Future neutrino oscillation experiments

parameters currently known: • $\theta_{12}, \theta_{13}, \theta_{23}$

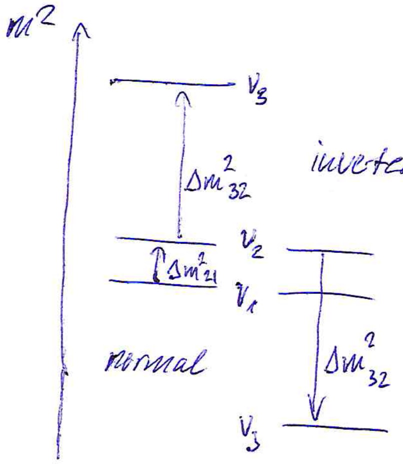
• Δm^2_{21} (with sign), absolute value of $|\Delta m^2_{32}|$

to be determined: • sign of Δm^2_{32} → mass ordering
(in 3-flavor picture)

• δ_{CP}

• octant of θ_{23} ($\gtrless 45°$)?

Neutrino mass hierarchy (MH)



Experimental approaches:

1) Long-baseline beam experiment

idea: • run in ν and $\bar{\nu}$ mode

• matter effects for $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ depend on MH

$$P_{\mu e(\bar{\mu}\bar{e})} \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{B_\mp}\right)^2 \sin^2\left(\frac{B_\mp L}{2}\right) \quad [1]$$

$$+ J \frac{\Delta_{12}}{A} \frac{\Delta_{13}}{B_\mp} \sin\left(\frac{AL}{2}\right) \sin\left(\frac{B_\mp L}{2}\right) \cos\left(\mp\delta - \frac{\Delta_{13} L}{2}\right) \quad [2]$$

with $\Delta_{ij} = \frac{\Delta m^2_{ij}}{2E}$, $A = \sqrt{2} G_F N_e$, $B_\mp = |A \mp \Delta_{13}|$

$J = \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$

Impact of matter effects:

- related to A; N_e is electron density (difference in crust, mantle, core)
- size of matter effects:

related to
$$\frac{\Delta_{13}}{B_\pm} = \frac{\Delta_{13}}{|A \pm \Delta_{13}|} \approx \frac{1}{\left|\frac{2\sqrt{2}G_F N_e E}{\Delta m^2_{13}} \pm 1\right|} = \begin{cases} 1 & \text{for } N_e = 0 \\ \sim(1 \mp 0.15) & \text{for } E \sim 2\,\text{GeV} \end{cases}$$

→ amplitude scales with E_ν

→ optimum baseline $\frac{L_{osc}}{2}$ scales with E_ν (1st osc. maximum), e.g. ~1000km for $E_\nu = 2$ GeV

→ longer baseline means larger effect!

- sign of term [2] for $\nu/\bar{\nu}$ depends on sign of $\Delta_{13} \equiv$ MH

Experiment: DUNE

new accelerator beam at FNAL → large LAr detector at Homestake

baseline: 1300km

Source: $\overset{(-)}{\nu}_\mu$ beam, P=1.2MW, wide-band spectrum, maximum at 3GeV

Far Detector: LAr TPC, 40kt mass

→ better vertex reconstruction than WCDs for DIS events

→ energy resolution, background discrimination

Signal: $\overset{(-)}{\nu}_e$ appearance, difference in $\nu \leftrightarrow \bar{\nu}$ amplitudes

backgrounds:
- ν_e beam contamination
- NCν, CC$\nu_{\mu,\tau}$ misidentified

Expected sensitivity:

- MH: 2-4σ for 300 kt MW yrs (depends on δ_{CP}, MH)
- CP: up to 5σ depending on true value of δ_{CP}

most important factors: baseline, background discrimination

2) Long-baseline atmospheric ν experiment

idea: • atmospheric ν's provide source with broad spectrum & many baselines
• matter effects observable in 1-10 GeV range
→ look for $\nu \leftrightarrow \bar{\nu}$ difference

Source: broad spectrum, but much lower intensity cf. beam
→ larger detector: ~1Mt

Oscillations: maximum baseline ~13000km, depends on Θ
→ 1^{st} oscillation maximum for 26 GeV
→ oscillation patterns $P_{\mu\mu}(E_\nu, \theta)$, $P_{\mu e}(E_\nu, \theta)$

detectors: PINGU, (ORCA)

• instrumented natural ice (water) volume: ~1Mt
• dense instrumentation for 1-2 GeV threshold
• PINGU: 20 additional strings in DeepCore array

Signal: • overlay of $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations
• both ν_μ and ν_e-channel
• problem: $\nu/\bar{\nu}$ cannot be separated,
but $\sigma(\nu) \approx 2\sigma(\bar{\nu})$
→ effective osc. pattern different for NH and IH

Expected sensitivity:

• MH: 2-6σ after 5 yrs

most important factors: event reconstruction capabilities (θ, E)
true value of θ_{23}, MH

3) Medium-baseline reactor neutrino experiments

idea: use small difference in Δm^2_{31} and Δm^2_{32} to study interference effect

oscillation probability: $P(\bar{\nu}_e \to \bar{\nu}_e)$ $\bar{\nu}_e$ disappearance

$$P_{\bar{e}\bar{e}} = 1 - P_{12} - P_{13} - P_{23} = 1 - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) \quad \leftarrow \text{solar osc.}$$

$$- \cos^2\theta_{12} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

$$- \sin^2\theta_{12} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

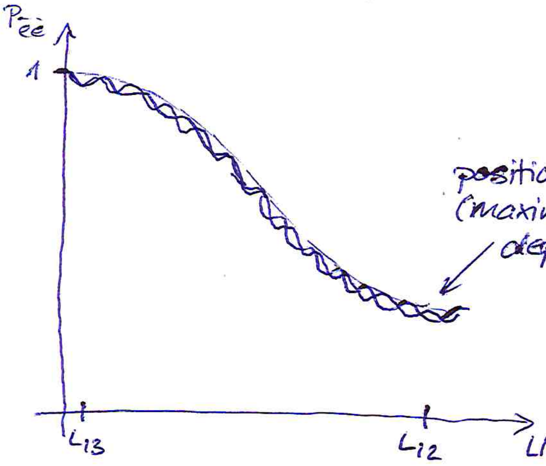
} for short distances, simplified to $\sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$

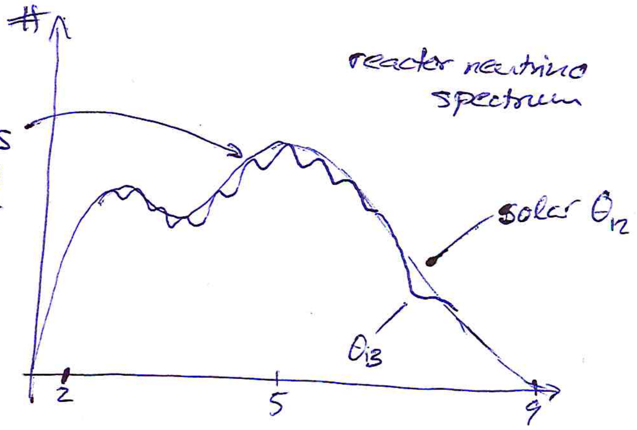
P_{31}, P_{32}: – different amplitudes: $A_{31} = 0.067$, $A_{32} = 0.028$

– different phases

→ maximum phase difference for

$$\left| \frac{\Delta m^2_{31} L}{4E} - \frac{\Delta m^2_{32} L}{4E} \right| = \frac{\Delta m^2_{21} L}{4E} = \frac{\pi}{2}, \text{ i.e. at } 1^{st} \text{ solar osc. max.}$$





spectral maximum (after θ_{12} oscillations) at 4–5 MeV

→ optimum baseline from reactors: 55 km

Experiments: JUNO, RENO 50

- layout: 2 reactor complexes (6 cores each) + 20 kt liquid-scintillator detector
  → very similar baselines ($\Delta \lesssim 500$ m) to avoid interference
- excellent energy resolution: $\lesssim 3\%$ at 1 MeV $\hat{=}$ 1,100 pe/MeV
  → to resolve spectral wiggles
- good knowledge/calibration of energy scale
  → position of wiggles determines MH

Expected sensitivity:

- MH: JUNO alone $\gtrsim 3\sigma$ after 5 yrs
  $\gtrsim 4\sigma$ including inputs on $\Delta m^2_{\mu\mu}$

most important factors: energy resolution & linearity