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 calorimeter (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.

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.

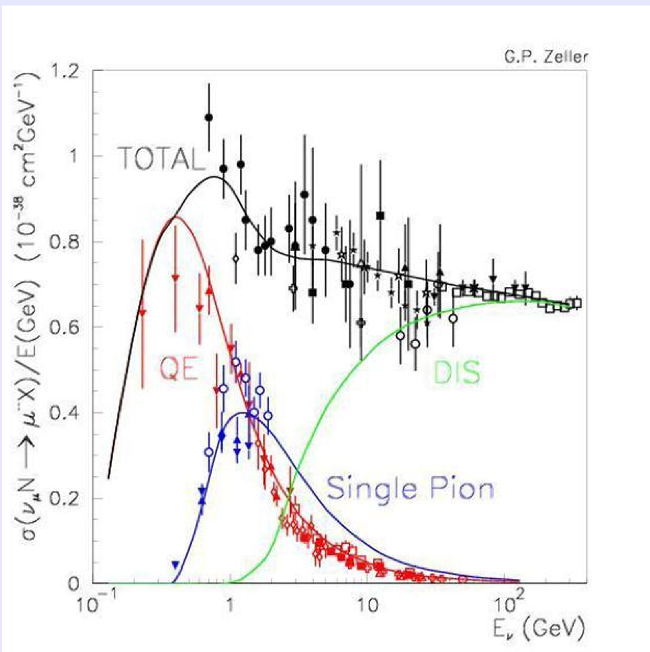

Figure 1: *The energy dependance of the cross sections of diferent interaction processes*[2].

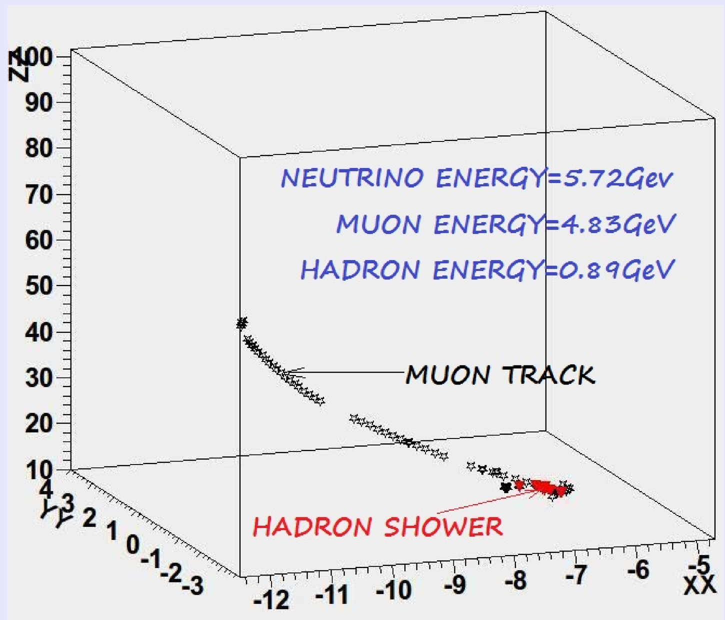

Figure 2: *A DIS event in INO-ICAL detector. Black points: muon track, red ones:hadron shower.*

2. THE IMPORTANCE OF HADRONIC RESPONSE IN INO-ICAL

- Measurement of neutrino energy (E_ν) and direction plays a crucial role in fulfilling the physics goals.
- $E_\nu = E_\mu - E_h$, where E_ν is the muon energy and E_h is the energy of the hadrons.
- 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.

3. 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.

4. THE HADRON ENERGY RESOLUTION FOR INO-ICAL

- The hadron hit distributions in ICAL follow Vavilov distribution function[5], which is used to calculate the energy loss of heavy charged particles in moderately thick absorbers.
- The average hadron hit varies with energy showing saturation effetcs at higher energies.
- In the energy region where the mean varies linearly with energy, the resolution function is $\frac{\sigma}{E} \sim \frac{\Delta E}{E}$.
- The resolution function is parametrized by

$$\frac{\sigma}{E} = \sqrt{(\frac{a}{\sqrt{E}})^2 + b^2}. \qquad (1)$$

- Example (Figure 3): $\frac{\sigma}{E}$ (for CC events with oscillation) as a funtion of E, giving $a = 0.731 \pm 0.027$, $b = 0.207 \pm 0.013$. Resolution (at E = 1GeV) $\sim$ 75.98%.
- The resolution function depends on the hadron shower direction too (Figure 4).

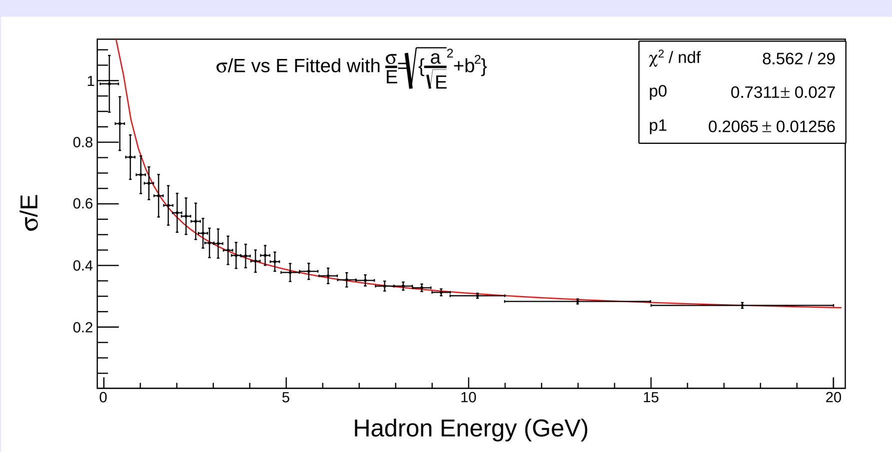

Figure 3: $\frac{\sigma}{E}$ *(for CC events with oscillation) as a function of E.*

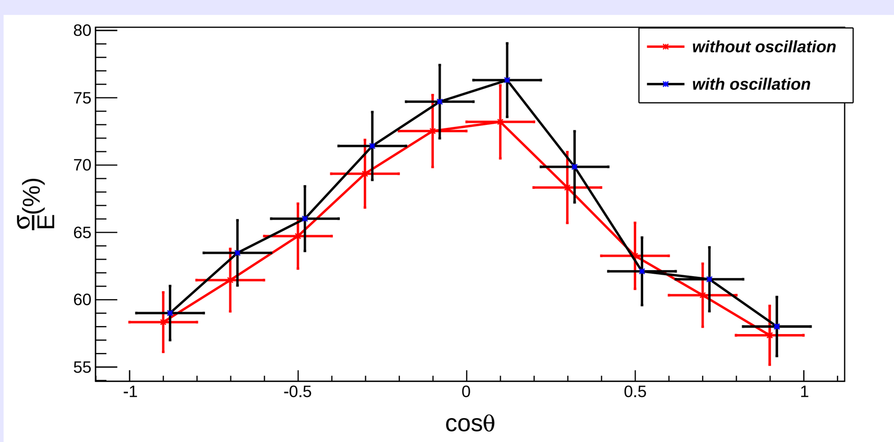

Figure 4: *The dependance of* $\frac{\sigma}{E}$ *with shower direction.*

- Tables showing $\frac{\sigma}{E}$ for diferent types of events:

Without oscillation:

$Events$	a	b	$\frac{\sigma}{E}\% at E = 1GeV$
CC	0.69 ± 0.03	0.27 ± 0.01	74.21
$CC + NC$	0.73 ± 0.03	0.21 ± 0.01	75.96

With oscillation:

$Events$	a	b	$\frac{\sigma}{E}\% at E = 1GeV$
CC	0.73 ± 0.03	0.22 ± 0.01	75.98
$CC + NC$	0.74 ± 0.03	0.29 ± 0.01	79.48

5. 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,

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

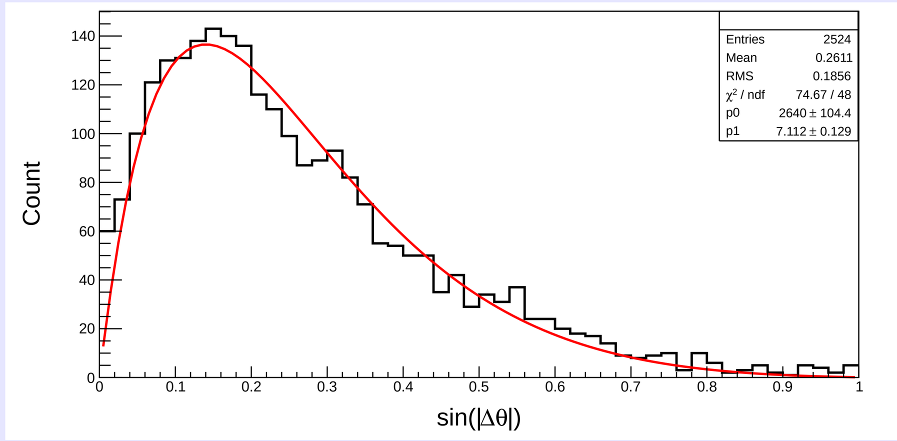

Figure 5: *The sin($\Delta\theta$) distribution in hadron energy bin (3.5-4) GeV.*

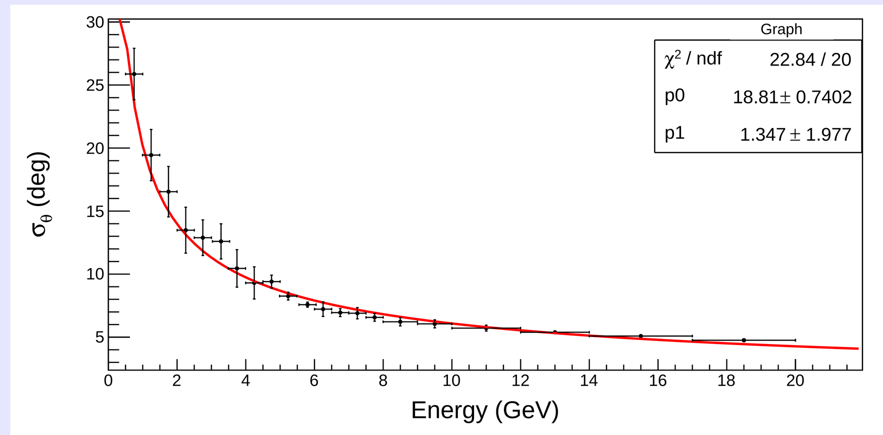

Figure 6: *Direction resolution vs energy plot for NUANCE neutrino events.*

- The σ_θ can be parametrized over the energy range by (Figure 6),

$$\sigma_\theta(deg) = \frac{18.81 \pm 0.74}{\sqrt{E(GeV)}} + \frac{1.35 \pm 1.98}{E(GeV)}. \qquad (4)$$

6. 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].

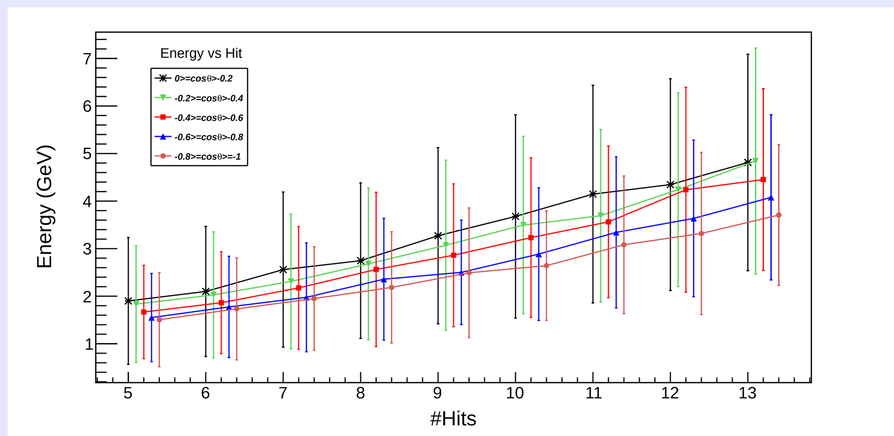

Figure 7: *Calibration of Hadron Energy with Hadron Hits.*

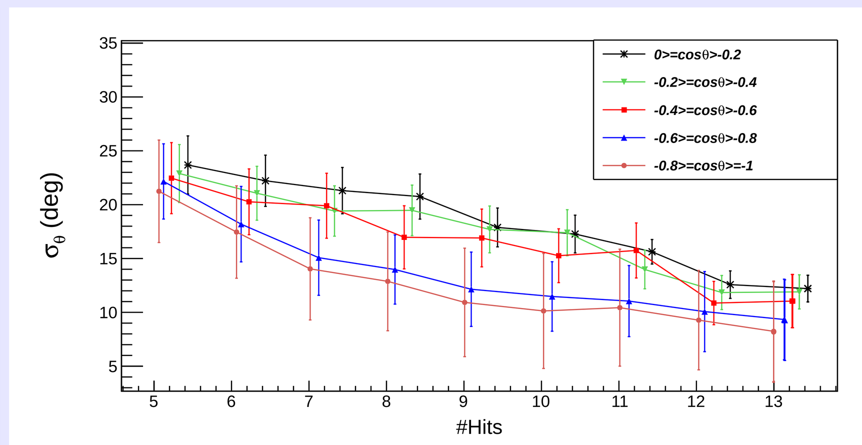

Figure 8: *Calibration of hadron shower direction resolution with hadron hits.*

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

7. RECONSTRUCTION OF NEUTRINO ENERGY USING HADRON DATA

- The distributions of E_ν in different E_μ bins can be fitted to $f(E_\nu) = A \times (E_\nu - E_\mu)^B \times \exp[-C(E_\nu - E_\mu)]$ giving $<E_\nu> = \frac{B+1}{C}, \sigma = \frac{\sqrt{B+1}}{C^2}$.
- $<E_\nu>$ in different E_μ bins are underestimated with $E_\nu \sim E_\mu$ approximation(the black points in Figure 9). Adding E_h takes the reconstructed E_ν closer to the actual value, but it increases the error by a large amount (the red points in Figure 9).
- Additional fine binning in hadron hits (h) help in reducing the errors, particularly in the lower h bins (Figure 10). Also it makes the exact distribution of E_ν, as a function of E_μ, immaterial.

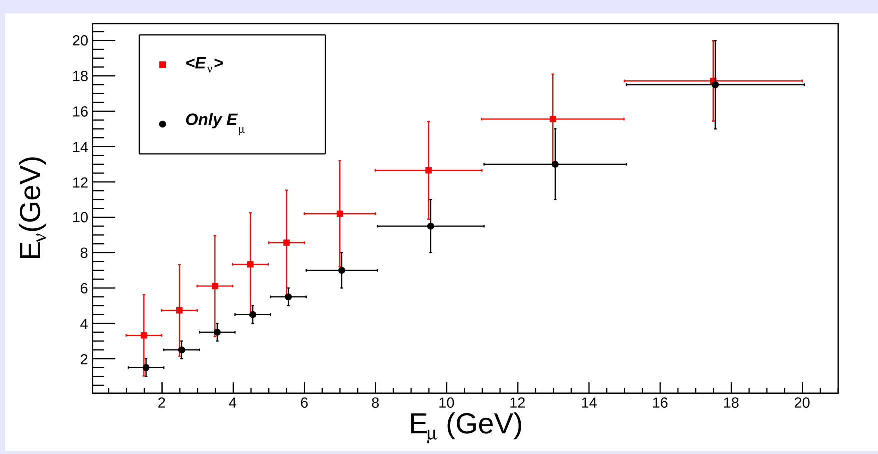

Figure 9: *($<E_\nu> \pm \sigma$) for different E_μ bins.*

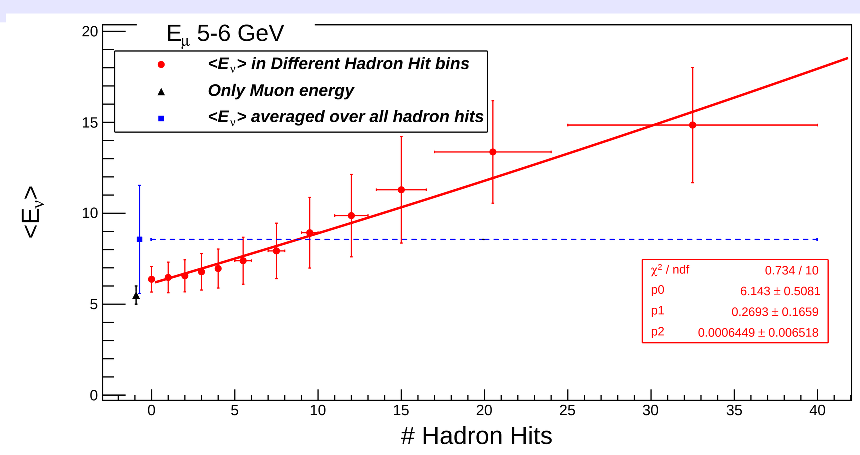

Figure 10: *$<E_\nu>$ in different h bins,$E_\mu = 5 - 6GeV$*

- Plots like the one in Figure 10 can directly be used as calibration plots for reconstructing E_ν.

8. CONCLUSIONS

The resolutions of hadron energy and shower direction in INO-ICAL detector both with MC pion events and hadrons shower in NUANCE neutrino events were studied. The hit pattern was fitted with Vavilov pdf and the energy resolution at 1GeV is ~ 75 %. The direction resolution at E=1GeV is $\sim 20°$. Calibration plots for reconstructing E_h and E_ν were obtained. The optimization of hadron shower direction reconstruction and neutrino direction resolution are in progress.

9. ACKNOWLEDGEMENT

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10. REFERENCES

1. INO Project Report, 2006.
2. arXiv:hep-ex/0312061v1, G. P. Zeller.
3. http://geant4.cern.ch.
4. http://nuint.ps.uci.edu/nuance.
5. A. Rotondi, P. Montagna, 'Fast calculation of Vavilov distribution', Nucl. Instrum. Methods B, vol 47, pp. 215-223,1990.