

Chapter 2

The MINOS and MINOS+ Experiments

This chapter gives an overview of the MINOS and MINOS+ experiments followed by descriptions of the NuMI beam-line, the NuMI targets and the MINOS detectors. The last section provides information on the type of neutrino interactions within the detectors.

2.1 MINOS

MINOS [1, 2] (the Main Injection Neutrino Oscillation Search) is a long-baseline neutrino oscillation experiment primarily designed to measure ν_μ and $\bar{\nu}_\mu$ disappearance. MINOS uses a beam of predominantly muon neutrinos provided by the NuMI (Neutrinos at the Main Injector) beam-line facility [3] at Fermilab located near Chicago, IL, USA. The MINOS experiment is a two-detector experiment. The Near Detector (ND) is situated 1.04 km downstream from the neutrino production target and makes precise measurements of the neutrino beam before neutrino oscillations have occurred. The Far Detector (FD) is 735 km downstream from the neutrino production target and is located in the Soudan Underground Laboratory, northern Minnesota. The FD measures the neutrino beam once oscillations have occurred. It is the comparison between both detectors that allows for the inference of neutrino oscillation by observing a deficit of muon-flavour neutrinos (or an appearance of electron neutrinos). The setup of the MINOS experiment is shown in Fig. 2.1.

MINOS began taking data in March 2005 and continued up until April 2012, collecting data in both ν_μ and $\bar{\nu}_\mu$ beam modes (explained in Sect. 2.3). A breakdown of the beam conditions for this data-taking period can be seen in Fig. 2.2. The majority of the data was taken in the low-energy configuration with a beam composed predominantly of ν_μ with an energy spectrum peaked at around 3 GeV. MINOS also uses an atmospheric neutrino sample of 37.88 kt-yr at the Far Detector, which is 705 m underground (2070 mwe) [4].



Fig. 2.1 The MINOS experiment. A beam of muon-type neutrinos is created at the NuMI facility. The neutrinos pass through the Near Detector located at Fermilab and the Far Detector located in the Soudan Mine in northern Minnesota. The baseline is 735 km

Using the low-energy dataset and the atmospheric neutrino sample a previous MINOS analysis measured the most precise value of Δm_{32}^2 to date along with a competitive measurement of θ_{23} [5]. This was achieved by combining the analyses of ν_μ and $\bar{\nu}_\mu$ disappearance and ν_e and $\bar{\nu}_e$ appearance for both beam and atmospheric neutrino samples using a three-flavour neutrino oscillation model. Figure 2.3 shows the confidence intervals for the final MINOS three-flavour analysis measuring Δm_{32}^2 and θ_{23} .

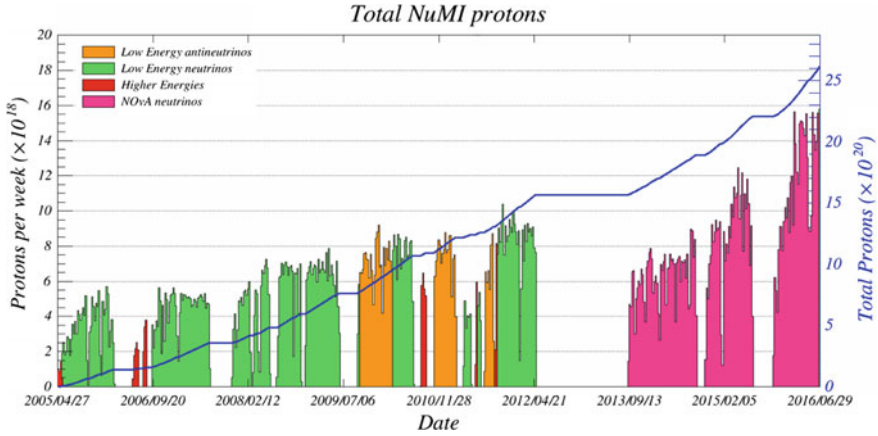


Fig. 2.2 The beam configuration for the MINOS and MINOS+ experiments. Most of the data for MINOS was taken in the low-energy ν_μ beam (in green) and $\bar{\nu}_\mu$ beam (orange). Special runs where the beam was configured to higher energies or the magnetic horns are switched off is indicated by the red. The magenta-coloured runs are the MINOS+ data-taking in the medium-energy ν_μ beam during the NOvA era

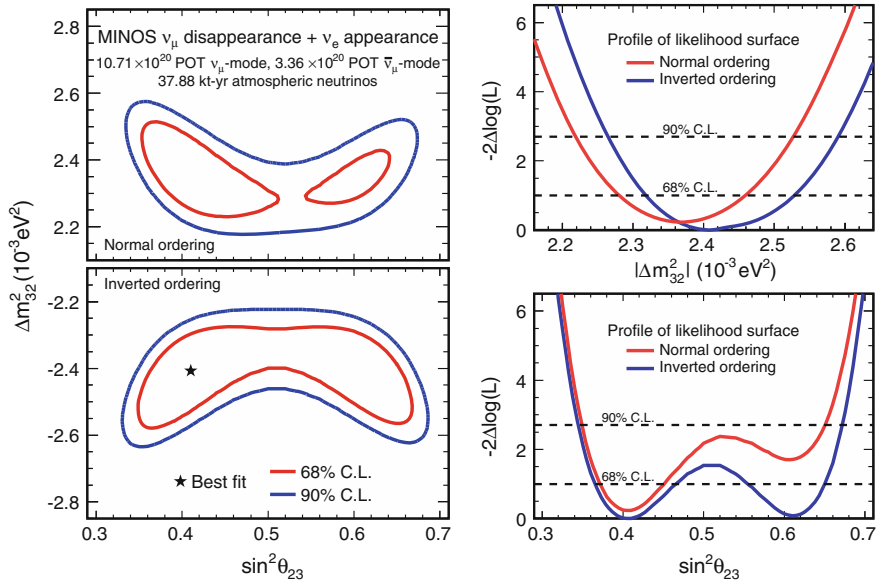
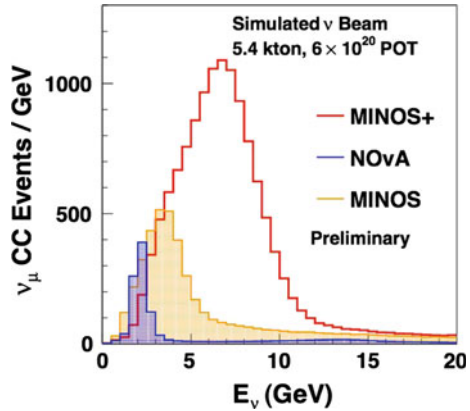


Fig. 2.3 The left panels show the 68 and 90% confidence limits on Δm_{32}^2 and $\sin^2 \theta_{23}$ for the normal ordering (top) and inverted ordering (bottom). At each point in this parameter space, the likelihood function is maximised with respect to $\sin^2 \theta_{13}$, δ_{cp} and the systematic parameters constrained in the fit. The likelihood surface is calculated relative to the overall best fit, which is indicated by the star. The right panels show the 1D likelihood profiles as a function of Δm_{32}^2 and $\sin^2 \theta_{23}$ for each mass ordering. The horizontal dotted lines indicate the 68 and 90% confidence limits. Figure taken from [5]

Fig. 2.4 The neutrino energy spectra for ν_μ charged-current events observed at the Near Detector for MINOS (yellow), MINOS+ (red) and the NO ν A [7] (blue) experiments



2.2 MINOS+

MINOS+ [6] is the continuation of the MINOS detectors with the NuMI beam configured to produce neutrinos at higher energies. Figure 2.4 shows the the neutrino energy spectra for ν_μ charged-current events observed at the Near Detector for MINOS, MINOS+ and the NO ν A experiments. MINOS and MINOS+ have the Near and Far Detectors on-axis, that is, they are situated along the longitudinal direction of the neutrino beam. MINOS+ observes a high flux of neutrinos at higher energies compared to the low-energy configuration with the beam peak shifting from 3 GeV to 7 GeV due to a change in the neutrino beam configuration. The NO ν A experiment is off-axis, being placed 14 mrad from the beam axis thereby increasing the number low-energy neutrinos around the oscillation dip, and heavily reducing the high-energy component.

MINOS+ took data from September 2013 until June 2016, and with the additional statistics will provide important contributions to the high-precision tests of the three-flavour oscillation formalism and will improve on the world-leading measurements of muon-neutrino disappearance made by MINOS. The beam exposure as a function of time for MINOS+ can be seen in Fig. 2.2.

With more statistics at high energies MINOS+ is in the unique position to probe and significantly extend the reach of the search presented in this thesis for sterile neutrino signatures in the regions of parameter space favoured by experiments such as LSND and MiniBooNE. MINOS+ can also search for non-standard neutrino interactions [8] and other sources of new physics such as Large Extra Dimensions [9].

2.3 The NuMI Beam

The Neutrinos at the Main Injector (NuMI) neutrino beam [3, 10] was built at Fermilab to provide neutrinos for the MINOS experiment. The NuMI beam typically had a beam power of 350 kW with a design specification of up to 400 kW. A high-intensity beam is required to achieve a meaningful event rate at the FD which is situated several hundred kilometres away. Such a distance significantly reduces the neutrino flux as it decreases as a function of distance away from the neutrino production target.

To produce a neutrino beam the first stage is to create protons from H^- ions. The ions are accelerated by a Radio Frequency (RF) quadrupole up to an energy of 750 keV. From there a linear accelerator accelerates the ions to an energy of 400 MeV, which subsequently pass through a thin carbon foil stripping the electrons off the ions to leave a beam of protons. The protons are fed into a rapid cycling synchrotron (Booster) and accelerated in batches up to energies of 8 GeV. Subsequently they are fed into the Main Injector where they are accelerated to 120 GeV. The Main Injector has a circumference seven times larger than the Booster and so up to six batches of protons can be inserted into the Main Injector at once with space to allow for the rise time of the pulse kicker. The pulse kicker bends the beam to align it towards the neutrino production target. It is the interaction between these high energy protons upon the fixed graphite target that results in a plethora of charged pions, kaons and muons.

Figure 2.5 shows how the charged particles pass through two parabolic, magnetic horns which focus either positive or negative particles depending on the direction of the electric current being pulsed through the horns into the decay pipe. The decay of muons into electrons contributes an intrinsic electron neutrino component in the beam. The focused hadrons travel along a 675 m decay pipe filled with helium. It is the decay of these particles inside the pipe that forms the predominately muon-flavour neutrino beam:

$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu \bar{\nu}_\mu, \quad (2.1)$$

$$K^\pm \rightarrow \mu^\pm + \nu_\mu \bar{\nu}_\mu, \quad (2.2)$$

$$\mu^\pm \rightarrow e^\pm + \bar{\nu}_\mu \nu_\mu + \nu_e \bar{\nu}_e. \quad (2.3)$$

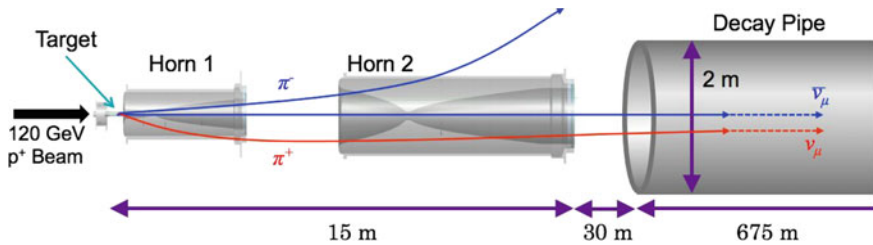


Fig. 2.5 The NuMI beam

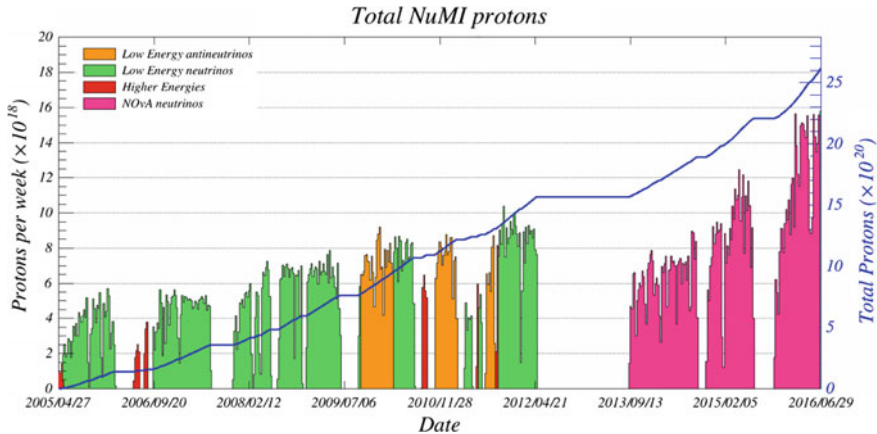


Fig. 2.6 Simulated events at the MINOS ND for the neutrino-dominated low-energy beam. The graph shows the relative contribution of the neutrino parents as a function of true neutrino energy

By focusing the positive hadrons a beam of predominately ν_μ is created (ν_μ -dominated beam mode); by focusing the negatively charged hadrons the $\bar{\nu}_\mu$ component can be increased ($\bar{\nu}_\mu$ -enhanced beam mode). The relative contribution of neutrino parents as a function of true neutrino energy for the low-energy neutrino-dominated beam is shown in Fig. 2.6. Pions are the main contribution, with a significant kaon contribution at higher energies. Figure 2.7 shows three of the possible energy spectra observed at the Near Detector by varying the current sent to the focusing horns and the relative position of the neutrino production target to the horns.

The compositions of the NuMI neutrino-dominated and antineutrino-enhanced beams for charged-current neutrino interactions observed in the MINOS Near Detector are compared in Fig. 2.8. The significant difference in composition and event rate between these beam modes arises mainly from the fact that the $\bar{\nu}_\mu$ interaction cross section is a factor of approximately two lower than the ν_μ interaction cross section.

2.3.1 Slip-Stacking

A method called “Slip-Stacking” can be performed in the Main Injector to allow the intensity of a proton batch to approximately double by merging two batches together in the Main Injector, therefore increasing the power of the NuMI beam [11]. The Main Injector cannot accommodate more than six batches at once, however by using three different RF cavities operating at different frequencies additional batches can be injected and coalesced together to produce double-intensity batches. The procedure to produce a slip-stacked batch is as follows:

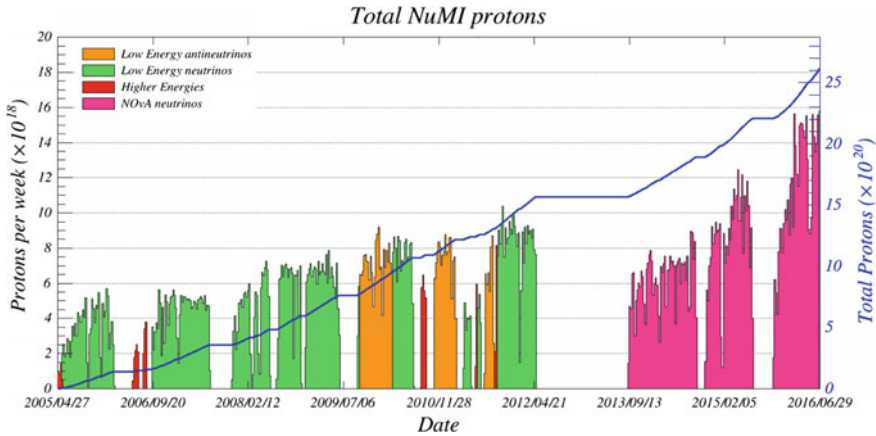


Fig. 2.7 The true energy distribution of Near Detector events from the three different NuMI configurations. The target position (distance upstream of a nominal position) and horn current of each configuration are shown in the legend. “0.1 m, 185 kA” is the “low-energy” configuration in which most of the MINOS data has been taken. “1.0 m, 200 kA” is the “medium-energy” configuration which is the beam configuration in the NO ν A era and therefore is the beam setup in which MINOS+ took data. The final configuration is the “pseudo-high-energy” configuration

1. A proton batch is injected from the Booster into the Main Injector at an energy of 8 GeV and is captured by the first RF system.
2. The frequency of the RF system is lowered resulting in the deceleration of the batch, causing its momentum to decrease, and hence it will have a smaller orbit around the Main Injector circumference. A second proton batch is injected into the Main Injector and is captured by a second RF system operating at a higher frequency than the first (a larger momentum and therefore orbit).
3. The two batches are moving at different speeds relative to another around the Main Injector. The two batches continue to accelerate around until they are aligned longitudinally where they are both picked up by a third RF system with a frequency which is an average of the first and second RF system. As a result the two batches coalesce and can be treated as a single batch with double the intensity.

Figure 2.9 shows the structure of a six-batch beam spill in which the first three batches have been slip-stacked.

2.3.2 The NuMI Target

The NuMI target, shown in Fig. 2.10, is composed of 47 graphite fins. Each fin is 6.4 mm wide, 15 mm tall and 20 mm long with a spacing of 0.3 mm. The total thickness of all 47 fins is 954 mm which is approximately 2 hadronic interaction lengths. The thin-fin design optimises the proton-carbon cross section whilst minimising the

Fig. 2.8 The reconstructed neutrino energy spectra at the MINOS Near Detector. The top graph shows the energy spectra produced when focusing positively-charged hadrons producing a predominately ν_μ beam. Below is when negatively charged hadrons are focused, increasing the number of $\bar{\nu}_\mu$ events seen at the detectors. Note how in anti-neutrino mode the event rate is significantly less due to different cross sections between neutrinos and anti-neutrinos

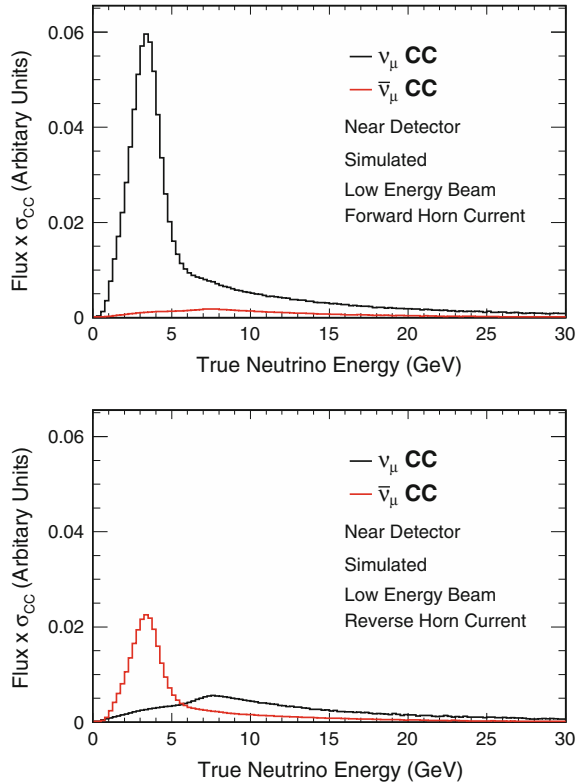
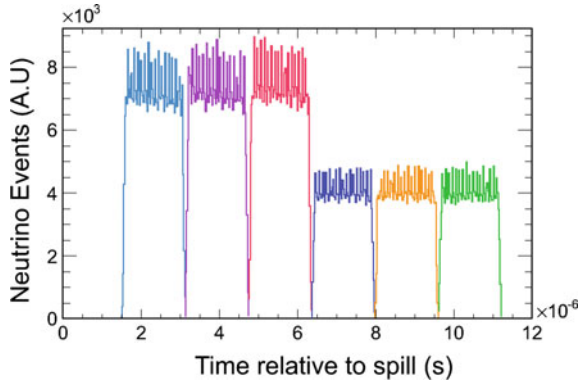


Fig. 2.9 Reconstructed neutrino events at the Near Detector (data). The x -axis is the time of the reconstructed neutrino event relative to the trigger that indicates a NuMI beam spill. The different colours indicate the different proton batches. The data shows the beam was delivering six proton batches. Three of the batches have been doubled in intensity due to being slip-stacked



number of secondary hadronic interactions from pions and kaons that would reduce the neutrino flux. Figure 2.10 also shows the fins are placed in an aluminium casing running parallel to two water lines for cooling.

The lifetime of a NuMI target is finite. During the duration of the MINOS-era data-taking seven NuMI targets were used. Assuming the target is not subjected to

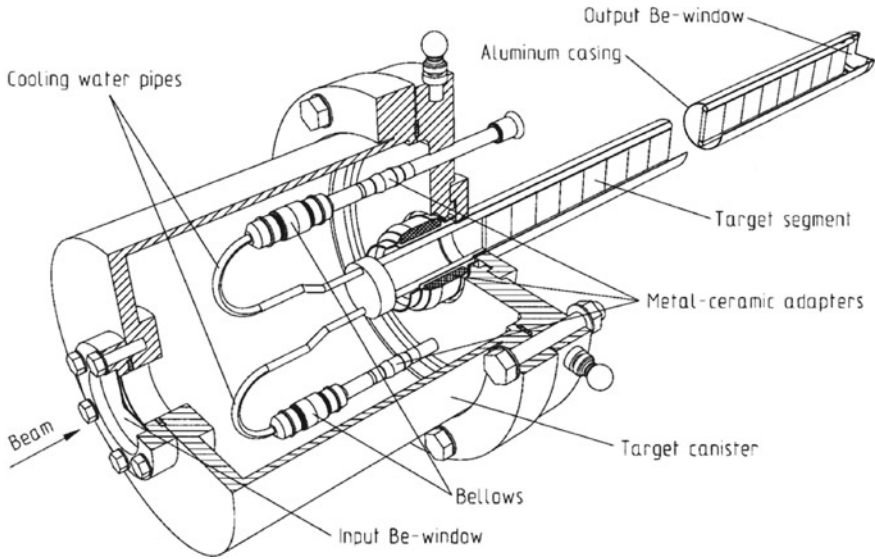


Fig. 2.10 Technical drawing of NuMI target and target housing used in the MINOS experiment. Image taken from [12]

any serious issues such as water leaks, or physical damage through an accident, the graphite will begin to degrade due to the periodic stresses, impacts and radiation from the beam. As a result the target will break up and become less dense and the neutrino flux will decrease. Chapter 8 will present the effect target decay has had on the neutrino energy spectrum for the dataset used in this thesis.

2.4 The MINOS Detectors

2.4.1 Overview

The MINOS detectors are tracking, sampling calorimeters made of alternating layers of 1 cm thick plastic scintillator and 2.54 cm thick steel planes; Fig. 2.11 shows how the plastic and steel are used to form a plane. Each adjacent plane is rotated by 90° with respect to its neighbour to allow for 3D reconstruction in the detectors. MINOS identifies events by observing the light produced by the final state charged particles in the scintillator. The scintillation light is sent along wavelength-shifting fibre and read out by Photomultiplier tubes (PMTs). Both detectors are magnetised so that the charge of a muon interacting within the detector can be inferred by the direction of bending. A co-ordinate system is defined as x being the horizontal direction perpendicular to the beam, y the vertical direction, and the beam direction defined

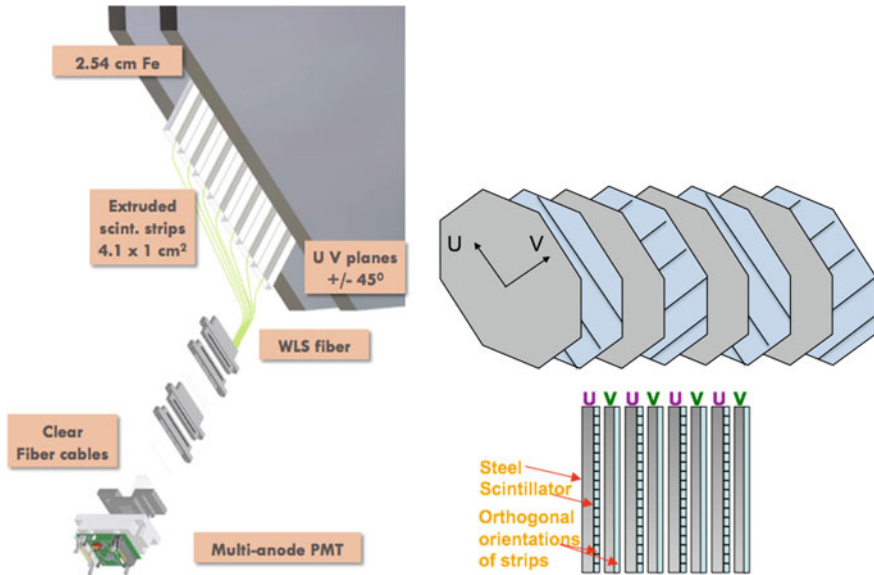


Fig. 2.11 The components of a MINOS plane comprise plastic scintillator and a steel plane (*left*). The arrangement of multiple planes at 90° to one another labelled U and V to allow for 3D reconstruction in the detectors is shown on the *right*

as z . An alternative right-handed co-ordinate system is also defined with the beam direction still defined as z but a UV plane being defined as a 45° rotation to the xy plane as displayed in Fig. 2.11. Both detectors are explained in great detail in [2].

2.4.2 Two-Detector Experimental Setup

MINOS is composed of two detectors, the ND and the FD. Both detectors are designed to be similar from the materials used in construction to their functionality. By looking at the relative differences between the reconstructed neutrino energy spectra in the two detectors rather than measuring the absolute neutrino flux, the impact of experimental systematic errors that affect both detectors are significantly reduced. Any mis-modelings such as neutrino cross-sections and flux will affect both detectors in the same way and therefore a relative comparison will cancel out any such effects. The analysis in this thesis will take advantage of this by fitting the ratio of the FD to ND energy spectra.

Near Detector

The ND lies 110 m underground, which corresponds to 225 meters-water-equivalent (mwe) overburden, and is 1.04 km downstream from the NuMI production target. The beam is powerful enough at this point to produce many tens of neutrino interactions per proton spill from the NuMI beam. Such a large flux allows the ND to be the smallest of the two detectors with a mass of 980 tonnes. The ND can be seen in Fig. 2.12; the detector is 4.8 m wide and 3.8 m tall with the coil hole for producing the magnetic field being off centre. The beam axis is displaced 1.48 m from the coil hole to reduce the number of particles depositing energy within the coil hole which is not well modelled in simulation.

The ND consists of 282 steel planes. The upstream part of the detector (the first 120 planes) is the calorimeter section and all except the first plane are instrumented with scintillator. Within the calorimeter section one in every five planes is fully instrumented, the others having a smaller region of scintillator around the beam axis. The calorimeter is designed to measure hadronic energy depositions. The remaining 162 planes act as the spectrometer, used to measure the momenta of energetic muons. Every fifth plane is instrumented with scintillator whilst the others have none.

Far Detector

The FD is 735.3 km downstream from the NuMI production target and 705 m underground (2070 mwe). The FD, shown in Fig. 2.13, consists of 484 octagonal steel planes constructed as two super-modules separated longitudinally by 1.15 m.

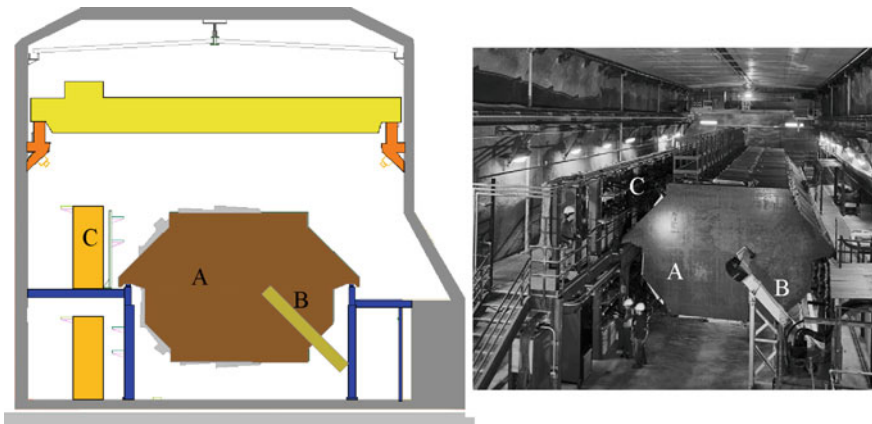


Fig. 2.12 End view of the MINOS ND (the NuMI beam going into the page). The drawing (*left*) helps illustrate and label the image of the MINOS ND (*right*). “A” is furthest upstream steel plane, “B” is the magnet coil, and “C” is the electronics rack. The NuMI beam axis is aligned near the “A” label. Image taken from [2]

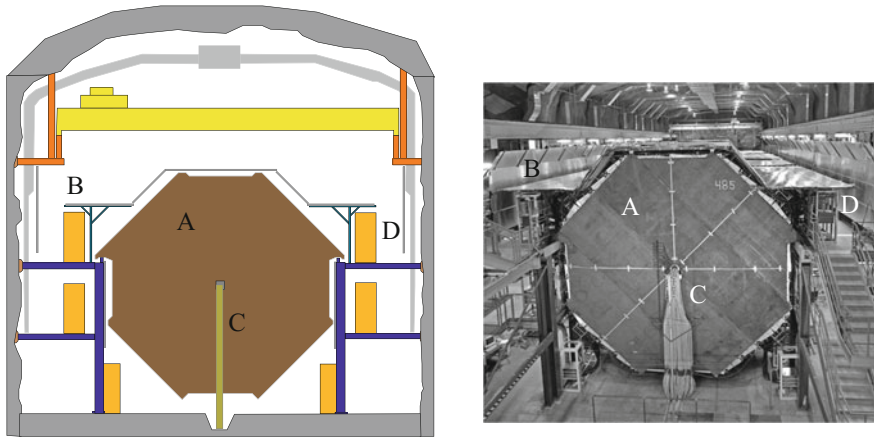


Fig. 2.13 The end view of the MINOS FD (beam coming out of page). The drawing (*left*) helps illustrate and label the image of the MINOS FD (*right*). “A” is the most downstream steel plane, “B” is the cosmic ray veto shield, “C” is the end of the magnet coil, and “D” is the electronics rack. Image taken from [2]

To compensate for the reduced flux from the neutrino beam (a factor of $\sim 10^5$) the FD is much larger than the ND with a mass of 5400 tonnes. The detector sees on average three neutrino interaction events per day in the low-energy NuMI beam.

The FD super-modules each have their own independently operated magnet coil. The super-module closest to the NuMI beam has 249 planes and is 14.78 m in length. The second super-module has 237 planes and is 14.10 m in length. No scintillator is instrumented onto the first plane of each super module.

A veto shield located around the top of the FD (over both super-modules) enables the selection of atmospheric neutrino events from the data [13]. The atmospheric neutrinos are selected from a large background of cosmic muons. The 2070 mwe overburden suppresses a significant amount of the cosmic ray background, however high energy cosmic muons can travel through the earth’s crust and enter the FD from above. Cosmic muons will have to pass through the veto shield which is made of the same scintillator modules as the scintillator planes in the detectors.

There are a number of reasons why a cosmic muon may not be tagged by the veto shield: a shield readout channel is dead due to noise or damage from radioactivity, a cosmic muon passes through the gap between the two modules or the activity left by the cosmic muon in the veto shield was too small to register a signal.

2.5 Steel

The steel has an average density of $7.85 \pm 0.03 \text{ g cm}^{-3}$ [2]. The high density increases the chance of a neutrino interaction within the detector. The typical RMS

deviation of plane masses is 0.35% (the plane thickness varying by 0.3%). Neighbouring steel planes are 5.95 cm apart [2].

2.6 Plastic Scintillator

As neutrinos travel through the detector they interact with the iron nuclei, and the charged final-state particles travel through the scintillator where the energy deposition is read out as light. The structure of a strip of scintillator can be seen in Fig. 2.14. The plastic-scintillator strips are made from extruded polystyrene, doped with organic scintillators PPO (1% by weight) and POPOP (0.03% by weight). The strips are coated with a reflective, uniformly distributed, thin (0.25 mm) layer of TiO_2 (15% by weight) that serves as a diffuse reflector to improve light yield [2]. The scintillator strips were produced by *Itasca Plastic*, producing over 300 tons of scintillator with the light emission spectrum peaked at $\sim 420 \text{ nm}$. Each strip has a groove along the surface containing a $1.20^{+0.02}_{-0.01} \text{ mm}$ diameter wavelength-shifting (WLS) fibre.

The WLS fibres are produced by Kuraray, Inc. in Japan and consists of double-clad polystyrene fibre with 175 ppm of Y11 (K27) fluorescent emitter. The WLS fibres minimise self-absorption by absorbing light peaked at $\sim 430 \text{ nm}$ and re-emitting it

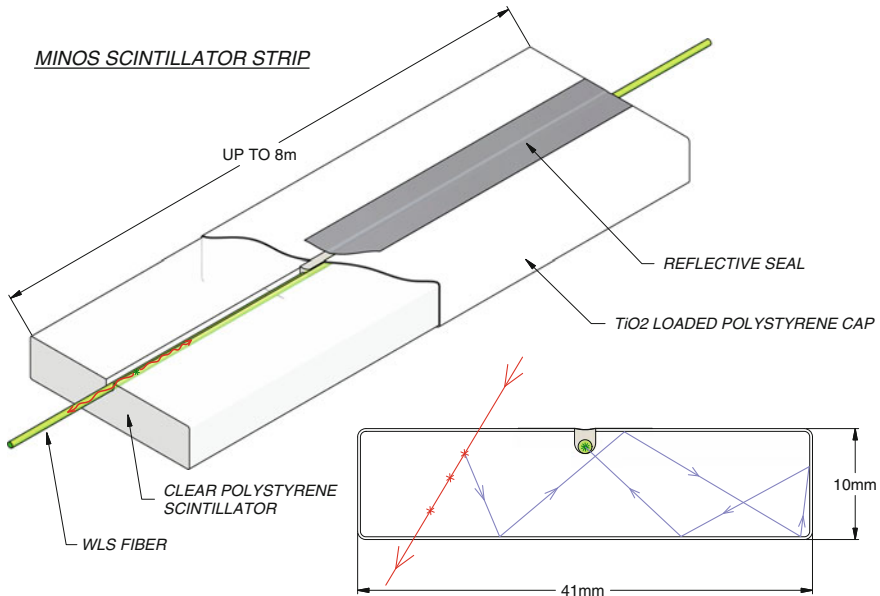


Fig. 2.14 A strip of MINOS scintillator with the WLS fibre installed along the centre. The image in the lower right corner depicts a charged particle (red line) depositing energy by producing light (blue line) as it passes through the strip. The light travels along the WLS fibre and is read out by a PMT. Image taken from [2]

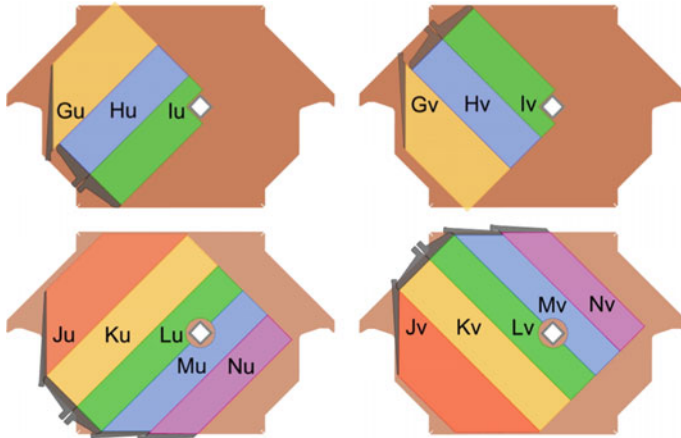


Fig. 2.15 The four different configurations of planes used in the ND, showing the different layouts of the scintillator modules. The figure shows partially instrumented U planes module (*top left*), partially instrumented V (*top right*), fully instrumented U (*bottom left*) and fully instrumented V (*bottom right*) where U and V are the coordinates used. Figure taken from [2]

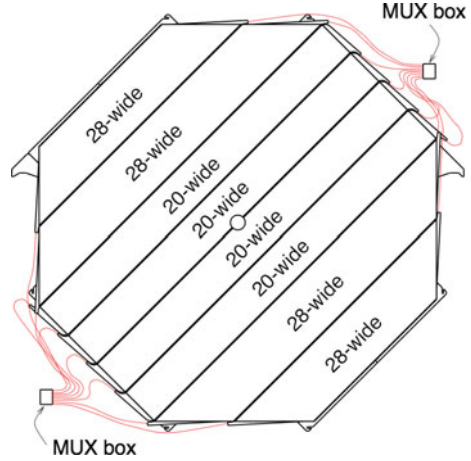
at a peak of 470 nm and beyond (from blue to green). The wavelength-shifted light is transported to an optical connector at the edge of the scintillator and into clear polystyrene fibres that transport the light to PMTs. More detailed accounts of the cost-effectiveness and practicality behind using a plastic-scintillator in the MINOS experiment can be found at [14].

The scintillator strips are closely packed into modules of 16 and 28 strips that are wrapped in aluminium to ensure a light-tight enclosure. The module design is advantageous as it provides a mechanically strong structure that holds strips together and is sufficiently robust for shipping and mounting to the steel plates. Once these modules are attached to the steel plates a MINOS steel-scintillator plane is complete. The designs for the Near and Far Detectors differ slightly and can be seen in Figs. 2.15 and 2.16.

2.7 Photomultiplier Tubes

The scintillation light is transported by the WLS fibres to clear optical wire bundles that transport the light to Hamamatsu multi-anode photomultiplier tube pixels. At the FD, 16-anode (Hamamatsu R5900-00-M16) PMTs are used with gains up to 1×10^6 . The ND uses 64-anode (Hamamatsu R5900-00-M64) PMTs with gains of 0.8×10^6 . The voltage required to achieve such gains for these PMTs is ~ 800 V. The PMTs are encased in boxes to ensure they are light-tight and to shield them from magnetic fields and ambient electronic noise [2].

Fig. 2.16 The arrangement of the scintillator modules on a MINOS Far Detector plane. Note that every plane at the Far Detector is fully instrumented. Figure taken from [2]



At the FD, each scintillator strip is read out at both ends requiring 1452 PMTs. Eight scintillator strips are read out by one PMT pixel; the WLS fibres are “multiplexed” onto the PMT pixels, meaning eight fibres are connected to a single pixel, with the fibre-to-pixel mapping intentionally different at each end of each strip allowing for the determination of correct track location with an eight-fold reduction in pixels. This setup yields a light output similar to the ND scintillator strips which are read out at one end and mirrored at the other; this is achievable due to the shorter length of the ND scintillator strips. The ND uses 194 PMTs.

2.8 Magnetic Field

Both the FD and ND are magnetised by a current-carrying coil. The geometric differences between the FD and ND mean different requirements for coils. Both detectors have a magnet coil passing through a hole along the whole length of the detector, equipped with water cooling. The FD has an independent magnet coil [15] within each super-module. At the FD the average toroidal magnetic field is 1.42 T whereas the ND has an average toroidal magnetic field of 1.28 T [16].

Magnetised detectors allow the MINOS experiment to distinguish oppositely charged muons on an event-by-event basis. This allows MINOS to distinguish ν_μ and $\bar{\nu}_\mu$ charged-current interactions within the detectors, allowing the collaboration to measure the oscillation parameters of anti-neutrinos and neutrinos separately providing a test of CPT violation [17, 18].

2.9 Electronics and Readout

The electronics differ between the detectors due to the difference in the number of neutrino interactions each detector experiences. The FD observes fewer neutrino interactions by many orders of magnitude due to the long-baseline from the NuMI target and the large overburden to suppress cosmic rays. The rate of cosmic ray interactions in the FD is 0.5 Hz with the majority of the data volume dominated by detector noise [19]. The FD electronics are explained in detail in [20].

The ND electronics are designed to address the larger instantaneous event rate due to the shorter distance from the production target. The NuMI beam is designed to deliver a high-intensity neutrino beam, which can produce an order of 10 neutrino events per beam spill in the ND. In order to accurately reconstruct each event the electronics are required to be fast and have no dead time during the 10 μ s duration of a beam spill. More details on the ND electronics can be found in [21].

2.10 Light Injection

The MINOS light injection system monitors the stability and linearity of the PMTs used in the calibration chain discussed in Sect. 3.1. Each detector is equipped with a light injection system that allows varying intensity pulses of ultra-violet light produced by LEDs (light-emitting diodes) to be injected into the FD and ND. The light injected into the detectors from the LEDs is monitored by PIN (Positive Intrinsic Negative) photodiodes, the signal from which is reshaped to mimic the signal from scintillation light read out by the PMTs. The signal from the photodiodes is then read out by the standard electronics of the detectors.

2.11 Triggering

The NuMI beam delivers the neutrinos in “spills”. When a beam spill occurs, a signal (spill trigger) is sent to the ND and FD triggering a detector readout window for 100 μ s around each spill. The FD requires additional triggers to address the high level of noise originating from dark noise from within the PMTs and spontaneous light emission in the WLS fibres [19]. A trigger is implemented that requires 2 out of 36 PMTs to produce a signal readout within a 400 ns window. Each set of 36 PMTs is read out and once the trigger is activated the data is digitised. Outside of the beam spill window offline triggers cause data from cosmic muons to be recorded and stored, basing the decision on either a minimum amount of energy deposited in a set of planes, or a certain number of planes hit within a group of planes.

2.12 The Calibration Detector

The Calibration Detector (CalDet) is the smallest of the MINOS detectors. CalDet was designed and built to measure the calorimetric response to hadrons and electrons, and the topology of hadronic and electromagnetic interactions in a number of test beams at CERN [22]. CalDet was built to be of similar design to the MINOS ND and FD to demonstrate they can be calibrated relative to one another to high precision. CalDet consisted of 60 unmagnetised planes, each plane a 1 m^2 of the same steel and scintillator composition as the two main MINOS detectors. However, the steel planes were $\sim 0.04 \text{ cm}$ thinner in the CalDet detector corresponding to a decrease in thickness of 1.6% meaning the average energy deposition of a particle of known energy will be $\sim 1.6\%$ higher in CalDet relative to the ND and FD. Each plane contained 24 scintillator strips, each 100 cm long. In an identical arrangement to the ND and FD, the planes were aligned so that adjacent planes were at 90° to each other. Both the ND and FD electronics were implemented at CalDet during testing to understand and quantify any differences in the read-out electronics; the responses were found to agree to within 0.06% [23].

The CalDet detector, through subsection of several test-beams of well-defined particle energies, was used to develop a calibration chain (discussed in Sect. 3.1) to allow the ND and FD responses to particle interactions to be related to one another, achieving an uncertainty in the relative calibration between the ND and FD of $\sim 2\%$ [22].

2.13 Neutrino Interactions in the Detectors

2.13.1 Event Topologies

There are three neutrino interactions that are of interest to MINOS as shown in Fig. 2.17. The main channel is the charged current (CC) ν_μ ($\bar{\nu}_\mu$) interaction,

$$\nu_\mu(\bar{\nu}_\mu) + X \rightarrow \mu^{-(+)} + X'.$$

The cascade of hadrons, X' , produces a diffuse shower of energy deposits near the interaction vertex and a long muon track. MINOS was constructed with steel planes so that it can contain a significant proportion of the final state muons. The muon curves due to the magnetic field. It is the direction of curvature that allows MINOS to identify the incoming neutrino as a ν_μ or a $\bar{\nu}_\mu$.

All active neutrino flavours undergo the neutral current (NC) interaction through the process

$$\nu + X \rightarrow \nu + X'.$$

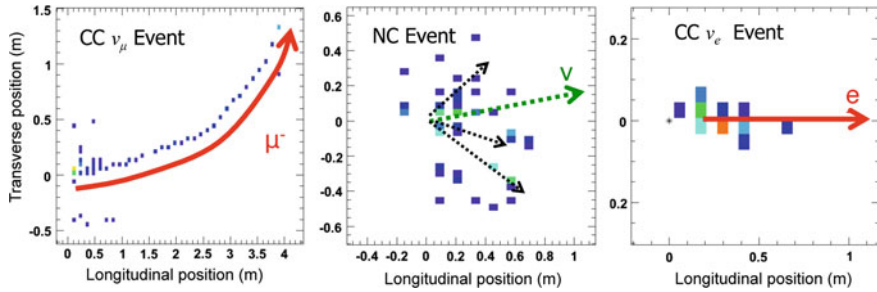


Fig. 2.17 Neutrino interaction topologies observed in the MINOS detectors. *Left* A charged current ν_μ interaction. *Middle*: A neutral current interaction. *Right* A charged current ν_e interaction. Each coloured pixel represents a scintillator strip with energy deposited from a charged particle. The colour scale displays the amount of light: *purple* and *blue* are low light levels, through to *orange* and *red* for the highest light levels

Only the hadronic shower is observed, producing a diffuse pattern of energy deposits within the detector. It is not possible to determine the flavour of neutrino.

Finally, electron neutrinos undergo CC interactions through the process

$$\nu_e(\bar{\nu}_e) + X \rightarrow e^{-(+)} + X'.$$

The electron gives rise to an electromagnetic shower, which produces a much denser, more compact shower of energy deposits. This interaction is difficult to identify due to the steel plate thickness, meaning that it can be difficult to separate these dense electromagnetic showers from the more diffuse hadronic showers.

2.13.2 Neutrino Cross Sections

The neutrinos used in the analysis presented in this thesis have energies in the range of 0.25–40 GeV. Within this energy range CC interactions can be divided into three dominant classes.

1. Quasi-elastic scattering dominates below 1 GeV:

$$\begin{aligned} \nu_\mu + n &\rightarrow \mu^- + p, \\ \bar{\nu}_\mu + p &\rightarrow \mu^+ + n. \end{aligned} \tag{2.4}$$

At this energy neutrinos can elastically scatter off an entire nucleon liberating a nucleon (or multiple nucleons) from the target. In MINOS, quasi-elastic interactions result in little or no hadronic activity leaving only a muon track visible in the detector.

- At a few GeV, resonance production becomes important. In this process, the struck nucleus (N) is excited to a baryon resonance (N^*) that most likely decays to a nucleon-pion final state:

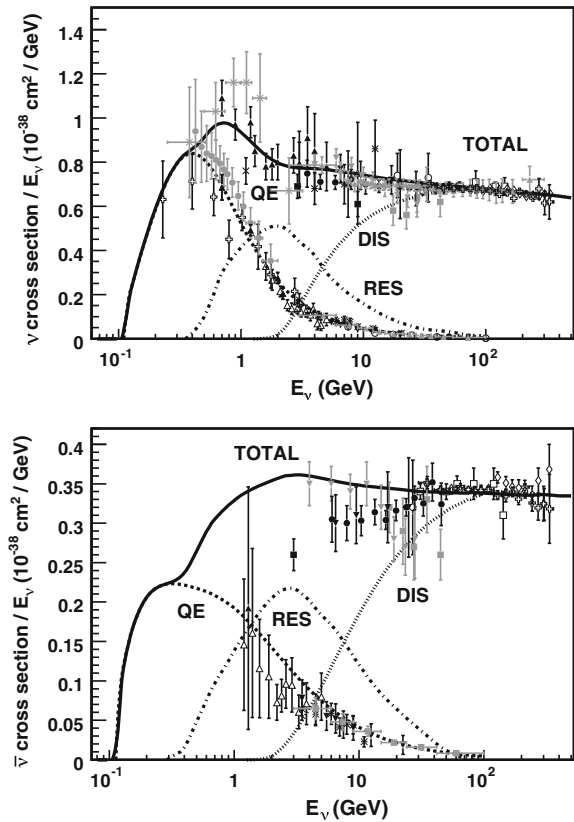
$$\begin{aligned}\nu_\mu + N &\rightarrow \mu^- + N^*, \\ N^* &\rightarrow \pi + N'.\end{aligned}\tag{2.5}$$

The pion can give a shower-like topology if it undergoes hadronic interactions, or else a track-like signature in the case of the $\pi^\pm$.

- Deep inelastic scattering (DIS) dominates above a few GeV. In this process, the neutrino has sufficient energy that it can resolve the individual quark constituents of the nucleon which manifests in the creation of a large hadronic shower.

Figure 2.18 shows the three dominating cross section processes in the energy range 0–100 GeV for both neutrinos and anti-neutrinos. At MINOS the oscillation dip observed in muon-neutrino disappearance at the FD occurs just below 2 GeV; therefore CCQE neutrino interactions provide a large source of signal events for a

Fig. 2.18 Total muon-flavoured neutrino (*top*) and anti-neutrino (*bottom*) charged-current cross-sections per nucleon. Figure taken from [24]



neutrino oscillation analysis. A detailed review on the current state of neutrino cross sections can be found in [24]. Recently a new cross-section channel has been found around the quasi-elastic and DIS region called “multi nucleon correlation” [25]. This new channel is not included in the simulation software used in this thesis. Chapter 5 discusses the systematic uncertainties included in this analysis and due to the two detector setup at MINOS the cross section systematic uncertainty is shown to not be one of the dominant systematics. Therefore the impact of not modelling this additional channel in this analysis is considered negligible.

References

1. D. Ayres et al., P-875: a long baseline neutrino oscillation experiment at Fermilab, MINOS Proposal, NuMI-L-63
2. MINOS Collaboration: D.G. Michael et al., The magnetized steel and scintillator calorimeters of the MINOS experiment, Nucl. Instrum. Meth. A **596**, 190 (2008)
3. P. Adamson et al., The NuMI Neutrino Beam. Nucl. Instrum. Meth. A **806**, 279 (2016)
4. MINOS Collaboration: P. Adamson et al., Measurements of atmospheric neutrinos and anti-neutrinos in the MINOS Far Detector, Phys. Rev. D **86**, 052007 (2012)
5. MINOS Collaboration: P. Adamson et al., Combined analysis of ν_μ disappearance and $\nu_\mu \rightarrow \nu_e$ appearance in MINOS using accelerator and atmospheric neutrinos, Phys. Rev. Lett. **112**, 191801 (2014)
6. MINOS+ Collaboration: G. Tzanankos et al., MINOS+: a Proposal to FNAL to run MINOS with the medium energy NuMI beam, (2011), FERMILAB-PROPOSAL-1016
7. NO ν A Collaboration: P. Adamson et al., First measurement of electron neutrino appearance in NO ν A, Phys. Rev. Lett. **116**, 151806 (2016)
8. MINOS Collaboration: P. Adamson et al., Search for flavor-changing non-standard neutrino interactions by MINOS, Phys. Rev. D **88**, 072011 (2013)
9. N. Arkani-Hamed, S. Dimopoulos, G.R. Dvali, The Hierarchy problem and new dimensions at a millimeter. Phys. Lett. B **429**, 263 (1998)
10. K. Anderson et al., The NuMI Facility Technical Design Report, (1998), FERMILAB-DESIGN-1998-01
11. S. Shukla et al., Slip stacking for the Fermilab luminosity upgrade. Conf. Proc. C **970512**, 144 (1997)
12. A. Radovic, Measuring the disappearance of Muon neutrinos with the MINOS detector. PhD thesis U. Coll. London 2013, FERMILAB-THESIS-2013-24
13. MINOS Collaboration: R.K. Plunkett, J.A. Thomas, Proposal for a cosmic ray veto shield for the MINOS far detector, 2002, FERMILAB-PROPOSAL-0934
14. MINOS Collaboration: I. Ambats et al., The MINOS Detectors Technical Design Report, (1998), FERMILAB-DESIGN-1998-02
15. MINOS Collaboration: J.K. Nelson, J. Kilmer, MINOS far-detector coil design, (1999), FERMILAB-TM-2408-E
16. MINOS Collaboration: J.K. Nelson, J. Kilmer, MINOS near-detector coil design, (1999), FERMILAB-TM-2407
17. MINOS Collaboration: P. Adamson et al., First direct observation of muon antineutrino disappearance, Phys. Rev. Lett. **107**, 021801 (2011)
18. MINOS Collaboration: P. Adamson et al., Improved search for muon-neutrino to electron-neutrino oscillations in MINOS, Phys. Rev. Lett. **107**, 181802 (2011)
19. S. Avvakumov et al., Spontaneous light emission from fibers in MINOS. Nucl. Instrum. Meth. A **545**, 145 (2005)

20. J. Oliver, N. Felt, G. Feldman, A. Lebedev, R. Lee, Design and performance of the readout system of the MINOS Far Detector. *IEEE Trans. Nucl. Sci.* **51**, 2193 (2004)
21. T. Cundiff et al., The MINOS near detector front end electronics. *IEEE Trans. Nucl. Sci.* **53**, 1347 (2006)
22. MINOS Collaboration: A. Cabrera et al., Comparisons of the MINOS near and far detector readout systems at a test beam. *Nucl. Instrum. Meth. A* **609**, 106 (2009)
23. A. Cabrera, Systematic comparison of the MINOS near and far detector readout systems, PhD thesis U. of Oxford 2005, FERMILAB-THESIS-2005-50
24. J.A. Formaggio, G.P. Zeller, From eV to EeV: neutrino cross sections across energy scales. *Rev. Mod. Phys.* **84**, 1307 (2012)
25. MINERvA Collaboration: P.A. Rodrigues et al., Identification of nuclear effects in neutrino-carbon interactions at low three-momentum transfer. *Phys. Rev. Lett.* **116**, 071802 (2016)

<http://www.springer.com/978-3-319-63768-6>

Search for Sterile Neutrinos with the MINOS
Long-Baseline Experiment

Timmons, A.M.

2017, XX, 162 p. 116 illus., 111 illus. in color.,
Hardcover

ISBN: 978-3-319-63768-6