Revisiting the T2K data using different models for the neutrino–nucleus cross sections

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1. Introduction

Recently the T2K Collaboration has released data in both $\nu_\mu \rightarrow \nu_e$ appearance [1] and $\nu_\mu \rightarrow \nu_\mu$ disappearance [2] modes; in the first case, six events passed all the selection criteria, implying (under the assumption of a normal ordering of the neutrino mass eigenstates):

$$\sin^2(2\theta_{13})_{\text{T2K}} = 0.11,$$

with the CP phase $\delta_{CP}$ undetermined. In the disappearance channel, the 31 events collected by T2K are fitted with:

$$\langle \sin^22\theta_{23}\rangle_{\text{T2K}} = 0.98, \quad |\Delta m^2_{31)|_{\text{T2K}} = 2.65 \times 10^{-3} \text{ eV}^2.$$  

The aim of this work is to reanalyse the T2K data to assess the impact of different models for the $\nu$–nucleus cross sections on the determination of oscillation parameters. This work can be considered as a generalization of Ref. [3], where the impact of different modelizations of quasielastic 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 [4]. 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 [5,6], MiniBooNE [7,8] and SciBooNE [9,10], we treat the several exclusive channels using the same models implemented in NEUT. As a consequence, we consider the Fermi gas [11] for the quasielastic channel and the Rein and Sehgal model [12] for pion production. The second model considered in our analysis is the one of Martini, Ericson, Chanfray and Marteau [13], 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. The agreement with the experimental data in the pion production channels [6,7,9] has been proved. Nevertheless the main feature of this MECM model is the treatment of the multinucleon emission channel in connection with the quasielastic. In fact, as suggested in [13,14], the inclusion of this channel in the quasielastic cross section is a possible explanation of the MiniBooNE quasieelastic total cross section [8], apparently too large with respect to many theoretical predictions [15] 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. Nowadays other models [16–19] have included the multinucleon contribution in the computation of the cross sections relevant for the MiniBooNE kinematics, improving the agreement with the experimental data. For a brief review see for example [20]. Recently, it has been shown [21] that the MECM model can also reproduce the MiniBooNE flux averaged double differential cross section [8] which is a directly measured quantity and hence free from the model-dependent uncertainties in the neutrino energy.

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reconstruction, and the total inclusive cross section [20] (also employed by T2K as described below) measured by SciBooNE [10]. 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 flavors $\nu_\mu$ and $\nu_e$. 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 $\nu_\mu$ inclusive CC at the ND; according to [1], we have to reproduce 1529 $\nu_\mu$ inclusive events, collected using $2.9 \times 10^{19}$ POT, in the energy range [0–5] GeV, with an active detector mass of 1529 kg\(^1\) at a distance of 280 m from the $\nu$ source and half a year of data taking (Run 1). Notice that only the muon neutrino cross sections can be correctly normalized: we assume that the same normalization also applies for the $\nu_e$ cross section, although they could differ at the $\mu$ production threshold (in any case away from the peak of the neutrino flux);
2. computation of the expected events (and energy distributions) at the far detector in the appropriate two-parameter plane ($\sin^2 2\theta_{13}, \Delta m^2_{\text{sol}}$) expected at the T2K ND and FD detectors. The fluxes of $\nu_\mu$ and $\nu_e$ and their CP-conjugate counterparts predicted at the FD in absence of oscillations have been extracted directly from Fig. 1 of [1], whereas the $\nu_\mu$ flux at the ND has been obtained from [2]. Such fluxes (the relevant ones summarized in Fig. 1) are given for 10\(^{20}\) POT. As already stressed, for the relevant cross sections we assumed that the T2K Collaboration uses some "sophisticated" version of the Fermi gas model [11]. In Fig. 2 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 $O(1)$ GeV drop very fast and we checked that different kind of extrapolations do not alter our conclusions.

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.

2. The appearance channel

The $\nu_\mu \rightarrow \nu_e$ transition probability is particularly suitable for extracting information on $\theta_{13}$ and $\delta_{CP}$: at the T2K energies ($E_\nu$) and baseline ($L$), one can expand the full 3-flavor probability up to second order in the small parameters $\theta_{13}, \Delta_{23}/\Delta_{13}$ and $\Delta_{12} L$, with $\Delta_{ij} = \Delta m^2_{ij}/4E_\nu$ [24]:

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

where

$$\tilde{J} = c_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} = s_{23} \sin \theta_{23}. \quad (3)$$

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 $\delta_{CP}$ when only the $\nu_\mu \rightarrow \nu_e$ channel (and the current luminosity) is considered.

2.1. Extracting the T2K data

Events in the far detector (obtained with $2.9 \times 10^{20}$ POT) are classified: $\nu_e$ CCQE from $\nu_\mu \rightarrow \nu_e$ oscillation, with main backgrounds given

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\(^1\) We thank Scott Oser for providing such a number to us.
by νe contamination in the beam and neutral current events with a misidentified π0. The experimental data have been grouped in 5 reconstructed-energy bins, from 0 to 1.25 GeV and they are summarized in Table 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 sin²2θ12 = 0.8794, sin²2θ13 = 0.1, sin²2θ23 = 1 and ∆m²sol = 7.5 × 10⁻⁵ eV², ∆m²atm = +2.4 × 10⁻³ eV². In order to normalize our event rates to the T2K Monte Carlo expectations, we extracted these numbers from Fig. 5 of [1] and reported them in Table 1.

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 choices, more related to reconstruction, we apply an energy smearing function to distribute

| Channel | bin 1 | bin 2 | bin 3 | bin 4 | bin 5 | Total |
|---------|-------|-------|-------|-------|-------|-------|
|νμ → νμ | 1.76  | 1.42  | 1.52  | 1.72  | 1.90  |       |
|νe → νe | 1.10  | 1.60  | 1.65  | 1.55  | 1.70  |       |
|NC      | 0.04  | 0.025 | 0.009 | 0.01  | 0.016 |       |

Table 2

Efficiencies computed after normalizing the event rates at the values for sin²2θ13 = 0.1.

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Table 1

Expected event rates for sin²2θ13 = 0.1.

2.2. Fit to the data

Equipped with these results, we performed a χ² analysis to reproduce the confidence level regions in the (sin²2θ13, δCP)-plane shown in Fig. 6 of [1]. 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 θ12 and ∆m²sol, 8% on θ23 and 6% on ∆m²atm. We use a constant energy resolution function σ(Eν) = 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 × 10⁻² for the backgrounds; normalization and energy calibration errors take into account the impact of systematic errors in the χ² computation.

Assuming a normal hierarchy spectrum, the best-fit point from the fit procedure is (obviously):

\[ \sin^2(2\theta_{13}) = 0.108, \quad \delta_{CP} = 0.04 \]

with \( \chi^2_{\text{min}} = 1.69 \); the related contour plot is shown in Fig. 3. Compared to the official release, the plot is in quite good agreement, although the allowed values of θ13 around maximal CP violation δCP = π/2 are a bit larger (this is the effect of including the errors of the atmospheric parameters into the fit procedure).

We now apply the same procedure to determine θ13 using the MECM cross sections described in [13] (Table 3). 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 assume that the efficiencies reported in Table 2 are exactly the same, since they are a property of the SK detectors and then independent on the cross section model. With these assumptions, we get the following number of expected rates for sin²2θ13 = 0.1.

It is clear that larger rates need smaller θ13 to reproduce the data (the effect of the CP phase δ is negligible with such a statistics). The best fit point is:

\[ \sin^2(2\theta_{13}) = 0.073, \quad \delta_{CP} = 0, \]

with \( \chi^2_{\text{min}} = 1.53 \), and the contour plot is shown in Fig. 4. We can appreciate a substantial improvement in the determination of the
Table 3
Total rates for $\sin^2 2\theta_{13} = 0.1$ in the MECM model.

| Channel | bin 1 | bin 2 | bin 3 | bin 4 | bin 5 | Total |
|---------|-------|-------|-------|-------|-------|-------|
| $\nu_\mu \to \nu_\mu$ | 0.234 | 1.205 | 2.808 | 1.121 | 0.295 | 5.665 |
| $\nu_\mu \to \nu_e$ | 0.029 | 0.194 | 0.280 | 0.227 | 0.179 | 0.909 |
| NC | 0.017 | 0.156 | 0.204 | 0.130 | 0.08 | 0.590 |

Table 4
T2K events and bin distributions for the $\nu_\mu$ CCQE and $\nu_\mu$ CC non-QE rates in the MECM model.

| bin | T2K data | MECM $\nu_\mu$ CCQE | MECM $\nu_\mu$ CC non-QE |
|-----|----------|----------------------|--------------------------|
|     | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| 1   | 1 | 5 | 3 | 1 | 2 | 1 | 2 | 3 | 4 | 2 | 1 | 3 | 3 |
| 2   | 0.6 | 3.2 | 2.2 | 0.7 | 1.8 | 0.8 | 2.0 | 2.8 | 3.5 | 1.2 | 1.3 | 0.8 | 0.6 |
| 3   | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.2 | 0.4 | 0.3 | 0.4 | 1.0 | 1.2 | 1.3 |

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

3. The disappearance channel

We extend the previous analysis to include the first disappearance $\nu_\mu \to \nu_\mu$ data [2]. In the two-flavor limit (the one where both $\theta_{13}$ and $\Delta m_{23}^2$ are vanishing) the $\nu_\mu \to \nu_\mu$ probability reads [28]:

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

(7)

Effects related to $\theta_{13}$ are clearly sub-dominant, so that this channel is particularly useful to extract information on the atmospheric parameters. The T2K Collaboration collected 31 data events, grouped in 13 energy bins, as one can see from Fig. 3 of [2]. The sample extend up to 6 GeV and it is mainly given by $\nu_\mu$ CCQE, $\nu_\mu$ CC non-QE, $\nu_e$ CC and NC. Differently from the appearance channel, we cannot normalize their energy distribution to the channel-by-channel T2K Monte Carlo expectation since, as far as we know, such information has not been released. We can only normalize our FG cross section to the total rates shown in Table 1 of [2], which amounts to 17.3, 9.2, 1.8 and $<0.1$ events for $\nu_\mu$ CCQE, $\nu_\mu$ CC non-QE, NC and $\nu_e$ CC, respectively. Such numbers refer to $\sin^2 2\theta_{23} = 1.0$ and $|\Delta m_{23}^2| = 2.4 \times 10^{-3} \text{ eV}^2$, with all other neutrino mixing parameters vanishing. For the sake of completeness, we summarize in Table 4 the T2K data as well as the energy distributions according to the FG and MECM cross sections.

We plot the 2 degrees of freedom (dof) confidence levels in the $\chi^2$ plane for $\theta_{13}$ and the MECM model (solid line), in the case of normal hierarchy. Again, the plots have been obtained marginalizing over the not shown parameters (a full three-flavor analysis); we considered a 50% error on $\sin^2 2\theta_{13}$ (with best fit at $\sin^2 2\theta_{13} = 0.0059$) and $\delta_{CP}$ undetermined. We obtained:

FG: $\sin^2 2\theta_{23} > 0.86$

$2.22 \times 10^{-3} < \Delta m_{23}^2 (\text{eV}^2) < 2.90 \times 10^{-3}$

MECM: $\sin^2 2\theta_{23} > 0.91$

$2.31 \times 10^{-3} < \Delta m_{23}^2 (\text{eV}^2) < 2.93 \times 10^{-3}$

(8)
Fig. 6. 90% contour levels for the MECM model (solid line) and FG (dashed line), in the $(\theta_{23}, \Delta m_{\text{atm}}^2)$ (left panel) and $(\sin^2 2\theta_{23}, \Delta m_{\text{atm}}^2)$ (right panel) planes. Star indicates the best fit obtained in the MECM model.

Fig. 7. 90% CL for 2 dof in the $(\sin^2 2\theta_{13}, \delta)$-plane (left panel) and $(\theta_{23}, \Delta m_{\text{atm}}^2)$-plane (right panel) for the MECM model (solid line) and FG (dashed one) in the case the current T2K statistics is increased by a factor of 10. Stars indicate the best fit values of the parameters as obtained in the MECM model.

with best fit points:

FG: $\sin^2 2\theta_{23} = 0.99 (47.9^\circ)$, $\Delta m_{\text{atm}}^2 = 2.56 \times 10^{-3}$ eV$^2$.
MECM: $\sin^2 2\theta_{23} = 1.00 (45.0^\circ)$, $\Delta m_{\text{atm}}^2 = 2.62 \times 10^{-3}$ eV$^2$.

\begin{align}
\sin^2 2\theta_{23}\bigg|_{\text{T2K}} &= 0.98 \\
\Delta m_{\text{atm}}^2\bigg|_{\text{T2K}} &= 2.65 \times 10^{-3} \text{ eV}^2,
\end{align}

Some comments are in order; first of all, we observe that, for both models, the best fit point is different from the T2K ones, which is $\left(\sin^2 2\theta_{13}, \delta\right)_{\text{T2K}} = 0.99 (47.9^\circ)$, $\Delta m_{\text{atm}}^2 = 2.65 \times 10^{-3}$ eV$^2$.

4. Future perspectives

The statistics used by the T2K Collaboration to make the disappearance study is only a 2% of the rates expected at the end of the experiment. It makes sense to ask how the previous results would modify if the accumulated statistics would be larger than the current one. We limit ourselves to consider a number of events with the same energy distribution as the experimental ones but bin contents larger by factor of 10, in both appearance and disappearance channels. In the analysis of the appearance channel, the (weak) information on $\theta_{13}$ contained in the disappearance sample should not be neglected (as we did previously); at the same time, the dependence on the atmospheric parameters from the appearance sample cannot in principle be neglected when studying the disappearance data. For this reason, we prefer to combine both $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_\mu$ oscillation data, and study the sensitivity to the reactor and atmospheric parameters as we did in the previous sections, marginalizing over the parameters not expressly shown.

Notice that such an approach would not give any additional information on the mixing parameters if adopted with the current T2K statistics: in fact, we see from Fig. 6 that the uncertainties on $\theta_{23}$ and $\Delta m_{\text{atm}}^2$ obtained from the T2K data are larger than the adopted external errors on these parameters in the appearance channel, so that adding the $\nu_\mu \rightarrow \nu_\mu$ data will not improve the
sensitivity to \( \theta_{13} \); similarly, the dependence on the reactor angle in \( P(\nu_{\mu} \rightarrow \nu_{e}) \) is sub-leading and the impact of the disappearance channel in the appearance measurement is also negligible. We stress that extracting information on the mixing parameters combining appearance and disappearance channels is also mandatory to avoid some inconsistencies emerged in the official T2K fits, where \(|\Delta m^2_{\text{atm}}| \) is fixed to \( 2.4 \times 10^{-3} \text{ eV}^2 \) in the analysis whereas the best fit point obtained from the disappearance data is \( 2.6 \times 10^{-3} \text{ eV}^2 \). The results of our procedure are shown in Fig. 7, where we display the 90% CL in the \( (\sin^2 2\theta_{13}, \delta_{\text{CP}}) \)-plane (left panel) and \((\theta_{23}, \Delta m^2_{\text{atm}}) \)-plane (right panel) for the MECM (solid line) and FG (dashed one) models in the case the current T2K statistics is increased by a factor of 10. The minimum of the \( \chi^2 \) still gets reasonable values: we obtain \( \chi^2_{\text{min}} \sim 20 \) in the appearance analysis and \( \chi^2_{\text{min}} \sim 30 \) in disappearance. In both panels we can appreciate the effects of the increased statistics, as expected: for a given model of cross section, the allowed regions are strongly restricted with respect to the current situation. The best fit values for \( \delta_{\text{CP}} \) are somehow different in the two models \( (\delta_{\text{CP}} \sim 0 \text{ and } \delta_{\text{CP}} \sim 144^\circ) \) for the FG and MECM models, respectively, although statistically not very significant. Such intervals for \( \sin^2 2\theta_{13}, \theta_{23} \) and \( \Delta m^2_{\text{atm}} \) are summarized in Table 5 (\( \delta_{\text{CP}} \) is obviously still unconstrained). We have checked that, if we only use the appearance channel to extract \( \theta_{13} \), the results are slightly different: although the best fit value is practically indistinguishable from the one quoted in Table 5, the confidence regions are a bit larger, with significant overlap with the above mentioned analysis. To see stronger effects due to the \( \theta_{13} \) dependence in the \( \nu_{\mu} \rightarrow \nu_{\mu} \) transition, we need a more accurate spectral information [29]. Similar conclusions can also be drawn for the disappearance channel: with only a factor of 10 more statistics and no appearance contribution, the best fit for the atmospheric parameters remain almost the same whereas the 90% CL region for \( \theta_{23} \) shows a smaller lower limit (from 40.1° to 39.8°) in the FG model.

For the sake of completeness, we have repeated the same computations as above under the hypothesis that the neutrino mass spectrum is of inverted type (IH). With the current T2K statistics, we cannot appreciate huge differences in the results obtained using the two different models for the cross section. Then, we limit ourselves here to the case where the statistics is larger by a factor of 10. Our results are summarized in Fig. 9 and Table 6. Comparing the left panel of Fig. 9 with the corresponding one in Fig. 7, we clearly see that an inverted spectrum prefers larger values for \( \theta_{13} \), in both models. The best fit of the CP phases is different among the two mass orderings but not really significant. In the atmospheric plane, right panel of Fig. 9, we observe the same pattern as in the normal hierarchy case, that is the MECM tends to give a better resolution for both \( \Delta m^2_{\text{atm}} \) and \( \theta_{23} \) than the FG model.

Table 5

| \sin^2 2\theta_{13} | \theta_{23} (°) | \Delta m^2_{\text{atm}} (10^{-3} \text{ eV}^2) |
|-----------------|----------------|----------------------------------|
| FG [0.041–0.211] | [40.1–51.3] | [2.45–2.67] |
| MECM [0.023–0.154] | [41.1–40.9] | [2.49–2.67] |

Fig. 8. \( \chi^2 - \chi^2_{\text{min}} \) as a function of \( \sin^2 2\theta_{13} \) for the MECM model (solid line) and FG (dashed line) in the case the event rates are increased by a factor of 10.

Finally, we observe that such an increased statistics is necessary to make marginally incompatible the FG and MECM \( \sin^2 2\theta_{13} \) results, see Fig. 8, obtained marginalizing over \( \delta_{\text{CP}} \) also. In fact, at 1σ we get:

\[
\sin^2 2\theta_{13}^{\text{MECM}} = 0.092^{+0.030}_{-0.052} \\
\sin^2 2\theta_{13}^{\text{FG}} = 0.138^{+0.031}_{-0.041}.
\]

5. The inverted hierarchy case
In this Letter we have studied the impact of using different models for the neutrino–nucleus cross section in the determination of the $\theta_{13,23}$ mixing angles and the atmospheric mass difference $\Delta m^2_{\text{atm}}$ using the recent T2K data, for both appearance and disappearance channels. Although the statistics is not large enough to draw definite conclusions, we have seen that a more refined treatment 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 $\theta_{13}$ needed to fit the data in the $\nu_{\mu} \rightarrow \nu_e$ channel. At the same time, a larger $\Delta m^2_{\text{atm}}$ is required to fit the data in the $\nu_{\mu}$ disappearance channel, since a smaller disappearance probability is needed to compensate for the larger cross sections. Interestingly enough, with 10 times more statistics the two models tend to give substantial different results in terms of best fit points and parameter uncertainties (of course, better than before) but their predictions are still compatible to each other.

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