Introduction to Neutrino Physics

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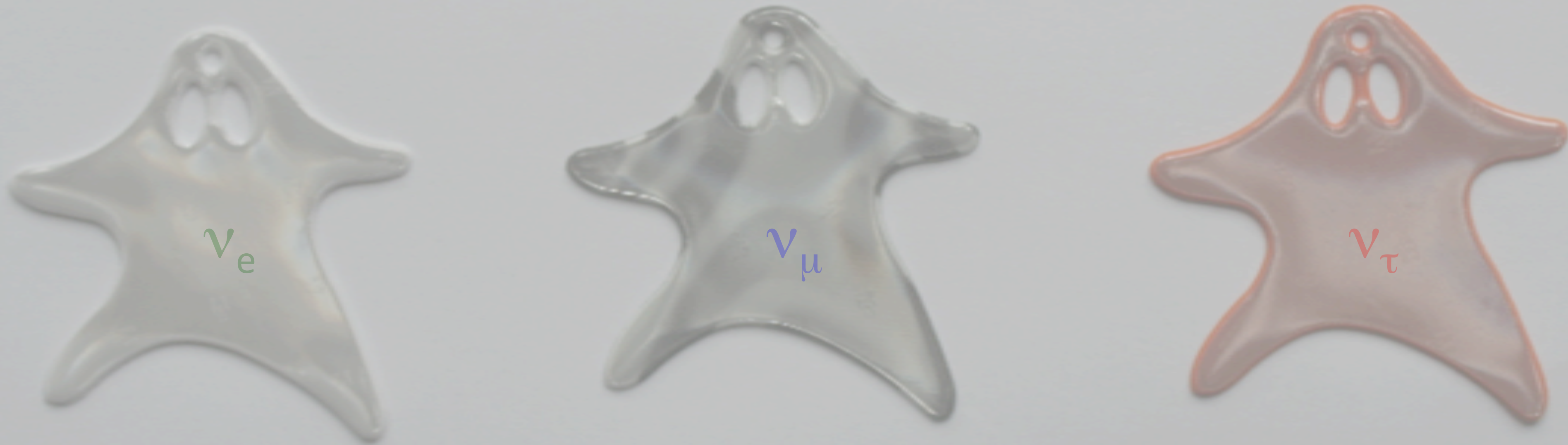


Lecture 2

Neutrino oscillations Part II

University of Sussex

Lunds universitet

Recap lecture 1

- Neutrinos oscillate between different flavours because they have non-zero mass AND their mass eigenstates are different from their flavour eigenstates

- Derivation of two-flavour mixing:

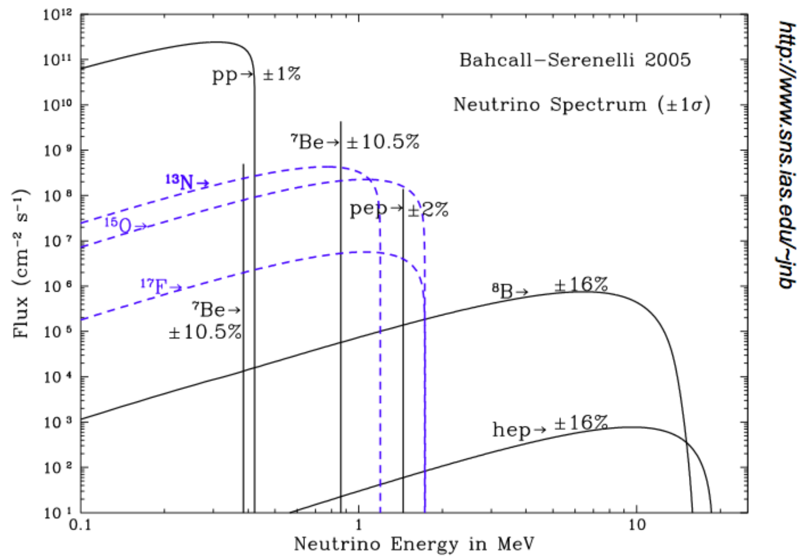
$$P_{\nu_\alpha \to \nu_\beta}(L) = \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$$

- The study of neutrinos from the sun showed an apparent deficit of neutrinos – we know now that it is due to oscillations

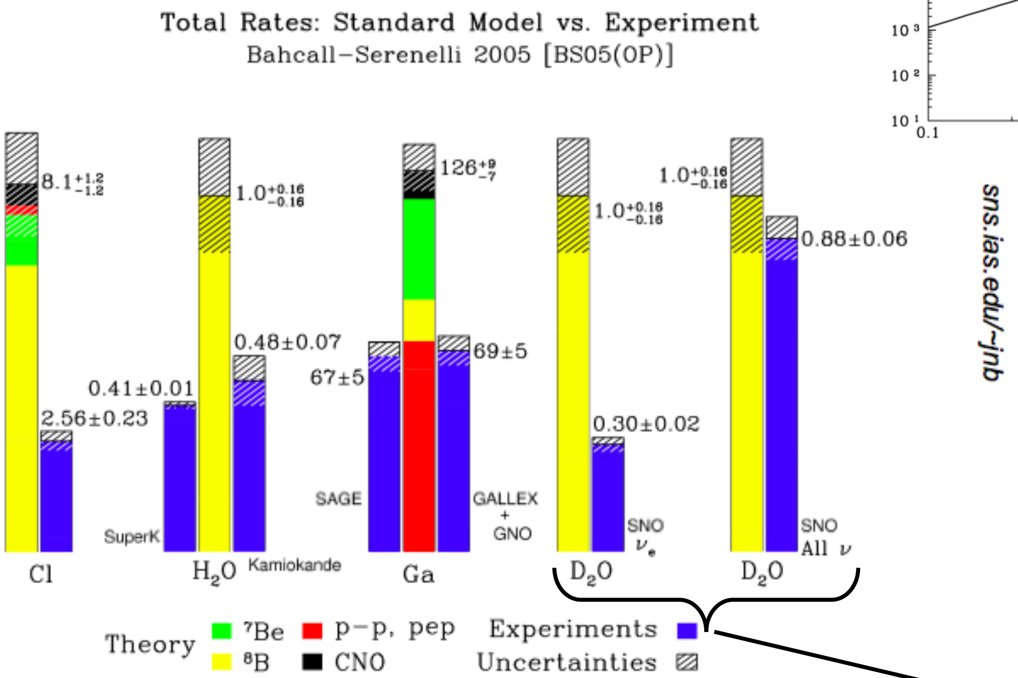
Outline lecture 2

- Solar neutrinos (continued from yesterday)
- Atmospheric and long-baseline neutrinos
- θ_{13} and CP violation

Solar neutrinos and the solar neutrino problem

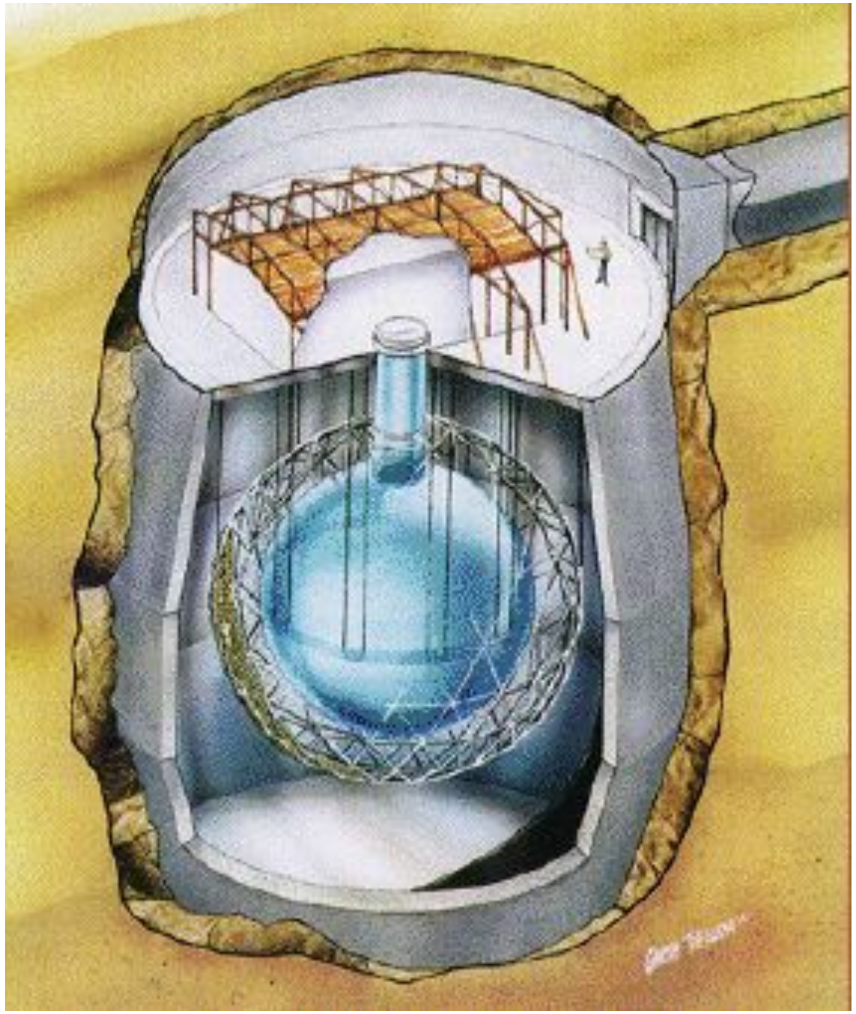


Neutrino energy O(1 MeV)



Solved in 2002 by SNO

SNO



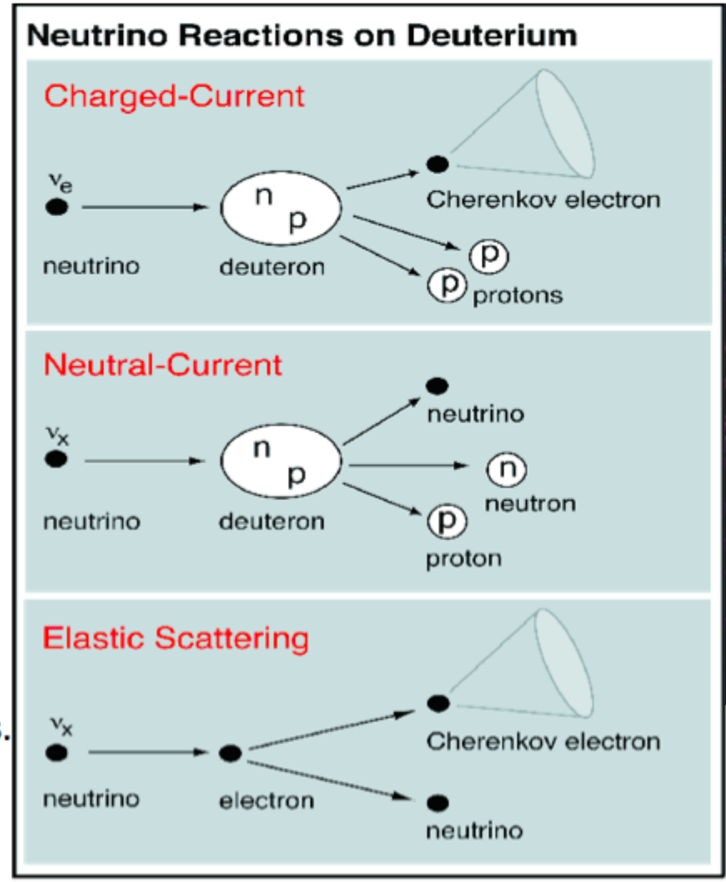
- Sudbury Neutrino Observatory in Creighton nickel mine, Canada
- Tank of 1 kton of heavy water
- 2002: Explained where the missing electron neutrinos have gone

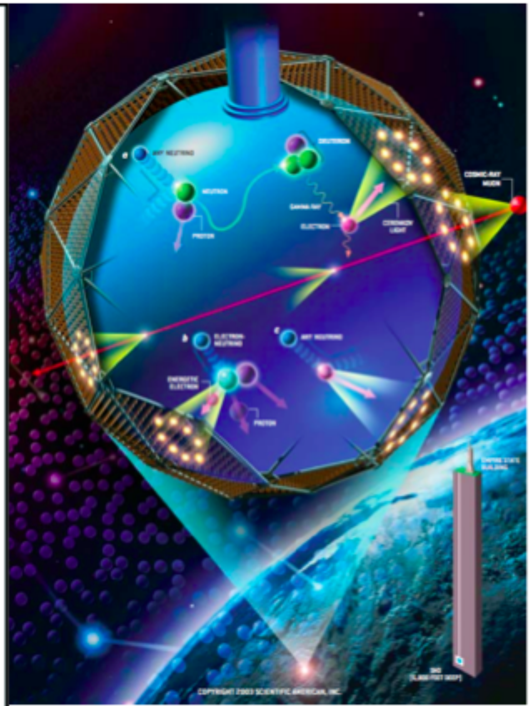
Signals in SNO

- Direct relation with ν_e energy spectrum
- Weak directional sens.
- Only sensitive to ν_e

•Equal sens. to all ν

- Rel. small cross sect.
- Mainly sensitive to ν_e
- Strong directional sens.

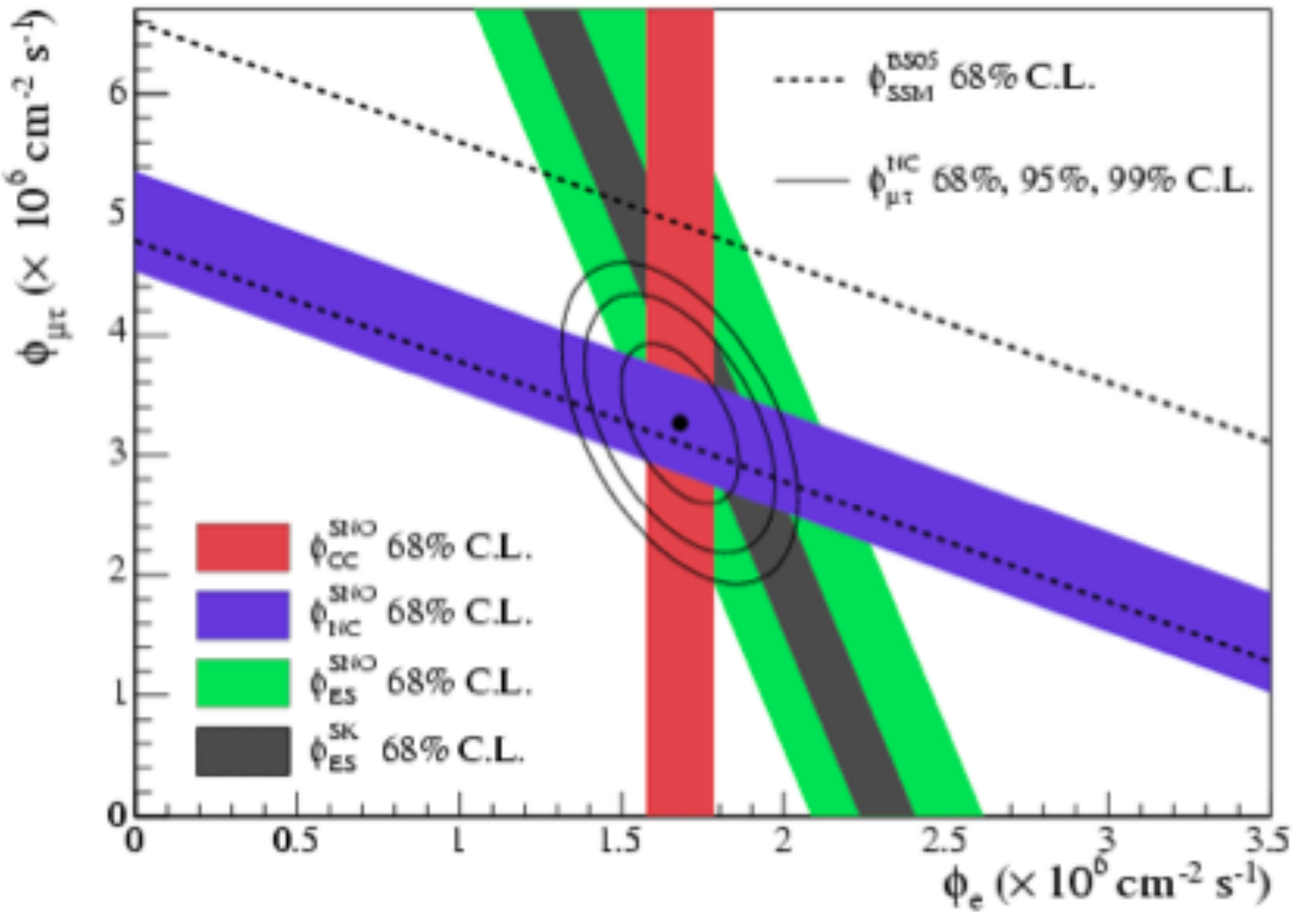




Different w.r.t. earlier experiments: Can measure total ν flux as well as ν_e

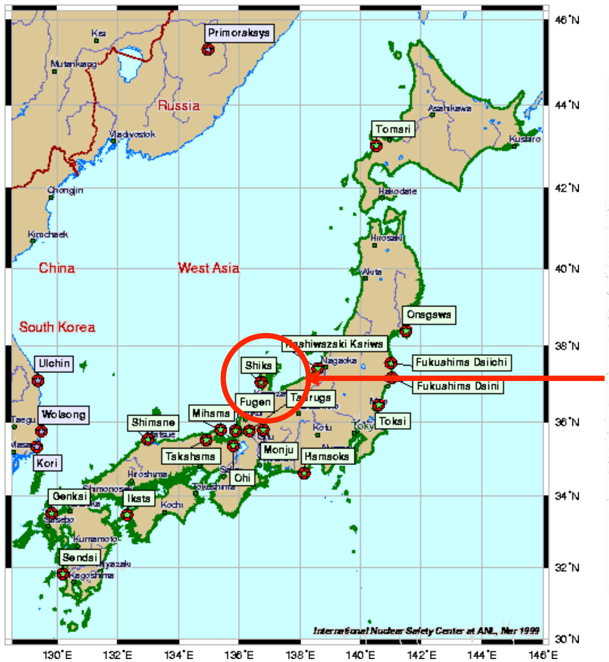
SNO results

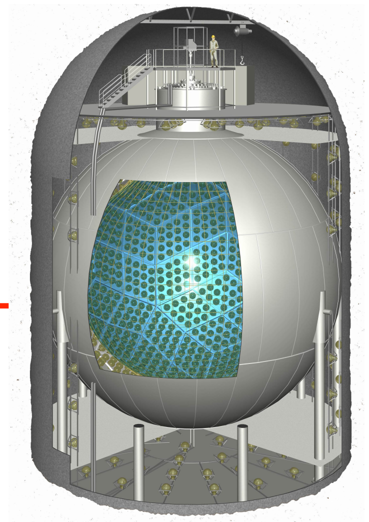
Flux of $\nu_{\mu\tau}$ vs flux of ν_e



KamLAND

Study solar neutrino mixing parameters with reactor antineutrinos
Assumes that anti-ν_e oscillates in the same way as ν_e: CPT conservation

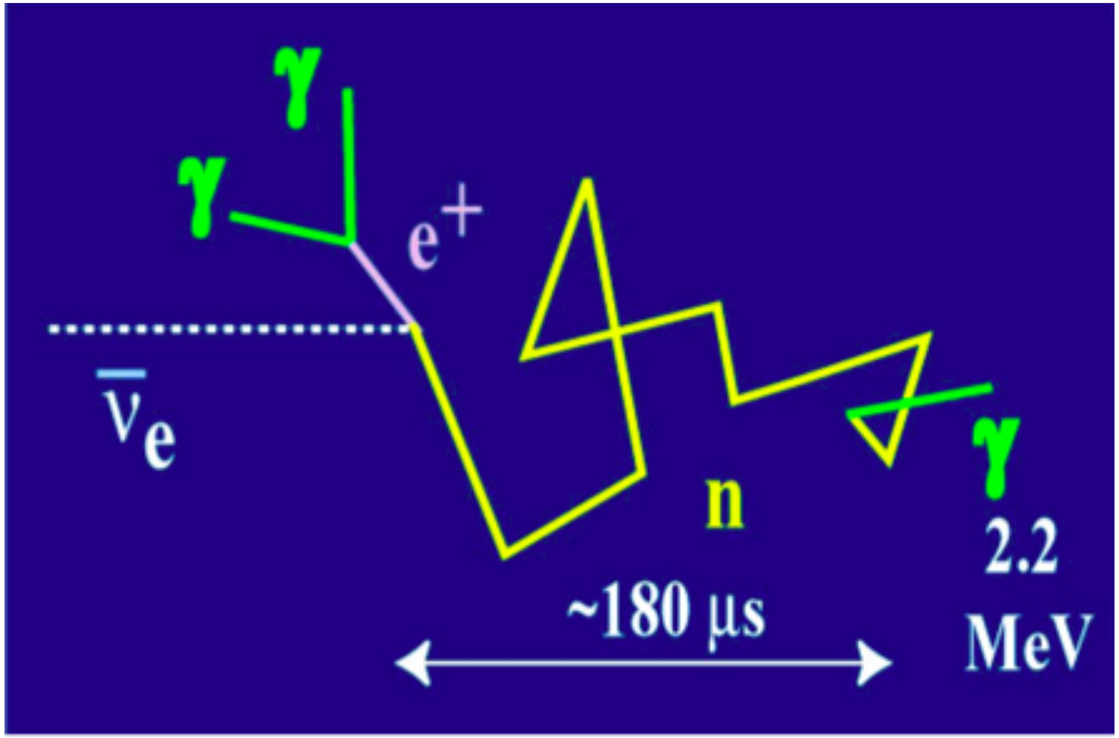




Kamioka mine in Japan
Multiple reactors with a
baseline of ~180 km

KamLAND

Liquid scintillator



Inverse beta decay on protons

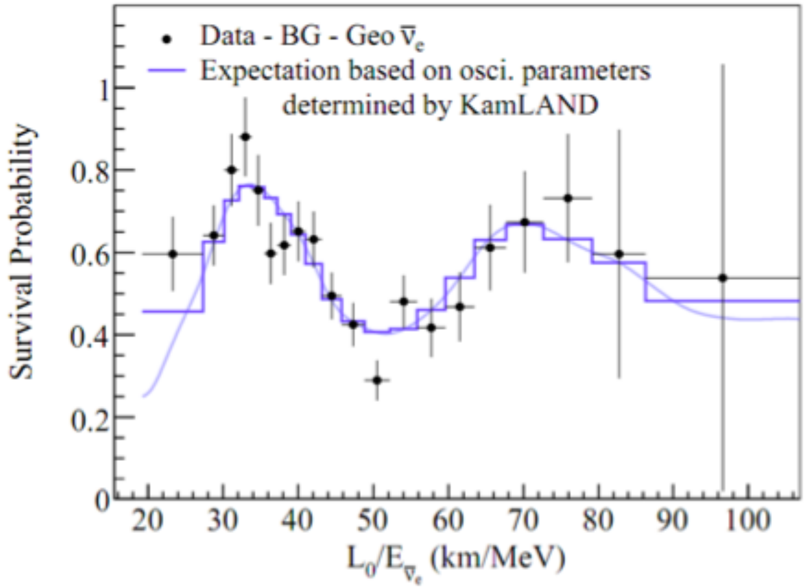
$\bar{\nu}_e + p \rightarrow e^+ + n$

Delayed co-incidence:

e^+: prompt
annihilation

n: delayed capture
release of 2.2 MeV γ

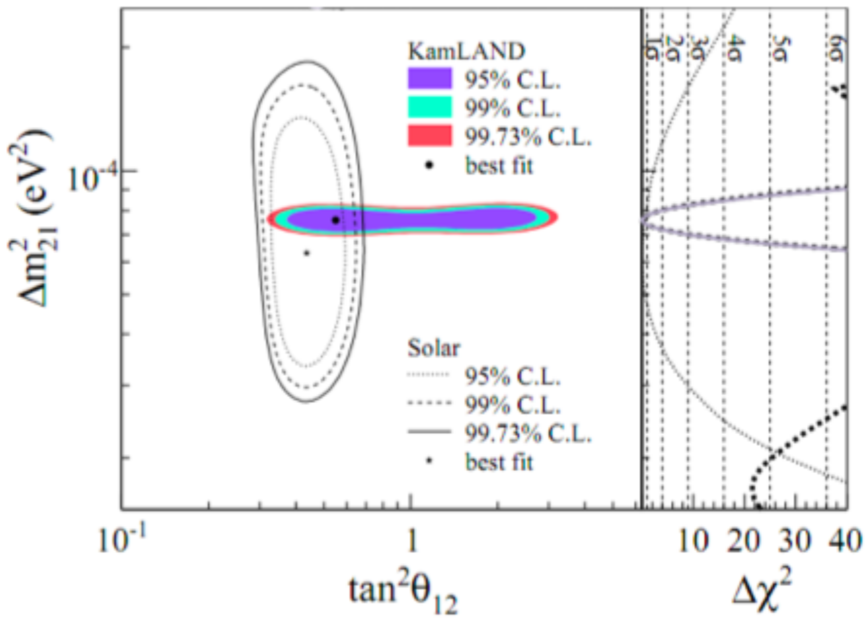
KamLAND result



Anti-ν_e survival probability

26 reactors from distance range 140-210 km (80% of flux)

KamLAND compared to solar results



Current knowledge

"Atmospheric" from atmosphere and accelerators

"Subdominant" or "third"

CP-violation phase = ?

"Solar" from sun + reactors

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times U_{Maj}^{diag}$$

Well measured:

$\theta_{23} = (45 \pm 7)^o$
-> ~equal mixing of ν_μ and ν_τ

$\Delta m^2_{32} \approx$
$\Delta m^2_{atm} = 2.4 \times 10^{-3}$ eV^2

Until this summer ~unknown:

θ_{13} <~ 10^o

Now ~3σ indications that $\theta_{13} < 10^o$

$|\Delta m^2_{31}| \approx \Delta m^2_{32}$
but $\Delta m^2_{31} > 0$ or < 0
(normal or inverted hierarchy)?

Well measured:

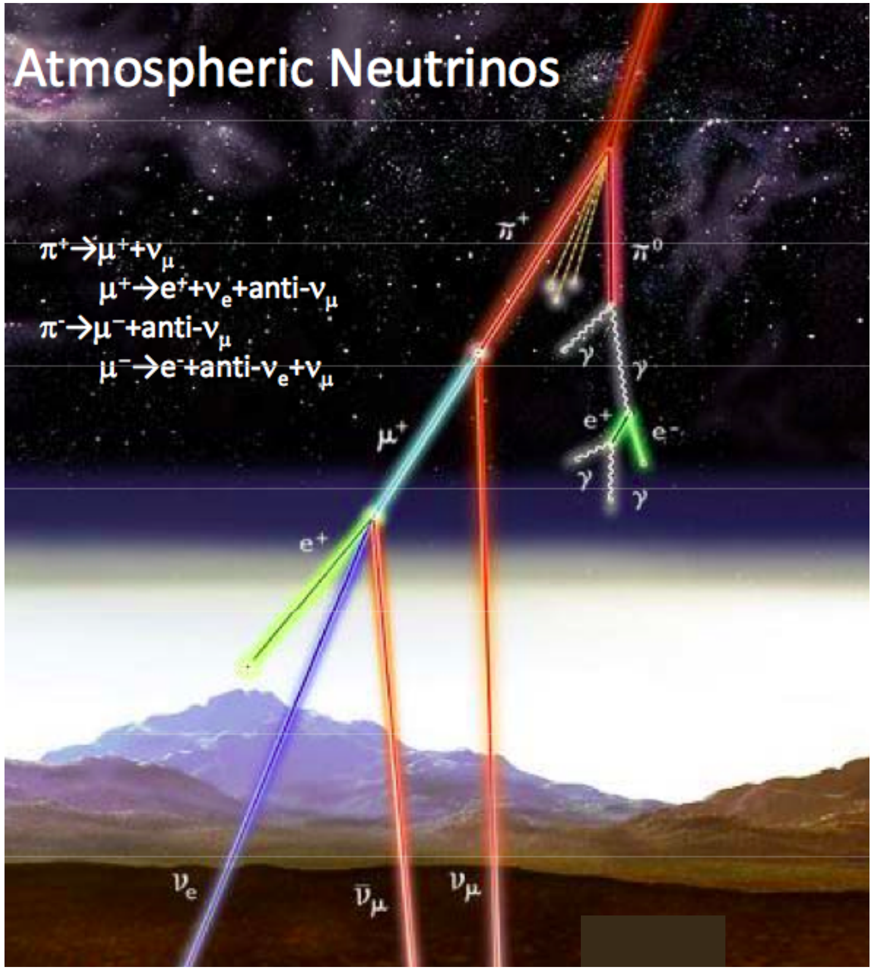
$\theta_{12} = (34 \pm 3)^o$
-> ν_1 is predominantly ν_e

$\Delta m^2_{21} = 7.6 \times 10^{-5}$ eV

$\nu_2 > \nu_1$ (sign of Δm^2_{21})
from matter effects in sun

Atmospheric neutrinos

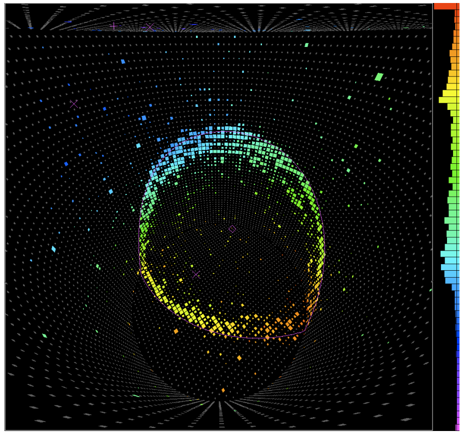
- Cosmic-ray protons strike the upper atmosphere of the Earth
- End of cascade:
  two ν_μ for ever ν_e
- Typical energy O(GeV)



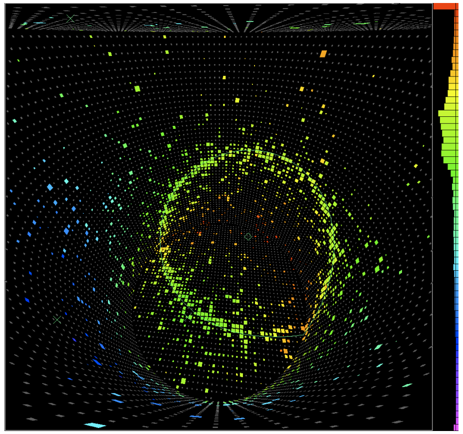
Super-Kamiokande

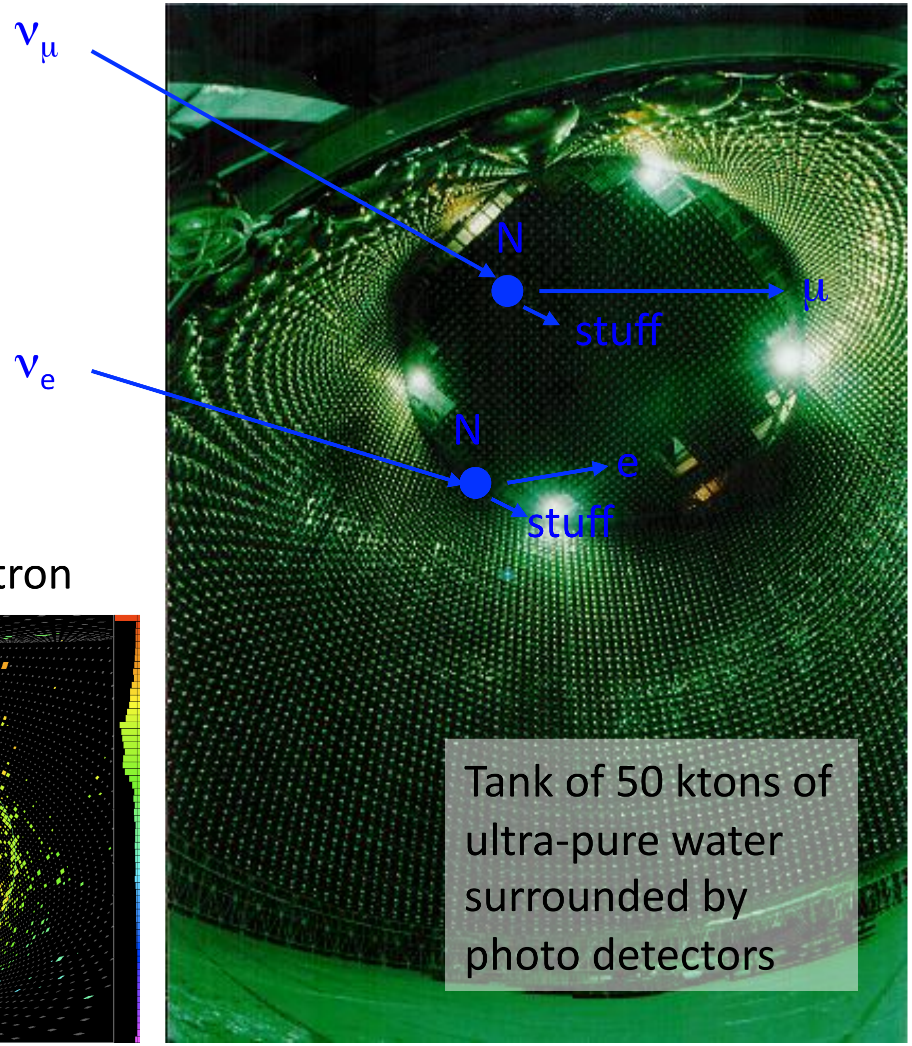
- Water Cherenkov detector located in the Kamioka mine in Japan
- **1998: First evidence for neutrino flavour change**
- Preceded by “atmospheric neutrino anomaly”

Muon

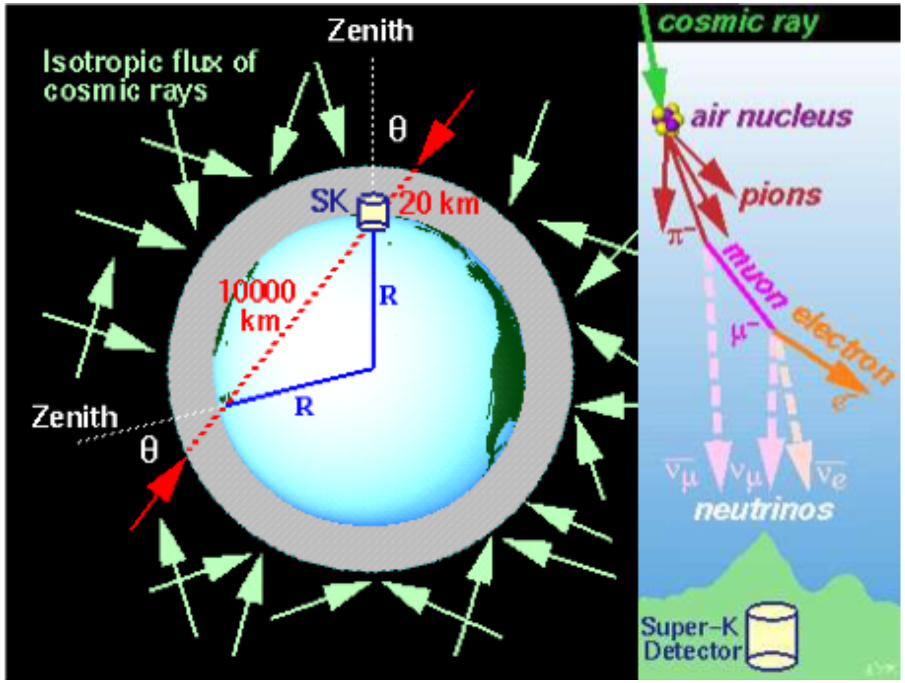


Showering electron

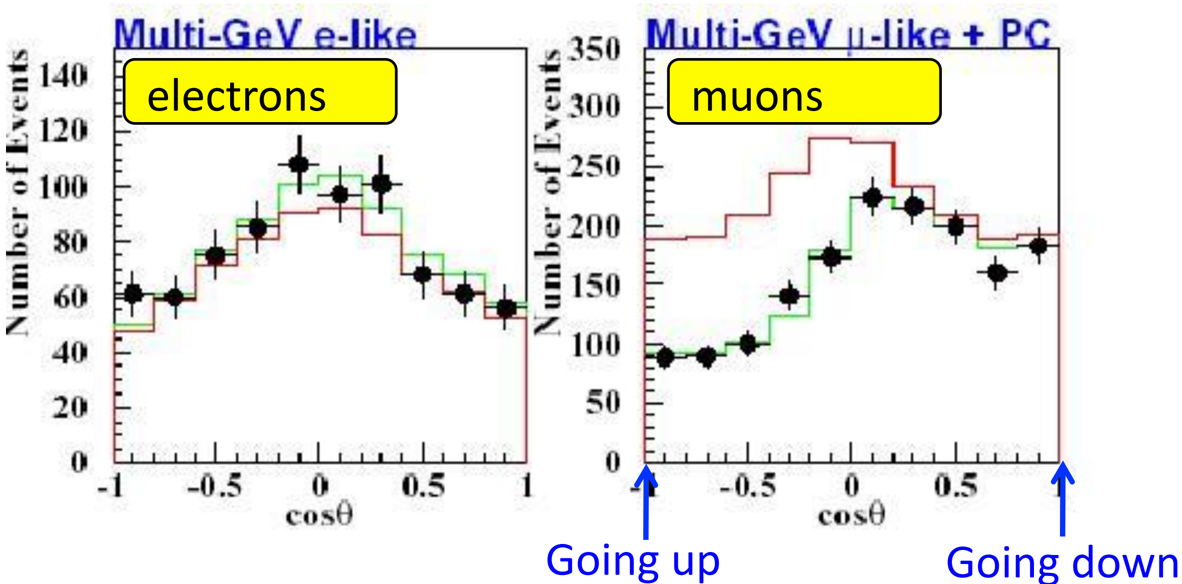




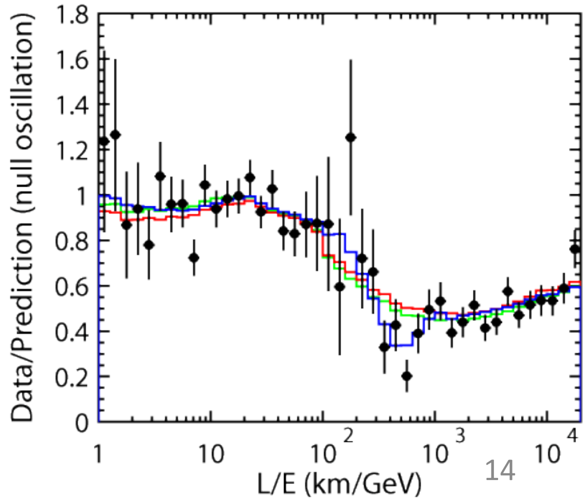
Super-Kamiokande results



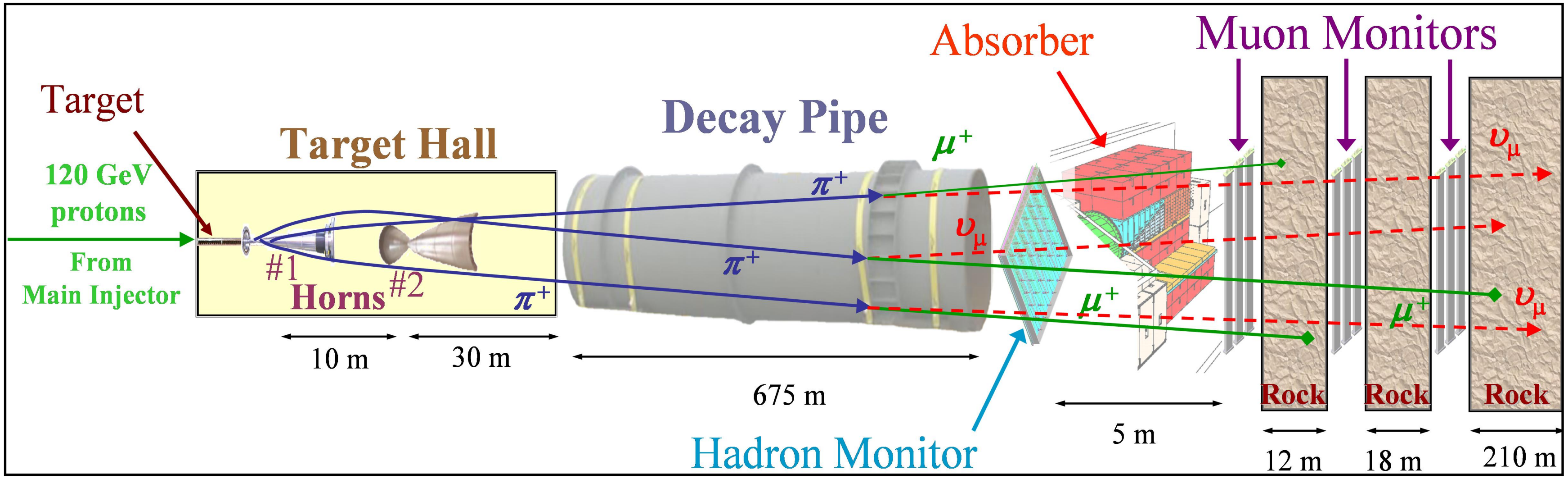
Observed:
Depletion of muon-neutrino events, but not of electron-neutrino events



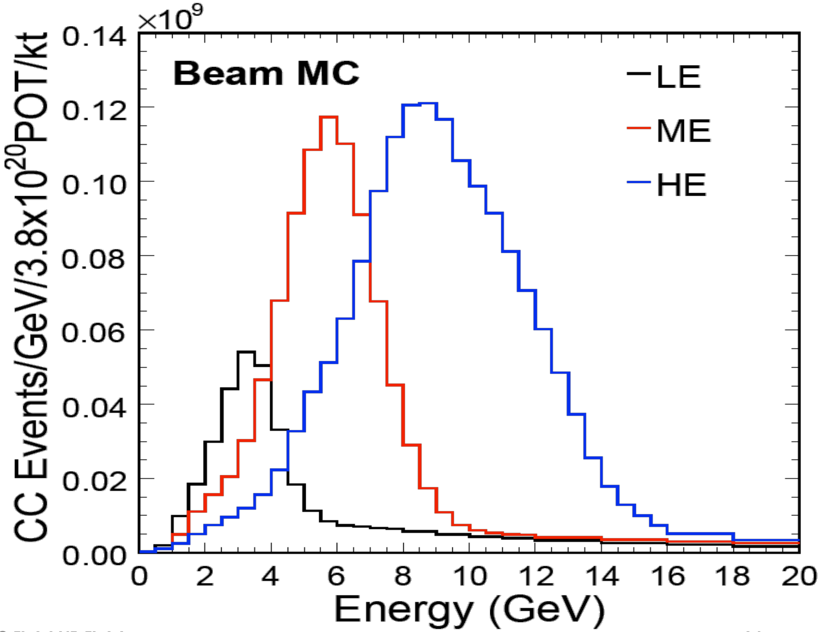
Later: sinusoidal survival probability as fnc of L/E



How to make a neutrino beam

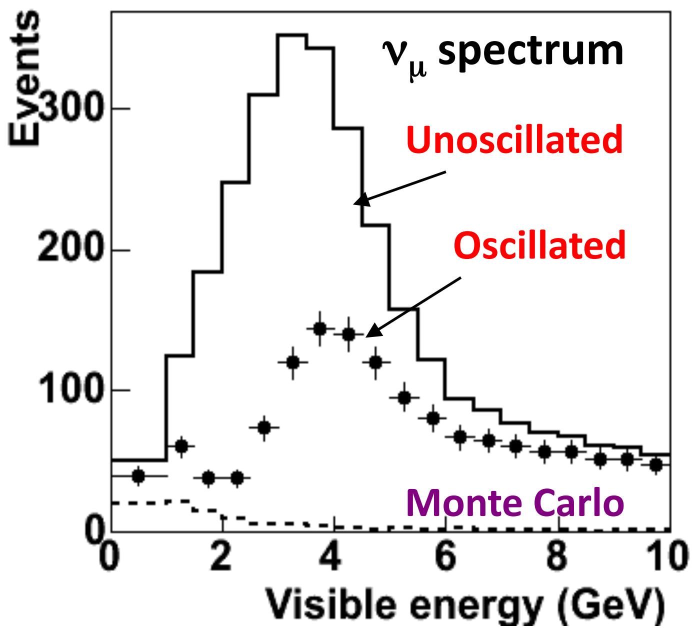


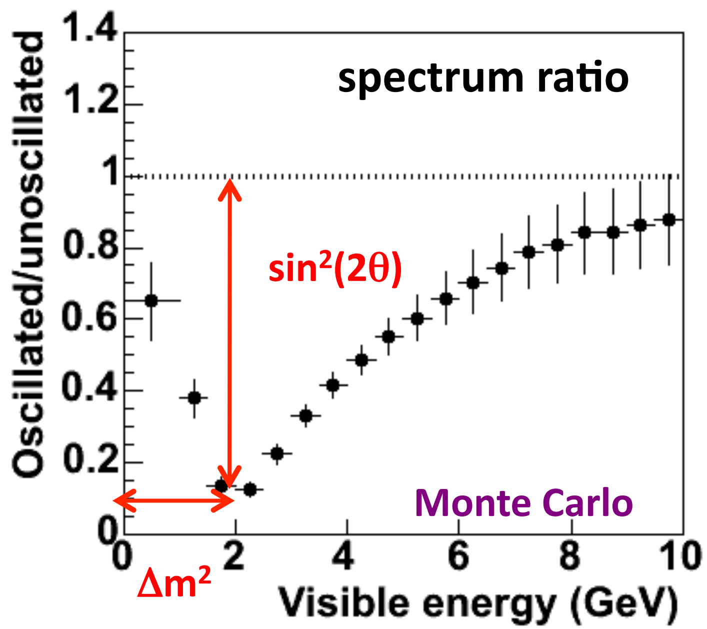
- Protons strike target
- Pulsed beam (~ few ms)
- Magnetic horns focus secondary π/K
  - Decay of π/K produces neutrinos
  - Neutrino spectrum changes with target position



Two-detector disappearance measurements

- Two-detector experiment to reduce systematic errors:
  - Flux, cross-section and detector uncertainties minimised
  - Measure unoscillated ν_μ spectrum at Near Detector
    - Extrapolate using MC
  - Compare to measured spectrum at Far Detector

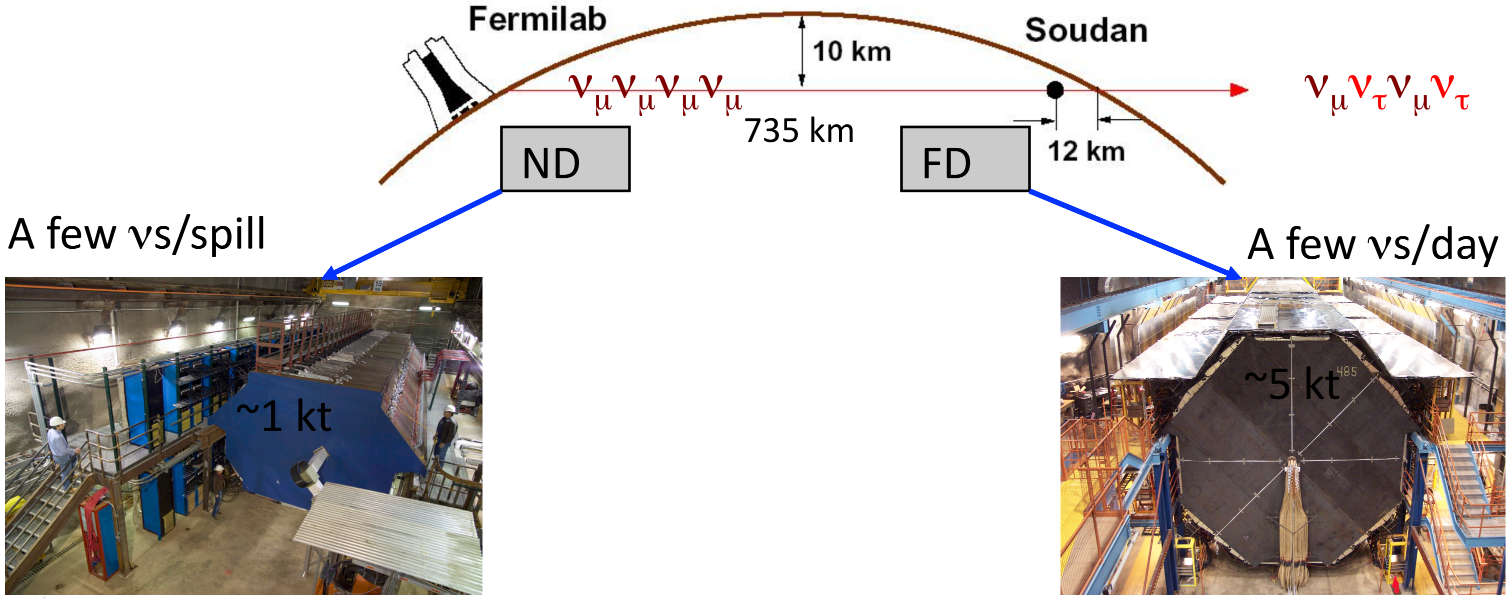




$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \boxed{\sin^2 2\theta}_{\,1} \sin^2(1.267 \boxed{\Delta m^2}_{\,2} L/E)$$

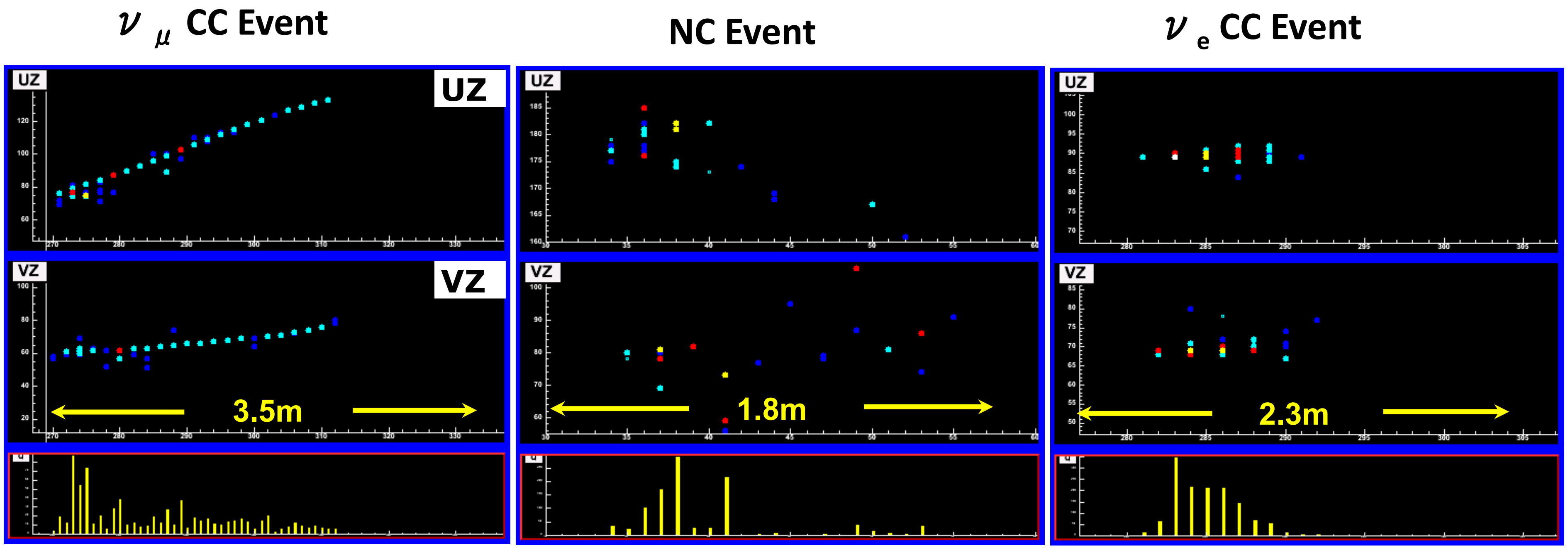
MINOS

- Tracking calorimeters:
  alternating layers of steel and scintillator
- Magnetic field measures charge of muons
- Data-taking since 2005
- Most precise measurement of Δm^2_{atm}
- → MINOS+ next year (in higher-E NOνA beam)



Event topologies

Monte Carlo

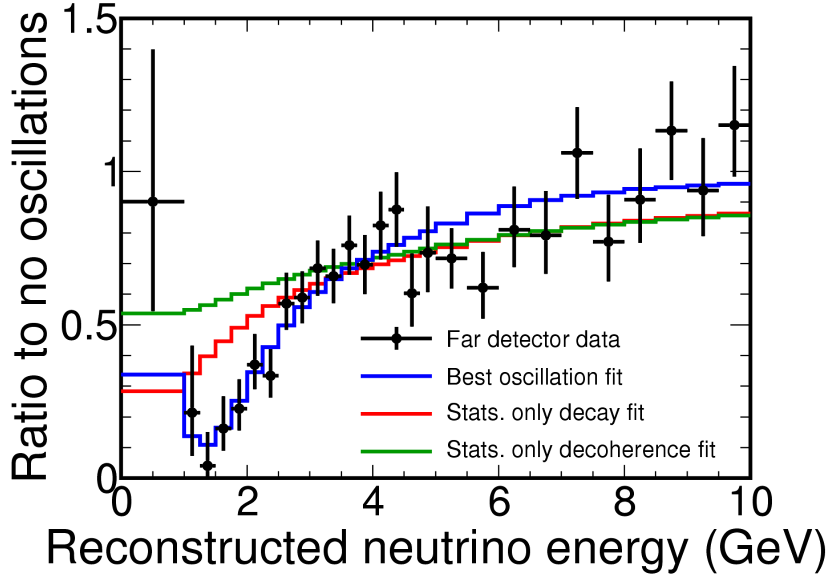


long μ track & hadronic activity at vertex

short event, often diffuse

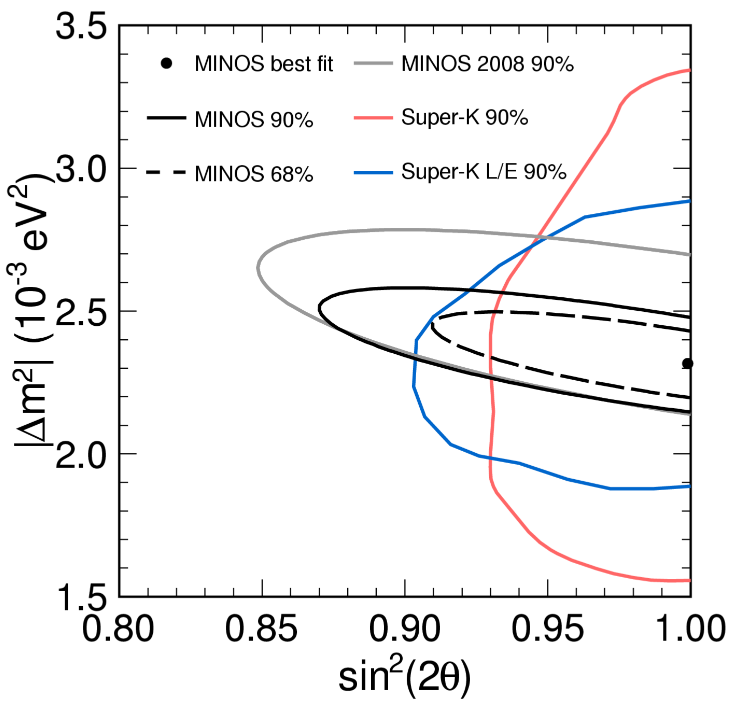
short, with typical EM shower profile

MINOS ν_μ disappearance result



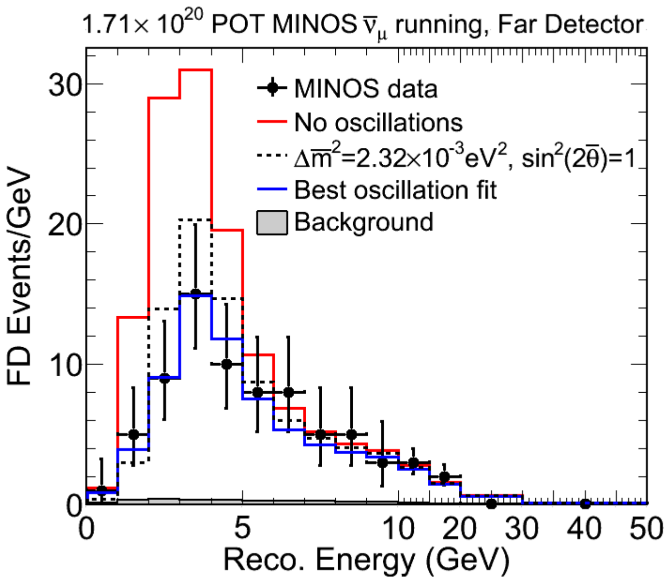
Δm^2=($2.32^{+0.12}_{-0.08}$) x 10^{-3} eV^2 and
$\sin^2(2\Theta)$ =1.00 ($\sin^2(2\Theta)$ > 0.90 at 90% CL)

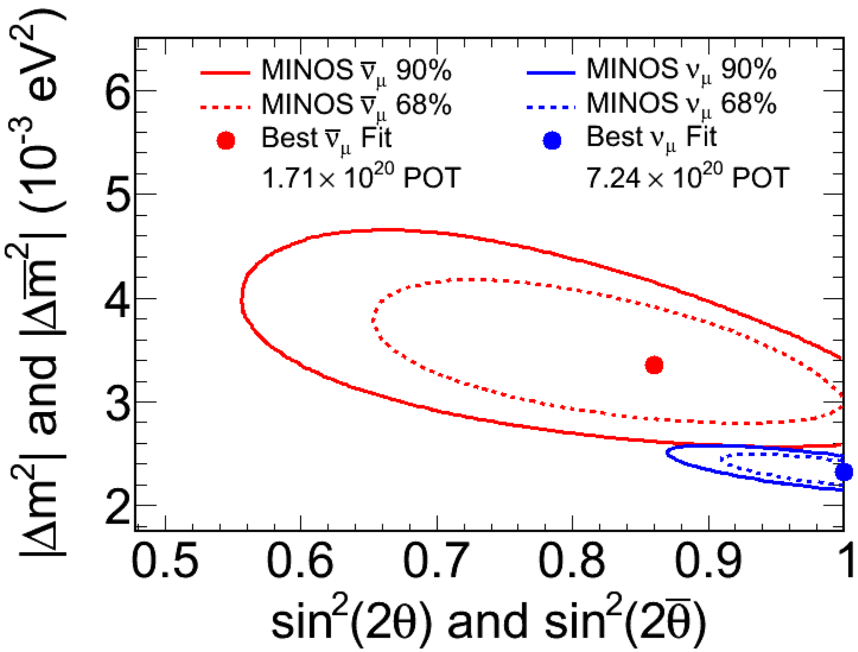
Will be overtaken by T2K,
who already have comparable
precision on Δm^2



MINOS anti-ν_μ disappearance: CPT test

- Reverse current through magnetic beam focusing horns to focus negatively charged particles → anti-ν_μ beam!
- $\overline{\nu}_\mu \rightarrow \overline{\nu}_\mu \overset{CPT}{\leftrightarrow} \nu_\mu \rightarrow \nu_\mu$





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from matter effects in sun

Interlude:
When does the two-flavour approximation work?

Two orders of magnitude difference:

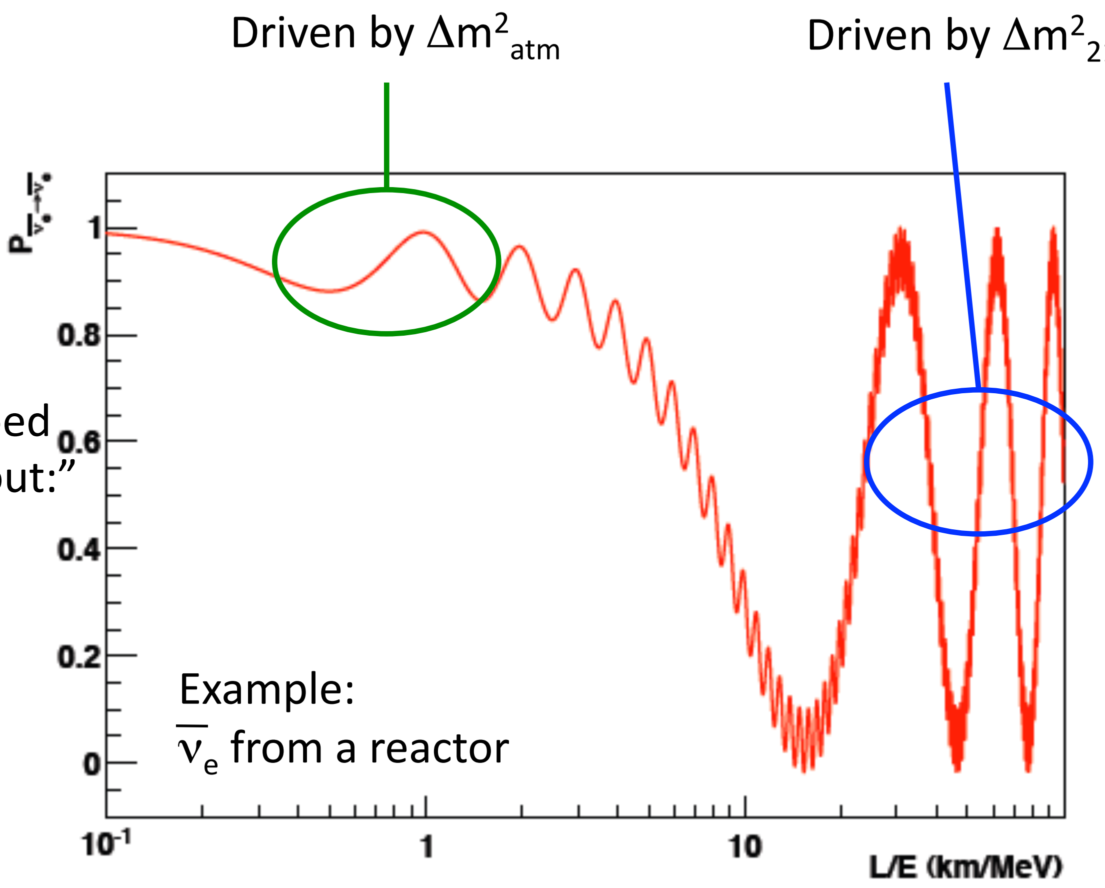
$$\Delta m^2_{\text{atm}} \sim O\left(10^{-3}\ \text{eV}^2\right) \text{ and}$$

$$\Delta m^2_{21} \sim O\left(10^{-5}\ \text{eV}^2\right)$$

At L/E~100 km:
Δm^2_{21} oscillations fully developed
Δm^2_{atm} oscillations "averaged out:"

At L/E~1 km:
Δm^2_{atm} oscillations developed
Δm^2_{21} not yet kicked in

Must use 3-flavour mixing for %-level precision



Leptonic CP violation

- Remember:
  CP violation in quarks not sufficient to explain the matter/antimatter asymmetry of the universe
- Leptogenesis:
  A heavy, right-handed, CP-violating neutrino could have created the asymmetry just after the Big Bang
- δ_{CP} can only be non-zero if all three mixing angles are non-zero → grouped with θ_{13}, as we know the other two are > 0

θ_{13}: Long-baseline accelerator vs. reactor experiments

LBL accelerator experiments:

- Look for appearance ($\nu_\mu \rightarrow \nu_e$) in pure ν_μ beam vs. *L* and *E*
- Near detector to measure background ν_es (beam + mis-id)
- $P(\nu_\mu \rightarrow \nu_e) = f(\delta, \text{sign}(\Delta m_{31}^2))$

Reactor experiments:

- Look for disappearance ($\bar{\nu}_e \rightarrow \bar{\nu}_e$) as a fnc of *L* and *E*
- Near detector to measure unoscillated flux
- $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ independent of δ; matter effects small

Combination of appearance and disappearance very powerful if comparable sensitivity

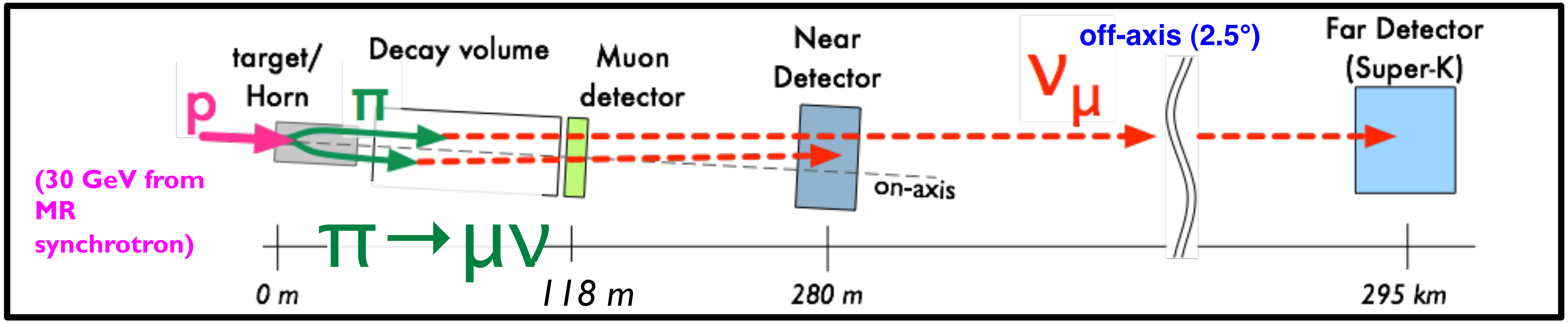
MINOS, T2K, NOνA

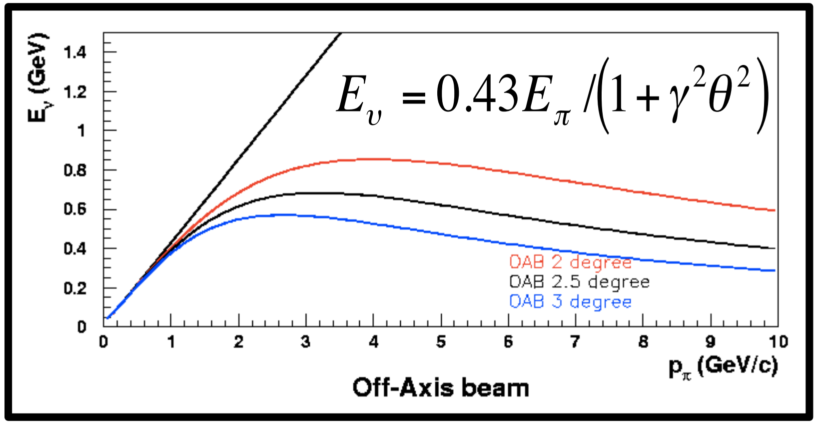
Double Chooz, Daya Bay, RENO

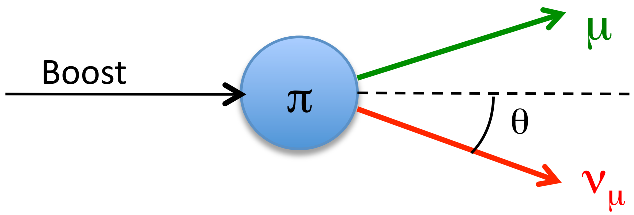
T2K

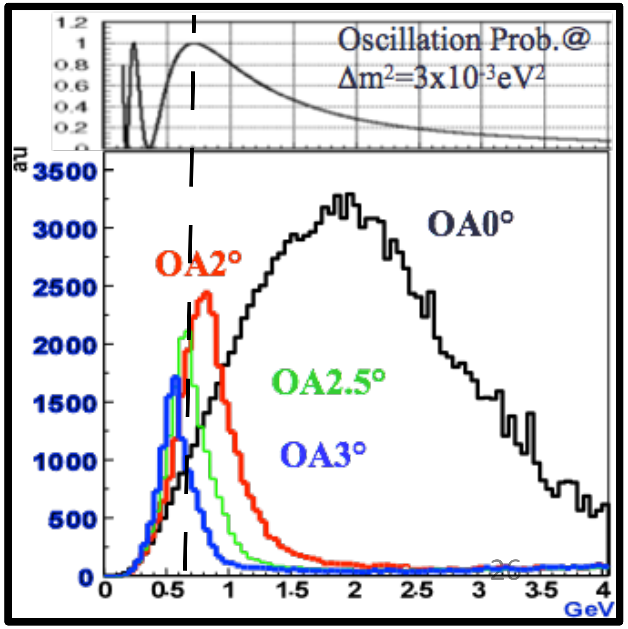
- FD: Super-Kamiokande
  Water Cherenkov detector 22.5 kton fiducial mass
- ND280: TPC + plastic scintillator
  Flux and cross-sections
- INGRID:
  beam intensity/direction

Off-axis beam







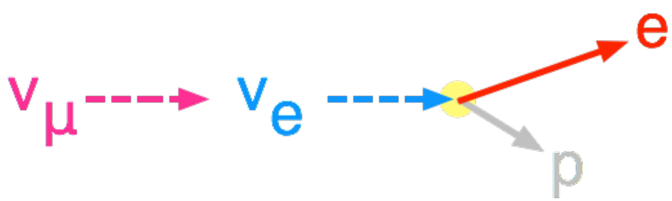


Off-axis beam reduces high-energy tail:

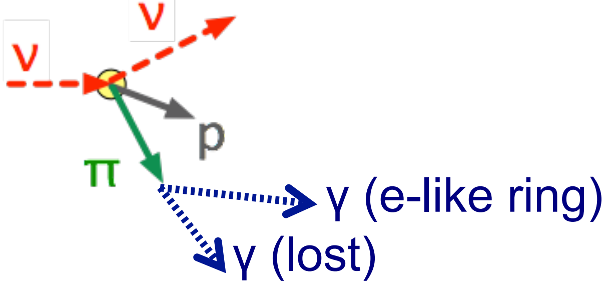
- Narrow-band beam around oscillation maximum
- Reduces feed-down from mis-reconstructed higher-E events

T2K ν_e appearance analysis

- Basic idea
  - Apply selection criteria to Super-K data to isolate **ν_e-CCQE** events



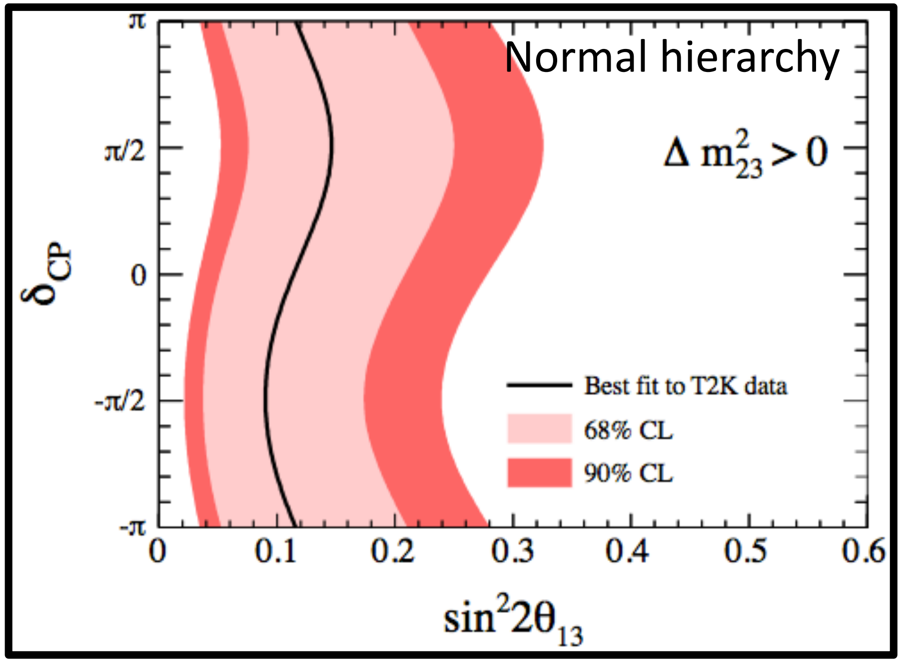
  - Compare with expected number of background events → measure appearance probability
- Backgrounds
  - **Intrinsic ν_e contamination** from μ, K decays in decay pipe
  - **NC-π^0** interactions of ν_μ (missed or merged gamma-rays → single e-like ring detected)

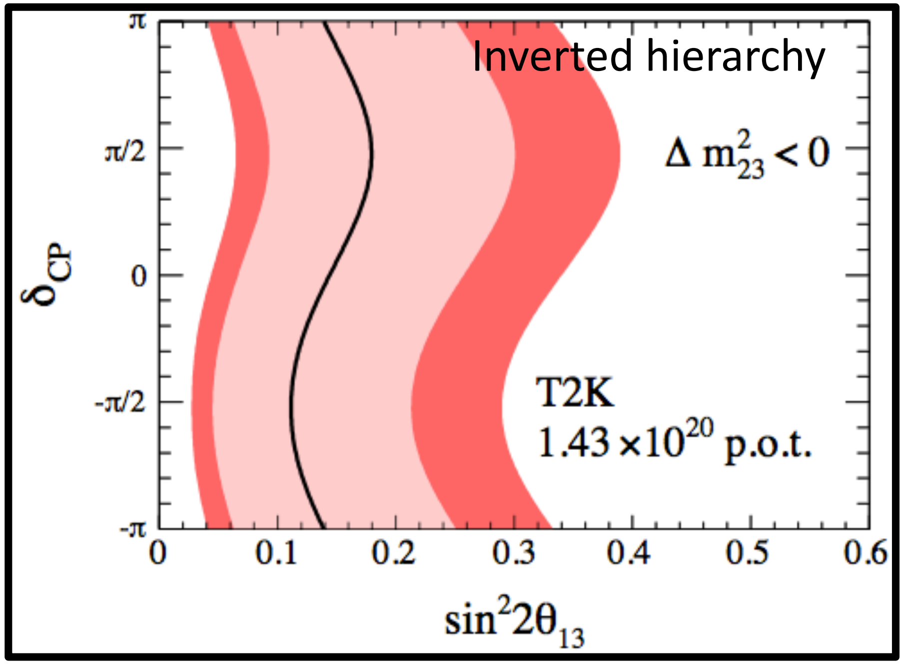


T2K first result (Jun 2011)

~ 1 year's worth of data
6 candidate ν_e events
Expected BG of 1.5+/-0.3 events for $\sin^2 2\theta_{13} = 0$
P-value of 0.7 % for null hypothesis

2.5σ indication for $\theta_{13} > 0$

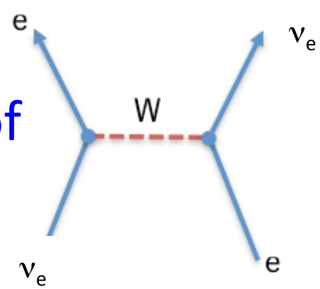


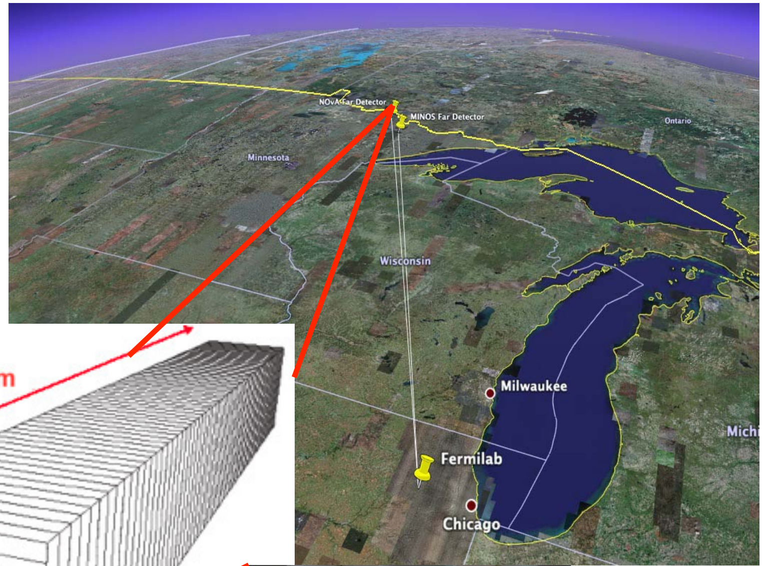


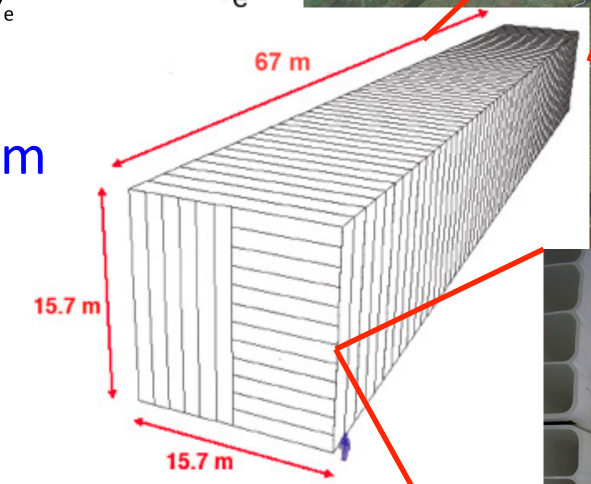
MINOS result from summer 2011:
Excludes for $\sin^2 2\theta_{13} = 0$ at 89% CL
Prefers smaller θ_{13} : $\sin^2 2\theta_{13}$ = 0.04(0.08) NH(IH)

NOνA

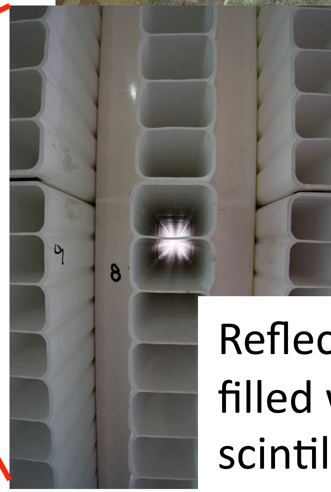
- Expected start in 2013
- Also sensitive to mass hierarchy: can make use of MSW effect over 810 km baseline
- Forward scattering of (anti) neutrinos in matter differ because of the extra diagram for scattering off electrons
- Oscillation probabilities: $P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
- Normal hierarchy: $P(\nu_\mu \rightarrow \nu_e) > P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$; inverted hierarchy: the other way around







+ smaller Near Detector



Reflective cells filled with liquid scintillator

Recap and outlook

- Neutrino mixing parameters (θ, Δm^2) for "solar" and "atmospheric" neutrino sectors have been well measured
- We are seeing the first results from experiments that will tell us about the subdominant θ_{13}
- θ_{13} must be > 0 for δ to exist
  - But there is another possibility for leptonic CP violation if neutrinos are Majorana particles
- $\sin^2 2\theta_{13}$ must be >~ 0.01 to be experimentally accessible
  - This would open up an avenue for leptonic CPv
- θ_{13} with reactors first in Lecture 3
- Then on to Majorana neutrinos and neutrinoless double beta decay

Back-ups