

Chapter 1 Introduction

The Standard Model of Particle Physics is the result of many years of experimental and theoretical endeavour. The model has been subjected to stringent experimental tests over a wide range of energies and the agreement between data and theory is remarkable, given that it is widely believed that physics beyond the Standard Model must exist. There are a number of arbitrary parameters in the model, for example neutrino masses are set to zero ‘by hand’ although there is no fundamental reason why this should be the case. The phenomenon of neutrino oscillations can occur if neutrinos are not massless and, over the past few years, it has become clear that the search for neutrino oscillations is a promising probe of physics beyond the Standard Model. The possible existence of neutrino oscillations is supported by the deficit of solar neutrinos and the anomalous flavour ratio of atmospheric neutrinos observed by large underground experiments.

The proposed MINOS (Main Injector Neutrino Oscillation Search) experiment plans to conduct a comprehensive investigation of neutrino oscillations using a neutrino beam produced by the Fermilab Main Injector and a large new detector located at the Soudan Mine in Minnesota, 730 km away. The experiment will be sensitive to neutrino oscillations in the same region of parameter space as the atmospheric neutrino experiments. Most discussions of the physics capability of MINOS have focussed on the limits that could be set on the oscillation parameters if no effect is observed. In this thesis I will assume that neutrino oscillations do exist, with parameters similar to those indicated by the atmospheric neutrino anomaly. The role of MINOS is therefore to provide a precision measurement of the

oscillation parameters. In the subsequent chapters I describe, with the aid of Monte Carlo simulations, several complementary methods to achieve this aim in MINOS.

The design of the MINOS detector has evolved significantly while this thesis was in preparation; the steel plate thickness has changed from 4 cm to 1 inch and the active detectors have evolved from limited streamer tubes to plastic scintillator. I have therefore attempted to make my arguments largely independent of the specifics of the detector design. The results of Appendix B were, however, used by the collaboration in deciding the optimum detector parameters for MINOS.

Chapter 2 summarises the results of experimental searches for neutrino oscillations. Experiments probing solar and atmospheric neutrinos have produced results that are strongly suggestive of oscillations and the excess of events observed by the LSND experiment can also be interpreted in terms of neutrino mixing. The recent results from CHOOZ and Super-Kamiokande are described and their implications for MINOS are assessed in the subsequent chapters.

The forthcoming MINOS experiment, which is designed to check the atmospheric neutrino anomaly, is described in Chapter 3. MINOS can perform a large number of measurements that are sensitive to neutrino oscillations. In Chapter 4 I describe how the neutrino oscillation phase can be measured by analysing the energy distribution of ν_μ charged-current events. This measurement is one of the most convincing demonstrations of neutrino oscillations in MINOS. I calculate the expected measurement errors on the mixing parameters for a range of oscillation scenarios. The effect of systematic errors on parameter measurement is studied. I have also investigated the physics potential of a preliminary low energy neutrino beam design for MINOS in Chapter 5, which may extend the sensitivity of

the experiment to the values of the mixing parameters that are suggested by the recent Super-Kamiokande atmospheric neutrino results.

Chapter 6 studies an independent and complementary method to measure the neutrino mixing parameters by analysing the energy distribution of ν_e charged-current events. This analysis is sensitive to $\nu_\mu \rightarrow \nu_e$ oscillations and can, when combined with the results of the ν_μ charged-current energy analysis described in Chapter 4, indicate whether the oscillation mode is $\nu_\mu \rightarrow \nu_e$, $\nu_\mu \rightarrow \nu_\tau$ or both.

Given that three-flavours of neutrino exist in nature, it is natural to assume that all three take part in the oscillations. Unlike previous experiments, MINOS data will be analysed in a three-flavour framework rather than the more restrictive two-flavour model. Moreover, MINOS has the statistical power and flavour identification capabilities to play a major role in the measurement of three-generation mixing parameters or in the exclusion of large regions of parameter space. In Chapter 7 I study the methods and prospects of a three-generation analysis of MINOS data. I also study the progress that MINOS could make to the measurement of a new CKM matrix for leptons and the prospects of observing CP violation in MINOS. The important consequences of the CHOOZ result for a three-generation analysis of MINOS are also discussed.

The atmospheric neutrino anomaly, which can be explained by $\nu_\mu \rightarrow \nu_\tau$ oscillations with large mixing strength, motivates the search for tau leptons in MINOS. The observation of tau lepton interactions would be a powerful indication of neutrino mixing since none are expected if oscillations do not occur. Chapter 8 describes a method to search for events of a particular topology that is more common in tau lepton interactions than in the background of ν_μ interactions. An excess of events with this topology is therefore indicative of $\nu_\mu \rightarrow \nu_\tau$ oscillations. Appendix B investigates how the sensitivity of this test changes as the major

parameters of the far detector (steel thickness, transverse granularity, active detector technology) are varied.

The important results of the thesis are summarised in Chapter 9. The interplay between MINOS measurements and those of other neutrino oscillation experiments and the implications of future MINOS results for models of neutrino mass and mixing are also discussed.