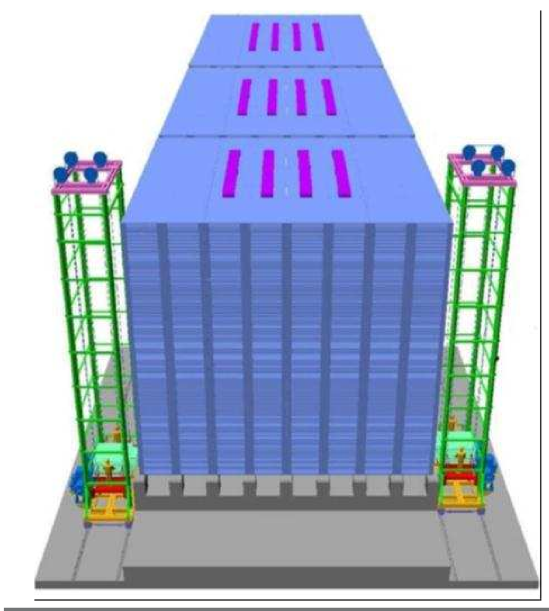

Hadron energy resolution as a function of iron plate thickness and hadron direction resolution in INO ICAL

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Introduction

The proposed India-based Neutrino Observatory (INO) is an underground laboratory designed primarily to study neutrinos from various sources. The main detector at INO will be a magnetised Iron CALorimeter (ICAL) detector aimed at studying neutrino properties using atmospheric neutrinos. ICAL is mainly sensitive to muons produced in the charged current interactions of (anti-)neutrinos with the target iron nuclei. In the interaction, $\overset{(-)}{\nu_\mu} + \mathbf{N} \rightarrow \mu^{\overset{(+)}{-}} + \mathbf{X}$, where $\mathbf{X}$ represents hadrons. In order to reconstruct the energy and direction of the incident neutrino it is necessary to be able to measure the energy and direction of the hadrons emitted in the final state. The physics reach of ICAL can be improved by adding the information from these final state hadrons. Unlike muons, hadrons do not leave a long clean track in the ICAL detector. Instead of measuring the energies of individual hadrons in a shower , total number of hits due to hadrons are used to reconstruct the energy deposited. The hits in the detector are used to reconstruct the net hadron direction too. Here,the GEANT4 based simulation studies of resolutions of hadron energy as function of iron plate thickness † and the hadron direction resolution for the default plate thickness 5.6 cm * and strip width of 1.96 cm for ICAL detector are presented.

Energy resolution as a function of plate thickness

Methodology

- Fixed energy single pions in the range [2–15 GeV], from GEANT4 particle gun.
- 11 plate thicknesses including the default ICAL plate thickness of 5.6 cm.
- Position : 1 m, 1 m, 0 m w.r.t the origin ; smearing $\rightarrow$ 1 m, 1 m, 1 m.
- θ smear : $\mathbf{0} - \pi$, ϕ smear : $\mathbf{0} - \mathbf{2}\pi$.
- Analyses in [2 – 5 GeV), [5 – 15 GeV] & [2 – 15 GeV].
- $\mathbf{E} \rightarrow$ energy in GeV ; $\mathbf{t} \rightarrow$ thickness in cm.

Hit distribution and Gaussian fit.

Gaussian fit over estimates the width of the hit distribution at lower energies and higher thickness. Arithmetic quantities can be used in all energy ranges.

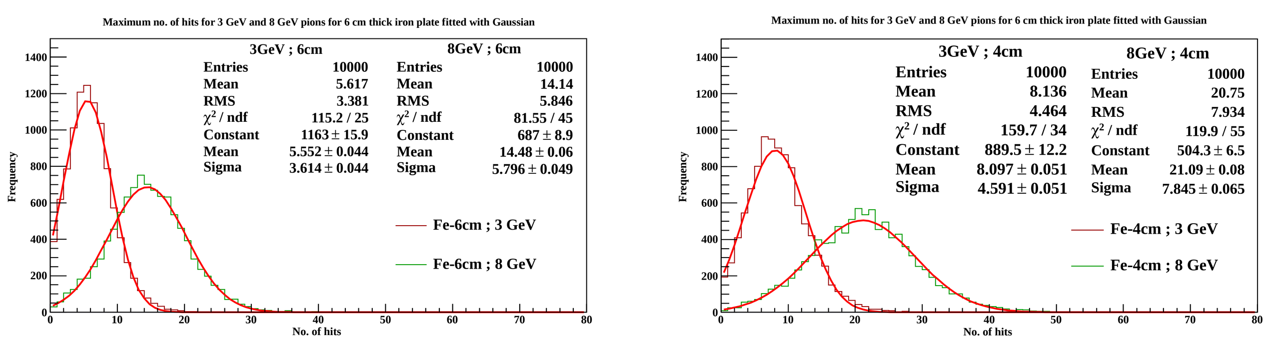


Figure 1: Hit distributions at different E & t fitted with Gaussian.

Energy resolution from mean number of hits.

- Mean hits as a function of energy : $\mathbf{n(E) = n_0[1 - \exp(-E/E_0)]}$; $\mathbf{n_0}$,$\mathbf{E_0} \rightarrow$ constants.
- Typically, $\mathbf{E_0 \gg E}$; $\mathbf{n/n_0 \simeq E/E_0}$ (linear behavior) in the range of interest $\mathbf{E \leq 15}$ **GeV**.
- Energy resolution : $\sigma\mathbf{(E)/E = \Delta n(E)/n(E) \equiv width/mean\ hits}$.
- Fit to a form $\sigma\mathbf{(E)/E} = \sqrt{\mathbf{a^2/E + b^2}}$; $\mathbf{a}$ = stochastic coefficient & $\mathbf{b}$ = a constant. Ideal case : $\mathbf{b} = 0$. Easier to analyse : $(\sigma/\mathbf{E})^2 = \mathbf{a^2/E + b^2}$; linear in $\mathbf{1/E}$.
- Thickness dependence of stochastic coefficient $\mathbf{a}$: $\mathbf{a(t) = p_0 t^{p_1} + p_2}$, where $\mathbf{p_0}$ = a constant , $\mathbf{p_1}$ = power giving the thickness dependence , $\mathbf{p_2}$ = residual resolution.

Results & conclusions

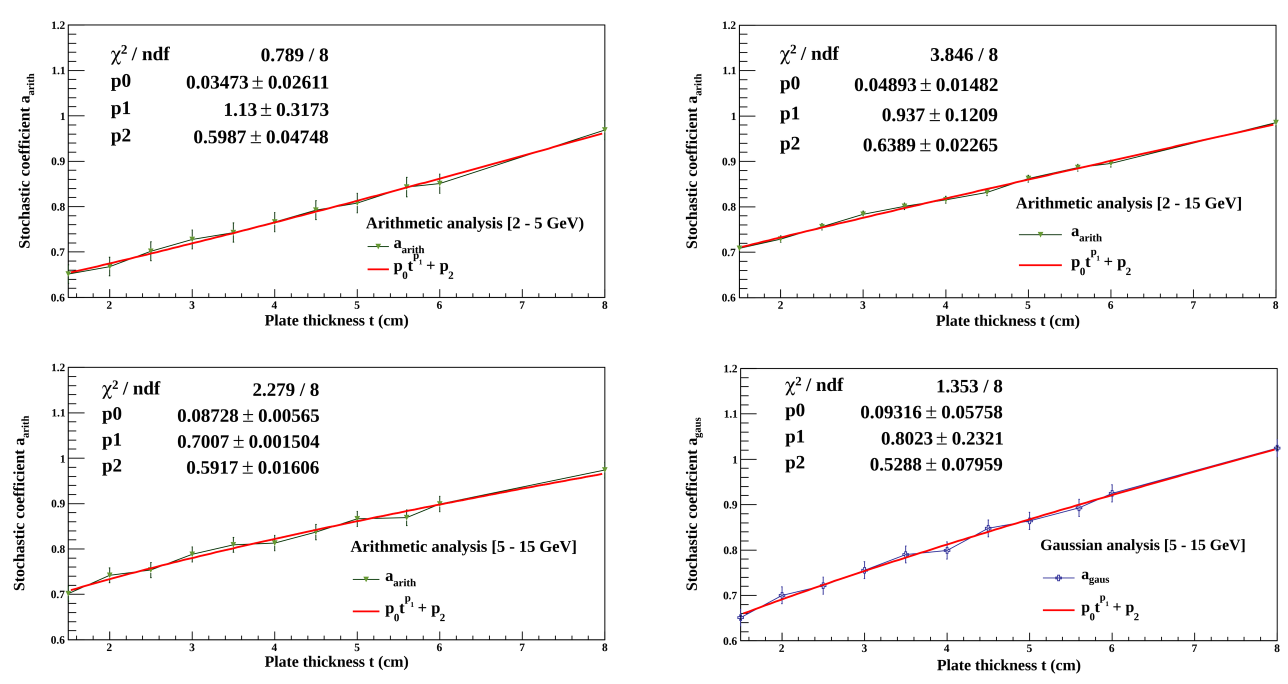


Figure 2: **a** as a function of **t** (cm) in various energy ranges.

- $\mathbf{p_0 t^{p_1} + p_2} = \alpha + \mathbf{p_2}$; $\alpha < \mathbf{p_2}$ for all $\mathbf{t}$ in all E ranges. $\mathbf{p_2} \rightarrow$ residual resolution.
- MINOS : $\sim \mathbf{70\%}/\sqrt{\mathbf{E\ (GeV)}}$ for gas detectors
  $\sim \mathbf{50\%}/\sqrt{\mathbf{E\ (GeV)}}$ for scintillator based detectors [2].
- MONOLITH (angle averaged) : $\sim \mathbf{90\%}/\sqrt{\mathbf{E\ (GeV)}} \oplus \mathbf{30\%}$ [3].
- Average hits decrease as thickness increases; sensitivity lost at higher t.

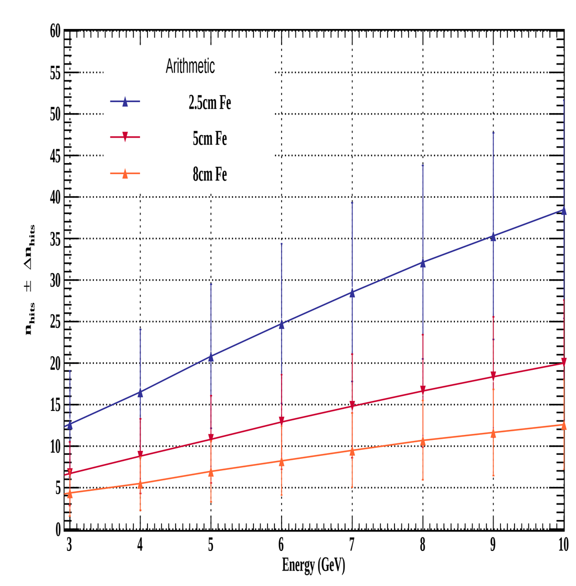


Figure 3: Mean hits as a function of $\mathbf{E}_\pi$(GeV)

Direction resolution

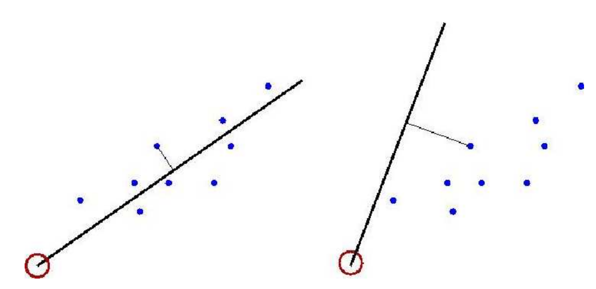
Methodology

- Single & double from GEANT4 particle gun and hadrons from NUANCE neutrino generator.
- For single and double pions : 1 m, 1 m, 0 m w.r.t origin and smearing of 1 m, 1 m, 1 m.
- Direction cosines for MC pions : 0.1 , 0.3 , 0.5 ,0.7 , 0.9 without smearing , ϕ fully smeared.
- Energy [1 – 10 GeV] without smearing for single and with smearing double pions.

Centroid method, orientation matrix method, raw hit method

- Centroid method : for each simulated event, the vertex position and the positions of hits forming the shower are taken and the centroid of the shower is found by summing over the position vectors (w.r.to the vertex) of each hit in that event. This is the reconstructed shower direction.
- Orientation matrix method: Orientation matrix T for a collection of unit vectors $(\mathbf{x_i}, \mathbf{y_i}, \mathbf{z_i})$, i=1,...,n is the symmetric matrix

$$\mathbf{T} = \begin{pmatrix} \Sigma x_i^2 & \Sigma x_i y_i & \Sigma x_i z_i \\ \Sigma x_i y_i & \Sigma y_i^2 & \Sigma y_i z_i \\ \Sigma x_i z_i & \Sigma y_i z_i & \Sigma z_i^2 \end{pmatrix}$$



Eigen analysis of $\mathbf{T}$ gives an idea of the shape of the underlying distribution. If a unit mass is placed at each point, moment of inertia of the $\mathbf{n}$ points about an arbitrary axis $(\mathbf{x_0}, \mathbf{y_0}, \mathbf{z_0})$ is,

$$\mathbf{n} - \left(\mathbf{x_0\ y_0\ z_0} \right) \mathbf{T} \begin{pmatrix} \mathbf{x_0} \\ \mathbf{y_0} \\ \mathbf{z_0} \end{pmatrix}$$

The variation of moment of inertia gives information about the scatter of the points as the choice of axis varies. The principal axis is the axis about which the moment is least and is taken as the reconstructed shower direction. Distributions of the sine of the error angles ($\mathbf{sin}\,\Delta\theta$) are fitted with the function : $\Delta\theta = \mathbf{A}\Delta\theta\,\mathbf{exp}(-\mathbf{B}\Delta\theta)$, where, $\mathbf{A}$, $\mathbf{B}$ are parameters.

- Raw hits and timing method : Requires no vertex position; only needs hit in X-Z & Y-Z plane separately. Hits only within a time window of 50 ns taken to avoid considering those due to some decaying particle. Average $\mathbf{x}$ and $\mathbf{y}$ positions in the $\mathbf{i^{th}}$ layer of an event are found separately & fitted with straight lines $\mathbf{x = m_x z + c_1}$ and $\mathbf{y = m_y z + c_2}$ separately in the X-Z and Y-Z planes. The slopes $\mathbf{m_x}$ & $\mathbf{m_y}$ are used to reconstruct hadron direction ; timing information is used to break the quadrant degeneracy of these slopes.All events UP $\uparrow$ in time have θ in $\mathbf{1^{st}}$ quadrant. All events DOWN $\downarrow$ in time have θ in $\mathbf{2^{nd}}$ quadrant.

Results & conclusions

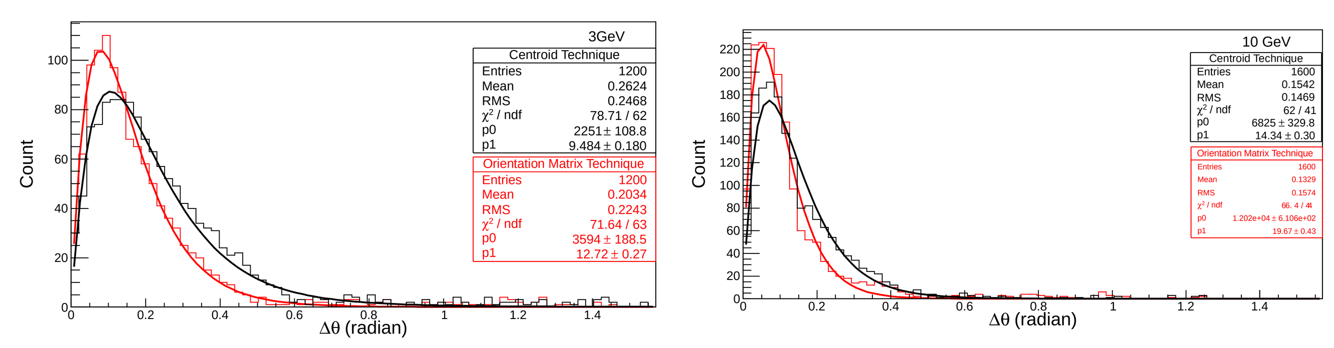


Figure 4: $\Delta\theta$: centroid and orientation matrix methods for 3,10 GeV pions.

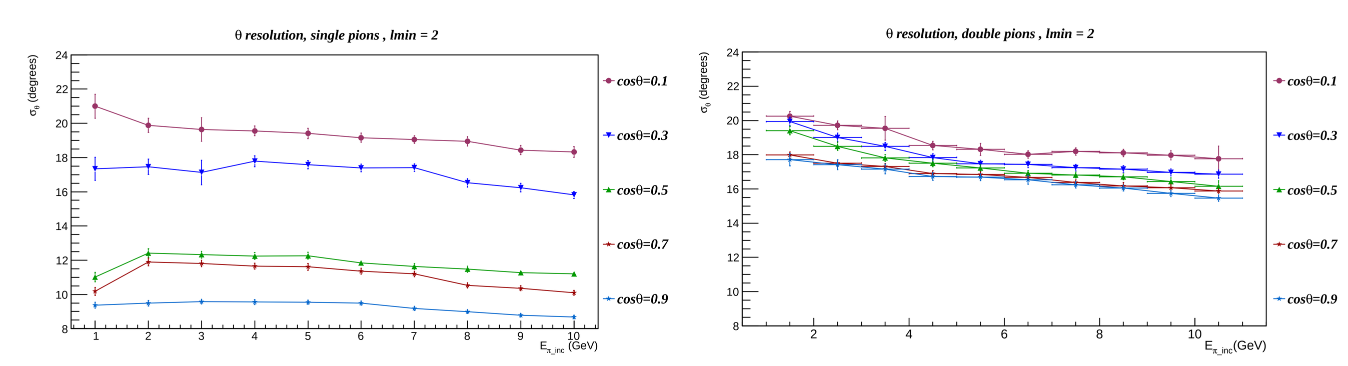


Figure 5: θ resolution from raw hit method, with lmin = 2 cut.

- $\sim \mathbf{10}^\circ$ resolution for vertical showers; almost doubles for horizontal directions as expected.
- Direction resolution of multipions is found to be almost double of that of single pions; due to larger spread of the shower. Relevant for DIS events with multiple hadrons in the final state.

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