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SUPA, School of Physics and Astronomy
Experimental Particle Physics Group
Kelvin Building, University of Glasgow,
Glasgow, G12 8QQ, Scotland
Telephone: +44 (0)141 330 2000 Fax: +44 (0)141 330 5881

A Neutrino Factory Toroidal MIND at Large θ_{13}

R. Bayes[1], A. Bross[2], A. Cervera-Villanueva[3], M. Ellis[4], T. Ghosh[3], A. Laing[1], F.J.P. Soler[1], R. Wands[2]
[1] School of Physics and Astronomy, University of Glasgow, Glasgow, G12 8QQ, UK
[2] Fermilab, P.O. Box 500, Batavia, IL 60510-5011, USA
[3] IFIC and Universidad de Valencia, Valencia, Spain
[4] Westpac Institutional Bank, NSW, Australia

Abstract

A neutrino factory has unparalleled physics reach for the discovery and measurement of CP violation in the neutrino sector. A far detector for a neutrino factory must have good charge identification with excellent background rejection and a large mass. An elegant solution is to construct a magnetized iron neutrino detector along the lines of MINOS, where iron plates provide a magnetic field and scintillator planes provide 3D space points. In this presentation, the current status of a simulation of MIND for a neutrino factory will be discussed, focussing on the ramifications of the recent measurement of large $\theta_1 3$. Particular detail will be applied to results using the new baseline 10 GeV neutrino factory configuration. A summary of the expected detector performance from the current reconstruction will be given with the resulting sensitivities.

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	Store μ^+	Store μ^-
Golden Channel	$\nu_e \rightarrow \nu_\mu$	$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$
ν_e Disappearance Channel	$\nu_e \rightarrow \nu_e$	$\bar{\nu}_e \rightarrow \bar{\nu}_e$
Silver Channel	$\nu_e \rightarrow \nu_\tau$	$\bar{\nu}_e \rightarrow \bar{\nu}_\tau$
Platinum Channel	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	$\nu_\mu \rightarrow \nu_e$
ν_μ Disappearance Channel	$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$	$\nu_\mu \rightarrow \nu_\mu$
Dominant Oscillation	$\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau$	$\nu_\mu \rightarrow \nu_\tau$

Table 1: Oscillation channels observable at a neutrino factory.

1 Introduction

The discovery of large θ_{13} by Daya Bay [An et al.(2012)] and others [Ahn et al.(2012), Okumura(2012), Yang(2011)] requires a shift in the priorities of the planning for the next generation neutrino experiments, including neutrino factory [Choubey et al.(2011)]. This discovery focusses the neutrino factory long baseline physics program on the optimized measurement of CP violation. The optimal experimental design consists of a single detector at a baseline of 2000 km with a stored muon energy of 10 GeV. This supersedes a two detector configuration with baselines of 4000 and 7500 km and a stored muon energy of 25 GeV which was required to resolve δ_{CP} degeneracies in the case of small θ_{13}.

A neutrino factory offers unique physics opportunities because of the clean neutrino beam generated by muon decays at an extremely high rate. The content of the beam is precisely known as 50% $\nu_e(\bar{\nu}_\mu)$ and 50% $\bar{\nu}_\mu(\nu_\mu)$, presenting six different channels for long baseline oscillations (see Table 1). The most easily detected channels are those where there is a $\mu^\pm$ in the final state of a neutrino charge current (CC) interaction. The significance of a measurement is limited by the ability to remove neutral current (NC) interactions and resolve the signal muon charge as a primary source of background with the opposite charge to the signal. For a neutrino factory, a magnetized iron neutrino detector (MIND) is the favoured far detector [Cervera et al.(2010), Bayes et al.(2012)] because it has excellent charge identification capabilities coupled with an easily scalable fiducial mass. These proceedings describe an optimization of the NF golden channel oscillation analysis, $\nu_e(\bar{\nu}_e) \rightarrow \nu_\mu(\bar{\nu}_\mu)$, in a realistic MIND.

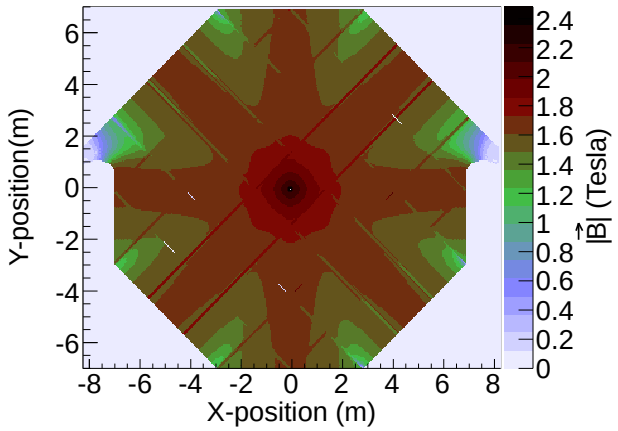

Figure 1: Magnetic field map of detector.

2 Simulation Overview

The neutrino factory MIND is an iron-scintillator calorimeter, analogous to MINOS[Michael et al.(2008)], consisting of alternating steel and scintillator planes. The detector has an octagonal cross-section 14 m×14 m with triangular support structures on either side of the steel plates. To produce the planned 100 kTon fiducial mass, this detector needs to be 140 m in length. The magnetic field is induced in the 3 cm thick steel planes using 120 kA of current to be carried by one or more turns of a 7 cm diameter super conducting transmission line (STL)[Ambrosio et al.(2001)]. The magnetic field magnitude from a simulated detector plate is shown in Fig. 1. The majority of magnetic field lines point in the azimuthal direction, which focus positive charges toward the

		Signal Eff		Background ($\times 10^3$)	
Event Cut	Description	$\bar{\nu}_\mu$	ν_μ	$\bar{\nu}_\mu$	ν_μ
Successful Track Fit	Failed Kalman reconstruction of event removed	85.3%	71.2%	291($\bar{\nu}_e$)	301(ν_e)
Fiducial	Event vertex more than 1.5 m from end of detector	84.9%	70.8%	288($\bar{\nu}_e$)	298(ν_e)
Maximum Momentum	Muon momentum less than $1.6\times E_\mu^{stored}$	84.0%	69.4%	253($\bar{\nu}_e$)	266(ν_e)
Fitted Proportion	60% of track nodes used in final fit.	83.8%	68.7%	238($\bar{\nu}_e$)	249(ν_e)
Track Quality	$\log(P(\sigma_{q/p}/(q/p)\|CC)/P(\sigma_{q/p}/(q/p)\|NC)) > -0.5$	80.7%	64.0%	66(ν_τ)	76(ν_e)
CC Selection	$\log(P(N_{hit}\|CC)/P(N_{hit}\|NC)) > 1.0$	79.4%	57.5%	3.4(ν_τ)	3.7(ν_e)
Kinematic	$Q_t > 0.15 GeV$	74.1%	54.7%	2.4(ν_τ)	0.9($\bar{\nu}_\tau$)

Table 2: Cuts used in the selection of good events from the simulation with the integrated signal efficiencies and leading backgrounds after each cut.

centre of the detector by default. The scintillator planes are a 2 cm thick lattice of 1 cm×3.5 cm scintillator bars in the x and y direction to measure a 3D space point between each steel plane with a 1 cm position resolution.

This geometry was simulated in GEANT4[Allison et al.(2006)] using the QGSP_BERT physics list for hadron interactions. The specifications of the detector geometry was set up so that it is easily altered for optimization studies and to test detector variations. Neutrino events were simulated using the GENIE event generator[Andreopoulos et al.(2010)]. Each of the simulated events was subject to a simple digitization wherein the positions of the hits were smeared, the energy deposition of each hit was attenuated, assuming a 5 m attenuation length, and the hits were clustered into 3.5 cm×3.5 cm units corresponding to the transverse width of the scintillator bars.

Tracks were identified using a Kalman filtering algorithm, or, if the longest set of single occupancy planes is less than 5 planes long, a Cellular Automaton method[Cervera et al.(2010)]. The identified tracks were subjected to a Kalman fitting algorithm to determine the momentum and the charge of the track based on its curvature. The algorithms used for this reconstruction are contained in the RecPack software package[Cervera-Villanueva et al.(2004)].

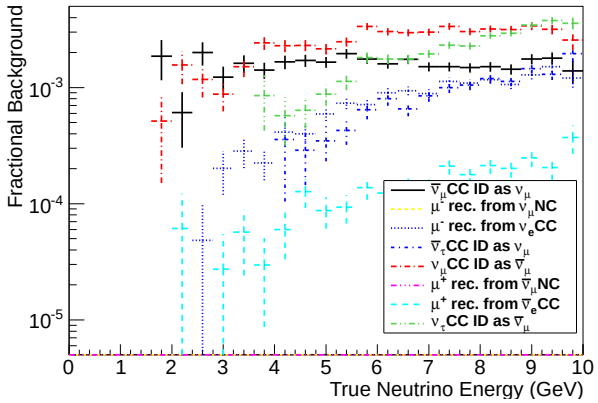

Figure 2: μ^+ focussed background.

3 Analysis

Subsequent analysis was done to separate the $\nu_\mu(\bar{\nu}_\mu)$CC signal events from the backgrounds. This was done through the successive application of a set of seven cuts; four cuts to remove poorly reconstructed events and three to explicitly differentiate CC signal events from background. These cuts and their impact on the signal and background are summarized in Table 2.

The most effective cuts were on the Track Quality and the CC selection. Both used a similar formalism to identify muons and reject backgrounds using the logarithm of the ratio of the probability that the given event was a charge current or neutral current event. For the track quality cut the probability was defined using the distribution of the scaled error in the measurement of the charge divided by the momentum, $\sigma_{q/p}/(q/p)$. The probability used for the CC selection cut is based on the distribution of the number of hits in a sample of CC trajectories and NC trajectories. The combination of these cuts suppressed the NC backgrounds to below the level of the statistics (parts in 10^{-6}) while all remaining backgrounds were suppressed by parts in 10^{-3}, as shown in Fig 2 for a positive focussing field and Fig. 3 for a negative focussing field. The reconstruction

efficiencies were at or above 50% after these cuts were applied. The detector performance depended on whether the detector field focused positive or negative charges as shown in Fig. 4 and Fig. 5, as a result of reconstructing different inelasticity distributions in ν_μ and $\bar{\nu}_\mu$ CC samples.

A multivariate analysis is under development for the MIND analysis. This analysis uses a larger subset of variables than those described above to identify and remove neutral current events, including the mean and variation of energy deposition along reconstructed tracks. Such a method should be able to select muons with a lower energy threshold than the existing cuts.

4 Sensitivity to δ_{CP}

The detector response was used to determine the sensitivity of a neutrino factory to CP violation in muon neutrino appearance channel. A set of migration matrices, one for the NC background and one for each of the oscillation channels, were defined using the flux normalized response as a function of the true neutrino energy versus the reconstructed neutrino energy. The fluxes and oscillation probabilities were calculated using the Neutrino Tool Suite (NuTS)[Burguet-Castell et al.(2001)]. Both θ_{13} and δ_{CP} were fit simultaneously by minimizing

$$\begin{aligned}\chi^2 \quad = 2 \times \sum_{e}^{E_\mu} \quad & \{AxN^e_+(\theta_{13},\delta_{CP}) - n^e_+ \\ & + n^e_+ \log\left(\frac{n^e_+}{AxN^e_+(\theta_{13},\delta_{CP})}\right) \\ & + AN^e_-(\theta_{13},\delta_{CP}) - n^e_-\end{aligned}$$

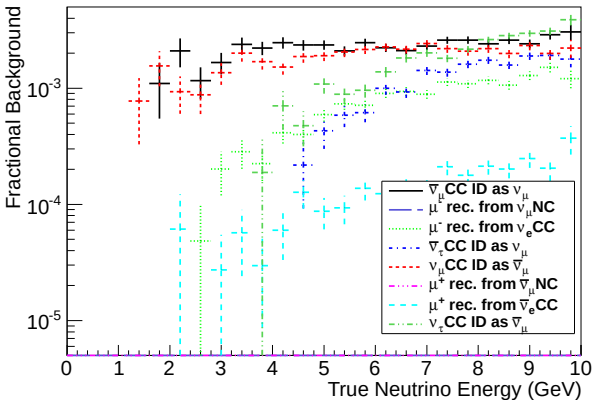

Figure 3: μ^- focussed background.

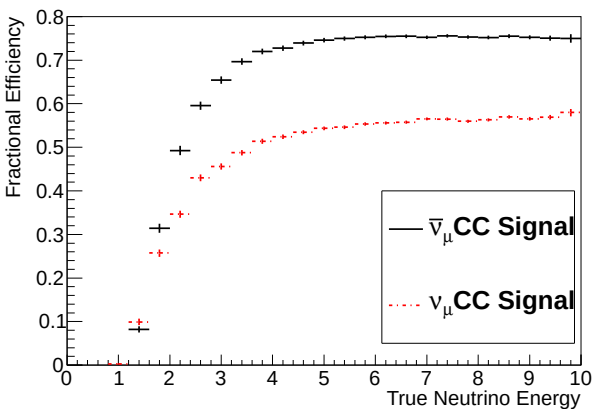

Figure 4: μ^+ focussing detector efficiency.

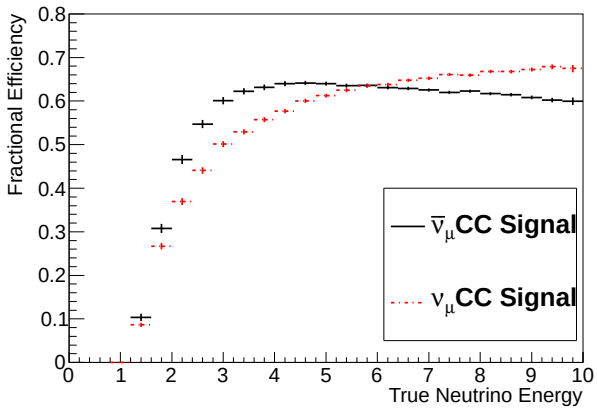

Figure 5: μ^- focussing detector efficiency.

$$+n^e_- \log\left(\frac{n^e_-}{A_j N^e_-(\theta_{13},\delta_{CP})}\right) + \frac{(A-1)^2}{\sigma_A^2} + \frac{(x-1)^2}{\sigma_x^2}\Bigg\} \quad (1)$$

where n^e_i is the "data" for an energy bin e, assuming a detector baseline of 2000 km from stored muons with charge i, and N^e_i is the prediction for the same bin. Two systematic uncertainties were assumed to dominate and appear explicitly in this χ^2 formulation; an uncertainty in the total number of interactions in the detector (σ_A), believed to be 1%, and the uncertainty in the ratio between ν_μ and $\bar{\nu}_\mu$ cross-sections (σ_x), also assessed as 1%. As the ratio of stored muon charges is not known for the apparatus and the ratio does not affect the final physics results, it is assumed that $5{\times}10^{20}$ muons of both charges will decay in the storage ring per year.

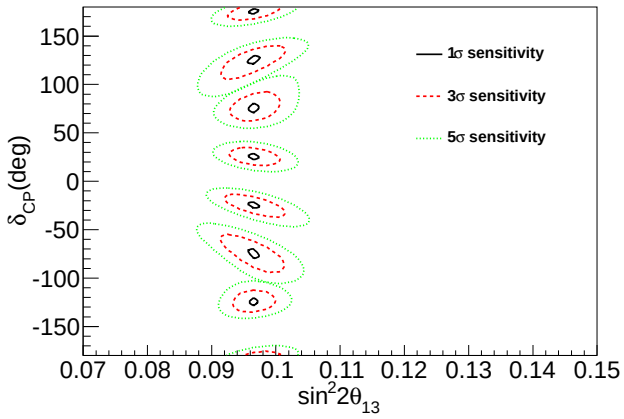

Figure 6: Fits to "data" assuming arbitrary δ_{CP} at $\theta_{13} = 9°$.

χ^2 contours derived from the Eq. 1 as functions of $\sin^2 2\theta_{13}$ and δ_{CP} for 10 years of running are shown in Fig. 6 assuming various true values for δ_{CP} and that the $\theta_{13} = 9°$. With the measurement of θ_{13} the precision of the experiment to δ_{CP} has become the primary figure of merit for the performance of the experiment. The one standard deviation error contour as a function of δ_{CP} is shown in Fig. 7 assuming the systematic uncertainties to be 1% and assuming $\sigma_x = 3\%$ and $\sigma_A = 2.5\%$, illustrating the sensitivity of the neutrino factory to variation in the systematics. The experiment is not sensitive to reversing the detector field polarity as the sensitivity contours are identical for positive and negative charge focussing magnetic fields.

The results using a toroidal magnetic field have backgrounds that are an order of magnitude larger than those achieved for interim analyses with a dipole field[Bayes et al.(2012)]. The reduction in background does not affect the experimental sensitivity, however. Gains in the experimental sensitivity will likely not be made by reducing background or improving efficiency without increased knowledge of the energy threshold of the experiment.

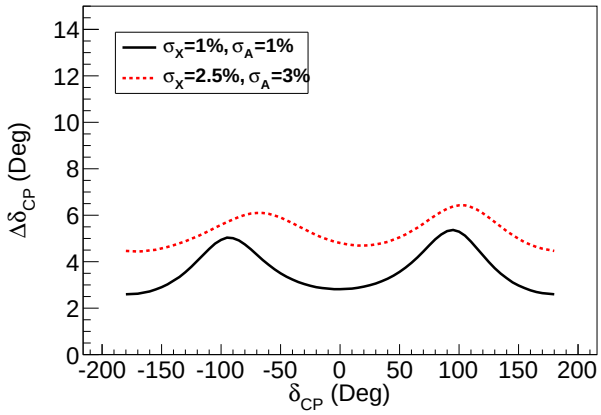

Figure 7: Precision in δ_{CP} as a function of δ_{CP}.

5 Conclusions

The simulation of the neutrino factory MIND has made a great deal of progress in the last year. The simulation has made a complete change to the GENIE event generator following the example of MINOS and others. A realistic octagonal geometry has been introduced with a corresponding magnetic field simulation. These modifications were accompanied by improvements in the track reconstruction to accommodate the new magnetic field map. However there is still work in progress. The reconstruction must be made to reconstruct hadronization and the analysis is being updated to use a multi-variate method for the rejection of neutral current events. Preliminary analyses show that aneutrino factory with a MIND can achieve a precision in δ_{CP} between 2.5° and 4.5°.

6 Acknowledgements

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