Neutrino Physics at Warwick

Gary Barker

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Outline of Talk

- Introducing Neutrinos and Neutrino Oscillations: Paul Harrison
- The T2K Project: Gary Barker
- The COBRA Project: Yorck Ramachers

Introducing Neutrinos

Neutrinos are everywhere!

They fill every cubic centimetre of space (≥ 336 cm^{-3}).

And even populate the space between the atoms in solid material (to a similar extent).

They pass right through the Earth, mostly undisturbed.

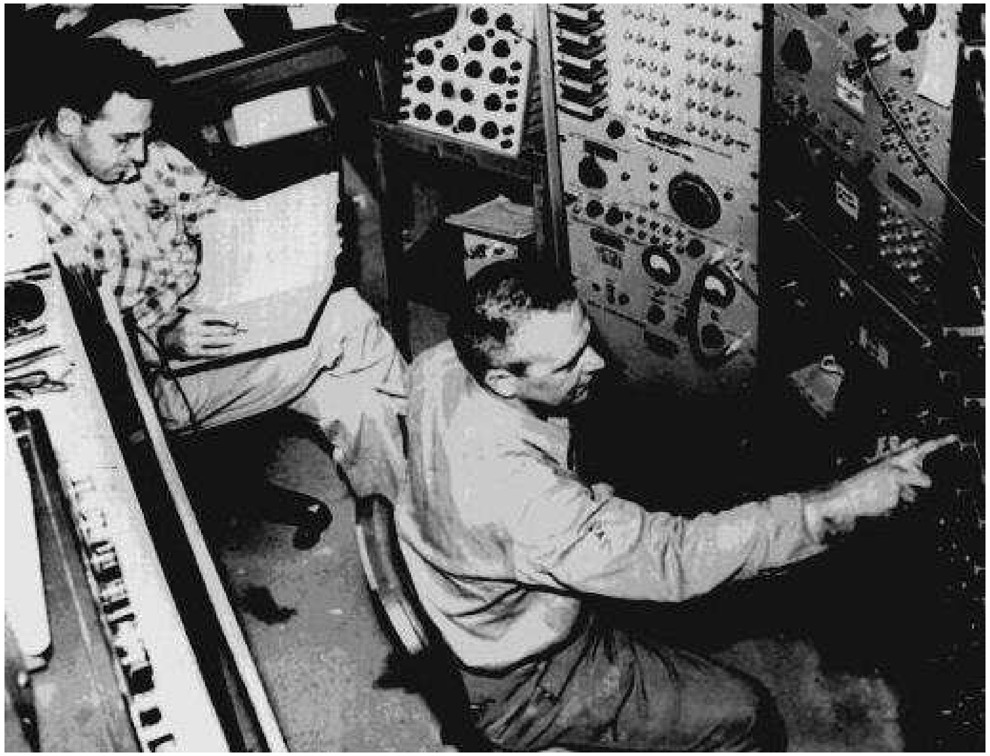
And every second, literally millions of them pass through our bodies, leaving no trace and doing no harm.

A Brief History of Neutrinos

Neutrinos ("little neutral ones") were first introduced by Pauli in 1930, to explain the fact that the beta decay spectrum looked like a 3-body decay spectrum, rather than a two-body one.

The (anti)-neutrino was first detected experimentally by Reines and Cowan in 1956.

The source was a nuclear reactor, and detector was 200 litres of water.



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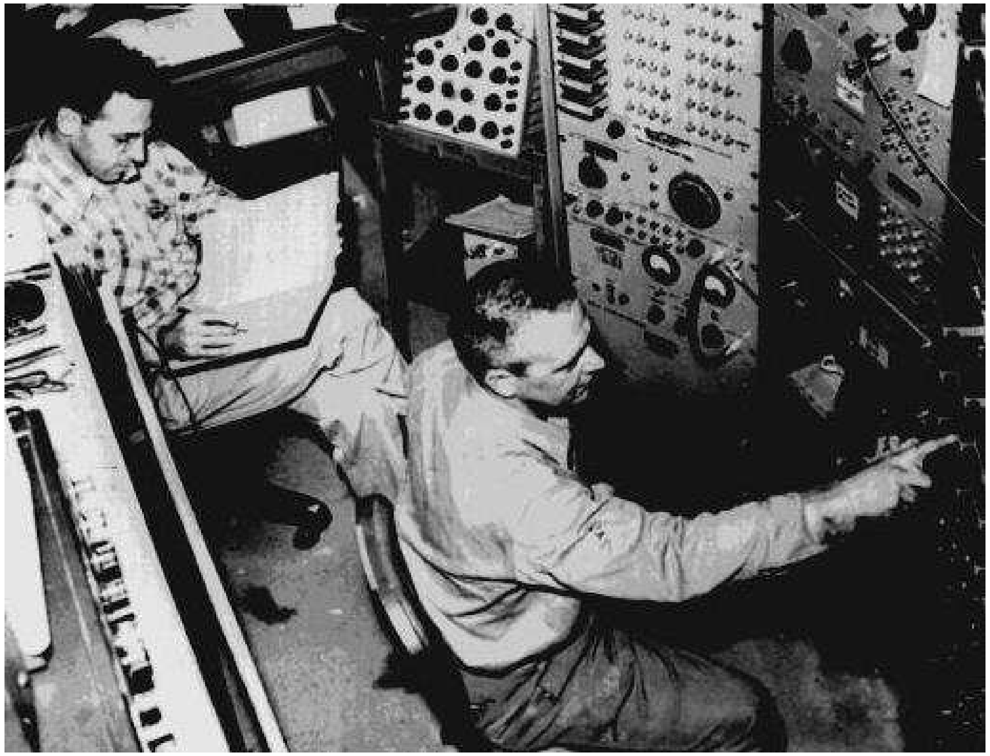


A second, distinct type of neutrino, the muon-neutrino (ν_μ) was discovered in 1962.

A third cousin, the tau neutrino (ν_τ) was discovered in 2000.

Where do Neutrinos Come From?

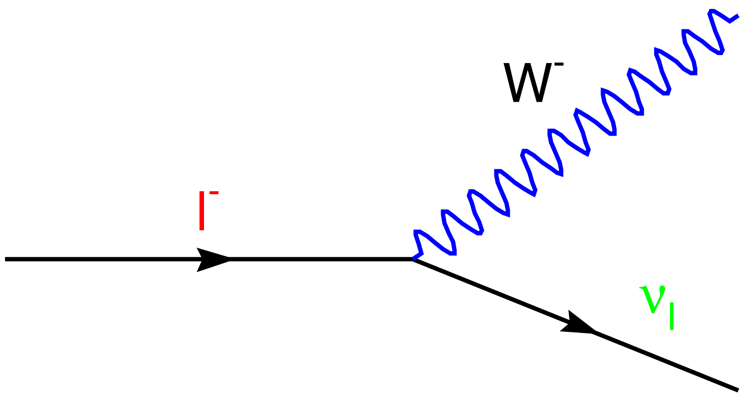
- Biggest source is the Big Bang itself - relic neutrinos remain throughout the Universe
- Produced naturally
  - by nuclear fusion in the Sun and stars
  - in supernova explosions
  - in collisions of cosmic rays with the Earth's atmosphere
  - in natural radioactivity (beta decays)
- Produced by man
  - in nuclear reactors
  - in particle accelerators

Basic Neutrino Properties

- Neutrinos are uncharged - do not participate in electromagnetism
- Neutrinos are light (until recently, were thought to be massless).
- Are extremely weakly interacting: a (1 MeV) neutrino would pass through, on average, 3×10^{19} m of ordinary matter, before interacting.
- They come in three distinct "flavours", each paired with a charged lepton:

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$$

These neutrino "flavour eigenstates" are coupled to their corresponding charged lepton and a $W^\pm$ boson with universal couplings.



What if Neutrinos had Mass?

- We would expect 3 distinct neutrino mass states, ν_1, ν_2, ν_3 (by analogy with other spin-$\frac{1}{2}$ particles).
- Expect them to be linear combinations of flavour eigenstates and vice versa:

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

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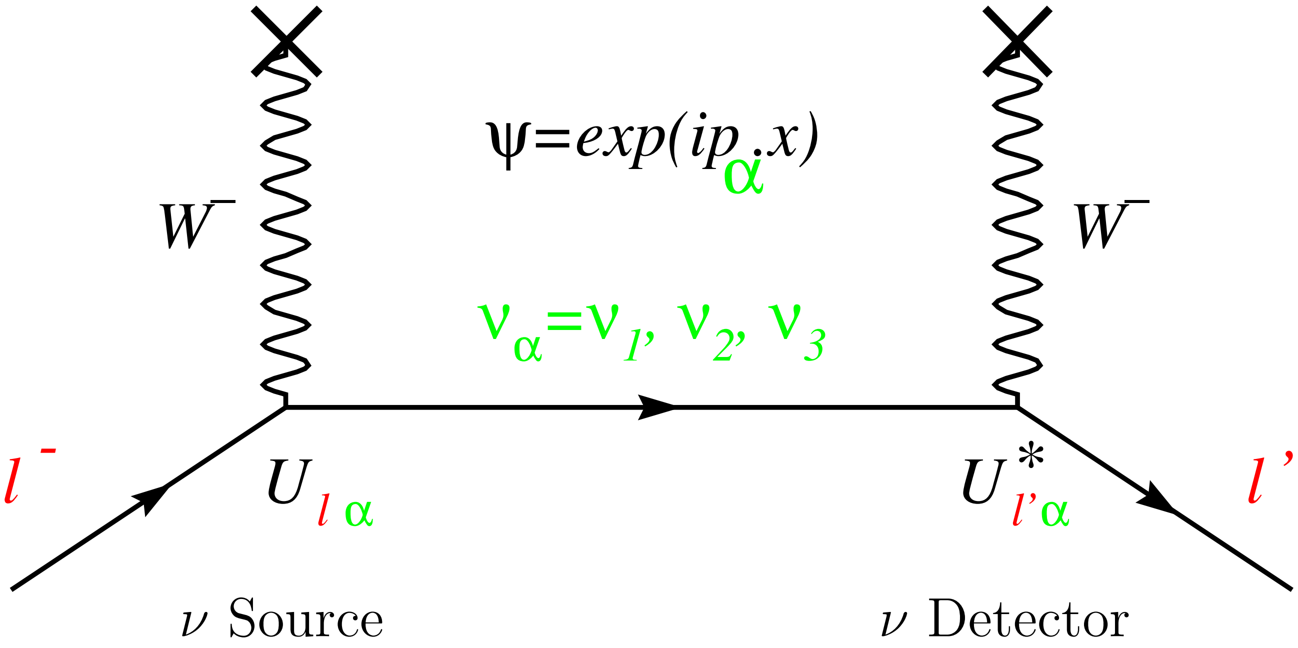
- U may be considered as an Euler rotation matrix, parameterised by 3 mixing angles, θ_{12}, θ_{13}, θ_{23}, with an extra complex phase $e^{i\delta}$.
- This leads inevitably to neutrino oscillations
- Additionally, the phase $e^{i\delta}$ will be responsible for a matter/anti-matter asymmetry (known as CP violation).

Neutrino Oscillations



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$l, l' = e, \mu, \tau$ $\alpha = 1, 2, 3$

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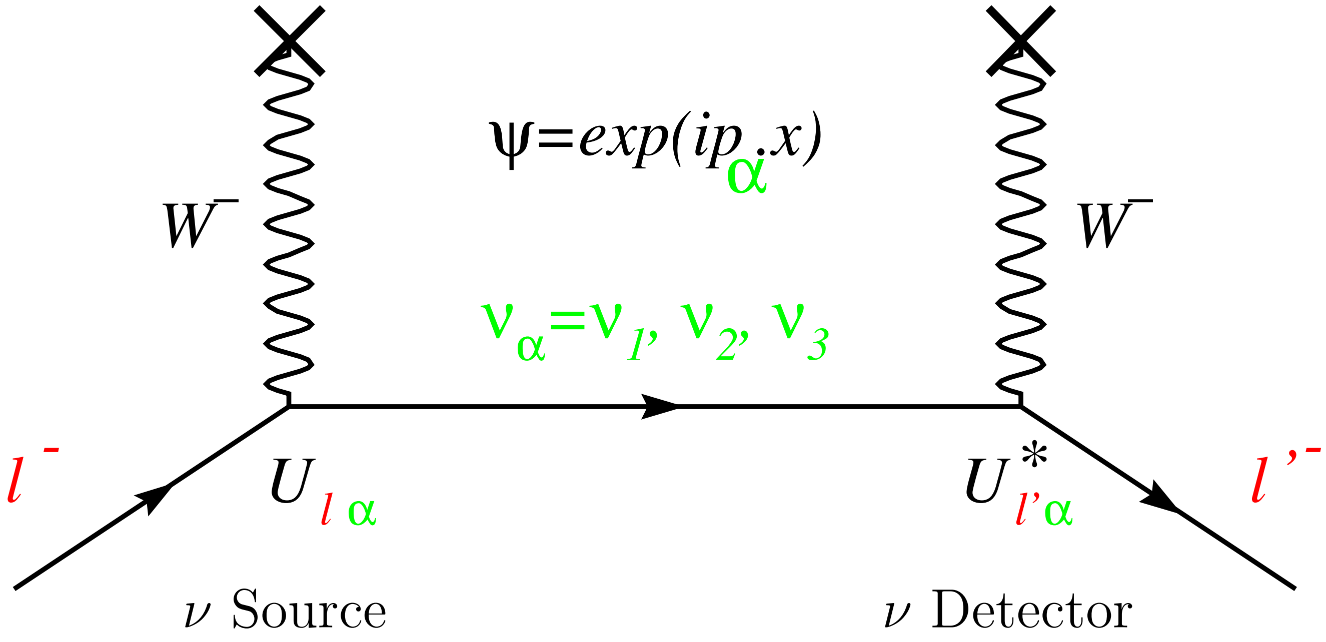


$$p_\alpha = \sqrt{E^2 - m_\alpha^2} \simeq E - \frac{m_\alpha^2}{2E} \qquad l, l' = e, \mu, \tau \qquad \alpha = 1, 2, 3$$

Amplitude is:

$$A_{ll'}(x) = \sum_{\alpha=1,3} U_{l\alpha} U^*_{l'\alpha} \exp\{i(E - \frac{m_\alpha^2}{2E})x\} \qquad \text{Define } \Delta m^2_{\alpha\beta} = m^2_\alpha - m^2_\beta$$

$$\sim U_{l1}U^*_{l'1} + U_{l2}U^*_{l'2}\exp\{-i\frac{\Delta m^2_{21}x}{2E}\} + U_{l3}U^*_{l'3}\exp\{-i\frac{\Delta m^2_{31}x}{2E}\}$$

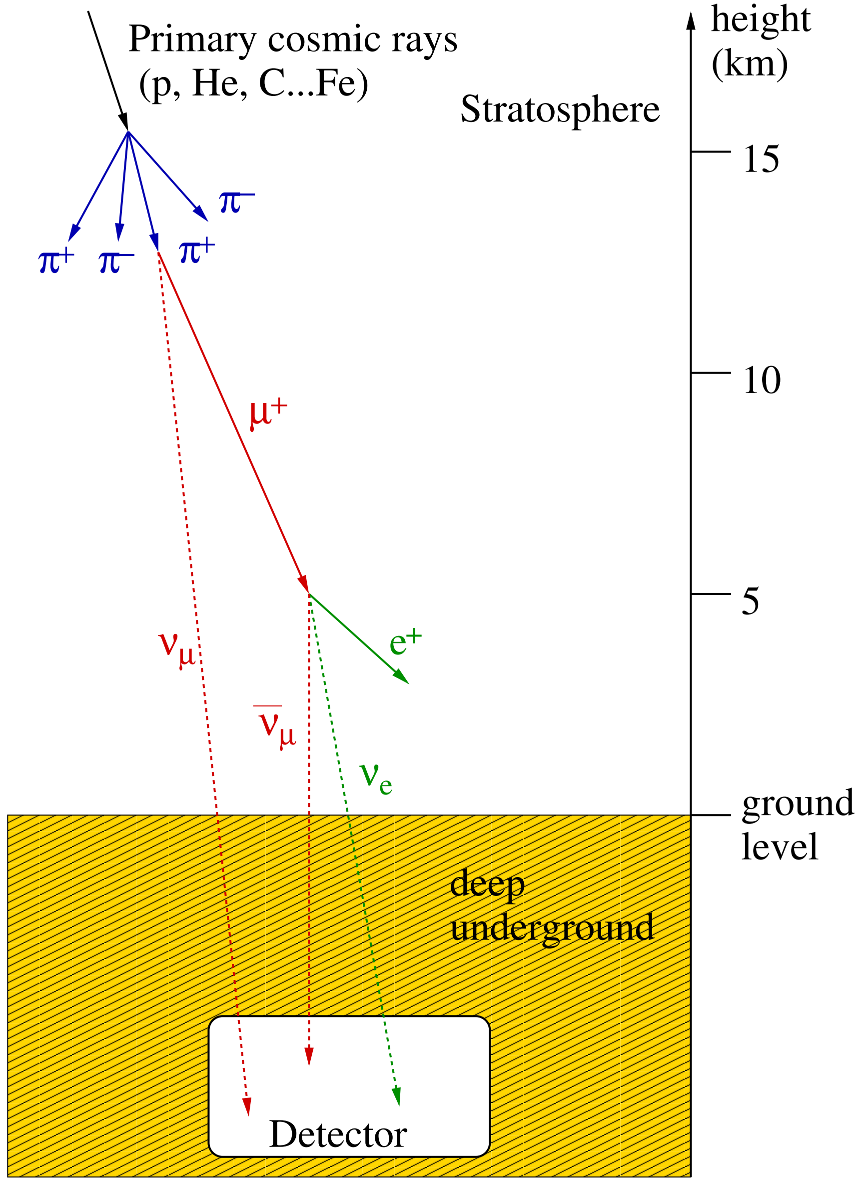
Evidence for Neutrino Oscillations

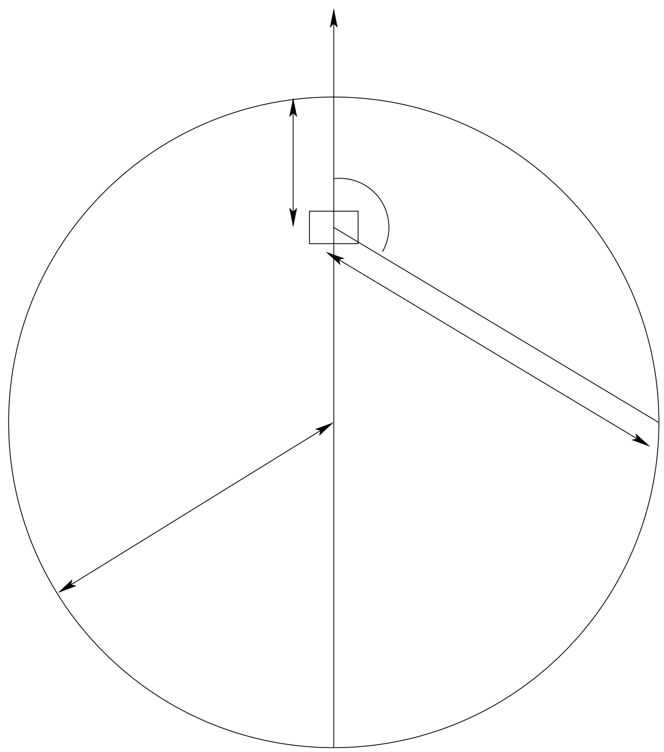
There are now 4 distinct types of evidence for neutrino oscillations:

- The atmospheric neutrino anomaly
- The solar neutrino problem
- Reactor neutrinos
- Accelerator-based neutrino experiments

I will briefly summarise the first two.

Origin of Atmospheric Neutrinos





$$
\begin{aligned}
L &= \sqrt{R^2\cos^2\theta + 2RH + H^2} - R\cos\theta \\
&\simeq \frac{H}{\cos\theta} \qquad \text{downwards} \\
&\simeq 2R\cos\theta \qquad \text{upwards}
\end{aligned}
$$

Atmospheric ν Zenith Angle Dependence

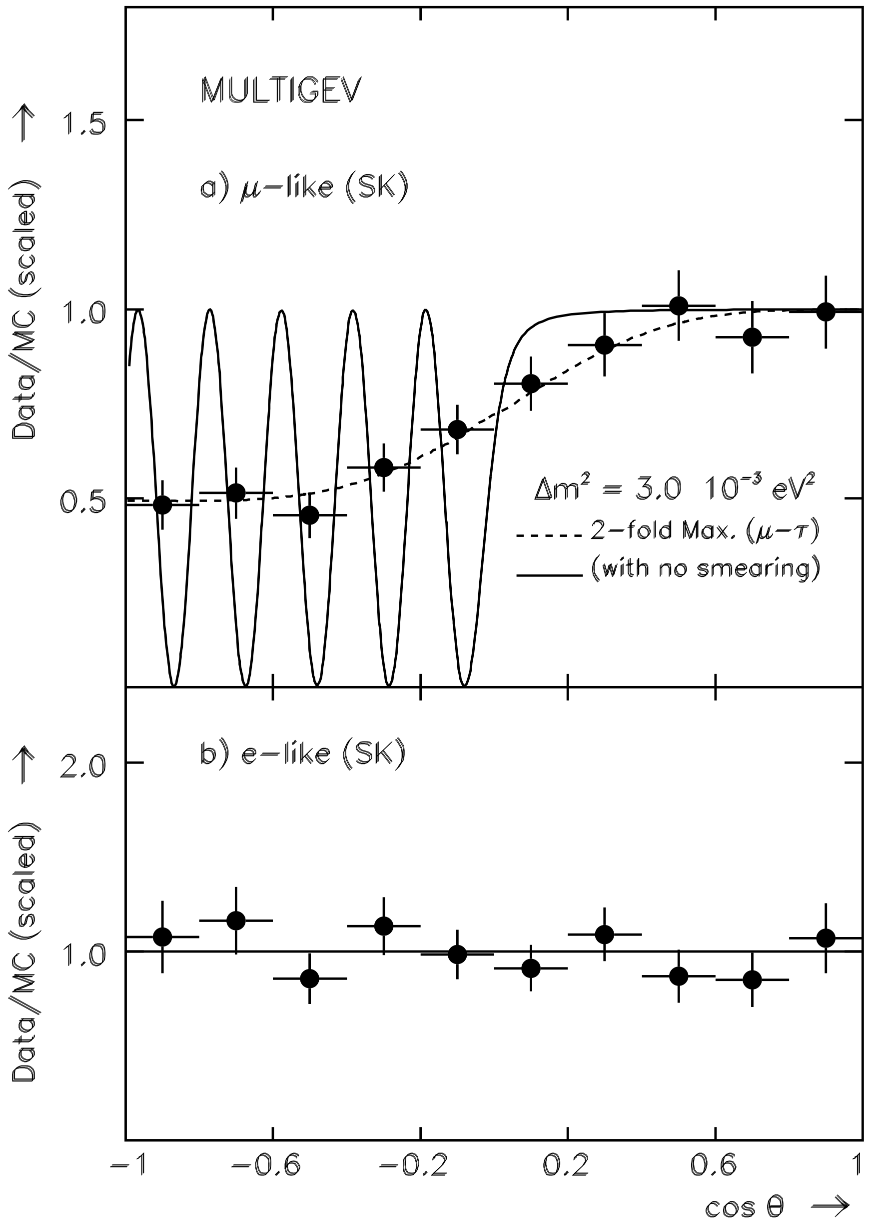
Atmospheric ν_μ data determine

$|U_{\mu 3}|^2 \equiv \sin^2\theta_{23} = 0.5 \pm 0.2,$

$\Delta m^2_{23} = (2.5 \pm 0.5) \times 10^{-3}\ \mathrm{eV}^2$

The ν_e data are totally insensitive to $|U_{e3}|^2$, because of compensation due to feedthrough:

$P(\nu_e \to \nu_e) + 2P(\nu_\mu \to \nu_e) = 1,\ \forall\, U_{e3}$

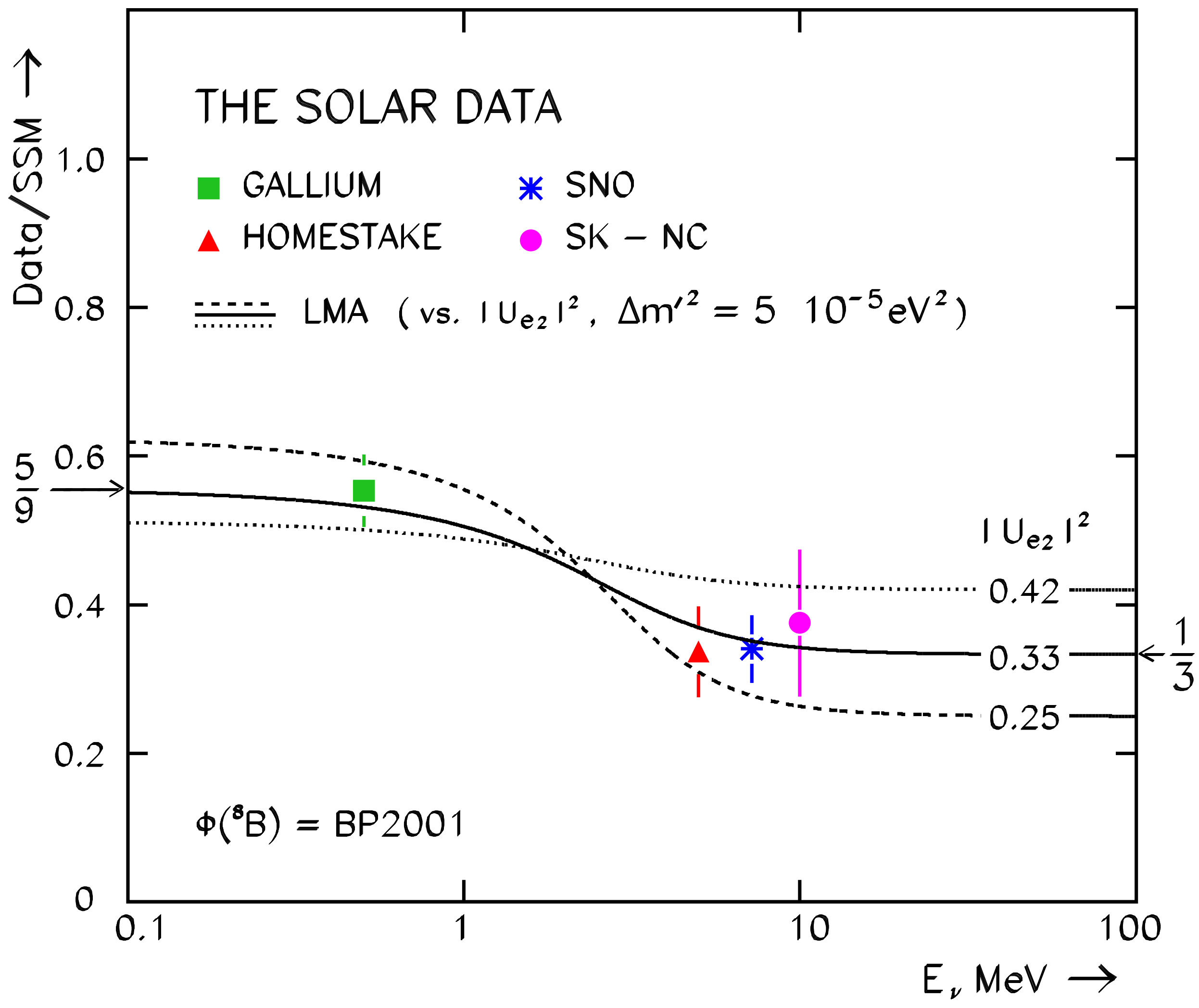


Solar ν_e Results

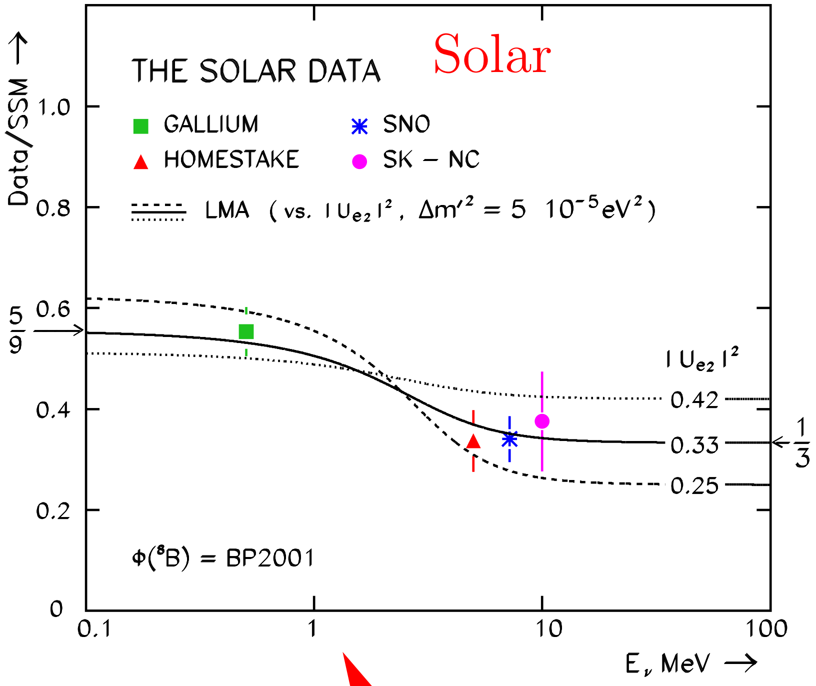
The Solar data determine $|U_{e2}|^2 \equiv \sin^2\theta_{12}$ and Δm^2_{12}.

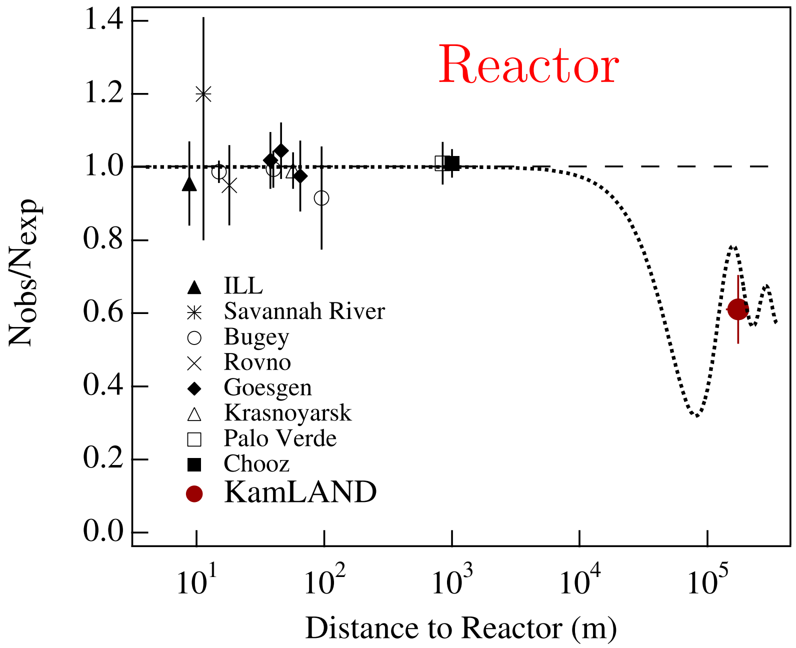
The curves show the Large Mixing Angle MSW solution to the Solar Neutrino problem.

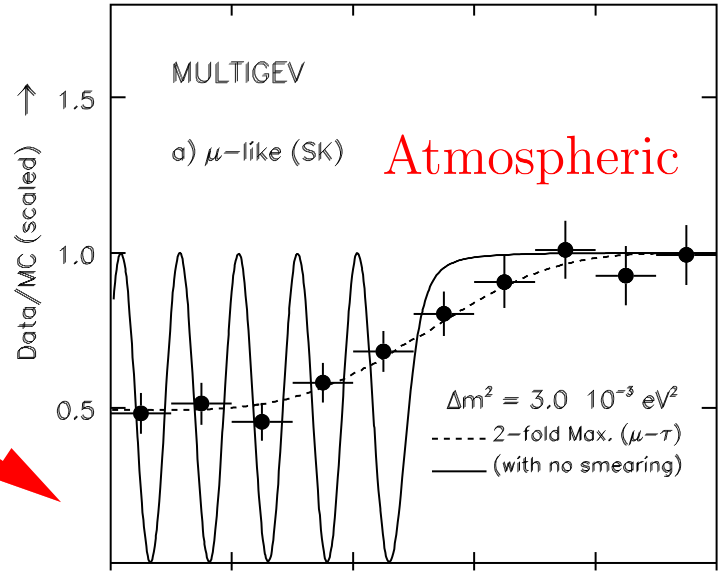
The data are fitted with $|U_{e2}|^2 \equiv \sin^2\theta_{12} = 0.32 \pm 0.07$, $\Delta m^2_{12} = 7.5 \times 10^{-5}$ ev^2



Summary of Neutrino Oscillation Data







$$
|U| \sim \begin{array}{c c}
 & \begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array} \\
\begin{array}{c} e \\ \mu \\ \tau \end{array} & \begin{pmatrix} 0.82 & 0.58 & < 0.17 \\ 0.41 & 0.58 & 0.71 \\ 0.41 & 0.58 & 0.71 \end{pmatrix}
\end{array}
$$

Outstanding Experimental Questions in Neutrino Physics

- What is the value of θ_{13}?

  To be addressed in the T2K neutrino “Super-Beam” experiment.

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- What is the absolute value ("offset") of the neutrino masses?

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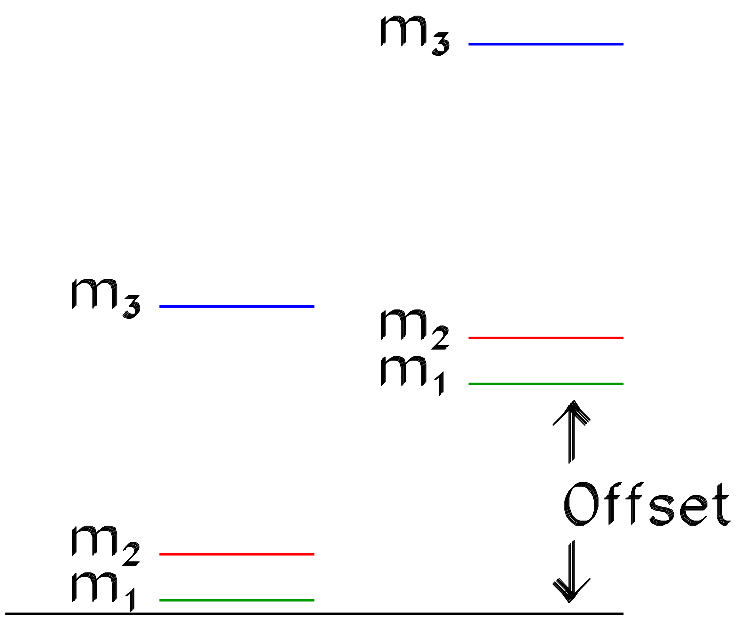

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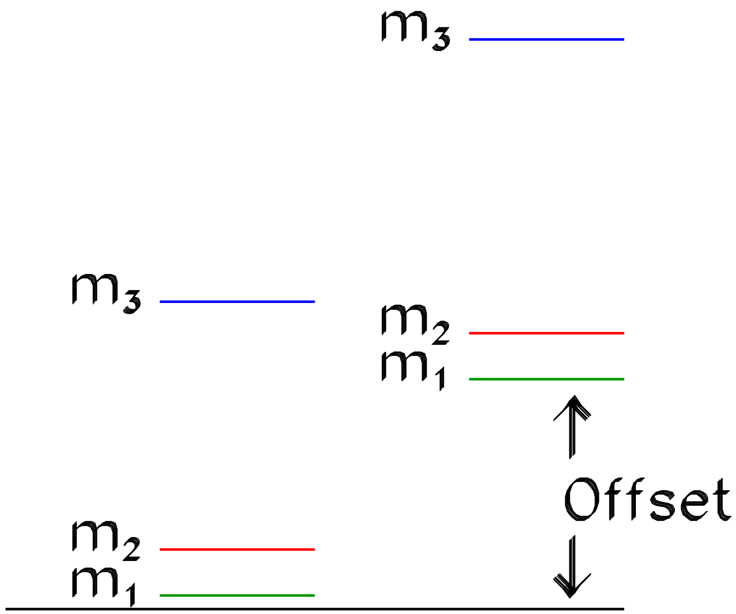

- Do neutrino oscillations exhibit CP violation?

  If so, what is the value of the phase δ?

  To be addressed (perhaps) at a neutrino factory

Conclusion

The Warwick EPP group is in a position now to make significant contributions to solving the outstanding problems of neutrino physics

- The first measurement of neutrino appearance, and θ_{13} at T2K
- The measurement of the absolute values of the neutrino masses with COBRA
- Possibly, CP violation in the lepton sector at a neutrino factory