Physics Possibilities of Future Atmospheric Neutrino Experiments

Raj Gandhi

Harish-Chandra Research Institute, Allahabad, India

Introduction . . .

- Atmospheric Neutrinos originate in the collisons of **Cosmic Rays (mainly protons and Helium nuclei)** with **the Earth's upper atmosphere**.

Introduction . . .

- **Atmospheric Neutrinos originate in the collisons of Cosmic Rays (mainly protons and Helium nuclei) with the Earth's upper atmosphere.**

- **The primary collision leads to (mainly) π and (some) K production, and at higher energies, charm mesons. This leads to an overall ratio of $\nu_\mu/\nu_e = 2$ at low (≤ 1 GeV) energies, and > 2 at higher energies. .**

Introduction . . .

- Atmospheric Neutrinos originate in the collisons of Cosmic Rays (mainly protons and Helium nuclei) with the Earth's upper atmosphere.

- The primary collision leads to (mainly) π and (some) K production, and at higher energies, charm mesons. This leads to an overall ratio of $\nu_\mu/\nu_e = 2$ at low (≤ 1 GeV) energies, and > 2 at higher energies. .

- With energy, the ν_μ and ν_e fluxes follow a power-law behaviour,$d\phi/dE \propto E^{-\gamma}$ with $\gamma = 3$ and 3.5 respectively, for $E \geq 1$ GeV.

Introduction . . . Stengths and Limitations

- **Historically atmospheric neutrinos provided us with the first solid evidence of neutrino oscillations, observed in the Water Cerenkov detectors IMB and Kamioka, later confirmed in the calorimeter detectors MACRO and SOUDAN II.**

Introduction . . . Stengths and Limitations

- **Historically atmospheric neutrinos provided us with the first solid evidence of neutrino oscillations, observed in the Water Cerenkov detectors IMB and Kamioka, later confirmed in the calorimeter detectors MACRO and SOUDAN II.**

- **Atmospheric Neutrino experiments have certain inherent limitations, at lower energies ($<$ 1 GeV), where the flux is high, energy resolution via quasi-elastic scattering is often limited by Fermi motion of target nucleons, and angular resolution by the fact that the neutrino and charged lepton directions differ.**

Introduction . . .

- In addition, significant uncertainties in the **neutrino-nucleon cross-section and the absolute fluxes of atmospheric neutrinos**. The **MiNERVA, T2K ND, SCiBOONE and MIPP Experiments** will help by measuring the low energy cross-sections and lead to better estimates of neutrino fluxes.

Introduction . . . Strengths and Limitations

- **Compared to LBL experiments, this limits the capability of atmospheric neutrino detectors to precisely measure L/E. Consequently, they have moderate sensitivity to a measurement dependant on this quantity, like Δm^2.**

Introduction . . . *Strengths and Limitations*

- Compared to LBL experiments, this limits the capability of atmospheric neutrino detectors to precisely measure L/E. Consequently, they have moderate sensitivity to a measurement dependant on this quantity, like Δm^2.

- On the other hand, in a single experiment they provide a very broad band of
  - L, from 20 km to 12000 km.
  - E, from 100 MeV to 10 TeV

Introduction . . .

- A significant common feature of **future atmospheric detectors** is their **size**, enabling them to combine this broad range in L and E with statistics much larger than present generation detectors like SK.

Introduction . . .

- **The agenda of the future for neutrino physics has** *precision as well as discovery* **as its goal, in contrast to the broader** *discovery* **questions like** *"Is it oscillations or is it something else?"* **that experiments over the past two decades tried to answer.**

Introduction . . .

- **The agenda of the future for neutrino physics has** *precision as well as discovery* **as its goal, in contrast to the broader** *discovery* **questions like** *"Is it oscillations or is it something else?"* **that experiments over the past two decades tried to answer.**
- **The** *design, planning and construction* **and ultimately,** *performance and physics contribution* **of future atmospheric detectors must be executed and judged in the context of this redefined agenda.**

Introduction . . .

- **The agenda of the future for neutrino physics has** *precision as well as discovery* **as its goal, in contrast to the broader** *discovery* **questions like** *”Is it oscillations or is it something else?”* **that experiments over the past two decades tried to answer.**
- **The** *design, planning and construction* **and ultimately,** *performance and physics contribution* **of future atmospheric detectors must be executed and judged in the context of this redefined agenda.**

Introduction . . .

- In order to maximize the physics yield over the next decade, the complementarity of the **broad-band capabilities of atmospheric experiments and the precision capabilities of LBL experiments** must be synergistically exploited.

Future Detector Types . . . Water Cerenkov

- **UNO (DUSEL), in Homestake, 300 kT fiducial mass , 1300 km baseline from Fermilab, 4800 m.w.e. depth**

Future Detector Types . . . *Water Cerenkov*

- **UNO (DUSEL), in Homestake, 300 kT fiducial mass , 1300 km baseline from Fermilab, 4800 m.w.e. depth**

- **Hyper-Kamiokande (HK), in Tochibora, Japan, 550 kT fiducial mass, 290 km baseline, 1500 m.w.e. .**

Future Detector Types . . .Water Cerenkov

- **UNO (DUSEL), in Homestake, 300 kT fiducial mass , 1300 km baseline from Fermilab, 4800 m.w.e. depth**
- **Hyper-Kamiokande (HK), in Tochibora, Japan, 550 kT fiducial mass, 290 km baseline, 1500 m.w.e. .**
- **MEMPHYS, in Frejus, 440 kT fiducial mass, 130 km from CERN, 4800 m.w.e depth.**

Some Features . . . Water Cerenkov

- **Water is the cheapest and most stable medium. Cost dependant only on PMTs and purification system, in addtion to civil engineering common to all large underground detectors.**

Some Features . . . *Water Cerenkov*

- **Water is the cheapest and most stable medium. Cost dependant only on PMTs and purification system, in addtion to civil engineering common to all large underground detectors.**

- **Well understood detection and seperation of e and μ leptons via ring topology, lower energy threshold compared to large mass iron calorimeter. .**

Some Features . . . Water Cerenkov

- Water is the cheapest and most stable medium. Cost dependant only on PMTs and purification system, in addtion to civil engineering common to all large underground detectors.

- **Well understood detection and seperation of e and μ leptons via ring topology, lower energy threshold compared to large mass iron calorimeter. .**

- **LBL experiments, while accurately measuring $(\sin^2\theta_{23} - 0.5)$, will not be sensitive to its sign. Octant sensitivity depends on $\nu_\mu \to \nu_e$ conversion modulated by Δm^2_{21}. Observational sensitivity via large L and small E accessibility of Water Cerenkov detectors.**

Future Detector Types . . . Iron Calorimeter

- **INO, 50-100 kT magnetized. 4000 m.w.e.depth.**

Future Detector Types . . .Iron Calorimeter

- **INO, 50-100 kT magnetized. 4000 m.w.e.depth.**
- **Detects muons only. Energy threshold 1-2 GeV.**

Future Detector Types . . . Iron Calorimeter

- INO, 50-100 kT magnetized. 4000 m.w.e.depth.
- Detects muons only. Energy threshold 1-2 GeV.
- A large magnetized iron calorimeter has :
  - Charge identification capability gives it an edge over other detectors for hierarchy determination, CP, CPT studies.

    (RG, Ghoshal, Goswami and Sankar)
  - Baseline from a European NF to INO is in the vicinity of the magic value of $\simeq$ 7000 Km.
  - The high Z medium allows a study of VHE CR muons via the pair meter method, probing the CR flux at energies of the knee and beyond (RG and Panda)

Detector Types . . .Liquid Argon

- **GLACIER, 100 kT Liquid Argon European effort. Also being planned is possible 100 kT Liq Ar detector for the DUSEL project in the US (part of a set of 2 large Water cerenkov + 1 Liq Ar detectors).**

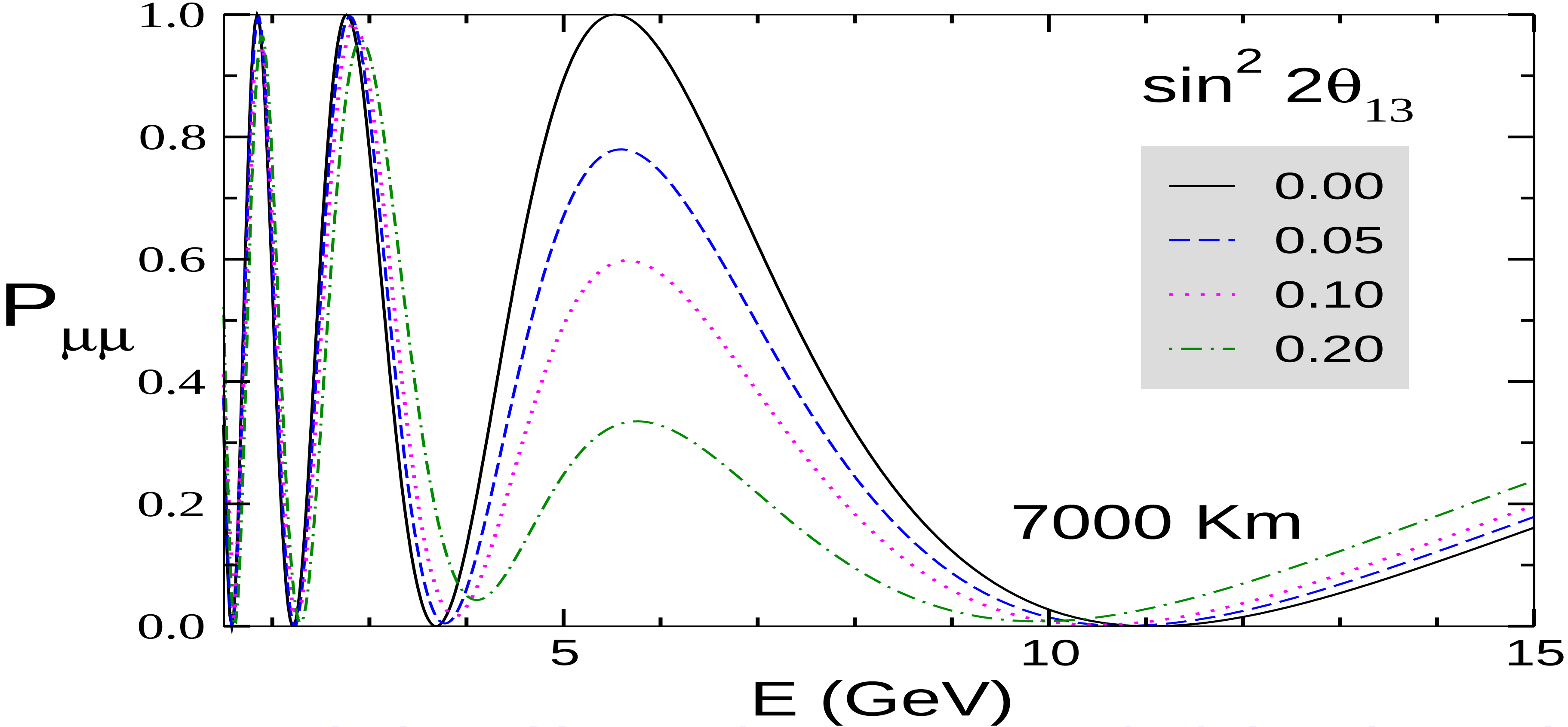
Detector Types . . .Liquid Argon

- GLACIER, 100 kT Liquid Argon European effort. Also being planned is possible 100 kT Liq Ar detector for the DUSEL project in the US (part of a set of 2 large Water cerenkov + 1 Liq Ar detectors).
- Bubble-chamber like Imaging of ionization tracks of drift electrons plus scintillation and Cerenkov light readout. Low energy threshold for detection of leptons (without charge id). Inclusion of B field adds a charge identification capability for muons above 800 MeV and electrons above 1 GeV. .

Detector Types . . .Liquid Argon

- **GLACIER, 100 kT Liquid Argon European effort. Also being planned is possible 100 kT Liq Ar detector for the DUSEL project in the US (part of a set of 2 large Water cerenkov + 1 Liq Ar detectors).**
- **Bubble-chamber like Imaging of ionization tracks of drift electrons plus scintillation and Cerenkov light readout. Low energy threshold for detection of leptons (without charge id). Inclusion of B field adds a charge identification capability for muons above 800 MeV and electrons above 1 GeV. .**
- **Superior particle identification ($e/\mu/\pi/p$ seperation) and calorimetry but relatively untested technology compared to well-understood Water Cerenkov and Iron Calorimeter detectors. Also, R & D required adds to time-scale.**

Physics Capabilities . . .θ_{13} Sensitivity



- **In principle,with large detectors, atmospheric baselines and energies provide sensitivity to θ_{13} via both oscillation and survival probabilities.**

Physics Capabilitis . . .θ_{13} Sensitivity

- **In practice, however, the potential for future atmospheric detectors to deliver a sufficiently informative result on θ_{13} is limited due to the following reasons:**
    - **Sensitivity is maximum at resonance. Resonance in $P_{\mu\mu}$ and $P_{\mu e}$ (for either neutrinos or antineutrinos, but not both) occurs in the energy range of $5-7$ GeV where fluxes are low. Also, L, E resolutions are a limiting factor.**
    - **Megaton Atmospheric detectors are several years down the line, while beam experiments are in the very near future (DCHOOZ, T2K, DAYA BAY...)**

Physics Capabilitis . . .θ_{13} Sensitivity

- **In practice, however, the potential for future atmospheric detectors to deliver a sufficiently informative result on θ_{13} is limited due to the following reasons:**
  - **Sensitivity is maximum at resonance. Resonance in $P_{\mu\mu}$ and $P_{\mu e}$ (for either neutrinos or antineutrinos, but not both) occurs in the energy range of $5 - 7$ GeV where fluxes are low. Also, L, E resolutions are a limiting factor.**
  - **Megaton Atmospheric detectors are several years down the line, while beam experiments are in the very near future (DCHOOZ, T2K, DAYA BAY...)**

Physics Capabilities . . . Sensitivity to the octant of θ_{23}

- **Atmospheric experiments are sensitive to the deviation $\sin^2\theta_{23}$ from $1/2$ via an excess Δn_e of electron events detectable in the sub-GeV region:**

$$\Delta n_e \quad = \quad (1/2 - \sin^2\theta_{23})\frac{\phi_\mu^0}{\phi_e^0}P_{2f}(\Delta m_{21}^2, \theta_{12}) \qquad (1)$$

$$\qquad (2)$$

(Kim and Lee; Peres and Smirnov; Yasuda; Teshima and Sakai; Marrone; Strumia; Gonzalez- Garcia, Maltoni and Smirnov;)

Physics Capabilities . . .θ_{23} Octant Sensitivity

- **The excess at low energies depends on solar parameters , is independant of θ_{13} (effects sub-dominant).**

Physics Capabilities . . . θ_{23} *Octant Sensitivity*

- **The excess at low energies depends on solar parameters , is independant of θ_{13} (effects sub-dominant).**
- **Multi-Gev atmospheric ν_μ events also register a decrease as the deviation increases. This is not predominantly solar parameter driven and does depend on θ_{13}. It also provides a handle on the octant.**

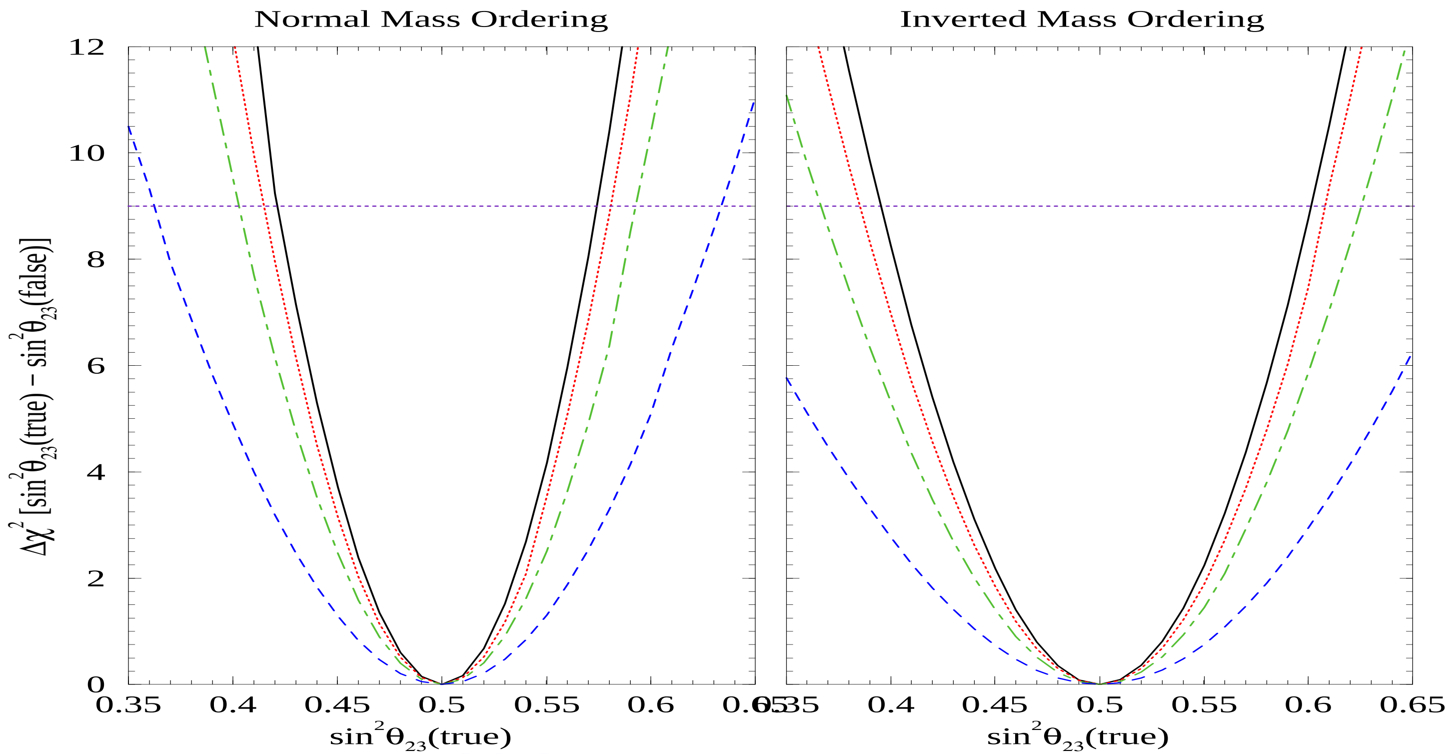
Physics Capabilities . . . θ_{23} *Octant Sensitivity*

- **The excess at low energies depends on solar parameters , is independant of θ_{13} (effects sub-dominant).**

- **Multi-Gev atmospheric ν_μ events also register a decrease as the deviation increases. This is not predominantly solar parameter driven and does depend on θ_{13}. It also provides a handle on the octant.**

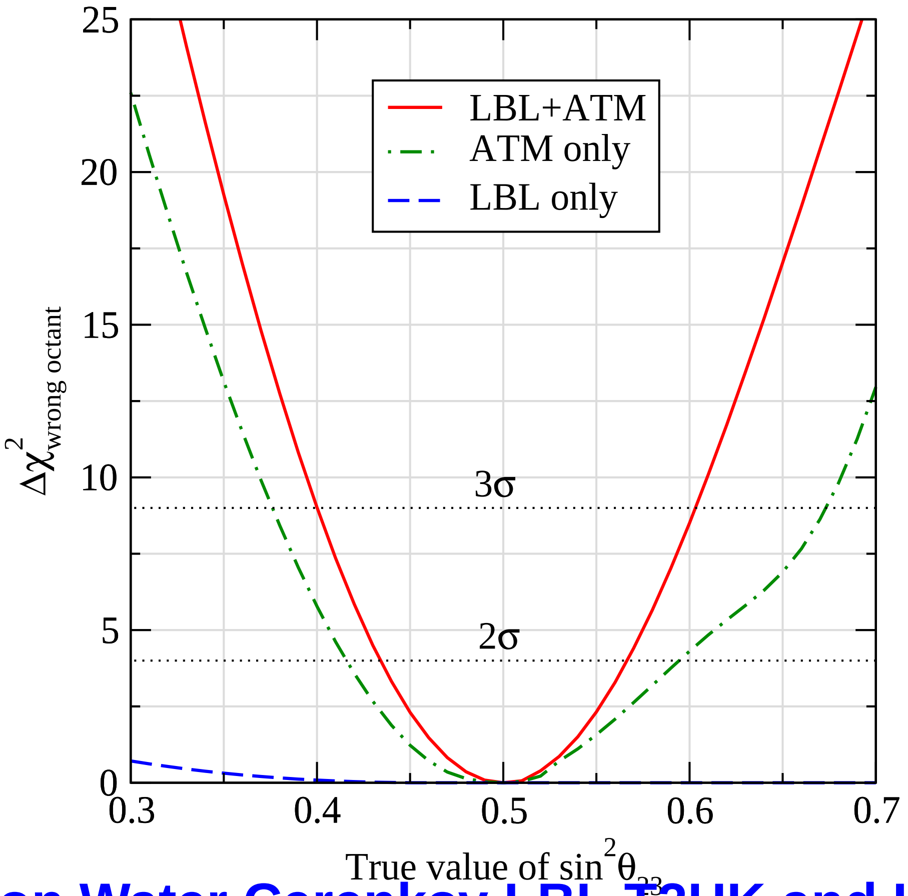
- **Water Cerenkov (HK, MEMPHYS) and Liquid Argon (GLACIER, DUSEL) sensitive to both electron excess (low energy) and muon (multi GeV) channels. Large Iron Calorimeter (INO) acceses muon events only.**

Octant Sensitivity . . .Iron Calorimeter



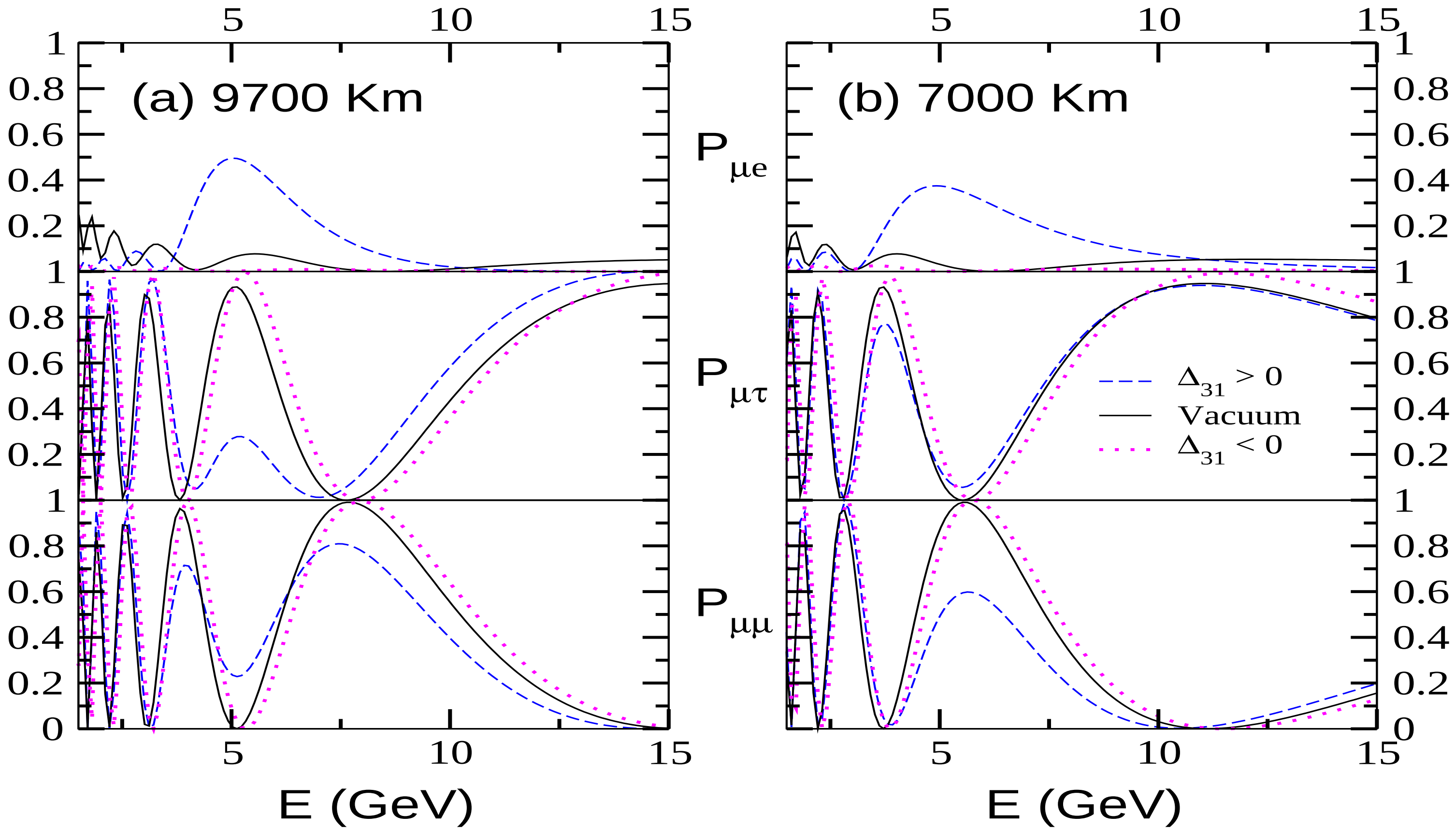
- **INO octant sensitivity 1 Mt-yr exposure, muon events at $>$ GeV energy only**
- **Matter effects at large baselines for either ν (NH) or $\bar{\nu}$ (IH).**
- **Sensitivity if $\sin^2\theta_{13} \geq 0.05$. Need detector of 100 kT.** (Choubey and Roy)

Atmospheric + LBL . . . Octant Sensitivity



- **Megaton Water Cerenkov LBL T2HK and HK Atmospheric.**
- **LBL sensitivity poor, Atmospheric sensitivity good.**
- **Best results obtained when both are combined.**
  (Huber, Maltoni and Schwetz)

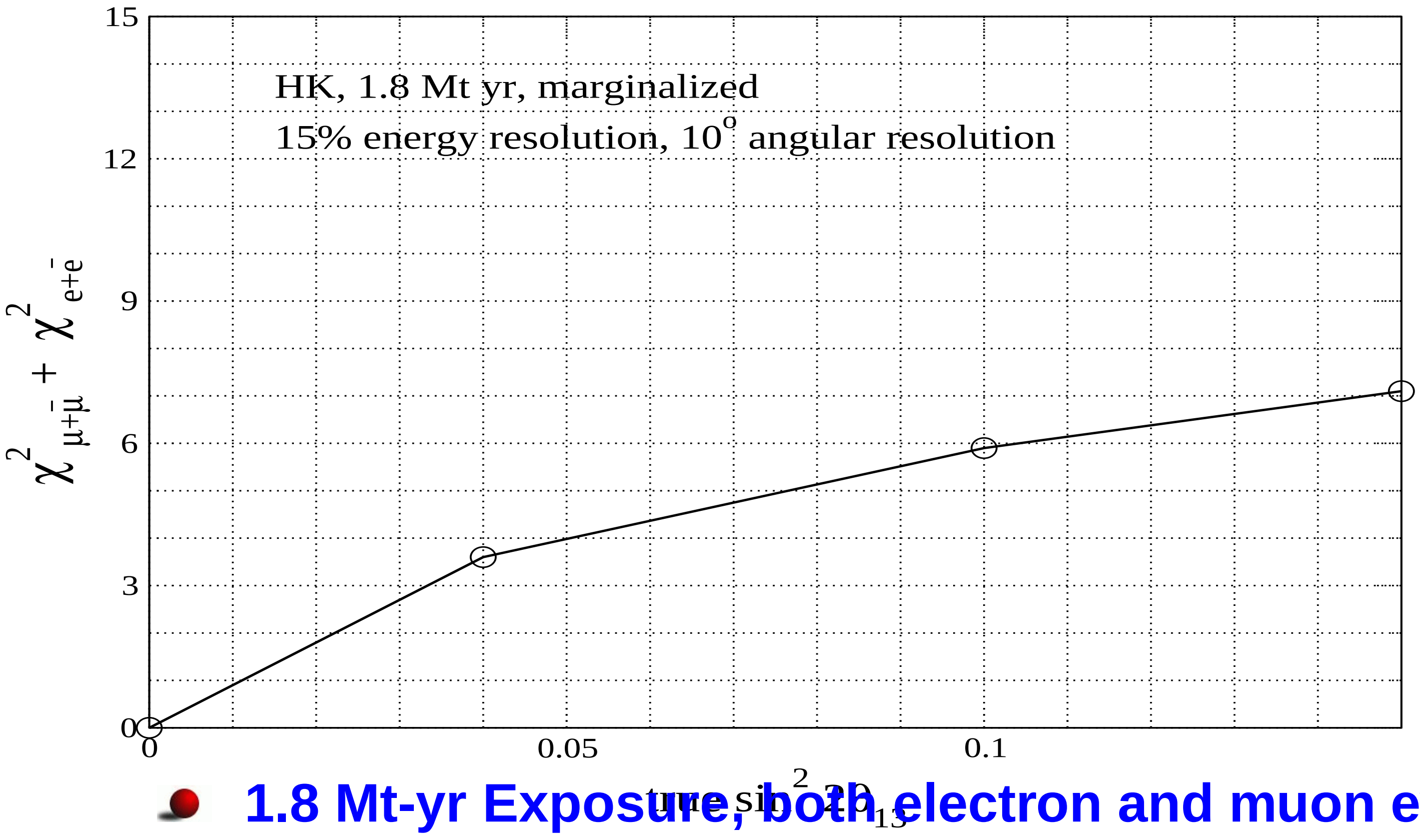
Physics Capabilities . . . Hierarchy Sensitivity in Probabilities



- **At the Very Long Baselines , Hierarchy Sensitivity resides in $P_{\mu\mu}, P_{\mu\tau}$ besides $P_{\mu e}$**
- **Effects most prominent in the range $E = 5 - 10$ GeV, $L = 5000 - 12000$ km.**

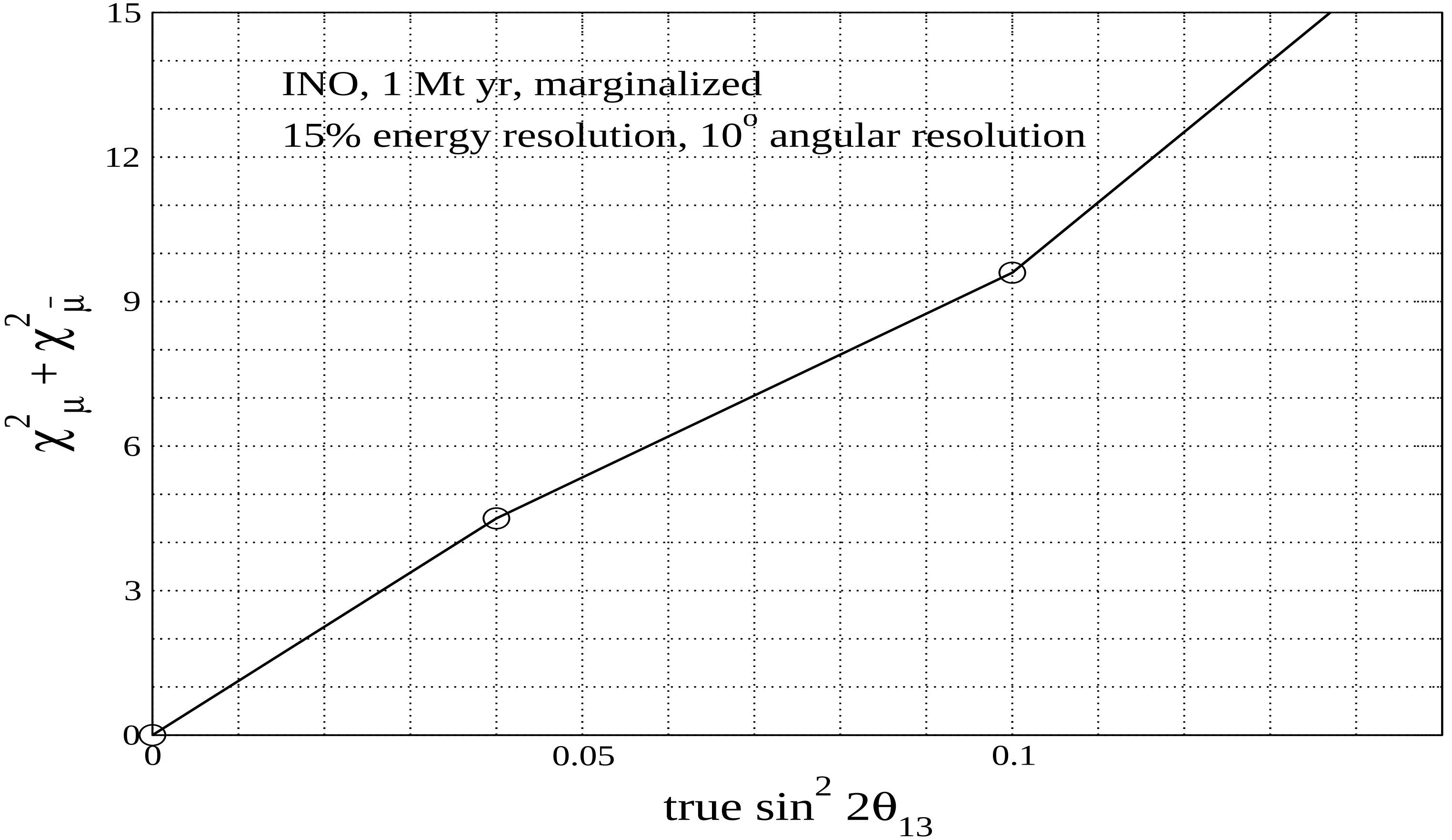
(Gandhi, Ghoshal, Goswami and Sankar)

Hierarchy Sensitivity . . .Large Water Cerenkov



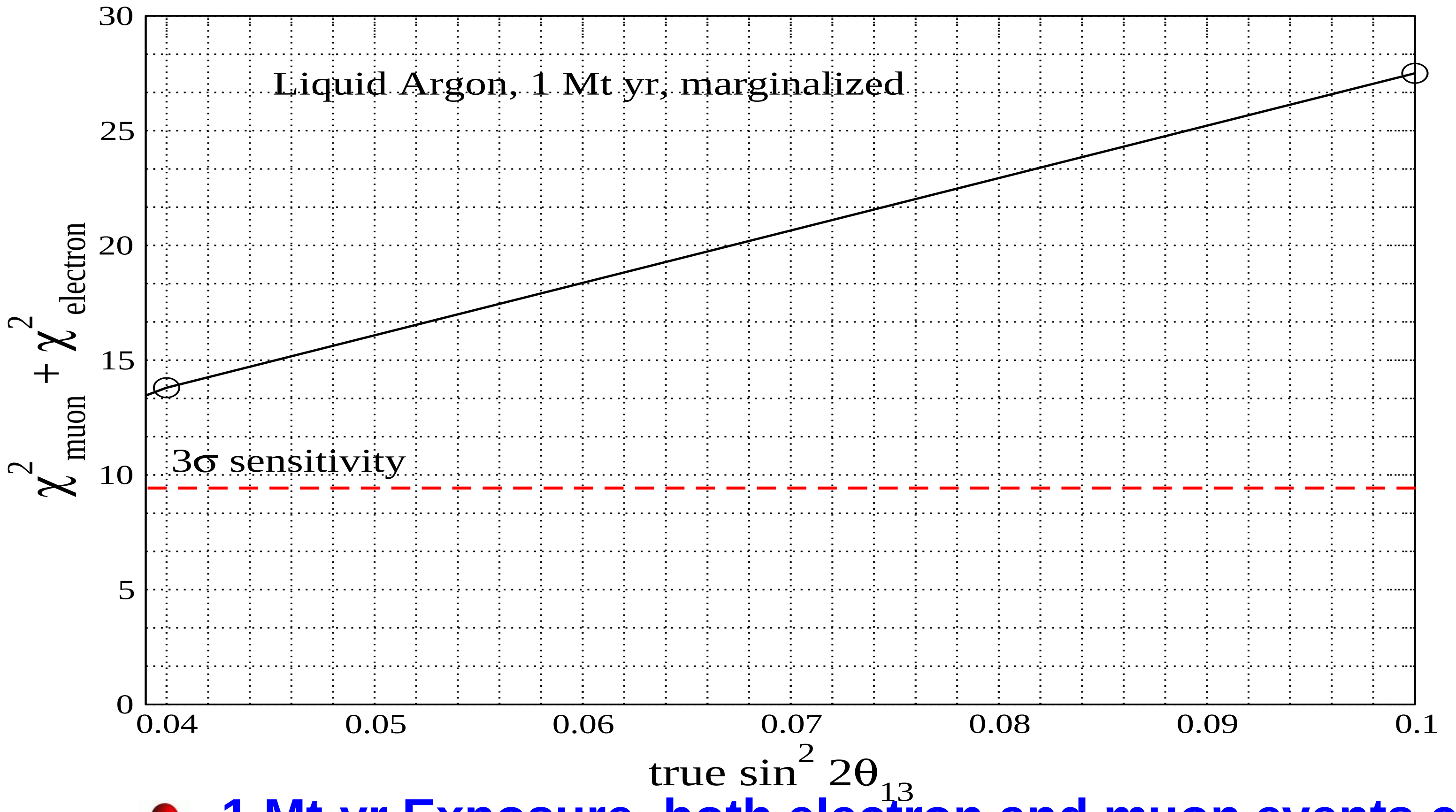
- **1.8 Mt-yr Exposure, both electron and muon events contribute.**
- **Difference between NH and IH in electron events flattens out at large θ_{13}.** (RG, Ghoshal, Goswami, Mehta, Sankar and Shalgar)

Hierarchy Sensitivity . . .Magnetized Iron Calorimeter



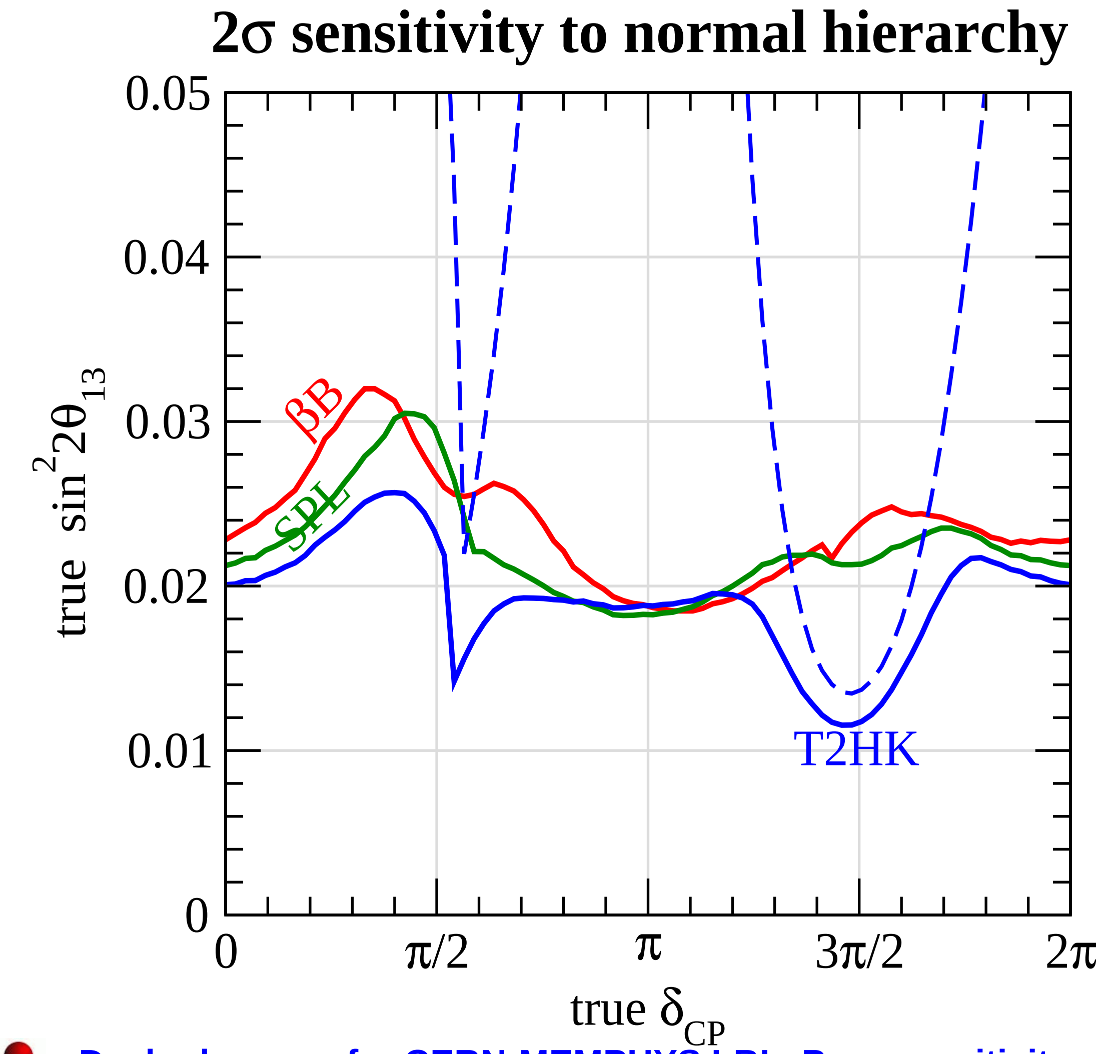
- **1 Mt-yr Exposure, muon events with charge identification.**
  (RG, Ghoshal, Goswami, Mehta, Sankar and Shalgar)

Hierarchy Sensitivity . . .Magnetized Liquid Argon



- **1 Mt-yr Exposure, both electron and muon events contribute.**
  (RG, Ghoshal, Goswami, Sankar)

Hierarchy Sensitivity . . .LBL + Atmospheric



- **Dashed curves for CERN-MEMPHYS LBL. Poor sensitivity**
- **Solid curves for LBL + Atm.** 2σ **sensitivity for** $sin^2 2\theta_{13} \geq 0.02$
  (Campagne, Maltoni, Mezzetto, Schwetz)

Degeneracies in LBL experiments . . .

- **The $(\delta_{\rm CP}, \theta_{13})$ degeneracy arises when different pairs of values of the parameters $\delta_{\rm CP}$ and θ_{13} give the same neutrino and anti-neutrino oscillation probabilities, assuming other parameters to be known and fixed. This may be expressed as**

$$\begin{aligned} {\rm P}_{\alpha\beta}(\delta_{\rm CP}, \theta_{13}) &= {\rm P}_{\alpha\beta}(\delta'_{\rm CP}, \theta'_{13}) \\ \bar{\rm P}_{\alpha\beta}(\delta_{\rm CP}, \theta_{13}) &= \bar{\rm P}_{\alpha\beta}(\delta'_{\rm CP}, \theta'_{13}) \end{aligned} \qquad (3)$$

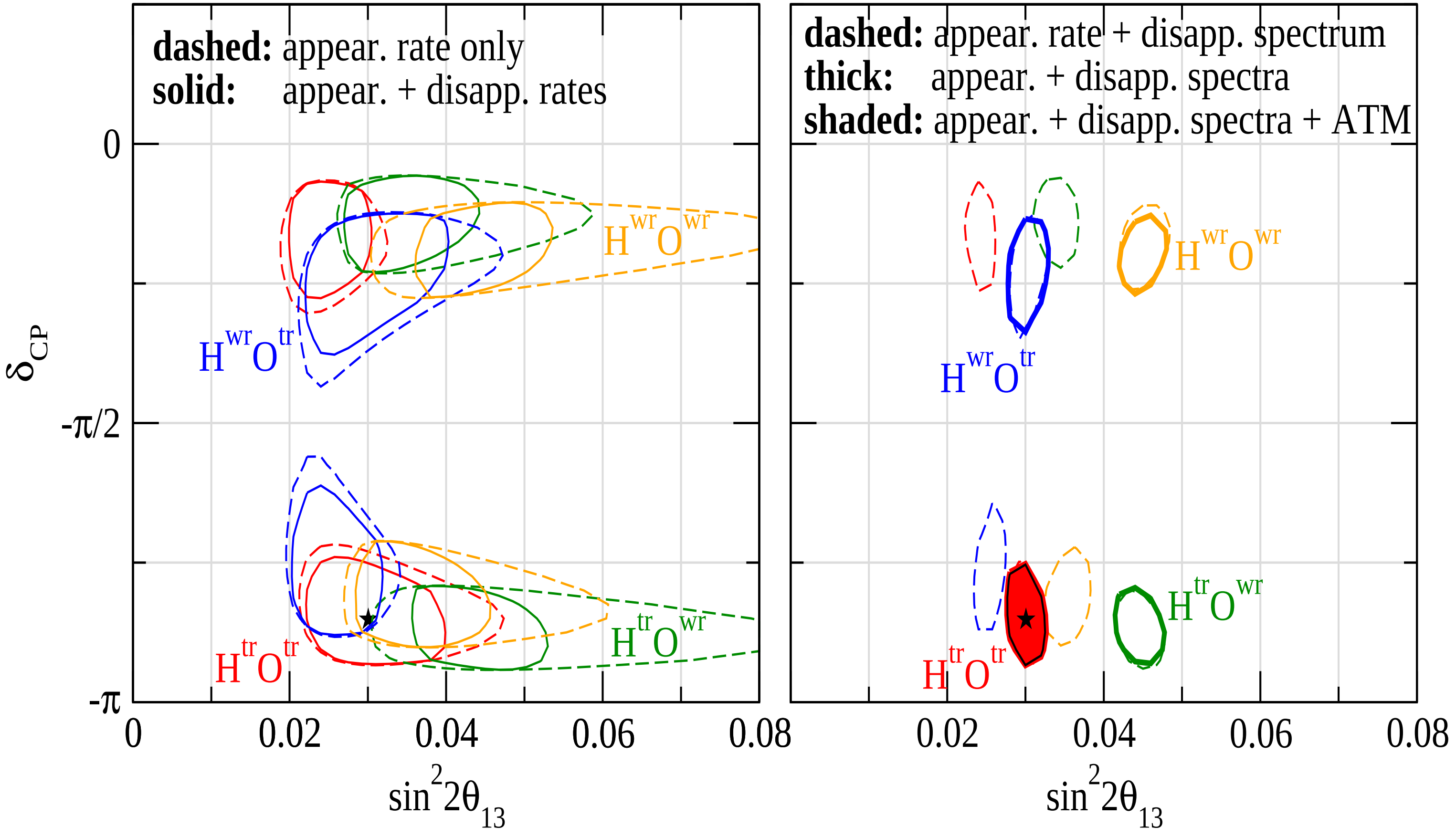
Degeneracies in LBL experiments . . .

- The mass hierarchy degeneracy occurs due to identical solutions for P and $\bar{\mathrm{P}}$ for different pairs of δ_{CP} and θ_{13} with opposite signs of Δ_{31} (again fixing other parameters):

$$\begin{aligned} \mathrm{P}_{\alpha\beta}(\Delta_{31} > 0, \delta_{\mathrm{CP}}, \theta_{13}) &= \mathrm{P}_{\alpha\beta}(\Delta_{31} < 0, \delta'_{\mathrm{CP}}, \theta'_{13}) \\ \bar{\mathrm{P}}_{\alpha\beta}(\Delta_{31} > 0, \delta_{\mathrm{CP}}, \theta_{13}) &= \bar{\mathrm{P}}_{\alpha\beta}(\Delta_{31} < 0, \delta'_{\mathrm{CP}}, \theta'_{13}) \end{aligned} \tag{4}$$

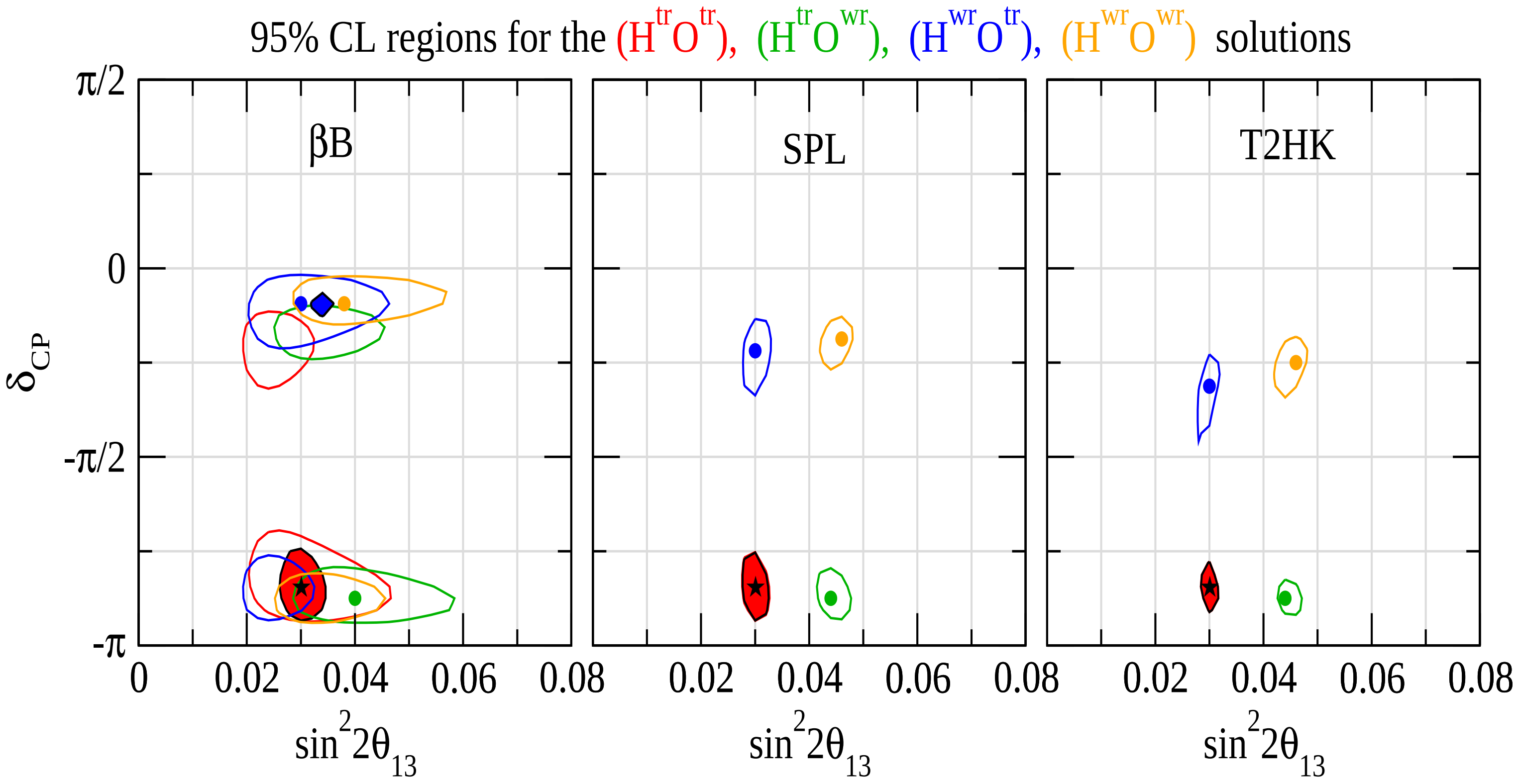
- **The $\theta_{23}, (\pi/2 - \theta_{23})$ degeneracy.**

Physics Capabilities . . . Degeneracies and their removal



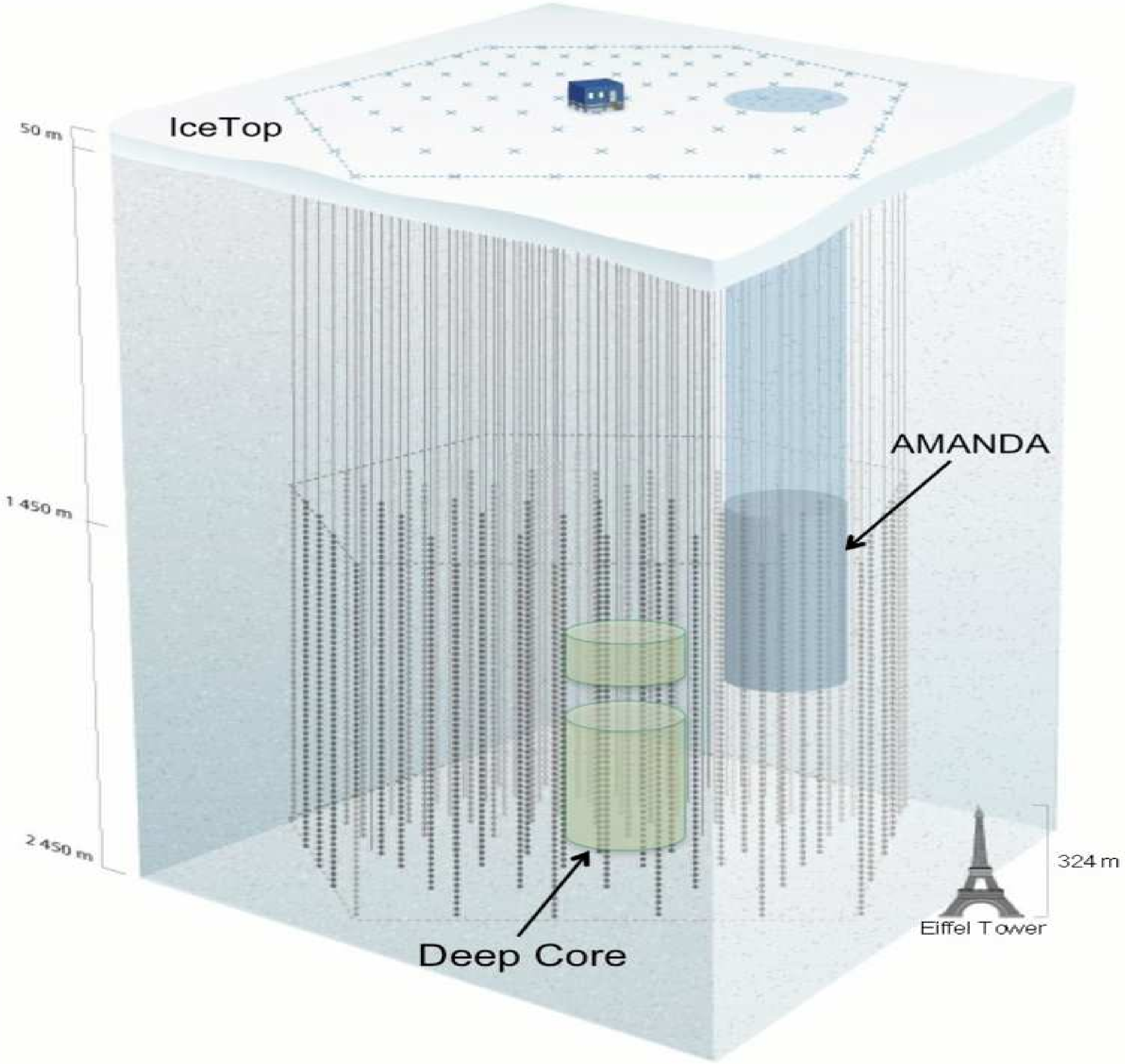
- LBL with appearance and disappearance rates exhibits full 8 fold degeneracy.
- Spectral information + rates reduces this to 4 fold degeneracy.
- Inclusion of atmospheric data isolates true solution by removing all degeneracy(Campagne, Maltoni, Mezzetto, Schwetz)

Physics Capabilities. . .Degeneracy and Atmospheric Neutrino

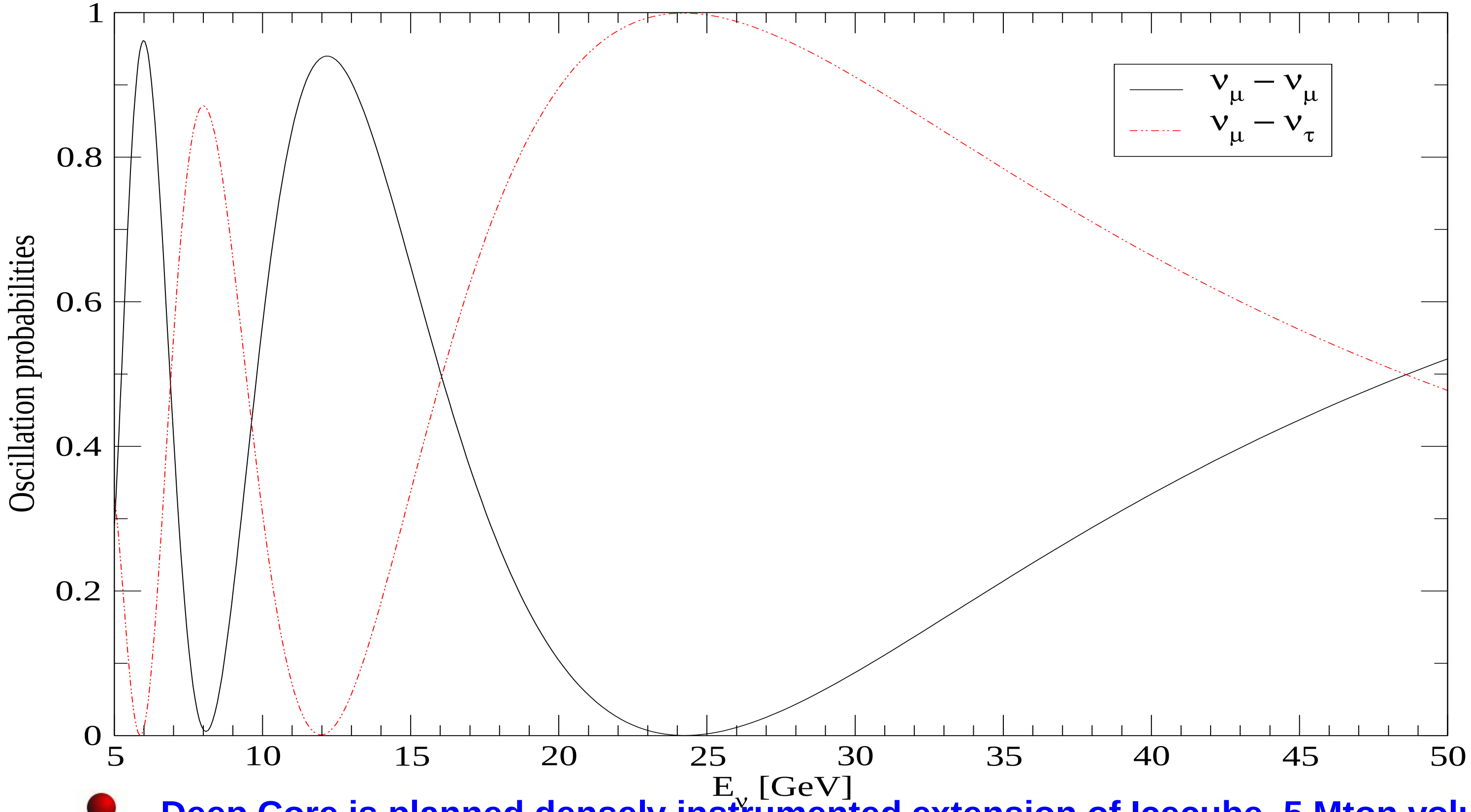


- **Beta beam only lacks appearance rate and spectrum, 8 fold degeneracy**
- **Degeneracy resolved for all on addition of atmospheric data**
  (Campagne, Maltoni, Mezzetto, Schwetz)

UHE Neutrino Detectors as Atmospheric Experiments . . .



VHE Atmospheric Detectors . . .DeepCore/ ICECUBE



- **Deep Core is planned densely instrumented extension of Icecube, 5 Mton volume**
- **Resonant matter effects and hierarchy sensitivity in 10-40 GeV range in upgoing neutrinos for large θ_{13}**
  (Mocioiu, Mena and Razzaque)

Non Standard Interactions . . . Atmospheric Neutrinos

- **Non-standard Interactions can be tested comprehensively in many types of neutrino experiments, atmospheric, super-beams, reactor, neutrino-factory etc...**

Non Standard Interactions . . . Atmospheric Neutrinos

- **Non-standard Interactions can be tested comprehensively in many types of neutrino experiments, atmospheric, super-beams, reactor, neutrino-factory etc...**
- **Atmospheric Neutrino experiments in large detectors have the special advantage of acting as degeneracy resolvers for the higher precision LBL and reactor experiments. (Huber and Valle)**

Conclusions . . .

- **Atmospheric Neutrino detectors of the future will combine large volume statistics and broad band access to L and E.**

Conclusions . . .

- **Atmospheric Neutrino detectors of the future will combine large volume statistics and broad band access to L and E.**
- **They will offer a high degree of sensitivity to the octant of θ_{23}, thus filling a much needed gap in the capabilities of upcoming LBL experiments .**

Conclusions . . .

- Atmospheric Neutrino detectors of the future will combine large volume statistics and broad band access to L and E.
- They will offer a high degree of sensitivity to the octant of θ_{23}, thus filling a much needed gap in the capabilities of upcoming LBL experiments .
- All three types of planned atmospheric detectors will be sensitive to the hierarchy at exposures of 1 Mt-yr

Conclusions . . .

- They provide excellent capabilities for degeneracy resolution, aiding the precesion capabilities of LBL experiments.

Conclusions . . .

- They provide excellent capabilities for degeneracy resolution, aiding the precesion capabilities of LBL experiments.
- They have a role to play in the effort to detect non-standard physics in neutrino experiments. .

Conclusions . . .

- They provide excellent capabilities for degeneracy resolution, aiding the precesion capabilities of LBL experiments.
- They have a role to play in the effort to detect non-standard physics in neutrino experiments. .
- Deep Core will provide a testing ground for high energy neutrino oscillation physics using atmospheric neutrinos.

Conclusions . . .

- **Two important consequences that emerge from these considerations to maximize the physics yield of atmospheric neutrino detectors of the future are:**
  - *Until stand-alone technologically advanced set-ups like neutrino factories take over perhaps in 12-15 years from now, the richest physics yeilds will be obtained when we combine the capabilities of LBL and atmospheric experiments.*
  - *Atmospheric detectors should be planned to double as end-detectors for future superbeams and factories.*

Conclusions . . .

- **Two important consequences that emerge from these considerations to maximize the physics yield of atmospheric neutrino detectors of the future are:**
  - *Until stand-alone technologically advanced set-ups like neutrino factories take over perhaps in 12-15 years from now, the richest physics yeilds will be obtained when we combine the capabilities of LBL and atmospheric experiments.*
  - *Atmospheric detectors should be planned to double as end-detectors for future superbeams and factories.*