Nuclear Instruments and Methods in Physics Research A 624 (2010) 601–614

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Performance of the MIND detector at a Neutrino Factory using realistic muon reconstruction

A. Cervera [a], A. Laing [b,*], J. Martín-Albo [a], F.J.P. Soler [b]

[a] Instituto de Física Corpuscular, CSIC and Universidad de Valencia, Valencia, Spain
[b] School of Physics and Astronomy, University of Glasgow, Glasgow, UK

ARTICLE INFO

Article history:
Received 16 April 2010
Received in revised form
14 August 2010
Accepted 14 September 2010
Available online 21 September 2010

Keywords:
Neutrino Factory
Detector
Neutrino oscillation

ABSTRACT

A Neutrino Factory producing an intense beam composed of $\nu_e(\overline{\nu}_e)$ and $\overline{\nu}_\mu(\nu_\mu)$ from muon decays has been shown to have the greatest sensitivity to the two currently unmeasured neutrino mixing parameters, θ_{13} and δ_{CP}. Using the 'wrong-sign muon' signal to measure $\nu_e \rightarrow \nu_\mu(\overline{\nu}_e \rightarrow \overline{\nu}_\mu)$ oscillations in a 50 kt Magnetised Iron Neutrino Detector (MIND) sensitivity to δ_{CP} could be maintained down to small values of θ_{13}. However, the detector efficiencies used in these previous studies were calculated assuming perfect pattern recognition. In this paper, MIND is reassessed taking into account, for the first time, a realistic pattern recognition for the muon candidate. Reoptimisation of the analysis utilises a combination of methods, including a multivariate analysis similar to the one used in MINOS, to maintain high efficiency while suppressing backgrounds, ensuring that the signal selection efficiency and the background levels are comparable or better than the ones in previous analyses. As a result MIND remains the most sensitive future facility for the discovery of CP violation from neutrino oscillations.

1. Introduction

The concept of a neutrino beam from the decay of muons in a storage ring was first proposed in 1980 [1]. More recently, such a facility was explored as a preliminary stage towards a muon collider and was renamed "Neutrino Factory". Its physics potential was originally described by Geer [2]. The great advantage of a Neutrino Factory over conventional neutrino beams from pion decay is that the decay of muons is very well described by the standard model and so the beam flux is easily calculable. Therefore, it is possible to perform high precision neutrino oscillation experiments at a high flux Neutrino Factory. Another significant feature of a Neutrino Factory is that one can accelerate muons of both signs into a storage ring, thereby enabling study of both neutrino and anti-neutrino oscillations with equal flux, vastly improving sensitivity to CP violation in the neutrino sector. For a more recent review, see Ref. [3].

Early papers on the physics outcomes of a Neutrino Factory concentrated on the sub-dominant $\nu_e \rightarrow \nu_\mu$ oscillation [4] in which a muon of opposite charge to that stored in the facility storage ring (wrong-sign muon) would be produced in a far detector by the charge current (CC) interactions of the oscillated ν_μ. The first analysis of the capabilities of a large magnetised iron detector to detect the wrong-sign muon signature was discussed in Ref. [5] (termed the Golden Channel), where it was demonstrated that this combination was capable of the extraction of the remaining unknown parameters in the neutrino sector, the third mixing angle θ_{13} of the Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix [6–8] and the *CP* violating phase δ_{CP}.

The Magnetised Iron Neutrino Detector (MIND) is a large scale iron and scintillator sampling calorimeter. As a result of the studies mentioned above it is considered the baseline detector for a Neutrino Factory (NF) storing muons in the energy range 20–50 GeV [9]. Under the remit of EUROnu [10] and the International Design Study for a Neutrino Factory [11] all aspects of possible future neutrino beam facilities including accelerator, detectors and physics must be studied and compared to select the best option to determine the remaining oscillation parameters.

Previous studies of MIND focused on the topology and kinematics of neutrino events in the detector, assuming perfect pattern recognition. By smearing the kinematic variables of the participant muon and hadronic shower it was demonstrated that using a combination of cuts on the relative length of the two longest particles in the event and the momentum and isolation of this candidate, high signal identification efficiency and background suppression could be achieved [12,13]. However, a full study without such assumptions is necessary to fully characterise the detector response.

While MIND is essentially a large scale version of the MINOS detector [14], the nature of the NF beam – containing 50% ν_e and

---

* Corresponding author.
E-mail addresses: anselmo.cervera@ific.uv.es (A. Cervera), a.laing@physics.gla.ac.uk (A. Laing), Justo.Martin-Albo@ific.uv.es (J. Martín-Albo), p.soler@physics.gla.ac.uk (F.J.P. Soler).

0168-9002/$ - see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2010.09.049

50% $\overline{\nu}_\mu$ in the case of stored μ^+ – means that the optimisation of the analysis is somewhat different. Incorrect charge assignment (charge misidentification) of non-oscillated $\overline{\nu}_\mu$ CC interactions present a significant possible background in this beam configuration, in addition to backgrounds from meson decays in the hadronic shower and misidentification of Neutral Current (NC) and ν_e CC events.

This current study revisits the problem by taking an un-biased look at the visible part of a large sample of neutrino interactions – generated using the same GEANT3 [15] simulation as in the above-mentioned studies with a uniform distribution in neutrino energy – and developing pattern recognition algorithms (first presented in Ref. [16]) – described in Section 3 – to extract a candidate muon for fitting using a Kalman filter. Successful fits are then subject to offline analyses – described in Section 4 – to determine the validity of those wrong-sign candidates. Analysis results are presented in Section 5.

2. MIND parameterisation and expected event yields

For the purpose of the described study, MIND is a cuboidal detector of 14 m × 14 m cross-section and 40 m length, segmented longitudinally as 4 cm of iron and 1 cm of plastic scintillator for a total mass of ~ 51.0 kt. No transverse segmentation was simulated, but transverse position smearing of $\sigma = 1$ cm was carried out, corresponding to an effective segmentation of 3.5 cm. Each scintillator plane currently represents two view matched planes. A dipole magnetic field of mean induction 1 T in the transverse plane provides the field necessary for charge and momentum measurements.

In the first part of the analysis, event vertices were generated centred in the detector plane at 1.5 m from the front of the detector in the beam direction (z) in order to study the nature of the backgrounds without detector edge effects. Section 4.3 discusses the expected fiducial effects when a more realistic randomly generated vertex is considered.

At a MIND placed 4000 km from the neutrino source and assuming the current best global fit oscillation parameters: $\theta_{12} = 33.5^\circ, \theta_{23} = 45^\circ, \Delta m^2_{21} = 7.65 \times 10^{-5}$ eV^2, $\Delta m^2_{32} = 2.40 \times 10^{-3}$ eV^2 [17], setting $\delta_{CP} = 45^\circ$ and calculating matter effects using the PREM model [18], the expected total number of interactions due to $10^{21} \mu^+$ decays at 25 GeV energy would be of order those shown in Table 1, for $\theta_{13} = 5.7^\circ$ and 0.2°.

Thus in order to successfully extract oscillation parameters from the golden channel, potential backgrounds from non-signal interactions must be suppressed to at most the 10^{-3} level in absolute terms with sensitivity to smaller values of θ_{13} requiring even more stringent suppression. Moreover, the existence of possible degenerate solutions due to uncertainty in the measured parameters and due to the nature of the oscillation probability (see Refs. [19,20]) means that spectral information is required to reliably determine δ_{CP}. This additional requirement dictates that backgrounds must be suppressed to below 10^{-3} in each energy bin while maintaining an efficiency threshold below 5 GeV, so that information on the rise of the first oscillation maximum is available for even very small θ_{13} values.

Table 1
Expected absolute number of interactions in a 51 kt MIND at a distance of 4000 km from $10^{21} \mu^+$ decays at 25 GeV in a NF storage ring.

θ_{13} (deg)	$\overline{\nu}_\mu$ CC	ν_e CC	$\overline{\nu}_\mu + \nu_e$ NC	ν_μ (signal)
5.7	1.27×10^5	3.50×10^5	1.56×10^5	5.92×10^3
0.2	1.27×10^5	3.60×10^5	1.59×10^5	1.12×10^2

3. Reconstruction tools

The reconstruction package was used to analyse a large dataset comprised of Deep Inelastic Scattering (DIS) neutrino interactions of $\overline{\nu}_\mu$ and ν_e generated by the LEPTO61 [21] package in the energy range 0–30 GeV and tracked through the GEANT3 simulation of MIND. Considering $\sim 10^6$ interactions each of $\overline{\nu}_\mu$ and ν_e CC with a dedicated study of events containing wrong-sign muons from meson decay ν_μ CC (performed with statistics equivalent to 5×10^6 interactions to give $\sim 6 \times 10^5$ wrong-sign events) and $\sim 2.5 \times 10^6$ NC interactions the main expected backgrounds were studied.

Each event considered comprised all 3D points with their associated energy deposit, which were recorded in the scintillator sections of the MIND simulation, with the x, y positions of these hits smeared according to a $\sigma = 1$ cm Gaussian before analysis began.

3.1. Muon candidate extraction

After ordering the hits from smallest to greatest z position in the detector the first step of the reconstruction was to extract a candidate muon from the event. Two methods were employed to perform this task depending on the event topology: a Kalman filter incremental fit was used to extract candidates from those events with one particle clearly longer than the others (described in Section 3.1.1), while a cellular automaton method was used in those events not viable for reconstruction through the first method (see Section 3.1.2). The criterion for the first category was that the five planes with activity furthest downstream should contain no more than one hit per plane.

3.1.1. Kalman filter candidate extraction

Using the Kalman filter algorithm provided by RecPack [22] it is possible to propagate the track parameters back through the planes using a helix model, which takes into account multiple scattering and energy loss. Since, in general, a muon will act as a Minimum Ionising Particle (MIP) and will travel further in the detector than the hadronic particles, those hits furthest downstream can be assumed to be muon hits and used as a seed for the Kalman filter. The seed state is then propagated back to each plane with multiple hits and the matching χ^2 to each of the hits is computed. Hits with matching χ^2 below 20 are considered and in each plane the one with the best matching among these is added to the trajectory and filtered (the track parameters are updated with the new information). All accepted hits constitute the candidate muon and are presented for fitting (Section 3.2), with the remaining hits being considered as hadronic activity. Fig. 1(left) shows the fraction of true muon hits in the candidate when using this method.

3.1.2. Cellular automaton candidate extraction

Events with high Q^2 transfer or low neutrino energy can tend to be rejected by the first method, since in general the muon will not escape the region of hadronic activity. Should this be the case reconstruction is attempted using a cellular automaton. The cellular automaton method (based on the method described in Ref. [23]) uses a neighbourhood function to first rank all the hits and then form all viable combinations into possible trajectories.

A 'neighbour' is defined as a hit in an adjacent plane within a pre-defined transverse distance of the projection into that plane of the straight line connecting hits in the previous two planes. Starting from the plane with lowest z position, hits are given a rank one higher than their neighbour in the previous plane should they have one. Trajectories are then formed from every possible