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Propagation of error in the Physics analysis with the variation in magnetic field in the ICAL detector

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The magnetized iron calorimeter (ICAL) detector proposed at the India-based Neutrino Observatory will be a 51 kton detector made up of 151 layers of 56 mm thick soft iron layers with 40 mm air gap in between where the RPCs, the active detectors, will be placed. The main goal of ICAL is to make precision measurements of the neutrino oscillation parameters using the atmospheric neutrinos as source. The charged current interactions of the atmospheric muon neutrinos and anti-neutrinos in the detector produce charged muons. The magnetic field, with a maximum value of ∼ 1.5 T in the central region of ICAL, is a critical component since it will be used to distinguish the charges and determine the momentum and direction of these muons. The geometry of the ICAL has been optimized to detect muons in the energy range of 1-15 GeV. It is difficult to measure the magnetic field inside iron, therefore measuring field using external methods can introduce error. In this study the effect of error in measurement of magnetic field in ICAL is studied. An attempt is made to know how the uncertainty in the magnetic field values will propagate in the reconstruction of momentum and other aspects of the physics analysis of the data from ICAL detector using GEANT4 simulations.

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1. Introduction

ICAL is a magnetized 51 k-Ton detector with $B_{max} \sim 1.5$ Tesla. This allows measuring the charge and momentum of muons produced in charged current interactions of atmospheric muon neutrinos. Since ICAL has excellent charge id efficiency it can help in studying matter effect on ν_μ and $\overline{\nu}_\mu$ that can resolve neutrino mass ordering by determining the sign of the 2–3 mass square of difference $\Delta m^2_{32} \equiv m^2_3 - m^2_3$. Recently, several measurements at the 85 ton mini-ICAL detector indicated that it may be possible to get agreement between measured and simulated field values to within a few percent [1]. Here we present a preliminary and first study of the effect of errors in the measurement of the magnetic fields on the physics goals of ICAL.

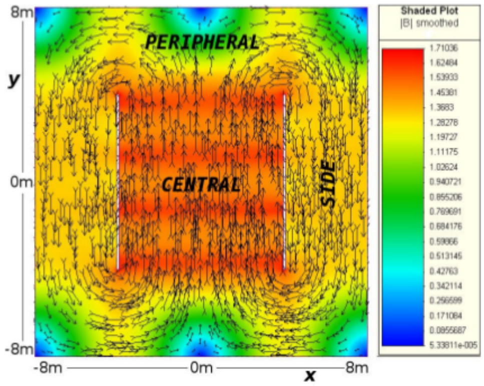

Figure 1: Field map of simulated magnetic field for ICAL detector

2. Simulations study of muons

The GEANT4 code is used to generate the ICAL geometry which comprises three modules of 151 layers of 56 mm iron, separated by a 40 mm gap in which the active detector elements, the RPCs, are inserted. The magnetic field map shown for a single iron layer in Fig. 1 is generated using MAGNET 6.0 software [2]. Muons of different energies are generated at different angles and location and their hit pattern is studied. There is a “true" magnetic field, $B(x, y, z)$, which bends the muons into the observed muon track. These tracks are fitted with the computed or simulated magnetic field map, which may be different from the actual one. For simplicity, 6 scenarios, when the fitted magnetic field is $0.8B, 1.2B, 0.95B, 1.05B, 0.98B, 1.02B$ are considered, that is 20%, 5% or 2% smaller or greater than the true magnetic field as given by the magnetic field map. The reconstructed energy E_{reco}, the energy resolution σ, and the charge identification efficiency in each case is calculated. It turns out that E^{fB}_{reco} is given to very good accuracy by a constant scale parameter compared to E^{B}_{reco} for the original map, where f = 0.8, 1.2, 0.95, 1.05 etc. This is shown in Table 1. The actual reconstructed values are shown along with this fit in Fig. 2 as a function of E_{true} for a range of $\cos\theta$ from 0.4 to 0.8 (closely overlapping data).

3. Precision measurement of θ_{23}

The true number of oscillated events is given by:

$$\begin{aligned} N_{\mu^-} &= N^0_{\mu^-} \times P_{\mu\mu} + N^0_{e^-} \times P_{e\mu} \,, \\ N_{\mu^+} &= N^0_{\mu^+} \times \overline{P}_{\mu\mu} + N^0_{e^+} \times \overline{P}_{e\mu} \,. \end{aligned}$$

The events $N^0_{\mu\pm}$ were generated for an exposure of 1000 years using the Nuance neutrino generator [3] and Honda 3-D fluxes. The events $N^0_{e\pm}$ were generated by swapping the ν_e and ν_μ fluxes. The binning of the events is done after including reconstruction efficiency and charge identification efficiency of the detector.

The events are oscillated using parameters given in Table -2. The normal ordering was assumed throughout. The data was scaled to 10 years so all results correspond to 10 years exposure at ICAL. The "theory" events were smeared as per the resolutions corresponding to the incorrect map by assuming the field to be fB_{map}, where f is 0.95 for instance.

B-field	f	E_{reco} vs E_{true}
B = $B_{correct}$	1.0	$E_{reco} \sim E_{true}$
B = 0.8$B_{correct}$	0.8	$E_{reco} = 0.865E_{true}$
B = 1.2$B_{correct}$	1.2	$E_{reco} = 1.135E_{true}$
B = 0.98$B_{correct}$	0.98	$E_{reco} = 0.987E_{true}$
B = 1.02$B_{correct}$	1.02	$E_{reco} = 1.014E_{true}$

Table 1: Change in the energy reconstruction (E_{reco}) of muon w.r.t. change in magnetic field by factor f across the entire map

Parameter	True value	Marginalization
θ_{13}	8.57°	[7.671°, 9.685°]
$\sin^2\theta_{23}$	0.5	[0.415, 0.616]
$\lvert\Delta m^2_{32}\rvert$	2.47×10^{-3} eV^2	[2.395, 2.564]$\times10^{-3}$ eV^2
$\sin^2\theta_{12}$	0.304	Not marginalised
Δm^2_{21}	7.6×10^{-5} eV^2	Not marginalised
δ_{CP}	0°	Not marginalised

Table 2: Value of oscillation parameters used for the analysis

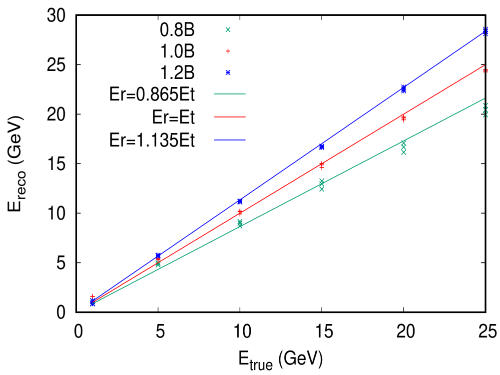

Figure 2: E_{reco} vs E_{true} for cosθ = 0.4, 0.6 and 0.8 for 0.8, 1.0 and 1.2 times the magnetic field map

In addition the width varies as $\sigma(\alpha B) = \alpha\sigma(B)$.

3.1 χ^2 analysis

The loss of sensitivity due to using incorrect field map is determined through

$$\chi^2 = \min_{\xi_l^\pm, \xi_6} \sum_{i=1}^{N_{E_\mu^{obs}}} \sum_{j=1}^{N_{\cos\theta_\mu^{obs}}} \left(\sum_{k=1}^{N_{E'^{obs}_{had}}} \right) 2\left[\left(T^+_{ij(k)} - D^+_{ij(k)} \right) - D^+_{ij(k)} \ln\left(\frac{T^+_{ij(k)}}{D^+_{ij(k)}} \right) \right] +$$
$$2\left[\left(T^-_{ij(k)} - D^-_{ij(k)} \right) - D^-_{ij(k)} \ln\left(\frac{T^-_{ij(k)}}{D^-_{ij(k)}} \right) \right] + \sum_{l^+=1}^{5} \xi^2_{l^+} + \sum_{l^-=1}^{5} \xi^2_{l^-}, \tag{1}$$

where T, D correspond to “theory" and “data", with

$$\Delta\chi^2(\lambda) = \chi^2_{ICAL}(\lambda) - \chi^2_0, \tag{2}$$

χ^2_0 being the minimum value of χ^2_{ICAL} in the allowed parameter range. With no statistical fluctuations, $\chi^2_0 = 0$. Here, λ is $\sin^2\theta_{23}$.

4. Results and Discussion

The analysis is performed for the two cases when the fitted magnetic field is 5% ($0.95B$)and 2% ($0.98B$) smaller than the true values. For a 2% variation, there is hardly any change in the precision measurement of θ_{23}. The precision at 2σ ($\Delta\chi^2 = 4$) worsens by 10% for a 5% variation of the magnetic field. Moreover, the mimimum is at $\theta_{23} = 42°$ rather than the true input value of $\theta_{23} = 45°$. The minimum is also quite broad in this case. Hence, it is clear that the magnetic field has to be measured to better than 5% accuracy in order to achieve the full potential of ICAL to precisely measure the neutrino oscillation parameters.

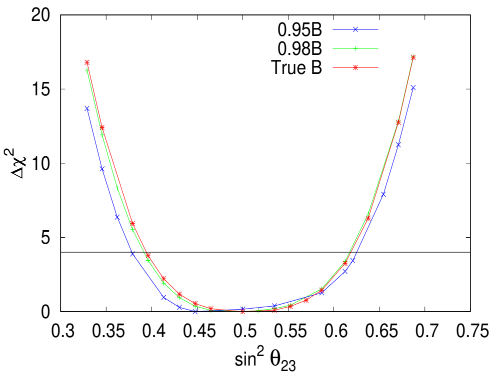

Figure 3: $\Delta\chi^2$ for $\sin^2\theta_{23}$ when the “theory" events are reconstructed using a field map which differs from the true one by $B^* = fB_{map}$

References

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[3] D. Casper, The Nuance neutrino physics simulation and the future, Nucl. Phys. Proc. Suppl. 112 (2002) 161. [hep-ph/0208030]