Neutrino cross sections in the GeV region

Davide Meloni

Dipartimento di Matematica e Fisica, RomaTre

& INFN, Sezione di Roma Tre

Main motivation of this talk

- Extracting neutrino oscillation parameters is a difficult experimental task

Main reason:

Nuclear dynamics is complicated

Neutrino flavour conversion

- Neutrinos can also be described in terms of mass eigenstates ν_i

$$|\nu_\alpha\rangle = \Sigma_{i=1}^{3} U_{\alpha i} |\nu_i\rangle$$

neutrino matrix
matrix

- Simple time evolutions of the vector $\nu(t) = (\nu_e(t), \nu_\mu(t), \nu_\tau(t))$:

$$i \frac{d}{dt} |\nu(t)\rangle = H |\nu(t)\rangle$$

$$H = \frac{1}{2E_\nu} U \, Diag[0, m_2^2 - m_1^2, m_3^2 - m_1^2] U^{dag}$$

there exist a probability of a change of the neutrino flavour

Neutrino flavour conversion

- Flavour changing transitions

$$P(\nu_\alpha \to \nu_\beta) = \left|\langle \nu_\beta | \nu_\alpha(t)\rangle\right|^2 = \left|\Sigma_j U_{\beta j} e^{\frac{-i m_j^2 L}{2 E_\nu}} U^{star}_{\alpha j}\right|^2$$

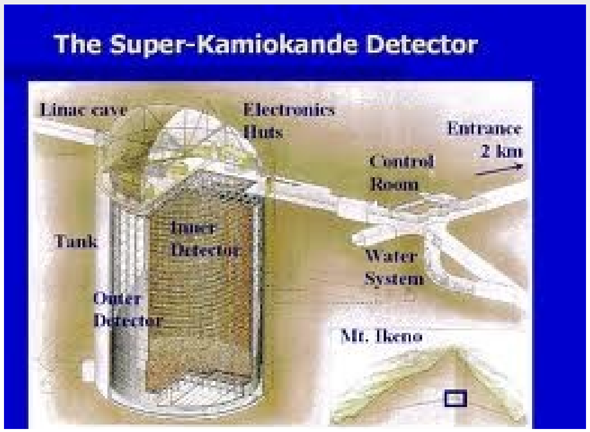
- In the case of three neutrinos:

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{atmospheric \;\; mixing} \times \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{-i\delta} & 0 & c_{13} \end{pmatrix}}_{reactor \;\; mixing} \times \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{solar \;\; mixing}$$

Summary of the experimental results

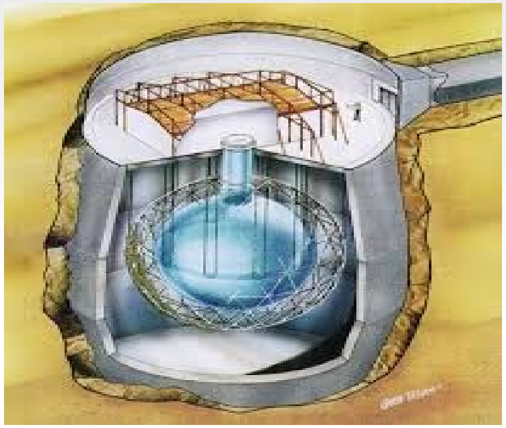
- Superkamiokande:

  $\theta_{23} \sim 45^o$



- SNO

  $\theta_{12} \sim 33^o$



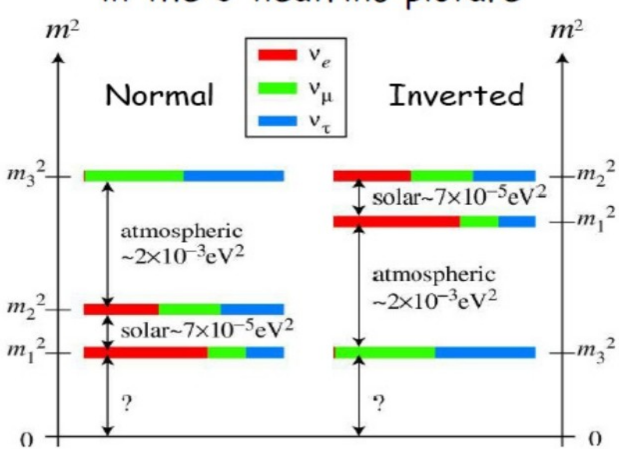
- T2K

  $\theta_{13} \sim 9^o$

$\Delta m^2_{12} \sim 7 \times 10^{-5}$ eV^2

$\Delta m^2_{23} \sim 2 \times 10^{-3}$ eV^2

in the 3-neutrino picture



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- **Hierarchy = ?**
- **δ = ?**

Systematics must be under control

Probabilities and events

- Here mainly interested to the Charge Current Quasi Elastic Scattering
- We want to measure mixing parameters, that is to understand transition probabilities

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

- P's are extracted from the number of expected events

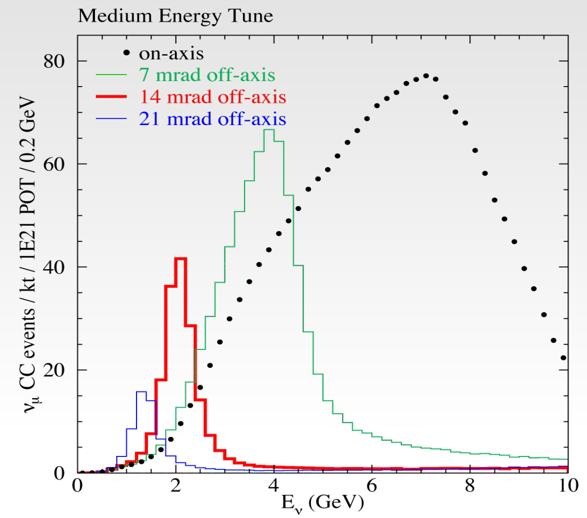
$$N_\beta \sim \underbrace{\Phi_{\nu_\alpha}(E_\nu)}_{\text{ν flux (prediction)}}\ \underbrace{\sigma_{\nu_\beta}(E_\nu)}_{\text{ν cross section (model)}}\ \underbrace{\varepsilon_{det.}}_{\text{Detector efficiency}}\ P_{\nu_\alpha \to \nu_\beta}(\{\Theta\}, \underbrace{E_\nu}_{\text{ν Energy in the oscillation probability}}))$$

Marco Martini, Séminaires LLR, 2015

- If E_ν is not well reconstructed, mixing parameters extraction is wrong !

Probabilities and events

Extraction of Eν is a quite difficult task:

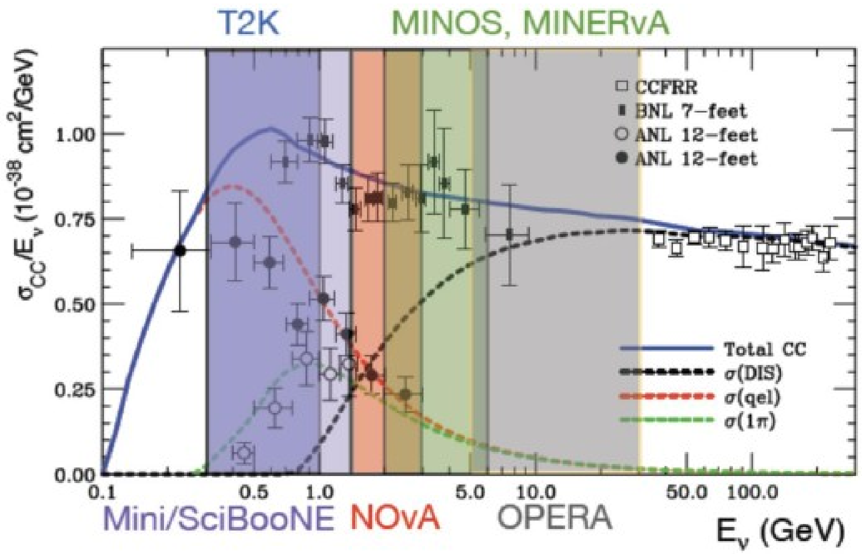


- Neutrino energies are not monochromatic

- Neutrino energies are reconstructed from the final states

⇓

the knowledge of the neutrino-nucleus cross section is crucial



- Different mechanisms contribute to the cross section

Probabilities and events

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

ν flux (prediction)

ν cross section (model)

Detector efficiency

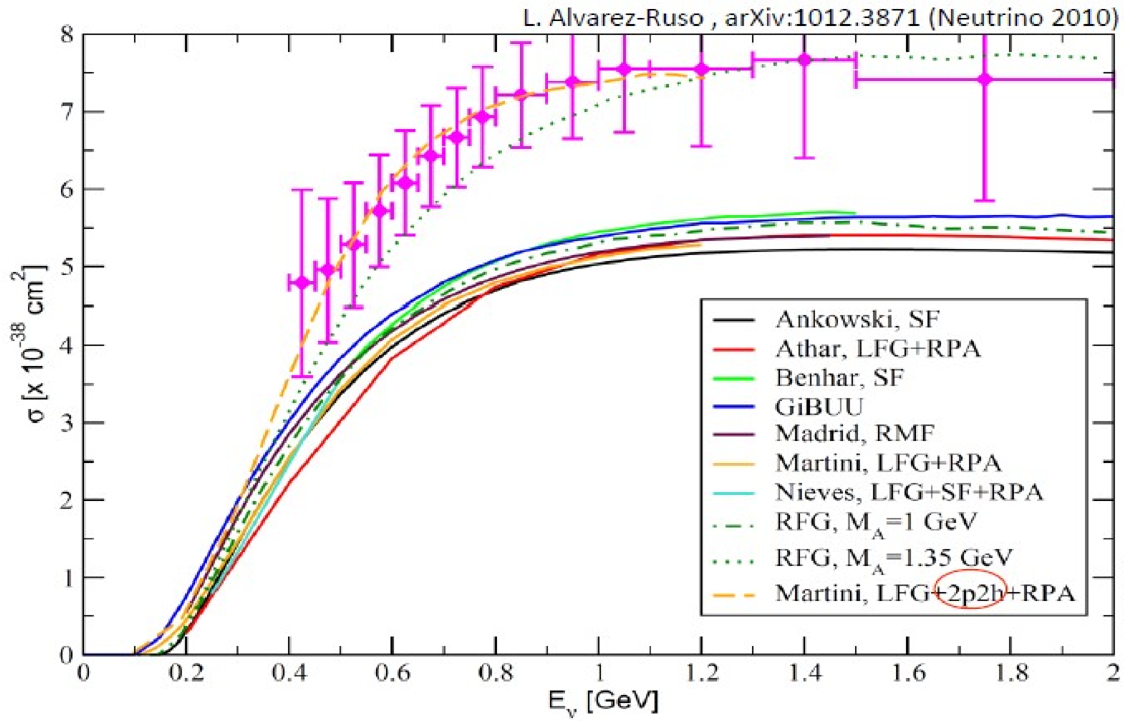
ν Energy in the oscillation probability

the understanding of the nuclear effects in the cross sections are extremely important

How are they parametrized ?

Some models for the CCQE ν-nucleus cross sections

- FG = Fermi Gas R. A. Smith, E. J. Moniz,Nucl. Phys. B43 (1972) 605
- SF= Spectral Function O. Benhar et al., Phys. Rev. D 72 (2005) 053005
- RMF=Relativistic mean field J. M. Udias et al., Phys. Rev. C 64 , 024614 (2001)
- RPA= Random Phase Approximation Martini et al., Phys. Rev. C80, 065501 (2009)



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

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The Relativistic Fermi gas model

- Many MonteCarlo codes (GENIE, NuWro, Neut, Nuance) use some versions of the Fermi model

  - target nucleons are moving (Fermi motion) subject to a nuclear potential (binding energy)
  - the ejected nucleon does not interact with other nucleons (Plane Wave Impulse Approximation)
  - Pauli blocking reduces the available phase space for scattered particle

- In terms of spectral function:

probability of removing a nucleon of momentum p, leaving the residual system with excitation energy E

Average binding energy

$$P_{RFGM} = \left(\frac{6\pi^2 A}{p_F^3} \right) \theta(p_F - \vec{p})\, \delta(E_{\vec{p}} - E_B + E)$$

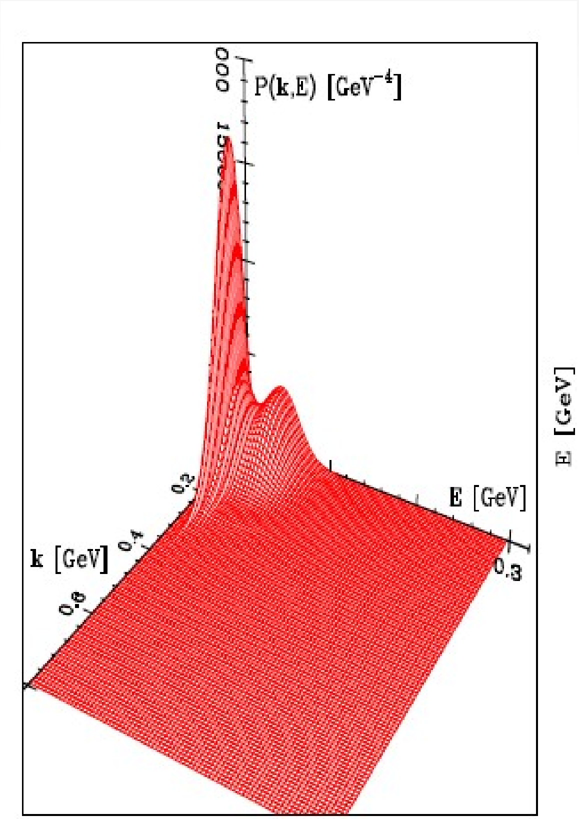
Fermi momentum

Benhar et al.,Nucl.Phys. A789 (2007) 379-402

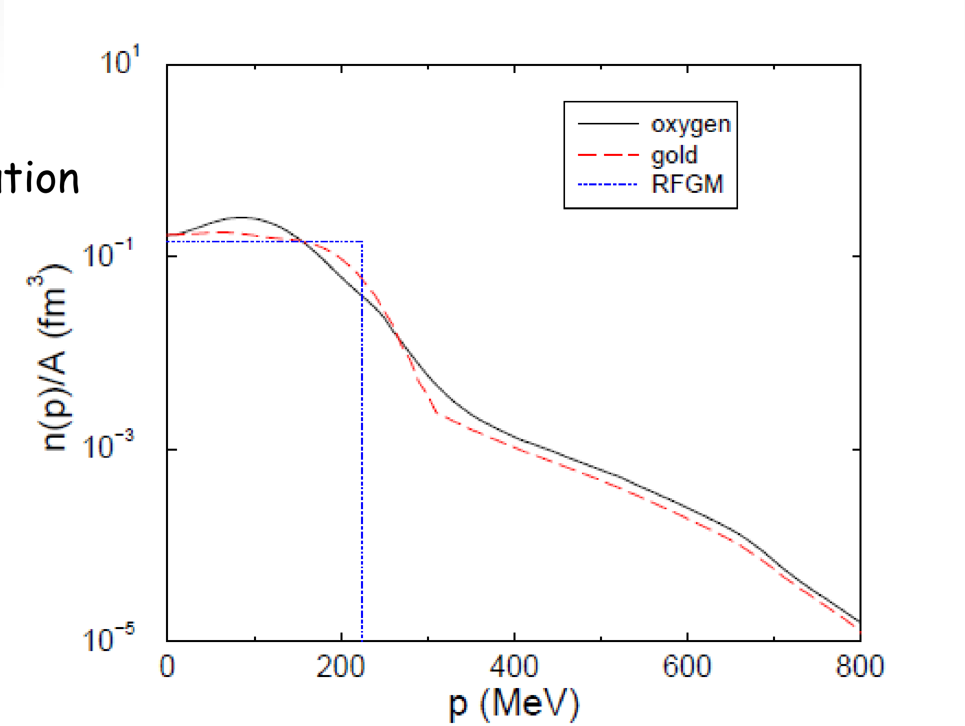
A more realistic spectral function

- Overwhelming evidence from electron scattering that the energy-momentum distribution of nucleons in the nucleus is quite different from that predicted by Fermi gas
- The most important features is the presence of strong NN correlations

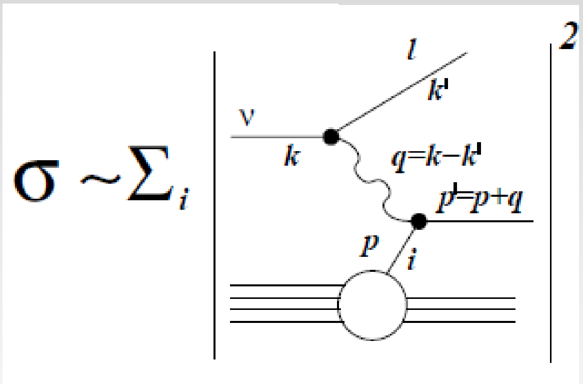
Benhar et al., Nucl.Phys. A579 (1994) 493-517



momentum distribution

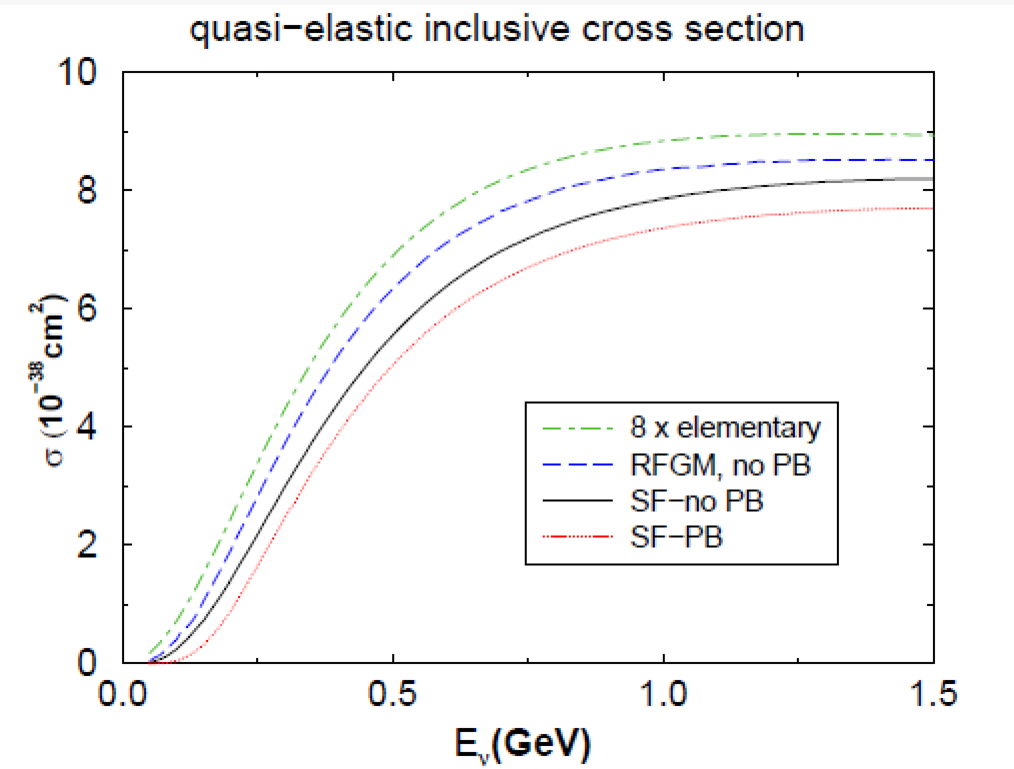


RFG vs SF



$$\frac{d^2\sigma_{IA}}{d\Omega dE_\ell} = \int d^3p\, dE\, P(\mathrm{p}, E)\, \frac{d^2\sigma_{\rm elem}}{d\Omega dE_\ell}$$

$$\frac{d^2\sigma_{\rm elem}}{d\Omega dE_\ell} = \frac{G_F^2\, V_{ud}^2}{32\,\pi^2}\, \frac{|\mathbf{k}'|}{|\mathbf{k}|}\, \frac{1}{4\, E_{\mathbf{p}}\, E_{|\mathbf{p}+\mathbf{q}|}}\, L_{\mu\nu} W^{\mu\nu}$$

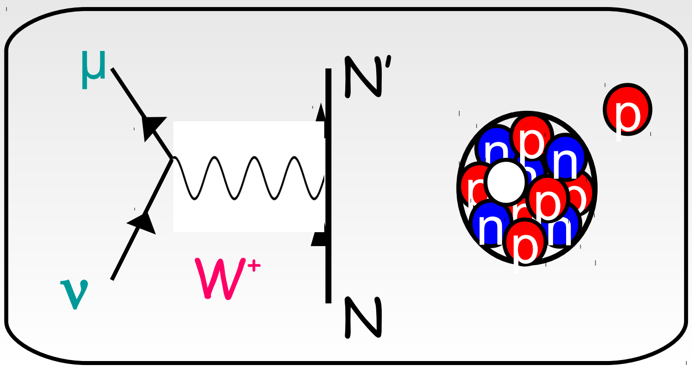


Important lines:
blue and black

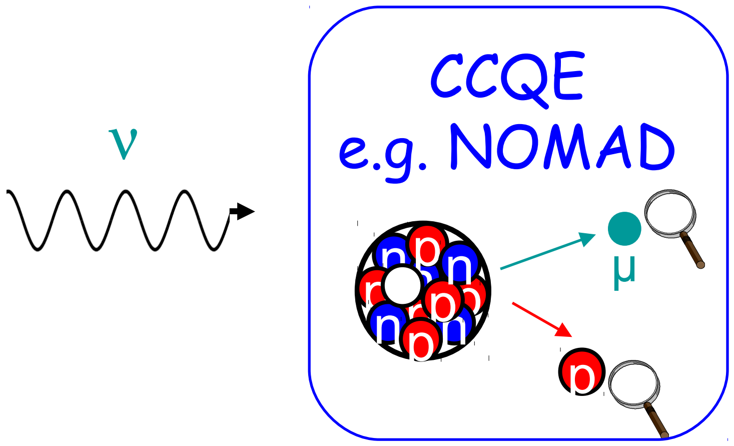
A ~20 % effect on a wide range of neutrino energies

Not the end of the story...

Genuine CCQE



one nucleon ejected from the nucleus

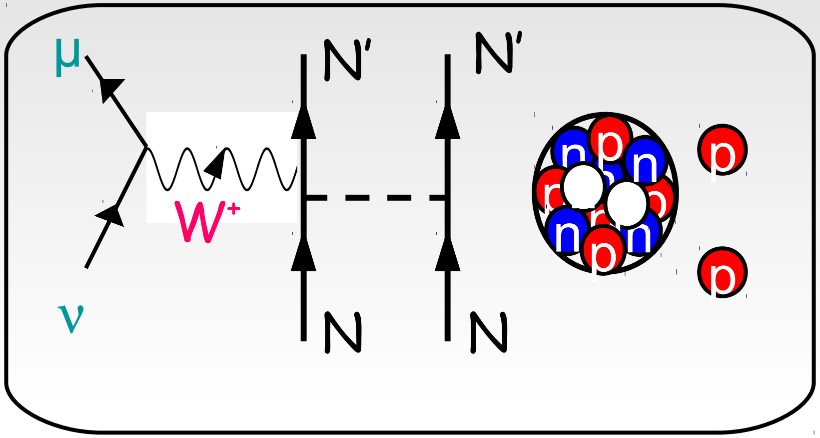


neutrino energy reconstructed
using the kinematic variables of
the charged lepton only

Figures from Marco Martini, talk given at Nufact11

Not the end of the story...

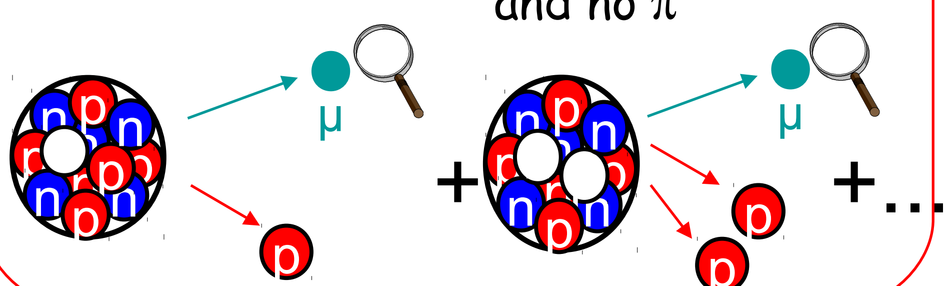
Two particles-two holes



Two nucleons ejected

CCQE-like, e.g. MiniBooNE

and no π



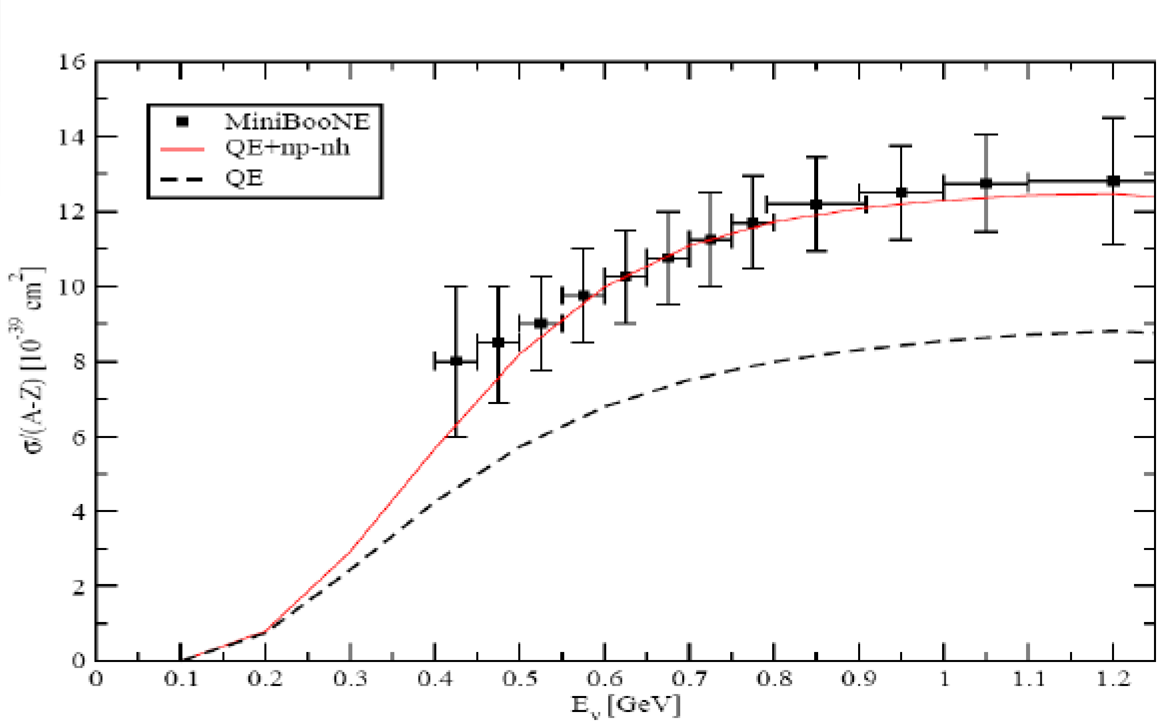
If you only measure the charged lepton, a lot of information is lost and one assigns such events to the true QE sample

Cross section computations must include such effects

A good example

model based on
Martini et al., Phys. Rev. C81, 045502 (2010)
Martini et al., Phys. Rev. C80, 065501 (2009)

Multi-nucleon emission taken into account



Miniboone data of cross section on Carbon is explained thanks to these new effects

Impact of nuclear effects in the extraction of oscillation parameters

- An example: the ν_μ disappearance channel

Coloma and Huber, 1307.1243

- a *quantitative* estimate of the impact of nuclear effects in the determination of θ_{23} and Δm^2_{23}

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta_{23})\ \sin^2\left(\Delta m^2 \frac{L}{4E}\right)$$

- Truly QE events (in the absence of nuclear effects)

$$N_i^{QE} = \sigma^{QE}(E_i)\,\phi(E_i)\,P_{\mu\mu}(E_i)$$

$$\Rightarrow \quad N_i^{QE-like} = \Sigma_j M_{ij}^{QE} N_j^{QE}$$

Migration matrix: prob. that an event with a E^{true} in the bin j ends up being reconstructed in the energy bin i (an almost diagonal matrix)

Impact of nuclear effects in the extraction of oscillation parameters

- non-QE with pion production where π is absorbed in the nucleus is not detected

These events are added in the QE sample

$$N_i^{QE-like} = \Sigma_j M_{ij}^{QE} N_j^{QE} + \Sigma_{non-QE} \Sigma_j M_{ij}^{non-QE} N_j^{non-QE}$$

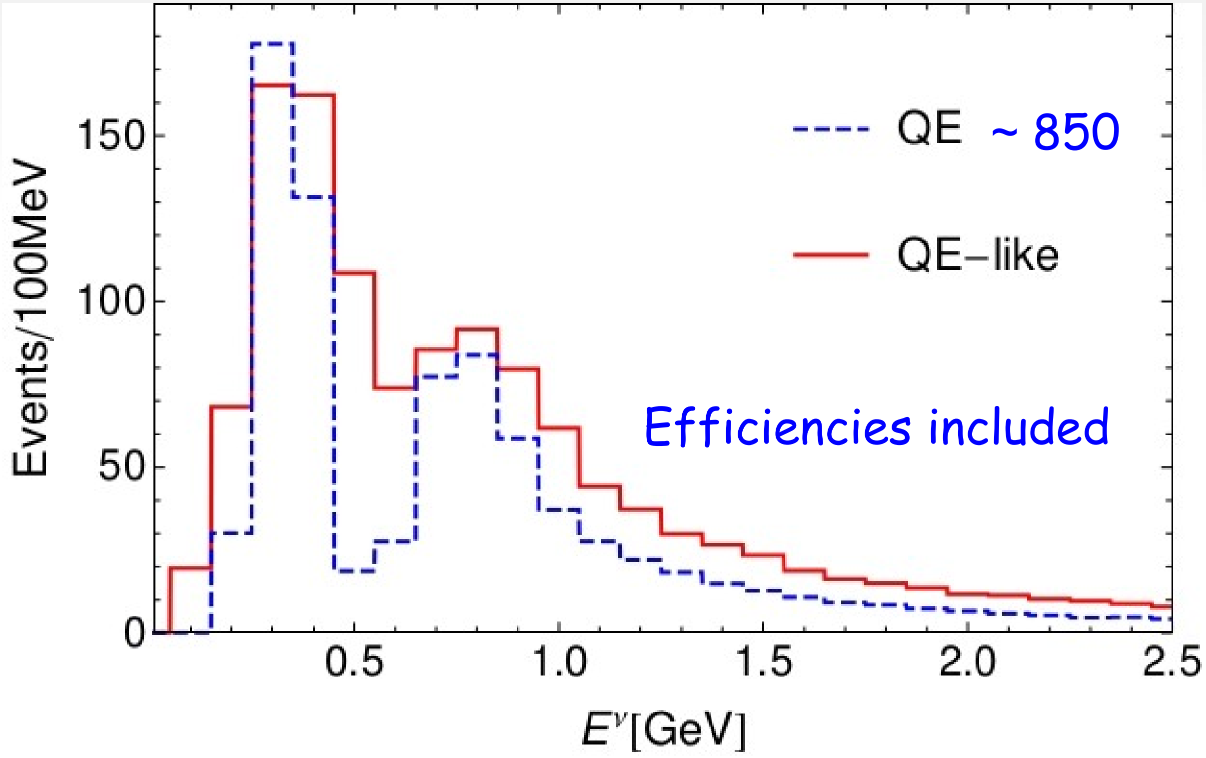
non-QE processes

Mij from Ankowski et al., Phys.Rev. D92 (2015) no.7, 073014

Phys.Rev. D92 (2015) no.7, 073014

QE vs QE-like

- Distribution of QE-like and truly-QE events as a function of the reconstructed E_ν
- Mean E=600 MeV, 5 years of data taking at nominal exposure in WC, $\nu_\mu \to \nu_\mu$ channel



Disappearance at T2K

- Input values: $\theta_{23} = 45°$, $\Delta m^2_{31} = 2.45 \times 10^{-3}$ eV^2
- Check the ability to reconstruct such *true* values
- *true* rates computed according to:

$$N_i^{QE-like} = \Sigma_j M_{ij}^{QE} N_j^{QE} + \Sigma_{non-QE} \Sigma_j M_{ij}^{non-QE} N_j^{non-QE}$$

- the fit to the true rates is done using

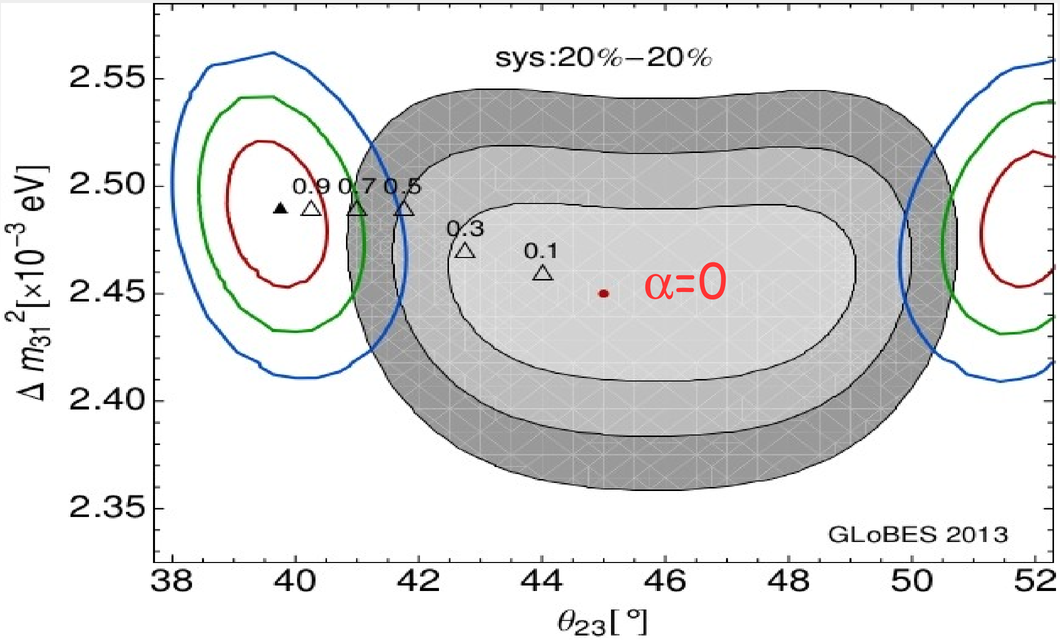
$$N_i^{test}(\alpha) = \alpha N_i^{QE} + (1-\alpha) N_i^{QE-like}$$

Two extreme situations

Nuclear effects completely ignored: α=1

Nuclear effects perfectly known: α=0

Disappearance at T2K



- Effects of a near detector included
- α=0.3 still in the 1 σ range
- interestingly enough:

$$\frac{(\Delta m_{23}^2)^{\alpha=0}-(\Delta m_{23}^2)^{\alpha=1}}{(\Delta m_{23}^2)^{\alpha=0}}\sim 0.02$$

$$\frac{(\theta_{23})^{\alpha=0}-(\theta_{23})^{\alpha=1}}{(\theta_{23})^{\alpha=0}}\sim 0.1$$

Conclusions

- Neutrino-nucleus cross sections strongly depend on the assumed nuclear model; huge effort in the community to systematically take them into consideration

- Relevant impact on the extraction of mixing parameters; huge effort in the community to systematically evaluate the uncertainties related to nuclear effects

Backup slides

The MECM model

model based on
Martini et al., Phys. Rev. C81, 045502 (2010)
Martini et al., Phys. Rev. C80, 065501 (2009)

- Nuclear response function calculated in random phase approximation
- Multinucleon emission taken into account

kinematical factors

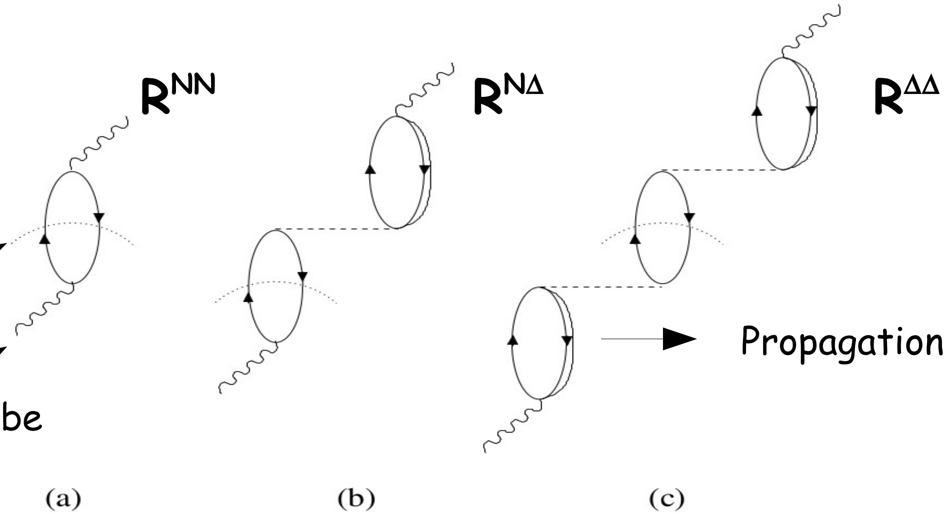
$$\frac{d^2\sigma_{IA}}{d\Omega\, dE_l} \propto \Sigma_i K_i R_i$$

response functions: $R_i(\omega, q) \propto \Im[\Pi(\omega, q)]$

Lowest order contributions
to genuine CCQE

Propagation of a nucleon (or a hole)

external probe



Propagation of a Δ

The MECM model

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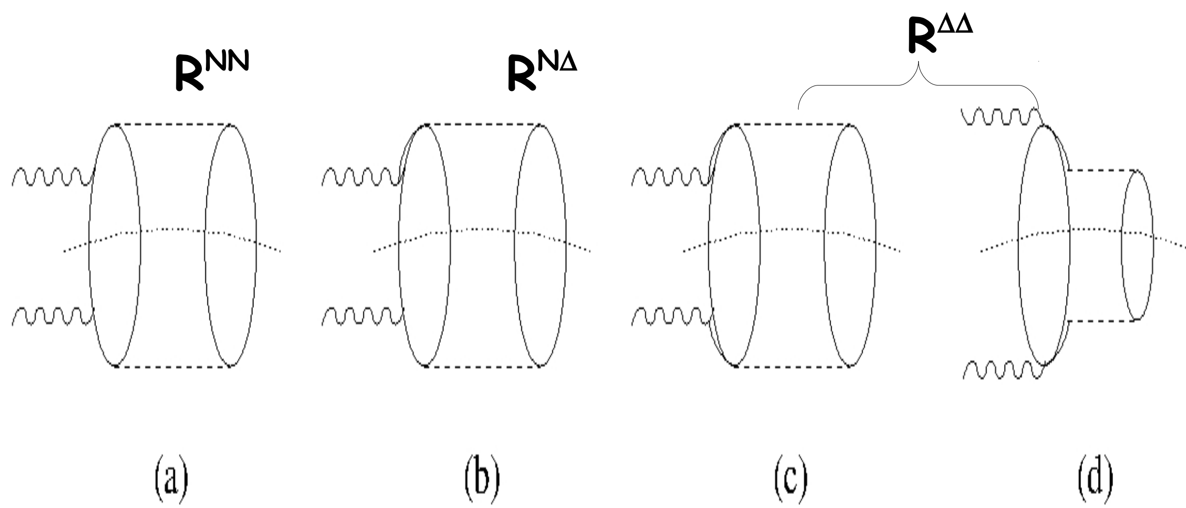
kinematical factors

$$\frac{d^2\sigma_{IA}}{d\Omega\, dE_l} \propto \Sigma_i K_i R_i$$

response functions: $R_i(\omega, q) \propto \Im[\Pi(\omega, q)]$

Lowest order contributions
to the 2 nucleon ejections



More on the uncertainty on neutrino energy reconstruction

O.Benhar and D.Meloni, Phys.Rev.D 80, 073003 (2009)
O.Benhar and N.Rocco, arXiv:1310.3869

- From the requirement of having a CCQE process:

$$E_\nu = \frac{M_p^2 - m_\mu^2 - E_n^2 + 2E_\mu E_n - 2\mathbf{k}_\mu \cdot \mathbf{p}_n + |\mathbf{p}_n|^2}{2(E_n - E_\mu + |\mathbf{k}_\mu| \cos\theta_\mu - |\mathbf{p}_n| \cos\theta_n)} ,$$

subscript "n" refers to the struck neutron

E_ν not uniquely determined by E_μ and θ_μ but distributes according to the energy and momentum distribution on the struck neutron

E_ν depends on the nuclear model employed for the target ground state

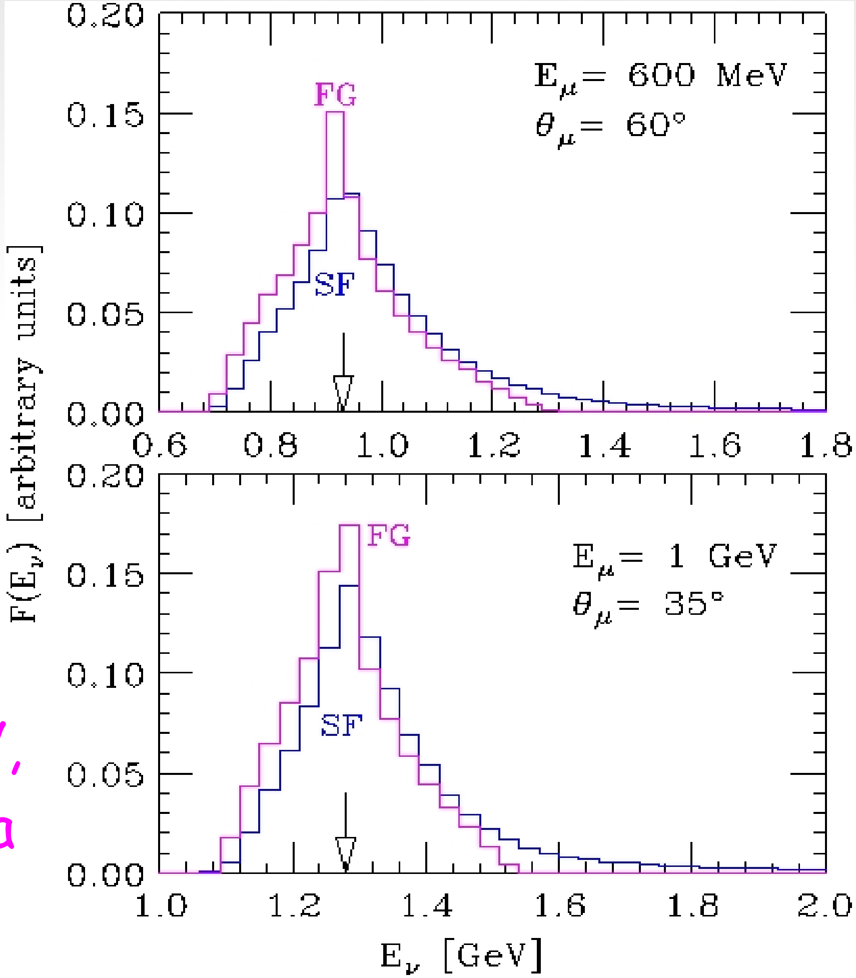
More on the uncertainty on neutrino energy reconstruction

- $|\bar{p}_n|$ and E can be sampled from the probability distribution

$$|\bar{p}_n|^2 \, P(\bar{p}_n, E)$$

Fermi gas (FG)

SF: O.Benhar et al.,
Phys.Rev.D 72, 053005 (2005)

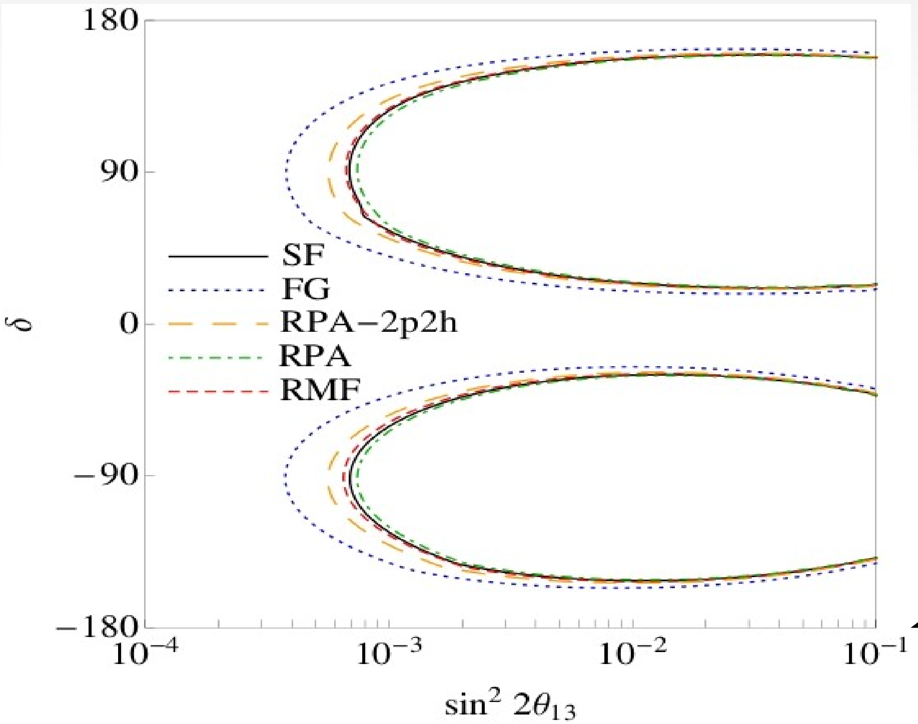


- 2×10^4 pairs of $(|\bar{p}_n|, E)$

shifted towards higher energy by ~ 20 MeV, with respect to the FG results, and exhibit a tail extending to very large values of Eν

θ_{13} and δ discovery potentials

- At a standard beta-beam: (γ;L) = (100; 130Km)



Appearance channel

We are in this region here, where the differences mong the model are quite limited