Neutrino Mass Hierarchy Determination via Atmospheric Neutrinos with Future Detectors

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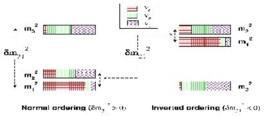
Neutrino 2008

Abstract: We demonstrate the feasibility of neutrino mass hierarchy determination using atmospheric neutrinos and future detectors in two cases: (A) Large θ_{13}, for which the sensitivity is governed by resonant matter effects, and (B) Small/vanishing θ_{13}, for which the hierarchy difference in $P_{\mu\mu}$ is proportional to $\Delta_{21}L/E$. To detect this difference in case (B) one requires L/E ∼ 10^4. Atmospheric neutrinos with L ∼ 10^4 Km and E ∼ 1 GeV can be used for observing this effect. We note that in this case, one requires exceptional precision ($\lesssim 2\%$) in $|\Delta_{31}|$ to obtain a significant hierarchy sensitivity, and mention the future prospects of achieving this.

Neutrino mass hierarchy



- The 2 possible hierarchies of neutrino masses:
  $\Delta_{21} = 8 \times 10^{-5} eV^2 << |\Delta_{31}| = 2.5 \times 10^{-3} eV^2$
- ν mass hierarchy is an important discriminator between large classes of unified theory models

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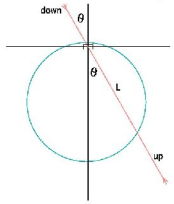
Atmospheric neutrinos as source

Advantages: ➢ Provides broad L/E band (1 to 10^5 km/GeV). Suitable ranges of L & E can be chosen.
➢ The longer baselines allow matter effects to develop for Sign(Δ_{31}) sensitivity.

$p + A_{air} \rightarrow \pi^+ + \ldots$
$\pi^+ \rightarrow \mu^+ + \nu_\mu$
$\mu^+ \rightarrow e^+ + \nu_\mu + \nu_e$



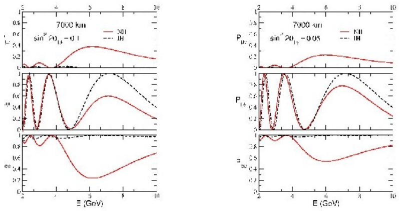
Future Detectors for Atm ν

- Magnetized Iron Detector (Prototype: INO)
  ➢ 50 - 100 kT
  ➢ Muon detection & charge discrimination capability
- Megaton Water Cerenkov Detector (Prototype: HK, UNO, MEMPHYS)
  ➢ SK-type detector with no charge ID
  ➢ Both electron and muon events can be used
- Liquid Argon detector (Prototype: ICARUS)
  ➢ Time projection chamber
  ➢ Both electron and muon events can be used, charge ID for both?
- Neutrino Telescope (Prototype: IceCube)

(A)Sensitivity for large θ_{13}

(Gandhi et al, PRD 76, 073012)

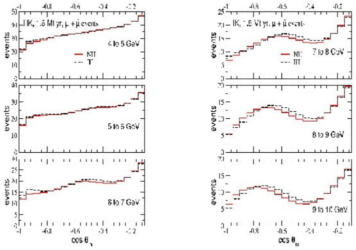
Arises due to resonant matter effects at long baselines..

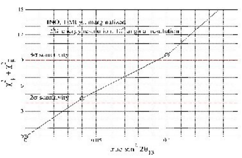


Numerical Analysis

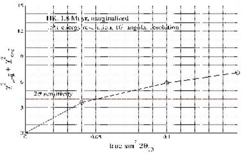
- Range for matter effects: E = 2 to 10 GeV, $\cos\theta_z$ = -0.1 to -1.0, 8 × 18 = 144 bins
- Muon event no: $(\phi_\mu \times P_{\mu\mu} + \phi_e \times P_{e\mu})$ × CC cross-section × detector efficiency
- Electron event no: $(\phi_\mu \times P_{\mu e} + \phi_e \times P_{ee})$ × CC cross-section × detector efficiency
- Detector resolution of 10° in θ_z, 15% in E in INO and HK
- $\chi^2_{pull} = \min_{\xi_k}\left[\sum_i^n \frac{(N^i_{theory} - N^i_{expt} + \sum_{k=1}^{npull} \xi_k c^k_i)^2}{(\sigma^i)^2} + \sum_{k=1}^{npull} \xi_k^2\right]$
  where $\sigma^i = \sqrt{N_{expt}}$, $N_{expt} = N_{NH}$, $N_{theory} = N_{IH}$
- INO $\chi^2 = \chi^2_\mu + \chi^2_{\bar\mu}$, HK $\chi^2 = \chi^2_{\mu+\bar\mu} + \chi^2_{e+\bar e}$
- Marginalization: Δ_{21}, θ_{12} fixed, other parameters varied in the range
  $\Delta_{31} = 2.35 \times 10^{-3} - 2.6 \times 10^{-3}$ eV^2, $\sin^2\theta_{23} = 0.4 - 0.6$,
- Priors added in the form:
  $\chi^2_{prior} = \frac{((\Delta_{31}) - (\Delta_{31})^{true})^2}{(\sigma_{\Delta_{31}})^2} + \frac{((\sin^2 2\theta_{13}) - (\sin^2 2\theta_{13})^{true})^2}{(\sigma_{\sin^2 2\theta_{13}})^2} + \frac{((\sin^2 2\theta_{23}) - (\sin^2 2\theta_{23})^{true})^2}{(\sigma_{\sin^2 2\theta_{23}})^2}$
  where $\sigma(\Delta_{31}) = 0.1 \times (\Delta_{31})^{true}$, $\sigma(\sin^2 2\theta_{13}) = 0.02$, $\sigma(\sin^2 2\theta_{23}) = 0.1(\sin^2 2\theta_{23})^{true}$

HK (1.8 Mt yr) Events





INO (1 Mt yr),
HK (1.8 Mt yr)
hierarchy sensitivity



(B)Sensitivity for small/zero θ_{13}

- Sensitivity to ν mass hierarchy for small/vanishing θ_{13} ($\sin^2 2\theta_{13} < 0.02$) with atm ν, detectors like INO, HK, Liquid Argon *(Gandhi et al, arXiv:0805.3474)*
- not due to matter effects; Δ_{21}-driven effect, max in 1-2 GeV range and for baselines ∼ 12000 Km
- In this range and for $\theta_{13} = 0$, $\Delta_{21} << A << \Delta_{31}$, and
  $P^m_{\mu\mu} = 1 - \sin^2 2\theta_{23} \sin^2\left[(\Delta_{31} - \Delta_{21} c^2_{12}) \frac{L}{4E}\right] \rightarrow$
  $P^m_{\mu\mu}(NH) - P^m_{\mu\mu}(IH) = \Delta_{21} \frac{L}{2E} c^2_{12} \sin(\frac{\Delta_{31} L}{2E})$
- Hierarchy difference proportional to $\Delta_{21} L/E$, *i.e.* $L/E \sim 10^4$ required.. $L \sim 10000$ Km, $E \sim 1$ GeV accessible in atmospheric neutrinos

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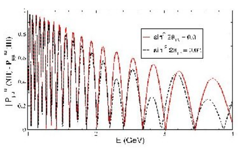
..Importance of Δ_{31} precision

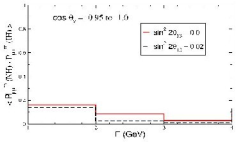
- $P^m_{\mu\mu}(NH) - P^m_{\mu\mu}(IH)$ vanishes if $\Delta^{IH}_{31} = -\Delta^{NH}_{31} + 2\Delta_{21} c^2_{12}$
- For present best-fit $\Delta_{21} = 8 \times 10^{-5}$ eV^2, $|\Delta_{31}| = 2.5 \times 10^{-3}$ eV^2, $|\Delta_{31}|$ allowed range $1.8 - 3.3 \times 10^{-3}$ eV^2, → $2\Delta_{21} c^2_{12} = 0.112 \times 10^{-3}$ eV^2, above Δ^{IH}_{31} within range
- If $|\Delta_{31}|$ allowed range covers this point, no sensitivity; closer the range to this point, lower is the sensitivity → Sharp dependence of $\theta_{13} = 0$ hierarchy sensitivity on Δ_{31} precision
- Projected $\sigma(\Delta_{31}) \sim 2\%$ in superbeams (T2K), wide-band LBL (BNL/Fermilab-DUSEL)

Small non-zero θ_{13}?

- For 1-2 GeV, $A << \Delta_{31}$ → neglecting matter-induced change in θ_{13},
  $P^m_{\mu\mu}(NH) - P^m_{\mu\mu}(IH) = \Delta_{21} \frac{L}{2E}(c^2_{12} - 2c_{12}s_{12}s_{13}) \sin(\frac{\Delta_{31} L}{2E})$
- Slight decrease in hierarchy sensitivity for small θ_{13}, $\sin^2 2\theta_{13} < 0.02$
- In final χ^2 for HK and Liquid Argon, small contribution of electron events due to matter-induced hierarchy sensitivity in $P_{\mu e}$ for non-zero θ_{13}



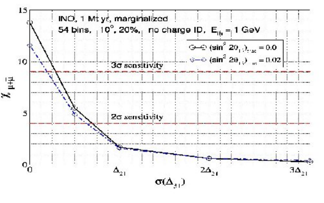
$P^m_{\mu\mu}$ NH-IH difference, absolute and average



Numerical analysis

- Range studied for small θ_{13} sensitivity: E = 1 to 10 GeV, $\cos\theta_z$ = -0.7 to -1.0, divided into 9 × 6 = 54 bins
- Maximum sensitivity from 1-2 GeV bin and highest baseline bin ($\cos\theta_z$ = -0.95 to -1.0), range chosen to be consistent with detector resolution and gather enough statistics for significant sensitivity in spite of systematic uncertainties
- Detector resolution of 10° in θ_z & 20% in E for both INO and HK, 3% in electron energy, 15% in muon energy, 30% in hadron energy for Liquid Argon detector
- No charge ID required, since $\theta_{13} = 0$ sensitivity due to matter-independent term in $P_{\mu\mu}$ →
  INO $\chi^2 = \chi^2_{\mu+\bar\mu}$
  HK and Liquid Argon $\chi^2 = \chi^2_{\mu+\mu} + \chi^2_{e+e}$
- During marginalization, $\sigma(\Delta_{31})$ varied from $0.016 \times (\Delta_{31})^{true}$ to $0.1 \times (\Delta_{31})^{true}$

INO χ^2_{min} vs $\sigma(\Delta_{31})$



HK,INO,Liq.Ar: small θ_{13}

$\sin^2 2\theta^{true}_{13}$	Δ_{31} precision	χ^2_{min}, INO	χ^2_{min}, HK	χ^2_{min}, Liq.Ar
0.0	$\Delta_{21}/2$	5.5	3.9	5.7
0.02	$\Delta_{21}/2$	4.9	3.8	6.1
0.0	Δ_{21}	1.7	1.5	1.8
0.02	Δ_{21}	1.6	1.7	2.2

Table 1: Values of χ^2_{min} with pull and priors for INO (1 Mt yr), HK (1.8 Mt yr) and a Liquid Argon detector (1 Mt yr) for two values of $\sin^2 2\theta^{true}_{13}$ and two possible values of Δ_{31} precision.

Summary

- For $\sin^2 2\theta_{13} > 0.05$, Sign($\Delta_{31}$) sensitivity in the muon oscillation and survival probabilities is due to earth matter effects. This may be observed at large future detectors like INO, HK and Liquid Argon detectors with good detector resolution.
- For small $\sin^2 2\theta_{13} < 0.02$ or vanishing θ_{13}, such detectors may still show statistically significant sensitivity to the neutrino mass hierarchy. This effect is independent of matter and is proportional to $\Delta_{21} L/E$. Hence atmospheric neutrinos with very long > 10000 Km baselines ang 1-2 GeV energies are suited for observing it.
- An exceptional precision of better than 2% in $|\Delta_{31}|$ is required to achieve this goal. This may be possible in superbeam/wide-band LBL experiments like T2K and BNL-DUSEL.
- With $\sigma(\Delta_{31}) = \Delta_{21}/2$, we find a $> 2\sigma$ sensitivity to be achievable by INO (1 Mt yr) for $\theta_{13} = 0$ with fairly realistic assumptions of detector resolution and systematic uncertainties.