The MINOS Experiment

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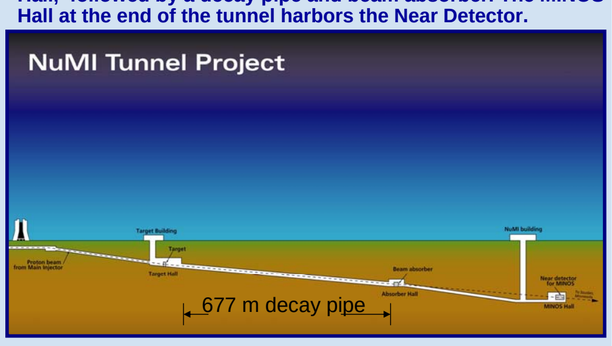
The **M**ain **I**njector **N**eutrino **O**scillation **S**earch experiment will use a long baseline ν_μ beam, measuring the ν signal 1 km downstream from production and 734 km later with similar Near and Far planar steel/scintillator detectors, located at Fermilab and at the Soudan mine respectively. With the Near detector installation underway and the 5.4 kiloton Far detector completed and taking quality atmospheric data, MINOS is preparing for beam turn on early next year. A general overview of the experiment along with the proposed physics goals and the latest results on atmospheric data is shown.

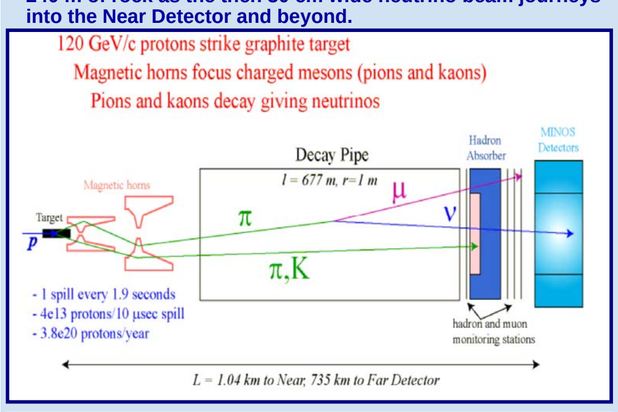
NuMI Facility

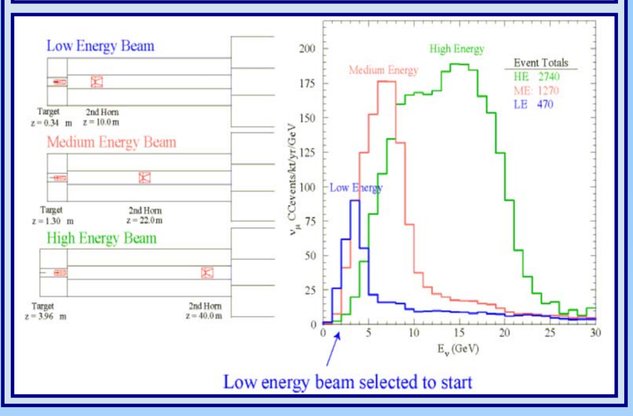
- Recently completed at Fermilab, the NuMI facility comprises several parts: an Extraction Hall, Carrier Tunnel, and Target Hall, followed by a decay pipe and beam absorber. The MINOS Hall at the end of the tunnel harbors the Near Detector.



NuMI Beam

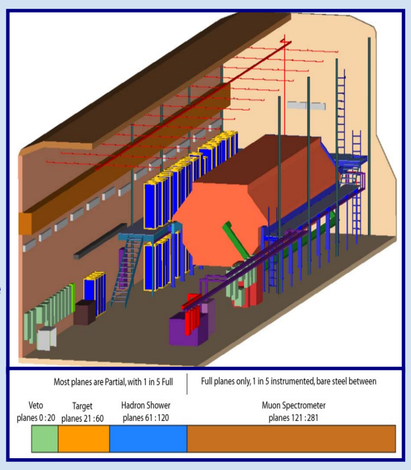
- The NuMI neutrino beam originates from collisions of 120 GeV/c protons, extracted from the Main Injector accelerator ring, with a graphite target. The beam is focused in the Soudan direction by two double parabolic magnetic horns. The emerging pions decay into neutrinos inside a ~1 torr vacuum pipe. The remaining hadrons are trapped by 5 m of steel-Al absorber. Finally, the surviving muons range out in 240 m of rock as the then 30 cm wide neutrino beam journeys into the Near Detector and beyond.

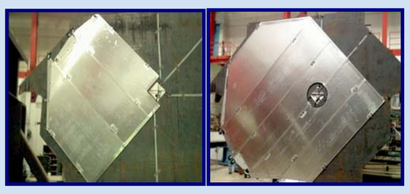




Near Detector

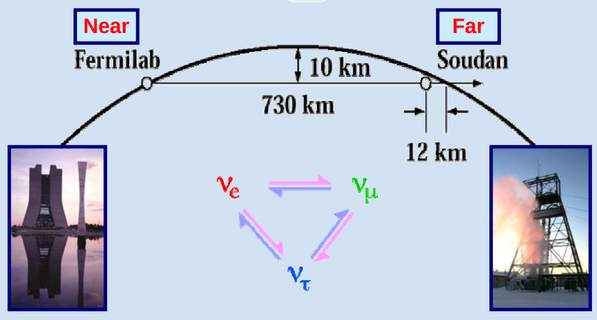
- The Near detector is currently under construction at Fermilab and is expected to be completed by December 2004.
- The detector weighs 980 ton and is made up from 282 planes each in the shape of an elongated octagon 3.8m by 4.8m.
- The detector comprises four functionally different components:
  - the upstream Veto section
  - the Target section
  - the Hadron Shower section
  - the Muon Spectrometer.
- QIE electronics are used to readout the Near Detector. The QIE integrated circuits form a deadtime-less, multi-ranging ADC system capable of dealing with the relatively high event rates in the Near Detector.





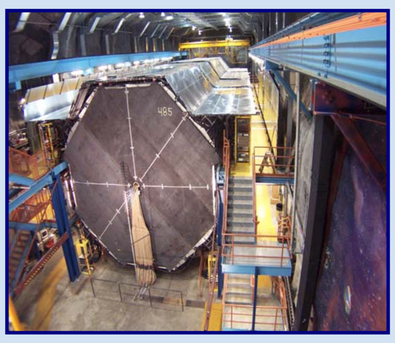
Baseline

- MINOS is a long baseline experiment. The neutrino beam leaves the Near Detector ~100m underground and travels through the Earth an additional 734 km, where, now ~1km wide, it is measured in the Far Detector. The Far Detector is located at a depth of 721m in an underground state park, once an iron mine, in Soudan, Northern Minnesota. During their path, the neutrinos in the beam undergo flavor oscillations. This effect is enhanced for the chosen baseline and beam neutrino energy.

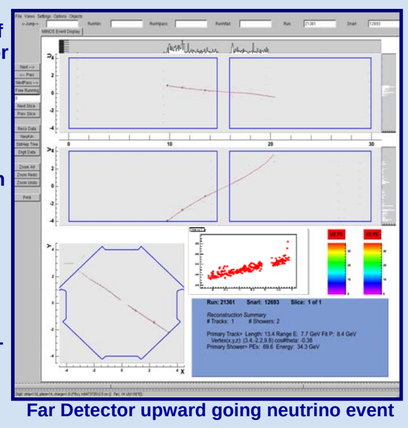


Far Detector

- Located at a depth of 2100m of water equivalent in the Soudan Underground Laboratory, the fully completed MINOS Far detector has been collecting data for atmospheric neutrino studies and calibration for approximately 1 year.



- The Far Detector has a total mass of 5.4 kt. It consists of 486 steel/scintillator octagonal planes each 8m in diameter. The planes are arranged as two supermodules, with a combined length of 31m. Each supermodule is individually fitted with a 15kA-turn coil which runs along its axis. The coil provides a 1.5T field in the inner region of the detector.

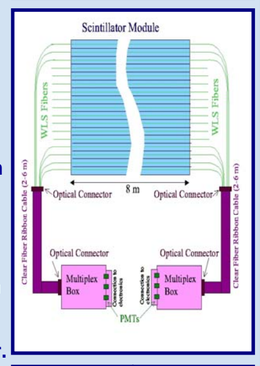


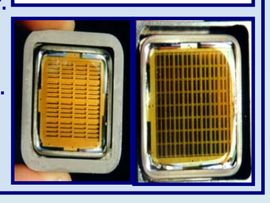
Far Detector upward going neutrino event

- A veto shield has been constructed above and to the sides of the detector to reduce the background from cosmic ray muons for the atmospheric neutrino analyses. The shield consists of a double layer of 20 strip wide scintillator modules. These strips are read out with Hammamatsu M16 phototubes.
- The Far Detector uses modified Viking VA Front End electronics. The VA chip contains 32 channels of shaping amplifiers used to sample and hold the phototube signals. Triggering is accomplished by monitoring the dynode signals on the phototubes.

Detector Technology

- The MINOS Detectors are fine grained tracking calorimeters with an absorber layer of steel and an active layer of plastic scintillator. The scintillator is extruded from polystyrene, infused with the fluor PPO (1%) and the wavelength shifter POPOP (0.03%).
- Each "plane" of a detector is a sandwich of 1" thick steel, 1cm thick scintillator and air with a pitch between planes of ~6cm. The scintillator layers are segmented transversely into 4.1cm strips and the orientation of the strips alternates with successive planes by 90° to enable 3D event reconstruction.
- The detector resolution is ~23%/sqrt(E) for electromagnetic showers and ~55%/sqrt(E) for hadronic showers, where E is measured in GeV. Muon momentum determination and charge identification is achieved by magnetizing the detectors using current-carrying coils.
- Each strip is embedded with 1.2mm diameter Kuraray Y11 wavelength shifting fibre to transmit scintillation light out of the detector. MINOS then employs Hammamatsu M16 and M64 phototubes at the Far Detector and Near Detector respectively to measure the signals.





Physics Goals

Neutrino Oscillations

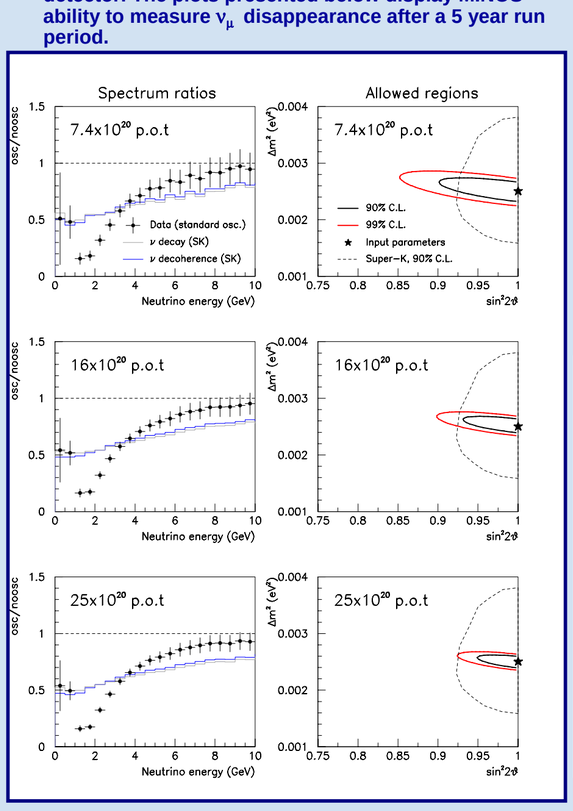
- The possibility that neutrinos may oscillate opens the door to probing Physics beyond the Standard Model, as flavor change can only occur for massive neutrinos. The oscillation probability depends on the flavor mixing angles, the mass difference between flavors, the neutrino energy and the distance traveled by the neutrino. For the simplified case of only two neutrino species, the oscillation probability in vacuum is given by:

$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2(eV^2)L(km)}{E_\nu(GeV)}\right)$$

- The three plots on the far left show the ratio of the oscillated spectrum to the unoscillated spectrum for different numbers of incident protons on the NuMI target with the Low Energy beam configuration. The oscillation parameters used are Δm^2 = 0.0025 eV² and $\sin^2(2\theta)$ = 1. To the right, the plots show the allowed regions in oscillation parameter space. It can be seen that even for a relatively small number of protons on target MINOS can significantly improve the current limits on Δm^2.

ν_μ Disappearance

- MINOS will measure ν_μ disappearance by comparing the Far detector neutrino energy spectrum with that predicted based on measurements at the Near detector. The plots presented below display MINOS ability to measure ν_μ disappearance after a 5 year run period.

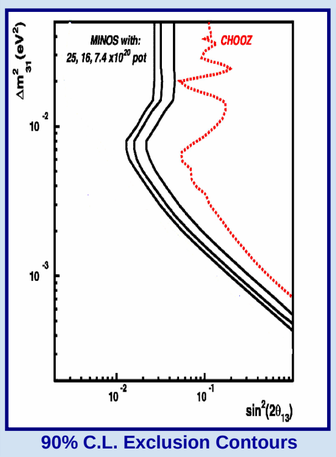


ν_e Appearance

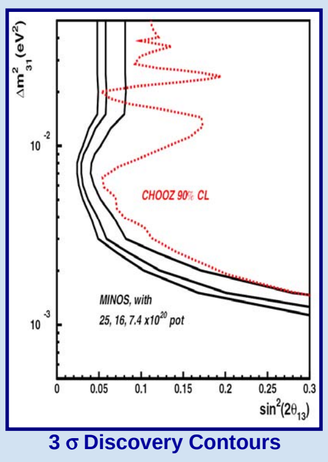
- Using the Near Detector to measure precisely the ν_e component of the mostly ν_μ NuMI beam, MINOS will be able to use the Far Detector to look for a ν_e excess due to $\nu_\mu \to \nu_e$ oscillations. The probability of ν_e appearance in the ν_μ beam in vacuum is, to leading order:

$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(1.27\frac{\Delta m^2_{23}(eV^2)L(km)}{E_\nu(GeV)}\right)$$

- The left plot shown below displays the MINOS exclusion contours in the $\sin^2 2\theta_{13}$ and Δm^2_{23} parameter space for different numbers of protons on target. The CHOOZ limit and the ICARUS prediction are overlaid. The plot on the right shows the MINOS 90% C.L. allowed regions along with the CHOOZ result. MINOS can potentially improve the CHOOZ limit on θ_{13}, making a noticeable contribution to one of the most exciting topics of current neutrino research.



90% C.L. Exclusion Contours



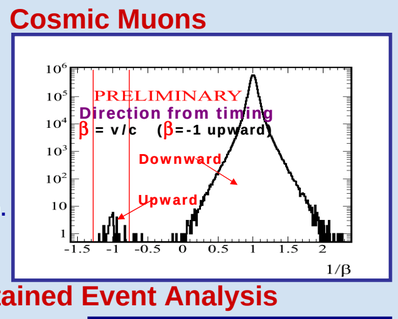
3 σ Discovery Contours

Results

- The MINOS Far Detector has been collecting atmospheric data since the beginning of and during construction. The exposure used in the data analysis consists of 138.77 live days with one supermodule and 230.45 live days with both supermodules. As the plots shown demonstrate, MINOS is steadily progressing towards readiness to collect and analyze the beam neutrinos, expected early 2005.

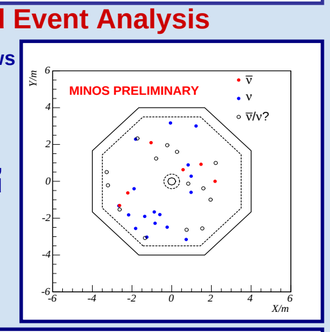
Cosmic Muons

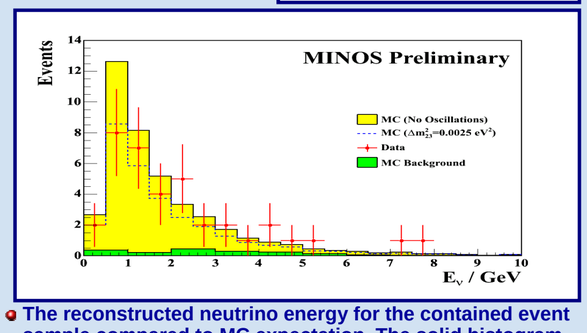
- The 1/β distribution for cosmic muons. Negative values correspond to muons originating from below the horizon.



Contained Event Analysis

- The plot on the right shows the positions of the reconstructed vertices of the selected sample of 37 contained events, color coded in three categories, antineutrino, neutrino and ambiguous induced.





- The reconstructed neutrino energy for the contained event sample compared to MC expectation. The solid histogram shows the MC expectation for the case of no neutrino oscillations, the green histogram shows the cosmic ray background and the points with error bars show the data. The dashed histogram shows the expectation for $\nu_\mu \to \nu_\tau$ oscillations with Δm_{23} = 0.0025eV²

- AS acknowledges the partial financial support of the Praxis XXI grant BD-18360/98 (Portugal).