The State of the Neutrino Mixing Matrix

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2009 APS April Meeting

Mixing Matrix

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \mathbf{U}^\dagger \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

- Neutrinos have mass
- ν_e, ν_μ, $\nu_\tau \leftrightarrow \nu_1$, ν_2, ν_3
  - Flavor states—creation and detection
  - Mass states—propagation
- Neutrinos born as one flavor can later be detected as another flavor
- PMNS matrix relates the two bases

Mixing Matrix

$$P(\nu_\alpha \rightarrow \nu_\alpha) = \left| \sum_j U^*_{\alpha j} e^{-i\frac{m_j^2 L}{2E}} U_{\alpha j} \right|^2$$

- Neutrinos have mass
- $\nu_e, \nu_\mu, \nu_\tau \Leftrightarrow \nu_1, \nu_2, \nu_3$
  - Flavor states—creation and detection
  - Mass states—propagation
- Neutrinos born as one flavor can later be detected as another flavor
- PMNS matrix relates the two bases

Mixing Matrix

$$U = \begin{pmatrix} \cos\theta_{13}\cos\theta_{12} & \cos\theta_{13}\sin\theta_{12} & \sin\theta_{13}e^{-i\delta} \\ -\cos\theta_{23}\sin\theta_{12} - \sin\theta_{13}\cos\theta_{12}\sin\theta_{23}e^{+i\delta} & \cos\theta_{23}\cos\theta_{12} - \sin\theta_{13}\sin\theta_{12}\sin\theta_{23}e^{+i\delta} & \cos\theta_{13}\sin\theta_{23} \\ \sin\theta_{23}\sin\theta_{12} - \sin\theta_{13}\cos\theta_{12}\cos\theta_{23}e^{+i\delta} & -\sin\theta_{23}\cos\theta_{12} - \sin\theta_{13}\sin\theta_{12}\cos\theta_{23}e^{+i\delta} & \cos\theta_{13}\cos\theta_{23} \end{pmatrix}$$

$$\times \mathrm{diag}(1, e^{i\alpha}, e^{i\beta})$$

α, β—Majorana phases not observable in oscillation expts.

- Neutrinos have mass
- $\nu_e, \nu_\mu, \nu_\tau \leftrightarrow \nu_1, \nu_2, \nu_3$
  - Flavor states—creation and detection
  - Mass states—propagation
- Neutrinos born as one flavor can later be detected as another flavor
- **PMNS matrix relates the two bases**

Pontecorvo, Maki, Nakagawa, Sakata

Why measure all these angles?

- Precision measurements provide valuable check that neutrino oscillations are the right solution to neutrino anomalies
- PMNS matrix analogous to CKM matrix governing quark mixing
  - mixing in lepton sector much larger than mixing in quark sector
  - θ_{23} maximal? θ_{12} moderately large—why?
  - θ_{13} small, is it zero?—why?
  - Is there CP violation in the lepton sector? Is it big enough to account for matter vs. antimatter asymmetry in the Universe?

Mixing Matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Factorizes—3 terms, 3 experimental regimes

Mixing Matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Factorizes—3 terms, 3 experimental regimes
- (12) Sector identified with solar mixing
  - driven by small $\Delta m^2 = 7.59 \times 10^{-5}$ eV^2
  - Reactor+Solar experiments at L/E~15,000 km/GeV

    (See M. Chen in Session Q2 for Recent Solar Neutrino Results)

Mixing Matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Factorizes—3 terms, 3 experimental regimes
- (23) Sector identified with atmospheric mixing
  - driven by larger Δm^2=2.43x10^{-3} eV^2
  - Atmospheric neutrinos
  - accelerator experiments with L/E~500 km/GeV

Mixing Matrix

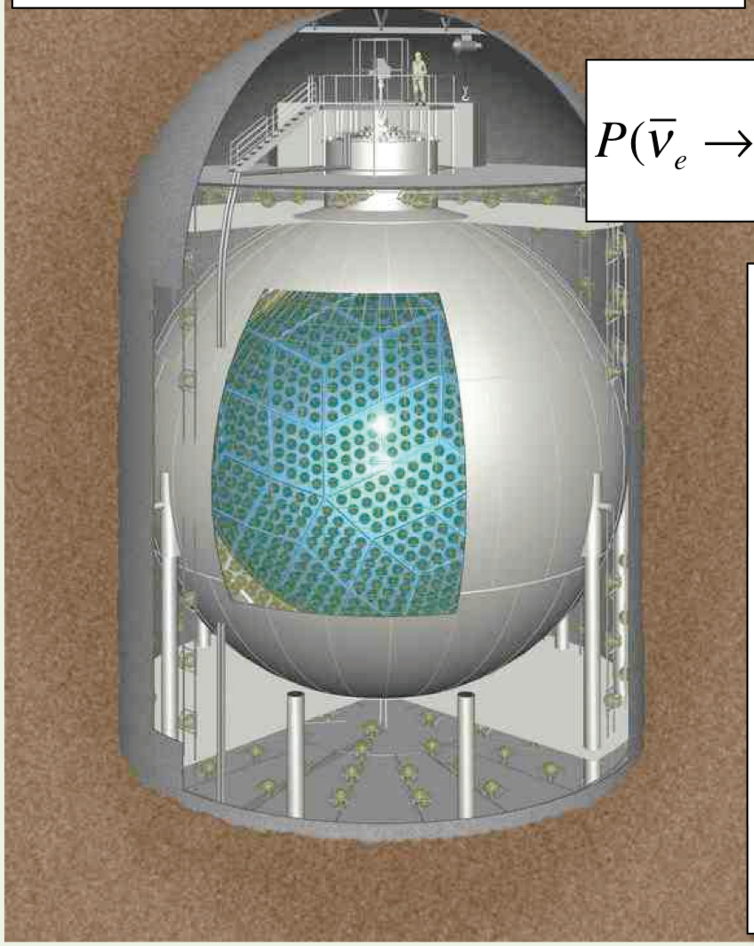
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Factorizes—3 terms, 3 experimental regimes
- (13) Sector mixing not yet observed
  - θ_{13} is small
  - accelerator experiments L/E~500 km/GeV
  - reactor experiments L/E~500 km/GeV (0.5 km/ MeV)

θ_{12}: KamLAND

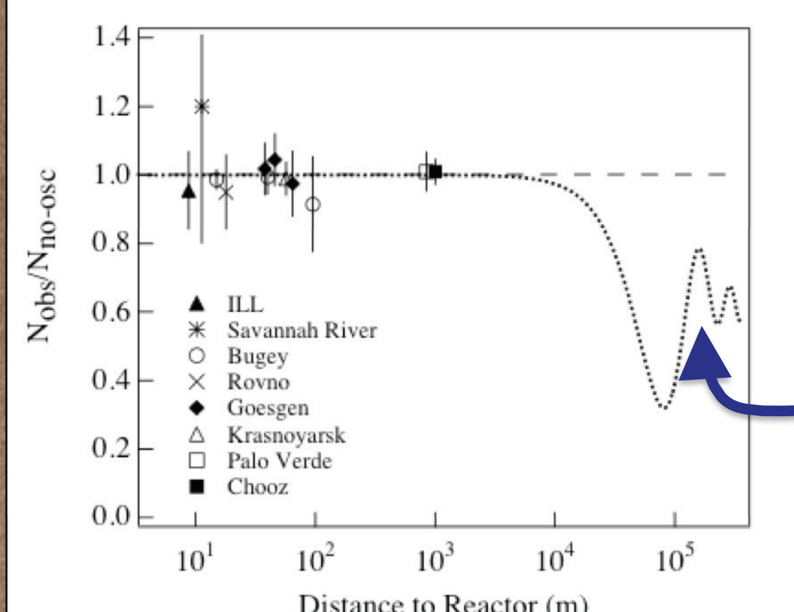
Liquid Scintillator Detector

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



Experimental strategy: electron antineutrino disappearance from 55 nuclear reactors around Japan

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \simeq \cos^4\theta_{13}\left(1 - \sin^2(2\theta_{12})\sin^2\frac{\Delta m^2_{12}L}{4E}\right) + \sin^4\theta_{13}$$



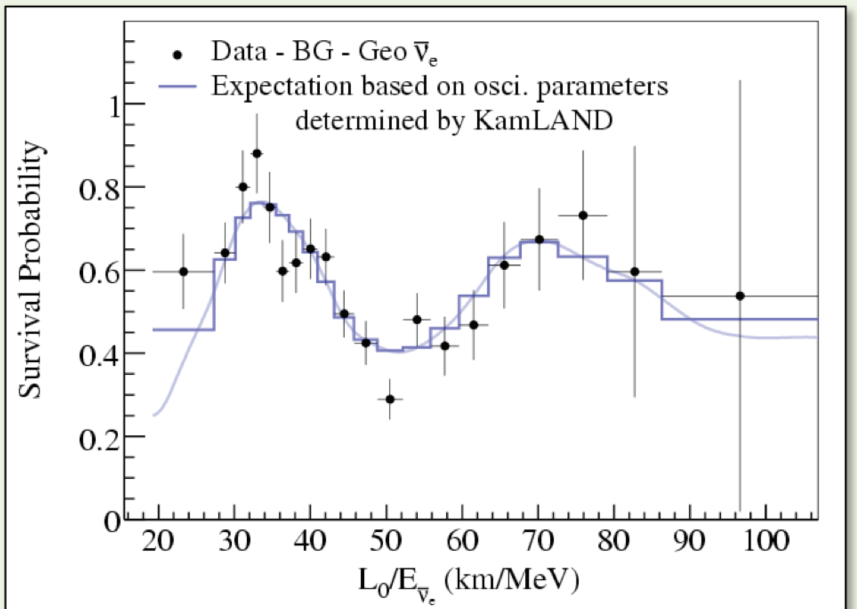
<L>=180 km

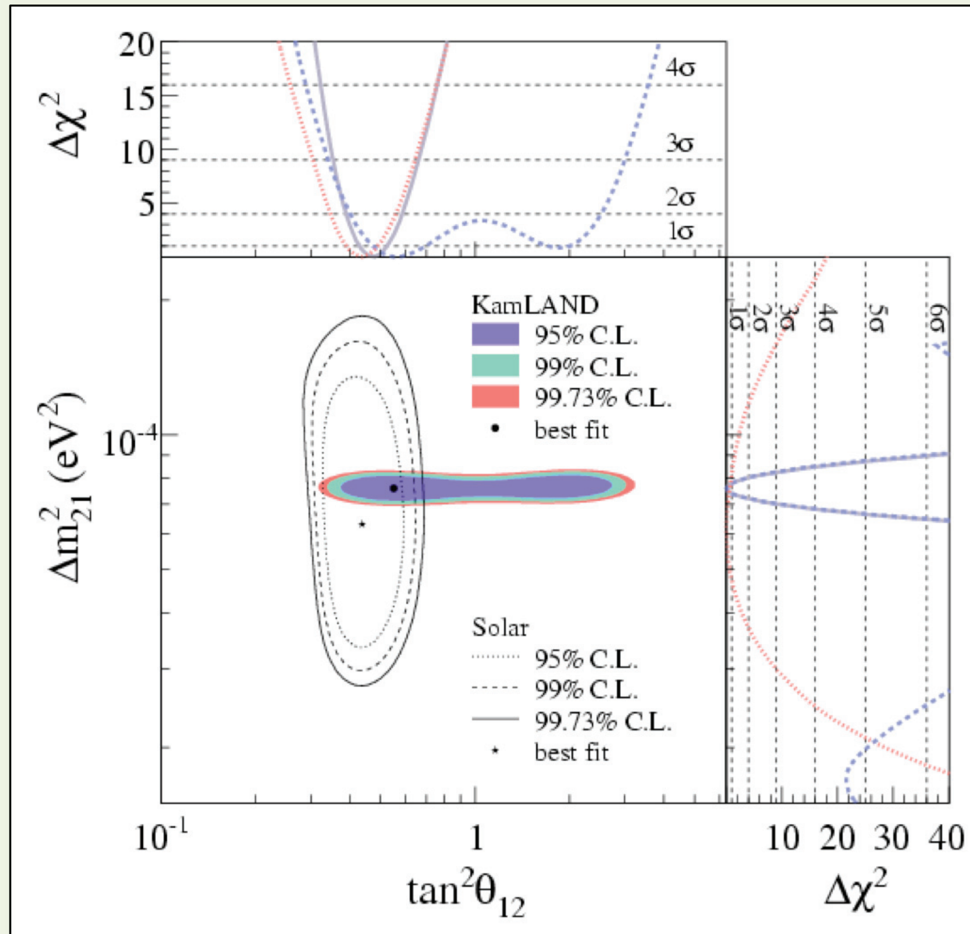
<E>=4 MeV

KamLAND

$$\textbf{KamLAND:}\ \tan^2\theta_{12} = 0.56^{+0.10}_{-0.07}(\text{stat.})^{+0.10}_{-0.06}(\text{syst.})$$

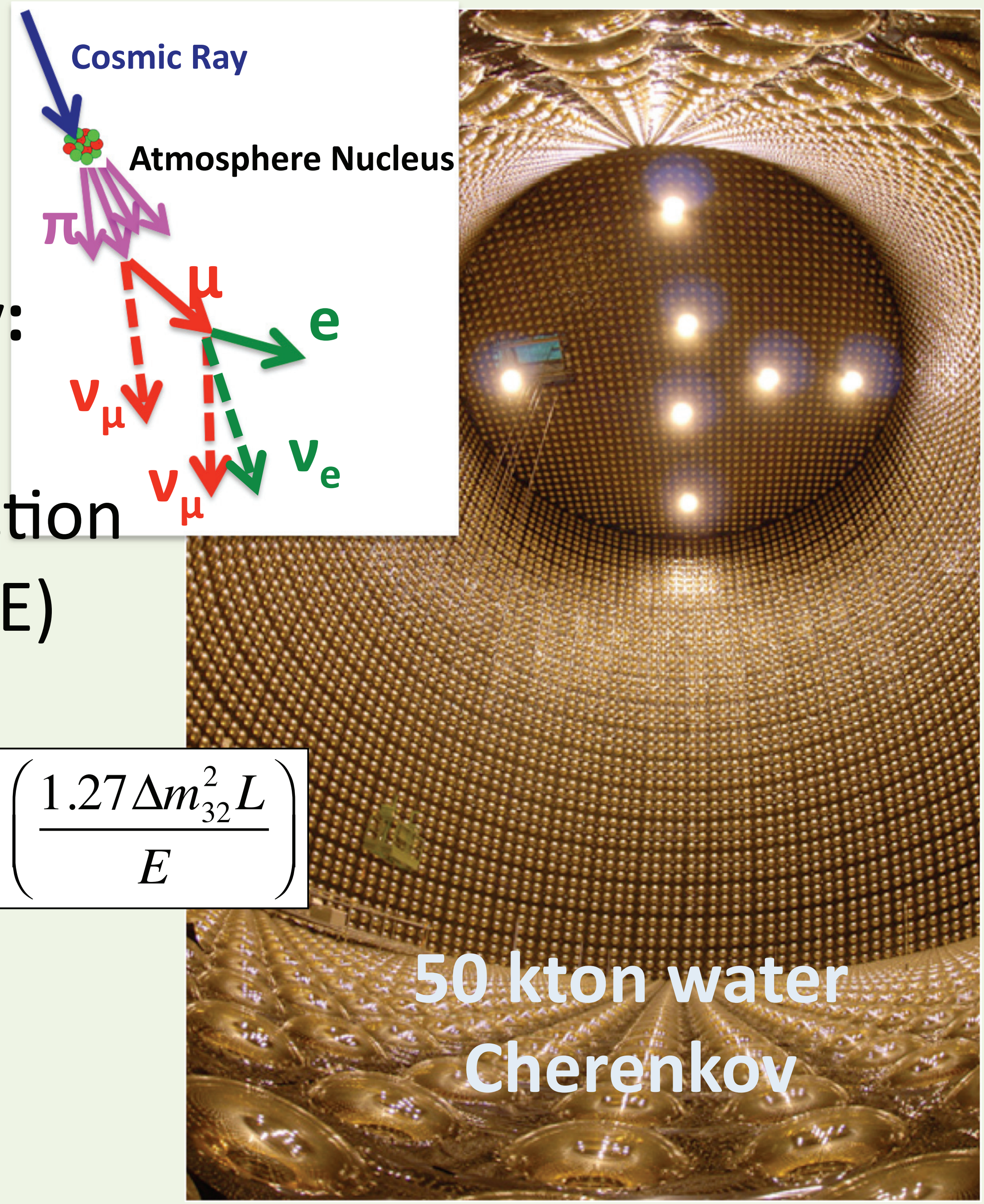
$$\textbf{KamLAND+Solar:}\ \tan^2\theta_{12} = 0.47^{+0.06}_{-0.05}$$





Phys.Rev.Lett.100:221803,2008

θ_{23}: SuperK



Experimental Strategy:

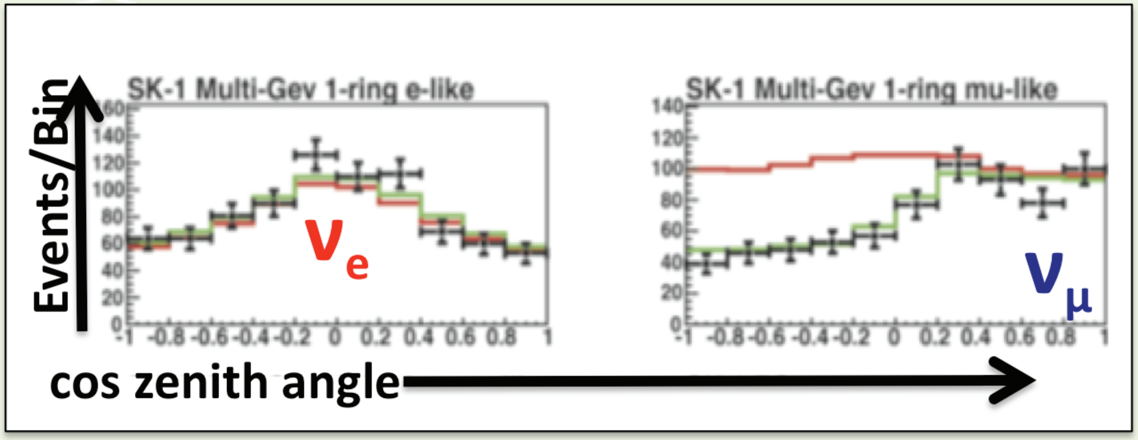
disappearance of atmospheric ν_μ as function of zenith angle (and L/E)

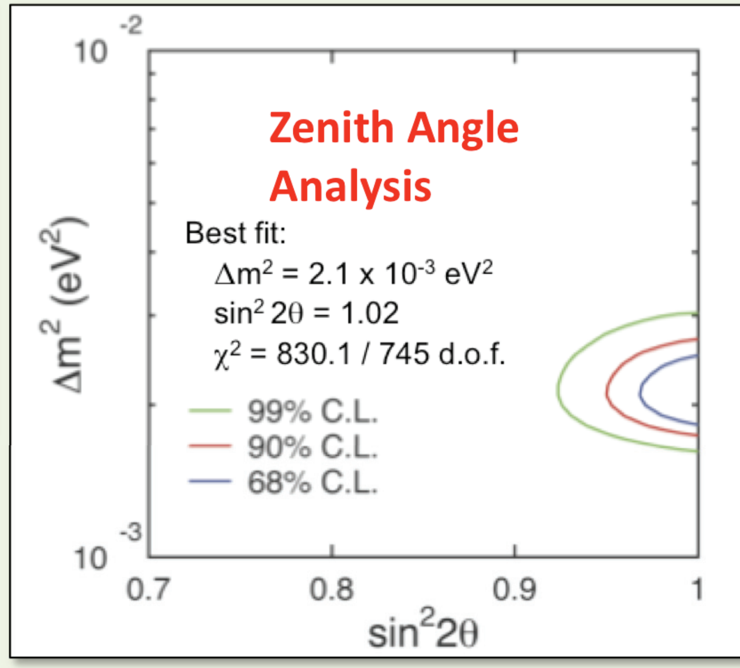
$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2(2\theta_{23})\sin^2\left(\frac{1.27\Delta m^2_{32} L}{E}\right)$$

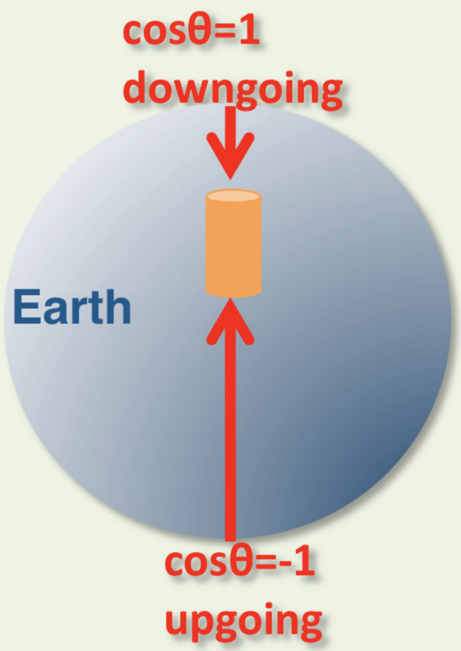
L: 15-13,000 km

E: 0.1-10,000 GeV

SuperK





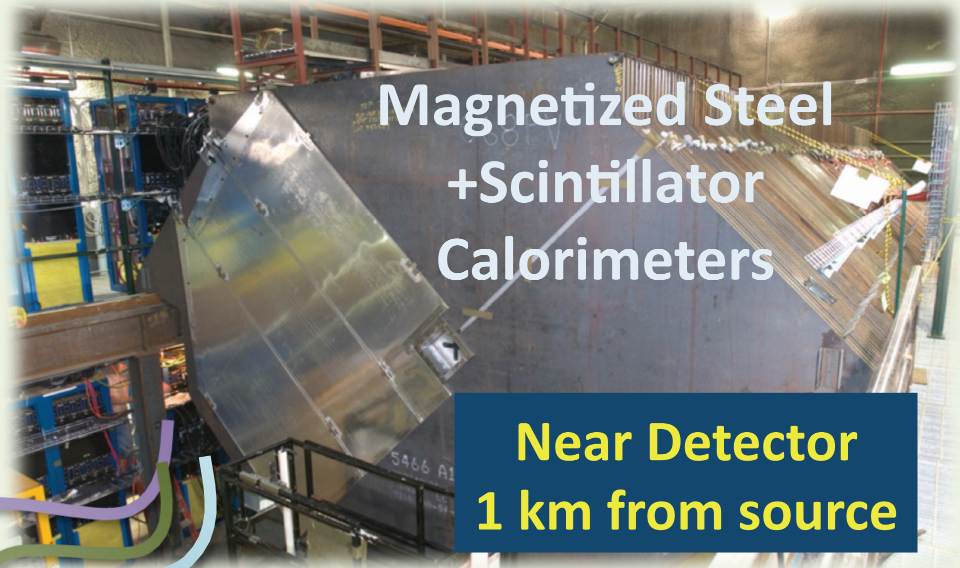


$$\sin^2 2\theta_{23} > 0.94 \ (90\% \text{ C.L.})$$

Ref: J. Raff Neutrino 2008

θ_{23}: MINOS

Experimental Strategy:
ν_μ disappearance as function of E



Neutrinos from NuMI Beam line

L=735 km

E_{peak}~3 GeV

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2(2\theta_{23}) \sin^2\left(\frac{1.27\Delta m_{32}^2 L}{E}\right)$$

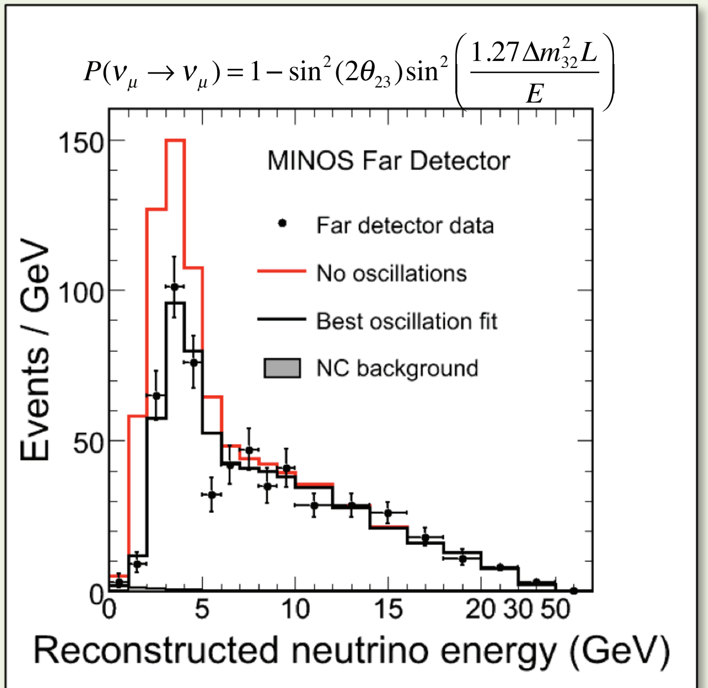
MINOS ν_μ CC Disappearance

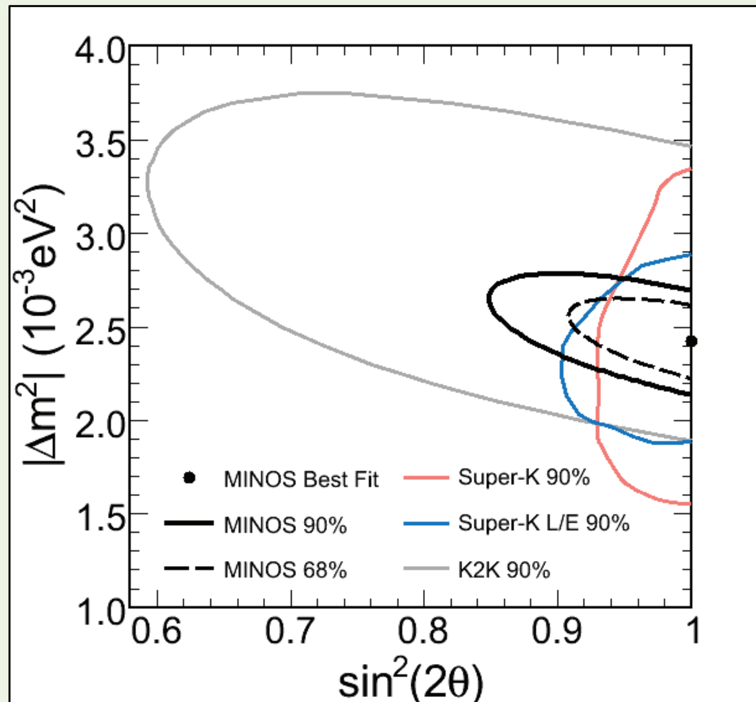
Far Data is consistent with two-flavor oscillations.
When constrained to physical region,

$|\Delta m^2_{32}|=2.43\pm0.13 \times 10^{-3}\ eV^2$ (68% C.L.)

$\sin^2(2\theta_{23})>0.90$ (90% C.L.)

With $\chi^2/NDF=90/97$



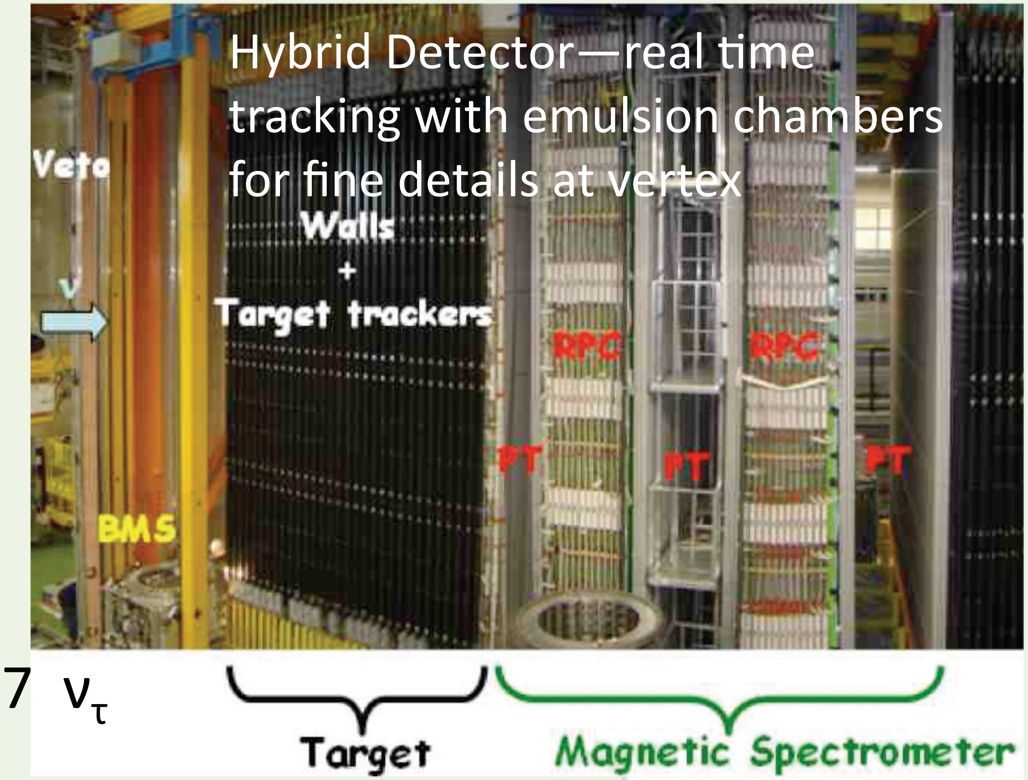


See J. Ma in Session G9
A. Himmel in G9 for antineutrino capabilities

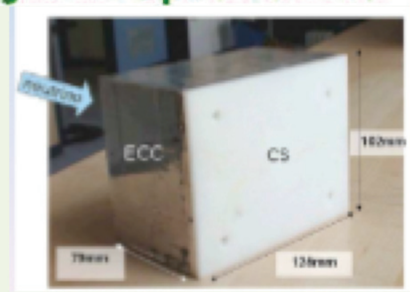
Phys.Rev.Lett.101:131802,2008

OPERA

Experimental Strategy: Look for ν_τ in a ν_μ beam

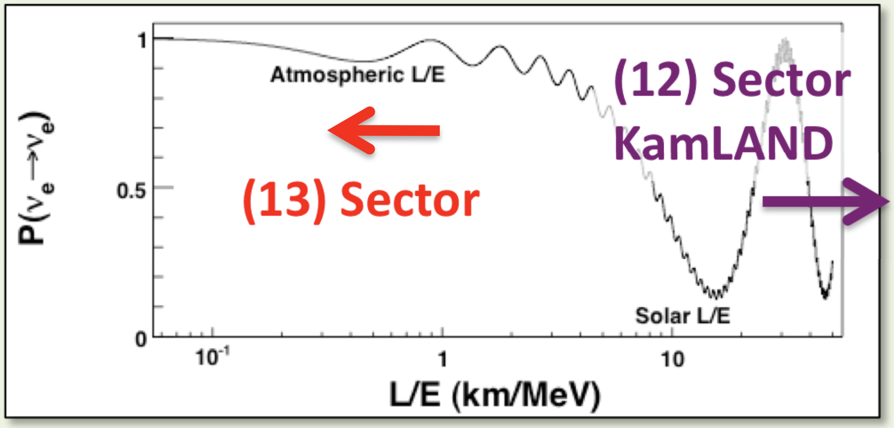


- Recorded ~2×10^{19} POT—0.7 ν_τ expected so far
- After 5 year exposure
  - 22.5×10^{19} POT
  - 10-15 ν_τ (depending on Δm^2)
  - fewer than 1 BG expected



θ_{13}

Two complimentary approaches available



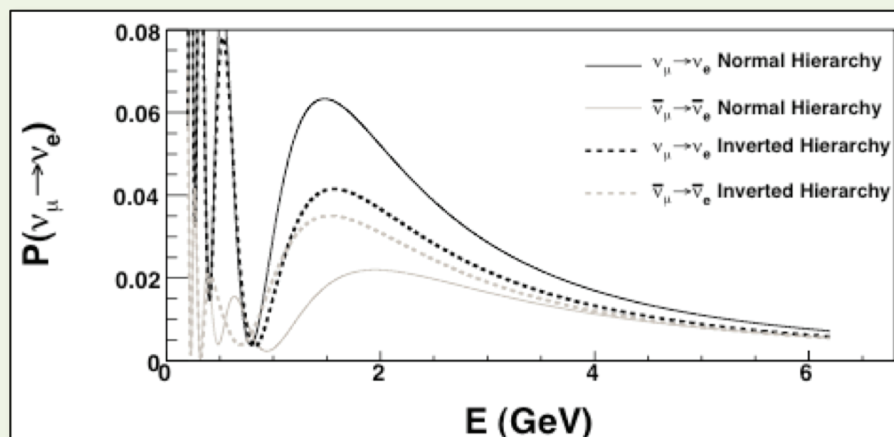
ν_e disappearance at reactors, L/E~0.5 km/MeV

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right) + O(\Delta m^2_{21})$$

$$\Delta m^2_{ee} = \cos^2\theta_{12}\left|m^2_{31}\right| + \sin^2\theta_{12}\left|m^2_{32}\right|$$

$\nu_\mu \rightarrow \nu_e$ at long baseline

- probability depends on δ_{CP}, and mass hierarchy (matter effects)
- neutrino oscillations could be different from antineutrino oscillations

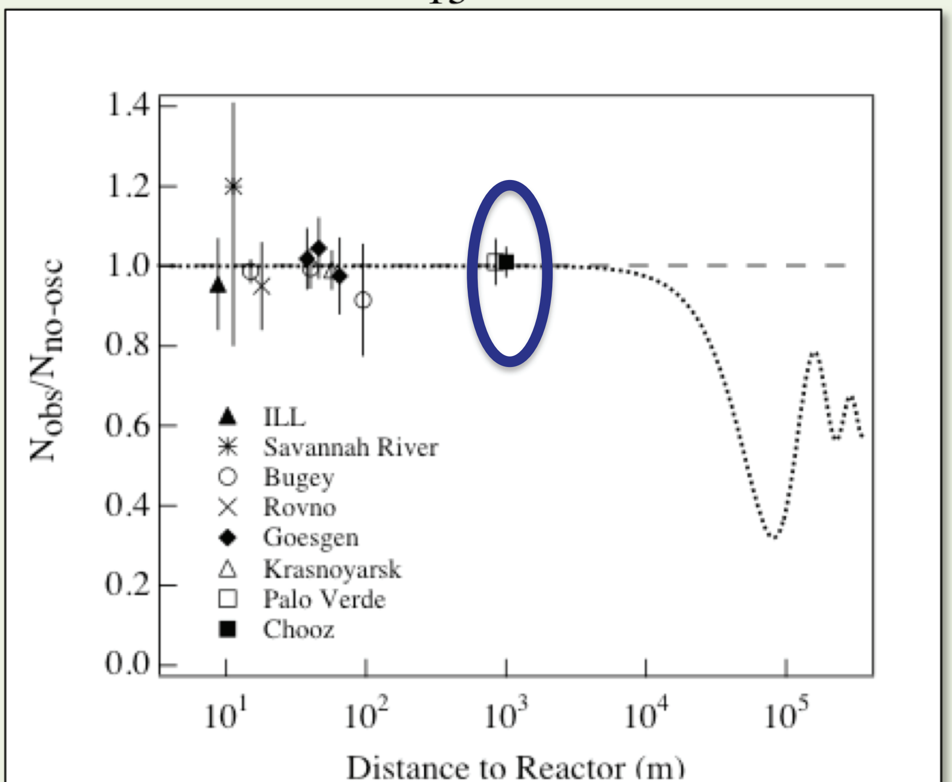


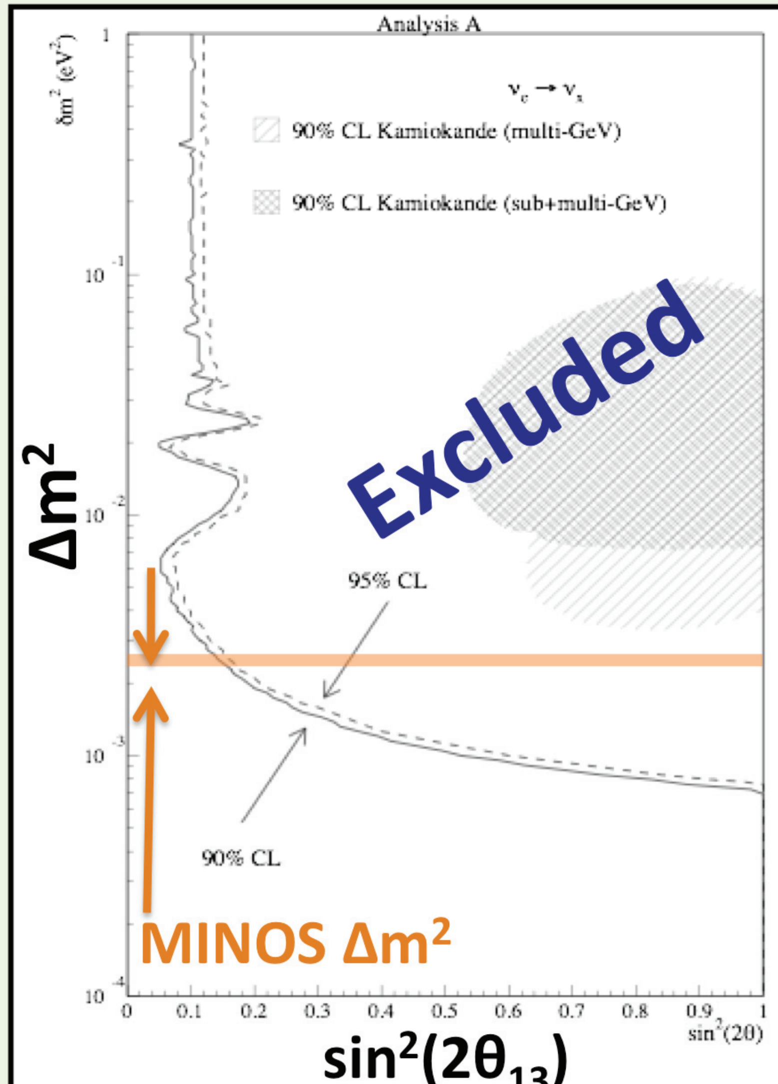
θ_{13}

As yet, no observation of oscillation in this sector

CHOOZ reactor experiment sets best upper limit

$$\sin^2(2\theta_{13}) < 0.15^{\dagger}$$





† at MINOS $\Delta m^2 = 2.43 \times 10^{-3}\,\mathrm{eV}^2$

Ref: Eur.Phys.J.C27:331-374,2003

θ_{13} in MINOS

$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2\left(1.27\Delta m^2_{31}\frac{L}{E}\right) +$$

$$\sin^2(2\theta_{12})\cos^2(\theta_{23})\sin^2\left(1.27\Delta m^2_{21}\frac{L}{E}\right) +$$

$$\sin(2\theta_{13})\sin(2\theta_{23})\sin(2\theta_{12}) \times$$

$$\sin\left(1.27\Delta m^2_{31}\frac{L}{E}\right)\sin\left(1.27\Delta m^2_{21}\frac{L}{E}\right)\cos\left(1.27\Delta m^2_{32}\frac{L}{E} \pm \delta_{CP}\right)$$

A few percent of the missing MINOS ν_μ could change into ν_e on the way to Minnesota

θ_{13} in MINOS

$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2\left(1.27\Delta m^2_{31}\frac{L}{E}\right) +$$

$$\sin^2(2\theta_{12})\cos^2(\theta_{23})\sin^2\left(1.27\Delta m^2_{21}\frac{L}{E}\right) +$$

SMALL IN MINOS

$$\sin(2\theta_{13})\sin(2\theta_{23})\sin(2\theta_{12})\times$$

$$\sin\left(1.27\Delta m^2_{31}\frac{L}{E}\right)\sin\left(1.27\Delta m^2_{21}\frac{L}{E}\right)\cos\left(1.27\Delta m^2_{32}\frac{L}{E} \pm \delta_{CP}\right)$$

A few percent of the missing MINOS ν_μ could change into ν_e on the way to Minnesota

Appearance probability depends on δ_{CP}

θ_{13} in MINOS

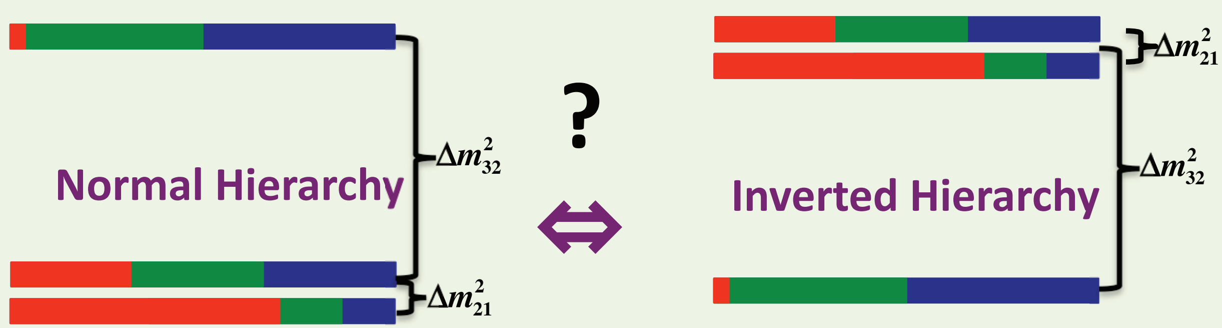
$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13})\sin^2(\theta_{23})\frac{\sin^2\left(1.27\Delta m^2_{31}\frac{L}{E} - aL\right)}{\left(1.27\Delta m^2_{31}\frac{L}{E} - aL\right)^2}\left(1.27\Delta m^2_{31}\frac{L}{E}\right)^2 +$$

$$\sin^2(2\theta_{12})\cos^2(\theta_{23})\frac{\sin^2(aL)}{aL}\left(1.27\Delta m^2_{21}\frac{L}{E}\right)^2 +$$

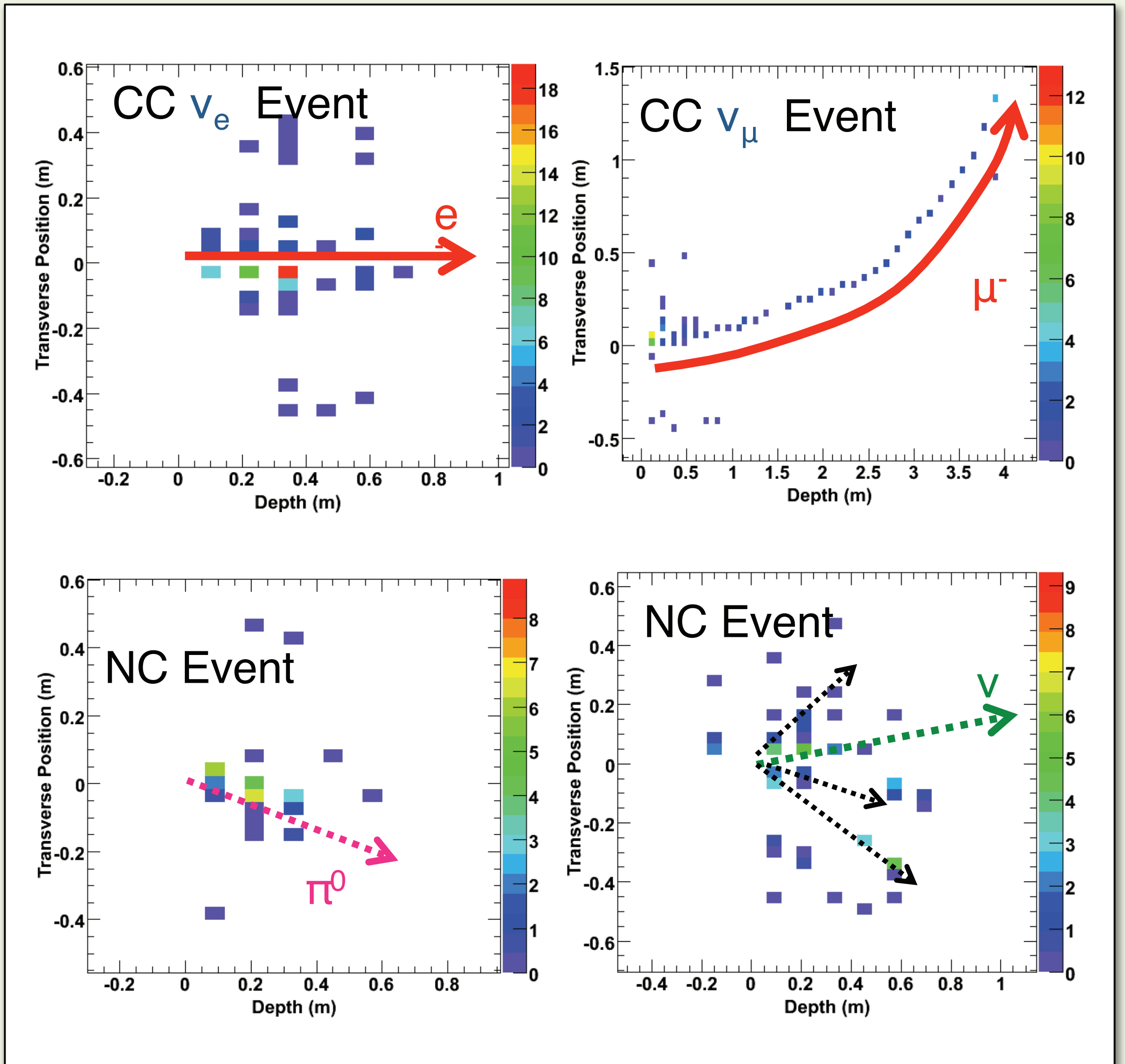
$$a = \pm\frac{G_F N_e}{\sqrt{2}} \approx \frac{1}{4000\ \mathrm{km}}$$

$$\sin(2\theta_{13})\sin(2\theta_{23})\sin(2\theta_{12})\frac{\sin\left(1.27\Delta m^2_{31}\frac{L}{E} - aL\right)}{\left(1.27\Delta m^2_{31}\frac{L}{E} - aL\right)}\left(1.27\Delta m^2_{31}\frac{L}{E}\right)\frac{\sin(aL)}{aL}\left(1.27\Delta m^2_{21}\frac{L}{E}\right)\cos\left(1.27\Delta m^2_{32}\frac{L}{E} \pm \delta_{CP}\right)$$

Matter Effects → probability depends on hierarchy



Finding ν_e in MINOS



- ν_μ easy—long track
- ν_e harder—dense energy deposited in narrow region

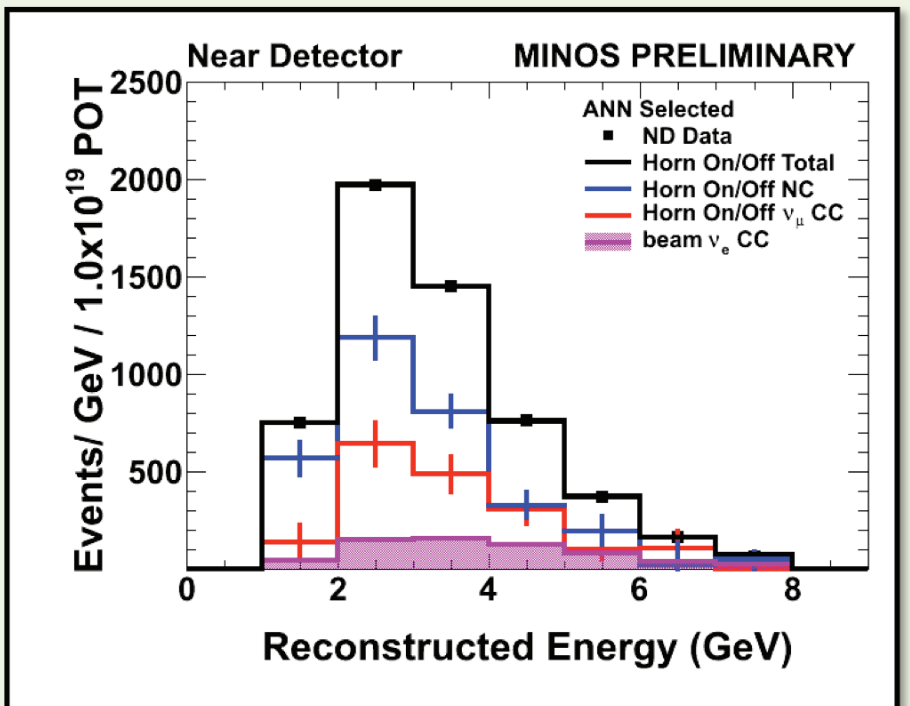
- MINOS Steel 2.5 cm thick=1.44 X
- Strip Width 4.1 cm=1.1 Moliere Radii

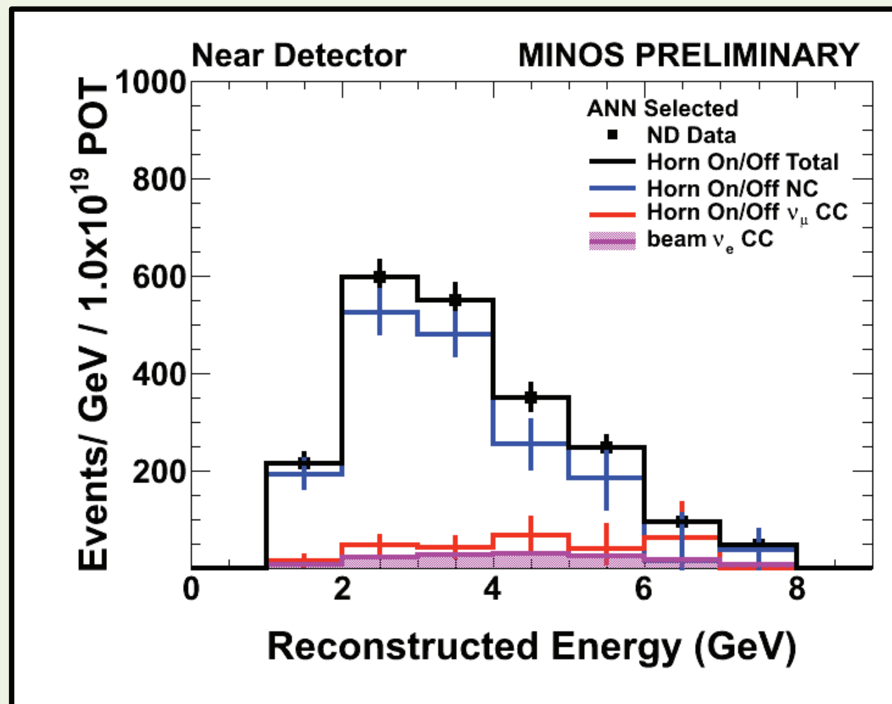
Backgrounds dominate, but we measure the BG in Near Detector

See Boehm and Ochoa in Session G9

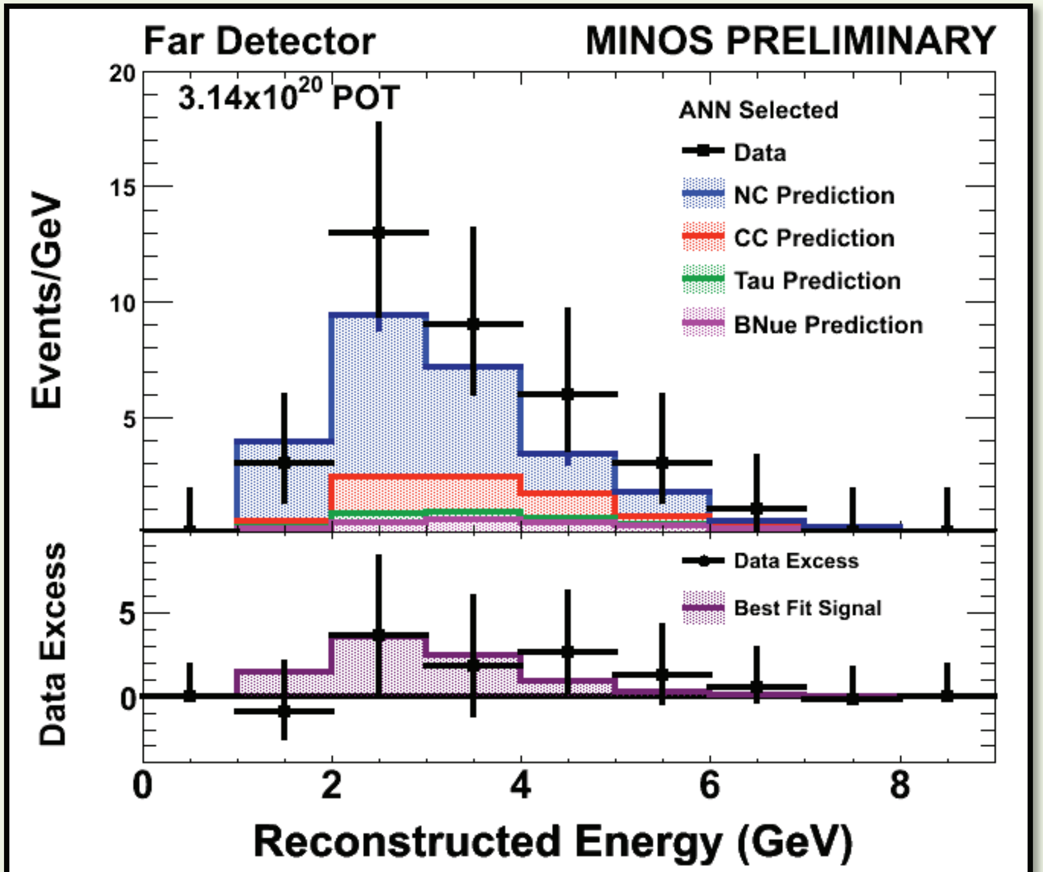
Measuring the Background

- Backgrounds from different sources—some oscillate on way to Far Detector
- Take advantage of beam flexibility!
- Turn off the focusing horns—Resulting spectrum is dominated by NC events
- Use ND data in two different configurations to extract relative components of background





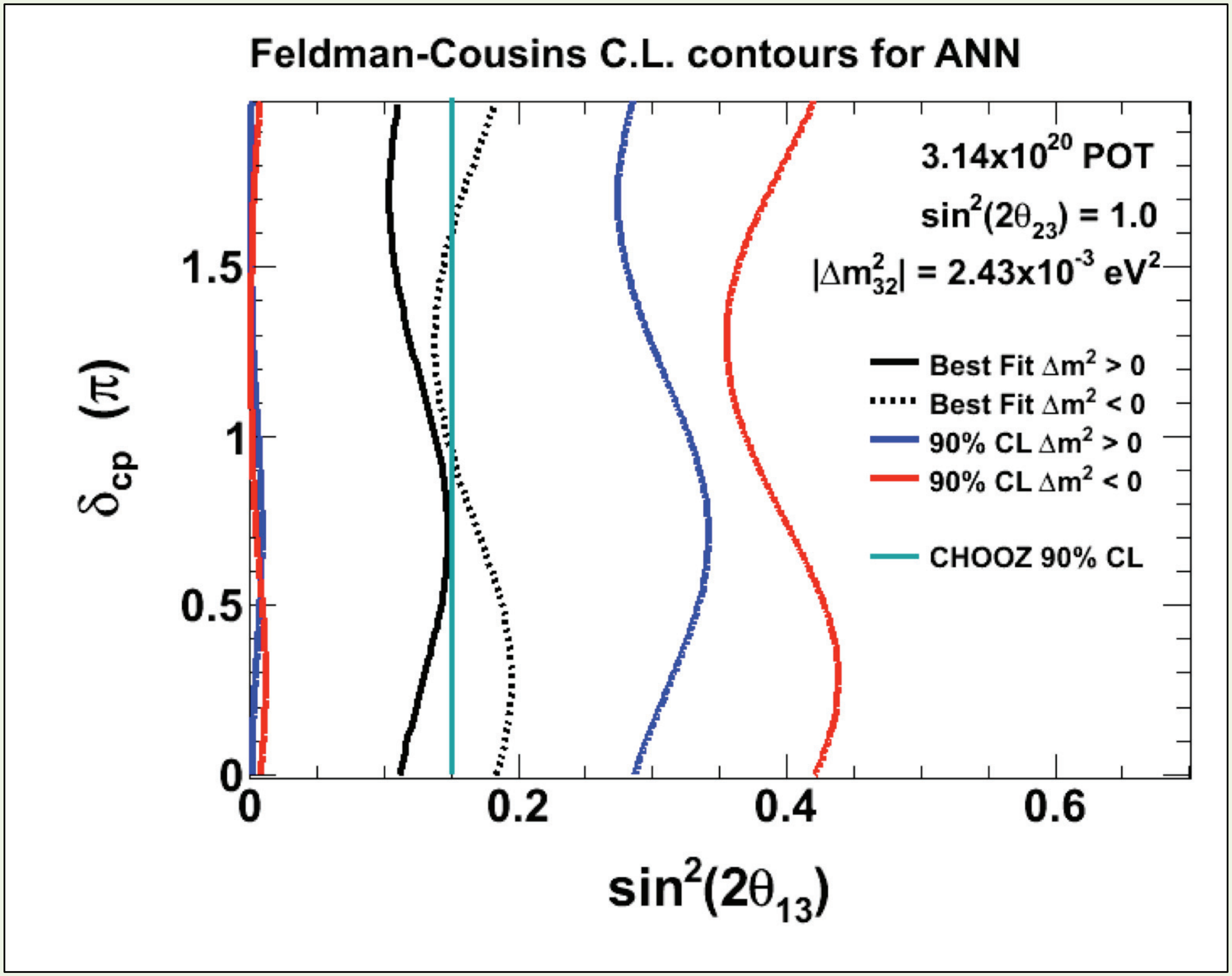
MINOS ν_e Appearance



- Expect: 27±5(stat)±2(syst)
- Observed: 35 events
- Observed is 1.5σ higher than background expectation
- We do observe a similar sized excess of events in a (independent, signal-less) sideband region

We will have more than double the exposure by this summer!

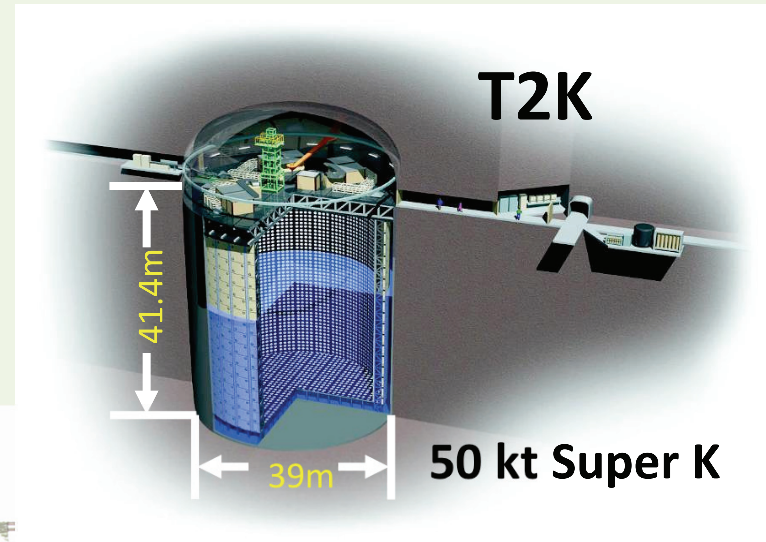
MINOS ν_e Appearance

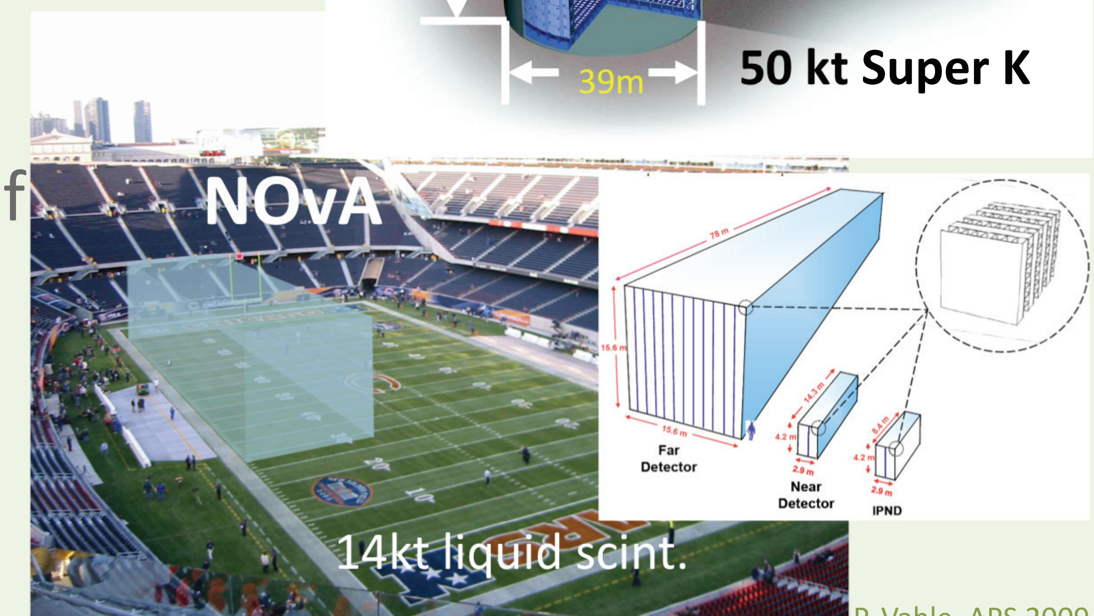


Aiming for (13)

Future long baseline experiments aim to push down limit by another order of magnitude

- Big Detectors
- Higher beam power
- Improved signal ID
- Lower backgrounds
- Improved knowledge of cross sections for backgrounds





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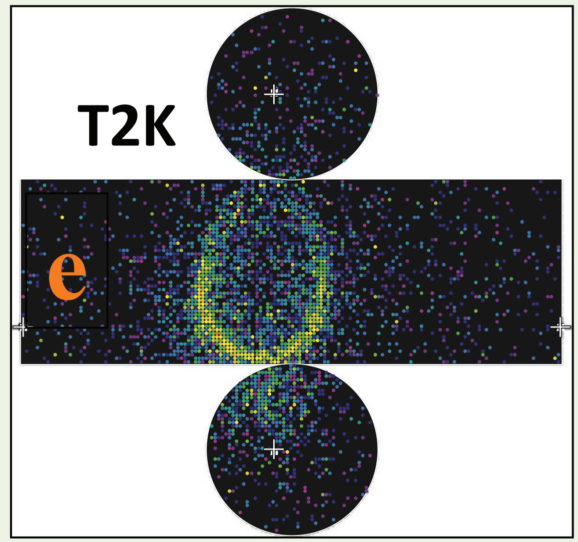

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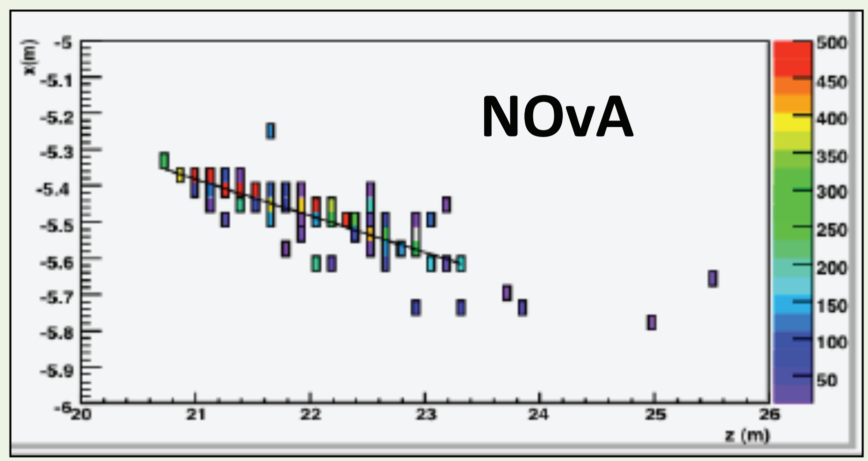

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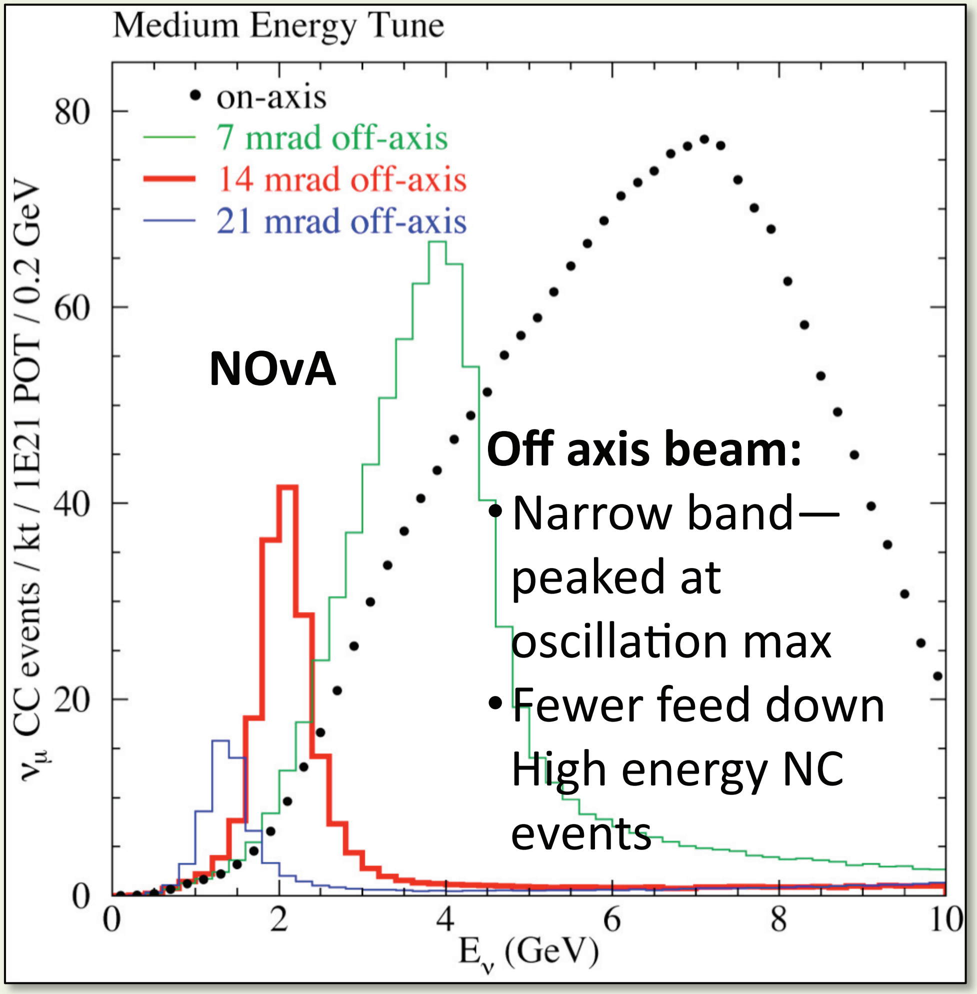

Aiming for (13)

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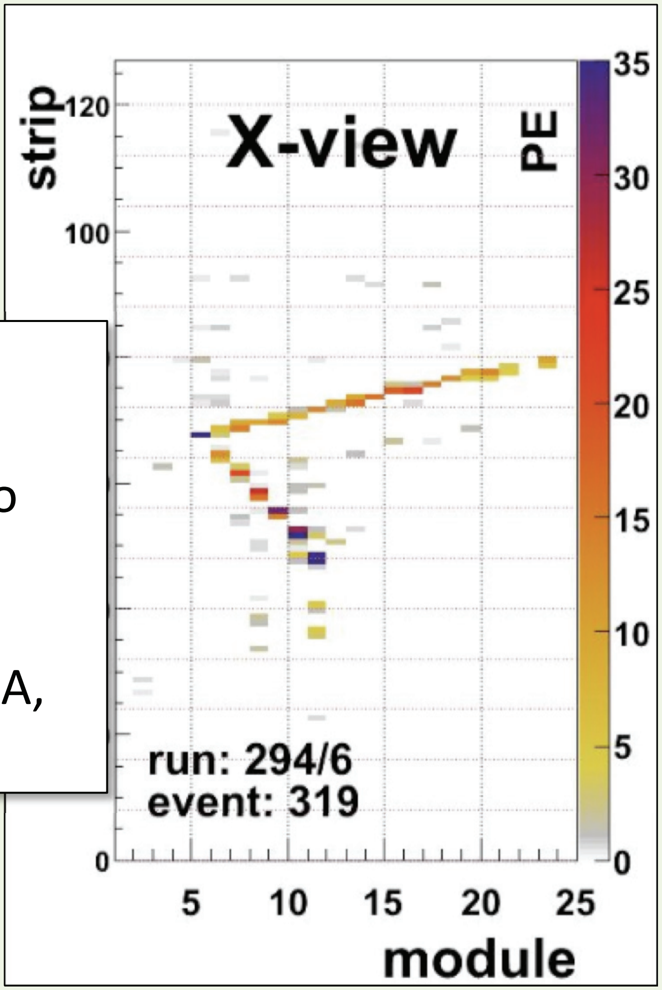
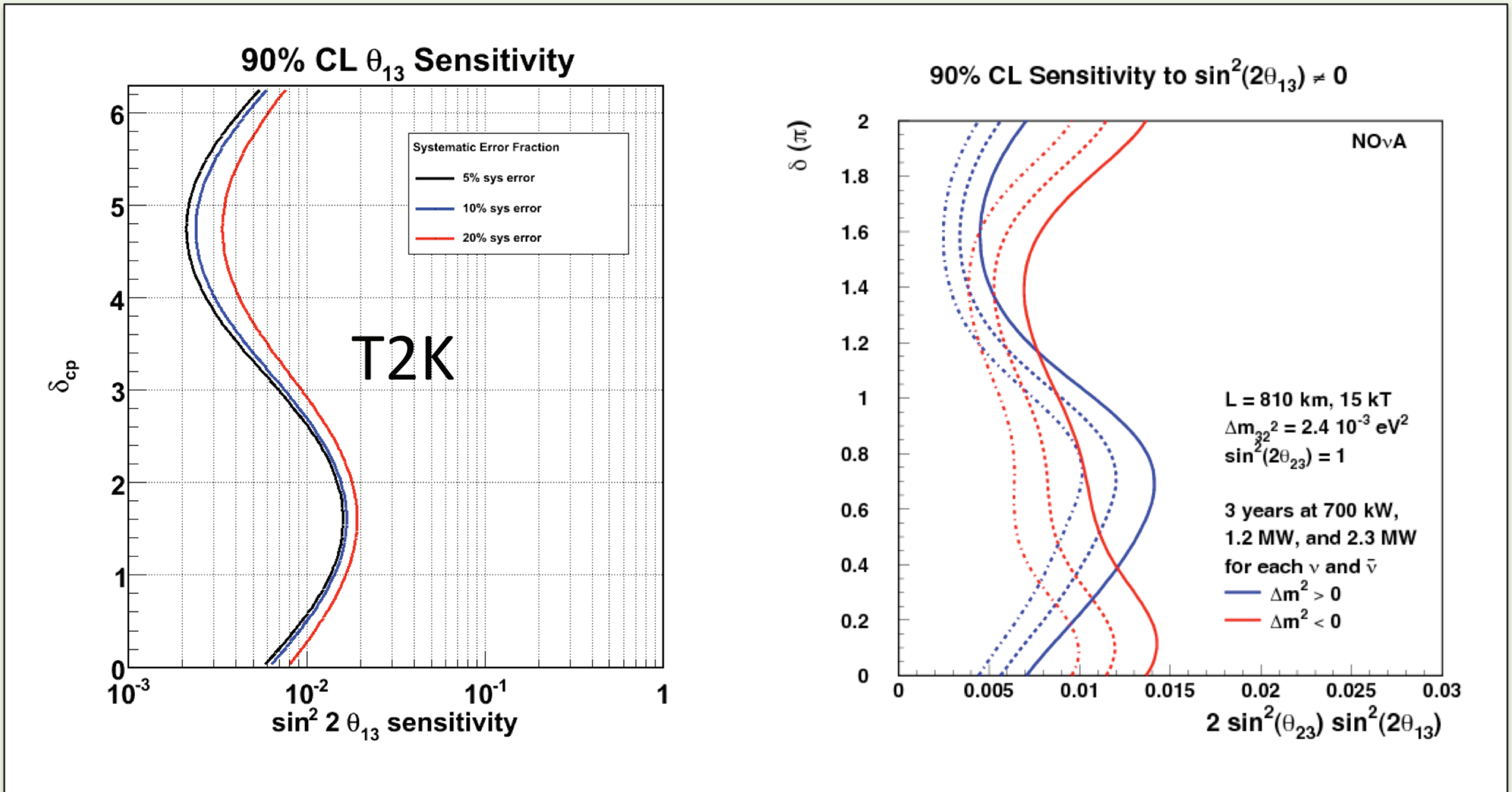
Benefit from Near Detector and dedicated neutrino scattering experiments SciBoone, MINERvA, MicroBoone



Aiming for (13)

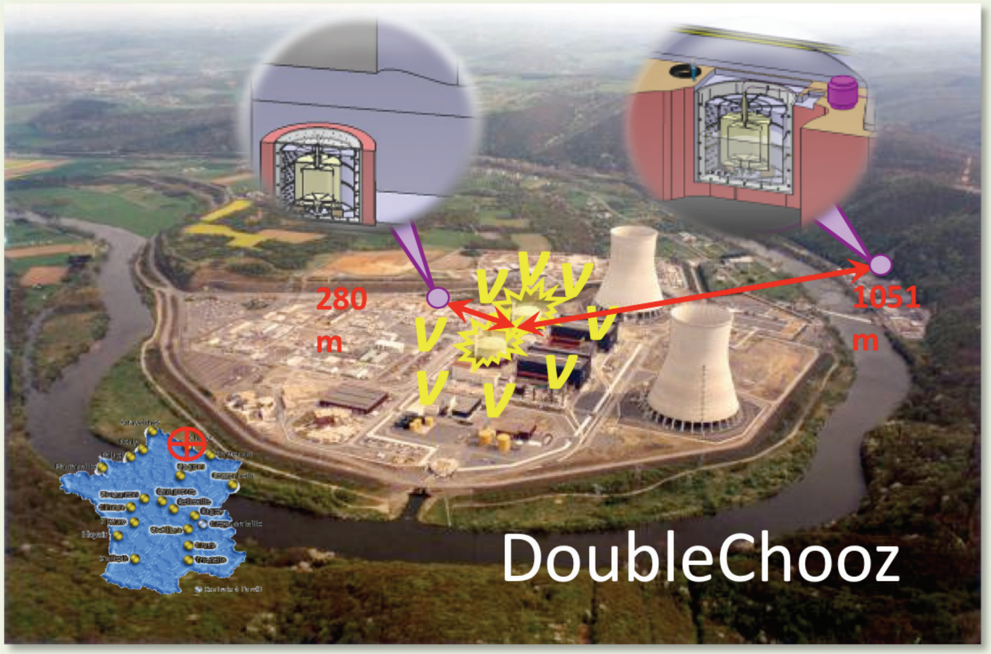


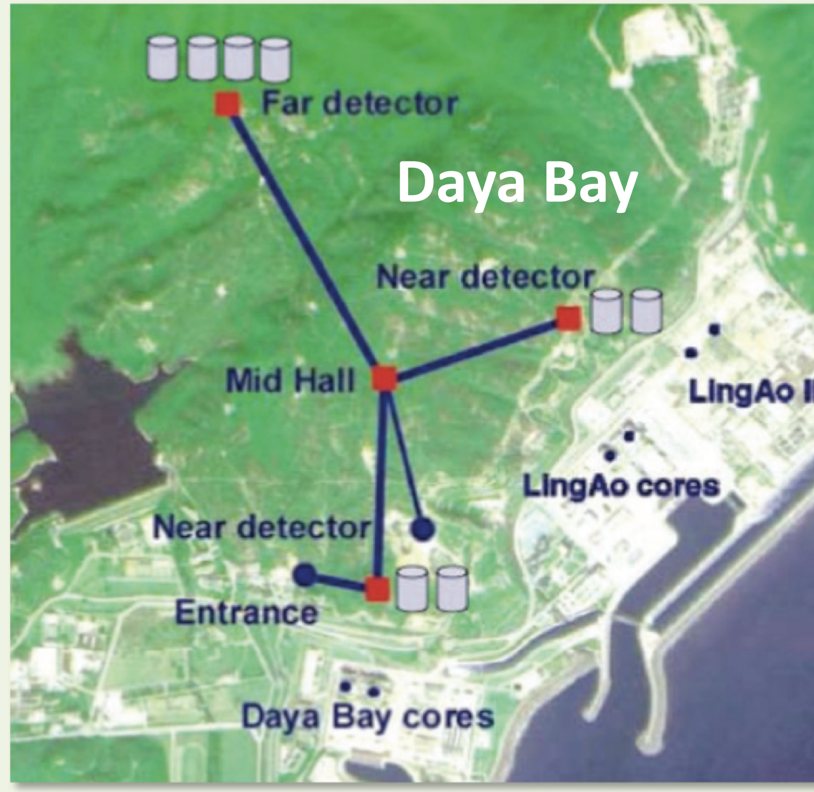
T2K: Assumes 5 years at 750 kW, 22.5 kton fiducial volume

NOvA: Assumes 3 years ν+ 3 years anti-ν, 10% systematic

Aiming for (13)

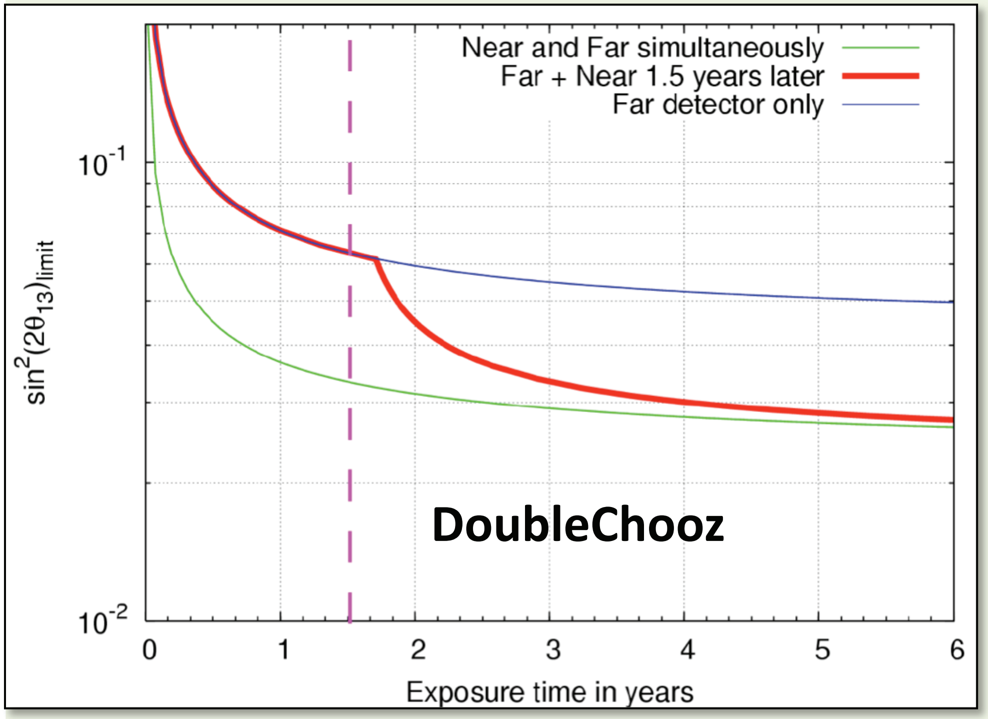
Improved reactor experiments underway too!





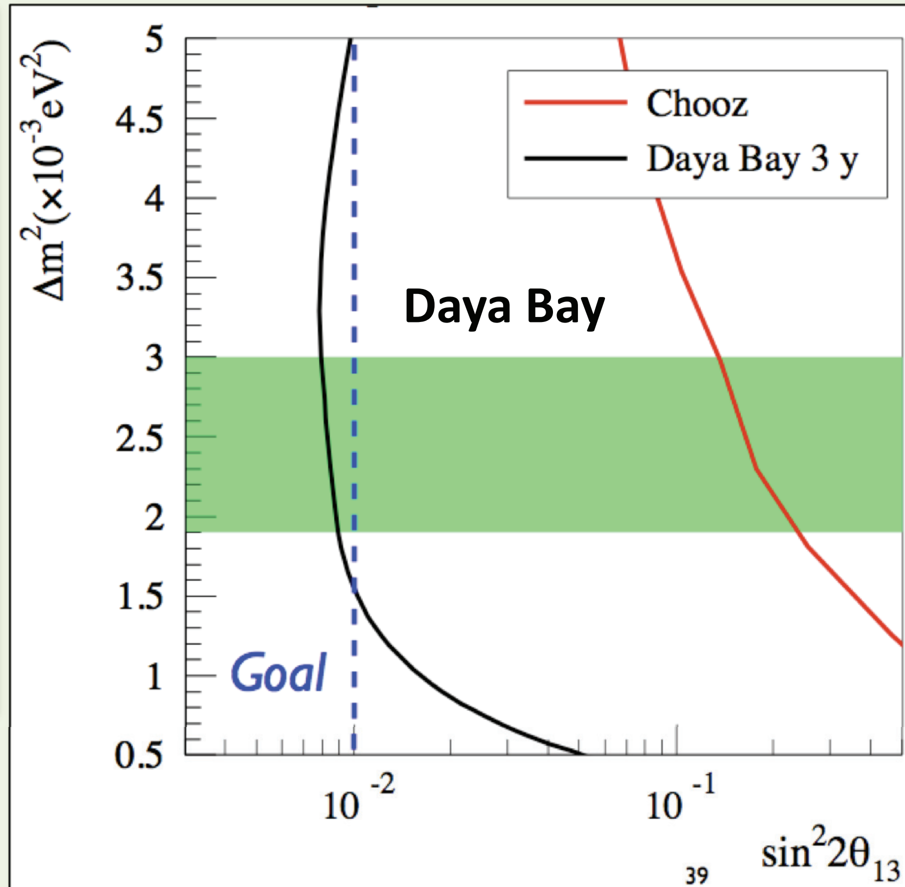
- Larger Detectors
- Vetos for backgrounds
- Near Detectors to beat down systematic errors

Aiming for (13)



Ref: hep-ex/0606025

J. Maricic B12, G Horton-Smith, M. Toups G9



Ref: K. Heeger, La Thuile 2009

K. Heeger B12, L. Whitehead B12

Timeline

- MINOS
  - Double the data in the can
  - Updated results in 2010
- T2K
  - Neutrino beam commissioned April 23
  - First physics run starts Dec./Jan. @ 100 kW
- DoubleChooz
  - Ready to fill Fall 2009, run with Far Det.
  - Near Det. end of 2011
- DayaBay
  - Summer 2011, FD hall ready for data
  - 3 years to full sensitivity
- NOvA
  - Ground breaking at Far Det. site May, 2009
  - First 2.5 kton FD, 2011
  - Full Far Det. 2012

Summary

- Broad range of neutrino oscillation experiments for precision measurements of mixing matrix elements
- Reactor+Solar experiments measure mixing in (12) sector

$$\tan^2\theta_{12} = 0.47^{+0.06}_{-0.05}$$

- Atmospheric+Long Baseline measure mixing in (23) sector

$$\sin^2 2\theta_{23} > 0.94 \ (90\% \text{ C.L.})$$

- Race is on for θ_{13}!