Indications on neutrino oscillations parameters from initial K2K and current SK data

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Abstract

We briefly discuss the impact of initial data from the KEK-to-Kamioka (K2K) neutrino experiment on the $\nu_\mu \to \nu_\tau$ oscillation parameters ($m^2, \tan^2 \psi$) currently indicated by the Super-Kamiokande (SK) atmospheric neutrino experiment. After showing the very good agreement between K2K and SK, we combine the two separate pieces of information. We find that the 99% C.L. range for $m^2$ allowed by SK only, $m^2 \in [1.3, 5.6] \times 10^{-3}$ eV$^2$, is reduced to $[1.5, 4.8] \times 10^{-3}$ eV$^2$ by including K2K data. By halving the uncertainties of the K2K total rate (with central value unchanged), the $m^2$ range would be ulteriorly reduced to $[1.8, 4.0] \times 10^{-3}$ eV$^2$. Such information appears to be already useful in planning (very) long baseline neutrino oscillation experiments.

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I. INTRODUCTION

The KEK-to-Kamioka (K2K) long baseline neutrino experiment [1] is designed to explore, with laboratory neutrinos, the mechanism of $\nu_{\mu}$ disappearance indicated by the Super-Kamiokande (SK) [2], MACRO [3], and Soudan 2 [4] atmospheric neutrino experiments. Such mechanism appears to be dominated by $\nu_{\mu} \rightarrow \nu_\tau$ oscillations [5–8] with mass-mixing parameters ($m^2, \tan^2 \psi$) close to $(3 \times 10^{-3} \text{ eV}^2, 1)$. The pathlength ($L = 250 \text{ km}$) and typical energies ($E \sim \text{few GeV}$) of K2K $\nu_{\mu}$'s are well suited to study $\nu_{\mu}$ disappearance effects for such parameter values [1].

The recent data released by the K2K experiment [9–11] (44 observed neutrino events vs 63.9 expected) are already inconsistent with the no-oscillation hypothesis at about 97% C.L. [9–12], and suggest disappearance of the muon neutrino flavor in the path from KEK to Kamioka. The K2K collaboration is being understandably rather conservative on the oscillation explanation of the data, pending more accurate estimates of the K2K neutrino spectrum and interaction uncertainties by means of the near detector [13]. However, it is tempting to use just the minimum amount of spectrum-integrated data (i.e., the total event rate, for which the error estimate appears to be relatively stable), in order to study the compatibility of K2K and SK data [14].

In this paper we attempt to investigate such a compatibility issue, by comparing predictions and data in both K2K and SK, within the simplest (two-family) $\nu_{\mu} \rightarrow \nu_\tau$ oscillation framework. We show that the K2K and the SK data are consistent, and that their combination starts to be useful in constraining further the oscillation parameters. In particular, the 99% C.L. range for $m^2$ allowed by SK only, $m^2 \in [1.3, 5.6] \times 10^{-3} \text{ eV}^2$, is reduced to $[1.5, 4.8] \times 10^{-3} \text{ eV}^2$ by including K2K data. Finally we show that, by halving the K2K total rate error, the $m^2$ range would be ulteriorly reduced to $[1.8, 4.0] \times 10^{-3} \text{ eV}^2$.

II. ANALYSIS OF K2K

Analyses of K2K data have to consider the energy spectrum of parent neutrinos at the far detector $S(E)$, i.e., the spectrum of neutrino that have produced a detected interaction at the Kamioka site. Such spectrum is, in general, given by the product of the unoscillated neutrino energy spectrum $\Phi$ at the far (SK) detector, times the interaction cross section $\sigma$, times the detection efficiency $\varepsilon$ (all in differential form), integrated over all the final state parameters (symbolically, $S = \int \Phi \cdot \sigma \cdot \varepsilon$). The spectrum $S(E)$ is important since, in the presence of neutrino mass and mixing, the oscillated event rate can be expressed as $r = \int dE \ S(E) \cdot P_{\mu\mu}(E)$ [to be compared with the unoscillated rate, $r_0 = \int dE \ S(E)$], where $P_{\mu\mu}$ is the $\nu_{\mu}$ survival probability.

At present, there is enough public information on $\Phi$ [9–11], but not yet on the product $\sigma \cdot \varepsilon$ relevant for the far detector specifications. Therefore, a direct and accurate reconstruction of the spectrum $S(E)$ and of its uncertainties is not possible outside the K2K collaboration, at least at present. However, an indirect, approximate reconstruction can be made, by considering that: (a) the neutrino spectrum is practically zero above 5 GeV [9]; and (b) according to the K2K MonteCarlo (MC) simulation, for the current exposure ($3.85 \times 10^{19}$ p.o.t.) one has $r_0 = 63.9$ events, while $r = 41.5, 27.4$, and 23.1 events for $m^2 = 3, 5, \text{and}$
$7 \times 10^{-3}$ eV$^2$, respectively, assuming maximal mixing [9–11]. We have then introduced an empirical functional form for the spectrum, $S(E) \propto x^\alpha(1-x)^\beta$ with $x = E/(5 \text{ GeV})$, which is found to reproduce well the above MC results for $(\alpha, \beta) = (1.50, 3.34)$. In the following analysis we use such interacted neutrino spectrum, since it gives—by construction—results close to the K2K MC simulation, after integration over $P_{\nu\mu}(E)$. A more accurate (and less tentative) parametrization of $S(E)$ shall be possible after the experimental specifications and selection cuts (relevant to determine $\sigma \cdot \varepsilon$ and its uncertainties) will be measured and described in detail.

Concerning the uncertainties, the current systematic error on the total rate is estimated to be 10% by the K2K Collaboration [9–11]. Spectral bins may be affected by larger (and correlated) errors [9–11], which, however, do not affect our spectrum-averaged analysis. Therefore, we attach a 10% fractional error to the oscillated number of events $r = r(m^2, \tan^2 \psi)$, while the statistical (Poisson) error $\sigma_{\text{stat}} = \sqrt{44}$ is attached to the number of observed events, $r_{\text{exp}} = 44$. The $\chi^2$ statistics for K2K is then simply given by $(r - r_{\text{exp}})^2/\sigma_{\text{tot}}^2$, where $\sigma_{\text{tot}}^2 = \sigma_{\text{stat}}^2 + (0.1 r)^2$. With such definition, the no oscillation hypothesis ($r = r_0$) is disfavored at 97% C.L. ($\chi^2 = 4.7$ for $N_{\text{DF}} = 1$), consistently with the current claim of the K2K Collaboration [9–12].

Figure 1 shows the number $r$ of K2K events for the current exposure ($3.85 \times 10^{19}$ p.o.t.), as a function of $m^2$, for maximal mixing ($\tan^2 \psi = 1$). The solid curve, corresponding to our calculation of $r(m^2)$, starts from 63.9 events in the no-oscillation limit ($m^2 \to 0$), and tends to the asymptotic value of 63.9/2 in the fast oscillation limit ($m^2 \to \infty$), after a few “wiggles” associated to the first oscillation cycles. The curve is very close to the four K2K MC points used to benchmark our calculation. The horizontal gray band represents the $\pm 1\sigma_{\text{tot}}$ interval for the total number of observed events in K2K. The allowed band disfavors no oscillations at $2.2\sigma$, and the first deep oscillation minimum at $2.7\sigma$. It is instead in very good agreement with the oscillated predictions for $m^2 \sim \text{few} \times 10^{-3}$ eV$^2$, the best fit being reached at $m^2 = 2.7 \times 10^{-3}$ eV$^2$. Such a value is very close to the one independently quoted by the SK Collaboration as the current best fit to their atmospheric neutrino data ($m^2 = 2.5 \times 10^{-3}$ eV$^2$) [13], under the same $\nu_\mu \to \nu_\tau$ oscillation hypothesis. Therefore, it makes sense to combine K2K and SK data, as we do in the following section.

### III. K2K AND SK: COMBINATION AND AND IMPLICATIONS

Given the very good agreement between the K2K and SK allowed ranges for $m^2$ at maximal mixing, it is interesting to study their compatibility for unconstrained 2$\nu$ mixing. Concerning the SK atmospheric 2$\nu$ analysis, we make use of the results recently reported by us in [6] (for 79.5 kTy SK data), specialized to the simplest scenario of pure $\nu_\mu \to \nu_\tau$ oscillations.\footnote{It is also very close to the best fit of upgoing muon data in MACRO, $m^2 = 2.4 \times 10^{-3}$ eV$^2$ [8].}

\footnote{Therefore, in this work we use $N_{\text{DF}} = 2$ to draw iso-$\Delta \chi^2$ contours, while we used $N_{\text{DF}} = 3$ for the more general 3$\nu$ and 4$\nu$ cases considered in [8].}
Figure 2 shows the regions allowed at 90% and 99% C.L. by SK, K2K, and their combination, in the $2\nu$ mass-mixing plane ($m^2, \tan^2 \psi$). The upper left panel corresponds to SK atmospheric data only, for which we find two degenerate best-fit points (stars) at $m^2 = 3 \times 10^{-3}$ eV$^2$ and at octant-symmetric mixing values, $(\tan^2 \psi)^\pm = 0.76$, corresponding to slightly nonmaximal oscillation amplitude, $\sin^2 2\psi = 0.98$.

The upper right panel in Fig. 2 shows the fit to K2K only. The locus of best-fit points is a continuous, octant-symmetric curve (not shown) passing through $m^2 = (2.7 \times 10^{-3}, 1)$. The K2K constraints in the mass-mixing plane are weaker than those placed by SK, especially on $\tan^2 \psi$. Therefore, one cannot expect a significant improvement on $\tan^2 \psi$ limits from the SK+K2K combination. Concerning $m^2$, the no-oscillation limit $m^2 \to 0$ is still allowed at 99% C.L., while values around $m^2 \simeq 8.5 \times 10^{-3}$ eV$^2$ are excluded (for large mixing). Such values correspond to the first (deep) oscillation minimum in Fig. 1, which is disfavored by the data at $2.7\sigma$, as previously noted. Therefore, in the SK+K2K combination, we expect “high” values of $m^2$ to be more disfavored than “low” values.

The lower left panel in Fig. 2 shows the combination of SK and K2K data. The best-fit points are located at the same values of $\tan^2 \psi$ as for SK alone and, in general, the bounds on $\tan^2 \psi$ are not significantly modified, as expected. The best-fit value of $m^2$ is only slightly lowered ($m^2 = 2.9 \times 10^{-3}$ eV$^2$) but, most importantly, the 90% and 99% C.L. ranges of $m^2$ are appreciably reduced both from below and (more strongly) from above. Such results show that the K2K experiment is already having a nonnegligible impact in the determination of the neutrino squared mass difference $m^2$ relevant for the $\nu_\mu \to \nu_\tau$ channel and for the leading oscillations in (very) long baseline experiments.

The lower right panel in Fig. 2 shows a prospective SK+K2K combination, with the same SK data and K2K data but with K2K total uncertainty hypothetically reduced by a factor of two. The $m^2$ range is significantly narrowed, while the $\tan^2 \psi$ range is still basically unchanged. In summary, the various panels of Fig. 2 demonstrate that K2K data are relevant for the determination of $m^2$, rather than of $\tan^2 \psi$. Therefore, it makes sense to discuss in more detail the results of Fig. 2 in terms of $m^2$ only, with $\tan^2 \psi$ unconstrained.

Figure 3 shows the results of such an exercise, in terms of the function $\chi^2(m^2)$. The 90% and 99% C.L. ranges for $m^2$ ($N_{DF} = 2$) are explicitly shown for the SK and SK+K2K fits. Numerically, we find that the 99% C.L. range for $m^2$ allowed by SK only, $m^2 \in [1.3, 5.6] \times 10^{-3}$ eV$^2$, is reduced to $[1.5, 4.8] \times 10^{-3}$ eV$^2$ by including K2K data. By halving the uncertainties of the K2K total rate, the $m^2$ range would be ulteriorly reduced to $[1.8, 4.0] \times 10^{-3}$ eV$^2$ (99% C.L.).

The reduction of the minimum values of $m^2$ in Fig. 3 (at a given C.L.) is relevant for future (very) long baseline experiments. For instance, in the OPERA experiment downstream the CERN-to-Gran Sasso neutrino beam, the $\tau$ appearance rate is approximately proportional to $(m^2)^2$ [17]; therefore, the increase of $m^2_{\min}$ from $1.3 \times 10^{-3}$ eV$^2$ (SK) to $1.5 \times 10^{-3}$ eV$^2$ (SK+K2K) at 99% C.L. implies an increase of the minimum expected $\tau$ event rate by a factor $\sim 1.3$ (at the same C.L.); the increase would be as high as a factor

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3However, such small deviations from maximal mixing at best fit (also found in [16]) are not statistically significant at present.
∼ 2 for the case with halved K2K errors ($m_{\text{min}}^2 = 1.8 \times 10^{-3} \text{eV}^2$). The reduction of the $m^2$ allowed range is also important to refine the energy or baseline optimization in future neutrino factory experiments, where the current $m^2$ uncertainty plays an important role (see, e.g., [18] and references therein). Finally, the increase of $m_{\text{min}}^2$ strengthens the accuracy of approximations based on the hierarchy of squared mass differences, which have long been used in global solar+terrestrial neutrino analyses (see, e.g., [6,10,19]).

A final remark is in order. Our current analysis is based on initial K2K data and on an approximate description of the K2K detector specification. Therefore, it cannot be a substitute of the (joint) official oscillation analysis that will be performed by the K2K (SK+K2K) collaboration(s). However, we think that our results, although necessarily approximate, are sufficiently indicative of the K2K potential in improving our current knowledge of $\nu_\mu \rightarrow \nu_\tau$ oscillations.

IV. SUMMARY

We have shown that, within the simplest (two-family) $\nu_\mu \rightarrow \nu_\tau$ oscillation scenario, the initial evidence for a $\nu_\mu$ flux suppression in K2K is perfectly consistent with the atmospheric $\nu_\mu$ flux anomaly. The range of the neutrino squared mass difference indicated by the SK atmospheric $\nu$ experiment is reduced by including the K2K data. As a consequence, K2K starts to be important in narrowing the range of predictions for future (very) long baseline experiment.

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FIG. 1. Number of events in K2K for the current exposure ($3.85 \times 10^{19}$ p.o.t.), as a function of $m^2$ (at $\tan^2 \psi = 1$). Our calculation (solid curve) is benchmarked by the K2K MC simulation (square markers). The horizontal gray band represents the current K2K data within one standard deviation.
FIG. 2. Separate two-flavor oscillation analyses of SK and K2K, together with their combination (with eventual halving of K2K errors). See the text for details.
FIG. 3. Bounds on $m^2$ at 90% and 99% C.L. ($N_{DF} = 2$) from the two-flavor $\chi^2$ analysis of the SK and K2K data.