Muon Response in ICAL Detector at India-based Neutrino Observatory

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Abstract. The magnetized Iron CALorimeter detector (ICAL), proposed to be built in the India-based Neutrino Observatory (INO) laboratory, aims to study atmospheric neutrino oscillations. A simulations study of response of muons to the ICAL detector is presented in the form of momentum reconstruction, angle resolution and reconstruction, charge identification efficiency.

1. Introduction

India-based Neutrino Observatory (INO) [1] is the proposed underground facility, primarily designed to determine neutrino oscillation parameters precisely with atmospheric muon neutrinos, and the sign of Δm^2_{32} with matter effect using a magnetised Iron CALorimeter (ICAL). Oscillation sensitivity for neutrinos and anti-neutrinos is different in the presence of matter effects. Oscillation signatures and mass hierarchy are sensitive to the momentum P and zenith angle $cos\theta$ of neutrinos. But, reconstruction of momentum and $cos\theta$ further depends on the energy and direction of muons and hadrons [2] together produced in charge-current interactions of the neutrinos in the detector, hence the resolution and efficiency studies are crucial. An important parameter of INO physics goals is the neutrino oscillation probability, which depends on the matter term $A = 7.6 \times 10^{-5}\rho(\text{ gm/cc})\,E(\text{GeV})(\text{eV})^2$; ρ is the density of matter and A is positive for neutrinos and negative for anti-neutrinos. Neutrinos further interact in ICAL to give μ^-, antineutrinos give μ^+; hence, charge identification (CID) is also important for the measurement of mass hierarchy and ICAL has good CID.

The paper is organised as follows: in Section 2 we briefly discuss some relevant details of detector. We present the results for the muon momentum resolution, angle resolution and efficiencies in different regions of ICAL in Section 3 and conclude in Section 4.

2. ICAL Detector

Iron CALorimeter (ICAL) consists of three identical modules of dimension 16 m $\times$ 16 m $\times$ 14.45 m, with 151 layers of 5.6 cm thick magnetized iron plates interleaved by Resistive Plate Chambers (RPCs) which are the active detector elements (see [1] for more details). Coil slots and support structures are the dead spaces that affect the muon reconstruction. In addition, the magnetic field is non-uniform everywhere and so the quality of reconstruction depends on the region where the event is located. The magnetic field lines in a single iron plate in the central module are shown in Fig. 1. In the figure, the thin white vertical lines represent the coil slots through which copper coils passes having the field that is generated by passing current through them. The direction and length of arrows denote the direction and magnitude of the magnetic field. The "central region" within the coils slots has the highest, and uniform (B_y) magnetic field while the magnetic field in the "side region" (outside the coil slots in the x direction) is about 15% smaller and in the opposite direction. The region labelled "peripheral region" (outside the central region in the y direction) has the most changing magnetic field in both direction and magnitude. Hence, both the side and peripheral regions will be affected by edge effects.

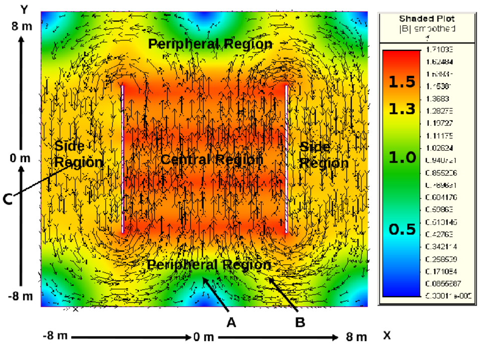

Fig. 1. Magnetic field map as generated by the MAGNET6 [3] software. Here, A: (x=0, y=-650, z=0) cm, B: (x=300, y=-650, z=0) cm, C: (x=-2270, y=0, z=0) cm; actually located in the left-most module.

2.1. Track reconstruction

Charged particles traversing a single RPC leave hits in that layer. The coordinates of hits are then determined from the strip information for both x and y and the layer number information for the z direction. Clusters of these hits in different layers form tracks. Muons are reconstructed with GEANT4 based INO-ICAL code [4] using a Kalman filter algorithm that returns both the magnitude and direction of the muon momentum by fitting these tracks, whereas, direction of curvature gives the charge of the muon. Fig. 2 shows a sample event generated in ICAL.

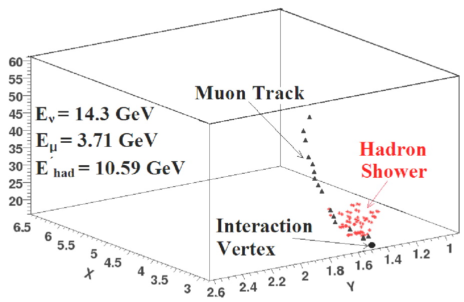

Fig. 2. A sample event generated in ICAL showing muon track and hadron shower.

3. Muon Reconstruction

In each region of ICAL, 10,000 events are generated with the muon vertex in the central region, in the peripheral region (with small and large (both x and y components non-zero) magnetic fields respectively) and in the side region, as highlighted in Fig. 1.

3.1. Central, Side and Peripheral Regions
Muons are generated in the peripheral region of vertex (x, y, z) = $(0, -600, 0)$ cm with a small smearing $\pm$ $(2420, 200, 720)$ cm with fixed input momenta P_{in} and $\cos\theta$. Muons with different ϕ ($\phi = 0$ corresponds to the x-direction) have different detector response due to the presence of the magnetic field besides support structures, etc. The muon sample is divided into four: Set I: $\phi < \pi/4$, Set II: $\pi/4 \leq \phi < 3\pi/4$, Set III: -$3\pi/4 \leq \phi$ -$\pi/4$, and Set IV: $\phi \geq 3\pi/4$. Tracks are fitted by a Kalman filter algorithm to obtain the reconstructed momentum, direction and charge, and events with a track fit of $\chi^2/\text{dof} < 10$ are chosen for analysis. Similar studies was done in central [5] and side regions with the vertex information changed, according to the regions.

The reconstructed momentum distribution is fitted separately in these regions with Landau convoluted Gauss functions for $E < 2$ GeV and with Gauss function for $E > 2$ GeV and then its mean and σ are determined. Fig. 3 shows Gauss fitted reconstructed momentum distributions of muons. The momentum resolution $R = (\sigma)/P_{\text{in}}$, and its error $(\delta R/R)^2 = (\delta\sigma/\sigma)^2$. Fig. 4 shows resolution as a function of input momentum for a sample zenith angle, $\cos\theta = 0.65$ in the peripheral region and a comparison of the ϕ averaged resolutions in the central, side and peripheral region as a function of input momentum P_{in} for the different values of $cos\theta$. As expected, the central region resolutions are better because of the higher magnetic field.

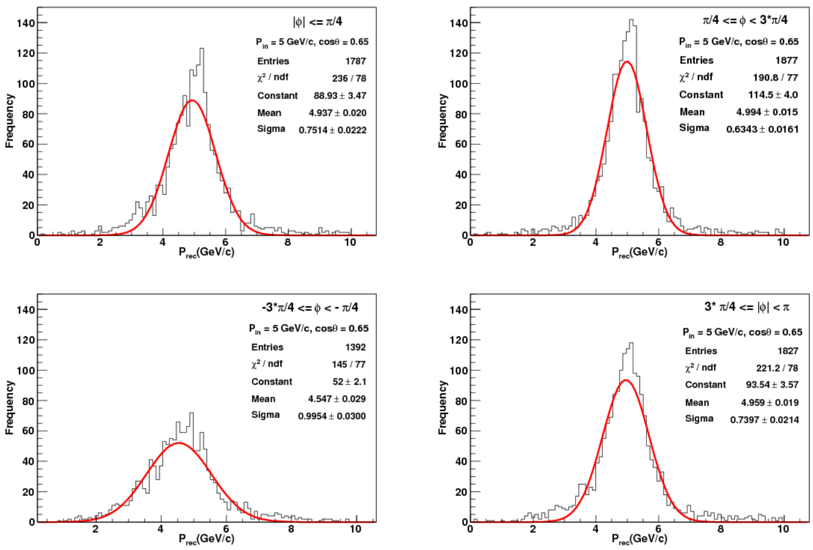

Fig. 3. Gaussian fits to reconstructed momentum distributions of muons with fixed energy (P_{in}, $\cos\theta$) = (5 GeV/c, 0.65) in four different bins of azimuthal angle.

The momentum resolution improves with the increase of energy as the number of hits increases but worsens at higher energy since particles leave the detector at higher energy.

The angular resolution of muons was found to be every good, better than a degree for $P_{in} >$ few GeV in all the regions. Fig. 5 shows angular resolution for peripheral region.

Efficiency studies have also been performed. The reconstruction efficiency is defined as the ratio of the number of reconstructed events n_{rec} (irrespective of charge) to the total number of events, N_{total}. We have

$$\epsilon_{\text{rec}} = \frac{n_{\text{rec}}}{N_{\text{total}}} , \quad (1)$$

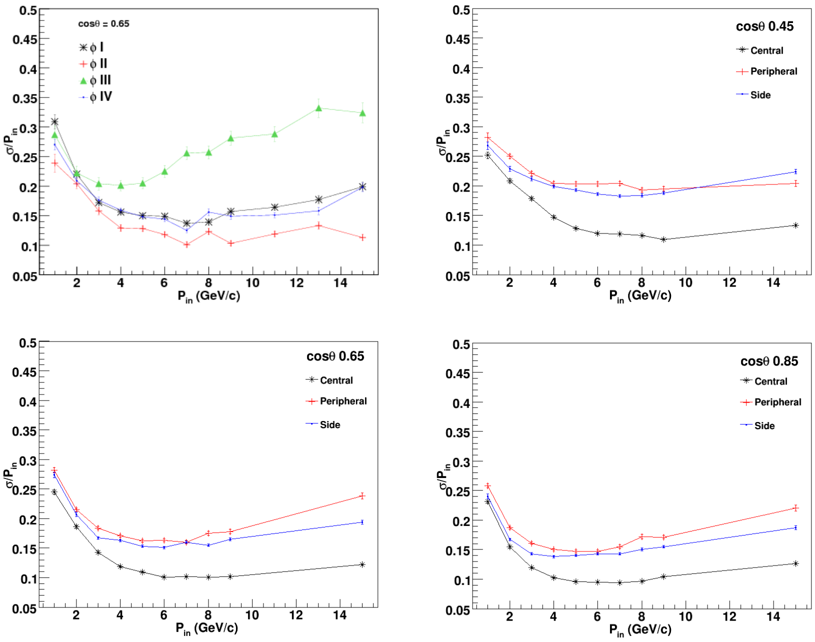

Fig. 4. Resolution in peripheral region (Top left). A comparison of resolution in central, peripheral, side region as a function of input momentum P_{in} for the different values of $cos\theta = 0.45$ (Top right), 0.65 (Bottom left), 0.85 (Bottom right) in the ϕ averaged bin.

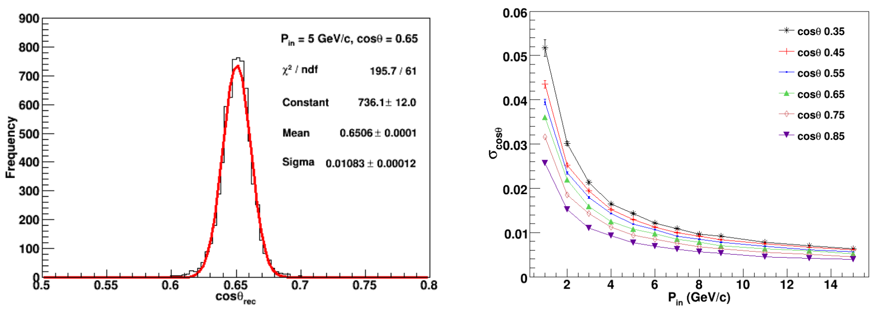

Fig. 5. Gauss fitted $Cos\theta_{rec}$ for $cos\theta_{in} = 0.65$ in the peripheral region (L). $Cos\theta$ resolution as a function of input momentum P_{in} in the peripheral region.

$$\delta\epsilon_{\rm rec} \quad = \quad \sqrt{r(1-r)/N_{\rm total}} \quad ; \quad r = \frac{n_{\rm rec}}{N_{\rm total}} \ .$$

Relative charge identification efficiency (CID) is defined as the ratio of number of events with correct charge identification, $n_{\rm cid}$, to the total number of reconstructed events, i.e.,

$$\epsilon_{\rm cid} \quad = \quad \frac{n_{\rm cid}}{n_{\rm rec}} \ , \tag{2}$$

where $\delta n_{\rm cid}$ and $\delta n_{\rm rec}$ are inter-dependent so that the error in the ratio is calculated as $= \sqrt{r(1-r)/n_{\rm rec}}$ where r is the ratio $n_{\rm cid}/n_{\rm rec}$.

Fig. 6 shows a comparison of reconstruction and CID efficiency in the central, side and peripheral region.

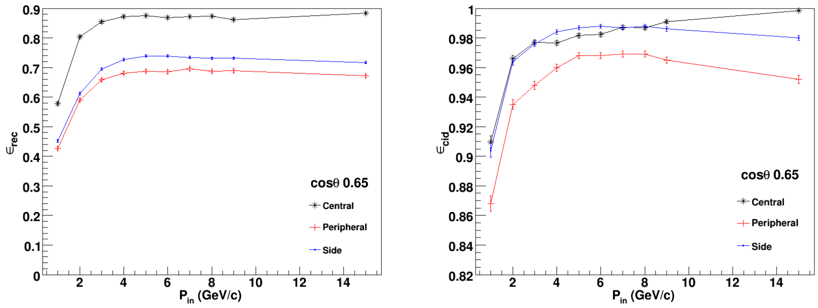

Fig. 6. A comparison of reconstruction (L) and CID efficiency (R) of central, peripheral, side region as a function of input momentum P_{in} for $cos\theta = 0.65$.

The reconstruction efficiency increases for all angles, since the number of hits increases as the particle crosses more number of layers. But CID efficiency is relatively poor at lower energies and as the energy increases CID efficiency also improves. Central region shows best efficiency than side and peripheral region.

4. Conclusions

The ICAL simulations indicate that the detector has a good response to muons, including momentum, direction (also determining whether the particle is up-going or down-coming), and charge identification (CID), with good reconstruction efficiency.

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References

[1] *India-based Neutrino Observatory Report*, http://www.ino.tifr.res.in/ino/OpenReports/INOReport.pdf, May2006.

[2] Devi M M *et.al* 2013,*Hadron energy response of the ICAL detector at INO*, arXiv 1304.5115 [hep-ex] http://arxiv.org/abs/1304.5115?context=hep-ex

[3] Infolytica Corp., Electromagnetic field simulation software, www.infolytica.com

[4] INO Collaboration, *ICAL simulation using GEANT tool-kit*, in preparation, 2013.

[5] A. Chatterjee *et.al* 2014, *A simulations study of the muon response of the Iron Calorimeter detector at the India-based Neutrino Observatory*, JINST 9 (2014) P07001, arXiv:1405.7243 [physics.ins-det]. http://arxiv.org/abs/1405.7243