A Simulations Study of the Response of ICAL Detector to Muons

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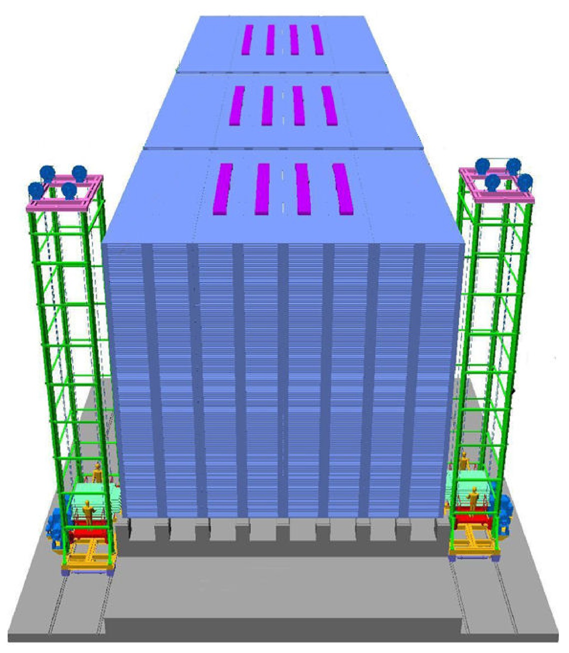
Introduction

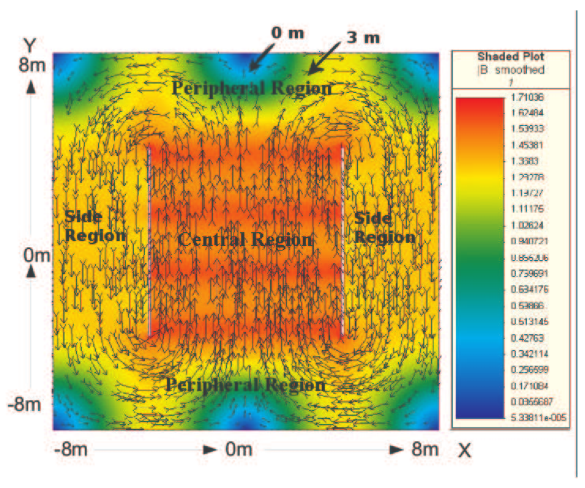
- An Iron CALorimeter (ICAL) detector is proposed at the India-based Neutrino Observatory (INO) laboratory.
- Three modules, each 16m × 16m × 14.45m; totally 52 ktons.
- 151 layers of magnetised iron plates (copper coils seen in purple) interleaved with Resistive Plate Chambers (RPCs) (1.84m × 1.84m) as active detector elements.



- To study neutrino flavor oscillations through atmospheric neutrinos: measure θ_{23}, $|\Delta m^2_{32}|$) and determine the neutrino mass hierarchy—the sign of Δm^2_{32}; $\Delta m^2_{32} \equiv m_3^2 - m_2^2$.

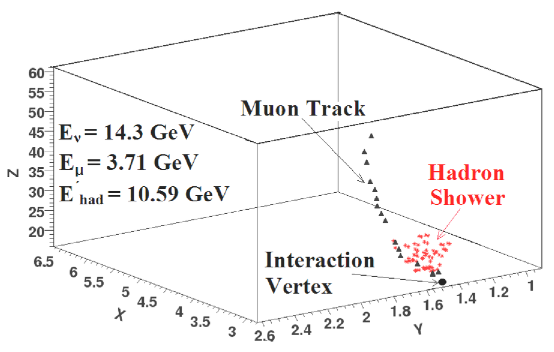
ICAL Detector Simulation

- Geant 4.9.4 p02 is used for the detailed simulation of ICAL geometry and propagation of particles.
- The iron sheets are separated by an air gap of 9.6 cm; supported every 2 m in both the x and y directions by (non-magnetic) steel support structures.
- RPCs placed in air gaps; the width of the pickup strip is 1.96cm.
- The magnetic field is obtained from simulations using MAGNET6.26 software. Typically $\mathbf{B} \sim 1.5\vec{y}$T in the CENTRAL region of the detector, changes direction in the SIDE region, and changes rapidly in the PERIPHERAL region.



Hit and Track Generation :

- Muons being minimum ionizing particles leave long, clean, tracks in the detector. Its momentum is determined from the curvature of its track as it propagates in the magnetized detector.
- x and y hits in a plane are combined in all possible ways to form a cluster. Clusters are combined into a single longest possible track using a Kalman filter algorithm that accounts for the local magnetic field.



- In the case of multiple tracks, the reconstructed track closest to the vertex is considered as the muon track.

Observations

Fixed vertex muons : Muons are generated with vertex $(x, y, z) = (100, 100, 0)$ (in cm) with a small smearing $(\pm 10, \pm 10, \pm 10)$ cm. Muons with different ϕ ($\phi = 0$ corresponds to the x-direction) have different detector response (Fig. 1(right)). So azimuth-averaged muon sample is divided into four: Set I with $|\phi| < \pi/4$, Set II with $\pi/4 \leq |\phi| < \pi/2$, Set III with $\pi/2 \leq |\phi| < 3\pi/4$, and Set IV with $|\phi| \geq 3\pi/4$ (Fig. 2).

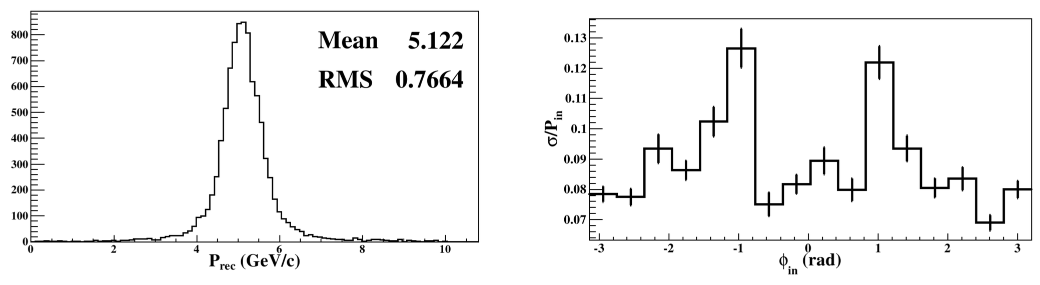


Figure 1: Left: Reconstructed muon momentum for $\cos\theta = 0.65$, $E = 5$ GeV. Right: Momentum resolution, σ/E, in bins of the azimuthal angle ϕ.

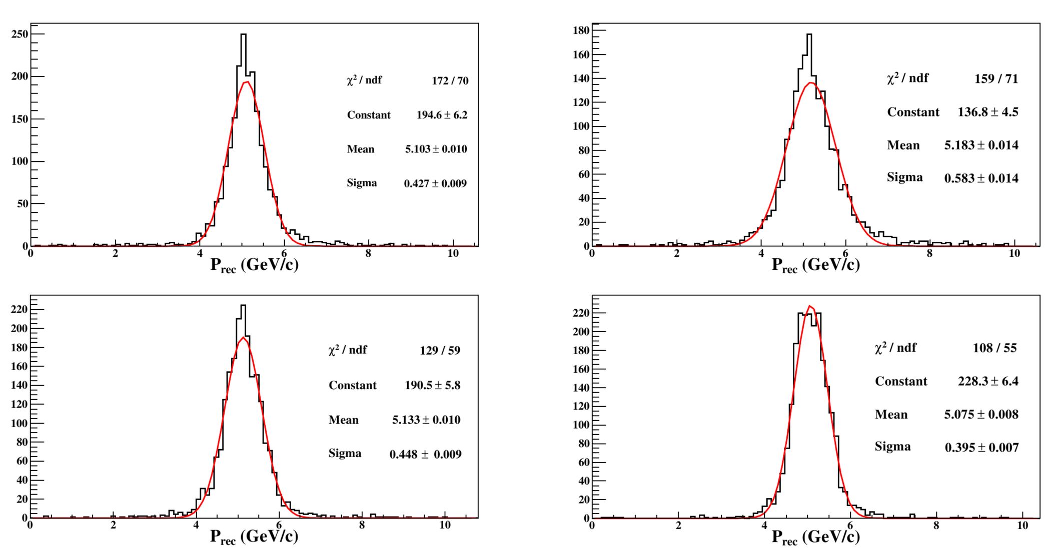


Figure 2: Gaussian fits to momentum distributions for muons with fixed energy $E = 5$ GeV, $\cos\theta = 0.65$ in four different bins of azimuthal angle, ϕ.

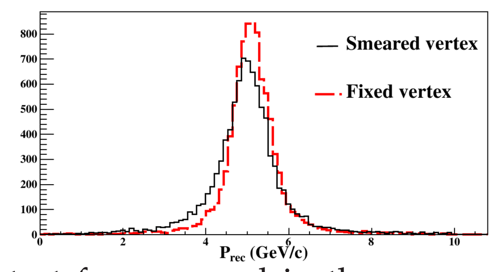
Contact Information

India-based Neutrino Observatory,
http:www.ino.tifr.res.in

Observations

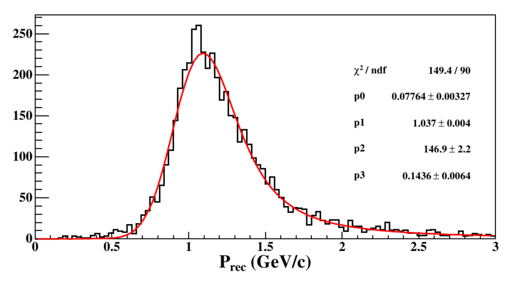
Smeared vertex muons :

- Muons are generated symmetrically in all azimuthal directions, smeared over the CENTRAL region in x, y, and over $-600 \leq z \leq 400$ cm where the magnetic field is uniform.
- The reconstructed momentum distribution is broader in the case of smeared vertex events (shown for $E = 5$ GeV, $\cos\theta = 0.65$).



- The events that start from or end in the support structure and the partially contained events worsen the quality of reconstruction.

Reconstructed momentum distribution for 1GeV and 2GeV are fitted with landau convoluted gaussian due to the tails. Momentum distributions for $E = 1$ GeV, $\cos\theta = 0.65$, fitted with landau-convoluted gaussian is shown. FWHM/2.354 is compared with the Gaussian fits at higher energies.



Results: Momentum resolution

The muon resolutions for fixed-vertex (left) and smeared-vertex muons (right) are shown as a function of muon energy for fixed values of $\cos\theta = 0.65$, for different ϕ regions (V corresponds to the average over ϕ.)

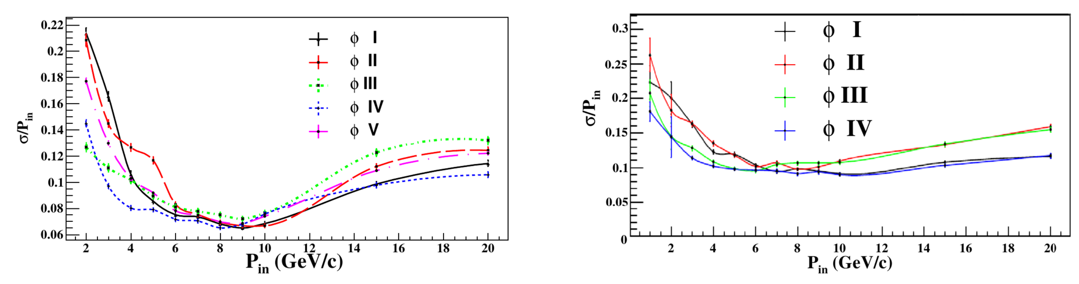


Figure 3: Momentum resolution as a function of energy for $\cos\theta = 0.65$ in four different bins of azimuthal angles.

The muon resolutions for muons whose vertex is smeared over the central region is shown below for smaller and larger $\cos\theta$ values.

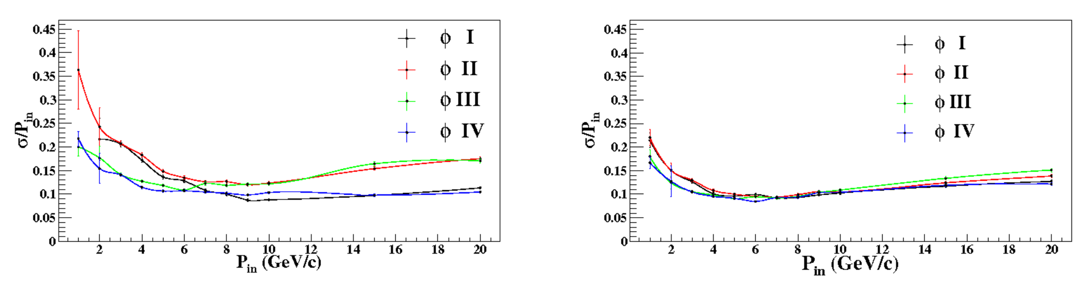


Figure 4: Momentum resolution as a function of energy for $\cos\theta = 0.45, 0.85$

Observations :

- The general behaviour is the same, with a worsening of the resolution when the muons are smeared.
- As expected the resolution improves as $\cos\theta$ increases, especially at lower energies which are important for matter effects in atmospheric neutrino studies.
- The best resolution at roughly $E \sim$ 6–8 GeV occurs for the longest track that is contained inside the detector; as the number of hits increases, the Kalman filter performs better.
- For larger $\cos\theta$, the best value shifts to smaller energies since the particle goes out from the top.
- Region IV has the best resolution for μ^- since the track has maximum bending here. Region III muons also show good resolution at small energies because they traverse more iron layers due to the bending in the magnetic field.
- In general, regions II and III have worse resolution at large E because they have large components of momentum parallel to the magnetic field and hence show least bending.

Reconstruction and CID Efficiencies

The reconstruction efficiency $\epsilon_{\rm rec}$ is the ratio of the reconstructed events $n_{\rm rec}$ (irrespective of charge) to the total number of events, N_{total}.

The charge identification of the particle plays a crucial role in the determination of the neutrino mass hierarchy.

Relative charge identification efficiency $\epsilon_{\rm cid}$ is the ratio of events with correct charge identification, $n_{\rm cid}$, to the total number of reconstructed events.

The charge of the particle is determined from the direction of curvature of the track in the magnetic field.

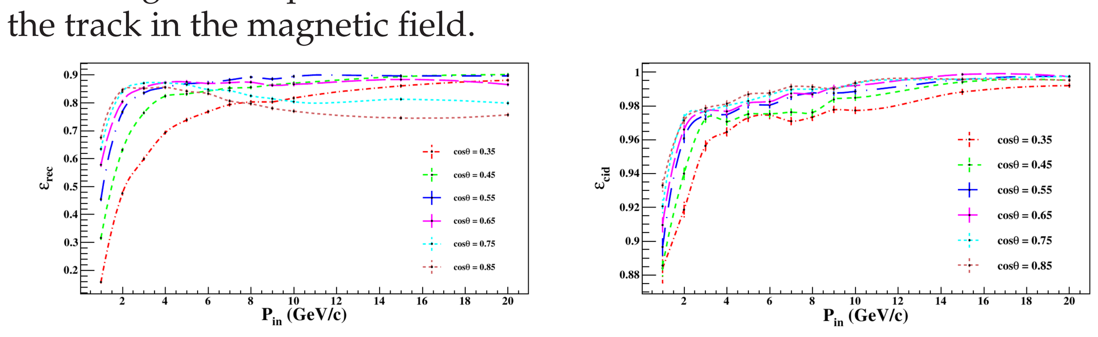


Figure 5: Reconstruction and cid efficiencies as a function of E for different $\cos\theta$.

- At larger angles, the reconstruction efficiency for small energies is smaller compared to vertical angles since the number of hits for reconstructing tracks is less.
- As the track length increases the cid efficiency increases. The value saturates at higher energy because of multiple scattering, etc.

Acknowledgements

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$\cos\theta$ Resolution

The reconstruction of the muon angle is crucial for oscillations since the oscillation probability is sensitive to the path length that the neutrino has traversed in the Earth; for E larger than few GeV, the muon direction is already a good approximation to that of the neutrino.
The long clean tracks of muons result in very good angular resolution; a sample histogram for $E = 5$ GeV, $\cos\theta = 0.65$, is shown below.

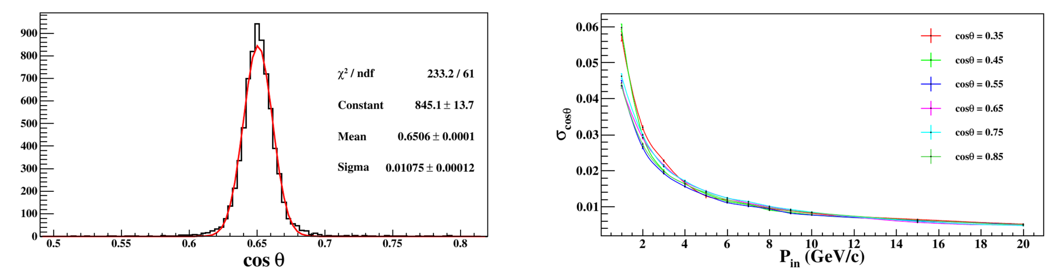


Figure 6: $\cos\theta$ resolution for $E = 5$ GeV, $\cos\theta = 0.65$ and as a function of E.

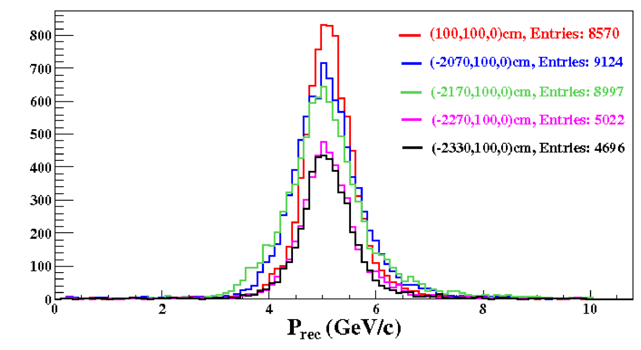
The angular resolution is roughly the same for all angles and is better than a degree for about $E > 4$ GeV.

Response in Side and Peripheral Region

- In addition to the presence of support structures and coil gaps, there are two kinds of effects in these regions.
- Edge effects are significant in both regions.
- The magnetic field is somewhat lower ($\sim$ 15%) and in the opposite direction in the SIDE region; it varies substantially in both direction and magnitude in the PERIPHERAL region.

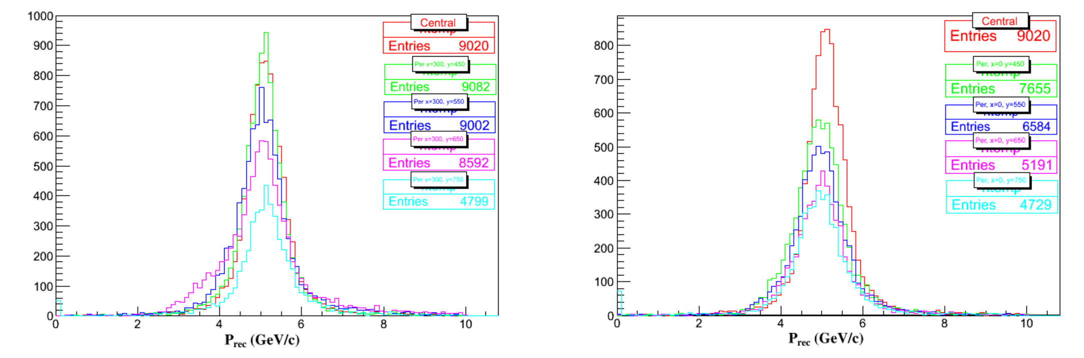
Comparison of CENTRAL and SIDE/PERIPHERAL regions :

SIDE Region : Muons are generated at fixed vertices just outside the coil region at $x = -2330, -2270, -2170, -2330$ cm (50 cm from the edge, and subsequently at 100 cm gaps), averaged over the entire azimuth. Here $x, z = 0, 0$ cm.

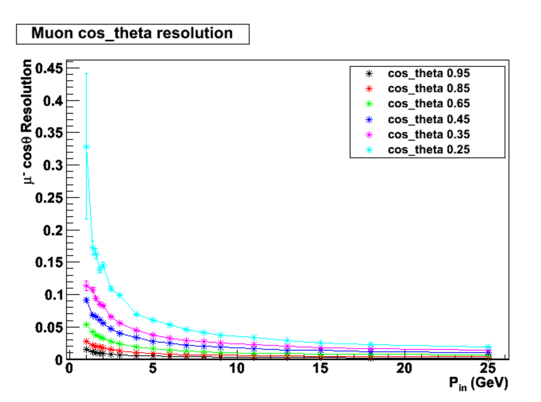


The results are consistent with the decreased magnetic fields. Note that in the edge region, half the events leave the detector (average over ϕ) and do not survive the cut $n_{\rm hits} > 20$.

PERIPHERAL Region : Muons are generated at fixed vertices just outside the coil region at $y = -750 - 650, -550, -450$ cm (50 cm from the edge, and subsequently at 100 cm gaps), averaged over the entire azimuth. Here $z = 0$ cm and $x = 0, 300$ cm (small, large magnetic field regions).



- The results at $x = 300$ cm are similar to the side/central region, except for the edge region.
- At $x = 0$, the magnetic field is much smaller; also, B_x changes sign across $x = 0$. The reconstruction efficiency is significantly smaller due to the cut $n_{\rm hits} > 20$. Also, the resolutions are distinctly worse than either the side or central region or even the peripheral region at $x = 300$ cm.
- However, angular resolution is still good *over the entire peripheral region* and only marginally worse than in the central region, as also the relative cid efficiency.



Conclusions

- The ICAL detector is mainly sensitive to charged-current events from interactions of atmospheric neutrinos with detector material.
- The ICAL geometry is simulated using GEANT4 software and the the response to muons are studied.
- The presence of the magnetic field breaks the azimuthal symmetry; hence the muon response is analysed in different ϕ bins.
- The momentum resolution is about 8–15% in the few GeV range; the reconstruction efficiency is better than 80% in the same range.
- The direction resolution is better than a degree for all angles for energies greater than about 4 GeV.
- The relative cid is also about 98% over this range.
- Similar but marginally worse results are obtained in the side and peripheral region of the detector.