Impact of systematic uncertainties for the neutrino parameter measurement in superbeam experiments

Davide Meloni

ROMA TRE UNIVERSITÀ DEGLI STUDI

Dipartimento di Fisica "E. Amaldi"

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Main motivation of this work

comparing the performances of different nuclear models for physically interesting neutrino observables

here I propose a simplified analysis of the T2K data based on D. Meloni and M. Martini,Phys. Lett. B **716** (2012) 186
BUT using the new appearance data shown in ICHEP

- fitting the T2K data in appearance for θ_{13} and δ
  - reproducing the T2K data for the $\nu_\mu \to \nu_e$ oscillation
  - the effect of using different cross sections
- fitting the T2K data in disappearance
  - analysis based on Phys. Rev. D **85** (2012) 031103
- assuming X 10 statistics in appearance

ν flavour conversion has been confirmed in many experiments

$$U = R_{23}(\theta_{23}) R_{13}(\theta_{13}, \delta) R_{12}(\theta_{12})$$

The neutrino oscillation probability (in matter)

$$P_{\alpha\beta} = |A_{\alpha\beta}|^2 = \sum_{i,j} \tilde{U}^*_{\alpha i} \tilde{U}_{\beta i} \tilde{U}_{\alpha j} \tilde{U}^*_{\beta j} \exp\left(i \frac{\tilde{m}_j^2 - \tilde{m}_i^2}{2E} L \right)$$

E is the neutrino energy, L is the baseline length, $\tilde{m}_i$ and $\tilde{U}_{\beta j}$ are the mass of the ith neutrino mass eigenstate and the mixing matrix in matter

- Usual assumption: U is a 3×3 unitary mixing matrix
- three angles θ_{ij} and one CP phase δ

$\Downarrow$

the standard framework implies 7 parameters to describe ν oscillation in matter

Great interest on θ_{13} and δ

The appearance neutrino oscillation probability ($\alpha \neq \beta$)

$$\begin{aligned} P_{\nu_\mu \to \nu_e} &= s_{23}^2 \sin^2 2\theta_{13} \sin^2(\Delta_{atm} L) + c_{23}^2 \sin^2 2\theta_{12} \sin^2(\Delta_{sol} L) \\ &+ \tilde{J} \cos(\delta_{CP} + \Delta_{atm} L) \ (\Delta_{sol} L) \sin(2 \Delta_{atm} L) \end{aligned}$$

Many future experiments will look for a precise measurement of θ_{13}.

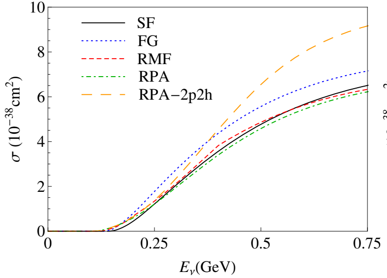
Large θ_{13} means good chance to reveal the CP violation in the leptonic sector

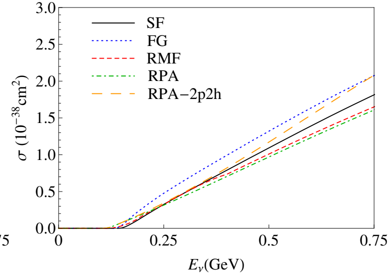
One needs to control:

- flux composition
- detector response
- nuclear cross sections

The ν-nucleus cross sections ($\nu A \to \mu X$)

- 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
  M. Martini et al., Phys. Rev. **C80**, 065501 (2009) $\hookrightarrow$ from now on: the MECM model





Useful 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

but see for a detailed discussion:

- M. Martini, M. Ericson and G. Chanfray, Phys. Rev. D **85** (2012) 093012
- J. Nieves, F. Sanchez, I. Ruiz Simo and M. J. Vicente Vacas, Phys. Rev. D **85** (2012) 113008
- O. Lalakulich and U. Mosel, arXiv:1208.3678 [nucl-th]

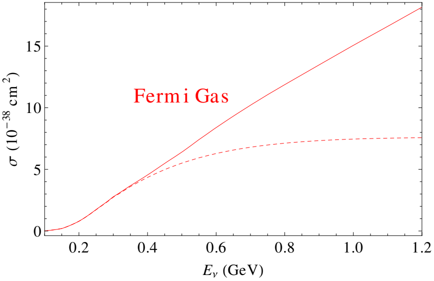
Playing with the T2K results

(in collaboration with Marco Martini–also thanks to Claudio Giganti for useful discussions)

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

STRATEGY

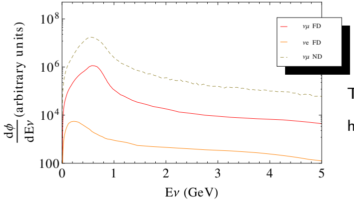
- we first used the software GLoBES to reproduce the official T2K analysis (cross sections are based on Fermi Gas)
  1. cross section normalization with the ν_μ inclusive CC at the ND (in the energy range $[0, 5]$ GeV, 3.01×10^{20} POT) we have to reproduce $\sim 1.6 \times 10^4$ ν_μ inclusive CC



solid: inclusive xs, dashed: CC

Playing with the T2K appearance data

2 computation of the expected events at the far detector and compare with the T2K MonteCarlo estimates (in the energy range $[0.1, 1.25]$ GeV)



T2K collaboration, Phys.Rev.Lett. 107 (2011) 041801;

https://indico.cern.ch/contributionDisplay.py?contribId=115&confId=114816

	channel	bin 1	bin 2	bin 3	bin 4	bin 5	total
exp data		0	4	3	3	1	11
MC estimates	$\nu_\mu \to \nu_e$	1.00	2.15	3.7	1.45	0.35	8.65
for	$\nu_e \to \nu_e$	0.10	0.35	0.40	0.35	0.30	1.50
$\sin^2 2\theta_{13} = 0.1$	NC	0.10	0.50	0.30	0.20	0.15	1.25

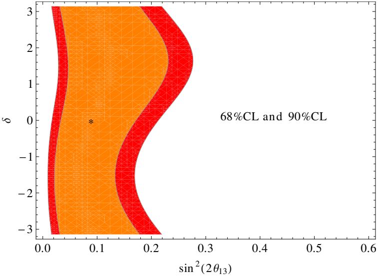
the comparison allows to "mimick" the experimental efficiencies ε_i bin-by-bin

it turns out that $\varepsilon \sim 0.3$

Playing with the T2K appearance data

we performed a very simple χ^2 analysis

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



- $S = (S_D N_D)^2 + (S_{NC} N_{NC})^2 + (S_D N_{\nu_e})^2$
- N_{com}, N_D are the *computed* number of oscillated events and the data, respectively
- N_{NC}, N_{ν_e} are the event rates for NC and ν_e contamination, respectively
- σ_D is the bin uncertainties on the data: $(0, 2, 1.5, 1.5, 0.5)$
- $S_D = 0.07$ and $S_{NC} = 0.3$ are systematic errors on the (data,ν_e) and NC events

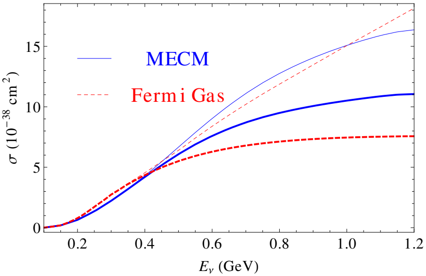
best fit $(\chi^2_{min} = 3.74)$**:** $\sin^2(2\theta_{13}) = 0.089$ $\delta_{CP} = 0.22$

obviously, good agreement with the official T2K results

Playing with the T2K appearance data

- for a different model, we repeat the previous steps using the same ε_i

redo the analysis for the MECM model



- total rates for $\sin^2 2\theta_{13}$=0.1

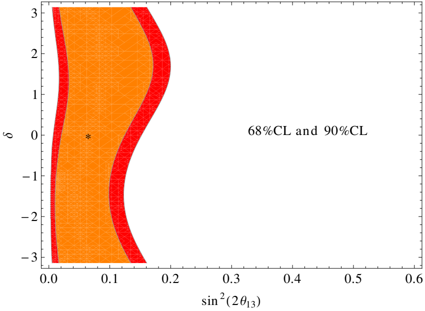
channel	exp result	MECM
$\nu_\mu \to \nu_e$	8.65	11.08
$\nu_e \to \nu_e$	1.5	1.97
NC	1.25	1.25*

Playing with the T2K appearance data

- total rates for $\sin^2 2\theta_{13}$=0.1

channel	exp result	MECM
$\nu_\mu \to \nu_e$	8.65	11.08
$\nu_e \to \nu_e$	1.5	1.97
NC	1.25	1.25*

- larger signal, must be compensated by smaller $\theta'_{13}s$



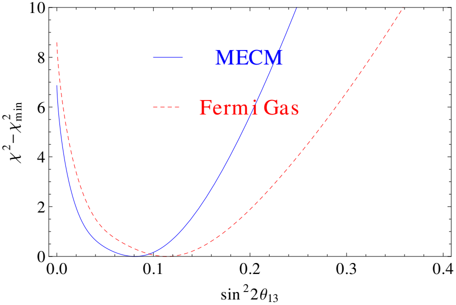
$$\chi^2_{min} = 3.65$$

$$\sin^2(2\theta_{13}) = 0.065$$
$$\delta_{CP} = 0.14$$

Playing with the T2K appearance data

comparing FG and MECM models

- showing the $\chi^2 - \chi^2_{min}$ function for 1 dof ($\delta_{CP} = 0$, good for both models)



$$\sin^2 2\theta_{13}^{MECM} = 0.081\left({}^{+0.047}_{-0.049}\right)$$
$$\sin^2 2\theta_{13}^{FG} = 0.114\left({}^{+0.060}_{-0.063}\right)$$

- results are clearly compatible at 1σ

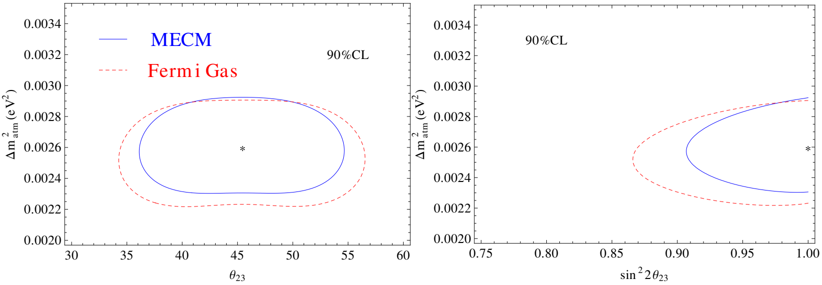
now the disappearance data

The disappearance neutrino oscillation probability ($\alpha = \beta$)

$$P(\nu_\mu \to \nu_\mu) \quad = \quad 1 - \sin^2 2\theta_{23} \sin^2 (\Delta_{atm} L)$$

- analysis based on Phys. Rev. D **85**, 031103 (2012):
  - The T2K collaboration collected 31 data events, grouped in 13 energy bins
  - the sample extends up to 6 GeV and it is mainly given by ν_μCCQE, ν_μCC non-QE, ν_e CC and NC.
  - we normalized the FG cross section to the total rates: 17.3, 9.2, 1.8 and $<$0.1 events for ν_μCCQE, ν_μCC non-QE, NC and ν_e CC, respectively.
  - we have adopted a conservative 15% normalization error and energy calibration error at the level of 10^{-3} for both signal and background.

now the disappearance data

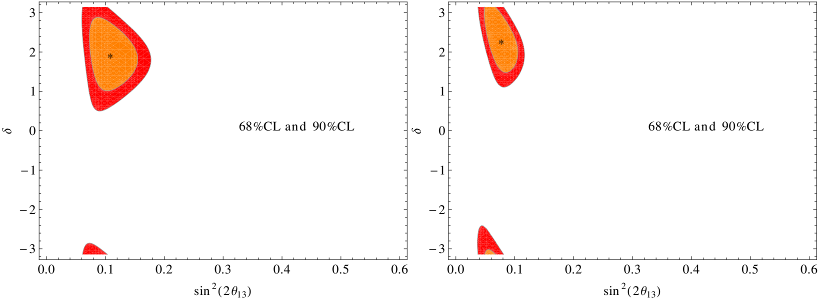


	best fit $(\sin^2 2\theta_{23}, \Delta m^2_{23})$	$\sin^2 2\theta_{23}$-range1	Δm^2_{23}-range
FG	(0.99,2.56)	>0.86	(2.22-2.90)
MECM	(1.00,2.62)	>0.91	(2.31-2.93)

Statistics × 10

- we assume the same energy distribution for the appearance channel and multiply the total ν_e by a factor of 10

FG MECM



$$\sin^2 2\theta_{13}^{FG} = 0.108^{\left(+0.024 \atop -0.028\right)} \qquad \delta \sim 111^\circ$$
$$\sin^2 \theta_{13}^{MECM} = 0.078^{\left(+0.019 \atop -0.018\right)} \qquad \delta \sim 131^\circ$$

indication for δ_{CP}? notice that $\delta_{CP}/\pi \sim 1$ in Lisi et al.

Summary

- we played a bit with the T2K data, comparing the results for θ_{13} and δ_{CP} obtained with the FG and MECM models
  - idea: give an estimate of the systematic effects encoded in the knowledge of the ν-N cross section (rough estimate)

	$\vert\Delta\theta_{13}\vert/\theta_{13}^{FG}$	$\vert\Delta\theta_{23}\vert/\theta_{23}^{FG}$	$\vert\Delta\Delta m_{23}\vert/(\Delta m_{23}^2)^{FG}$
X 1	30%	6.0%	2.3%
X 10	28%	4.6%	1.5%

- $\Delta\delta_{CP}/\delta_{CP}^{FG} \sim 15\%$

Backup slides

The Random Phase Approximation (RPA)

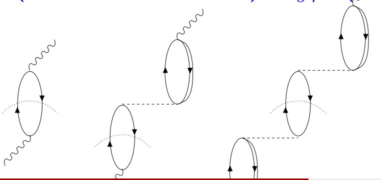
model based on
M. Martini, M. Ericson, G. Chanfray, J. Marteau, Phys. Rev. C81, 045502 (2010)
M. Martini, M. Ericson, G. Chanfray, J. Marteau, Phys. Rev. C80, 065501 (2009).

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

- K_i = kinematical factors
- R_i = response functions,

$$R(\omega, q) = -\frac{\mathcal{V}}{\pi}\,\mathrm{Im}[\Pi(\omega, q, q)].$$

To lowest order the QE cross section is given by the terms in R^{NN} [R^{NN}_{τ} (isovector interaction), $R^{NN}_{\sigma\tau}$ (isospin spin-transverse interaction)]



Lowest-order contribution from R^{NN}, $R^{N\Delta}$ and $R^{\Delta\Delta}$.
Wiggly lines represent the external probe,
solid lines correspond to the propagation of a nucleon (or a hole),
double lines to the propagation of a Δ
and dashed lines to an effective interaction between nucleons and/or Δs.

Dotted lines show which particles are placed on-shell

The Relativistic Fermi Gas Model

- many MonteCarlo codes (GENIE, NuWro, Neut, Nuance) use some version 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:

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

where

$$\begin{aligned} p_F &= \text{Fermi momentum} && \text{(225 MeV for Oxygen)} \\ E_B &= \text{average binding energy} && \text{(25 MeV for Oxygen)} \\ E &= \text{removal energy} \end{aligned}$$

Before and after normalization