

# Neutrino-nucleus interactions: from nuclear dynamics to neutrino oscillations

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Preamble:  
neutrino oscillations physics

# Neutrino Oscillations

Flavor neutrinos  $\nu_e, \nu_\mu, \nu_\tau$  produced in Weak interactions

Massive neutrinos  $\nu_1, \nu_2, \nu_3$  propagate from source to detector

A flavor neutrino is a superposition of massive neutrinos

$$\nu_\alpha = U_{\alpha i} \nu_i \quad \begin{array}{l} \alpha = e, \mu, \tau \\ i = 1, 2, 3 \end{array}$$

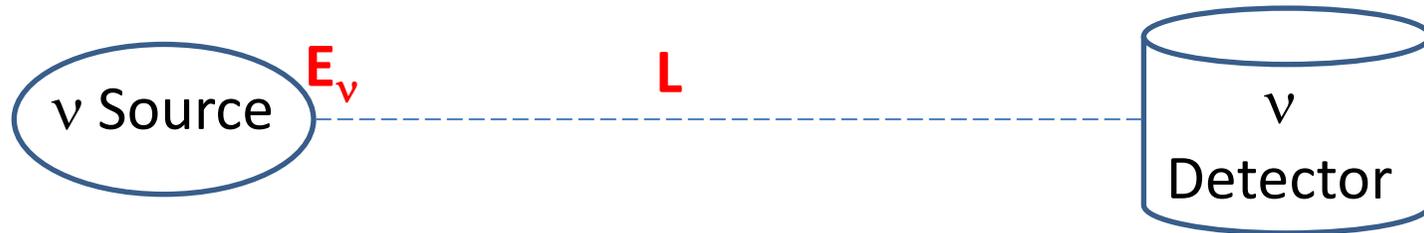
↑  
Mixing Matrix  
(PMNS)

Neutrino oscillations are flavor transitions

$$\begin{array}{cccc} \nu_e \rightarrow \nu_\mu & \nu_e \rightarrow \nu_\tau & \nu_\mu \rightarrow \nu_e & \nu_\mu \rightarrow \nu_\tau \\ \bar{\nu}_e \rightarrow \bar{\nu}_\mu & \bar{\nu}_e \rightarrow \bar{\nu}_\tau & \bar{\nu}_\mu \rightarrow \bar{\nu}_e & \bar{\nu}_\mu \rightarrow \bar{\nu}_\tau \end{array}$$

# Neutrino physics

Perform appearance and/or disappearance experiments using different neutrino sources and baselines



$$P(\nu_\alpha \rightarrow \nu_\beta) = \sum_{ij} U_{\alpha i} U_{\beta i}^* U_{\alpha j}^* U_{\beta j} e^{-i \frac{(m_i^2 - m_j^2)L}{2E}}$$

Reactor  $\nu$

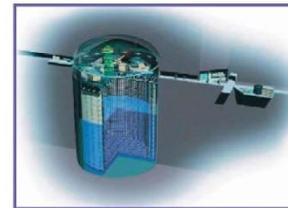
$E \sim 5$  MeV ;  $L \sim 1$ -100 km

e.g. Double Chooz  $E \sim 5$  MeV ;  $L \sim 1$  km

Accelerator  $\nu$

$E \sim 0.6$  - 20 GeV ;  $L \sim 300$  - 1300 km

e.g. T2K:  $E \sim 0.6$  GeV ;  $L \sim 300$  km



Super-Kamiokande  
(ICRR, Univ. Tokyo)



J-PARC Main Ring  
(KEK-JAEA, Tokai)



# The Pontecorvo-Maki-Nakagawa-Sakata Mixing Matrix

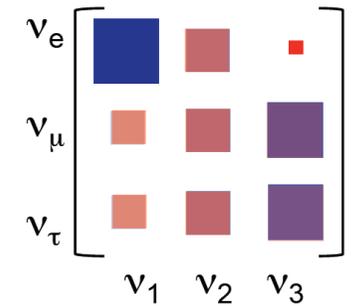
$$U_{\text{PMNS}} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\substack{\text{Atmospheric } \nu \\ \text{Accelerator } \nu}} \underbrace{\begin{pmatrix} c_{13} & 0 & e^{-i\delta_{\text{CP}}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\text{CP}}} s_{13} & 0 & c_{13} \end{pmatrix}}_{\substack{\text{SBL reactor } \nu \\ \text{Accelerator } \nu}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\substack{\text{solar } \nu \\ \text{LBL reactor } \nu}}$$

$(\theta_{12}, \theta_{23}, \theta_{13})$

3 mixing angles

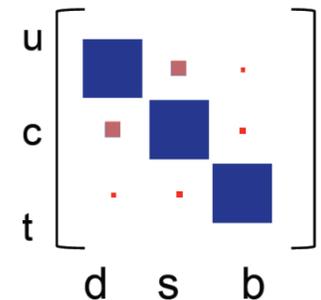
$\delta_{\text{CP}}$   
CP-violating phase

$$|U_{\text{PMNS}}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.1 \\ 0.5 & 0.6 & 0.7 \\ 0.3 & 0.6 & 0.7 \end{pmatrix}$$



## The Cabibbo-Kobayashi-Maskawa Quark Mixing Matrix

$$|V_{\text{CKM}}| \sim \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$



# Present and future of neutrino oscillation physics

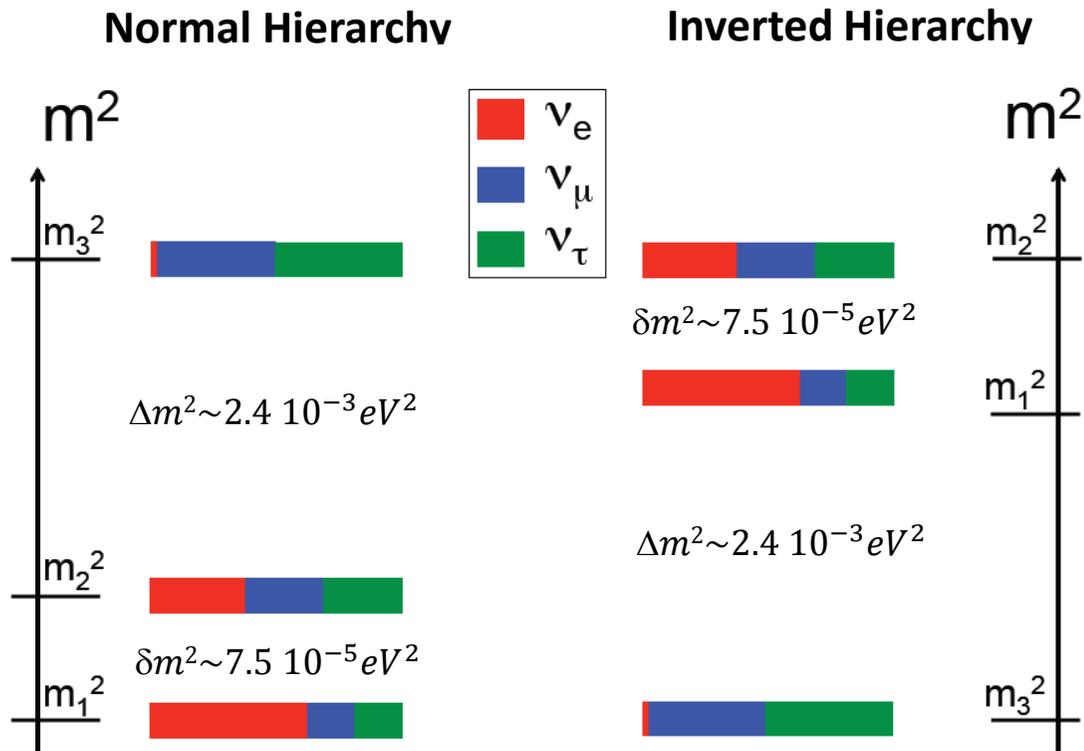
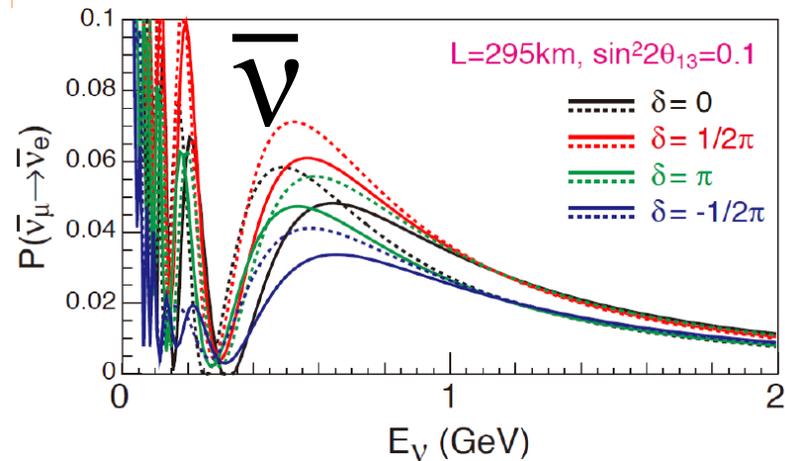
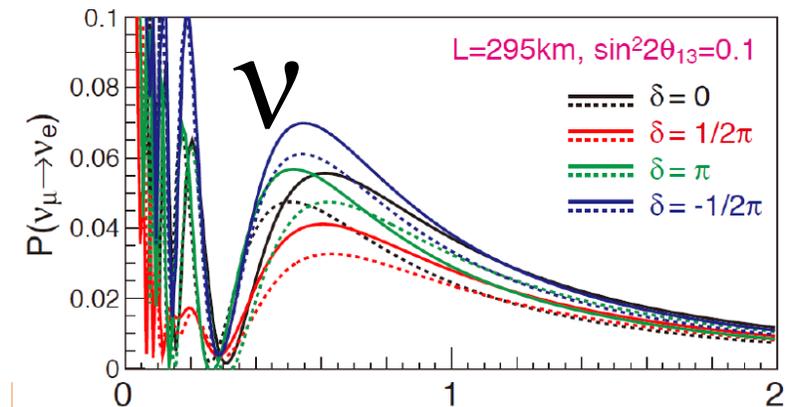
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

sun reactors →  $U_{e1}$     $U_{e2}$     $U_{e3}$   
Atmosph., Accel. ↑  $U_{\tau3}$

- The mixing parameters not known to the same precision as those in the quark sector

- The value of  $\delta_{CP}$  is undetermined

- The ordering of the mass states i.e. the **neutrino mass hierarchy** is undetermined



# Neutrino oscillation experiments

Number of events

$$N_{\beta} \sim \Phi_{\nu_{\alpha}}(E_{\nu}) \sigma_{\nu_{\beta}}(E_{\nu}) \varepsilon_{det.} P_{\nu_{\alpha} \rightarrow \nu_{\beta}}(\{\Theta\}, E_{\nu})$$

$\nu$  flux  
(prediction)

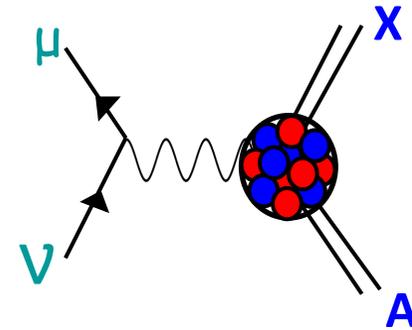
$\nu$  cross section  
(model)

Detector  
efficiency

$\nu$  Energy in the  
oscillation probability

Modern accelerator-based neutrino oscillation experiments:

- Nuclear targets (C, O, Ar, Fe...)
- The neutrino energy is reconstructed from the final states

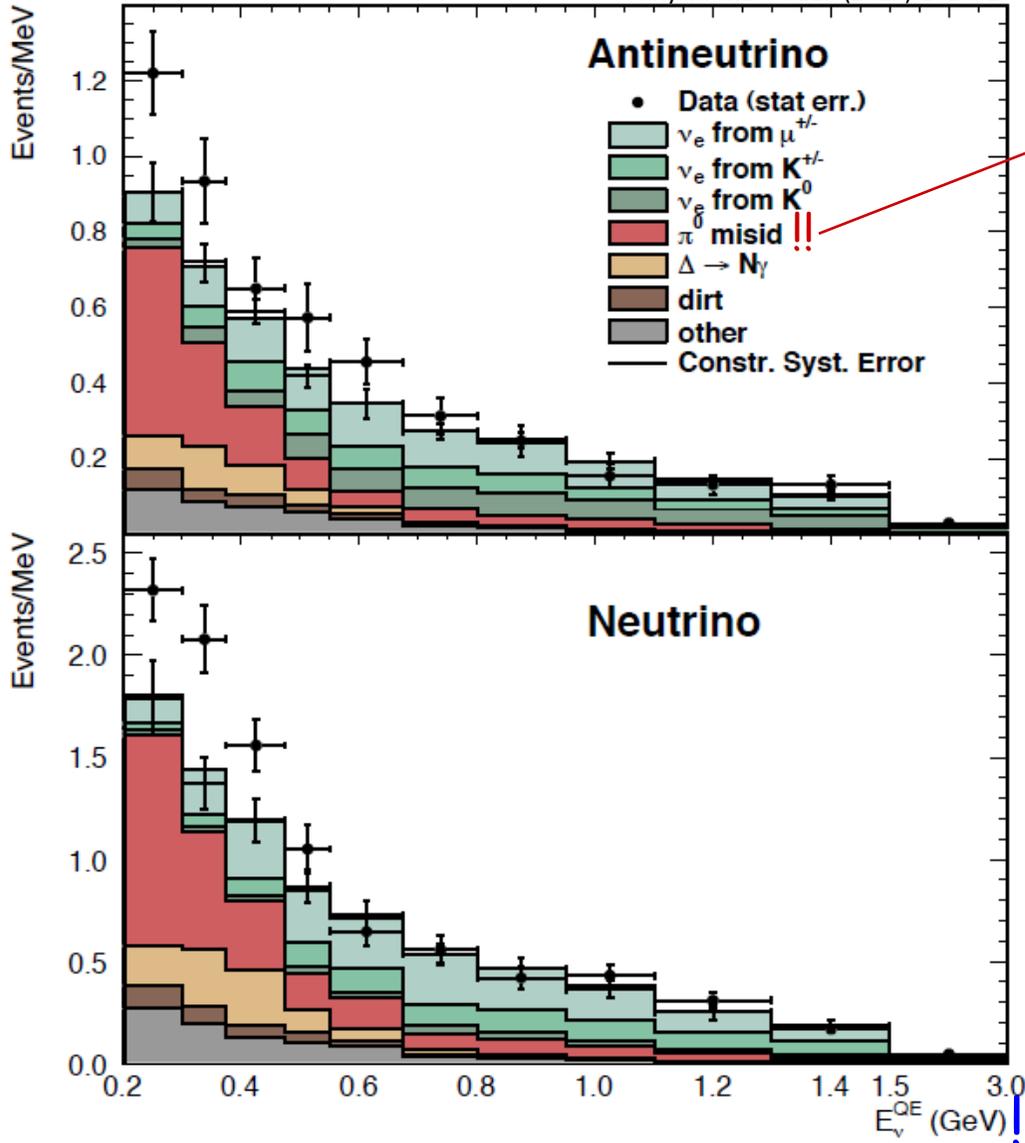


the knowledge of the neutrino-nucleus  
cross section is crucial

# $\nu_\mu \rightarrow \nu_e$

## MiniBooNE

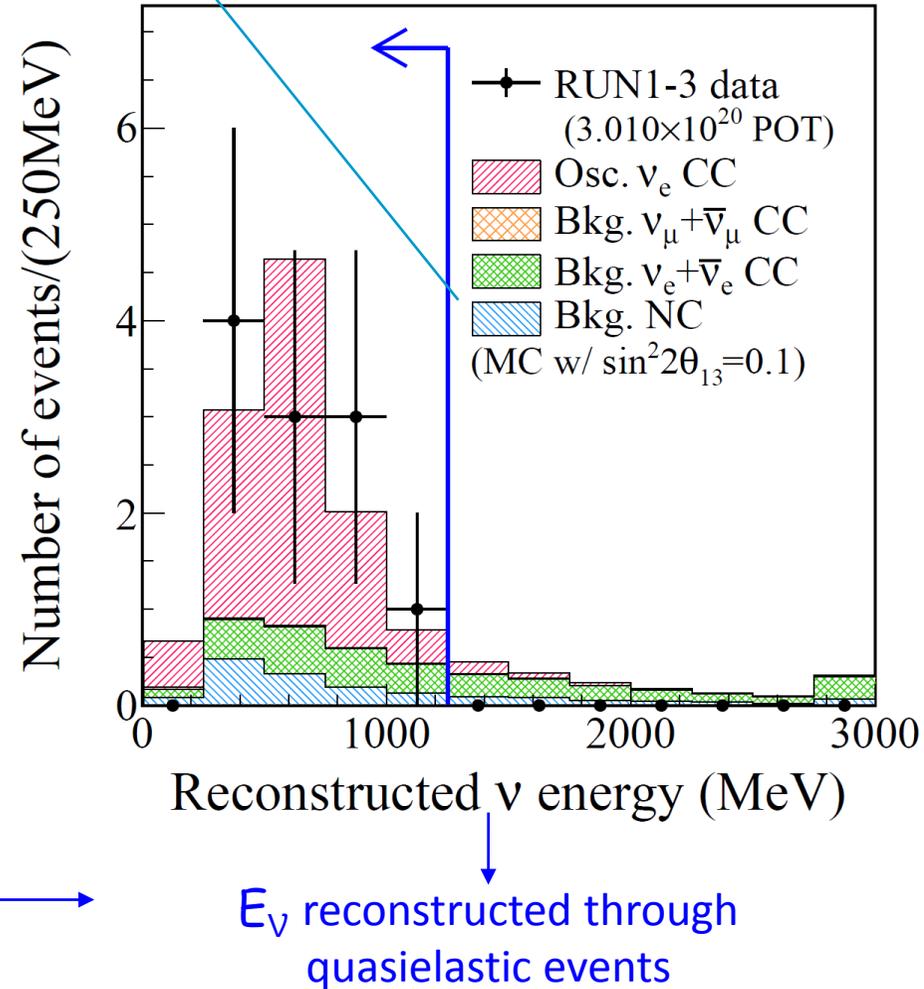
Phys.Rev.Lett. 110 (2013) 161801



NC  $\pi^0$  important background

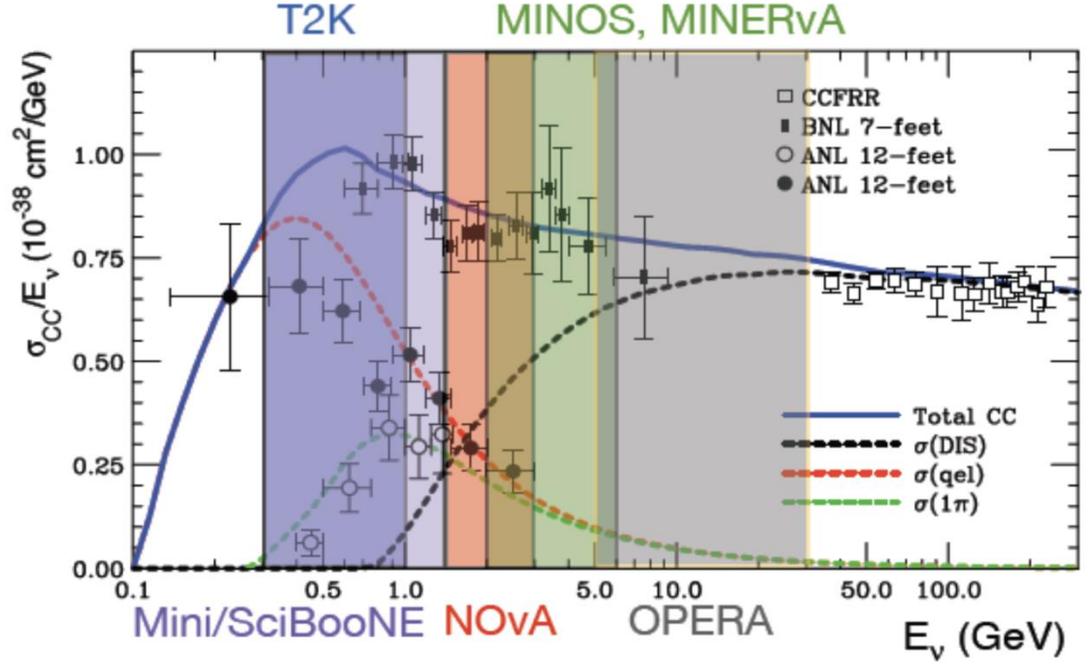
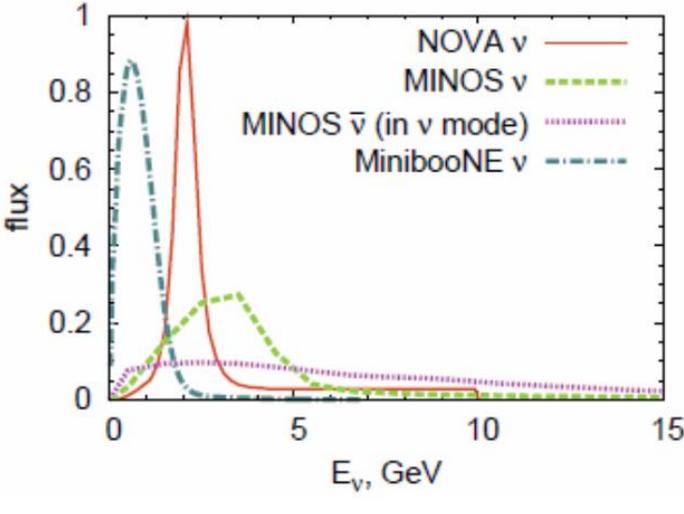
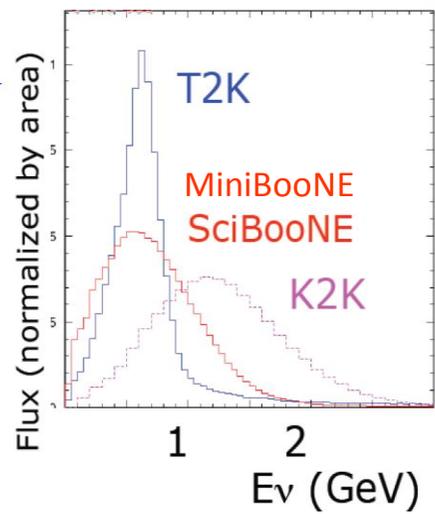
Phys.Rev. D88 (2013) 032002

## T2K



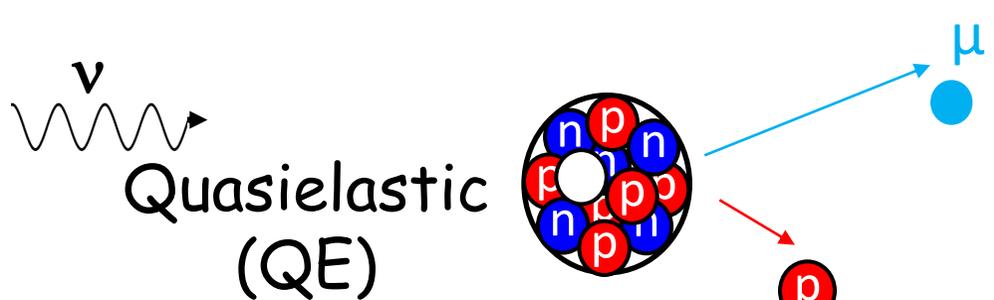
# Some crucial points of the accelerator-based $\nu$ experiment

- 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

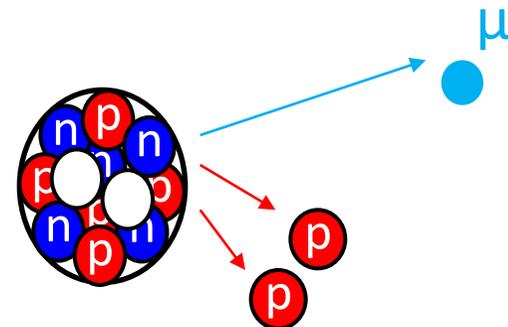


# Neutrino - nucleus interaction @ $E_\nu \sim 0$ (1 GeV)

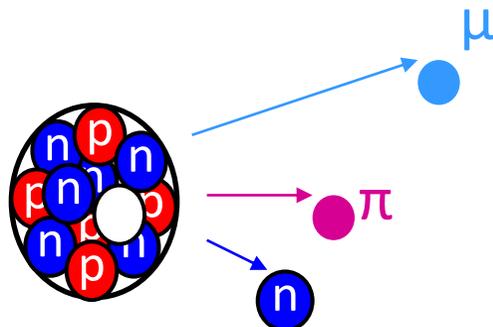
[MiniBooNE, T2K energies]



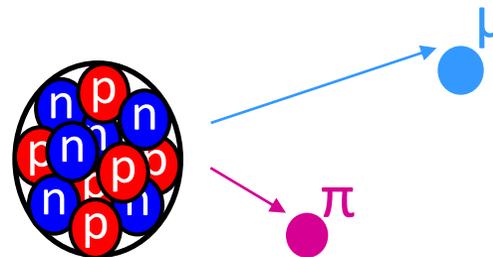
Two Nucleons  
knock-out  
(2p-2h)



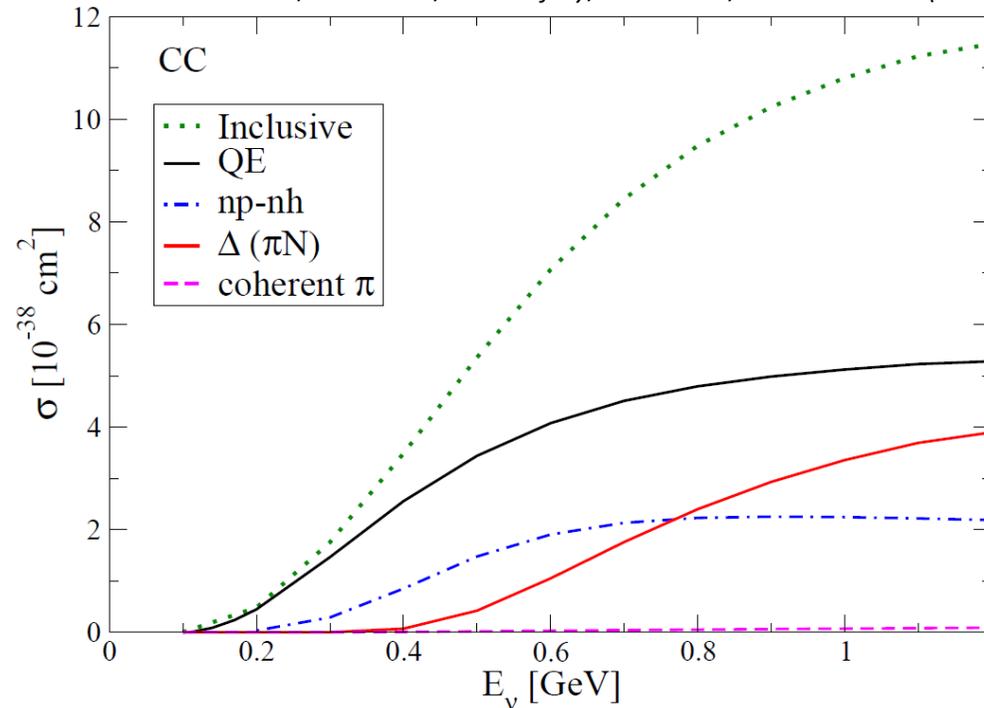
Incoherent  $\pi$  production



Coherent  $\pi$  production



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



Different processes are entangled

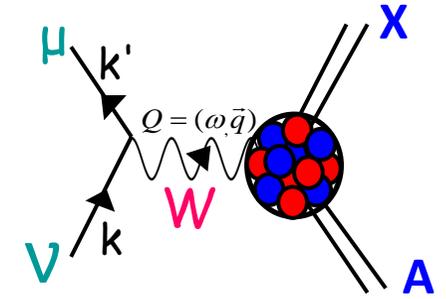
# Neutrino-nucleus cross sections

- In collaboration with:
  - Magda Ericson (CERN, IPN Lyon)
  - Guy Chanfray, Jacques Marteau (IPN Lyon)

# Neutrino-nucleus cross section

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

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



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

Leptonic tensor Hadronic tensor

The cross section in terms of the response functions:

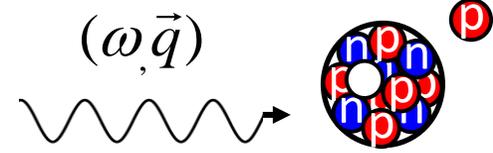
$$\frac{\partial^2 \sigma}{\partial \Omega \partial \epsilon'} = \frac{G_F^2 \cos^2 \theta_c}{2 \pi^2} k' \epsilon' \cos^2 \frac{\theta}{2} \left[ \frac{(q^2 - \omega^2)^2}{q^4} \underline{G_E^2} \underline{R_\tau} + \frac{\omega^2}{q^2} \underline{G_A^2} \underline{R_{\sigma\tau(L)}} + 2 \left( \tan^2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

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

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

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

# The nuclear response



## Nucleon-Nucleon interaction switched off

Nucleons respond individually

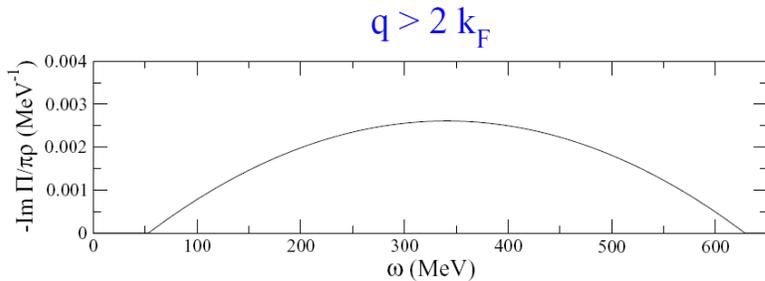
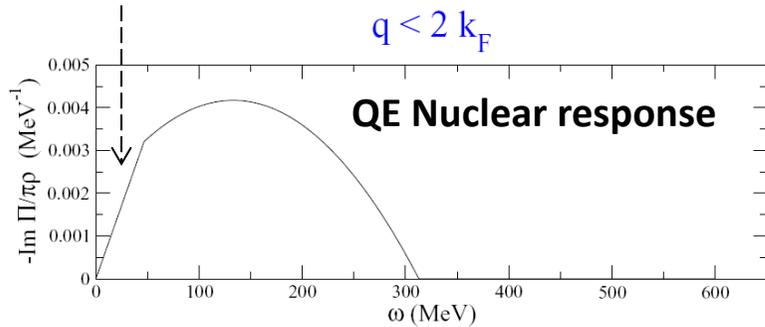
Nucleon at rest:

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

Nucleon inside the nucleus:

**Fermi motion** spreads  $\delta$  distribution (**Fermi Gas**)

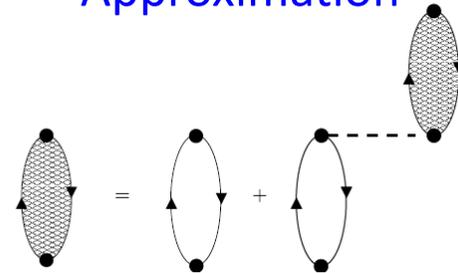
**Pauli blocking** cuts part of the low momentum Resp.



## Nucleon-Nucleon interaction switched on

The nuclear response becomes collective

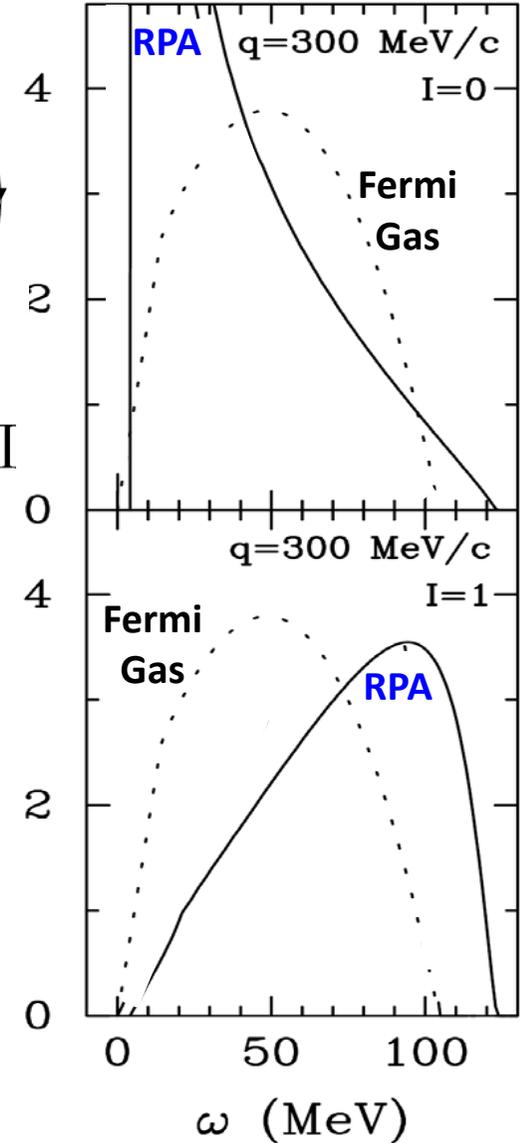
**Random Phase Approximation**



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

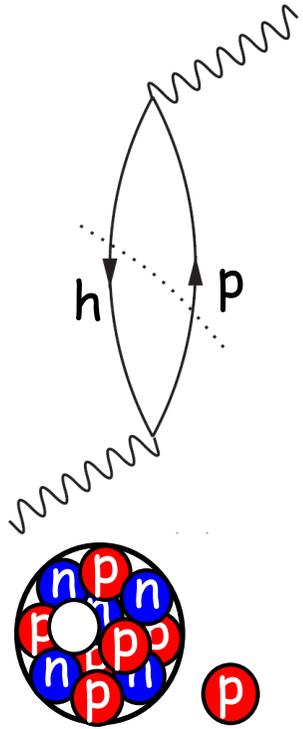
\*Force acting on one nucleon is transmitted by the interaction  
\*Shift of the peak with respect to Fermi Gas, decrease, increase,...

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

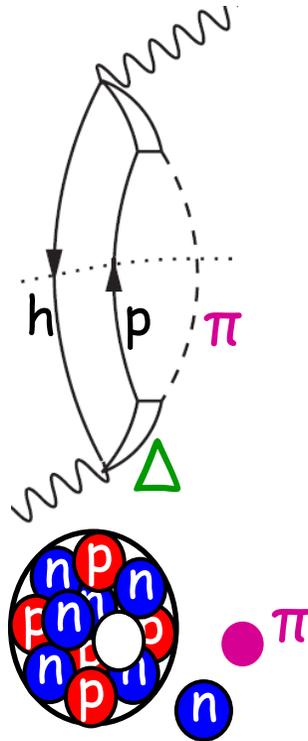


# Nuclear Response Functions

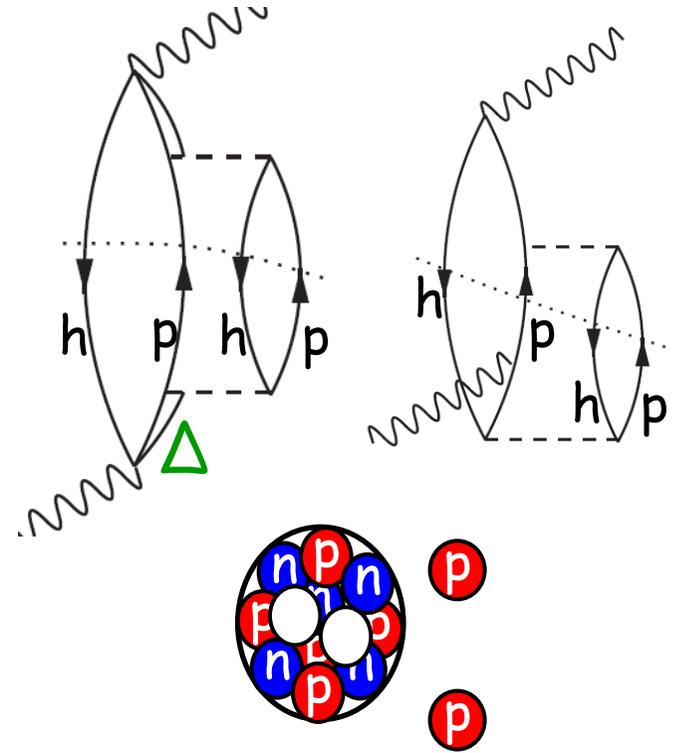
1p-1h  
QE



1p-1h  
 $1\pi$  production

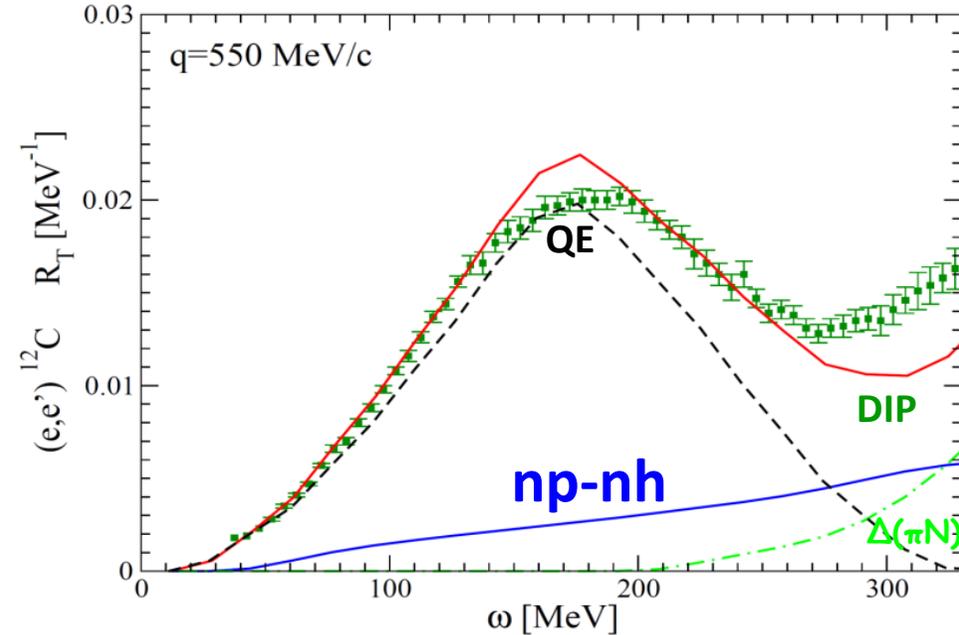
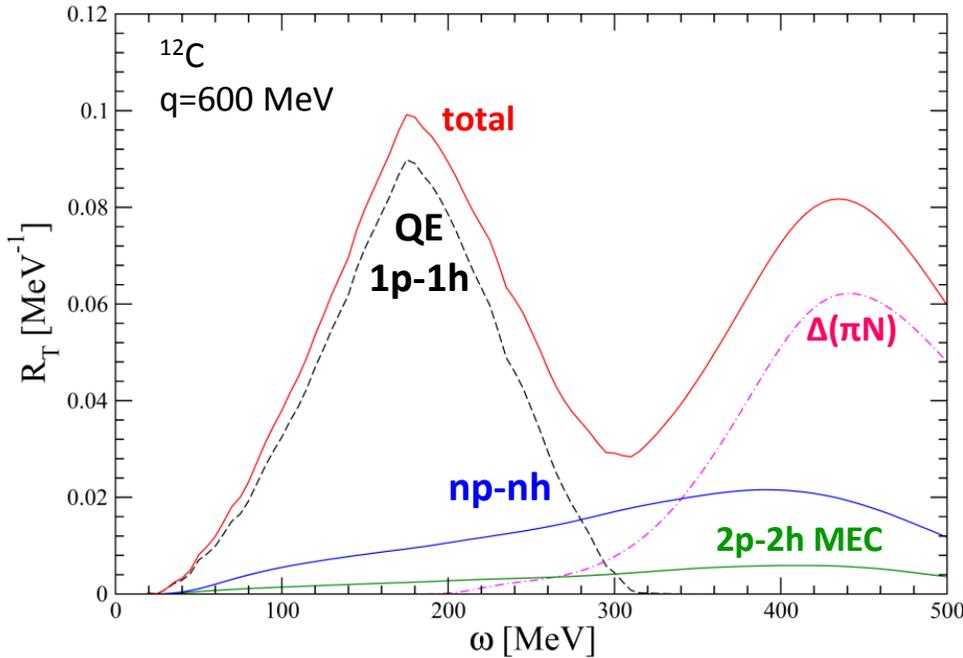


2p-2h:  
two examples



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

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



**QE peak:**

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

**$\Delta$  peak:**

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

**np-nh excitations fill the DIP region**

# Form Factors

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

Standard dipole parameterization

Vector

$$\underline{G_E}(Q^2) = \underline{G_M}(Q^2) / (\mu_p - \mu_n) = (1 + Q^2 / M_V^2)^{-2} \quad Q^2 = q^2 - \omega^2 \\ M_V = 0.84 \text{ GeV} / c^2$$

Axial

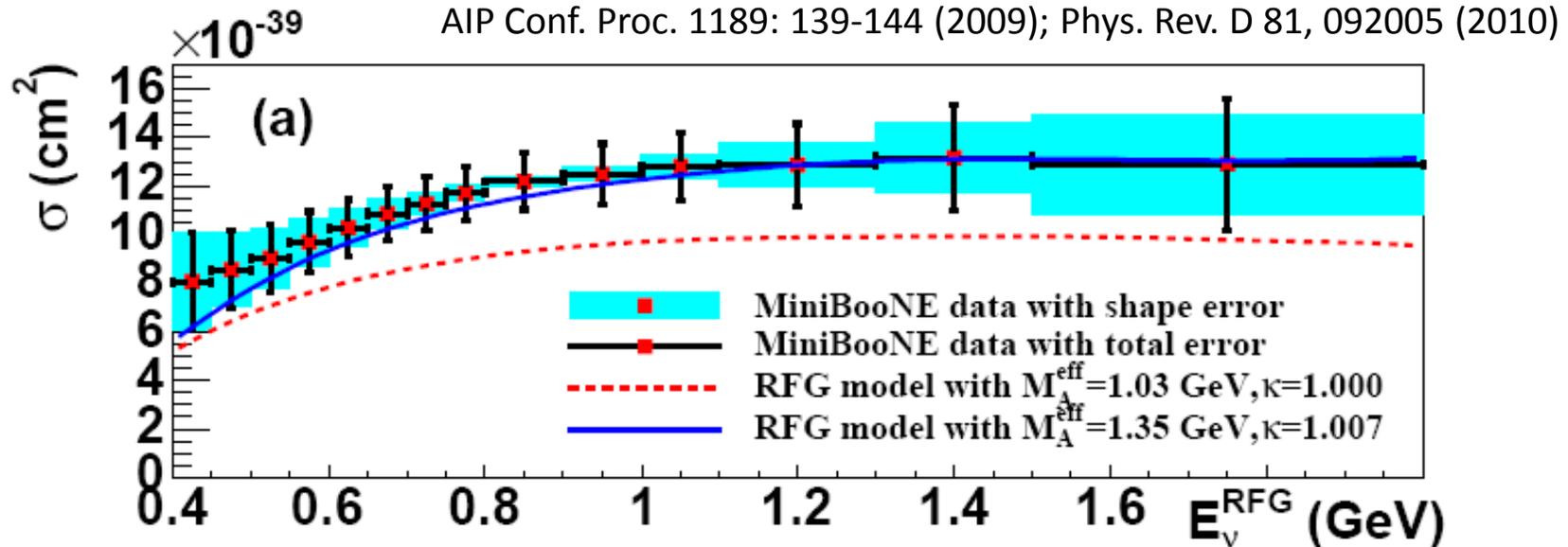
$$\underline{G_A}(Q^2) = g_A (1 + Q^2 / M_A^2)^{-2} \quad g_A = 1.26 \text{ from neutron } \beta \text{ decay}$$

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

from  $\nu$ -deuterium CCQE and from  $\pi$  electroproduction

# Quasielastic and MiniBooNE

# MiniBooNE CC Quasielastic cross section on Carbon and the $M_A$ puzzle



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

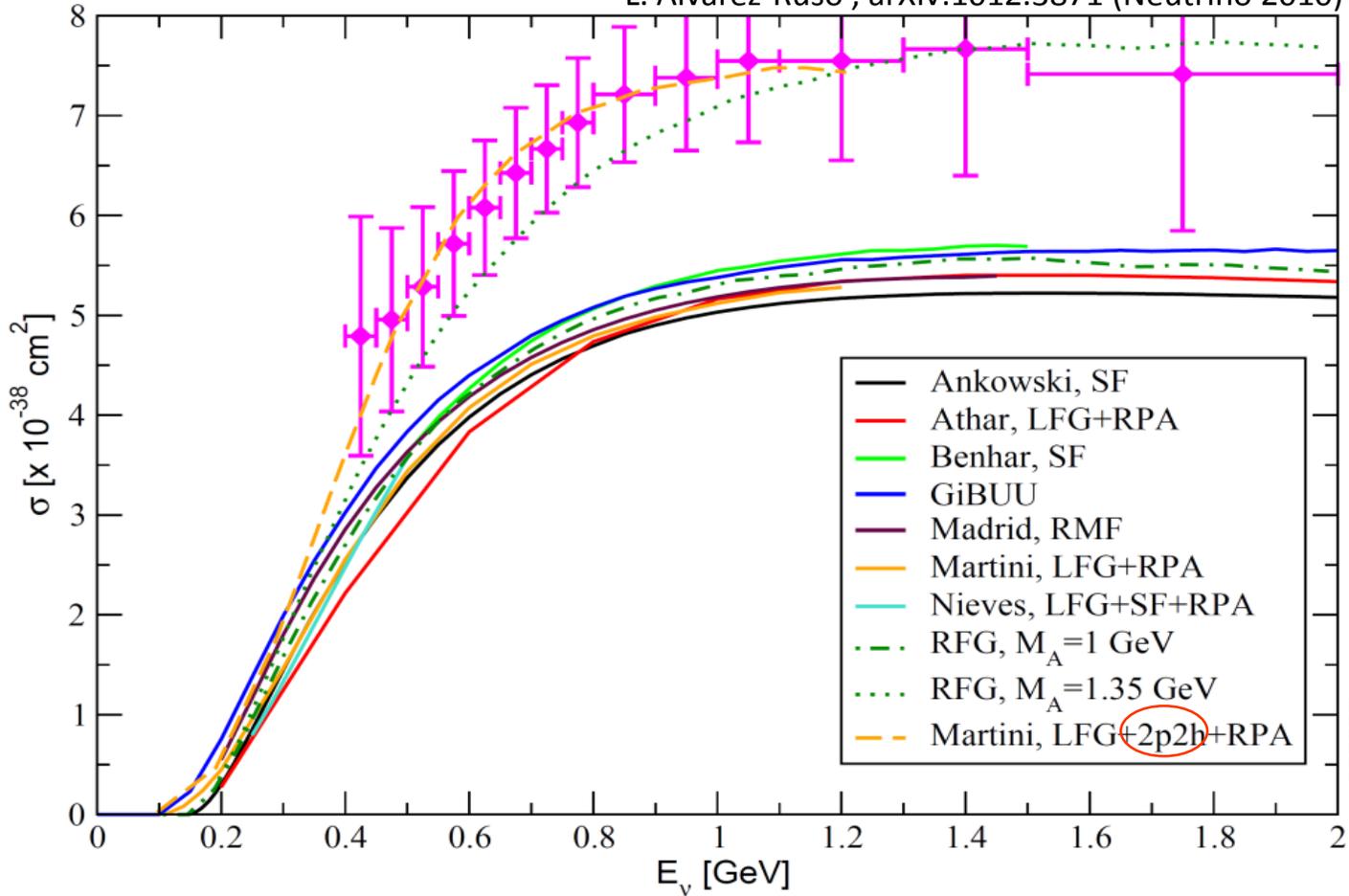
In the Relativistic Fermi Gas (RFG) model an axial mass of 1.35 GeV is needed to account for data

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

**puzzle??**

# Comparison of different theoretical models for Quasielastic

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



SF: Spectral Function

LFG: Local Fermi Gas

RPA: Random Phase Approximation

RMF: Relativistic Mean Field

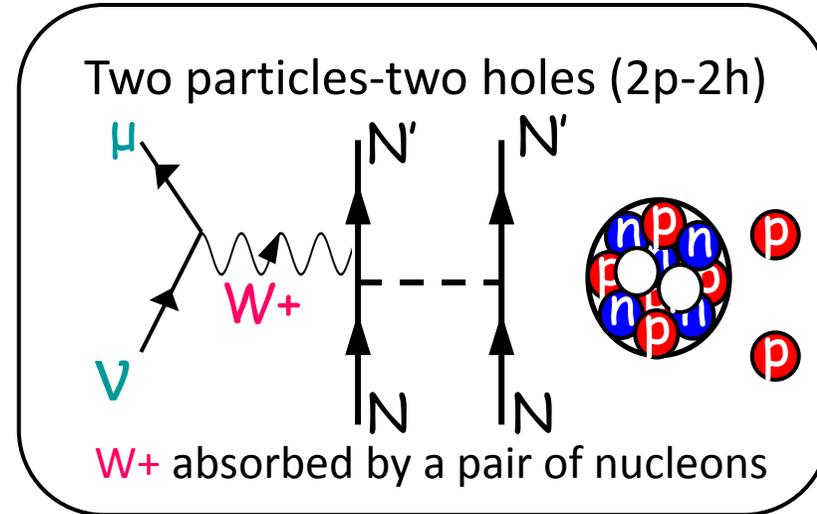
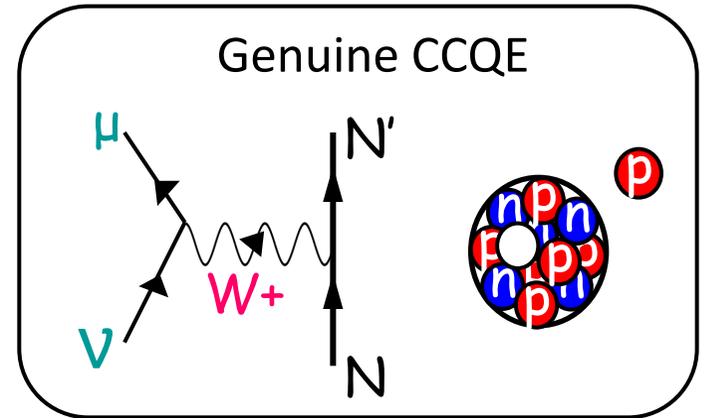
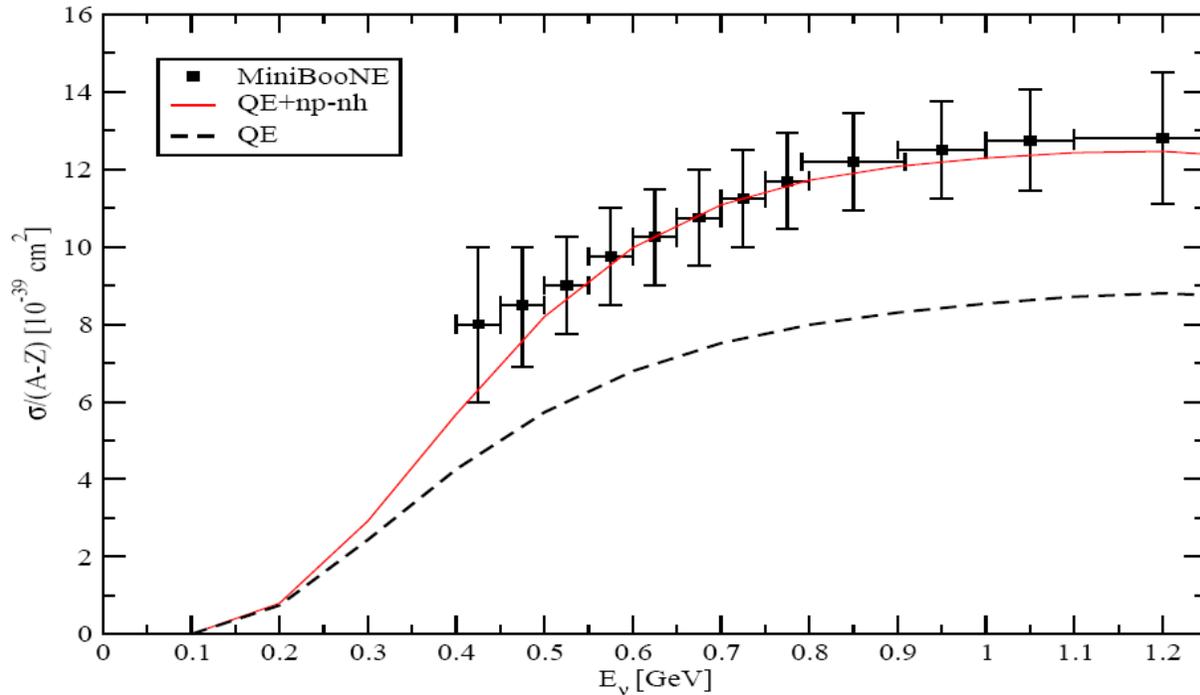
GiBUU: Transport Equation

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

puzzle??

# An explanation of this puzzle

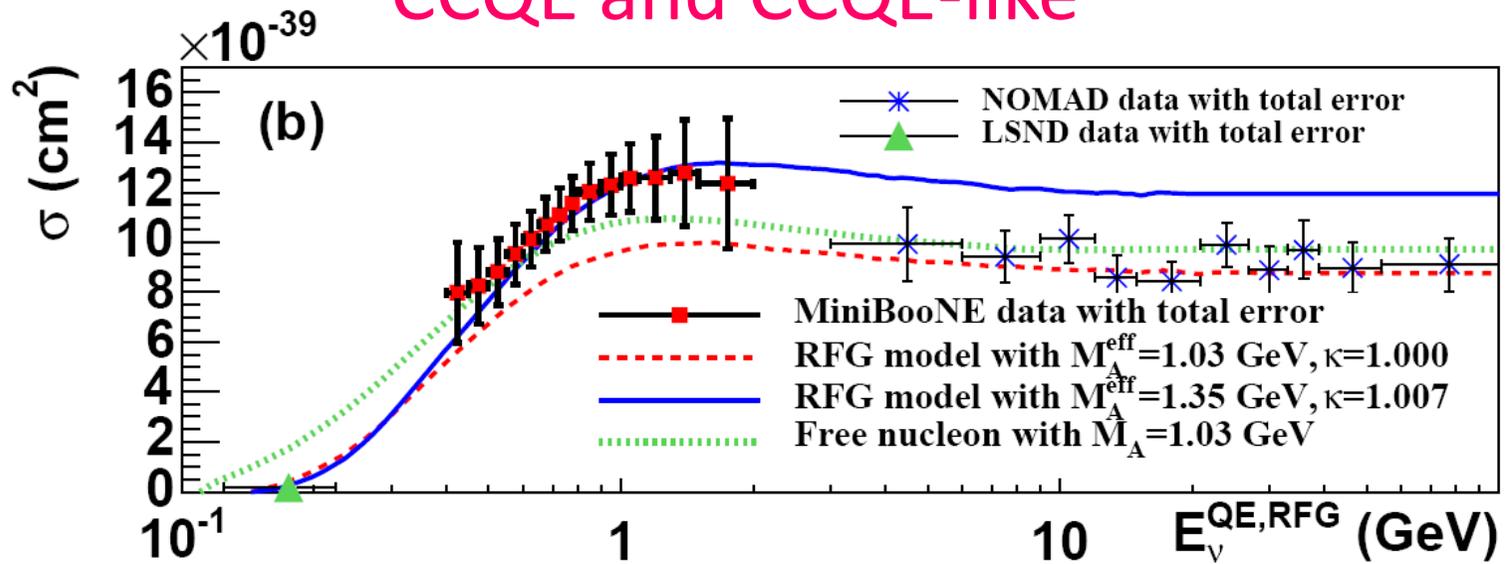
## Inclusion of the multinucleon emission channel (np-nh)



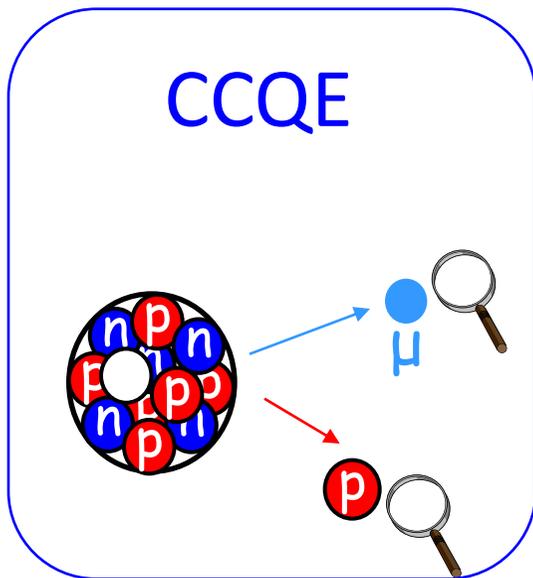
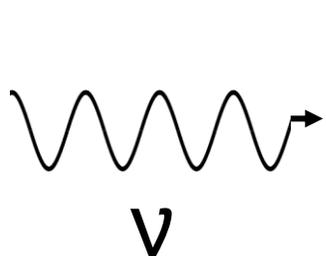
M. Martini, M. Ericson, G. Chanfray, J. Marteau *Phys. Rev. C* 80 065501 (2009)

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

# CCQE and CCQE-like

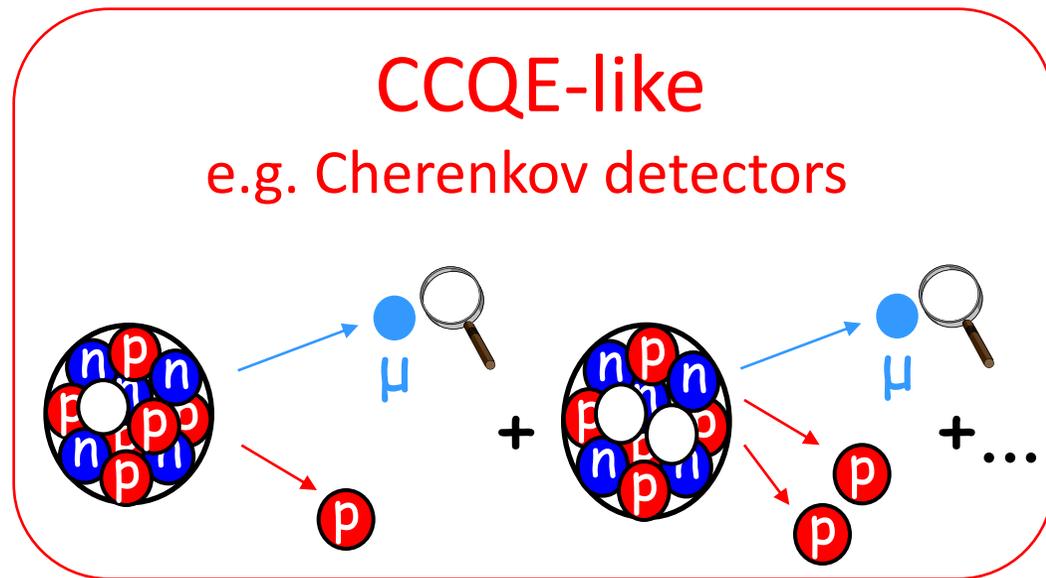


CCQE

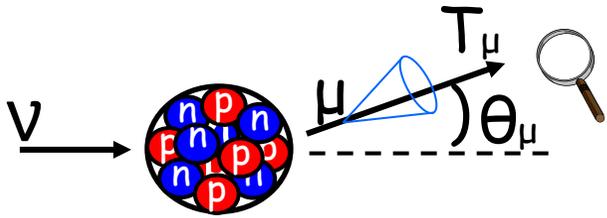


CCQE-like

e.g. Cherenkov detectors

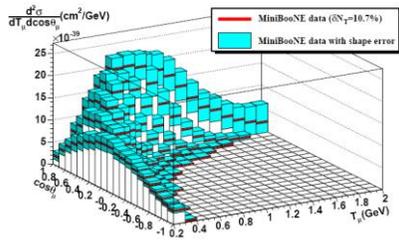
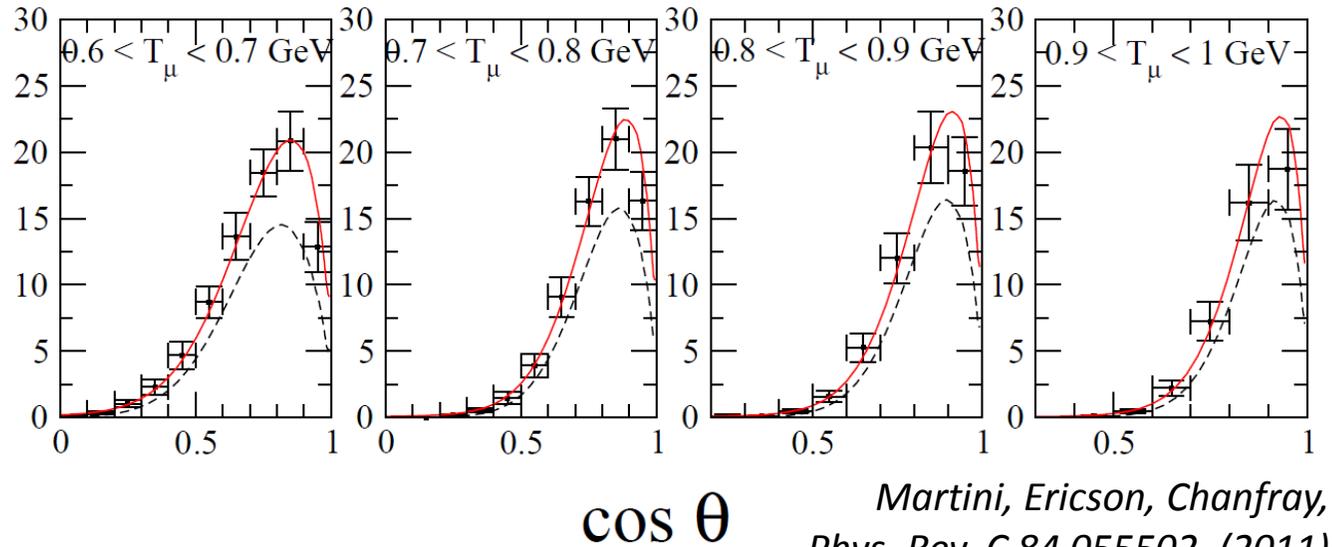
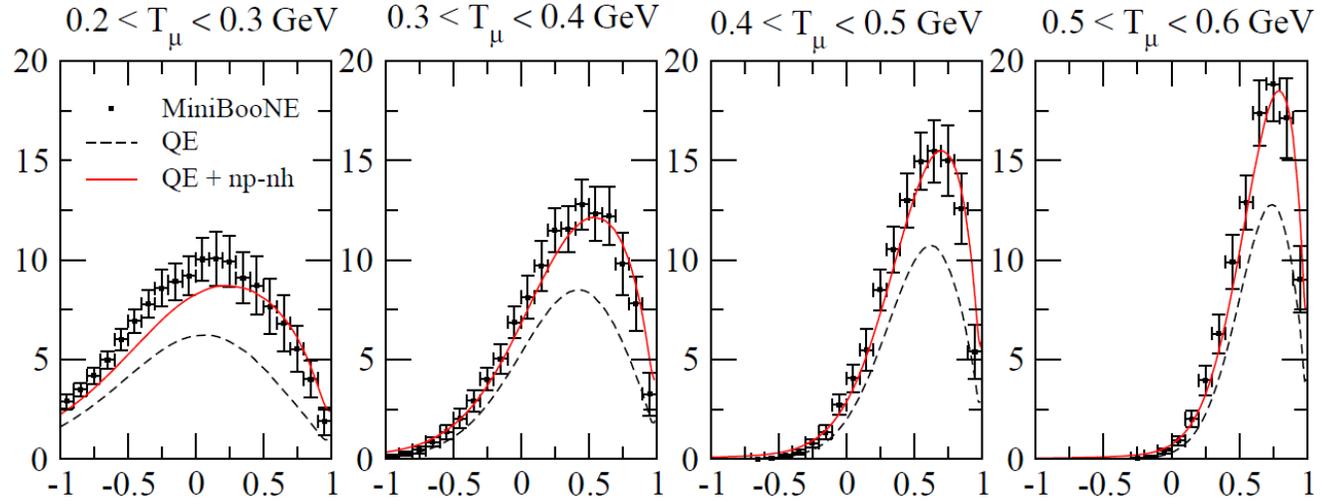


# MiniBooNE CCQE-like flux-integrated double differential cross section



**V**

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



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

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

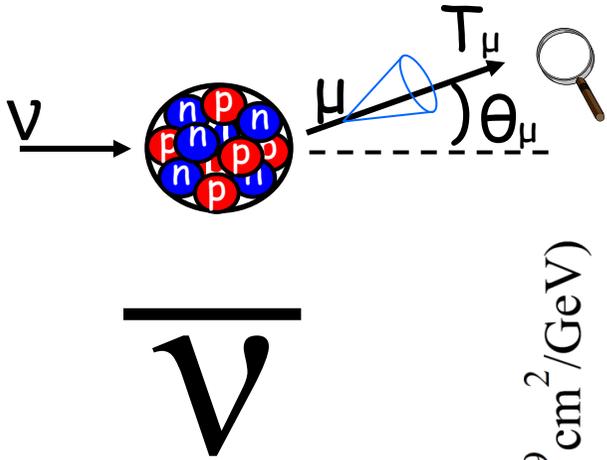
$\cos \theta$

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

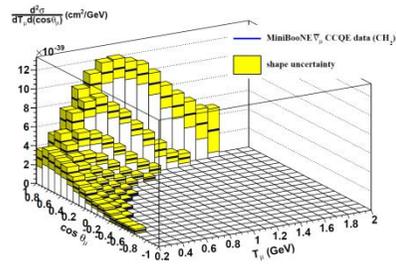
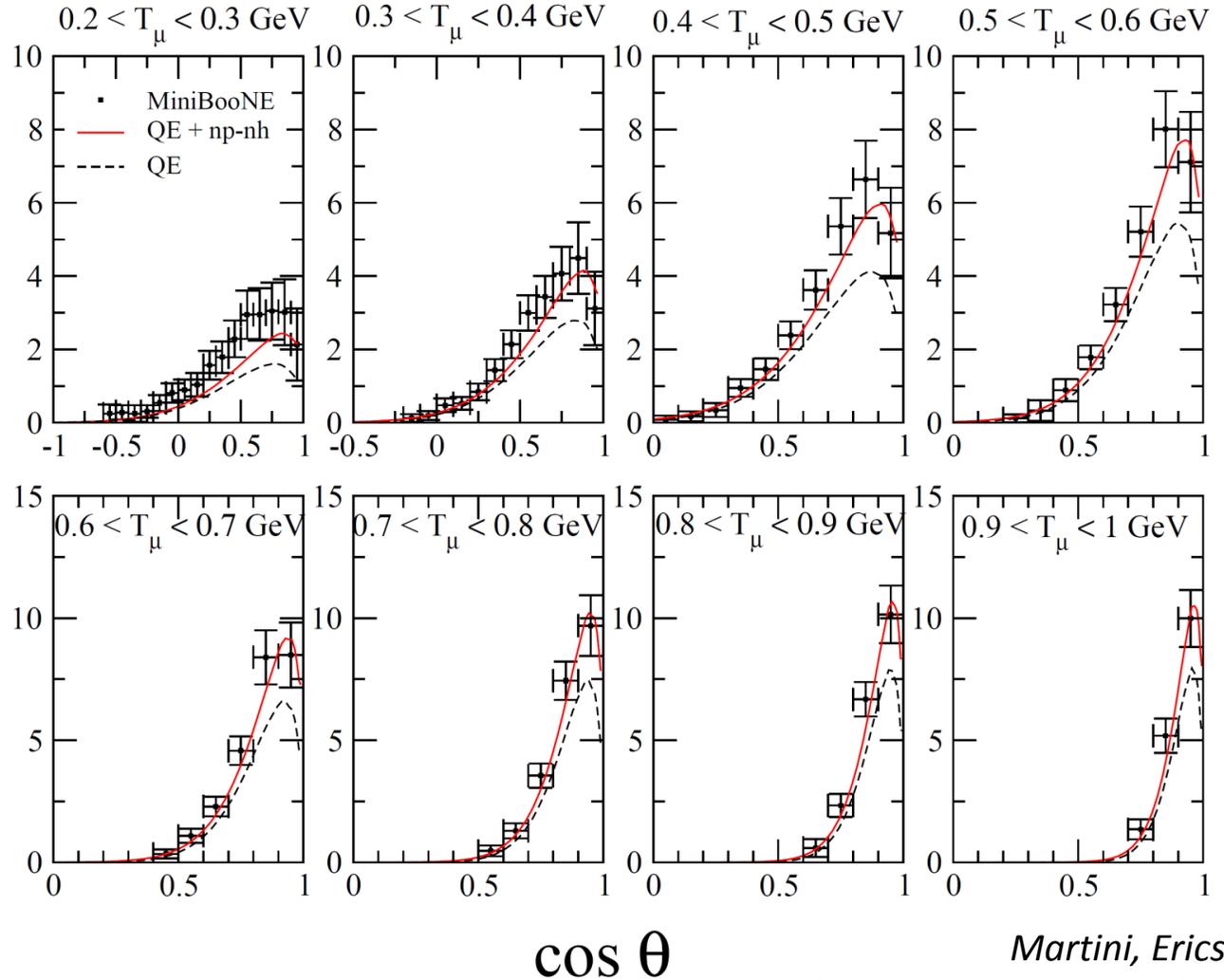
**Agreement with MiniBooNE without increasing  $M_A$  once np-nh is included**

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

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



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



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

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

$\cos \theta$

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

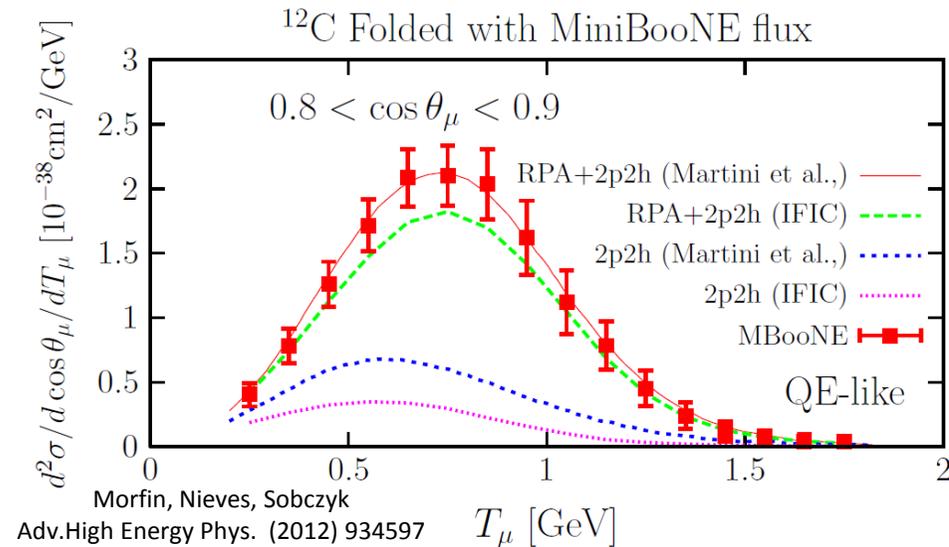
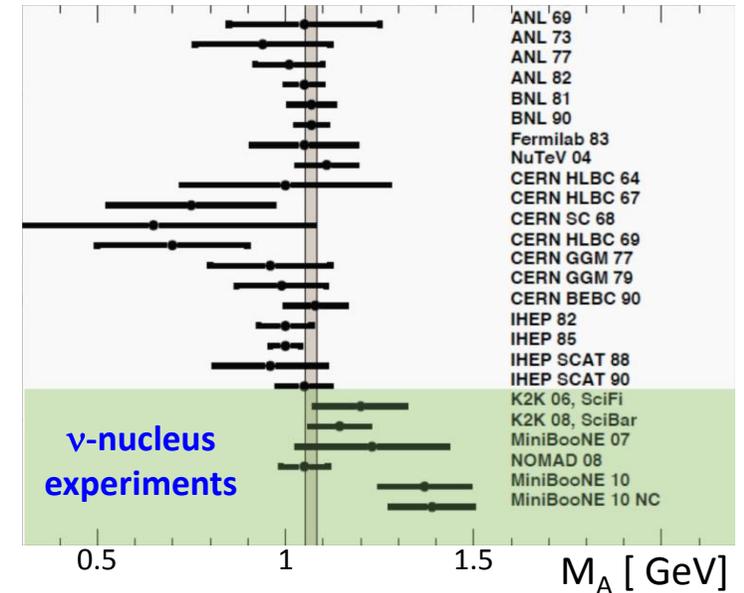
**Agreement with MiniBooNE without increasing  $M_A$  once np-nh is included**

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  $\nu$  cross sections and oscillations experiments
- Neutrino energy reconstruction and neutrino oscillation analysis are affected by np-nh
- Today there is an effort to include this np-nh channel in several Monte Carlo
- Several theoretical calculations agree on its crucial role 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 $\nu$ -nucleus cross sections

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

Phys. Rev. C 80 065501 (2009)  $\nu$   $\sigma_{\text{total}}$

Phys. Rev. C 81 045502 (2010)  $\nu$  vs antiv ( $\sigma_{\text{total}}$ )

Phys. Rev. C 84 055502 (2011)  $\nu$   $d^2\sigma$ ,  $d\sigma/dQ^2$

Phys. Rev. D 85 093012 (2012) impact of np-nh on  $\nu$  energy reconstruction

Phys. Rev. D 87 013009 (2013) impact of np-nh on  $\nu$  energy reconstruction and  $\nu$  oscillation

Phys. Rev. C 87 065501 (2013) antiv  $d^2\sigma$ ,  $d\sigma/dQ^2$

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

Phys. Rev. C 91 035501 (2015) combining  $\nu$  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)  $\nu$ , antiv  $\sigma_{\text{total}}$

Phys. Lett. B 707 72-75 (2012)  $\nu$   $d^2\sigma$

Phys. Rev. D 85 113008 (2012) impact of np-nh on  $\nu$  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, G. Megias, I. Ruiz Simo et al. (Superscaling)*

Phys. Lett. B 696 151-155 (2011)  $\nu$   $d^2\sigma$

Phys. Rev. D 84 033004 (2011)  $\nu$   $d^2\sigma$ ,  $\sigma_{\text{total}}$

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

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  $\nu$   $d^2\sigma$

## 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)  $\nu$   $\sigma_{\text{total}}$ ,  $d^2\sigma$ ,  $d\sigma/dQ^2$

Phys. Rev. C 86 054606 (2012) impact of np-nh on  $\nu$  energy reconstruction and  $\nu$  oscillation

Phys. Rev. Lett. 112 151802 (2014) energy reconstruction in LBNE

Phys. Rev. D 89 093003 (2014) reaction mechanisms at MINERvA

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

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

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

## np-nh work in progress: generalization to $\nu$ of approaches used for e scattering

*O. Benhar, A. Lovato, N. Rocco*

Phys. Rev. C 92, 024602 (2015) Factorization ansatz and two-nucleon spectral function

*T. Van Cuyck, N. Jachowicz, J. Ryckebusch et al. (Ghent)*

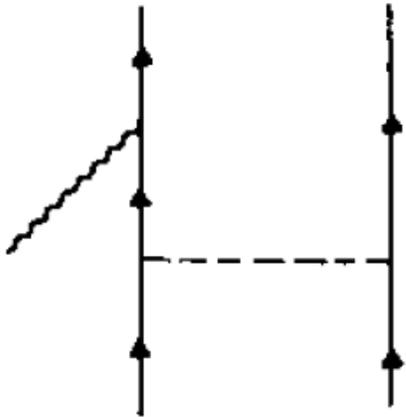
 A lot of theoretical activity in recent years

Some theoretical details on 2p-2h

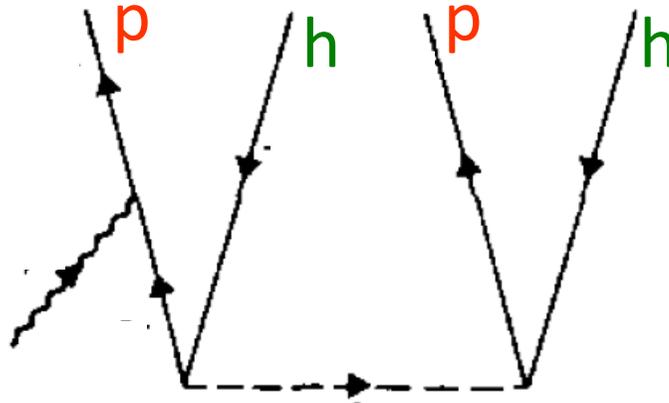
# Two particle-two hole sector (2p-2h)

## Three equivalent representations of the same process

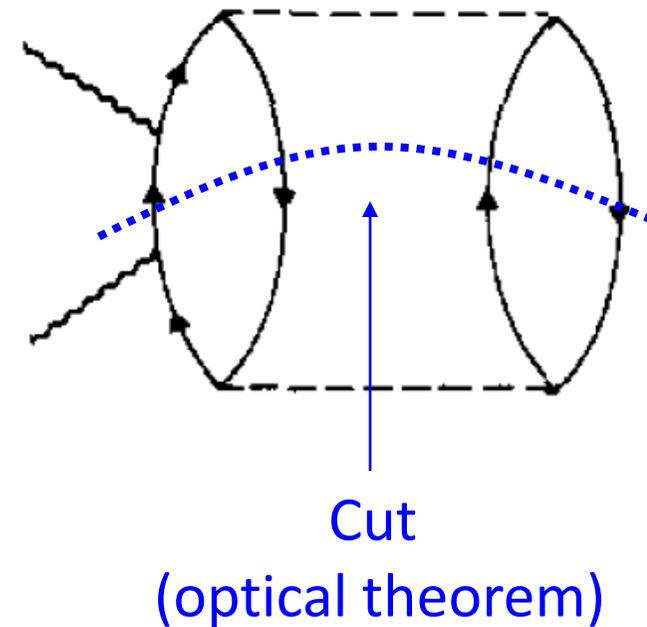
2 body current



2p-2h matrix element



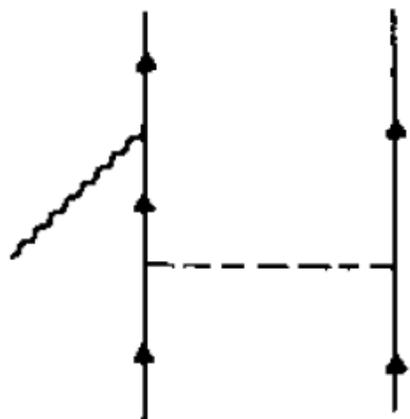
2p-2h response



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

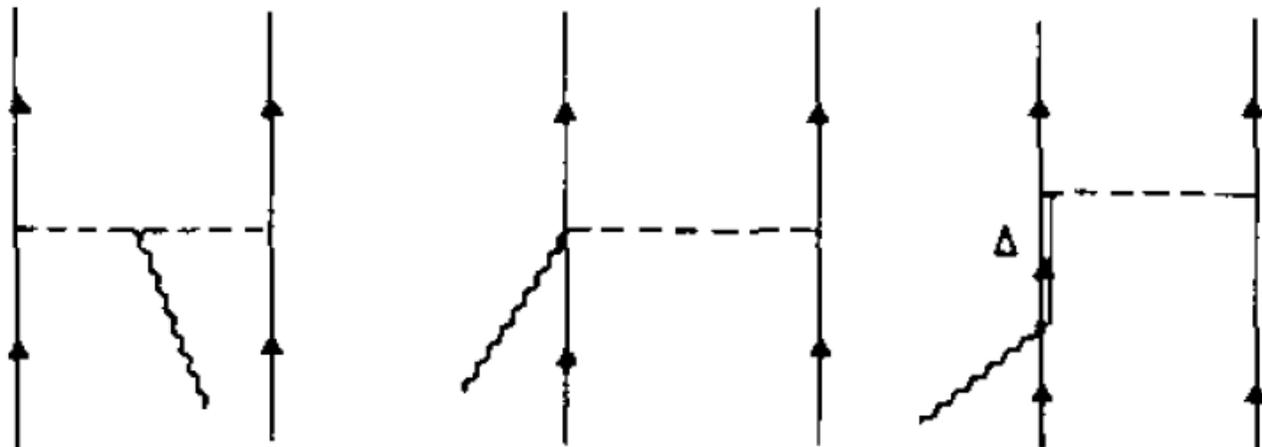
# Some diagrams for 2 body currents

Nucleon-Nucleon correlations



$J_{\text{corr}}$

Meson Exchange Currents (MEC)



Pion in flight

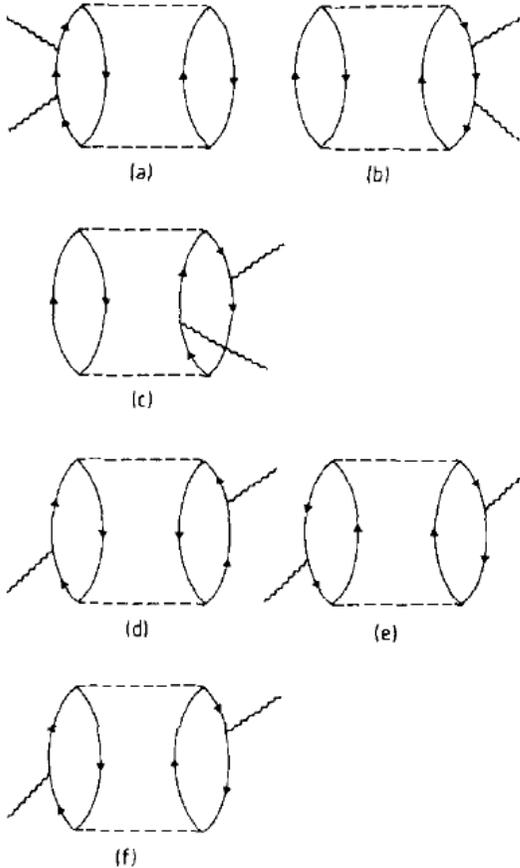
Contact

Delta

$J_{\text{MEC}}$

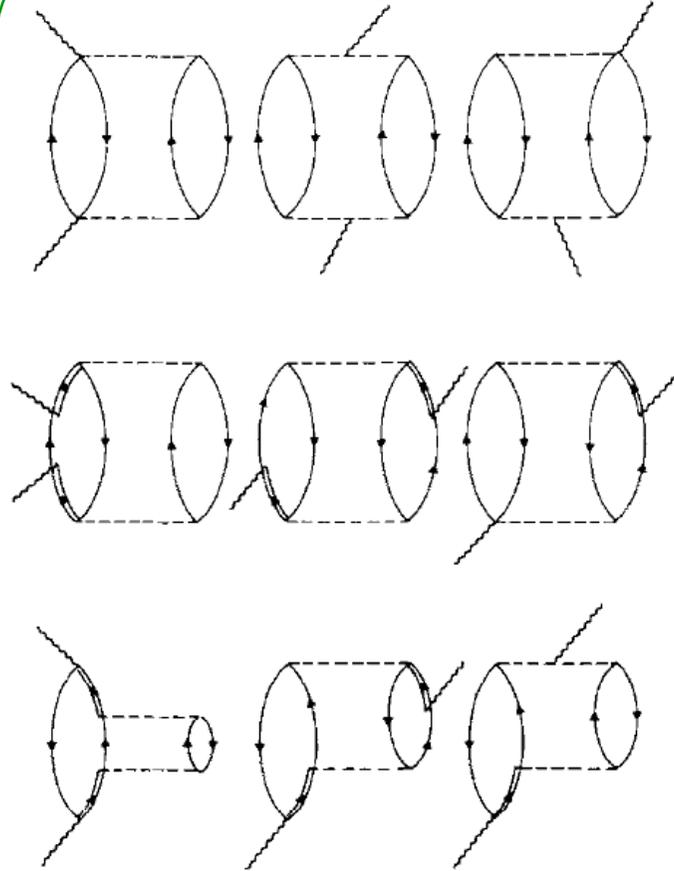
# Some diagrams for 2p-2h responses

## NN correlations



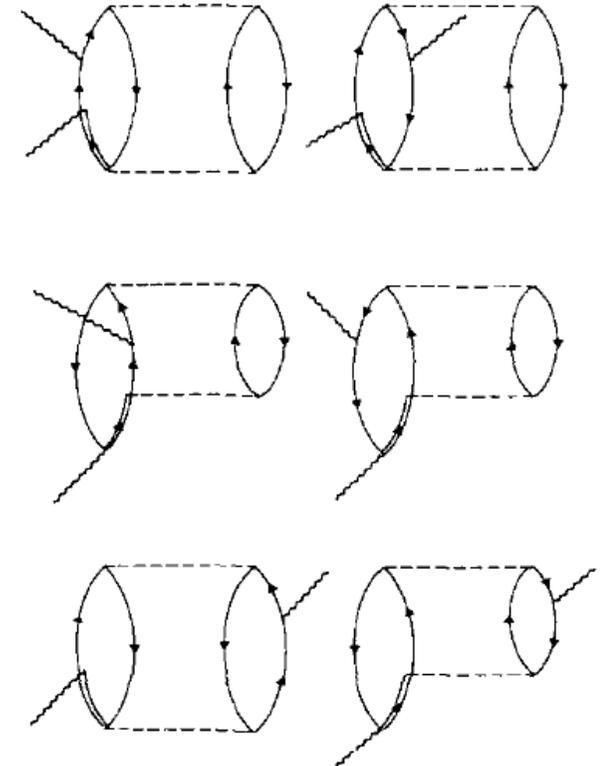
16 diagrams

## MEC



49 diagrams

## NN correlation-MEC interference



56 diagrams

# Main difficulties in the 2p-2h sector

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

- 7-dimensional integrals  $\int d^3 h_1 d^3 h_2 d\theta'_1$  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

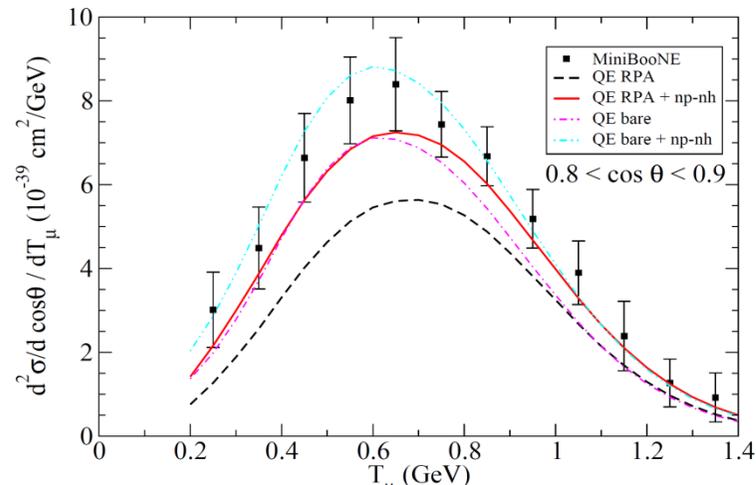
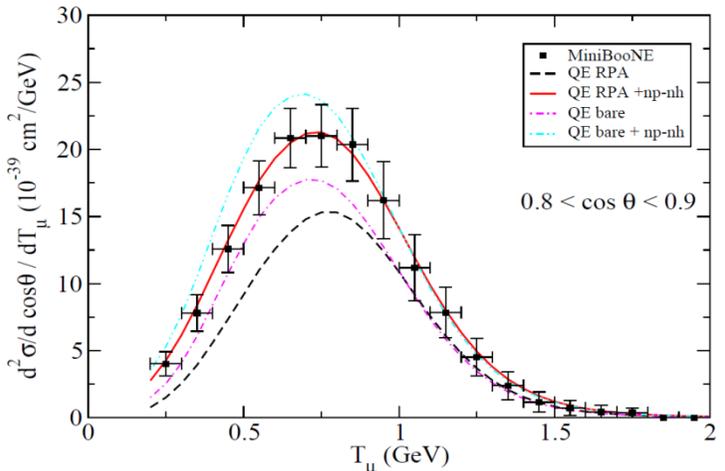
Hence different approximations by different groups:

- 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  $h_1 = h_2 = 0$ )

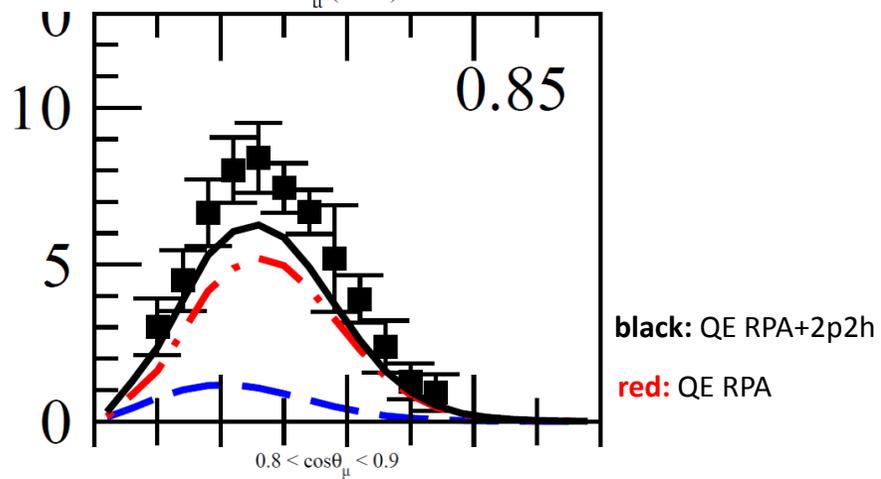
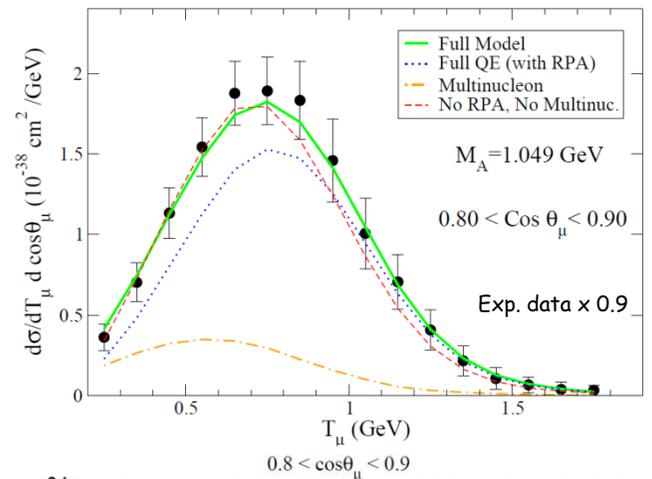
⇒ **Different final results**

# V

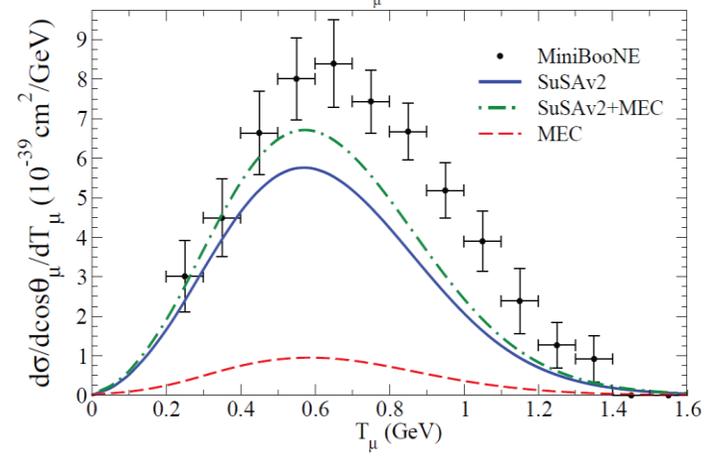
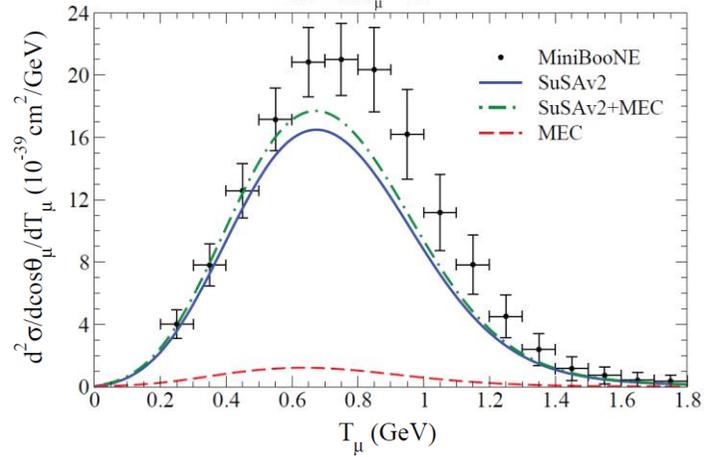
Martini et al.



Nieves et al.



Amaro et al.



# V

# Neutrino vs Antineutrino interactions and CP violation

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

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

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

**Vector-Axial interference**

Vector-Axial interference:  
**basic asymmetry from weak interaction theory**

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

The  $\nu$  and anti  $\nu$  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: ]

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

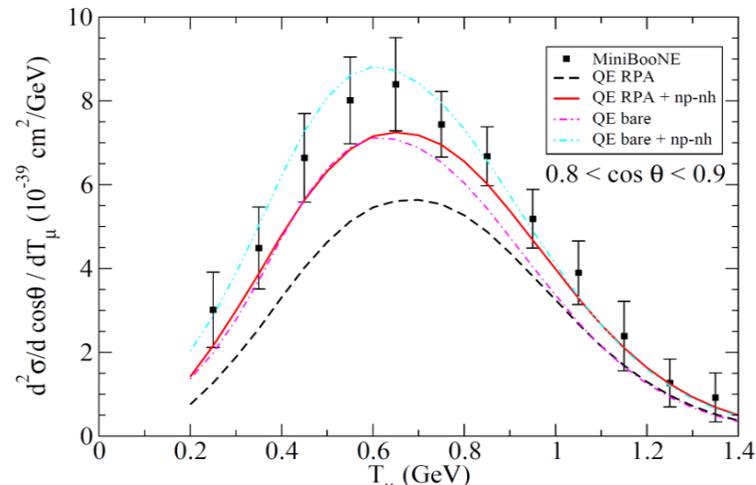
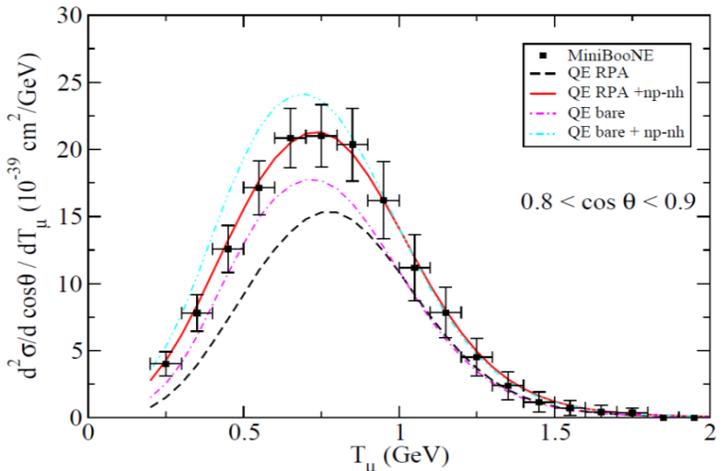
An example of difference:

in Amaro et al. there are no 2p-2h in the axial and vector-axial interference terms

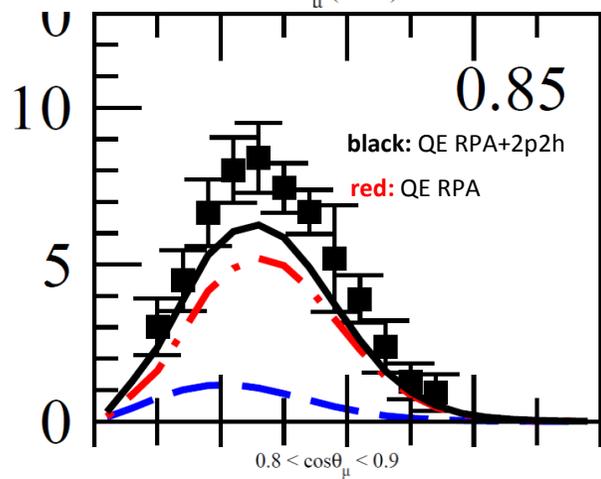
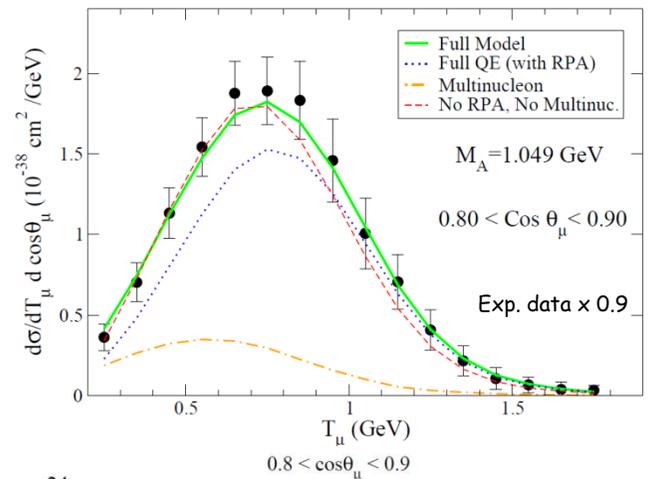
→ the relative role of 2p-2h contributions for neutrinos and antineutrinos is different in the different approaches

# V

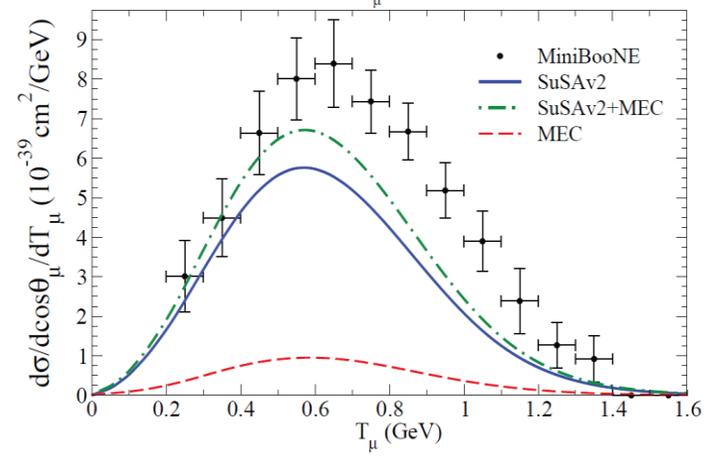
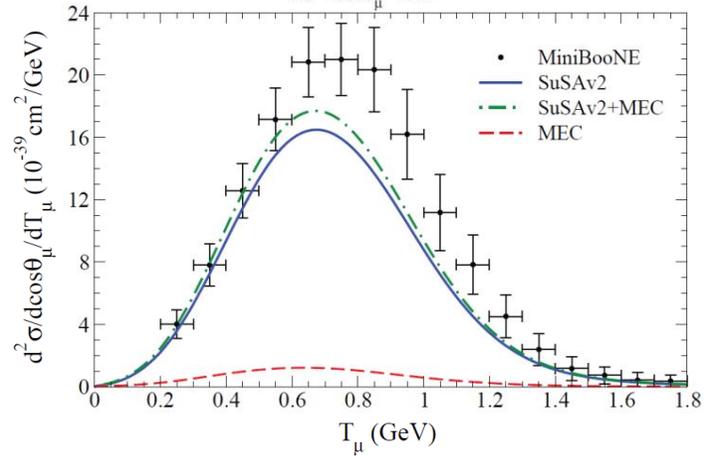
Martini et al.



Nieves et al.



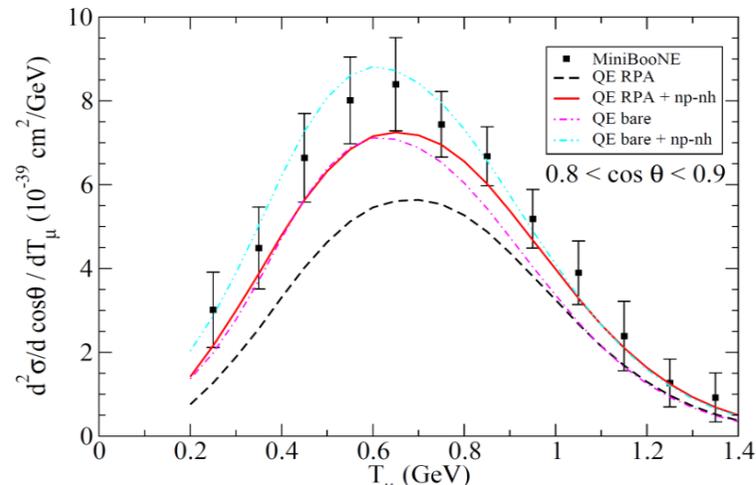
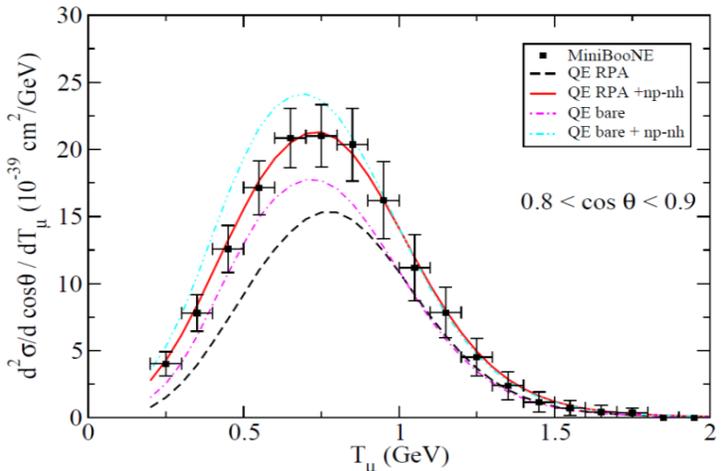
Amaro et al.



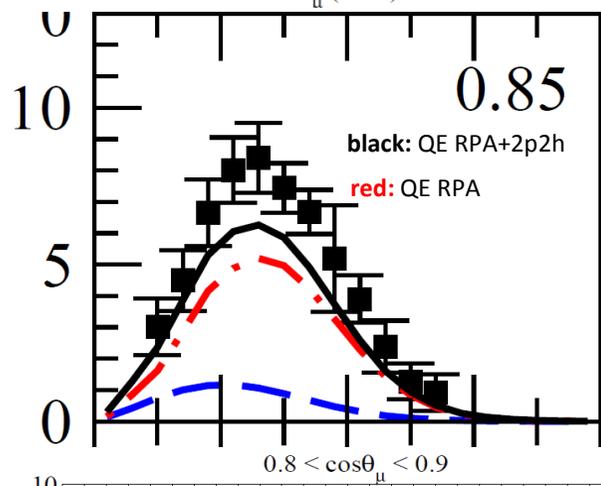
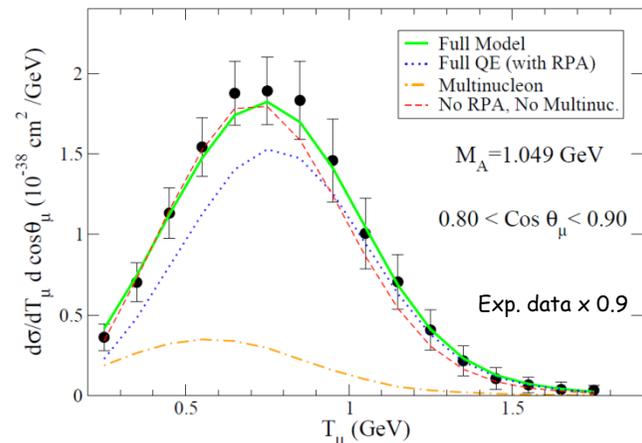
# V



Martini et al.

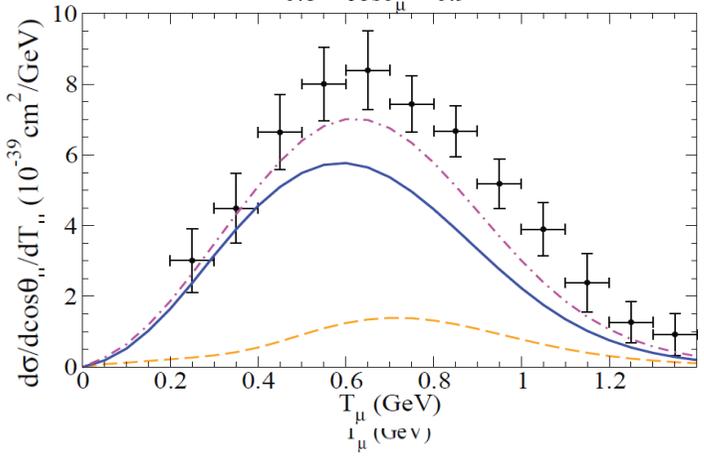
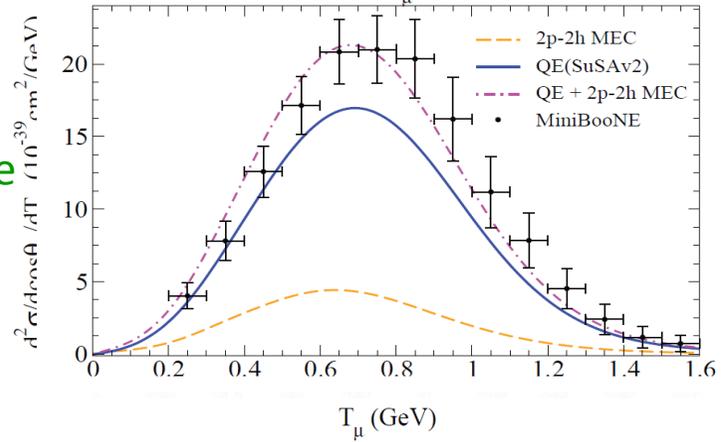


Nieves et al.



NEW, preliminary:

Inclusion of MEC also in the axial sector  
Megias talk  
NuFact 2015

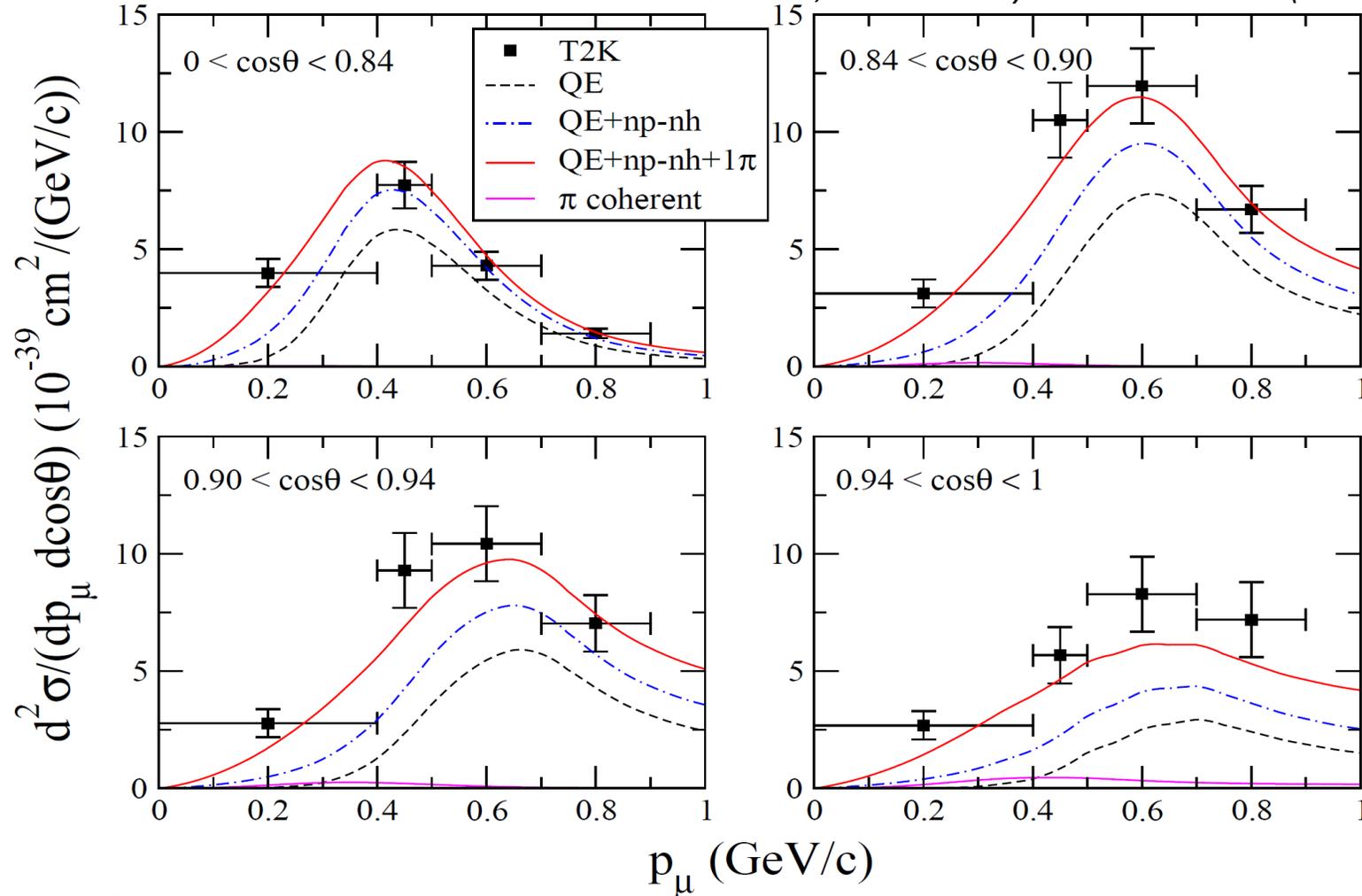


# T2K flux-integrated inclusive double differential cross section on carbon

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

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

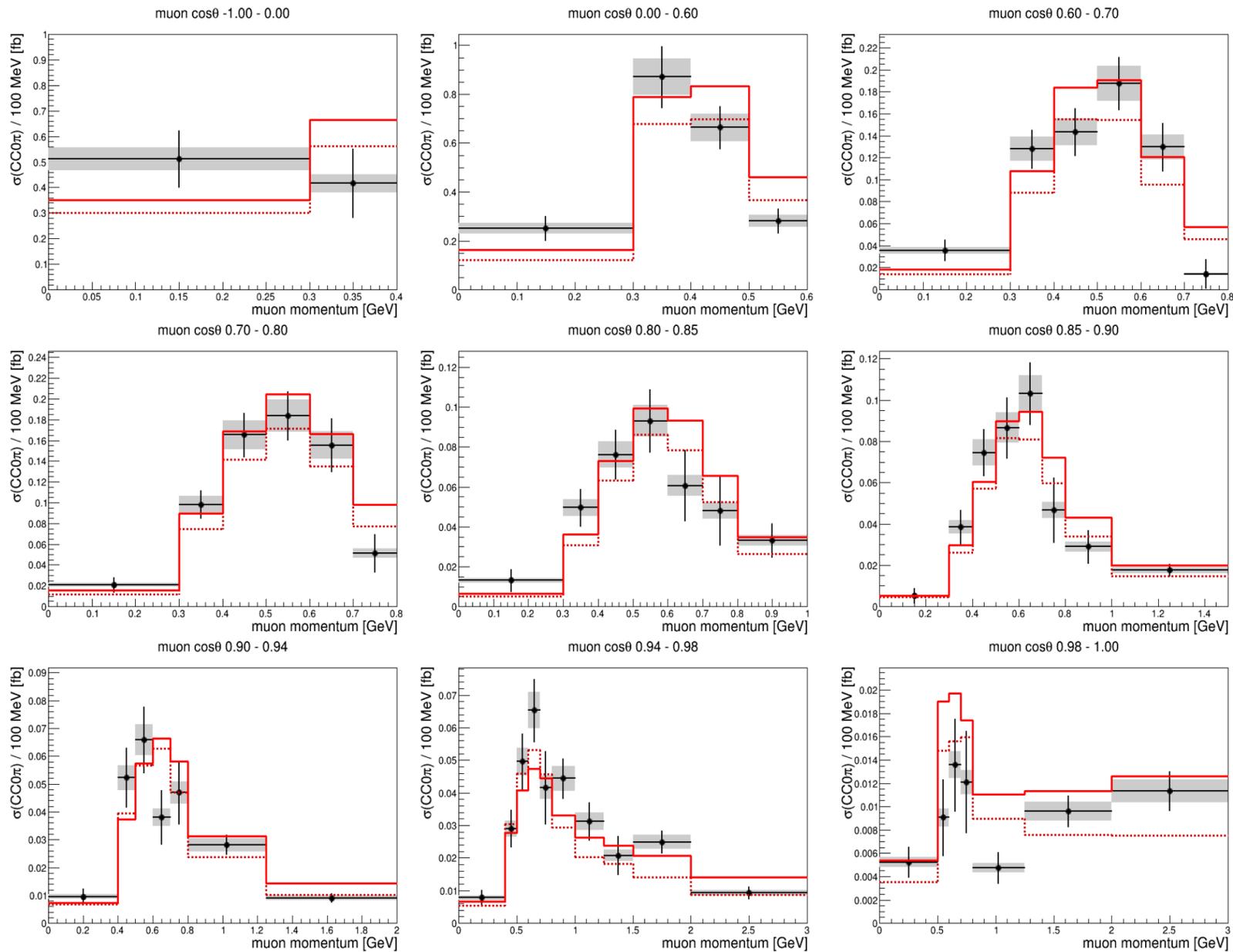
M. Martini, M. Ericson *Phys. Rev. C* 90 025501 (2014)



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

# $\nu_\mu$ T2K flux-integrated $CC0\pi$ measurement vs $CCQE+np-nh$ calculations

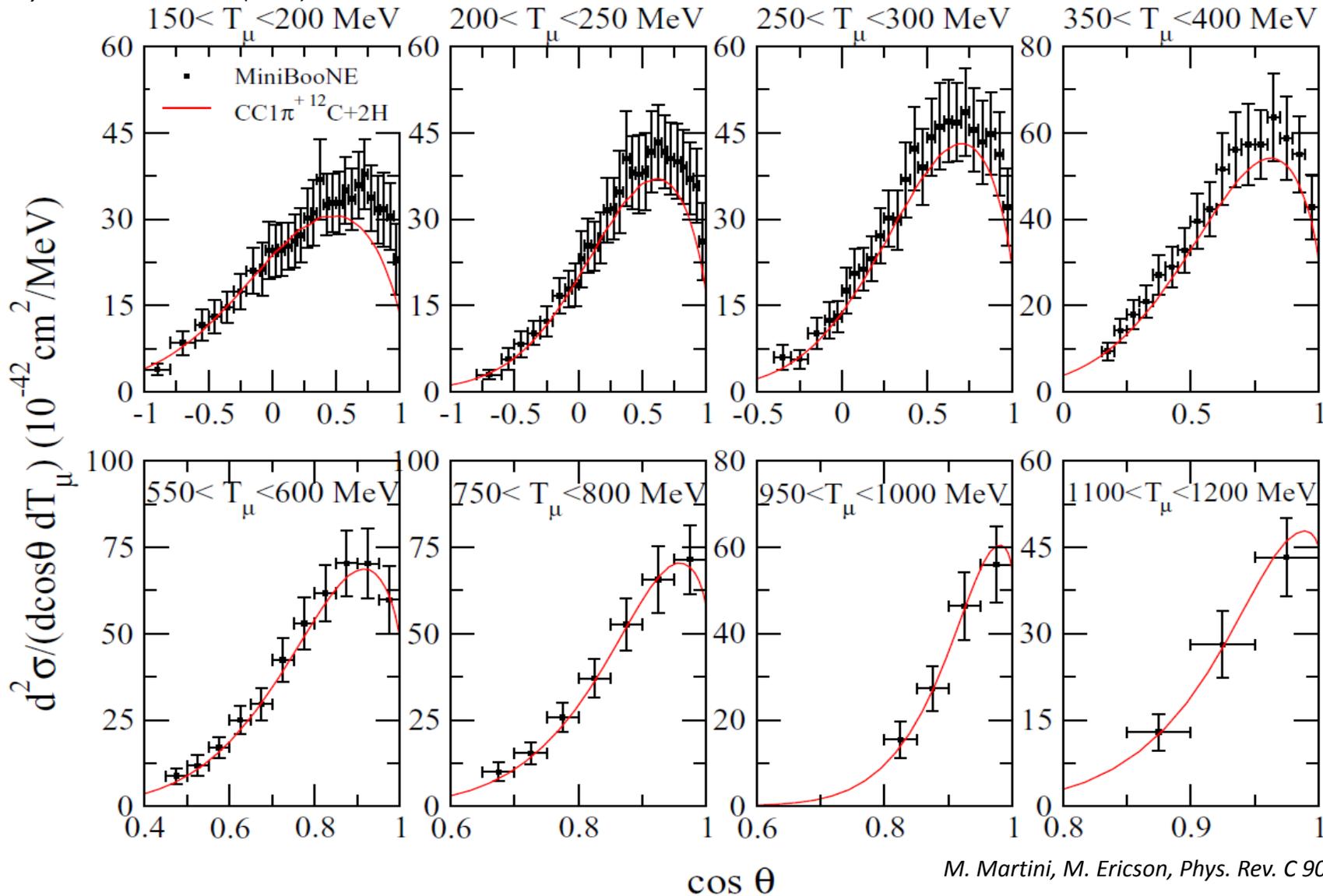
S. Bognesi: plenary talk at NuFact 2015



— *Martini et al.*  
 - - - *Nieves et al.*

# MiniBooNE flux-integrated CC1 $\pi^+$ double differential cross section

MiniBooNE Phys. Rev. D 83 052007 (2011)



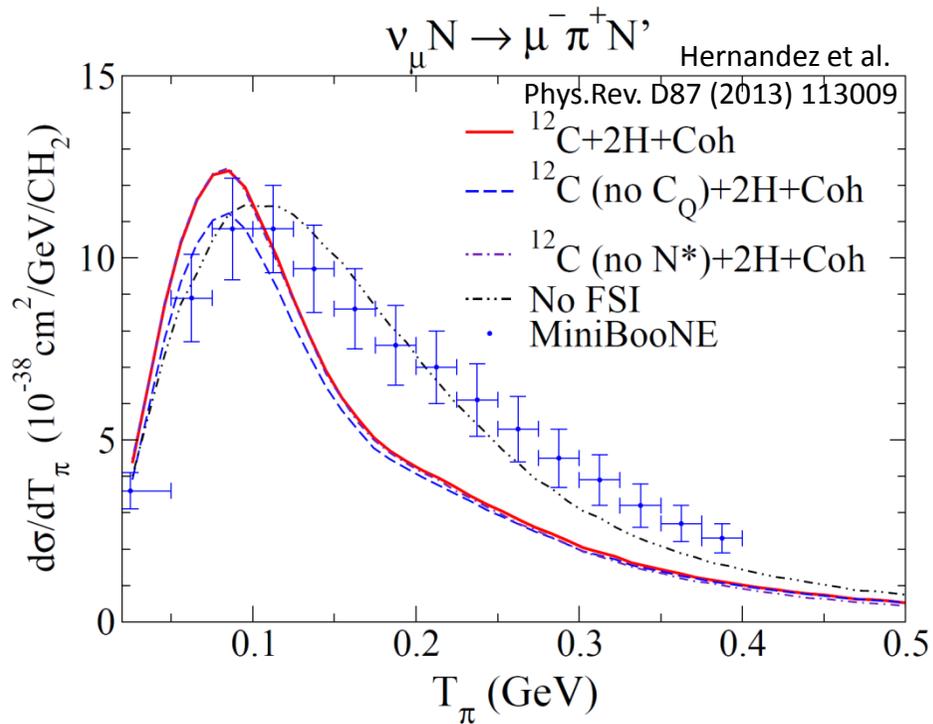
M. Martini, M. Ericson, Phys. Rev. C 90 025501 (2014)

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

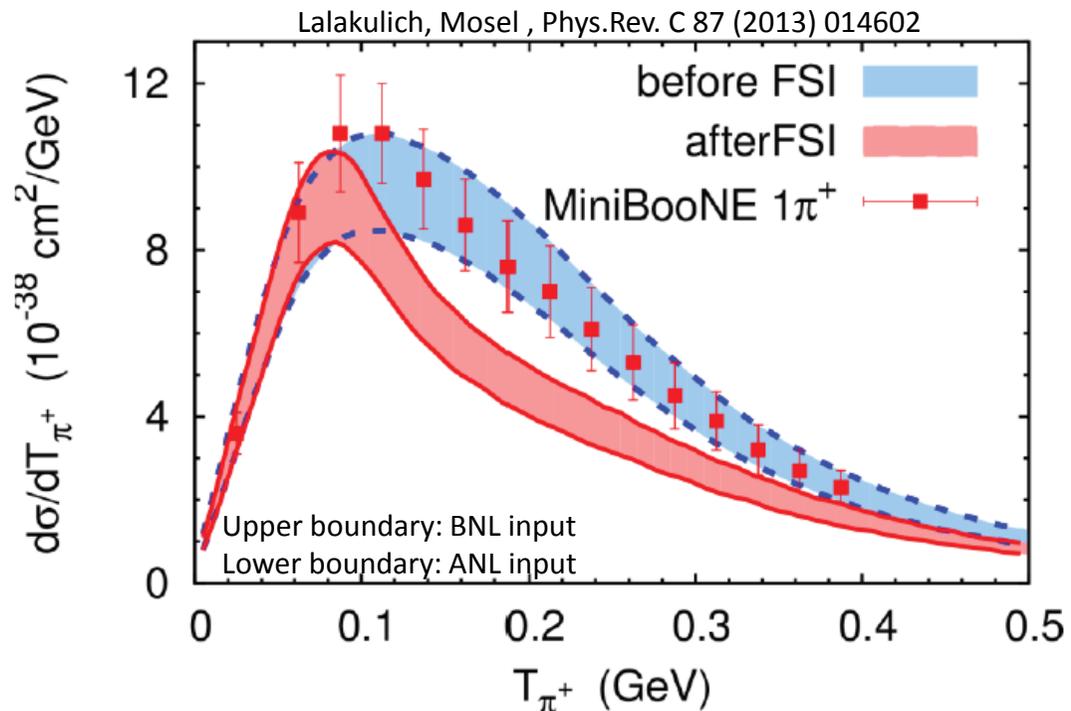
# MiniBooNE flux-integrated CC1 $\pi^+$ differential cross section

MiniBooNE Phys. Rev. D 83 052007 (2011)

function of  $T_\pi$



Valencia

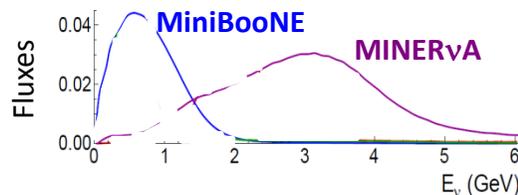


GiBUU

controversy

- Theories (with  $\Delta$  medium effects and pion rescattering) do not agree with pion KE spectrum

# MiniBooNE vs MINERvA CC1 $\pi^+$ production

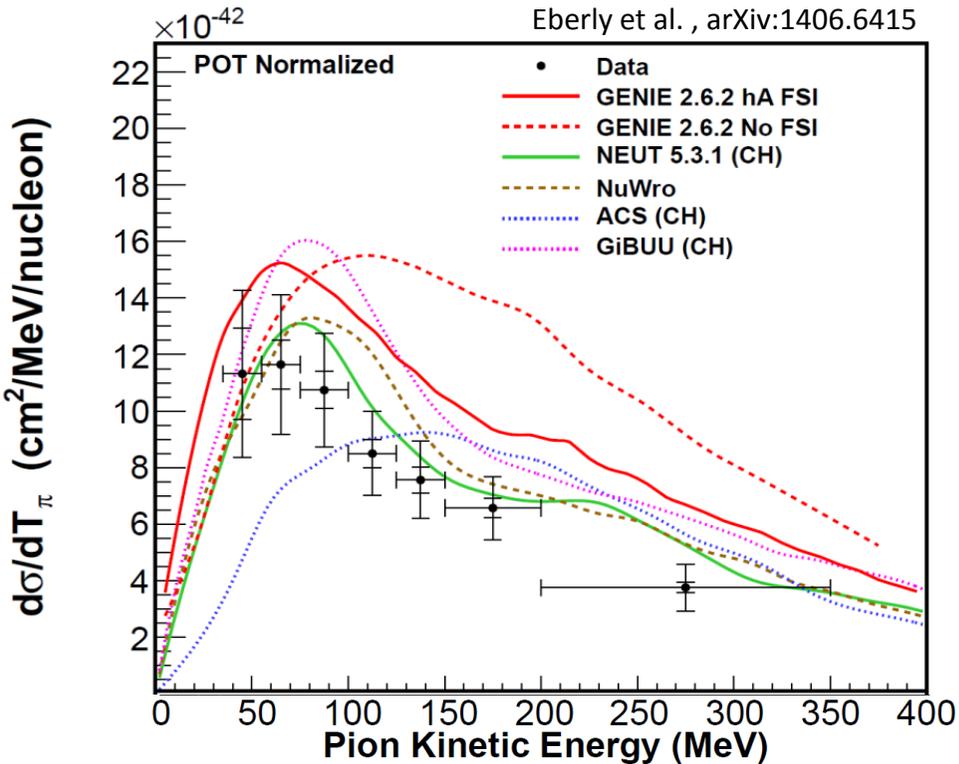
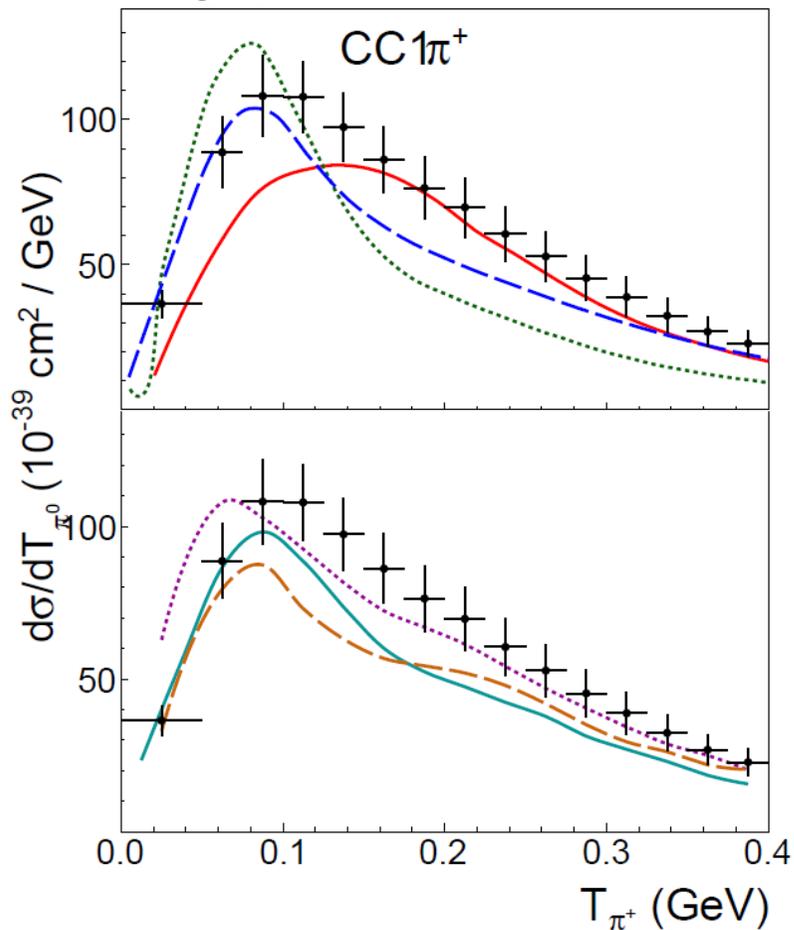


MiniBooNE

MINERvA

Rodrigues, arXiv:1402.4709

Eberly et al., arXiv:1406.6415



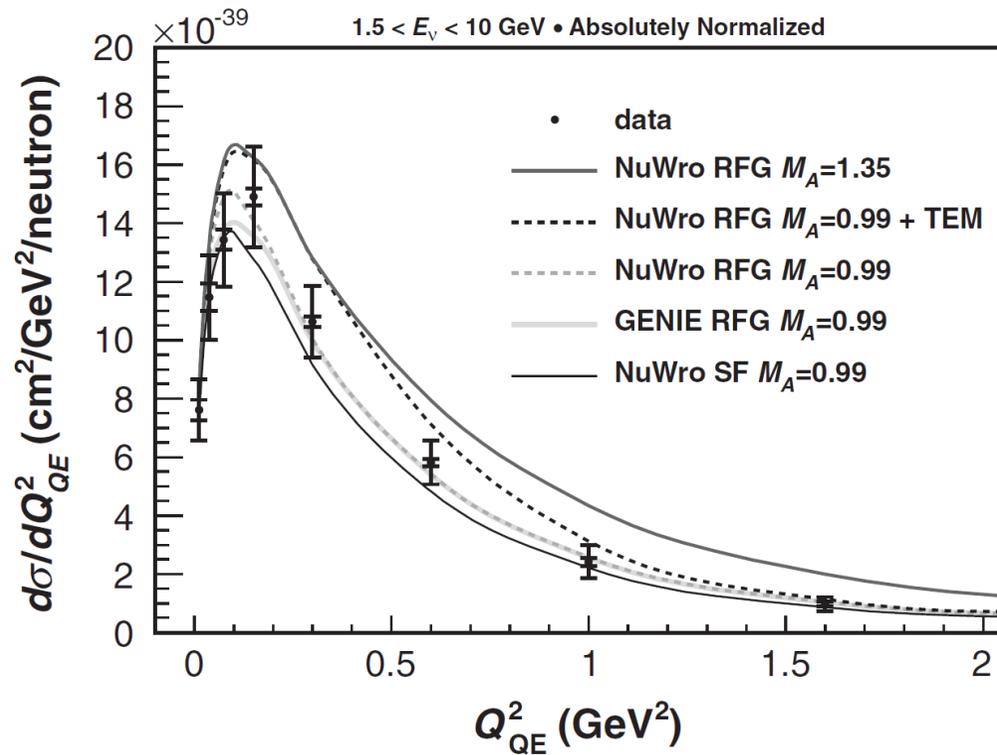
- Athar *et al.*    - - - Nieves *et al.*    - - - GiBUU    — NuWro
- - - GENIE    - - - NEUT    — + MB data

Some tension

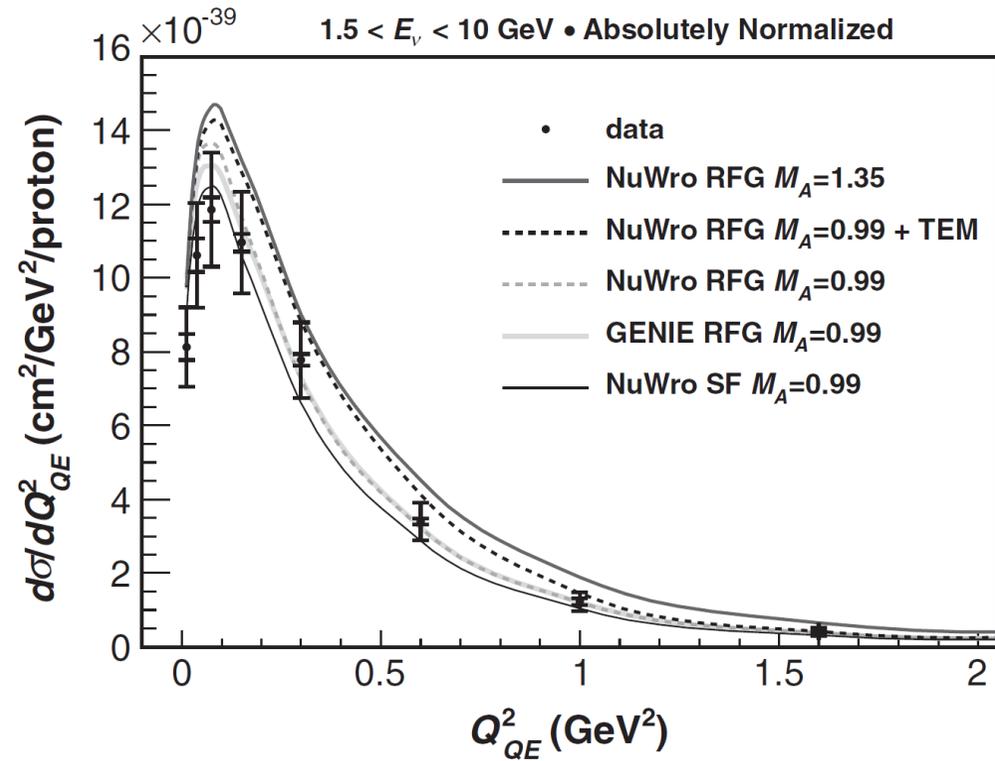
# MINERvA ( $E_\nu \sim 3.5$ GeV) CCQE $Q^2$ distribution

$\nu$

$\bar{\nu}$



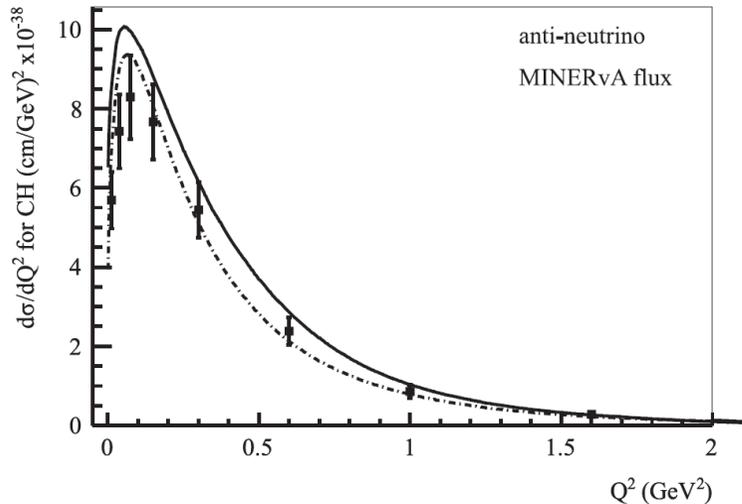
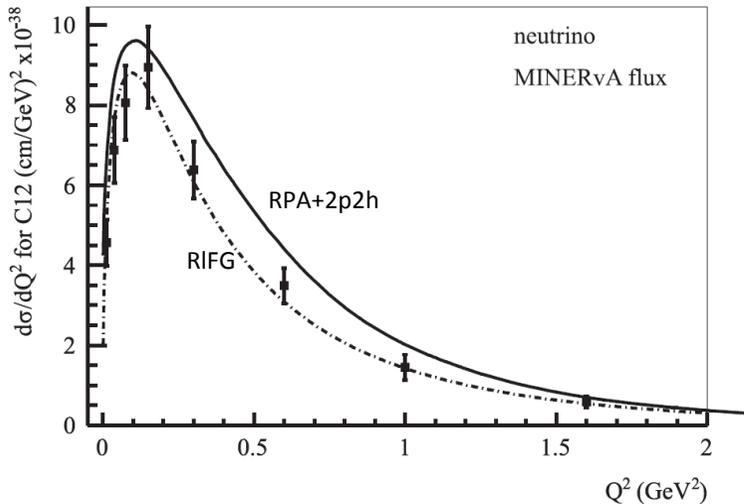
PRL 111 022502 (2013)



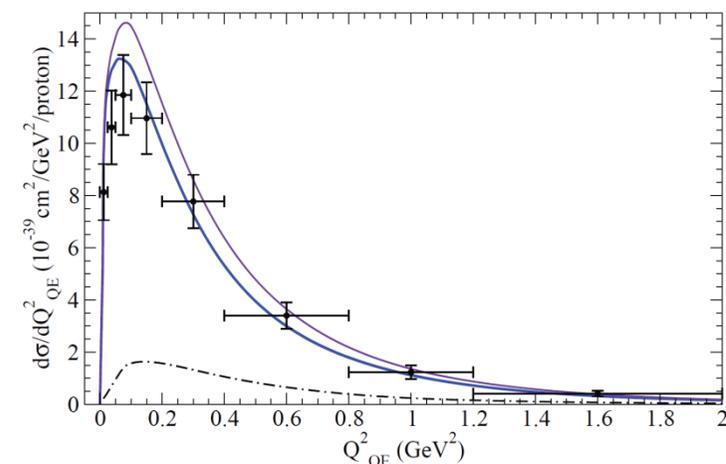
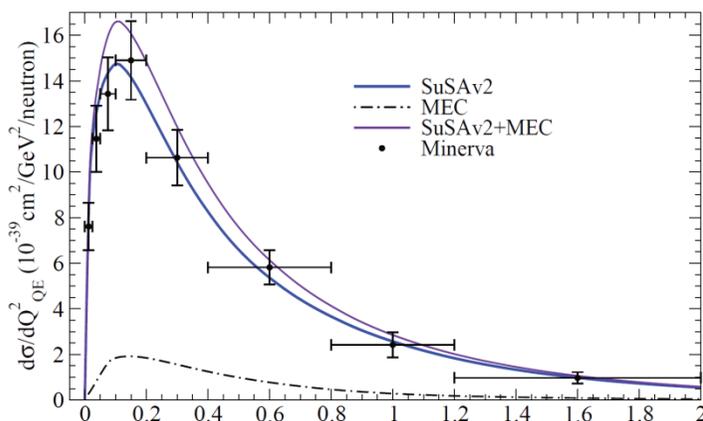
PRL 111 022501 (2013)



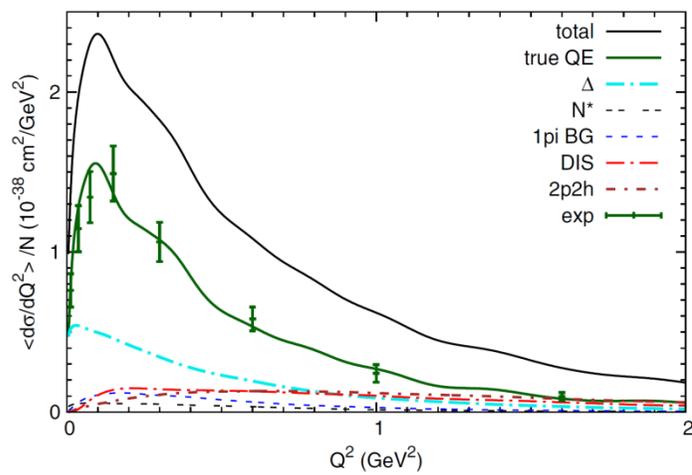
Gran, Nieves  
et al.  
PRD 88 (2013)



Megias, Amaro  
et al.  
PRD 91 (2015)



Mosel et al.  
PRD 89 (2014)



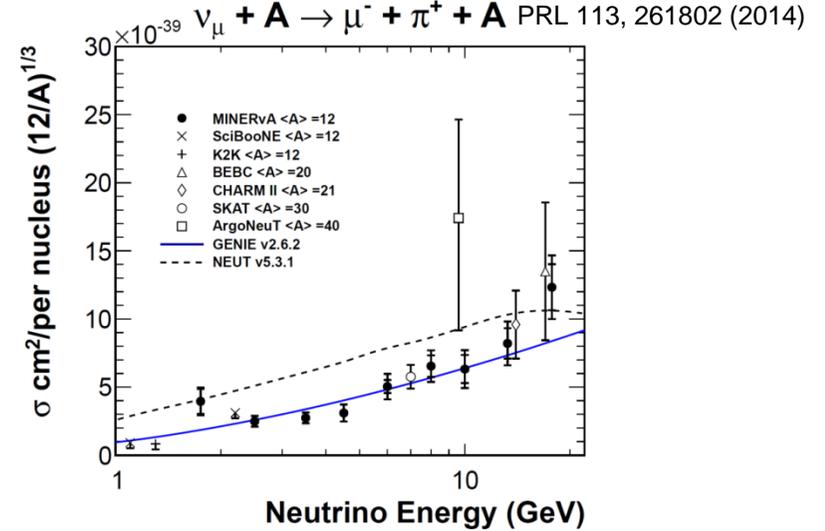
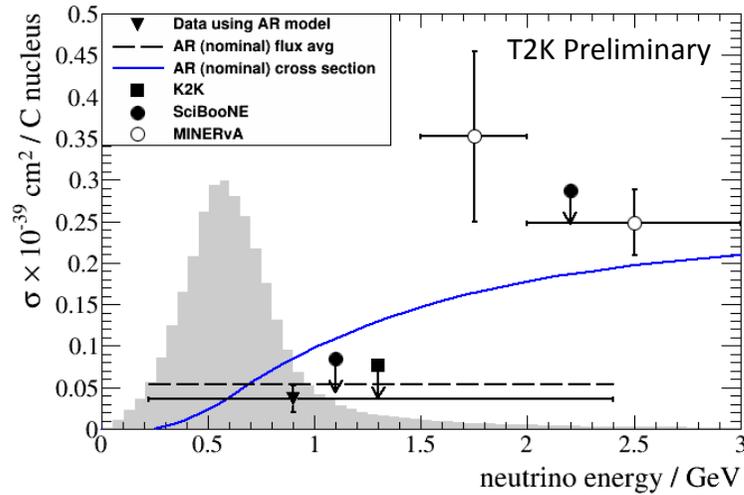
- **MINERvA CCQE  $Q^2$  distributions can be reproduced also without the inclusion of np-nh**
- **This is not the case of the MiniBooNE  $Q^2$  distributions**
- Mosel et al: “The sensitivity to details of the treatment of np-nh contributions is smaller than the uncertainties introduced by the  $Q^2$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

# Coherent $\pi$ production

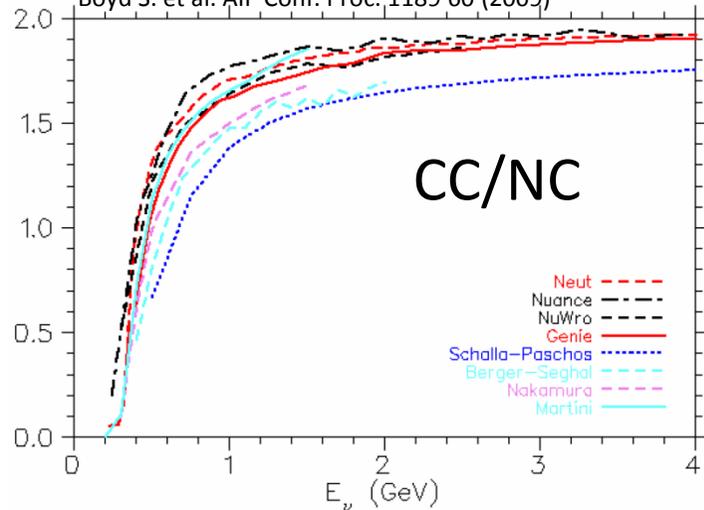
K2K and SciBooNE: only upper limits for coherent  $\pi^+$  production at neutrino energies  $\sim 1$  GeV

Recently MINERvA and ArgoNeut see evidence for CC coherent pion production

T2K preliminary results:  $\sim 2.5 \sigma$  indication of coherent  $\pi^+$  production at neutrino energies  $\sim 1$  GeV



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



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

Theoretical models:

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

SciBooNE:

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

Kurimoto et al, PRD 81 (2010)

# Neutrino energy reconstruction problems and neutrino oscillations

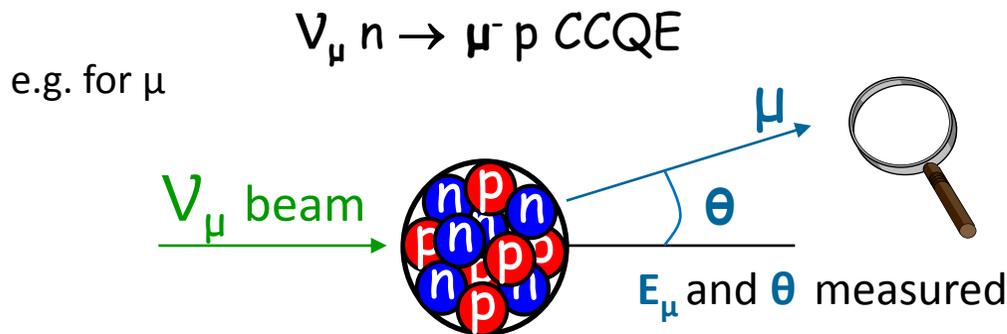
in collaboration with Magda Ericson (CERN, IPN Lyon)

# 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.



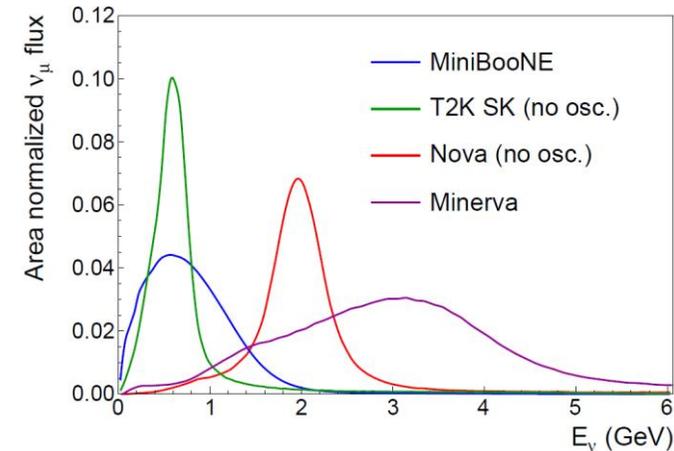
Reconstructed neutrino energy

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

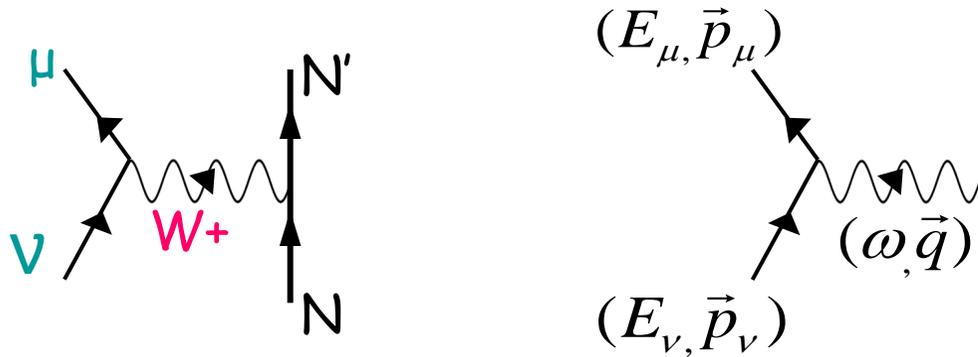
via two-body kinematics

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

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



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



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

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

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

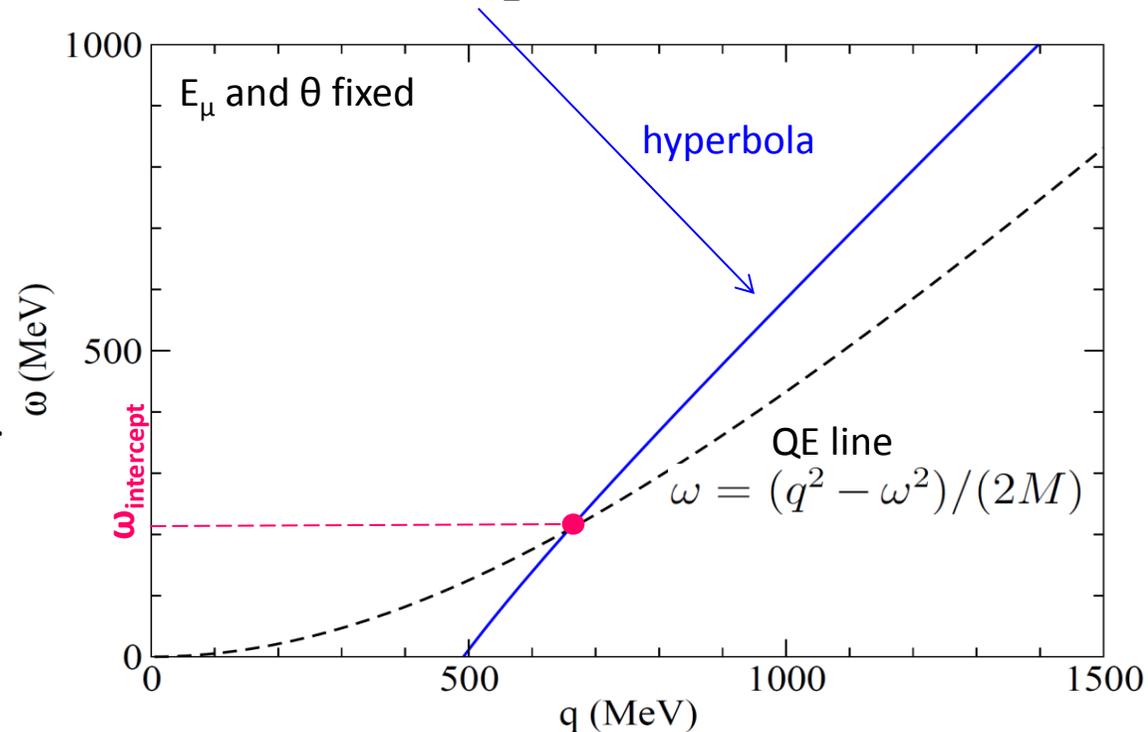
The nuclear response function is proportional to the delta distribution

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

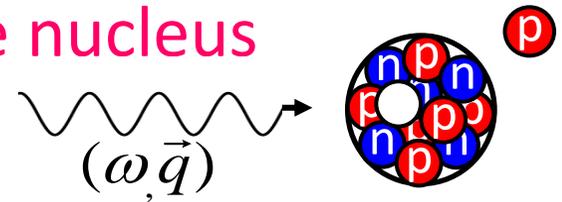
The intercept of the **hyperbola** with the **QE line** fixes the possible  $\omega$  and  $q$  values for given  $E_\mu$  and  $\theta$ .

Hence the neutrino energy is determined

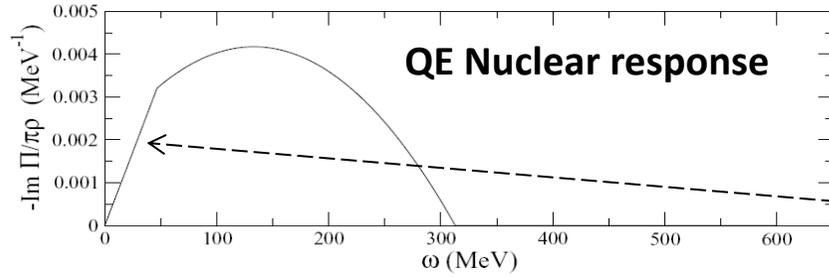
$$E_\nu = E_\mu + \omega_{\text{intercept}}$$



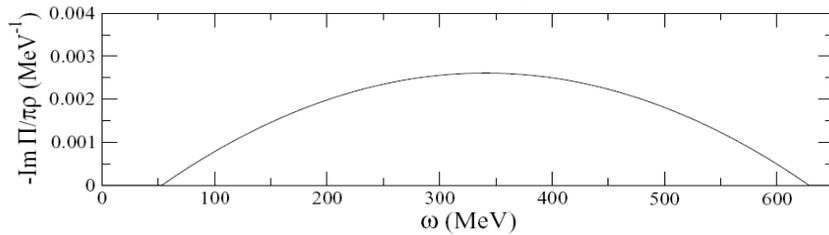
# QE Scattering with nucleon inside the nucleus



$q < 2 k_F$



$q > 2 k_F$



**Particle-hole (p-h) excitation**

**Fermi motion** spreads  $\delta$  distribution  
(Fermi Gas)

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

**RPA** collective effects

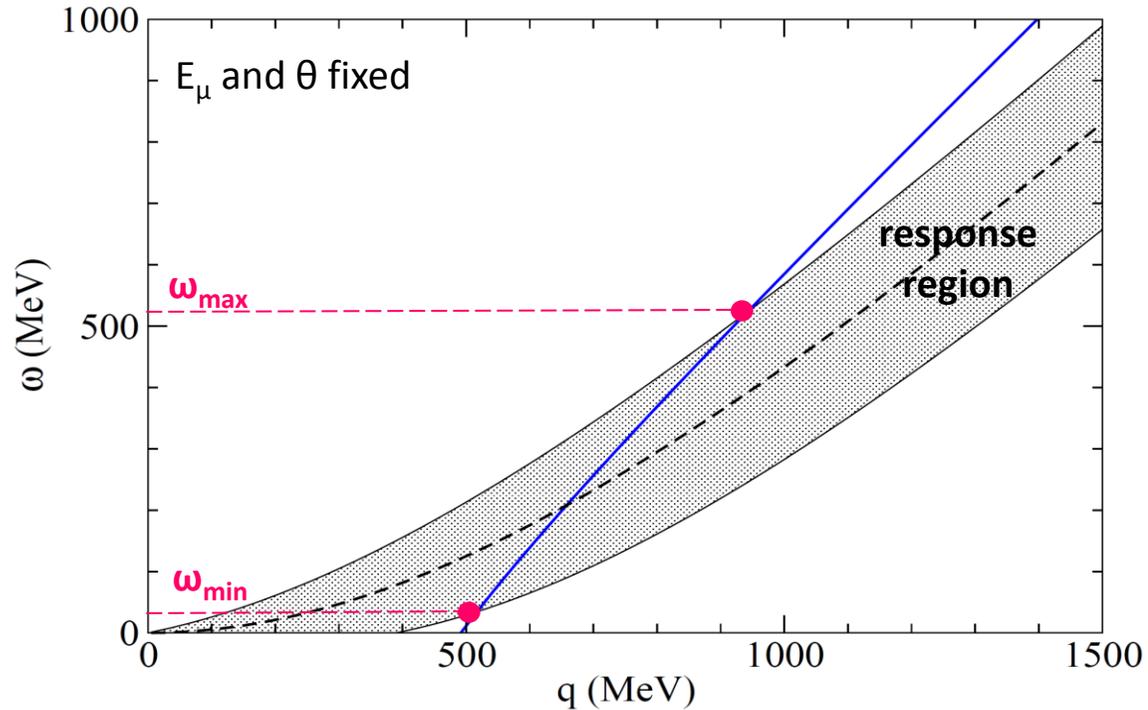
**Fermi motion** introduces a  
broadening around the QE line:  
**response region**

$$\sqrt{q^2 - 2qk_F + M^2} - M \leq \omega \leq \sqrt{q^2 + 2qk_F + M^2} - M$$

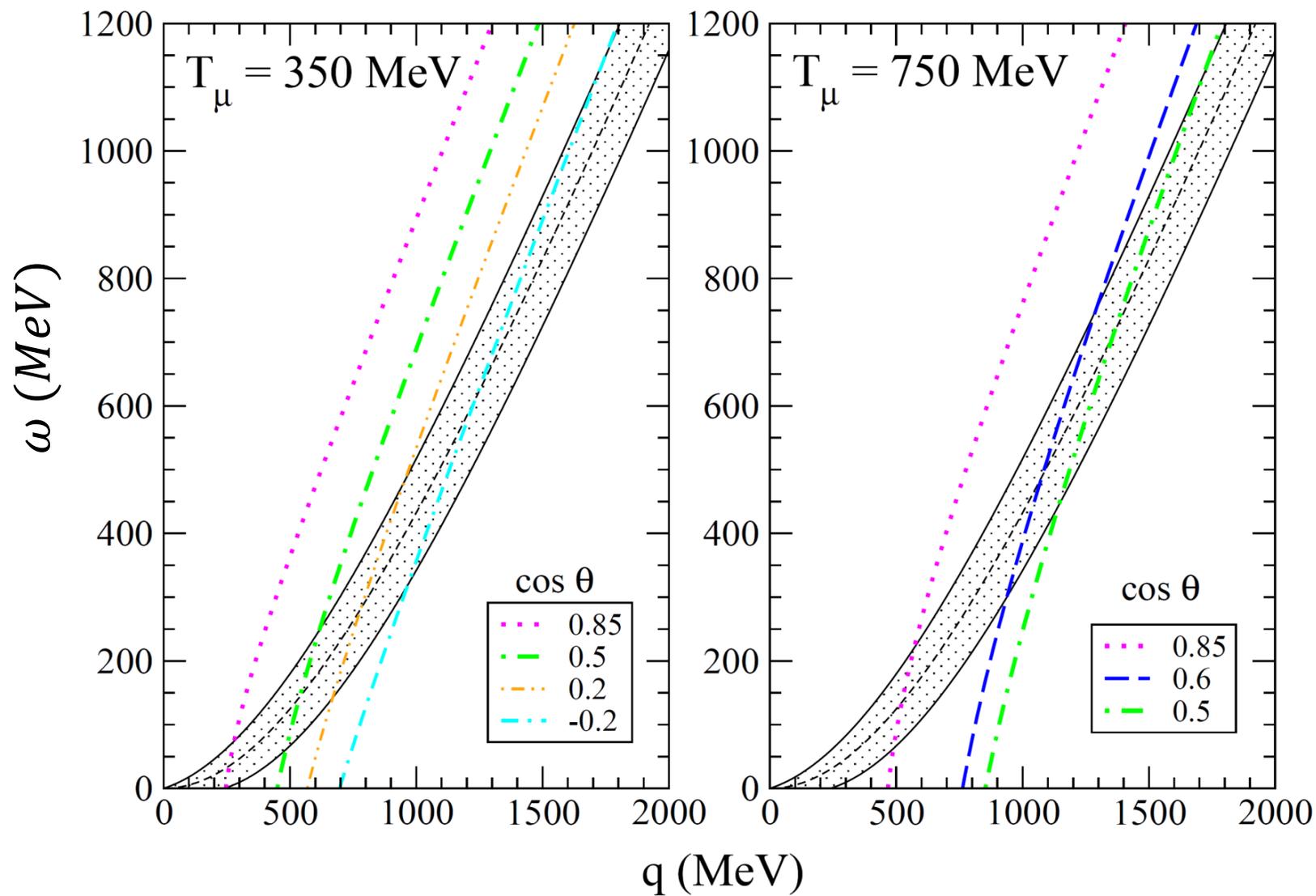
The intercept of the **hyperbola** with the **response region**  
gives several possible  $\omega$

**Broadening of the neutrino energy**

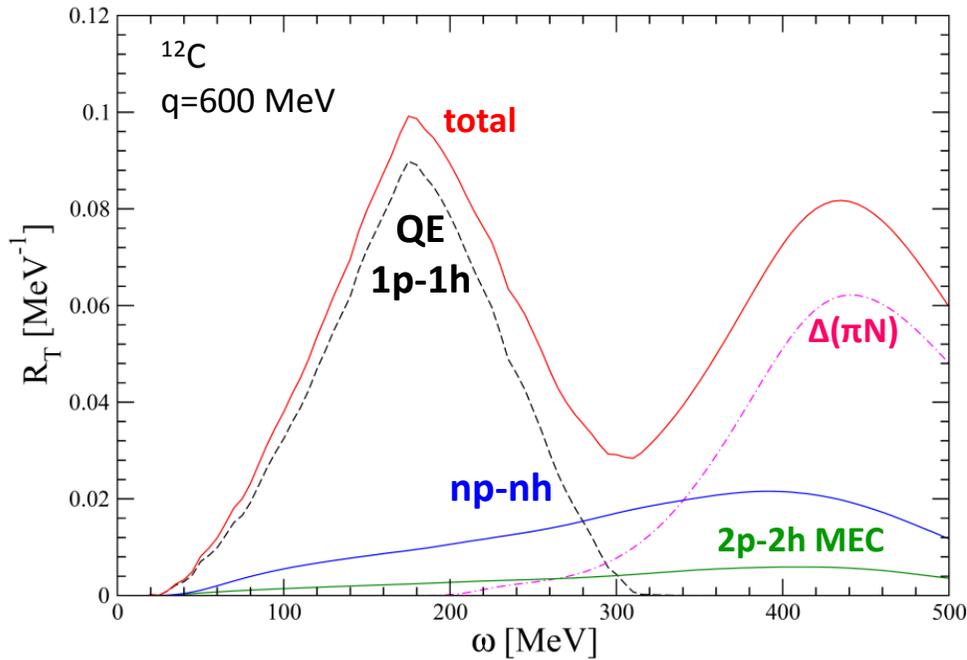
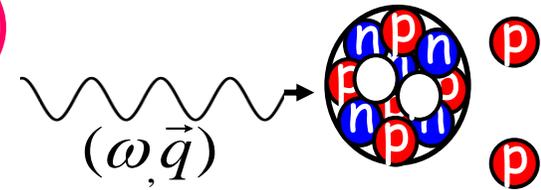
$$E_\nu = E_\mu + (\omega_{\min} \leq \omega \leq \omega_{\max})$$



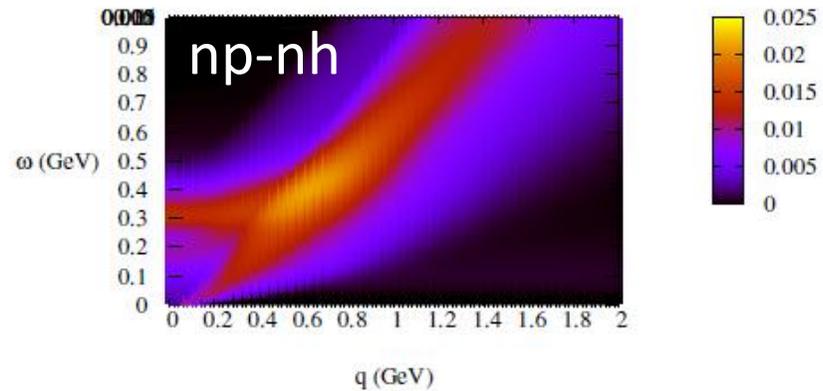
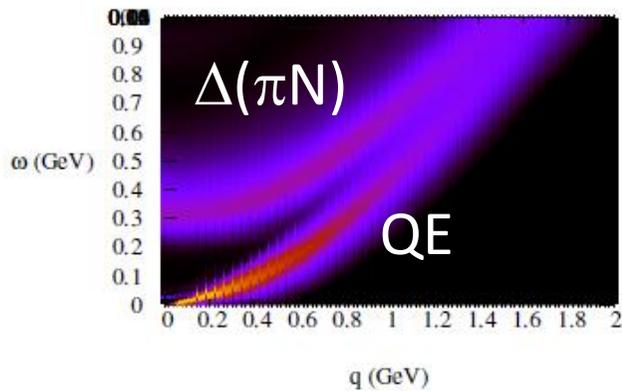
# QE Response region and hyperbolas for several $T_\mu$ and $\theta$



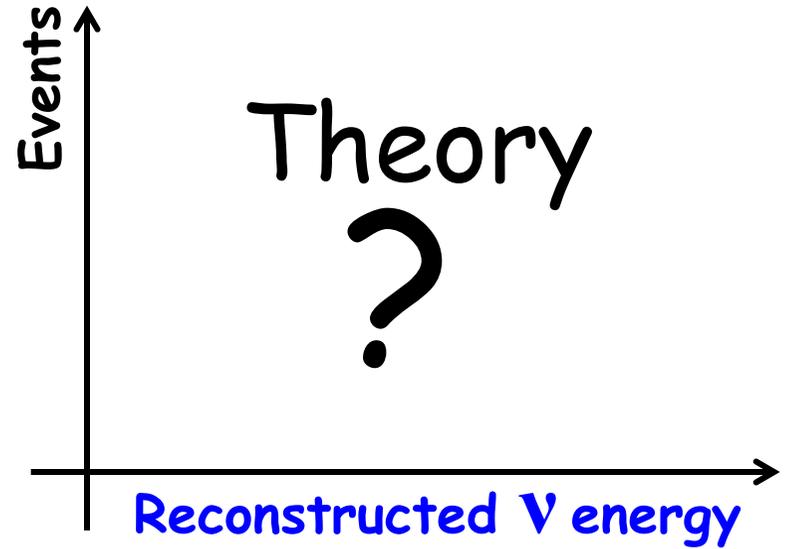
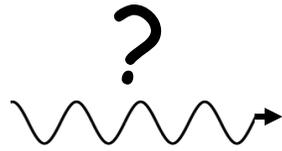
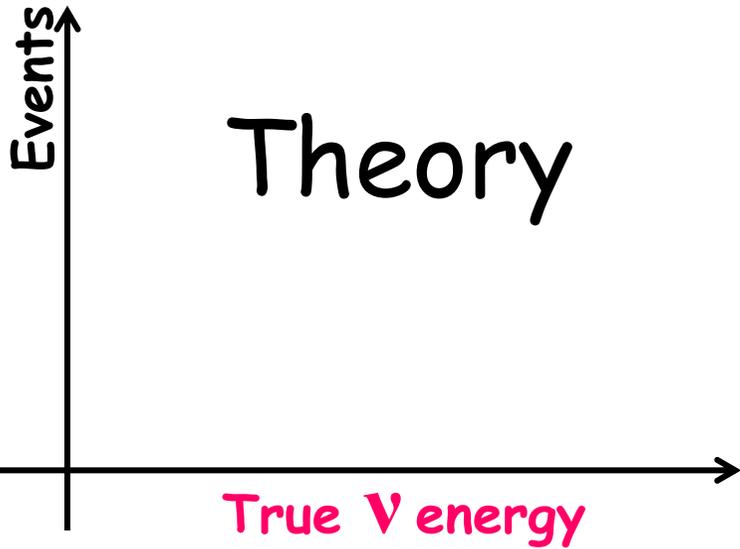
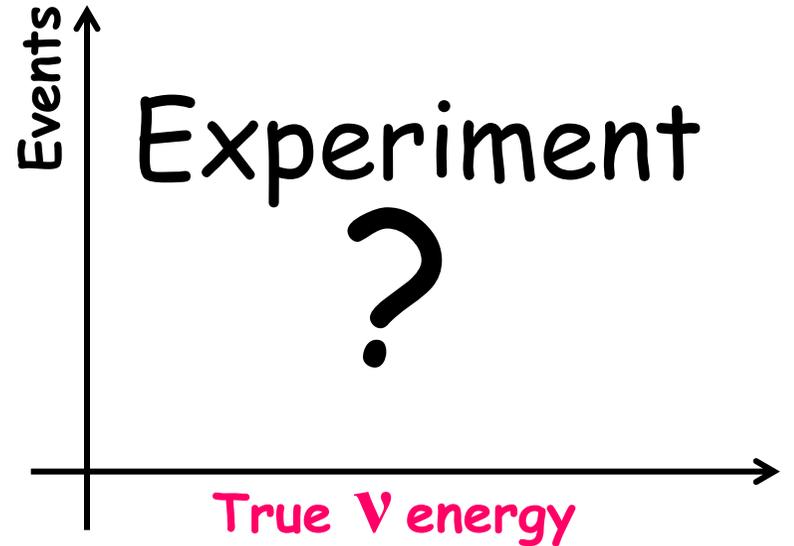
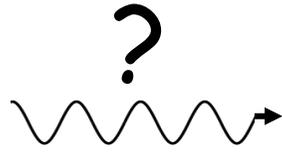
# Multinucleon emission (np-nh)



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



- np-nh enlarges the region of response to the whole  $(\omega, q)$  plane  
no reason to fulfill the QE relation for  $E_\nu$  reconstruction



# From true neutrino energy to reconstructed neutrino energy

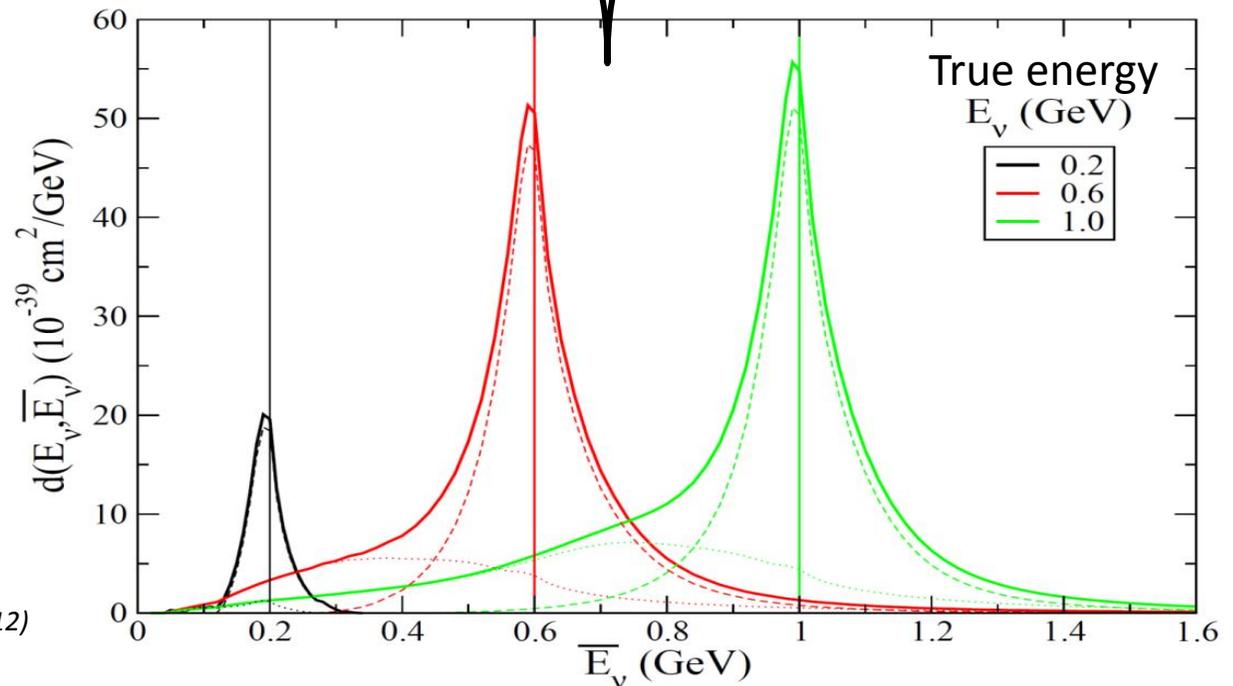
Probability energy distribution ( $E_\nu, \bar{E}_\nu$ )

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

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)

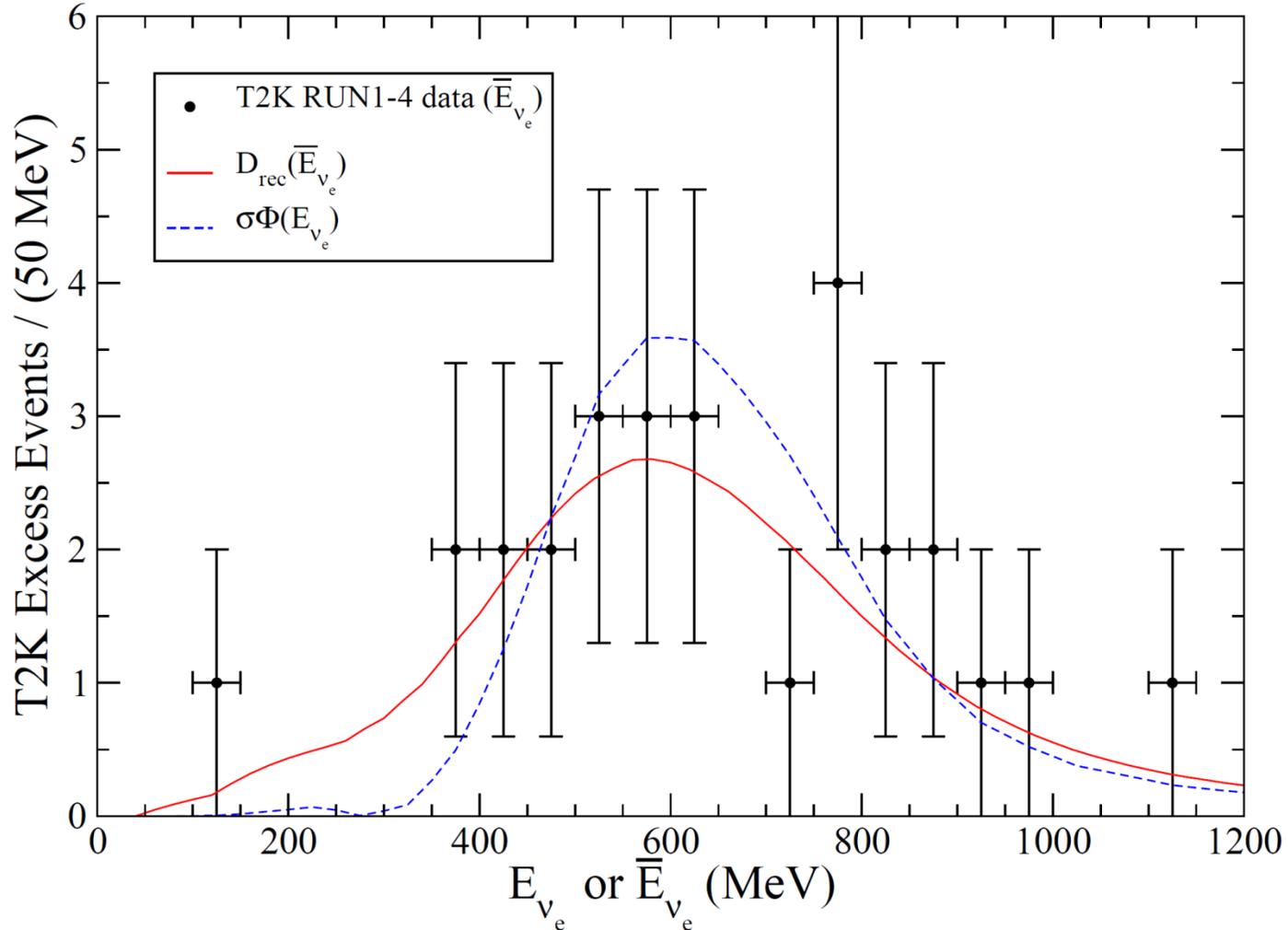


- Distributions not symmetrical around  $E_\nu$
- Crucial role of np-nh: low energy tail

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

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

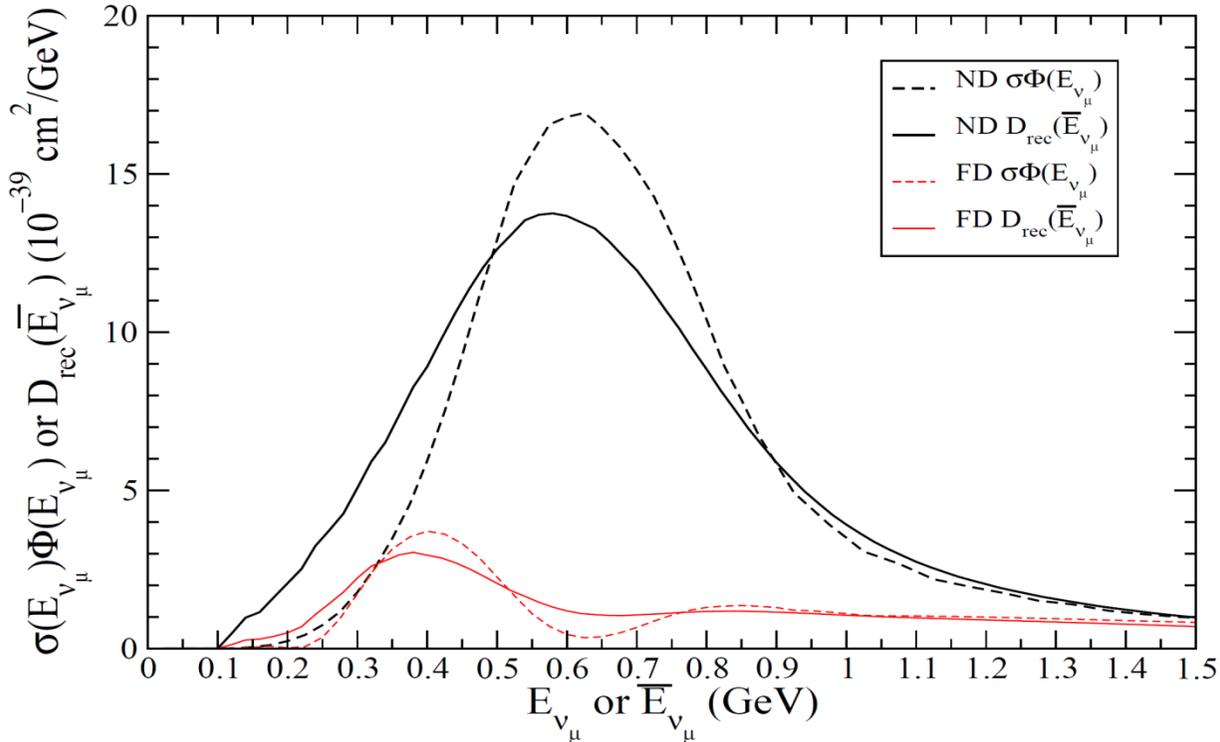
## 2013: 28 events



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

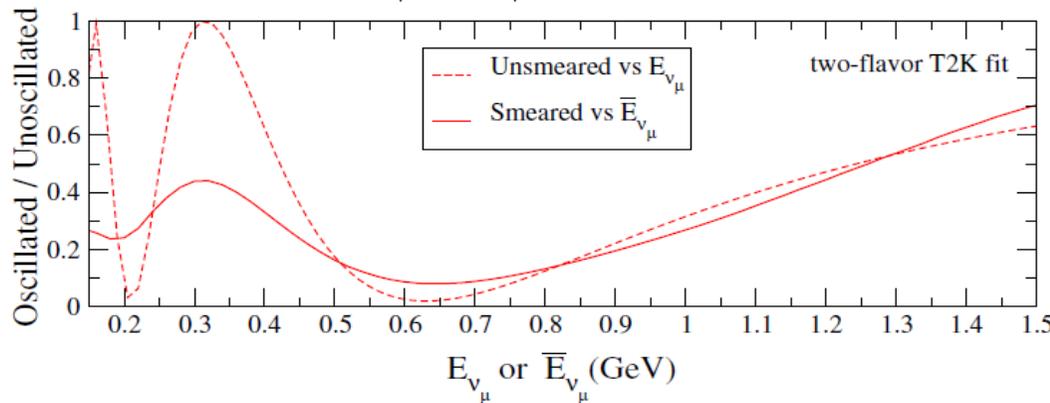
# $\nu_\mu$ disappearance T2K

PRD85 (2012); PRL 111 (2013)



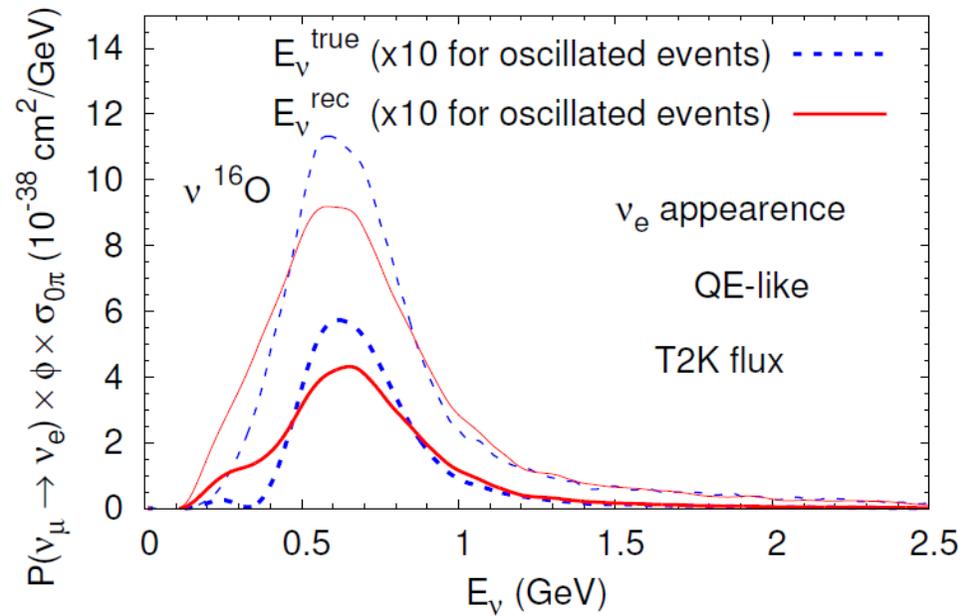
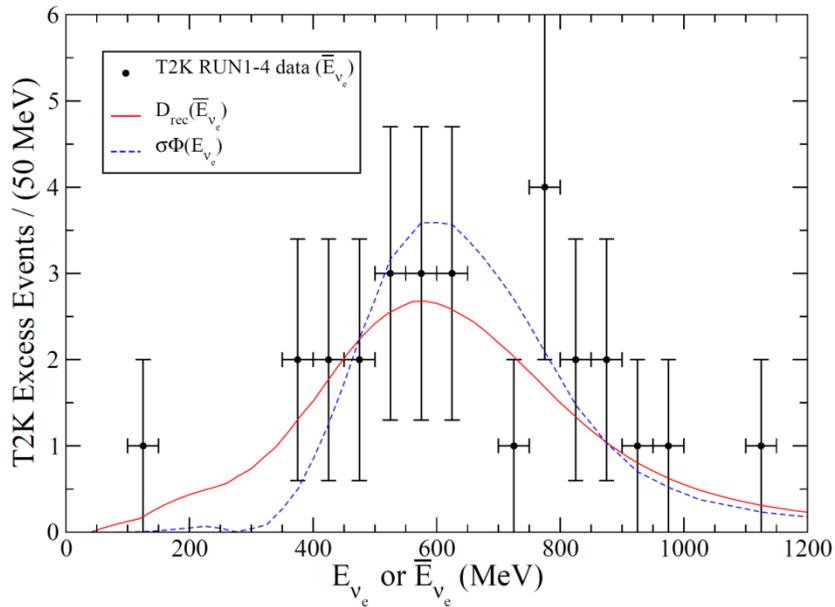
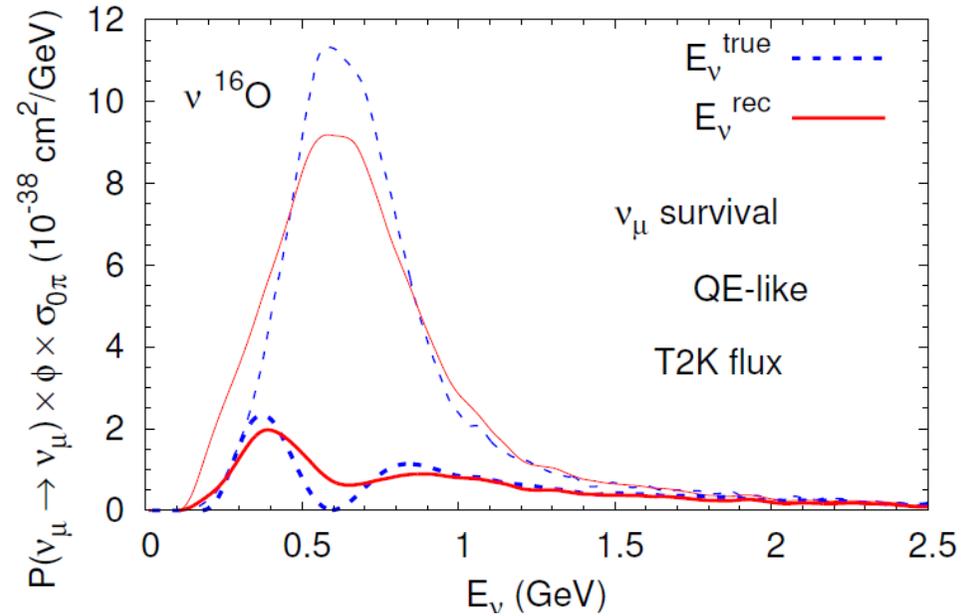
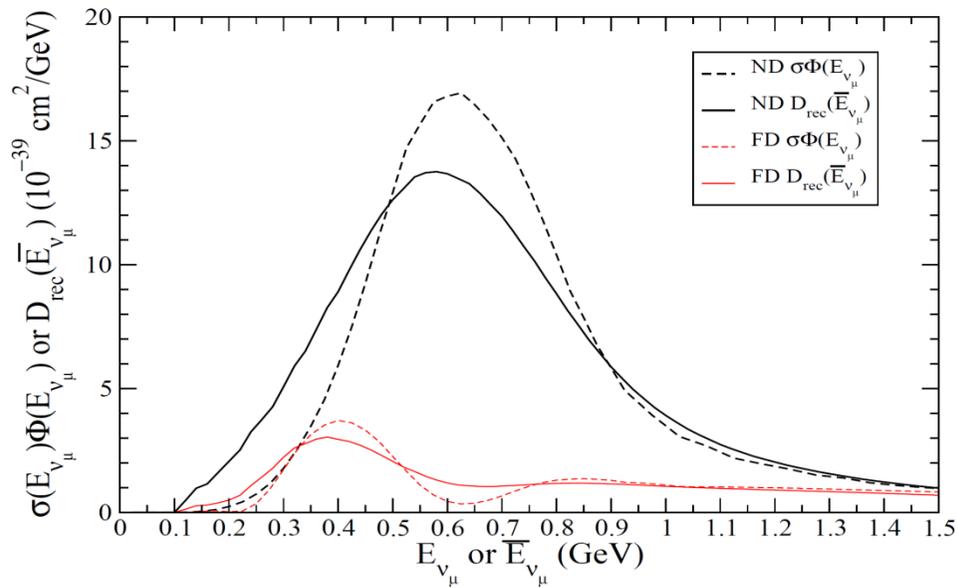
## After reconstruction:

- Near Detector:  
clear low energy enhancement
  - Far Detector:  
low energy tail and  
the middle hole is largely filled
- Effects largely due to np-nh

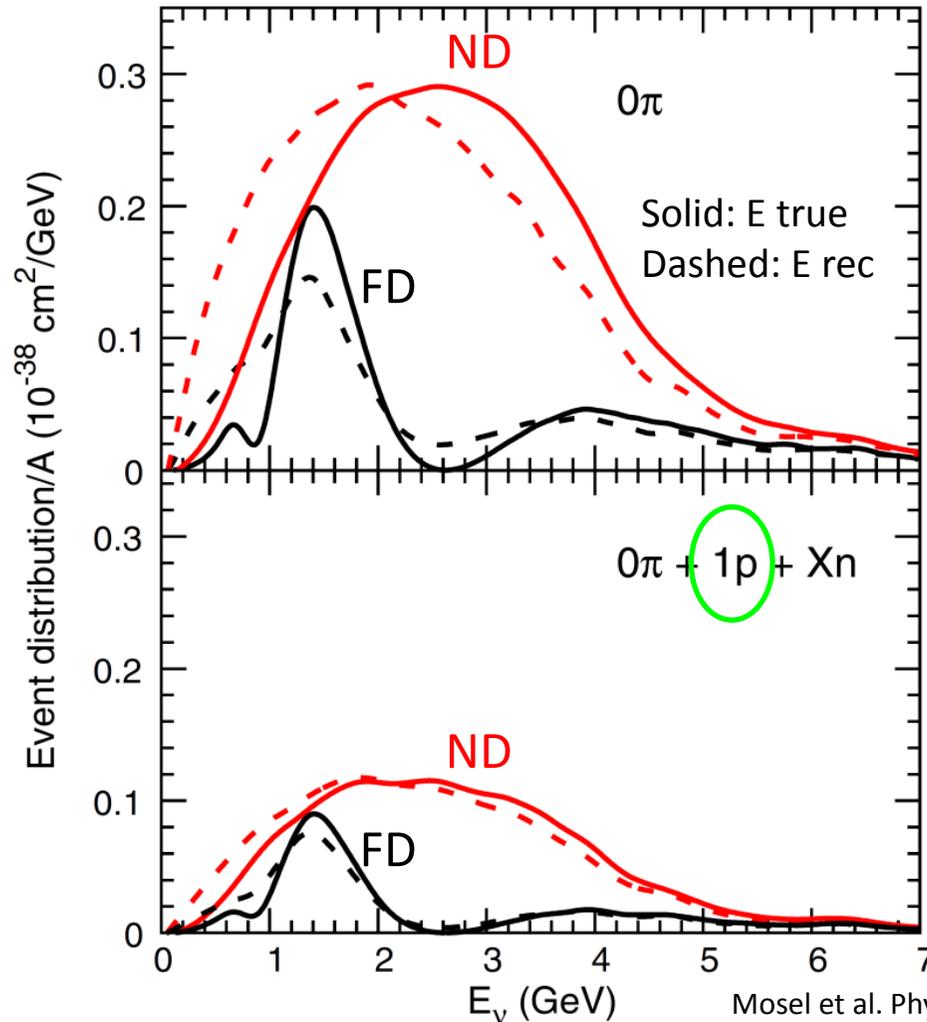
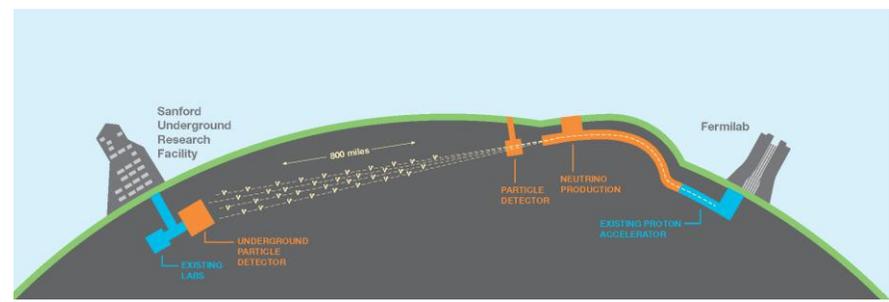


M. Martini, M. Ericson, G. Chanfray, PRD 87 013009 (2013)

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



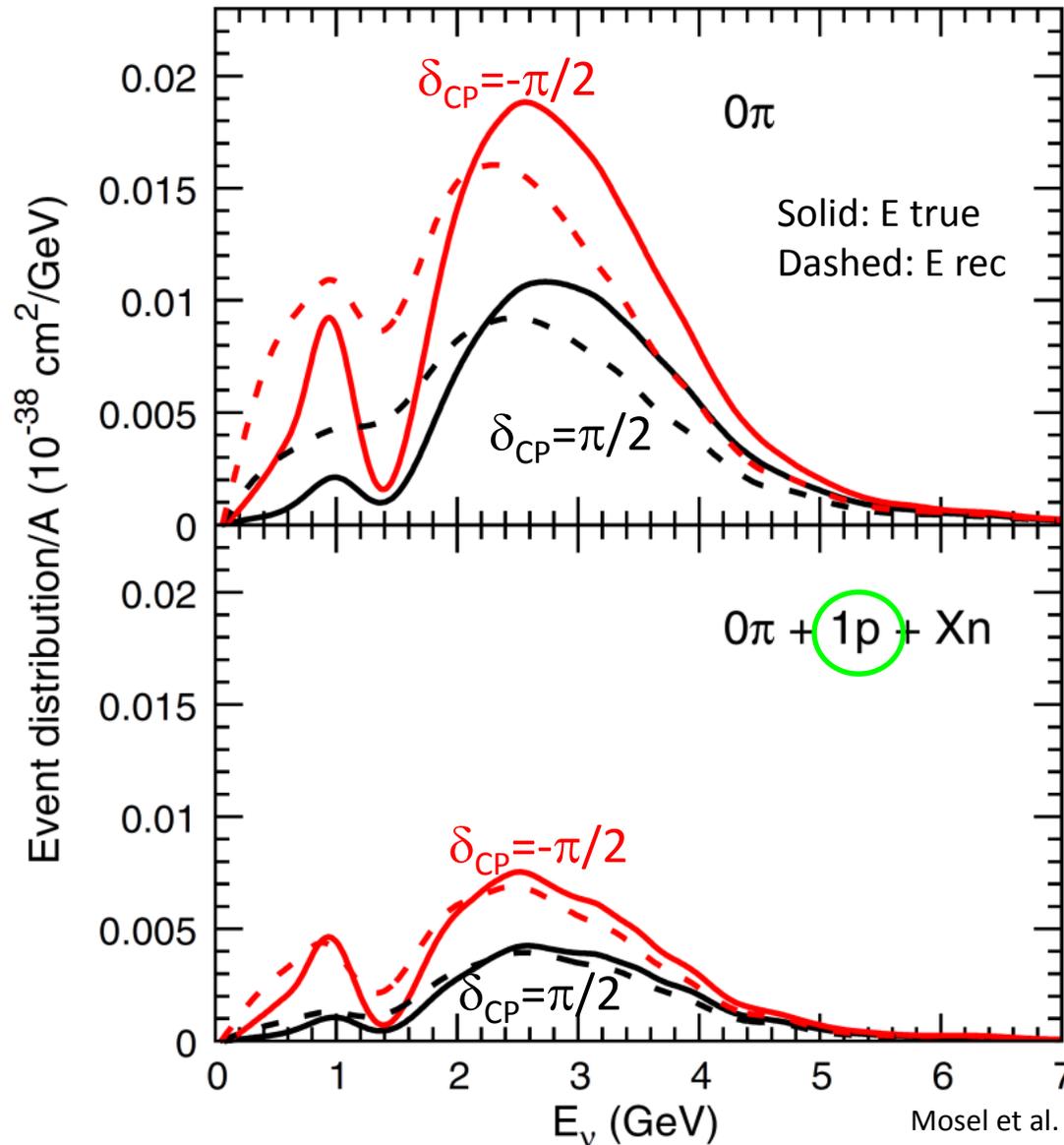
# $\nu_\mu$ disappearance DUNE



Mosel et al. Phys. Rev. Lett. 112 151802 (2014)

- Nearly 500 MeV difference between true and reconstructed event distribution
- Major improvement in  $0\pi + 1p + Xn$  sample, down by only factor 3

# $\nu_\mu \rightarrow \nu_e$ DUNE: sensitivity to $\delta_{CP}$



- Major improvement in  $0\pi + 1p + Xn$  sample, down by only factor 3

# Nuclear effects in neutrino interactions

## Summary

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

Very exciting period from a theoretical and an experimental point of view

# Experimental plans

CEA/Irfu/SPP; LLR



# Experimental plans

Collaboration of T2K LLR and CEA/IRFU/SPP groups for neutrino cross-section measurements at

- **T2K near detector (ND280)**

CC0 $\pi$  measurement on carbon

← *public*

CC0 $\pi$  measurement of proton kinematics

first CC0 $\pi$  measurement on water

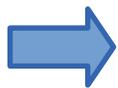
} *on-going*  
(requested shared  
P2IO post-doc)

- **WAGASCI (4 $\pi$  acceptance):**

carbon/water ratio 3% accuracy for CC inclusive

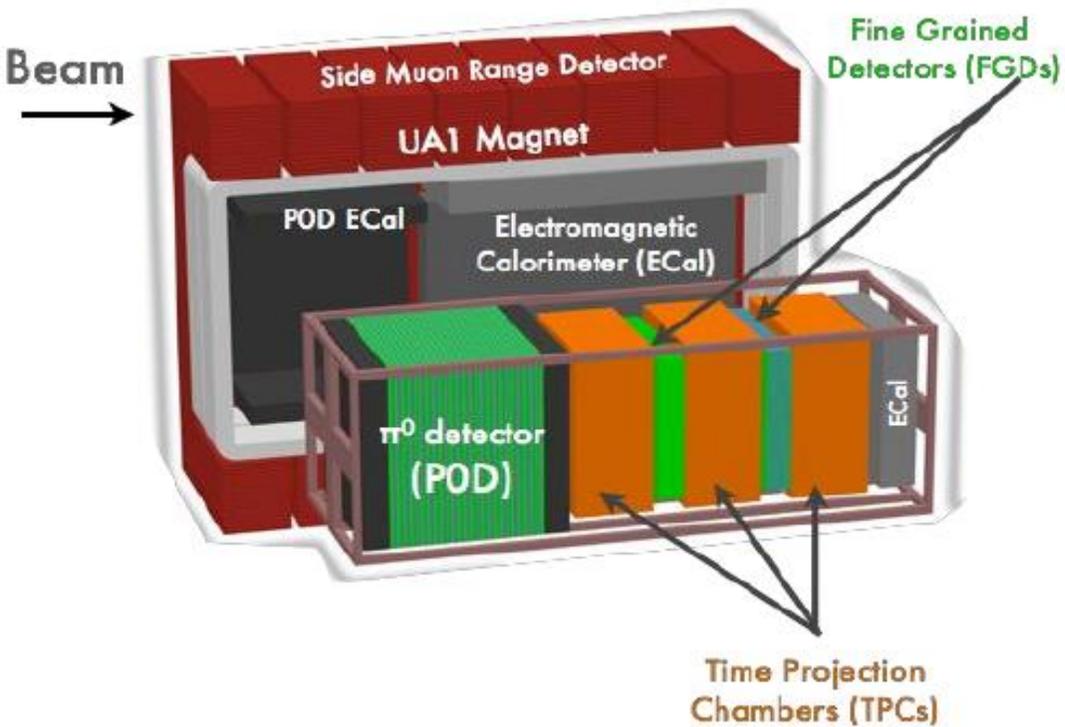
absolute water CC inclusive cross-section with 10% accuracy

*under construction*



crucial for (present and) future long baseline experiment (HyperKamiokande, DUNE)

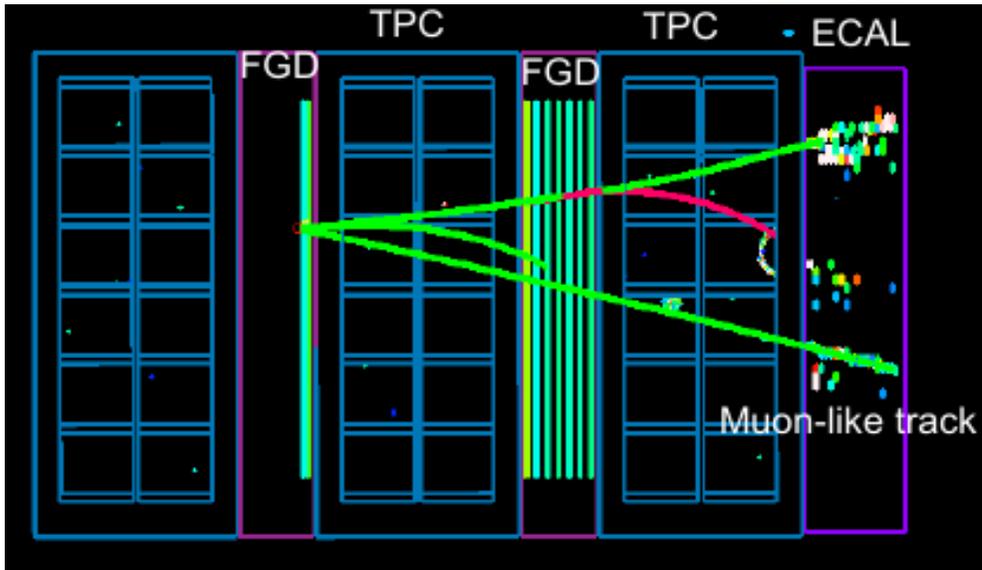
# T2K Near Detector (ND280)



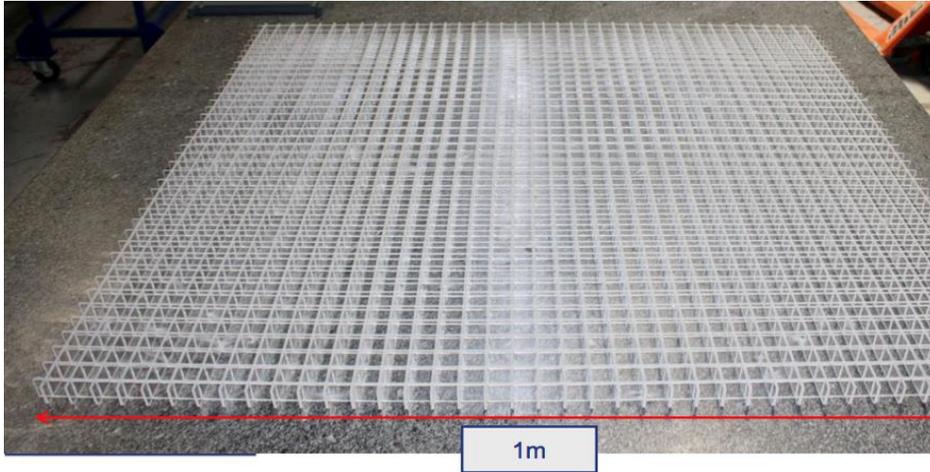
Analyses mainly with central tracker:

- main target FGD scintillators
- (CH + H<sub>2</sub>O)
- TPC → **good tracking efficiency** (acceptance enlarged to backward tracks),
- **resolution** (6%  $p_T < 1\text{GeV}$ ) **and particle identification**

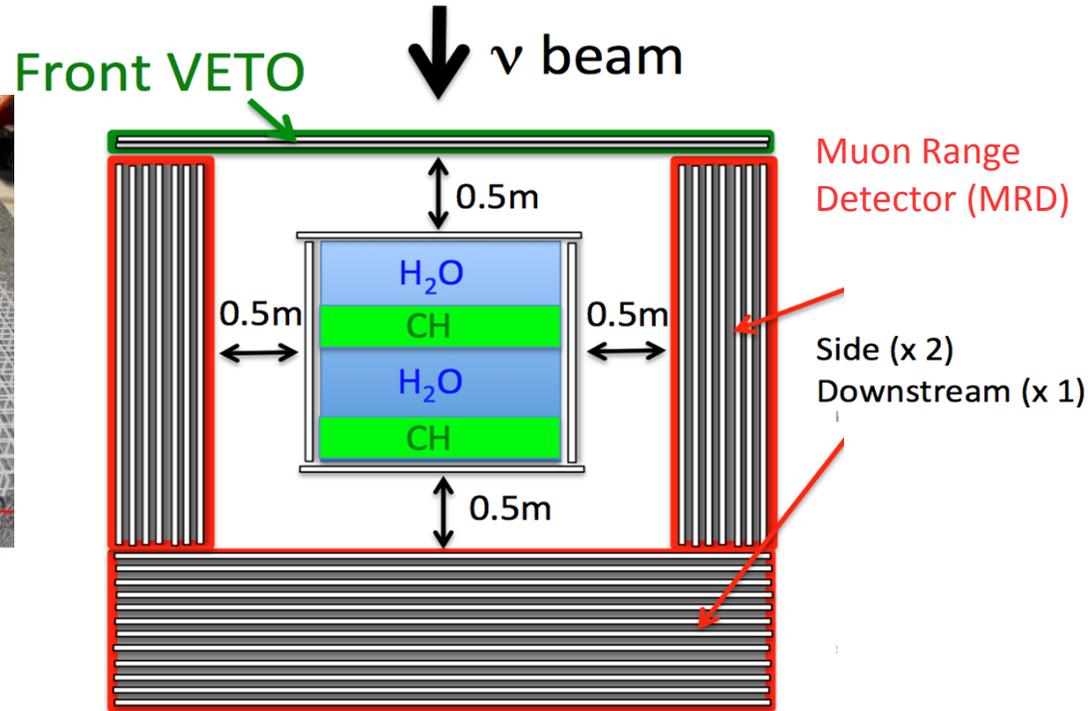
(electronics with Micromegas technology fully developed and assembled at CEA)



# Water Grid And SCIntillator detector (WAGASCI)



Grid of plastic scintillator bars, filled with Water or Hydrocarbon



• **H<sub>2</sub>O(signal):CH(BG) = 79:21** (= 46:54 -> T2K ND280)

• **4 $\pi$  angular acceptance** for charged particles

(electronics, mechanics and sMRD design optimization performed at LLR)



## Collaboration theory – experiments:

(few months of visiting professorship in LLR and IRFU funded by P2IO)

- evaluation of proper systematics for new analysis using 2p2h models
- design and optimization of analyses for measurement of 2p2h contribution

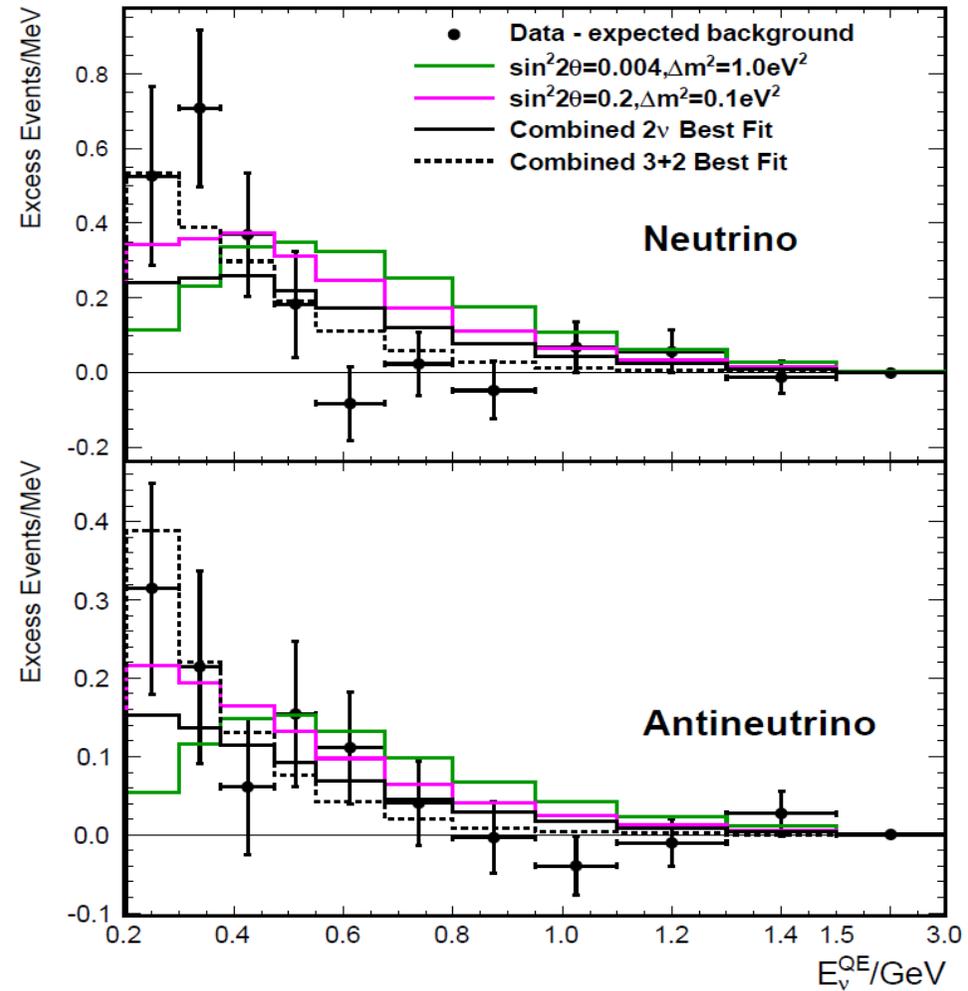
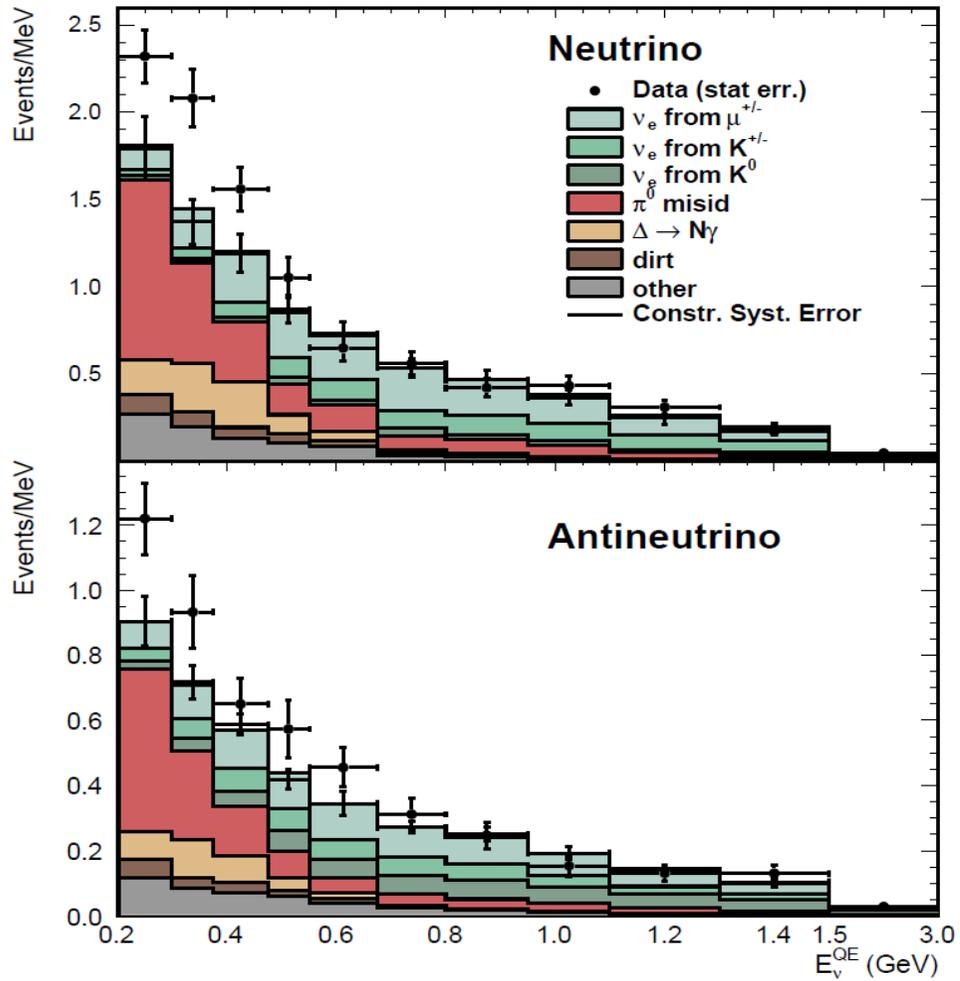
→ long term plans for improvements in neutrino interaction understanding

- development of common language  
(seminars and lectures at LLR and IRFU)

Spare

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

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

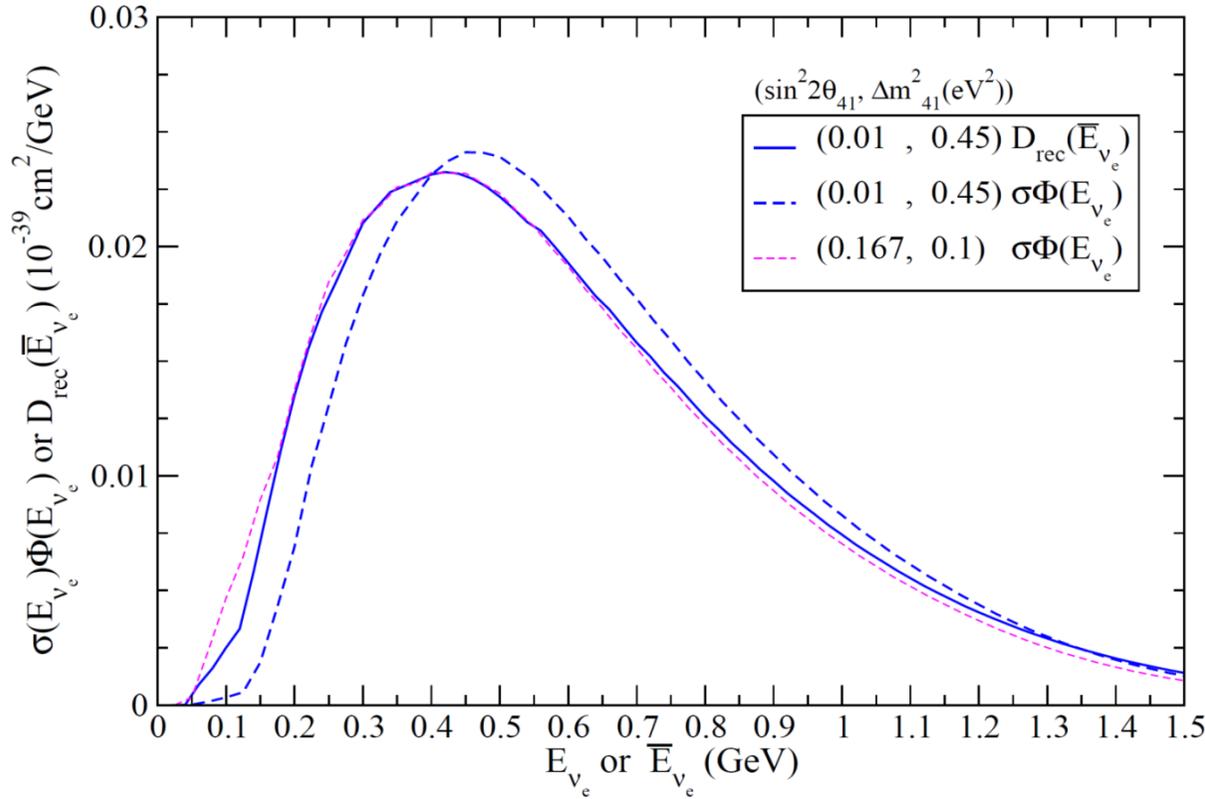


MiniBooNE Anomaly: Excess of events at low energies

Sterile neutrino??

# Taking into account the energy reconstruction correction

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



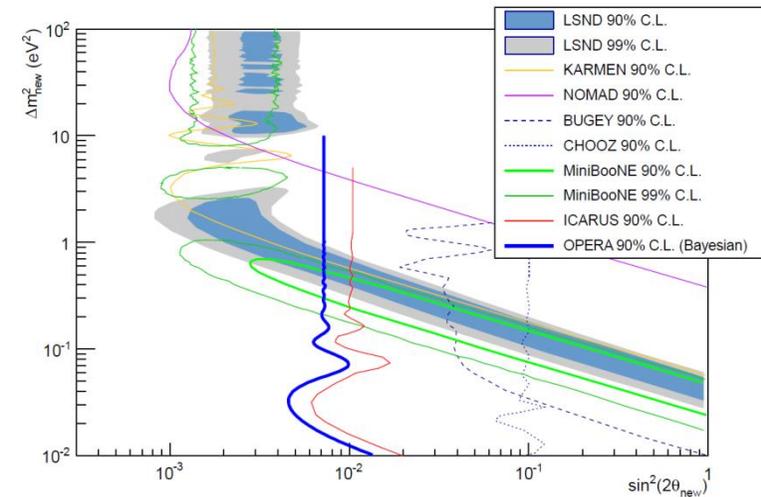
A large mass value allows the same quality of fit of data than is obtained in the unsmeared case with a much smaller mass.

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

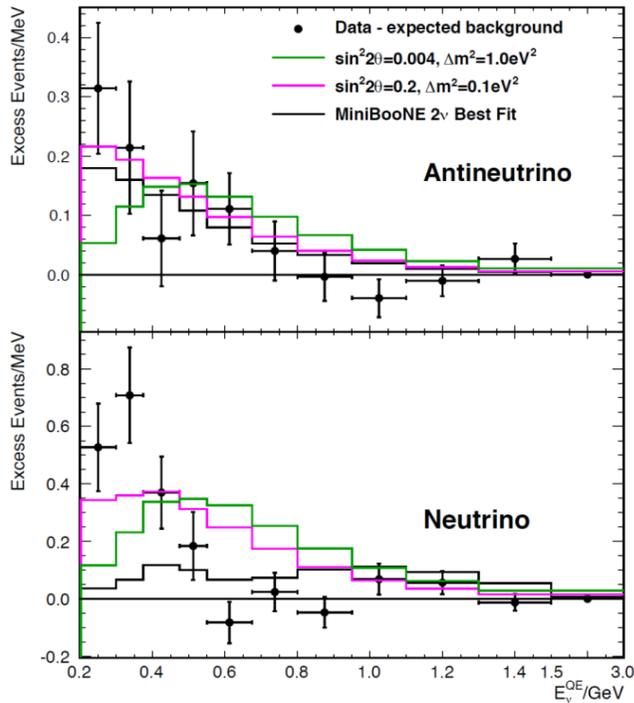
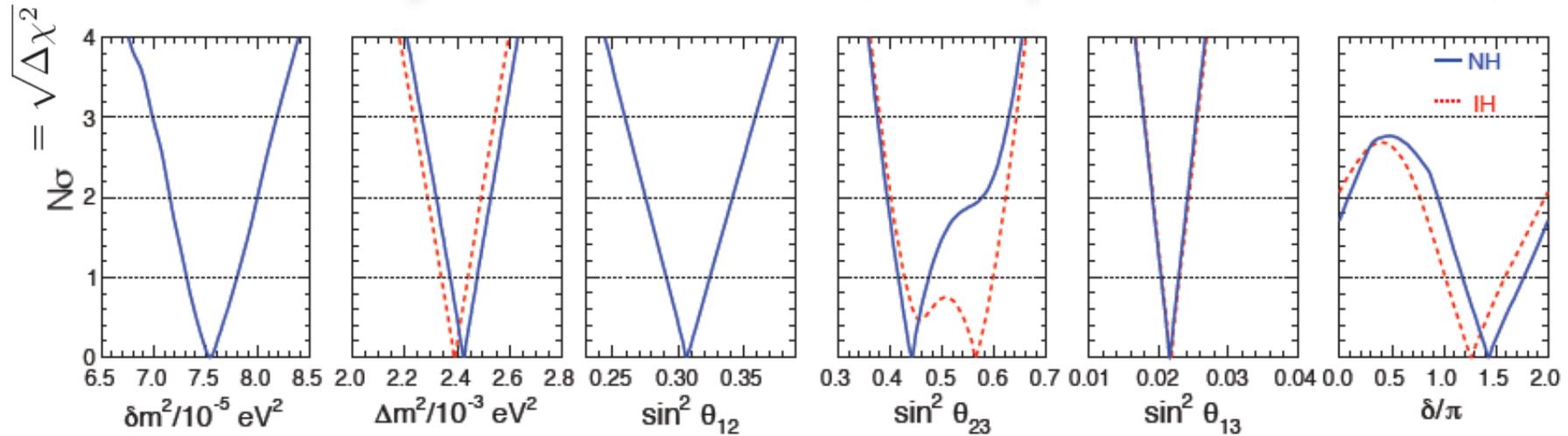


TABLE II:  $\chi^2$  values from oscillation fits to the antineutrino-mode data for different prediction models. The best fit  $(\Delta m^2, \sin^2 2\theta)$  values are  $(0.043 \text{ eV}^2, 0.88)$ ,  $(0.059 \text{ eV}^2, 0.64)$ , and  $(0.177 \text{ eV}^2, 0.070)$  for the nominal, Martini, and disappearance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

# Global Analysis: Summarizing our present knowledge



## PMNS

$3\sigma$

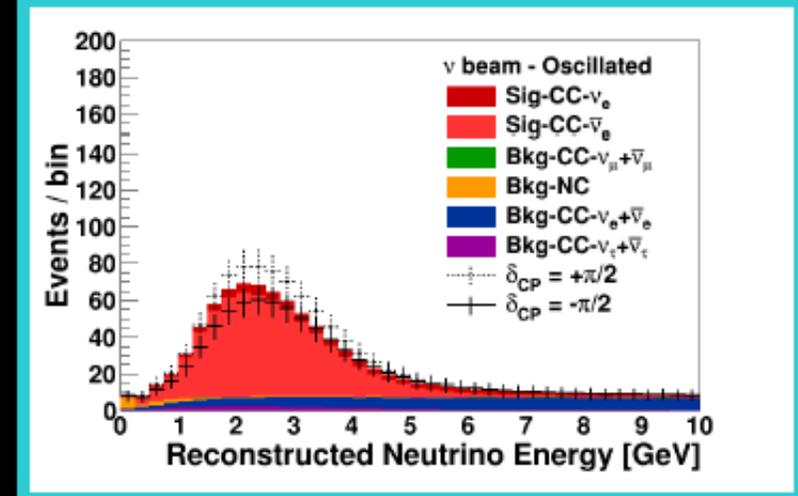
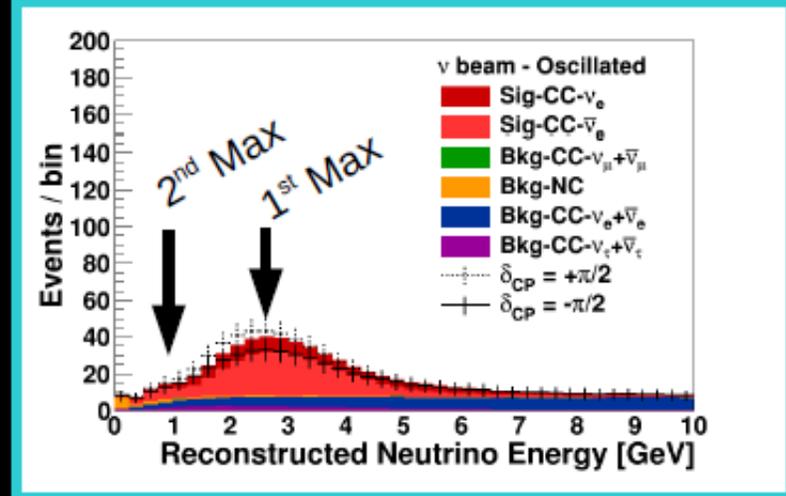
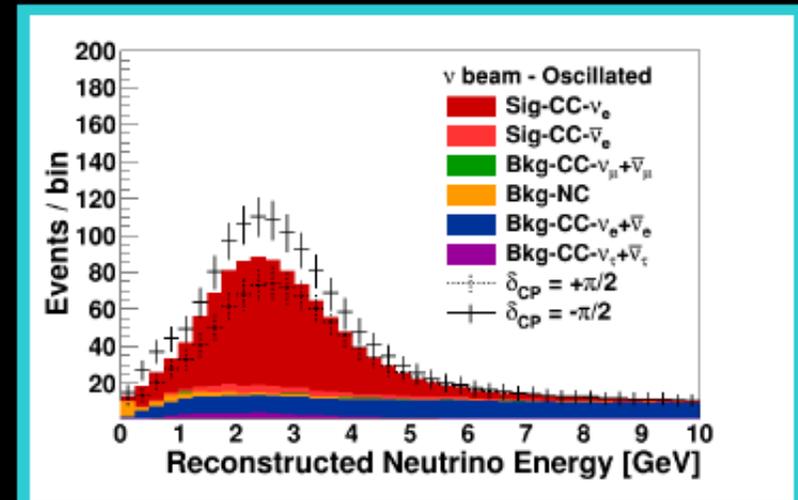
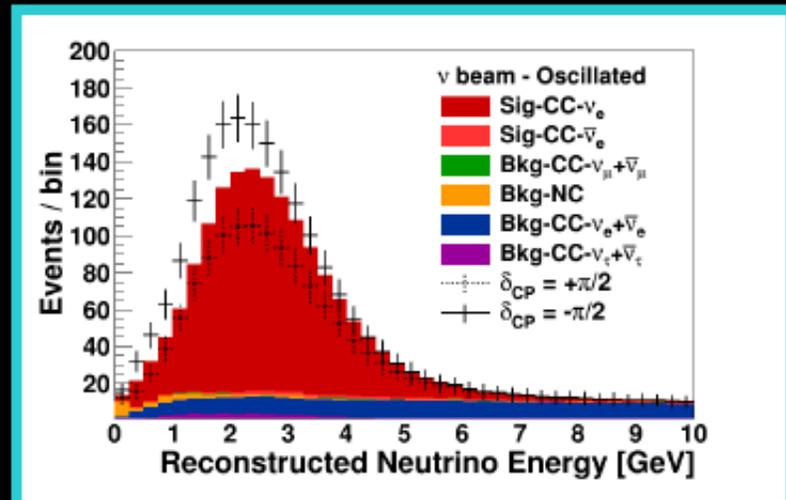
$$|U| = \begin{pmatrix} 0.801 \rightarrow 0.845 & 0.514 \rightarrow 0.580 & 0.137 \rightarrow 0.158 \\ 0.225 \rightarrow 0.517 & 0.441 \rightarrow 0.699 & 0.614 \rightarrow 0.793 \\ 0.246 \rightarrow 0.529 & 0.464 \rightarrow 0.713 & 0.590 \rightarrow 0.776 \end{pmatrix}$$

## CKM

$$|V|_{\text{CKM}} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.0065 & (3.51 \pm 0.15) \times 10^{-3} \\ 0.2252 \pm 0.00065 & 0.97344 \pm 0.00016 & (41.2_{-5}^{+1.1}) \times 10^{-3} \\ (8.67_{-0.31}^{+0.29}) \times 10^{-3} & (40.4_{-0.5}^{+1.1}) \times 10^{-3} & 0.999146_{-0.000046}^{+0.000021} \end{pmatrix}$$

# DUNE

## Spectral Differences: $\nu_e$ Appearance

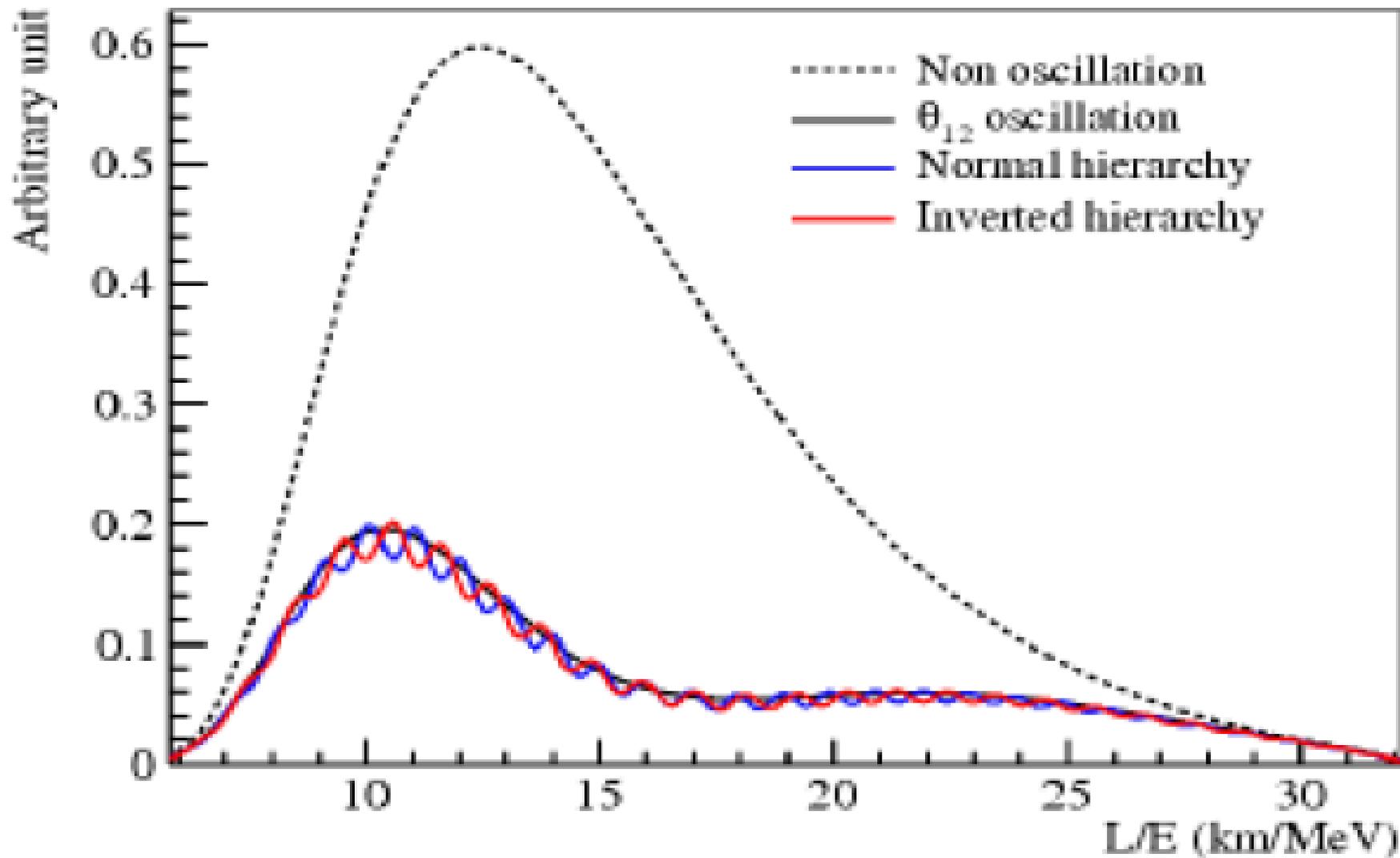


Normal Hierarchy

Inverted Hierarchy

# JUNO

$$\bar{\nu}_e \rightarrow \bar{\nu}_e$$



# Sources and References of 2p-2h

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

- Alberico, Ericson, Molinari, Ann. Phys. 154, 356 (1984)*  $(e,e')$   $\gamma$   $\pi$   
*\*Oset and Salcedo, Nucl. Phys. A 468, 631 (1987)*  $\pi$   $\gamma$   
*Shimizu, Faessler, Nucl. Phys. A 333,495 (1980)*  $\pi$   
*Delorme, Ericson, Phys.Lett. B156 263 (1985)*  
*Marteau, Eur.Phys.J. A5 183-190 (1999); PhD thesis*  
*Marteau, Delorme, Ericson, NIM A 451 76 (2000)* }  $\nu$  pioneer works

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

- Gil, Nieves, Oset, Nucl. Phys. A 627, 543 (1997)*  $(e,e')$   $\gamma$   
*\*Oset and Salcedo, Nucl. Phys. A 468, 631 (1987)*  $\pi$   $\gamma$

**J.E. Amaro, M.B. Barbaro, T.W. Donnelly G. Megias et al.**

- De Pace, Nardi, Alberico, Donnelly, Molinari, Nucl. Phys. A741, 249 (2004)*  $(e,e')$   $\gamma$   
*Amaro, Maieron, Barbaro, Caballero, Donnelly, Phys. Rev. C 82 044601 (2010)*  $(e,e')$

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

- Lovato, Gandolfi, Butler, Carlson, Lusk, Pieper, Schiavilla, Phys. Rev. Lett. 111 092501 (2013)*  $(e,e')$   
*Shen, Marcucci, Carlson, Gandolfi, Schiavilla, Phys. Rev. C 86 035503 (2012)*  $\nu$ -deuteron

# Analogies and differences of 2p-2h

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

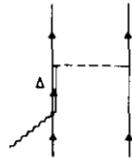
[ Genuine QE (1 body contribution): LRFQ+RPA ]

NN correlations

$\Delta$ -MEC

NN correlations - MEC interference

Axial and Vector



$\pi, g'$

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

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

NN correlations

MEC

NN correlations - MEC interference

Axial and Vector

$\pi, \rho, g'$

**J.E. Amaro, M.B. Barbaro, T.W. Donnelly, G. Megias, I. Ruiz Simo et al.**

[ Genuine QE (1 body contribution): Superscaling ]

MEC

Only Vector

[ Generalization to axial in progress ]

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

$\pi$

**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