The Status of MINOS

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The MINOS long-baseline neutrino oscillation experiment is now entering its construction phase, and data-taking is anticipated to begin late in 2002. The experiment will cover large regions of the ν_e-ν_μ and ν_μ-ν_τ mixing parameter spaces, and will be extremely sensitive to the region favoured by the latest results from Super-Kamiokande.

1. INTRODUCTION

In the face of mounting evidence supporting the hypothesis that neutrino oscillations [1] are responsible for the solar [2] and atmospheric neutrino anomalies [3], a definitive experiment is needed to measure the mixing parameters with high precision. To this end, it is necessary to use a well-controlled neutrino source, preferably with an energy above the ν_τ production threshold; there should be a pair of detectors, with one being placed close to the source in order to control systematics; a large reach in parameter space requires considerable flexibility in L/E; and, naturally, a precision measurement requires high statistics. The MINOS (Main Injector Neutrino Oscillation Search) experiment, in which a beam of ν_μ will be sent 731 km from Fermilab to a detector in Soudan, Minnesota, is the only candidate that will fulfil all of these criteria within the timescale of 2002-2005 [4].

2. NEUTRINO BEAM

2.1. Neutrino beam

The Fermilab Main Injector, which is now in operation, will provide an extremely intense source of neutrinos: there are expected to be 3.7×10^{20} 120 GeV protons on target per year. The beam will be almost exclusively ν_μ, with a small ($\simeq 0.5\%$) ν_e contamination expected.

The latest results from SuperKamiokande favour a Δm^2 as small as $\simeq$ 3-5 $\times 10^{-3}$ eV^2 for ν_μ-ν_τ mixing [3]. If this is the case, the transition probability for the MINOS baseline would be maximised at a neutrino energy of $\simeq$ 2-3 GeV, which is just above the τ production threshold. The neutrino beam therefore incorporates a moveable focussing horn, allowing the experiment to use any one of three possible configurations, corresponding to a high, medium or low energy beam. The expected ν_μ charged-current (CC) event rates as a function of neutrino energy are shown in Figure 1.

The neutrino beam is expected to become available to MINOS in the autumn of 2002, and, during the following two years of data taking, approximately 30,000 beam-related neutrino events are expected to be seen in the far detector.

3. MINOS DETECTORS

3.1. Far detector

The MINOS cavern at the Soudan site is situated 690 m below the surface. The detector will be an 8 m wide octagonal tracking calorimeter, consisting of 480 inch-thick layers of steel interleaved with scintillator, giving a total mass of 5.4 kilotons (see Figure 2). There will be a toroidal magnetic field, of approximately 1 T strength; this will be the first large underground neutrino detector to be magnetized.

The scintillator strips will be 4 cm wide and 1 cm thick, with a coextruded TiO_2 cladding to maximise internal reflection, and will be read out by means of wavelength shifting fibres carrying light to Hammamatsu M16 photomultiplier tubes

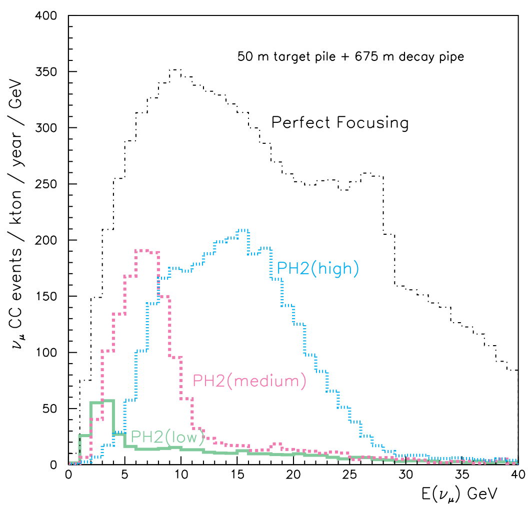

Figure 1. ν_μ CC event rates for the three possible neutrino beam configurations. Perfect focussing refers to the ideal situation in which all of the pions would be parallel.

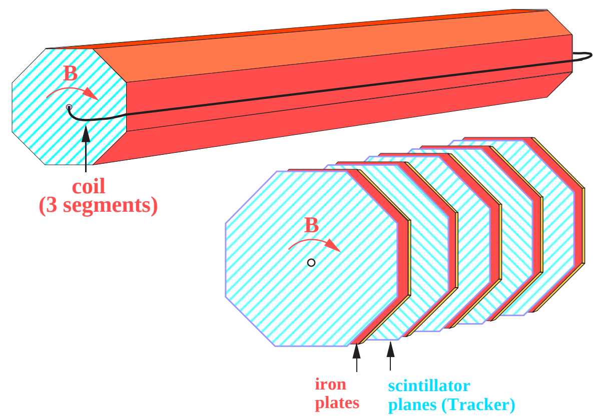

Figure 2. The MINOS far detector, consisting of 480 octagonal layers of magnetized steel interleaved with scintillator.

situated around the edge of the detector. Scintillator strips will be in orthogonal directions in alternate planes. Relative calibration will be carried out in the short term by injecting light from pulsed LEDs; absolute energies will be calculated (over longer timescales) by studying cosmic-ray muons. A study to compare the energy deposition by muons with that from hadronic showers will be carried out using a sample module in a test beam.

At the time of writing, a four-plane prototype detector is being assembled for testing at Fermilab. Three of the planes are to be fully instrumented with scintillator and readout. Testing will be carried out over several months, prior to the startup of full-scale module production.

3.2. Near detector

The near detector is designed to be functionally identical to the far detector, although it will be somewhat different in physical appearance due to the differences in nature of the neutrino beam at the two sites. In particular, the beam at the near detector will be tightly collimated, and all interactions of interest are expected to occur within 25 cm of the beam axis, whereas the "flat top" of the beam profile will be about a mile wide at the far detector. In the 3 m long upstream section of the near detector, in which only one quadrant will be instrumented, the first 0.5 m will be used to veto external events; the next 1 m will be a target region for events of interest; and the final 1.5 m will be used as a hadron spectrometer. The downstream section will be a fully-instrumented 11 m long muon spectrometer. The beam axis will be offset from the centre of the detector, in order to minimize the number of interactions within the region of the magnetic coil. A diagram of the near detector is shown in Figure 3.

The near detector has been designed so that the average magnetic field seen by a muon will be almost identical in both near and far detectors. The nature of the beam in the near detector will be studied carefully (in particular to measure ν_e contamination), and a Monte Carlo projection may then be used with confidence to provide an understanding of the beam at the far detector.

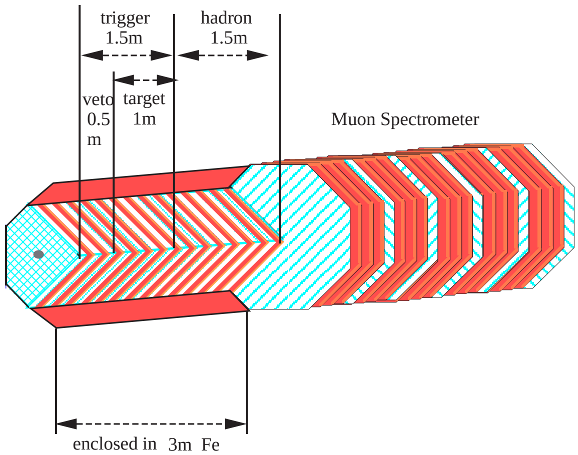

Figure 3. A cutaway diagram of the MINOS near detector. The neutrino beam spot is shown towards the left, centred on the instrumented quadrant of the upstream section.

4. OSCILLATION MEASUREMENTS

4.1. T-test

The most robust oscillation measurement that MINOS will make will be a determination of any change in the ratio of the numbers of neutral current vs. charged current events between the near and far detectors. The parameter

$$T = \frac{(NC/CC)_{\rm near}}{(NC/CC)_{\rm far}} \qquad (1)$$

will be reduced from its nominal value of unity in the presence of neutrino oscillations, since there will be fewer than expected muon-like charged current events, and a corresponding increase in short, shower-like events. Using the ratio of ratios reduces systematic uncertainties arising from Monte Carlo based acceptance calculations: the acceptances essentially cancel, as do uncertainties in the absolute neutrino flux. The expected ratio of neutral to charged current events in the absence of oscillations is fairly constant over the entire range of neutrino energies, as shown in Figure 4.

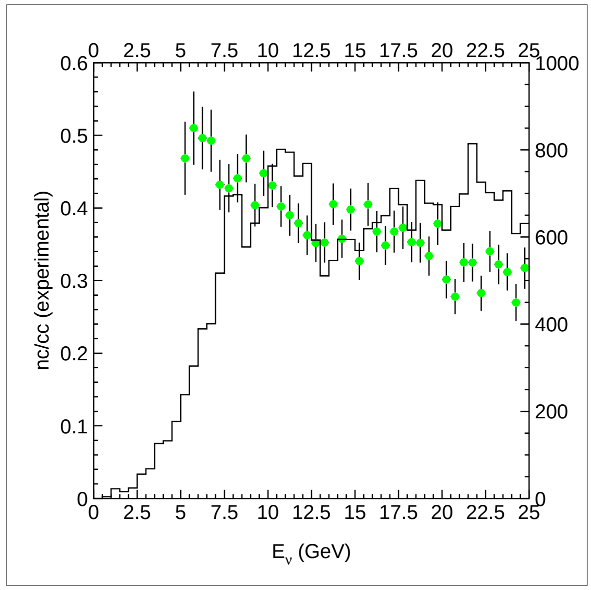

Figure 4. The expected ratio of neutral to charged current events in the MINOS far detector, as a function of neutrino energy, in the absence of neutrino oscillations. The solid line shows the expected neutrino flux.

Figure 5 shows the limits that are expected to be achieved with this test.

A simple and powerful primary mechanism to discriminate between neutral- and charged-current ν_μ events is a cut based upon event length. More sophisticated techniques include pattern recognition of the muon track, and the use of artificial neutral networks to identify event types.

4.2. Charged-current energy test

Neutrino oscillations will selectively deplete the ν_μ flux at certain neutrino energies. The highest energy at which maximal depletion occurs is dependent only upon Δm^2, and the extent of the depletion is determined by $\sin^2 2\theta$. (Dips at lower energy tend to be smeared out by the energy resolution.) A measurement of the ν_μ energy spectrum will therefore yield the mixing parameters directly. The total energy resolution is dominated

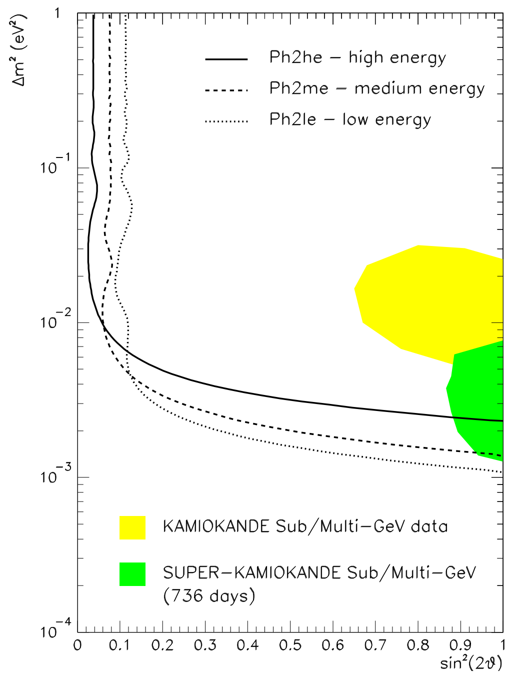

Figure 5. Expected 90% confidence limits from the T-test in MINOS. The three lines correspond to the three different neutrino beam energies.

by the resolution on the total hadronic energy, which is expected to be $53\%/\sqrt{E}$. Measurements of Δm^2 and $\sin^2 2\theta$ down to 10^{-3} eV^2 and 0.05 respectively can be obtained in this way. If, as the SuperKamiokande results seem to indicate, $\Delta m^2 \simeq 5 \times 10^{-3}$ eV^2 and $\sin^2 2\theta \simeq 1$ for ν_μ-ν_τ mixing, the MINOS charged-current energy test should be able to determine these parameters to within about 5%.

The energy distribution of neutral current events will provide a less sensitive test, but may help to determine the oscillation modes if Δm^2 is sufficiently large.

4.3. ν_μ disappearance

The measurement that has the greatest statistical power, although potentially the most difficult systematics, is a straightforward ν_μ disappearance experiment based upon the ratio of the number of ν_μ charged-current events seen in the two detectors. This relies heavily upon the Monte Carlo calculations of the flux as well as the extensive monitoring of the neutrino beam that will occur both in the beam tunnel and the near detector. It is expected that systematic errors on the beam extrapolation can be controlled to within 2%, and the expected limits on Δm^2 and $\sin^2 2\theta$ if this can be achieved are shown in Figure 6.

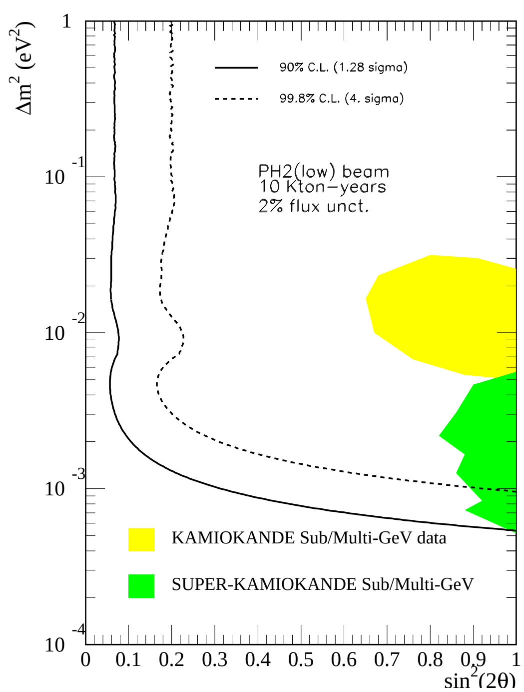

Figure 6. 90% confidence limits obtainable from the CC disappearance test in MINOS.

4.4. Appearance experiments

MINOS potentially has the capability to provide a convincing demonstration of both ν_e and ν_τ appearance, based upon the characteristic signatures of the different types of event. Charged-current electron neutrino events, for example, are typically compact in both longitudinal and lateral dimensions, and have a large deposit of energy near the vertex. Tau appearance is a little more ambiguous, and is probably best observed via the decay $\tau \to \pi^{\pm} X \nu_\tau$ for which the reach in Δm^2 extends down to $\approx 6 \times 10^{-3}$ eV^2 at $\sin^2 2\theta = 1$; the signature for the π is an isolated track that undergoes a secondary interaction producing a "star" of several outgoing particles. The electron from $\tau \to$ e $\nu_\tau \bar{\nu_e}$ is impossible to distinguish from that of a charged-current ν_e event on an event-by-event basis, but the overall energy distribution is of course lower as the pair of neutrinos carry away some of the energy. Likewise, $\tau \to \mu \bar{\nu_\mu} \nu_\tau$ events will be distinguishable from ν_μ charged-current events on a statistical basis if a narrow-band beam is used so that the initial neutrino energy is well determined. Overall, then, while the identities of ν_e and ν_τ events will prove difficult to establish on an individual basis, the statistical distributions should provide overwhelming and unambiguous evidence of the existence and nature of the oscillations.

4.5. Limits

The approximate 90% confidence level limits that are expected to be obtained in MINOS both for $\nu_\mu \to \nu_\tau$ and for $\nu_\mu \to \nu_e$ are shown in Figure 7. Also shown are the positions of currently favoured areas and the best exclusion limits from other experiments.

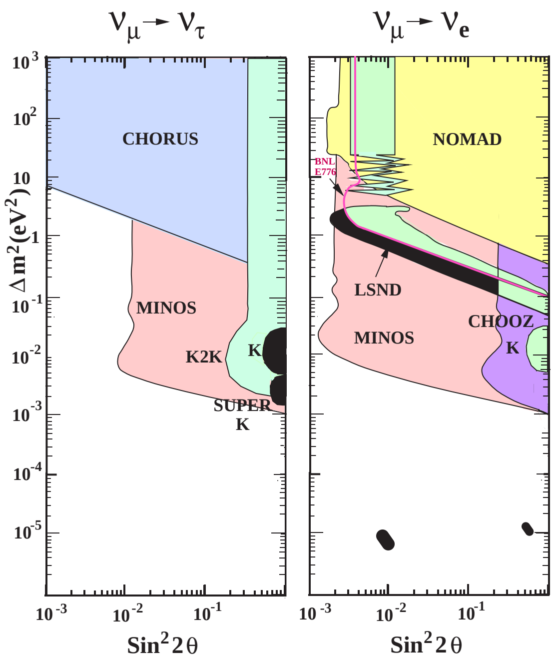

Figure 7. 90% confidence limits of MINOS and other experiments. Regions that are currently favoured as possible solutions are shown in black.

5. EMULSION DETECTOR UPGRADE

A proposal to extend the capabilities of the MINOS detector via the incorporation of an emulsion detector to observe ν_τ appearance directly is currently being prepared, and is expected to be considered by the U.S. Department of Energy during spring 2000. The goal would be to provide a total mass of 1 kton, consisting of stacked acrylic-backed emulsion layers interleaved with lead plates. Each 10 cm by 10 cm lead plate would be 1 mm thick, and the matching 0.8 mm thick acrylic plates would be coated on both sides with 0.1 mm of emulsion. The entire assembly would then be mounted at the upstream end of the MINOS far detector. If approved, probably no more than 100 tons of this detector would be in place by the time the neutrino beam turns on in 2002; the full mass would be attained gradually over the following year or so. Based upon the SuperKamiokande best-fit estimates of the mixing parameters, such a detector might reasonably be expected to observe about 40 τ events during the lifetime of MINOS.

6. CONCLUSION

MINOS will be the first major accelerator-based experiment to study in detail the exciting phenomenon of neutrino oscillations. The experiment has already passed (with flying colours) several important funding milestones. Large-scale production will begin next year, and the beam is expected to turn on in autumn 2002. Two full years of data-taking will provide sufficient statistics for the first ever high-precision measurement of neutrino mixing parameters.

7. ACKNOWLEDGEMENTS

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