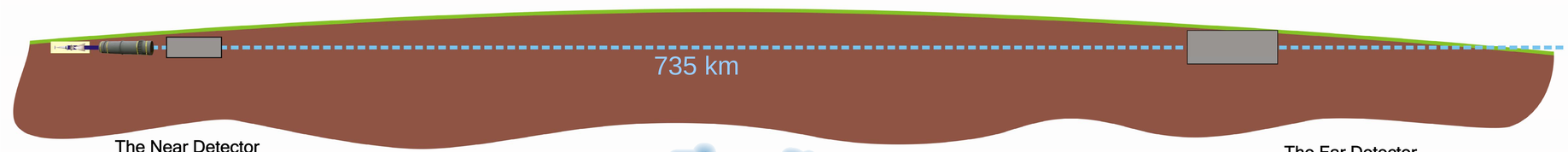
Precision Neutrino Oscillation Physics with MINOS

Jeffrey Hartnell[(a)], Masaki Ishitsuka[(b)] and Tobias Raufer[(c)]
on behalf of the MINOS Collaboration
(a) CCLRC, Rutherford Appleton Laboratory, (b) Indiana University, (c) University of Oxford

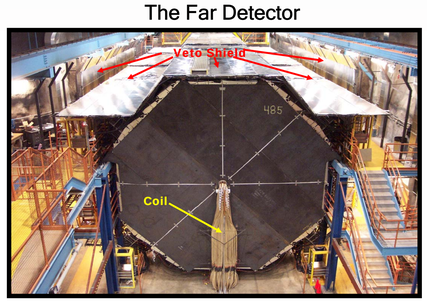
MINOS is a long-baseline neutrino oscillation experiment that uses the NuMI facility at Fermilab.

Two massive detectors are used to sample the NuMI beam: on-site at Fermilab and again 735 km away at the Soudan Underground Laboratory in Minnesota. MINOS has several key physics goals: to confirm the oscillation hypothesis and in doing so make a precision measurement of the atmospheric scale oscillation parameters; search for a non-zero value of θ_{13}, beyond the region probed by the CHOOZ experiment; and look for evidence of oscillations to sterile neutrinos.



The Near Detector

The Far Detector



Physics Goals of MINOS

Neutrino Oscillation

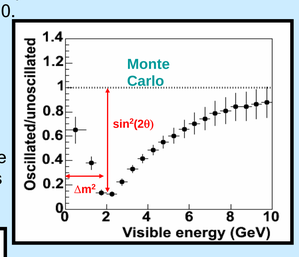
In the Standard Model neutrinos are regarded as exactly massless particles. However, there is no fundamental reason to forbid finite masses. Neutrino oscillation is proposed as a consequence of the finite mass of neutrinos. If neutrinos have finite mass, and their flavour eigenstates are the superposition of the mass eigenstates then flavour oscillations occur. The survival probability of a neutrino in a two flavour scenario is given as:

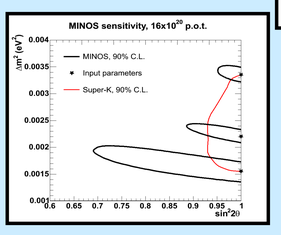
$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2\left(1.267\Delta m^2 L(km)/E(GeV)\right)$$

ν_μ Disappearance Measurement

The energy spectrum of the neutrino beam is measured by the MINOS Far detector after travelling a distance of 735 km. A deficit of ν_μ events compared to that measured in the Near detector is observed. The measurement is currently statistically limited but a factor of 10 more data is expected to be collected by 2010.

The plot to the right shows a Monte Carlo simulation of the energy dependence of the deficit expected for our final result, assuming $\Delta m^2_{23} = 0.0033$ and $\sin^2(2\theta_{23})=1$. As shown in the plot: the position of the dip is a measure of Δm^2_{23} and the depth of the dip is a measure of $\sin^2(2\theta_{23})$.



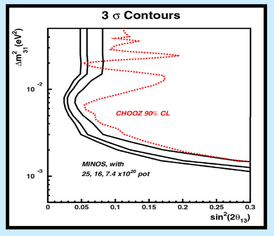


The plot to the left shows the projected final sensitivity of MINOS to Δm^2_{23} and $\sin^2(2\theta_{23})$ for several different values of Δm^2_{23} that fall inside the Super-K 90% confidence region. As can be seen from the plot, MINOS can significantly improve the measurement of Δm^2_{23}.

ν_e Appearance Search

If θ_{13} is non-zero then it is possible to look for a ν_e appearance signal at the Far detector. The appearance of ν_e at the atmospheric mass-splitting scale is due to the sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillation mode.

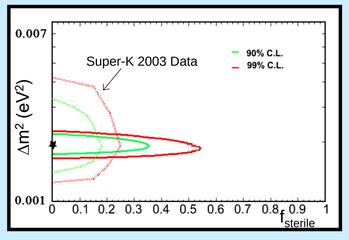
The plot on the right shows the projected sensitivity for a 3-σ discovery of θ_{13} for different sized data sets: 7.4, 16 and 25x10^{20} Protons On Target (POT). It can be seen that MINOS has the potential to look beyond the CHOOZ experiment's limit and make the first measurement of θ_{13} after a few years of running.



Sterile Neutrino Search

Results from the LSND experiment suggest the existence of a fourth neutrino. However, the width of the Z^0 resonance shows that there are only 3 light neutrinos. Thus, if a fourth light neutrino does exist it does not couple to the Z^0 - hence it is given the name "sterile".

The spectrum of neutral current interactions is not affected by $\nu_\mu \rightarrow \nu_\tau$ oscillations. But if $\nu_\mu \rightarrow \nu_{sterile}$ oscillations occur then the neutral current spectrum will show a deficit.



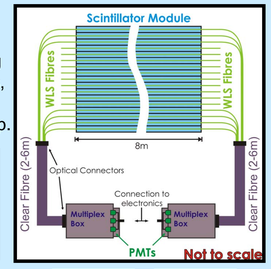
The plot to the above right shows the sensitivity to oscillations with a sterile fraction $f_{sterile}$ as a function of Δm^2_{23} for 7.4x10^{20} POT.

The MINOS Detectors and the NuMI Neutrino Beam

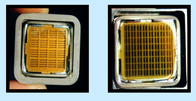
The MINOS Detectors

The MINOS detectors are magnetised, tracking calorimeters that are made from hundreds of steel-scintillator planes. Each plane of scintillator is divided up in to 4 cm wide strips; the strips are orientated perpendicularly in consecutive planes to allow 3D track reconstruction.

The scintillation light is extracted from the point of interaction using wave-length shifting (WLS) fibres, which are glued in a groove that runs along the length of each strip.



At the edge of the detectors, clear fibres transmit the green light from the WLS fibres on to multi-anode photo-multiplier tubes.



The **Far Detector** is constructed of 486 planes and weighs 5400 tons. The electronics and data acquisition system is continuously live with each PMT triggering independently. An online trigger farm writes out hits in time windows where there are clusters of strips. Furthermore, by buffering a few seconds of data in the trigger farm and sending the GPS beam-spill time over the internet an online "spill trigger" is formed, which allows low-energy neutral current events to be captured with high efficiency.

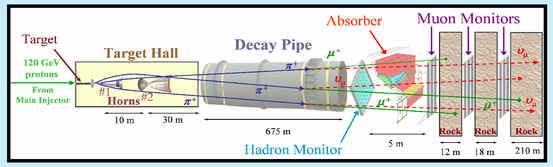
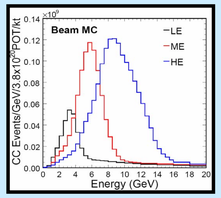
The **Near Detector** has 282 planes and weighs nearly 1000 tons. The electronics and data acquisition system operates in two main modes called "cosmics" and "spill". During the beam "spill" mode data is digitised at 53 MHz and buffered for up to 20 μs, which allows events to be reconstructed in the high rate environment. The "cosmics" mode is very similar to the Far detector operation.

The **Calibration Detector** has 60 planes and was exposed to protons, pions, muons and electrons from the CERN PS accelerator test beams in 2001-2003.

Data from the Calibration detector is used to tune the Monte Carlo simulation and to set the absolute energy scale.

The NuMI Beam

The Neutrinos at the Main Injector (NuMI) facility at Fermilab produces intense pulses of neutrinos every 2-3 seconds. Five or six batches of 120 GeV protons are extracted from the Main Injector accelerator in 10 μs and directed onto a graphite target. The secondary pions and kaons are focussed using two magnetic horns pulsing at 185 kA; these secondaries travel down a 675 m water cooled vacuum pipe where they decay to give predominantly muon neutrinos. The remaining protons, pions and kaons are stopped by the hadron absorber; whereas the muons are removed from the beam by several hundred meters of rock.



A special feature of the NuMI facility is that the energy spectrum of the neutrino beam can be tuned. This is achieved by moving the target relative to the horns, moving the horns relative to each other and adjusting the horn current. The resulting spectra for high, medium and low energy (HE, ME and LE) beam settings are shown in the figure to the right. The low energy beam is being used currently to give maximum sensitivity to Δm^2_{23}<0.005.