THE NEUTRINO ENERGY & DIRECTION RESOLUTIONS IN THE INO-ICAL DETECTOR

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1. INTRODUCTION

- The India-based Neutrino Observatory (INO) [1] 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. 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 Scattering (RS) interaction events. They produce single pion events.

The energy dependence of the cross section of these interactions are shown in Fig. 1 [2]. At lower energies ($E_\nu < 5$ GeV) QECC and RS interaction events are more prominent, while as energy increases DIS events dominate.

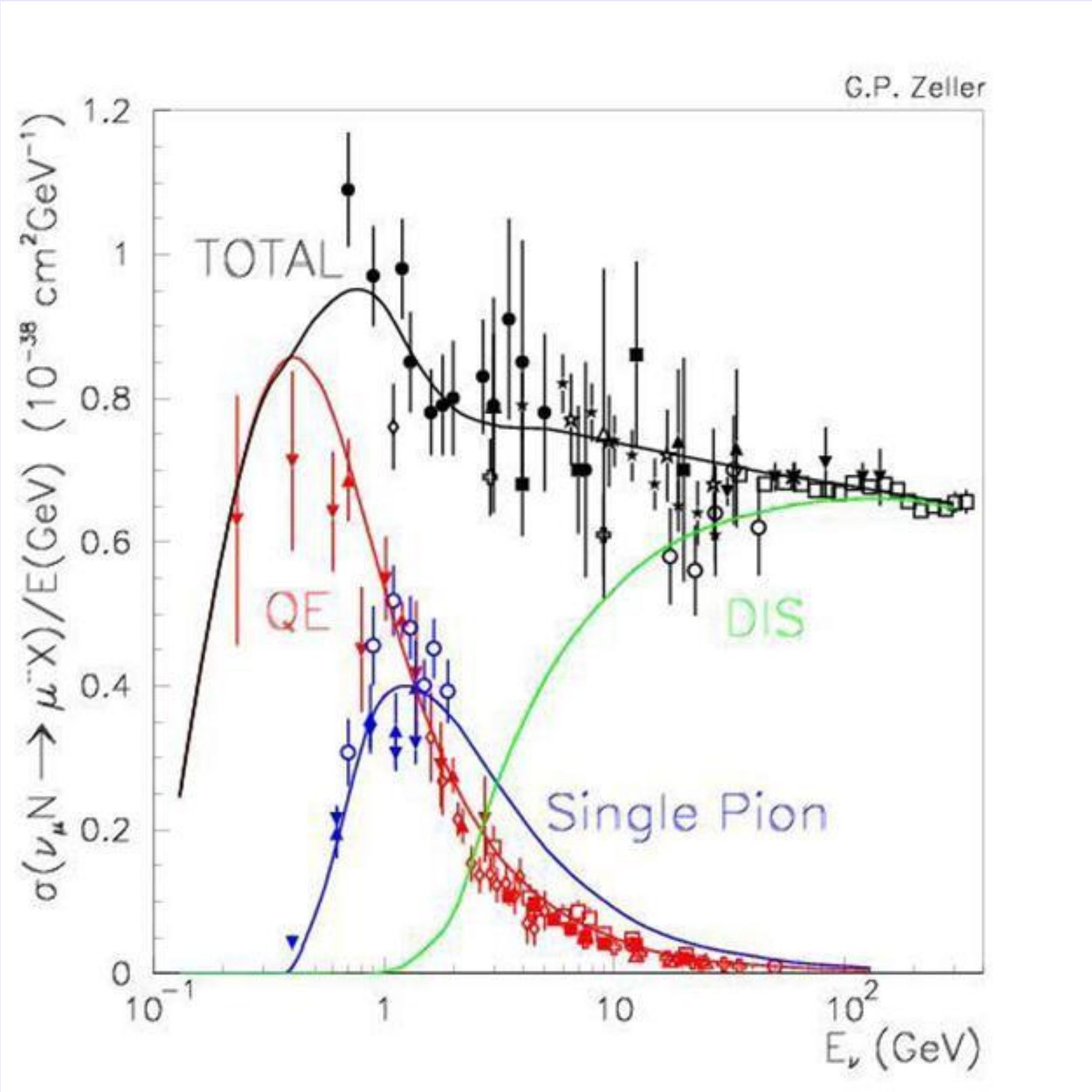

Figure 1: The energy dependence of cross section of different processes.

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

- The muon momentum (P_μ) is reconstructed using a Kalman filter algorithm.
- For the hadron shower, the useful information is the hadron hits.
- The hadron energy and momentum are calibrated using the frequency distribution of hadron hits.
- The direction of hadron shower is reconstructed using orientation matrix technique. The position vectors of hadron hits with respect to the interaction vertex are used.

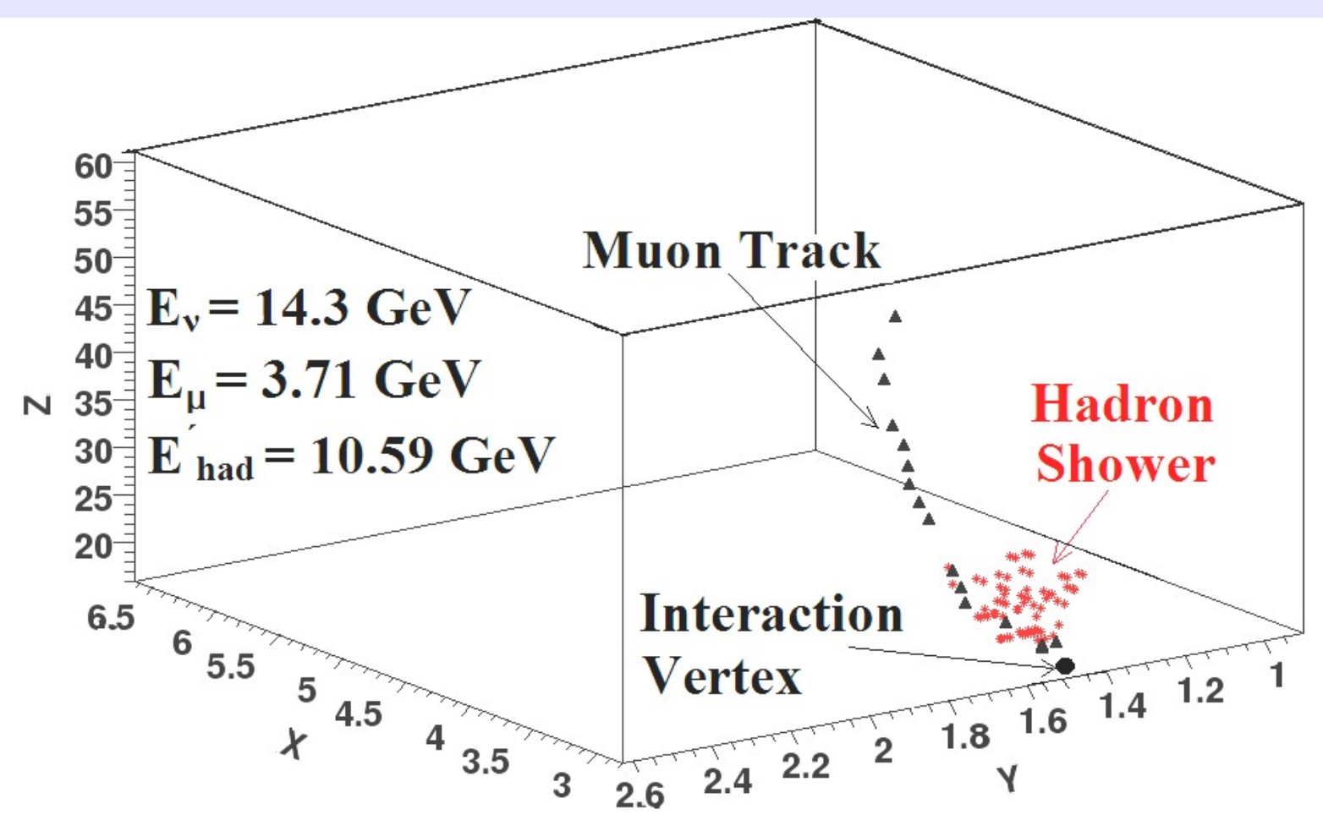

Figure 2: A DIS event event in the simulated ICAL detector using VICE event display package [3].

2. THE DETECTOR SIMULATION

- Simulation Toolkit: GEANT4 [4]. Storage of output & analysis: ROOT.
- The simulation framework consists of the following:
  1. Event Generation (GEANT4 / NUANCEv3 [5]): 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 neutrino response of INO-ICAL are studied using both ν and $\bar{\nu}$ CC events generated using NUANCE gererator.

3. EFFICIENCIES OF NEUTRINO EVENT RECONSTRUCTION AND DISTINCTION BETWEEN NEUTRINO AND ANTI NEUTRINOS

For a (E_ν, cos θ_ν) bin if we define,

- A = The total number of events in the bin.
- B = The total number of events with reconstructed μ track.
- C = The total number of events with right μ charge reconstruction.

Then, Reconstruction Efficiency = $\frac{B}{A}$, and ν Identification Efficiency = $\frac{C}{B}$.

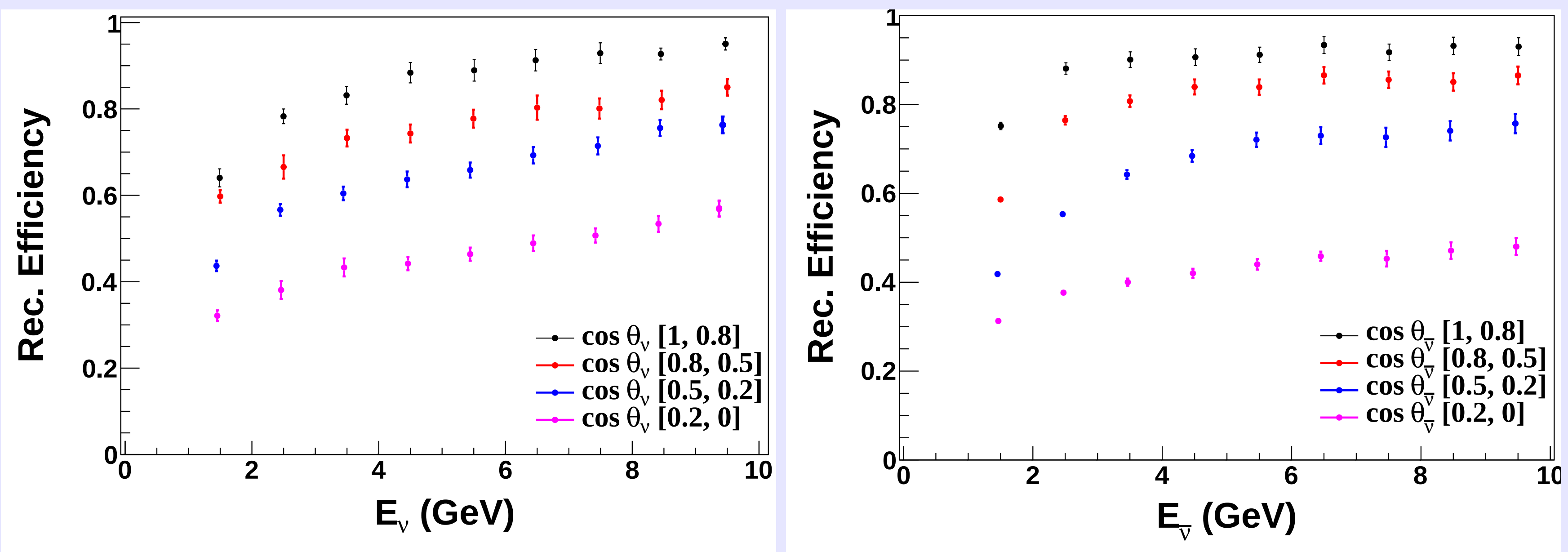

Figure 3: Reconstruction efficiency of ν (left) and $\bar{\nu}$ (right) events.

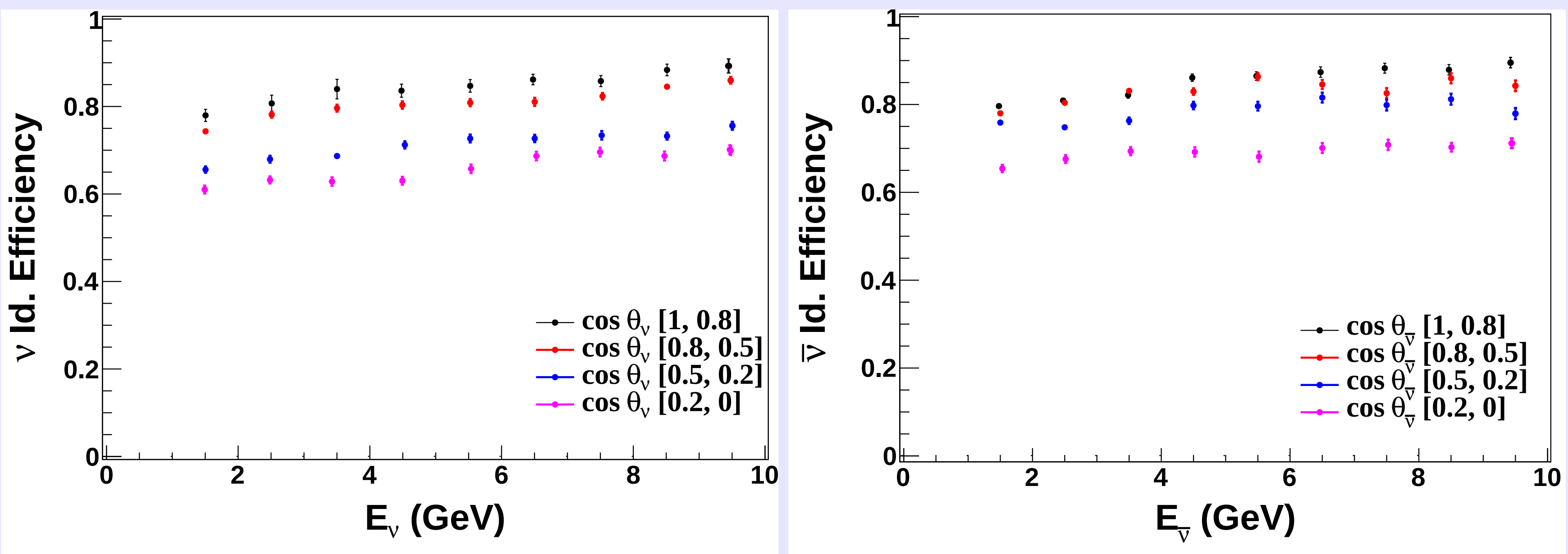

Figure 4: *ν (left) and $\bar{\nu}$ (right) identification efficiency.*

4. NEUTRINO ENERGY RESOLUTION

- The muon energy (E_μ) is reconstructed using kalman filter techniques.
- We define E'_{had} as $E'_{had} = E_\nu - E_\mu$.
- A calibration of E'_{had} with hadron hits is used to estimate the hadron energy.
- $E^{rec}_\nu = E^{rec}_\mu + E'^{rec}_{had}$.
- The distributions of $E^{rec}_\nu - E^{true}_\nu$ for different (E_ν, cos θ_ν) bins are fitted to Gaussian.
- Fig. 5 shows an example of the $E^{rec}_\nu - E^{true}_\nu$ frequency distribution in the bin (E_ν = 3.5 - 4 GeV, cos θ_ν = [1, 0.8]).
- E_ν resolution is defined to be $\sigma_{\text{Gaussian fit}}/E_\nu$.

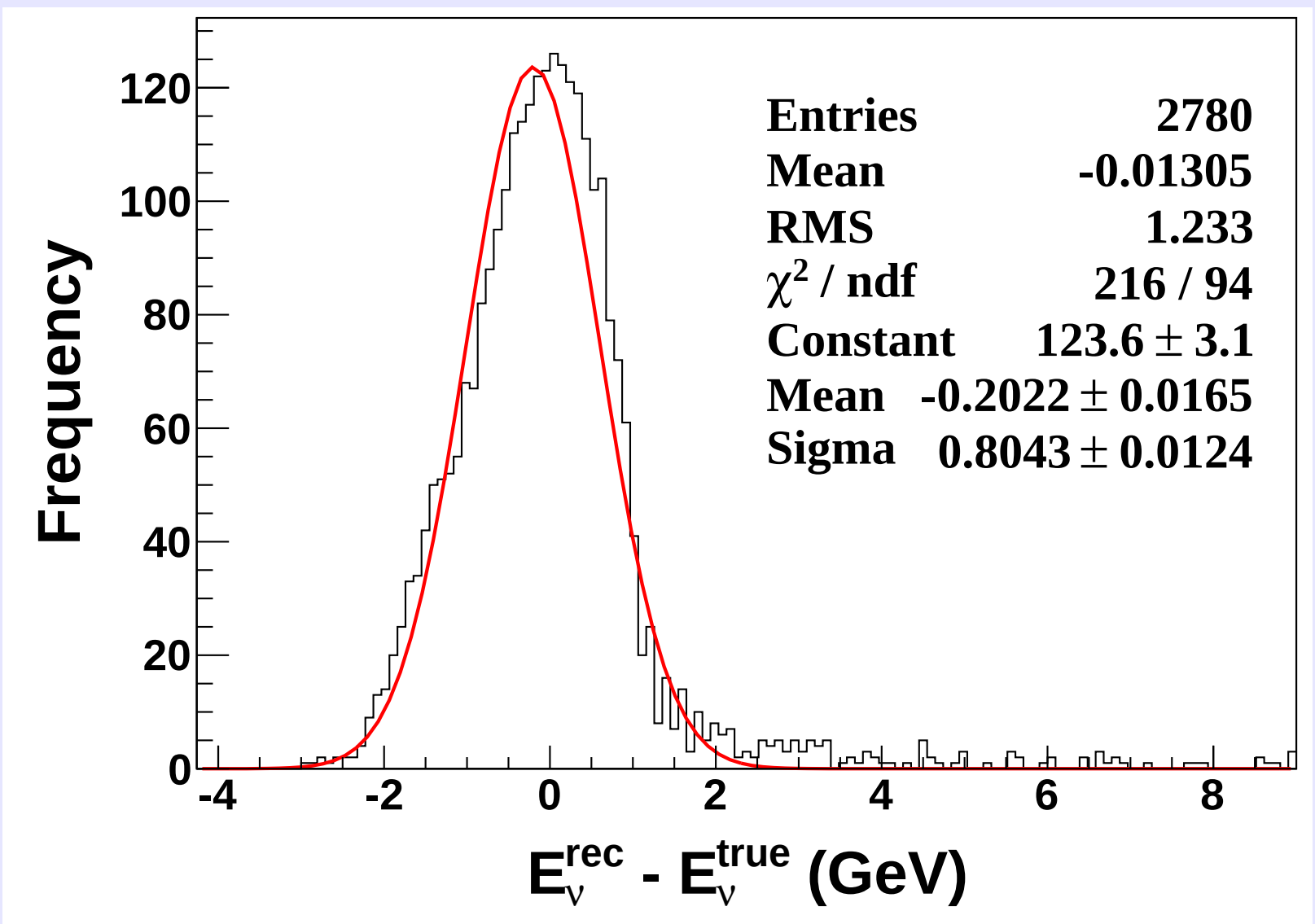

Figure 5: Distribution of (E_ν, cos θ_ν) for events with (E_ν = 3.5 - 4 GeV, cos θ_ν = [1, 0.8]).

The energy resolutions of ν and $\bar{\nu}$ are plotted agains energy in Fig. 6.

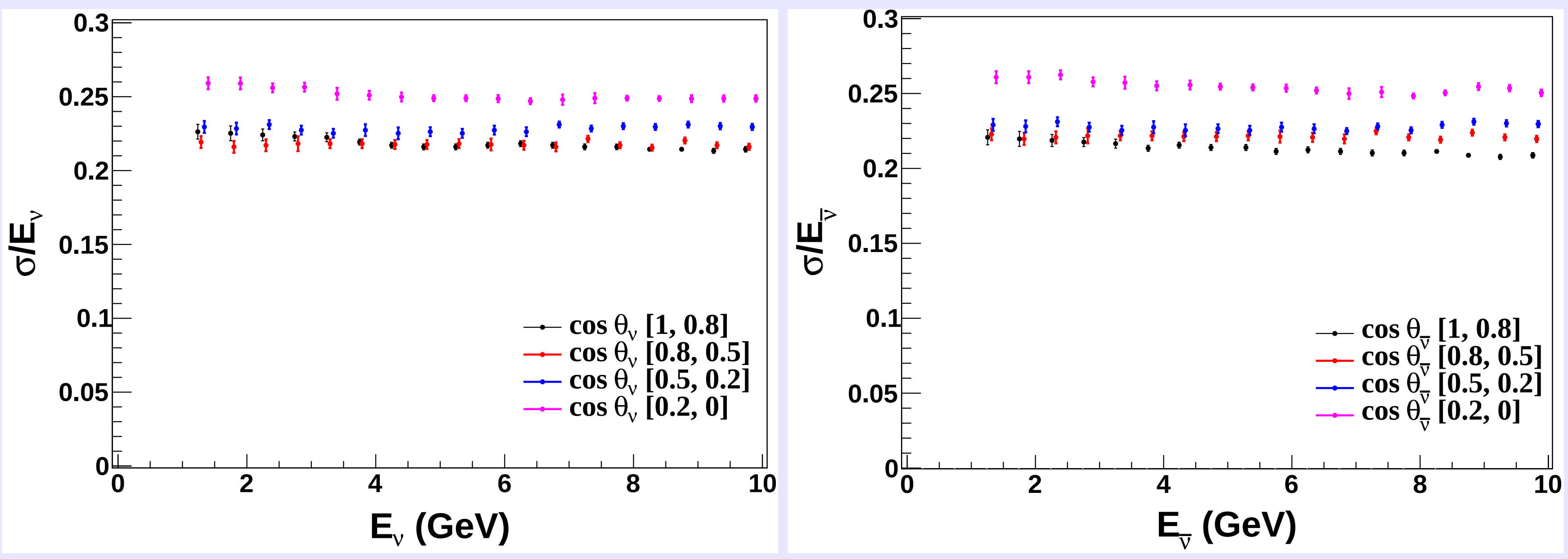

Figure 6: Plots of resolution of E_ν and $E_{\bar{\nu}}$ vs energy.

5. NEUTRINO DIRECTION RESOLUTION

From the kinematics we can write the X, Y, Z projections of the neutrino momentum as,

$$P_{\nu X} = P_\mu \times \sin\theta_\mu \times \cos\phi_\mu + P_{had} \times \sin\theta_{had} \times \cos\phi_{had}$$
$$P_{\nu Y} = P_\mu \times \sin\theta_\mu \times \sin\phi_\mu + P_{had} \times \sin\theta_{had} \times \sin\phi_{had}$$
$$P_{\nu Z} = P_\mu \times \cos\theta_\mu + P_{had} \times \cos\theta_{had}$$

wherefrom, θ_ν can be calculated as $\tan\theta_\nu = \frac{\sqrt{P^2_{\nu X}+P^2_{\nu Y}}}{P_{\nu Z}}$.

- P_μ, θ_μ, and ϕ_μ are reconstructed using the Kalman track fit algorithm.
- P_{had} is reconstructed using the calibration of P^{true}_{had} with hadron hit number. P^{true}_{had} is the sum of the momentum of all the hadrons in an event.
- θ_{had} and ϕ_{had} are reconstructed from the hadron hit information using orientation matrix technique.

- The distributions of $\theta_{\nu_{true}} - \theta_{\nu_{rec}}$ can be fitted to the Lorentzian distribution function.
- Functional form of Lorentzian $L(x) = \frac{1}{\pi}\frac{\frac{\Gamma}{2}}{(x-x_0)^2+\frac{\Gamma}{2}^2}$.
- Fig. 7 shows an example of the frequency distribution of $\theta_{\nu_{true}} - \theta_{\nu_{rec}}$ in the bin (E_ν = 4-5 GeV, cos $\theta_{\nu true}$ = [1, 0.8]).
- Lorentzian fit parameters are mean (x_0) and FWHM (Γ).
- We define, the fit parameter Γ as the direction resolution.

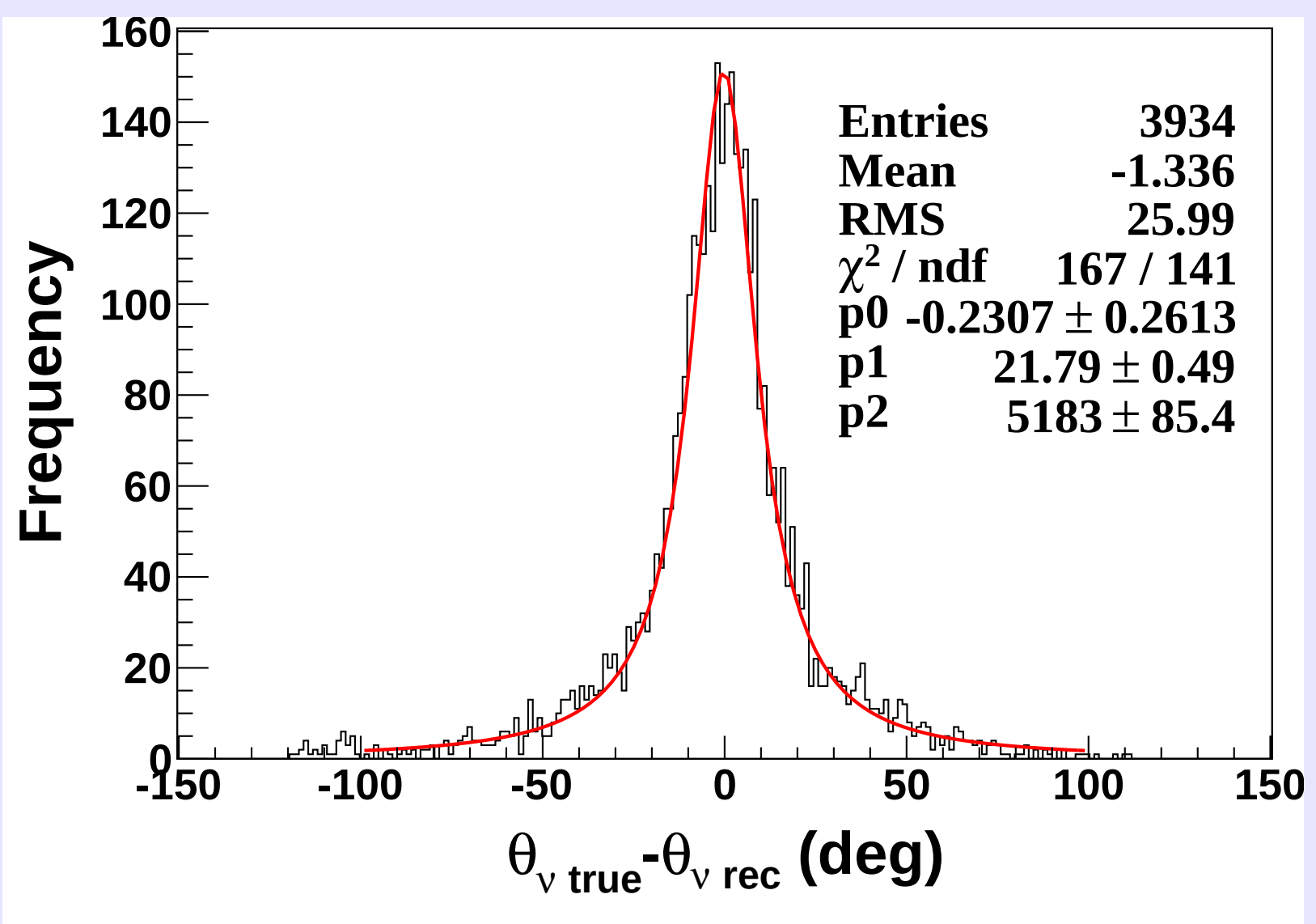

Figure 7: Distribution of $\theta_{\nu_{true}} - \theta_{\nu_{rec}}$ in the bin (E_ν = 4-5 GeV, cos $\theta_{\nu true}$ = [1, 0.8]).

In Fig. 8, the direction resolutions of ν and $\bar{\nu}$ are plotted againg neutrino energy.

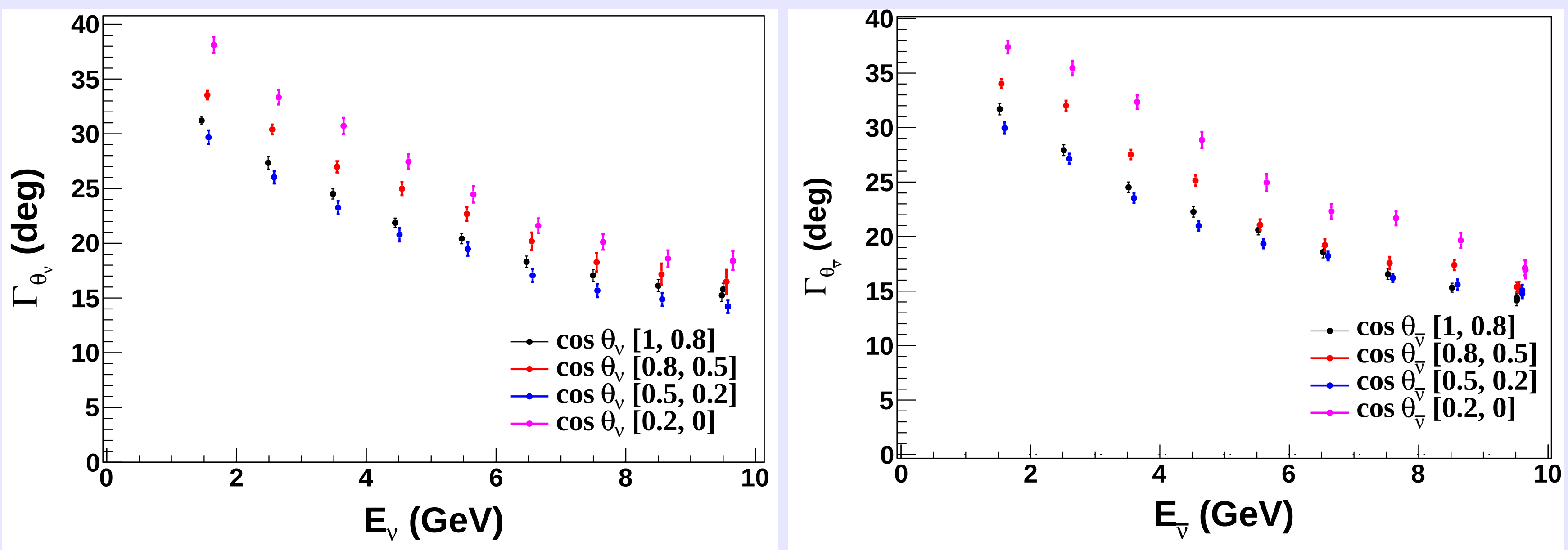

Figure 8: The direction resolutions of ν and $\bar{\nu}$ vs neutrino energy, fitted to Lorentzian distribution.

6. CONCLUSIONS

The resolutions of neutrino energy and direction in INO-ICAL detector have been studied using ν and $\bar{\nu}$. The neutrino energy is reconstructed by summing up the reconstructed muon and hadron energies and the energy resolutions are obtained to be in the range 21% - 26%. The neutrino direction is reconstructed using reconstructed information on muon and hadrons, and the direction resolution is found to be in the range 15° - 38° at different energies. Work to improve the results is in progress.

7. ACKNOWLEDGEMENT

I would like to thank Prof. A. Dighe, Prof. D. Indumathi, Prof. N. K. Mondal, Prof Md. Naimuddin and Tarak for their suggestions in the course of this work. I am also thankful to the members of INO collaboration for the useful discussions during the meetings and presentations.

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XX DAE-BRNS High Energy Physics Symposium, Visva-Bharati, 13-18 January, 2013.