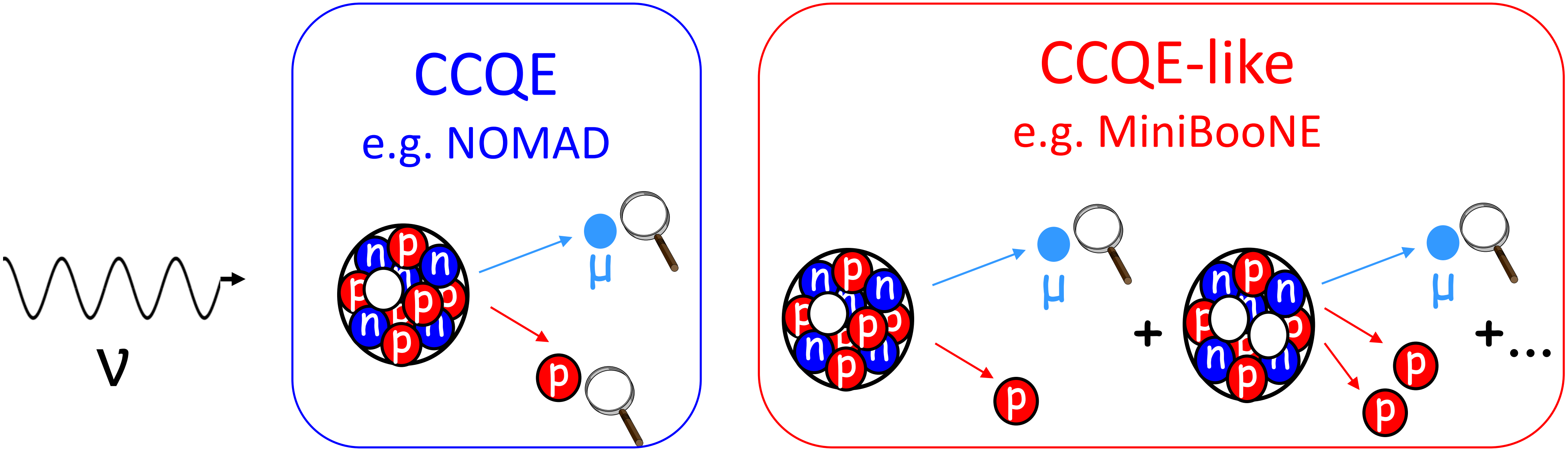
W+ absorbed by a pair of nucleons

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

Agreement with MiniBooNE without increasing M_A

CCQE and CCQE-like





CCQE

e.g. NOMAD

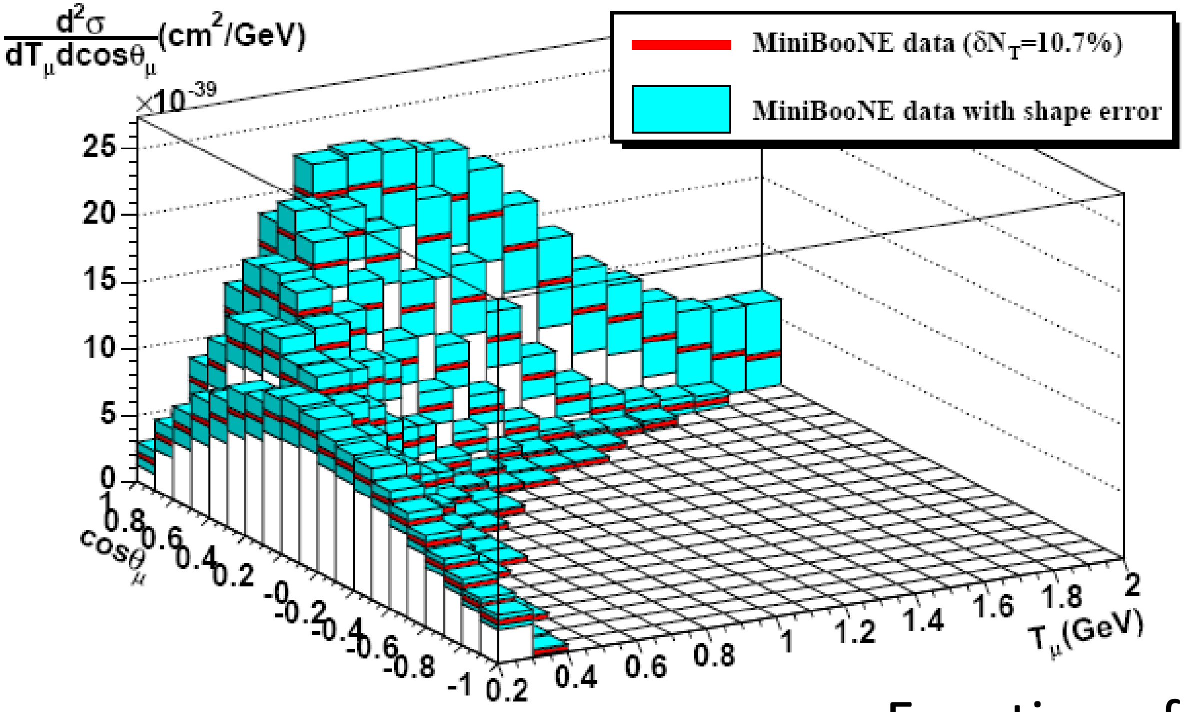
CCQE-like

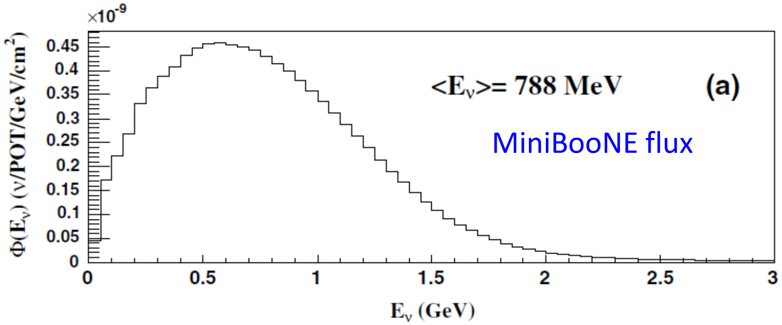
e.g. MiniBooNE

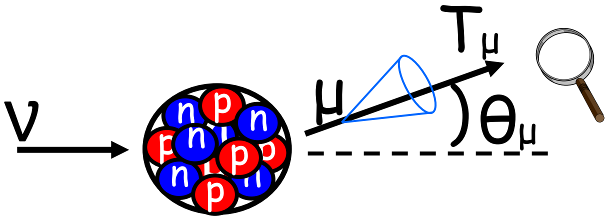
Cherenkov detectors measure CCQE-like which includes np-nh contributions

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

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



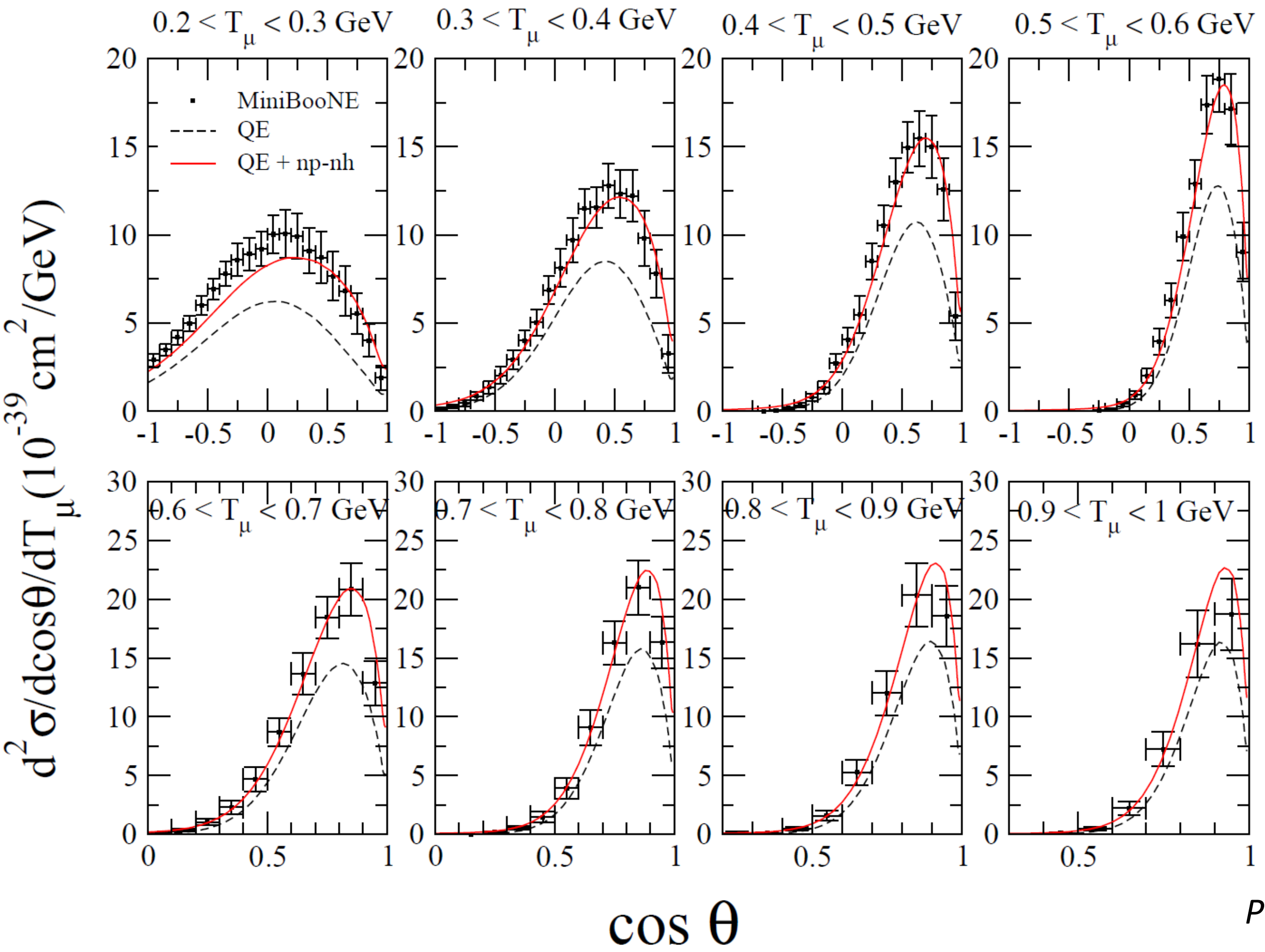




Function of two measured variables

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)*

Theoretical studies on np-nh excitations in CCQE-like

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

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

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

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

J.E. Amaro, M.B. Barbaro, J.A. Caballero, T.W. Donnelly , J.M. Udias, C. F. Williamson (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

Effective models taking into account np-nh excitations

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

Phys. Rev. C 86 014614 (2012) ν σtotal, $d^2\sigma$, $d\sigma/dQ^2$
Phys. Rev. C 86 054606 (2012) impact of np-nh on ν energy reconstruction and ν oscillation

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

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

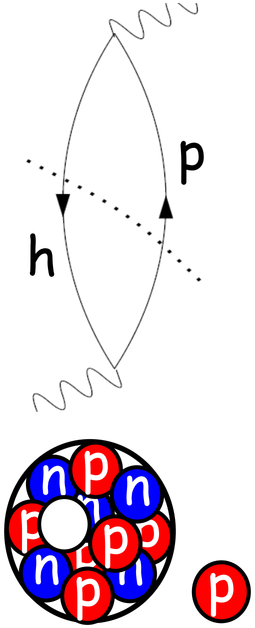
In the neutrino interaction generators corresponding to experimental studies on ν cross sections and oscillations published up to now the np-nh channel was not included

Today there is an effort to include this np-nh channel in several Monte Carlo

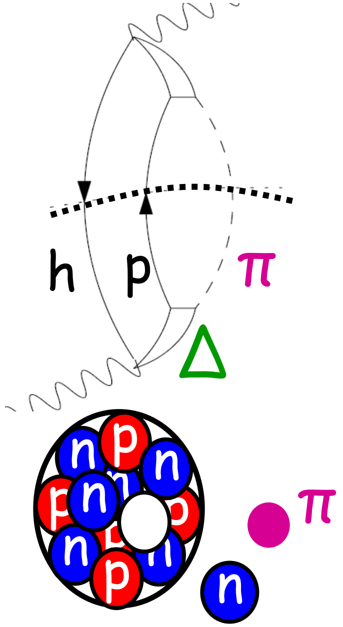
Some theoretical details

Nuclear Response Functions

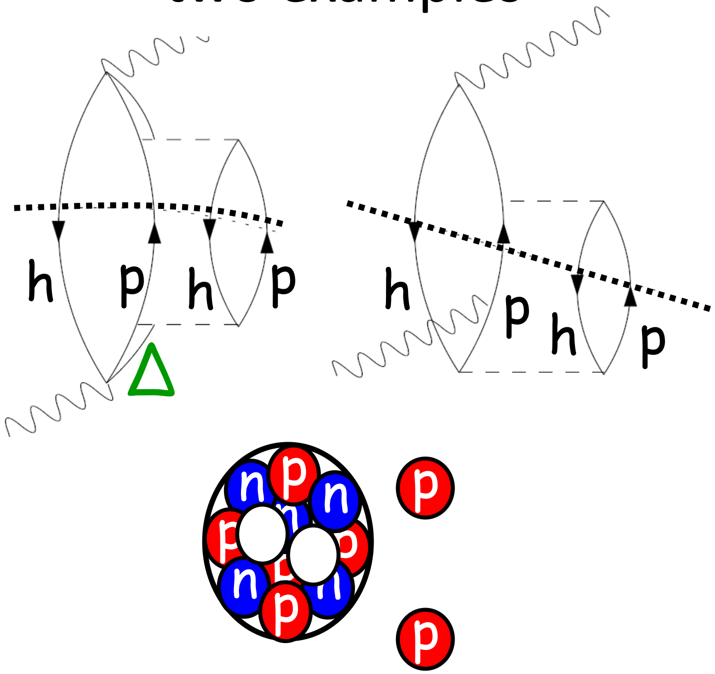
1p-1h
QE



1p-1h
1π production



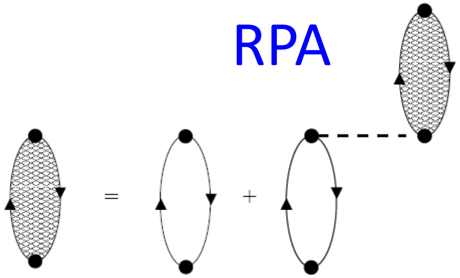
2p-2h:
two examples



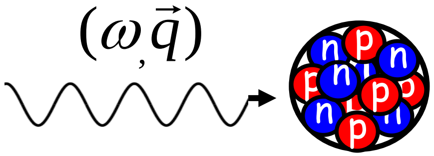
Nuclear response in Random Phase Approximation

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

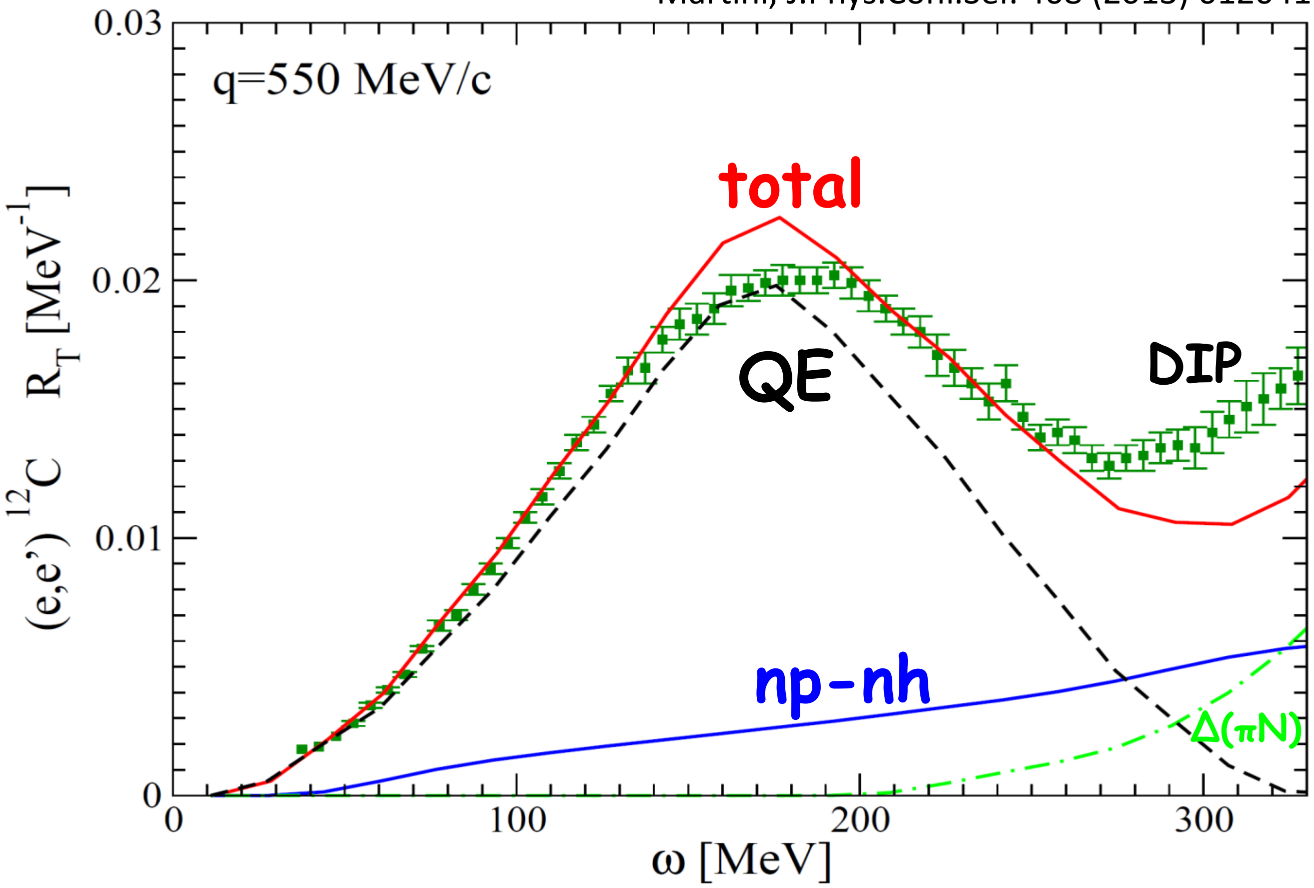
RPA



An example of nuclear response : transverse response in electron scattering



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



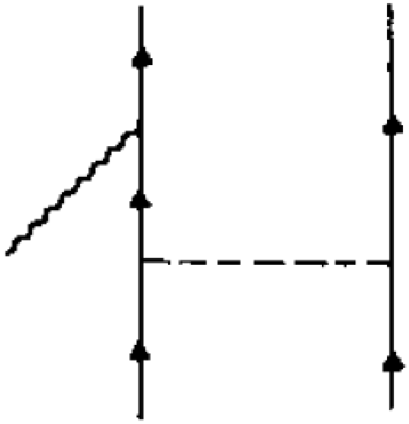
np-nh creates a high energy tail in the nuclear response above the QE peak

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

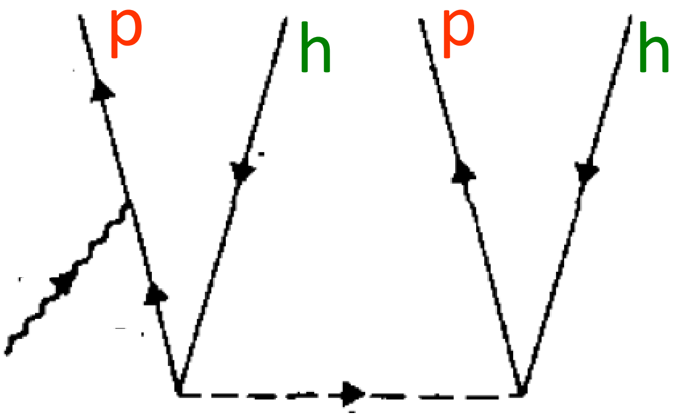
Two particle-two hole sector (2p-2h)

Three equivalent representations of the same process

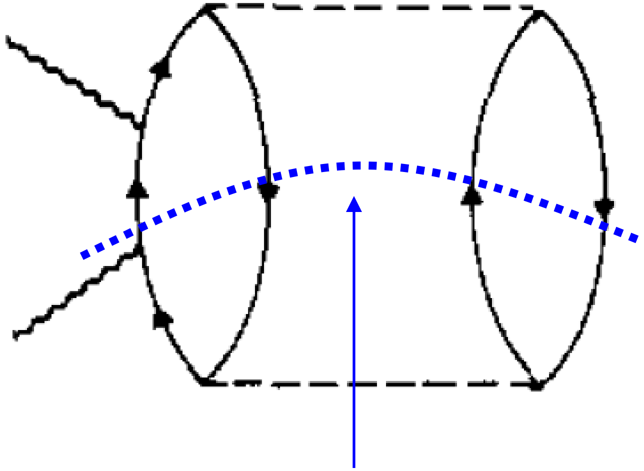
2 body current



2p-2h matrix element



2p-2h response

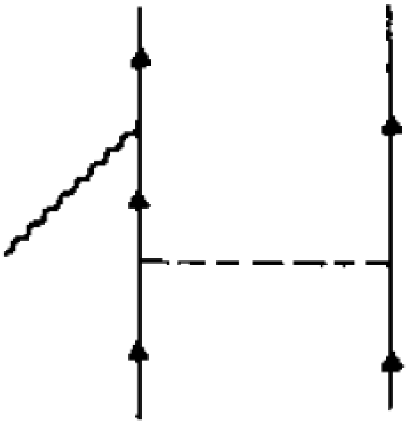


Cut
(optical theorem)

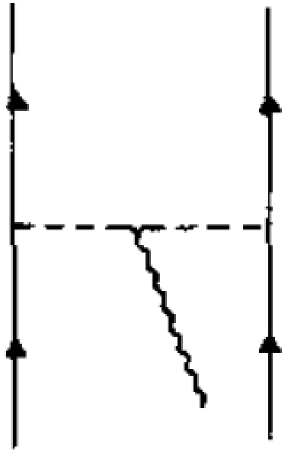
Final state: two particles-two holes

Some diagrams for 2 body currents

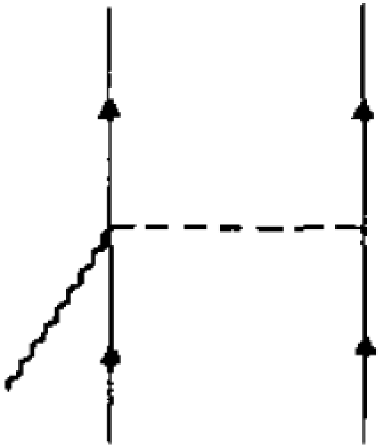
Nucleon-Nucleon correlations



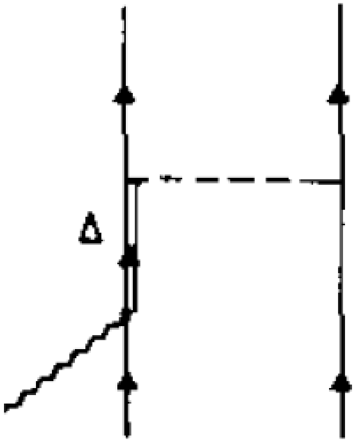
Meson Exchange Currents (MEC)



Pion in flight



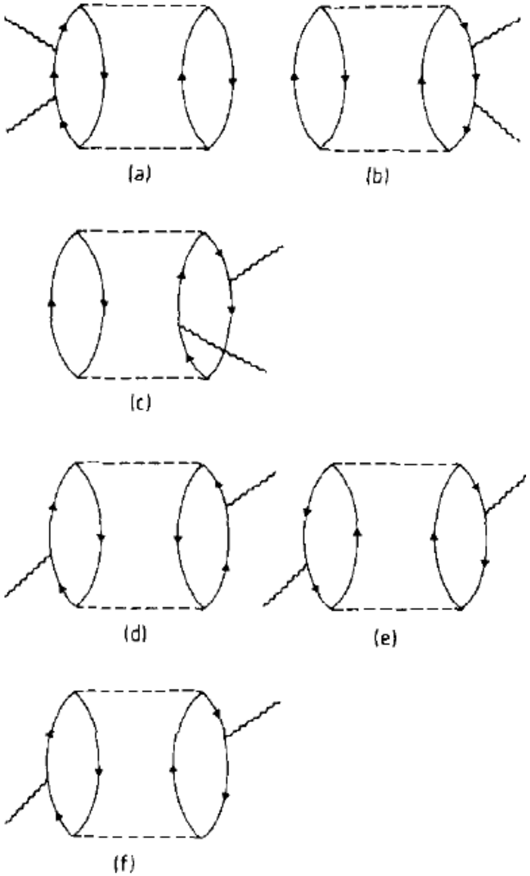
Contact



Delta

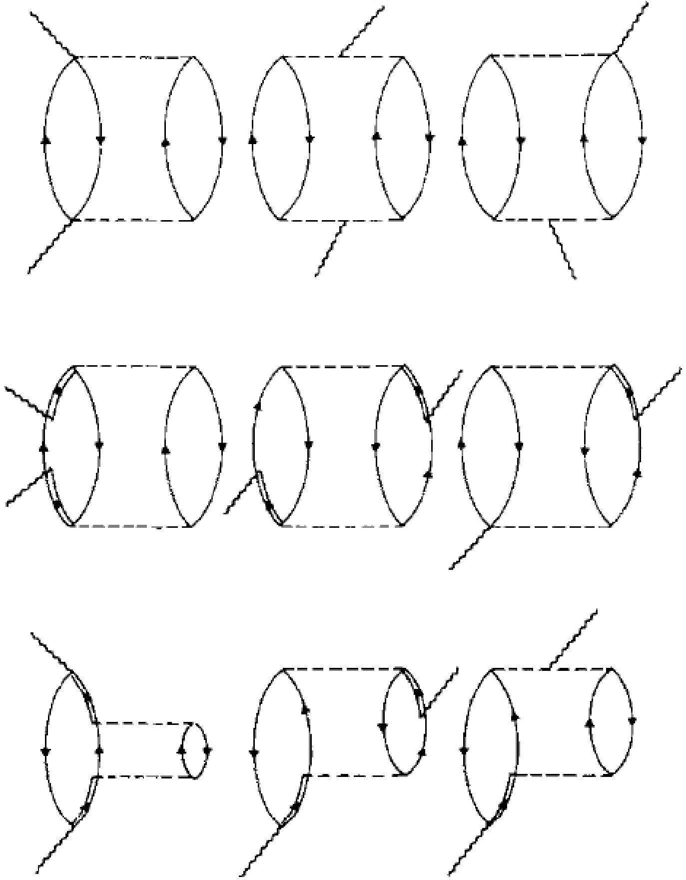
Some diagrams for 2p-2h responses

NN correlations



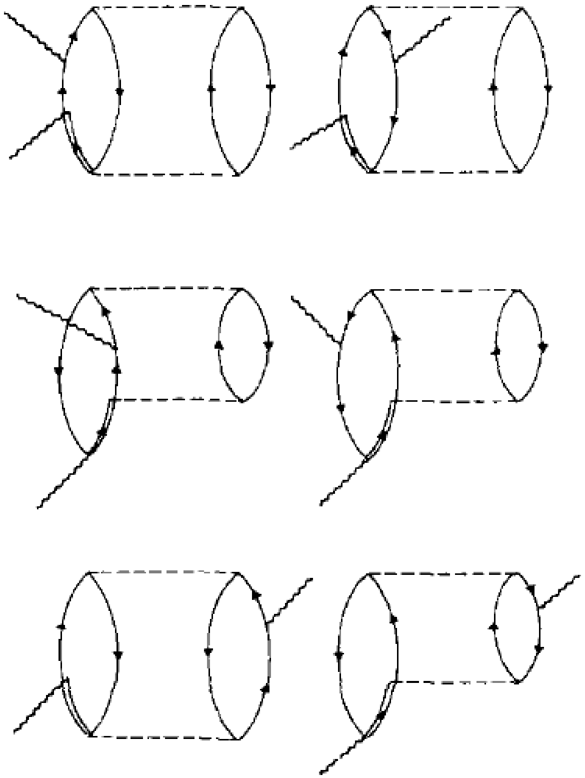
16 diagrams

MEC



49 diagrams

NN correlation-MEC interference



56 diagrams

Neutrino *vs* Antineutrino

Neutrino *vs* Antineutrino-nucleus cross-section

The asymmetry between neutrinos and antineutrinos interactions is important for the investigation of CP violation effects.

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

charge nuclear response

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

isospin spin-longitudinal

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

$$\left\{\begin{matrix} + & (\nu) \\ - & (\bar{\nu}) \end{matrix}\right.\;\boxed{\pm}\;2\,G_A\,G_M\,\frac{k+k'}{M_N}\,\tan^2\frac{\theta}{2}\,\boxed{R_{\sigma\tau(T)}}\;\Big]$$

isospin spin-transverse

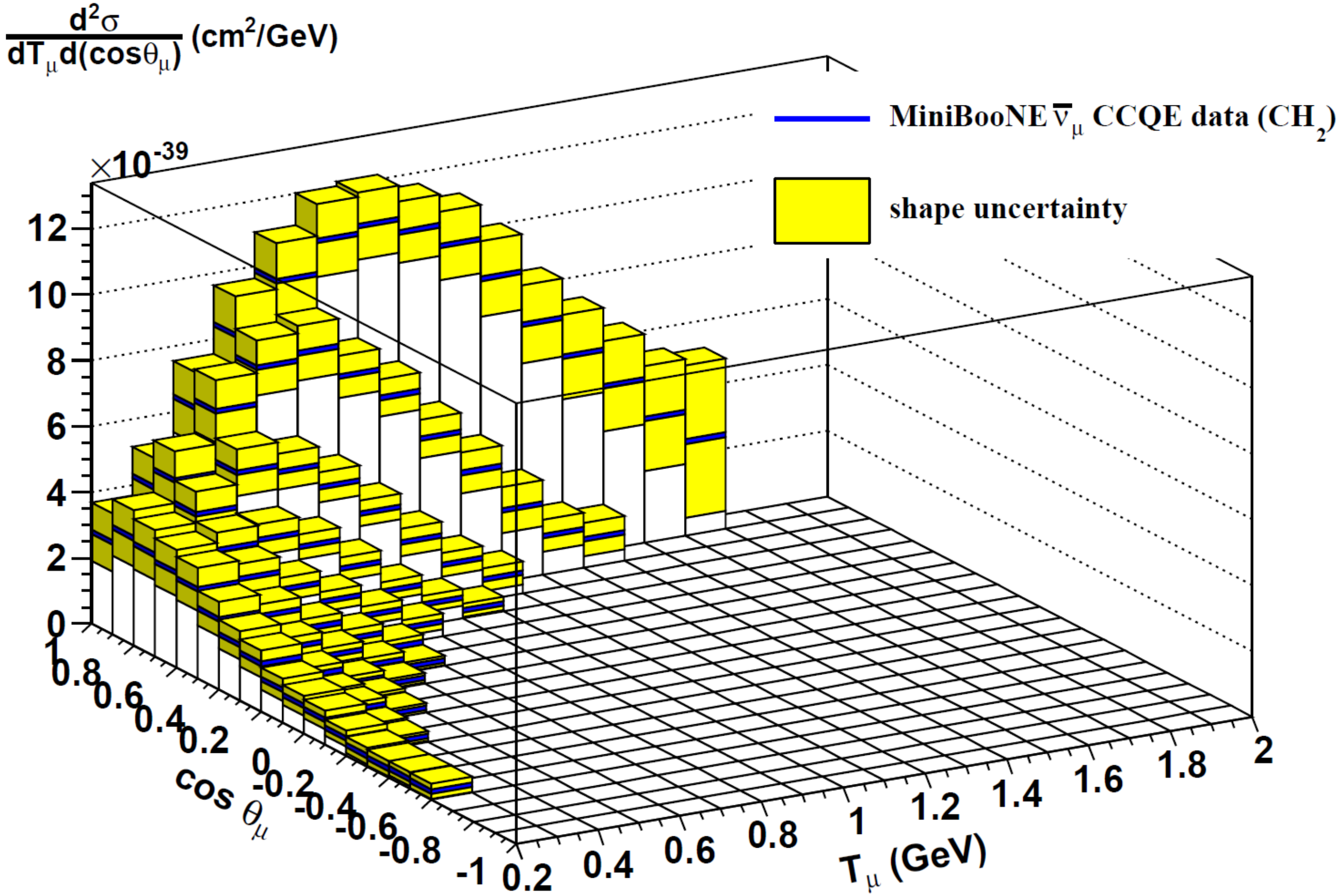
interference V-A

Nuclear effects generate an additional asymmetry due to the **interference term**

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

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

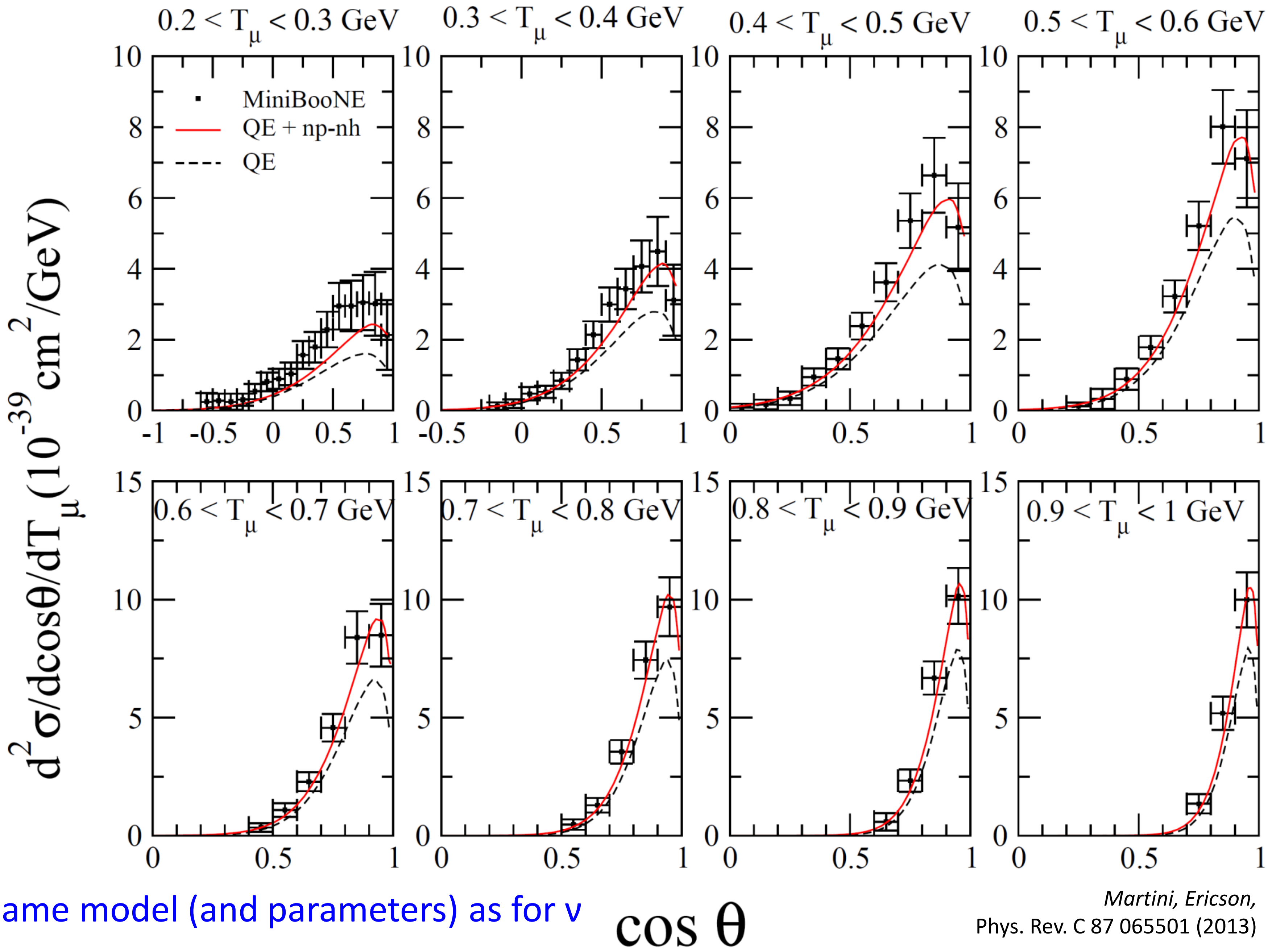
Recent Measurement



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

CH_2 and Carbon

Our results for $\overline{\nu}$



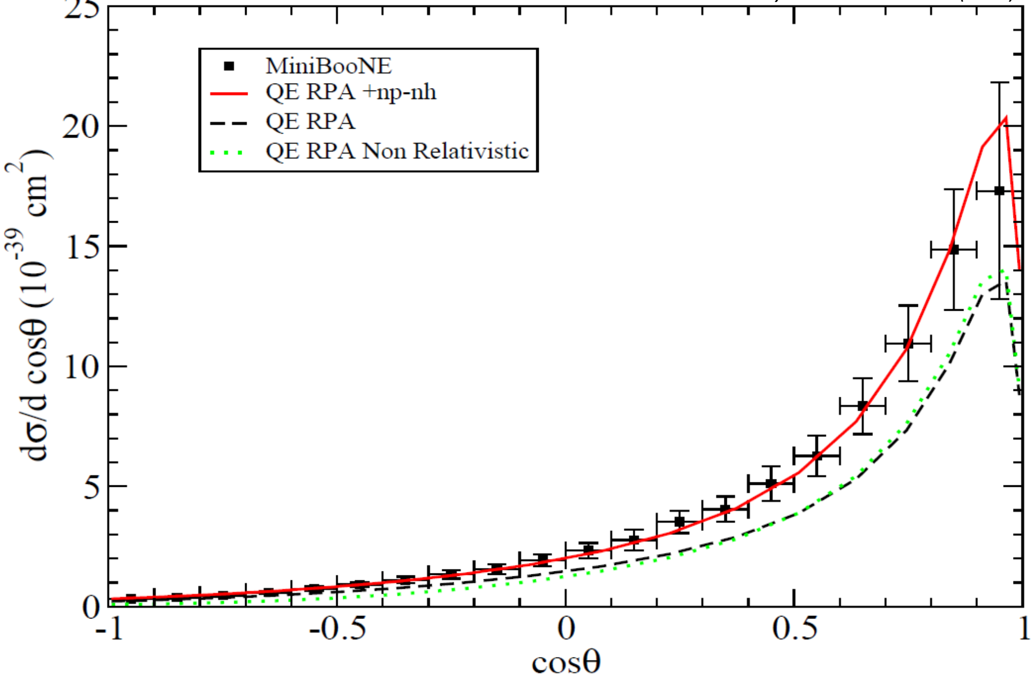
same model (and parameters) as for ν

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

dσ/dcosθ

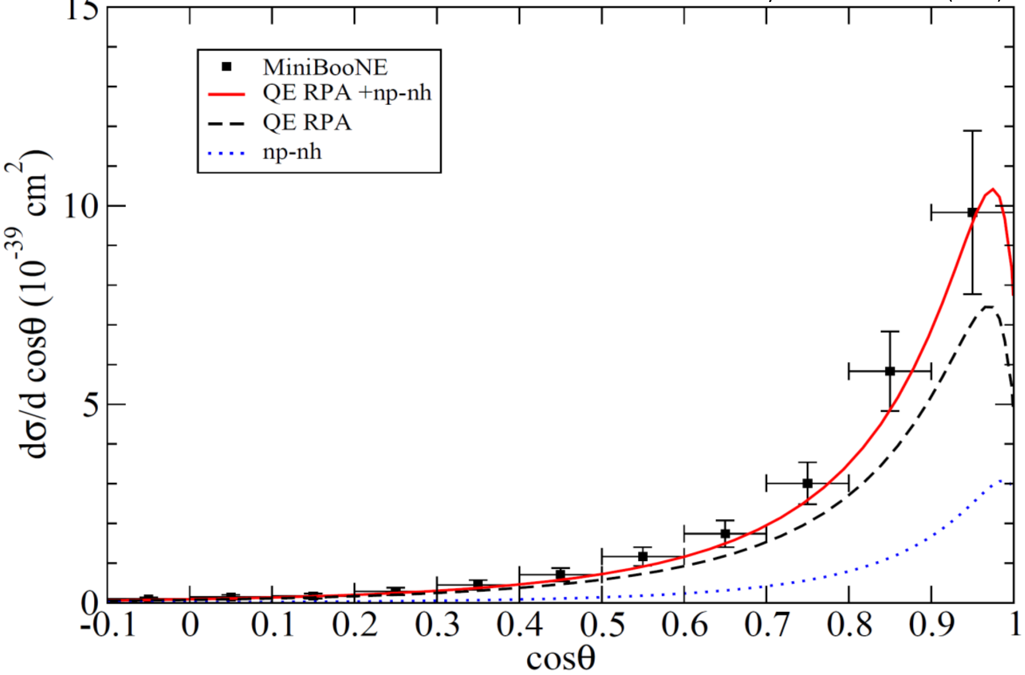
ν

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



$\bar{\nu}$

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

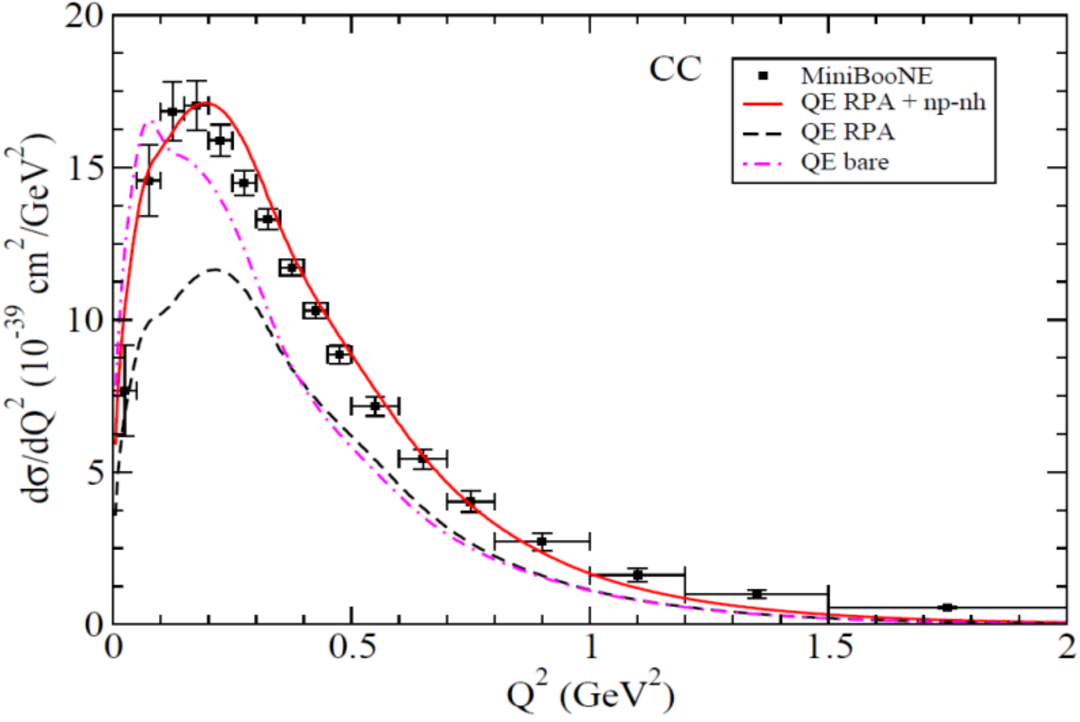


Antineutrino cross section falls more rapidly with angle than the neutrino one

CC Q^2 distribution

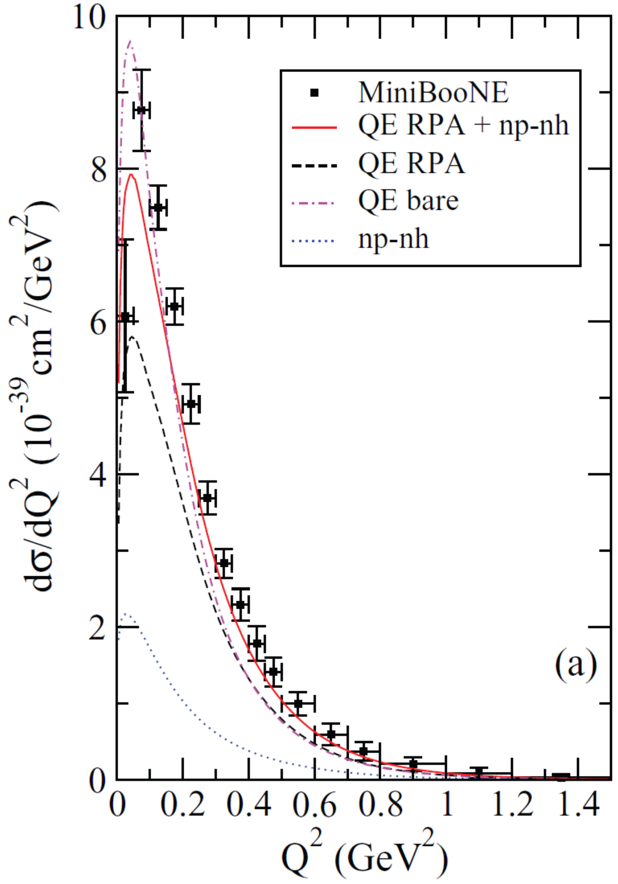
ν

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



$\bar{\nu}$

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



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

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

2p-2h contributions in the different approaches

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

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

Contribution to all terms in G_M and G_A (spin-isospin, $\sigma\,\tau$ excitation operator)

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

all the terms

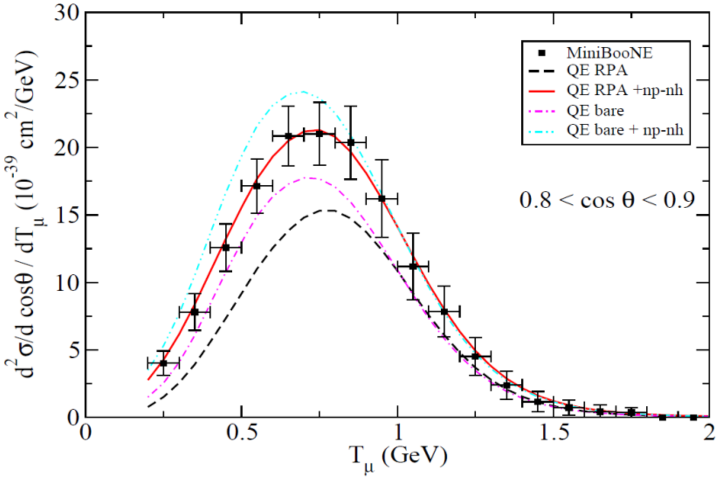
J.E. Amaro, M.B. Barbaro, J.A. Caballero, T.W. Donnelly et al.

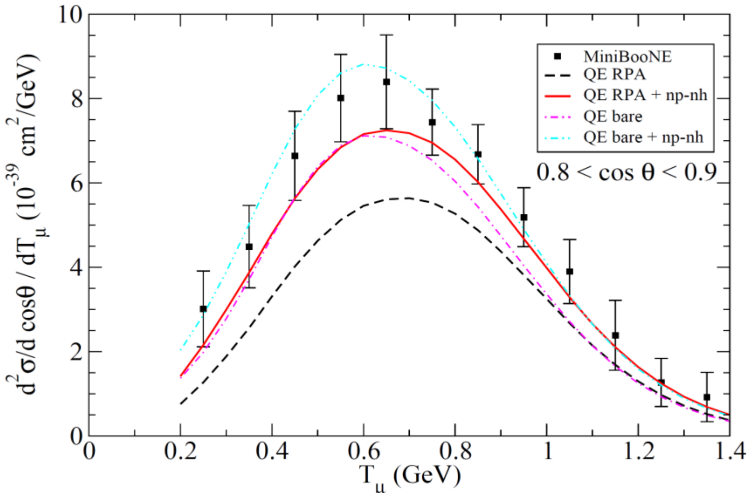
only in the G_M^2 term

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

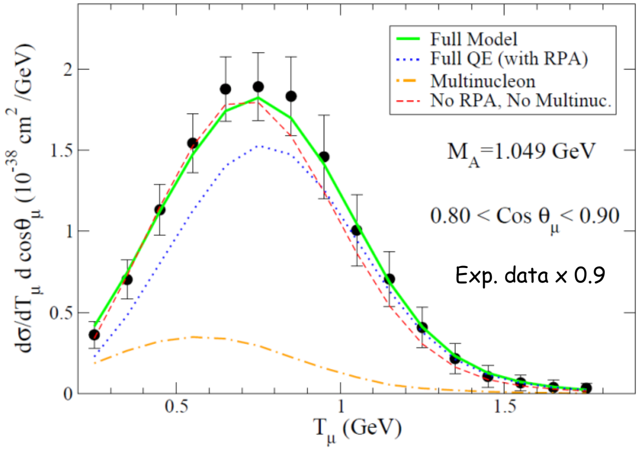
ν $\overline{\nu}$

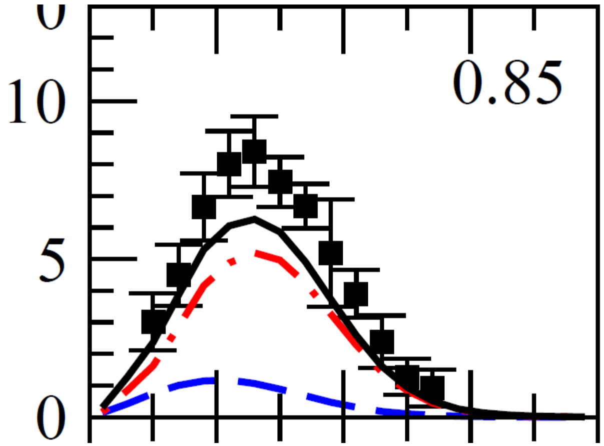
Martini et al.





Nieves et al.

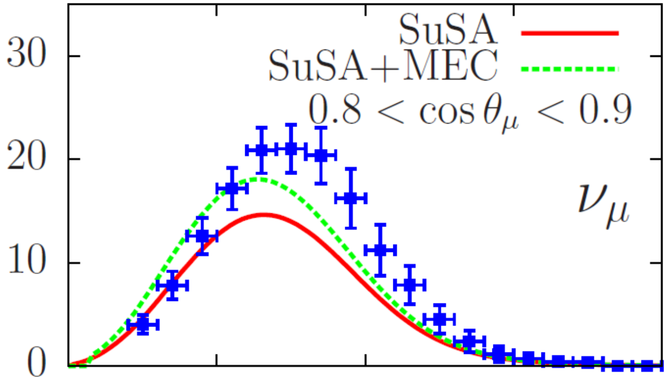


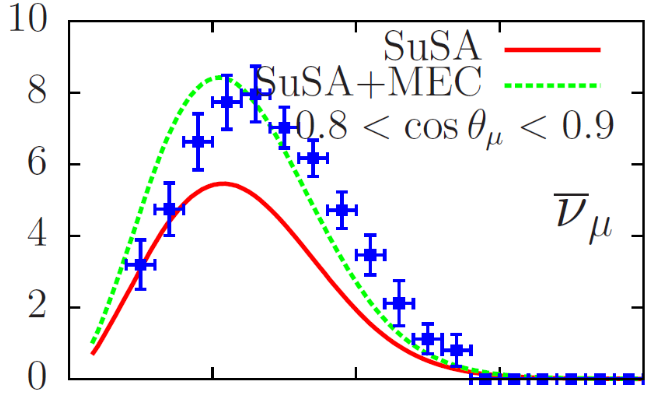


black: QE RPA+2p2h

red: QE RPA

Amaro et al.





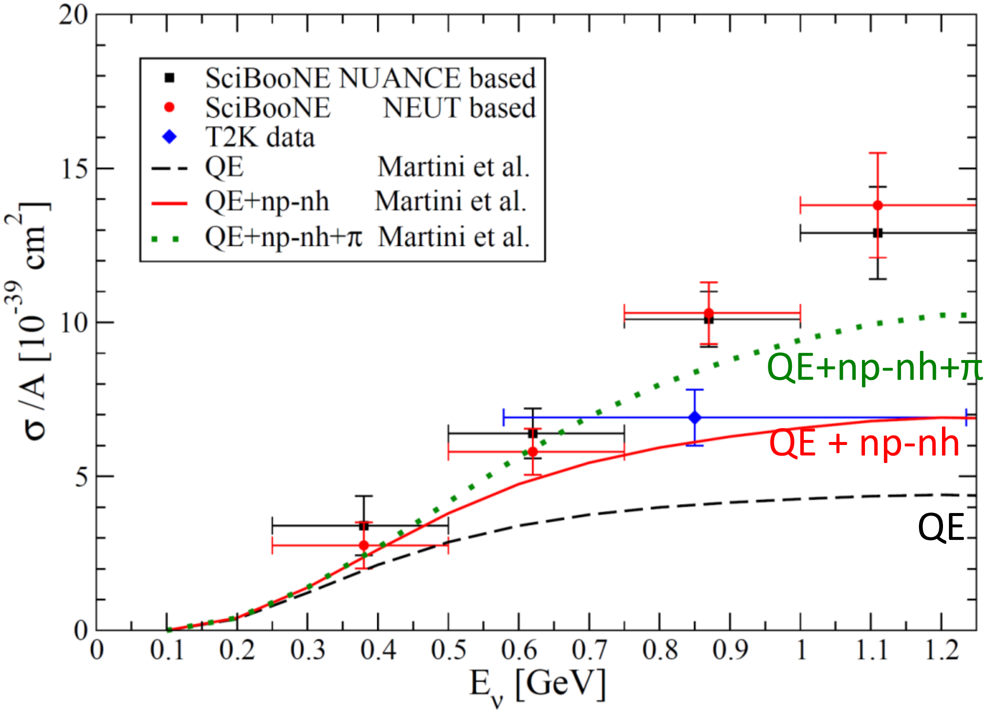
Beyond Quasielastic

Inclusive CC cross section on Carbon

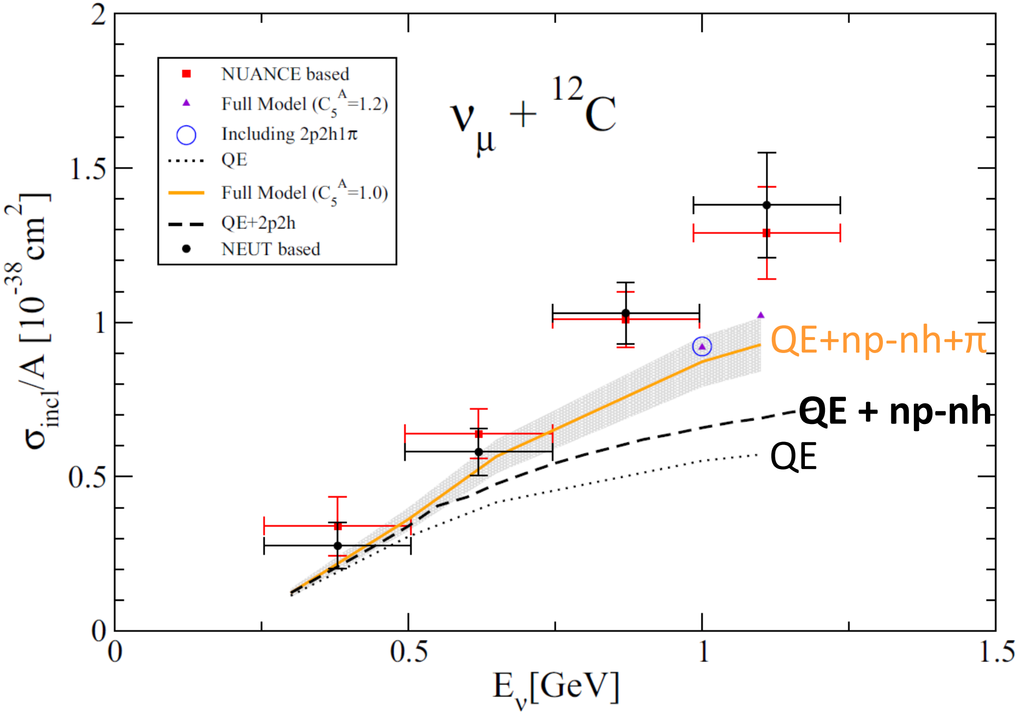
Less affected by background subtraction with respect to exclusive channels

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

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

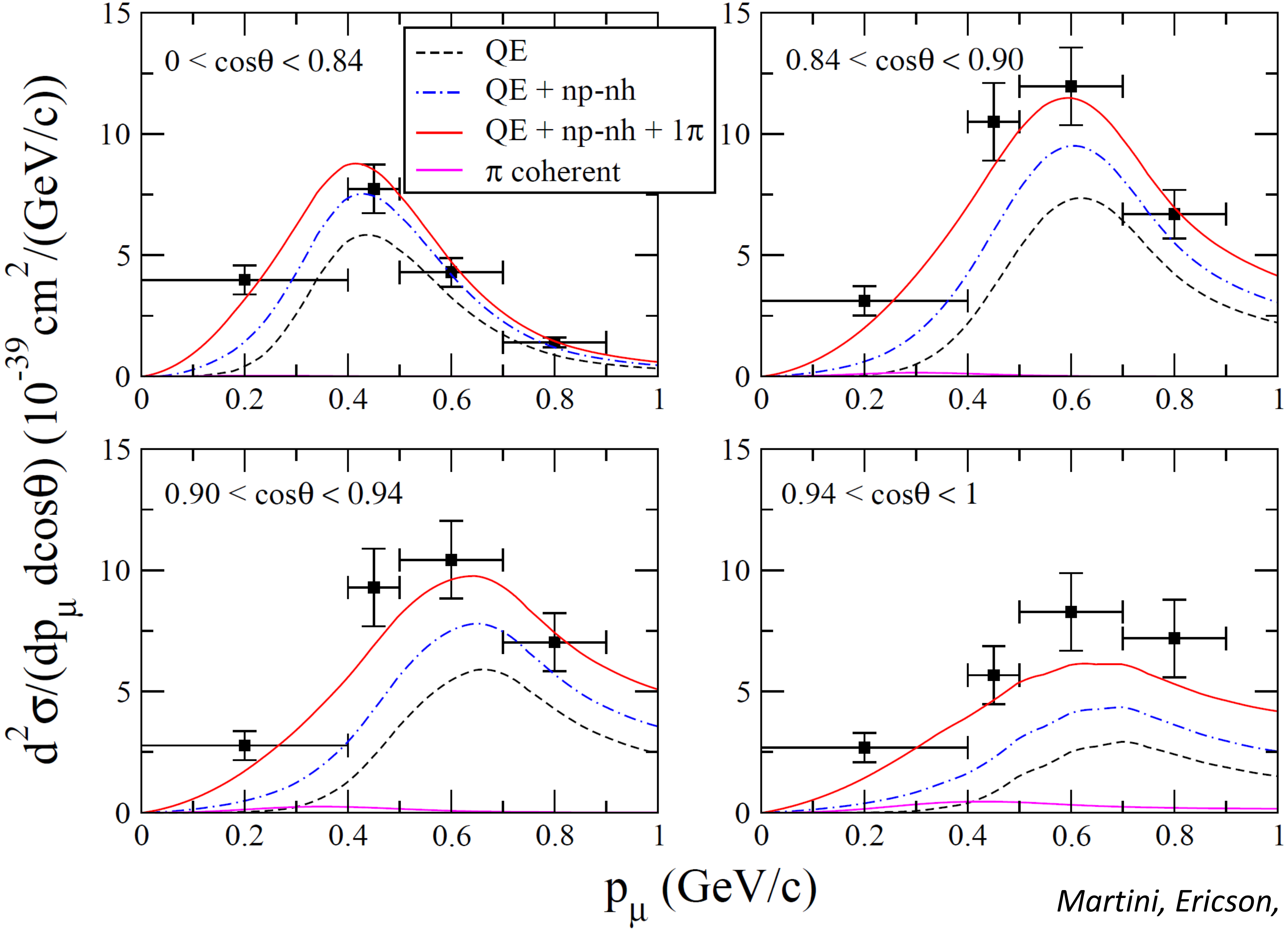


M. Martini, M. Ericson, G. Chanfray, J. Marteau
Phys. Rev. C 80 065501 (2009)



J. Nieves, I. Ruiz Simo, M.J. Vicente Vacas
Phys. Rev. C 83 045501 (2011)

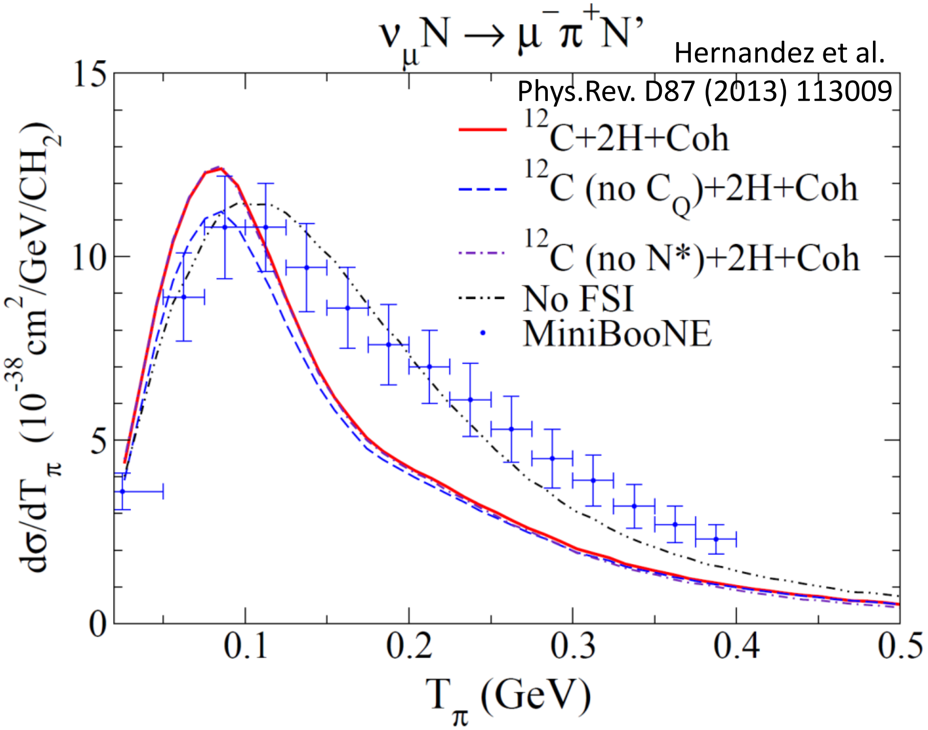
T2K Flux-integrated inclusive double differential cross section



Martini, Ericson,
to be submitted

1 Pion production controversy

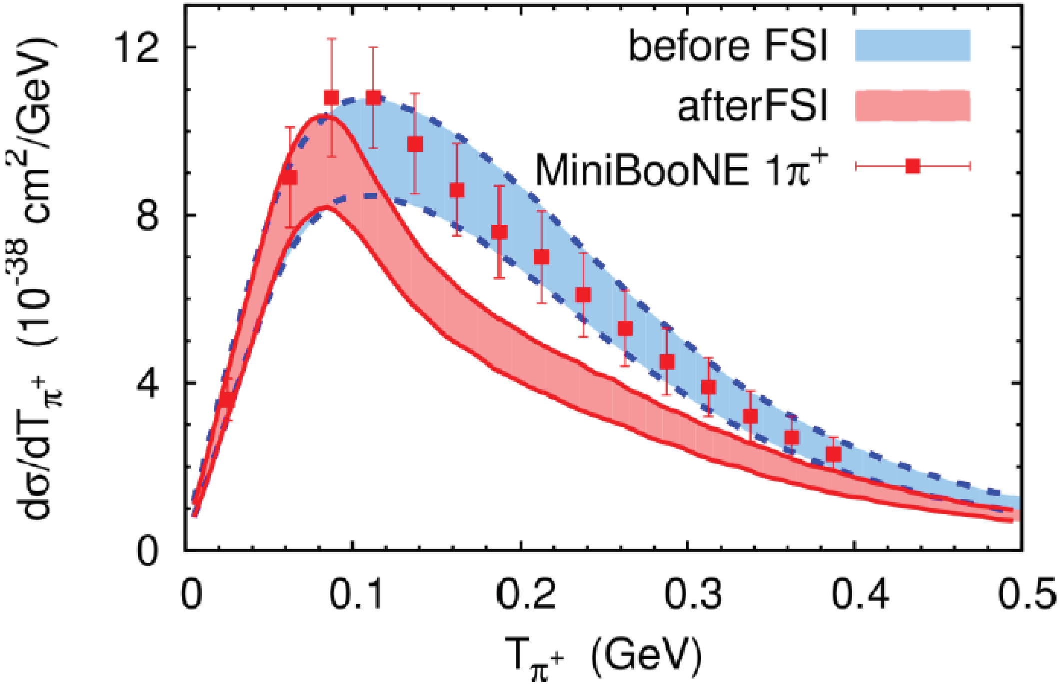
Best theories (with Δ medium effects and pion rescattering) do not agree with pion KE spectrum



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

Valencia

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

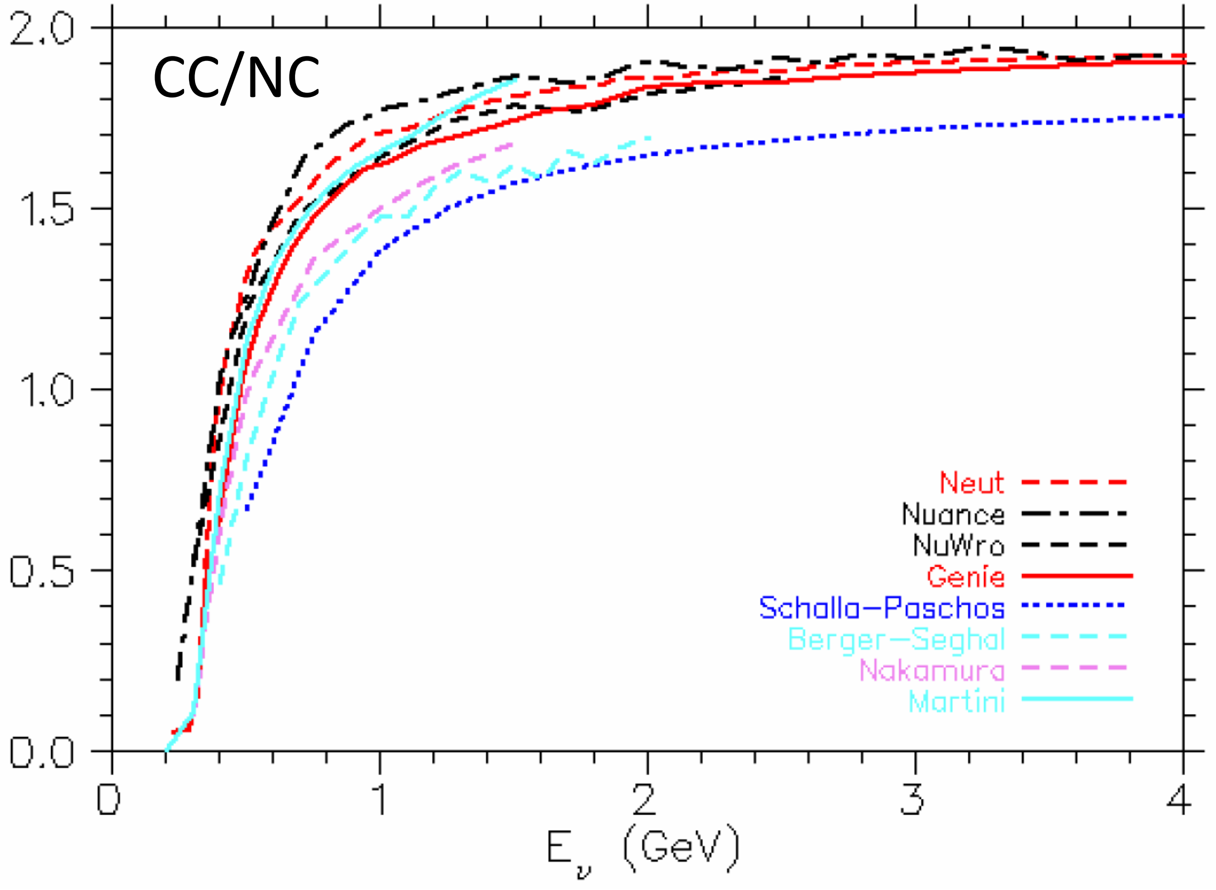


GiBUU

Data prefer calculations with no Final State Interaction for the pion

Coherent puzzle

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



SciBooNE:

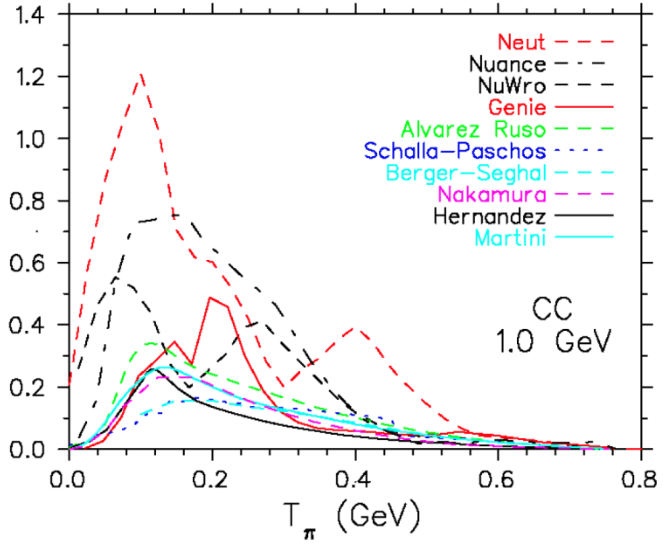
$$\frac{\pi\text{+ coh. CC}}{\pi 0\text{ coh. NC}} = 0.14^{+0.30}_{-0.28}$$

Kurimoto et al, PRD 81 (2010)

Theoretical models:

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

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

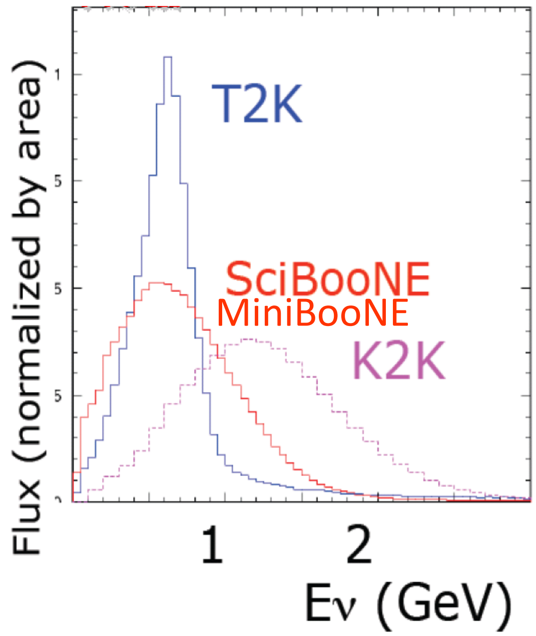


Discrepancy between Monte Carlo and microscopic models

Neutrino energy reconstruction problems and neutrino oscillations

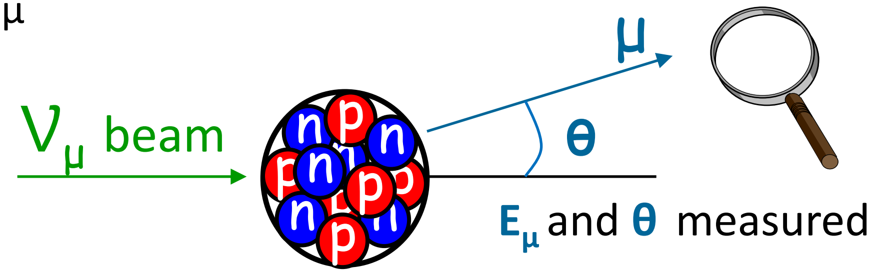
Towards the neutrino oscillation physics

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.



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

e.g. for μ



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

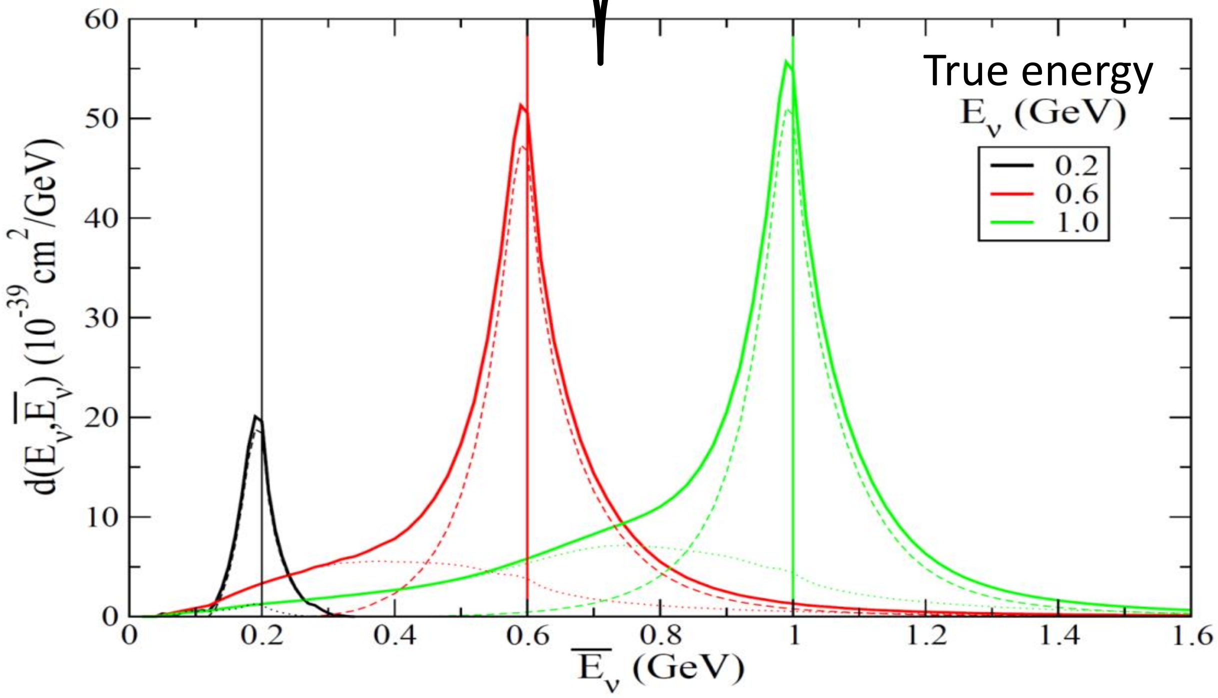
$\overline{E_\nu} = E_\nu$ is exact only for CCQE with free nucleon

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

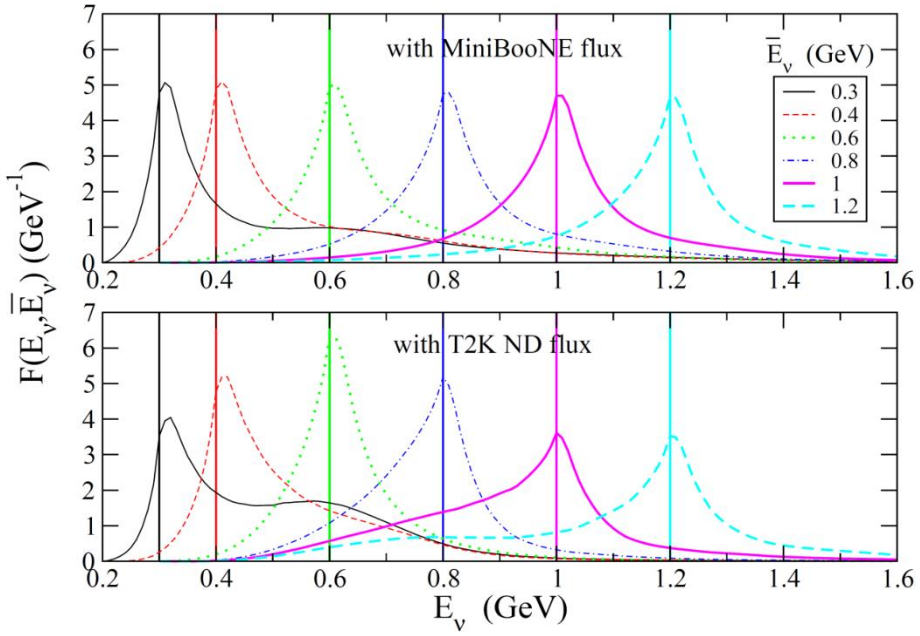


Crucial role of np-nh: low energy tail

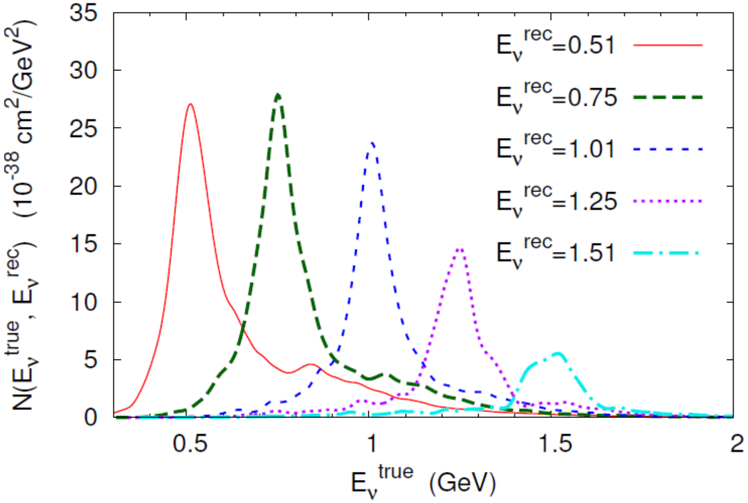
M. Martini, M. Ericson, G. Chanfray
- Phys. Rev. D 85 093012 (2012)
- Phys. Rev. D 87 013009 (2013)

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

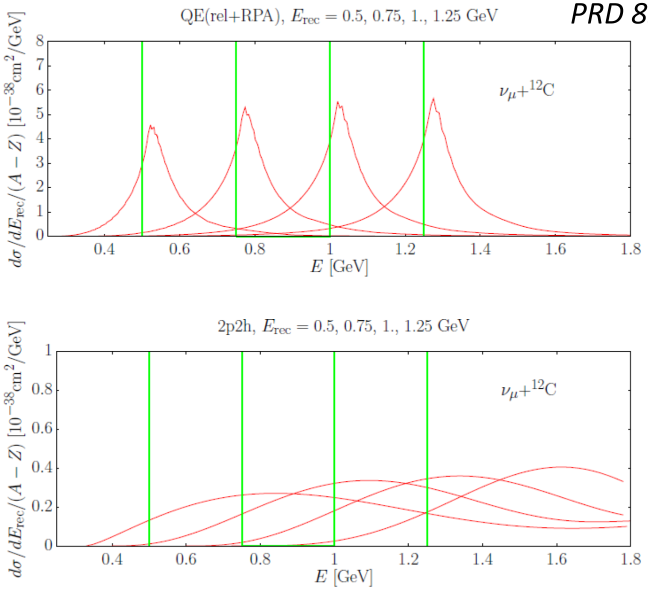
Martini, Ericson, Chanfray, PRD 85 093012 (2012)



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



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



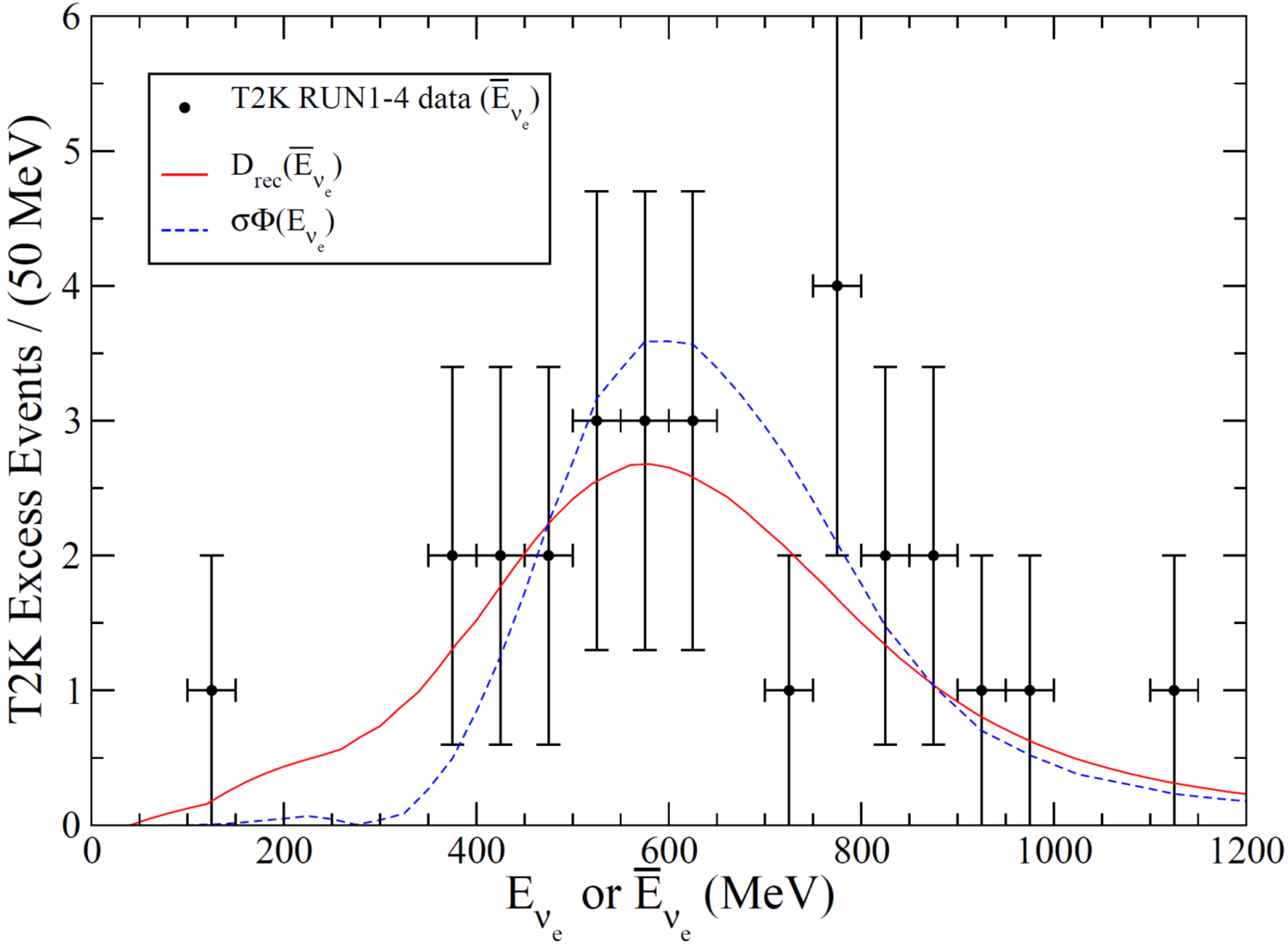
- The distributions are not symmetrical around Ēν.
- The asymmetry favors higher energies at low Ēν and smaller energies for large Ēν.
- Crucial role of neutrino flux.

Application to ν oscillation analysis

$\nu_\mu \rightarrow \nu_e$ T2K

PRL 107 (2011), PRD 88 (2013), 1311.4750 (2013)

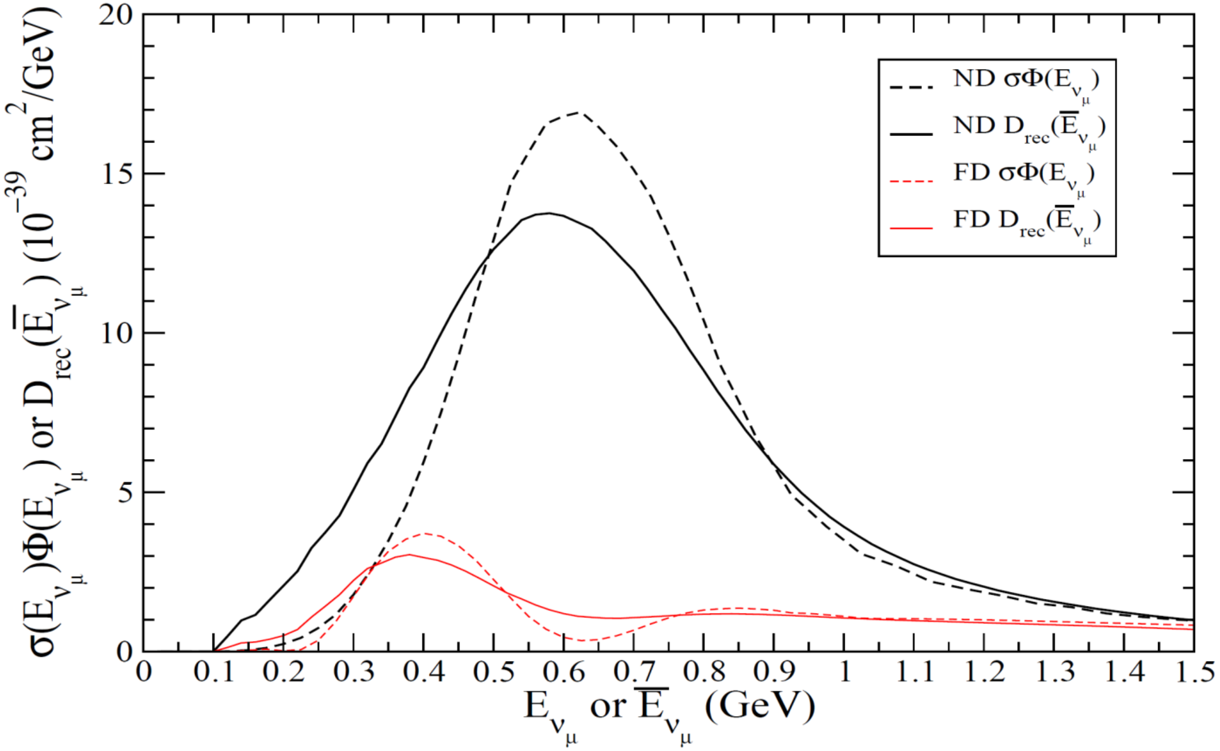
2013: 28 events



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

ν_μ disappearance T2K

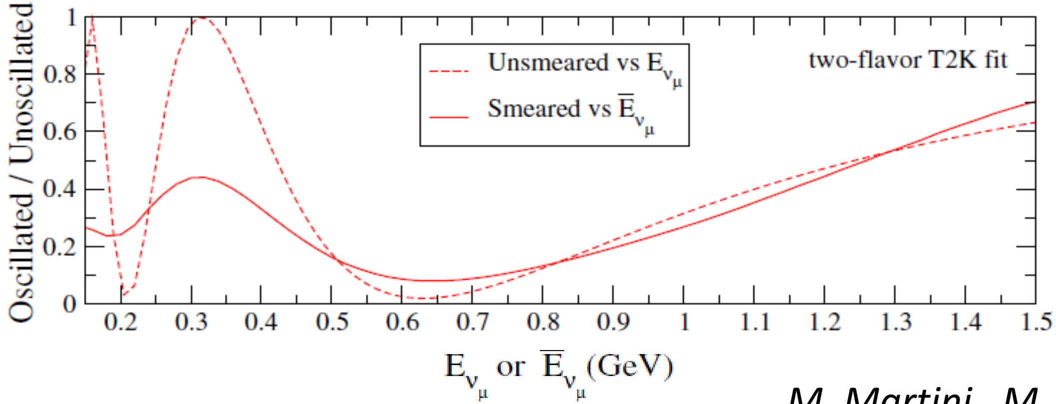
PRD85 (2012); 1308.0465 (2013)

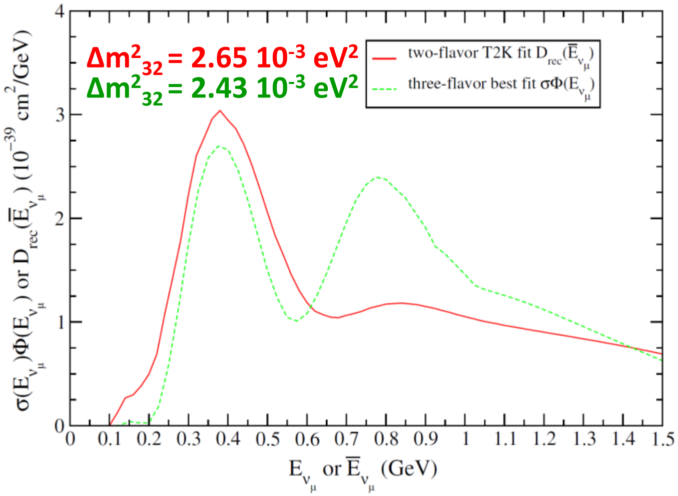


After reconstruction:

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

Effects largely due to np-nh



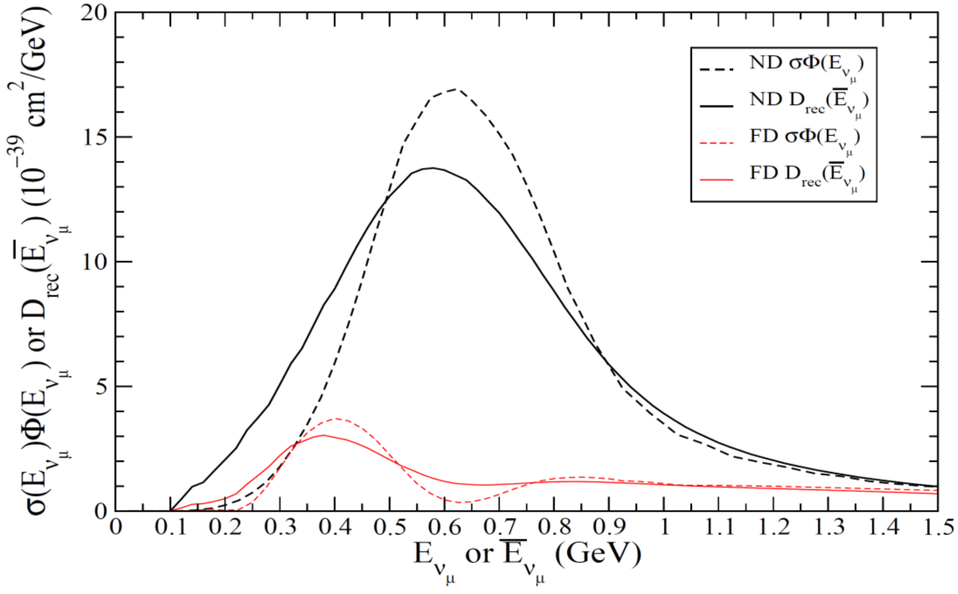


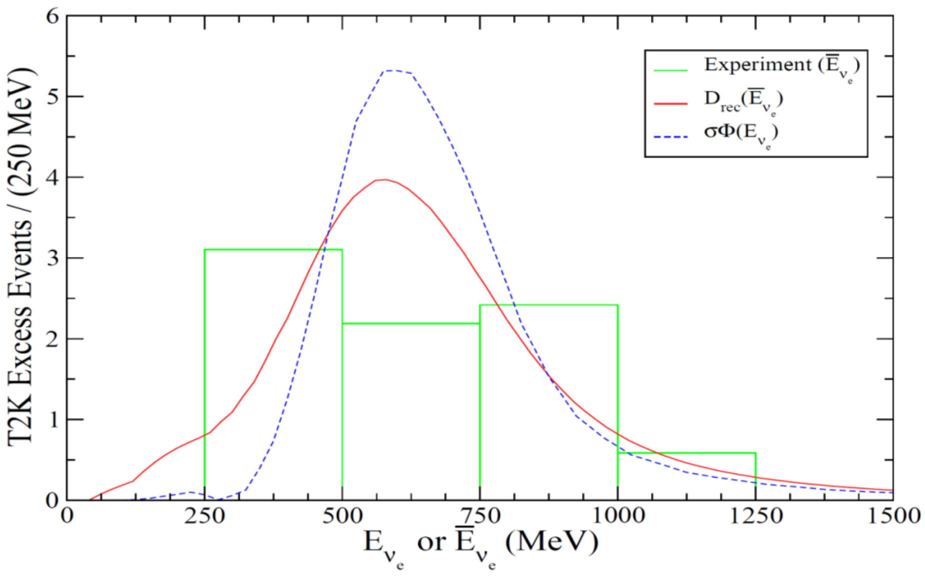
E_ν reconstruction leads to an increase of oscillation mass parameters

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

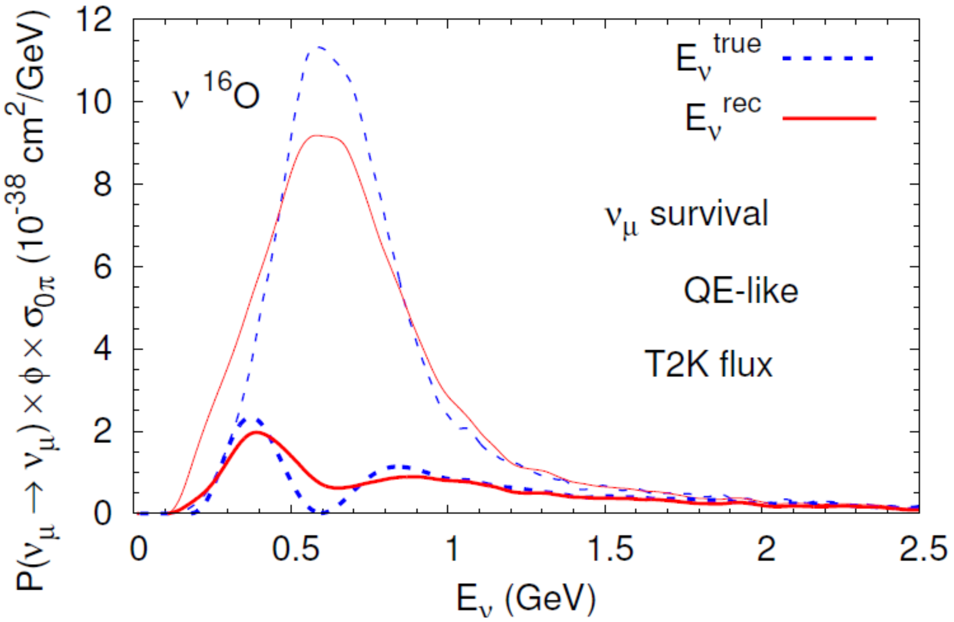
Similar results in: O. Lalakulich, U. Mosel, K. Gallmeister, PRC 86 054606 (2012)

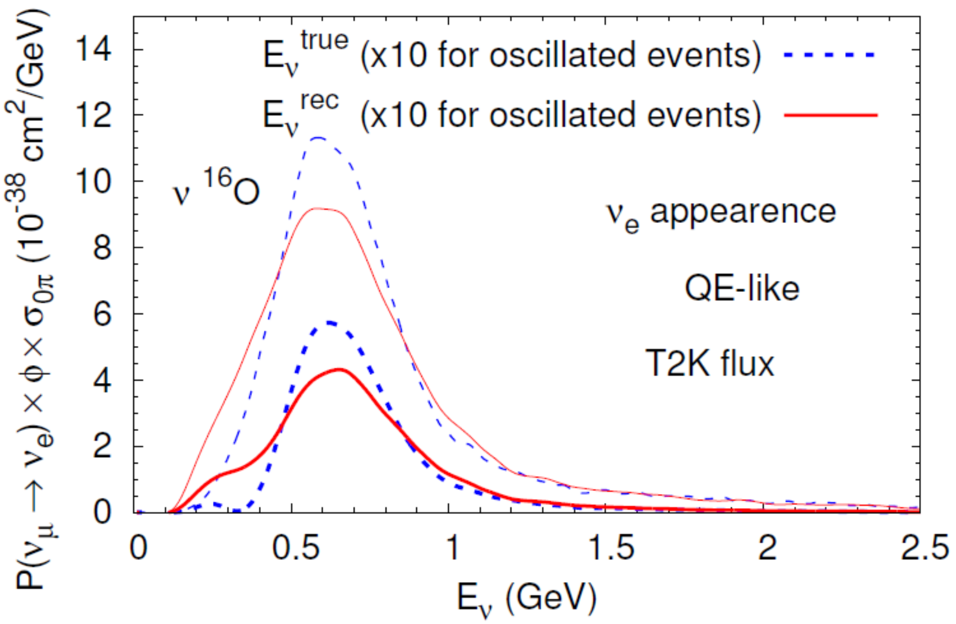
M. Martini, M. Ericson, G. Chanfray, PRD 87 013009 (2013)





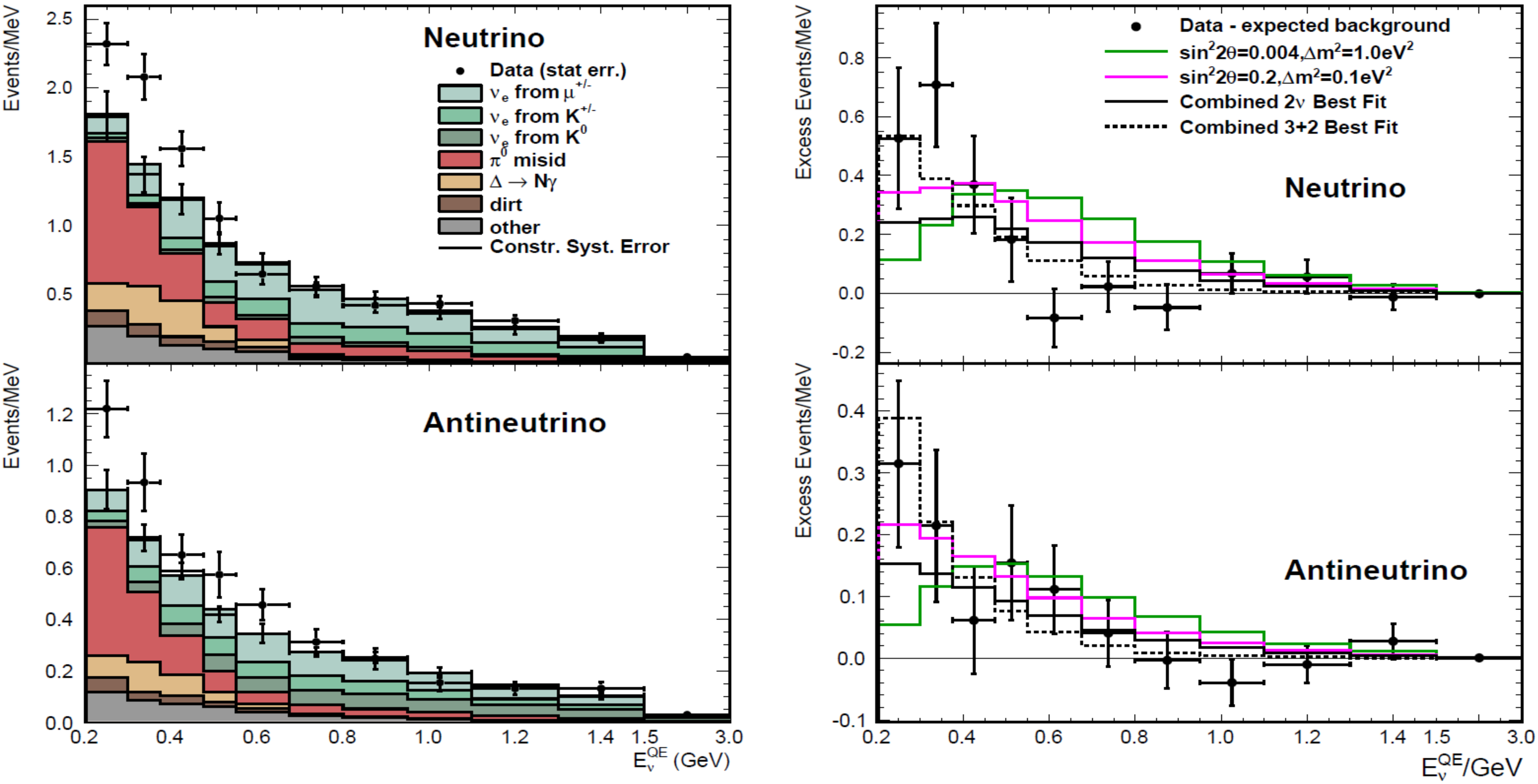
O. Lalakulich, U. Mosel, K. Gallmeister, PRC 86 054606 (2012)





$\nu_\mu \longrightarrow \nu_e$ MiniBooNE

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

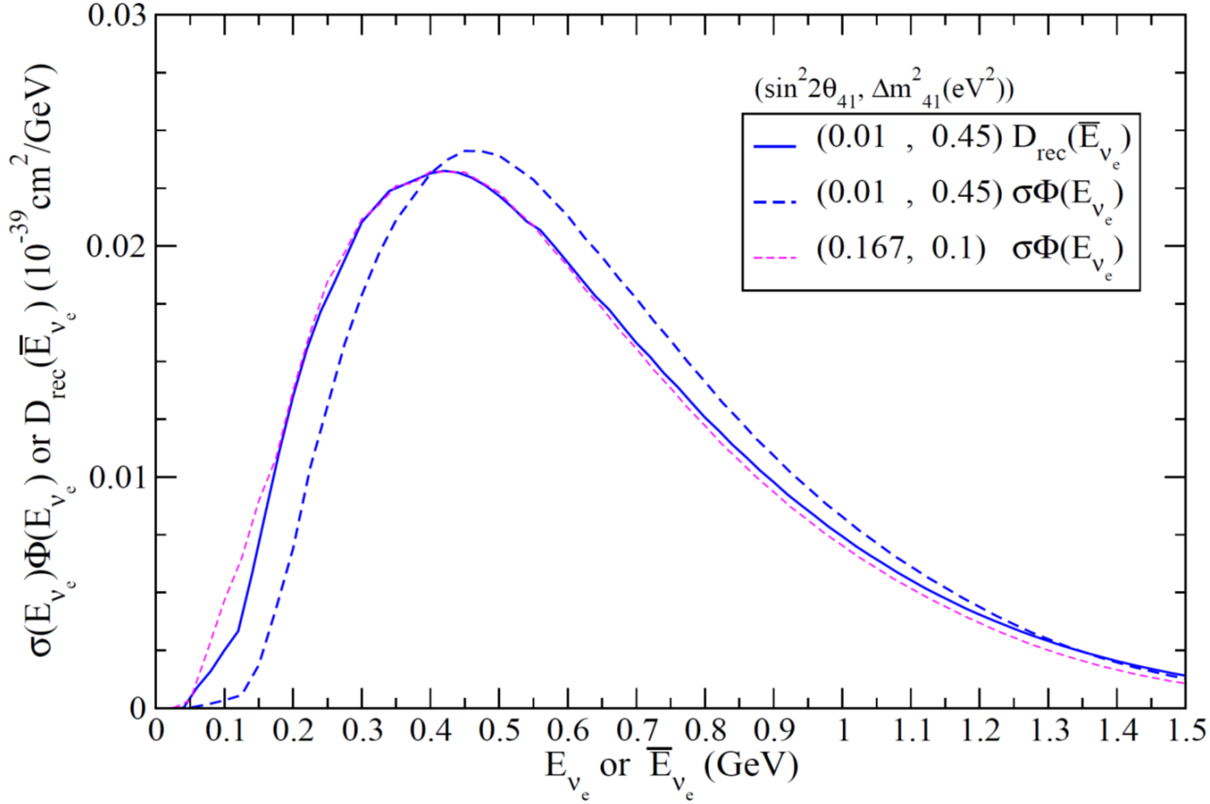


MiniBooNE Anomaly: Excess of events at low energies

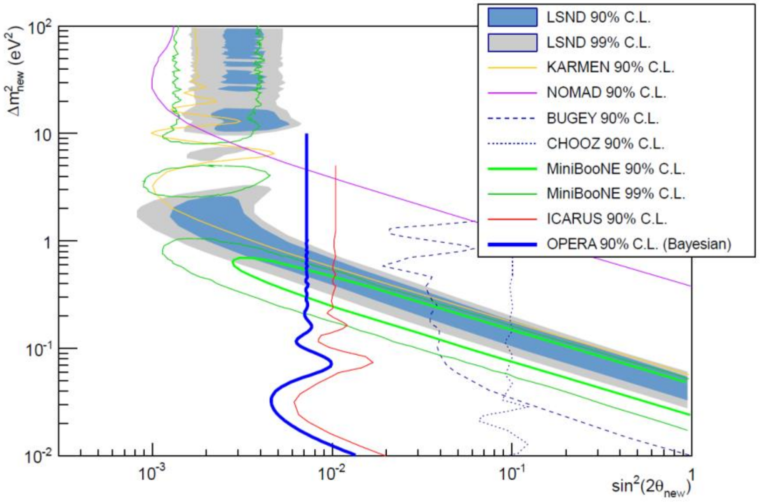
Sterile neutrino??

Taking into account the smearing procedure

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



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



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

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

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

Nuclear effects in neutrino interactions

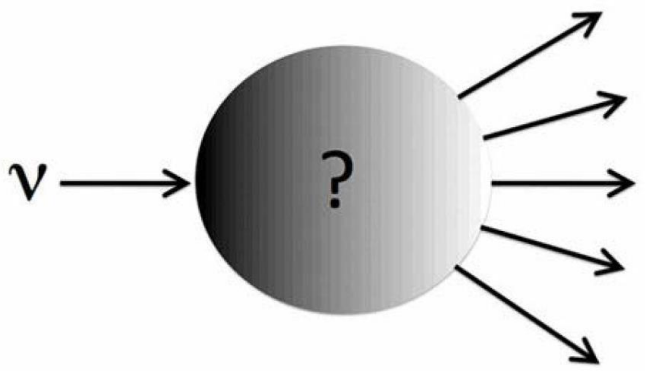
Summary and conclusions

- Quasielastic σ , $d^2\sigma/(dT_\mu\, d\cos\theta)$, $d\sigma/dQ^2$ measured by MiniBooNE and inclusive σ (SciBooNE), $d^2\sigma/(dp_\mu\, d\cos\theta)$ (T2K) can be explained without any modification of M_A including the np-nh channel
- Several theoretical calculations agree on the crucial role of the multinucleon channel in order to explain data but there are some differences on the way to treat this channel
- Nuclear effects generate an asymmetry between ν and antiν interaction: important for the investigation of CP violation effects
- Neutrino energy reconstruction and neutrino oscillation analysis are affected by np-nh
- Neutrino energy reconstruction requires reliable event generators, of same quality as experimental equipment
- Precision era of neutrino physics requires sophisticated generators and a dedicated effort in theory

Latest workshop

INT December 3-13, 2013

Neutrino-Nucleus Interactions for Current and Next Generation Neutrino Oscillation Experiments



http://www.int.washington.edu/PROGRAMS/13-54w/

Next workshop

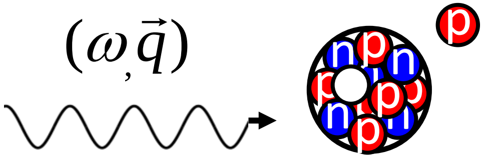
NuInt 14

9th International Workshop on Neutrino-Nucleus Interactions in the Few GeV Region

19-24 May 2014 - London

Spares

Genuine Quasielastic Scattering



Nucleon-Nucleon interaction switched off

Nucleons respond individually

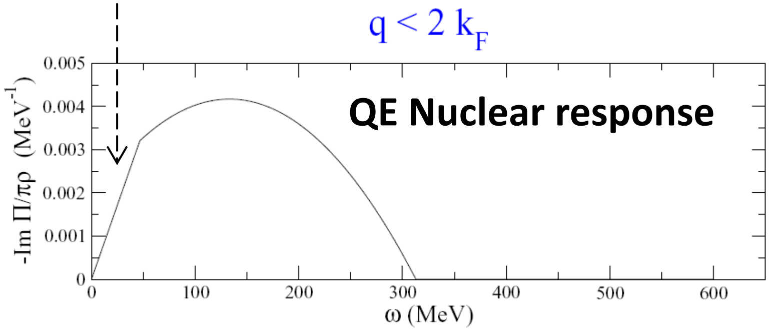
Nucleon at rest:

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

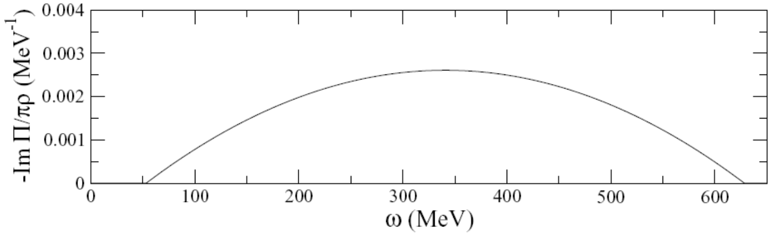
Nucleon inside the nucleus:

Fermi motion spreads δ distribution (Fermi Gas)

Pauli blocking cuts part of the low momentum Resp.



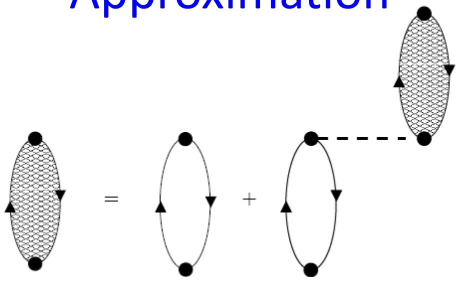
$q > 2\ k_F$



Nucleon-Nucleon interaction switched on

The nuclear response becomes collective

Random Phase Approximation

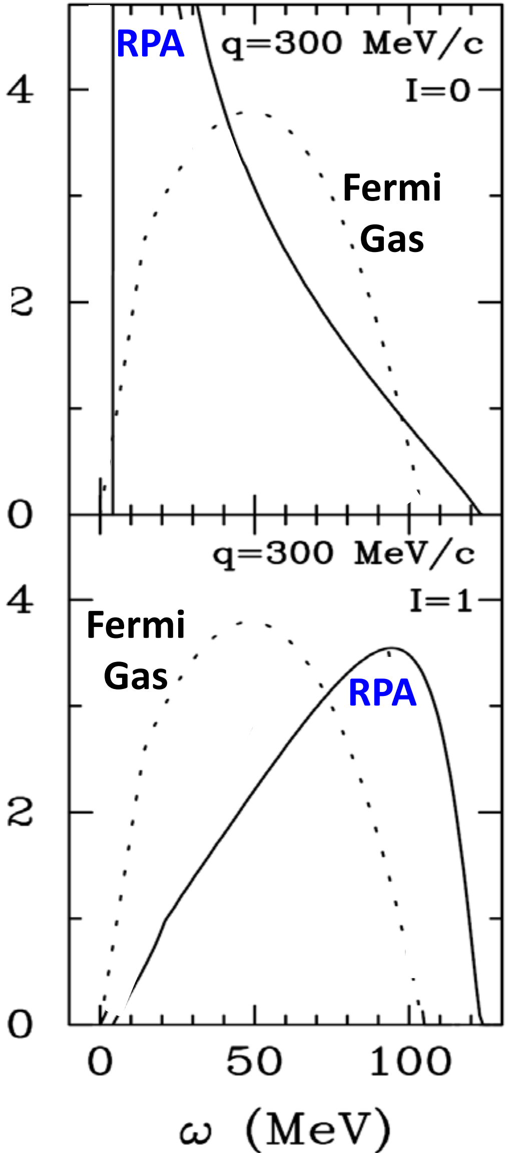


$$\Pi = \Pi^0 + \Pi^0 V \Pi$$

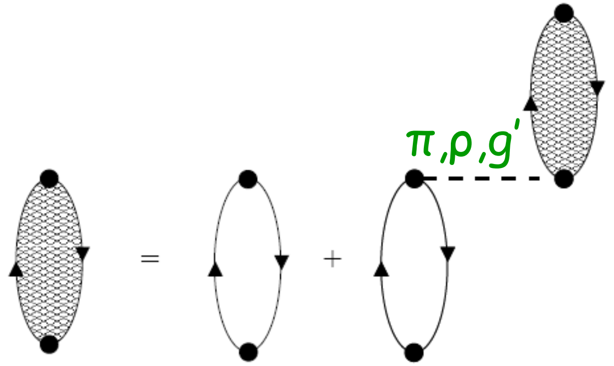
*Force acting on one nucleon is transmitted by the interaction

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

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



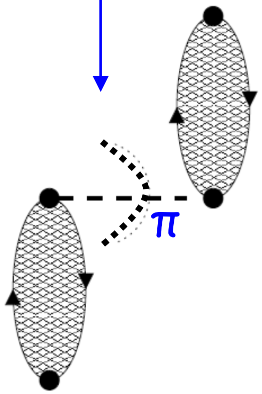
Switching on the interaction: random phase approximation



RPA

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

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

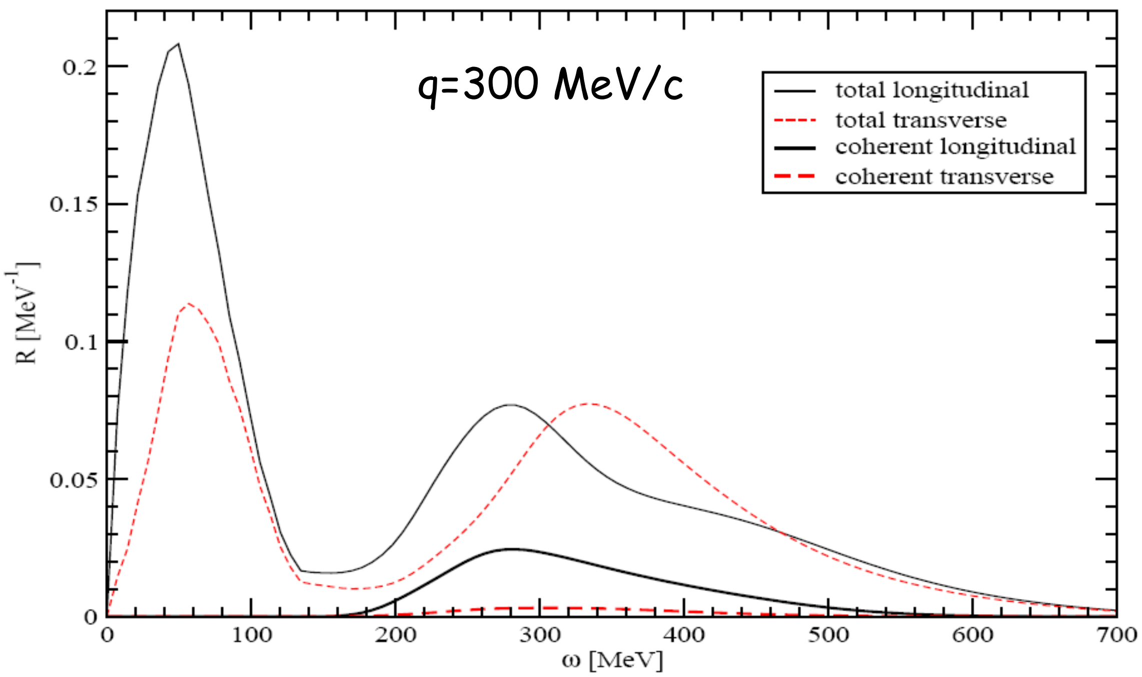


coherent π production

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

exclusive channels:
QE, 2p-2h, Δ→πN …

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



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

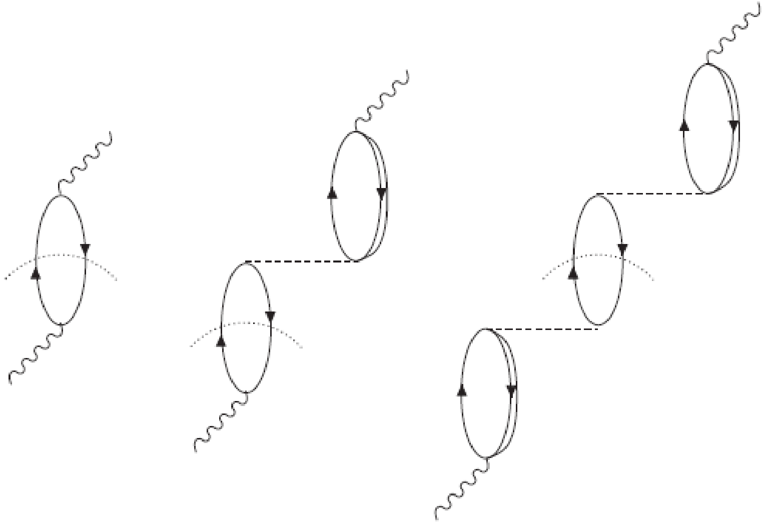
Effects of the RPA in the ν genuine quasielastic scattering

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

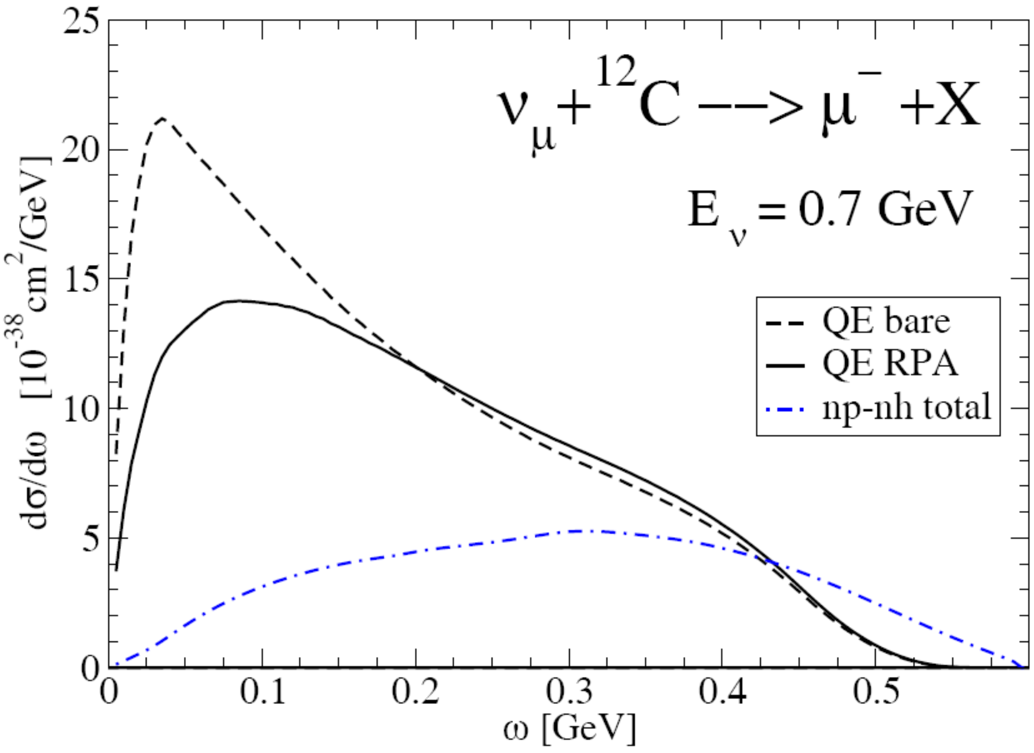
RPA reduction

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

Lowest order contribution to QE



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



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

$$
\begin{aligned}
\frac{\partial^2\sigma}{\partial\Omega\,\partial k'} = \; & \frac{G_F^2\,\cos^2\theta_c\,(\boldsymbol{k}')^2}{2\,\pi^2}\,\cos^2\frac{\theta}{2}\,\Big[G_E^2\,\Big(\frac{q_\mu^2}{\boldsymbol{q}^2}\Big)^2\,R_\tau^{NN} && \text{isovector nuclear response}\\
& + G_A^2\,\frac{(M_\Delta - M_N)^2}{2\,\boldsymbol{q}^2}\,\boxed{R_{\sigma\tau(L)}} && \text{isospin spin-longitudinal}\\
& + \left(G_M^2\,\frac{\omega^2}{\boldsymbol{q}^2} + G_A^2\right)\left(-\frac{q_\mu^2}{\boldsymbol{q}^2} + 2\tan^2\frac{\theta}{2}\right)\boxed{R_{\sigma\tau(T)}} && \text{isospin spin-transverse}\\
& \pm\; 2\,G_A\,G_M\,\frac{k+k'}{M_N}\,\tan^2\frac{\theta}{2}\,\boxed{R_{\sigma\tau(T)}}\Big] && \text{interference V-A}
\end{aligned}
$$

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

(terms in G_M , G_A)

(spin-isospin, στ excitation operator)

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

- Transverse response in electron scattering

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

- Photon absorption

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

- Pion absorption

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

Dominated by p-n initial pairs

ν scattering

Ejected pairs will be predominantly:

p-p for ν CC

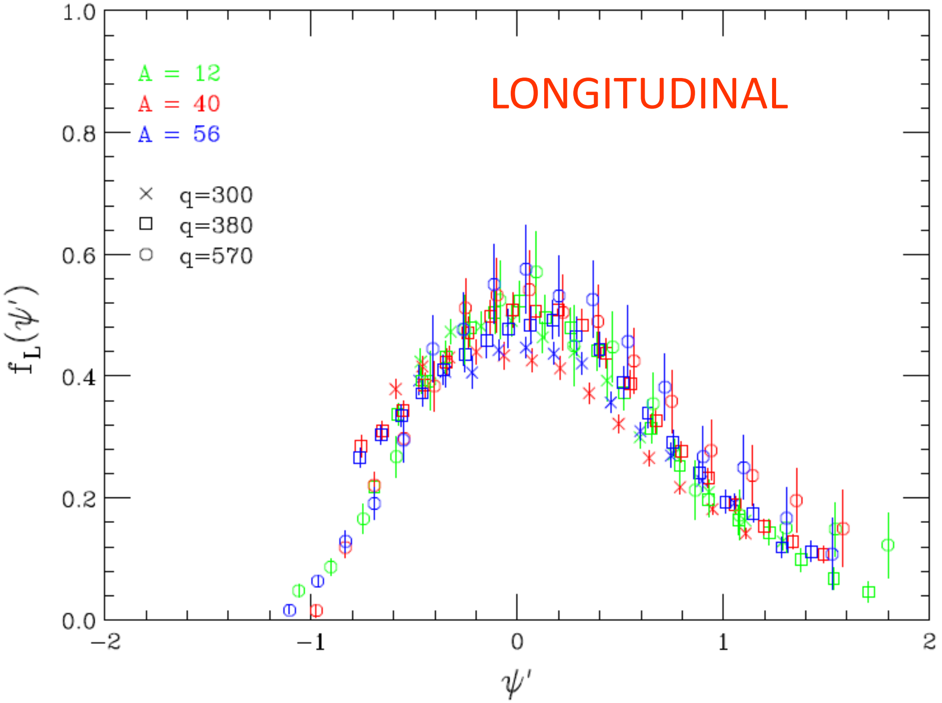
n-n for antiν CC

p-n for NC

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

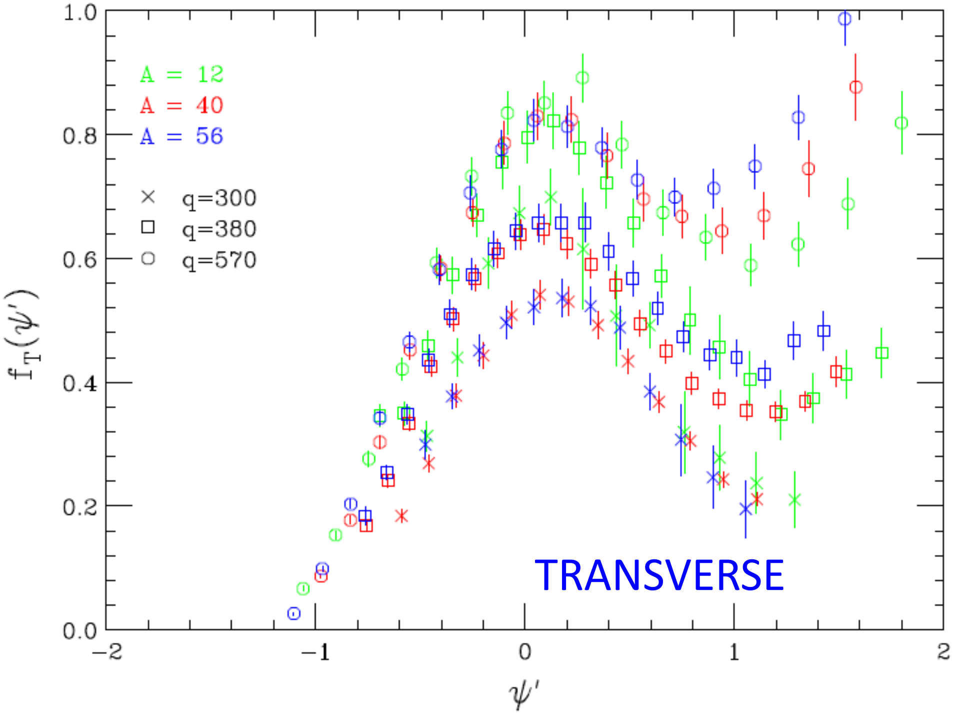
Electron scattering

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



$$f_L(\Psi) = k_F \frac{q^2-\omega^2}{q\, m} \frac{R_L(\omega,q)}{Z(G_E^p)^2 + N(G_E^n)^2}$$

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



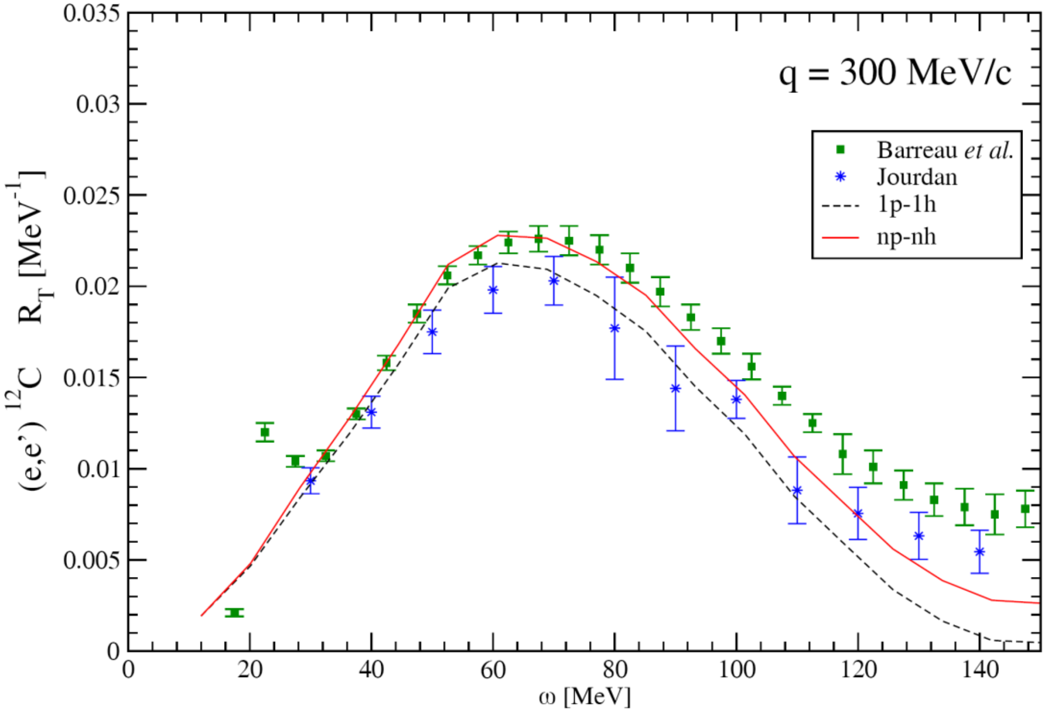
$$f_T(\Psi) = 2\, k_F \frac{q\, m}{q^2-\omega^2} \frac{R_T(\omega,q)}{Z(G_M^p)^2 + N(G_M^n)^2}$$

Excess in the transverse channel likely due to 2-body currents

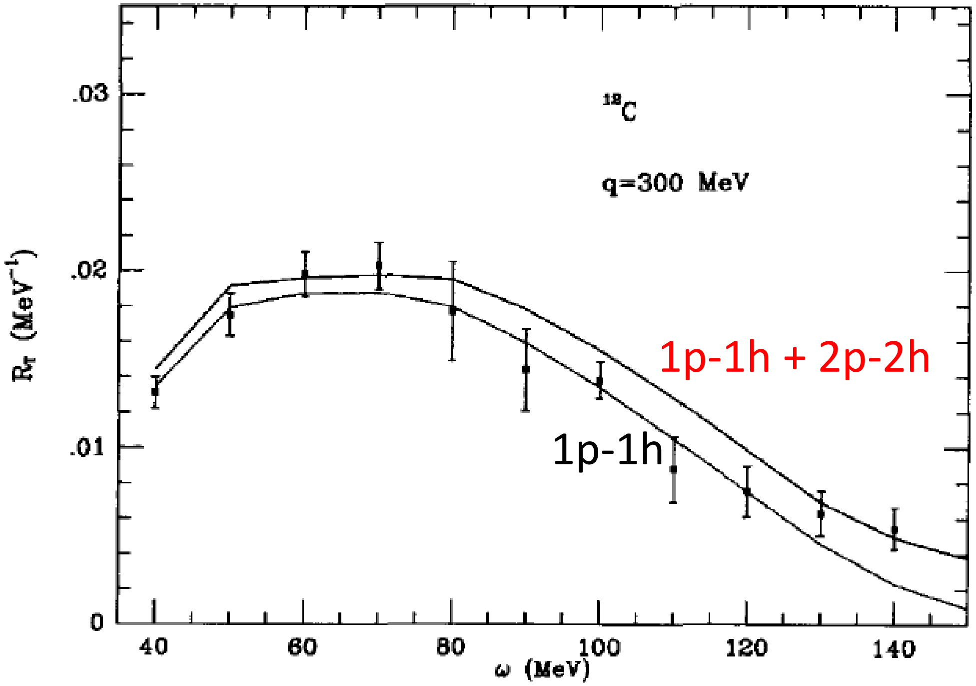
The 2p-2h term affects the transverse (magnetic) response (spin-isospin, στ excitation operator)

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

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



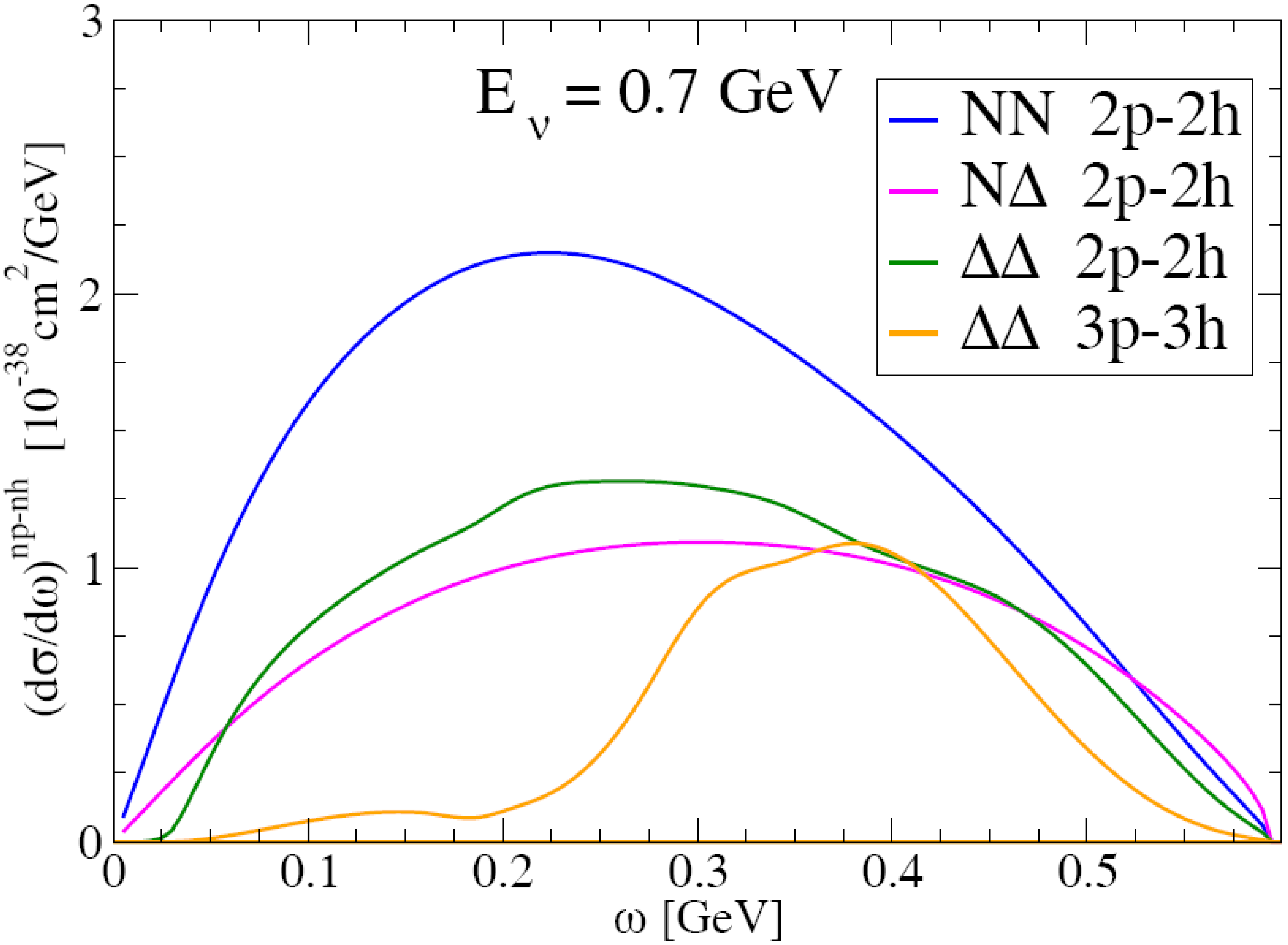
Gil, Nieves, Oset NPA 627, 543 (1997)



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

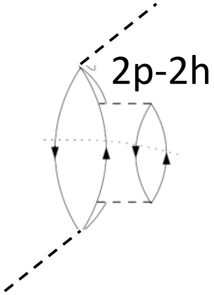
This test is important for ν cross section which is dominated by R_T

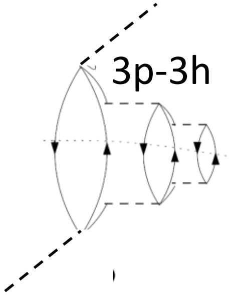
Further details of our model in the np-nh sector



ΔΔ contributions to np-nh in our model

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





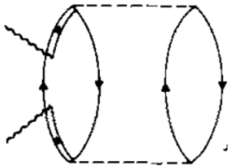
E. Oset and L. L. Salcedo, Nucl. Phys. A 468, 631 (1987):

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

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

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

- Not reducible to a modification of the Delta width



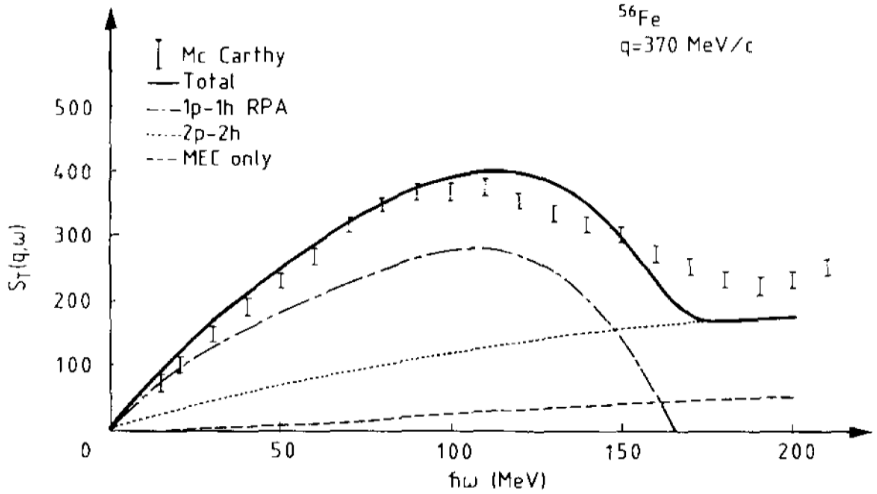
Microscopic calculation of π absorption at threshold: **$\omega=m_\pi$**

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

Extrapolation to other energies

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

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



Starting point: a microscopic evaluation of R_T

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

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

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

Our work

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

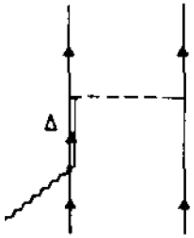
- Global reduction ≈ 0.5 applied to reproduce the absorptive p-wave π-A optical potential

Analogies and differences of 2p-2h

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

Axial and Vector NN corr. Δ-MEC NΔ interf.

[Genuine CCQE (1p-1h): LRFG+RPA]



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

Axial and Vector NN corr. MEC N-MEC interf.

[Genuine CCQE (1p-1h): LRFG+SF+RPA]

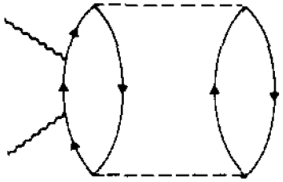
J.E. Amaro, M.B. Barbaro, J.A. Caballero, T.W. Donnelly et al.

Only Vector MEC

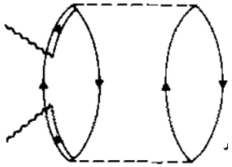
[Genuine CCQE (1p-1h): Superscaling]

Main difficulties in the 2p-2h sector

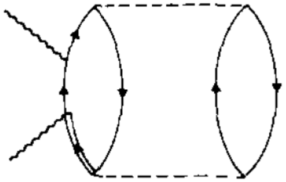
- Huge number of diagrams and terms



16 from NN correlations



49 from MEC



56 from interference

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

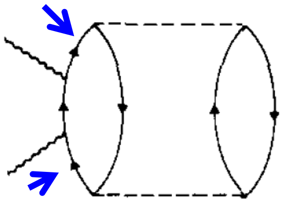
fully relativistic calculation (just of MEC !):

3000 direct terms

More than **100 000** exchange terms

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

- Divergences in NN correlations



prescriptions:

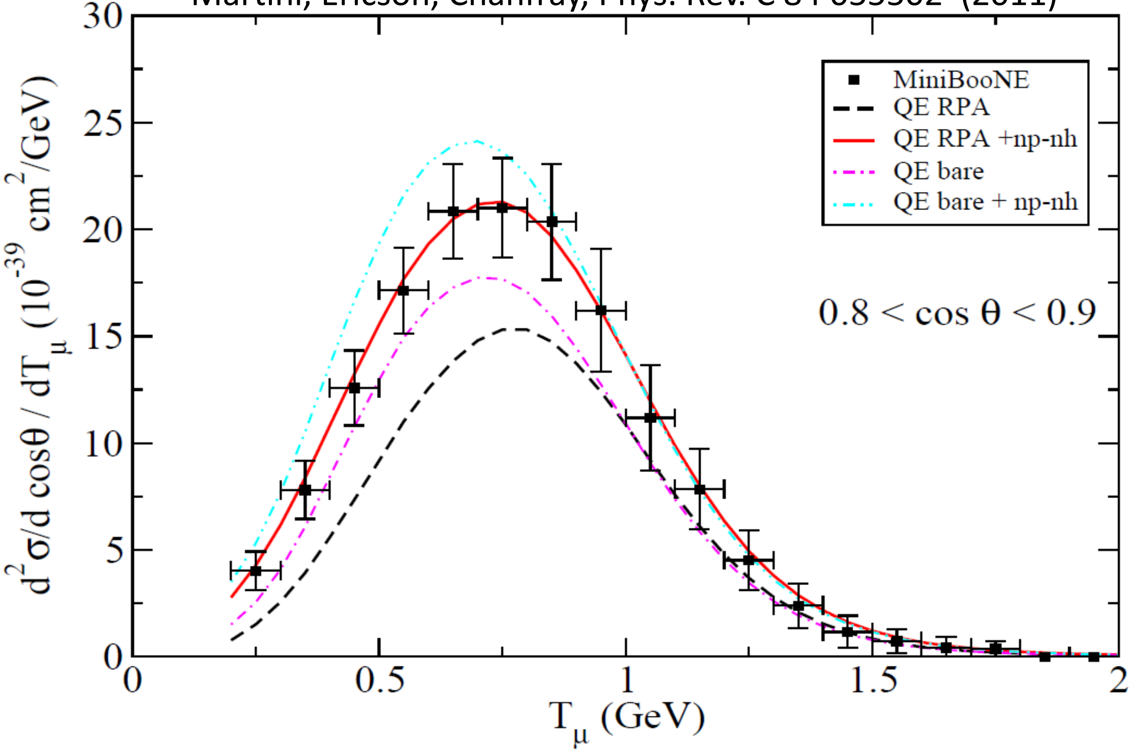
-nucleon propagator only off the mass shell (*Alberico et al. Ann. Phys. 1984*)

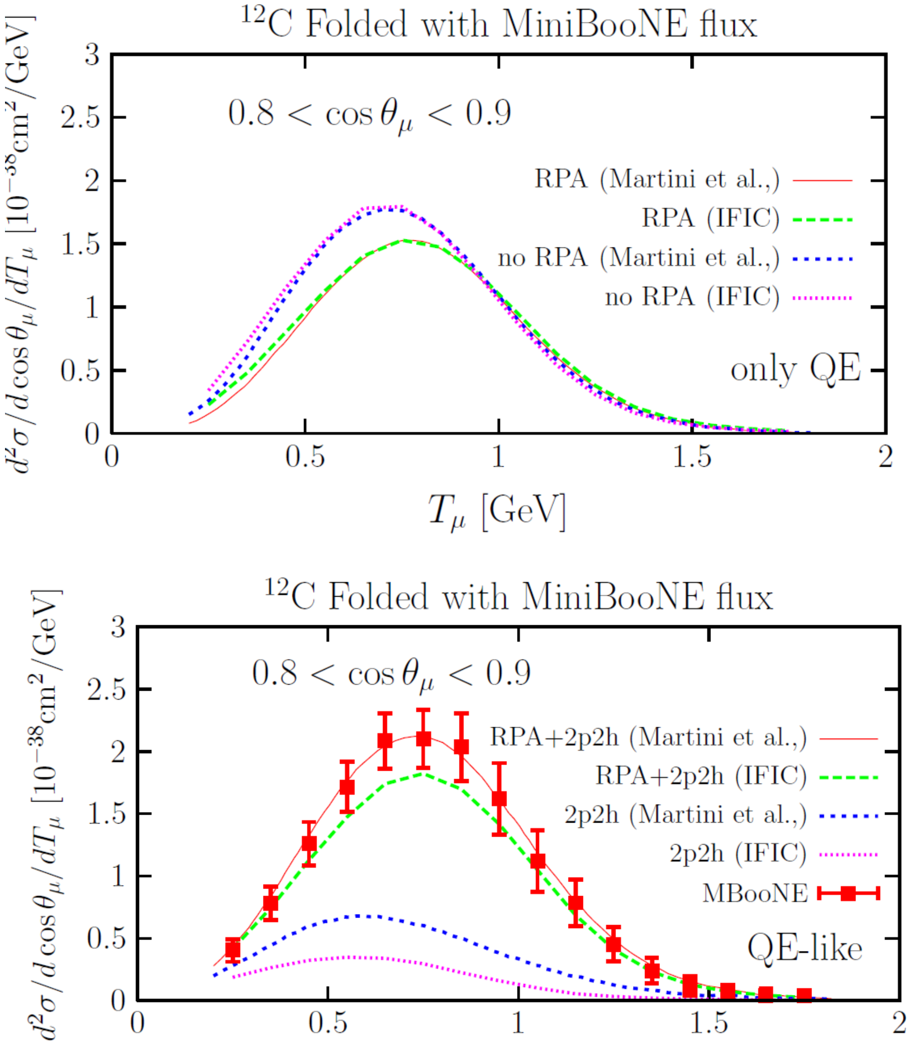
-kinematical constraints + nucleon self energy in the medium (*Nieves et al PRC 83*)

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

Flux-integrated ν CCQE double differential X section versus Tμ

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





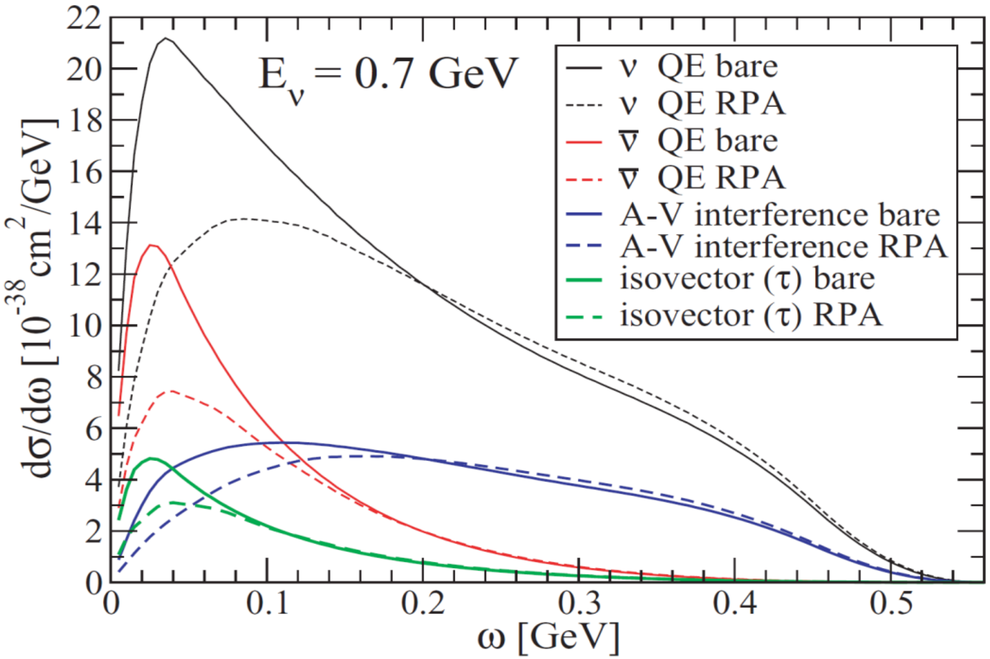
Morfin, Nieves, Sobczyk
Adv.High Energy Phys. 2012 (2012) 934597

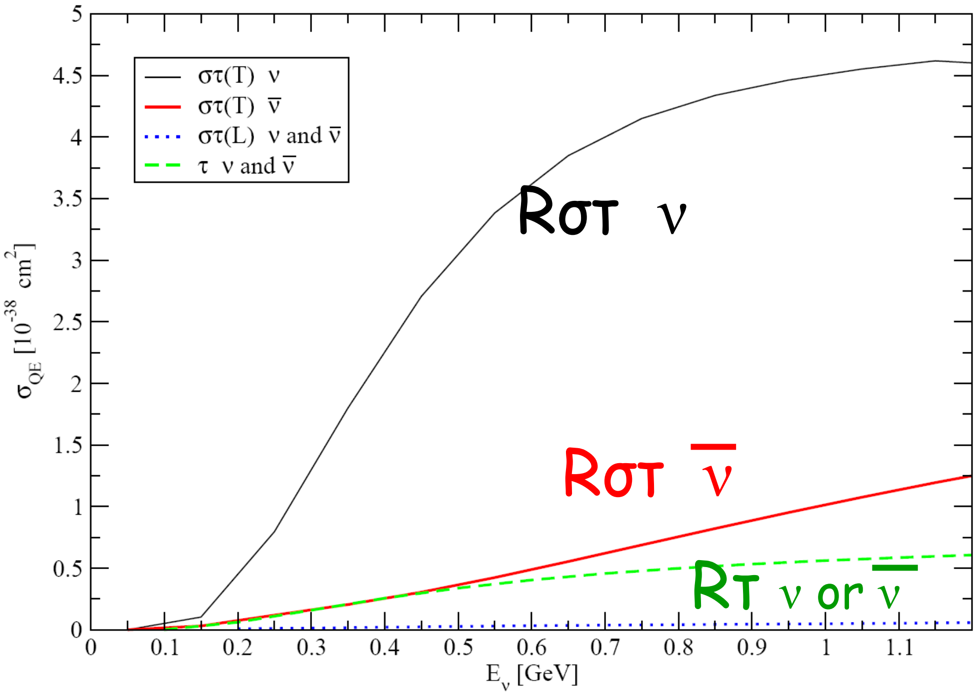
Delicate balance between
RPA quenching and np-nh enhancement

- 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)

Various response contributions to the ν and $\bar{\nu}$ CCQE





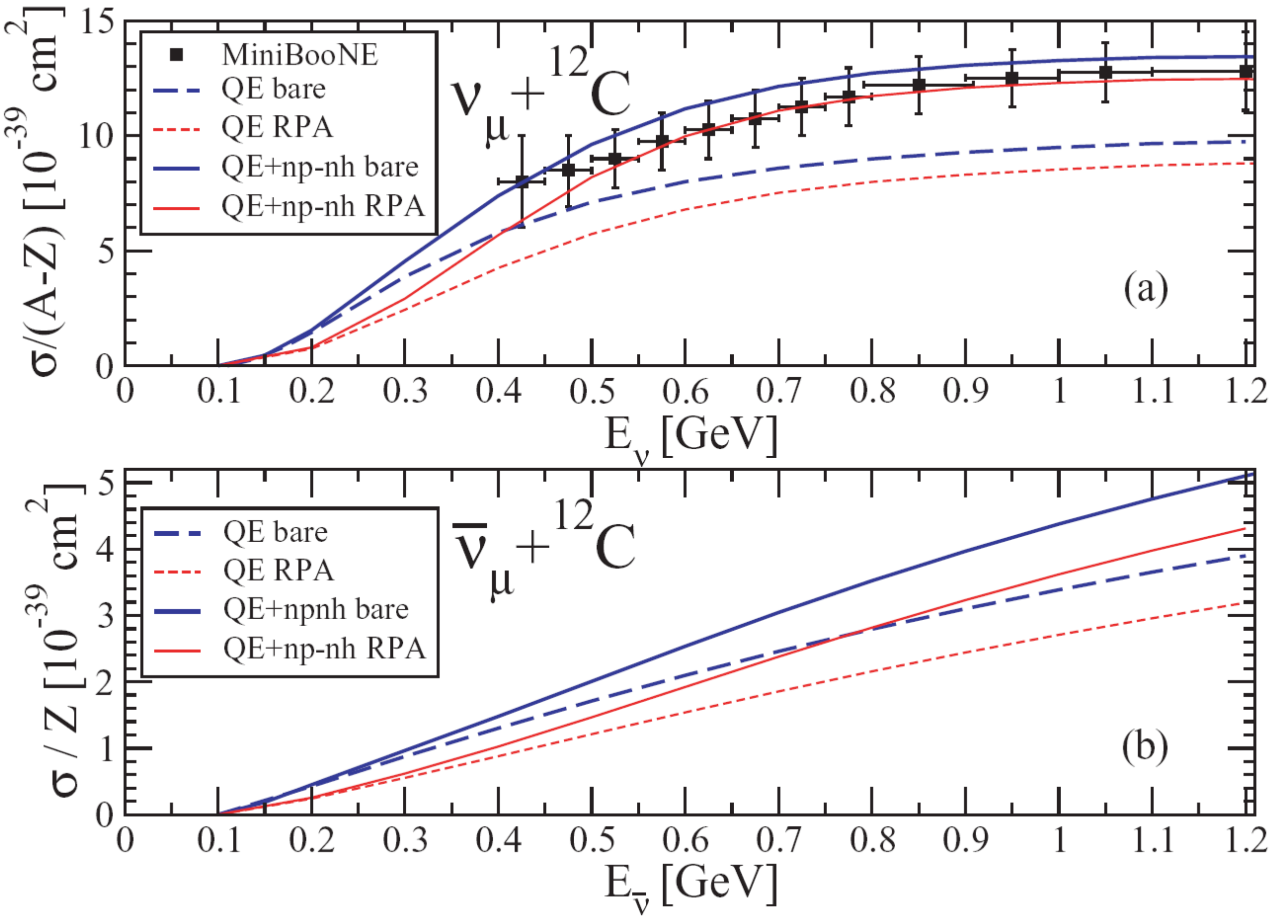
The role of interference term (in $G_A G_M$) is crucial:

it enhances the contribution of Rστ(T) for neutrinos.

For antineutrinos instead the destructive interference partially suppresses this contribution leaving a larger role for isovector Rτ which is insensitive to 2p-2h.

Hence the **relative** role of 2p-2h should be smaller for antineutrinos

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

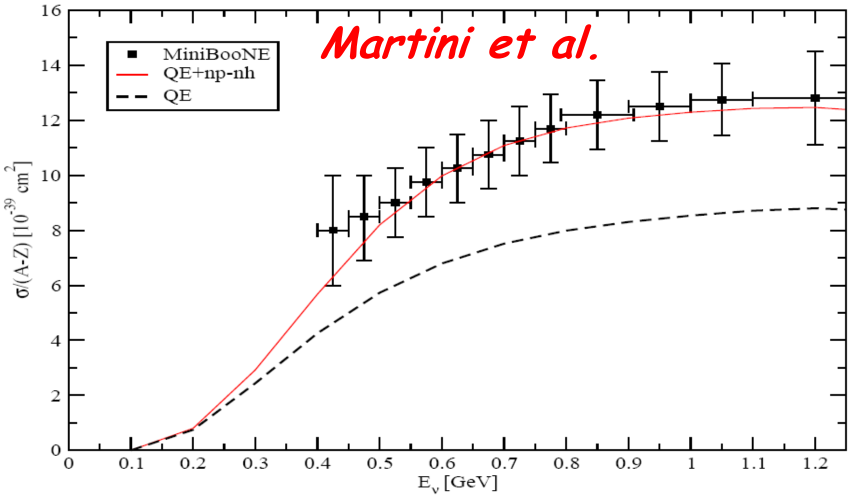


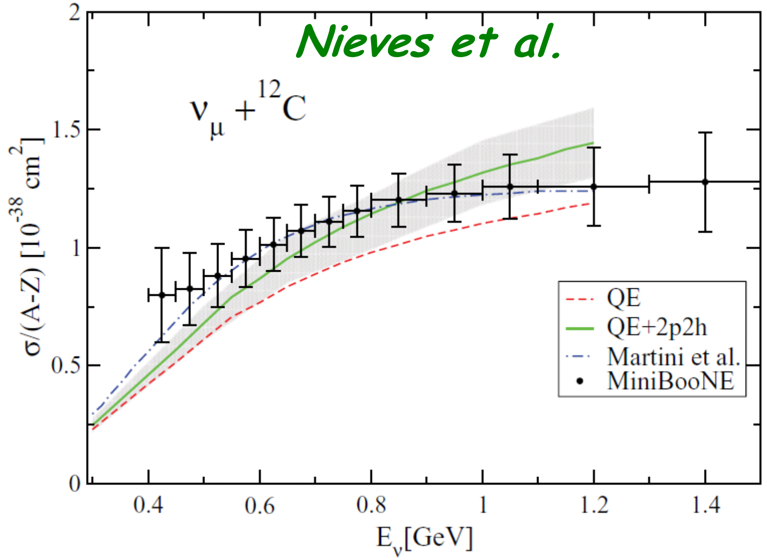
Relative role of 2p-2h smaller for antineutrinos

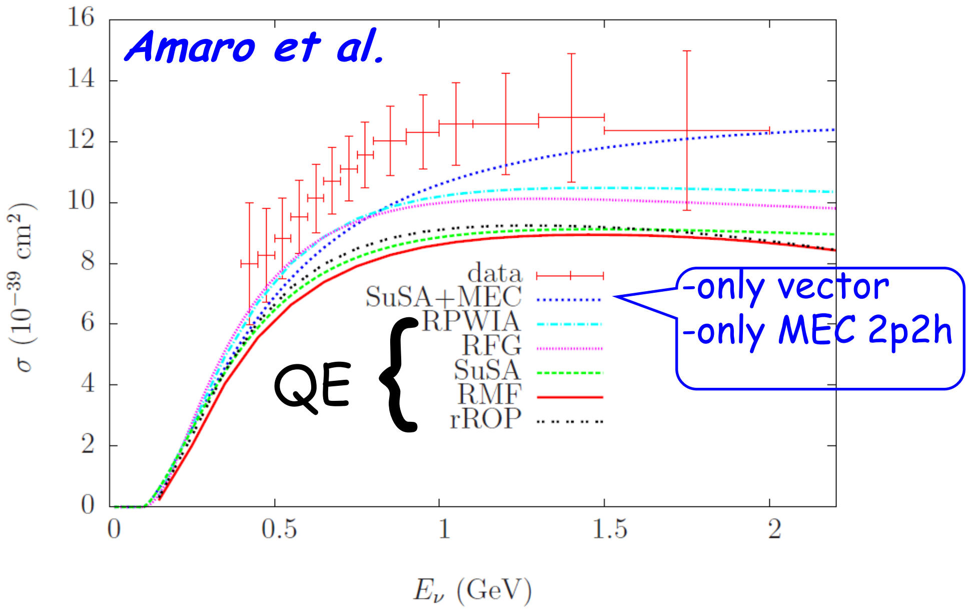
Antineutrino X section very sensitive to RPA

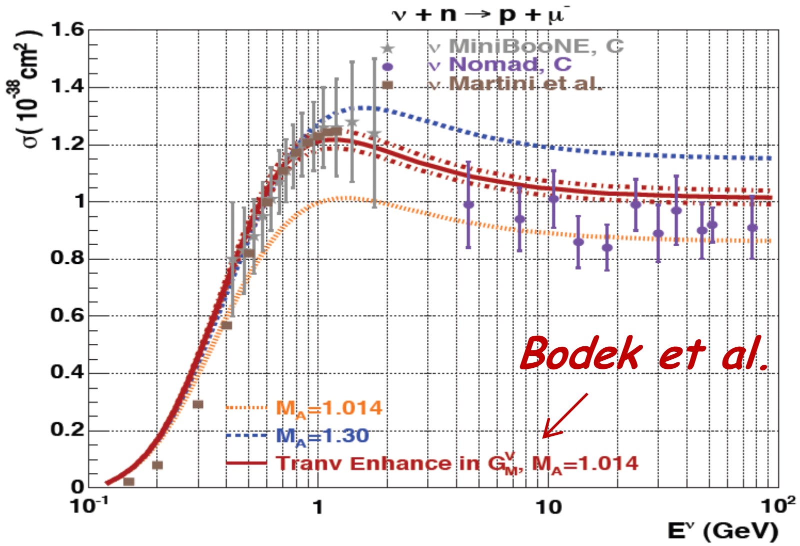
M. Martini, M. Ericson, G. Chanfray, J. Marteau, Phys. Rev. C 81 045502 (2010)

Total CCQE and comparison with flux unfolded MB









N.B. The experimental unfolding is model dependent

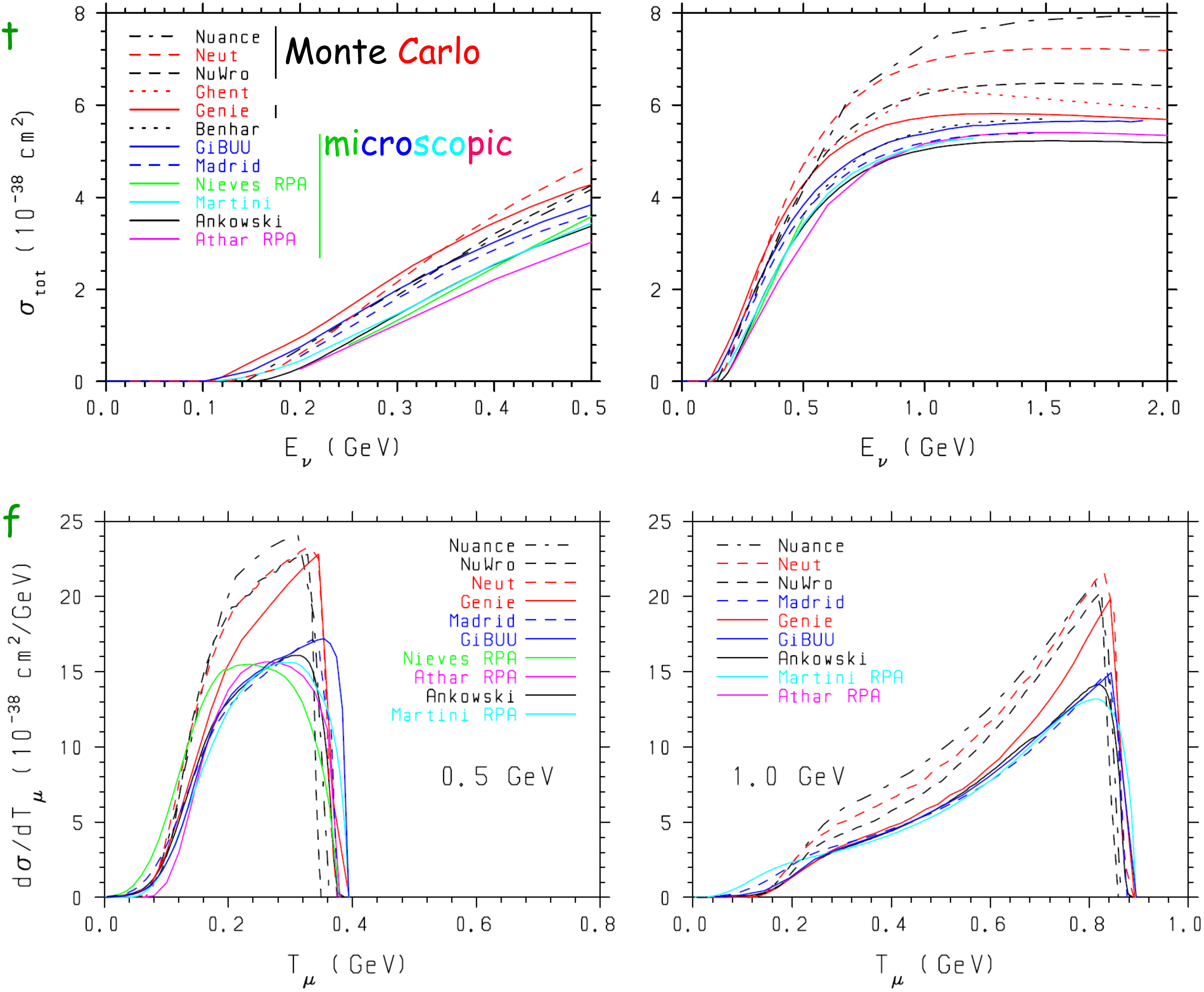
Comparison of Models of Neutrino-Nucleus Interactions

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

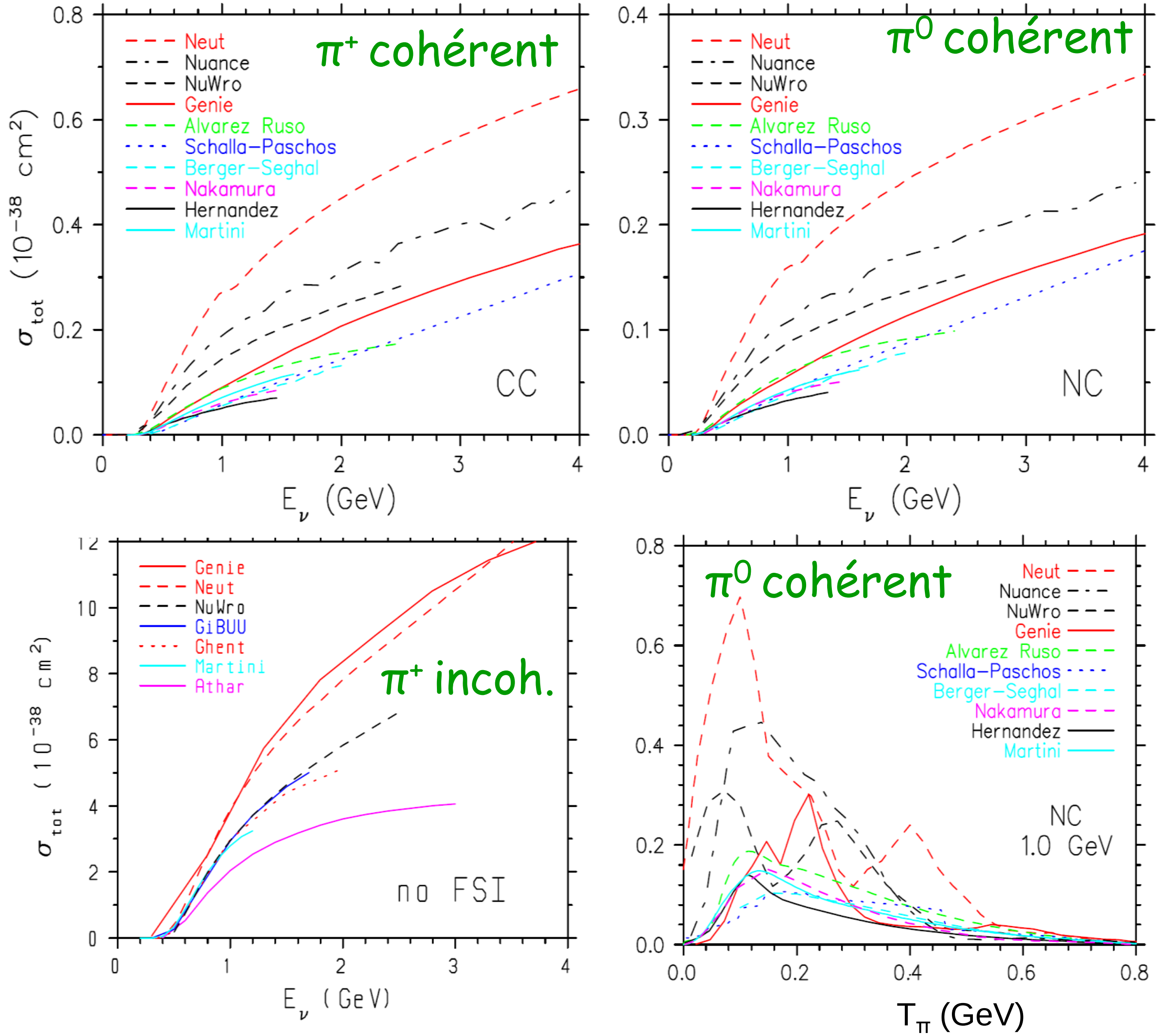
QE tot

QE diff

N U I N T 0 9



NUINT09



Monte Carlo

QE: Fermi Gas

π prod:Rein-Sehgal

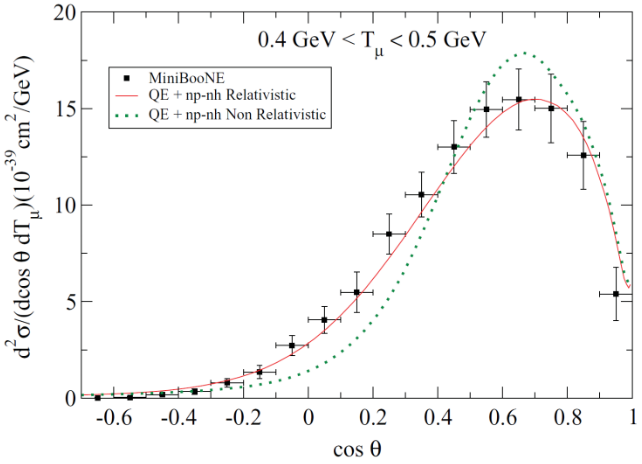
- **Neut**: SuperKamiokande, K2K, T2K, SciBooNE
- Nuance: SuperKamiokande, MINOS, MiniBooNE
- **Genie**: T2K, MINOS, Minerva, NOvA,ArgoNEUT
- NuWro:Wroclaw theo. group

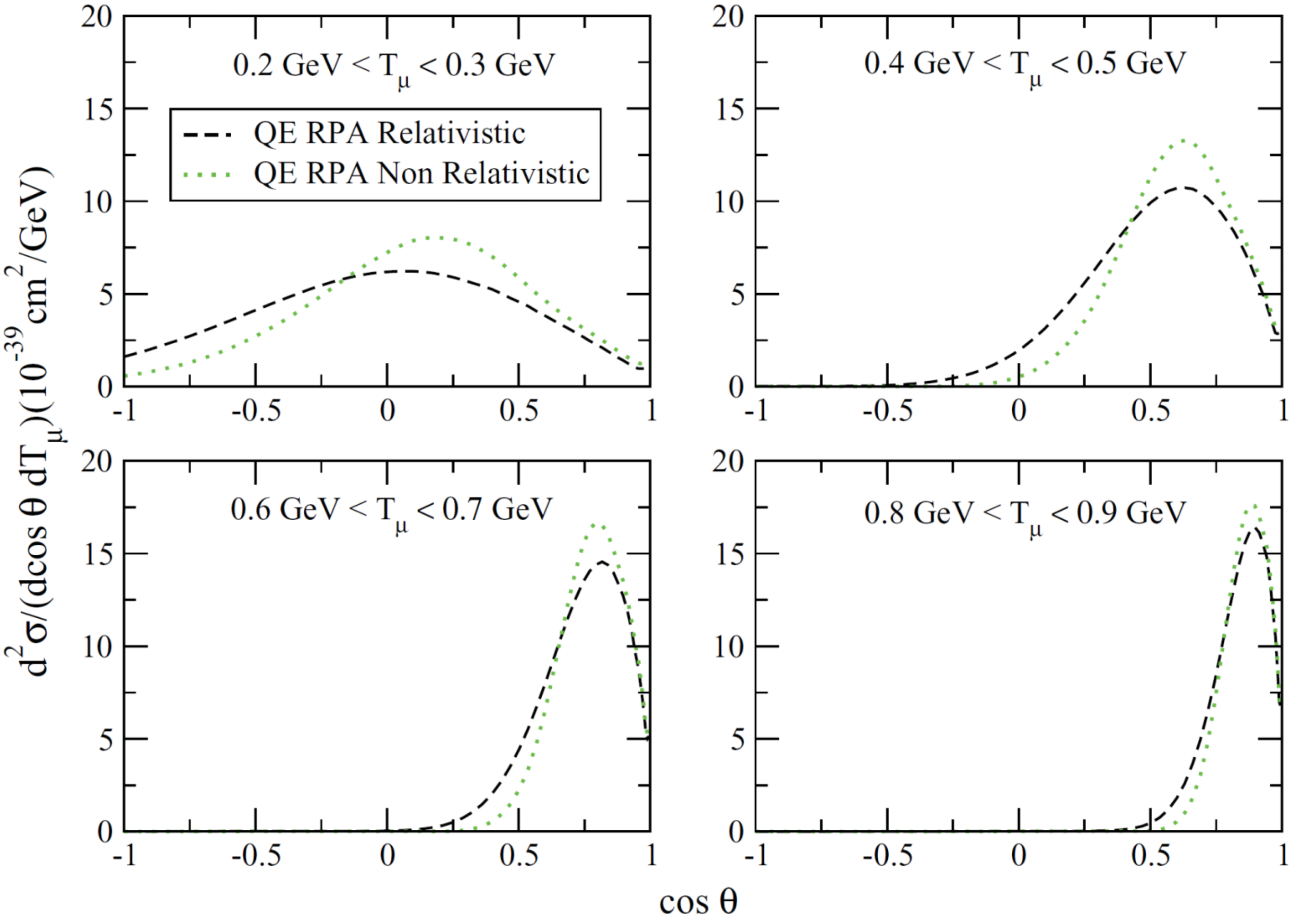
MC larger than microscopic models

Relativistic corrections

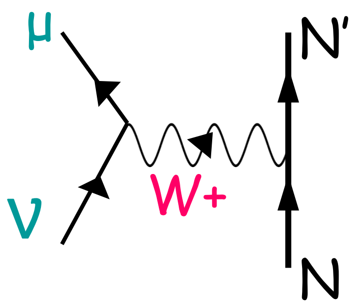
$$\omega \rightarrow \omega\left(1 + \frac{\omega}{2M_N}\right)$$

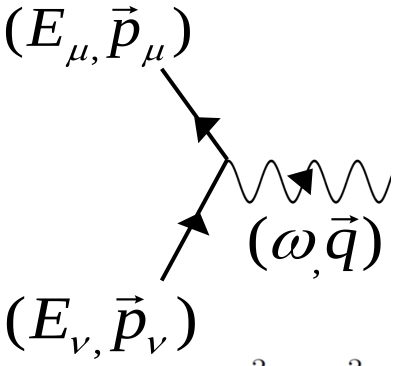
$$\Pi \longrightarrow \left(1 + \frac{\omega}{M_N}\right) \Pi$$





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





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

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

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

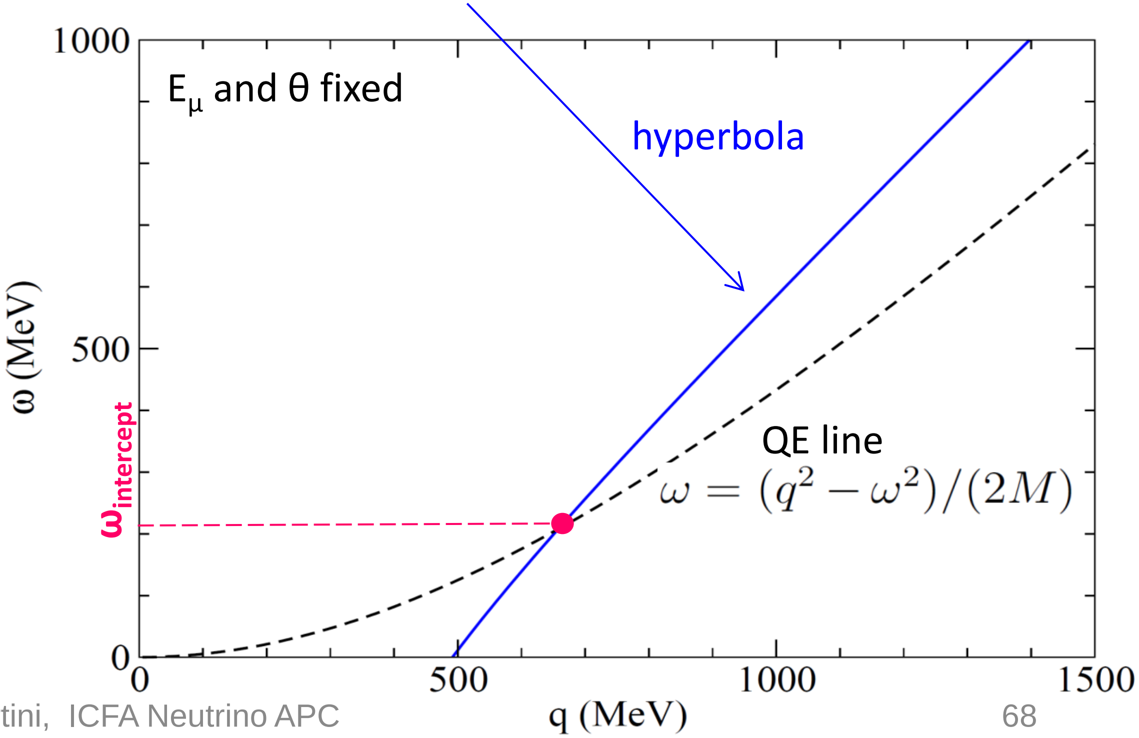
The nuclear response function is proportional to the delta distribution

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

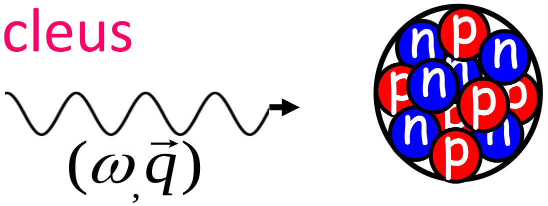
The intercept of the **hyperbola** with the **QE line** fixes the possible ω and q values for given E_μ and θ.

Hence the neutrino energy is determined

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

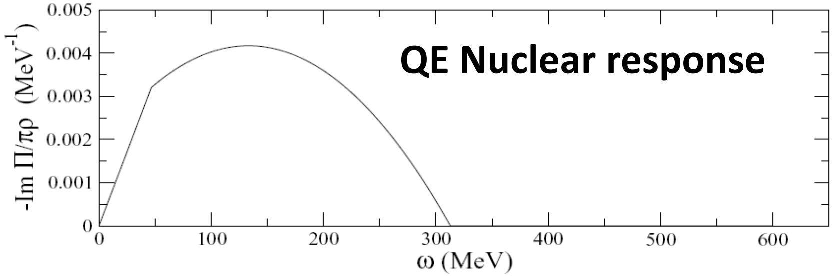


QE Scattering with nucleons inside the nucleus



1 particle- 1 hole (p-h) excitation

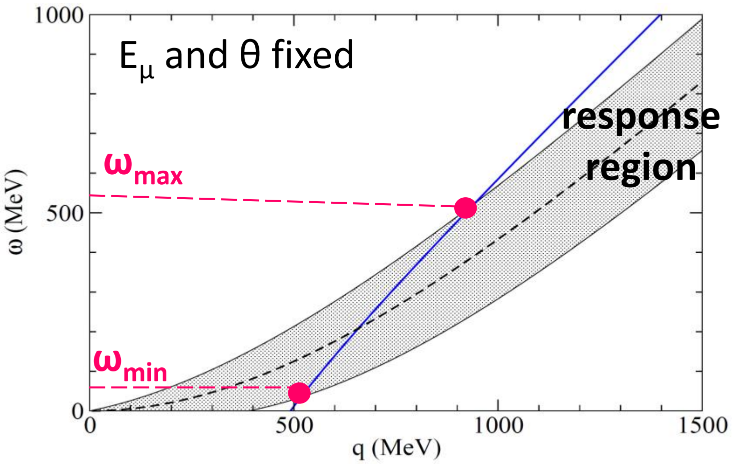
$q < 2\ k_F$



Fermi motion spreads δ distribution (Fermi Gas)

Pauli blocking cuts part of the
low momentum nuclear response

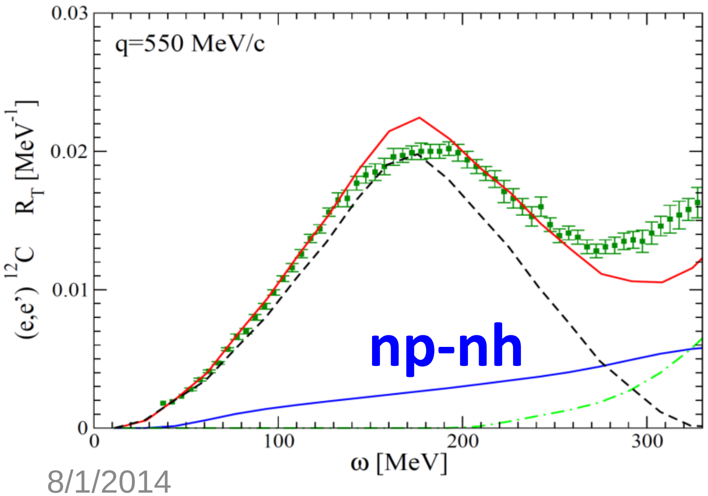
RPA collective effects



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

Neutrino energy distributions with no specification of lepton observables

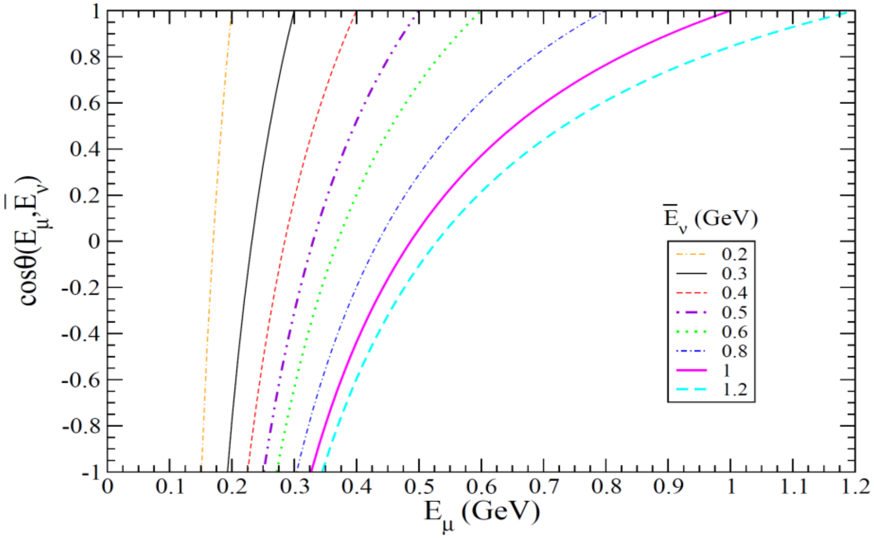
Neutrino reconstructed energy **Ēν is fixed**

Many couples of Eμ and θ can lead to the same Ēν

One has to sum over these couples

$$\overline{E_\nu} P_\mu \cos\theta + M(\overline{E_\nu} - E_\mu) - \overline{E_\nu} E_\mu + m_\mu^2/2 = 0 \Longleftrightarrow \overline{E_\nu} = \frac{E_\mu - m_\mu^2/(2M)}{1 - (E_\mu - P_\mu \cos\theta)/M}$$

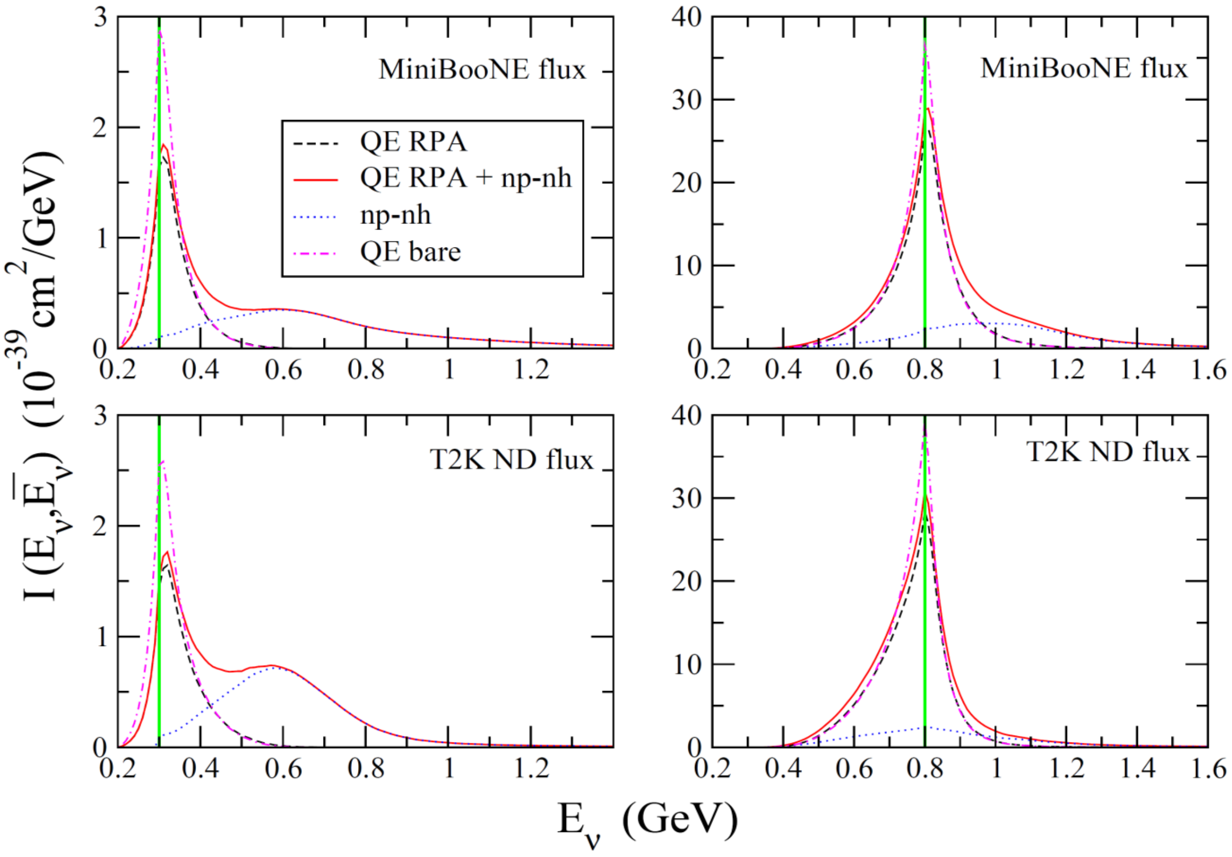
$\cos\theta(E_\mu, \overline{E_\nu})$ is the cosine solution of this equation for given Ēν and Eμ



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

Probability distribution before normalization

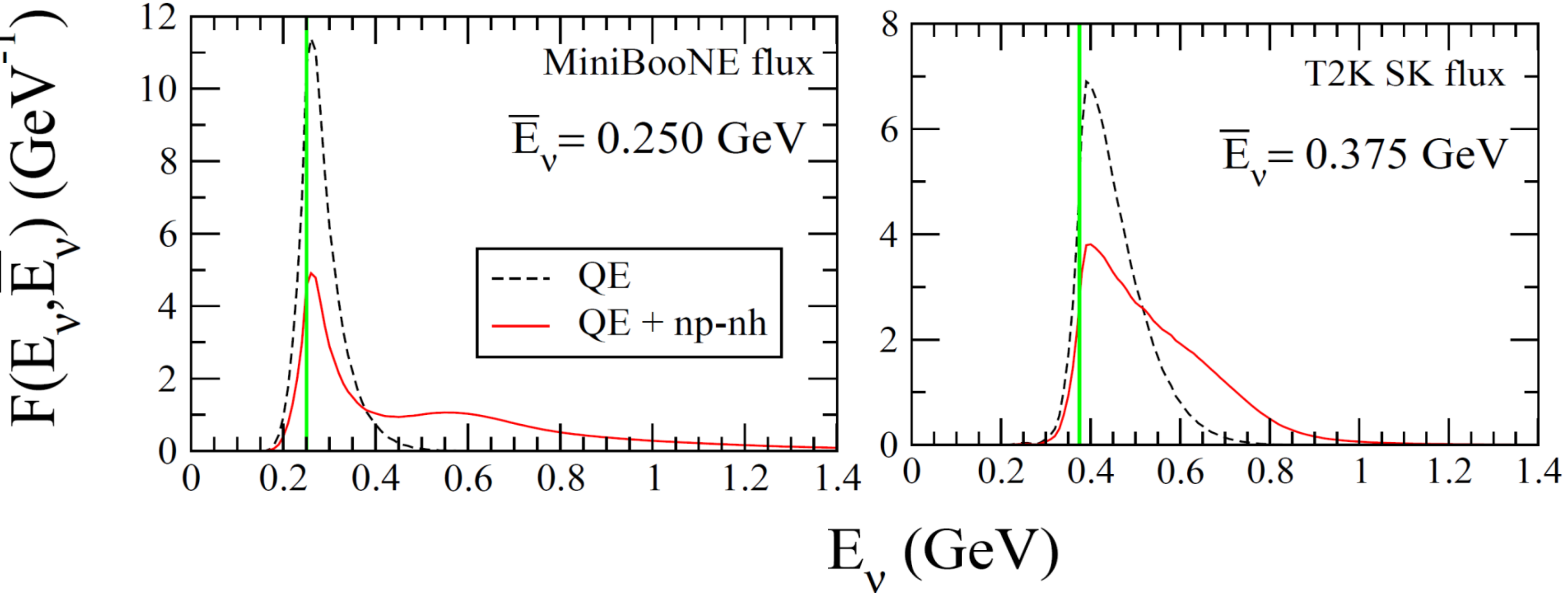
$$F(E_\nu,\overline{E_\nu}) = c\frac{\Phi(E_\nu)}{\int dE_\nu \Phi(E_\nu)} \int_{E_\mu^{\min}}^{E_\mu^{\max}} dE_\mu \left[\frac{d^2\sigma}{d\omega\ d\cos\theta}\right]_{\omega=E_\nu-E_\mu,\ \cos\theta=\cos\theta(E_\mu,\overline{E_\nu})} = cI(E_\nu,\overline{E_\nu})$$



Probability energy distributions with no specification of lepton observables

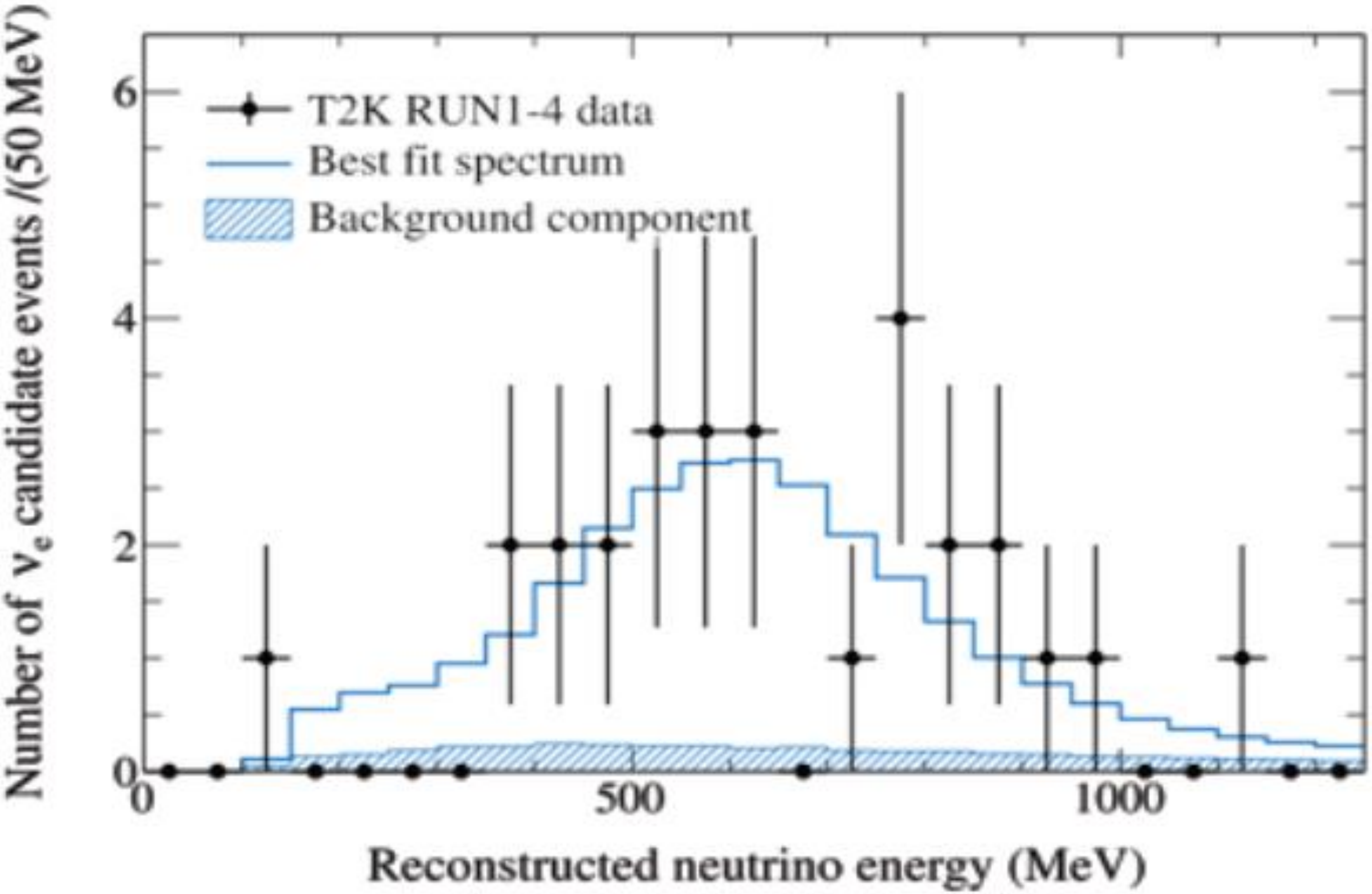
$$F(E_\nu,\overline{E_\nu}) = c\frac{\Phi(E_\nu)}{\int dE_\nu \Phi(E_\nu)} \int_{E_\mu^{\min}}^{E_\mu^{\max}} dE_\mu \left[\frac{d^2\sigma}{d\omega\ d\cos\theta}\right]_{\omega=E_\nu-E_\mu,\ \cos\theta=\cos\theta(E_\mu,\overline{E_\nu})}$$

$$\int dE_\nu\ F(E_\nu,\overline{E_\nu}) = 1$$



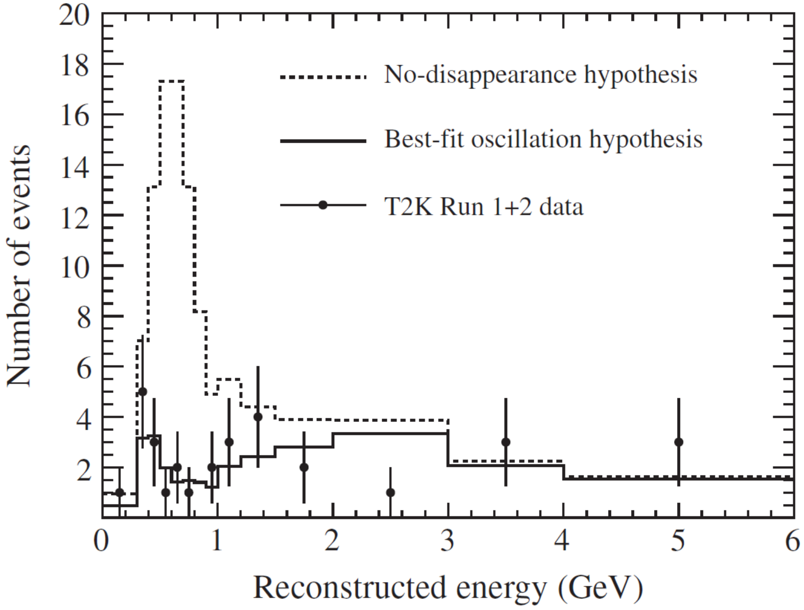
$\bar{E}\nu$:
vertical green line

High energy tail due to the np-nh contribution

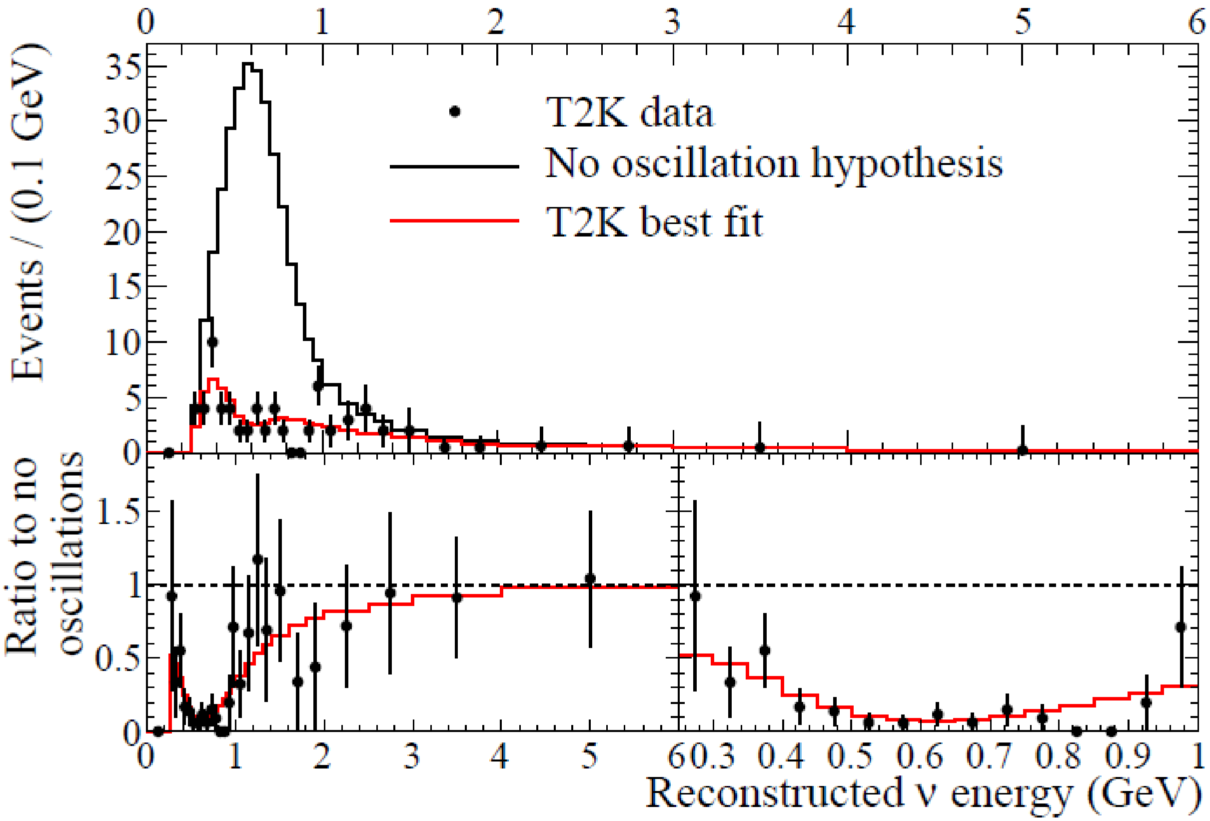

Number of ν_e candidate events /(50 MeV)
0
2
4
6
0
500
1000
Reconstructed neutrino energy (MeV)
T2K RUN1-4 data
Best fit spectrum
Background component

T2K ν_μ disappearance

T2K PRD 85, 031103 (2012)

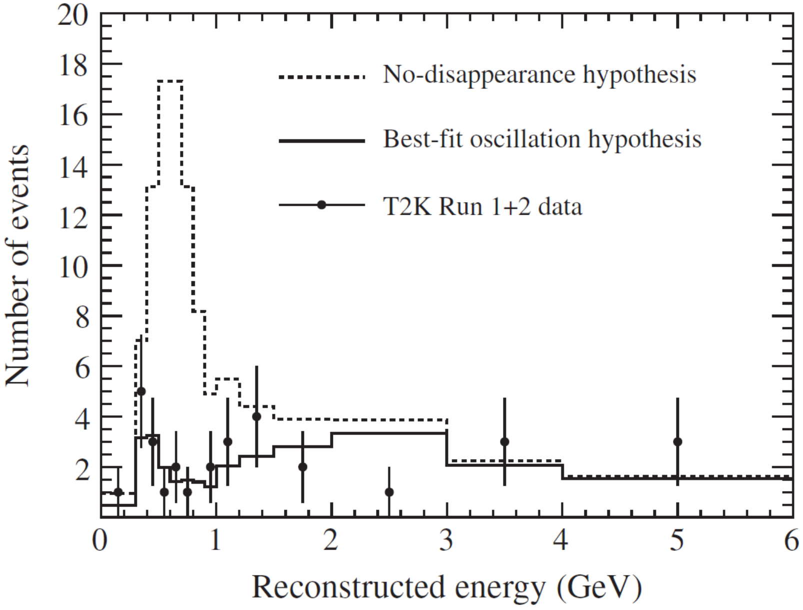


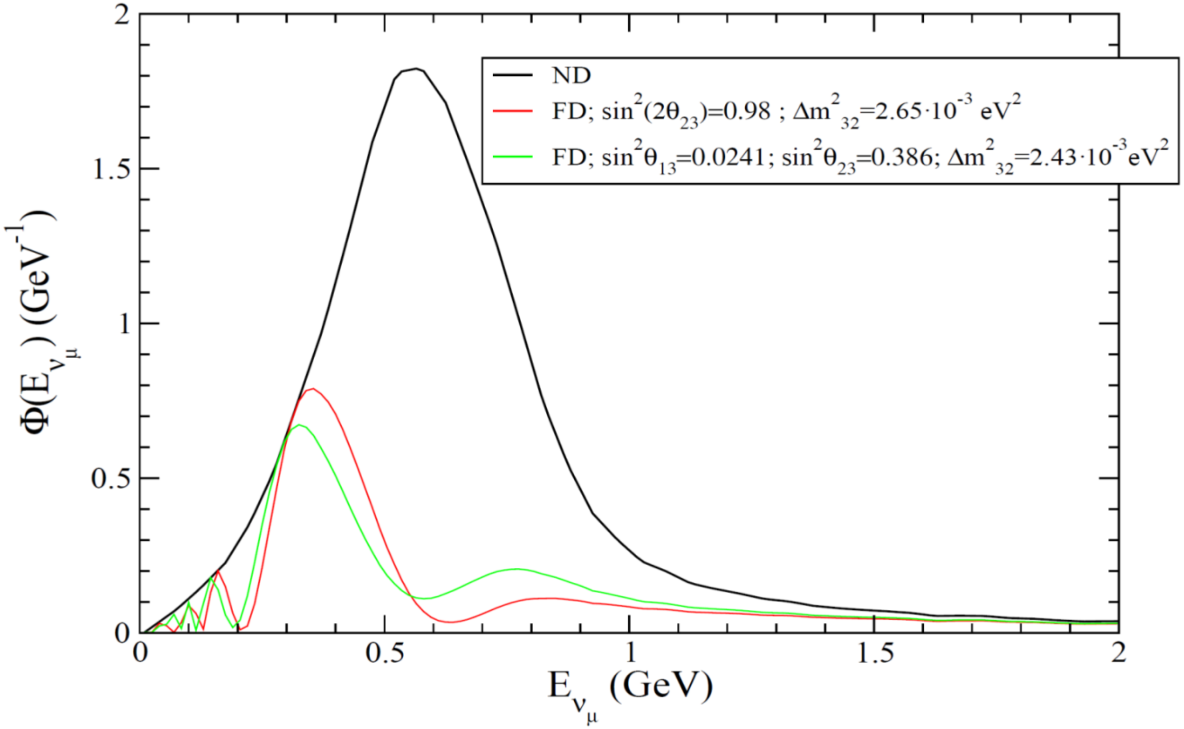
T2K arXiv 1308.0465 (2013)



T2K ν_μ disappearance

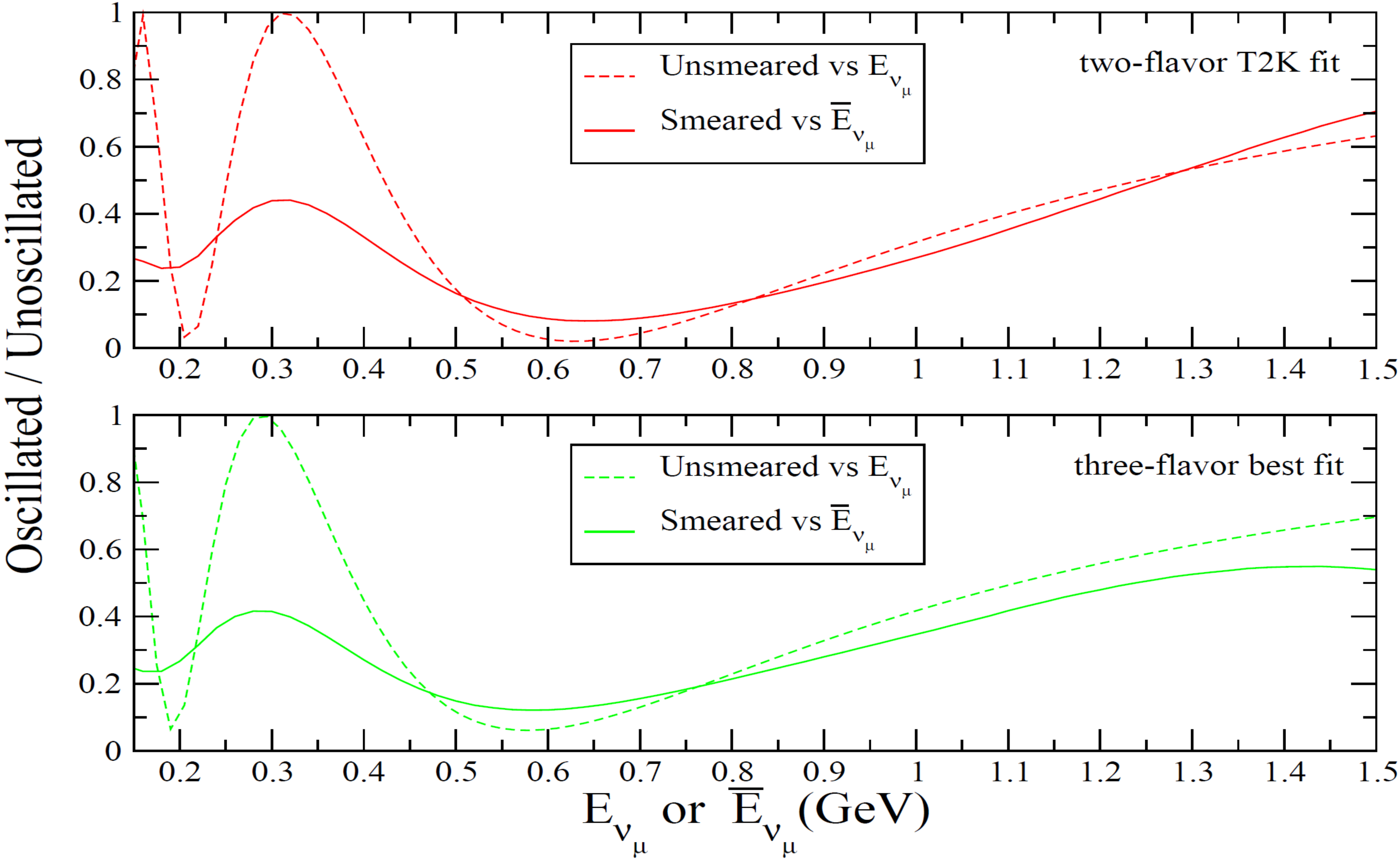
T2K PRD 85, 031103 (2012)



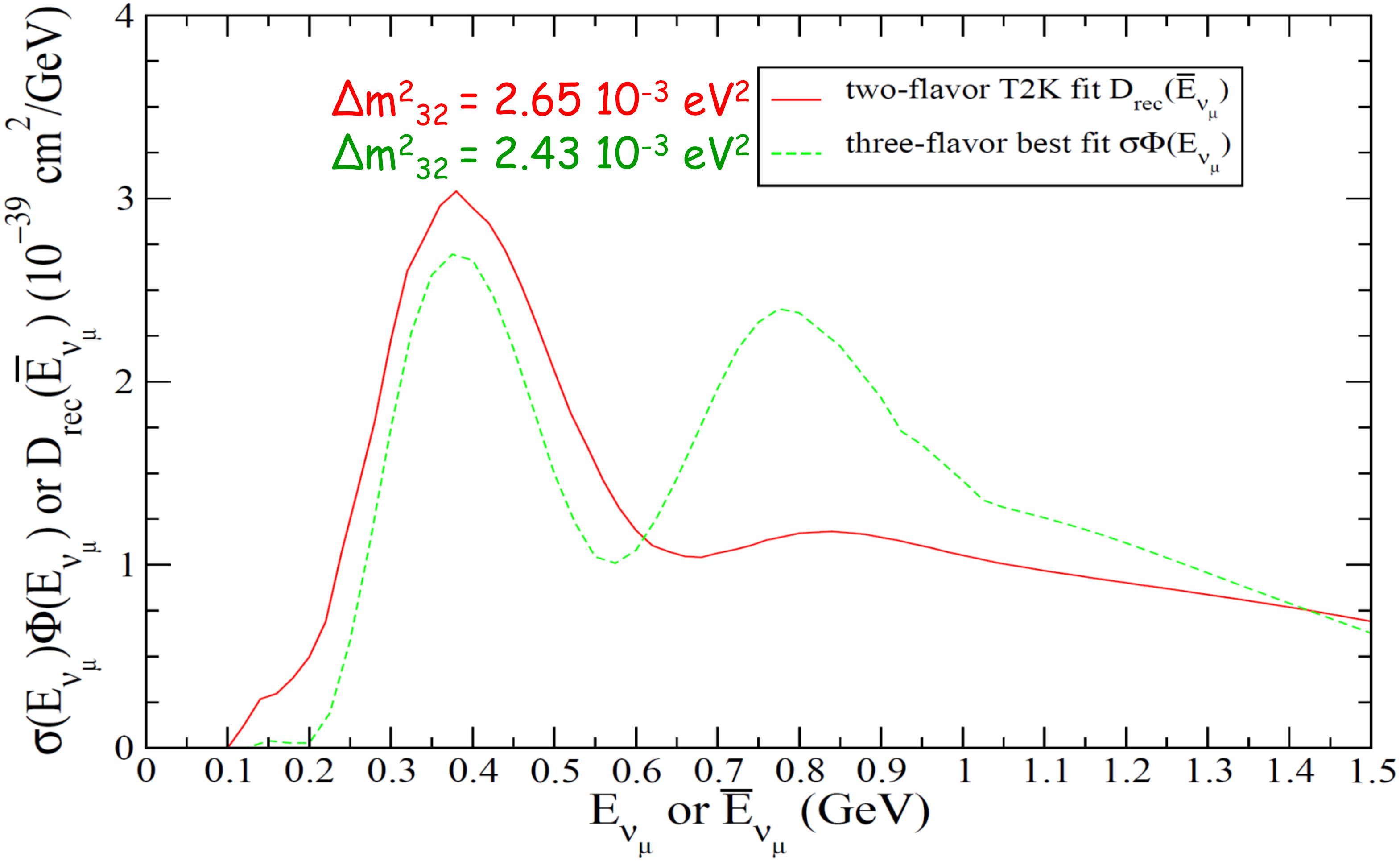


$$\Phi^{FD}_{\nu_\mu}(E_{\nu_\mu}) = \left[1 - 4\cos^2\theta_{13}\sin^2\theta_{23}(1-\cos^2\theta_{13}\sin^2\theta_{23})\sin^2\left(\frac{\Delta m^2_{32}L}{4E_{\nu_\mu}}\right)\right]\Phi^{ND}_{\nu_\mu}(E_{\nu_\mu})$$

Ratio of the distributions FD/ND



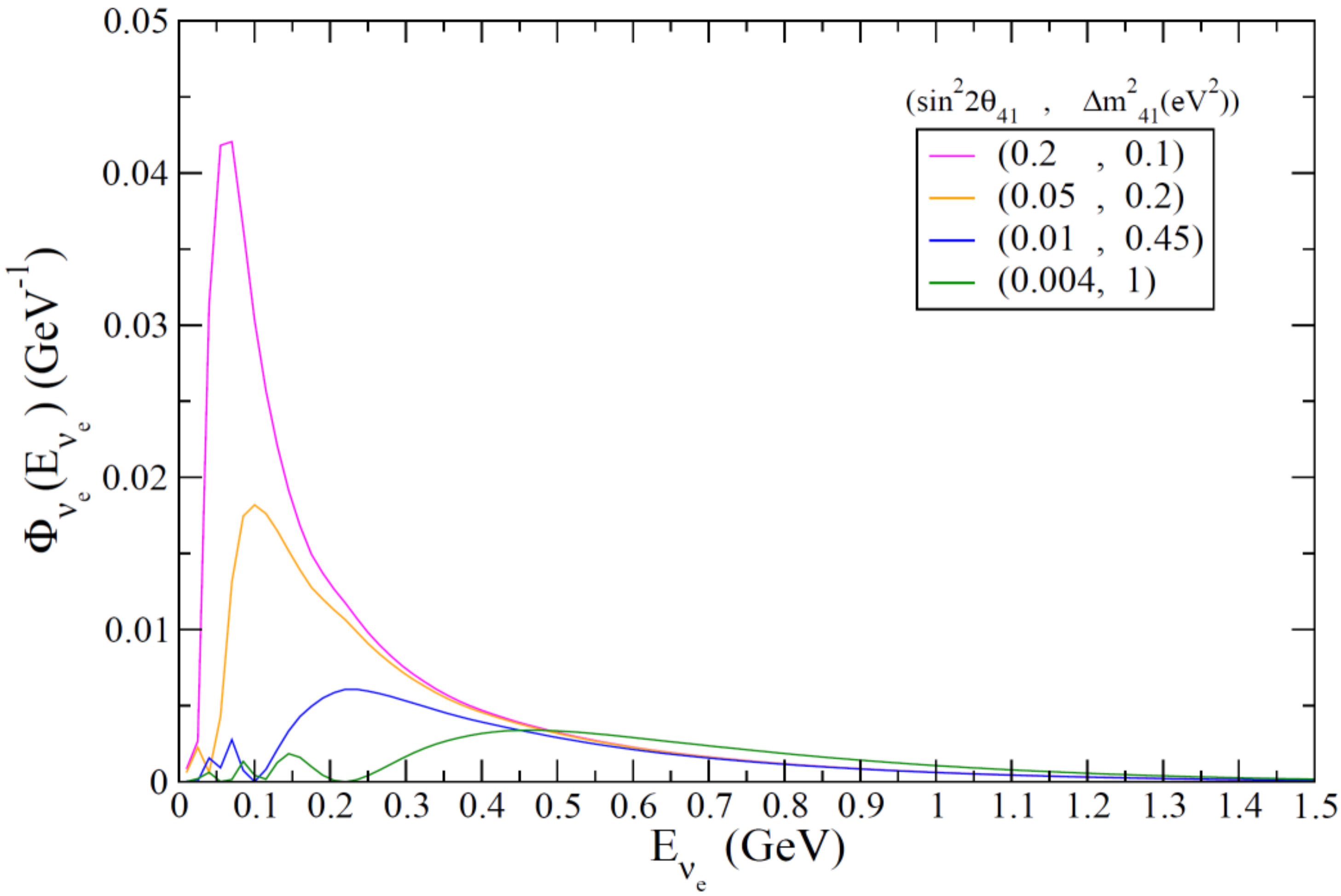
T2K far detector



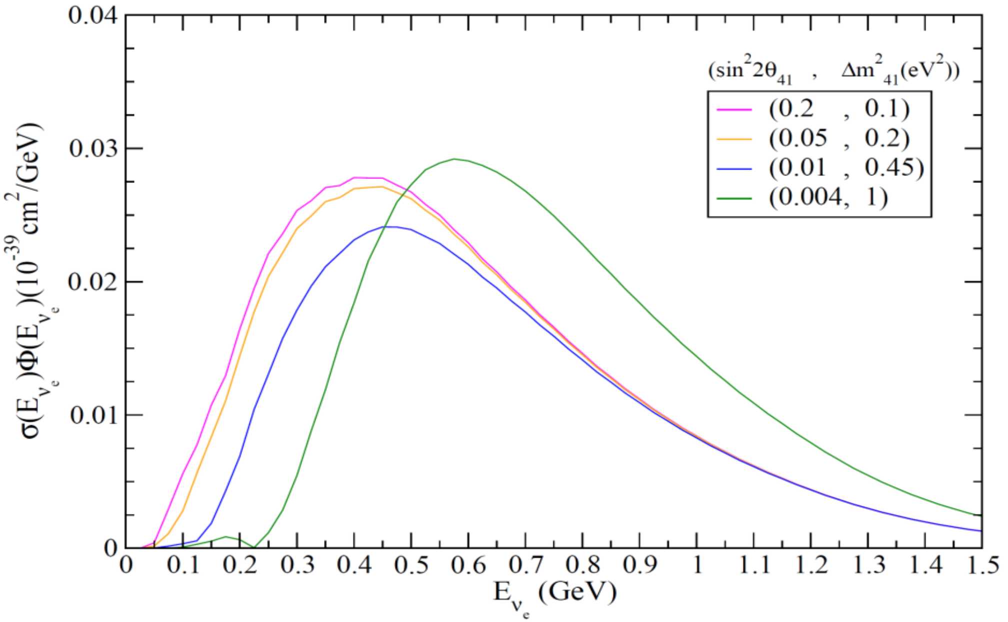
In the first peak region: the smeared curve can be reproduced in the unsmeared case with a lower value of the oscillation mass parameter

Oscillations induced by sterile neutrino; 3+1 hypothesis

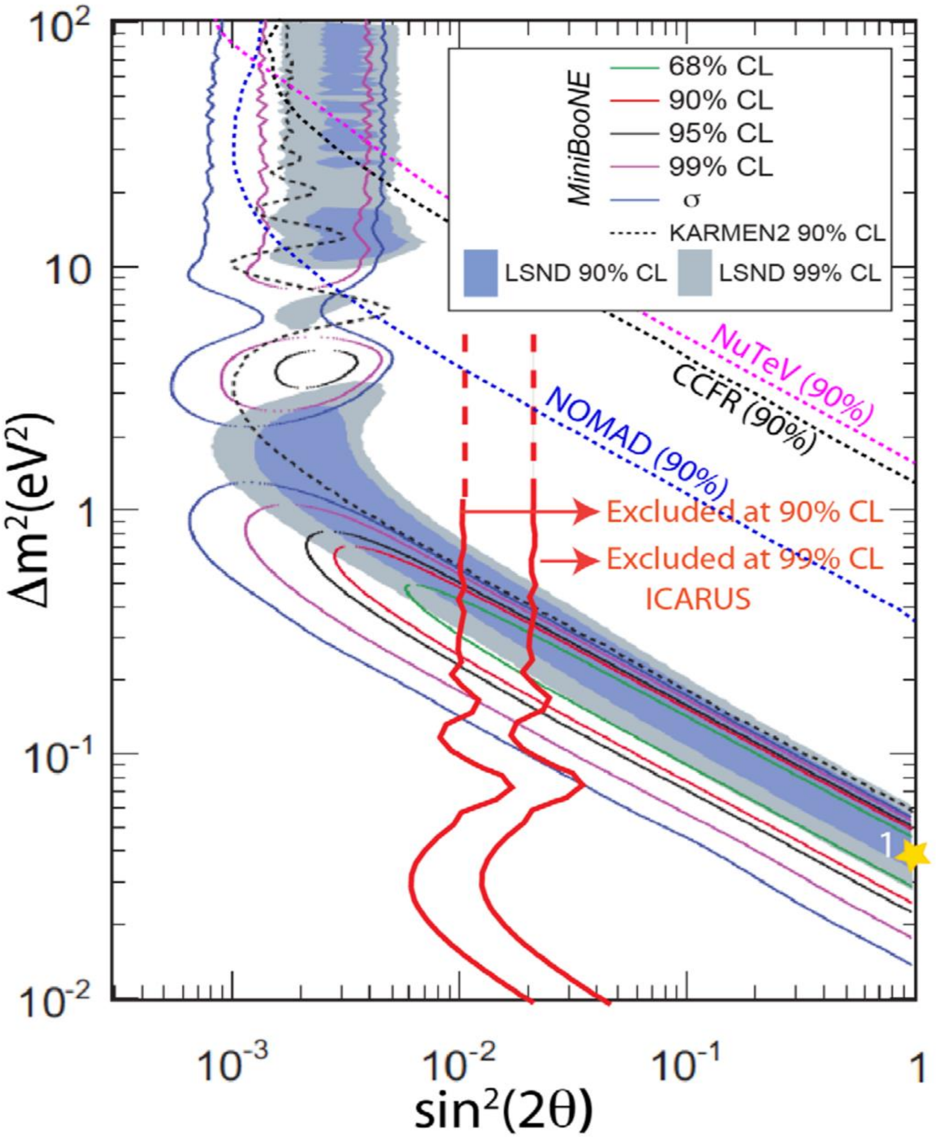
$$\Phi_{\nu_e}(E_{\nu_e}) = \Phi_{\nu_\mu}(E_{\nu_\mu})\sin^2(2\theta_{41})\sin^2\left(\frac{\Delta m^2_{41}L}{4E_\nu}\right)$$



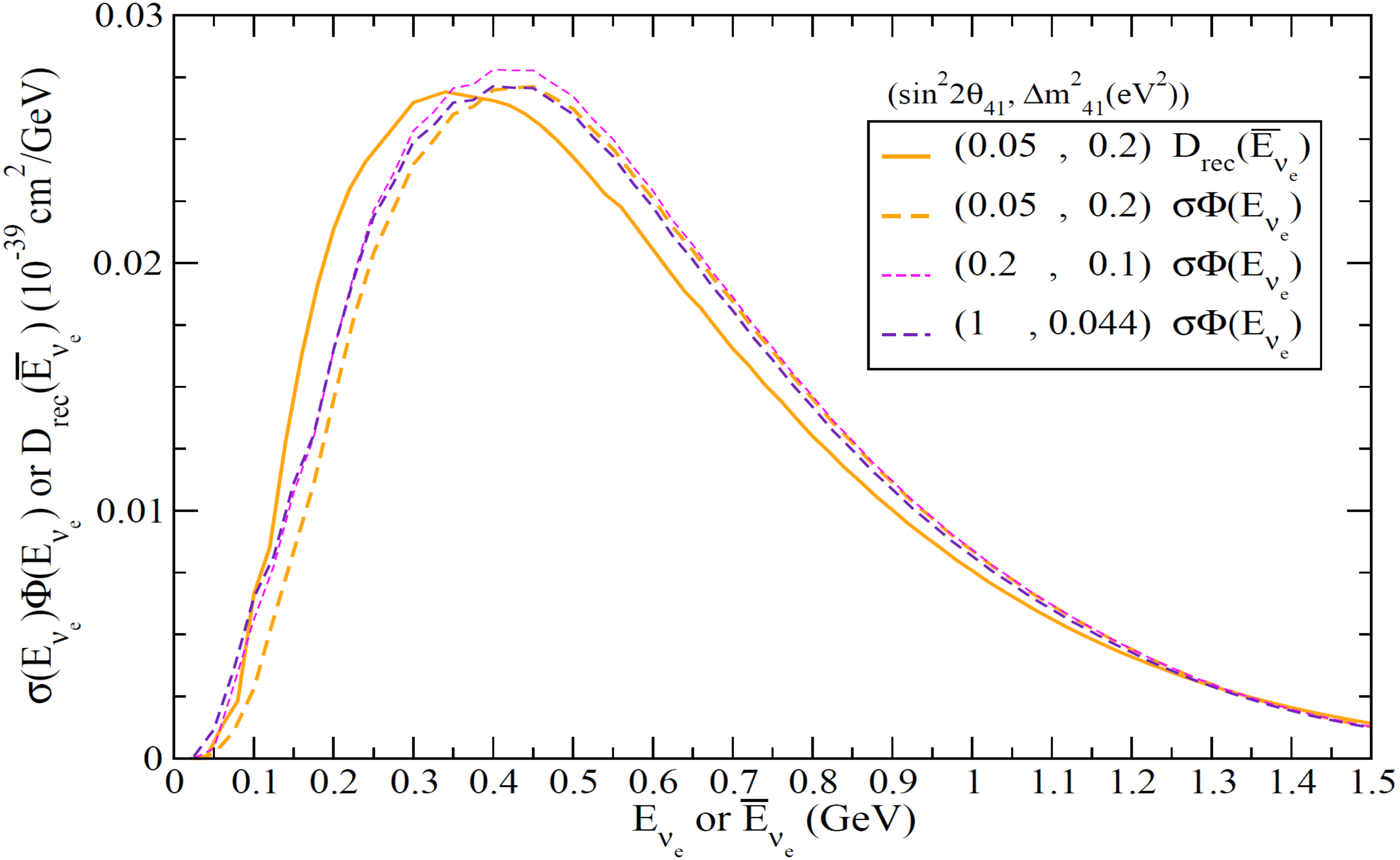
Some considerations on the oscillation parameters



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.



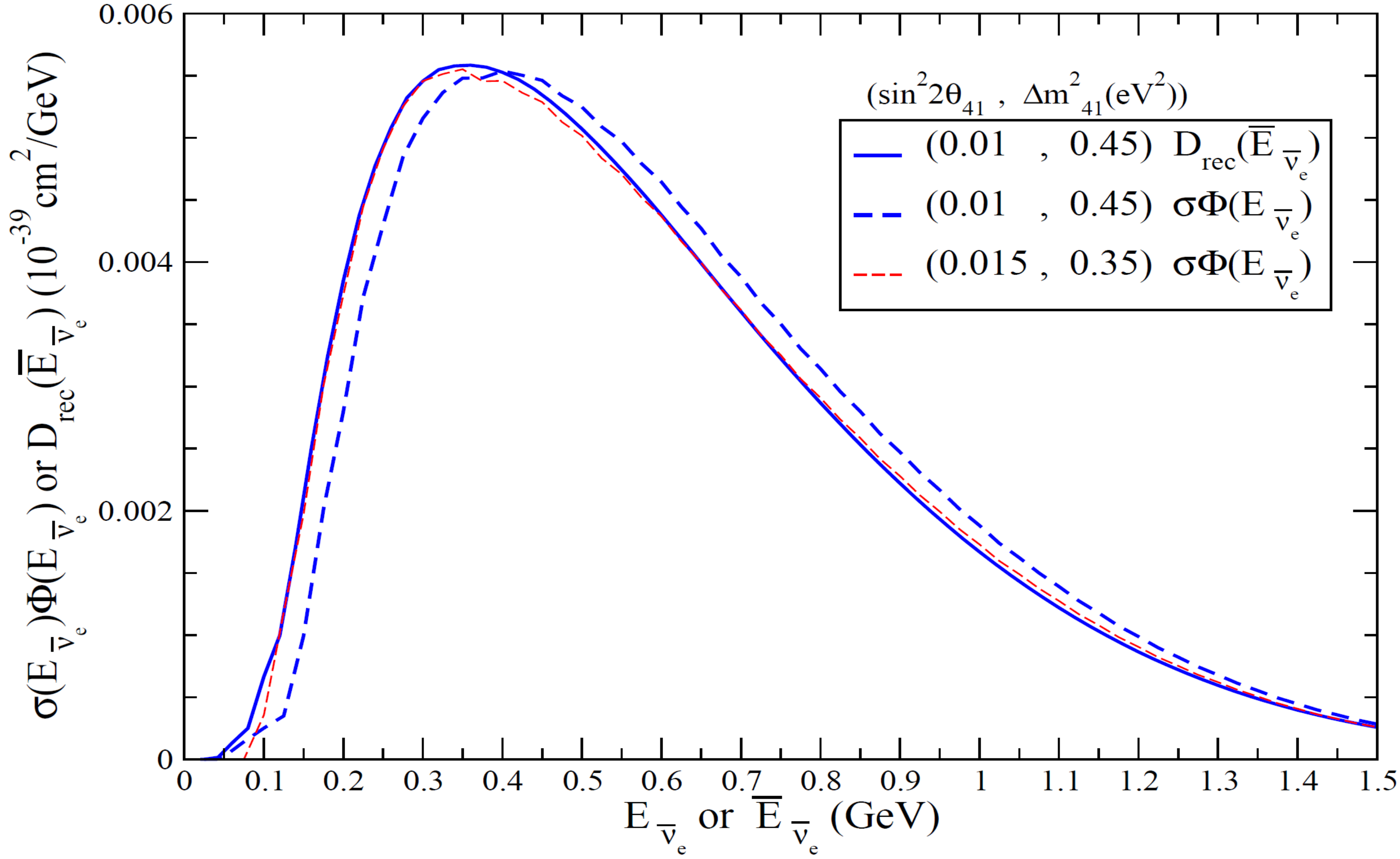
The case of smaller mass values



The smeared curve is shifted at lower energies (displacement of the peak ≈ 80 MeV).

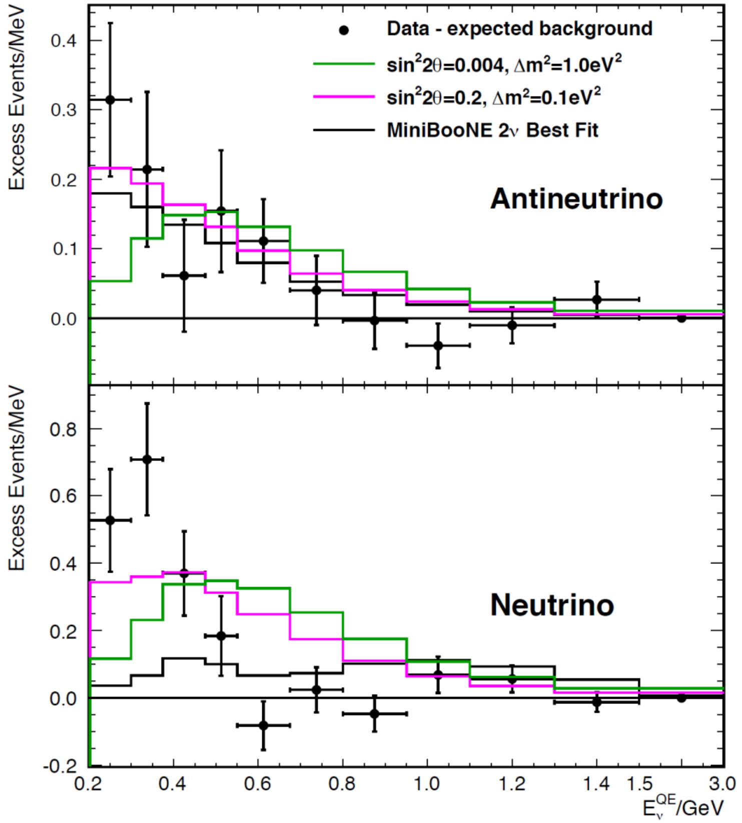
It is impossible to reproduce the smeared curve with an unsmeared one even taking a very small mass.

Antineutrinos



Similar effects, although less pronounced, are present for antineutrinos.

$\nu_\mu \longrightarrow \nu_e$ MiniBooNE



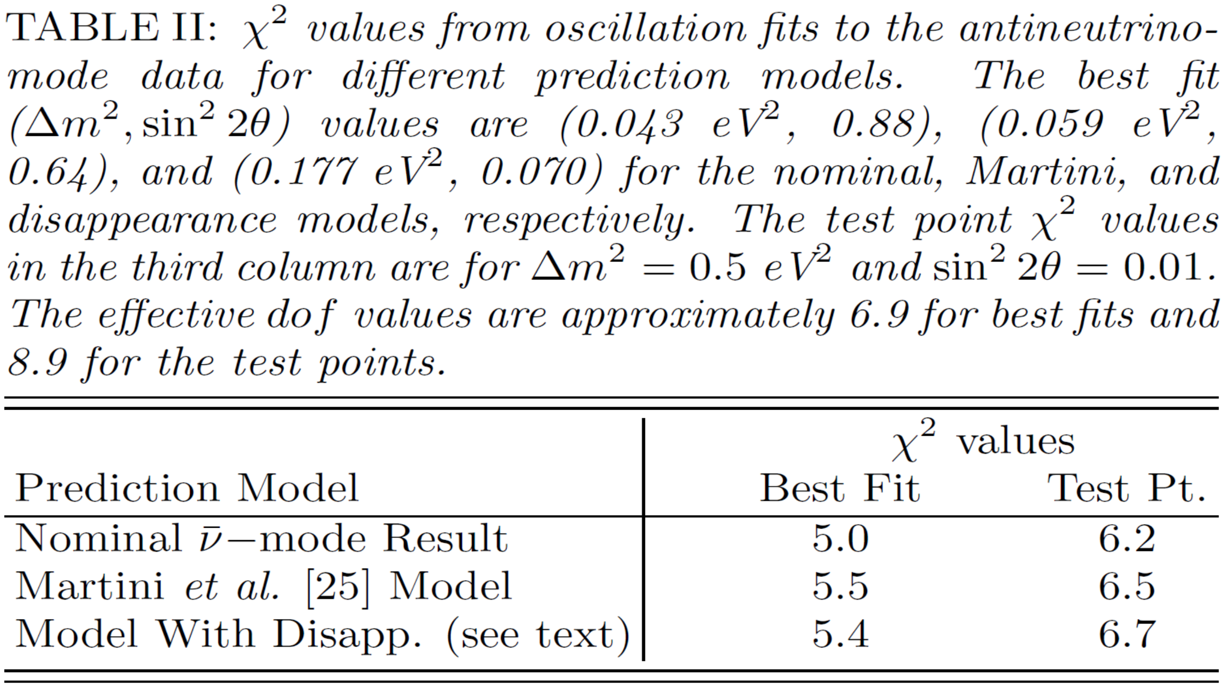
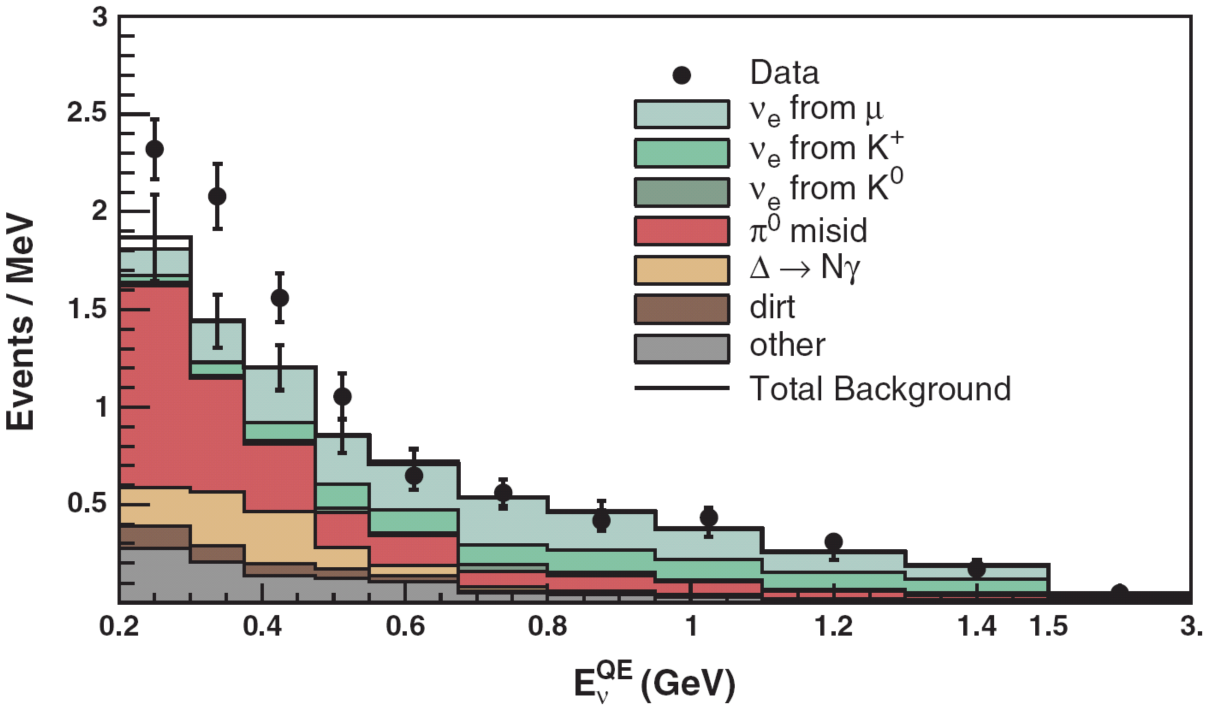


TABLE II: χ^2 *values from oscillation fits to the antineutrino-mode data for different prediction models. The best fit* $(\Delta m^2, \sin^2 2\theta)$ *values are* (*0.043* eV^2, *0.88*), (*0.059* eV^2, *0.64*), *and* (*0.177* eV^2, *0.070*) *for the nominal, Martini, and disappearance models, respectively.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

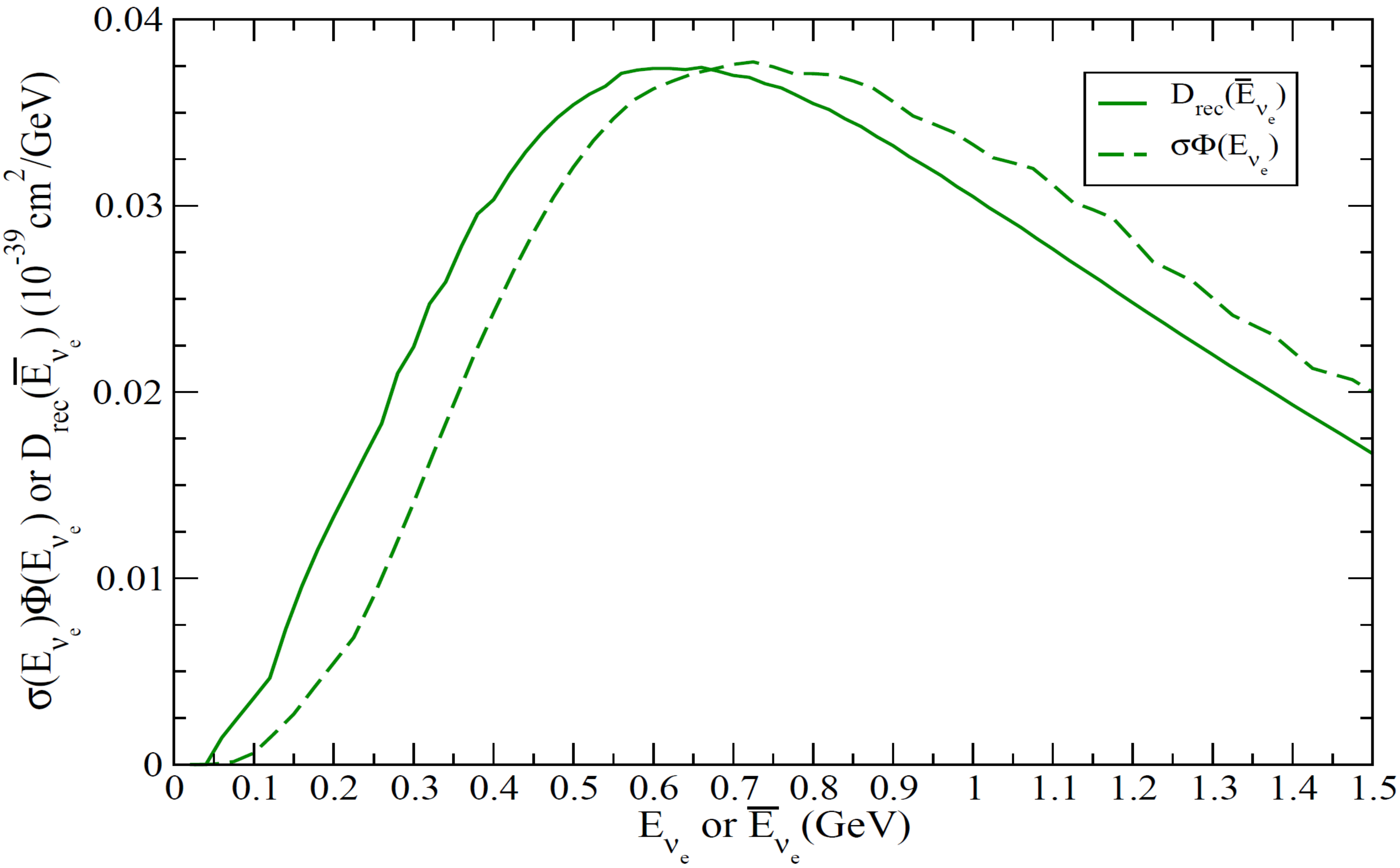
	χ^2 values	
Prediction Model	Best Fit	Test Pt.
Nominal $\bar{\nu}$−mode Result	5.0	6.2
Martini *et al.* [25] Model	5.5	6.5
Model With Disapp. (see text)	5.4	6.7

PRL 110 (2013)

ν_e background and effective cross sections

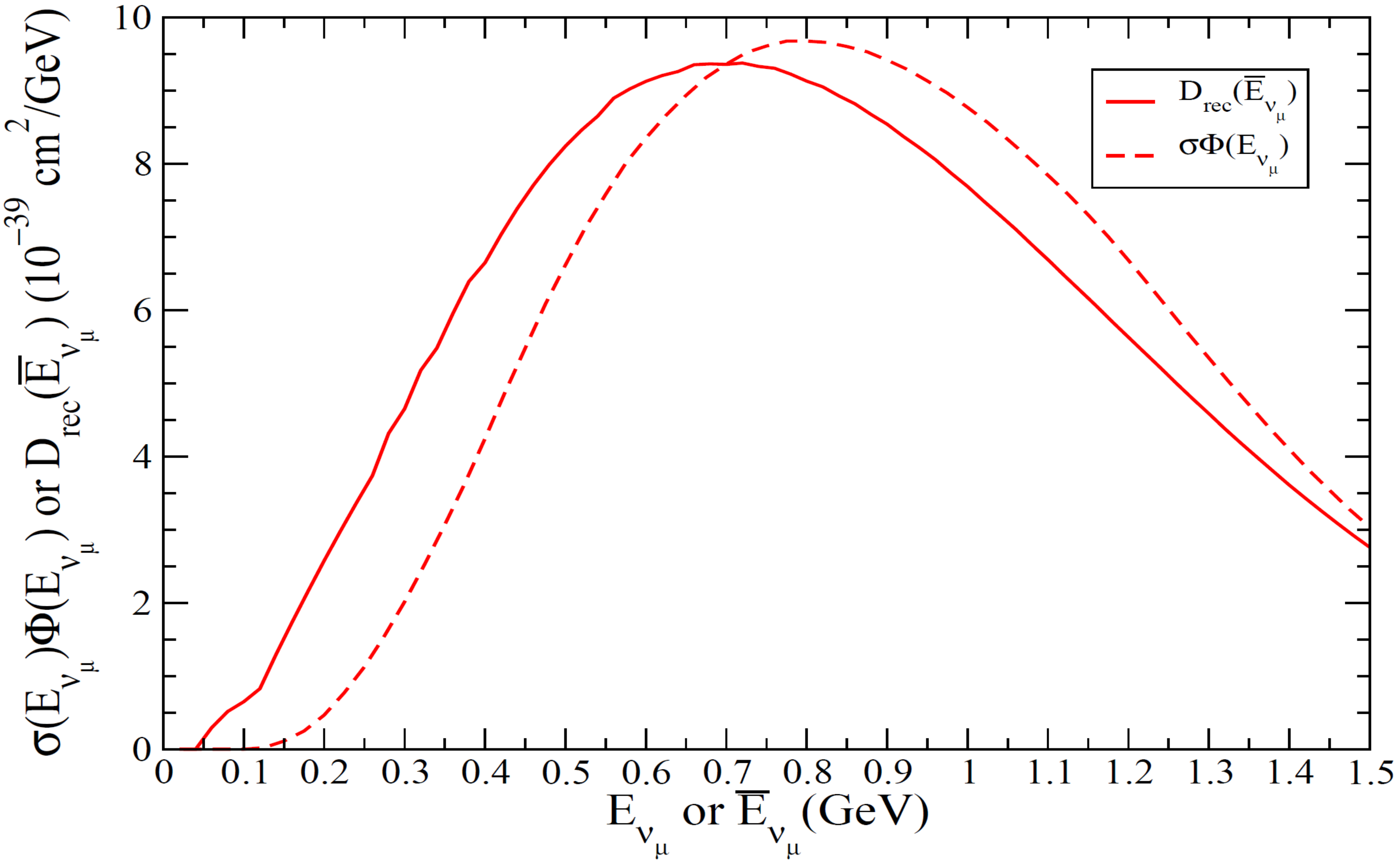


MiniBooNE electron events distribution for νe background



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

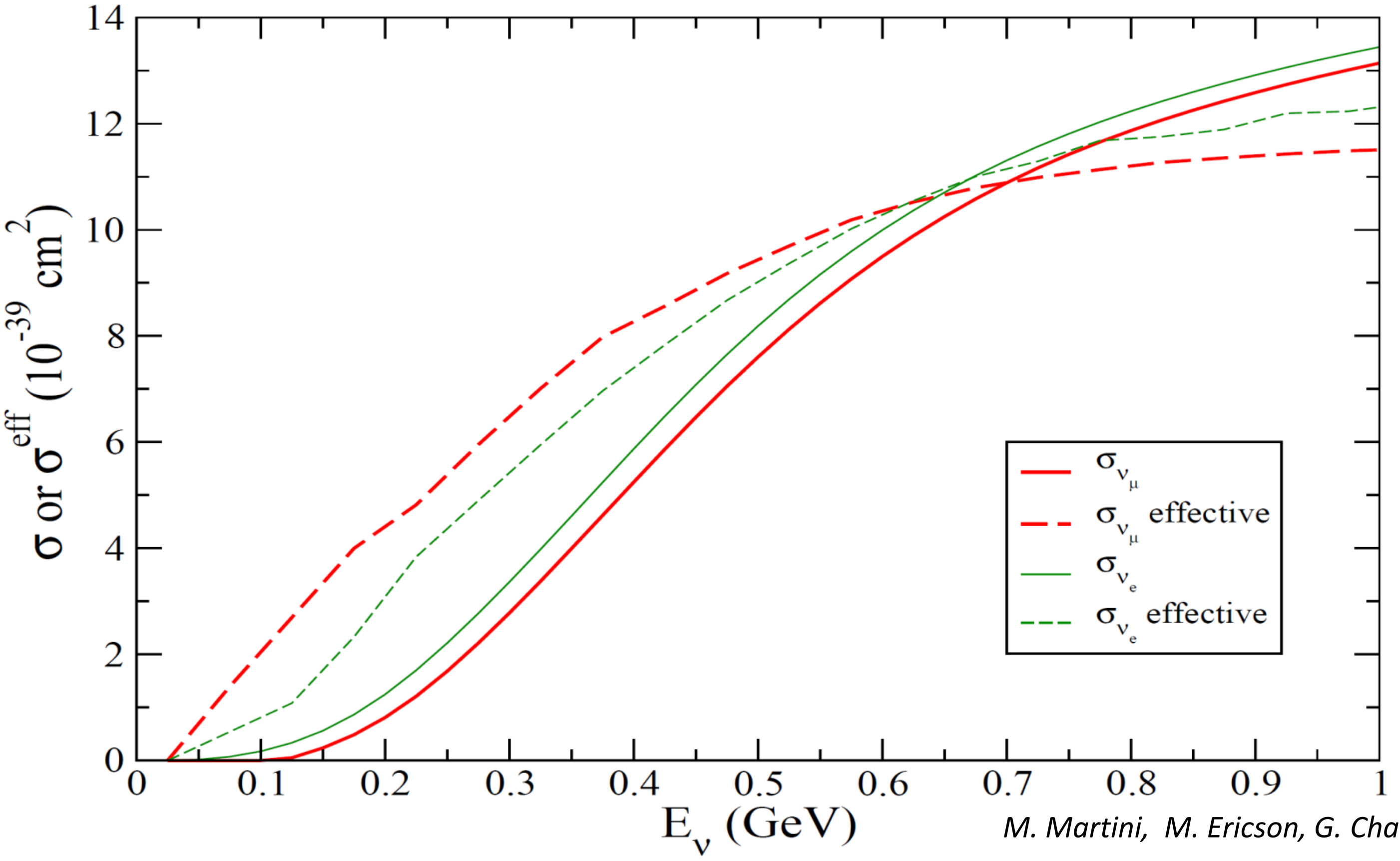
MiniBooNE muon events distribution



Real and effective cross sections for ν_μ and ν_e

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

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



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

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

(here we used ν_μ and ν_e MiniBooNE fluxes)

Real and effective cross sections for μ