1. Introduction

The work in the present thesis concerns the analysis of the atmospheric neutrino data collected using the Soudan 2 detector between August 1991 and December 1996. This chapter introduces the concept of atmospheric neutrinos and the challenges presented in their analysis. A brief overview of the contents of each chapter follows.

Atmospheric neutrinos are generated in the interactions of cosmic rays in Earth's upper atmosphere and allow for possibilities into the exploration of new Physics. Over the past 10 years experiments measuring the atmospheric neutrino flavour ratio have reported an inconsistency when compared to the expectation from the Standard Model of Particle Physics: in the data, there is a deficit of muon neutrinos relative to the number of electron neutrinos. Moreover, results from experiments measuring the solar neutrino flux and from experiments monitoring Man-made neutrino beams have also added to the controversy over the properties of the neutrino. The question of *neutrino mass* and its manifestations in Nature is prevailing and is open and constitutes one of the puzzles in modern Particle Physics. Neutrino mixing, which might account for the atmospheric neutrino anomaly, is a popular explanation which could occur if neutrinos had mass. The ultimate aim of an atmospheric neutrino analysis is to explore the possibility of neutrino mass mixing and oscillations.

The Soudan 2 detector collects approximately 13.5 million events every year. The number of atmospheric neutrino interactions above detection threshold in Soudan 2 is of the order of 200 every year. Two thirds of them are rejected in order to minimise the background contamination of the final neutrino sample. The statistics of the final event sample are very low and the challenge of the selection of the neutrino sample with minimum background contamination is considerable. The Physics analysis of the neutrino sample follows. It consists of identifying the flavour (electron or muon) and determining the energy and direction of the neutrino interactions. This will allow to search for neutrino mixing, which would point back to neutrino mass.

The data in Soudan 2 has been traditionally scanned with two aims in mind: (i) to achieve the selection of the final neutrino data sample; (ii) to manually reconstruct and then classify the data sample into the muon-like and electron-like flavours. The work is undertaken by Physicists who exert their knowledge of neutrino interactions. In order to remove biases between the data and the expectation, exactly the same analysis is performed on a MC-simulated neutrino interactions event sample. The task is very laborious and time consuming and the **MC** sample analysed is of an exposure only six times that of the real data. Moreover, no results on the flavour content of "multi-prong" events (i.e. inelastic interactions where the lepton is accompanied by hadronic activity) have been reported yet because of the complexity of their reconstruction. More significantly, however, the process is prone to human biases. For this reason, an *automated analysis* has been developed and is presented in this thesis. Its main advantages over the scanned procedure follow:

- The element of subjectivity is removed.
- The analysis is fast and not labour-intensive.
- The element of feedback has been built in the process. The complete analysis may be repeated to incorporate new ideas and developments in our understanding of Physics and the detector.
- The **MC** statistics can be as large as desired or practically possible, removing the statistical errors involved.
- The whole data set is analysed for neutrino flavour and L/E_ν phase, including the neutral current and the charged current events with pion production. The

contribution of all neutrino scattering processes is therefore properly described. All available information is used in the analysis.

- The large-statistics **MC** sample has been generated in such a way as to provide the proper mix of neutrino flavours, energies and fluxes for any given neutrino mixing parameters. This allows for the comparison of the data to neutrino mixing hypotheses of interest. In the present thesis the $\nu_\mu \leftrightarrow \nu_\tau$, $\nu_\mu \leftrightarrow \nu_e$ and 3-generation one-mass-scale-dominance maximal neutrino mixing modes are explored.

The material in the present thesis is divided into seven chapters, the first of which is this short introduction. The second chapter introduces the neutrino and the concept of neutrino mass. The experimental evidence on searches for massive neutrinos and its manifestation in nature is described. It is hoped to unfold the motivations for the present research and to describe the methodology of atmospheric neutrino oscillation searches.

The third chapter presents an overview of the Soudan 2 detector, which has been used to collect the atmospheric neutrino data analysed in this thesis. Technical terms and concepts of the event reconstruction which are used throughout this thesis are defined. Examples of the experiment's operation are given using two events.

Chapter four provides a description of the Monte Carlo simulation package that has been purpose-built for the experiment by the Soudan 2 Collaboration. The discussion is very brief and does no justice to the amount of research and work that has gone into the development of the software. Emphasis is given to the small additions to the package that concern the present analysis, namely the possibility of generation of an "all flavour" neutrino event sample that allows for very fast simulations of any neutrino mixing mode.

Chapter five describes in detail the event selection process, RINSE, which is broken down into a series of cuts. The motivation and workings of each cut are presented in detail. The final data, background and **MC** event samples which will be used in the subsequent analysis are defined. The question of background contamination of the data sample is addressed for the first time in this thesis.

Chapter six defines the experimentally measured quantities, to be referred to by the name of "estimators", that are used to define the flavour and L/E_ν phase of a neutrino event. The motivation of each algorithm is presented and its performance is studied by analysing the **MC** event sample that has passed all the event selection cuts. The estimators are optimised on the **MC** sample and not on the data.

Finally, the seventh chapter presents the analysis of the data in terms of the neutrino flavour and L/E_ν phase estimators. The atmospheric neutrino flavour Ratio of Ratios is calculated. The present analysis confirms the atmospheric neutrino anomaly reported by water Čerenkov experiments. The "flavour" ratio in the background sample is examined and it is demonstrated that background contamination could not account for the observed anomaly. A multi-variable fit is introduced and is used to compare the data to the No Oscillations expectation, as well as with the $\nu_\mu \leftrightarrow \nu_\tau$, $\nu_\mu \leftrightarrow \nu_e$ and 3-generation maximal neutrino mixing hypotheses, always allowing for background contamination of the data. Limits on the neutrino mixing parameters are presented and the probability of agreement between data and model is calculated with two independent methods.