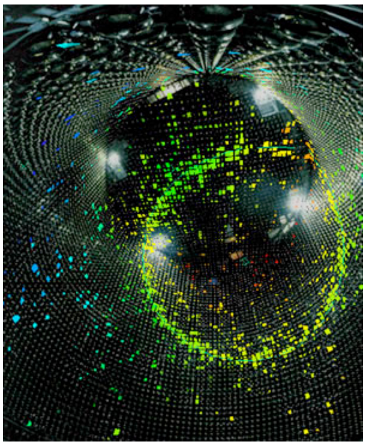
Particle Physics

Dr Victoria Martin, Spring Semester 2012

Lecture 16: Neutrinos



Shock-wave photon ring produced an electron with $v > c_{(\mathrm{water})}$ produced by $\nu_e + n \to p + e^-$

★Neutrinos
★Neutrinos mixing
★Solar neutrinos
★Atmospheric neutrinos
★PNMS matrix

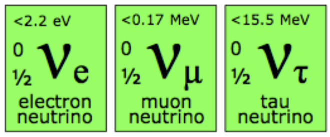
The three neutrino mass eigenstates: ν_e is strawberry, ν_μ is chocolate, ν_τ is vanilla

From Tuesday: Summary

- The *CP* symmetry describes the difference between matter and anti-matter - almost a good symmetry in the weak interactions.
- Small amounts of *CP* violation observed in K^0 B^0 D^0 $B_s{}^0$ through decays and mixing.
- Three types of *CP* violation:
  1. Direct *CP* violation in decay amplitudes
  2. *CP* violation in neutral meson mixing
  3. Indirect *CP* violation due to interference of mixing and decay.
- *CP* violation is accommodated in the Standard Model through a complex phase in the CKM matrix.
- The unitarity triangle of the CKM matrix is used to understand observation of the *CP* violation, and see if measurements are consistent.
- The amount of *CP* observed in the Standard Model not enough to explain the matter – anti-matter asymmetry of the universe.

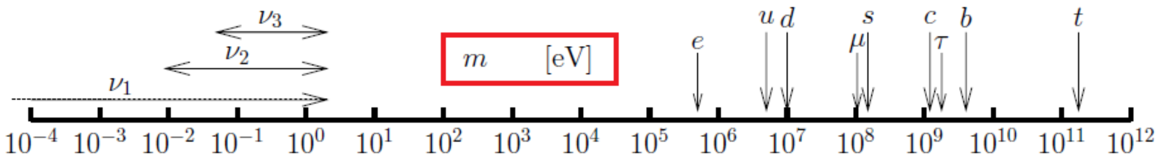
Introduction: Neutrinos

- Neutrinos are least understood Standard Model fermions.
- Zero electric charge and zero colour charge ⇒ only interactions are due to the weak force and gravity

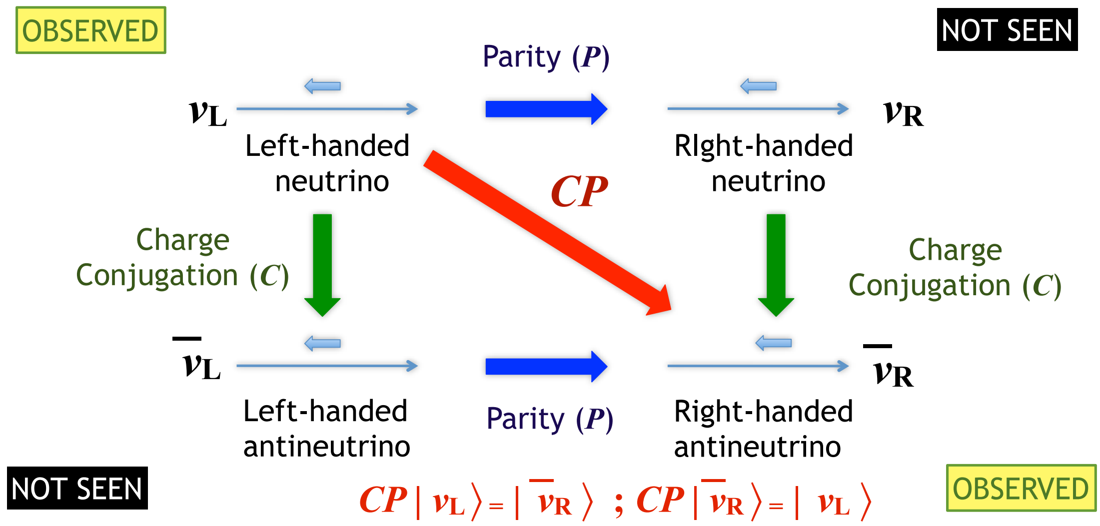


- Known to be exactly three neutrinos with $m < m_Z/2$
- Until ~1999, the prevailing belief was that neutrinos were massless.
- We now know they have a very small mass, but we don't know values for the absolute masses.
- Mass eigenstates of the neutrinos are not identical to the flavour eigenstates.
- Flavour eigenstates are ν_e, ν_μ, ν_τ , interact with the W and Z boson.
- Mass eigenstates are ν_1, ν_2, ν_3, propagate through matter / vacuum.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



Neutrino States



- Only left-handed neutrinos and right-handed antineutrinos are observed.
- Descriptions of mass in quantum field theory requires both left-handed and right-handed components: would need ν_R and $\bar{\nu}_L$ states to describe mass.
- Two (unproved) speculations
  - ➡ ν_R and $\bar{\nu}_L$ exist but are very heavy m(ν_R) ~ 10^{15} GeV
  - ➡ Neutrinos are their own antiparticles: $\nu_R = \bar{\nu}_R$, $\nu_L = \bar{\nu}_L$

Two Neutrino Mixing

- Let's start with the case of two neutrino mixing. Write the mixing matrix in terms of a mixing angle θ_{12} (to reflect the unitarity of the matrix):

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & -\sin\theta_{12} \\ \sin\theta_{12} & \cos\theta_{12} \end{pmatrix} = \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

- The time evolution of the two mass eigenstates is:

$$\begin{aligned} \nu_1(t) = \nu_1(0)e^{-iE_1 t} &= \quad [\nu_e(0)\cos\theta_{12} + \nu_\mu(0)\sin\theta_{12}] \quad e^{-iE_1 t} \\ \nu_2(t) = \nu_2(0)e^{-iE_2 t} &= \quad [-\nu_e(0)\sin\theta_{12} + \nu_\mu(0)\cos\theta_{12}] \quad e^{-iE_2 t} \end{aligned}$$

- For a initial state of pure ν_e, $\nu_e(0)=1$, time evolution:

$$\begin{aligned} \nu_\mu(t) &= (\cos\theta_{12}\sin\theta_{12})(e^{-iE_1 t} - e^{-iE_2 t}) \\ \nu_e(t) &= (1 - \cos\theta_{12}\sin\theta_{12})(e^{-iE_1 t} - e^{-iE_2 t}) \end{aligned}$$

- Probability for an ν_e to turn into ν_μ: $P(\nu_e \to \nu_\mu) = |\nu_\mu(t)|^2$

$$\begin{aligned} P(\nu_e \to \nu_\mu) &= (\cos\theta_{12}\sin\theta_{12})^2(e^{iE_1 t} - e^{iE_2 t})(e^{-iE_1 t} - e^{-iE_2 t}) \\ &= \left[\sin(2\theta_{12})\sin\left(\frac{E_2 - E_1}{2}t\right)\right]^2 \end{aligned}$$

Description of Oscillations

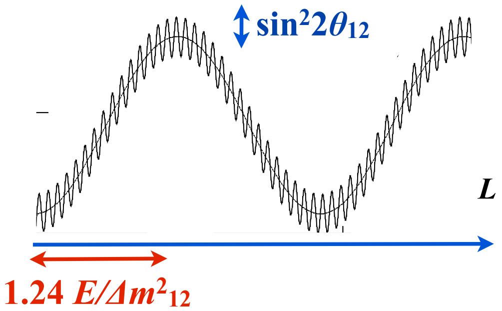
- Neutrinos are highly relativistic, travelling very close to c.
- Write the neutrino energy as: $E^2 = \vec{p}^2 + m^2 \Rightarrow E \sim |\vec{p}| + m^2/2|\vec{p}|$

$$E_1 - E_2 \sim (m_1^2 - m_2^2)/2E \equiv \Delta m_{12}^2/2E$$

$$P(\nu_e \to \nu_\mu) = \sin^2(2\theta_{12})\,\sin^2\left(\frac{E_2 - E_1}{2}t\right) = \sin^2(2\theta_{12})\,\sin^2\left(\frac{\Delta m_{12}^2 L}{4E}\right)$$

- Where $L = c\,t$ is the distance the neutrino has travelled.
- Useful to express with in of Δm in eV, L in metres and E in MeV:

$$P(\nu_e \to \nu_\mu) = \sin^2(2\theta_{12})\,\sin^2\left(\frac{1.27\Delta m_{12}^2 L}{E}\right)$$



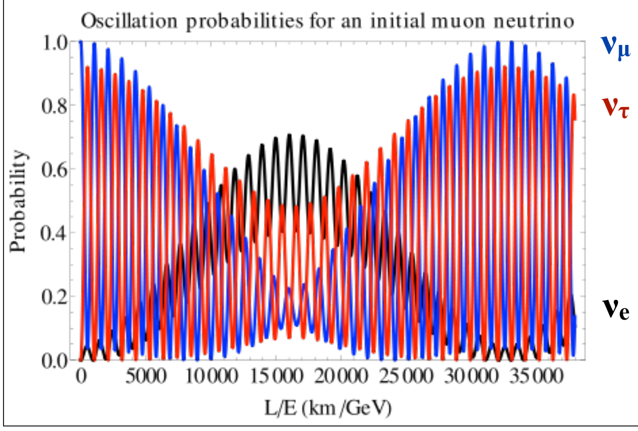
- After a distance $L \sim 1.24\ E/\Delta m^2_{12}$ second term becomes maximal.
- Maximal mixing between ν_e and ν_μ occurs if mixing angle $\theta_{12}=\pi/4$.
- The parameters Δm^2 and $\sin\theta_{12}$ must be determined experimentally.

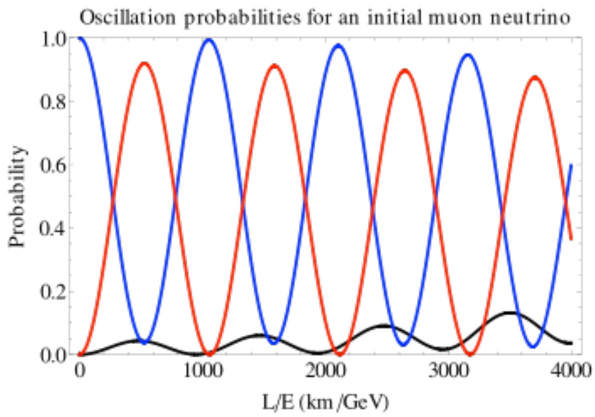
Three Flavour Oscillations

- Described by the Pontecorvo-Maki-Nakagawa-Sakata Matrix

$$U_{\text{PMNS}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- PMNS Matrix has a complex phase: ***CP*** violation possible in neutrinos, not yet observed: will require lots more data!
- Same phenomena as for two neutrino mixing. Oscillations can be used to determine the mixing angles θ and Δm^2 between the three states.





Neutrino Experiments

- Neutrinos cross sections are very small.

- Need source of huge neutrino flux:
  - ➡Solar Neutrinos: ν_e produced in the sun
  - ➡Atmospheric Neutrinos: ν_e, ν_μ from decay of cosmic rays
  - ➡Reactor Neutrinos: $\bar{\nu}_e$ from fusion reactions
  - ➡Accelerator Neutrinos: ν_μ $\bar{\nu}_\mu$ from $\pi^\pm$ decay

- Need large amount of matter to increase chances of an interaction. Different detection techniques are sensitive to different reactions. Main techniques are:
  - ***W***-boson interactions (charged current)

$$\nu_e + n \to p + e^- \qquad \bar{\nu}_e + p \to n + e^+$$
$$\nu_\mu + n \to p + \mu^- \qquad \bar{\nu}_\tau + p \to n + \tau^+$$
$$\nu_\tau + n \to p + \tau^- \qquad \bar{\nu}_\mu + p \to n + \mu^+$$

  - ***Z***-boson interactions (elastic scattering):

$$\nu_e + e^- \to \nu_e + e^- \qquad \nu_\mu + e^- \to \nu_\mu + e^- \qquad \nu_\tau + e^- \to \nu_\tau + e^-$$

Solar Neutrinos

Standard Solar Model suggests:

Many different nuclear fusion processes in the sun produce ν_e.

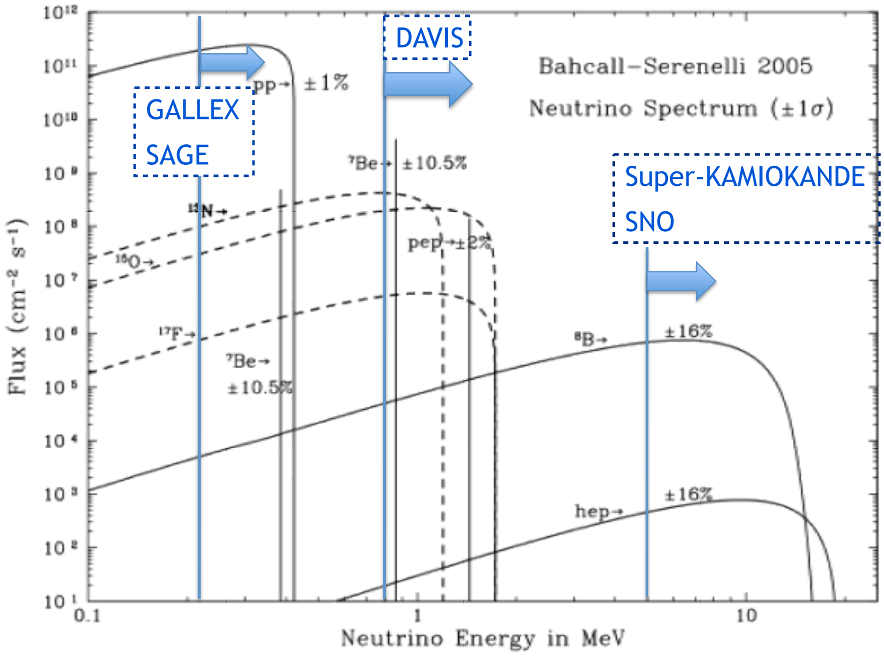
Large flux from:

$p + p \rightarrow d + e^+ + \nu_e$

$E(\nu) < 400$ keV

Processes with Be and B give small flux with higher energy

$E(\nu) < 15$ MeV



GALLEX, SAGE, DAVIS, Super-KAMIOKANDE and SNO experiments sensitive to different energies of ν_e

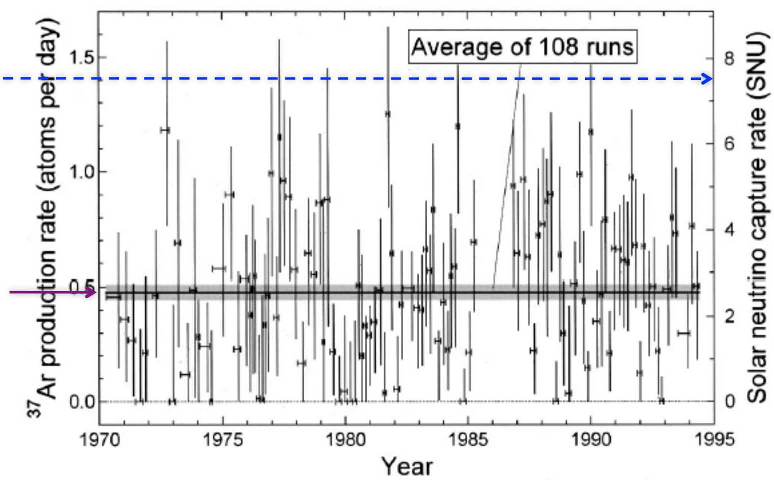
The Solar Neutrino Deficit

- Davis experiment (1971-1994) $\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$
- 615 Tonnes of cleaning fluid in a mine in South Dakota

Solar Neutrino Unit = $10^6 cm^{-2}s^{-1}$

Standard Solar Model (SSM)

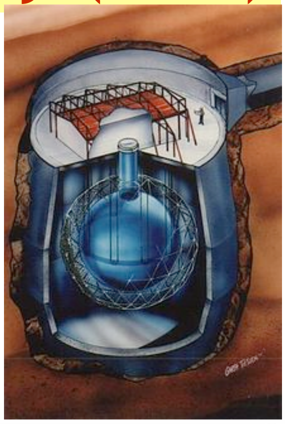
0.5 Argon atoms per day were found by chemical extraction!



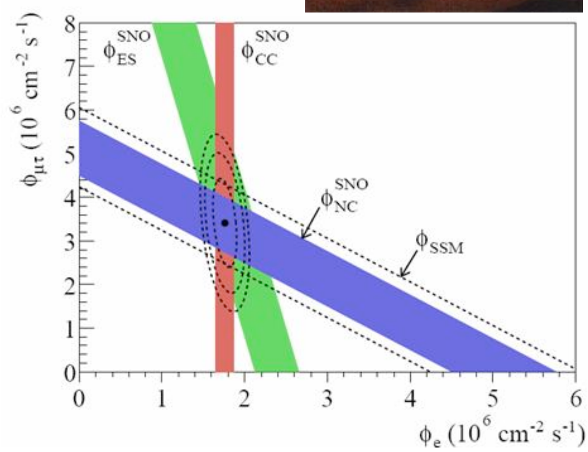
Observed only 0.33 ± 0.06 of expected rate

- Super-Kamiokande (Japan), Gallex (Italy), Sage(Russia) observed similar deficit in ν_e with respect to Standard Solar Model prediction.

Sudbury Neutrino Observatory (SNO)



- Observes the total solar neutrino flux: not just ν_e
- **10,000** tonnes of heavy water $\mathbf{D_20}$
  - $\nu_e + d \rightarrow p + p + e^-$ (CC: charged current)
  - $\nu_x + d \rightarrow n + p + \nu_x$ (NC: neutral current)
  - $\nu_x + e^- \rightarrow \nu_x + e^-$ (ES: elastic scattering)



- Total solar neutrino flux consistent with Standard Solar Model.
- Implies 67% of ν_e change flavour between the sun and arriving in SNO (to either ν_μ or ν_τ)

Neutrino Oscillations in Matter

- Mikheyev-Smirnov-Wolfenstein (MSW) effect
- Neutrino oscillations in matter modified where there is high density of electrons due to weak interactions with potential $\mathbf{G_F N_e}$, where $\mathbf{N_e}$ is the number of electrons. ($\mathbf{N_e}$ depends on solar radius.)

➡Inside the sun the neutrinos propagate in a different eigenstate than in a vacuum (energy dependent effect).

➡The mixing angle between ν_e and ν_μ is modified:

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta_{12}}{(\cos 2\theta_{12} - \alpha)^2 + \sin^2 2\theta_{12}} \qquad \alpha = G_F N_e E / \Delta m_{12}^2$$

➡Suppresses the number of ν_e leaving the sun with $\mathbf{E \sim 2MeV}$

- Including the MSW effect gives a better fit to the data for solar neutrinos.

Atmospheric Neutrinos

- Primary cosmic rays (protons) interact in upper atmosphere to produce pions which then decay into muons and neutrinos:

$$\pi^+ \to \mu^+ \nu_\mu \quad \mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$

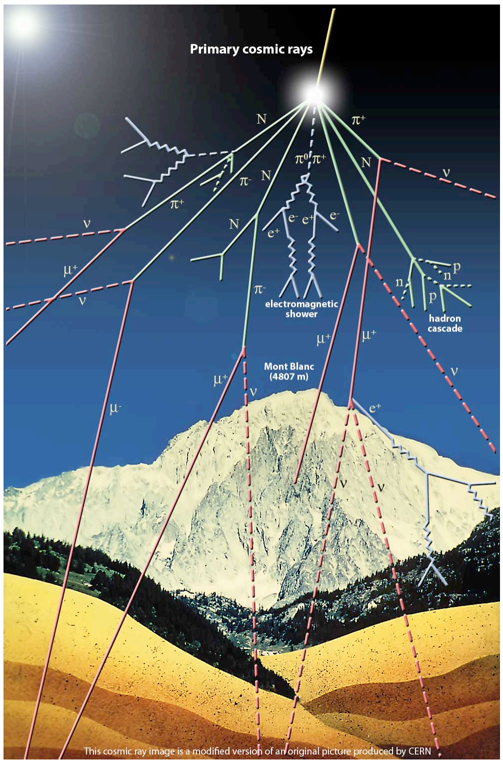
$$\pi^- \to \mu^- \bar{\nu}_\mu \quad \mu^- \to e^- \bar{\nu}_e \nu_\mu$$

- Ratio of neutrino flavours is $\nu_\mu : \bar{\nu}_\mu : \nu_e : \bar{\nu}_e = 2 : 2 : 1 : 1$
- Can detect atmospheric neutrinos and measure their direction and flavour using charged current interactions (CC):

$$\nu_e + n \to p + e^- \qquad \nu_\mu + n \to p + \mu^-$$

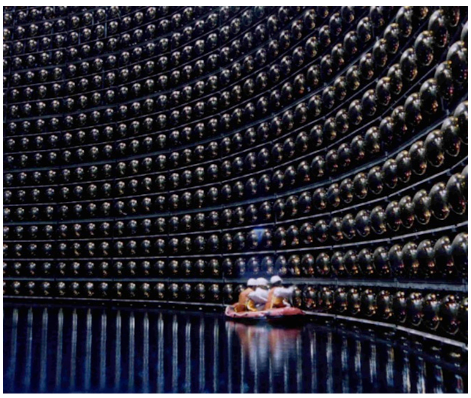
$$\nu_e + p \to n + e^+ \qquad \nu_\mu + p \to n + \mu^+$$

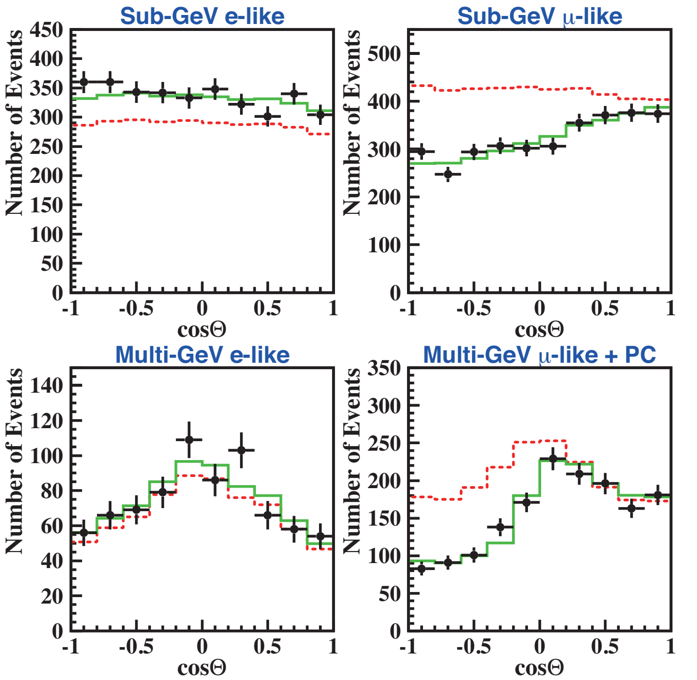
- Upward going ν have passed through the Earth with $L \sim 13000$ km
- Downward going ν have passed through atmosphere with $L \sim 10$ km



Super-Kamiokande Atmospheric Neutrinos

- 50,000 tonnes of ultra-pure water in Japan
- Super-K observed a deficit of upwards-going ν_μ
- Evidence for ν_μ changing into ν_τ (while going through Earth)





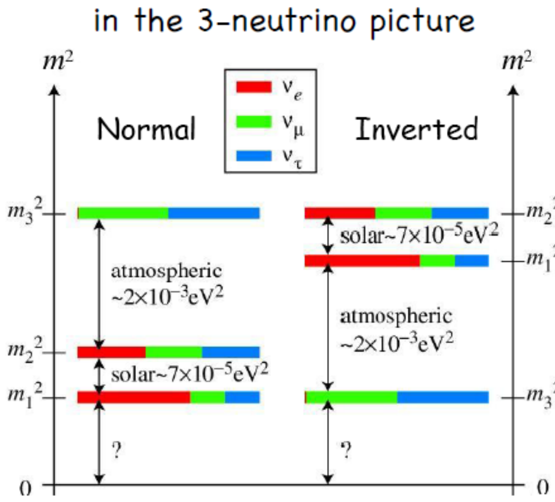
- - - - - - Expected for no oscillations

—— Expected for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations

Experimental Results

Experimentally measured mixing angles and Δm^2 between neutrinos:

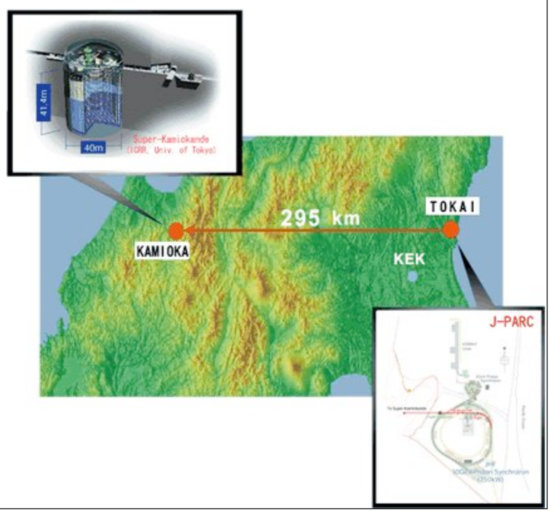
- $\Delta m_{12}^2 = (7.6 \pm 0.2) \times 10^{-5}\ \mathrm{eV}^2$
- $\Delta m_{23}^2 = (2.3 \pm 0.1) \times 10^{-3}\ \mathrm{eV}^2$
- $\sin^2 2\theta_{12} = 0.87 \pm 0.04$
- $\sin^2 2\theta_{23} > 0.92$
- $\sin^2 2\theta_{13} \sim 0.04$
- δ is unknown *CP* violating phase



$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \sim \begin{pmatrix} 0.85 & 0.53 & 0.1e^{i\delta} \\ -0.37 & 0.60 & 0.71 \\ 0.37 & -0.60 & 0.71 \end{pmatrix}$$

OPERA and T2K

- Neutrinos produced in CERN in proton collisions: $p+Be \to \pi^+ + X;\ \pi^+ \to \mu^+ \nu_\mu$ aimed at Gran Sasso underground laboratory in Italy. **OPERA** detector measures an interactions of the neutrinos in the detector: $\nu_\mu n \to p\, \mu^+$ or $\nu_\tau n \to p\, \tau^+$
- Have observed $\nu_\mu \to \nu_\tau$, can be used to measure Δm_{23}^2, $\sin^2 2\theta_{23}$
- Observation of $\nu_\mu \to \nu_e$ could be used to measure $\sin^2 2\theta_{13}$
- Excitement last year about potential superluminal measurements of neutrinos.
- Potential problems found with cabling and GPS synchronisation.
- New data expected in May 2012.



- **T2K** in Japan uses Super-Kamiokande detector to search for $\nu_\mu \to \nu_e$ to measure $\sin^2 2\theta_{13}$

Summary

- Three neutrinos in the Standard Model: ν_e, ν_μ, ν_τ
- Only left-handed neutrinos and right-handed antineutrinos are observed.

- Mass eigenstates propagate through matter or a vacuum ν_1, ν_2, ν_3
- Masses are very small, < 1 eV absolute masses unknown.
- Large mixing is observed between the flavour eigenstates

- Many experiments and observations of neutrinos used to measure Δm^2 and mixing angle between the mass eigenstates.

- CP violation may be present in neutrinos, unobserved as yet!