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Testing LSND at long-baseline neutrino experiments

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Abstract

Recently it was suggested that two very different mass-squared differences play a role in atmospheric neutrino oscillations. The larger of these also accounts for the LSND result and the smaller of these also drives the solar neutrino oscillations. We consider the predictions of this scheme for long-baseline experiments. We find that high statistics experiments, such as MINOS, can observe a clean signal for this scheme, which is clearly distinguishable from the usual scheme of atmospheric neutrino oscillations driven by a single mass-squared difference.

I. INTRODUCTION

At present there are three pieces of evidence for neutrino flavour conversion:

1. Solar Neutrino Problem The measured flux of ν_e from the Sun is smaller than the expected flux [1].

2. Atmospheric Neutrino Problem The measured flux of ν_μ, generated by the cosmic ray interactions in the atmosphere, is smaller than the Monte Carlo expectation [2].

3. LSND The LSND experiment has observed signals for both $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ and $\nu_\mu \rightarrow \nu_e$ transitions [3].

If each set of data is analysed under the assumption that only two neutrino flavours oscillate into each other, then the following constraints are obtained:

$$
\begin{aligned}
10^{-6}\ \text{eV}^2 < \Delta m^2_{sol} < 10^{-4}\ \text{eV}^2, &\qquad \theta_{sol} \sim 3^\circ \text{ or } \sim 30^\circ \\
10^{-3}\ \text{eV}^2 < \Delta m^2_{atm} < 10^{-2}\ \text{eV}^2, &\qquad \theta_{atm} \sim 45^\circ \\
0.2\ \text{eV}^2 < \Delta m^2_{LSND} < 0.4\ \text{eV}^2, &\qquad 0.01 < \sin^2 2\theta_{LSND} < 0.1.
\end{aligned} \tag{1}
$$

The data from the Bugey accelerator provide the lower limit on Δm^2_{LSND} [4] and the CDHSW data provide the upper limit [5].

From the constraints on various Δ's, it seems as if one may not be able to account for all the positive results in the framework of three-flavour neutrino oscillations. Very often, three-flavour oscillation fits are done using solar and atmospheric neutrino data only. In this scheme, which we call the standard scheme, there are two independent mass-squared differences and three mixing angles. The solar neutrino oscillations depend on only the smaller mass-squared difference (which is set equal to Δm^2_{sol}) and two mixing angles θ_{12} and θ_{13} [6]. The atmospheric neutrino oscillations depend on the larger mass-squared difference (which is set equal to Δm^2_{atm}) and two mixing angles θ_{13} and θ_{23} [7]. The CHOOZ experiment constrain θ_{13} to be very small ($< 9^\circ$) [8,9]. Since the common parameter between solar and atmospheric neutrino oscillations is very small, these two oscillations effectively become two different two-flavour oscillations. Hence, the above constraints on θ_{sol} and θ_{atm} apply directly to θ_{12} and θ_{23}, respectively. Thus we find that, in this scheme, the preferred solution to the atmospheric neutrino problem is $\nu_\mu \rightarrow \nu_\tau$ oscillations with maximal mixing.

The long-baseline experiments are designed to test the hypothesis that $\nu_\mu \rightarrow \nu_\tau$ oscillations, with $\Delta m^2_{atm} \simeq 3 \times 10^{-3}$ eV^2, are the cause of the atmospheric neutrino deficit. K2K and MINOS will look for muon neutrino disappearance. The number of ν_μ charged current (CC) events in these experiments is given by the convolution of their neutrino spectrum with the ν_μ survival probability:

$$P_{\mu\mu} = 1 - \sin^2 2\theta \sin^2 \left(1.27 \frac{\Delta m^2 L}{E} \right), \tag{2}$$

where Δm^2 is in eV^2, L is in km and E is in GeV. In most neutrino oscillation experiments, there is a single constraint involving two unknowns, θ and Δm^2. We can constrain one of them, only by making an assumption about the other parameter. However, MINOS is a very high statistics experiment and can measure the spectrum of ν_μ CC events. This spectrum will have a minimum at $E = E_{min}$, where $(1.27 \Delta m^2 L / E_{min}) = \pi/2$. The number of events at this minimum is proportional to $(1 - \sin^2 2\theta)$. Hence MINOS can determine the mass-squared difference and the mixing angle independently. If the standard scenario is correct, then $\sin^2 2\theta_{atm} = 1$ and the number of events at $E = E_{min}$ should be zero. The energy of the neutrino beam for MINOS can be tuned in such a way that the minimum will occur where the beam flux is substantial. Hence MINOS is sensitive to the whole range of Δm^2_{atm} suggested by the atmospheric neutrino data.

To account for the three signals for oscillations, it seems as if three-flavour oscillations are inadequate and one must introduce at least one more light neutrino. Since the measurement of the invisible width of Z^0 boson shows that there are only three light active neutrinos, the forth neutrino must be sterile. Four-flavour oscillations between three active and one sterile neutrino, with three independent mass-squared differences set equal to the above three scales, are considered extensively [10].

Since no direct evidence for any sterile neutrino has been seen, then it is worth re-examining the simple assumption that only a single Δ plays a role in each of the above evidences for oscillations. Recently it was suggested by Scheck and Barenboim (SB) that oscillations between three active flavours may be able to account for all three signals [11]. In this scheme it is assumed that the larger mass-squared difference, Δ_{32}, is about 0.3 eV^2 and drives the LSND oscillations. The smaller mass-squared difference Δ_{21} is assumed to be small enough that LSND is not sensitive to it. The key assumption in this scheme is that both Δ's play a role in creating the deficit of ν_μ flux in the atmospheric neutrino problem. Δ_{32} drives the oscillations of the downward going neutrinos. Since the path length of these neutrinos is small, these oscillations are not sensitive to Δ_{21}. The magnitude of Δ_{21} is fixed by two requirements: a) the zenith-angle dependence of the deficit of upward going ν_μ's should be reproduced and b) the solar neutrino deficit should be adequately explained. These requirements fix Δ_{21} to be in the range 10^{-4}–10^{-3} eV^2. This value of Δ_{21} is much larger than Δm^2_{sol} given in Equation (1). However, the latest Super-Kamiokande data on solar neutrinos do prefer $\Delta m^2_{sol} \simeq 10^{-4}$ eV^2 [1].

In this letter, we consider the signals that will be observed at K2K and MINOS in the SB scheme. We find that at K2K the signals in the SB scheme are somewhat different from those in the standard scheme. With an accumulation of events over a period of time, it may be possible to differentiate between the two schemes using K2K data. However for MINOS, the signals predicted by SB scheme for the ν_μ CC event spectrum are qualitatively different from those in the standard scenario. Moreover, the oscillations due to the $\Delta_{32} \simeq 0.3$ eV^2 should be clearly visible if MINOS runs in its high energy beam mode.

II. SCHECK-BARENBOIM (SB) SCHEME

Let us briefly recall the salient features of the SB scheme. The three active flavours mix to form three mass eigenstates

$$|\nu_\alpha\rangle = U|\nu_i\rangle, \tag{3}$$

where U is a 3×3 mixing matrix parametrized by three mixing angles and a CP-violating phase. Here for simplicity we set the phase to zero. The matrix U can be written in the form

$$U = U_{23}(\theta_{23})U_{13}(\theta_{13})U_{12}(\theta_{12}). \tag{4}$$

Without loss of generality, we can assume that the masses satisfy the inequalities $m_1 < m_2 < m_3$. Then the mixing angles should have the range $(0, \pi/2)$ to cover all the possibilities that are physically distinguishable. The independent mass-squared differences are taken to be $\Delta_{21} = m_2^2 - m_1^2$ and $\Delta_{32} = m_3^2 - m_2^2$. It is assumed that $\Delta_{32} \simeq 0.3$ eV^2 to account for the LSND results, and the magnitude of Δ_{21} is taken to be in the range 10^{-4}–10^{-3} eV^2 so that the zenith-angle dependence of atmospheric neutrinos and solar neutrino suppression are reproduced.

In Ref. [11] the ranges of the mixing angles allowed by solar, atmospheric and LSND data were obtained, with values of Δ's as given above. We have updated their results by including the further constraints from Bugey [4], CHOOZ [8], CHORUS [12] and NOMAD [13]. CHORUS and NOMAD have very small values of (L/E) and hence they give no meaningful constraints on mixing angles for the values of Δ's we consider here. For Bugey the average value of (L/E) is about 11 and it is sensitive to Δ_{32} but not to Δ_{21}. The oscillations driven by Δ_{32} are averaged out at CHOOZ because it has $\langle L/E \rangle \sim 300$. CHOOZ is sensitive to Δ_{21} if it is as large as 10^{-3} eV^2, but it is insensitive to smaller values. Both Bugey and CHOOZ require θ_{13} to be small and together they yield the constraint

$$\theta_{13} \leq 9^\circ. \tag{5}$$

Depending on the value of Δ_{21} CHOOZ also constrains θ_{12}. If $\Delta_{21} \simeq 10^{-3}$ eV^2, then we get the constraint $\theta_{12} \leq 10^\circ$. However, if $\Delta_{21} \leq 7 \times 10^{-4}$ eV^2 then θ_{12} is unconstrained.

The $\nu_\mu \to \nu_e$ oscillation probability relevant to LSND in this scheme is given by

$$P_{\mu e} = \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(1.27 \frac{\Delta_{32} L}{E}\right). \tag{6}$$

We need both θ_{13} and θ_{23} to be non-zero to explain the positive signal of LSND. The allowed range of θ_{23} is a function of θ_{13}. The smallest allowed value of θ_{23}, which will be relevant to long-baseline experiments, occurs for the largest value of $\theta_{13} = 9^\circ$. For this value, we have

$$20^\circ \leq \theta_{23} \leq 50^\circ. \tag{7}$$

In Ref. [11], it was shown that, to explain the atmospheric neutrino problem, one needs $\theta_{23} \simeq 27^\circ$, which is well within the above range.

III. SIGNALS AT LONG-BASELINE EXPERIMENTS

The ν_μ survival probability for the case of three active flavour oscillations is given by

$$P_{\mu\mu} = U_{\mu 1}^4 + U_{\mu 2}^4 + U_{\mu 3}^4 + 2U_{\mu 1}^2 U_{\mu 2}^2 \cos\left(2.53\frac{\Delta_{21} L}{E}\right) + \\ 2U_{\mu 1}^2 U_{\mu 3}^2 \cos\left(2.53\frac{\Delta_{31} L}{E}\right) + 2U_{\mu 2}^2 U_{\mu 3}^2 \cos\left(2.53\frac{\Delta_{32} L}{E}\right). \quad (8)$$

The K2K experiment has a baseline length of 250 km and its neutrino energy spectrum is peaked around 1 GeV [14], so it has an (L/E) value of about 250. For this large a value of (L/E), the oscillations due to Δ_{32} of the SB scheme get averaged out. K2K is not sensitive to values of mass-squared differences smaller than 10^{-3} eV^2, hence Δ_{21} of the SB scheme can be set to zero. Under these approximations, the ν_μ survival probability relevant to K2K is

$$P_{\mu\mu}^{K2K} = (U_{\mu 1}^2 + U_{\mu 2}^2)^2 + U_{\mu 3}^4 = (1 - U_{\mu 3}^2)^2 + U_{\mu 3}^4. \quad (9)$$

Here, $U_{\mu 3} = \sin\theta_{23}\cos\theta_{13} \simeq \sin\theta_{23}$ because θ_{13} is constrained to be small. For $\theta_{23} \simeq 27^\circ$, we have $P_{\mu\mu}^{K2K} = 0.67$. The expected number of ν_μ CC events at K2K is obtained by convoluting $P_{\mu\mu}$ with the energy spectrum of the neutrino beam; the integral of the spectrum gives the expected number of events in case of no oscillations. The ratio of the above two numbers is purely a function of the oscillation parameters. We saw above that in the SB scheme $P_{\mu\mu}$ for K2K is independent of energy. Hence the ratio of expected number of events with and without oscillations is equal to the constant $P_{\mu\mu} = 0.67$. This number, predicted by the SB scheme, is to be contrasted with 0.46, which is the prediction of the standard scheme, in which the atmospheric neutrino problem is assumed to be due to $\nu_\mu \to \nu_\tau$ oscillations with maximal mixing and $\Delta m^2_{atm} \simeq 3 \times 10^{-3}$ eV^2 and $\Delta m^2_{sol} \ll \Delta m^2_{atm}$. The prediction of the standard scheme rises to 0.8, if one takes $\Delta m^2_{atm} \simeq 10^{-3}$ eV^2, which is the smallest value allowed by Super-Kamiokande data in that scheme. Thus K2K data may rule out the SB scheme if the measured suppression turns out be less than 0.5. For larger values of the suppression, however, the K2K data will not be able to distinguish between the two schemes.

Because of the limited statistics in K2K, one measures only the total number of ν_μ CC events but not their spectrum. Because of this, the K2K results will not be able to provide an unambiguous signal for the two Δ solutions to the atmospheric neutrino problem. MINOS, being a high statistics experiment, measures the spectrum of ν_μ CC events. This measurement allows them to determine the mass-squared difference and mixing angle independently if only one mass-squared difference plays a role in atmospheric neutrino oscillations. The same measurement will also enable them to determine if two mass-squared differences play a role in atmospheric neutrino oscillations.

MINOS has a baseline length of 730 km and it has three options for the energy of its neutrino beam. For the low energy option, the energy is peaked around 3 GeV, which corresponds to $(L/E) \sim 250$. For the medium energy option, $E_{peak} = 7$ GeV, which means $(L/E) \sim 100$. For the high energy option, $E_{peak} = 15$ GeV with $\langle L/E \rangle \simeq 50$. We obtained the spectra for these three options from Ref. [15] and multiplied them with $P_{\mu\mu}$ to obtain the energy distribution of ν_μ CC events. The distributions for the low energy option are plotted in Fig. 1, where the thick line is the prediction of the SB scheme, the dotted line is the expected spectrum in case of no oscillations, and the thin line is the prediction of the standard scheme with $\Delta m^2_{atm} = 3 \times 10^{-3}$ eV^2 and $\theta_{atm} = 45°$. As mentioned in the introduction, the event distribution touches zero at the point where the energy satisfies the equation $1.27 \Delta m^2_{atm} 730/E = \pi/2$. This is an unavoidable feature of atmospheric neutrino oscillations with one mass-squared difference, because in such a scenario the corresponding mixing angle is constrained to be maximal. However, we see that in the SB scheme, where two Δ's play a role in atmospheric neutrino oscillations, the event distribution will not touch zero because of the interplay between the two types of oscillations. Between 1 and 5 GeV, the smallest suppression in any energy bin is about 0.5. Such a signal can give a striking proof regarding the role of two Δ's in atmospheric neutrino oscillations. The predictions for the SB scheme are plotted for $\Delta_{32} = 0.3$ eV^2, $\Delta_{21} = 3 \times 10^{-4}$ eV^2, $\theta_{12} = 35°$, $\theta_{13} = 9°$ and $\theta_{23} = 27°$. Changing the value of Δ_{21} in the allowed range does not qualitatively affect the form of the signal. For neutrino energies above 10 GeV, one clearly sees oscillations of 0.3 eV^2 generated by Δ_{32}. This signal can be more clearly seen in the high energy neutrino beam of MINOS. In Fig. 2 we plotted the prediction of the SB scheme (thick line) along with the expectation in the case of no oscillations. The oscillations are more clearly visible in this case. This may be the first instance of the observation of a variation of oscillations as a function of energy.

In plotting Figs. 1 and 2, we assumed that the energy resolution of MINOS is very good, better than 0.5 GeV or so. Therefore the number of events is not smeared with the energy resolution. However, the signal for the SB scheme is markedly different from that of the standard scheme, even if the energy resolution is worse than 1 GeV. Then in the low energy option, the suppression seen will be about 0.6 for the SB scheme whereas it will be about 0.3 for the standard scheme. But it is in the high energy option that the predictions of the SB and standard schemes are qualitatively different. Here the standard scheme predicts no suppression at all for the entire allowed range of Δm^2_{atm}. The SB scheme predicts a minimum suppression of about 0.6 in the high energy option, for all the allowed values of the parameters. Hence even with bad energy resolution, MINOS is capable of distinguishing between the standard scheme and the SB scheme.

It was mentioned in the introduction that four-flavour oscillations (three active and one sterile) are considered to account for LSND results. In these schemes each of the pieces of evidence for flavour conversion of neutrinos (solar, atmospheric and LSND) is explained by oscillations driven by their own individual Δ. The various types of four-flavour oscillations are summarized in Ref. [10]. The combined data restrict the solar neutrino oscillations to be essentially $\nu_e \to \nu_s$ (where ν_s is the sterile neutrino) and the atmospheric neutrino oscillations to be essentially $\nu_\mu \to \nu_\tau$ oscillations. We calculated the predictions of four-flavour oscillations for MINOS for the following values of the parameters:

- $\Delta m^2_{LSND} = 0.3$ eV^2 and $\sin^2 2\theta_{LSND} = 0.1$

- $\Delta m^2_{atm} = 3 \times 10^{-3}$ eV^2 and $\sin^2 2\theta_{atm} = 1$

The long-baseline experiments are not sensitive to Δm^2_{sol}. The results we obtained are indistinguishable from those of the standard scheme for both low and high energy beams of MINOS. This occurs for the following reason. The mass-squared difference to which the long-baseline experiments are the most sensitive is Δm^2_{atm}. In both the standard scheme and the four-flavour scheme, it has the same value. Hence $P_{\mu\mu}$ in both schemes is very similar. In the four-flavour scheme, the larger mass-squared difference Δm^2_{LSND} gives rise to some modification of $P_{\mu\mu}$, but these modifications are small because θ_{LSND} is small. This is illustrated in Fig. 3.

IV. CONCLUSION

We considered the signals at the long-baseline experiments K2K and MINOS as predicted by two different mixing schemes of three active flavours. In the standard scheme only one Δ is assumed to drive atmospheric neutrino oscillations, while the other Δ is much smaller. In the SB scheme both Δ's play a role in atmospheric neutrino oscillations and the larger Δ also drives LSND oscillations. The K2K experiment may be able to distinguish between these two schemes for some values of the allowed parameters. However, the energy distribution of the events at MINOS, in both low and high beam energy options, can provide a clear distinction between the two scenarios for any of the allowed values of the parameters.

We also considered the signals at MINOS from four-flavour oscillations. These signals are indistinguishable from those of the standard scheme. However the BooNE experiment at Fermilab [16] can verify or rule out LSND results. If BooNE confirms LSND results, then the high energy option of MINOS should be pursued. The results of MINOS will tell us whether LSND results can be incorporated within three active flavour oscillations or whether a sterile, fourth neutrino is required.

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REFERENCES

[1] Y. Suzuki, talk presented at *Neutrino 2000*, Sudbury, Canada, June 2000.

[2] H. Sobel, talk presented at *Neutrino 2000*, Sudbury, Canada, June 2000.

[3] G. Mills, talk presented at *Neutrino 2000*, Sudbury, Canada, June 2000.

[4] B. Achkar *et al.*, Nucl. Phys. **B420** (1995) 503; K. Eitel, talk presented at *Neutrino 2000*, Sudbury, Canada, June 2000; and Ref. [3].

[5] F. Dydak *et al.*, Phys. Lett. **134B** (1984) 281.

[6] T. K. Kuo and J. Pantaleone, Rev. Mod. Phys. **61** (1989) 937.

[7] J. Pantaleone, Phys. Rev. **D49** (1994) R2152.

[8] CHOOZ Collaboration: M. Appollonio *et al.*, Phys. Lett. **466B** (1999) 415.

[9] M. Narayan, G. Rajasekaran and S. Uma Sankar, Phys. Rev. **D58** (1998) R031301.

[10] S. M. Bilenky, C. Giunti and W. Grimus, Prog. Part. Nucl. Phys. **43** (1999) 1.

[11] G. Barenboim and F. Scheck, Phys. Lett. **440B** (1998) 332.

[12] CHORUS Collaboration: E. Eskut *et al.*, Phys. Lett. **424B** (1998) 202; Phys. Lett. **434B** (1998) 205.

[13] NOMAD Collaboration: P. Astier *et al.*, Phys. Lett. **453B** (1999) 169.

[14] Y. Oyama, preprint hep-ex/0004015, talk presented at *Rencontres de Moriond*, Les Arcs, Savoie, France, March 2000.

[15] MINOS Technical Design Report, Nu-MI-L-337, October 1998.

[16] A. Bazarko, talk presented at *Neutrino 2000*, Sudbury, Canada, June 2000.

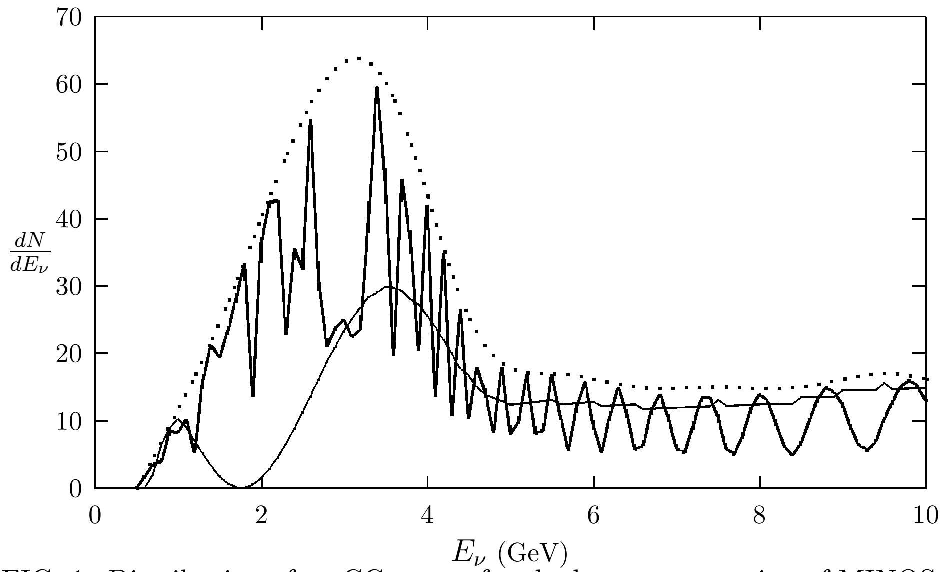

FIG. 1. Distribution of ν_μ CC events for the low energy option of MINOS: Prediction from the SB scheme (thick line), for no oscillations (dots), from the standard scheme (thin line). The plot from the SB scheme is drawn for $\Delta_{32} = 0.3$ eV^2, $\Delta_{21} = 3 \times 10^{-4}$ eV^2, $\theta_{12} = 35°$, $\theta_{13} = 9°$ and $\theta_{23} = 27°$. The plot from the standard scheme is drawn for $\Delta m^2_{atm} = 3 \times 10^{-3}$ eV^2, $\theta_{atm} = 45°$.

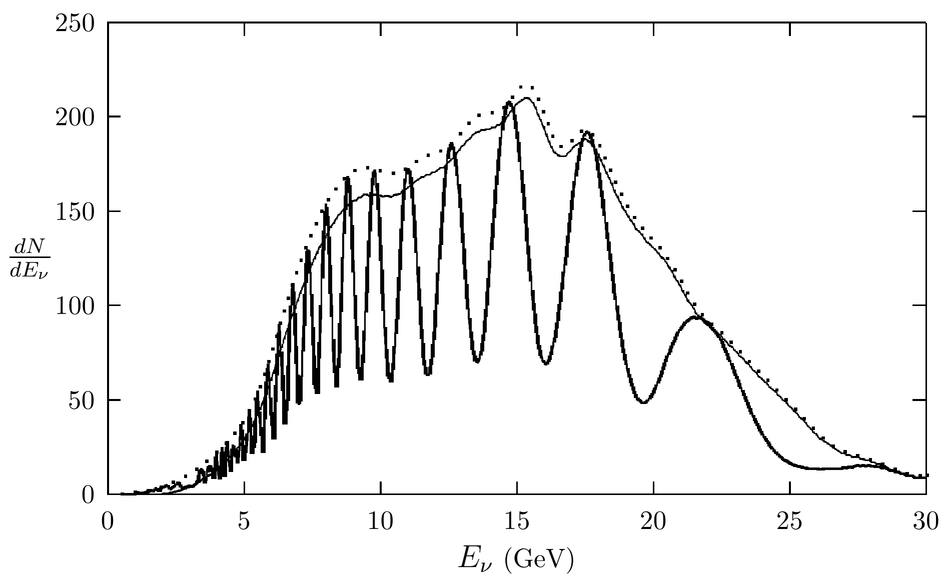

FIG. 2. Same as Fig. 1, but for the high energy option of MINOS.

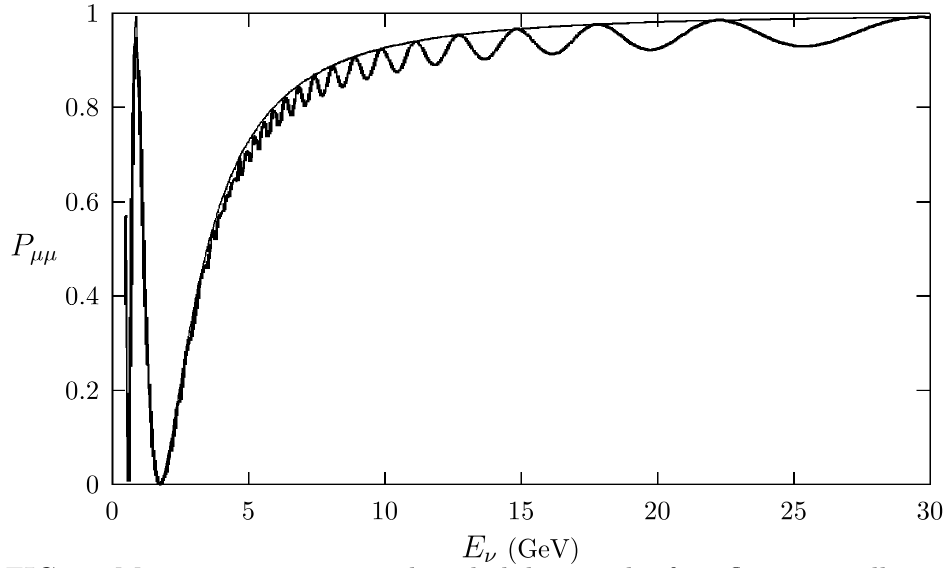

FIG. 3. Muon neutrino survival probability in the four-flavour oscillation scheme (thick line) and the standard scheme (thin line). Both plots are drawn for $\Delta m^2_{atm} = 3 \times 10^{-3}$ eV^2 and $\theta_{atm} = 45°$. For the four-flavour plot, we took $\Delta m^2_{LSND} = 0.3$ eV^2 and $\sin^2 2\theta_{LSND} = 0.1$.