A SIMULATION STUDY ON THE HADRONIC RESPONSE OF THE INO-ICAL DETECTOR

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1. INTRODUCTION

- The India-based Neutrino Observatory (INO) is a proposed underground facility for hosting decisive neutrino experiments. The magnetized iron caloriemeter (ICAL) detector at INO with charge identification capability will study the oscillation pattern of atmospheric neutrinos. In the 1^{st} phase it aims at precise measurement of oscillation parameters, probing neutrino mass hierarchy as well as new physics.

- A brief overview of ICAL detector:
  - Dimension: 48m $\times$ 16m $\times$ 14.4m (3 modules of dimensions 16m $\times$ 16m $\times$ 14.4m each)
  - Mass: 50 kTon (approximately).
  - Absorber: Iron plates of thickness 5.6 cm.
  - Active detector volume: Resistive Plate Chamber (RPC) (2m $\times$ 2m $\times$ 8mm). The readout of the RPC is carried out by external orthogonal pick up strips (X $\&$ Y strips).
  - Magnetic Field 1.4 Tesla.

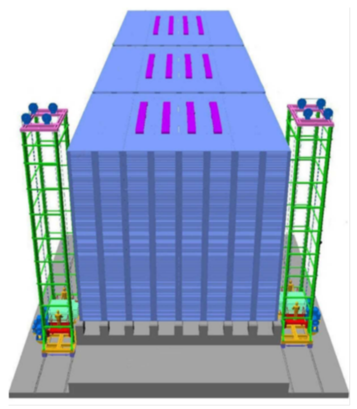

Figure 1: *A sketch of the proposed INO-ICAL detector.*

2. NEUTRINO INTERACTIONS IN THE DETECTOR

The atmospheric neutrinos inside the detector may interact through different processes:

- The Quasi-Elastic Charge Current (QECC) interaction events. They produce associated leptons.
- Deep Inelastic Scattering (DIS) interaction events. They produce associated leptons and hadrons.
- Resonance Interaction events. They produce single pion events.

ICAL is most sensitive to muon neutrinos. Muon gives distinct track, and hadron produces shower.

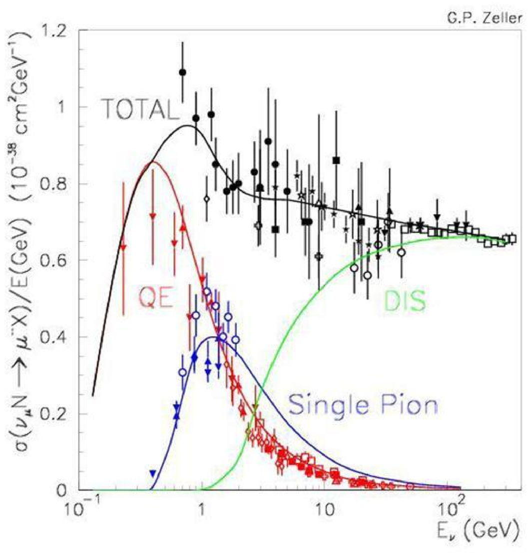

Figure 2: *The energy dependance of the cross sections of diferent interaction processes.*

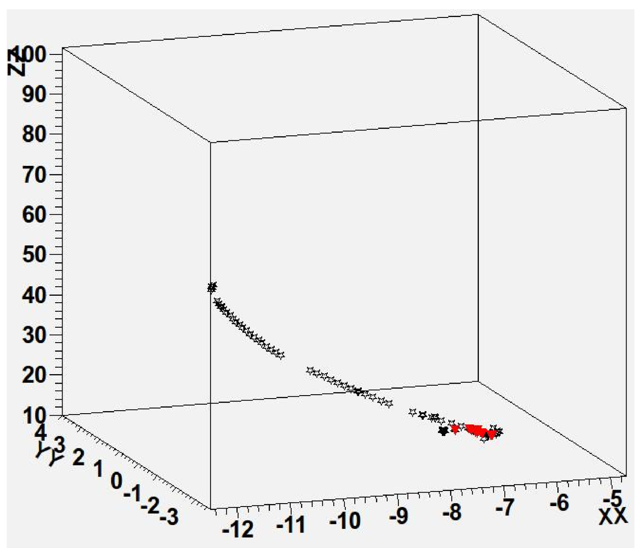

Figure 3: *An DIS event in INO-ICAL detector. Black points: muon track, red ones:hadron shower.*

3. THE IMPORTANCE OF HADRONIC RESPONSE OF INO-ICAL

- Measurement of neutrino energy (E_ν) and direction plays a crucial role in fulfilling the physics goals.
- The precision in reconstructing E_ν depends on how precisely the energies of muon and the hadrons are measured.
- E_μ's are reconstructed from the track radius in the detector.
- From the hit information of the hadron shower, the hadron energy needs to be estimated.
- To reconstruct the incident neutrino direction, the information of the directions of muon and hadrons are needed.
- For hadron shower, fluctuation in energy loss is much larger than the e.m. process.
- The hadron energy resolution is affected by energy leakage and invisible energy loss mechanism.

4. THE DETECTOR SIMULATION

- Simulation Toolkit: GEANT4. Storage of output $\&$ analysis: ROOT.
- The simulation framework consists of the following:
  1. Event Generation (GEANT4 / NUANCEv3): Particles resulting from random interactions of neutrinos with matter using theoretical models are generated. The outputs are : Reaction channels, vertex information, energy and momentum of the particles.
  2. Event Simulation (GEANT4): Propagation of the particles through the detector are simulated. The outputs are: position and time of the particles at the vertex, the energy deposited and the momentum.
  3. Event digitisation (GEANT4): The detector efficiency and noise are added. The output of simulation is digitised in this step.
  4. Event reconstruction (GEANT4): Track finding and track fitting are done.
- The hadronic response of INO-ICAL are studied using both single pion events from GEANT4 and atmospheric neutrino events from NUANCE.

5. ANALYSIS OF HADRON HIT PATERN

The hadron hit pattern:

- The hadron hit distributions in ICAL follow Vavilov distribution function, which is used to calculate the energy loss of heavy charged particles in moderately thick absorbers.
- Example : Figure 4: hit distribution for MC $\pi^\pm$ at 6 GeV.
- Figure 5: The variation of average hadron hits with energy. The average hadron hit varies with energy showing saturation effetcs.
- In the energy region where the mean varies linearly with energy, the resolution function is $\frac{\sigma}{E} \sim \frac{\Delta E}{E}$.

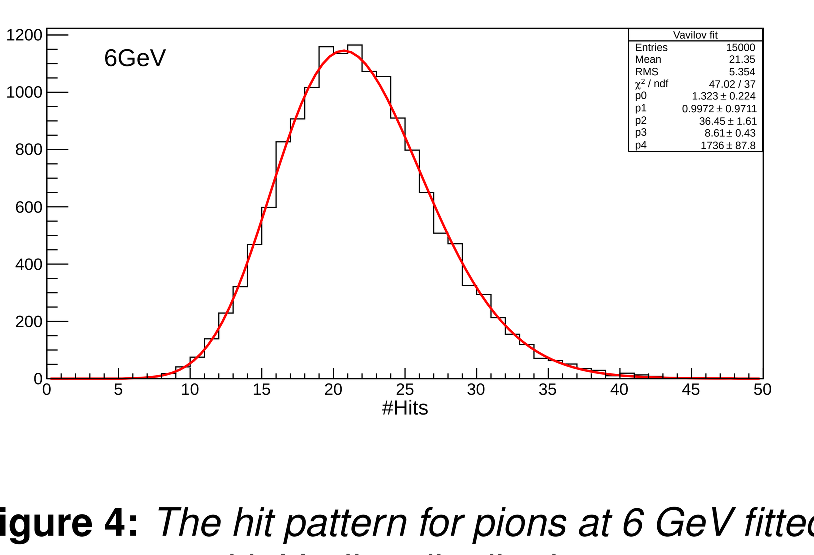

Figure 4: *The hit pattern for pions at 6 GeV fitted with Vavilov distribution.*

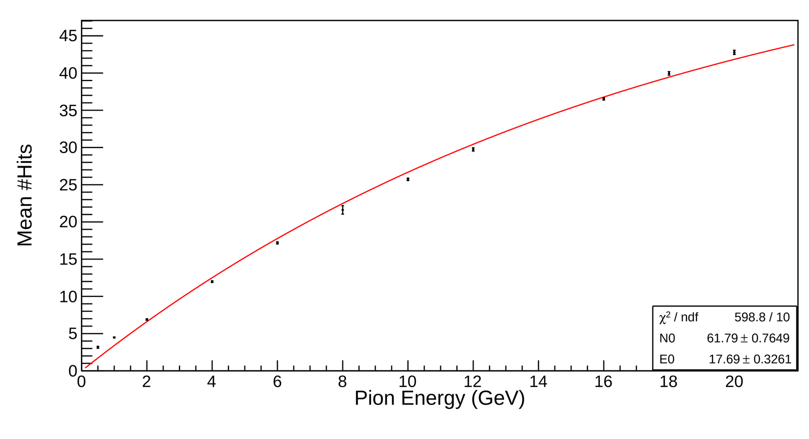

Figure 5: *The variation of average hadron hits of MC $\pi^\pm$ with energy.*

6. THE HADRON ENERGY RESOLUTION FOR INO-ICAL

The resolution function is parametrized by

$$\frac{\sigma}{E} = \sqrt{\left(\frac{P_0}{\sqrt{E}}\right)^2 + P_1^2}. \qquad (1)$$

- For vertically falling Monte Carlo $\pi^\pm$ events.
- For NUANCE atmospheric neutrino events.

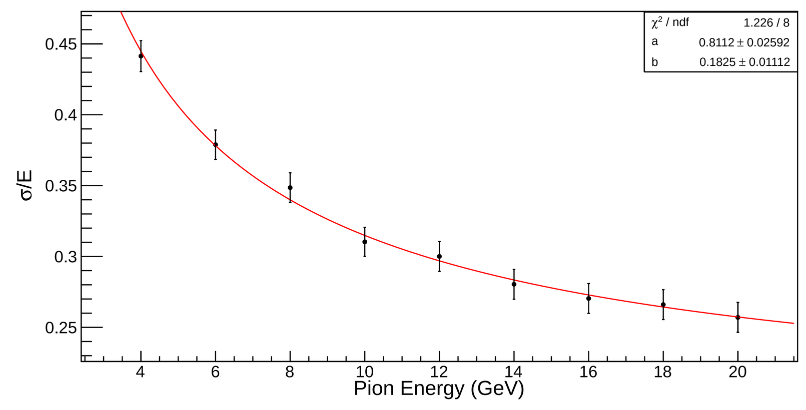

Figure 6: *Hadron energy resolution for MC $\pi^\pm$ events.*

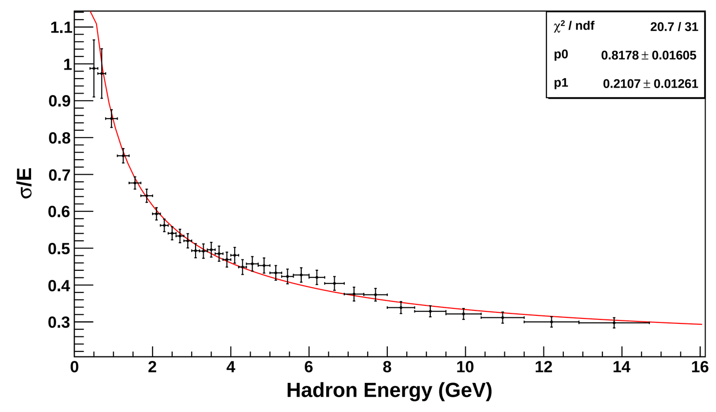

Figure 7: *Hadron energy resolution for NUANCE neutrino events.*

- $P_0 = 0.811 \pm 0.026$, $P_1 = 0.183 \pm 0.011$.
- Resolution (at E = 1GeV) $\sim$ (81.16 $\pm$ 2.59)%.

- $P_0 = 0.818 \pm 0.016$, $P_1 = 0.211 \pm 0.013$.
- Resolution (at E = 1GeV) $\sim$ (84.45 $\pm$ 1.58)%.

7. THE DIRECTION RESOLUTION OF THE HADRON SHOWER

The direction reconstruction of a hadron shower:

- The centroid of the hadron shower is formed by summing over the positions of the hits in each event.
- The direction vector of the centroid from the vertex gives the reconstructed shower direction.
- We define $\Delta\theta$ as the angle between the reconstructed shower direction and the true shower direction. The distribution of $\Delta\theta$ is fitted using the function

$$f(\Delta\theta) = A \times \Delta\theta \times \exp(-B \times \Delta\theta). \qquad (2)$$

- We define the direction resolution as,

$$\sigma_\theta = \sqrt{<(\Delta\theta)^2> - <\Delta\theta>^2}. \qquad (3)$$

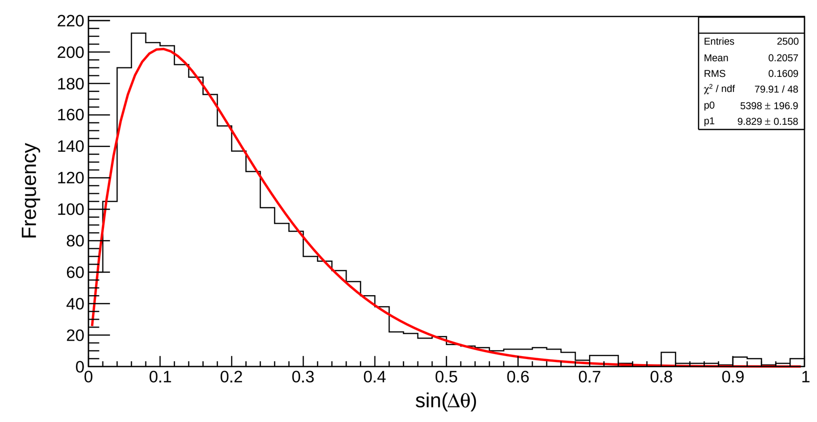

Figure 8: *The sin($\Delta\theta$) distribution in hadron energy bin (6.2-6.8) GeV.*

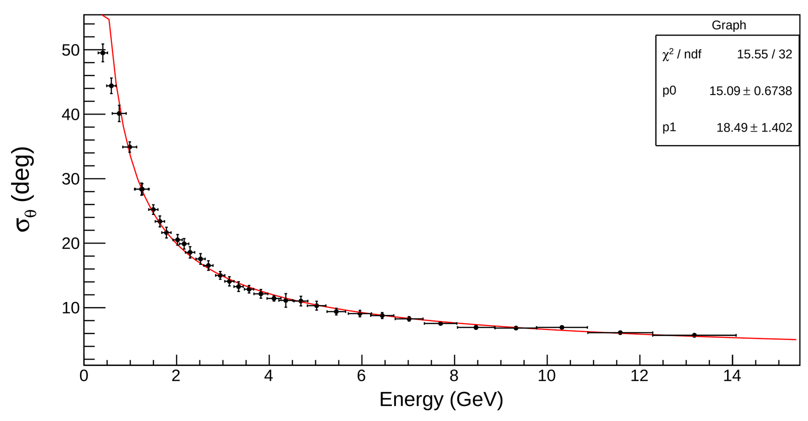

Figure 9: *Direction resolution vs energy plot for NUANCE neutrino events.*

- The σ_θ can be parametrized over the energy range by (Figure 9),

$$\sigma_\theta(deg) = \frac{15.09 \pm 0.67}{\sqrt{E(GeV)}} + \frac{18.49 \pm 1.40}{E(GeV)}. \qquad (4)$$

8. CALIBRATION OF HADRON ENERGY $\&$ SHOWER DIRECTION FROM HADRON HITS

- The simulated data are divided into some (reconstructed hadron direction, number of hadron hits) bins and for each bin, calibration plots are obtained for hadron energy and direction resolution.
- Examples of calibration plot: for the cosθ bins [0,-0.2), [-0.2,-0.4), [-0.4,-0.6), [-0.6,-0.8), [-0.8,-1].

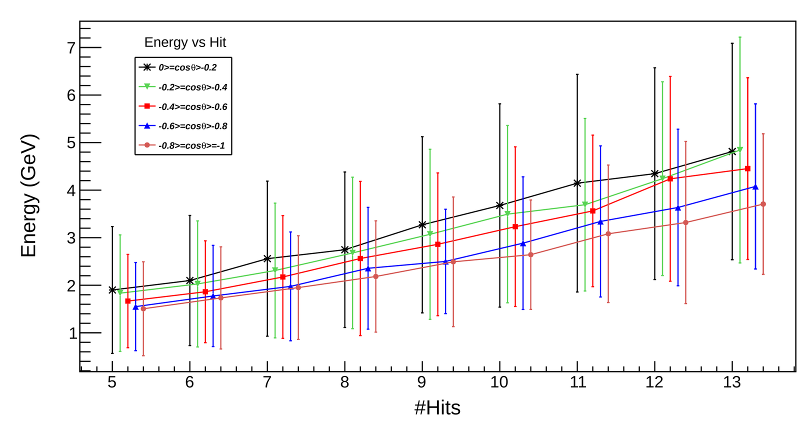

Figure 10: *Calibration of Hadron Energy with Hadron Hits.*

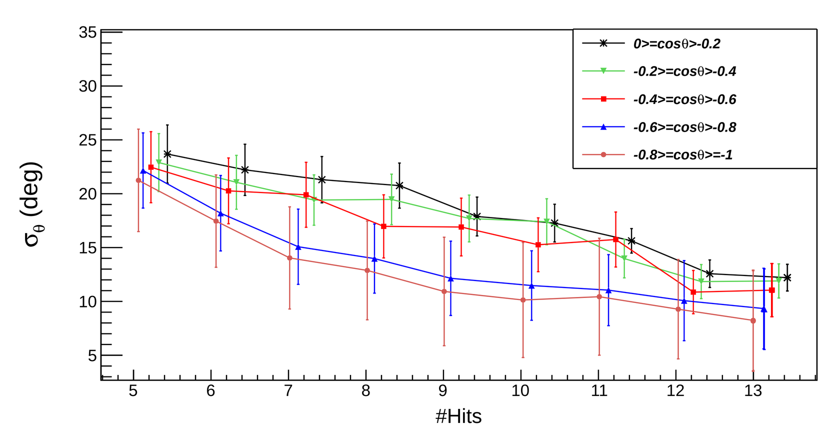

Figure 11: *Calibration of hadron shower direction resolution with hadron hits.*

- Using these calibration plots, the hadron energy and shower direction of an event can be estimated from the hit information.

9. CONCLUSIONS

- We have analysed the hadron energy resolution and reconstruction of direction in INO-ICAL detector both with MC pion events and hadrons shower in NUANCE neutrino events.
- The hit pattern was fitted with Vavilov pdf and the energy resolution at 1GeV is around 80 percent.
- The optimization of INO-ICAL Code for hadronic energy calibration and direction reconstruction is in progress.

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11. REFERENCES

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