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Detecting appearance ν_τ in the spectra

of quasielastic CC events

The data of Super-Kamiokande [1] favor the transition $\nu_\mu \to \nu_\tau$ as the source of the deficit of muon neutrinos from the atmosphere. However, this still has to be verified by directly observing ν_τ appearance in accelerator long-baseline experiments. The options discussed thus far, all involving fine instrumentation on a large scale, are to detect the secondary τ by range in emulsion [2], by Cherenkov light [3], or by the transverse momentum carried away by the decay neutrino(s) [4]. By contrast, in this paper we wish to formulate a τ signature that is solely based on the energy spectra of CC events, and therefore should be accessible to relatively coarse calorimeters with muon spectrometry. We assume that the experiment includes a near detector of the same structure as the far detector, irradiated by the same neutrino beam but over a short baseline that rules out any significant effects of neutrino oscillations [5]. Thereby, the systematic uncertainties in comparing the interactions of primary and oscillated neutrinos are largely eliminated. Our aim is to distinguish the muonic decays of τ leptons against the background of ν_μ-induced CC events. In order to minimize the effects of ν_μ disappearance, the data collected with a harder τ-producing beam are compared with those for a softer reference beam in which τ production is suppressed by the threshold effect. The analysis is restricted to quasielastics (QE), that is, to neutrino events featuring a muon and small hadronic energy.

As soon as the first maximum of the oscillation lies below the mean energy of muon neutrinos in the beam, or $\Delta m^2 L/\langle E_\nu\rangle < 1.24$ eV^{2}km/GeV, much of the signal from QE production and muonic decay of the τ is at relatively low values of visible energy E. That is because the tau neutrinos arising from $\nu_\mu \to \nu_\tau$ are softer on average than muon neutrinos, the threshold effect is relatively mild for quasielastics, and a large fraction of incident energy is taken away by the two neutrinos from $\tau^- \to \mu^-\nu\bar{\nu}$. Let $f(E)$ be the spectrum of QE events observed in the far detector, $n(E)$—the spectrum of similar events in the near detector that has been extrapolated and normalized to the location of the far detector, and $R(E)$—the ratio of the two: $R(E) = f(E)/n(E)$. In the case of ν_μ disappearance through the transitions $\nu_\mu \to \nu_e$ or $\nu_\mu \to \nu_s$, where ν_s is the hypothesized sterile neutrino, the ratio R for the harder beam should be identically equal to that for the softer beam: $R_{\text{hard}}(E) = R_{\text{soft}}(E)$. However, in the case of $\nu_\mu \to \nu_\tau$ this equation is violated by the process of τ production and muonic decay, that predominantly occurs in the harder beam and shows up as a low-E enhancement of the corresponding "far" spectrum $f_{\text{hard}}(E)$. This causes the ratio R_{hard} to exceed R_{soft} towards low values of visible energy E. The latter effect, that may provide a specific signature of ν_τ

appearance, is investigated in this paper.

The simulation assumes that the MINOS detector [5], a 5.4-kton iron–scintillator calorimeter under construction in the Soudan mine in Minnesota, is irradiated by neutrinos from Fermilab over a baseline of 730 km. In this detector, secondary muons will be sign-selected by curvature in magnetic field and momentum-analyzed by range and/or curvature. In the NuMI program due to start in 2003 [6], the experiment will use a variety of neutrino beams generated by the Main Injector (MI), a 120-GeV proton machine. At a later stage, MINOS may be irradiated by a Neutrino Factory (NF) at Fermilab [7]. For the soft reference beam of muon neutrinos, we always select the MI low-energy beam foreseen by the NuMI program [6]. The harder τ-producing ν_μ beam is assigned either as the MI high-energy beam [6], or as that generated by a neutrino factory storing 20-GeV negative muons. The mean ν_μ energies in the MI low-energy, MI high-energy, and NF beams are 5, 12, and 14 GeV, respectively. We assume that the neutrino factory delivers 10^{20} useful μ^- decays per year of operation. Apart from higher intensity, an important advantage of the NF beam compared to the MI high-energy beam is that less of the total ν_μ flux is at low energies.

Charged-current interactions of the ν_μ and ν_τ are generated using the NEUGEN package that is based on the Soudan-2 Monte Carlo [8]. The response of the detector is not simulated in full detail; instead, the resolution in muon energy is approximated as $\delta E_\mu = 0.11 \times E_\mu^{\text{true}}$ and in energy transfer to hadrons—as $\delta\nu \text{ (GeV)} = 0.55 \times \sqrt{\nu^{\text{true}}}$ [9]. Quasielastic events are selected as those with $E_\mu > 800$ MeV and $\nu < 1$ GeV, where E_μ and ν are the smeared values of muon energy and of energy transfer to hadrons, respectively[1]. Given the characteristic topology of such events in the detector (a single track traversing more than three nuclear interaction lengths in iron plus a few scintillator hits near the primary vertex), we assume that they are reconstructed with 100% efficiency and that the background from pion punchthrough is insignificant. The visible energy E of a CC event is again estimated in terms of smeared quantities: $E = E_\mu + \nu$. The near spectrum $n(E)$ has to be corrected for the neutrino source not being pointlike (see, for example, [10]). For the MI beams, the corresponding systematic uncertainty on $n(E)$ has been estimated as some 2% in each 1-GeV bin, the errors for different bins being uncorrelated [9]. A similar uncertainty of $n(E)$ is assumed for the NF beam (it could be an overestimate since the characteristics of the NF beam are fully governed by the known kinematics of muon decay). We have verified that the final results are virtually insensitive to such variations of the near spectra. Furthermore, we may expect that systematic uncertainties on $n(E)$ for the MI high- and low-energy beams are correlated and will partially cancel in the difference of far-to-near ratios for these two beams. In the results presented below, the systematic uncertainties on the near spectra are neglected.

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[1] These selections should be viewed as illustrative. The actual selections will be based on a detailed simulation of detector response to CC events with small hadronic energy.

Shown in Fig. 1 are the oscillation-free near spectra of QE events, $n(E)$, for the three beams considered. In the absence of oscillations, equal exposures of 10 kton–years in the MI low-energy, MI high-energy, and NF beams will yield some 1200, 4600, and 17900 ν_μ-induced QE events, respectively[2]. Assuming either $\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_s$ driven by $\Delta m^2 = 0.01$ eV^2 and maximal mixing of $\sin^2 2\theta = 1$, the far-to-near ratios $R(E)$ for the three beams are illustrated in Fig. 2[3]. That the ratios $R(E)$ for the transitions $\nu_\mu \to \nu_\tau$ and $\nu_\mu \to \nu_s$ diverge towards low values of E is evident for the MI high-energy and NF beams in which τ production is not suppressed. Always assigning the MI low-energy beam as the reference beam and again considering $\nu_\mu \to \nu_\tau$ and $\nu_\mu \to \nu_s$ with maximal mixings, in Fig. 3 we plot the difference

$$\Delta R(E) = R_{\text{hard}} - R_{\text{soft}}$$

for various values of Δm^2. Indeed, at visible energies below some 5 GeV $\Delta R(E)$ deviates from zero for the transition $\nu_\mu \to \nu_\tau$, while staying close to zero for $\nu_\mu \to \nu_s$. This deviation may be viewed as a signature of ν_τ appearance. The naive expectation for $\nu_\mu \to \nu_s$, $\Delta R(E) = 0$, is slightly violated by the smearing of neutrino energy.

By the time the proposed test can be implemented, the actual value of Δm^2 will probably be estimated to some 10% by analyzing the ν_μ disappearance in the MI low-energy beam [9]. Given the value of Δm^2, a consistent approach would be to fit $\Delta R(E)$ to the predicted shape in order to estimate the mixing between the muon and tau neutrinos. A cruder measure of the effect is provided by the integral $S = \int \Delta R(E) dE$, which we estimate between $E = 1$ and 3 GeV. Allowing for either $\nu_\mu \to \nu_\tau$ and $\nu_\mu \to \nu_s$ with maximal mixing, the respective integrals $S(\nu_\mu \to \nu_\tau)$ and $S(\nu_\mu \to \nu_s)$ are plotted in Fig. 4 as functions of Δm^2.

Since the selected reference beam produces many more low-energy events than the MI high-energy and NF beams, the statistical error on the integral S is largely determined by the statistics accumulated with the harder beam. Therefore, we fix the exposure in the reference beam at 10 kton–years and assume similar or bigger exposures in the MI high-energy and NF beams. The successive error corridors in Fig. 4 are the statistical uncertainties on $S(\nu_\mu \to \nu_\tau)$ for the exposures of 10, 20, and 50 kton–years in the latter beams. And finally, dividing the difference between $S(\nu_\mu \to \nu_\tau)$ and $S(\nu_\mu \to \nu_s)$ by the statistical error on $S(\nu_\mu \to \nu_\tau)$, we estimate the statistical significance of the enhancement that is also depicted in Fig. 4. We estimate that at a level of 3σ, the exposures of 10, 20, and 50 kton–years in the MI high-energy (NF) beam will allow to probe ν_τ appearance down to the Δm^2 values of some 0.008 (0.005), 0.006 (0.004), and 0.005 (0.003) eV^2, respectively. Thus in the NuMI program with the existing Proton Booster [6], the proposed test may be sensitive to Δm^2 values in the

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[2] In all numerical estimates, we do not take into account the discussed upgrade of the proton driver at Fermilab [11] that may result in a substantial increase of neutrino flux from the Main Injector.

[3] In the Figures, statistical fluctuations are suppressed for the data points themselves, but the error bars are for the statistics as indicated.

Kamiokande-allowed region [12], but not below some 5×10^{-3} eV^2 as suggested by the more recent results of Super-Kamiokande [13]. Irradiating MINOS by a 20-GeV neutrino factory may allow to probe Δm^2 values in the upper part of the region favored by Super-Kamiokande.

To conclude, we have proposed a test of ν_τ appearance that consists in comparing the far-to-near ratios of the spectra of quasielastic CC events generated by different beams of muon neutrinos, and therefore may be accessible to big calorimeters with muon spectrometry like MINOS. The test is limited by statistics rather than systematics, and its significance crucially depends on the exposure in the harder beam in particular.
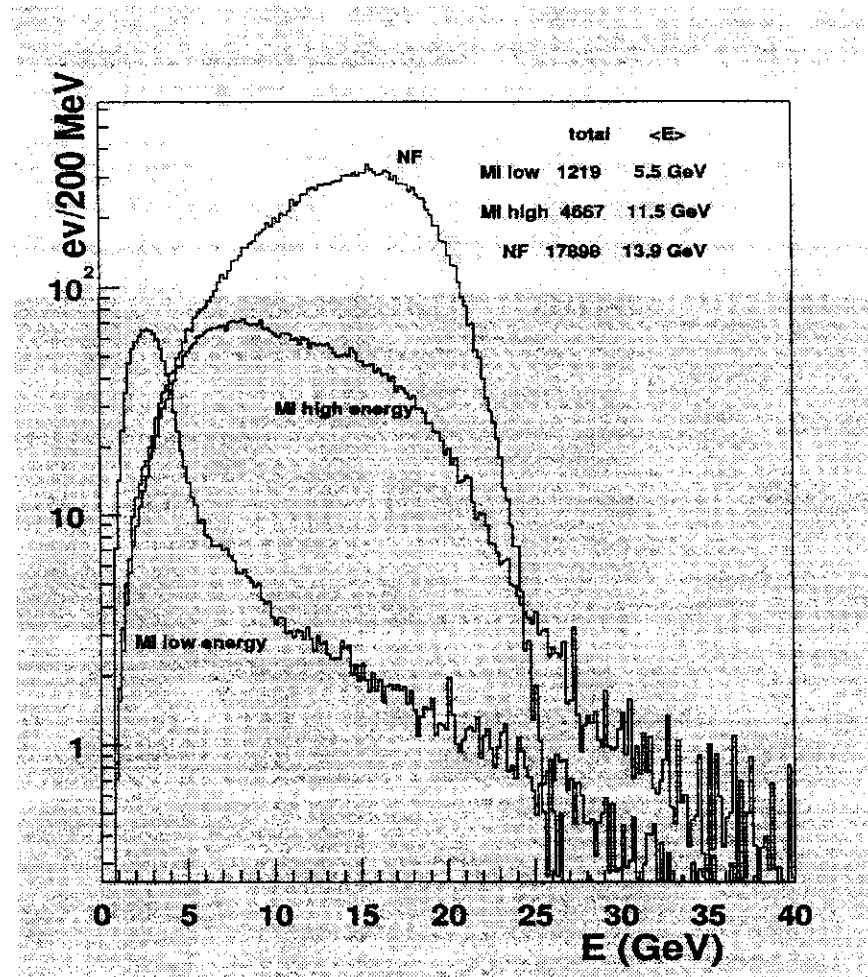

Figure 1: The oscillation-free "near" spectra of ν_μ-induced quasielastic events, $n(E)$, for the MINOS detector irradiated by the low-energy and high-energy beams from the Main Injector and by the beam from a neutrino factory storing 20-GeV negative muons. The assumed exposure in either beam is 10 kton-years.
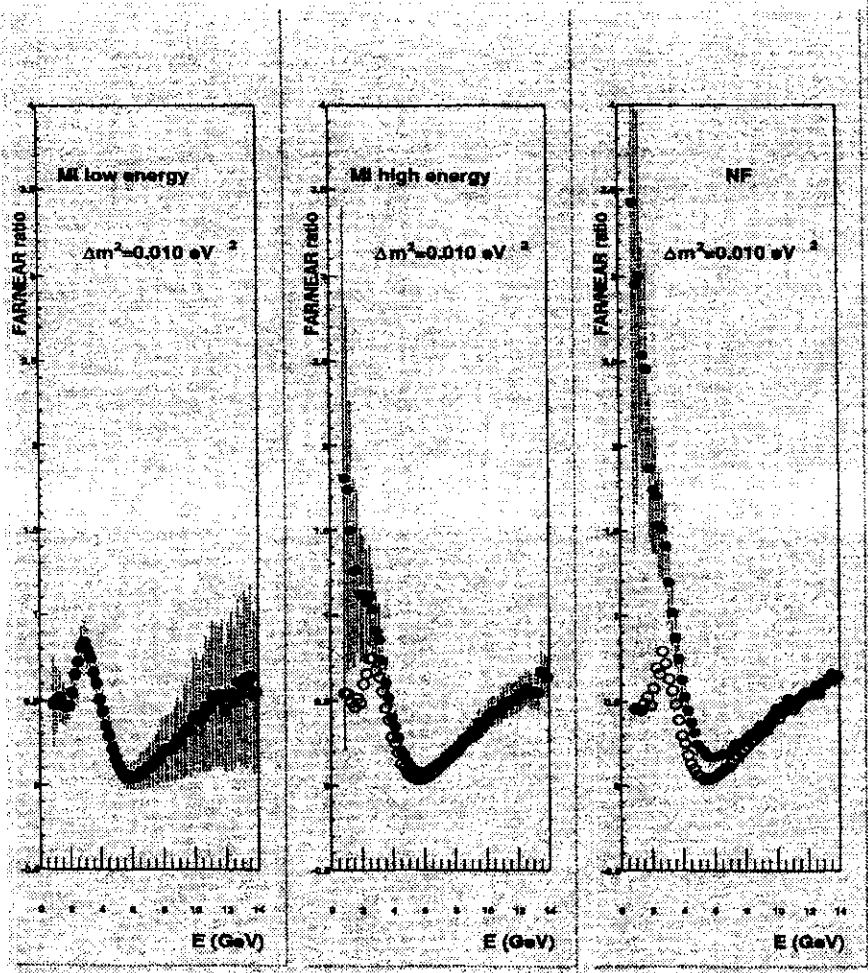
Figure 2: Assuming the transitions $\nu_\mu \to \nu_\tau$ and $\nu_\mu \to \nu_s$ (solid and open dots, respectively) driven by $\Delta m^2 = 10^{-2}$ eV^2 and $\sin^2 2\theta = 1$, the far-to-near ratio $R(E) = f(E)/n(E)$ for quasielastic events produced by the MI low-energy (a), MI high-energy (b), and NF (c) beams. The error bars on $R(E)$ for the transition $\nu_\mu \to \nu_\tau$ are the statistical uncertainties corresponding to exposures of 10 kton–years in either beam.
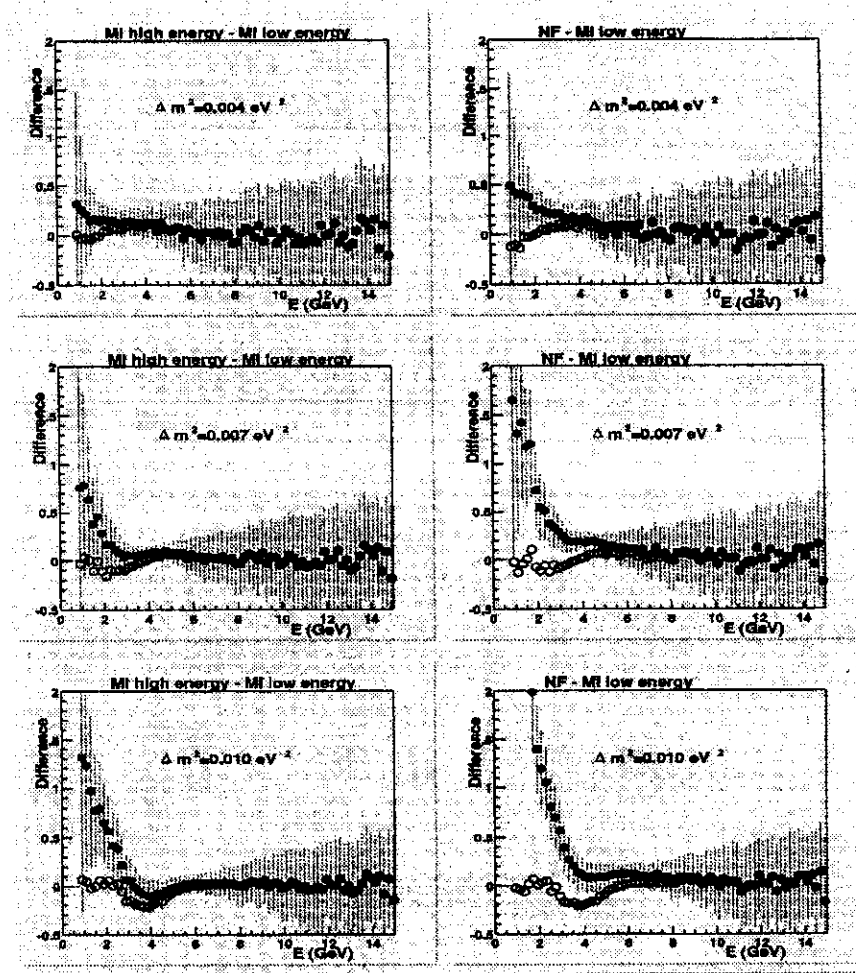
Figure 3: Assuming either $\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_s$ (solid and open dots, respectively) with maximal mixing, the difference $\Delta R(E)$ between the far-to-near ratios for: the MI high-energy and low-energy beams (left-hand panels); the NF and MI low-energy beams (right-hand panels). The top, middle, and bottom panels are for $\Delta m^2 = 0.004$, 0.007, and 0.010 eV^2, respectively. Depicted by error bars are the statistical errors that correspond to exposures of 10 kton–years in either beam.

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Figure 4: Assuming either $\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_s$ (solid and open dots, respectively) with maximal mixing, the integrated difference S (see text) as a function of Δm^2 for the MI high-energy (top left) and NF (top right) beams, with the MI low-energy beam assigned as the reference beam in both cases. Shown by successive error corridors are the statistical errors on $S(\Delta m^2)$ corresponding to exposures of 10, 20, and 50 kton–years in the τ-producing beam and of 10 kton–years in the reference beam. The bottom panels show the statistical significance of the τ signal for either case.

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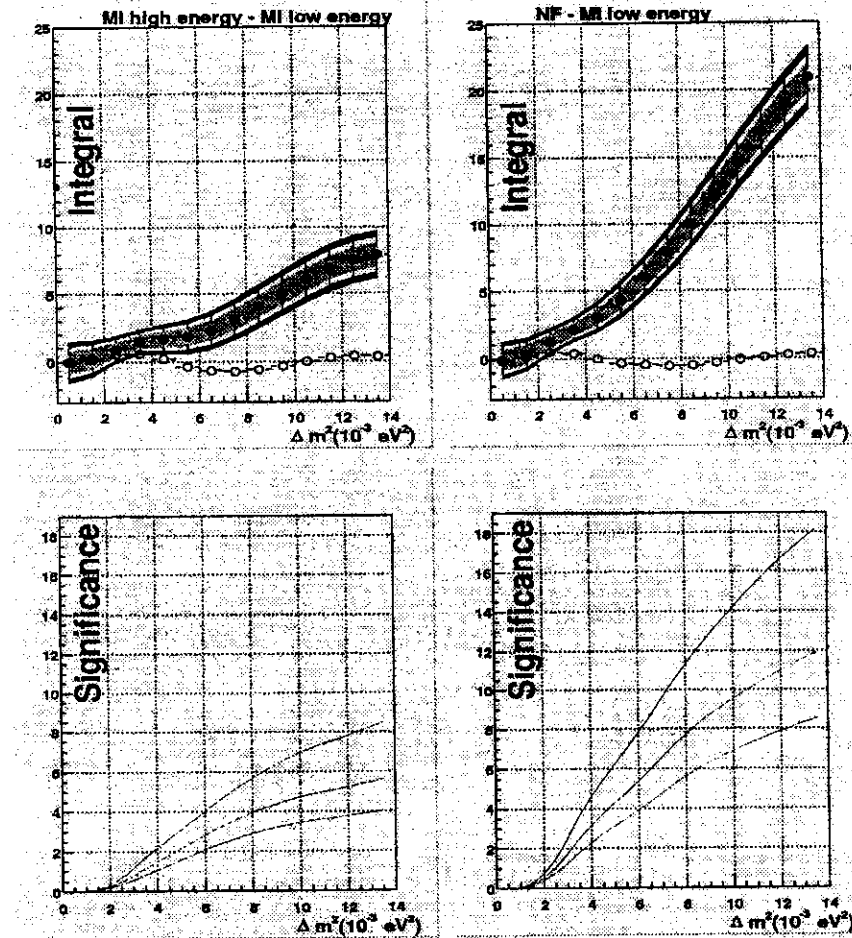[13] H. Sobel (for the Superkamiokande Coll.),Proc. XIX Int. Conf. on Neutrino Physics and Astrophysics(Neutrino 2000), Sudbury, Canada, June 16--21, 2000.