Neutrino oscillation experiments

Oscillation parameters

- Three-flavor mixing: PMNS matrix with mixing angles

$$\underbrace{\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}}_{\text{flavor states}} = \underbrace{\begin{pmatrix}1&\cdot&\cdot\\ \cdot&c_{23}&s_{23}\\ \cdot&-s_{23}&c_{23}\end{pmatrix}}_{\substack{\text{atmospheric mixing}\\ \Theta_{23}\simeq 45^\circ}} \underbrace{\begin{pmatrix}c_{13}&\cdot&s_{13}e^{-i\delta}\\ \cdot&1&\cdot\\ -s_{13}e^{i\delta}&\cdot&c_{13}\end{pmatrix}}_{\substack{\text{reactor mixing}\\ \text{\& CP phase}\\ \theta_{13}\approx 9^\circ,\ \delta=?}} \underbrace{\begin{pmatrix}c_{12}&s_{12}&\cdot\\ -s_{12}&c_{12}&\cdot\\ \cdot&\cdot&1\end{pmatrix}}_{\substack{\text{solar mixing}\\ \Theta_{12}\simeq 33^\circ}} \underbrace{\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}}_{\text{mass states}}$$

$\longrightarrow$ oscillation amplitudes!

- Mass-squared differences

solar $\delta m^2 = \Delta m^2_{21} \approx +7.5\cdot 10^{-5}\,\text{eV}^2$

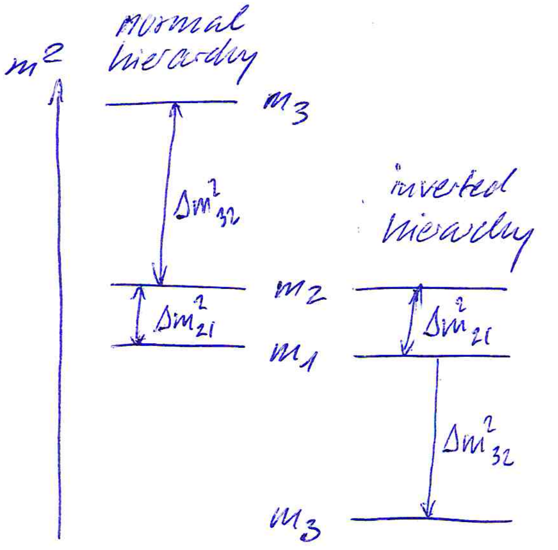
atmospheric $\Delta m^2 = |\Delta m^2_{32}| = 2.4\cdot 10^{-3}\,\text{eV}^2$

for many purposes:

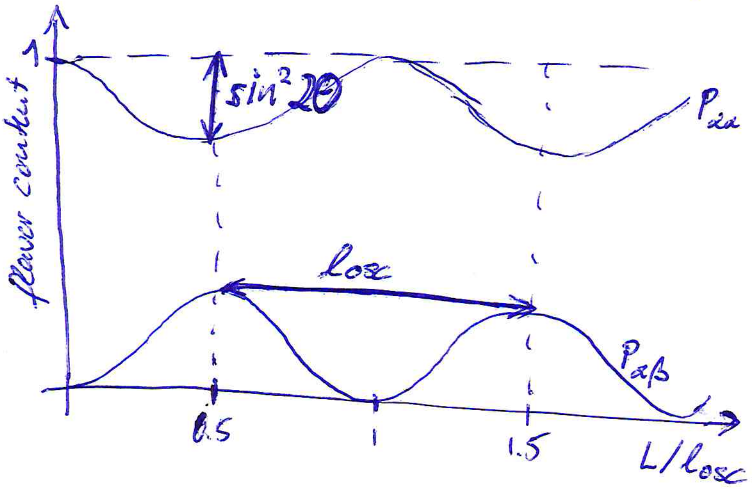
$$\Delta m^2 \simeq |\Delta m^2_{32}| \simeq |\Delta m^2_{31}|$$

because $|\Delta m^2_{32}| \gg \Delta m^2_{21}$

$\longrightarrow$ oscillation lengths!



Simplification: Two-flavor mixing



$$P_{\alpha\alpha} = 1 - \underbrace{\sin^2 2\Theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)}_{P_{\alpha\beta}}$$

oscillation amplitude:

$\sin^2 2\Theta \in [0..1]$

$\rightarrow$ maximum for $\Theta = 45°$

oscillation length:

$$l_{osc} = 4\pi\hbar c \frac{E}{\Delta m^2}$$

$$\approx 2.48\,\text{m}\,\frac{E/\text{MeV}}{\Delta m^2/\text{eV}^2}$$

often usable, e.g. short-baseline (~1km) from reactors (~4MeV)
→ only $\sin^2$ matters and $\sin^2 2\theta_{13}$
but also long-baseline reactors (~120km)
because $\sin^2 2\theta_{12} \gg \sin^2 2\theta_{13}$

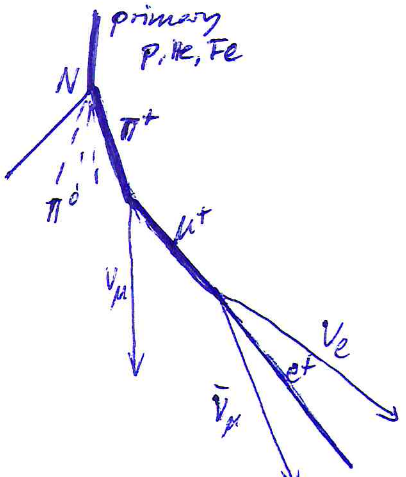
Two basic approaches to oscillation search:

- Appearance experiments:
  source: $\nu_\alpha \longrightarrow \nu_\beta$: detector
  } beam experiments (SNO)

- Disappearance experiments:
  Source: $\nu_\alpha \longrightarrow \nu_\alpha$: detector
  } solar ν's, reactor ν's, atmospheric ν's, many beams

1) Atmospheric mixing

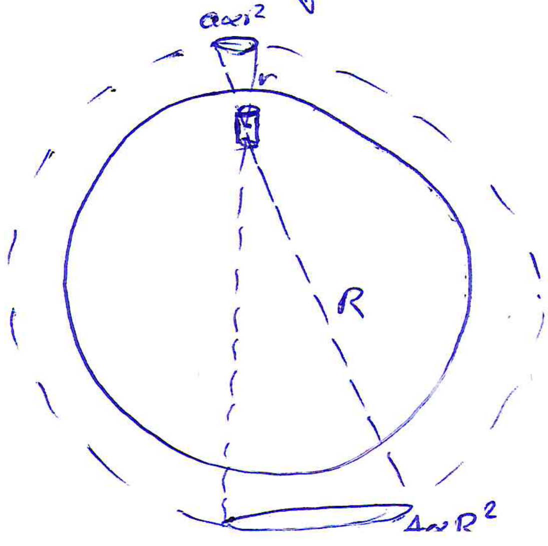
ν Source: Cosmic ray interactions in atmosphere



Decay of charged mesons: $\pi^\pm, K^\pm$

e.g. $\pi^+ \longrightarrow \mu^+ \nu_\mu$
$\quad\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$

$K^- \longrightarrow \mu^- \bar{\nu}_\mu$
$\quad\hookrightarrow e^- \bar{\nu}_e \nu_\mu$

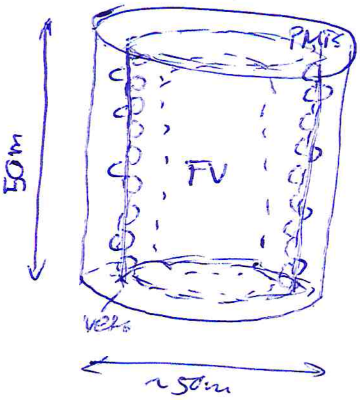


- flavor ratio at low energies (all μ's decay)

$$R_{th} \approx 2 = \frac{n_{\nu_\mu} + n_{\bar{\nu}_\mu}}{n_{\nu_e} + n_{\bar{\nu}_e}}$$

- no angular dependence of flux (in 1st approximation)
- spectral maximum ~2GeV

Experiment: Super-Kamiokande $\rightarrow \theta_{23}, \Delta m^2_{23}$

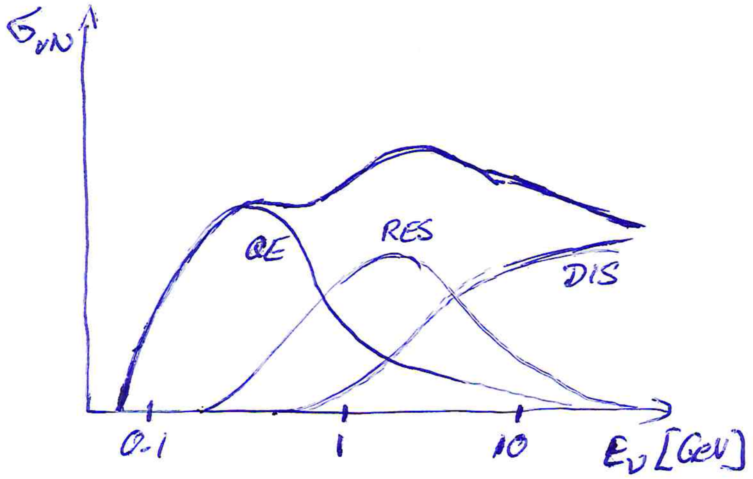


- Water-Čerenkov Detector
- total volume: 50kt
  → fiducial volume: ~22kt
- PMTs for light detection
  11,200 PMTs (20" diameter)
  → 40% coverage
  +2000 PMTs for external veto

Oscillation search: ν_μ disappearance

$$P_{\mu\mu} = 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right) \quad (\nu_\mu \rightarrow \nu_\tau)$$

Neutrino interaction types @ GeV energies



QE: quasi-elastic scattering

e.g. $\bar{\nu}_\mu + X \xrightarrow{CC} X' + \mu^+$ ($X=p$, $X'=n$ etc.)

RES: resonant inelastic scattering
↳ pion production

CC: $\nu_\mu + p \longrightarrow \mu^- + \Delta^{++}$
$\hookrightarrow p + \pi^+$

NC: $\nu + p \longrightarrow \nu + \Delta^+$
$\hookrightarrow p + \pi^0 \searrow \gamma\gamma$

DIS: deep inelastic scattering
→ multi-pion production

Neutrino detection: Charged leptons in final state

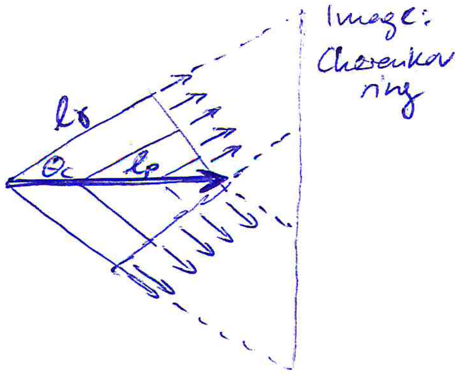
Chesenkov effect

- Opening angle:

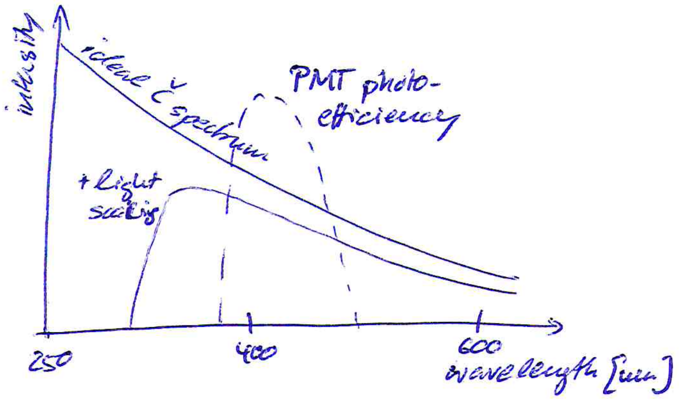
$$\cos\Theta_c = \frac{l_\gamma}{l_p} = \frac{\frac{c}{n}t}{\beta c t} = \frac{1}{n\beta}$$

for high energies: $\beta \to 1$: $\cos\Theta_c \to \frac{1}{n}$

in water: $n = 1.33 \to \Theta_c = 42°$



- light / photoelectron yield:



- total light yield ~ 300ph/MeV
- spectral maximum in water: 330nm
- PMT quantum efficiency ~20%
- optical coverage ~40%

→ photoelectron yield: ~ 6pe/MeV

↓ detection threshold!

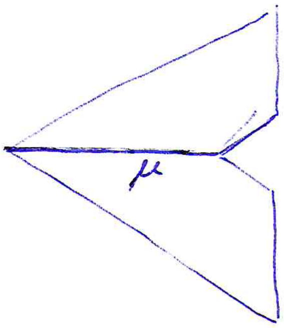
systematic contributions $\frac{\Delta E}{E} = 10\text{–}30\%$ ⊕ statistical energy resolution:

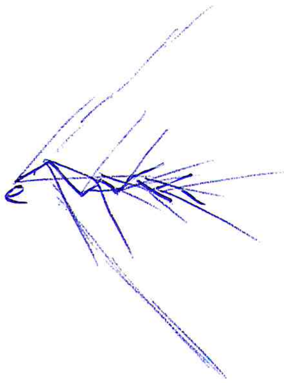
$E \propto N_{pe}$; $\Delta E \propto \sqrt{N_{pe}} \implies \frac{\Delta E}{E} \propto \frac{1}{\sqrt{N_{pe}}}$

- flavor identification:

$\nu_\mu \to \mu$: straight, long track → sharp ring

$\nu_e \to e$: scattering, em-showers → fuzzy ring





Event categories

- single-ring vs. multi-ring

  $\downarrow$ elastic scattering $\qquad$ $\downarrow$ RES+DIS

- event energy: sub-GeV vs. multi-GeV
- containment: fully-contained vs. partially-contained tracks

Sub-GeV region: $R_{th} = 2 = \frac{n_{\nu_\mu}}{n_{\nu_e}}$

observation: $\frac{R_{exp}}{R_{th}} = 0.63 \pm 0.03_{stat} \pm 0.05_{syst}$

multi-GeV region:
- clear correlation between f.s. lepton and neutrino direction
- oscillation baseline depends on neutrino direction

  minimum: from above ($\cos\Theta = 1$) ~20km

  maximum: from below ($\cos\Theta = -1$) ~13000 km

→ asymmetry in ν_μ events: $A = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$

$A_{th} = 0$;

$A_{exp} = -0.296 \pm 0.048_{stat} \pm 0.010_{syst}$

→ disappearance oscillations of $\nu_\mu \rightarrow ?$

expected oscillation lengths @ 5 GeV:

$l_{osc}(\nu_\mu \rightarrow \nu_\tau, \Delta m^2_{32}) \approx 5000 km$

$l_{osc}(\nu_\mu \rightarrow \nu_e, \Delta m^2_{21}) \approx 180{,}000 km$

⊕ no disappearance observed for ν_e

→ oscillations: $\nu_\mu \rightarrow \nu_\tau$

(could have been explained also by ν_μ decay)

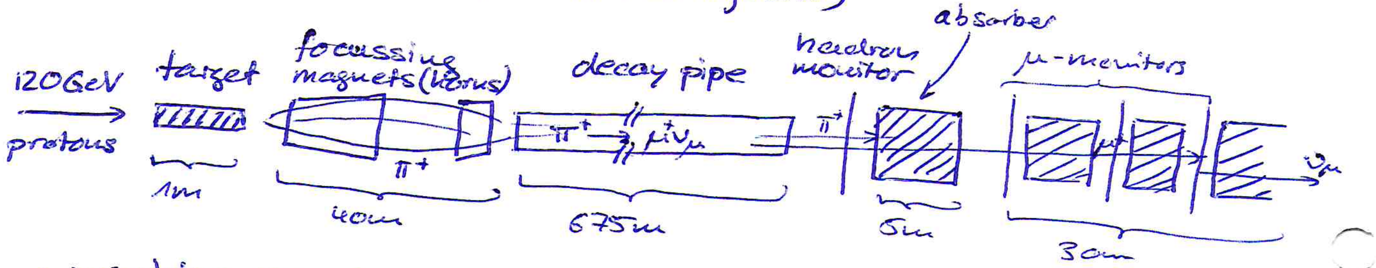
MINOS Experiment → $\Delta m^2_{32}, \theta_{23}$

- Long-baseline neutrino beam experiment

$$\underbrace{\text{Long-baseline}}_{735\,\text{km}}\ \underbrace{\text{neutrino}}_{\nu_\mu \text{ or } \bar{\nu}_\mu}\ \underbrace{\text{beam}}_{\text{NuMI beam (Fermilab)}}$$

- Disappearance search: $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$

Beam source: NuMI (ν at main injector)



- neutrino spectrum: peaked at 3 geV
- baseline to detector: 735km

→ maximum sensitivity for

$$\Delta m^2 \simeq 2.48\,m \frac{E[\text{MeV}]}{\underbrace{l_{osc}/2\,[m]}_{1^{st}\text{ maximum of oscillation}}} \approx 5\cdot 10^{-3}\,\text{eV}^2$$

- possibility to select mainly ν_μ or $\bar{\nu}_\mu$ by switching polarity of focussing horus

e.g. neutrino mode:

$$\pi^+ \to \mu^+ \nu_\mu$$
$$\text{few\%} \hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$

beam composition

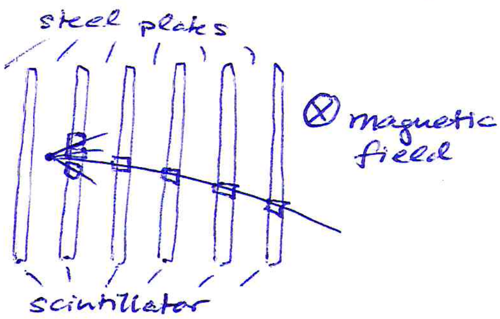
92% ν_μ

7% $\bar{\nu}_\mu$ ← π^- decays

1% $\overset{(-)}{\nu}_e$ ← μ^+ decays

Neutrino detectors:

- tracking / sampling calorimeter: alternating steel & scintillator
- magnetized: μ^+/μ^- separation
- two "functionally identical" detectors → reduce systematics



Near detector: $m = 1\,\text{kt}$, $d = 1\,\text{km}$ from target
→ beam spectrum before oscillations

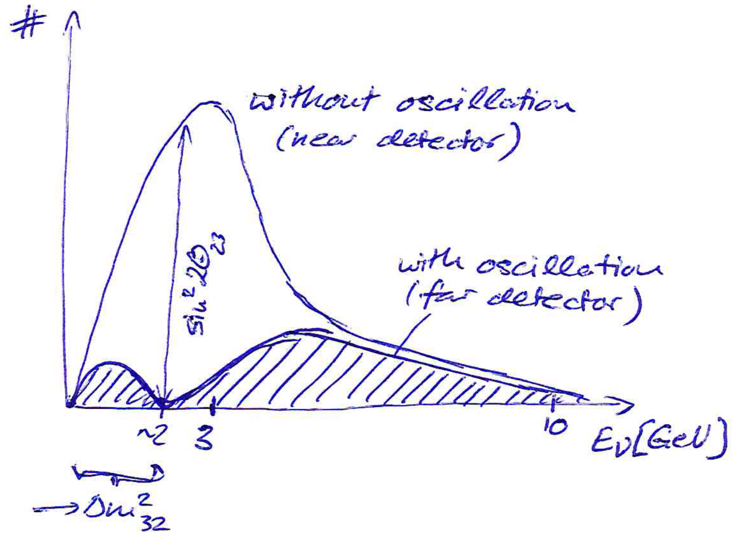
Far detector: $m = 5.4\,\text{kt}$, $d = 735\,\text{km}$ → oscillation signal

Neutrino interaction types → Discrimination

• $CC\overset{(-)}{\nu_\mu}$: $\nu_\mu + N \to \mu + X$	μ track, deflected by B-field
• NC : $\nu + N \to \nu + X$	short, diffuse shower
• $CC\overset{(-)}{\nu_e}$: $\nu_e + N \to e + X$	compact shower with em core

Oscillation sensitivity:

- from comparison of spectral shapes + rate



- position of oscillation maximum
  → accurate measurement of Δm^2 (baseline known!)

- oscillation amplitude close to maximal

$$\sin^2 2\theta_{23} \approx 1$$

→ θ_{23} either smaller or larger than 45°