Measuring $\theta_{13}$

- Reactor and LBL experiments
  - Determining sign($\Delta m^2_{31}$)
- LBL (appearance) experiments
- Reactor exp. will help in resolving degeneracies

Can atmospheric neutrinos help?

YES!
Earth Effect

Constant density ! MSW effect

\[ \sin^2 \theta_m = \frac{\Delta m^2 \sin \theta}{\sqrt{(2E V_e - \Delta m^2 \cos \theta)^2 + (\Delta m^2 \sin \theta)^2}} \]

Thus, \[ P(v_e \rightarrow v_\mu)^{\text{MSW}} = s^2_{23} \sin^2 \left( \frac{\Delta m_{31}^2 \frac{L}{4E_{\text{res}}} \sin 2 \theta_{13}}{\pi} \right) \]

\[ (L_m)_{\text{Res}} = \left( \frac{\pi}{\sqrt{2G_F N_e \tan 2 \theta_{13}}} \right)(2k - 1) \quad k = 0,1,2,\ldots \]

\[ L_{\text{min}} = \frac{(L_m)_{\text{Res}}}{\sqrt{2\cos 2 \theta_{13}}} \sim 8000 \text{ km} \]

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Water-Cherenkov detectors

- No discrimination of the charge of the produced lepton in an event-by-event basis.
- Measurement of $N_\mu$ and $N_e$ events.
- Could we then distinguish the type of mass spectrum with these detectors?
Water-Cherenkov detectors

- $N \sim \frac{2}{3} N(\nu\text{-like events}) + \frac{1}{3} N(\bar{\nu}\text{-like events})$
- Normal (inverted) hierarchy: the effect is enhanced for (anti)neutrinos
- Effect larger for normal hierarchy
- Effect larger for larger $\sin^2 \theta_{23}$
- Negligible for sub-GeV ($r' < 2$ and non-resonant)
- Multi-GeV sample: Increase of $N_e$ and decrease of $N_\mu$! Should consider $N_\mu/N_e$

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$N_\mu / N_e$

$E_\nu = [2, 10] \text{ GeV}$

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$N_\mu / N_e$

$E_\nu = [2, 10] \text{ GeV}$

$\cos \theta^n = [0.4, 1.0]$}

$\sin^2 \theta_{23} = 0.36$

$\sin^2 \theta_{23} = 0.50$

$\sin^2 \theta_{23} = 0.64$

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Magnetized detectors

- Discrimination of the charge of the produced lepton.
- Measurement of $N_\mu^-$ and $N_\mu^+$: distinction between neutrinos and antineutrinos
- Neutrino energy determination
- CPT-matter induced asymmetry is measurable
Mantle interaction

\[ A_{\text{CPT}} = \frac{P(\nu_\mu \rightarrow \nu_\mu) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)}{P(\nu_\mu \rightarrow \nu_\mu) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)} \]

Different $\theta_{13}$

Neutrino Energy [GeV]
Core-mantle

Mantle

SPR and S. T. Petcov, in preparation
Conclusions

- If $\sin^2 \theta_{13} \neq 0$, Earth matter effects can show up in atmospheric neutrinos.
- Present in multi-GeV neutrinos crossing deeply the mantle or the mantle and the core, and are larger for Normal Hierarchy, larger $\sin^2 \theta_{13}$ and larger $\sin^2 \theta_{23}$.
- Observable in water-Cherenkov ($N_\mu/N_e$) and magnetized detectors ($N_\mu^- - N_\mu^+$ asymmetry).
- Constrains on $\theta_{13}$ and determination of $\nu$-mass hierarchy could be possible with atmospheric neutrinos.
$|U_{e3}|^2$ and $\beta$ Decay Expts.

\[ m^2(\nu_e) = \sum_{i=1}^{3} |U_{ei}|^2 \cdot m_i^2 \]

\[ m_{ee} < m(\nu_e) < \frac{m_{ee}}{||\cos 2\theta_\odot(1 - |U_{e3}|^2) - |U_{e3}|^2||}, \quad (10) \]

The $\nu_e$ mixing parameters in (10) can be deduced from the results of oscillation experiments using solar neutrinos (solar mixing angle $\theta_\odot$) and reactor antineutrinos ($|U_{e3}|^2$).

![Graph of $sin^2(2\theta)$ vs. $\Delta m^2 / 4\pi^2$ showing bounds and measurements.](image)