Impact of systematic uncertainties for the CP violation measurement in superbeam experiments

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Abstract. We present a three-flavour fit to the recent $\nu_\mu \to \nu_e$ T2K oscillation data with different models for the neutrino-nucleus cross section. We show that, even for a limited statistics, the allowed regions and best fit points in the $(\theta_{13}, \delta_{CP})$ plane are affected if, instead of using the Fermi Gas model to describe the quasielastic cross section, we employ a model including the multinucleon emission channel [1].

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INTRODUCTION

Recently the T2K collaboration has released data in both $\nu_\mu \to \nu_e$ appearance [2] and $\nu_\mu \to \nu_\mu$ disappearance [3] modes; in the first case, 11 events passed all the selection criteria, implying (under the assumption of a normal ordering of the neutrino mass eigenstates):

$$\sin^2(2\theta_{13})_{T2K} \sim 0.09\,, \tag{1}$$

with the CP phase δ_{CP} undetermined. The aim of this work is to reanalyse the T2K data to assess the impact of different models for the ν-nucleus cross sections on the determination of oscillation parameters. This work can be considered as a generalization of Ref. [4], where the impact of different modelizations of quasielatic cross sections in the low-gamma beta-beam regime was analyzed. In the present case we consider two different models involving not only quasielastic but also pion production and inclusive cross sections. On one hand, we choose a model as similar as possible to the one used by the T2K collaboration. They simulate the neutrino-nucleus interaction using the NEUT Monte Carlo Generator [5]. Even if we do not know the details of the last tunings performed by the collaboration to take into account for the recent measurements of K2K [6, 7], MiniBooNE [8, 9] and SciBooNE [10, 11], we treat the several exclusive channels using the same models implemented in NEUT. As a consequence, we consider the Fermi Gas [12] for the quasielastic channel and the Rein and Sehgal model [13] for pion production. The second model considered in our analysis is the one of Martini, Ericson, Chanfray and Marteau [14], in the following called "MECM model". It is based on the nuclear response functions calculated in random phase approximation and allows an unified treatment of the quasielastic, the multinucleon emission channel and the coherent and incoherent pion production. As suggested in [14, 15], the inclusion of this channel in the quasielastic cross section is a possible explanation of the MiniBooNE quasielastic total cross section [9], apparently too large with respect to many theoretical predictions [16] employing the standard value of the axial mass. Since the MiniBooNE experiment, as well as many others involving Cherenkov detectors, defines a "quasielastic" event as the one in which only a final charged lepton is detected, the ejection of a single nucleon (a genuine quasielastic event) is only one possibility, and one must in addition consider events involving a correlated nucleon pair from which the partner nucleon is also ejected. This leads to the excitation of 2 particle-2 hole (2p-2h) states; 3p-3h excitations are also possible. Recently, it has been shown [18] that the MECM model can also reproduce the MiniBooNE flux averaged double differential cross section [9] which is a directly measured quantity and hence free from the model-dependent uncertainties in the neutrino energy reconstruction, and the total inclusive cross section [17] (also employed by T2K as described below) measured by SciBooNE [11]. In the following we will use the cross sections obtained in the two different approaches described above in several exclusive channels (quasielastic and pion production), as well as in the inclusive one, for both charged current (CC) and neutral current (NC) interactions on carbon and oxygen (the targets used in near and far T2K detectors, respectively) and for two neutrino flavours ν_μ and ν_e. Although all exclusive channels are involved in the analysis, we will refer to the first model as "the Fermi Gas model" and to the second approach as "the MECM model".

In order to perform our comparison among the above-mentioned models, we first need to correctly normalize the Fermi gas to the T2K event rates, at both near (ND) and far (FD) detectors; we use the following algorithm:

1- normalization of the cross section with the ν_μ inclusive CC at the ND; according to [2], we have to reproduce 1.6×10^4 ν_μ inclusive events, collected using 3.01×10^{19} POT, in the energy range $[0-5]$ GeV, with an active detector mass of 1529 Kg at a distance of 280 m from the ν source;

2- computation of the expected events (and energy distributions) at the far detector in the appropriate two-parameter plane ($(\sin^2 2\theta_{13}, \delta_{CP})$);

3- normalization to the T2K spectral distributions.

Step #3 is needed to get rid of the experimental efficiencies applied by the T2K collaboration to the signal and background events. This means that the bin contents of our simulated distributions (obtained at point #2) are corrected by coefficients, generally of $\mathcal{O}(1)$ that we consider as a detector property, and then not further modified. For a different model, we repeat step #1 and then go to step #2, using the same normalization coefficients extracted in step #3 with the Fermi gas. We make use of the GloBES [19] and MonteCUBES [20] softwares for the computation of event rates (and related χ^2 functions) expected at the T2K ND and FD detectors. The fluxes of ν_μ, ν_e and their CP-conjugate counterparts predicted at the FD in absence of oscillations have been extracted directly from Fig.1 of [2], whereas the ν_μ flux at the ND has been obtained from [3]. As already stressed, for the relevant cross sections we assumed that the T2K collaboration uses some "sophisticated" version of the Fermi gas model [12]. In Fig.1 we show the inclusive and QE cross sections in the FG model (dashed lines) and in the MECM model (solid line) used in our simulation, after having correctly normalized the inclusive cross sections to the event rate at the ND. Especially for the MECM model, this procedure involves a degree of extrapolation of the inclusive cross sections towards neutrino energies beyond the validity of model itself. However, neutrino fluxes above $\mathcal{O}(1)$ GeV drop very fast and we checked that different kind of extrapolations do not alter our conclusions.

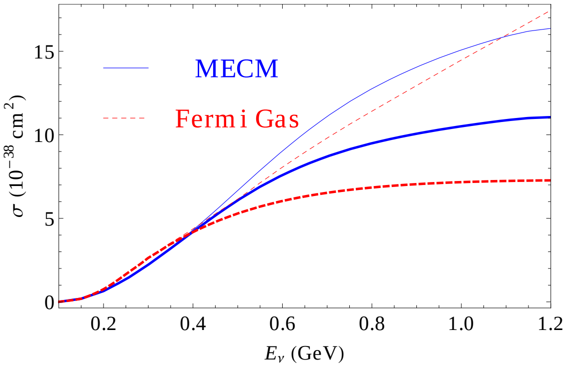

FIGURE 1. *Inclusive (thin lines) and QE (thick lines) ν_μ CC cross sections on oxygen in the FG model (dashed lines) and in the MECM model (solid line) after the normalization of the inclusive cross sections to the event rate at the ND.*

The important feature here is that, even after the normalization procedure, the MECM CCQE cross section is still larger than the FG predictions, in the energy range relevant for appearance studies. This is due to the inclusion of the multinucleon component and will be the main reason of the differences between the results obtained in the two models. Note on the contrary that the inclusive cross sections are not really different.

THE APPEARANCE CHANNEL

The $\nu_\mu \to \nu_e$ transition probability is particularly suitable for extracting information on θ_{13} and δ_{CP}; at the T2K energies (E_ν) and baseline (L), one can expand the full 3-flavour probability up to second order in the small parameters $\theta_{13}, \Delta_{12}/\Delta_{13}$ and $\Delta_{12}L$, with $\Delta_{ij} = \Delta m^2_{ij}/4E_\nu$ [21]:

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

where

$$\tilde{J} \equiv c_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \,, \qquad s_{23} = \sin\theta_{23} \,. \tag{3}$$

We clearly see that CP violating effects are encoded in the interference term proportional to the product of the solar mass splitting and the baseline, implying a scarce dependence of this facility on δ_{CP} when only the $\nu_\mu \to \nu_e$ channel (and the current luminosity) is considered.

Extracting the T2K data

Events in the far detector are ν_e CCQE from $\nu_\mu \to \nu_e$ oscillation, with main backgrounds given by ν_e contamination in the beam and neutral current events with a misidentified π^0. The experimental data have been grouped in 5 reconstructed-energy bins, from 0 to 1.25 GeV and they are summarized in Tab.1. The expectations for signal and backgrounds have been computed by the T2K collaboration from Monte Carlo simulations, for fixed value of the oscillation parameters, namely $\sin^2 2\theta_{12} = 0.8794, \sin^2 2\theta_{13} = 0.1, \sin^2 2\theta_{23} = 1$ and $\Delta m^2_{sol} = 7.5 \times 10^{-5} eV^2, \Delta m^2_{atm} = +2.4 \times 10^{-3} eV^2$. In order to normalize our event rates to the T2K Monte Carlo expectations, we extracted these numbers from Fig.5 of [2] and reported them in Tab.1.

TABLE 1. *Expected event rates for* $\sin^2 2\theta_{13}$=*0.1.*

	channel	bin 1	bin2	bin3	bin4	bin5	total
exp data		0	4	3	3	1	11
estimates	$\nu_\mu \to \nu_e$	1.00	2.15	3.70	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

Notice that we used the central bin energy as a reference value for the neutrino energy in a given bin; this could be different from the reconstructed neutrino energies used by the T2K collaboration. To mimic possible uncertainties associated to the neutrino energy reconstruction, we apply an energy smearing function to distribute the rates in the various energy bins. Other choiches, more related to microscopical calculations [22, 23, 24] are also possible. The result of the computation of the ratios among our rates and the T2K data (*energy dependent* efficiencies) corresponds to step #3 of the previous paragraph and allows us to take into account all the detection efficiencies to different neutrino flavours in the Super Kamiokande detector. Once computed, these corrective factors are used in the simulations done with a different cross section, since we assume here that they are features of the detector and not of the neutrino interactions. For $\nu_{e,\mu} \to \nu_e$ transitions these numbers are just $\mathscr{O}(1)$ coefficients, which makes us confident that the normalization procedure correctly accounts for the main experimental features. The same is not true for the NC events which, however, have not been normalized to the ND as for the CC interactions. As a check, we also computed the expected events for $\sin^2 2\theta_{13}$=0, obtaining 0.1 $\nu_\mu \to \nu_e$ events and 0.72 $\nu_e \to \nu_e$ events (and the same neutral current rate), in good agreement with the T2K expectations [2].

Fit to the data

Equipped with these results, we performed a χ^2 analysis to reproduce the confidence level regions in the $(\sin^2 2\theta_{13}, \delta_{CP})$-plane shown in Fig.6 of [2]. Contrary to what has been done in the official T2K paper, we make a complete three-neutrino analysis of the experimental data, marginalizing over all parameters not shown in the confidence regions. As external input errors, we used 3% on θ_{12} and Δm^2_{sol}, 8% on θ_{23} and 6% on Δm^2_{atm}. We use a constant energy resolution function $\sigma(E_\nu) = 0.085$ and, for simplicity, we adopt a 7% normalization error for the signal and 30% for the backgrounds. We also used energy calibration errors fixed to 10^{-4} for the signal and $5 \cdot 10^{-2}$ for the backgrounds; normalization and energy calibration errors take into account the impact of systematic errors in the χ^2 computation.
Assuming a normal hierarchy spectrum, the best-fit point from the fit procedure is (obviously):

$$\sin^2(2\theta_{13}) = 0.089 \qquad \delta_{CP} = 0.22 \tag{4}$$

with $\chi^2_{min} = 3.74$.

We now apply the same procedure to determine θ_{13} using the MECM cross sections described in [14]. In doing that, we normalize the cross sections to the ND events and then compute the number of oscillated events (and related backgrounds), to be compared with the experimental T2K data. We get the following number of expected 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	$1.25^{\star}$

It is clear that larger rates need smaller θ_{13} to reproduce the data (the effect of the CP phase δ is negligible with such a statistics). The best fit point is:

$$\sin^2(2\theta_{13}) = 0.065 \qquad \delta_{CP} = 0.14\,, \tag{5}$$

with $\chi^2_{min} = 3.65$, and the contour plot is shown in Fig.2. We can appreciate a substantial reduction of the value of the reactor angle. To make a more direct comparison on θ_{13} between the FG and MECM results, in Fig.3 we show the $\chi^2 - \chi^2_{min}$ function, computed marginalizing over all other oscillation parameters (including δ_{CP}). At 1σ, we get:

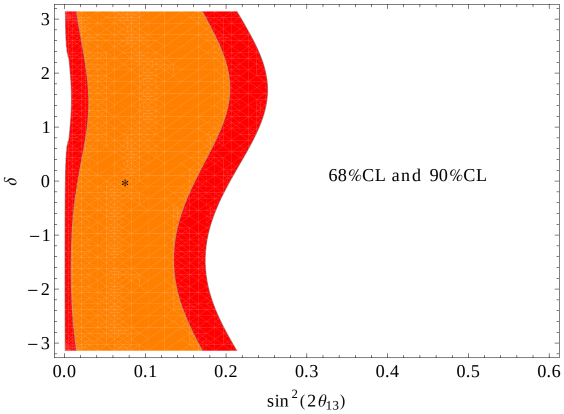

FIGURE 2. *The 68% and 90% C.L. regions for* $(\sin^2 2\theta_{13}, \delta_{\rm CP})$ *for the MECM model. Star indicates the best fit point.*

$$\begin{aligned} \sin^2 2\theta_{13}^{MECM} &= 0.081\binom{+0.047}{-0.049} \\ \sin^2 2\theta_{13}^{FG} &= 0.114\binom{+0.060}{-0.063}\,. \end{aligned} \tag{6}$$

They are clearly compatible although, as expected, $\theta_{13}^{MECM} < \theta_{13}^{FG}$.

CONCLUSIONS

In this paper we have studied the impact of using different models for the neutrino-nucleus cross section in the determination of the θ_{13} mixing angle and the CP violating phase using the recent T2K data, for the appearance channel. Although the statistics is not large enough to draw definite conclusions, we have seen that a more refined treatments of nuclear effects in neutrino interactions can have some impact in the achievable precision on the mixing parameters. In particular, the MECM model predicts a large CCQE cross section, compared to the FG model, which results in a small θ_{13} needed to fit the data in the $\nu_\mu \to \nu_e$ channel.

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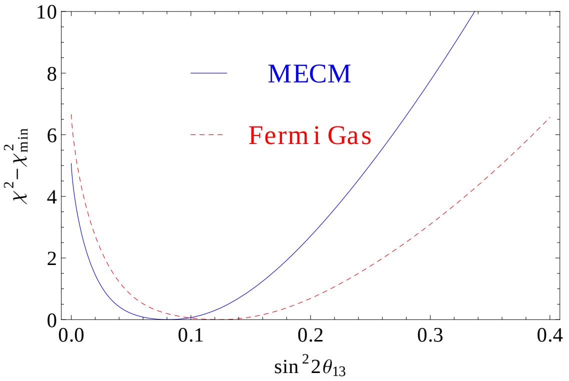

FIGURE 3. χ^2 *as a function of* θ_{13} *for the MECM model (solid line) and FG (dashed line).*

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