

# The Physics potential of ICAL

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# Introduction.....

- The general theoretical and experimental status of Neutrino Physics has been summarized elsewhere.  
*(Talks by A Joshipura and N Mondal)*
- This talk will focus on attempting to give an overview of the physics possibilities of ICAL, the 50 kT iron calorimeter detector with a proposed 1.3 T magnetic field at the Indian Neutrino Observatory (INO).
- Both near and far future physics potential of the detector will be considered.

# Introduction.....What makes ICAL unique?

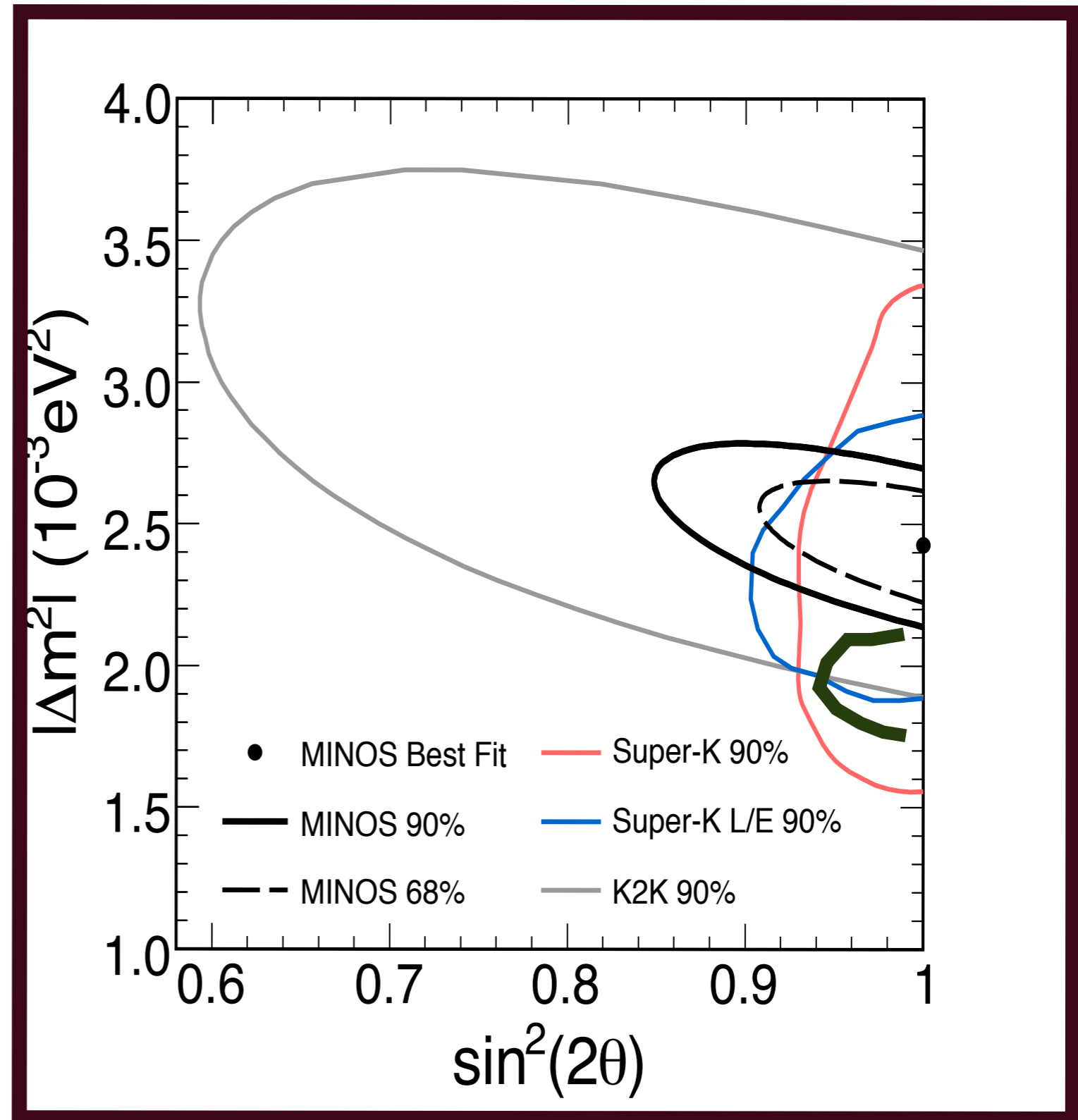
- *SIZE*.....largest magnetized iron calorimeter , at 50 (100) kT ten (twenty) times the size of MINOS.
- Its *charge-id capability* allows separate identification of muon and anti-muon events, opening up new physics capabilities compared to other types of detectors.

# Introduction.....

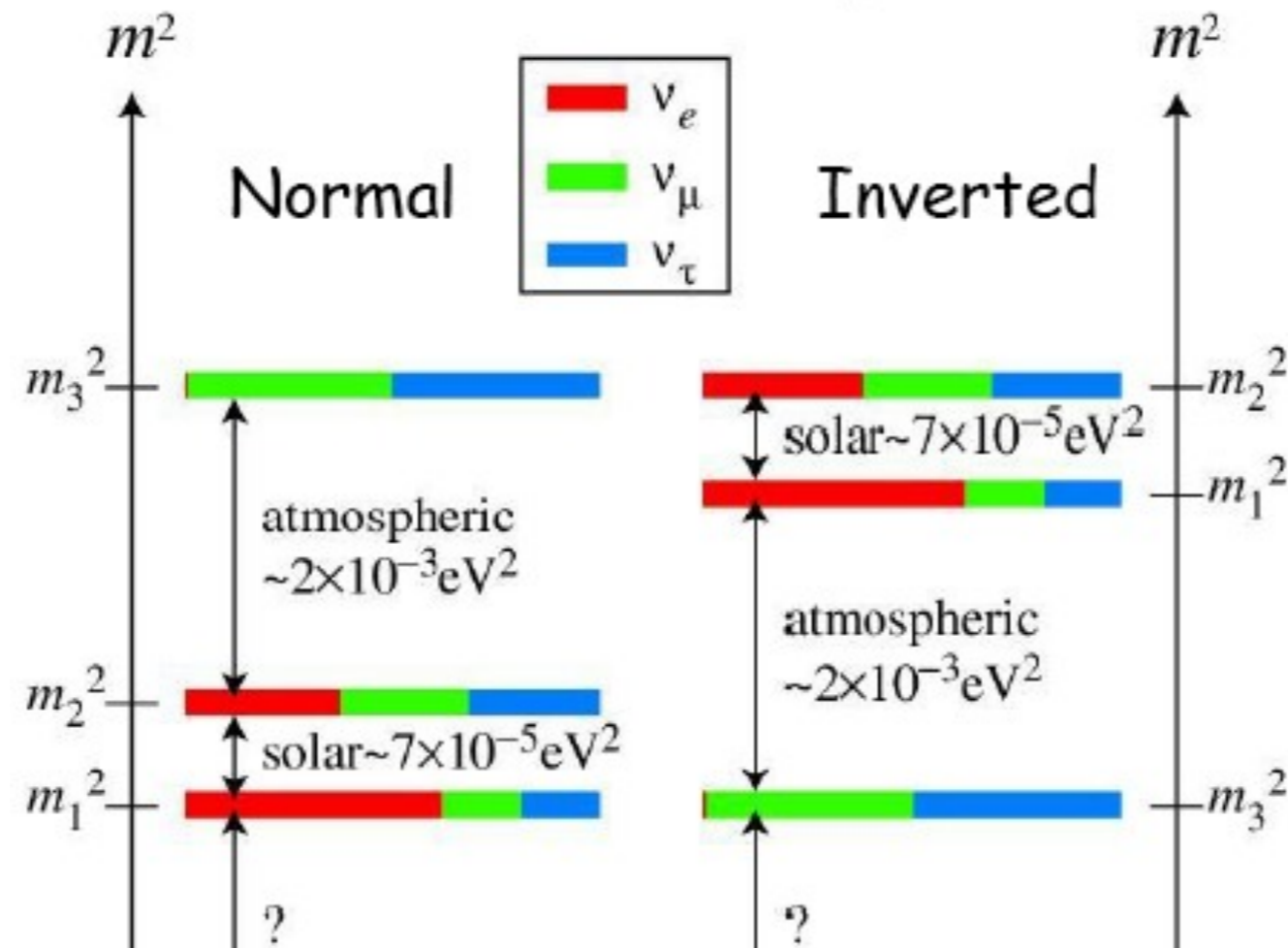
- *The Physics Possibilities of ICAL may be categorized as follows:*
- Stand-Alone Physics Capabilities
- Physics in conjunction with the next generation Long-baseline Experiments
- Physics with future Neutrino Factories and Beta Beams

# Stand-alone physics: *Measuring the atmospheric neutrino parameters.....*

- ICAL will quickly (over 3 years) provide complementary measurements of the atmospheric mass squared difference and mixing angle
- It offers superior sensitivity to small mass squared differences compared to other detectors.



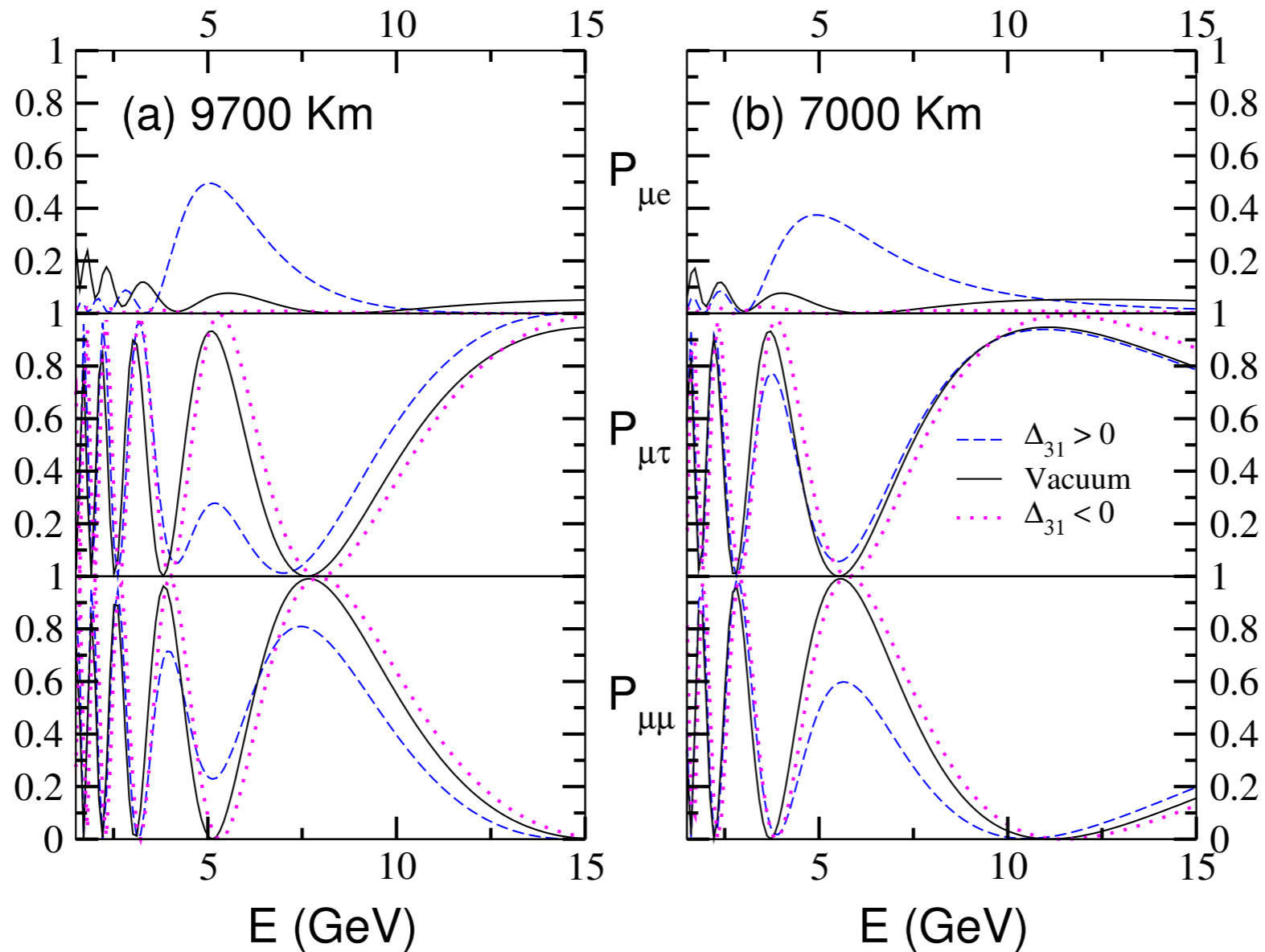
# Stand-alone physics: The Mass Hierarchy...



The mass hierarchy of neutrinos is a crucial unknown, knowledge of which will dictate a preferred class of theories beyond the Standard Model.

Extant and previous detectors have lacked the necessary sensitivity to matter effects required for its determination.

# Stand-alone Physics..... Mass hierarchy



RG, Ghoshal,  
Goswami, Sankar,

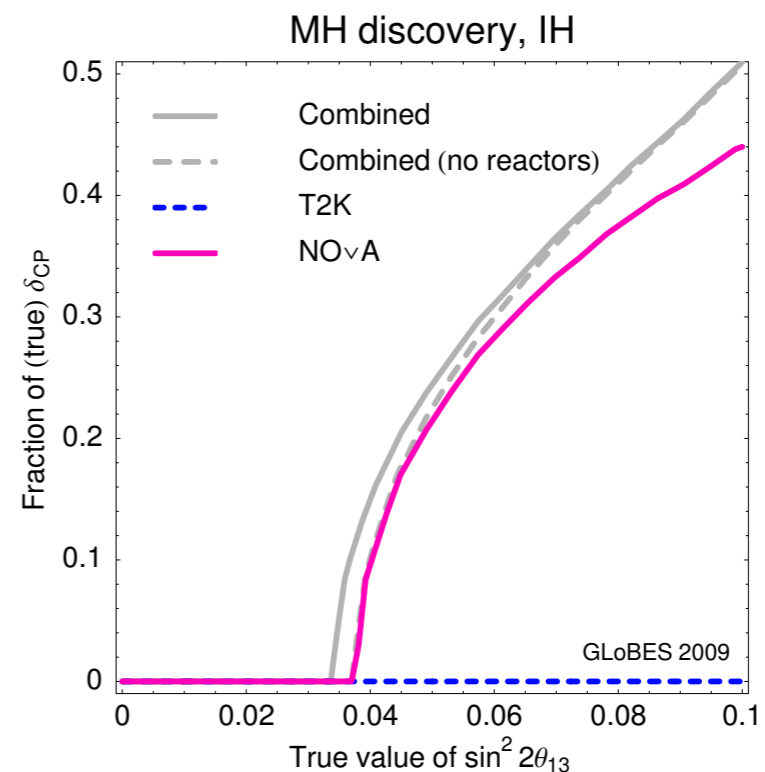
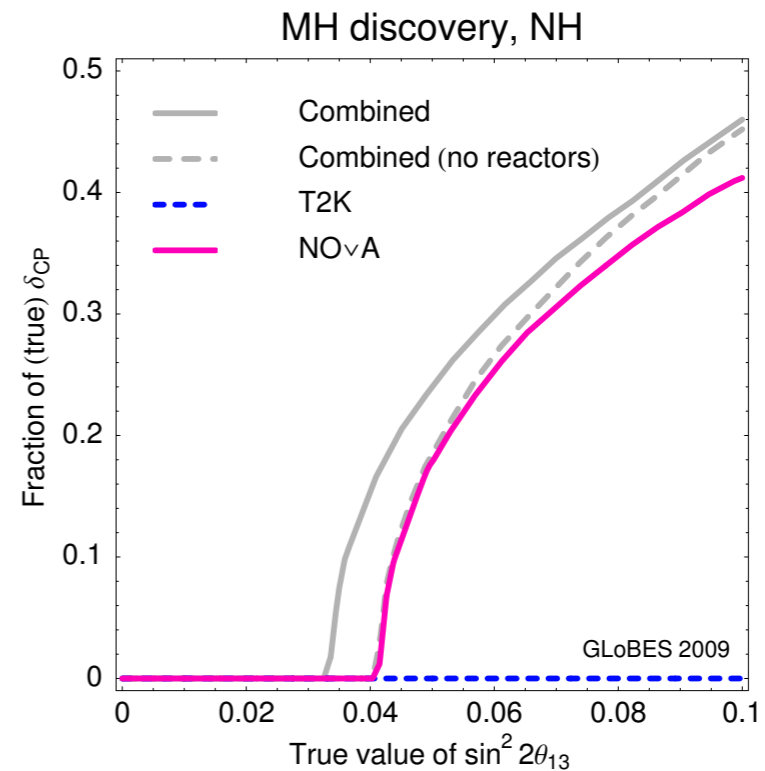
Phys.Rev.Lett.  
94:051801,2005.

Differences in the survival probabilities for the 2 hierarchies emerge at very long baselines due to matter effects

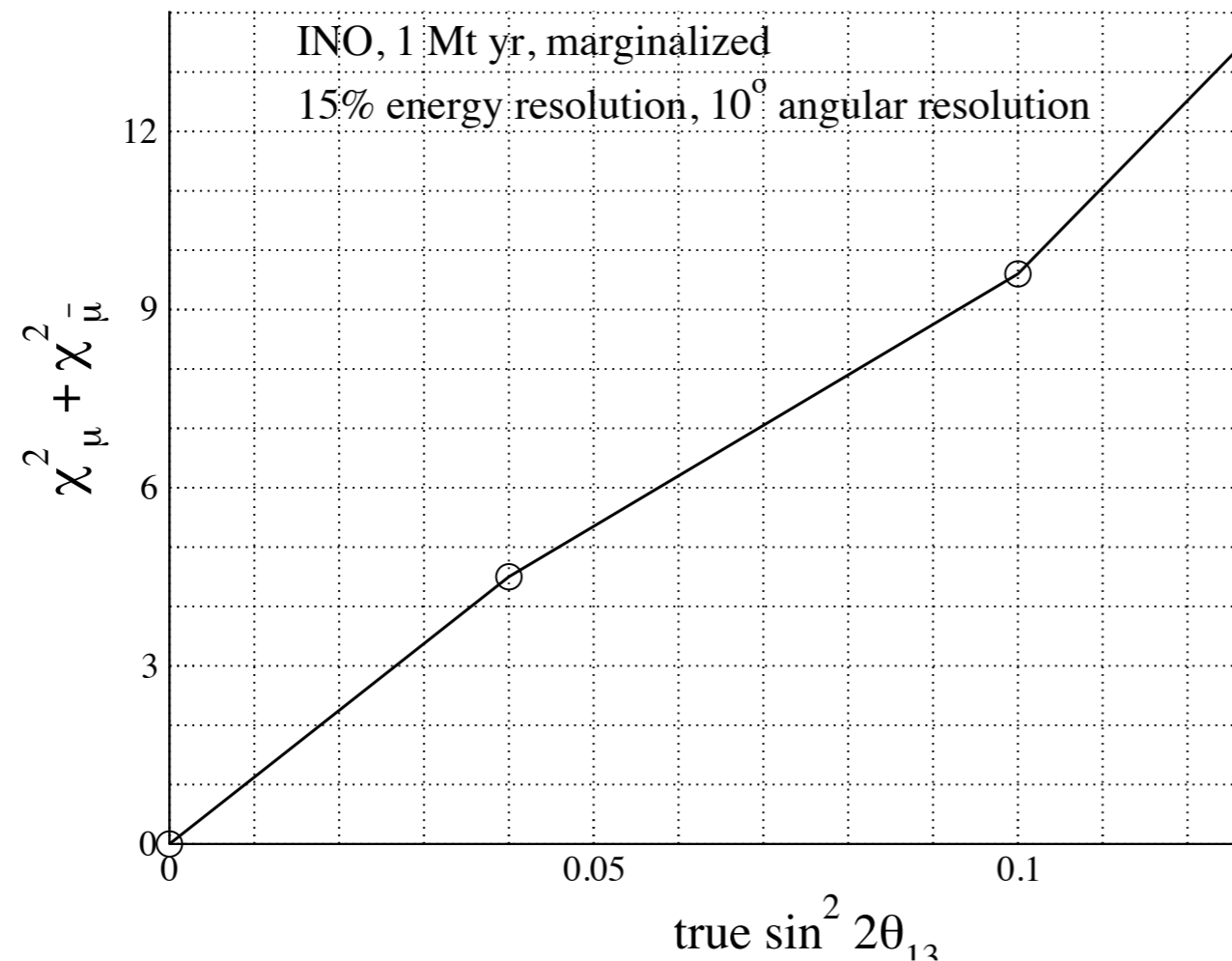
# Stand alone...Future Detector Hierarchy

Up coming LBL experiments  
will  
be able to determine the  
hierarchy for only a limited  
range of values of those  
possible for the CP parameter.

(Huber, Lindner and Schwetz,  
**JHEP 0911:044,2009.**)



# Stand-alone physics.... Mass Hierarchy



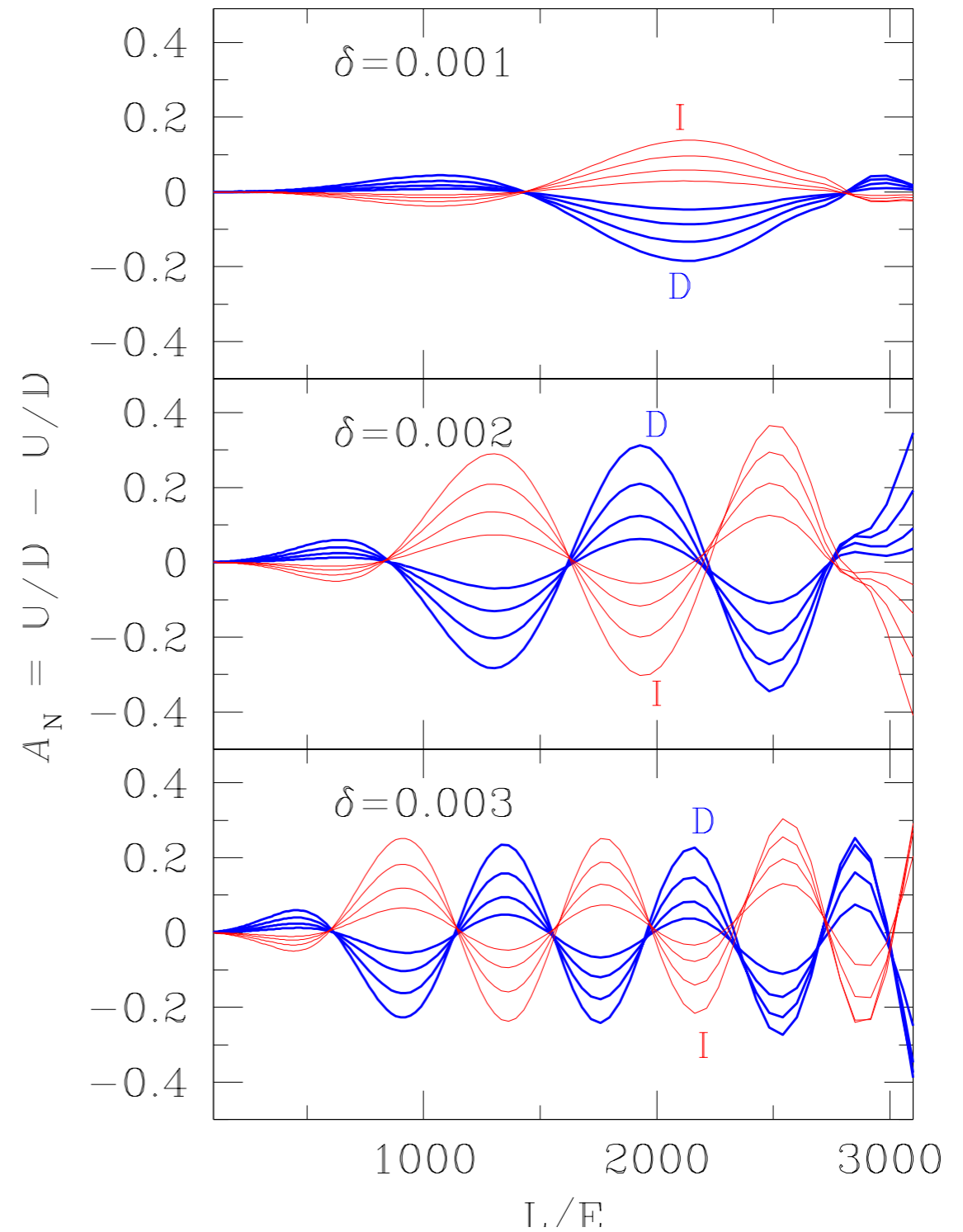
RG, Ghoshal, Goswami,  
Sankar,  
Phys.Rev.D76:073012,2007.

Due to its sensitivity to matter effects via charge discrimination, ICAL may provide a clue to the hierarchy if it is made a 100 kT detector

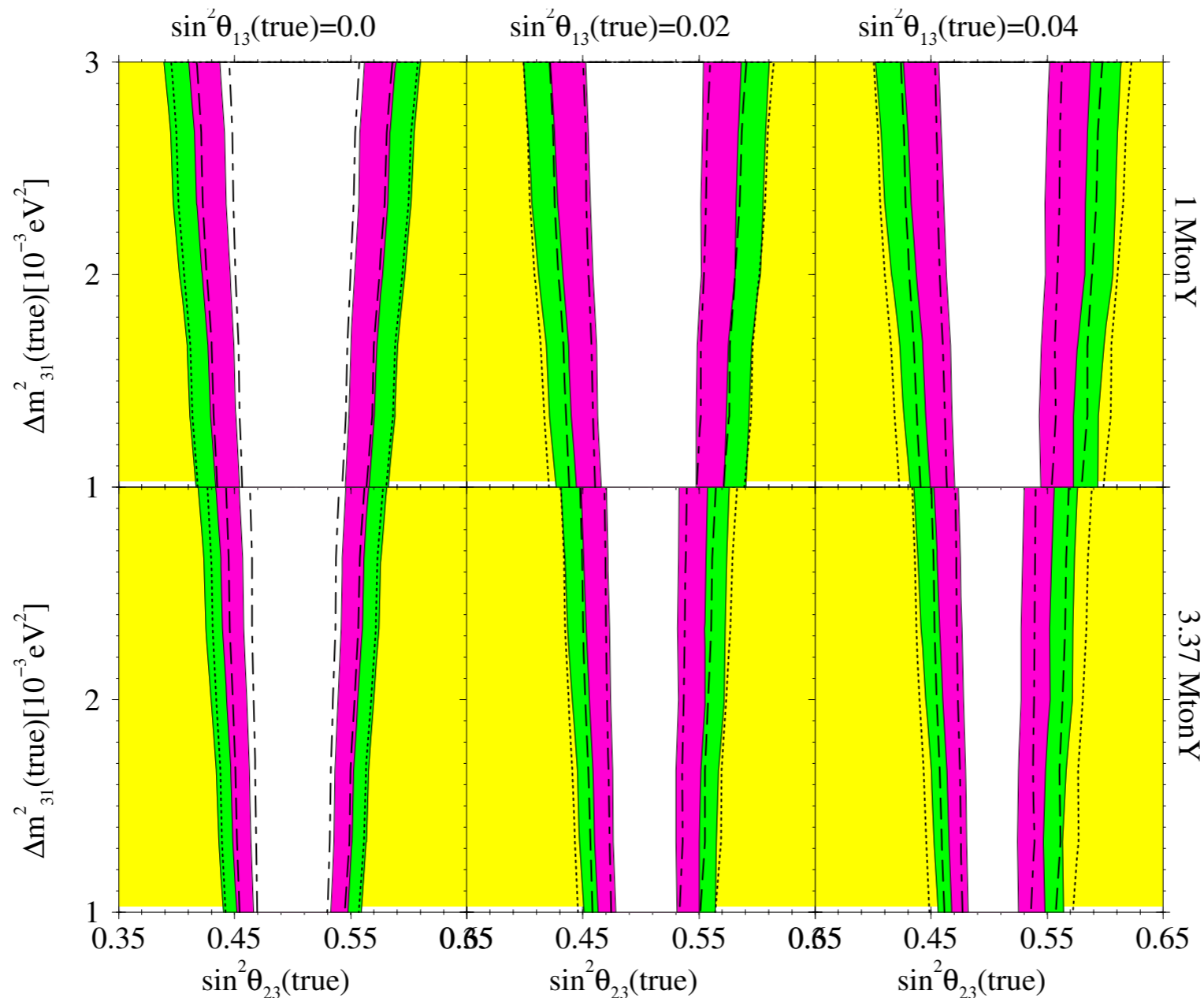
# Stand-alone Physics.....Hierarchy

A measurable for the hierarchy in ICAL is the Asymmetry in the ratio of Up vs Down event rates for neutrino vs antineutrino rates.

Indumathi and Murthy, Phys.Rev.D71:013001,2005.



# Stand-alone Physics.....Deviation from maximality

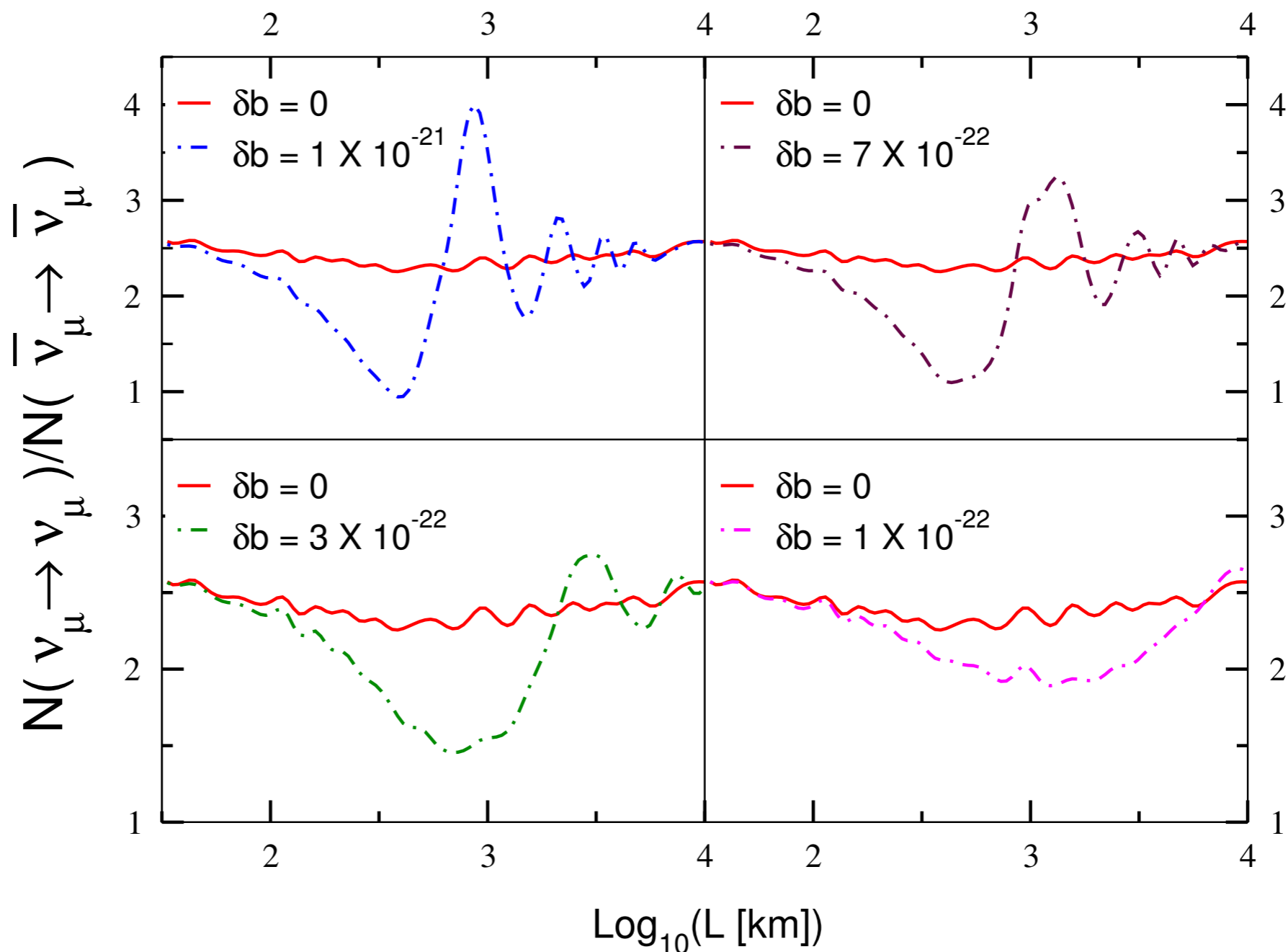


Choubey & Roy  
[PhysRevD.73.013006](https://arxiv.org/abs/1306.0130)

The octant of  $\theta_{23}$ , as yet undetermined, also plays an important role in models of mass and mixing. ICAL offers the opportunity of obtaining a handle on it via matter effects.

# Stand-alone Physics.....CPT Violation

Datta, RG,  
Mehta &  
Sankar,  
Phys.Lett.B597:356  
-361,2004.



Due to its charge -id capability, ICAL offers sensitivity to very low levels of CPT violation,

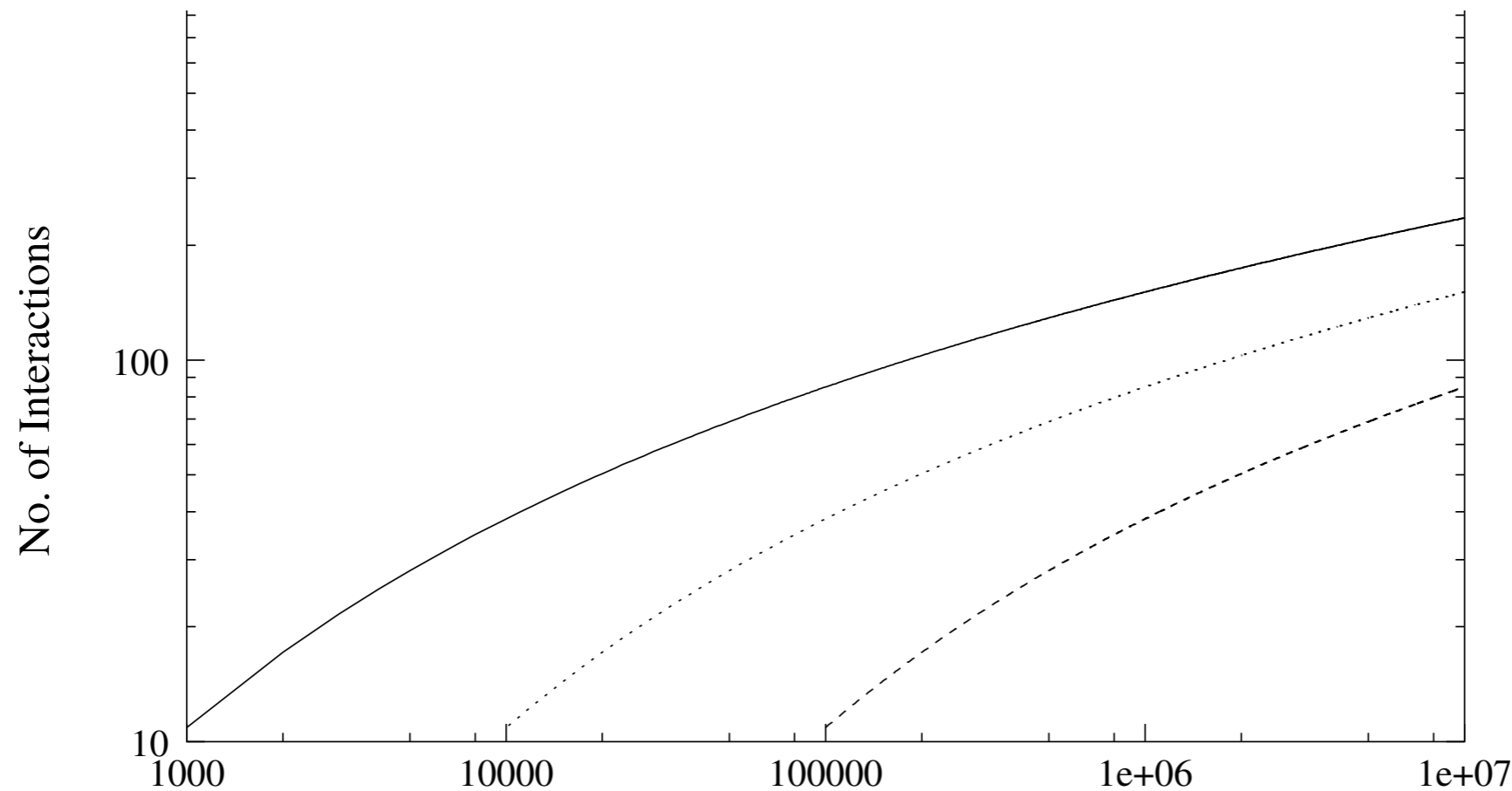
# Stand-alone Physics.....UHE Muons from Cosmic Rays

- The CR spectrum extends over 10 orders of magnitude in energy. The origin of the “knee” around 5000 TeV remains large un-understood.
- An important reason for this is the paucity of data on VHE muons ( $> 1$  TeV).
- VHE muons would also add importantly to our knowledge of VHE neutrino fluxes, to which they are co-related.
- In addition, they would help understand the prompt contribution (due to charm) to muon and neutrino fluxes.
- This would, in turn, assist in constraining models of the gluon structure function at high energies.

# Stand-alone Physics.....UHE Muons from Cosmic Rays

- Magnetic spectrometry, even for a detector as large as INO, fails as an effective method of muon detection above several tens of TeV.
- An effective technique which can be used all the way up to several thousand TeV is the pair-meter method
- This relies on the measurements of the energy and frequency of electron-positron pair cascades produced by the passage of a high energy muon in dense matter.
- ICAL is potentially an excellent pair-meter (Iron medium and large size)

# Stand-alone Physics.....UHE Muons from Cosmic Rays



RG and Panda  
JCAP 0607:011,2006.

Average number of pair cascades produced by an energetic muon above a threshold  $E_0$  vs. muon energy for  $E_0 = 1$  GeV (solid line), 10 GeV (dotted) and 100 GeV (dashed).

ICAL mass of 50 Kt assumed

# Stand-alone Physics.....Long Range Forces

- The SM has several global flavour symmetries which can, in principle, be gauged in an anomaly free way. ( $L_e - L_\mu$ ,  $L_e - L_\tau$ ).
- If the gauge bosons corresponding to these are massless or very light, long-range forces may arise.
- Due to the flavour dependence, these may alter oscillation probabilities at a measurable level, which can be detected in an atmospheric neutrino detector.
- SK data has been used to set such bounds, which can be complemented or improved by ICAL.

Joshipura and Mohanty,  
[Physlett. B, 2004.01.057](#)

# Physics in Conjunction with LBL Experiments.....

- *Despite their stellar role as discovery instruments in the past, atmospheric detectors have certain inherent limitations:*
- Absolute atmospheric fluxes are uncertain by 10-20%.
- Rapidly falling flux.
- At energies where flux is significant, the neutrino-nucleon  $\sigma$  is dominated by quasi-elastic scattering, which has significant uncertainties.
- Produced charged lepton direction and that of incoming neutrino can differ significantly at low energies.

# Physics in conjunction with LBL experiments.....

- Due to these reasons, determinations of  $\Delta m^2$  (which depend on L/E) in atmospheric detectors are usually not as accurate as those possible in LBL setups.
- Similarly, the precision likely to be achieved by experiments like T2K and NOvA for  $\sin^2 2\theta_{23}$  may be higher than what may be possible in future atmospheric detectors.
- Results of LBL experiments, while providing precision, must confront the existence of several types of parameter degeneracies.

# Physics in conjunction with LBL experiments.....

- The intrinsic, or  $\{\delta, \theta_{13}\}$  degeneracy, which arises when different pairs of values of the parameters  $\delta$  and  $\theta_{13}$  give the same neutrino and anti-neutrino oscillation probabilities, assuming other parameters to be known and fixed.

$$P(\delta, \theta) = P(\delta', \theta') \quad (\text{neutrinos})$$

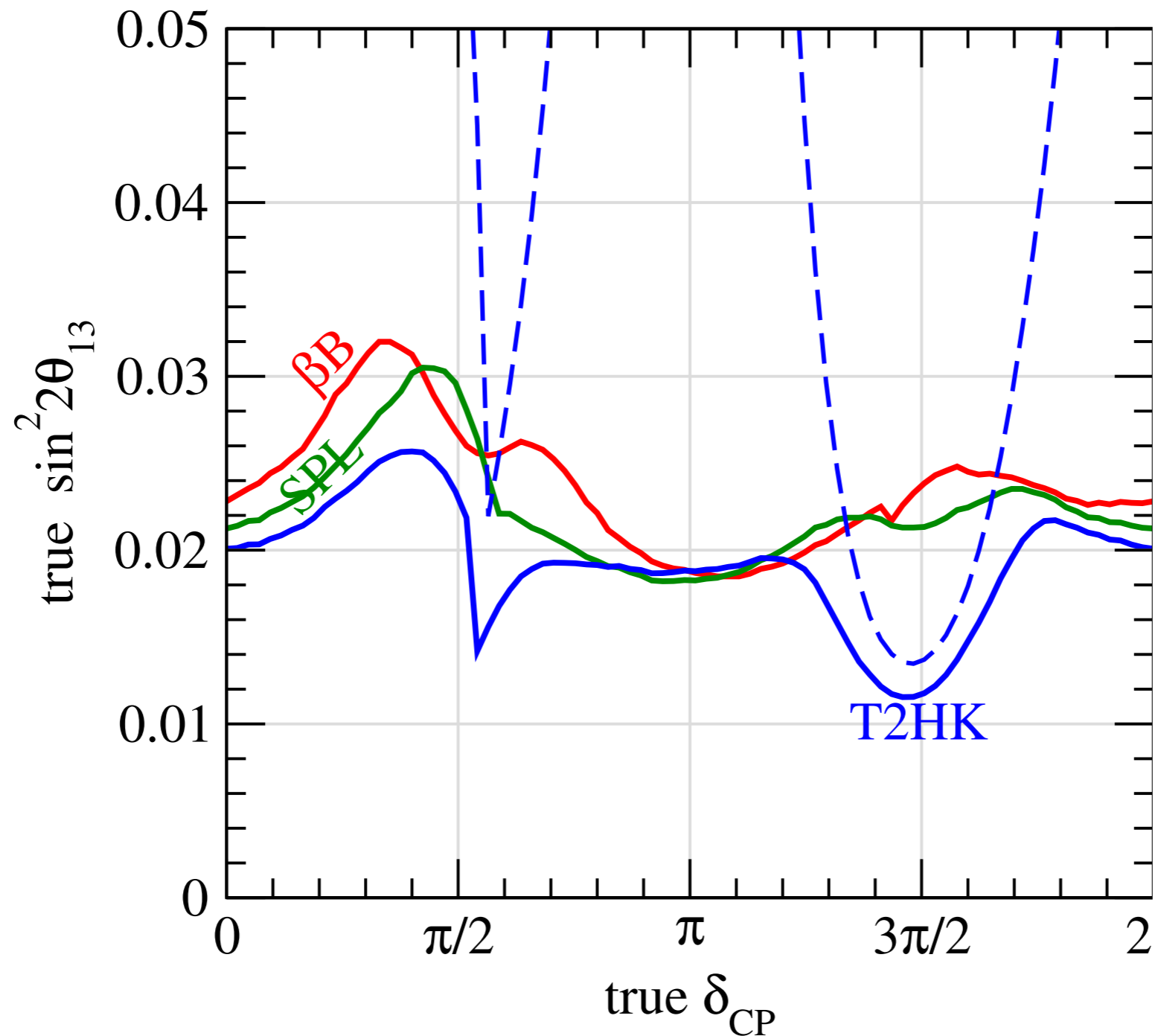
$$P(\delta, \theta) = P(\delta', \theta') \quad (\text{anti-neutrinos})$$

**The octant degeneracy.** LBL experiments being mainly sensitive to  $\sin^2 2\theta_{23}$ , one obtains two solutions of equal statistical significance, but associated with different pairs of values of  $(\delta_{CP}, \theta_{13})$ .

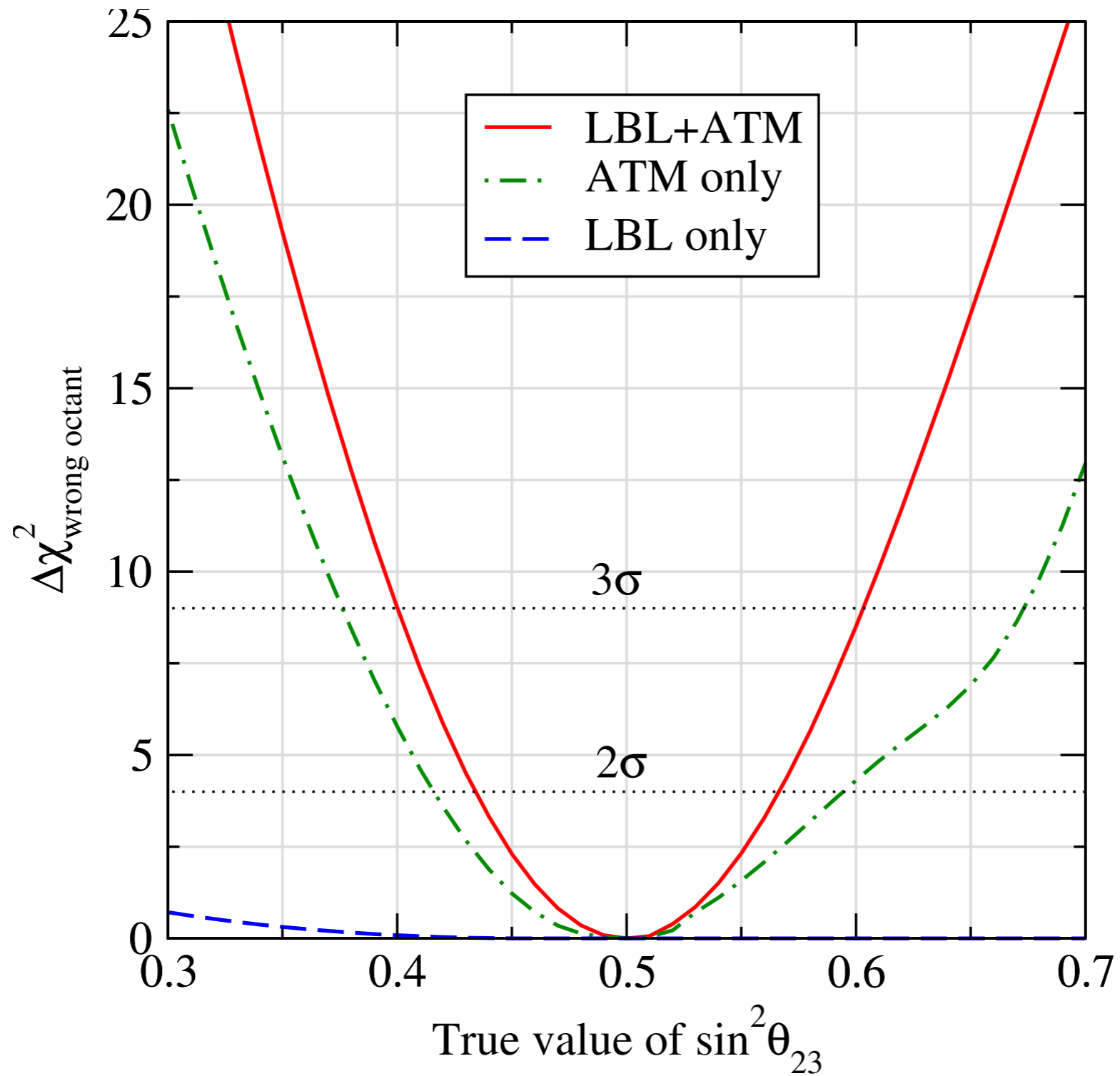
# Physics in conjunction with LBL experiments.....

- Similarly, the mass hierarchy degeneracy occurs due to identical solutions for  $P$  and  $\bar{P}$  for different pairs of  $\delta_{CP}$  and  $\theta_{13}$  with opposite signs of  $\Delta_{31}$  (fixing other parameters).
- Consequently, while providing high precision measurements of  $|\Delta m^2_{31}|$  and  $\sin^2 2\theta_{23}$ , LBL experiments of the (near) future will not be able to provide definitive information on the mass hierarchy, the CP phase or the octant in which  $\theta_{23}$  lies.
- However, combining the precision measurements of upcoming LBL experiments with the wide-band (in L and E) capabilities of data gathered by a large mass atmospheric experiment like ICAL can lead to a resolution of these problems, as we illustrate by a couple of examples.

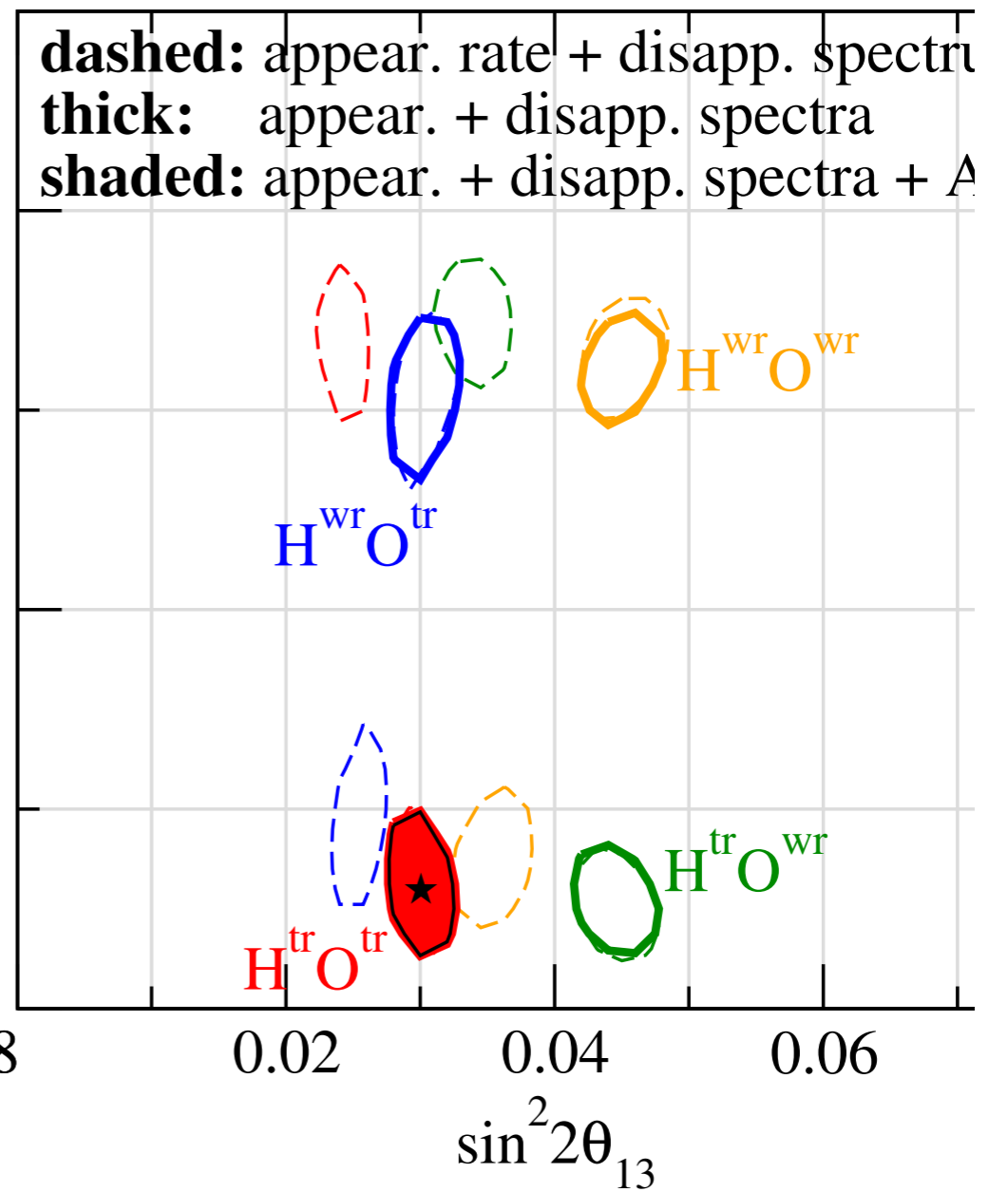
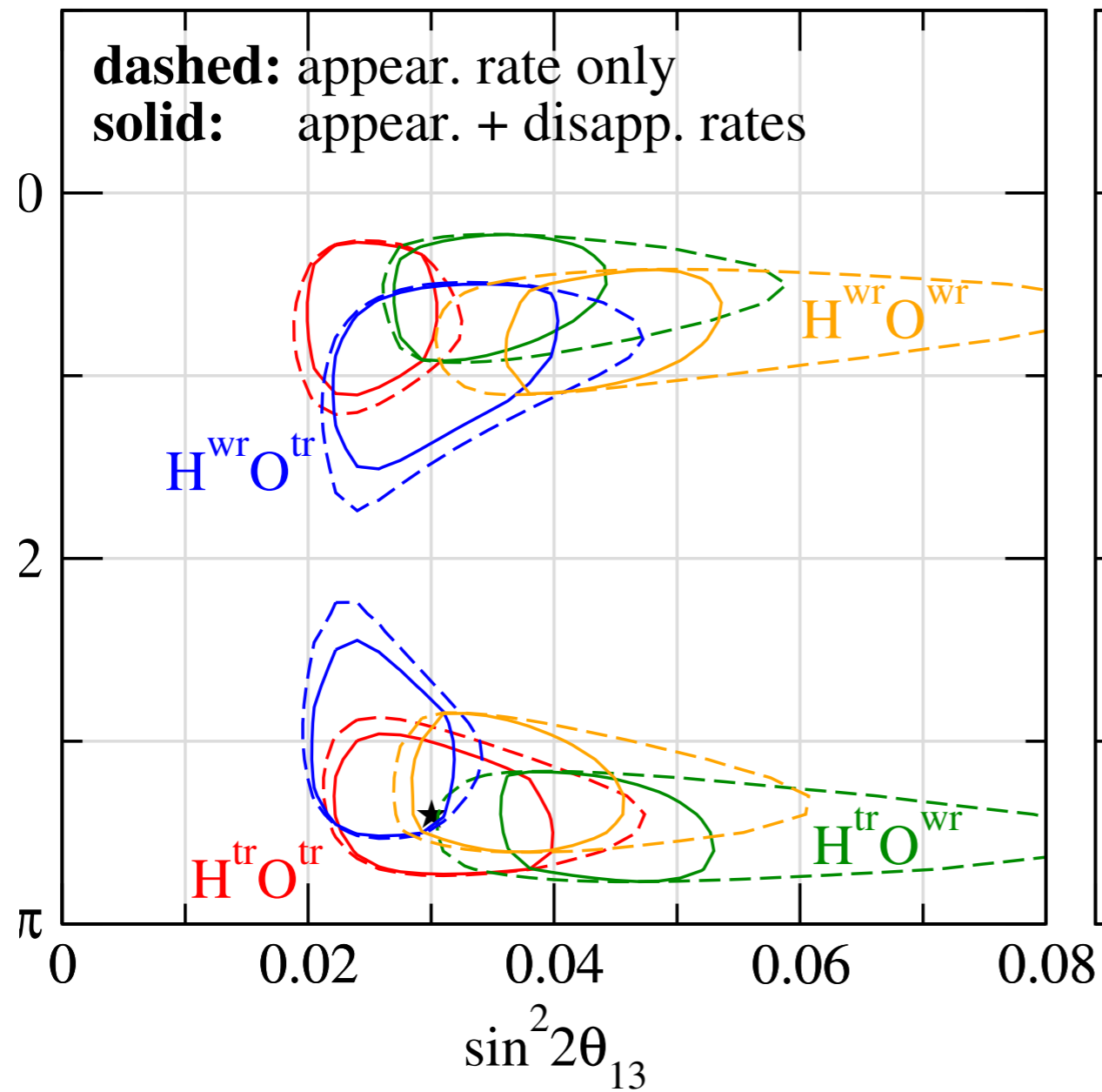
## 2 $\sigma$ sensitivity to normal hierarchy



Hierarchy sensitivity of CERN-MEMPHYS LBL on its own (dashed curves) and when combined with atmospheric data (solid curves).



Octant discrimination capabilities of LBL and atmospheric detectors, both individually and when combined.

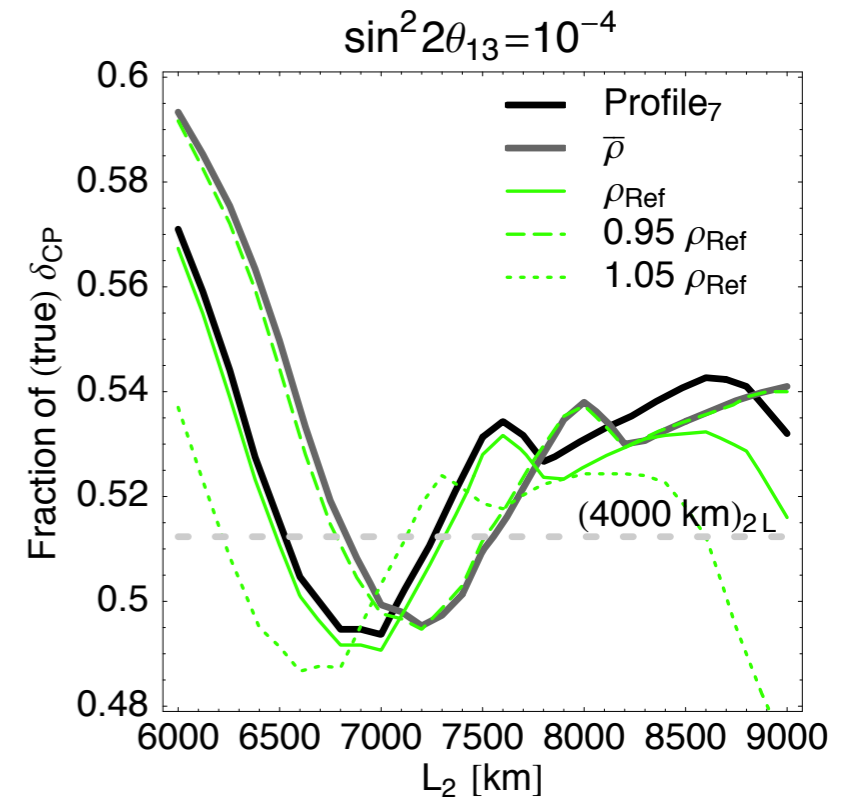
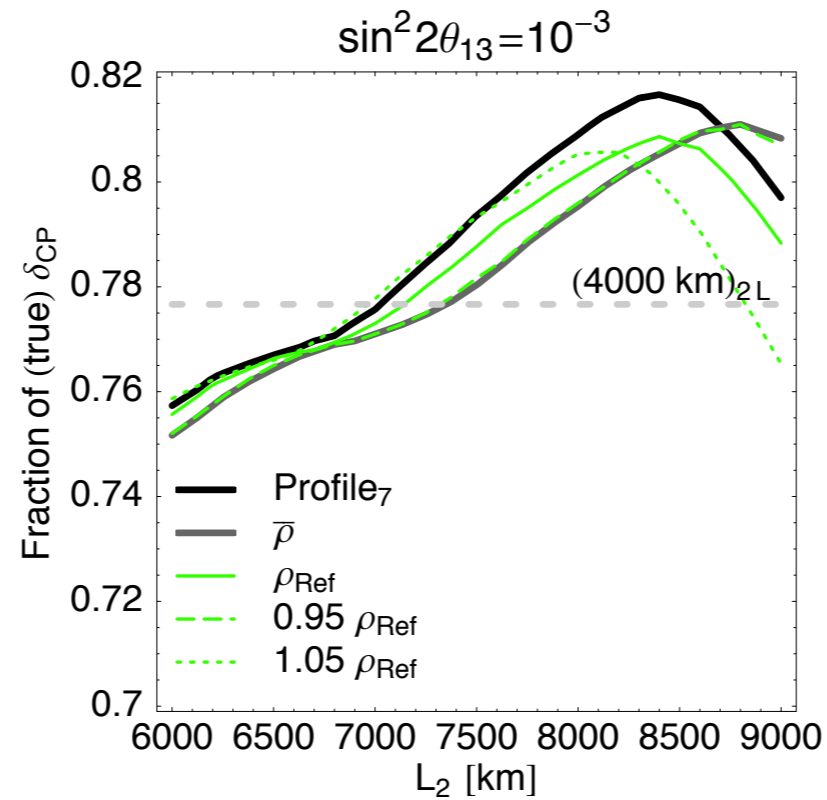
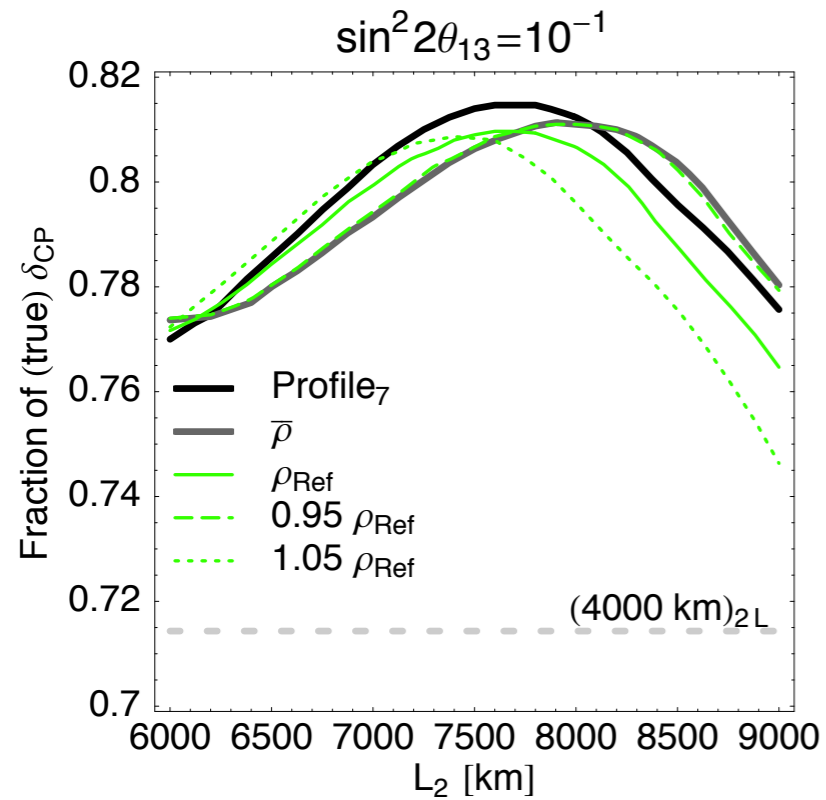


Degeneracy resolution by combining LBL and atmospheric data.

# Physics in conjunction with Neutrino factories and Beta beams.....the Magic Baseline

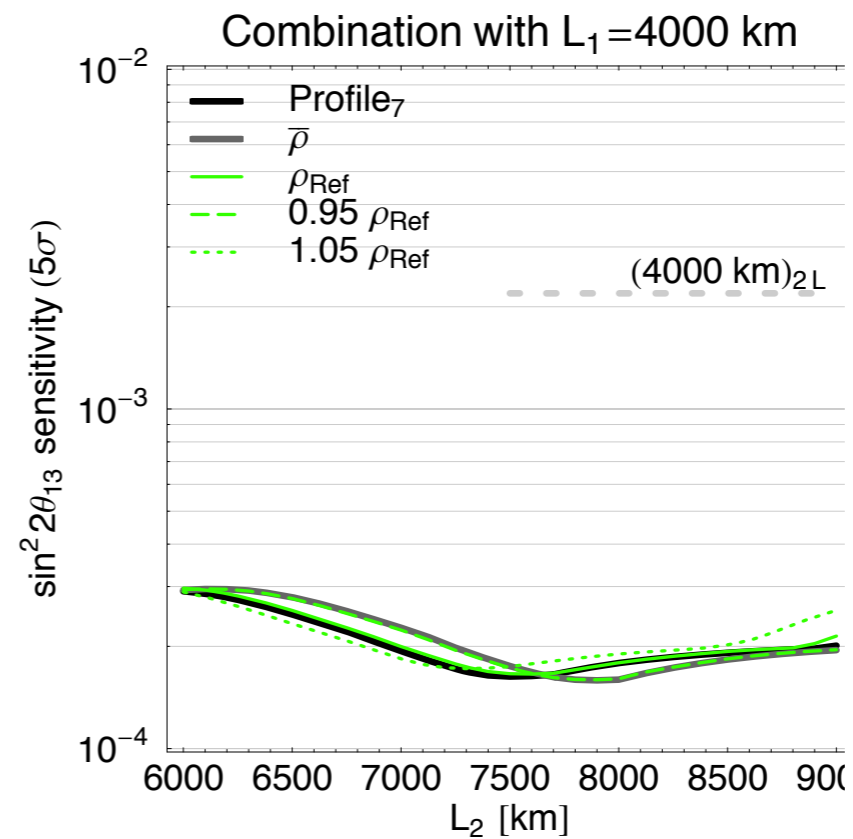
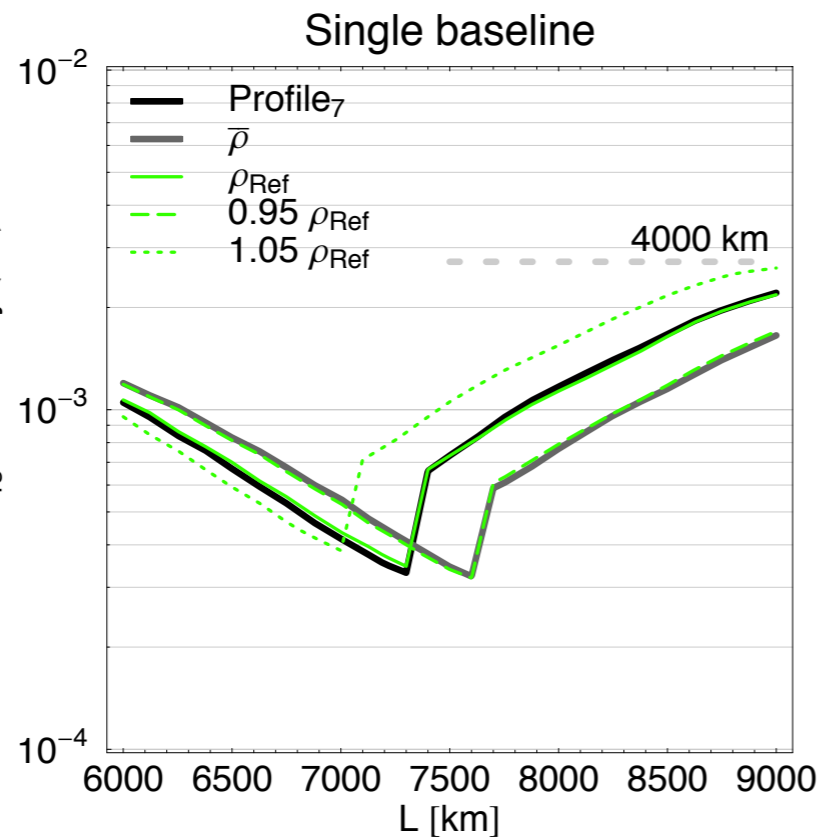
At a baseline length of about 7000-7500 km, terms which contain a CP dependence drop out of the probability. This lifts the degeneracies which afflict the precision measurements of oscillation parameters.

The CERN-ICAL distance is close to the magic baseline, as is the UK (RAL) - ICAL distance. This provides very attractive possibilities for factories and beta beams which may use ICAL as an end detector.



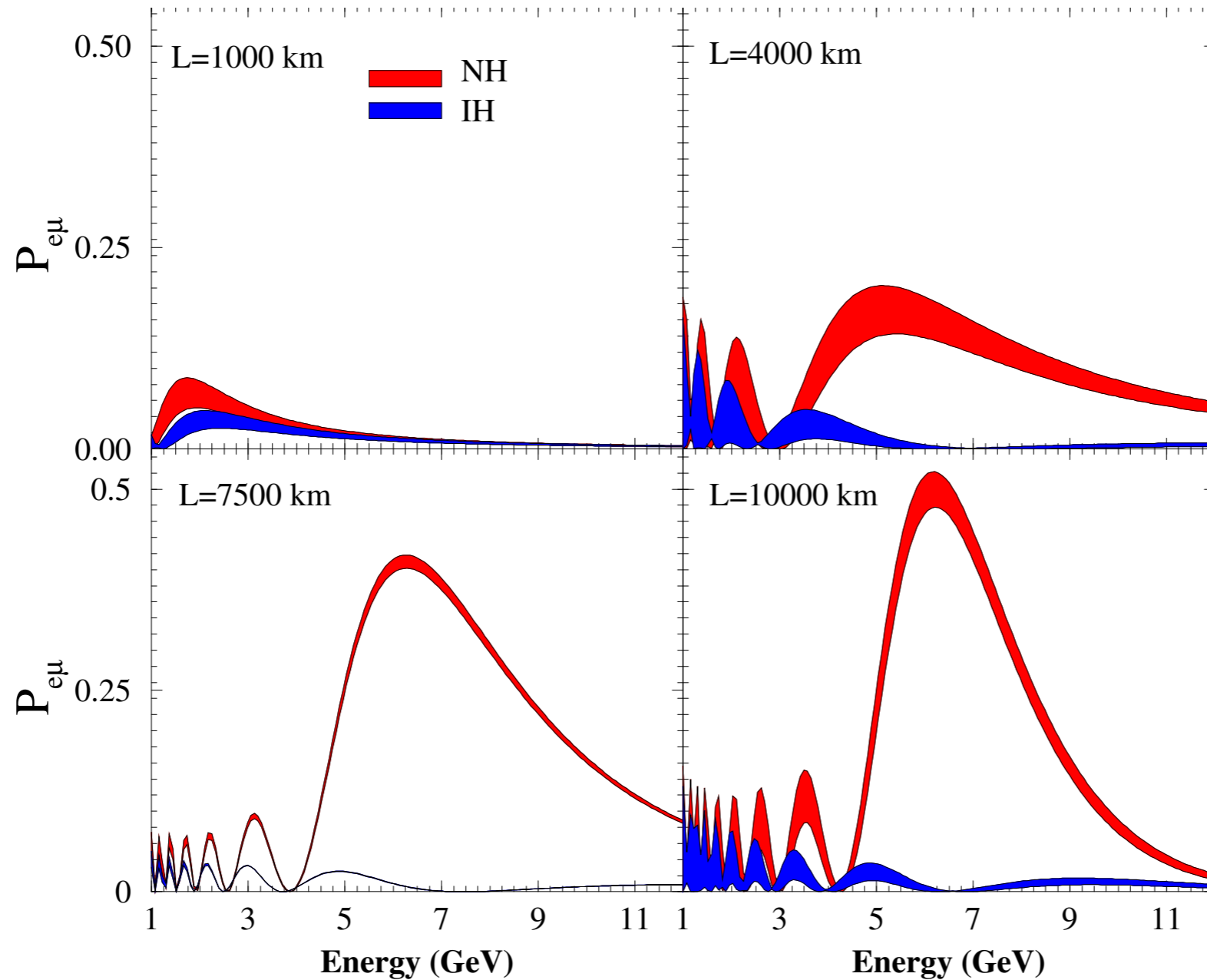
The “fraction of (true)  $\delta_{CP}$ ” for which CP violation can be detected as function of  $L$  at the  $3\sigma$  confidence level.

Gandhi and Winter  
Phys.Rev.D75:053002,2007.



The  $\sin^2 2\theta_{13}$  sensitivity as function of  $L$  including systematics, correlations, and degeneracies at the  $5\sigma$  confidence level.

Gandhi and Winter  
 Phys.Rev.D75:053002,2007.



Agarwalla, Choubey and  
Raychaudhuri,  
PoS NUFACT08:034,2008.

The energy dependance of the e-mu oscillation probability, at four different  
baselines, with bands showing the spread due to the CP parameter.

# Conclusions.....

- ICAL promises to offer a rich program of Stand-alone physics, from offering crucial information on the mass hierarchy, octant, CPT , UHE muons to tests of long range forces.
- If used in conjunction and in tandem with LBL experiments of the next decade, it would help resolve crucial degeneracies and add substantially to our knowledge of oscillation parameters.
- Its magic distance from Europe and Japan make it an attractive option for an end detector for factories and beta beams
- Much work needs to be done in the physics and simulation to fully and reliably explore its potential.