A short review on the interplay among nuclear effects and oscillation parameters

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Papers on E_{true} vs E_{rec} and mixing parameters

- E.Fernandez-Martinez and D.Meloni, Phys.Lett.B697, 477 (2011) → β-beams: far in the future
- Martini,Ericson,Chanfray Phys.Rev.D85 (2012) 093012,Phys.Rev.D87 (2013) 013009 → MiniBooNE,T2K
- Meloni&Martini, Phys.Lett.B716 (2012) 186-192 → Effects evaluated on T2K real data
- Nieves,Sanchez,Ruiz Simo, Vicente Vacas Phys.Rev.D85 (2012) 113008 → Only E_{true} vs E_{rec}
- Lalakulich, Mosel, Gallmeister Phys.Rev.C86 (2012) 054606 → MiniBooNE,T2K (repetita juvant)
- P.Coloma, P.Huber, arXiv:1307.1243 [hep-ph] → T2K
- P.Coloma, P.Huber, C.-M.Jen and C.Mariani, ArXiv:1311.4506 [hep-ph] → To be discussed by Camillo
- Lalakulich, Mosel, Gallmeister, arXiv:1311.7288 → LBNE (repetita juvant)

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

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

Fogli et al. Phys.Rev.D86,013012 (2012)

Parameter	Fit results
θ_{12}	$33.36^{+0.81}_{-0.78}$
θ_{13}	$8.66^{+0.44}_{-0.46}$
θ_{23}	$40.0^{+2-1}_{-1.5}$
δ	300^{+66}_{-138}
Δm^2_{23} (10^{-3} eV^2)	$2.47^{+0.07}_{-0.07}$
Δm^2_{12} (10^{-5} eV^2)	$7.50^{+0.18}_{-0.19}$

More precision: systematics must be taken under control

Problems...

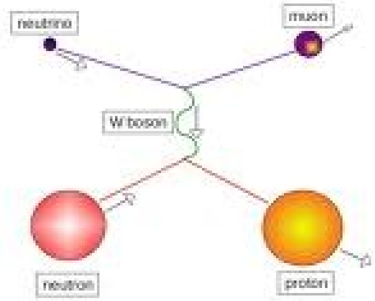
- Here mainly (but not only) interested to the Charge Current Quasi Elastic Scattering (CCQE)

- We want to measure mixing parameters, that is to understand transition probabilities

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

- P's are extracted from the number of the "easy to see" CCQE events

$$N_i^{QE} = \sigma^{QE}(E_i)\phi(E_i)P(E_i)$$



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

Grazie Camillo...

Problems...

- E_ν reconstruction is necessary because of the broad neutrino beam
- Inaccuracies in the reconstructed energies can be larger than previously assumed if the reaction process is not correctly identified

First category of problems

The reaction process of QE scattering must be unequivocally identified

↓

Other reaction mechanism may look indistinguishable in the experiment

Second category of problems

The nuclear effects can smear out the reconstructed energy

↓

Final state interactions make difficult to identify the initial QE scattering on a bound, Fermi-moving nucleon

Defining true QE

- Let us define the true QE:

$$\nu\, n \rightarrow \mu^-\, p$$

very well identified in a tracking detector,
not so in a Cherenkov detector

Signal is defined as a single Cherenkov ring from the outgoing μ

No further rings should appear in such an event

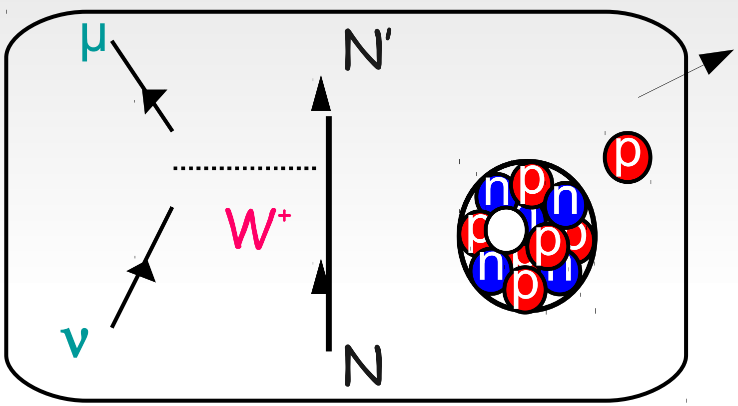
true QE events are defined as those with 1 muon, 0 mesons and any number of nucleons in the final state

Defining true QE

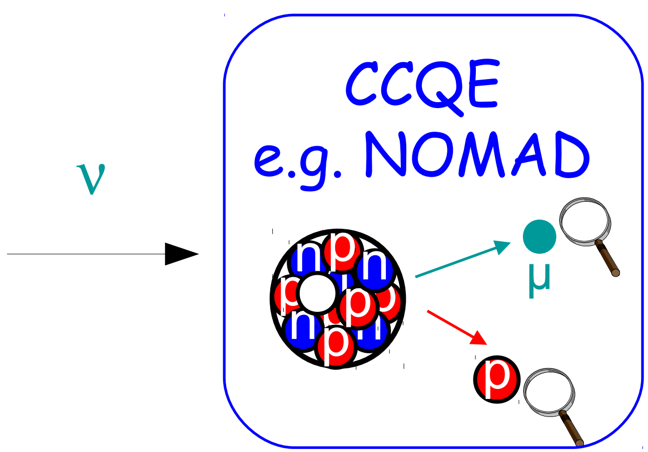
Marco Martini, talk given at Nufact11

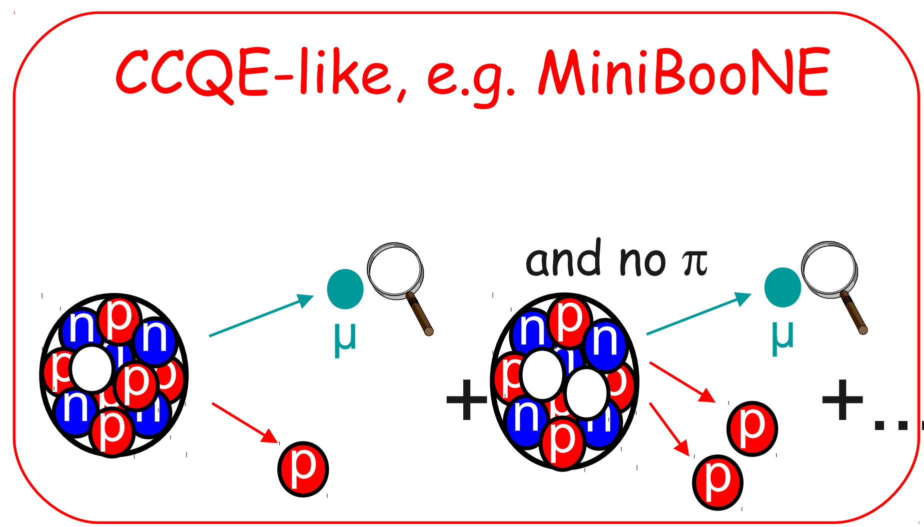
- Let us define the true QE:

Genuine CCQE



one nucleon ejected





Defining QE-like

- non true-QE origin:

$$\nu\, p \rightarrow \mu^{-}\, p\, \pi^{+} \qquad \nu\, p \rightarrow \mu^{-}\, \Delta^{++}$$

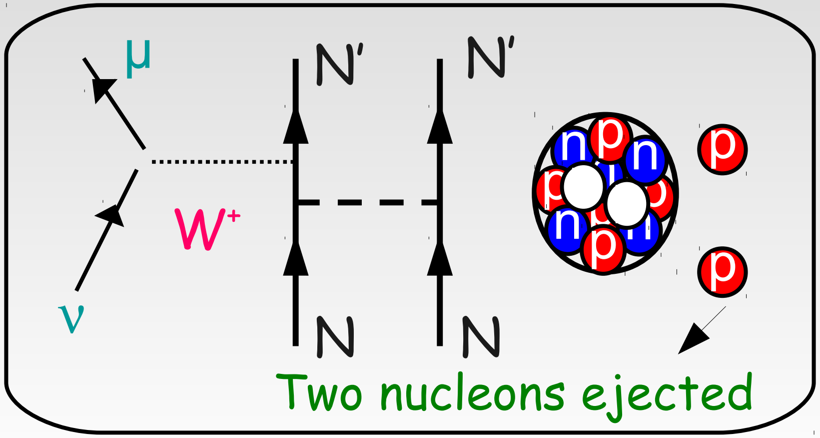
π's are absorbed in the nucleus through final state interactions (stuck pion events)

⇓

Such an event is counted as QE-like

Two other difficulties

- 2p-2h



Events in which the incoming neutrino interacts with 2 or more nucleons

non QE-origin + 2p-2h = fake QE events

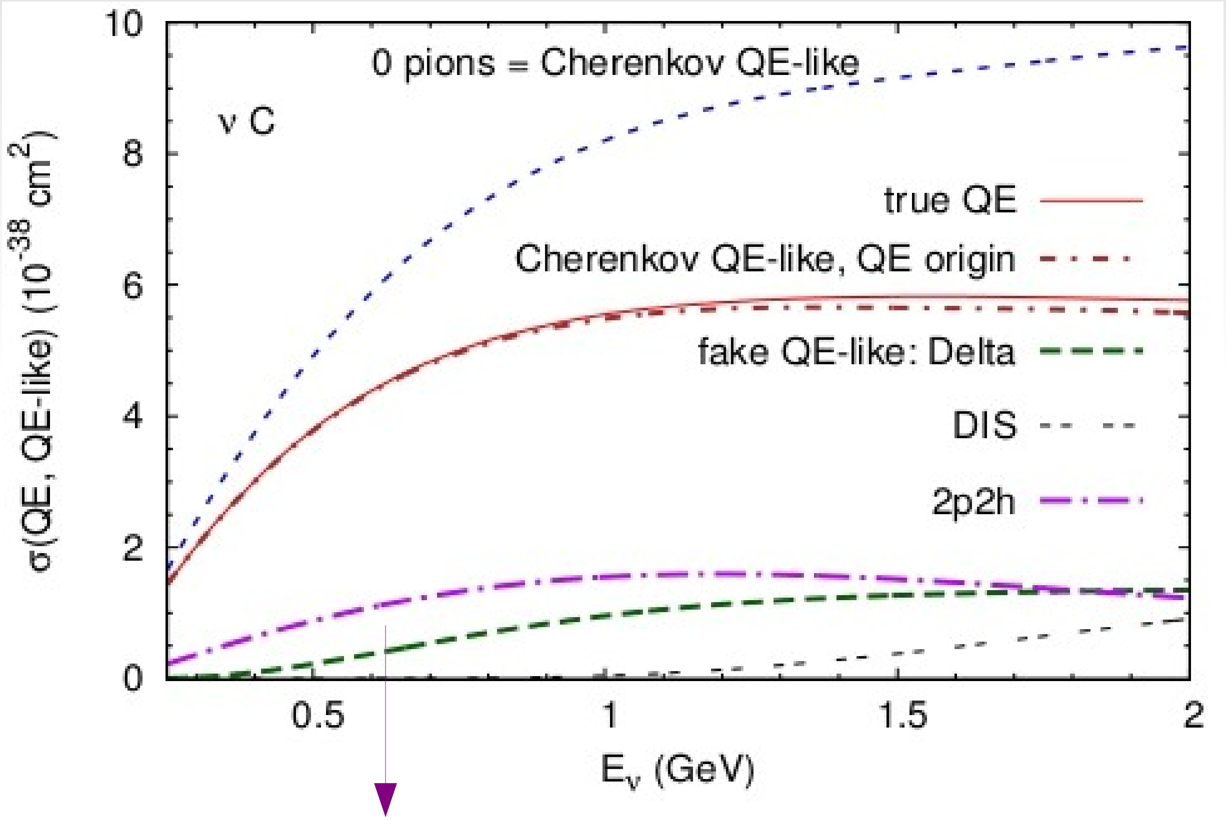
The measured QE cross section is contaminated by these events

- Nucleon may rescatter and produce pions → Disregarded as QE event

Putting all together

Lalakulich, Mosel, Gallmeister
Phys.Rev.C86 (2012) 054606

GiBUU model for neutrino CC scattering



a Cherenkov detector sees almost all true QE events, but also a large part of the fake QE-events

only 2p-2h because other processes are kinematically forbidden

Energy reconstruction based on QE kinematics

- Example: how it works in MiniBooNE

Formula based on the assumption of QE scattering on a nucleon at rest

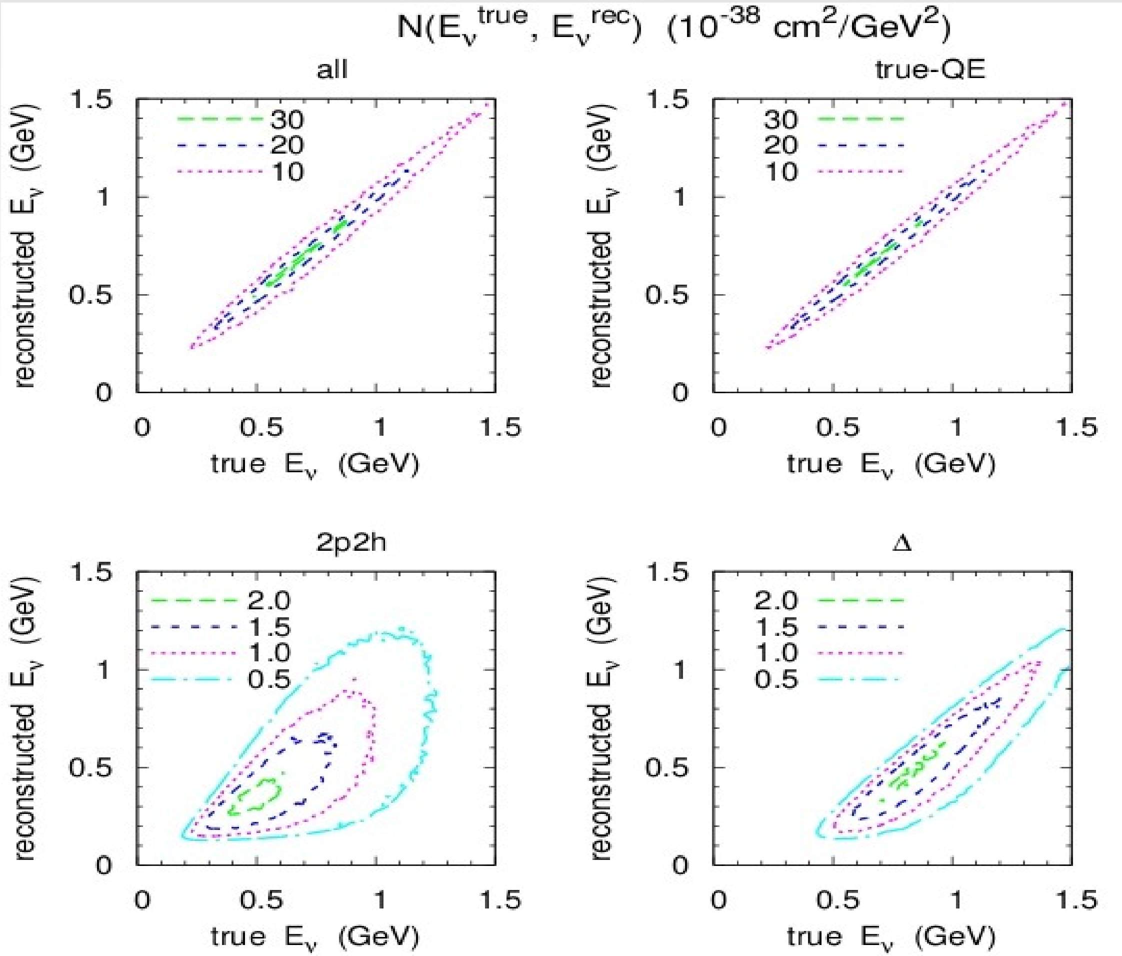
$$E_\nu^{\mathrm{rec}} = \frac{2(M_n - E_B)E_\mu - (E_B^2 - 2M_n E_B + m_\mu^2 + \Delta M^2)}{2\left[M_n - E_B - E_\mu + |\vec{k}_\mu| \cos\theta_\mu\right]}$$

- Neglected any Fermi motion effects
- Binding taken into account with a constant binding energy E_B

Admixture of other reaction mechanism leads to an incorrect reconstruction of energy

E_{true} vs E_{rec}

Lalakulich, Mosel, Gallmeister
Phys.Rev.C86 (2012) 054606



$$\int N\left(E^{true}, E^{rec}\right) dE^{rec}\, dE^{true} = \langle \sigma_{0\,\pi} \rangle$$

for the MiniBooNE flux

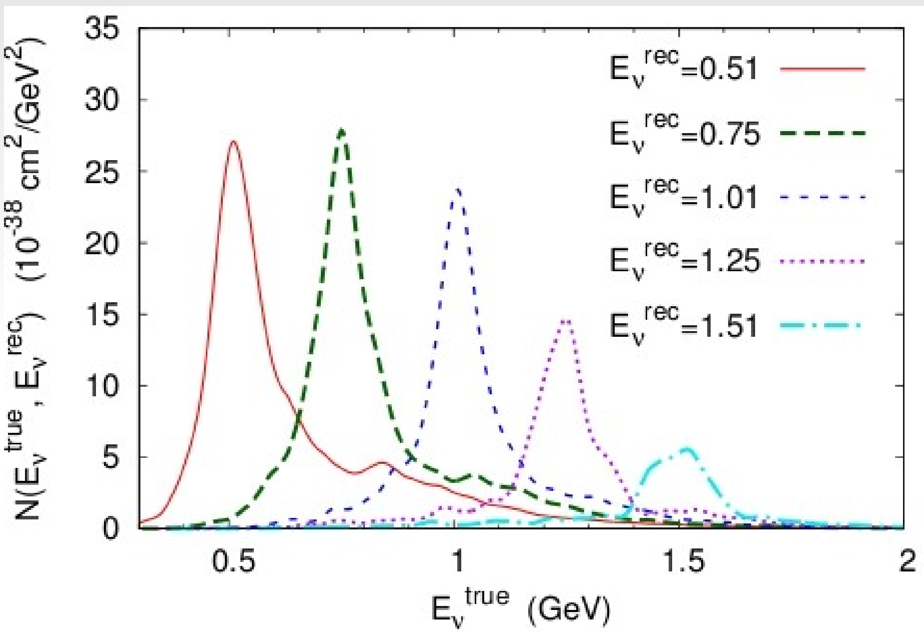
- for true QE:
  symmetric around $E_{true}=E_{rec}$

- for 2p2h:
  $E_{rec} \in [0, \sim E_{true}]$ for small E_{true}

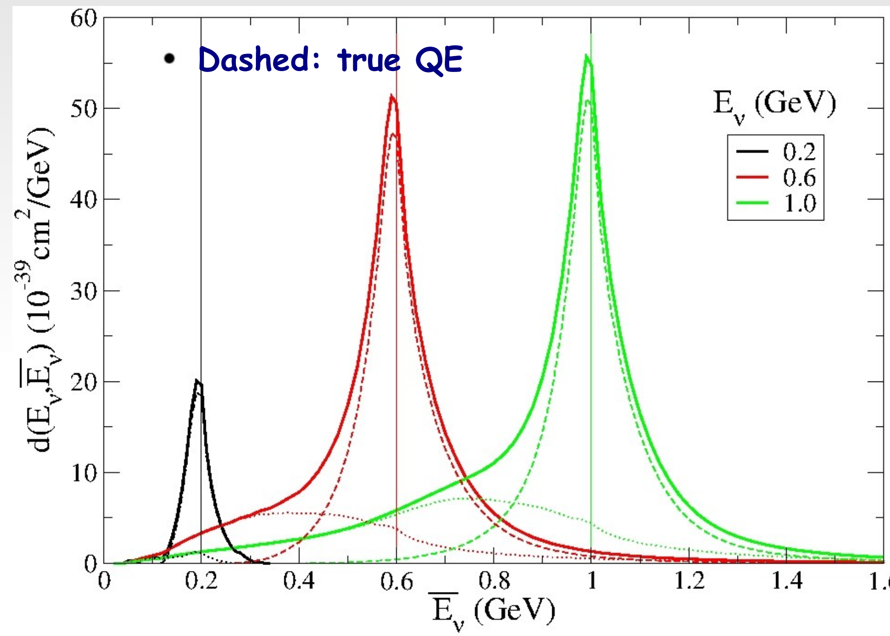
- for Δ:
  $E_{rec} \in [0, \sim E_{true}]$ always

E_{true} vs E_{rec}

Lalakulich, Mosel, Gallmeister
Phys.Rev.C86 (2012) 054606



Martini,Ericson,Chanfray
Phys.Rev.D87 (2013) 013009

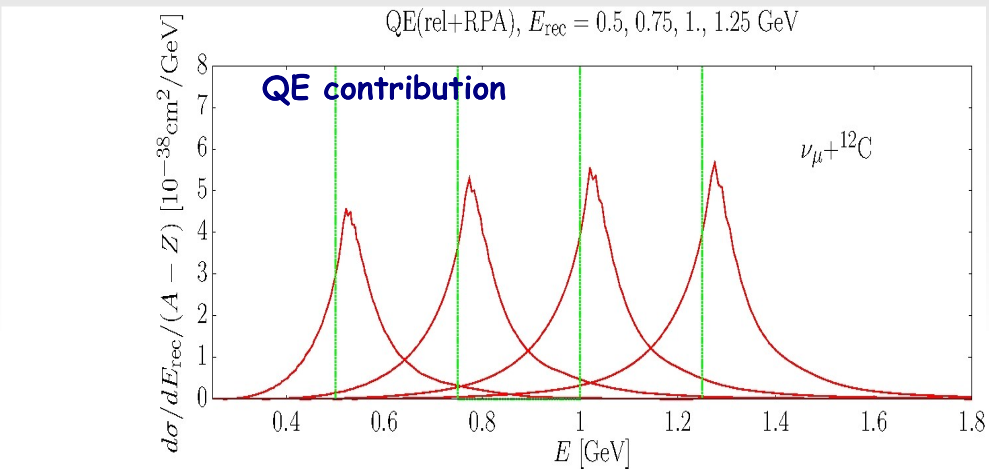


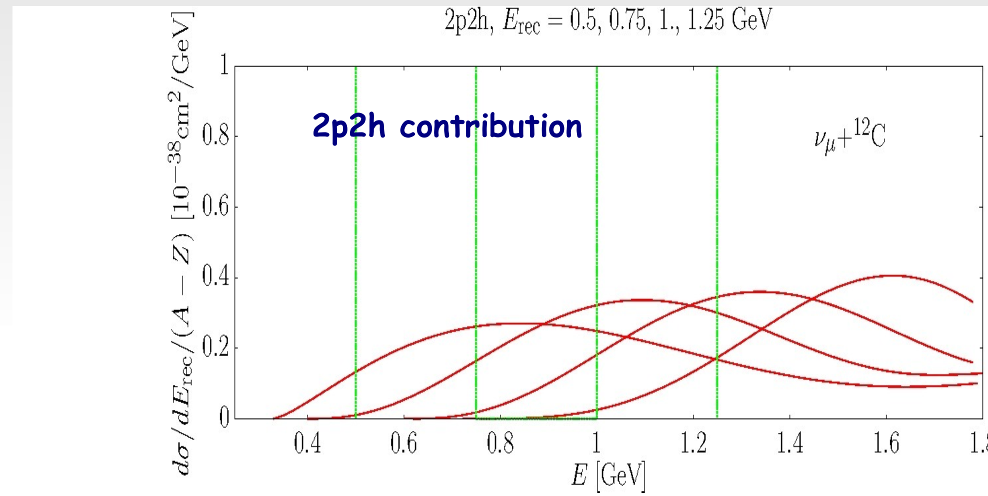
reconstructed

- sizable long tails towards larger true energies
- 2p2h (left&right plots) + stuck-pions (left only) events lead to a shift of the reconstructed energies toward <u>smaller</u> values

E_{true} vs E_{rec}

Nieves,Sanchez,Ruiz Simo, Vicente Vacas
Phys.Rev.D85 (2012) 113008

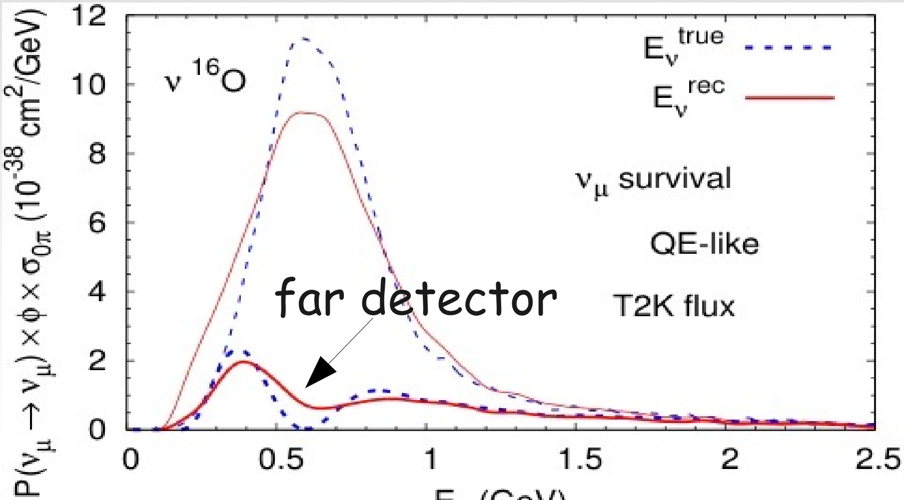




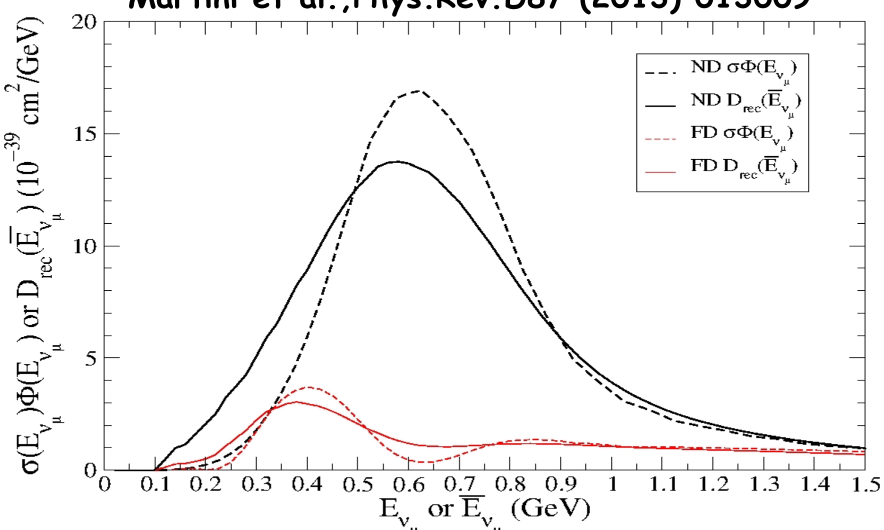
- sizable long tails towards larger true energies
- 2p2h (left&right plots) + stuck-pions (left only) events lead to a shift of the reconstructed energies toward <u>smaller</u> values

Effects on the oscillation probabilities in T2K

Lalakulich et al.,Phys.Rev.C86 (2012) 054606



Martini et al.,Phys.Rev.D87 (2013) 013009



$\Delta m^2_{23} = 2.5 \times 10^{-3}\, eV^2 \qquad \sin 2\theta_{23} = 1$

-main effect: minimum shifted to a higher energy, by about 50 MeV

the situation can be mimicked by a smaller Δm^2 in E_{true}

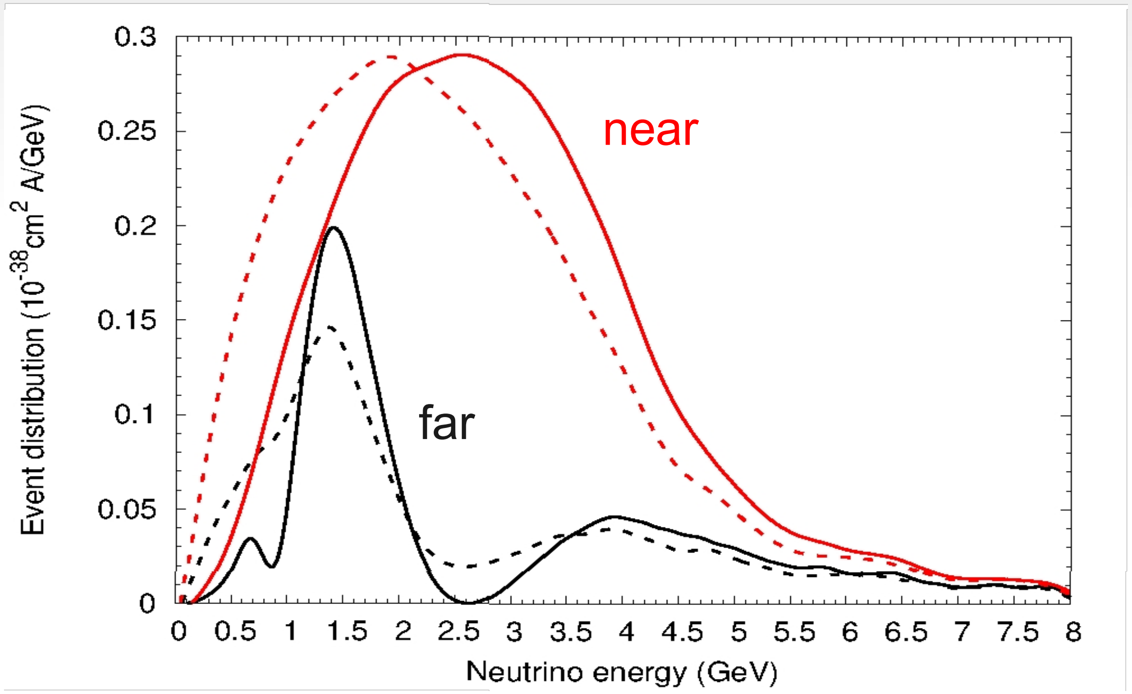
$$\Delta m^2_{23}: \quad 2.65 \times 10^{-3}\, eV^2 \rightarrow 2.43 \times 10^{-3}\, eV^2$$

rec true

Effects at the LBNE

Flux picked at around 2.5 GeV and extending to several tens of GeV

Lalakulich, Mosel, Gallmeister, arXiv:1311.7288



0-pion events distribution

ND:

- 0.5 GeV shift at the ND

FD:

- filling and flattening of the minimum

A quantitative estimate

- in Coloma and Huber, 1307.1243: a *quantitative* estimate of the impact of nuclear effects on the determination of θ_{23} and Δm^2_{23}

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

↓

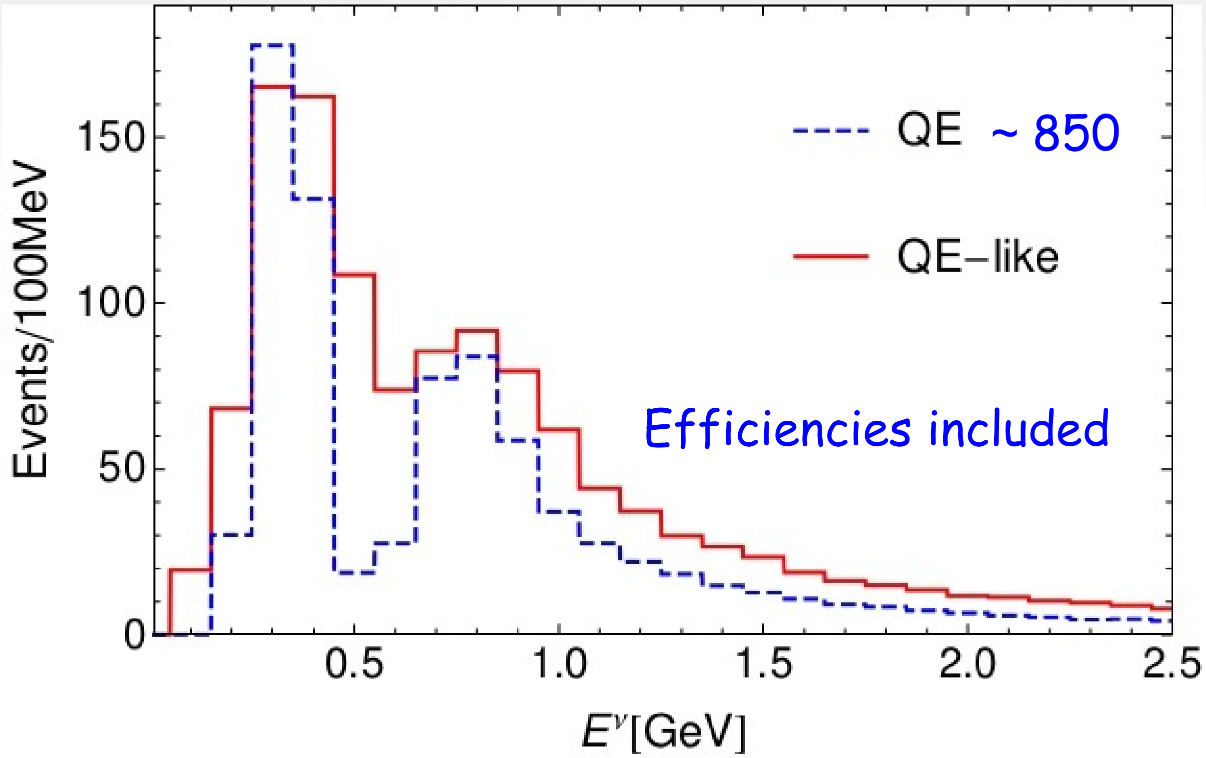
Events added in the QE sample

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

non-QE processes

QE vs QE-like

- Mij from Lalakulich, Mosel and Gallmeister, Phys.Rev. C86 (2012) 054606
- 5 years of data taking at nominal exposure, $\nu_\mu \to \nu_\mu$ 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
- χ^2 analysis including: 20% normalization error, 20% shape error with true distribution computed according to:

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

Two extreme situations

Nuclear effects completely ignored

$$N_i^{QE} = \sigma(E)\varphi(E)P_{\mu\mu}(E)$$

Nuclear effects perfectly known

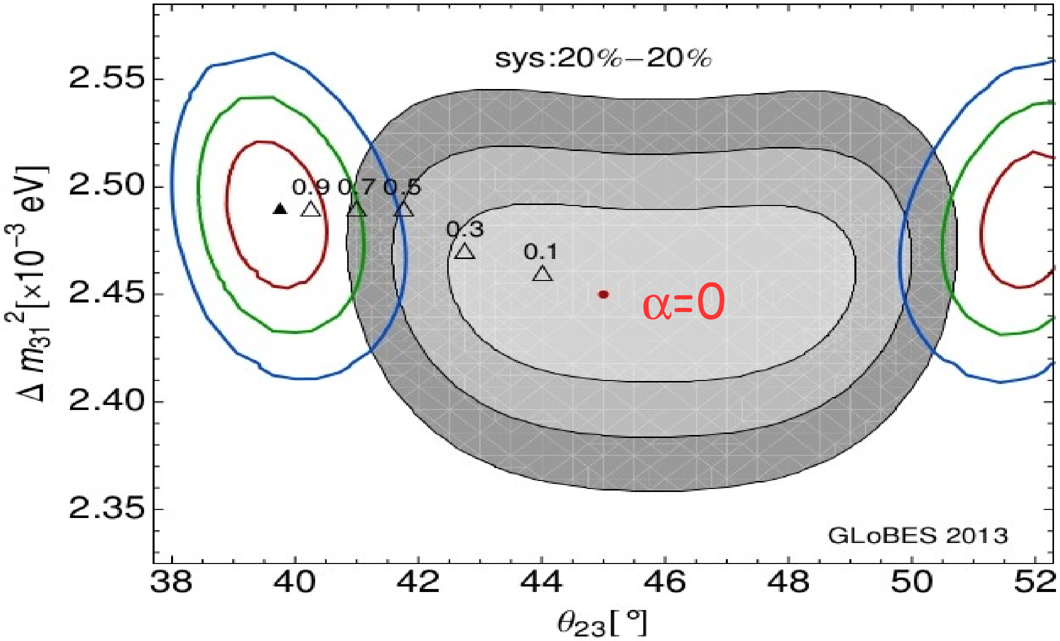
$N_i^{QE\text{-}like}$ as above

Disappearance at T2K

- Between the two extremes:

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

Nuclear effects completely ignored: α=1 | Nuclear effects perfectly known: α=0



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

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

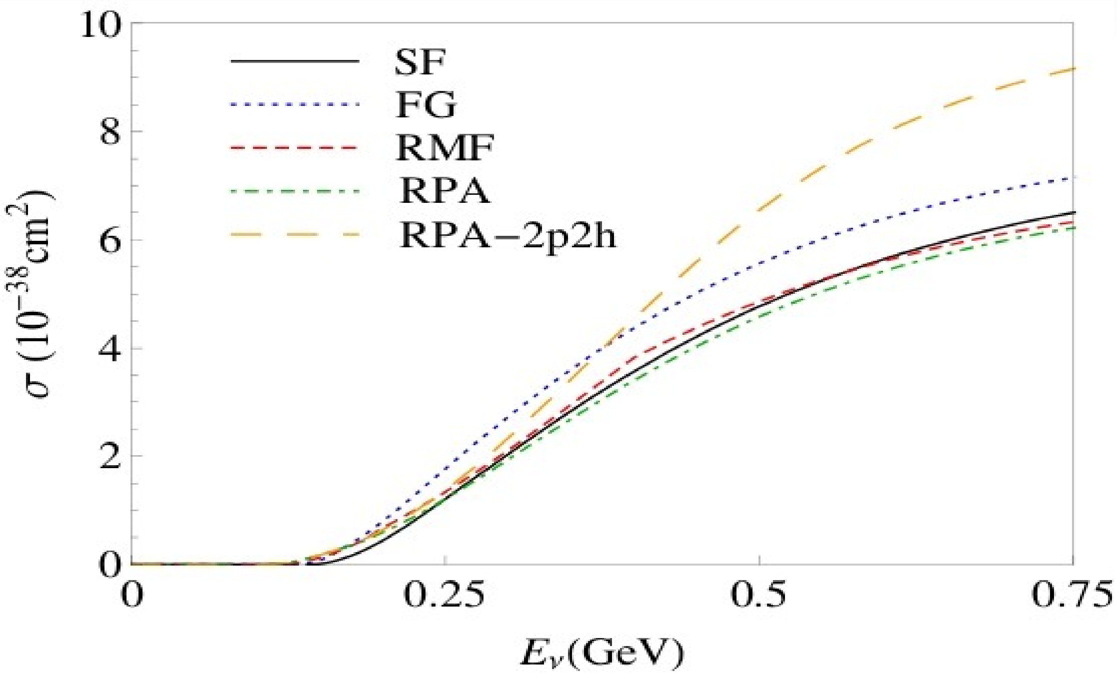
$$\frac{(\sin^2\theta_{23})^{\alpha=1}-(\sin^2\theta_{23})^{\alpha=0}}{(\sin^2\theta_{23})^{\alpha=0}}\sim 0.09$$

Now on real data

Meloni&Martini,Phys.Lett. B716 (2012) 186-192

Effects of considering two different cross sections

- FG = Fermi Gas R. A. Smith, E. J. Moniz,Nucl. Phys. B43 (1972) 605
- RPA= Random Phase Approximation Martini et al., Phys. Rev. C80, 065501 (2009)



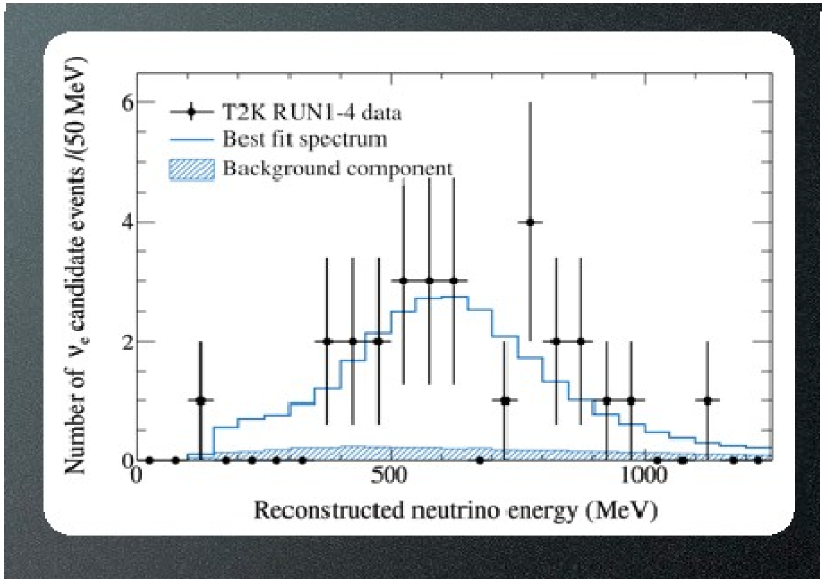
Latest T2K results in appearance

Michael Wilking, talk at the EPS Conference in July 2013

- Run 1-4 data → 6.39×10^{20} pot
- Observed 28 events (expected 20.4 ± 1.8 for $\sin^2 2\theta_{13}=0.1$) against 4.64 background events

→ ν_e beam contamination

→ π^0



$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta_{13})\ \sin^2(\theta_{23})\ \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

7.5 σ significance for non-zero θ_{13}

(for $\sin^2 2\theta_{23}=1$, $\delta_{CP}=0$, and normal mass hierarchy)

Reproducing the T2K data

- We compute the appearance events (in the energy range [0; 1.25] GeV)
- To take into account detection efficiencies ε, we normalize to the expected events (for $\sin^2 2\theta_{13}=0.1$)
- Energy smearing to mimic uncertainties in the reconstructed ν energy

$$N_i^{QE} = \sigma^{QE}(E_i)\,\varphi(E_i)\,P_{\mu\mu}(E_i) \quad \Rightarrow \quad N_i^{QE-like} = \Sigma_j M_{ij}^{QE} N_j^{QE}$$

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

Meloni&Martini,Phys.Lett. B716 (2012) 186-192

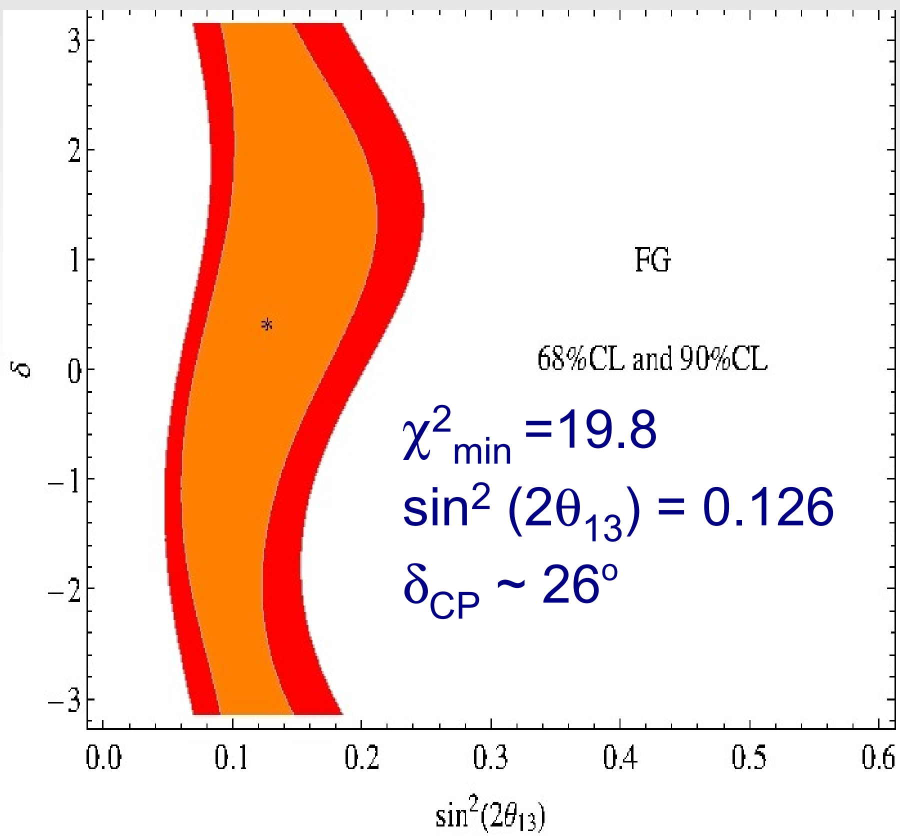
signal=20.4 total bkg=4.64

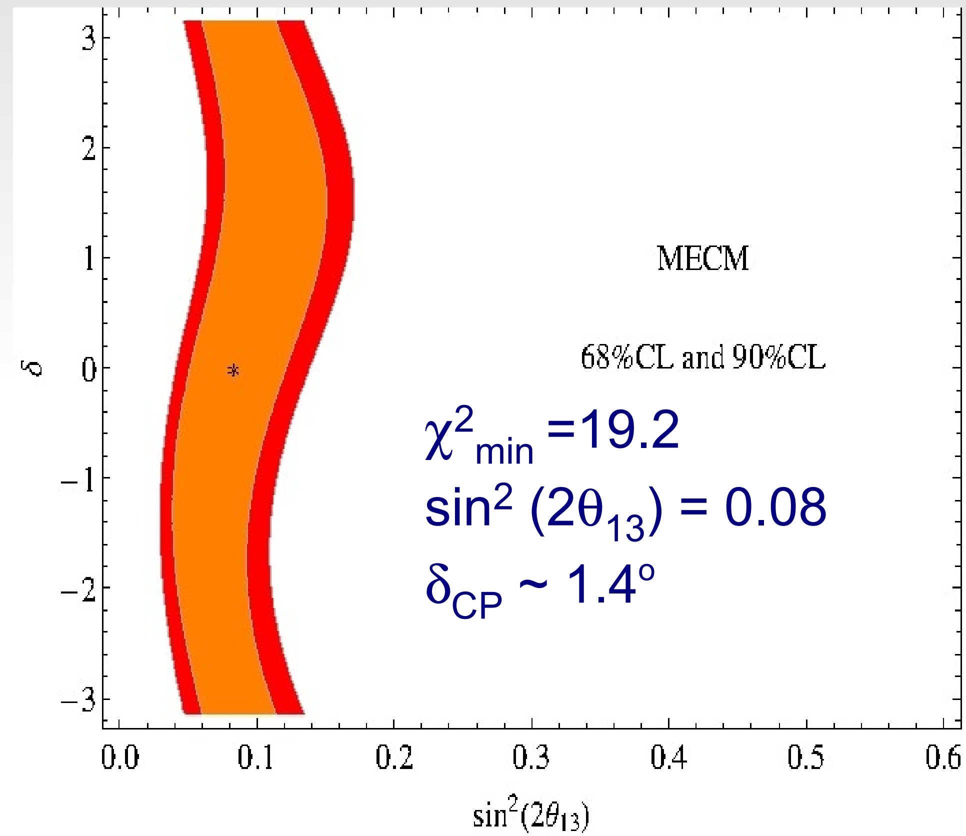
1.52 = NC 3.12 = ν_e beam contamination

It turns out that $\varepsilon \sim 0.34$

Reproducing the T2K data

Marginalized over all other parameters (kept fixed in the T2K analysis)

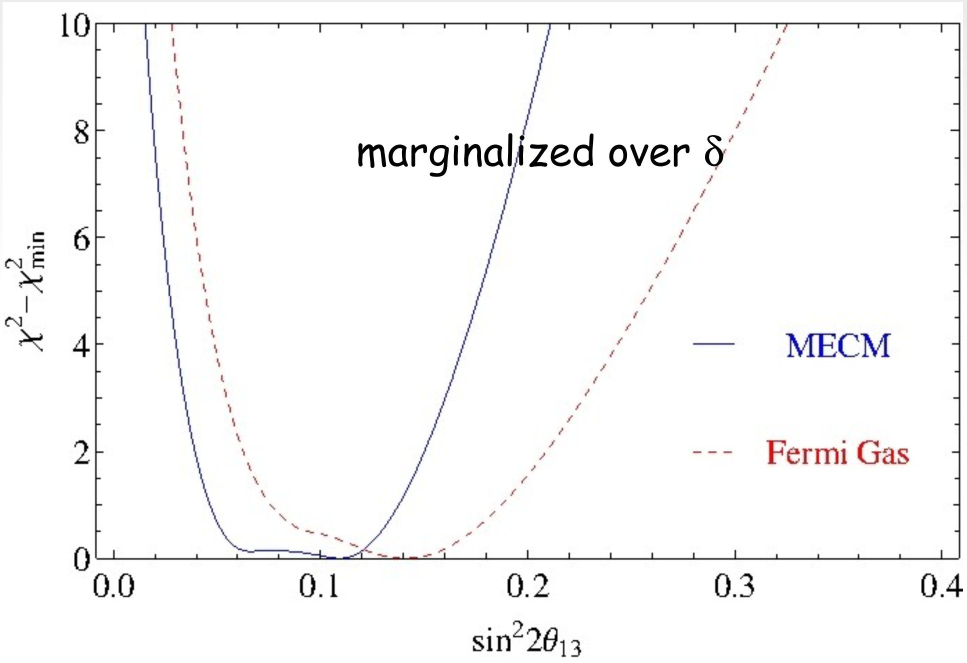




larger signal, must be compensated by smaller θ_{13}

Comparing FG and MECM

- Showing the difference χ^2-χ^2_{min} as a function of θ_{13}

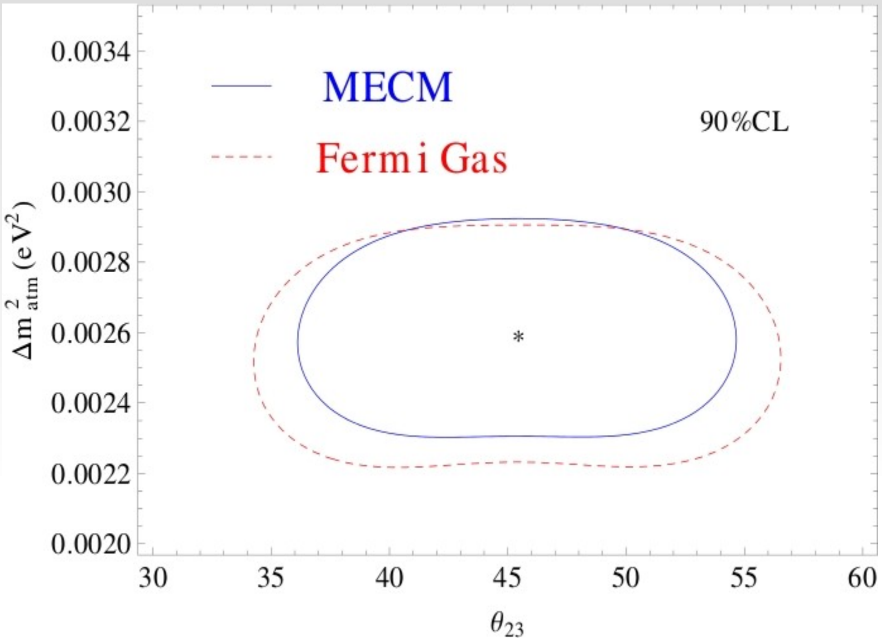


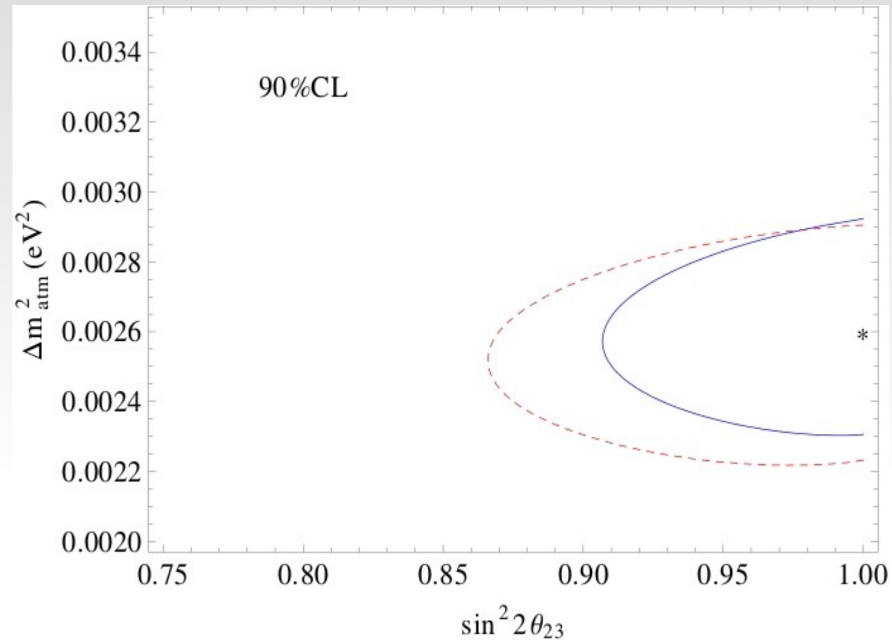
$$\sin^2 2\theta_{13}^{FG} = 0.14^{+0.05}_{-0.06}$$

$$\sin^2 2\theta_{13}^{MECM} = 0.11^{+0.03}_{-0.06}$$

$$\frac{\Delta \sin^2 2\theta_{13}}{(\sin^2 2\theta_{13})^{MECM}} \sim 0.2$$

The disappearance channel





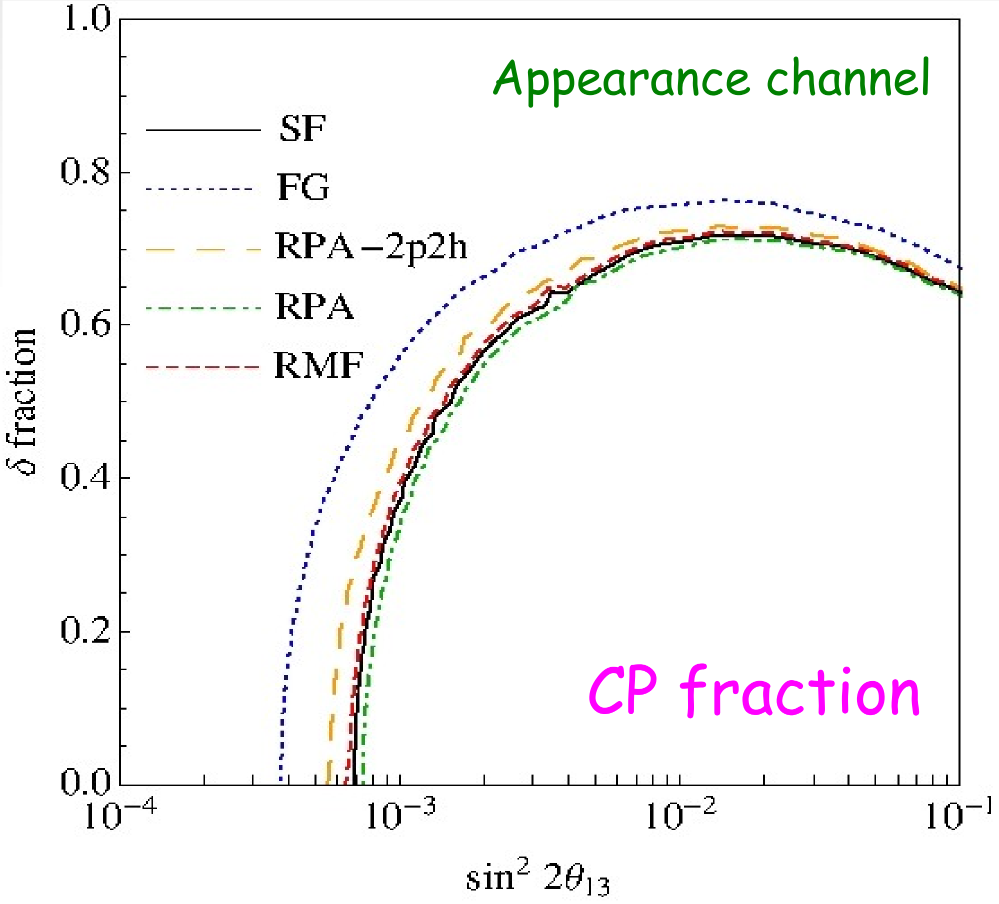
	Best fit ($\sin^2 2\theta_{23}$, Δm^2_{23})	$\sin^2 2\theta_{23}$ range	Δm^2_{23} range (eV^2)
FG	(0.99,2.56)	> 0.86	(2.22-2.90)
MECM	(1.00,2.62)	> 0.91	(2.31-2.93)

$$\frac{\Delta\left(\Delta m^2_{23}\right)}{\left(\Delta m^2_{23}\right)^{MECM}} \sim 0.02$$

θ_{13} and δ discovery potentials at β-beams

antineutrinos from β decays

- $(\gamma;L)$ = (100; 130 Km)



We are in the region around 0.1, where the differences among the models and FG is roughly 7%

E.Fernandez-Martinez and D.Meloni, Phys.Lett.B697, 477 (2011)

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

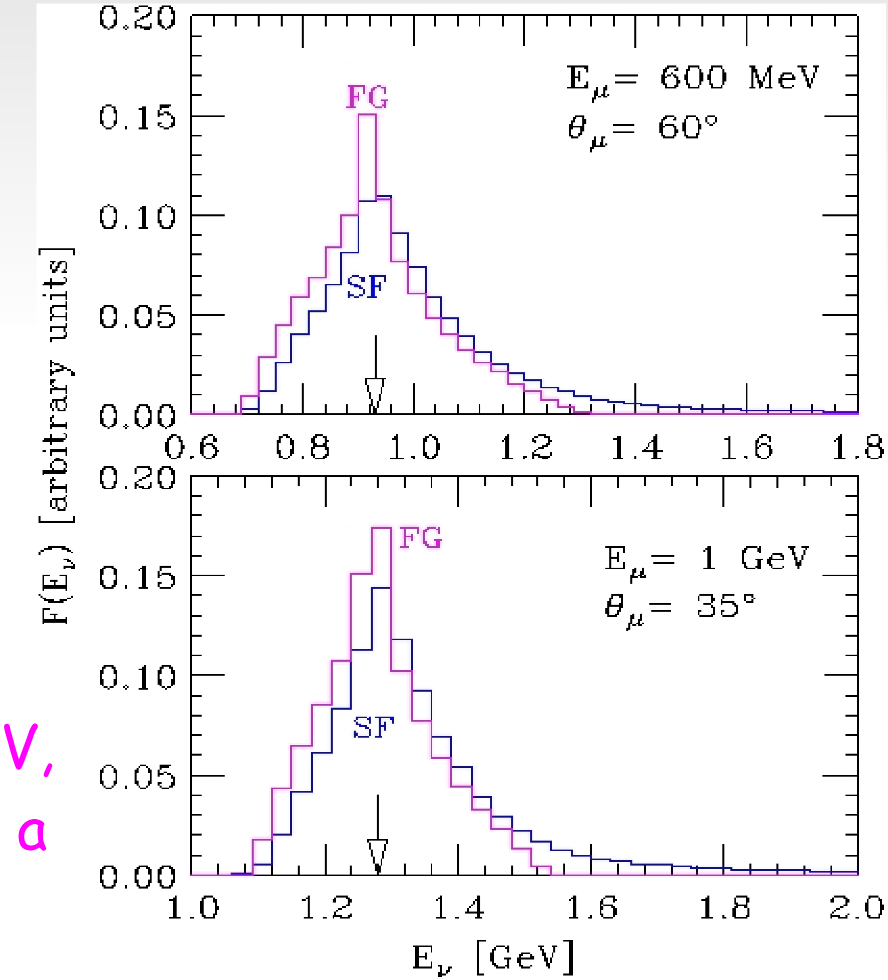
More on the uncertainty on neutrino energy reconstruction

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

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

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

Fermi gas (FG)



- 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

Conclusions

- Energy reconstruction based on QE kinematics is a key issue for oscillation experiments
- Minima and maxima of probabilities shifted by tens of MeV

Rough estimate of systematic uncertainties on the extraction of mixing parameters

$\Delta\sin^2 2\theta_{13}/\sin^2 2\theta_{13}$	$\Delta(\Delta m^2_{23})/\Delta m^2_{23}$	$\Delta\sin^2 2\theta_{23}/\sin^2 2\theta_{23}$
~20%	~2%	~4%

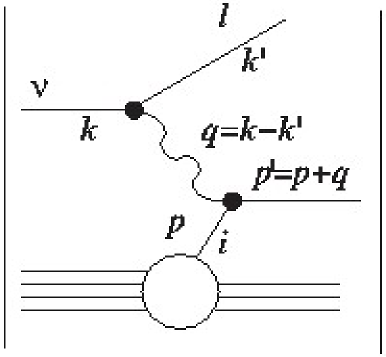
from T2K data,
at the best fit points

from Coloma-Huber

Backup slides

The Spectral Function Approach

Benhar et al., Phys.Rev.D72:053005,2005

- $\sigma \sim \sum_i \left| \right.$  $\left. \right|^2$

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

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

$$W_A^{\mu\nu} = \frac{1}{2} \int d^3p\, dE\, P(\mathbf{p}, E) \frac{1}{4\, E_{\mathbf{p}}\, E_{|\mathbf{p}+\mathbf{q}|}} W^{\mu\nu}(\tilde{p}, \tilde{q})$$

- $P(\mathbf{p}, E)$ is the target spectral function: probability distribution of finding a nucleon with momentum $\mathbf{p}$ and removal energy E in the target nucleus

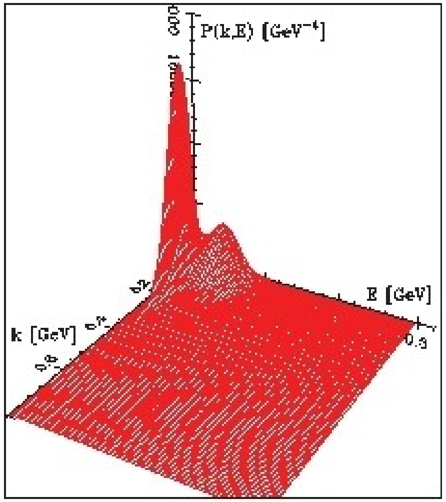
it encodes all the informations about the initial struck particle

Benhar et al.,Nucl. Phys. A 579 (1994) 493

Phys. Rev D72 (2005) 053005

- 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 feature is the presence of strong nucleon-nucleon (NN) correlations (virtual scattering processes leading to the excitation of the participating nucleons to states of energy larger than the Fermi energy)

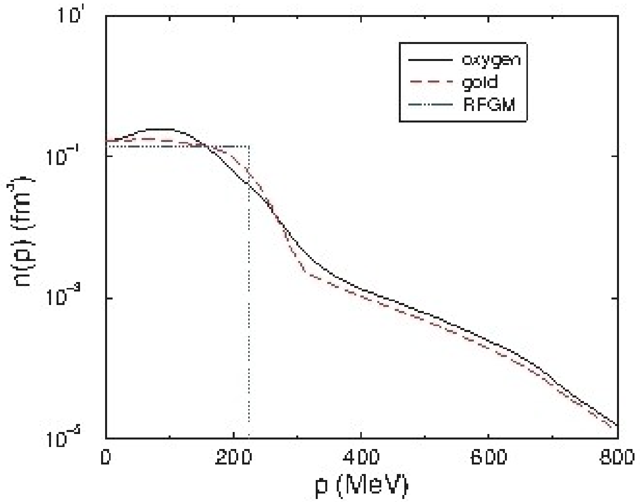
spectral function extends to $|\mathbf{p}| \gg p_F$ *and* $E \gg \varepsilon$



momentum distribution

$$n(\mathbf{p}) = \int dE\, P(\mathbf{p}, E)$$

$\Longrightarrow$



The MECM model

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

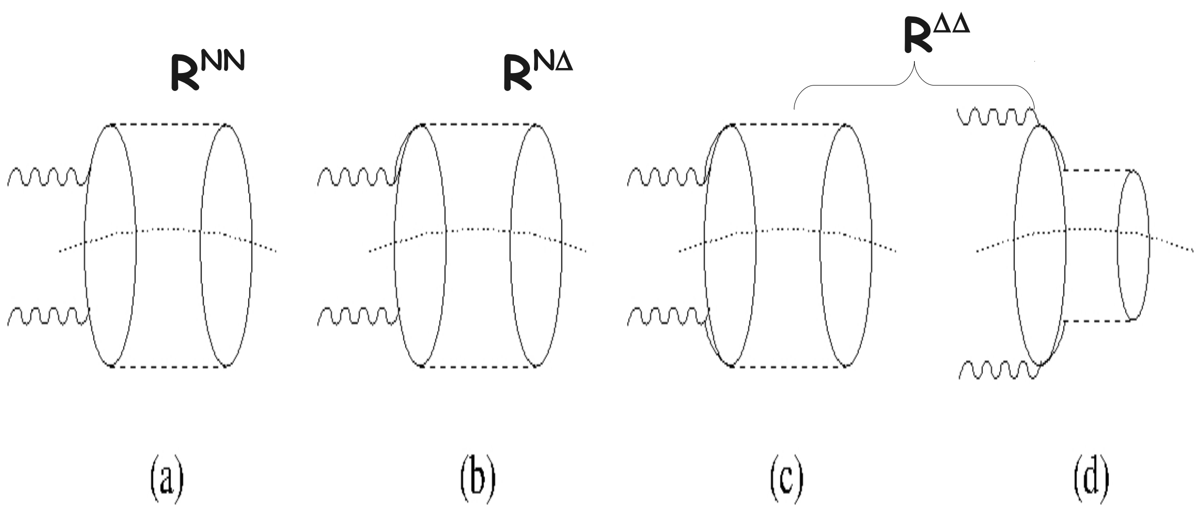
- Nuclear response function calculated in random phase approximation
- Multinucleon emission taken into account

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 the 2 nucleon ejections



Numerical tools

- **GloBES**, to simulate the T2K experiment

  P. Huber, M. Lindner, W. Winter, Comput. Phys. Commun. 167, 195 (2005)

  P. Huber, J. Kopp, M. Lindner, M. Rolinec, W. Winter, Comput. Phys. Commun. 177, 432-438 (2007)

- **MonteCUBES**, to fit the experimental data

  M. Blennow and E. Fernandez-Martinez, Comput. Phys. Commun. 181, 227 (2010)

Caveat:

-we use an energy resolution function to "mimick" the relation between the true and reconstructed neutrino energy (more on this later)

-we assume nuclear effects completely known

- M. Martini, M. Ericson and G. Chanfray, Phys. Rev. D 85 (2012) 093012
- J. Nieves et al., Phys. Rev. D 85 (2012) 113008
- O. Lalakulich and U. Mosel, Phys.Rev. C86 (2012) 054606

Strategy

statistics is too small to draw definite conclusions but the exercise may serve to illustrate how to use "real" data to study ν-N cross sections

- we first use GLoBES to reproduce the official T2K analysis

(cross sections are based on Fermi Gas)

Normalization at the ND

Computation of events at the FD

- we then change the cross section and repeat the analysis

Estimate of the systematics related to the cross section

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

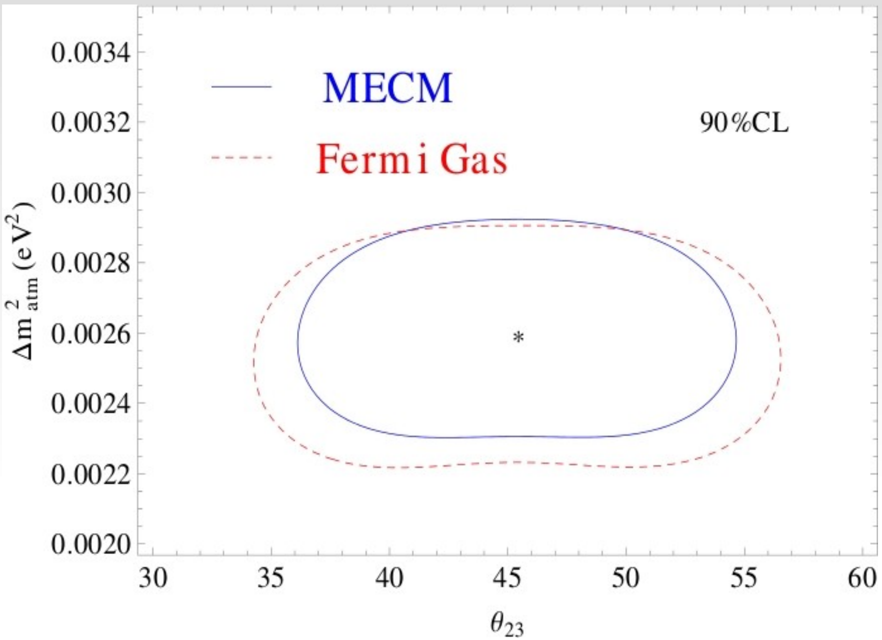
The disappearance channel

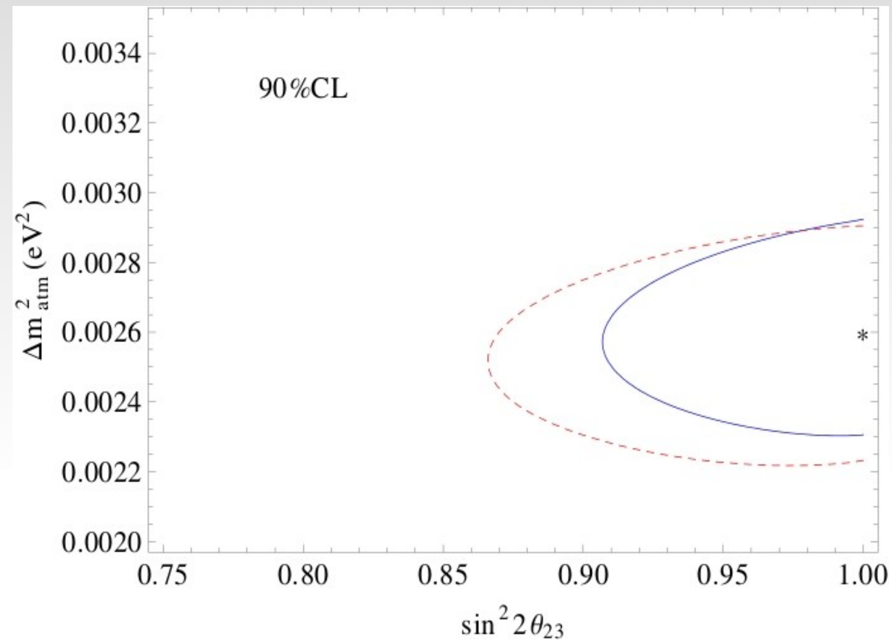
- Disappearance probability

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

- Analysis based on Phys. Rev. D 85, 031103 (2012):
  - 31 data events, grouped in 13 energy bins
  - the sample extends up to 6 GeV and it is mainly given by ν_μ CCQE, ν_μ CC non-QE, ν_e CC and NC
  - FG cross section normalized to the total rates: 17.3, 9.2, 1.8 and < 0.1 events for ν_μ CCQE, ν_μ CC non-QE, ν_e CC and NC
  - adopted a conservative 15% normalization error and energy calibration error at the level of 10^{-3} for both signal and back

The disappearance channel





	Best fit ($\sin^2 2\theta_{23}$, Δm^2_{23})	$\sin^2 2\theta_{23}$ range	Δm^2_{23} range (eV^2)
FG	(0.99,2.56)	> 0.86	(2.22-2.90)
MECM	(1.00,2.62)	> 0.91	(2.31-2.93)

$$\frac{\Delta\left(\Delta m^2_{23}\right)}{\left(\Delta m^2_{23}\right)^{MECM}} \sim 0.02$$

Reproducing the T2K data

- Simple χ^2 analysis

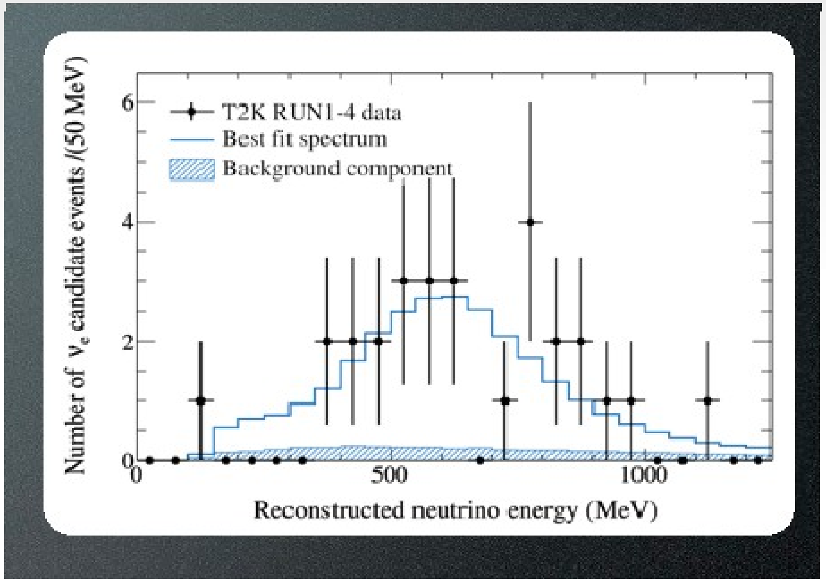
$$\chi^2 = \frac{(N_{com} - N_{Data})^2}{\sigma_D^2 + N_{NC} + N_{\nu_e} + S}$$

- S =total systematic effects = $(S_D N_D)^2 + (S_{NC} N_{NC})^2 + (S_D N_e)^2$

- N_{com}, N_D = computed number of oscillated events and the data

- N_{NC}, N_e = event rates for NC and ν_e contamination

28 data in 25 energy bins



- σ_D = bin uncertainties on the data

- S_D = 0.07 and S_{NC} = 0.3 are sys. errors on the (data, ν_e) and N_C