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Status of the MIND simulation and analysis

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Abstract

A realistic simulation of the Neutrino Factory detectors is required in order to fully understand the sensitivity of such a facility to the remaining parameters and degeneracies of the neutrino mixing matrix. Here described is the status of a modular software framework being developed to accomodate such a study. The results of initial studies of the reconstruction software and expected efficiency curves in the context of the golden channel are given.

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1 Introduction

The Magnetised Iron Neutrino Detector (MIND) is a large scale iron/scintillator sampling calorimeter currently under study as the baseline detector for the golden channel at a Neutrino Factory (NF) [1]. As such, a full study of all aspects of such a detector is required to determine its performance with the aim of achieving or surpassing the level of sensitivity presented in [2], in which a fast simulation and reconstruction were used. A modular software framework is currently being developed in this context with first results being presented in [3]. These proceedings summarise the current status of a new Geant4 [4] simulation of MIND and physics results from reconstruction analysis using the old Geant3 [5] simulation.

2 The Detector simulation

Developement of a new Geant4 simulation of MIND is underway. The simulation was designed to give as much flexibility to the geometry as possible. The dimensions and spacing of all scintillator and iron pieces as well as all external dimensions of the detector can be controlled. This will allow for easy comparison of the simulation itself and the subsequent analyses to other potential NF detectors. Moreover, the ability to perform a direct comparison with an existing detector like MINOS [6] would lend considerable weight to any results published from this exercise.

Neutrino interactions will be generated using either the Nuance [7] or GENIE [8] generators independently. Both allow for the consideration of all types of neutrino interaction including quasi-elastics and resonances. Digitization of the hit information from Geant4 will be carried-out in a free-standing package and will ultimately be developed into a full simulation of light passage through appropriately shaped plastic scintillator. The resultant information will be passed to an independent reconstruction package which is described in the following section.

In the analysis results presented here $\overline{\nu}_\mu$ charge and neutral current (CC,NC) deep inelastic scattering (DIS) events were used to study key backgrounds to the $\nu_e \rightarrow \nu_\mu$ appearance channel. Signal efficiency is considered using these interactions due to the symmetry of the current MIND parameterisation in its response to ν_μ and $\overline{\nu}_\mu$ interactions.

3 Reconstruction

The reconstruction algorithms are now well developed, having been first presented in [3], and have been tested using the Geant3 simulation of MIND used in previous analyses [9, 10]. In these studies and in the initial studies which will be carried out using Geant4 the reconstruction will be presented with the full set of 3D hits produced in particle tracking with digitization consisting of a Gaussian smear on the transverse resolution with $\sigma = 1$ cm.

3.1 Muon extraction

Two methods are employed in the extraction of a candidate muon from an event. The first requires one particle to extend at least 5 planes beyond those with other activity and uses the Kalman Fitter provided by RecPack [11] to filter back through those planes containing multiple hits, accepting that with the lowest matching χ^2.

Events with high Q^2 transfer or low neutrino energy can tend to be rejected by this first method. In order to recover these events which do not pass the minimum 'free' hit cut a second more complicated method is employed. The Cellular Automaton method (based on the method described in [12]) uses a neighbourhood function to first rank all the hits and then form all combinations of viable trajectories.

A 'neighbour' is defined as a hit in an adjacent plane within a pre-defined transverse distance to the projection into that plane of the straight line connecting hits in the previous two planes. Starting from the plane with lowest longitudinal 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 combination of one hit per plane starting with those of highest rank using the neighbourhood function with a stricter condition.

Those trajectories formed using this method are then subject to a number of tests to determine that most likely to be a muon. After having a basic helix fit performed and being assessed according to their length, trajectories are rejected for being short, having high fit χ^2 or high relative curvature error. The candidate muon is then selected as the longest remaining trajectory with the lowest χ^2. All other hits in the event are considered to be from hadronic activity. The purity achieved using the two methods is shown in figure 1.

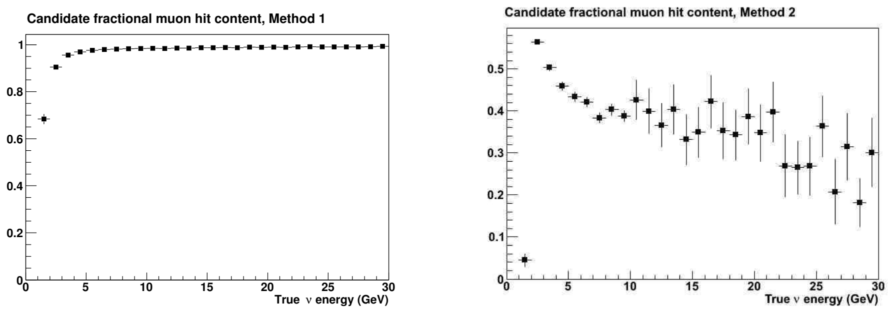

Figure 1: *Candidate muon purity for (left) Kalman filter method and (right) Cellular automaton method*

3.2 Muon candidate fitting

All candidates successfully extracted from their event which have more than 6 hits are presented to the fitter as a candiate muon. The same Kalman filter algorithm is used here as in the previous section. Fitting the candidate iteratively improves seeding and thus, using a more constricted χ^2 condition than in pattern recognition the maximum number of successful, reliable fits were achieved.

3.3 Hadron reconstruction

The remaining hits must be used to reconstruct the energy in the hadronic part of the neutrino interaction. In addition, reconstruction of a direction vector for the hadronic activity would enable cuts on the isolation of the candidate which were shown to be a powerful handle in the rejection of candidates from hadronic decays in [10].

Studies are underway into possible methods for reconstructing the hadronic activity. However, the current Geant3 simulation does not contain a fully developed hadron shower and as such reconstruction will be further developed in the era of the full Geant4 simulation.

In order to have an idea of the reconstructed neutrino energy in the current results (described in the analysis section) the true hadronic energy is smeared according to the MINOS CalDet [6, 13] findings (Eq. 1).

$$\frac{\sigma}{E} = \frac{0.55}{\sqrt{E}} + 0.03 \tag{1}$$

3.4 Analysis

Successful fits are considered according to the charge assigned to them by the fit as signal or potential background. A series of methods are considered in order to suppress the maximum amount of wrong sign candidates which occur because of charge mis-assignment or arising from interactions other than ν_μ CC.

3.4.1 Quality cuts

A candidate trajectory fit with the incorrect charge will tend to be dominated by multiple scattering and hence the quality of the fit will be affected. Examining the relative error on the curvature variable of the fitted state vector shows significant separation for correctly and incorrectly fitted trajectories (Fig. 2). In addition, the trajectory χ^2 can be used as a powerful separator. Cutting as described in Eq. 2 can reduce backgrounds due to charge mis-ID significantly. Alternatively, the curvature error can be used as a PDF to form a likelihood discriminator ($\mathcal{L}_{\frac{q}{p}}$) and treated in a similar way to the parameters considered in the likelihood analysis section.

$$\left|\frac{\sigma_{\frac{q}{p}}}{\frac{q}{p}}\right| < 0.7 \text{ and } \chi^2_{prob} > 0.9999 \tag{2}$$

3.4.2 Likelihood analysis

Using parameters easily obtainable from the extracted candidates a log likelihood method has been developed based on that used in the MINOS analysis [14]. Distributions of the number of hits in the candidate, the fraction of the visible energy in the candidate and the variance of the energy deposit along the candidate are shown in Fig. 3. These parameters are used to form the likelihood discriminators described in eq. 3 and 4, where $\mathcal{L}_2$ is

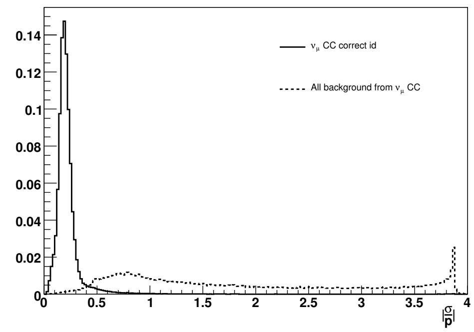

Figure 2: *PDFs for signal and background in the curvature error variable, used to form likelihood* $\mathcal{L}_{\frac{q}{p}}$.

formed from separate PDFs of events with visible energy fraction greater than 0.99 where this variable is not useful.

$$\mathcal{L}_1 = \log\left(\frac{f_{hit}^{CC} \times f_{frac}^{CC} \times f_{var}^{CC}}{f_{hit}^{NC} \times f_{frac}^{NC} \times f_{var}^{NC}}\right) \quad (3)$$

$$\mathcal{L}_2 = \log\left(\frac{f_{hit}^{CC^{frac=1}} \times f_{var}^{CC^{frac=1}}}{f_{hit}^{NC^{frac=1}} \times f_{var}^{NC^{frac=1}}}\right) \quad (4)$$

The most promising analysis considered involves the requirements that a candidate muon be fit so that the likelihood of the curvature error variable $\mathcal{L}_{\frac{q}{p}} > 1.0$ and that $\mathcal{L}_{1/2} > 0$. As can be seen in Fig. 4 this affords a high level of rejection of background events. A summary of key background and signal efficiency for this analysis chain is shown in Fig. 5.

4 Plans

Development of the full simulation and analysis framework will continue with the introduction of G4 simulated data to the pattern recognition analysis. Thus in the future the full spectrum of possible interactions can be considered in order to exploit the full potential of this detector technology.

5 Conclusions

Considering the efficiencies presented in [1] as the baseline detector for the NF it can be seen in Fig. 5 that some work remains to be done to achieve the same level of suppression of the backgrounds. However, reconstruction of the hadronic parameters including the direction would allow for the use of these parameters to further suppress backgrounds. It is expected, thus, that implementation of the full analysis chain including all types of interaction and application of a further developed analysis algorithm would result in achievement of the stated goals of the study.

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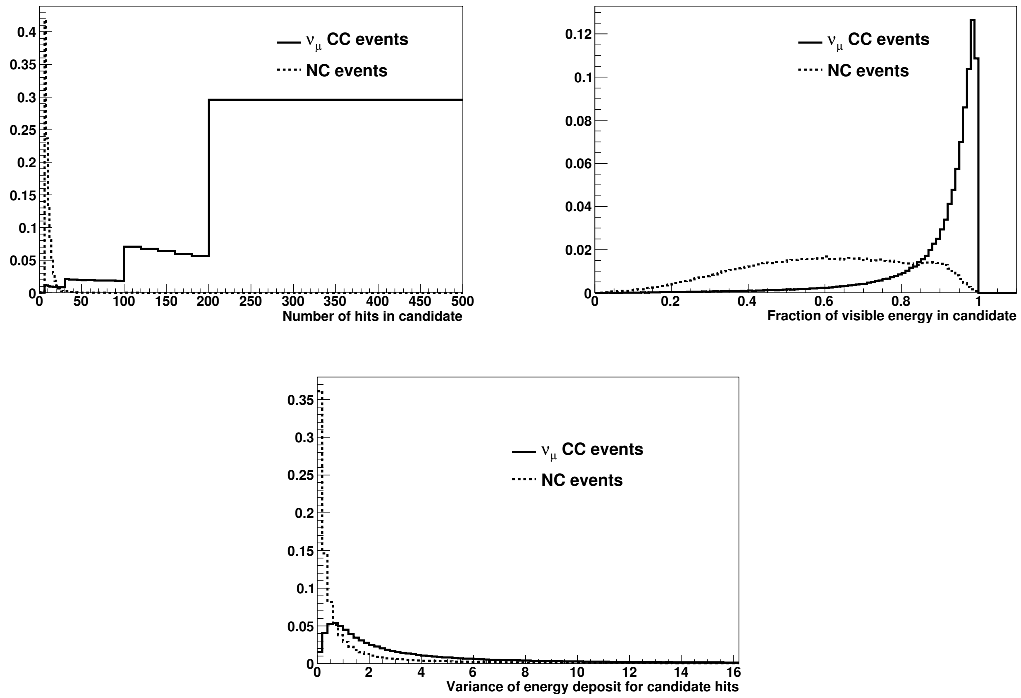

Figure 3: *PDFs of the three parameters used for likelihood separation. (1) Number of hits in candidate, (2) Fraction of visible energy in candidate, (3) Variance of energy deposit in candidate.*

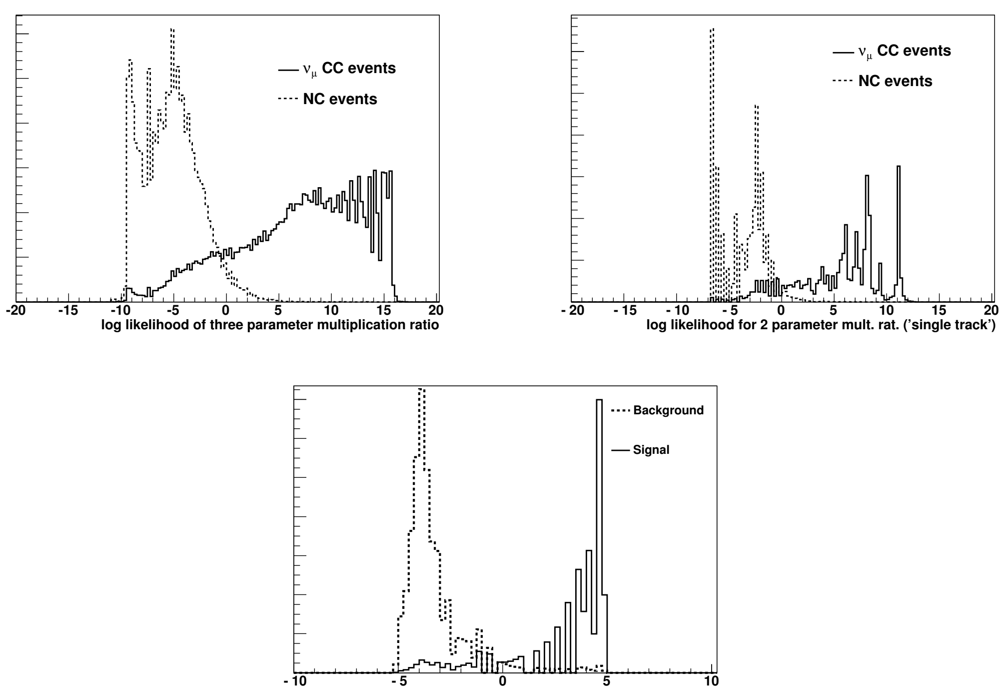

Figure 4: *Distribution of likelihood discriminators: (1) $\mathcal{L}_1$, (2) $\mathcal{L}_2$ and (3) $\mathcal{L}_{\frac{q}{p}}$*

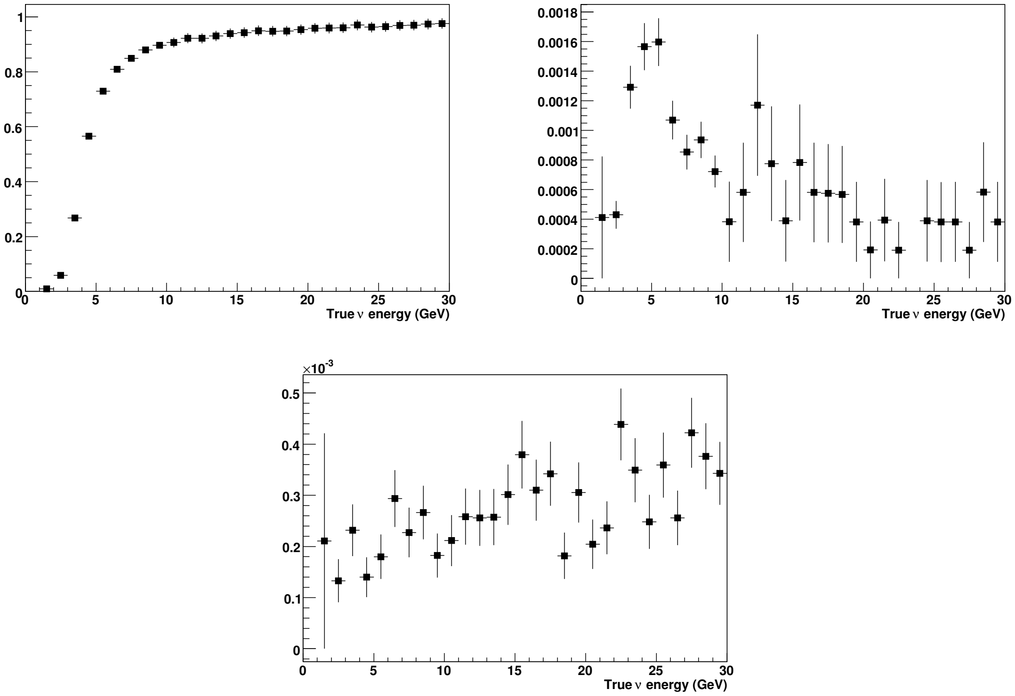

Figure 5: *Summary of current status of efficiencies with true ν energy, (1) Signal efficiency, (2) Charge mis-ID background, (3) NC background*

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