What's ν?

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Outline of Talk

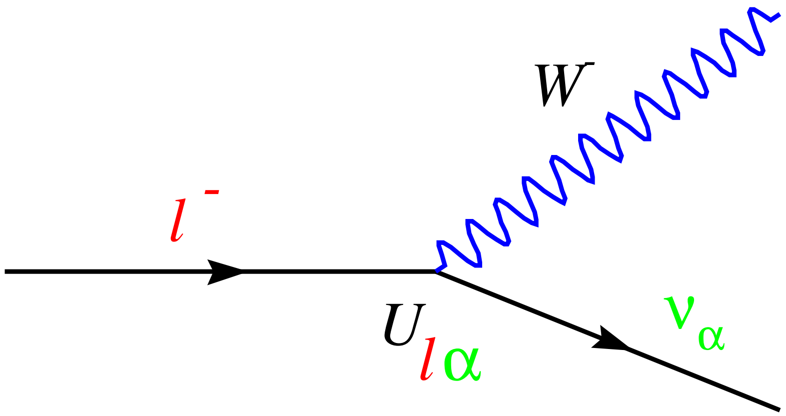
- ν Oscillations in 2 slides
- νs: The movie
- Oscillations in Atmospheric Neutrinos
- Summary of Neutrino Oscillation Data
- Neutrinoless Double Beta Decay

If Neutrinos have Mass

- Expect 3 mass eigenstates, ν_1, ν_2, ν_3, each a linear combination of flavour eigenstates, and vice versa, ($\Longrightarrow$ ν oscillations):

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

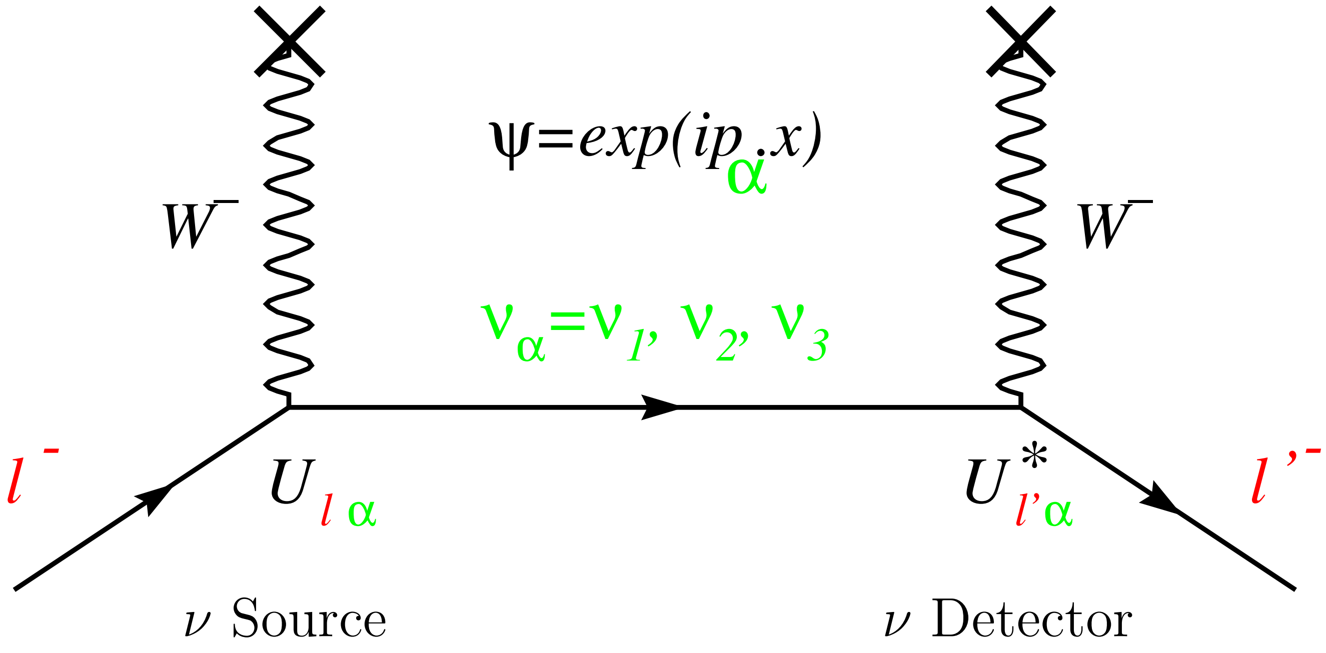
- U is a unitary matrix known as the MNS lepton mixing matrix. Gives couplings of e, μ, τ to ν_1, ν_2, ν_3:



- U is parameterised by 3 mixing angles, θ_{12}, θ_{13}, θ_{23}, with an extra complex phase, $e^{i\delta}$,

  $\Longrightarrow$ CP violation.

Neutrino Oscillations



$$p_\alpha = \sqrt{E^2 - m_\alpha^2} \simeq E - \frac{m_\alpha^2}{2E}$$

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

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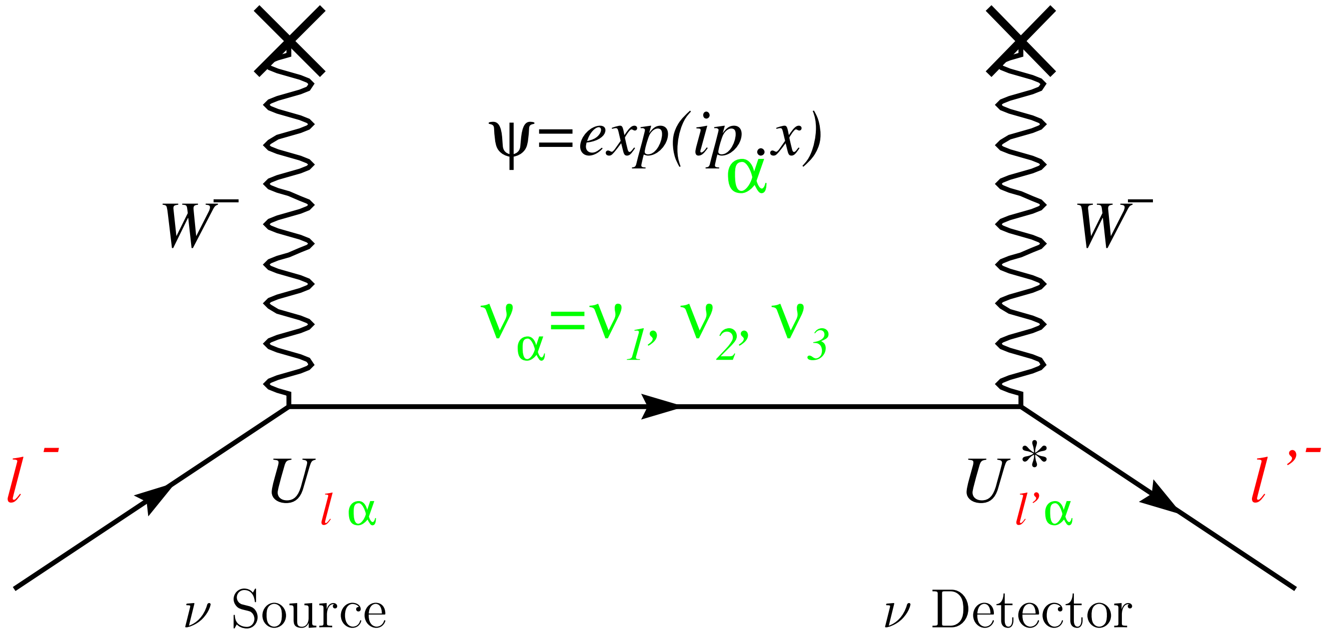


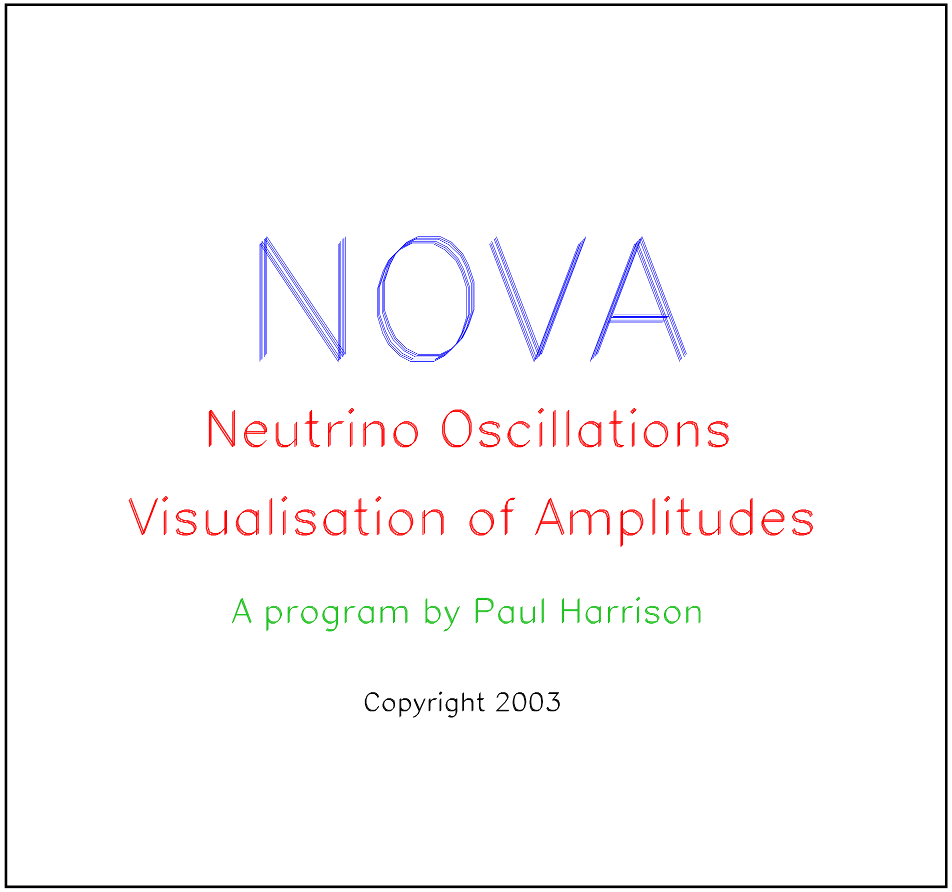
$$p_\alpha = \sqrt{E^2 - m_\alpha^2} \simeq E - \frac{m_\alpha^2}{2E} \qquad l, l' = e, \mu, \tau \qquad \alpha = 1, 2, 3$$

Amplitude is:

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

Define $\Delta m^2_{\alpha\beta} = m^2_\alpha - m^2_\beta$

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



NOVA, the neutrino movie I showed during my talk, can be downloaded from here:

http://www.slac.stanford.edu/~pfh/Nova/nova.tar.gz

The documentation can be found at:

http://www.slac.stanford.edu/~pfh/Nova/doc.txt

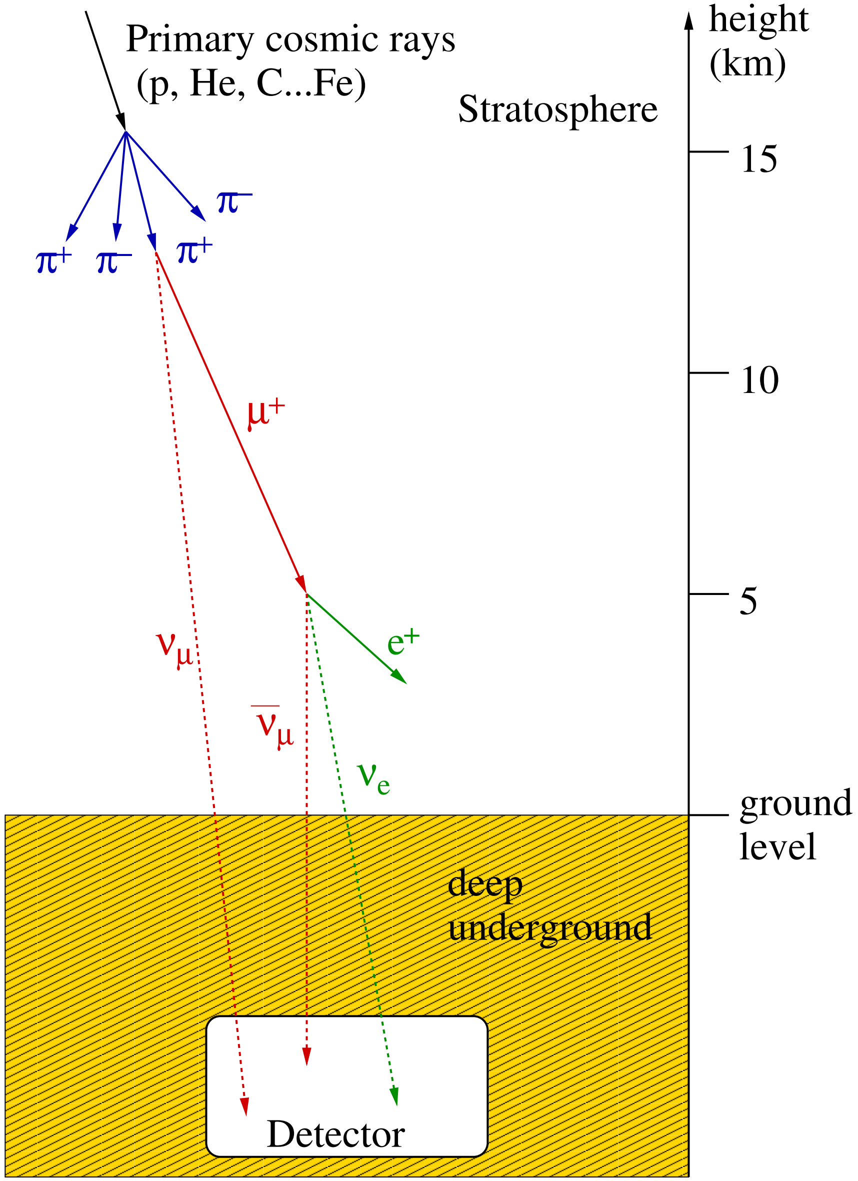
Neutrino Oscillations?

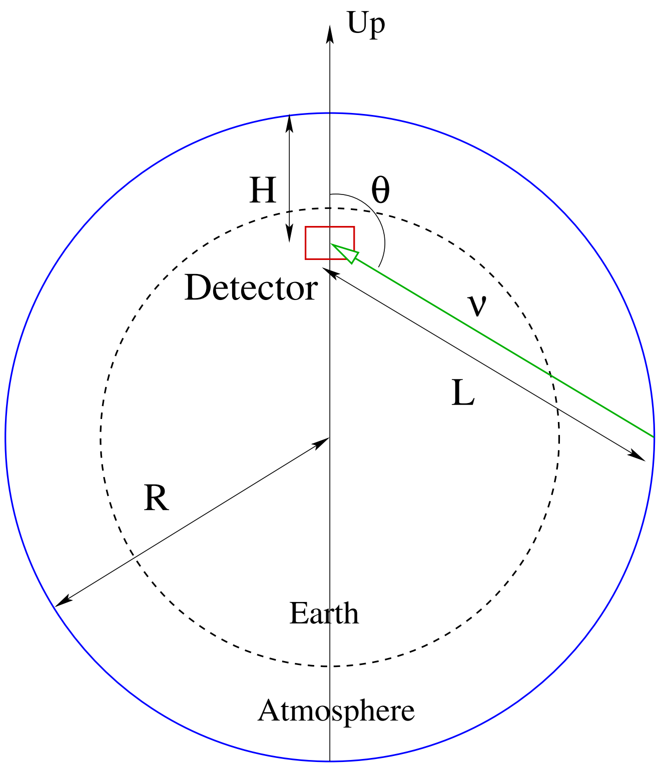
Now considerable evidence for neutrino oscillations:

- HOMESTAKE evidence for solar neutrino deficit confirmed by 2 Ga experiments, and SuperKamiokande, and now SNO.
- Atmospheric neutrino anomaly seen by KAMIOKANDE, SUPER-K and MACRO.
- KAMLAND reactor neutrino experiment sees deficit consistent with solar neutrino results
- K2K experiment sees deficit of accelerator neutrinos and spectrum distortion at SuperK, consistent with atmospheric anomaly.

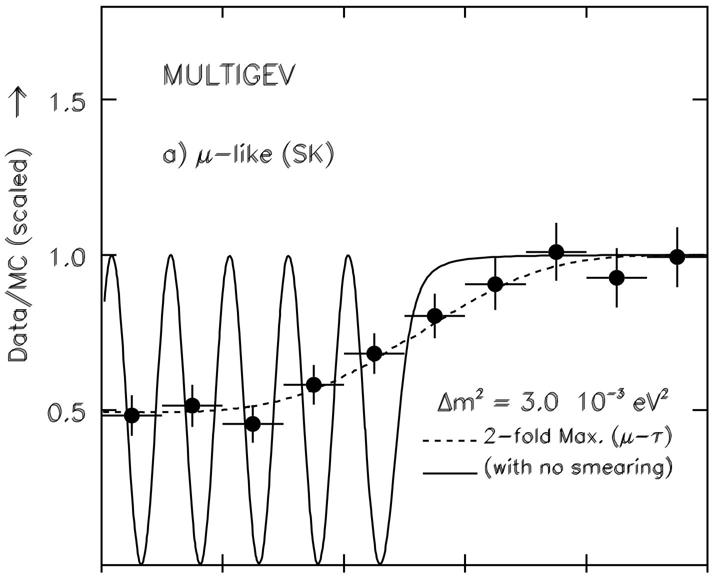
BUT no-one has ever seen an actual oscillation! Until now.

Origin of Atmospheric Neutrinos

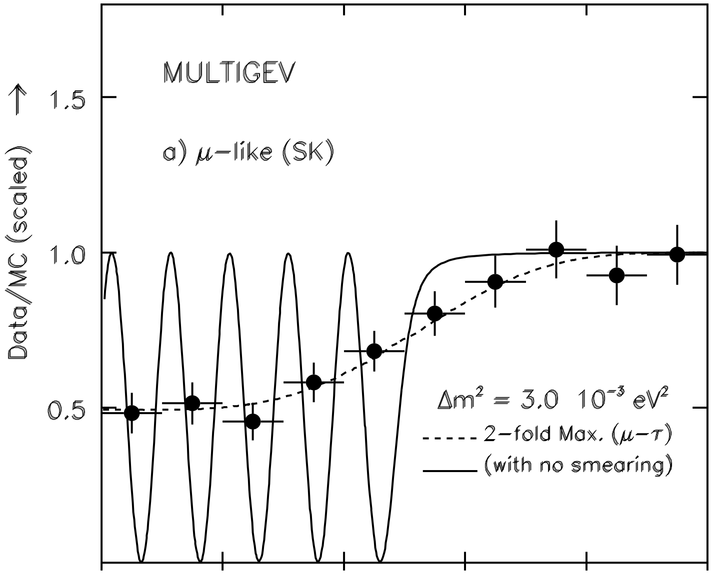




$$
\begin{aligned}
L &= \sqrt{R^2\cos^2\theta + 2RH + H^2} - R\cos\theta \\
&\simeq \frac{H}{\cos\theta} \qquad \text{downwards} \\
&\simeq 2R\cos\theta \qquad \text{upwards}
\end{aligned}
$$

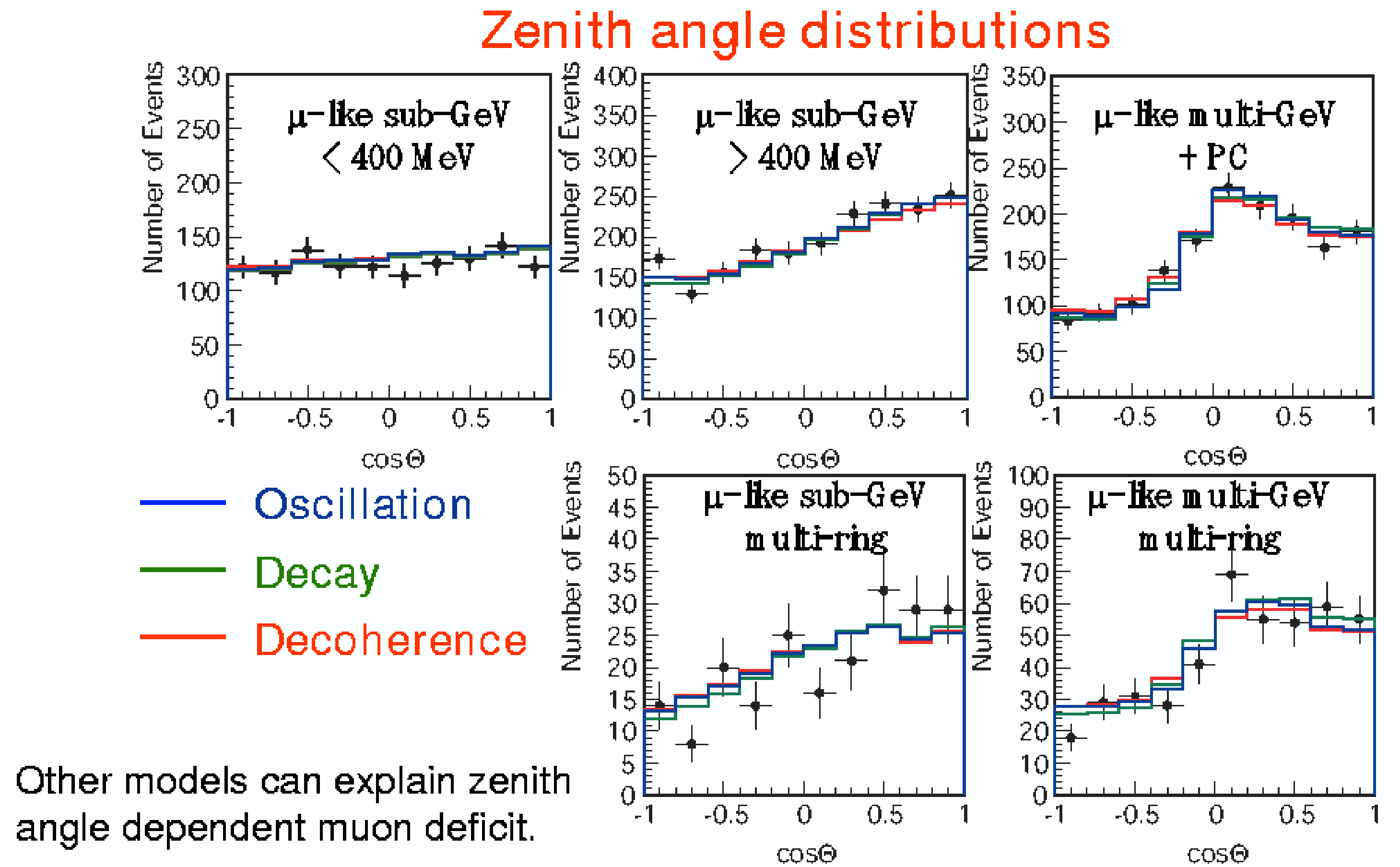


The Standard Presentation of SuperK Atmospheric Neutrinos



The Standard Presentation of SuperK Atmospheric Neutrinos

Has little discrimination between different explanations:

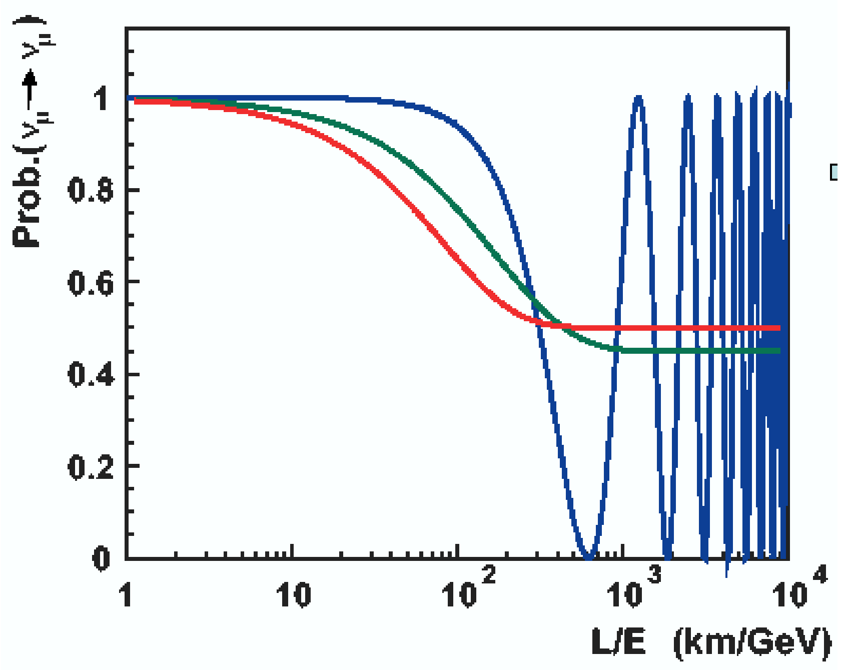


L/E is Much More Natural Variable

Neutrino oscillations: $$P_{\mu\mu} = 1 - K\sin^2(1.27\frac{\Delta m^2 L}{E})$$

Neutrino decay: $$P_{\mu\mu} = (A + B\exp(-\frac{\Delta}{2\tau}\frac{L}{E}))^2$$

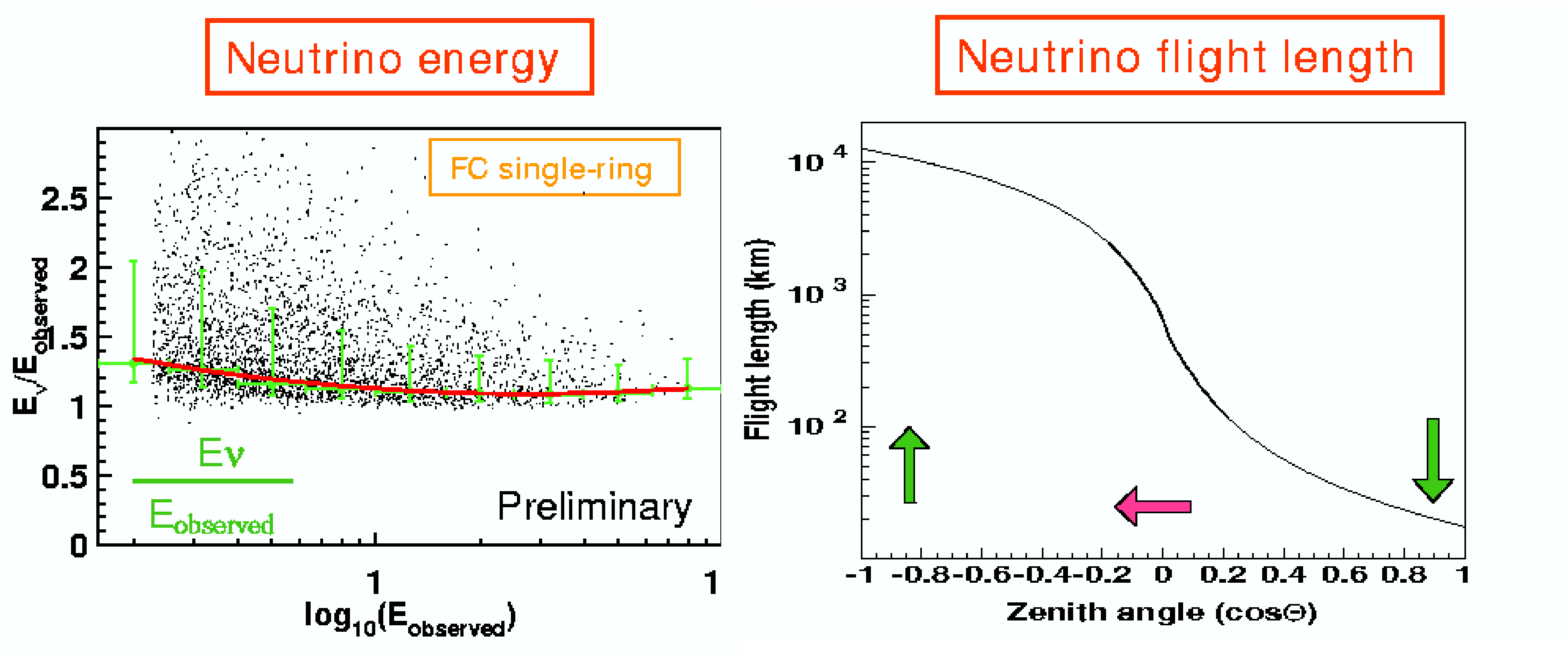
Neutrino decoherence: $$P_{\mu\mu} = 1 - \frac{1}{2}K(1 - \exp(-\gamma_0\frac{L}{E}))$$



Using events with best L/E resolution, is it possible to resolve first "dip"?

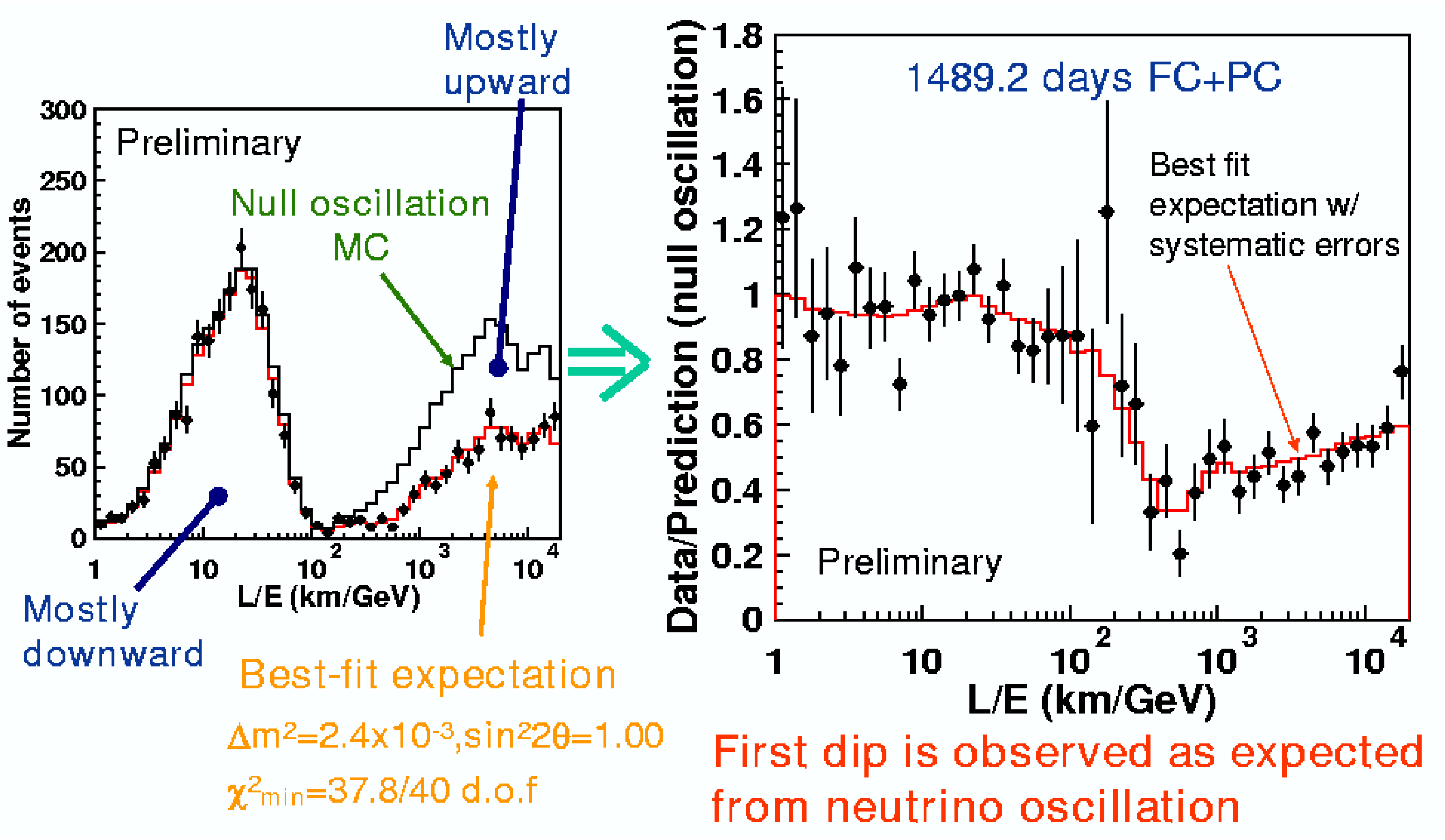
- First evidence for oscillation as mechanism
- Best resolution on Δm^2

E and L as Functions of Observables



For good L/E resolution, events are selected at higher energies and/or large $|\cos\theta|$.

L/E Distribution, and L/E-dependence of Suppression

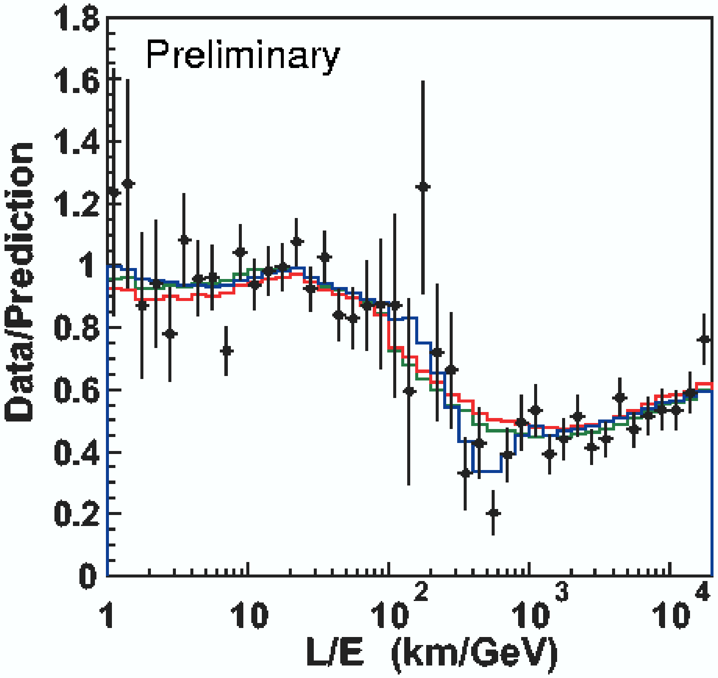


What about Other Explanations of Suppression?

Oscillation χ^2_{min}=37.8/40 d.o.f

Decay χ^2_{min}=49.2/40 d.o.f → $\Delta\chi^2$=11.4

Decoherence χ^2_{min}=52.4/40 d.o.f → $\Delta\chi^2$=14.6

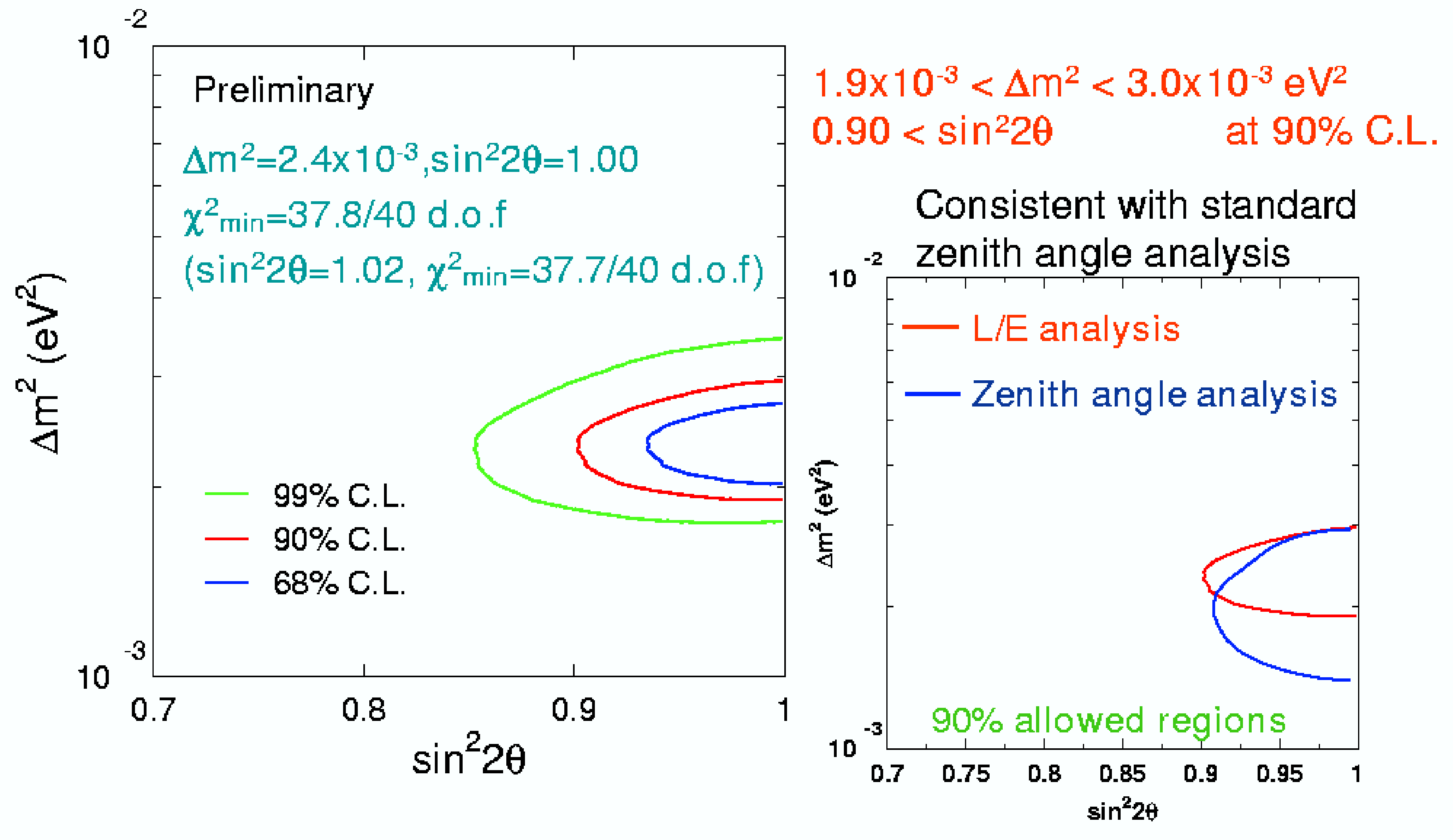


3.4 σ to ν decay

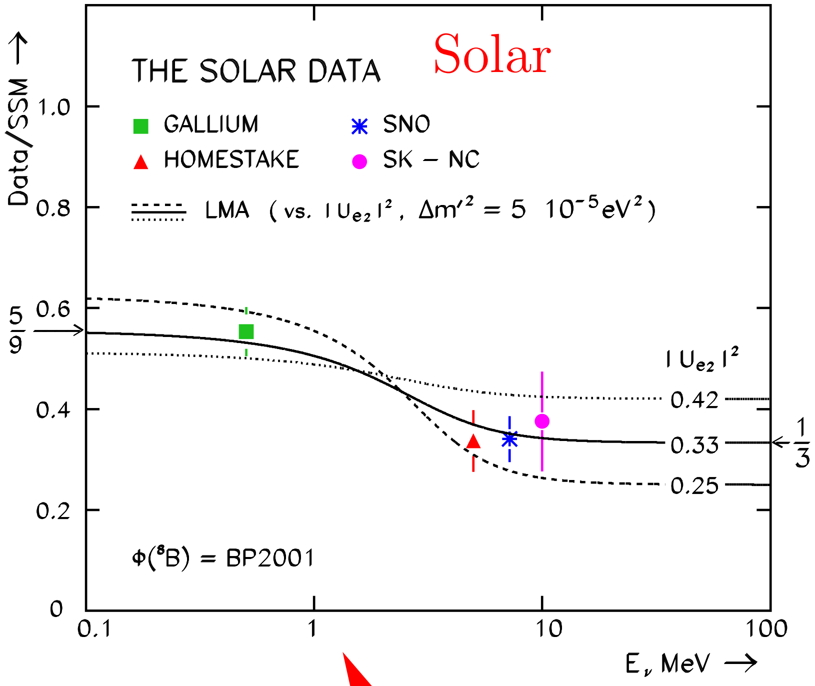
3.8 σ to ν decoherence

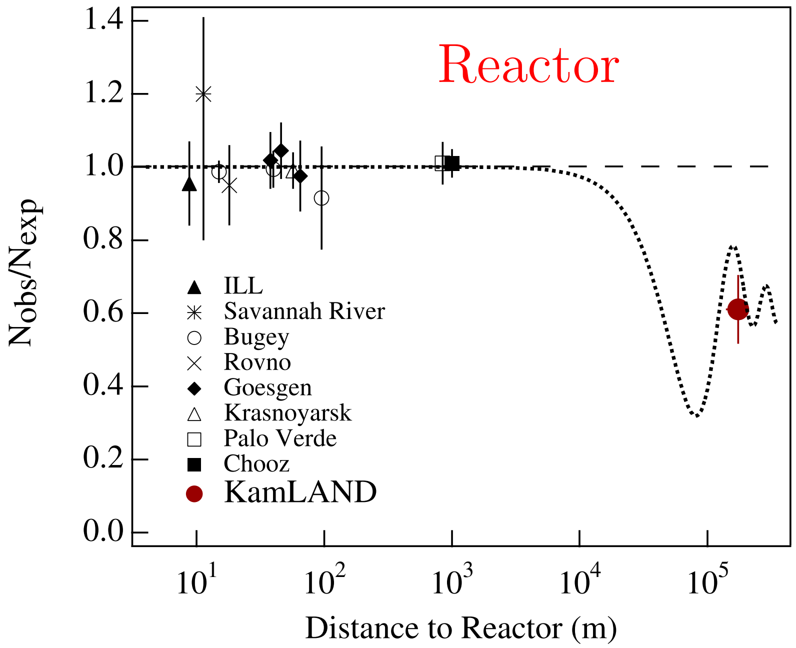
First dip observed in data cannot be explained by alternative hypotheses

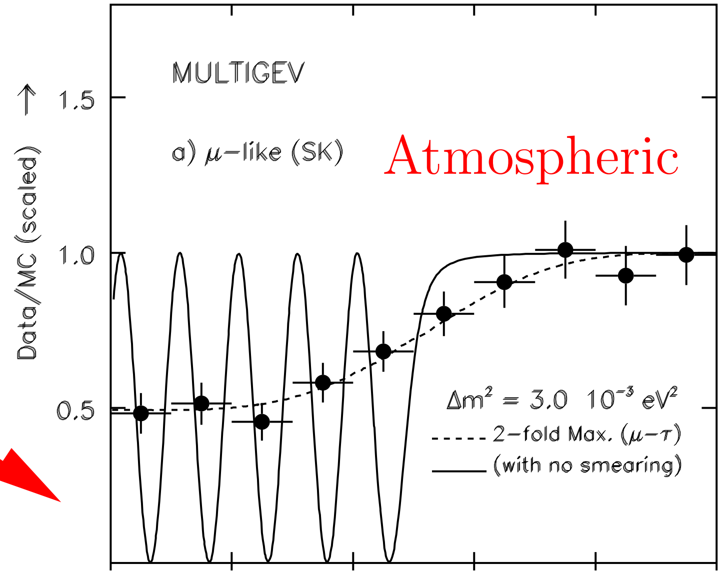
Constraints on Oscillation Parameters



Summary of Neutrino Oscillation Data







$$
|U| \sim \begin{array}{c c}
 & \begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array} \\
\begin{array}{c} e \\ \mu \\ \tau \end{array} & \left(\begin{array}{ccc} 2/\sqrt{6} & 1/\sqrt{3} & < \epsilon \\ 1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \\ 1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \end{array} \right)
\end{array}
$$

Outstanding Experimental Questions in Neutrino Physics

- What is the value of θ_{13}?

  To be addressed in a new generation of neutrino "Super-Beam" experiments.

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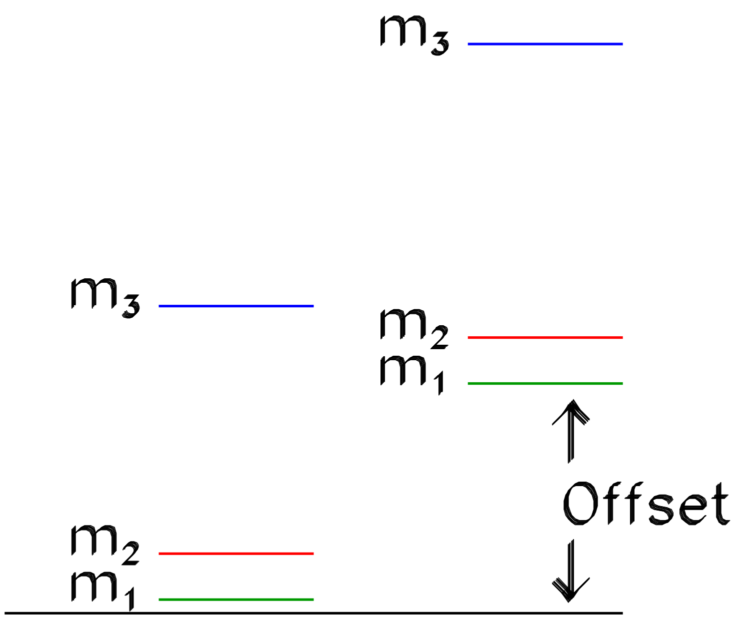

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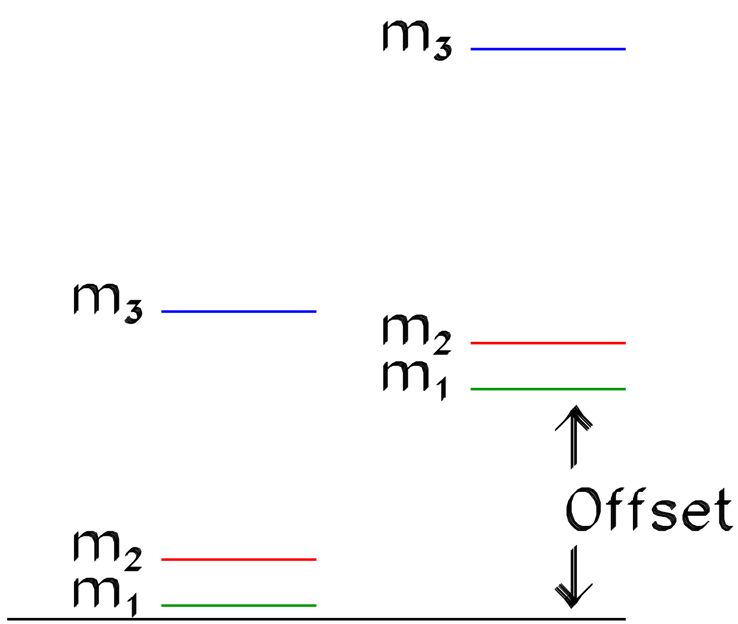
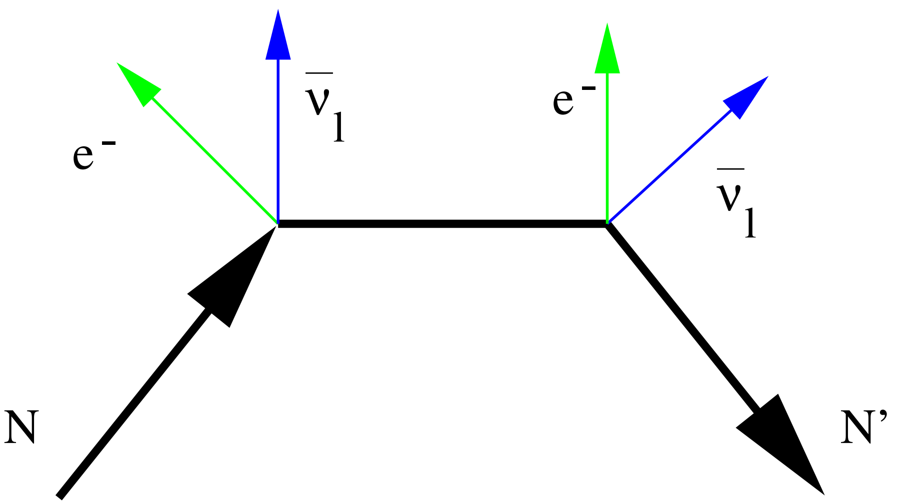
  Both can be answered by discovering neutrinoless double β decay



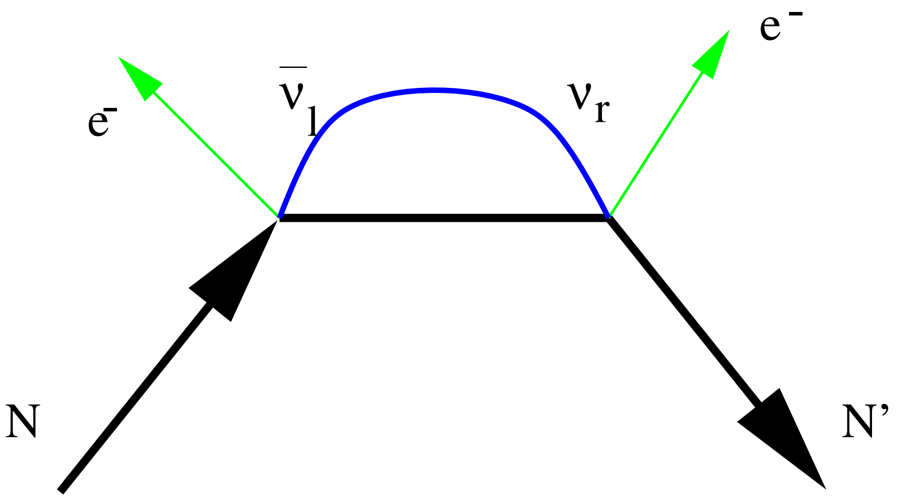
Two Neutrino Double Beta Decay

$2\nu 2\beta$ decay is a standard second-order nuclear process



Neutrinoless Double Beta Decay

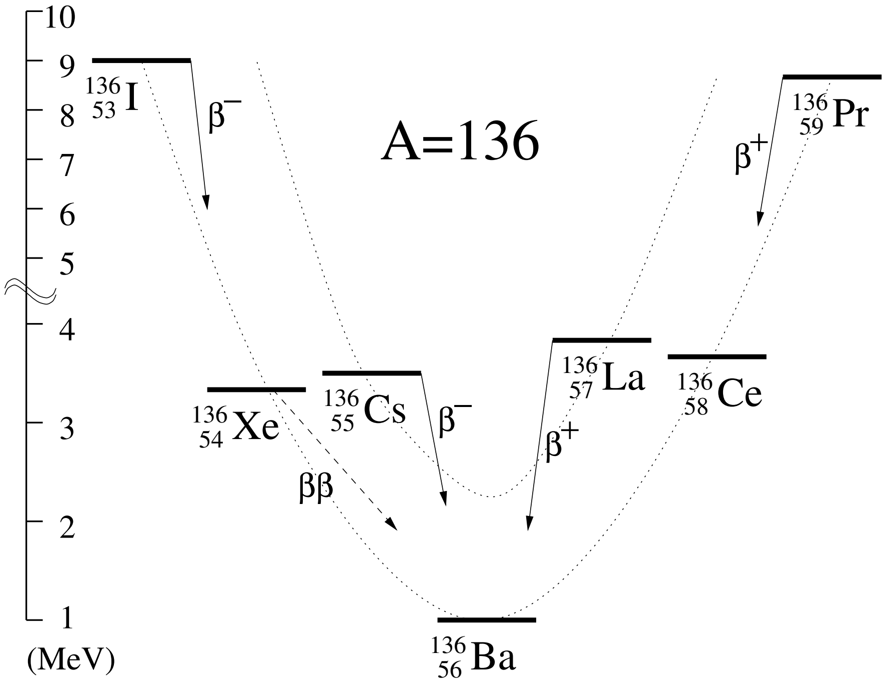
If neutrinos are Majorana particles, then total lepton number is violated and the two neutrinos may annihilate each other:

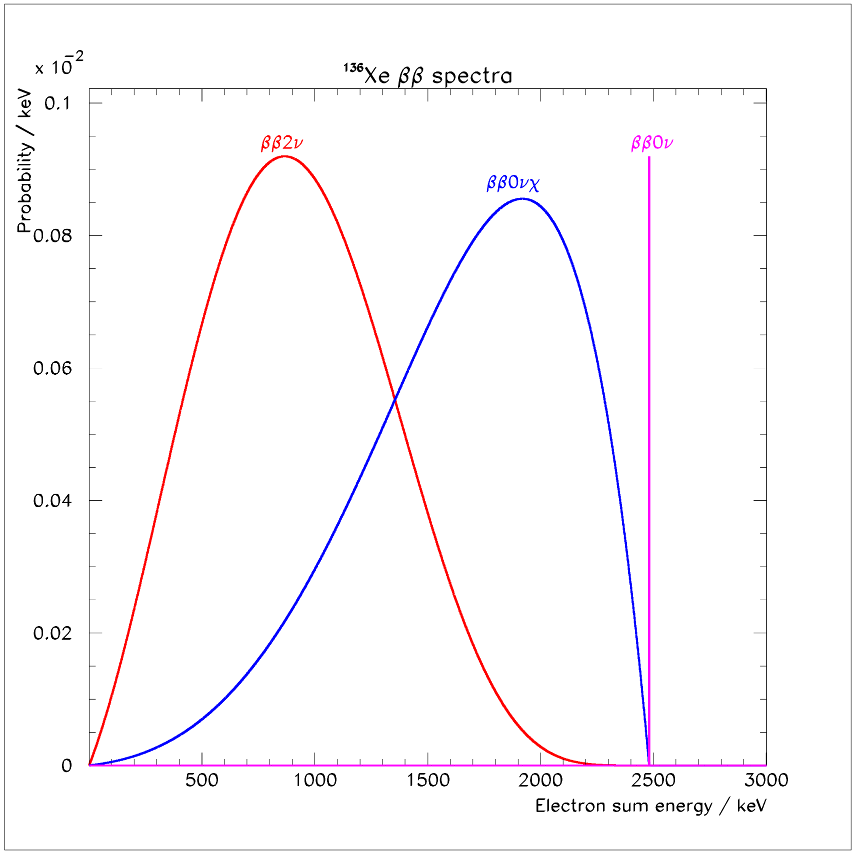


Double Beta Decay

Double beta decay can only be observed when single beta decay is prohibited.

Then (if ν is Majorana) both types occur simultaneously:



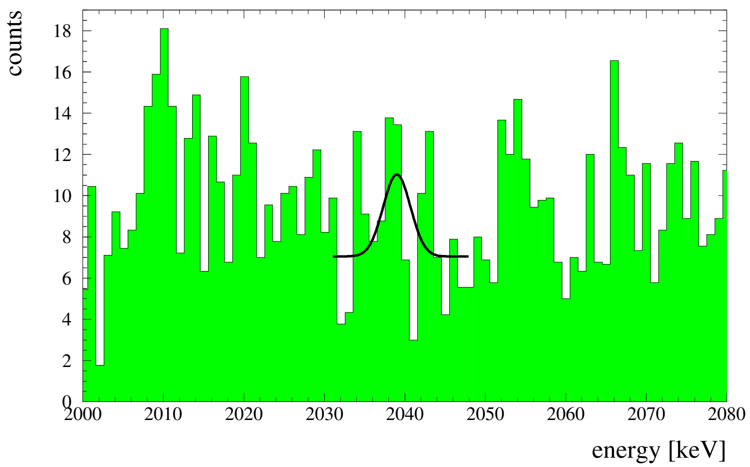


$0\nu2\beta$ decay rate $\propto \ < m >^2$ where $< m >= \sum_i m_i U_{ei}^2 \sim$ few 10s of meV.

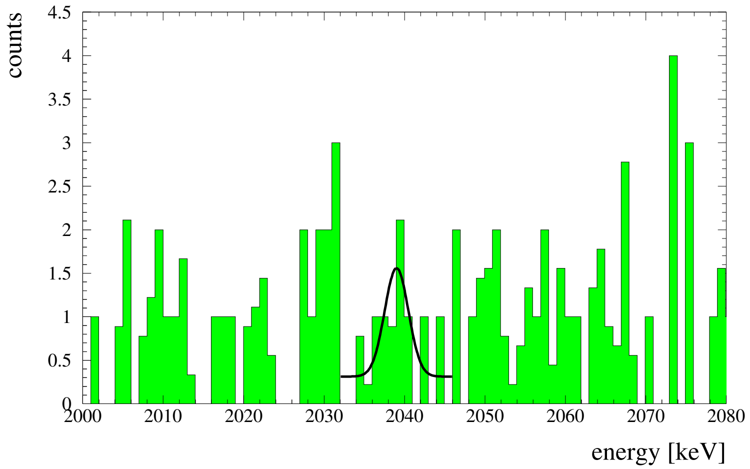
$2\nu2\beta$ decay has been observed in 7 nuclei, but never $0\nu2\beta$.

Observation of Double Beta Decay??

One claim for observation in ^{76}Ge - from 2001 (Green), updated 2004 (Yellow):



Full spectrum



Pulse shape analysis for single site events

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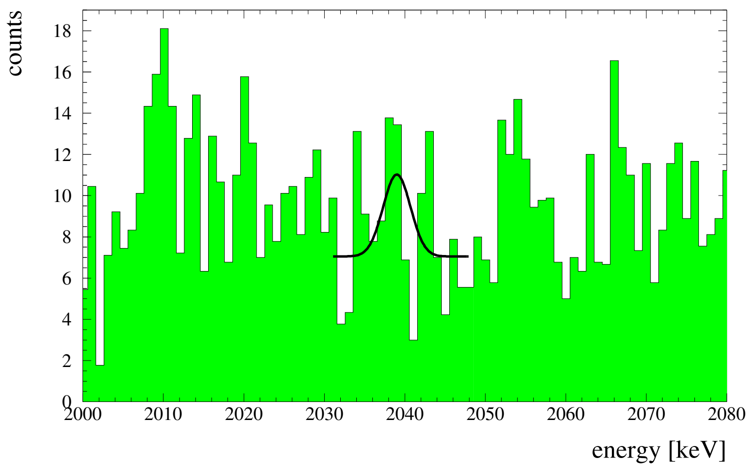

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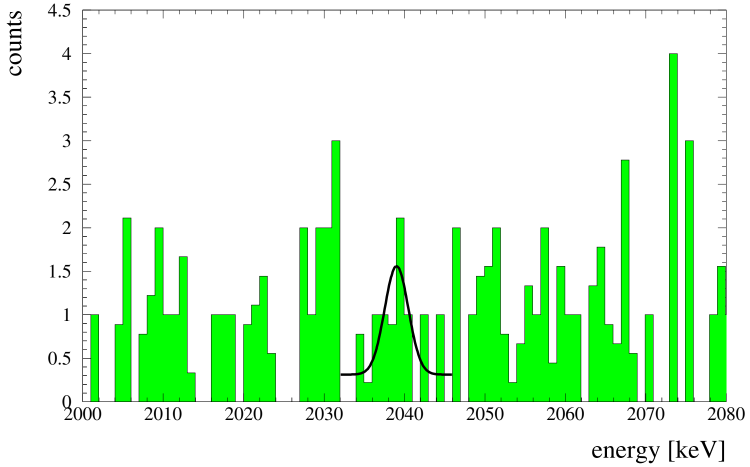

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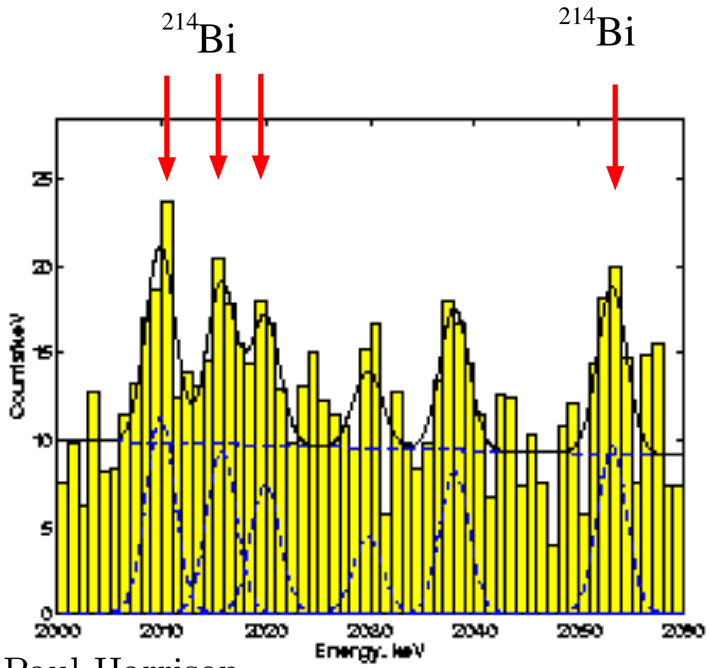
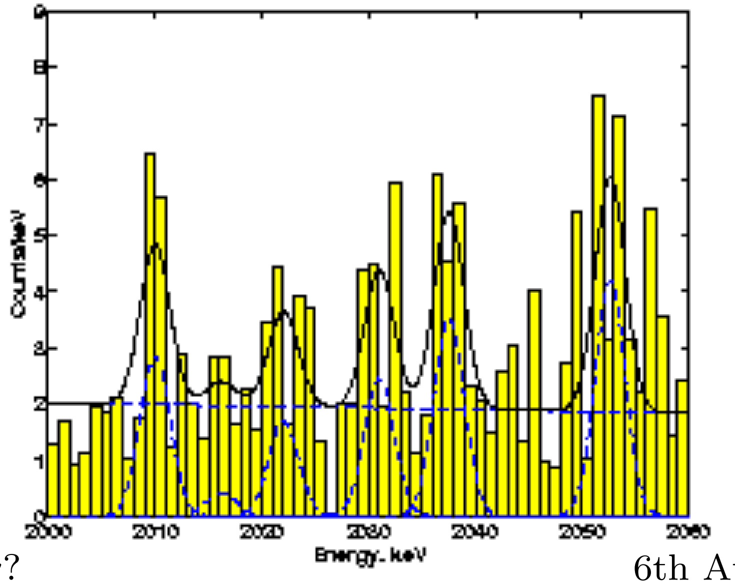




Observation of Double Beta Decay??

Currently two running $0\nu2\beta$ experiments.

Hope to confirm or refute $0\nu2\beta$ decay. One has UK involvement:

- CUORICINO - a TeO_2 bolometer.
- NEMO 3 - a large tracking chamber (UK involvement = UCL).

New generation of experiments planned for the future ($\sim$ 2008), another with UK involvement:

- MAJORANA - Similar to Heidelberg-Moscow, but much bigger (500 kg).
- EXO - Using liquid Xenon in a TPC (1-10 tons)
- COBRA - Similar to H-M, but using CdTe (UK involvement = Birmingham, Liverpool, Sussex, Warwick, York).
- + several more...

NEMO 3:

The Neutrino Ettore Majorana Observatory

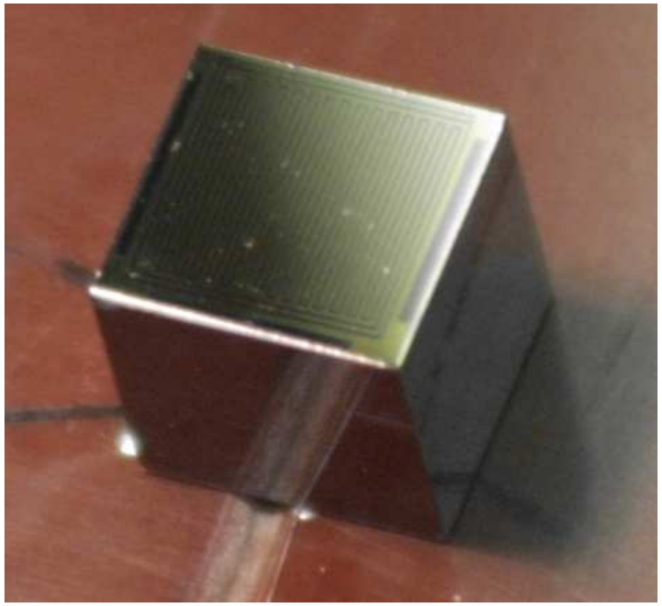
- Located at the Frejus underground laboratory.
- A large tracking chamber
- Can work with several different isotopes
- Aims to resolve two electron tracks and reconstruct kinematics
- Sensitivity by 2008 predicted to be 0.2-0.6 eV.

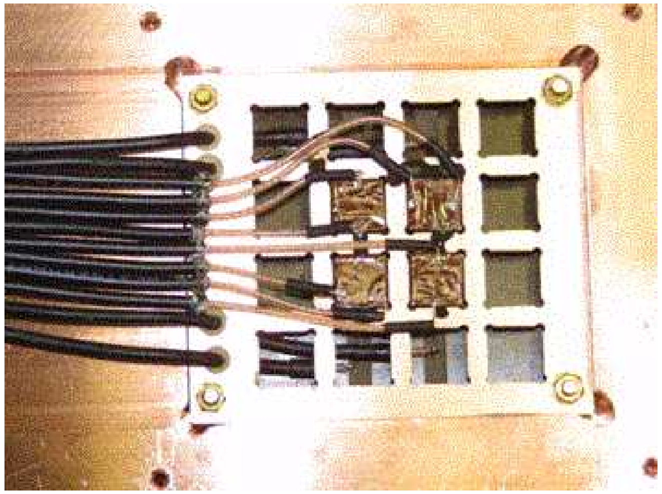
COBRA:

The CaTe 0-neutrino double-Beta Research Apparatus.

Advantages of the COBRA approach are:

- Source = detector
- Semiconductor (Good energy resolution, clean)
- Room temperature
- Modular design (Coincidences)
- Two isotopes at once
- Industrial development of CdTe detectors
- Possibility of Tracking ("Solid state TPC")





Summary and Conclusion

- Overall form of MNS lepton mixing matrix is now determined
- Details, especially in top RH corner are essential
- ν mass-squared differences $\sim$ determined
- Hints of $0\nu2\beta$ decay which need to be confirmed/refuted
- UK is involved in an exciting array of neutrino experiments which address all the outstanding questions

Shameless Plug...

or The Simplest Neutrino Mass Matrix

The following neutrino mass(-squared) matrix is the simplest one which describes the data:

$$M_\nu M_\nu^\dagger \sim aI + x \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} + i\frac{d}{\sqrt{3}} \begin{pmatrix} 0 & 1 & -1 \\ -1 & 0 & 1 \\ 1 & -1 & 0 \end{pmatrix}$$

with

$$x \simeq -\frac{\Delta m^2_{\rm atm}}{2}, \qquad d \simeq \sqrt{\Delta m^2_{\rm sol} \Delta m^2_{\rm atm}} \simeq 0.34x, \tag{1}$$

gives $U_{e2} = 1/\sqrt{3}$ and $|U_{\mu 3}| = |U_{\tau 3}|$ and $|U_{e3}| = \sqrt{2\Delta m^2_{\rm sol}/3\Delta m^2_{\rm atm}} \simeq 0.13 \pm 0.03$, consistent with the phenomenology.

(PFH and Bill Scott, hep-ph/0403278).