Physics reach of ICAL at INO

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The ICAL Experiment at INO

The iron calorimeter detector (ICAL) experiment at the India-based Neutrino Observatory (INO) is designed to study neutrino mixing parameters using atmospheric neutrinos. The underground lab facility for the experiment is being constructed at Theni in Southern India. The ICAL setup consists of 150 layers of 5.6 cm thick iron plates interspersed with Resistive Plate Chambers (RPCs) as active elements. The detector has a mass of about 50 kt, and is optimized primarily to measure the muon momentum with high efficiency in the GeV range. It is magnetized with a field of nearly 1.5 Tesla in order to identify the muon charge. The ICAL is also sensitive to hadrons of GeV energies. The primary goals of the experiment are the identification of neutrino mass hierarchy and the precision measurements of atmospheric oscillation parameters ($\sin^2\theta_{23}$, $|\Delta m^2_{32}|$).

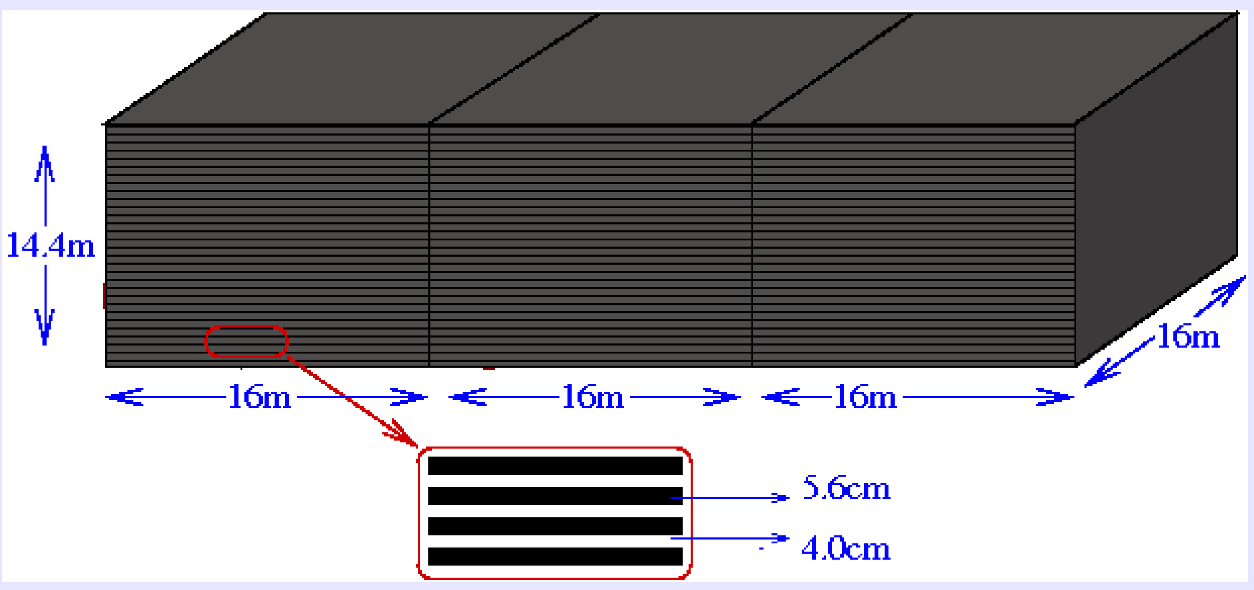

Figure 1: *Schematic layout of the INO detector*

Response of ICAL to muons and hadrons

A GEANT4-based detector simulation algorithm is used for determining the detector response to muons and hadrons. The muon hits give track-like features, while hadron hits produce showers.

The muon energy and direction are reconstructed using a Kalman Filter-based track reconstruction algorithm. Figure 2 shows the energy and direction resolutions for muons, as well as their reconstruction and charge-identification efficiencies, for a few representative directions.

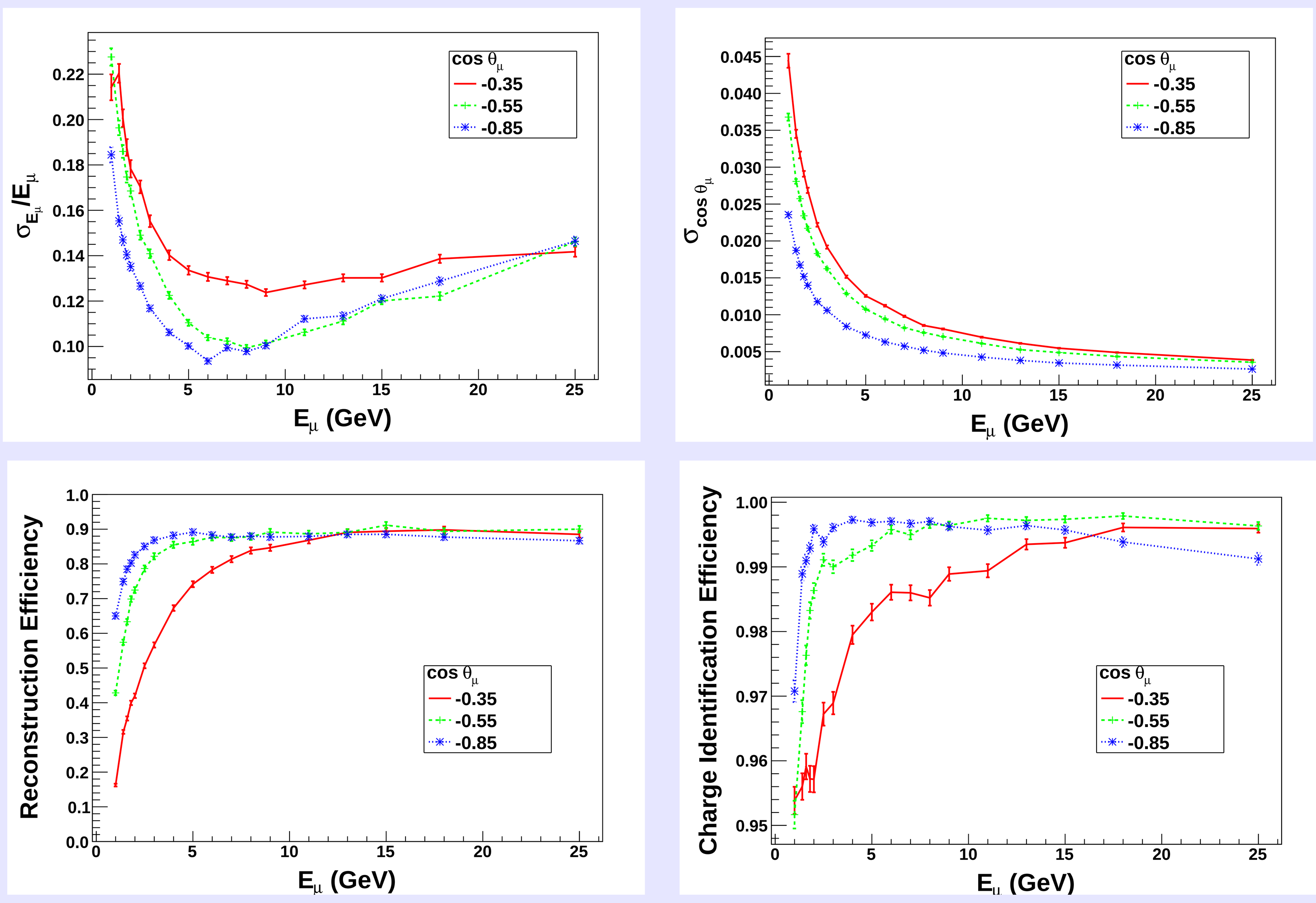

Figure 2: *The energy resolution (top left), $\cos\theta_\mu$ resolution (top right), the reconstruction efficiency (bottom left), and the charge identification efficiency (bottom right), for μ^- as a function of the true muon energy and for three cases of true muon zenith angle. The azimuthal angle has been averaged over.* arXiv:1303.2534,arXiv:1405.7243

The hadron energy is parametrized in terms of $E'_{\rm had} \equiv E_\nu - E_\mu$, and is calibrated against the number of hadron hits in each event. The hit distribution for a fixed $E'_{\rm had}$ gives a good fit to the Vavilov distribution. Figure 3 shows the hadron energy resolution and the calibration of $E'_{\rm had}$ against the number of hits.

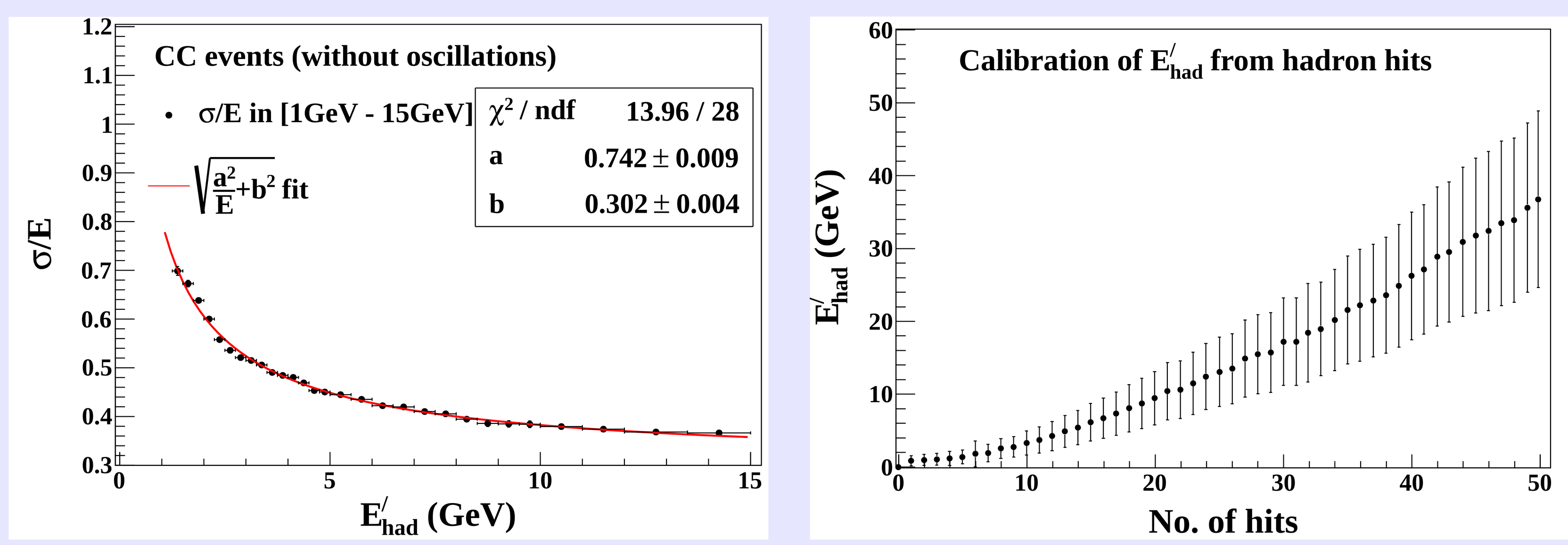

Figure 3: *The energy resolution for hadrons as a function of the hadron energy (left). The calibration of hadron energy against hadron hits (right).* arXiv:1304.5115

Event generation

- The events from CC interactions of $\nu_\mu/\bar\nu_\mu$ are generated from the neutrino event generator NUANCE, using the HONDA3D atmospheric neutrino flux at the SK location, and incorporating oscillations via a reweighting algorithm.
- It is assumed that muon and hadron hits can be cleanly separated in each event.
- The reconstruction and charge identification efficiencies, as well as the energy and the direction resolutions are folded in, to get the distribution for the measured values of $(E_\mu, \cos\theta_\mu, E'_{\rm had})$.
- A non-uniform binning of 10 E_μ bins (1–11 GeV), 21 $\cos\theta$ bins, and 4 $E'_{\rm had}$ bins (0–15 GeV) has been used, for both μ^- and μ^+ events.

The χ^2 analysis

The $\chi^2_\pm$ for events with a $\mu^\pm$ observed in the final state is defined as

$$\chi^2_\pm = \min_{\xi_l} \sum_{i=1}^{N_{E'_{\rm had}}} \sum_{j=1}^{N_{E_\mu}} \sum_{k=1}^{N_{\cos\theta_\mu}} \left[2(N^{\rm theory}_{ijk} - N^{\rm data}_{ijk}) - 2N^{\rm data}_{ijk} \ln\left(\frac{N^{\rm theory}_{ijk}}{N^{\rm data}_{ijk}}\right)\right] + \sum_{l=1}^{5} \xi_l^2 ,$$

where the systematic errors due to the flux normalization, cross sections, spectral tilt, zenith angle distribution and other factors are taken into account using the pull method. The total $\chi^2_{\rm ICAL} \equiv \chi^2_- + \chi^2_+ + \chi^2_{\rm prior}$ is marginalized over the pull variables ξ_l and over the 3σ-allowed range of the relevant oscillation parameters. An 8% prior over $\sin^2 2\theta_{13}$ has been used.

Sensitivity to the Neutrino Mass Hierarchy

- $\Delta\chi^2_{\rm ICAL-MH} \equiv \chi^2_{\rm ICAL}$(false hierarchy) $- \chi^2_{\rm ICAL}$(true hierarchy)

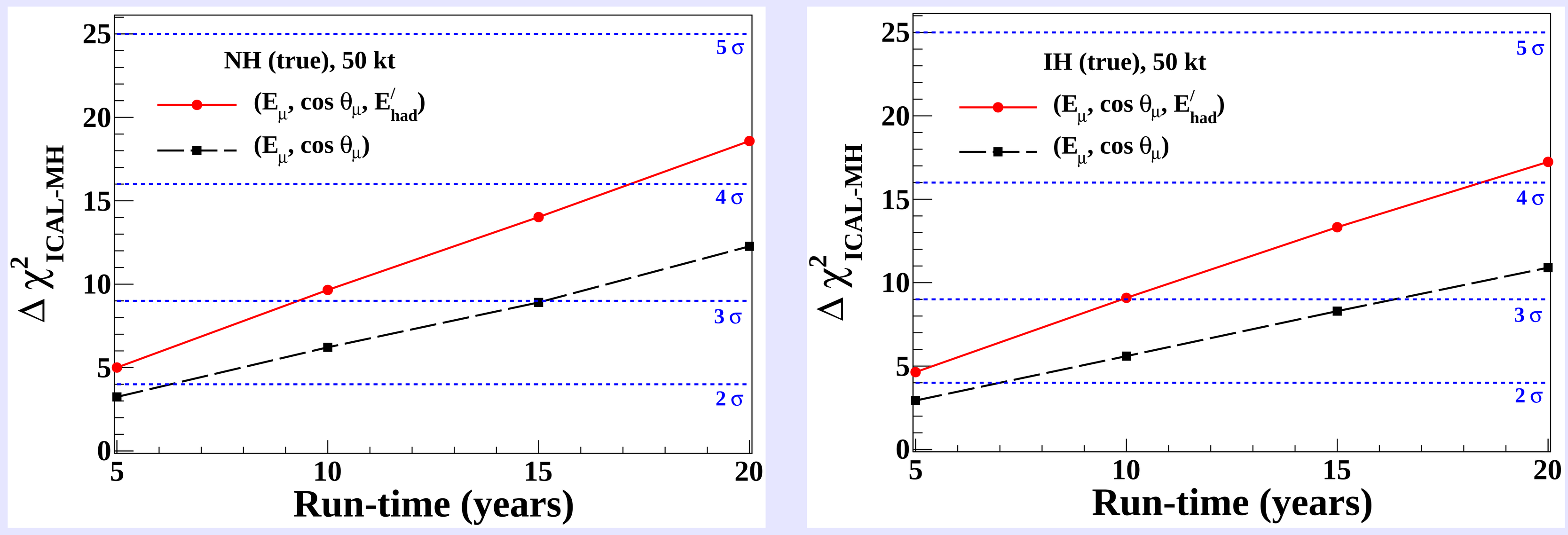

Figure 4: *Mass hierarchy sensitivity for true NH (left) and true IH (right), as a function of the run-time of 50 kt ICAL. The enhancement in sensitivity with the inclusion of $E'_{\rm had}$ information may be observed.* arXiv:1406.3689

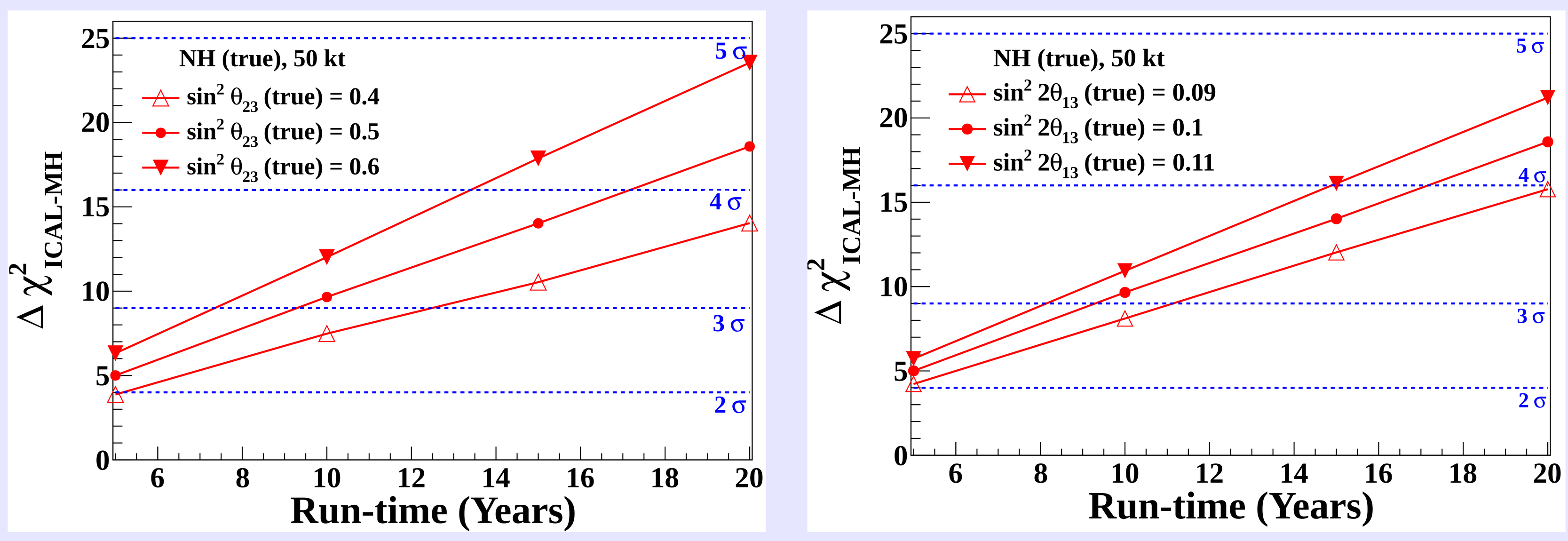

Figure 5: *The variation of mass hierarchy sensitivity to true values of θ_{23} (left) and θ_{13} (right), for true NH, as a function of the run-time of 50 kt ICAL.*

Precision Measurements of $|\Delta m^2_{32}|$ and $\sin^2\theta_{23}$

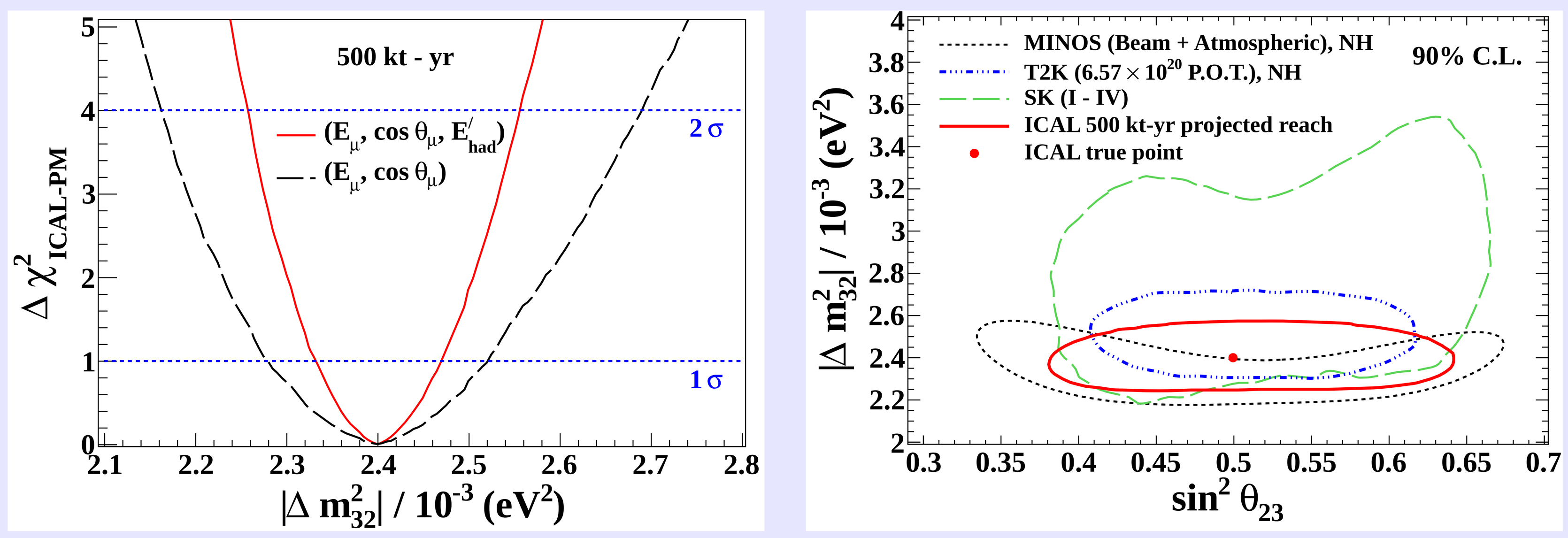

Figure 6: *The enhancement in precision on $|\Delta m^2_{32}|$ with the inclusion of $E'_{\rm had}$ information, for true NH (left). The comparison of 90% C.L. (2 d.o.f.) contours in the plane $\sin^2\theta_{23}$–$|\Delta m^2_{32}|$ with the current data at MINOS, SK, T2K and expected data at ICAL with 500 kt-yr (right).*

Sensitivity to the octant of θ_{23}

- $\Delta\chi^2_{\rm ICAL-OS} \equiv \chi^2_{\rm ICAL}$(false octant) $- \chi^2_{\rm ICAL}$(true octant)

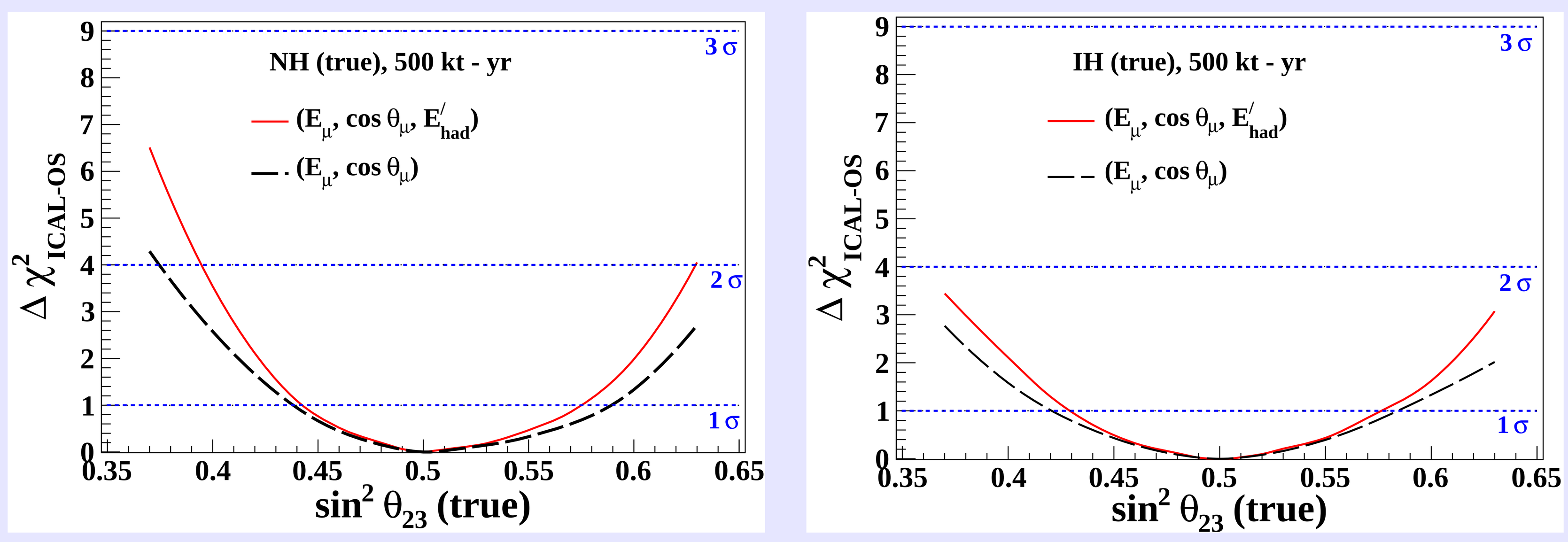

Figure 7: *Sensitivity to the θ_{23} octant with 500 kt-yr exposure at ICAL, as a function of true $\sin^2\theta_{23}$, for true NH (left) and true IH (right).*

Concluding remarks

The information on hadron energy significantly improves the ICAL sensitivities for the determination of mass hierarchy and $|\Delta m^2_{32}|$, compared to the muon-only analysis. Development of algorithms to extract the hadron information more efficiently is in progress.