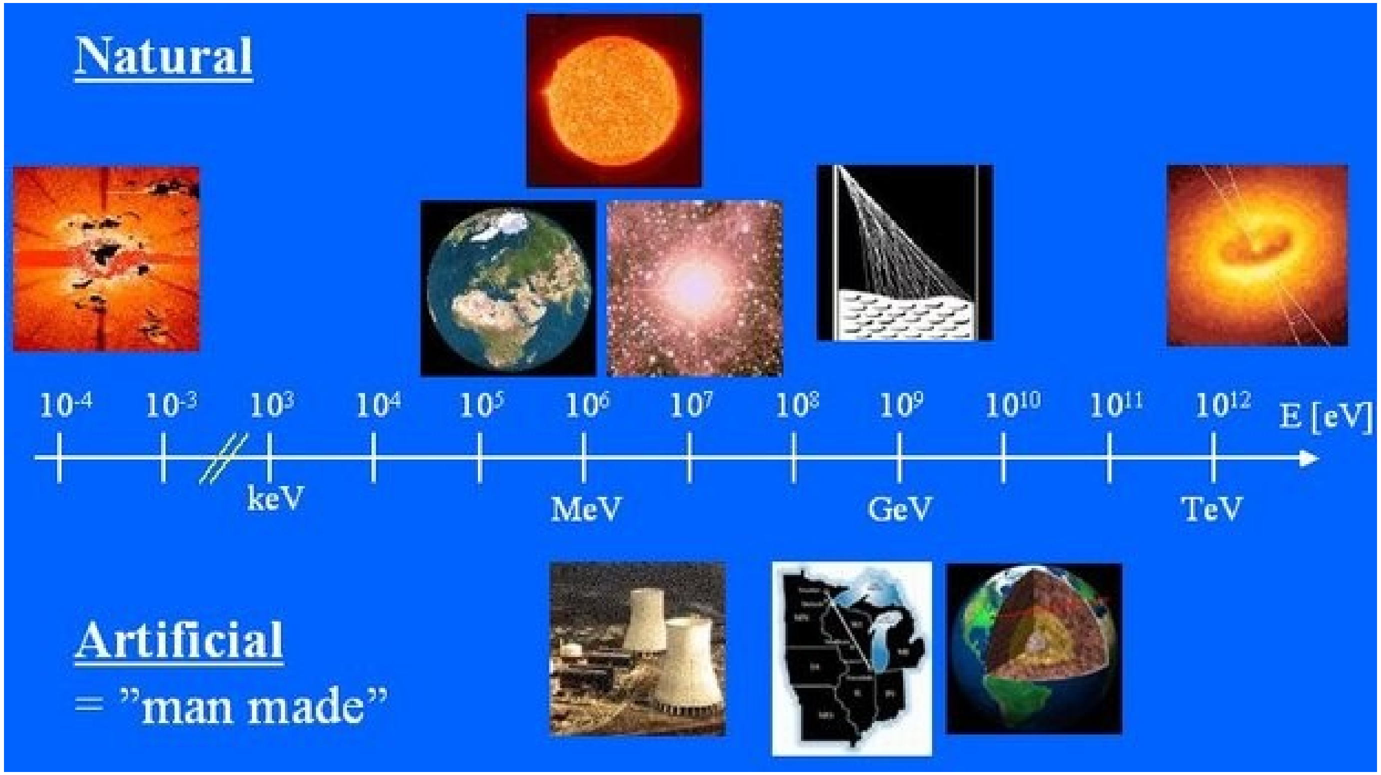
Neutrino Physics Overview



http://www.physik.uni-wuerzburg.de/~winter/neutrinos.htm

Lisa Whitehead
University of Houston

Brookhaven Forum - May 2, 2013

UNIVERSITY of HOUSTON

Introduction: Neutrino Masses and Mixing

Neutrino Mixing

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

α, β = flavor states
1,2 = mass states

Probability of flavor change:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$$

θ = mixing angle
L = flight distance
E = neutrino energy

$$\Delta m^2 = m_2^2 - m_1^2$$

A neutrino created in one flavor state can be observed some time later in a different flavor state!

1.27 in units of (GeV)/(eV^{2}km)

3-Flavor Mixing

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

Mixing can generally be represented by 3 mixing angles (θ_{12}, θ_{23}, θ_{13}) and one phase (δ) *

(same as standard parameterization of the CKM matrix)

*If neutrinos are Majorana particles, there are two more phases, but they don't affect neutrino oscillations.

Probability of flavor change:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i>j} \mathrm{Re}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$

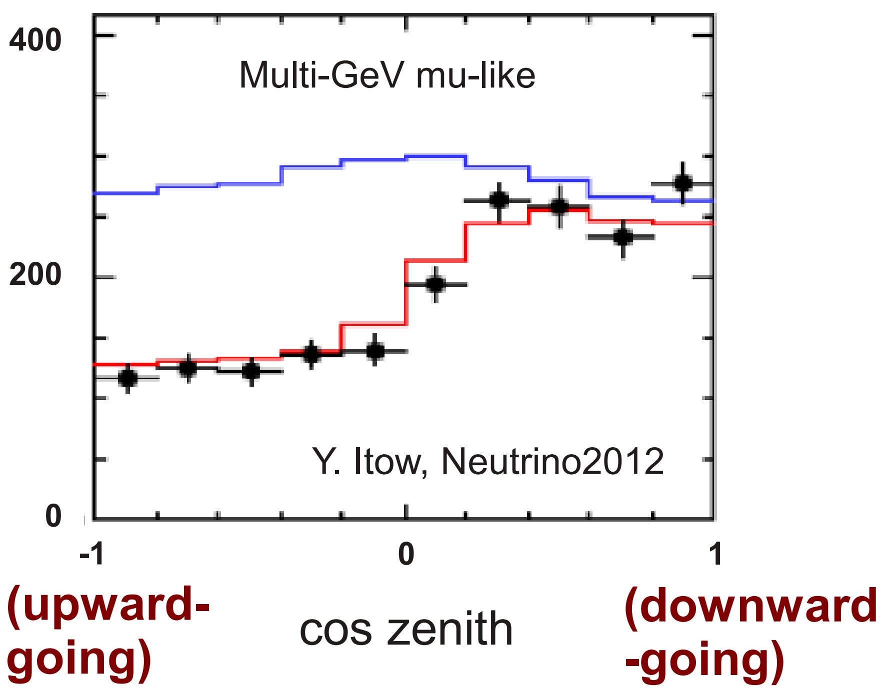
$$-2 \sum_{i>j} \mathrm{Im}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2\left(\frac{\Delta m^2_{ij} L}{2E}\right)$$

Natural units
$\hbar = c = 1$

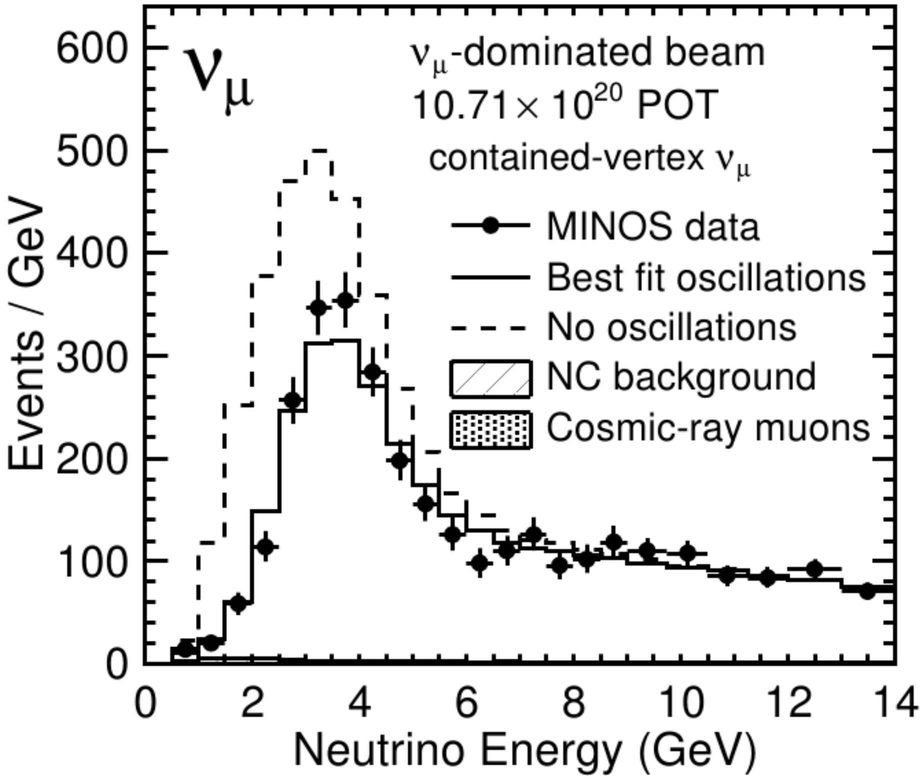
Evidence: Atmospheric Sector

Disappearance of atmospheric or accelerator muon neutrinos
Experiments: Super-Kamiokande, K2K, T2K, MINOS

Atmospheric neutrinos in SuperK

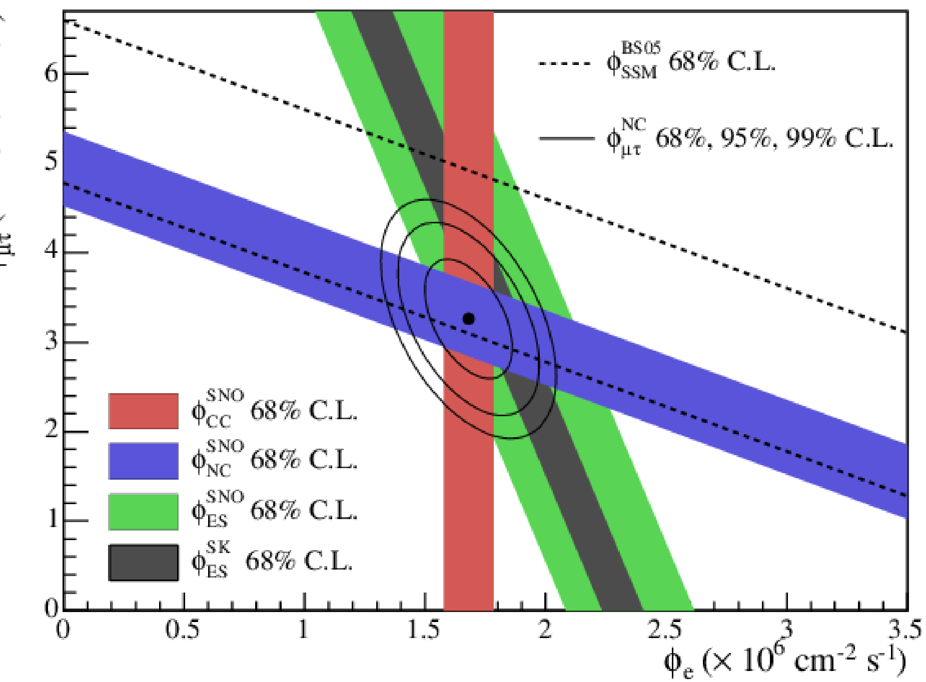


Beam neutrinos in MINOS



arXiv:1304.6335

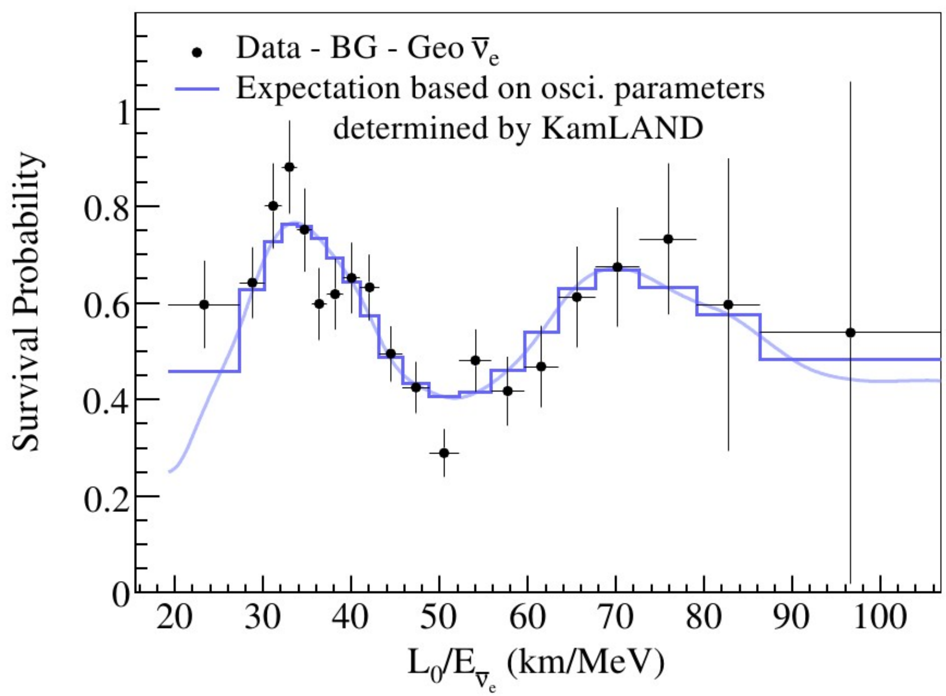
Neutrinos created in the sun are electron flavor, but only ~1/3 of solar neutrinos are ν_e when observed on Earth



Phys. Rev. C 72, 055502 (2005)

SNO showed that the total flux of neutrinos is consistent with solar models

KamLAND observed disappearance of electron antineutrinos from reactors at ~180 km (probes the same oscillation parameters as solar neutrino disappearance)



Phys. Rev. Lett. 100, 221803 (2008)

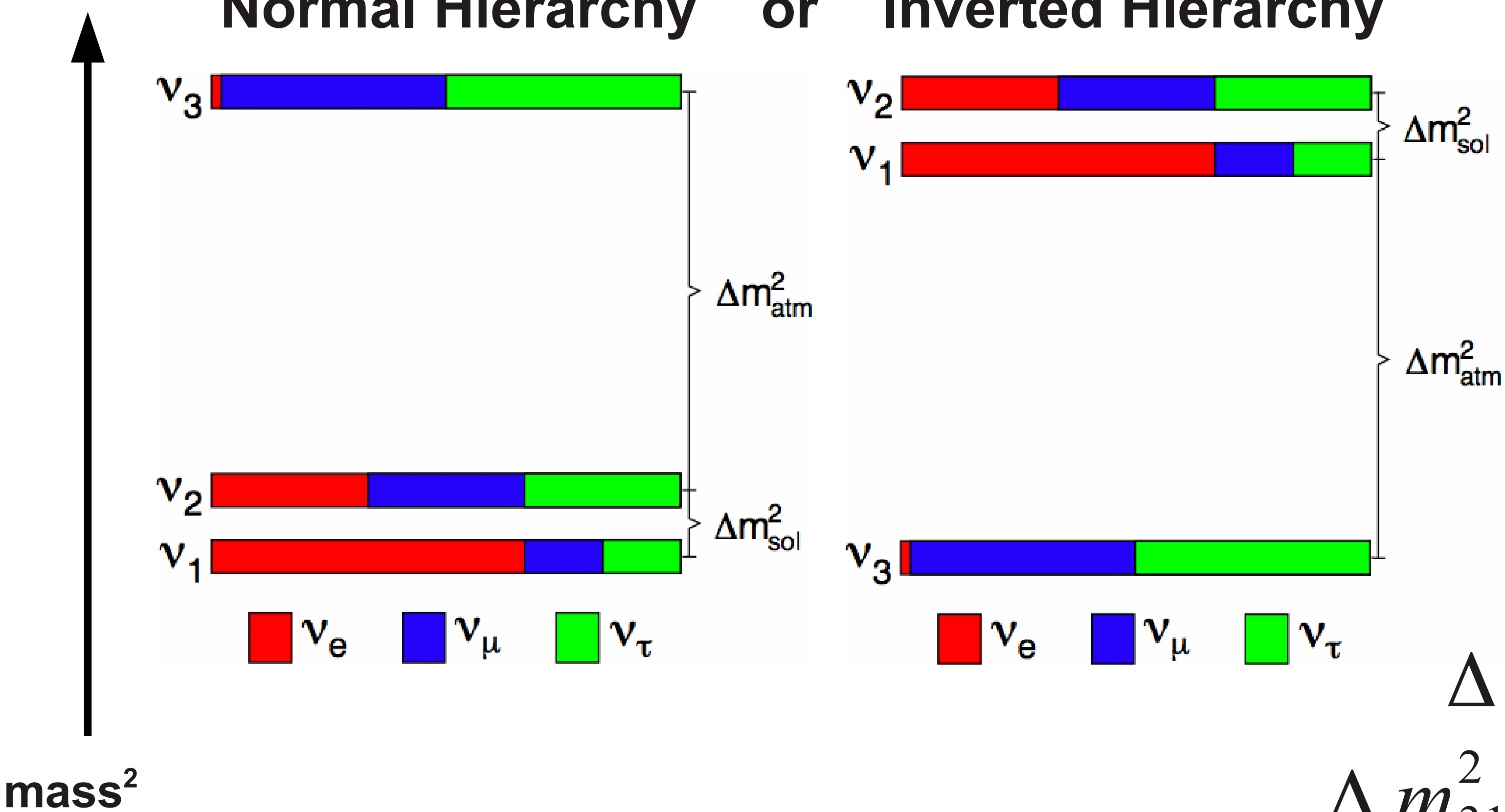
Experimental Status

$\theta_{12} \approx 34^{o}$ **solar+KamLAND** $\Delta m^2_{sol} = 7.6 \times 10^{-5} \mathrm{eV}^2$

$\theta_{23} \approx 45^{o}$ **Atmospheric/accelerator** $|\Delta m^2_{atm}| = 2.4 \times 10^{-3} \mathrm{eV}^2$

New in 2012!! $\theta_{13} \approx 9^{o}$ **Reactor**

Normal Hierarchy or Inverted Hierarchy



Observation of neutrino oscillations implies neutrinos have mass!

3 neutrinos → 2 independent mass squared differences:

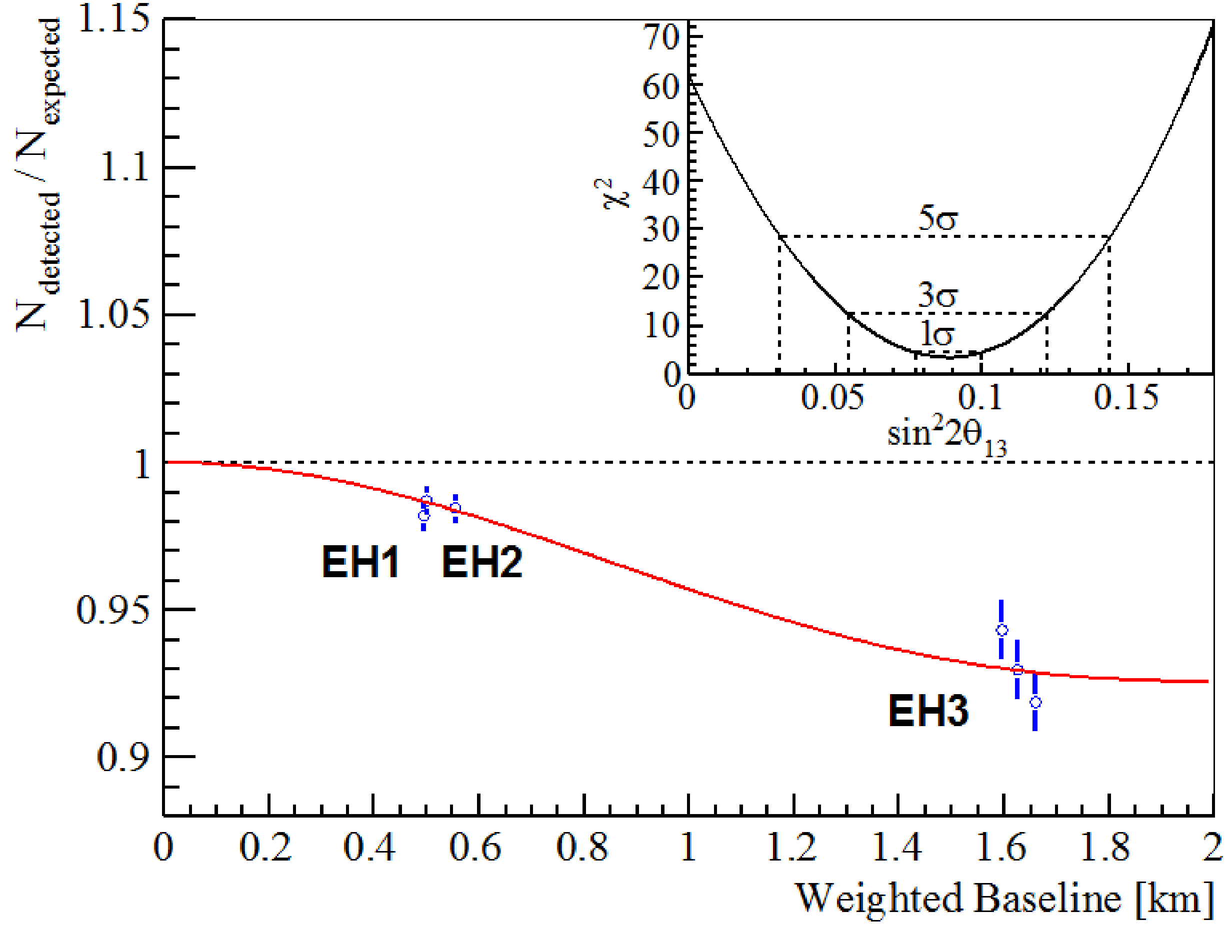
$$\Delta m^2_{ij} = m^2_i - m^2_j$$

$$\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21}$$

Some Big Questions

- What are the absolute masses of the neutrinos?
- Are neutrinos Dirac or Majorana particles? (Majorana particles are their own antiparticles)
- What is the ordering of the neutrino masses? (Mass hierarchy)
- Is θ_{23} maximal?
- Is there CP violation in the neutrino sector? (Nonzero θ_{13} means we can study this now!)
- Are there sterile neutrinos? Non-standard neutrino interactions?

Neutrino Oscillation Experiments

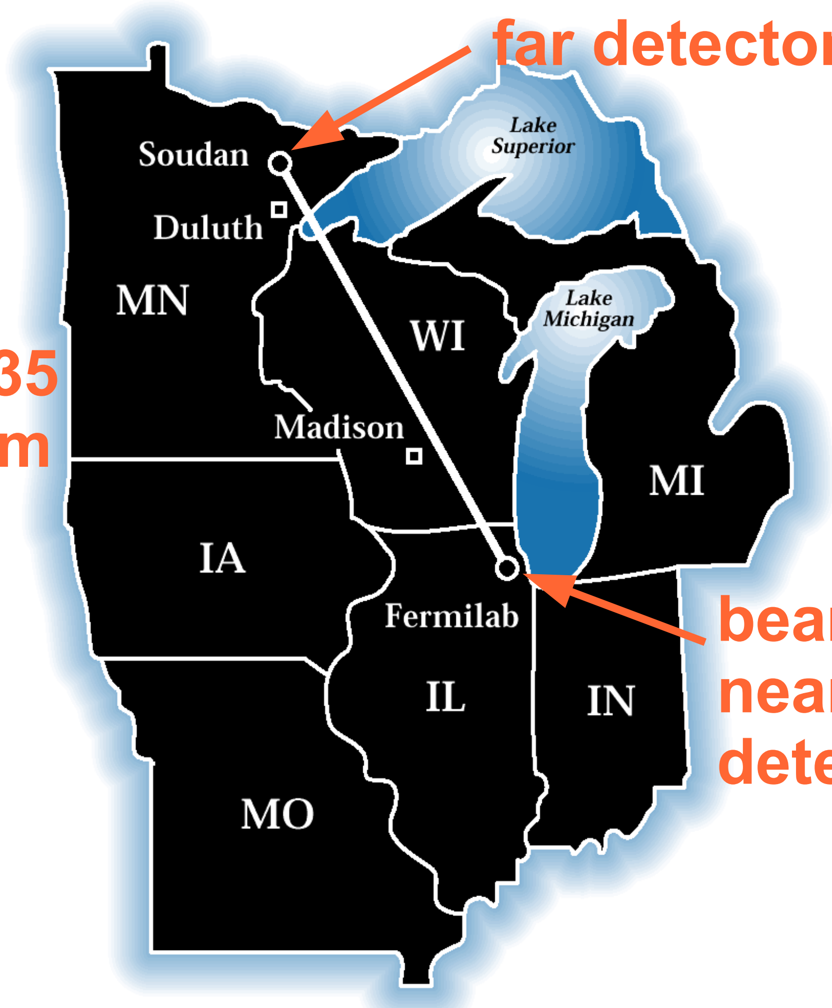


Accelerator Neutrinos

MINOS (2005-2012):
muon neutrino or antineutrino beam; atmospheric neutrinos

far detector

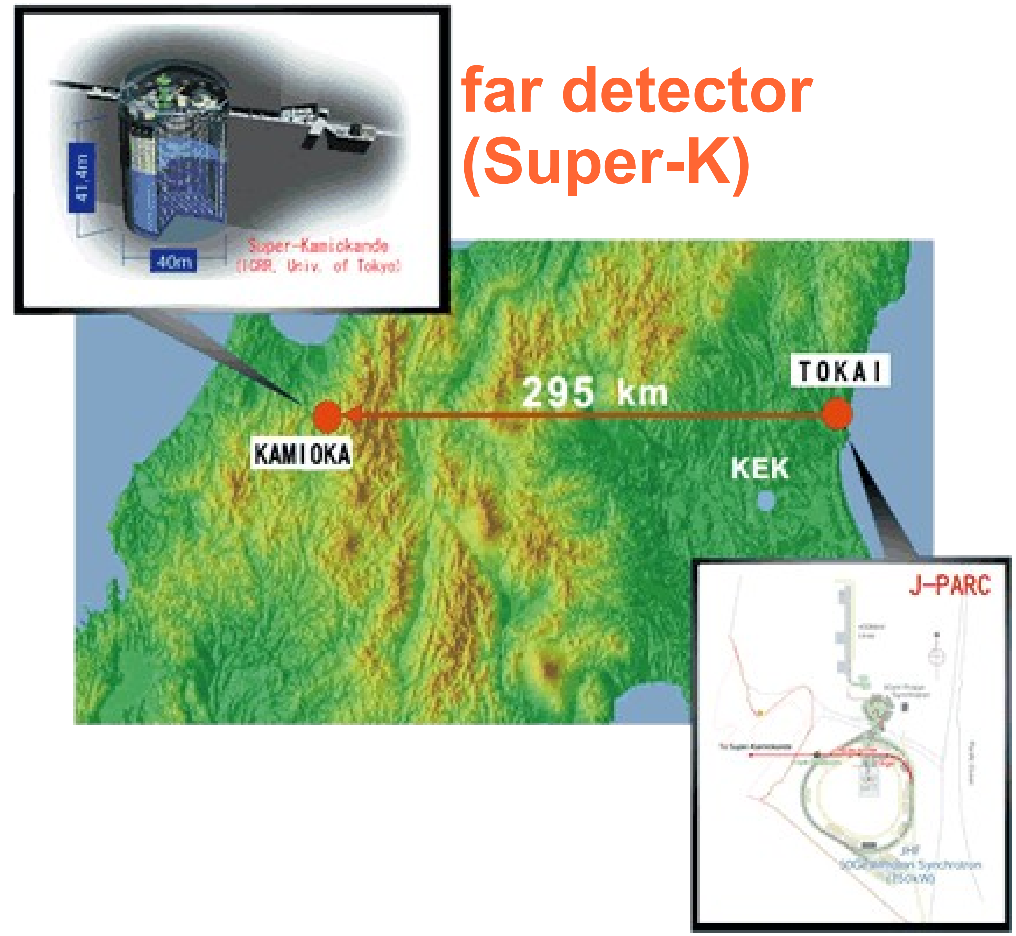
735 km



beam, near detector

T2K (2010-present):
muon neutrino beam

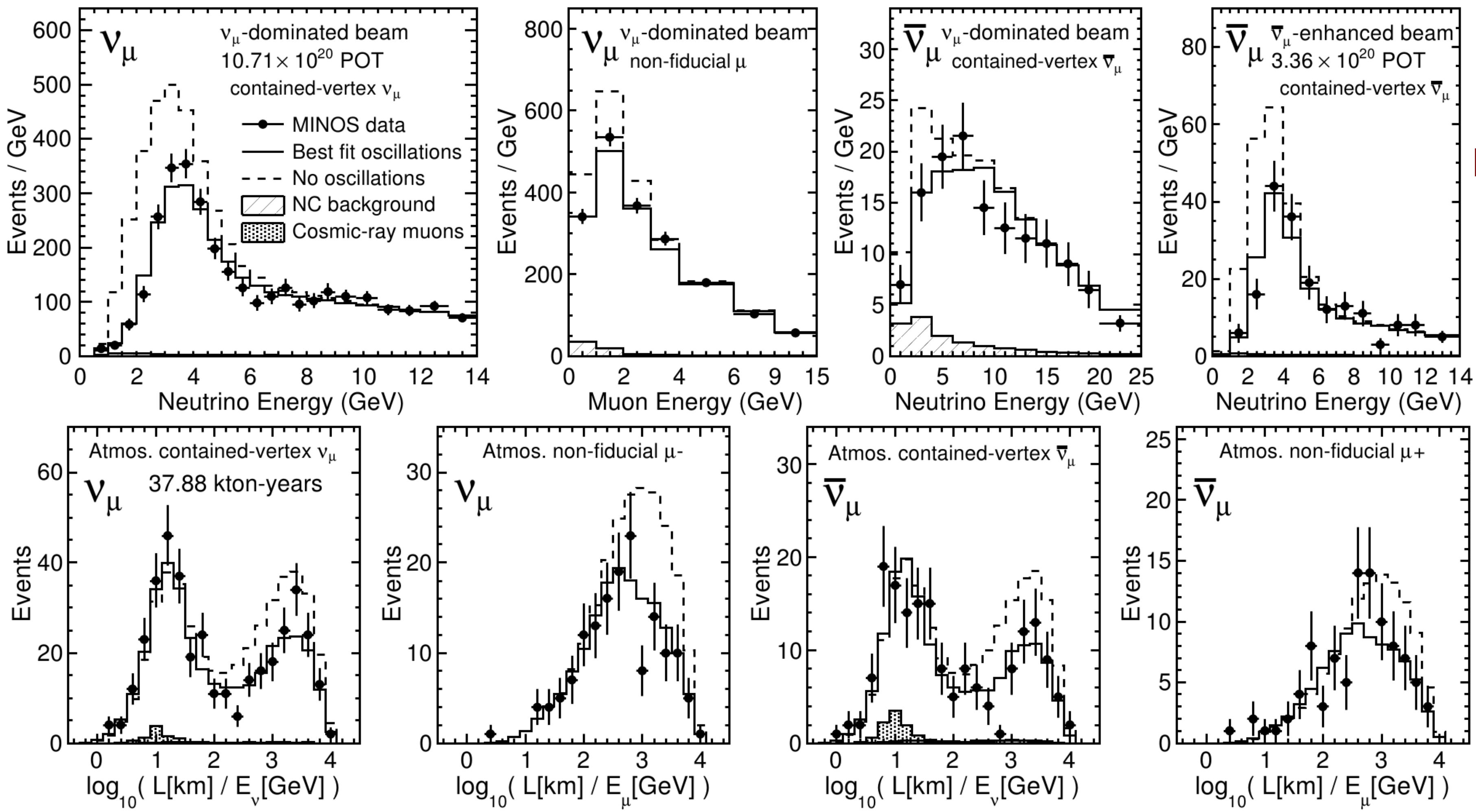
far detector (Super-K)



Beam, near detector

MINOS

- Final results for muon neutrino and antineutrino disappearance from combined beam and atmospheric data



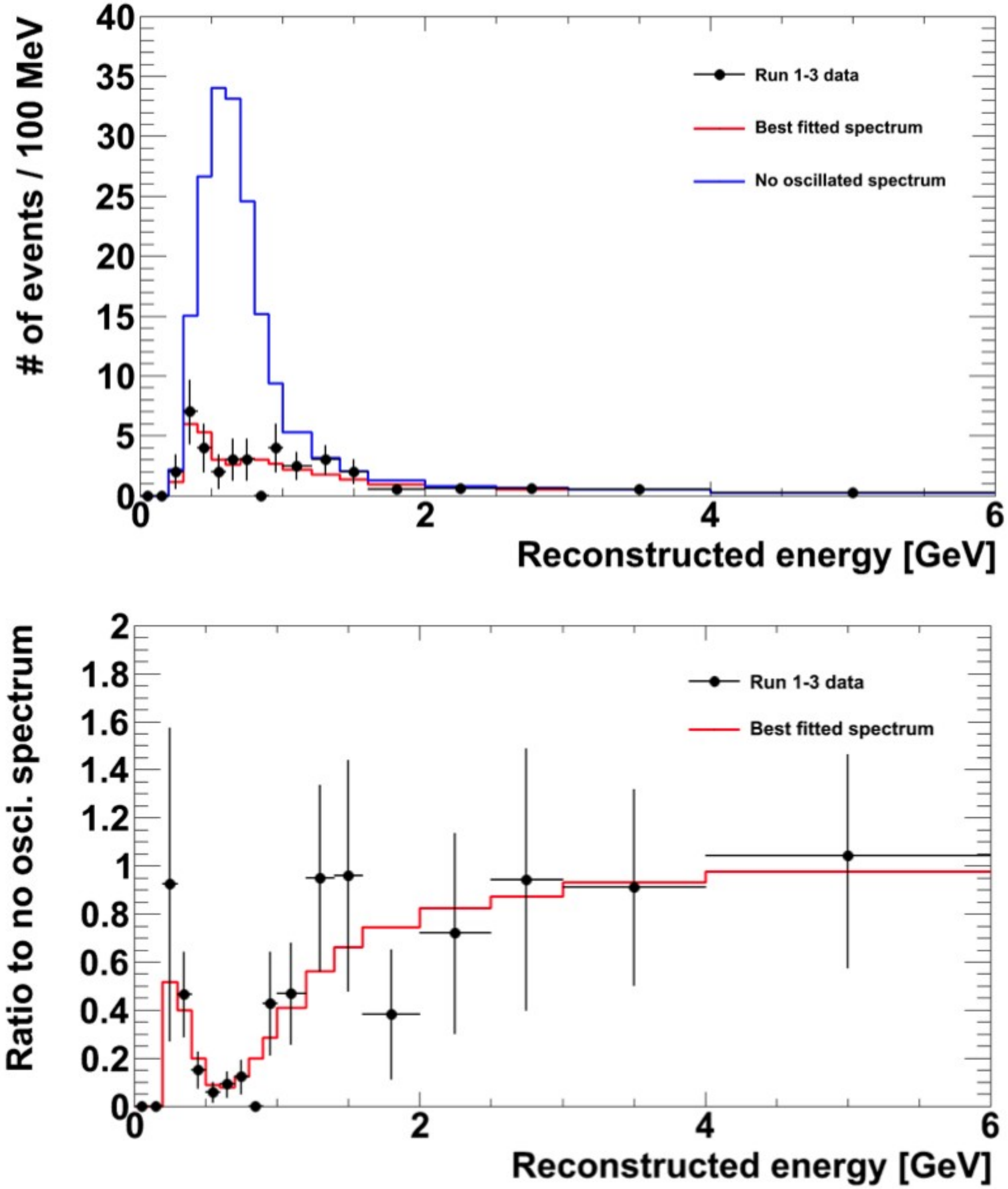
Beam

Atmos.

arXiv:1304.6335

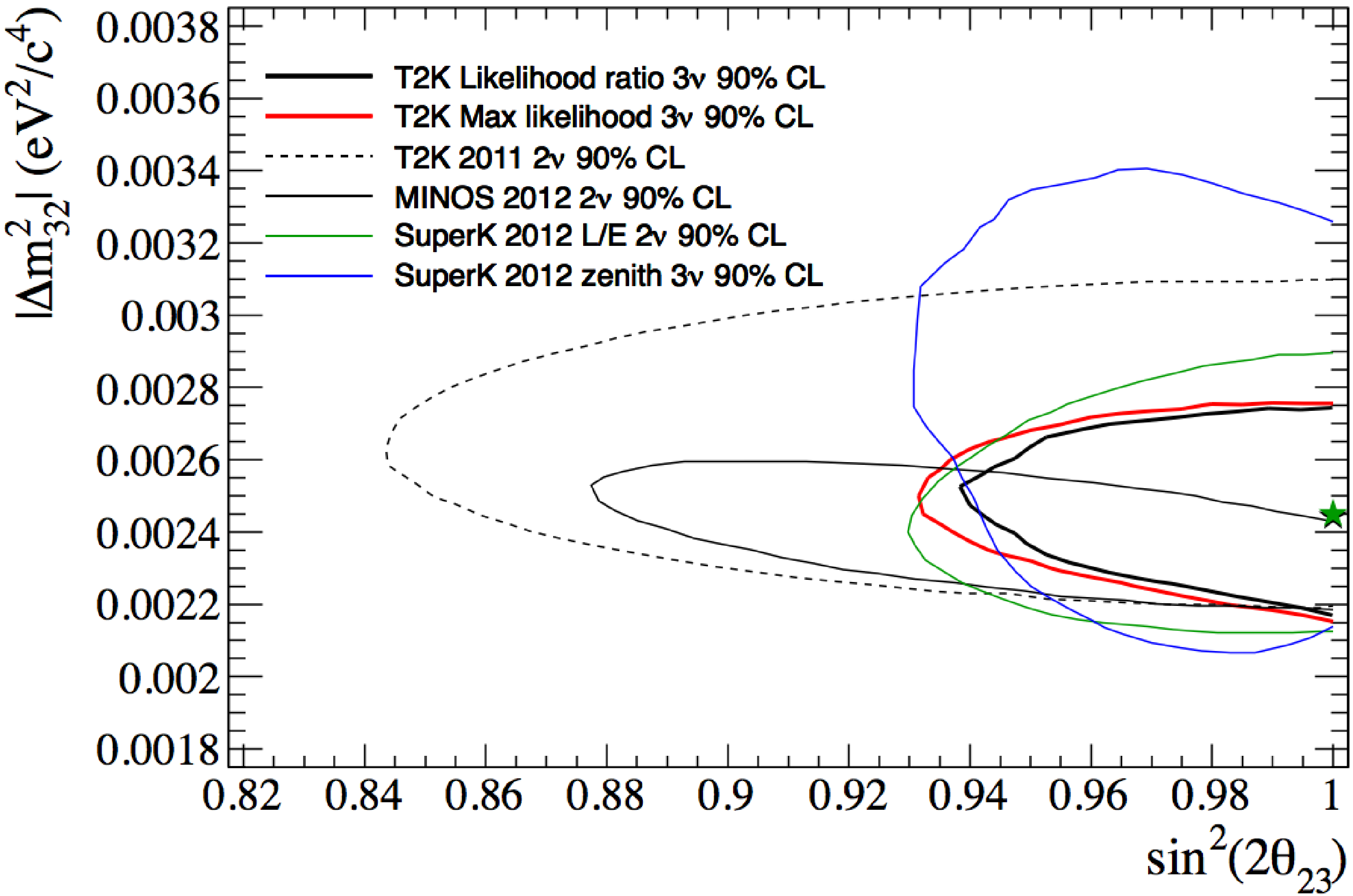
T2K

Recently updated results for muon neutrino disappearance



Kobayashi, NeuTel2013

Muon Disappearance Results



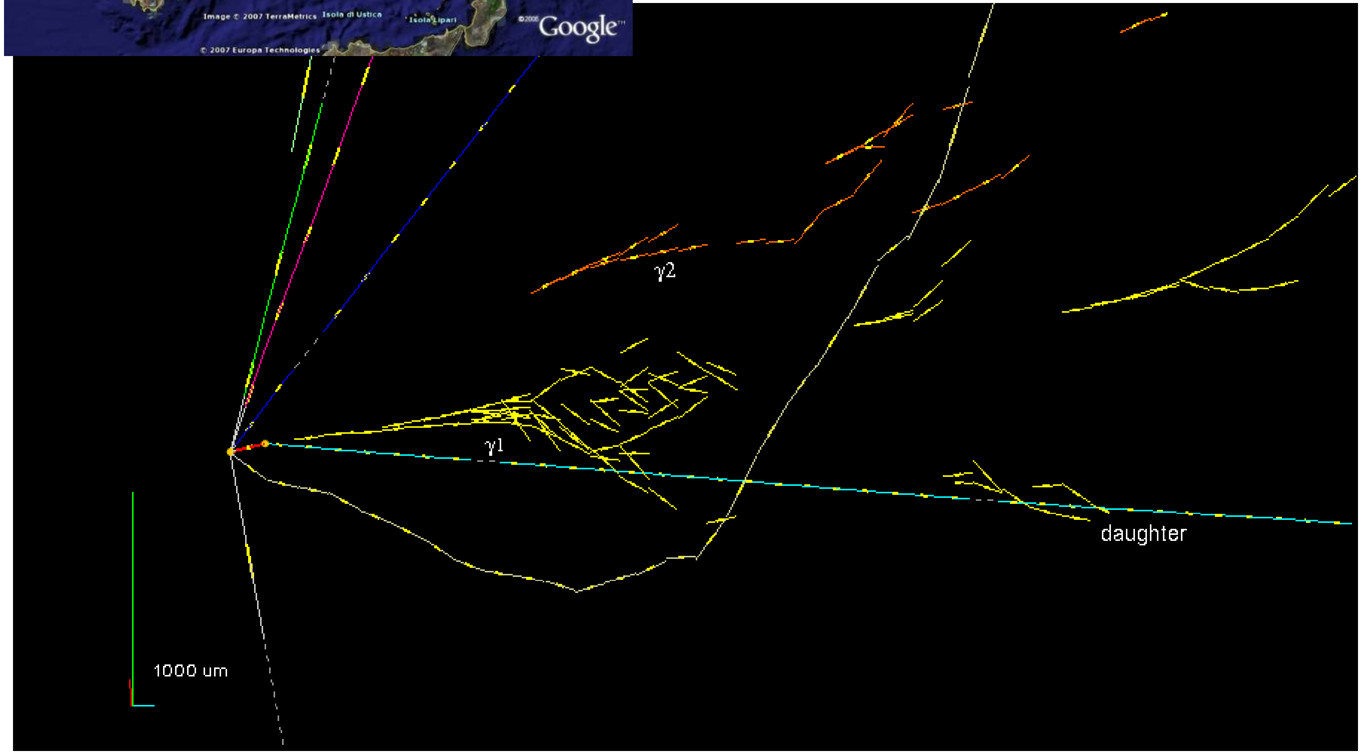
- MINOS makes most precise measurement of atmos. mass splitting
- T2K makes most precise measurement of mixing angle

Kobayashi, NeuTel2013

Tau Neutrino Appearance

Most of the disappearing muon neutrinos turn into tau neutrinos

OPERA (2008-present):
direct observation of tau neutrino appearance in muon neutrino beam



3 tau neutrino events observed so far

(Third event announced in March!)

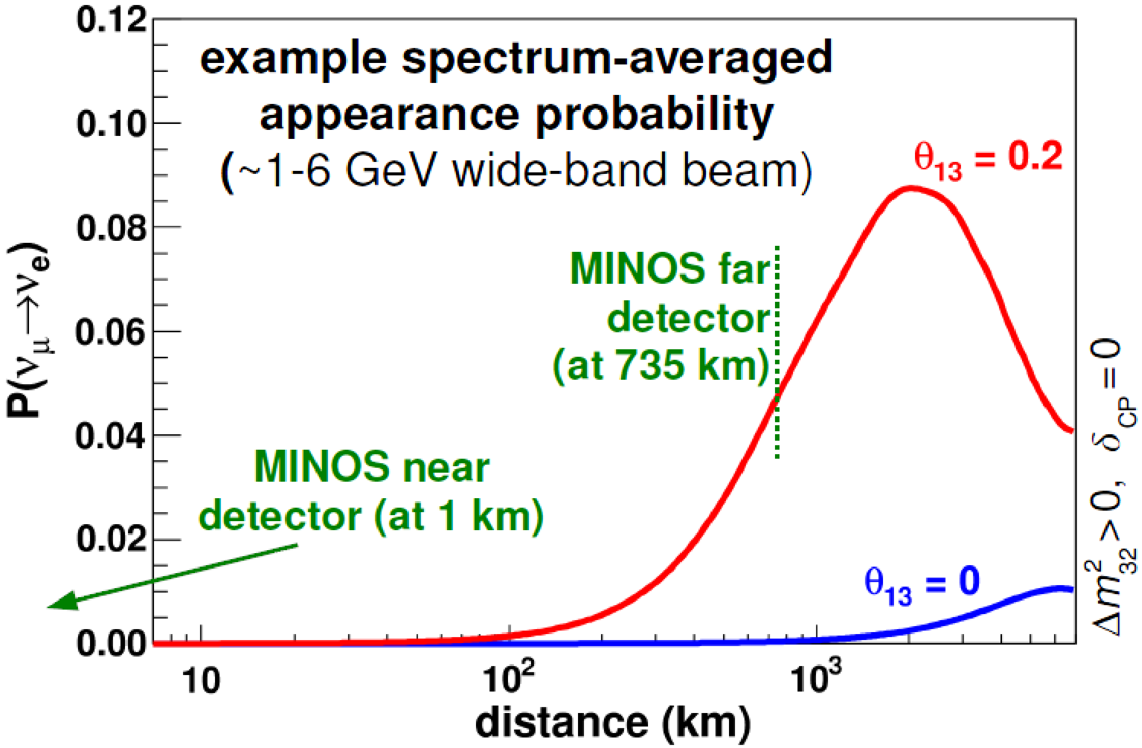
Measuring θ_{13} with accelerator ν's

appearance of ν_e in a ν_μ beam

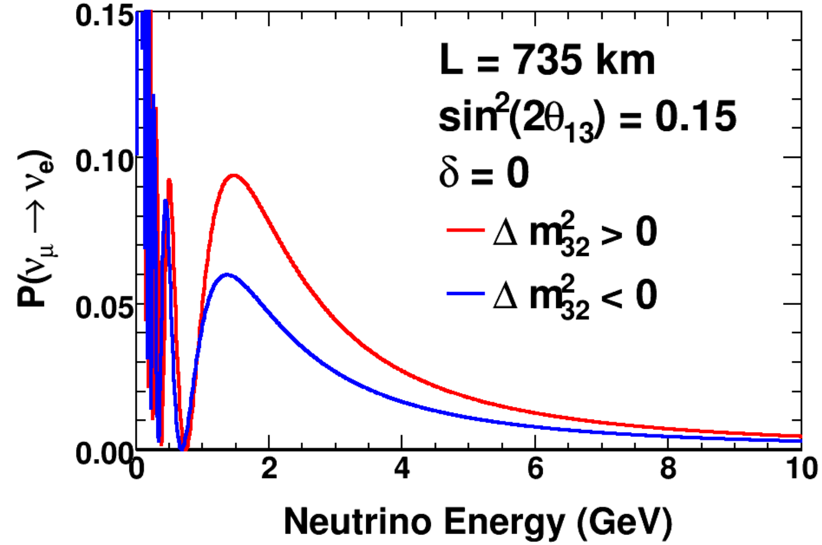
$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(2\theta_{13})\sin^2\theta_{23}\sin^2\left(\frac{\Delta m^2_{atm} L}{4E}\right)$$

(Dominant term)

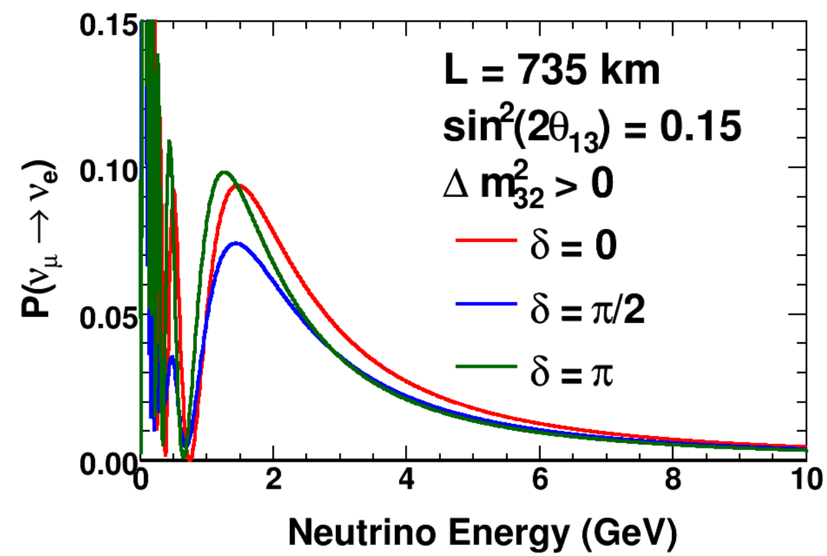
(+ higher order terms that depend on the unknown value of δ and the mass hierarchy)



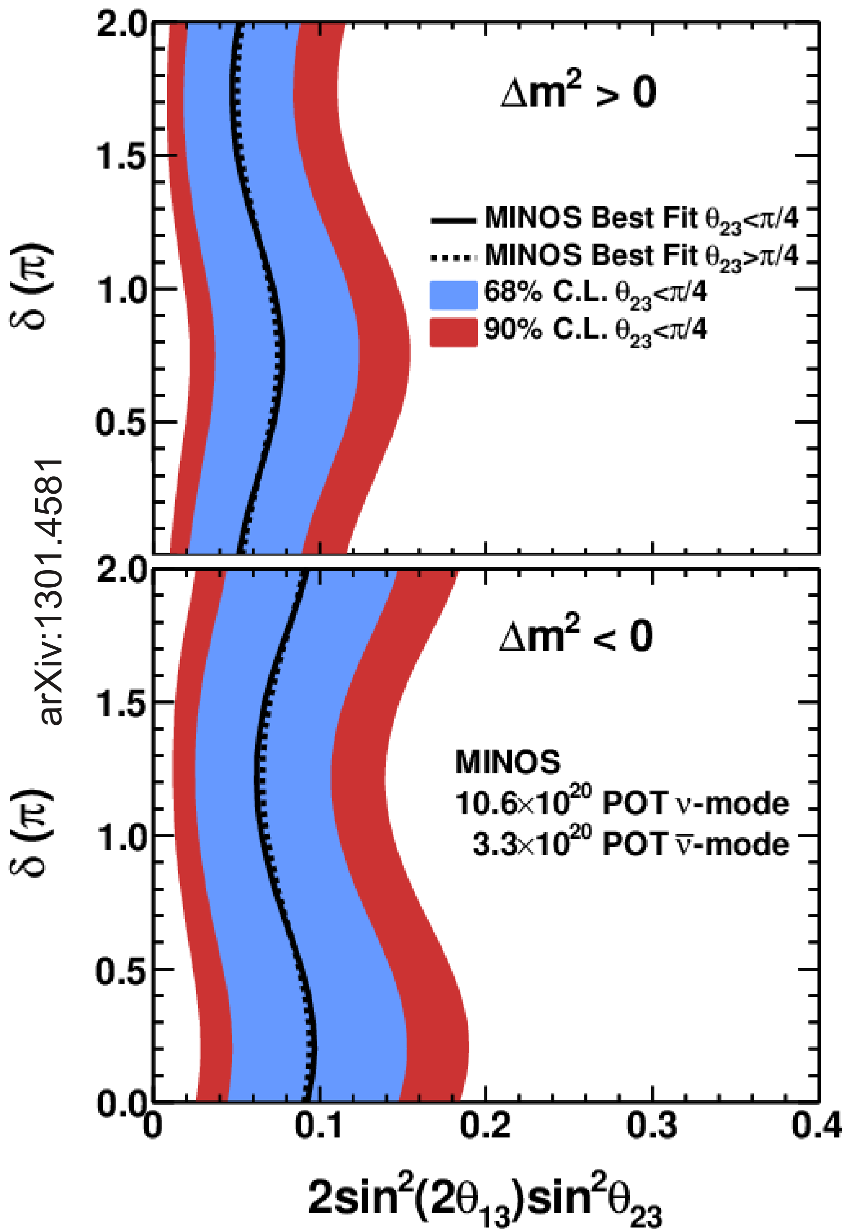
mass hierarchy dependence



δ dependence

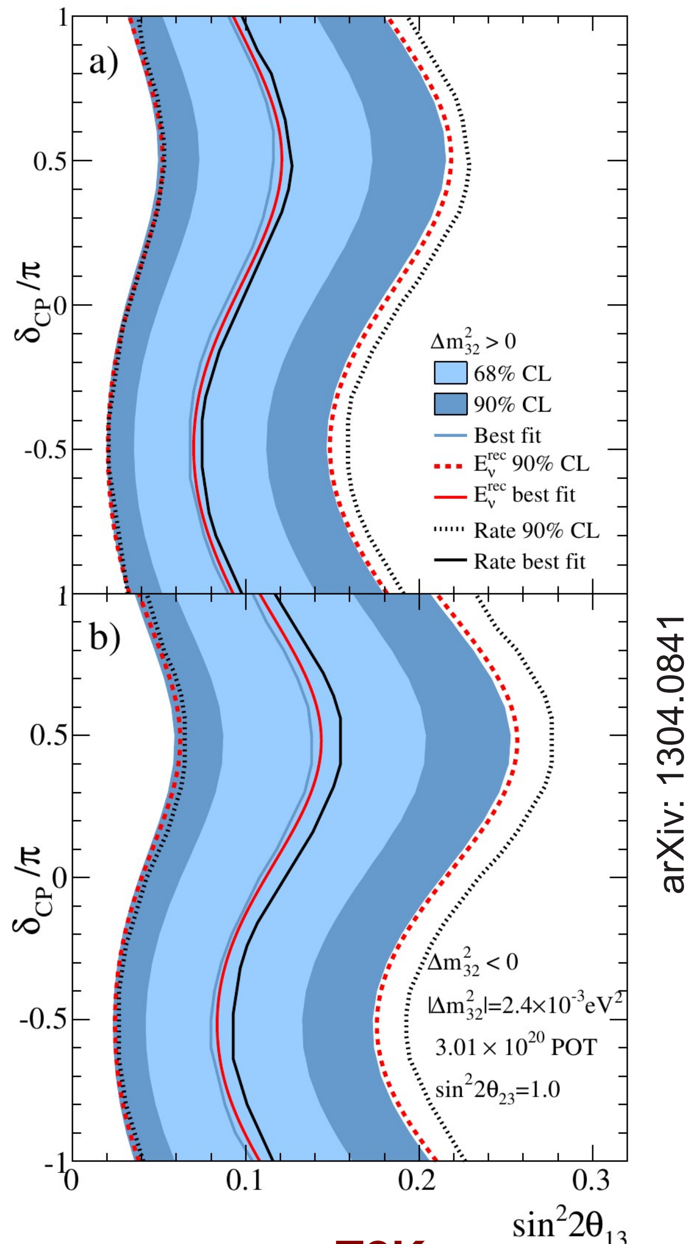


Electron Neutrino Appearance



MINOS Final Results

MINOS analysis includes both neutrino and antineutrino data: 1st search for electron antineutrino appearance!



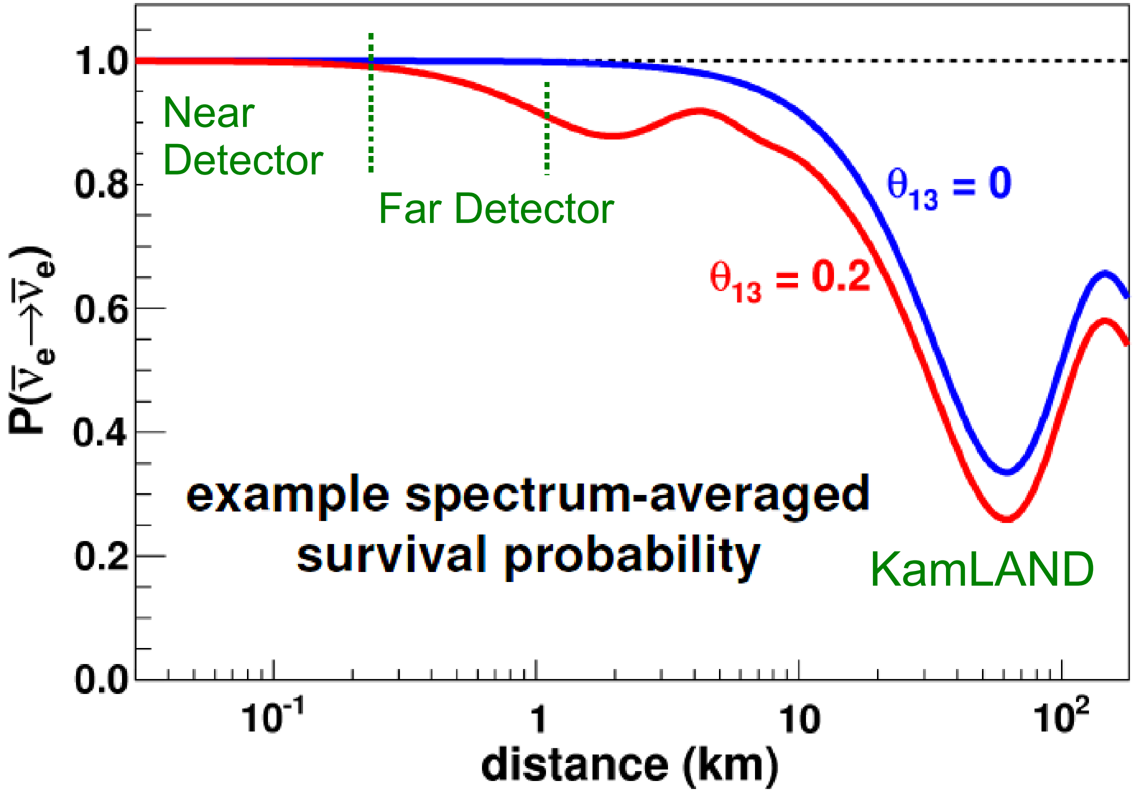
T2K

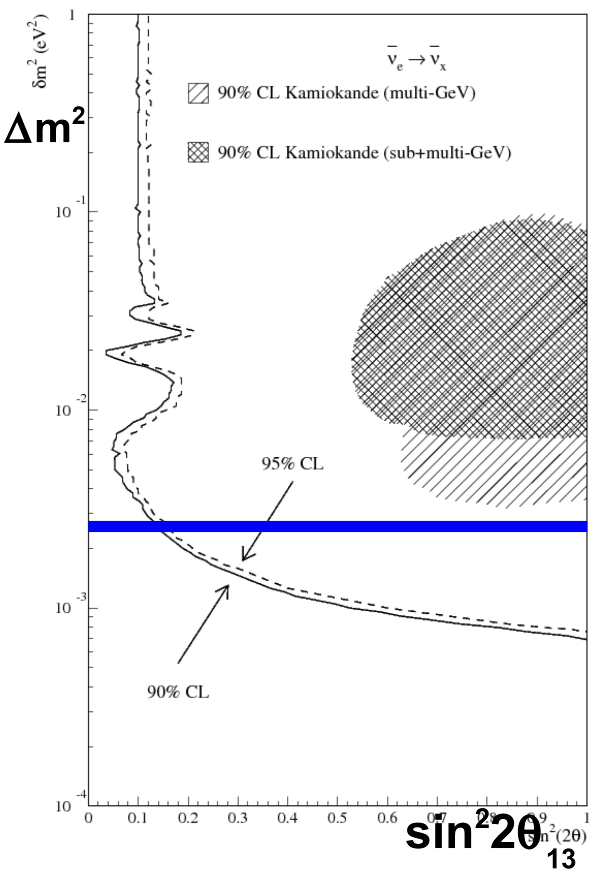
Measuring θ_{13} with reactor ν's

disappearance of $\overline{\nu}_e$ from a reactor

$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2(1.27 \Delta m^2_{atm} L/E) - C^4_{13} \sin^2 2\theta_{12} \sin^2(1.27 \Delta m^2_{sol} L/E)$$

- Can probe either mass difference and θ_{13} or θ_{12}, depending on baseline
- Short-baseline (~1 km) oscillations depend on θ_{13}





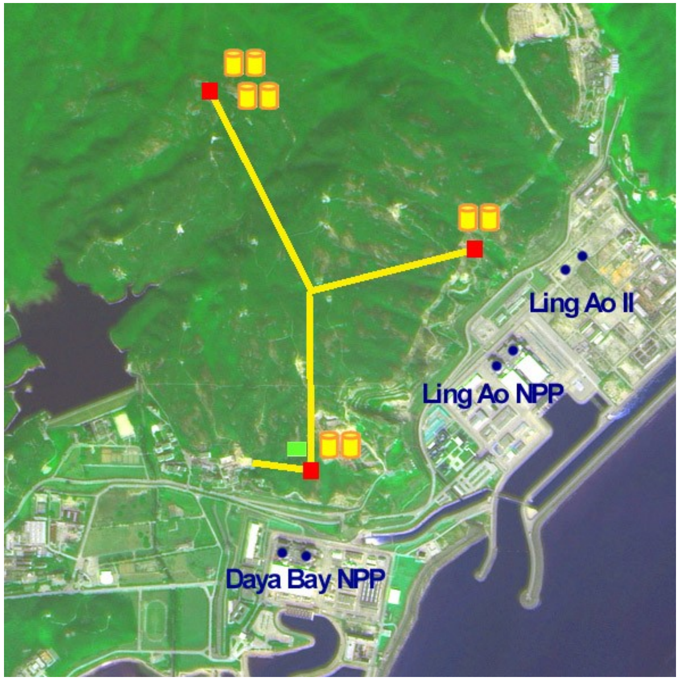
CHOOZ reactor neutrino experiment: $\sin^2 2\theta_{13}$<0.15

@ Δm^2_{atm} = 2.4×10^{-3} eV^2

Phys.Lett.B466: 415-430,1999

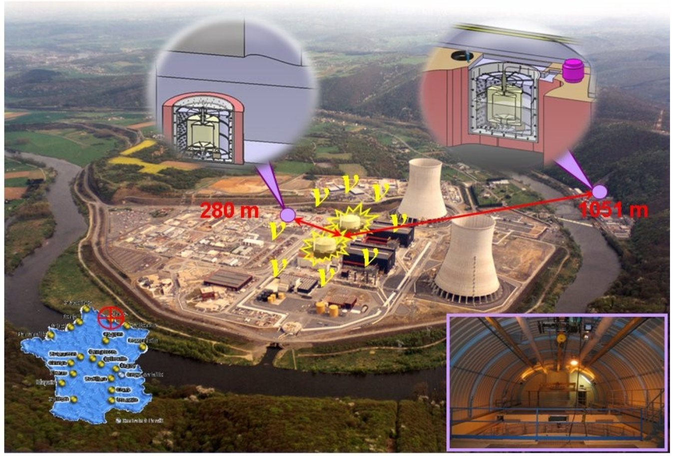
Eur. Phys. J. C27, 331 (2003)

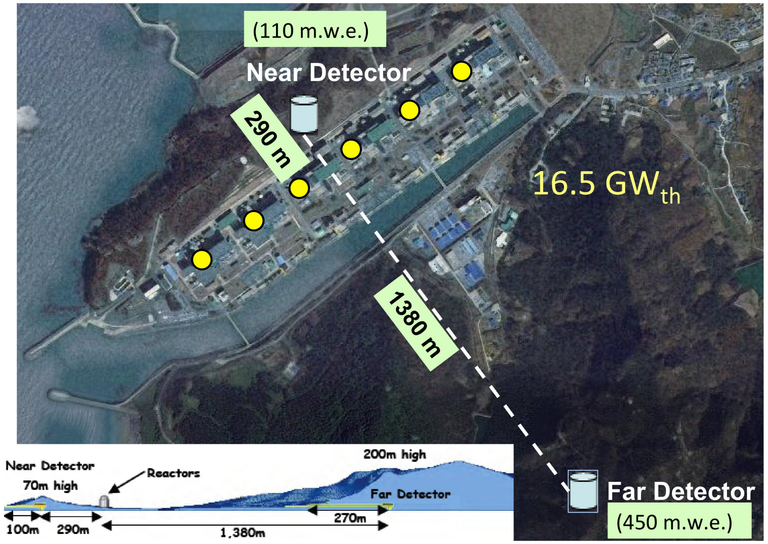
Reactor Experiments



Daya Bay (China)
Data in Sep 2011
17.4 GW
8 20-ton detectors

Double Chooz
(France)
Data in Apr 2011
8.5 GW
1 8-ton detector
(ND online in 2014)

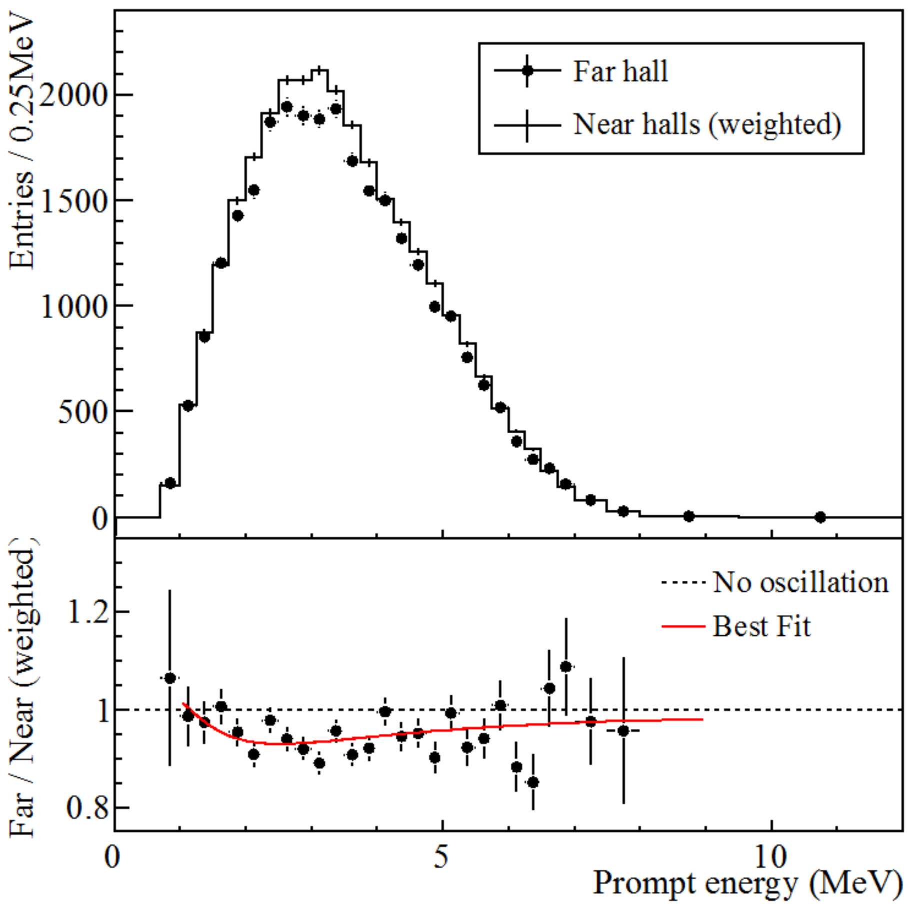


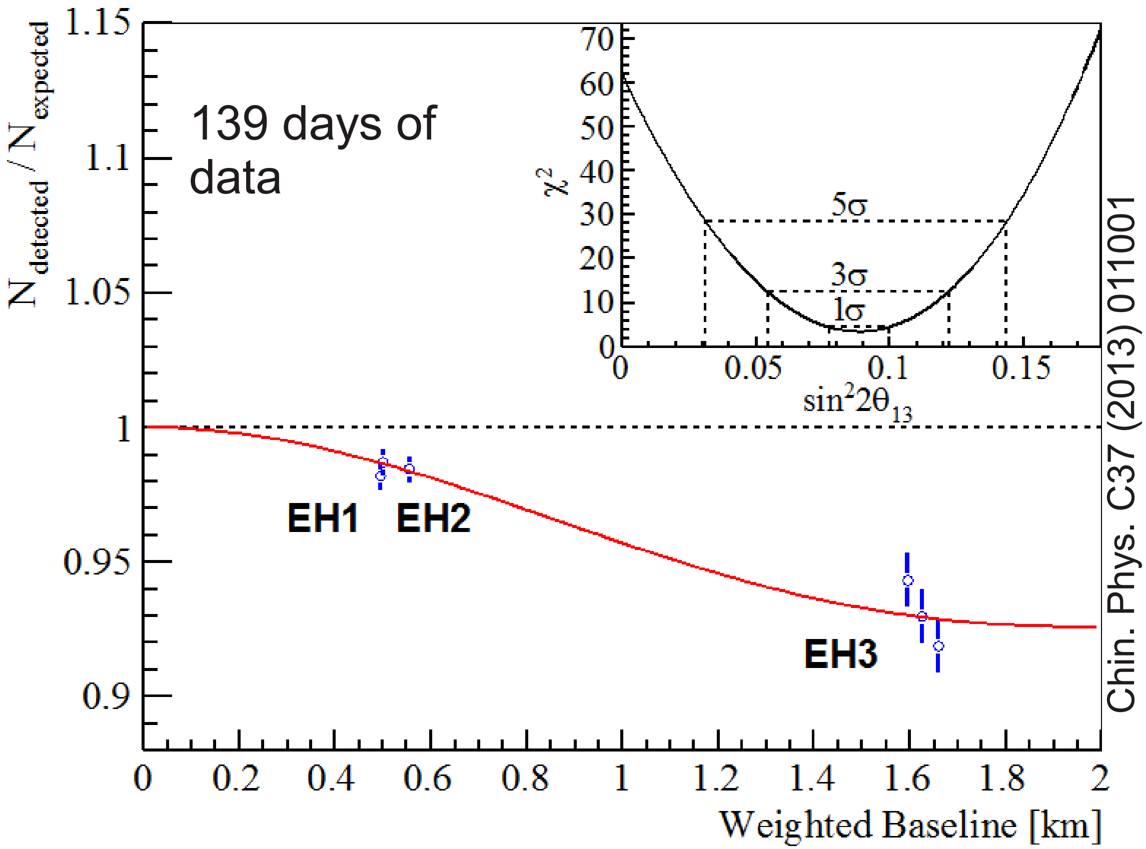


RENO (Korea)
Data in Aug 2011
16.5 GW
2 16-ton detectors

Daya Bay

$\sin^2 2\theta_{13}$ = 0.089 ± 0.010 (stat) ± 0.005 (syst)



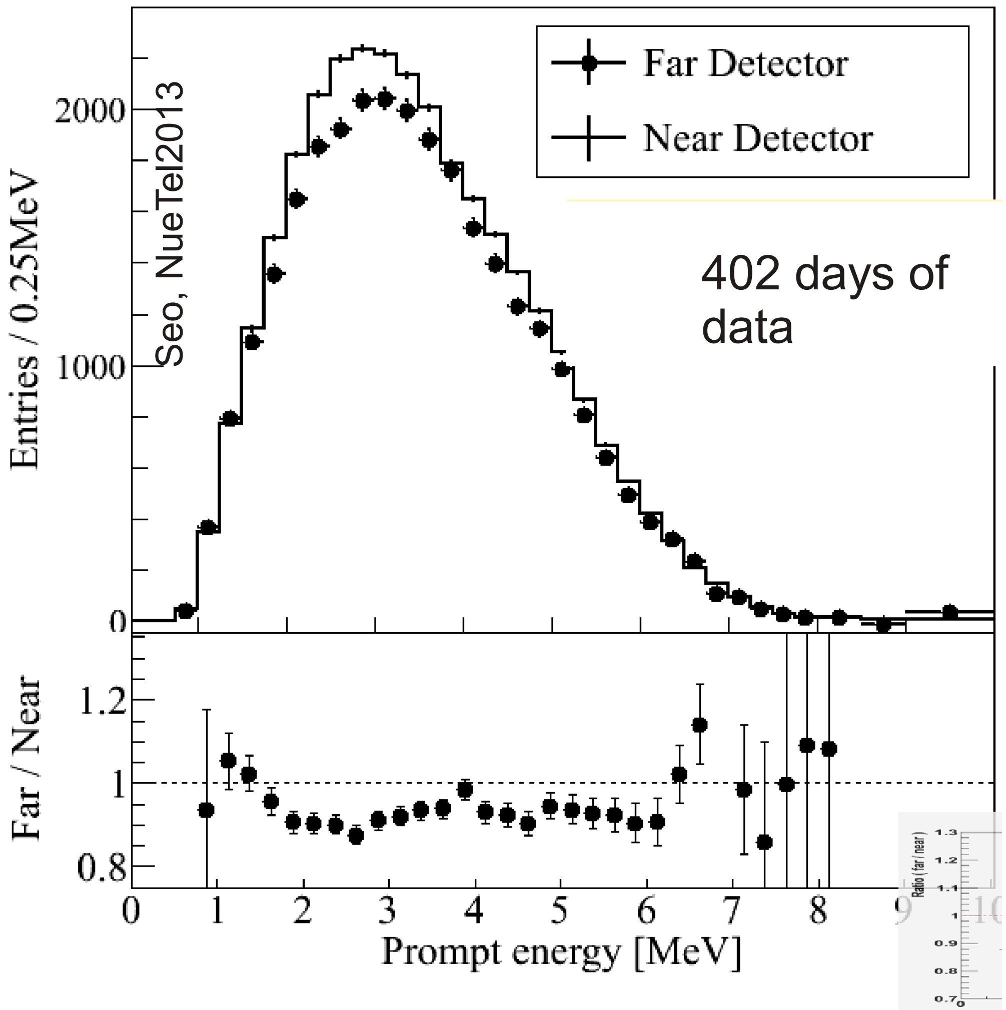


R = 0.944 ± 0.007 (stat) ± 0.003 (syst)

Most precise measurement of $\sin^2 2\theta_{13}$ to date!

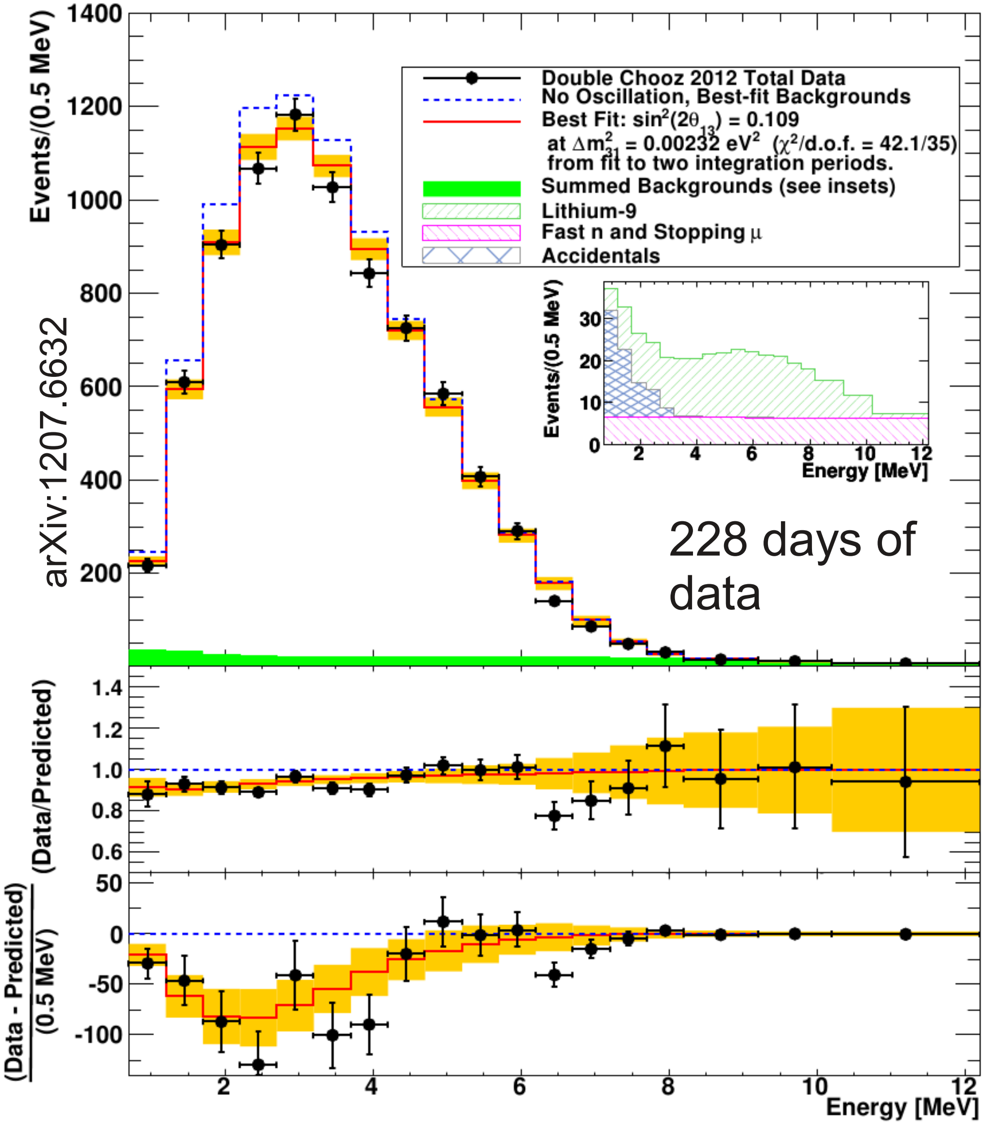
RENO and Double Chooz

RENO



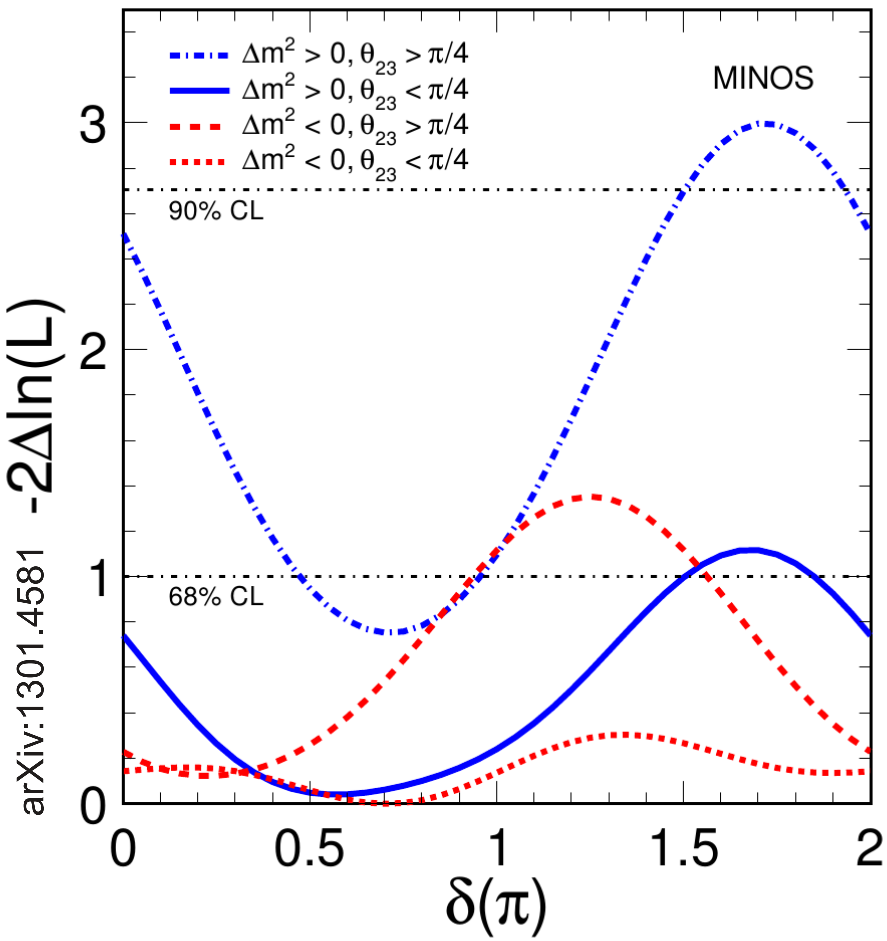
$\sin^2 2\theta_{13}$ = 0.100 ± 0.010 (stat) ± 0.015 (syst)

Double Chooz



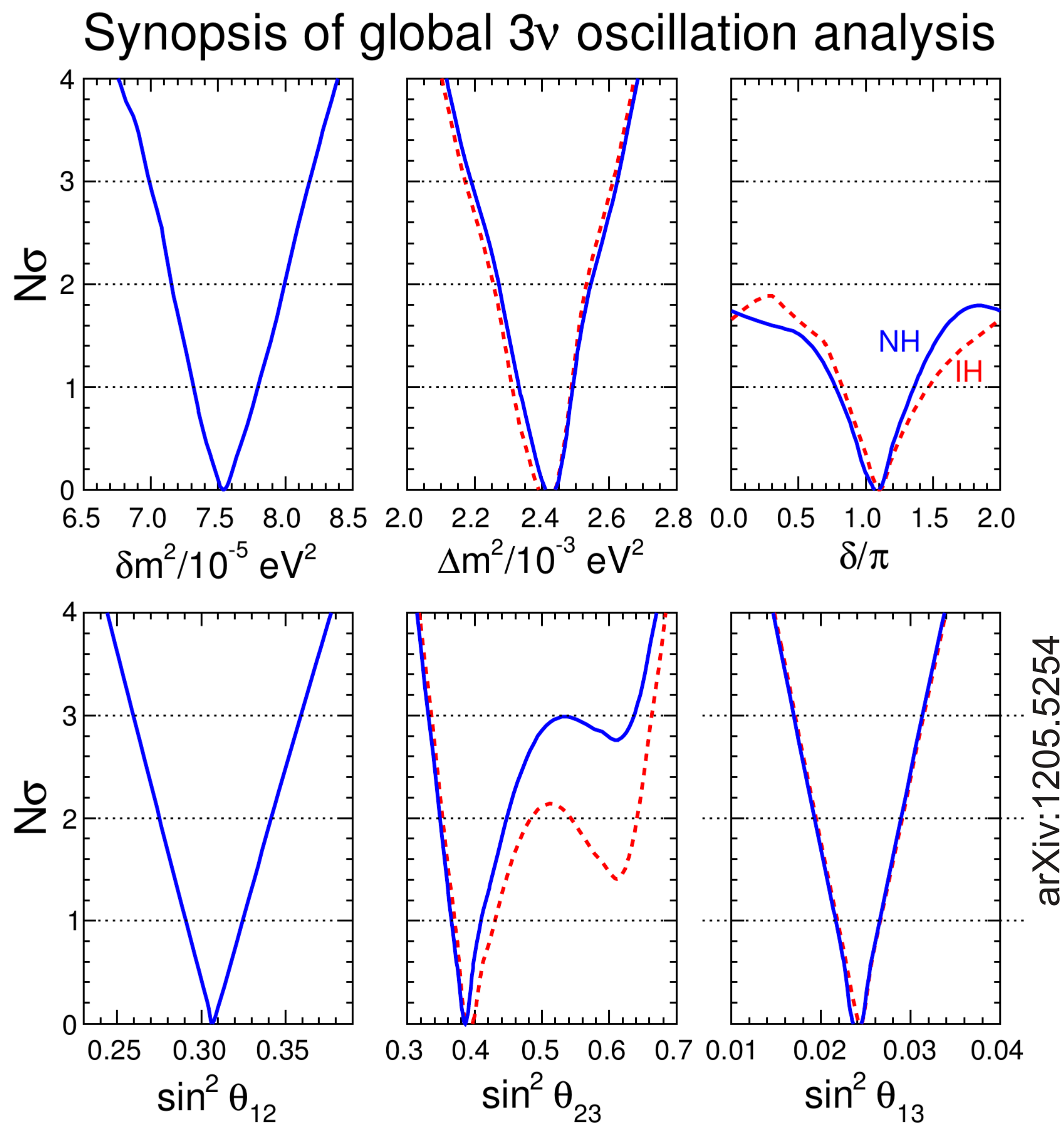
$\sin^2 2\theta_{13}$ = 0.109 ± 0.030 (stat) ± 0.025 (syst)

Now what?



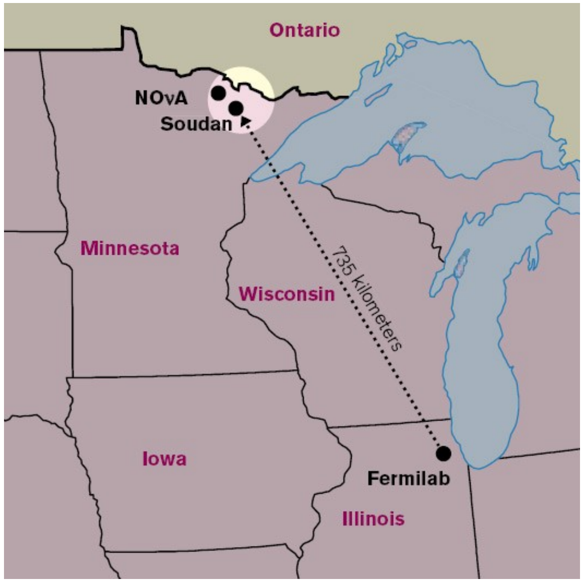
MINOS

Fit to CP phase δ using reactor constraint on θ_{13}

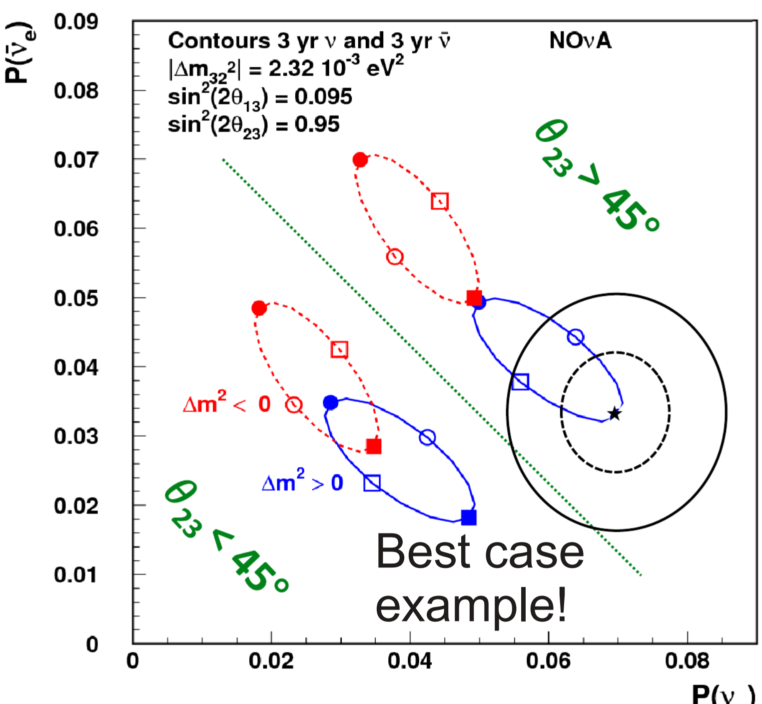


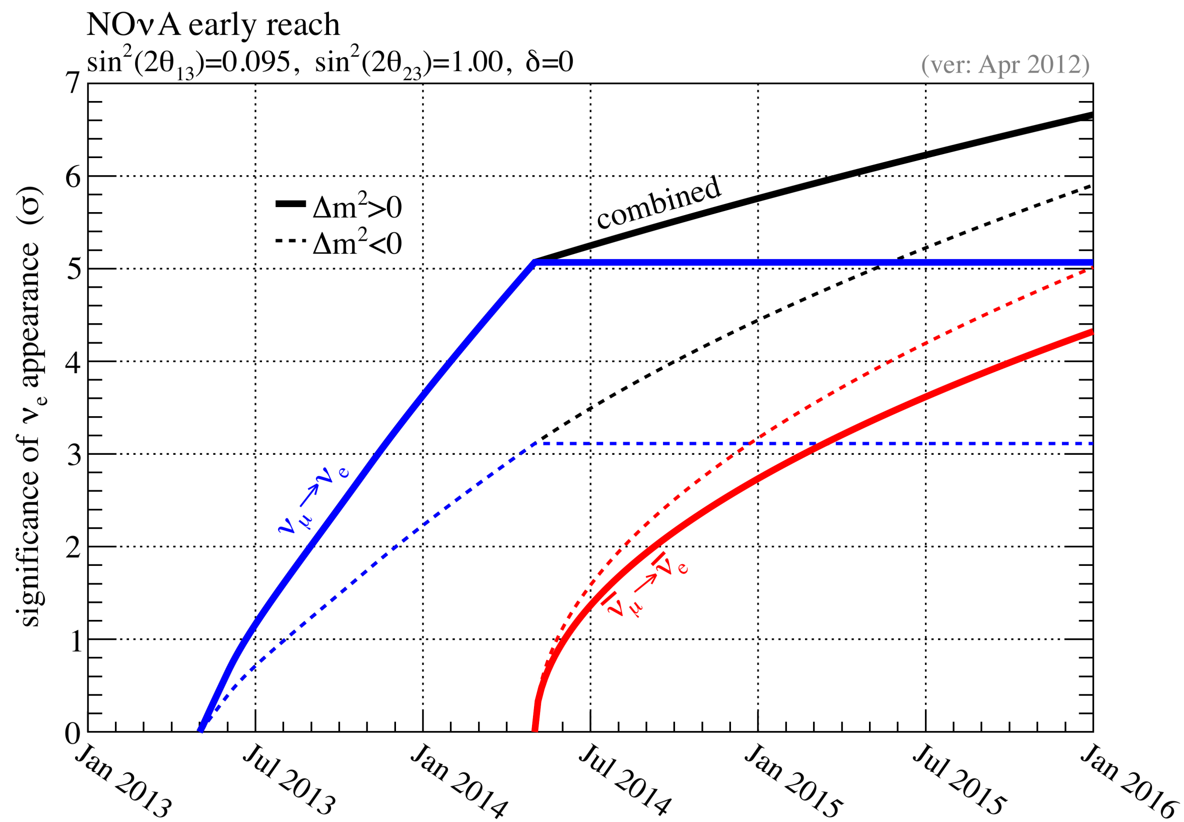
A global fit example

NOvA



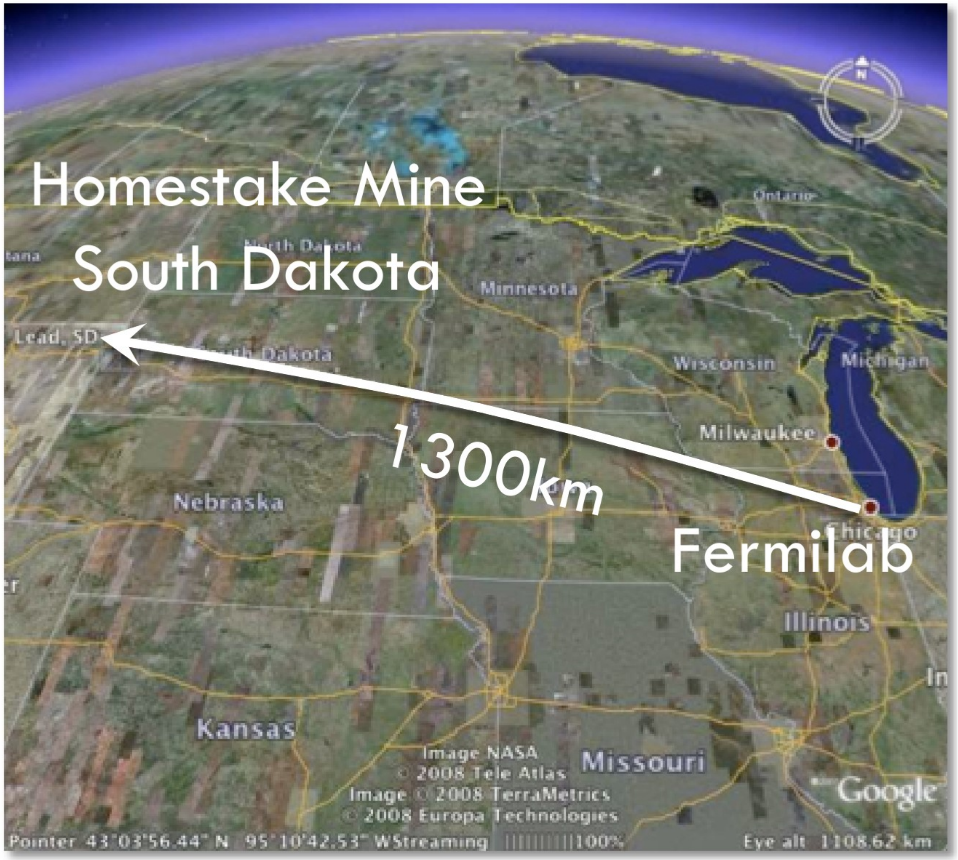
- Will study electron neutrino and antineutrino appearance (810 km)
- First data in far detector expected June 2013
- Fully operational by end of 2014





Corwin, NeuTel2013

LBNE



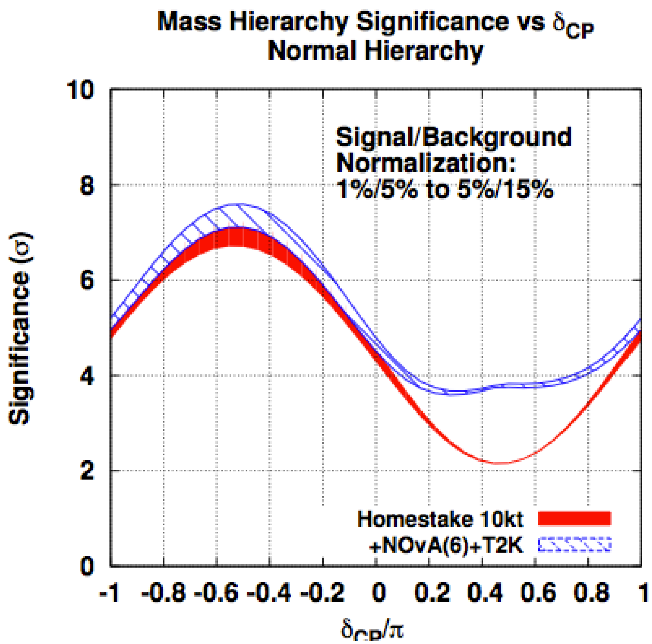
- New wide band neutrino beam at Fermilab
- LAr TPC detector
- 1300 km baseline optimized for CP violation discovery and mass hierarchy determination

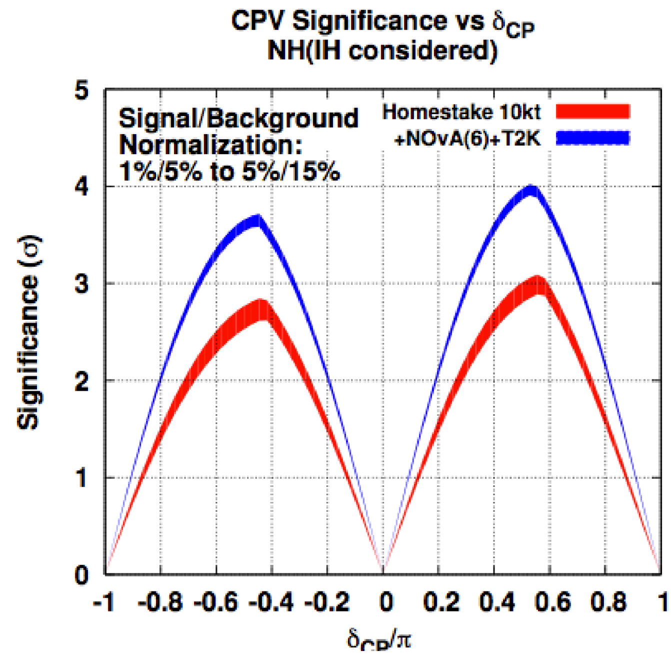
Physics goals:

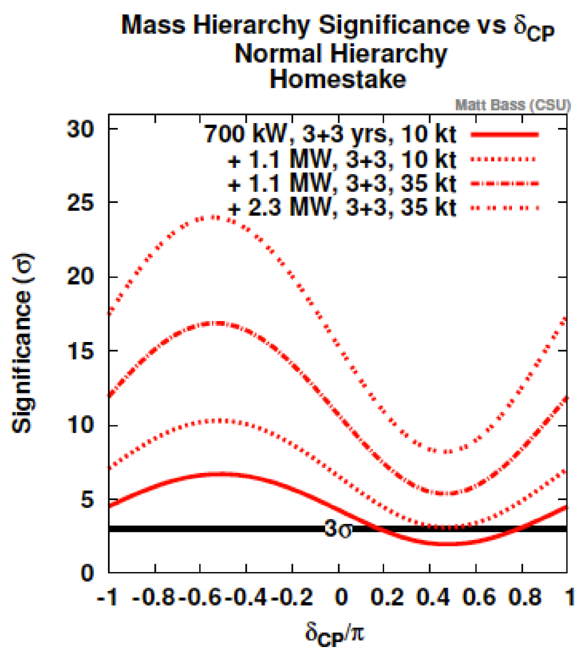
- Discover CP violation in the neutrino sector
- Unambiguously resolve the mass hierarchy
- Precision measurements of all oscillation parameters
- Search for new physics (sterile neutrinos, NSI)
- Proton decay
- Supernova burst neutrinos
- Atmospheric neutrinos

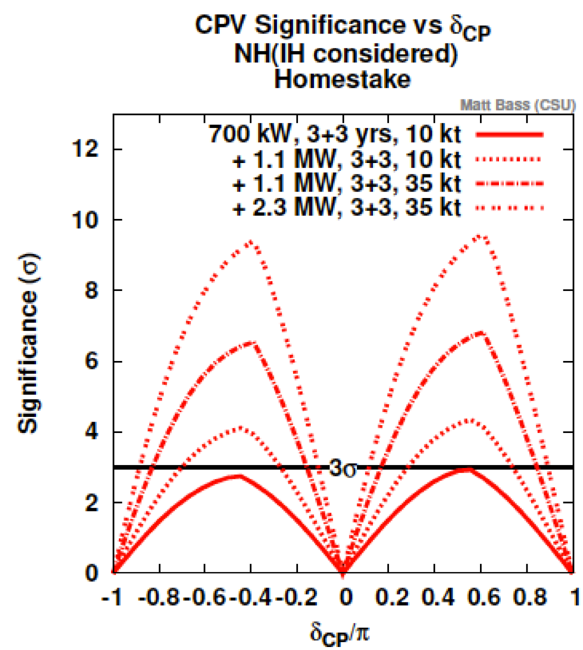
First phase (10 kton, 700 kW beam) granted DOE CD1 approval in Dec. Long range plan includes increasing to 35 kton detector, 2.3 MW beam in phases

LBNE



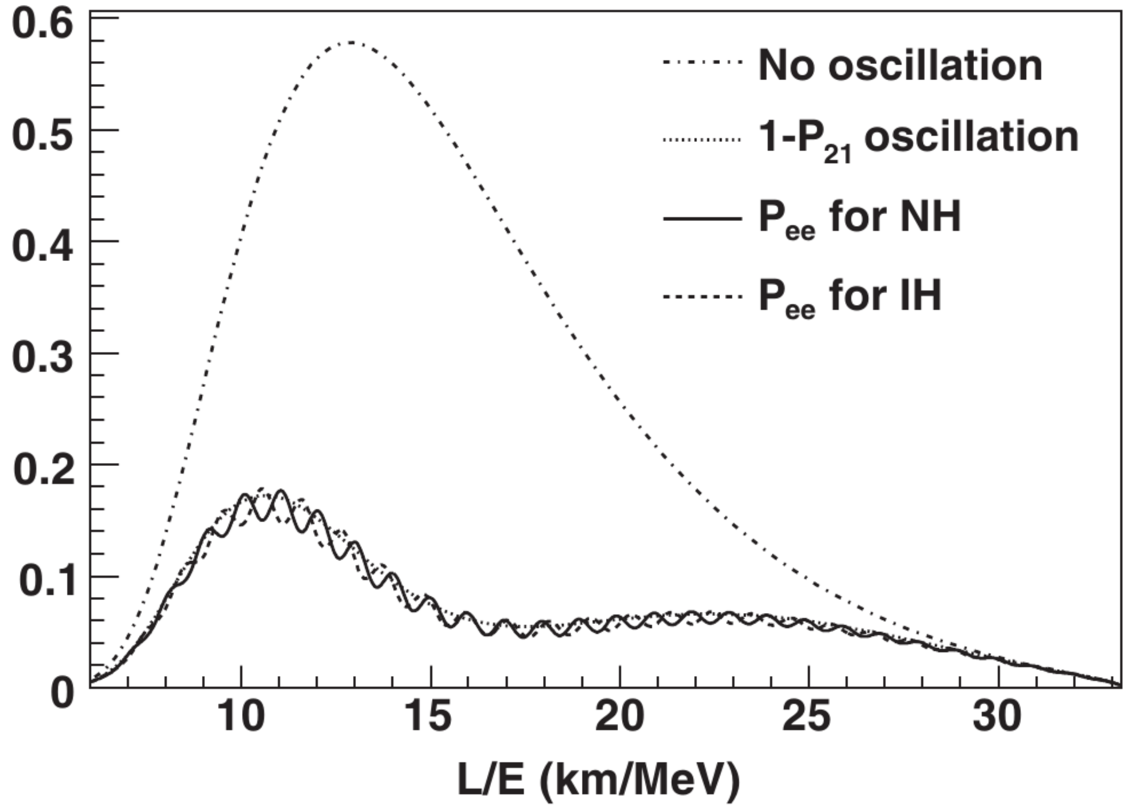






Diwan, NeuTel2013

Daya Bay II



Phys Rev D78, 111103R (2008)

$$P_{ee}(L/E) = 1 - P_{21} - P_{31} - P_{32}$$

$$P_{21} = \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21})$$

$$P_{31} = \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31})$$

$$P_{32} = \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32}),$$

Proposed experiment in China (no longer expected to be at Daya Bay)

20 kton LS detector at ~60 km from reactors

Main goal: Measure mass hierarchy

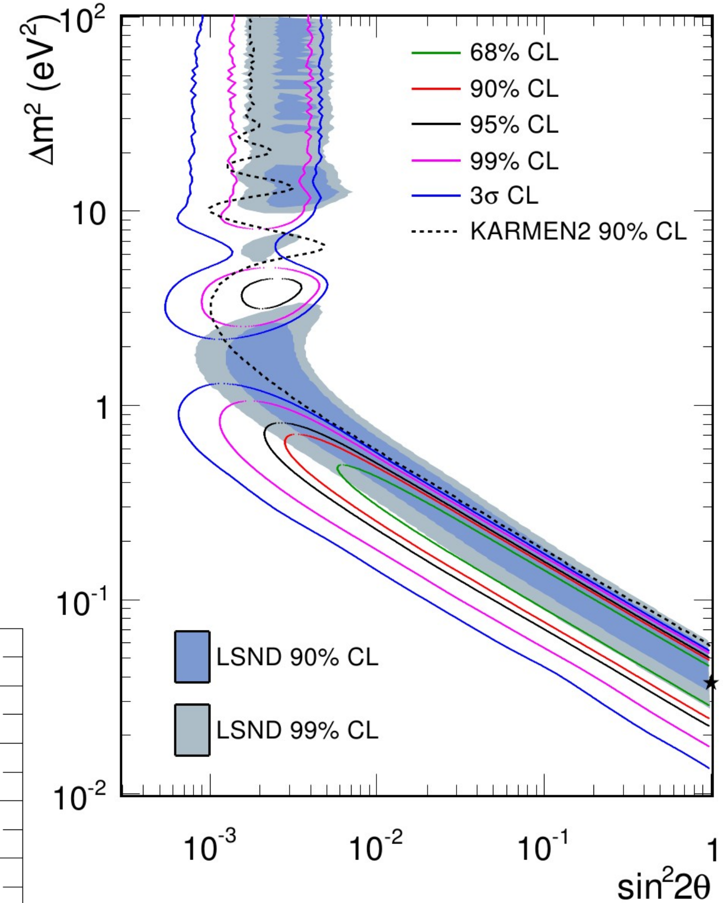
Other physics:
- precision measurement of oscillation parameters
- supernova neutrinos
- geoneutrinos
- sterile neutrinos
- atmospheric neutrinos

Wang, NeuTel2013

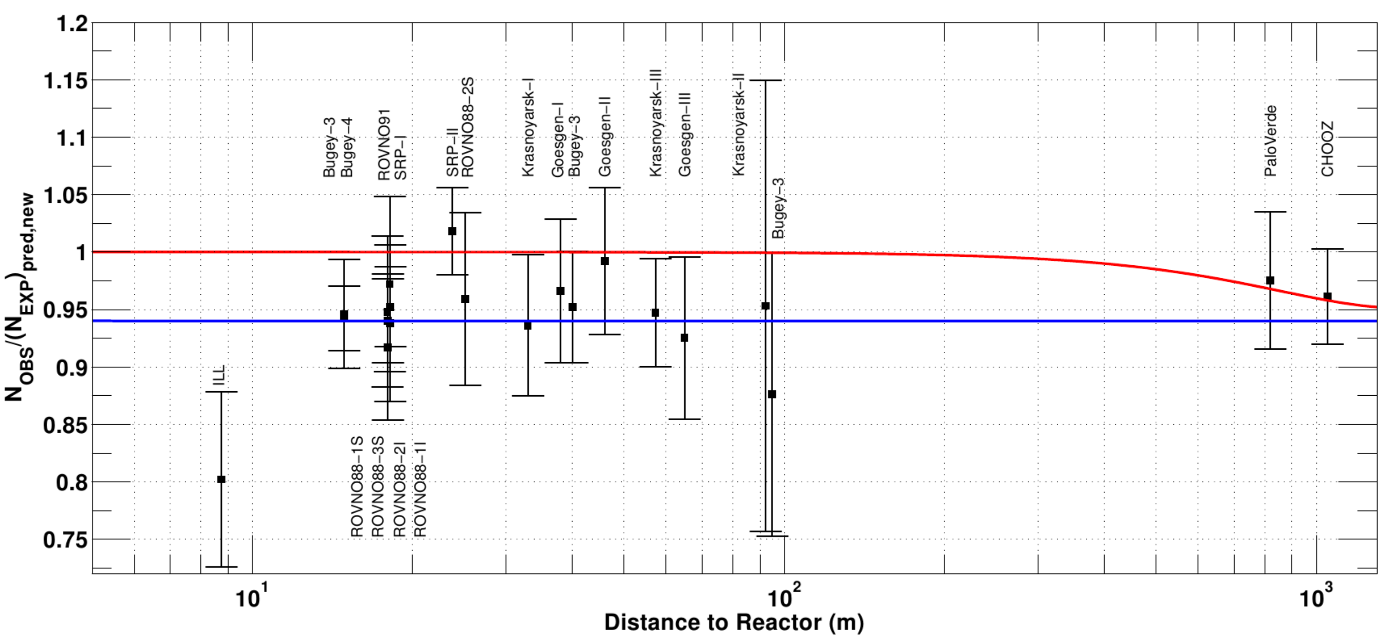
Anomalies

Still some mysteries:
- MiniBooNE/LSND
- Reactor neutrino anomaly

Sterile neutrino(s)?

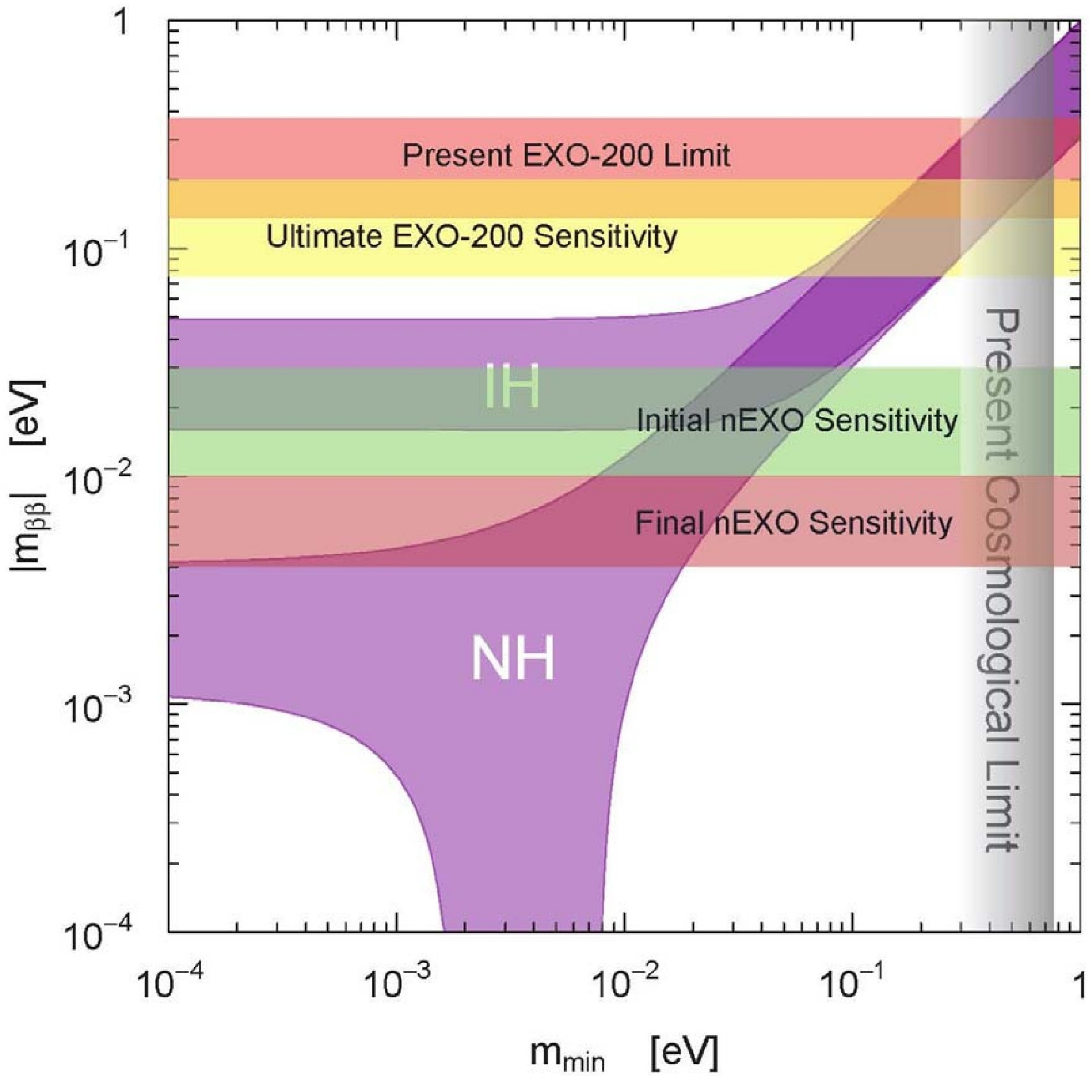


arXiv:1207.4809



arXiv:1101.2755

Neutrino Mass Measurements



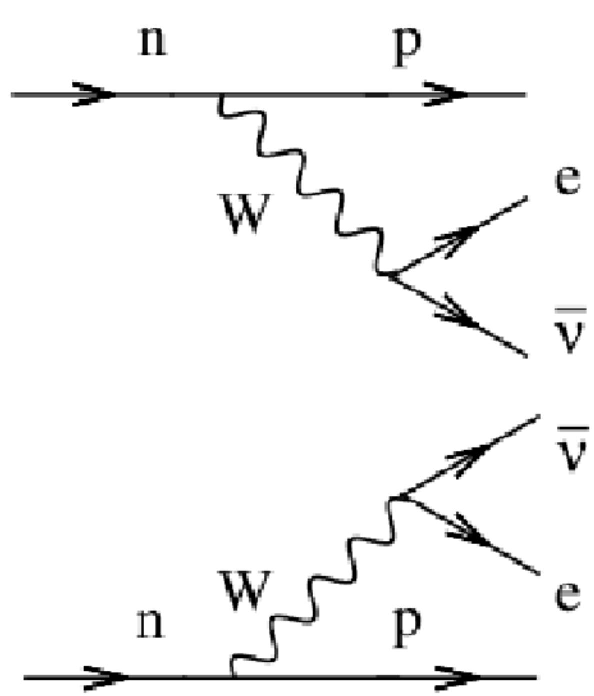
Double Beta Decay

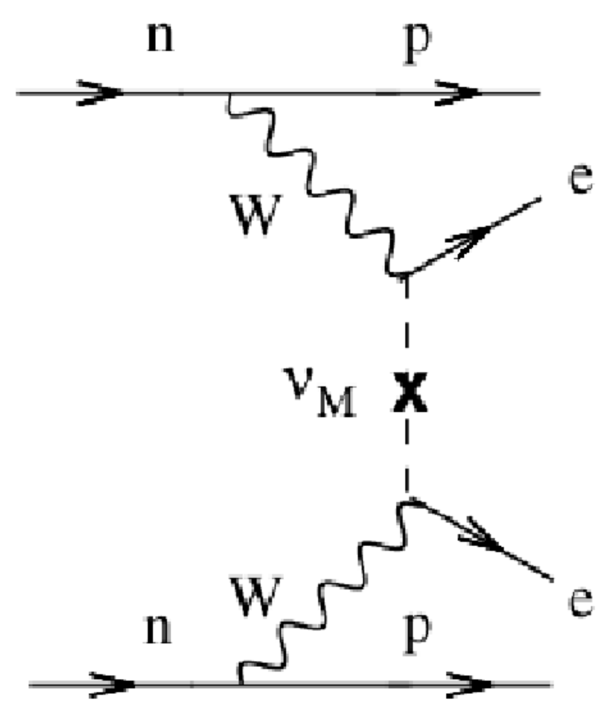
2ν DBD – allowed by standard model and observed

$$(A,Z) \rightarrow (A,Z+2) + 2e^{-} + 2\overline{\nu}_e$$

neutrinoless DBD – never observed*, would imply violation of total lepton number conservation

$$(A,Z) \rightarrow (A,Z+2) + 2e^{-}$$





$$\overline{\nu} = \nu$$

*There is an unconfirmed claim on Ge from Klapdor, et al

Double Beta Decay

Decay rate → Phase space factor → Nuclear Matrix Element

$$1/\tau = G|M|^2 |m_{\beta\beta}|^2$$

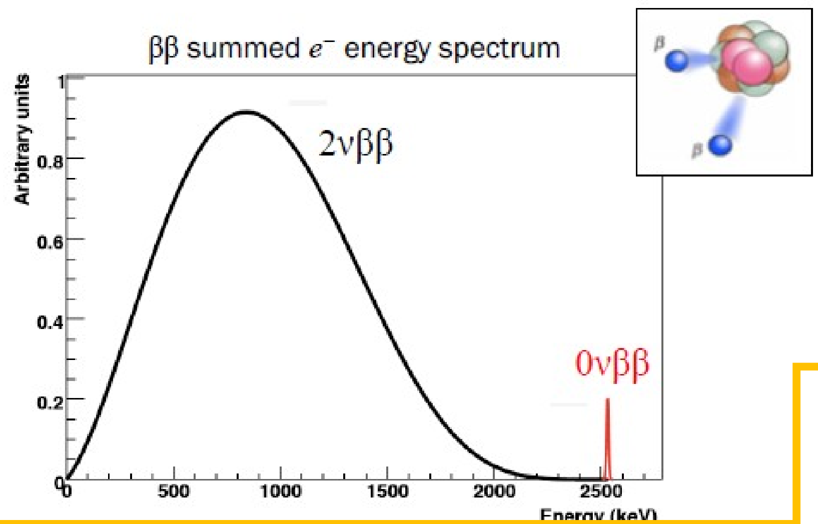
Effective Majorana mass

$$m_{\beta\beta} = \sum U_{ei}^2 m_i$$

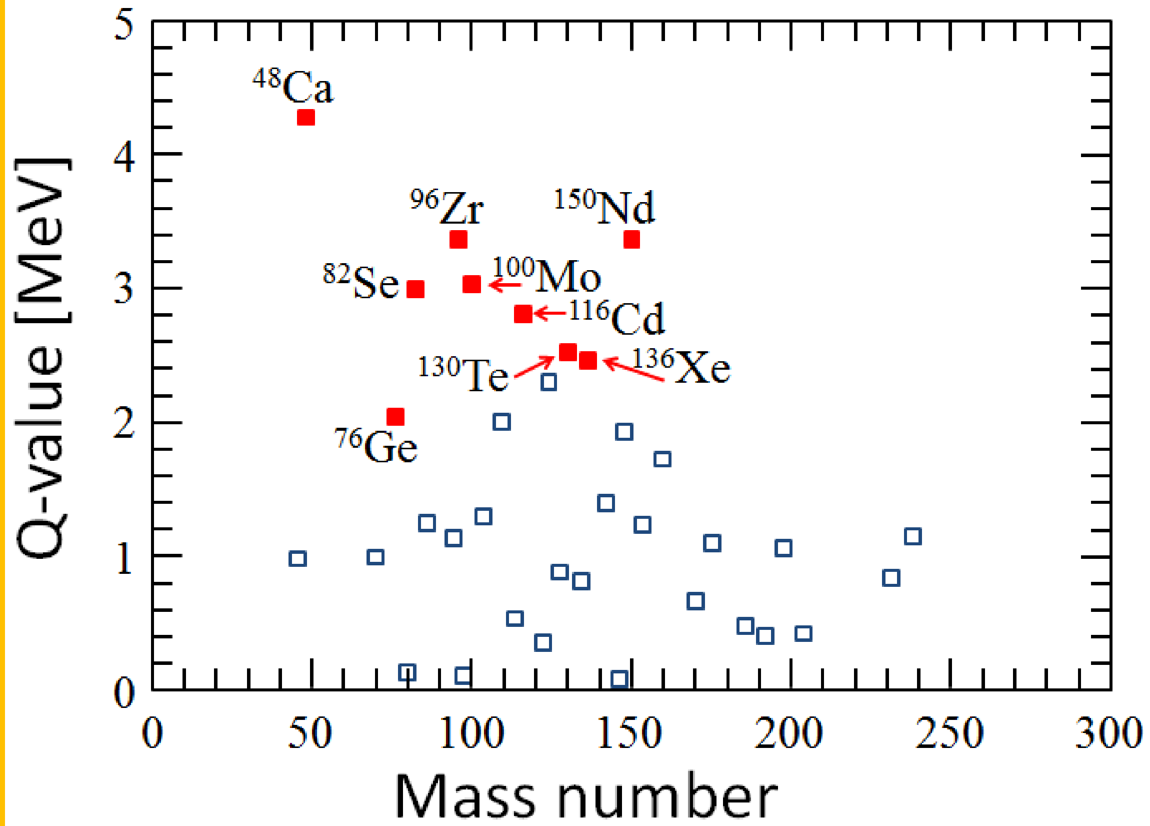
Access to absolute neutrino mass scale

Only way to tell if neutrinos are
Dirac particles (total lepton number conserved, neutrinoless DBD forbidden)
OR
Majorana particles (total lepton number not conserved, neutrinoless DBD allowed)

Double Beta Decay Experiment



Isotope selection

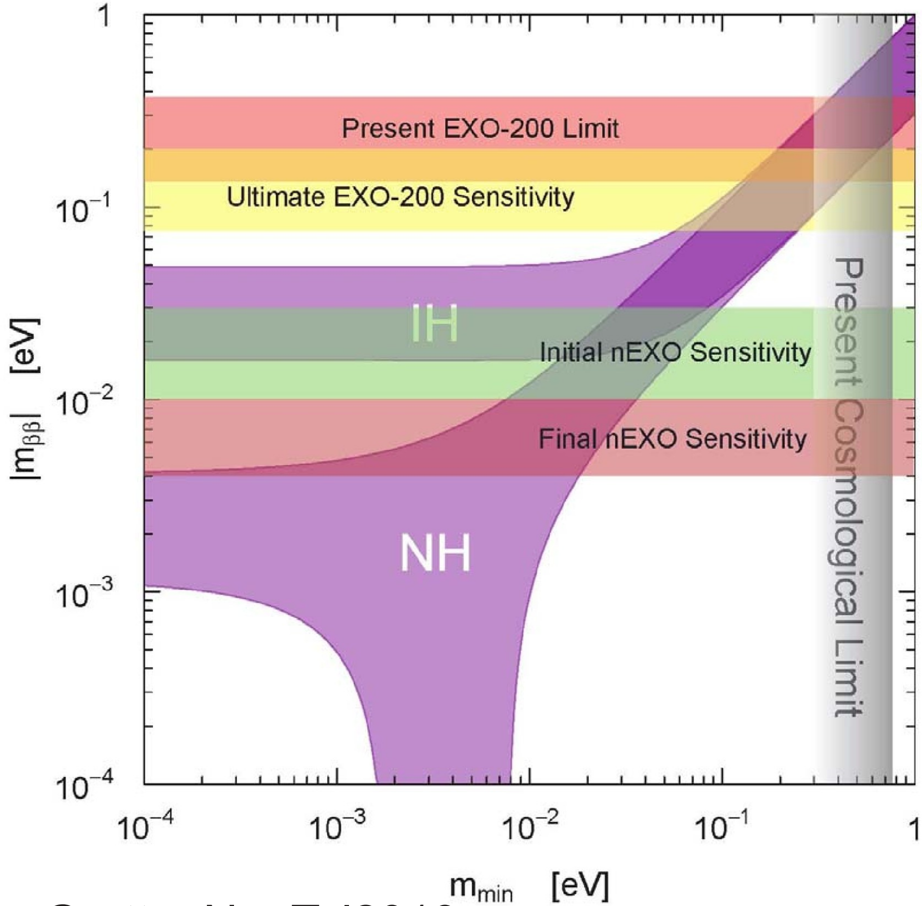


Huge background from 2ν DBD in addition to radioactivity, cosmic muon induced background

Guiliani, NeuTel2013

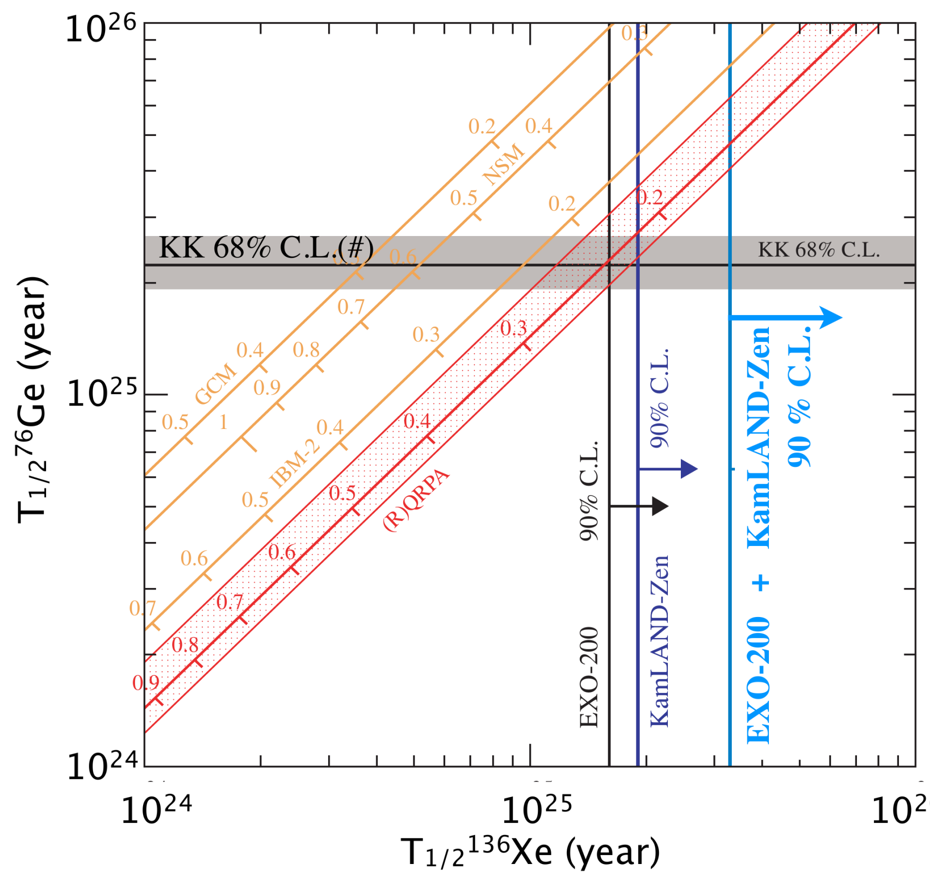
Currently Running Expts (Xe)

EXO-200
- Running since 2011
- Approved to run until end of 2014
- First observation of 2ν DBD in 136Xe



Gratta, NeuTel2013

KamLAND-Zen
- LS loaded with 136Xe in KamLAND
- Data since 2011
- Consistent 2ν DBD in 136Xe with EXO



Nakamura, NeuTel2013

Currently Running Expts

GERDA (76Ge)
- Phase I - Nov 2011
- Modifications for phase 2 start this summer

Phase I:
- reach sensitivity of $T_{1/2} = 2 \cdot 10^{25}$ yr at 90% C
- $<m_{\beta\beta}> \leq$ 0.23-0.39 eV
- → **check claim!**

Phase II:
- reach background of **10^{-3} cts/(keV·kg·yr)**
- Exposure of 100 kg·yr → $T_{1/2} > 1.35 \cdot 10^{26}$ yr
- $<m_{\beta\beta}> \leq$ 0.09-0.15 eV

Brugnera, NeuTel2013

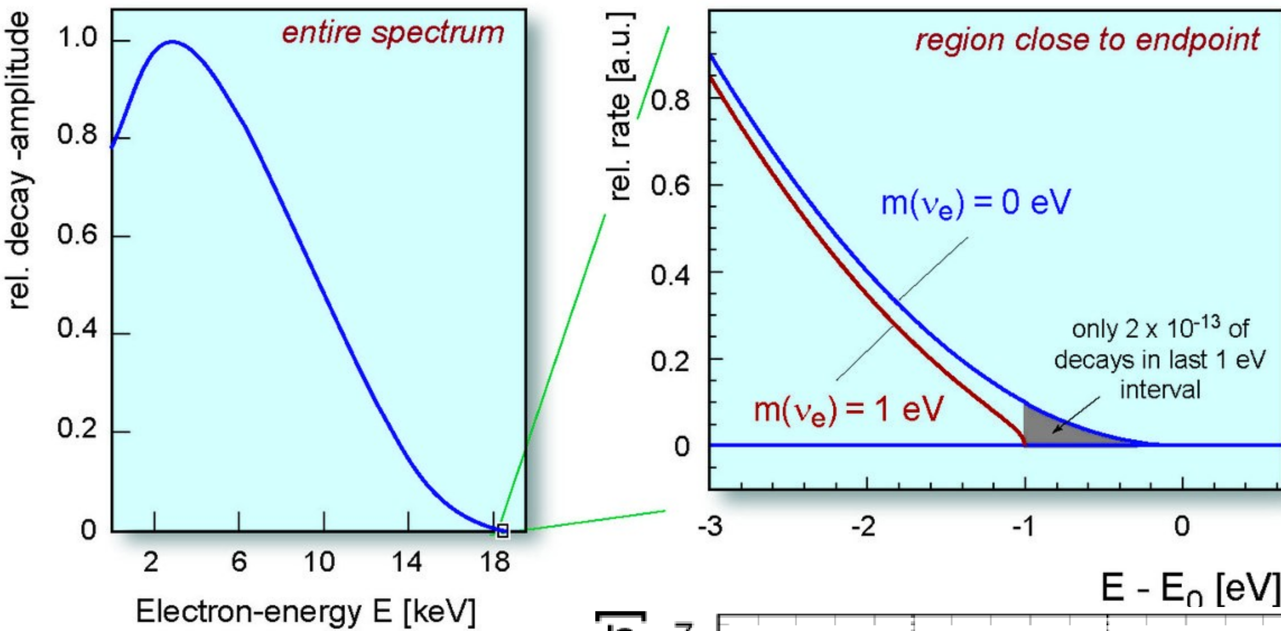
CUORE (130Te)
- Bolometric detector
- under construction, expected start end of 2014
- CUORE-0 running now

Brofferio, NeuTel2013

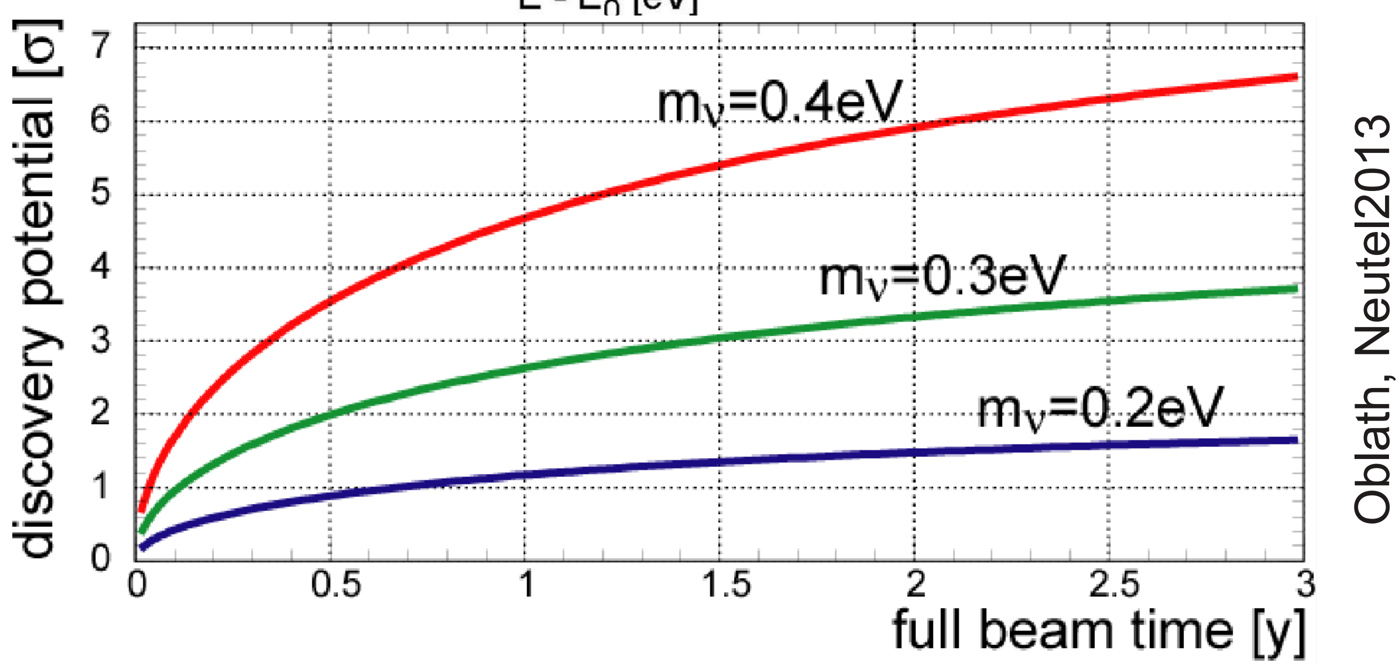
Sensitivity		CUORE-0	CUORE
$T_{1/2}$	1σ CL	9.4×10^{24} y	1.6×10^{26} y
	90% CL	**5.9×10^{24} y**	**9.5×10^{25} y**
$<m_{ee}>$ ***	1σ CL	162 – 422 meV	39 – 102 meV
	90% CL	**204 – 533 meV**	**51 – 133 meV**

+ others under construction and planned!

Neutrino Mass from Beta Decay



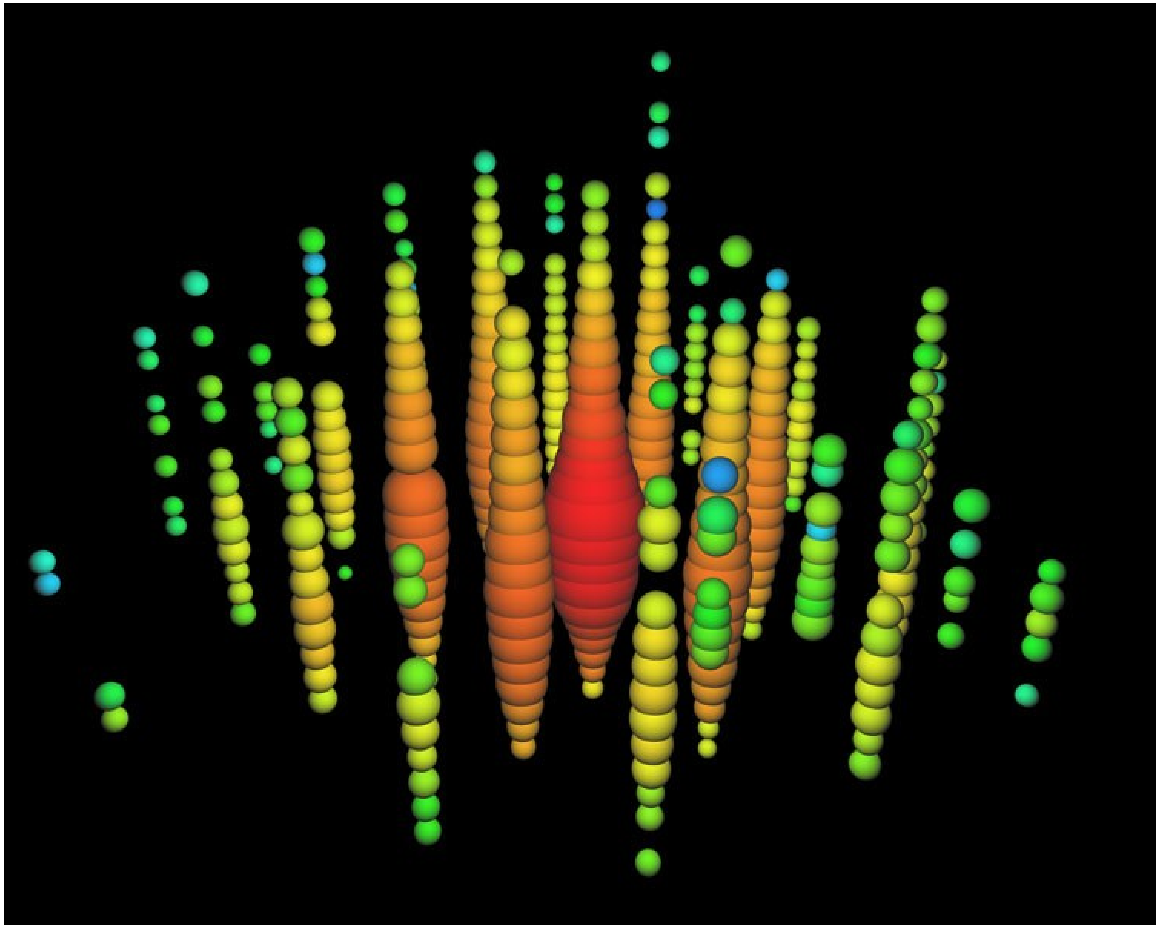
KATRIN
- Next gen tritium decay
- Goal sensitivity 0.2 eV
- expected to start 2015



What I Didn't Talk About

- MINERvA, MiniBooNE – neutrino interaction measurements
- MicroBooNE (170 ton LAr), ArgoNEUT
- Other LAr test programs
- ICARUS
- LAGUNA/LBNO
- Hyper-K
- Number of neutrinos from cosmology
- PeV neutrinos in IceCube
- Geoneutrinos (new results from KamLAND and Borexino)
- Updated solar mixing parameters from KamLAND
- Proposed sterile neutrino experiments
- And more...

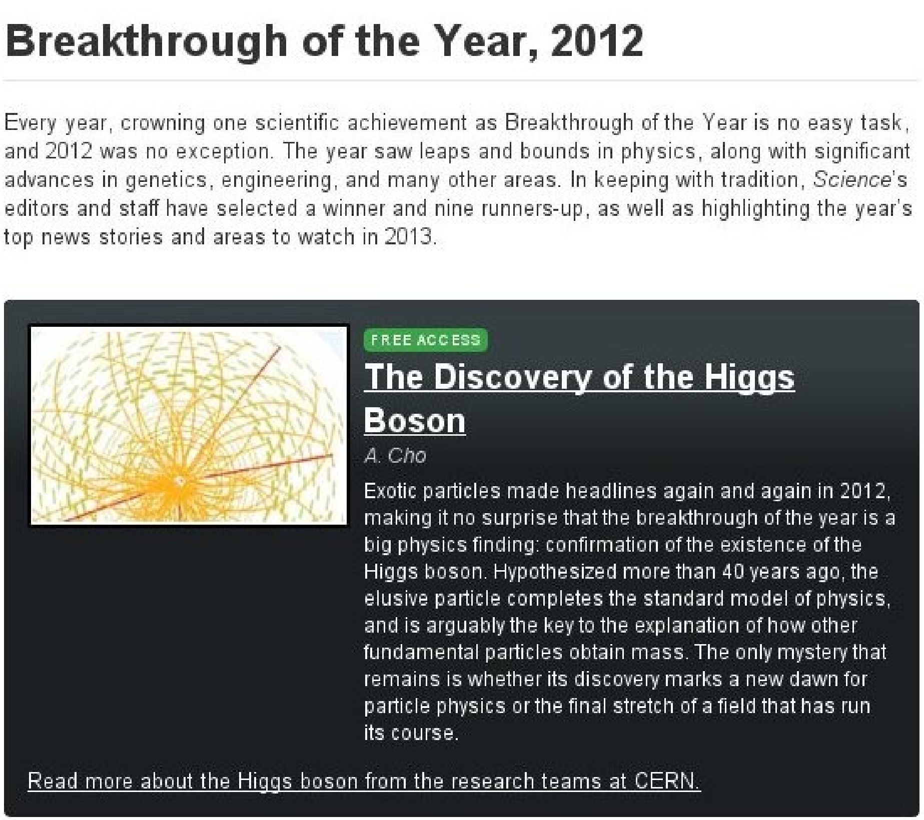
Highest energy neutrinos ever observed in IceCUBE!!



arXiv:1304.5356

Summary

- It's been an exciting year in neutrino physics!!!
- Measurement of θ_{13} opens the door to the next step: CP violation, mass hierarchy
- All the big questions are actively being explored



Breakthrough of the Year, 2012

Every year, crowning one scientific achievement as Breakthrough of the Year is no easy task, and 2012 was no exception. The year saw leaps and bounds in physics, along with significant advances in genetics, engineering, and many other areas. In keeping with tradition, *Science*'s editors and staff have selected a winner and nine runners-up, as well as highlighting the year's top news stories and areas to watch in 2013.

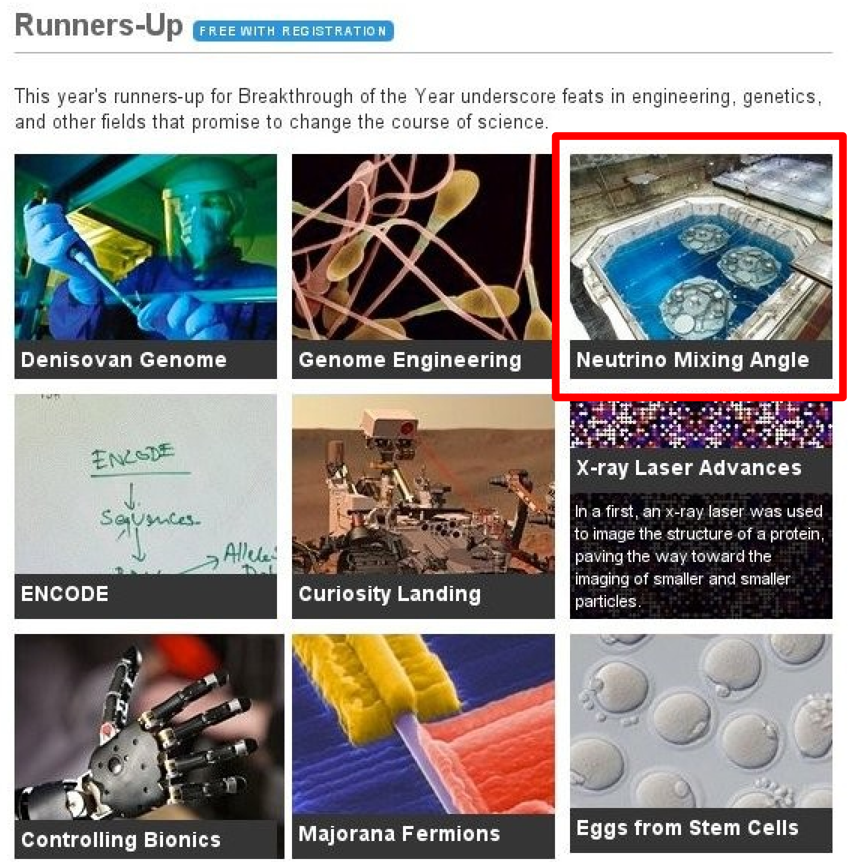
FREE ACCESS

The Discovery of the Higgs Boson

A. Cho

Exotic particles made headlines again and again in 2012, making it no surprise that the breakthrough of the year is a big physics finding: confirmation of the existence of the Higgs boson. Hypothesized more than 40 years ago, the elusive particle completes the standard model of physics, and is arguably the key to the explanation of how other fundamental particles obtain mass. The only mystery that remains is whether its discovery marks a new dawn for particle physics or the final stretch of a field that has run its course.

Read more about the Higgs boson from the research teams at CERN.



Runners-Up

FREE WITH REGISTRATION

This year's runners-up for Breakthrough of the Year underscore feats in engineering, genetics, and other fields that promise to change the course of science.

Denisovan Genome

Genome Engineering

Neutrino Mixing Angle

ENCODE

Curiosity Landing

X-ray Laser Advances

In a first, an x-ray laser was used to image the structure of a protein, paving the way toward the imaging of smaller and smaller particles.

Controlling Bionics

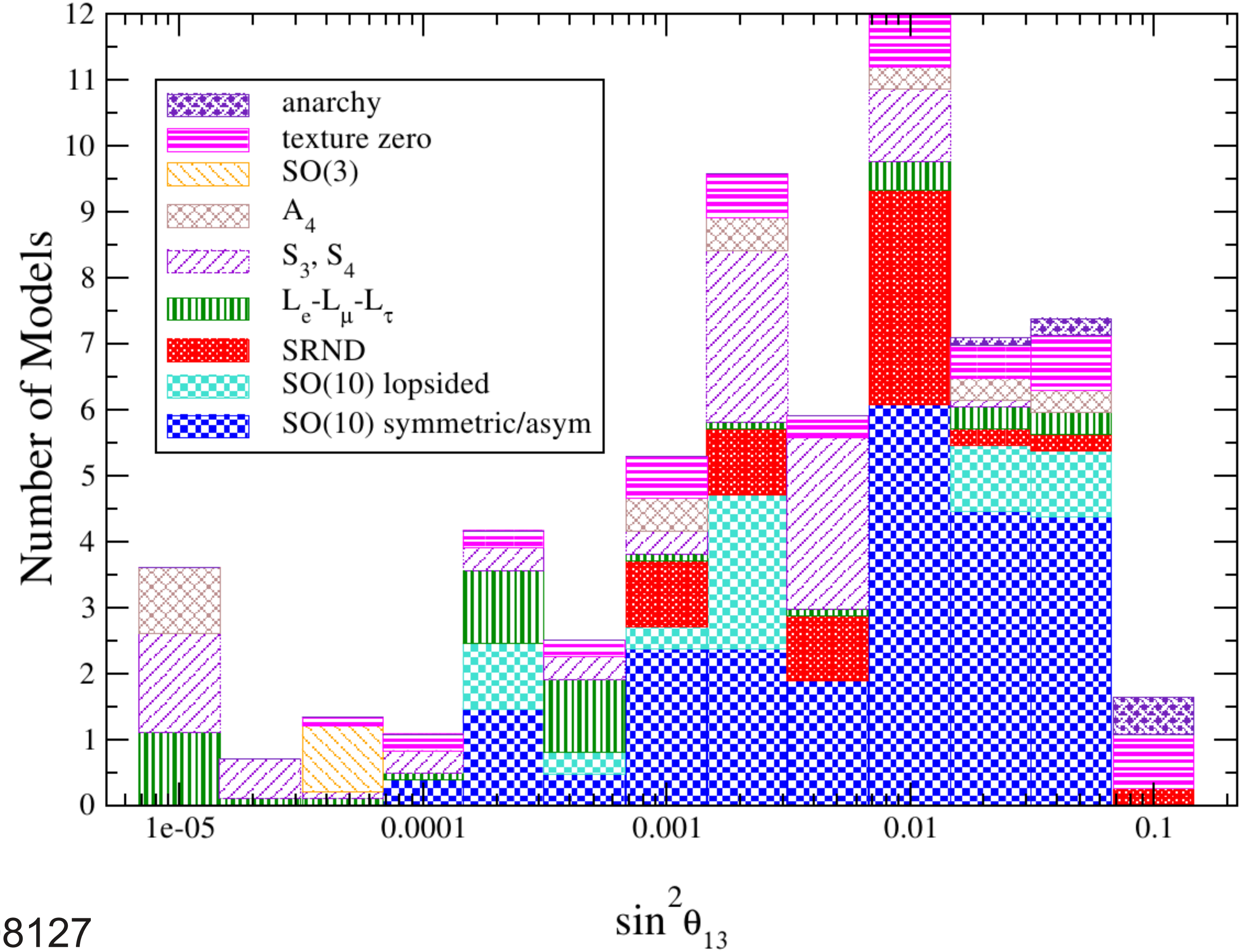
Majorana Fermions

Eggs from Stem Cells

Not bad!

Backup

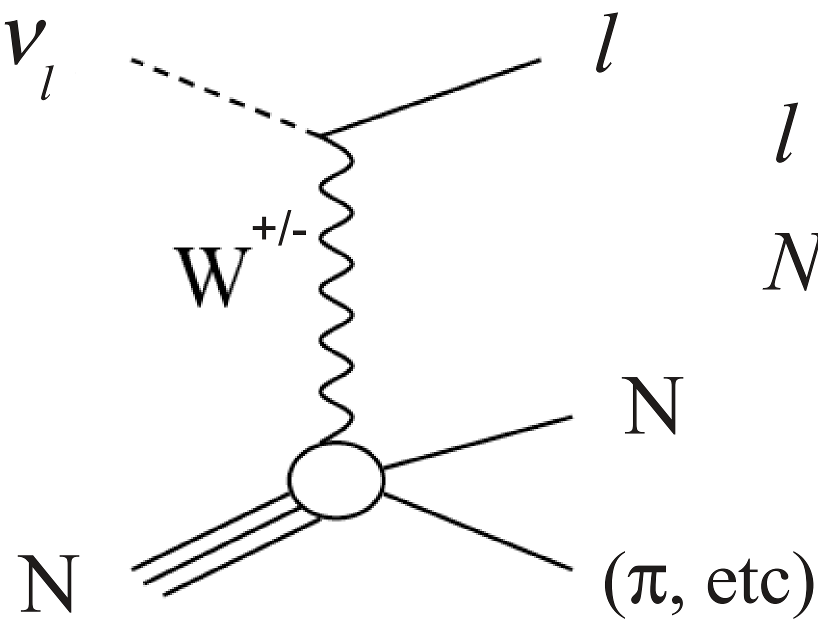
Predictions of All 63 Models



hep-ex:0608127

Neutrino Interactions

Charged-current (CC)

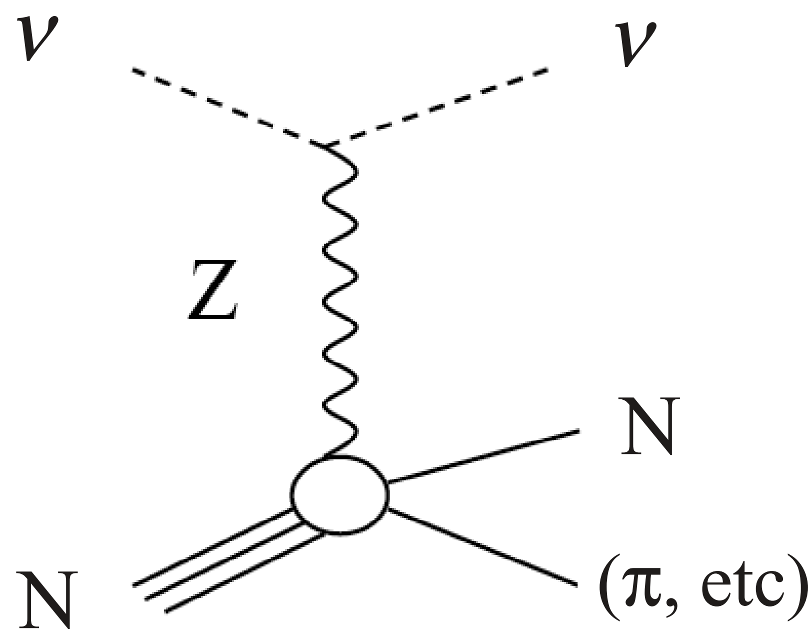


$l = e, \mu, \tau$

$N = p, n$

$$\nu_l \, N \rightarrow l \, N (X)$$

Neutral-current (NC)



$$\nu \, N \rightarrow \nu \, N (X)$$

Neutrino Mixing

Suppose neutrinos are massive and the flavor (ν_e, ν_μ, ν_τ) eigenstates are not the same as the mass eigenstates ...

→ each flavor state is a mixture of the different mass states

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

α, β = flavor states
1,2 = mass states

The mixture changes as neutrinos propagate

$$|\nu_\alpha(L)\rangle = \cos\theta \exp\frac{-i\, m_1^2 L}{2E} |\nu_1\rangle + \sin\theta \exp\frac{-i\, m_2^2 L}{2E} |\nu_2\rangle$$

t ≈ L, the distance traveled

Natural units
$\hbar = c = 1$

Neutrino Oscillations

Probability to observe a neutrino in the same flavor state after traveling a distance L:

$$P(\nu_\alpha \rightarrow \nu_\alpha) = |\langle \nu_\alpha | \nu_\alpha(\mathrm{L}) \rangle|^2 = 1 - \sin^2(2\theta)\sin^2(1.27\,\Delta m^2 L/E)$$

Probability to observe a neutrino in the other flavor state after traveling a distance L:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta)\sin^2(1.27\,\Delta m^2 L/E)$$

θ = mixing angle
L = flight distance
E = neutrino energy

$$\Delta m^2 = m_2^2 - m_1^2$$

A neutrino created in one flavor state can be observed some time later in a different flavor state!

1.27 in units of $(\mathrm{GeV}c^4)/(\mathrm{eV}^2\mathrm{km})$

Detecting Neutrino Oscillations

Tag the flavor of the incoming neutrino by identifying the outgoing lepton from a charged-current interaction

$$P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \underline{\sin^2(2\theta)} \sin^2(1.27\, \underline{\Delta m^2}\, L/E)$$

"Disappearance" measurement probes $P(\nu_\alpha \rightarrow \nu_\alpha)$

Can also do "appearance" measurement to probe $P(\nu_\alpha \rightarrow \nu_\beta)$