

Status of India-based neutrino observatory

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(For INO-ICAL Collaboration)



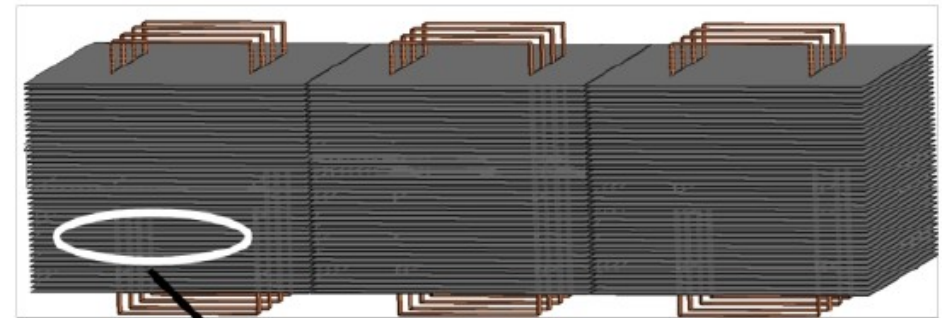
India based neutrino observatory

- **The India-based Neutrino Observatory (INO) is proposed to be built in Bodi West Hills, in Theni district of Tamil Nadu in South India.**
- **50kt magnetized iron calorimeter detector**
- **It will study atmospheric neutrinos and antineutrinos over a wide range of energies (1-10 GeV) and path lengths (except those for which muons travel horizontally)**
- **Sensitive to earth matter effects in multi GeV range**



The details of detector

- **3 modules each of dimension 16m X 16 m X 14.5 m**
- **151 layers of iron plates of thickness 5.6 cm with a gap of 4 cm for RPC trays**
- **Magnetic field of about 1.5 Tesla**



5.6 cm thick iron plate

4 cm air gap for RPC detector



The RPC details

- **RPC units of dimension 2m X 2m**
- **Readout strip width of 3 cm**
- **64 RPC's per layer per module (about 30000 RPC's in total)**
- **About 3.9×10^6 electronic readout channels**



Physics goals

- **Precision measurement of neutrino oscillation parameters**
- **Mass hierarchy determination**
- **ICAL might contribute to discovery of CP violation in lepton sector.**
- **ICAL can probe new physics scenarios like CPT violation and magnetic monopoles.**



Capabilities

- **ICAL can reconstruct the energy and direction of the muons produced in the CC interactions of the atmospheric muon neutrinos to a high precision.**
- **Fast response time (\sim ns) of RPC's will allow distinguishing upward-going and downward-going muons.**
- **It is sensitive to multi-GeV hadrons.**
- **It's able to distinguish neutrinos and antineutrinos with good charge identification.**
- **ICAL is an efficient detector for mass hierarchy determination.**



Current update

- **The Government of India has recently (December 2014) given its approval for the establishment of INO.**
- **The site has been identified. Site infrastructure development has started.**
- **Detector R&D is over.**
- **Detailed Project Report for Detector and DAQ system is ready.**
- **Industrial production of RPCs & associated front-end electronics to start soon.**



INO-ICAL white paper

INO/ICAL/PHY/NOTE/2015-01

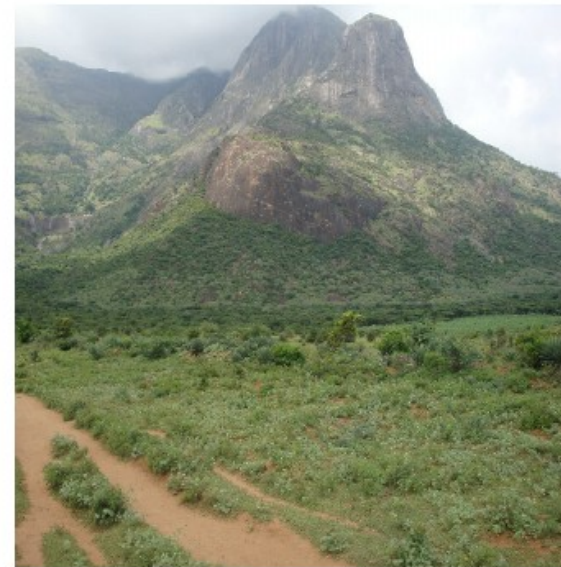
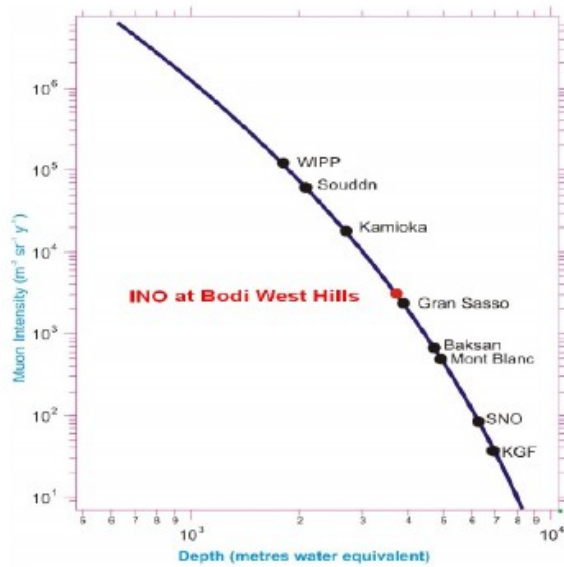
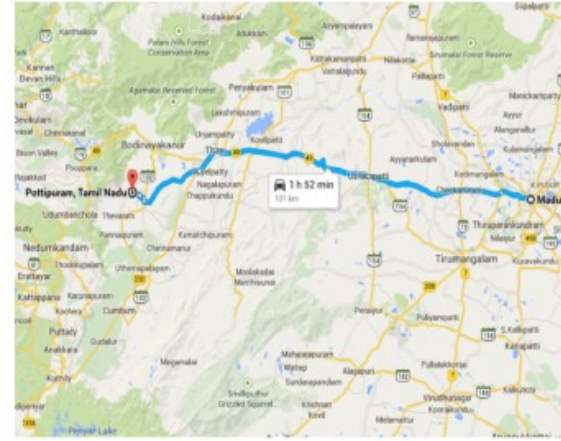
Physics Potential of the ICAL detector at the India-based Neutrino Observatory (INO)

The ICAL Collaboration

arXiv:1505.07380v1 [physics.ins-det] 27 May 2015

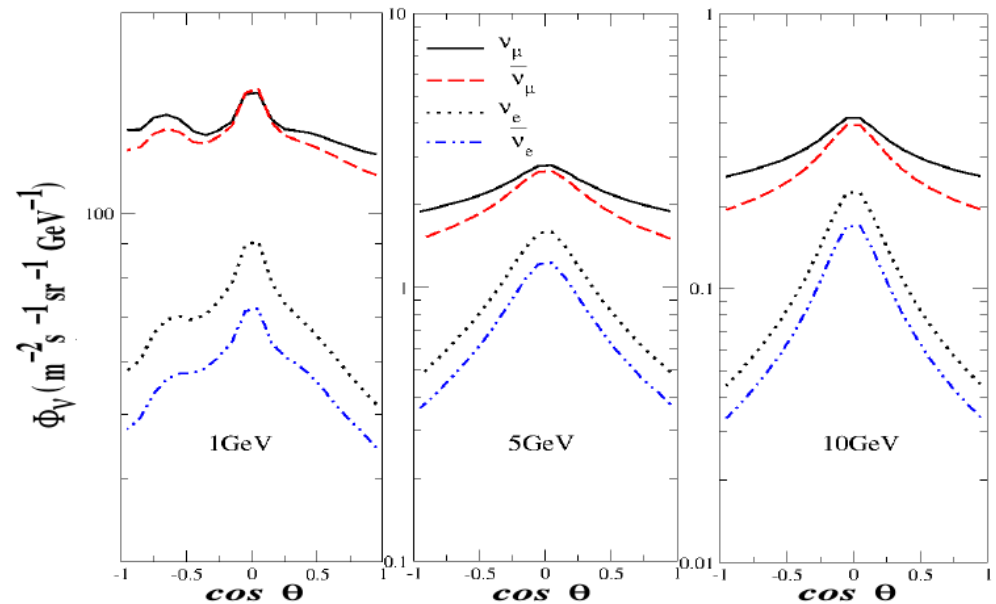


The INO site



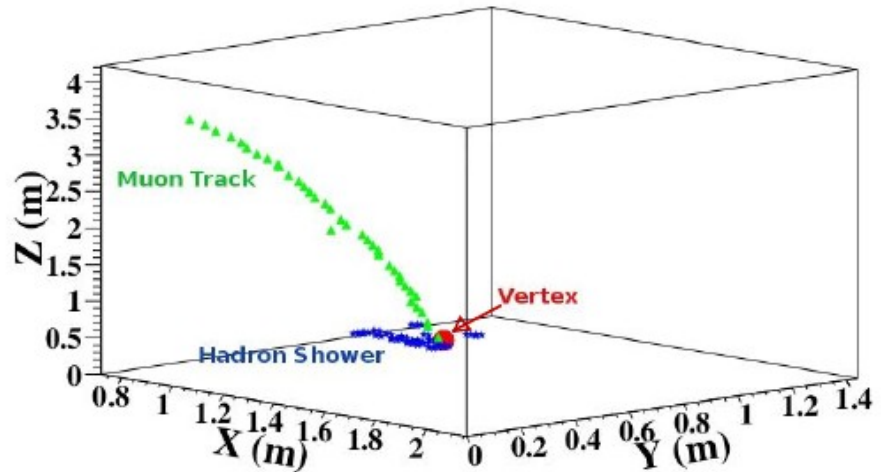
- **Atmospheric neutrino flux**

- **Atmospheric neutrino flux has been generated with NUANCE using Honda 3d fluxes for the Kamioka site in Japan.**
- **The Honda atmospheric fluxes at the INO site will be incorporated in the analyses soon.**

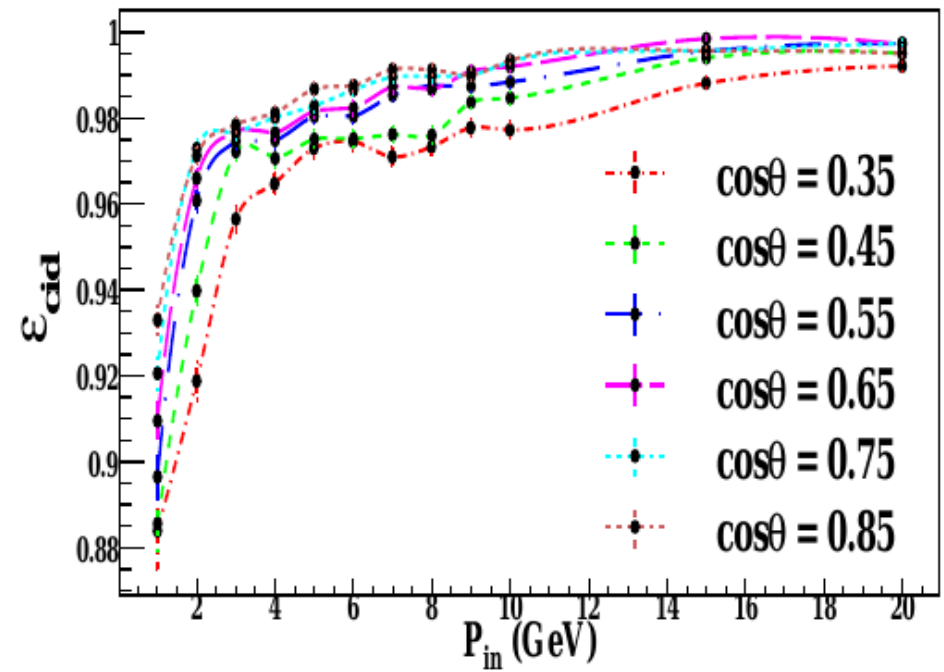
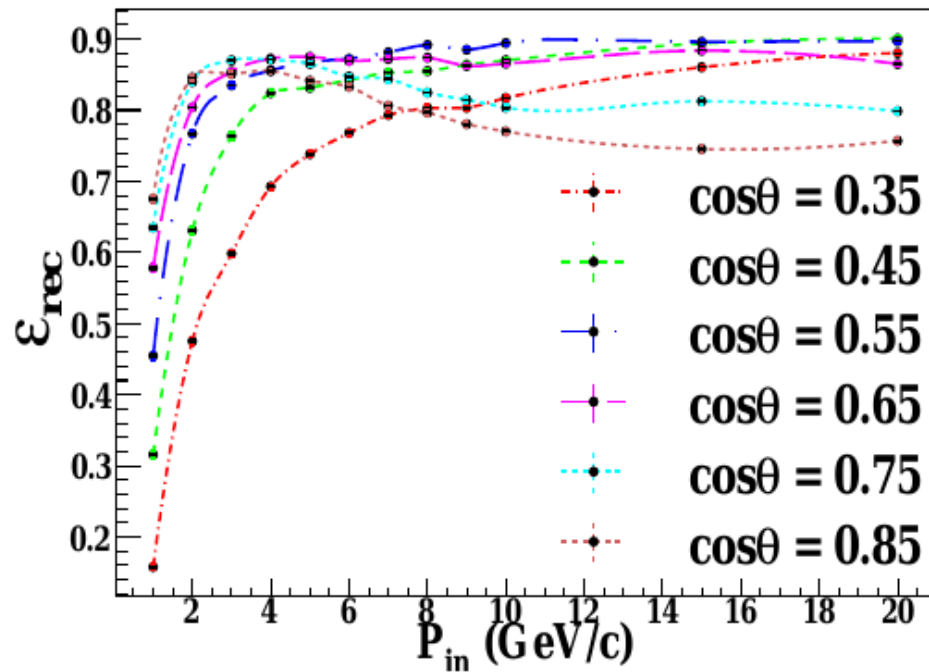


A typical event

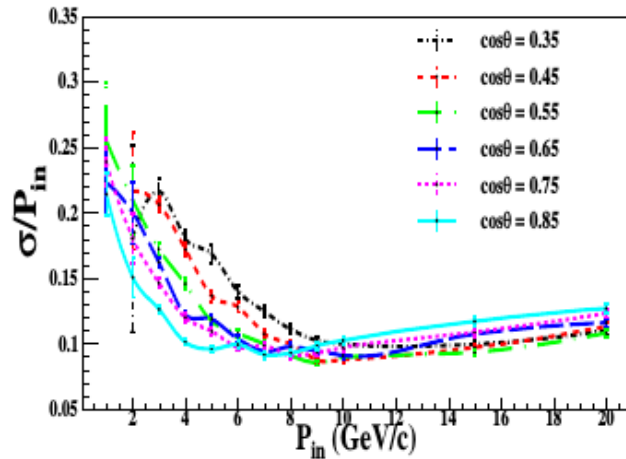
- CC interaction of a muon neutrino in the detector gives rise to a charged muon that leaves a track and single or multiple hadrons that give rise to a shower like feature.
- The muon track length and curvature are used to reconstruct muon energy.
- The number of hits for the hadron showers are used to reconstruct hadron energy.
- The neutrino energy can be reconstructed as the sum of the muon energy and hadron energy.



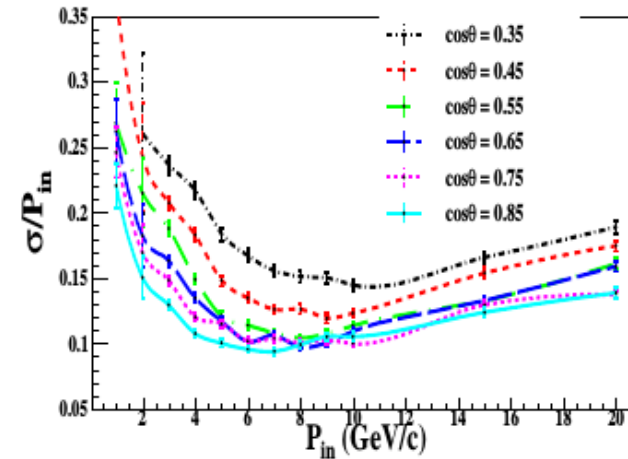
Charge identification efficiencies for muons (reconstruction efficiency)



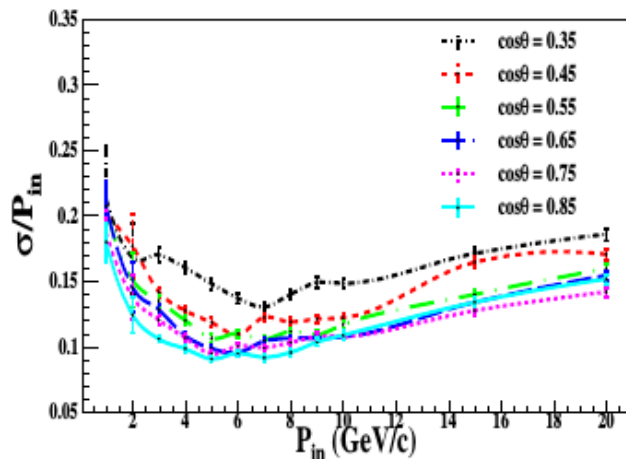
Muon momentum resolution at different azimuthal angles



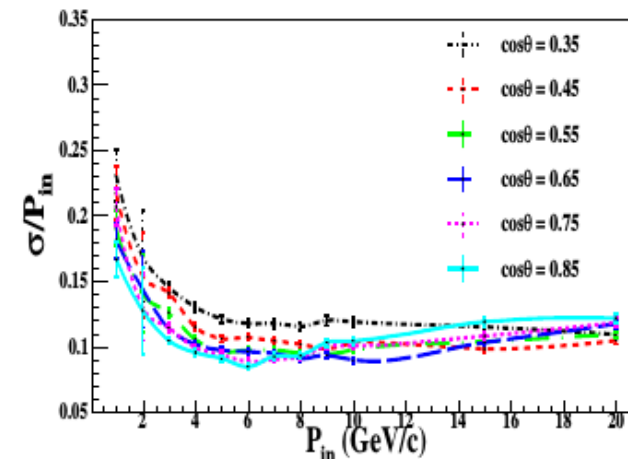
(a) $|\phi| \leq \pi/4$



(b) $\pi/4 < |\phi| \leq \pi/2$



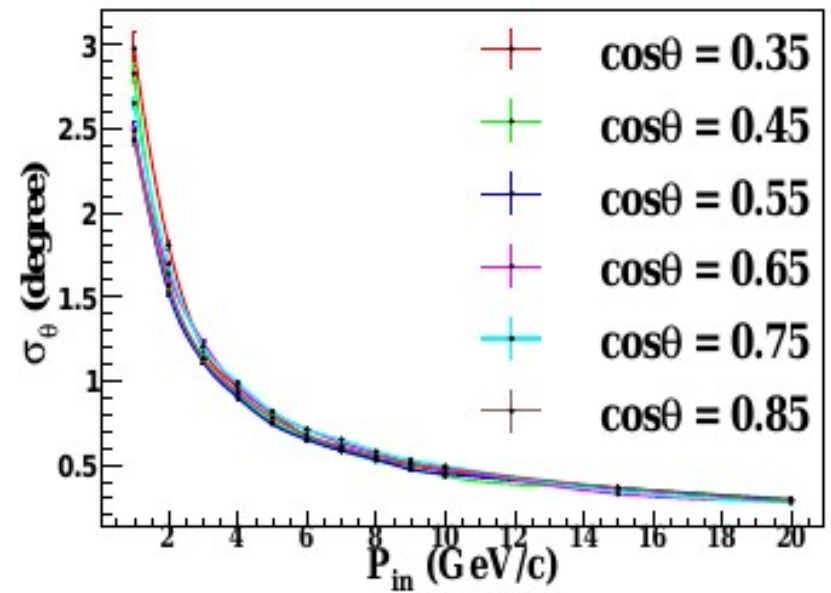
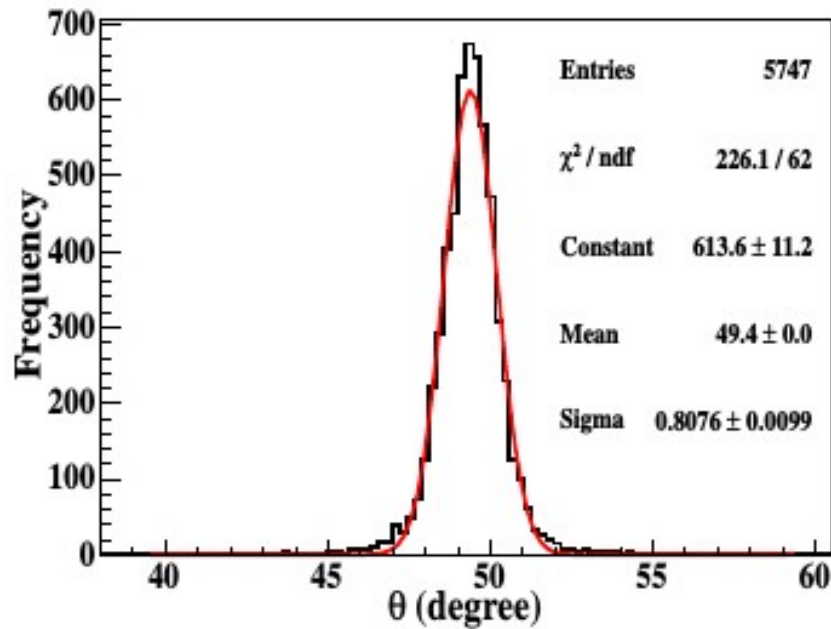
(c) $\pi/2 < |\phi| \leq 3\pi/4$



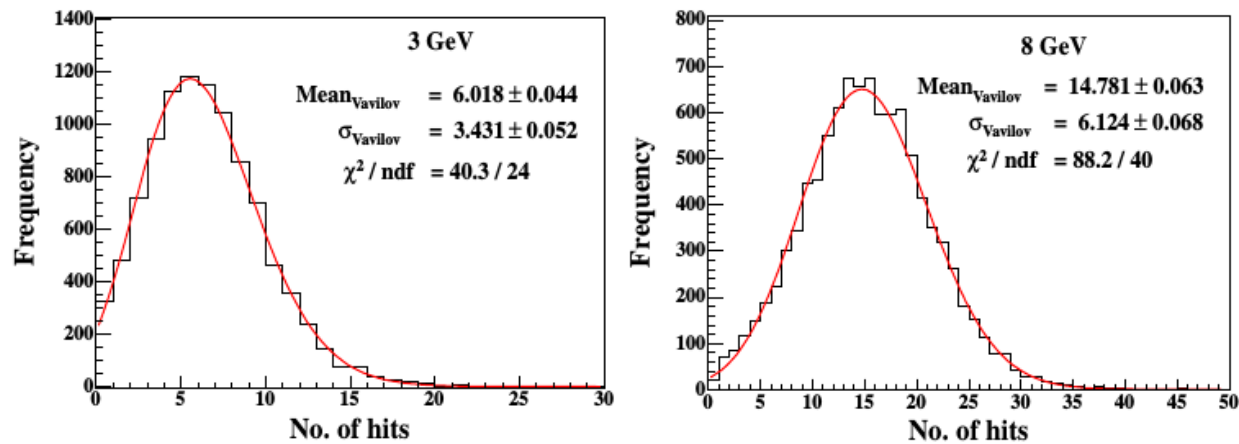
(d) $3\pi/4 < |\phi| \leq \pi$



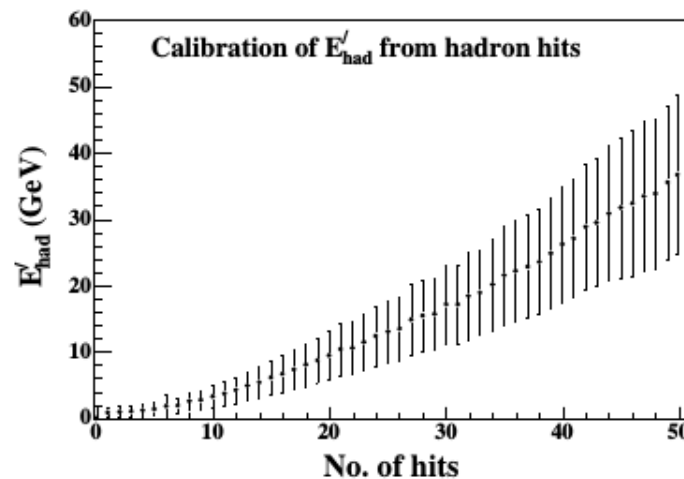
Angular resolution of muons



The hit distribution of pions from vertices smeared over the detector



$$\bar{n}(E) = n_0[1 - \exp(-E/E_0)]$$



$$\frac{\sigma}{E} = \sqrt{\frac{a^2}{E} + b^2}$$

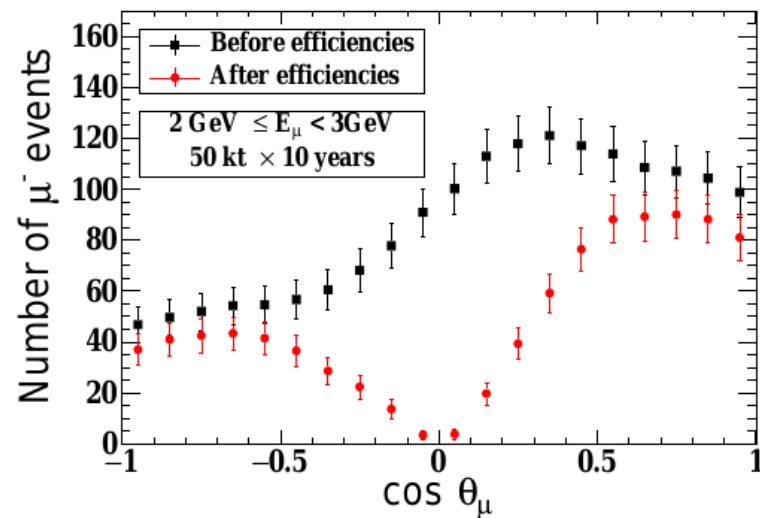
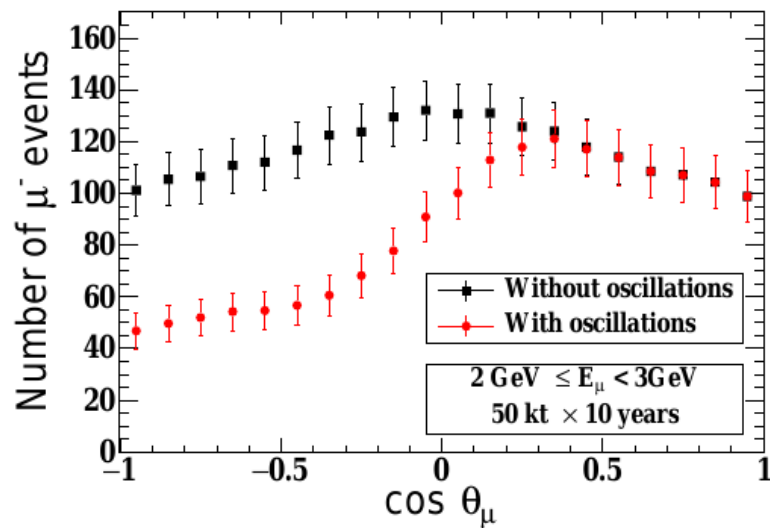


Physics analysis

- **Start with 1000 years of unoscillated events scaled later to a suitable exposure**
- **Include oscillations using a reweighting algorithm**
- **The energies and directions of the relevant particles are smeared using the detector resolutions and efficiencies.**
- **A complete GEANT based simulation is in progress.**



Zenith angle distribution of muon events



	μ^-	μ^+
Unoscillated	14311	5723
Oscillated	10531	4188
After Applying Reconstruction and CID Efficiencies	4941	2136
After Applying (E , $\cos \theta$) Resolutions	5270	2278



Chi-square function

- **We generate the data at benchmark values of oscillation parameters.**

- **Define chi-square function:**

- $$\chi^2(\mu^-) = \min_{\{\xi_k\}} \sum_{i,j} \left[2 \left(N_{ij}^{\text{theory}}(\mu^-) - N_{ij}^{\text{data}}(\mu^-) \right) + 2N_{ij}^{\text{data}}(\mu^-) \ln \left(\frac{N_{ij}^{\text{data}}(\mu^-)}{N_{ij}^{\text{theory}}(\mu^-)} \right) \right] + \sum_k \xi_k^2, \quad (5.7)$$

- where

$$N_{ij}^{\text{theory}}(\mu^-) = N_{ij}^{0 \text{ theory}}(\mu^-) \left(1 + \sum_{k=1}^l \pi_{ij}^k \xi_k \right). \quad (5.8)$$

- **Poissonian distribution of errors**

- $$\chi^2 = \chi^2(\mu^-) + \chi^2(\mu^+).$$



Systematic errors

- **Five systematic errors:**

- 1. 20% error in flux normalization**

- 2. 10% error in cross-section normalization**

- 3. 5% uncertainty in the zenith angle dependence of fluxes**

- 4. Energy dependent tilt factor: $\delta = 5\%$**

$$\Phi_{\delta}(E) = \Phi_0(E) \left(\frac{E}{E_0} \right)^{\delta} \simeq \Phi_0(E) \left(1 + \delta \ln \frac{E}{E_0} \right),$$

- 5. An overall 5% uncertainty**

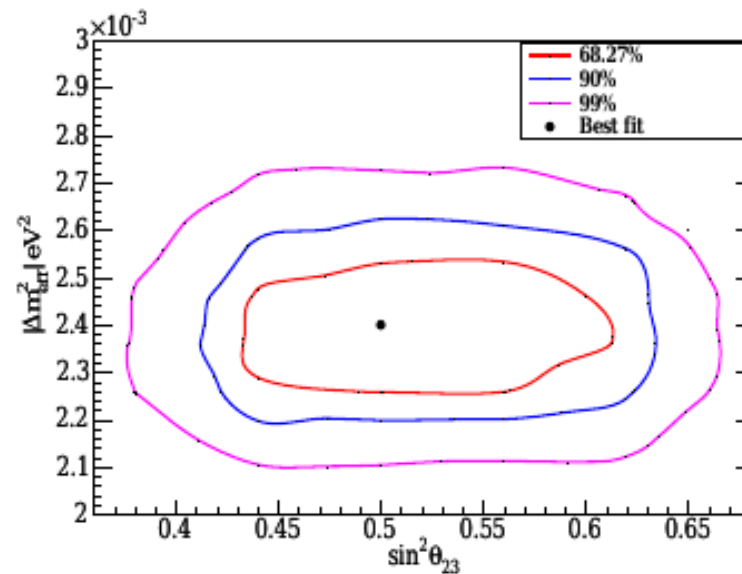
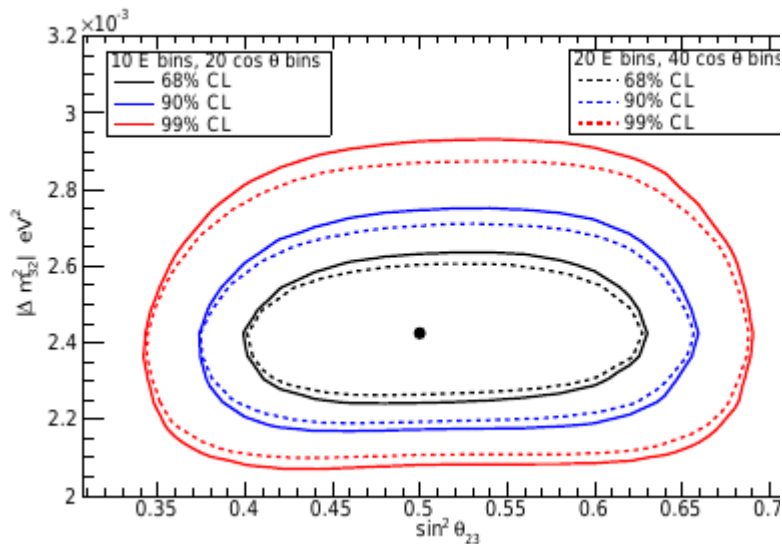
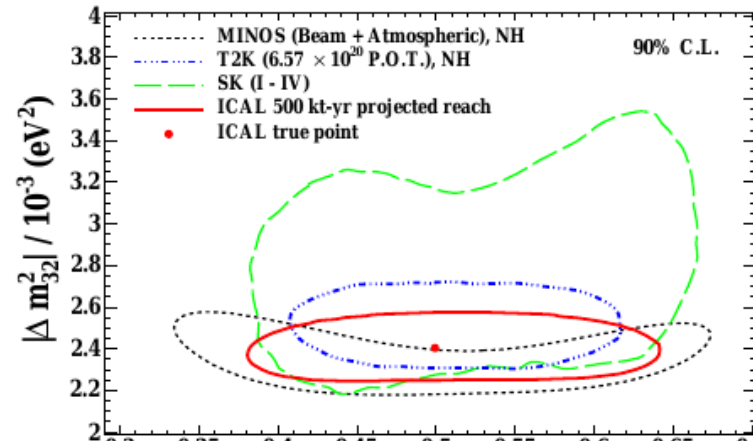


Binning scheme

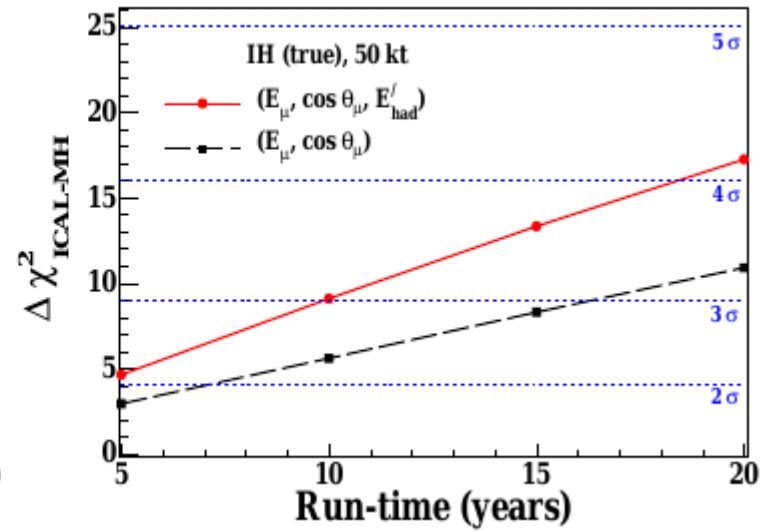
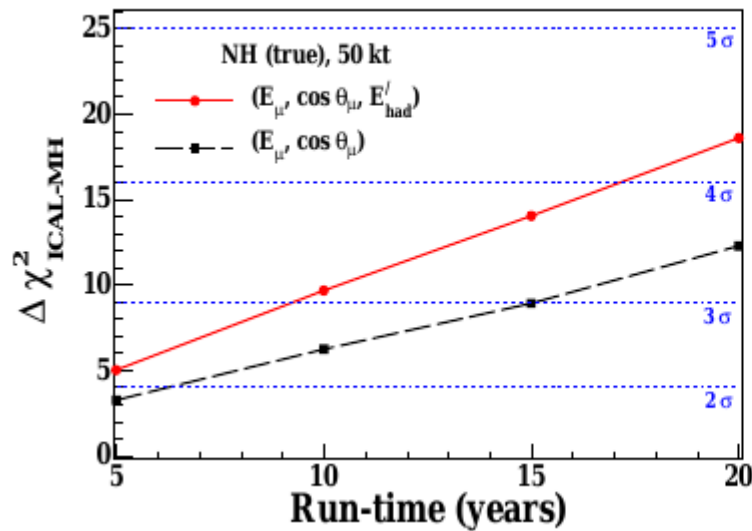
- **We studied three binning schemes systemetically:**
 - I. Binning in muon energy and muon angle [T. Thakore, A. Ghosh, S. Choubey, and A. Dighe, JHEP 1305 (2013) 058, [arXiv:1303.2534]**
 - II. Binning in neutrino energy and muon angle [D. Kaur, M. Naimuddin, and S. Kumar, Eur.Phys.J C75 (2015), arXiv:1409.2231]**
 - III. Binning in muon energy, muon angle, hadron energy [M. M. Devi, T. Thakore, S. K. Agarwalla, and A. Dighe, JHEP 1410 (2014), arXiv:1406.3689]**



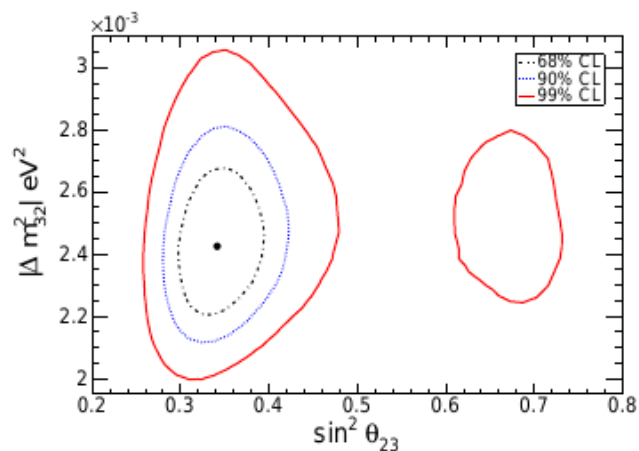
Sensitivity to atmospheric neutrino oscillation parameters (top-III, bottom left - II, bottom right III)



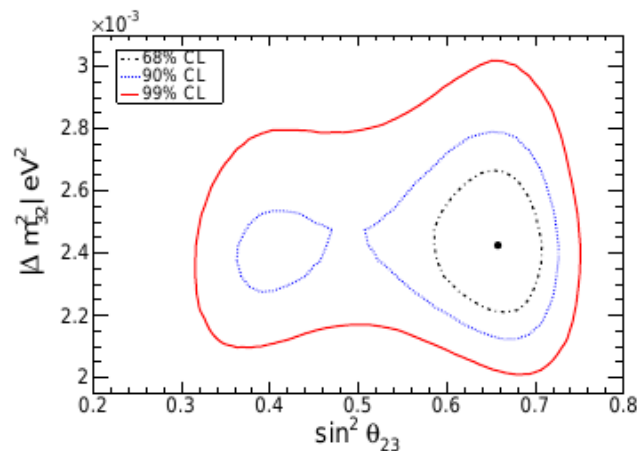
Sensitivity to mass hierarchy



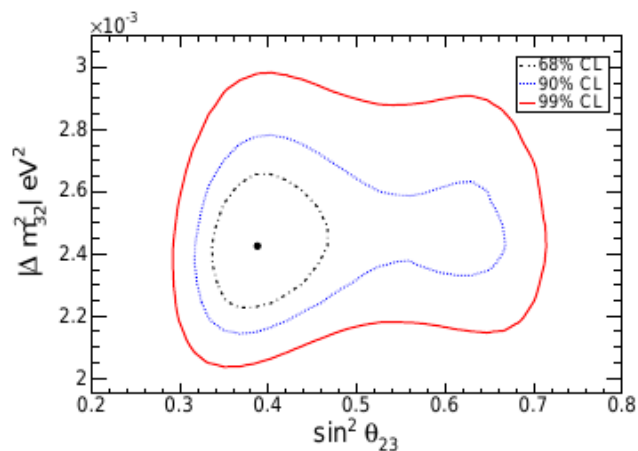
Octant sensitivity (binning in neutrino energy and muon angle)



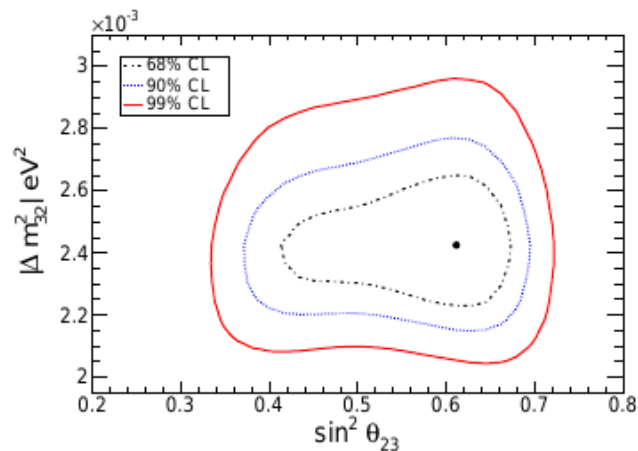
(a) $\sin^2 2\theta_{23} = 0.9$, first octant ($\sin^2 \theta_{23} = 0.342$)



(b) $\sin^2 2\theta_{23} = 0.9$, second octant ($\sin^2 \theta_{23} = 0.658$)



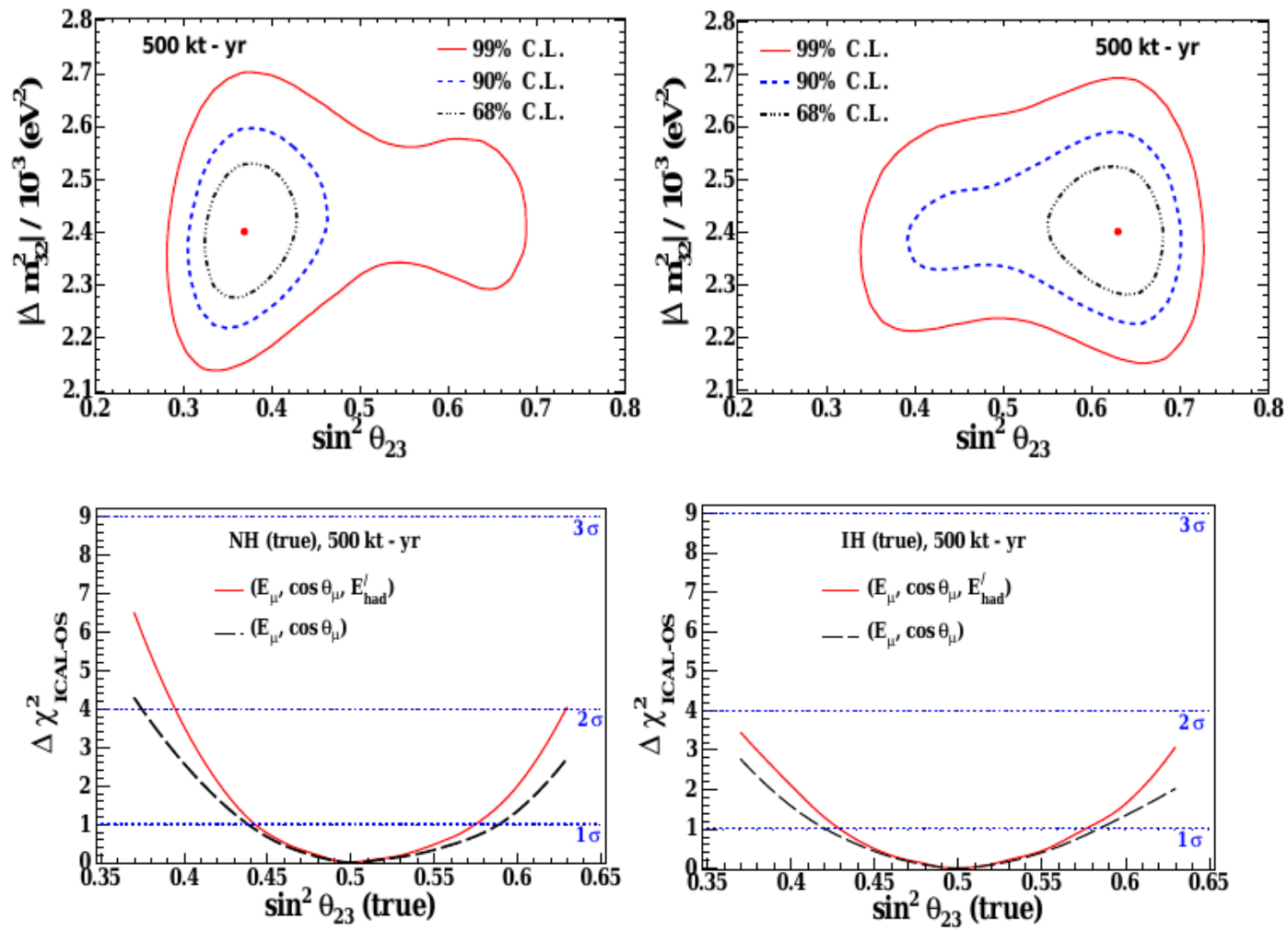
(c) $\sin^2 2\theta_{23} = 0.95$, first octant ($\sin^2 \theta_{23} = 0.388$)



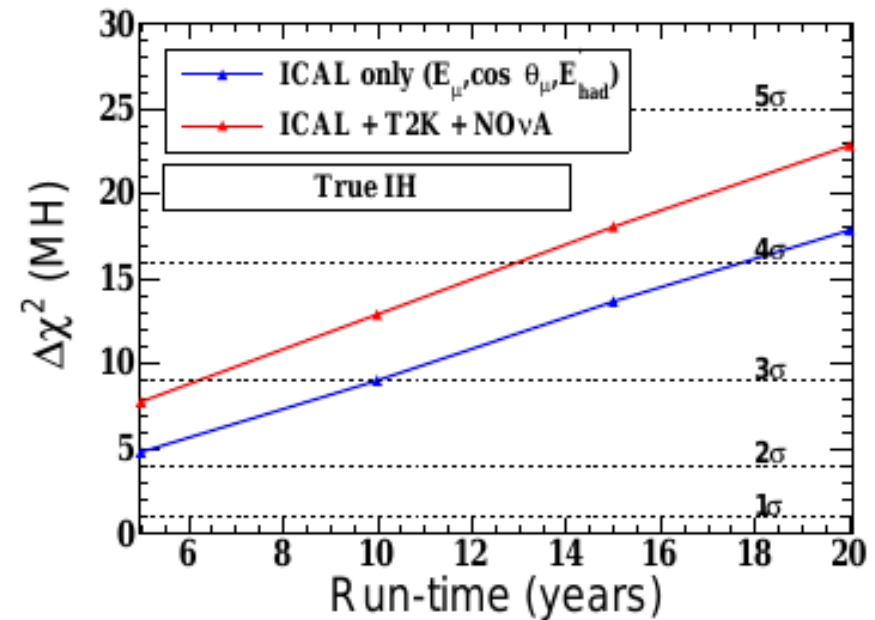
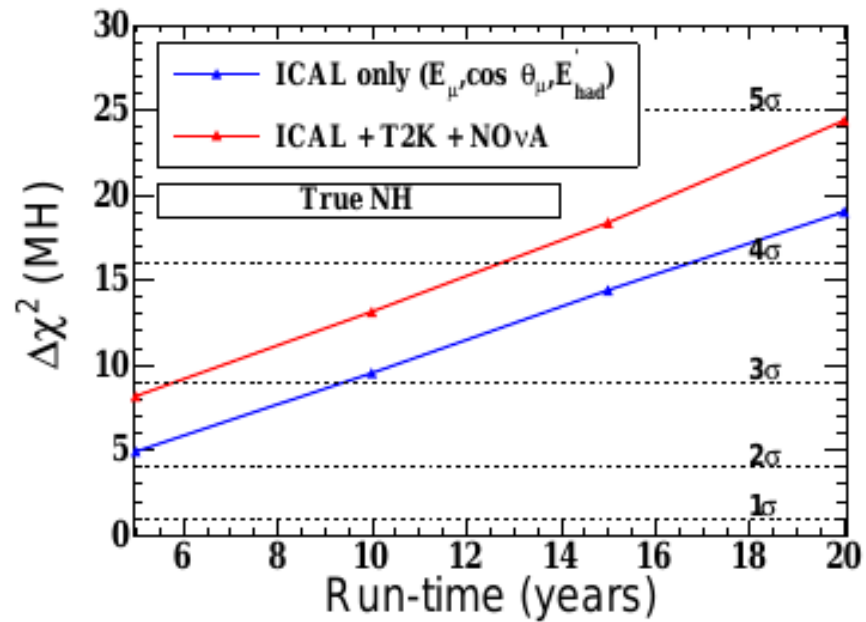
(d) $\sin^2 2\theta_{23} = 0.95$, second octant ($\sin^2 \theta_{23} = 0.612$)



Octant sensitivity (binning in muon energy, muon angle, hadron energy)

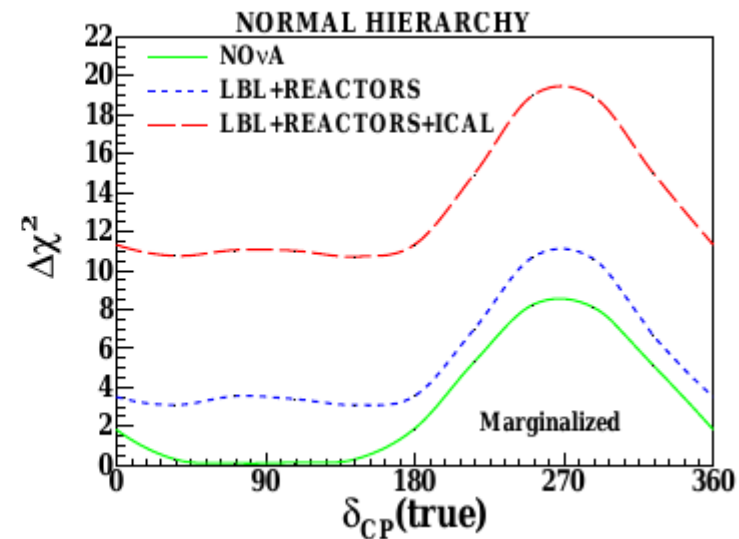
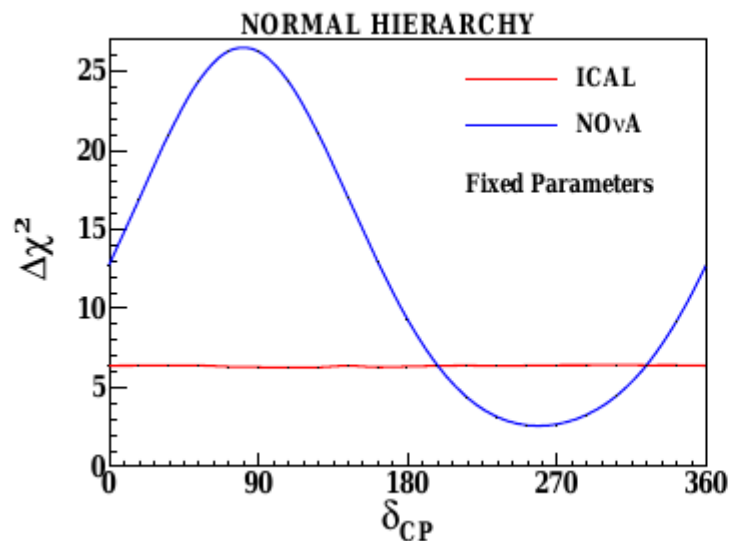


Combined analysis of INO with T2K and NOvA



Synergy with other experiments

- Though ICAL itself is rather insensitive to δ_{CP} , data from ICAL can still improve the determination of δ_{CP} itself, by providing input on mass hierarchy.
- This is especially crucial in the range $0 \leq \delta_{CP} \leq \pi$, precisely where the ICAL data would also improve the hierarchy discrimination of NOvA and other experiments



Concluding remarks

- **A detector will excellent abilities for detection, charge identification, energy measurement and direction determination for charged muons of GeV energies**
- **The magnetic field enables separation of μ^- from μ^+ , thus increasing the sensitivity to the matter induced differences on neutrino and antineutrino oscillations.**
- **ICAL can also help in precision measurements of other neutrino mixing parameters, and can probe exotic physics issues even beyond neutrinos.**

