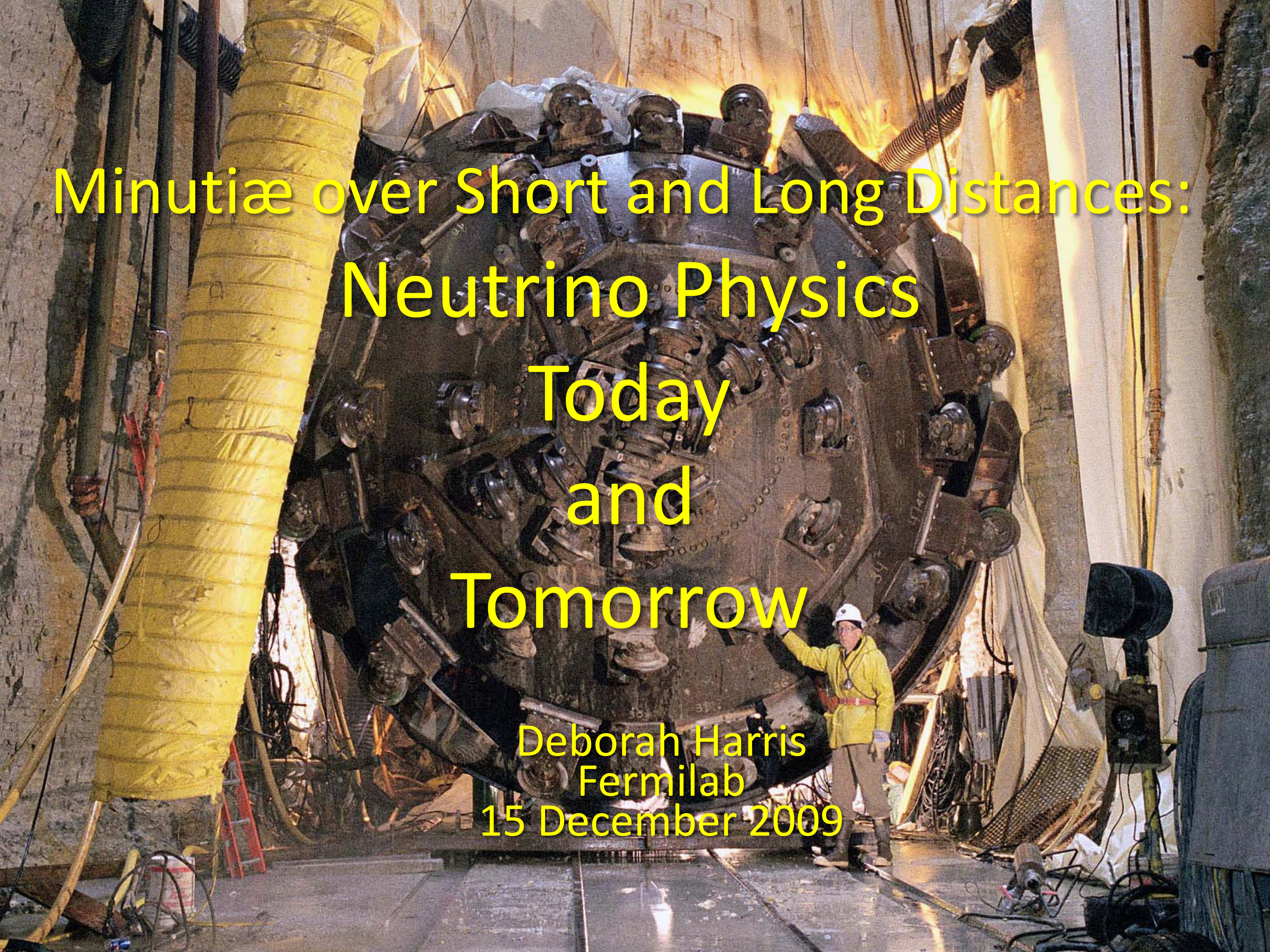


# Minutiæ over Short and Long Distances:

# Neutrino Physics Today and Tomorrow

Deborah Harris
Fermilab
15 December 2009

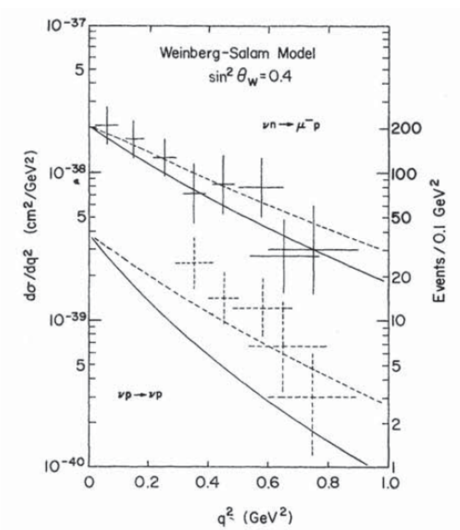
# Brief prologue

PHYSICAL REVIEW D VOLUME 14, NUMBER 7 1 OCTOBER 1976

**Neutrino-proton elastic scattering: Implications for weak-interaction models**

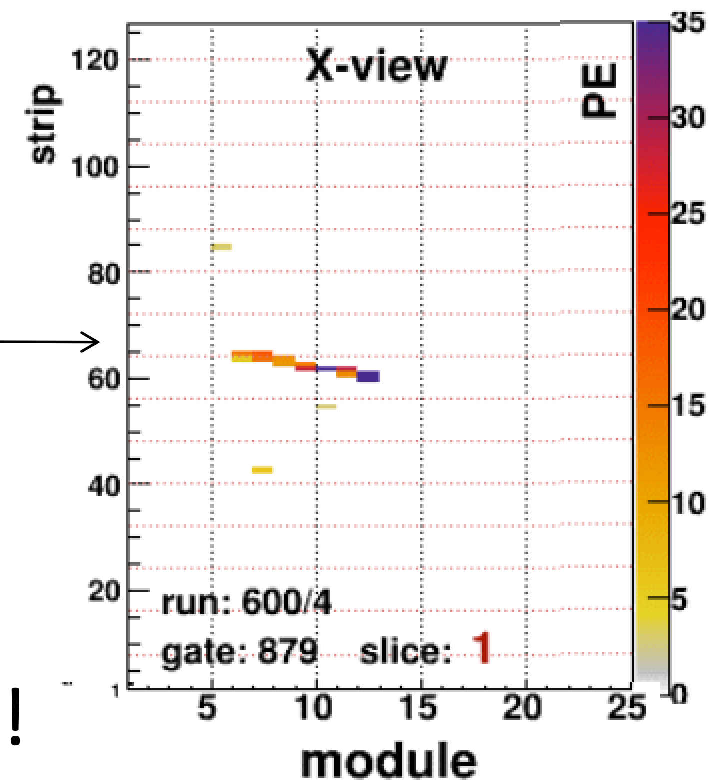
Carl H. Albright,* C. Quigg,† R. E. Shrock, and J. Smith‡
*Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510§*
(Received 21 May 1976; revised manuscript received 9 July 1976)

- When did Chris really start thinking about neutrinos?




Actual event from MINERvA June 7, 2009

$\nu$ →




$\nu p \rightarrow \nu p$ candidate

Happy Birthday!

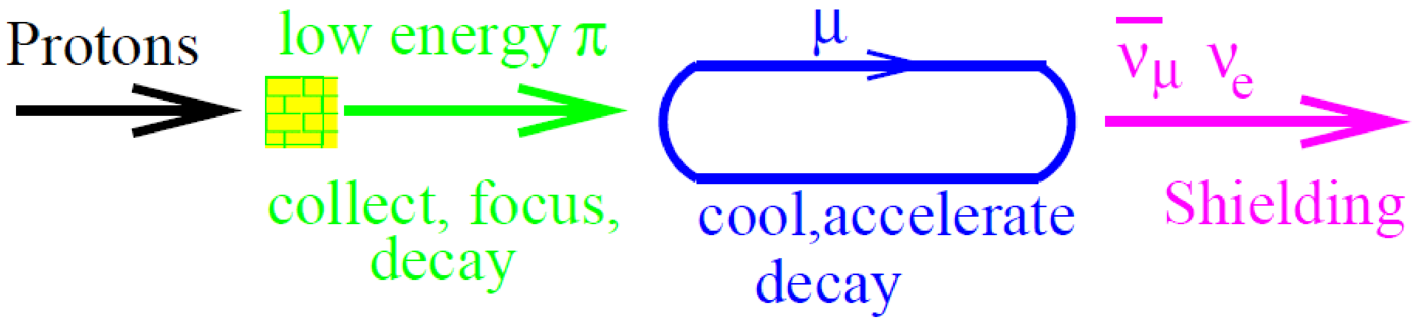
# Outline

- Preamble…Chris's opening talk at NuFact99
- What we know now
- First lights and next steps
- Neutrino factory ideas now…

- Conclusion:
  Are we following Chris's advice?

# Neutrino Factories in ‘99

- Picture the scene…neutrino oscillations “discovered” after decades-old hints
- Fringe element is very excited about neutrino factories…first NuFact conference held in Lyon




- Neutrino factory seems like perfect place to be:
  – $\mu^+ \rightarrow e^+ \nu_e \overline{\nu}_\mu$, and if in the detector you see $\nu_\mu N \rightarrow \mu^+ X$ then you know you’ve seen $\nu_e \rightarrow \nu_\mu$

# What did Chris tell us?

- Don’t design the neutrino factory for what you want to do now, think about what you’ll want to know in 10 years…

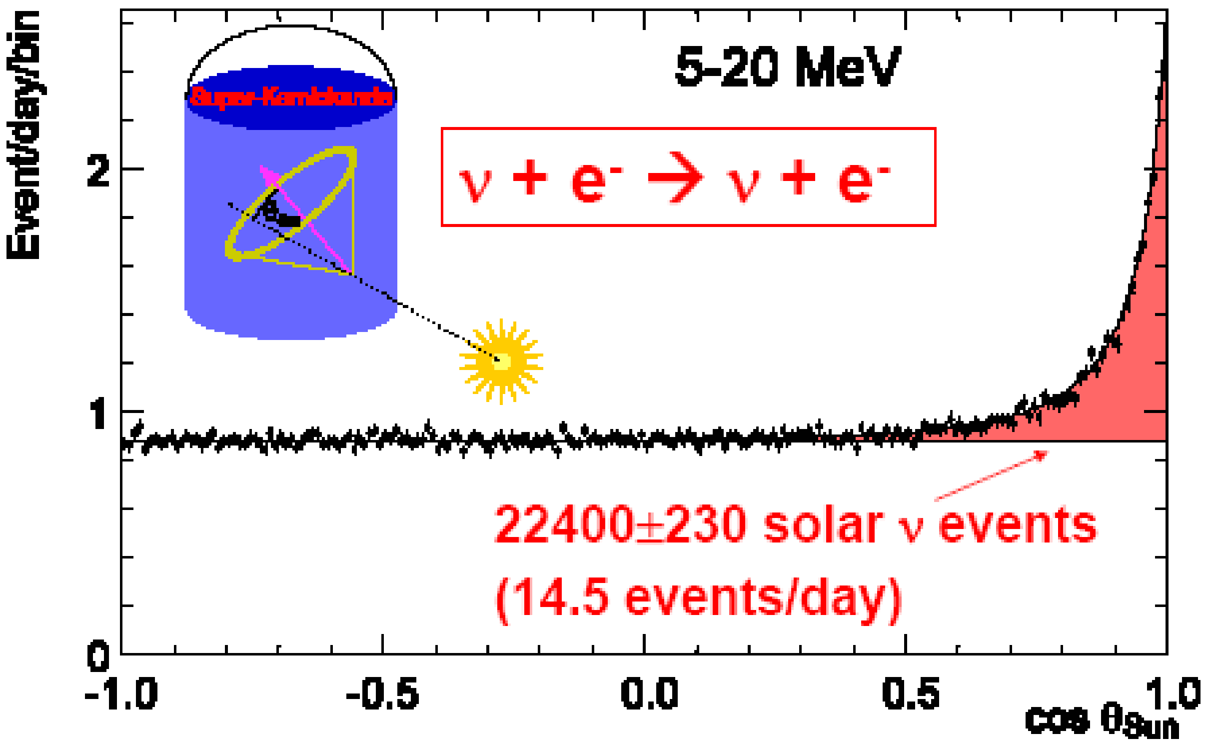
- Don’t stop trying to figure out other ways to see oscillations, neutrino factory may not be the only way to get there

# Outline for rest of the talk

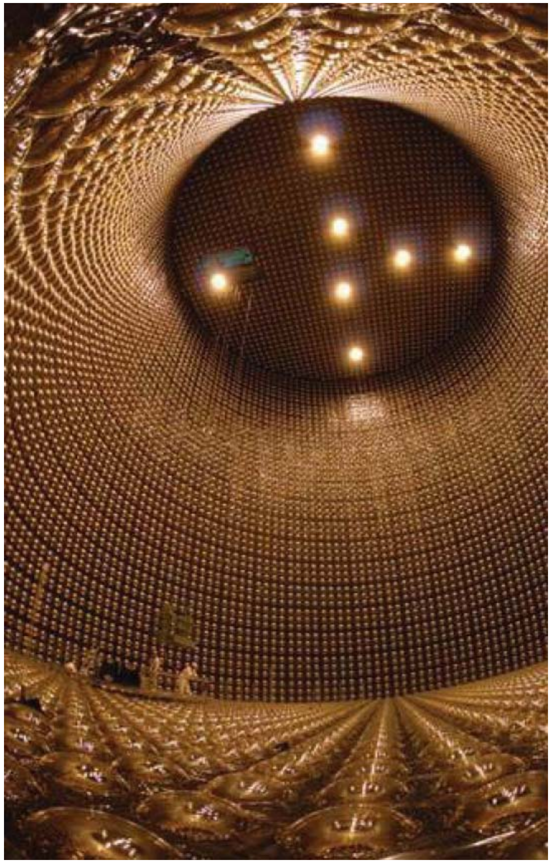
- What we know today about neutrinos
  - How they oscillate
    - How to describe all these oscillation signals
  - How they interact
    - Outstanding Mysteries
- Next Steps in neutrino physics:
  - First Light this year for many of us
- What designs for a neutrino factory look like now
  - Are we heeding Chris's advice?

# Solar Neutrinos from Super-K

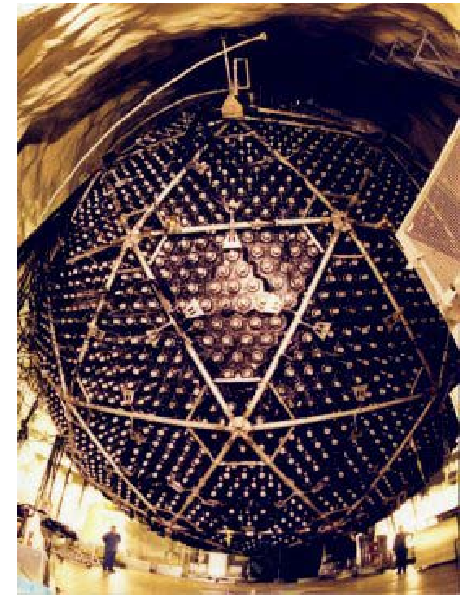
- Glorious history of solar neutrino physics:
  - original goals: demonstrate fusion in the sun
  - first evidence of oscillations
  - Neutrino – electron Elastic Scattering makes all this possible
  - Events Seen/Expected: $0.451^{+0.017}_{-0.015}$



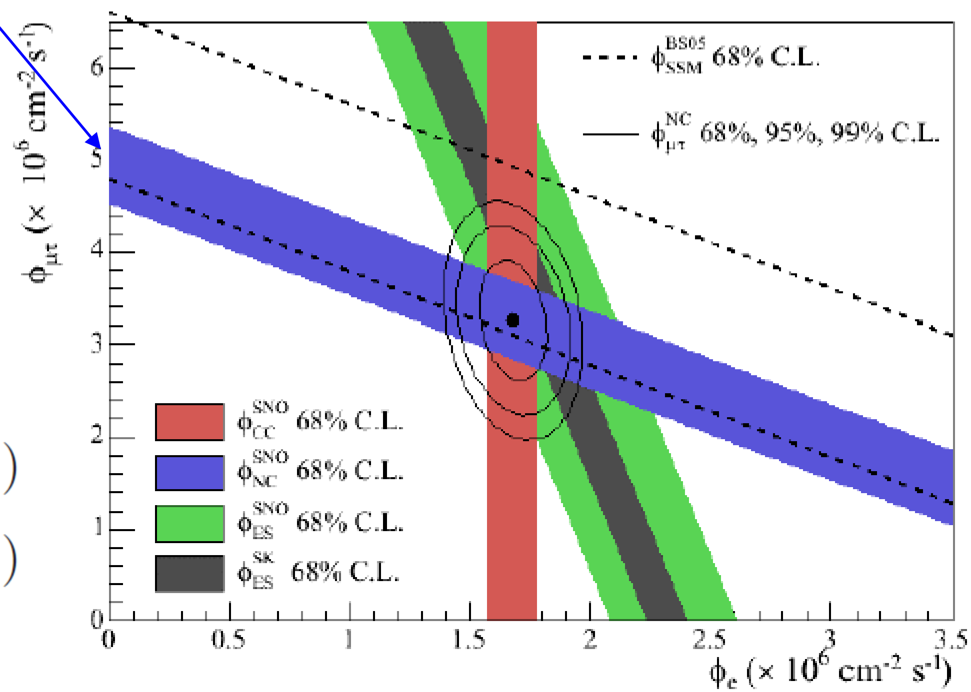

Ref: Super-Kamiokande
PRL **86,** 5656 (2001)



# Solar Neutrinos à la SNO



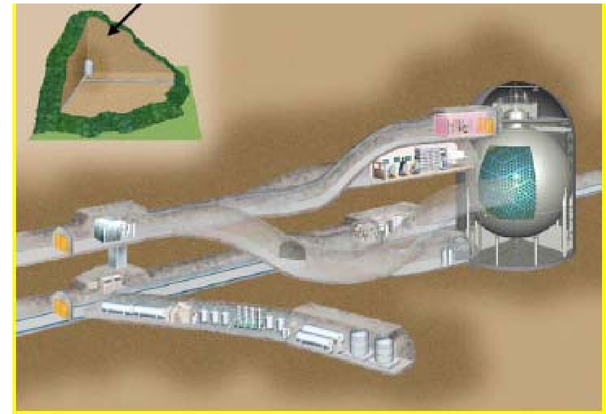
- $D_2O$ target means not only elastic scatters can be used:
  - – charged-current $\nu_e d \rightarrow ppe^-$
  - – neutral-current $\nu_X d \rightarrow \nu_X pn$
- The former is only observed for $\nu_e$
  (lepton mass)
- The latter for all types
- $$\phi_e = 1.76^{+0.05}_{-0.05}(\text{stat.})^{+0.09}_{-0.09}\ (\text{syst.})$$
  $$\phi_{\mu\tau} = 3.41^{+0.45}_{-0.45}(\text{stat.})^{+0.48}_{-0.45}\ (\text{syst.})$$

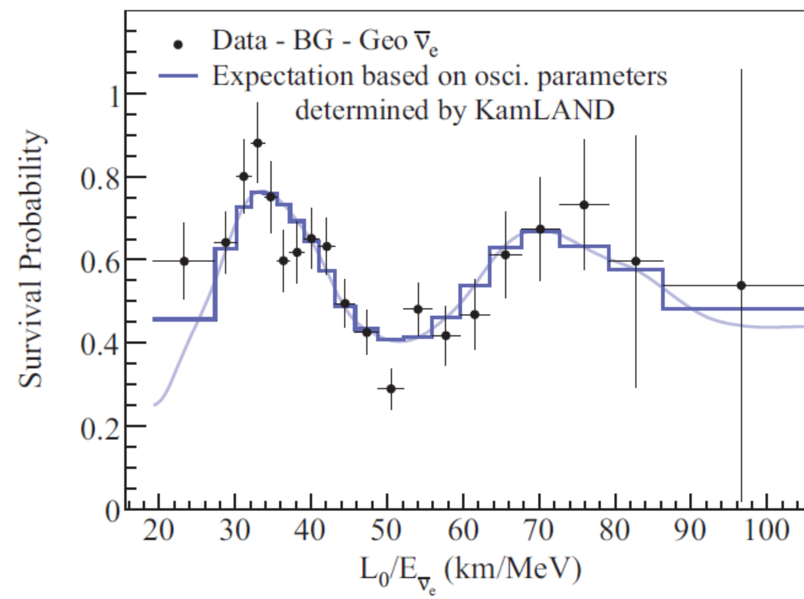



Ref: SNO, PRL.89:011301,2002

# Precision Measurements of solar Neutrino Sector: KAMLAND

- Sources are Japanese reactors
  - *150-200 km* for most of flux.
  - *Rate uncertainty ~4%*
  - *Total uncertainty ~6%*
- 1 kTon scint. detector in old Kamiokande cavern
  - Confirmation of oscillatory nature of disappearance



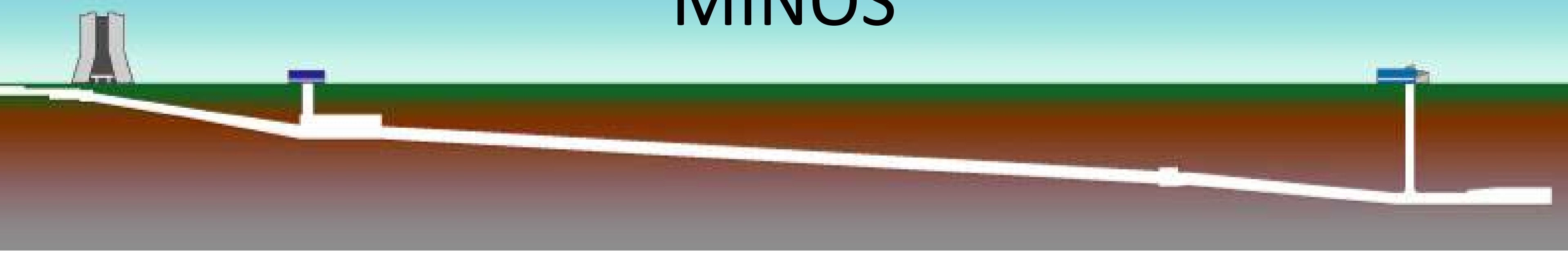



$$\theta_{12} = 34.06 \,^{+1.16}_{-0.84} \text{ degrees}$$

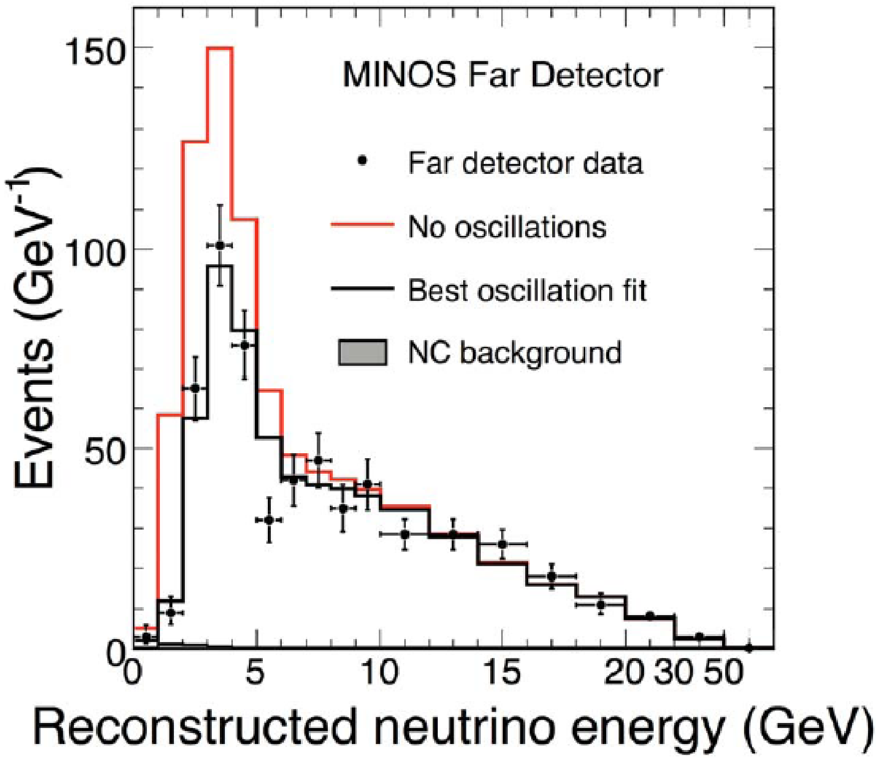
$$\Delta m^2_{21} = 7.59 \,^{+0.20}_{-0.21} \times 10^{-5} \text{ eV}^2$$

Kamland, PRL.100:221803,2008

# Best knowledge of large mass splitting: MINOS



- MINOS: NuMI Beamline at Fermilab produces $\nu_{\mu}$ at 100× the intensity ever produced before
- Aims that beam of neutrinos towards Soudan Minnesota



# Minimal Oscillation Formalism

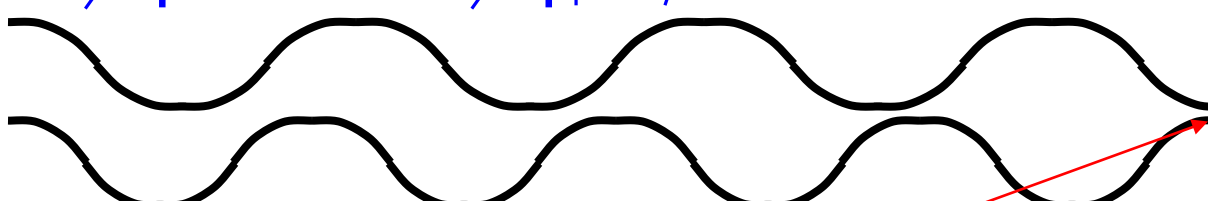
- If neutrino mass eigenstates: $\nu_1$, $\nu_2$, $\nu_3$, etc.
- … are not flavor eigenstates: $\nu_e$, $\nu_\mu$, $\nu_\tau$
- … then one has, e.g.,

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

take only two generations for now!

$$|\nu_\alpha\rangle = \cos\tfrac{\pi}{4}|\nu_i\rangle + \sin\tfrac{\pi}{4}|\nu_j\rangle$$

different masses alter time evolution



time

$$|\nu_\beta\rangle = -\sin\tfrac{\pi}{4}|\nu_i\rangle + \cos\tfrac{\pi}{4}|\nu_j\rangle$$



*Slide courtesy K.McFarland*

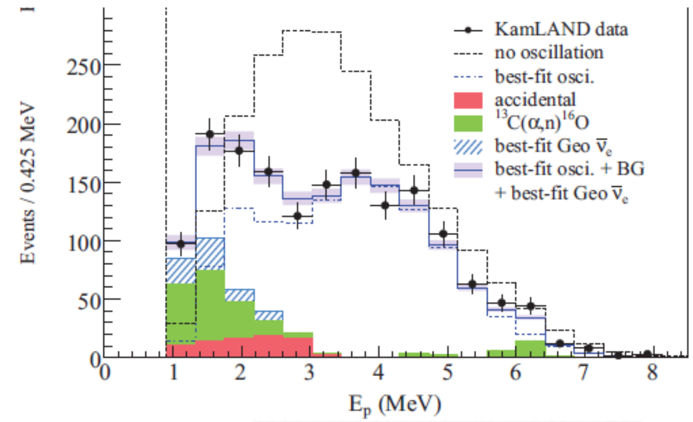
# Oscillation Formalism (cont'd)

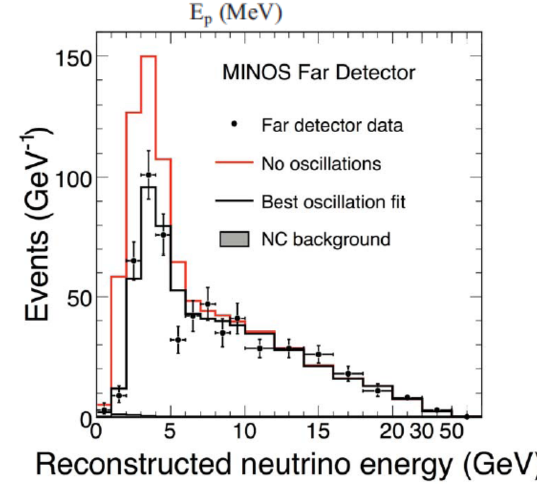
- So, still for two generations…

$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \sin^2\left(\frac{(m_2^2 - m_1^2)L}{4E}\right)$$

appropriate units give the usual numerical factor **1.27 GeV/km-eV²**

- Oscillations require mass differences
- Oscillation parameters are mass-squared differences, $\Delta m^2$, and mixing angles, $\theta$.
- But remember the signals:
  - Kamland: 3MeV neutrinos, 180km
  - MINOS: 3000MeV neutrinos, 735km
- There must be more than two mass differences



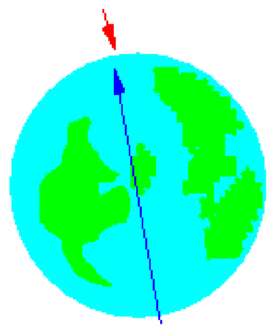
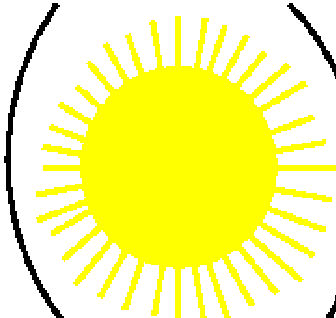



# Three Generation Mixing

Lesson Learned from CKM: 3 mixing angles and a phase

Call them $\theta_{12}, \theta_{23}, \theta_{13}, \delta$ if $s_{ij} = \sin\theta_{ij}, c_{ij} = \cos\theta_{ij}$, then

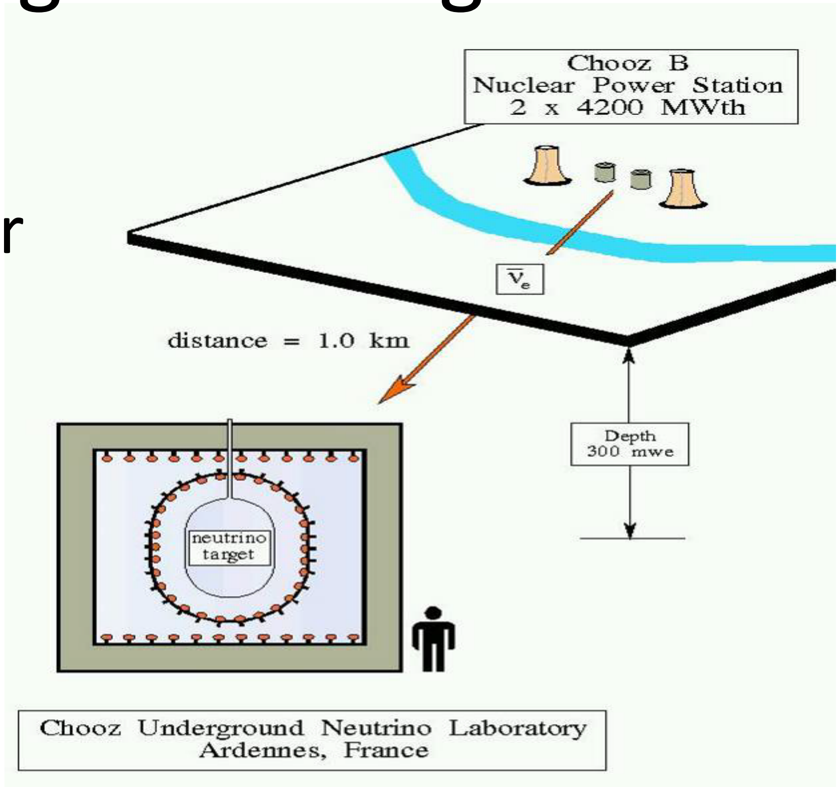
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

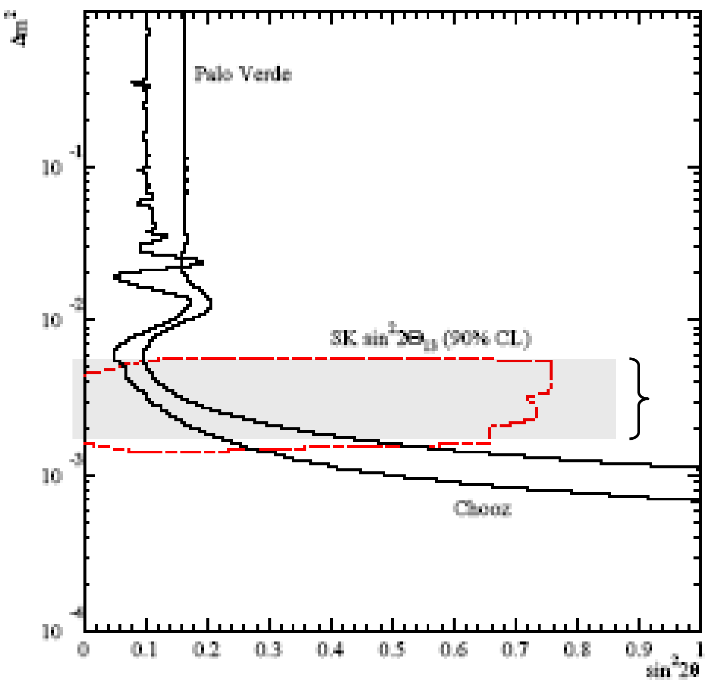
U= (  ) ( Reactor and/or Accelerator $\nu_e$ ) (  )

- Note the new mixing in middle, and the phase, $\delta$

# But not all mixing angles are large…

- CHOOZ and Palo Verde expt's looked at anti-$\nu_e$ from a reactor
  - compare expected to observed rate, $\sigma$~4%



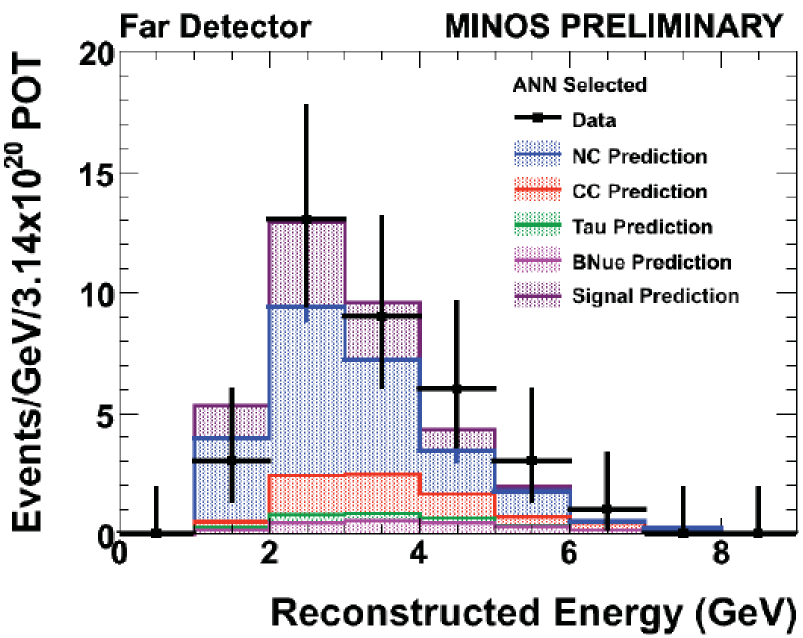

$\eta^2_{23}$

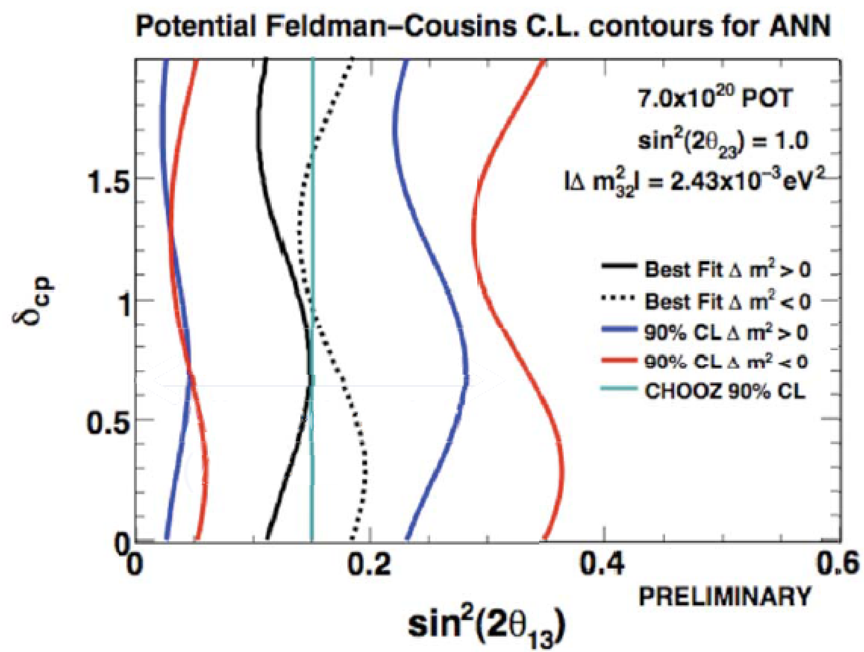
- If electron neutrinos don't disappear, they don't transform to muon neutrinos
  - limits $\nu_\mu$->$\nu_e$ flavor transitions at and therefore one mixing angle is "small"

*Slide courtesy K.McFarland*

# MINOS Electron Neutrino Appearance Search

- First results: consistent with no oscillations
  - 35 events measured, 25±2 predicted w/o oscillations
- Very challenging analysis, Neutral Current background levels high, multiple data-driven cross-checks needed
- Over twice this data set already taken, results pending…

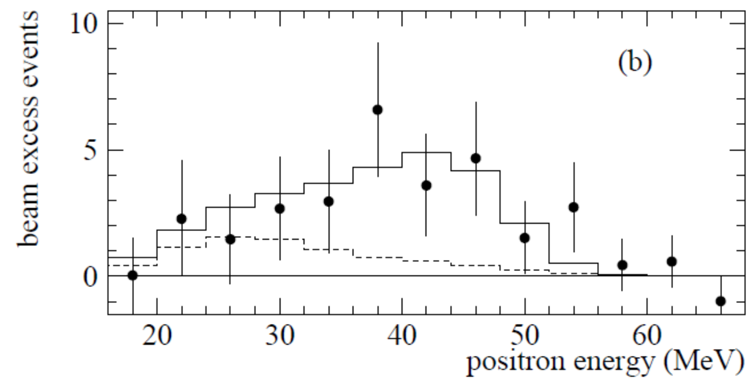



Ref: MINOS, arXiv:0909.4996 [hep-ex]

# Sterile Neutrinos

- Based on LSND result for electron appearance at short baseline, an industry of Sterile Neutrino phenomenology blossomed
- Realize that there may be several generations of sterile neutrinos that don't interact with Z

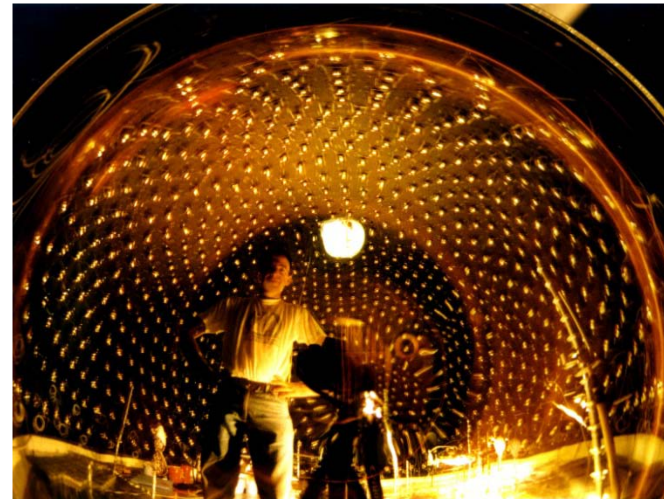



Ref: LSND, PRL77:3082,1996.

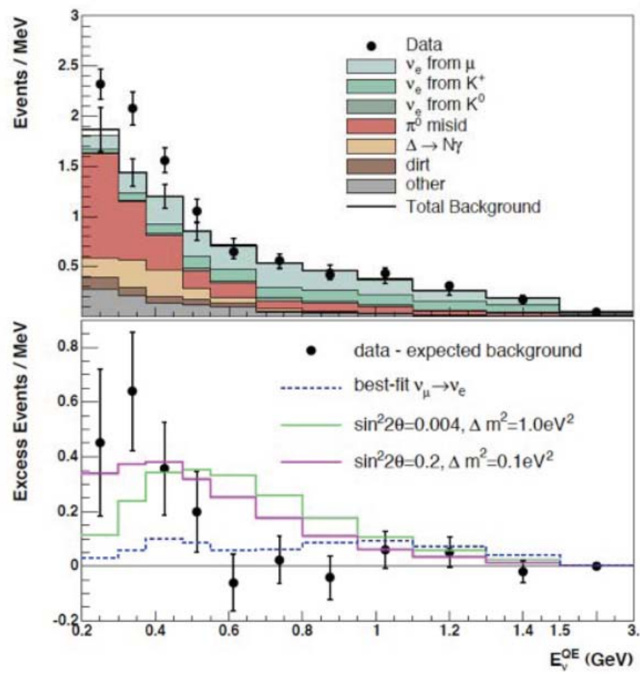
- Two (of many) ways to look for sterile $\nu$'s
  - Measure oscillations occurring at three independent mass differences (MiniBooNE)
  - See if the number of neutral current events is right, even if charged current rates have changed from oscillations (SNO, MINOS)

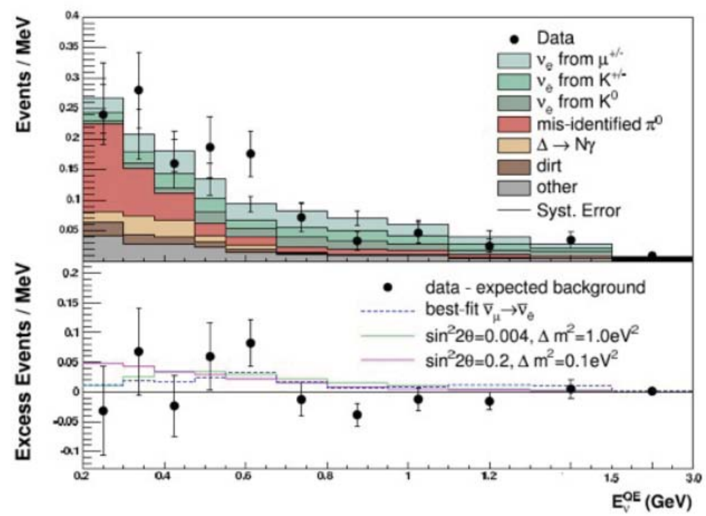
# What we know about sterile sector: MiniBooNE

- MiniBooNE has not confirmed LSND result in either neutrinos or antineutrinos
- Rules out simple sterile ν models



Ref: MiniBooNE, PRL102:101802,2009

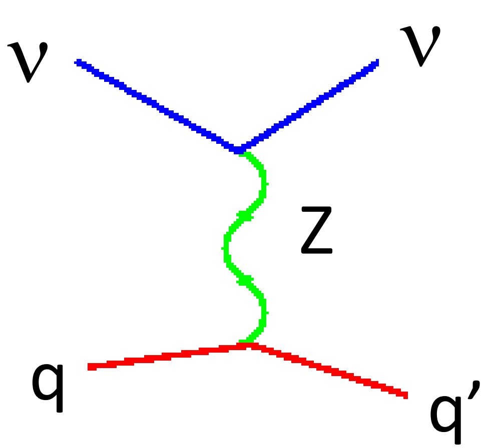


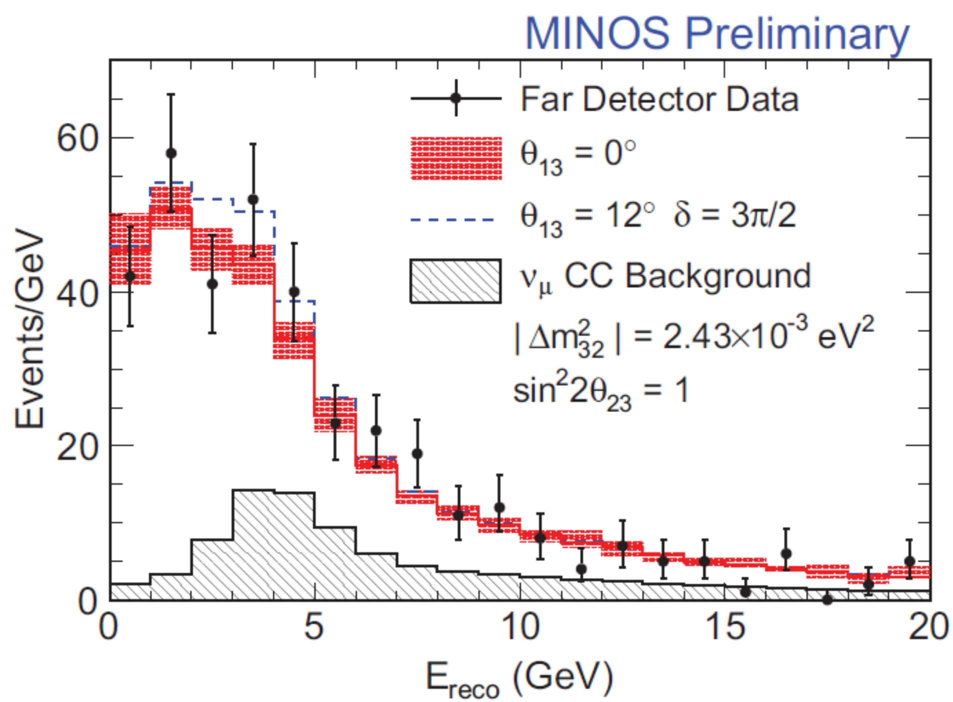




Ref: MiniBooNE PRL103:111801,2009

# What we know about sterile sector: MINOS

- MINOS sees the same number of neutral current events in its far detector as expected (388 events over 732km away!))




- Neutral Current Signal/expected: 1.04±.08+.07-.10

Ref: Sousa et al, (MINOS), arXiv:0910.1369 [hep-ex]

# So what do we know now?

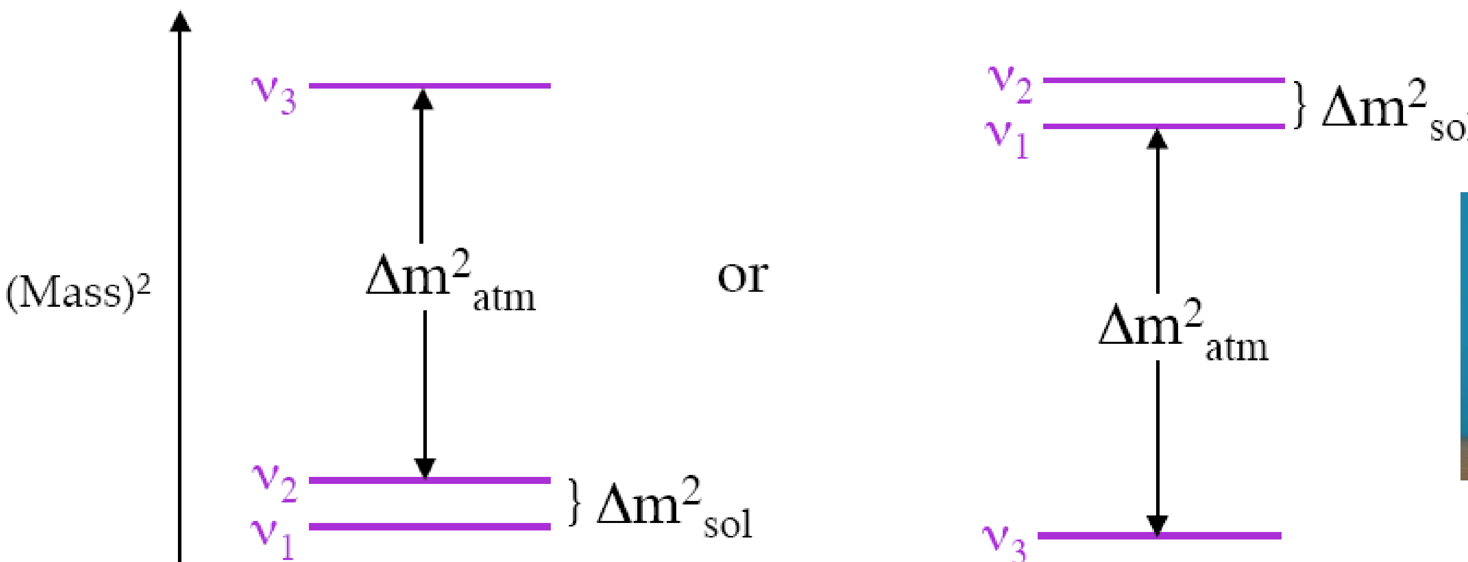
- Mass differences:
  - One is large $2.5\times10^{-3}\text{eV}^2$ (±8%)
  - One is small $8\times10^{-5}\text{eV}^2$ (±2.6%)
  - LSND signal 1-0.1$\text{eV}^2$ , not consistent with oscillations (thanks to MiniBooNE results)


- Mixing angles:
  - one is around ~45°
  - one is ~35°
  - one is smaller than 9°

# What don’t we know yet?

- Do Neutrinos violate CP conservation?
  - We know there’s lots of matter in the universe, no antimatter
  - We know quark sector CP violation is very small
- Do neutrino mass states have the same hierarchy as the quark

*figures courtesy B. Kayser*



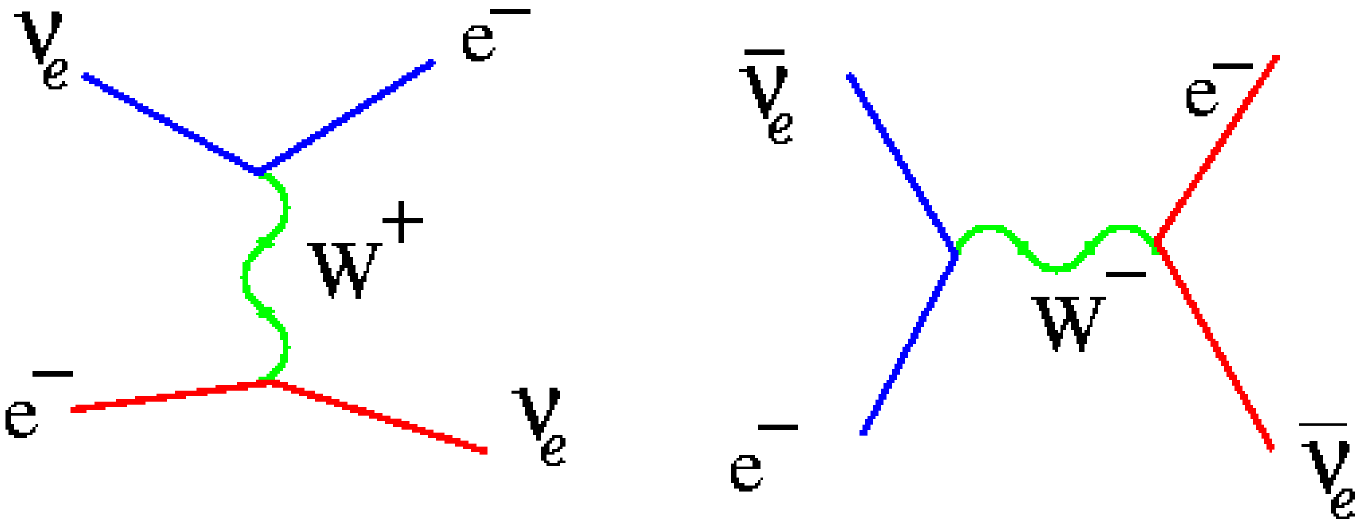

$\Delta m_{sol}^2 \rightarrow \delta m_{12}^2 \approx 8x10^{-5} eV^2$ $\Delta m_{atm}^2 \rightarrow \delta m_{23}^2 \approx 2.5x10^{-3} eV^2$

# Measuring ν Mass Hierarchy

- Recall the 2-generation formula…

$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \sin^2\left(\frac{(m_2^2 - m_1^2)L}{4E}\right)$$

- Matter changes θ, L for $\nu_e$ and $\bar{\nu}_e$'s differently




Wolfenstein, PRD (1978)

$$x = \frac{2\sqrt{2}G_F n_e E_\upsilon}{\Delta m^2}$$

$n =$ e⁻ density

$$\sin^2 2\Theta_M = \frac{\sin^2 2\Theta}{\sin^2 2\Theta + (\pm x - \cos 2\Theta)^2} \quad L_M = L \times \sqrt{\sin^2 2\Theta + (\pm x - \cos 2\Theta)^2}$$

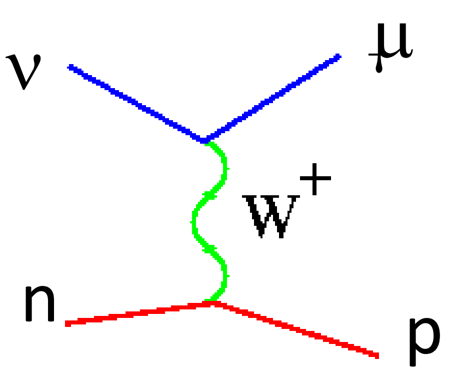
# Current Steps

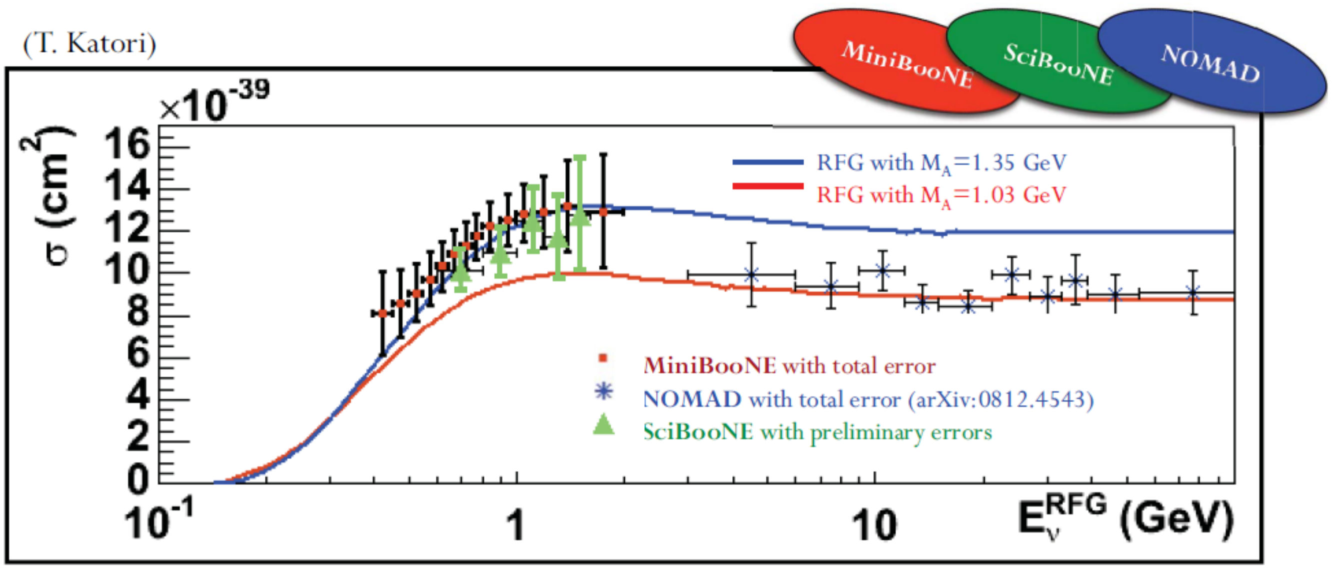
- First things first: need to see if that last mixing angle $\Theta_{13}$ is not zero
  - Reactor experiments at 2km
    - Double-Chooz
    - Daya Bay
    - RENO
  - Electron neutrino appearance in muon neutrino beam at 150km/1GeV

- Lessons learned here guide the path to CP violation and matter effects

# What else don't we know (signal)?

- Quasi-elastic events: mysterious transition from low to high energies
- BUT: this is the signal for Water Cerenkov Events!
  - Kinematics means you can fully reconstruct neutrino energy with muon measurements alone (given ν direction)

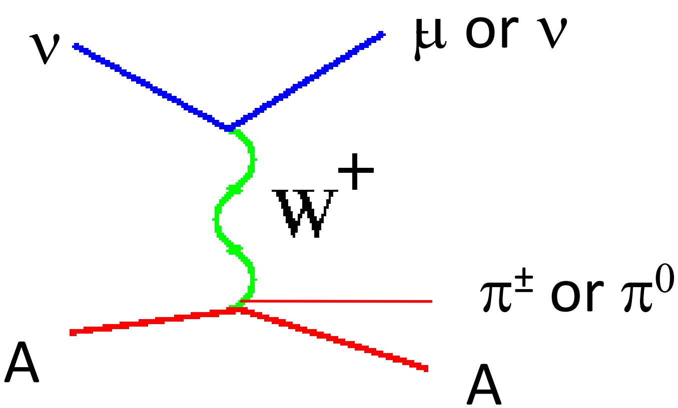



Plot from D. Schmitz, WIN'09 plenary talk

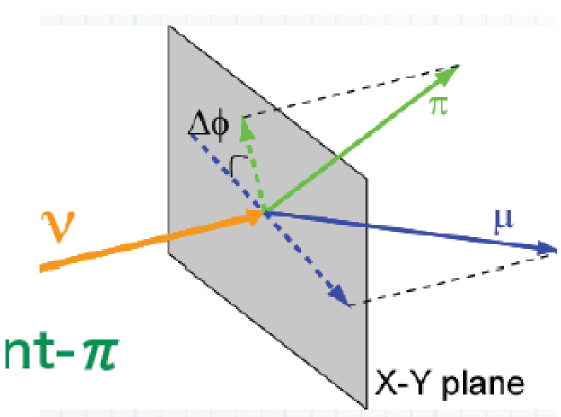
# What don't we know (background)?

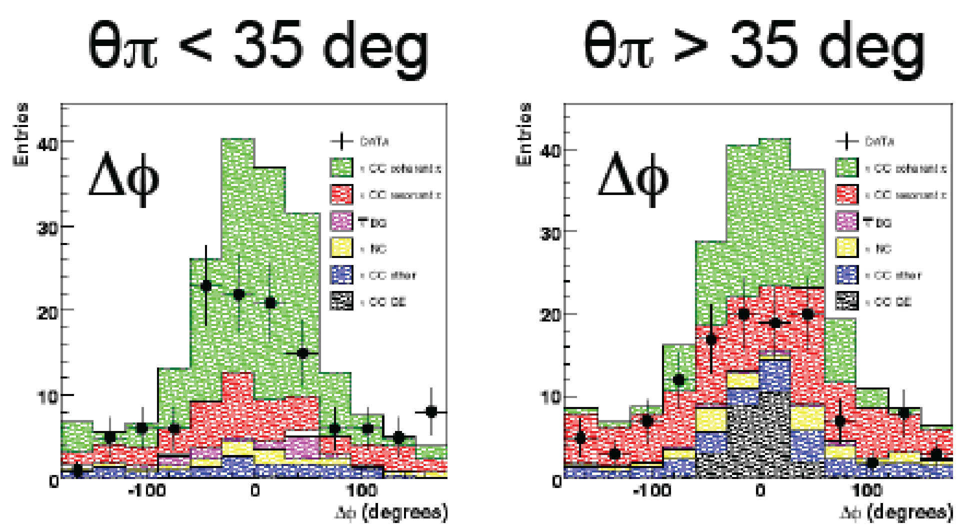
- Coherent neutrino scattering: now you see it, now you don't…




SciBooNE getting first detailed understanding of this

Neutral Current channel is tough background for $\nu_e$ appearance searches




Hiraide, NuINT09

# Just some of the reasons to study neutrino interactions
## (note, no ordering given…)

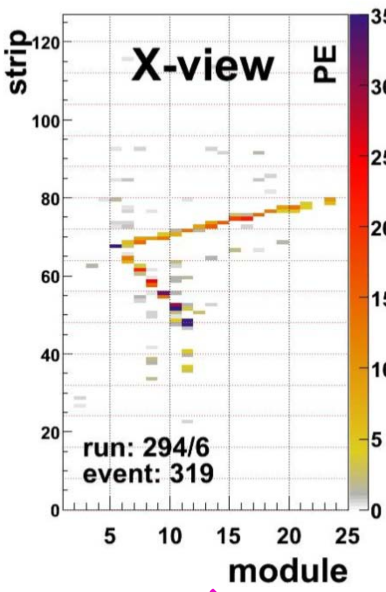
- Because Chris Quigg said to study them…
- Because Galileo said to study them…(Quigg, Neutrino Telescopes ’09 proceedings)

Io stimo più il trovar un vero, benchè di cosa leggiera, ch’l disputar lungamente delle massime questioni senza conseguir verità nissuna.[d]

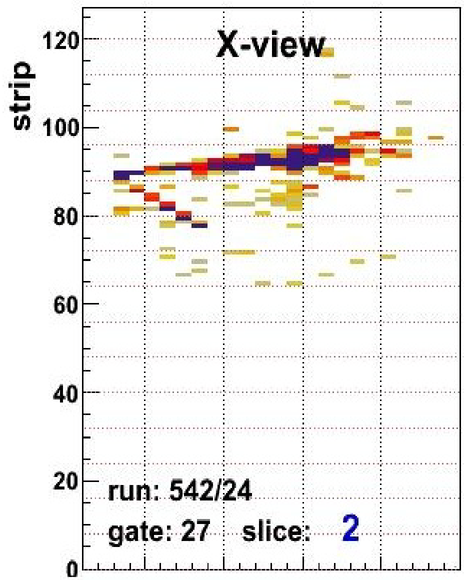
- Because there may be non-standard interactions we’ve never had the ability to see before (neutrino-photon interactions?)
- Because they let us see the nucleus like never before
- **Because getting to CP-violation and mass ordering of neutrinos requires it: will be looking for small probability differences between neutrinos and anti-neutrinos**

# MINER$\nu$A

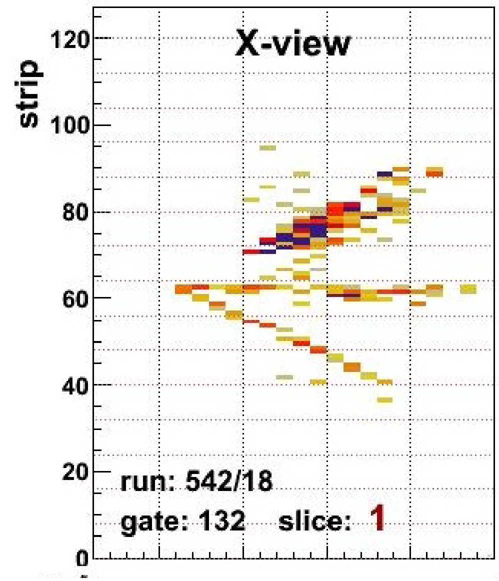
- Compact, fully active neutrino detector designed to study $\nu$-N interactions
- Detector with several different nuclear targets allows 1st study of neutrino nuclear effects:
  - He, C, Fe, Pb (and maybe water!)
  - Data below, candidate reaction given




$\nu_\mu + n \rightarrow \mu^- + p$

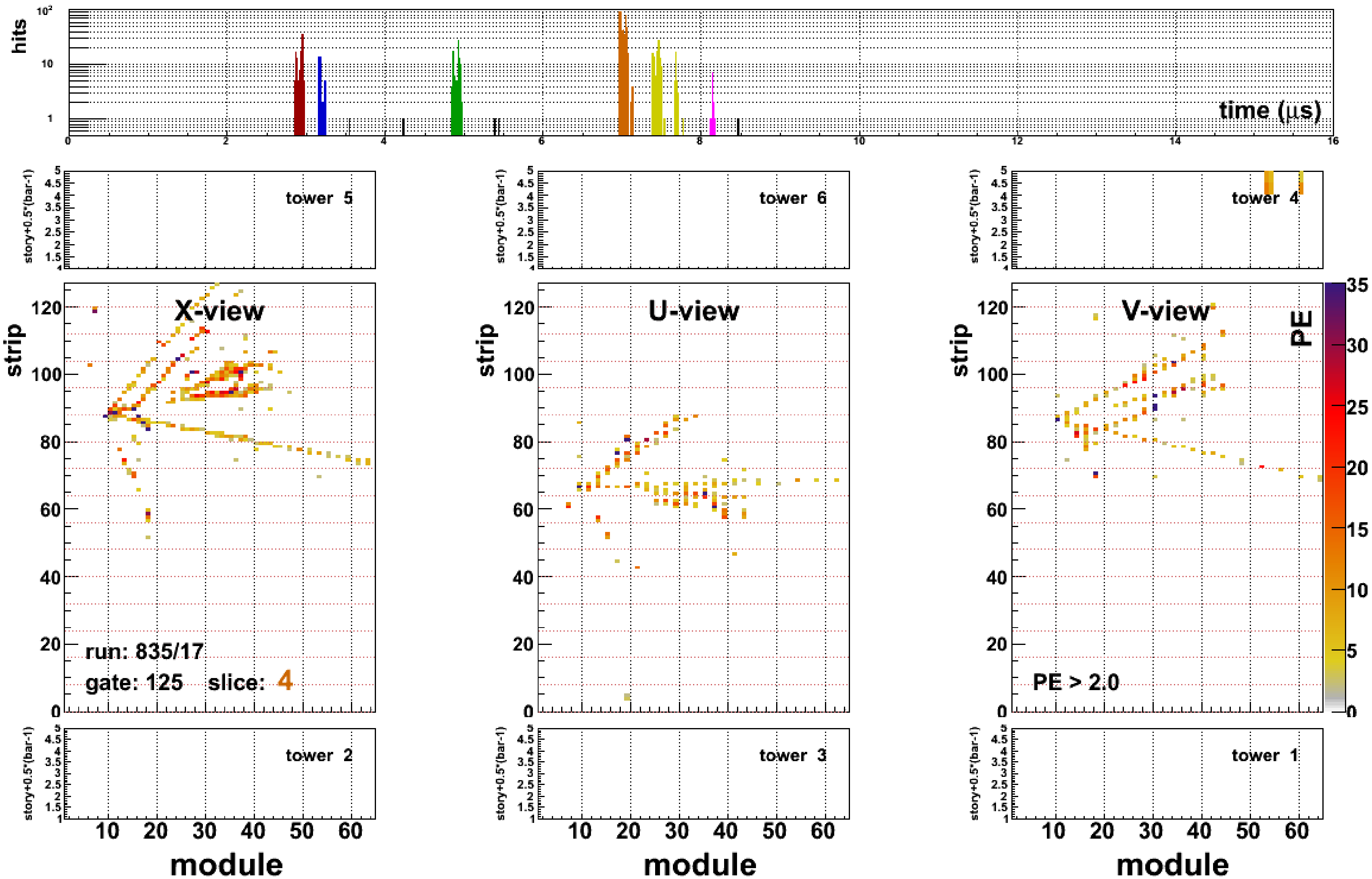



$\nu_e + n \rightarrow e^- + p$




$\nu_\mu + n \rightarrow \mu^- + \pi^0 + X$

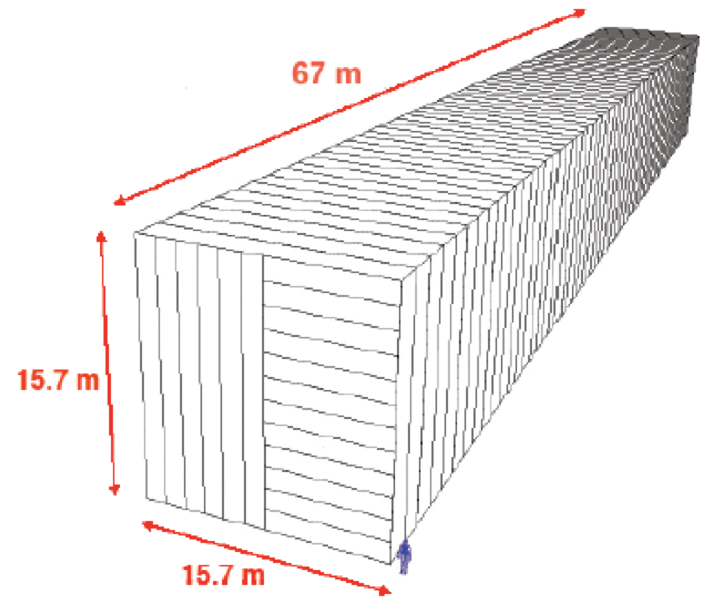
# MINERvA's First (Anti-Neutrino) Light!

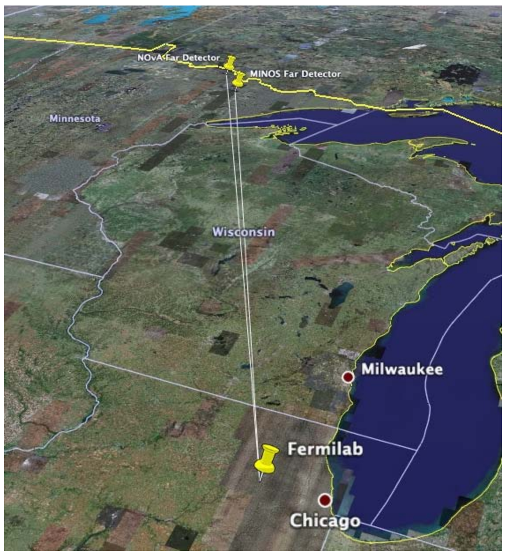


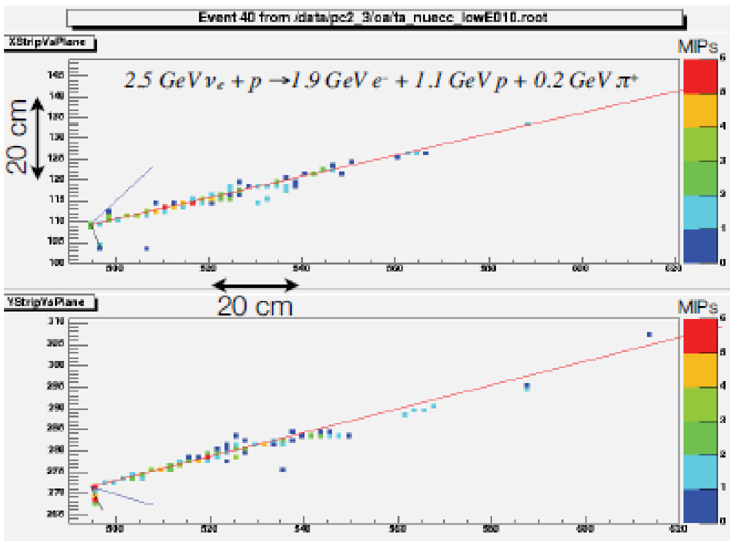

Taking data with 55% of full detector + Pb, Fe, CH targets

# NOvA Overview and Status

- NOvA is second generation experiment on NuMI beamline
- Optimized for $\nu_\mu \rightarrow \nu_e$
- Upgrade of almost factor of 2 in neutrino beam intensity (700kW)
- 15kton totally active liquid scintillator (810km)
- 220 ton near detector (to run this summer above ground!)
- Both 14mrad off NuMI axis, 2GeV neutrinos



# NOvA: Learning about shipping

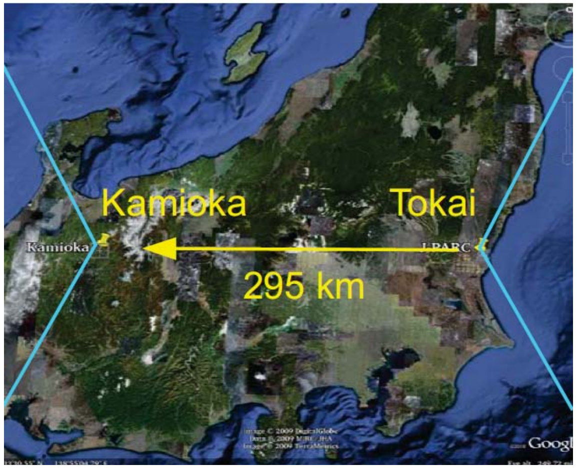

Photo courtesy Karen Kephart

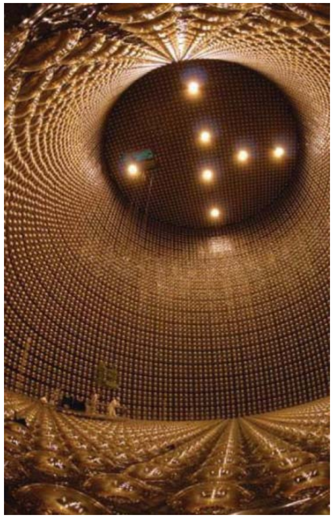
# NOvA: Far Detector Building

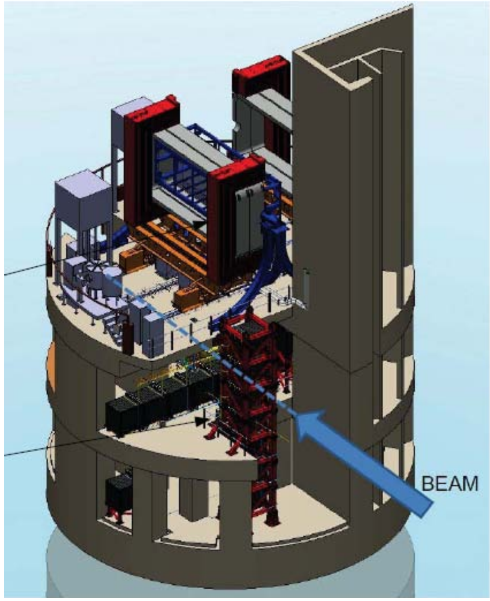

Ref: S. Dixon, FNAL All Experimenter's Meeting 12/7

# T2K Overview and Status

- T2K is a 3rd generation experiment with the Super-Kamiokande detector (50kton)
- New neutrino beamline from Tokai to Kamioka, 295km away
- Same off axis strategy, peak neutrino energy at 770MeV
- Optimized for $\nu_\mu \rightarrow \nu_e$
- New near detector complex (on and off axis both)





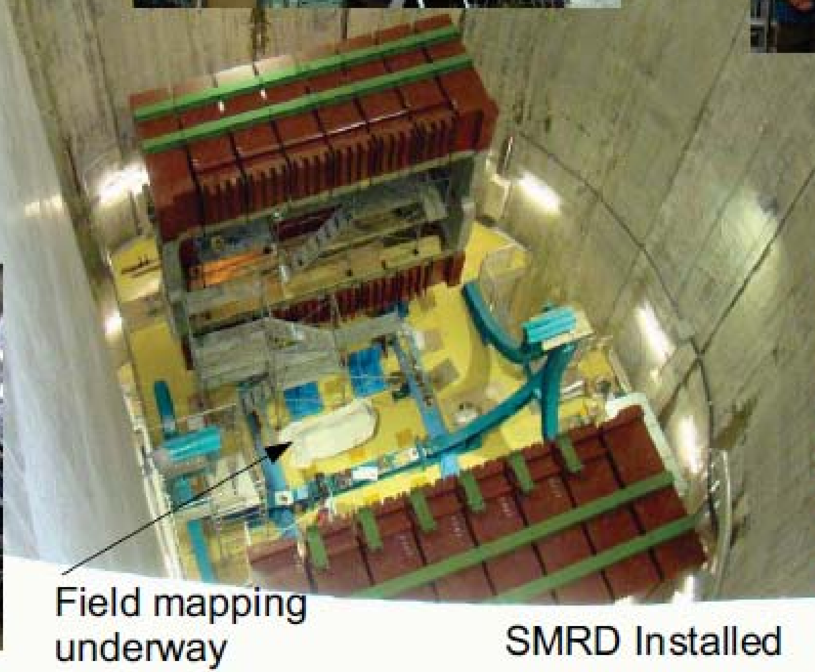
# Status of Near Detector


P0D being installed now

Both FGDs shipped
2of 3 TPCs complete

DSECAL in Japan
40% of rest by end of the year

INGRID Complete



Field mapping underway

SMRD Installed

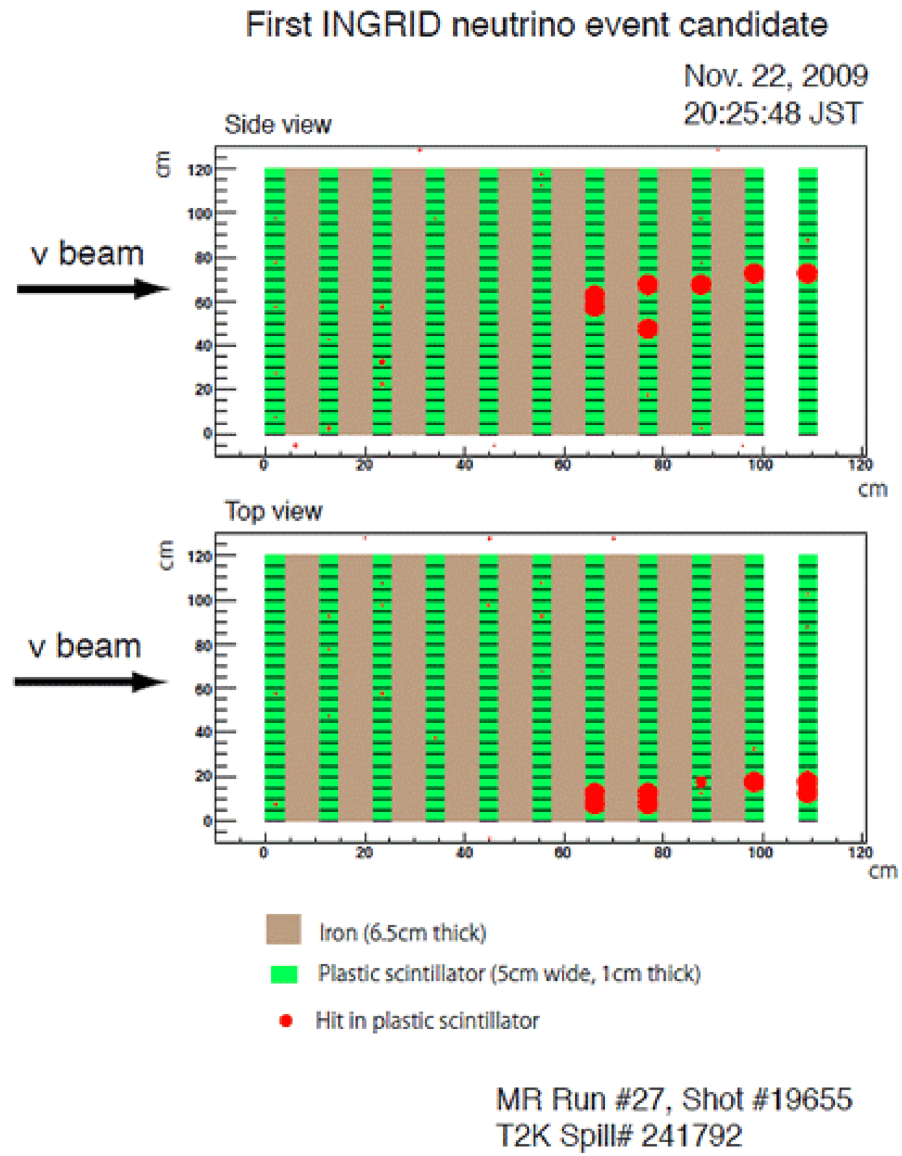


Slide courtesy S. Boyd, WIN'09

# First Light for T2K

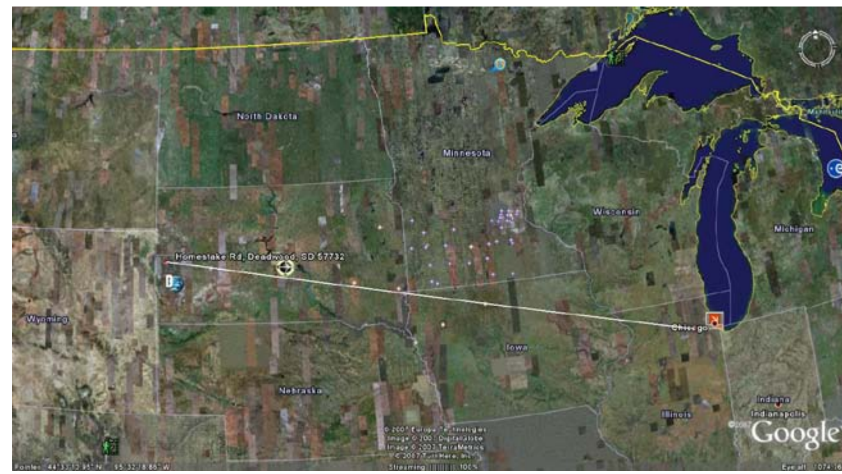
- First proton beam sent all the way through beamline August

- Press release for first neutrino candidate November 22



# Getting to CP-violation and mass hierarchy

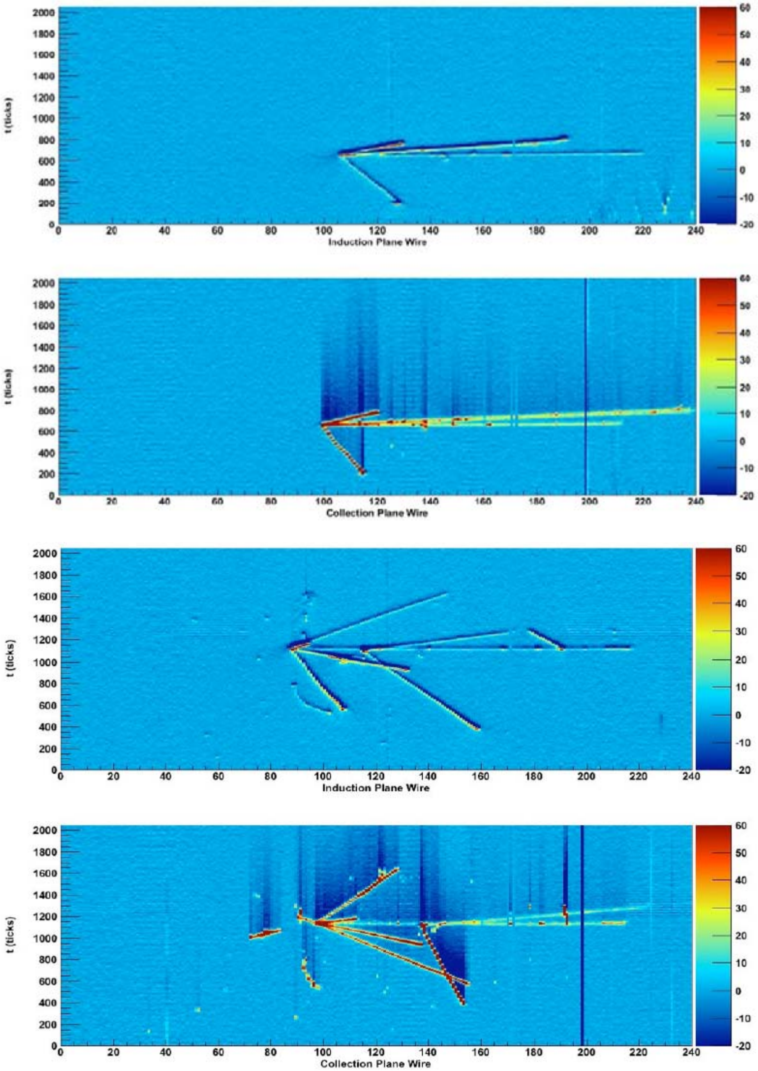
- Long baseline wide band neutrino beams:
  - Fermilab to Homestake
  - JPARC to Korea
  - CERN or FNAL to India




- Ingredients left to figure out:
  - Which detector(s) to build
    - Need hundeds of kilotons!
  - How to take next step in intense conventional beamlines: is 2MW possible?
  - Neutrino Interactions!

# First Light: Argoneut

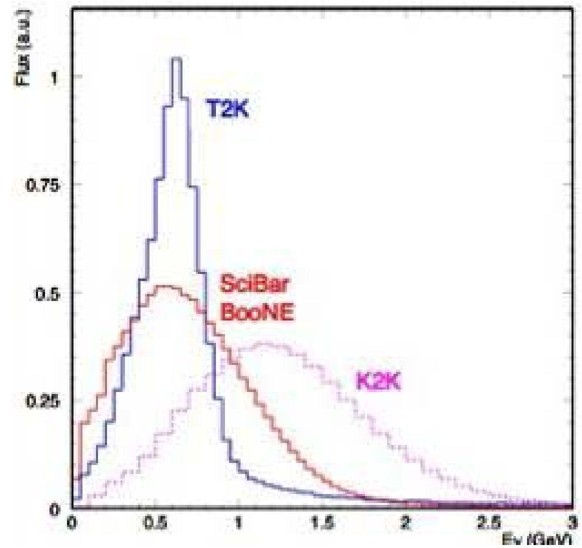
- Argoneut is a test of the Liquid Argon TPC detector concept
- “Electronic Bubble Chamber”
- running in NuMI Beamline now through late February





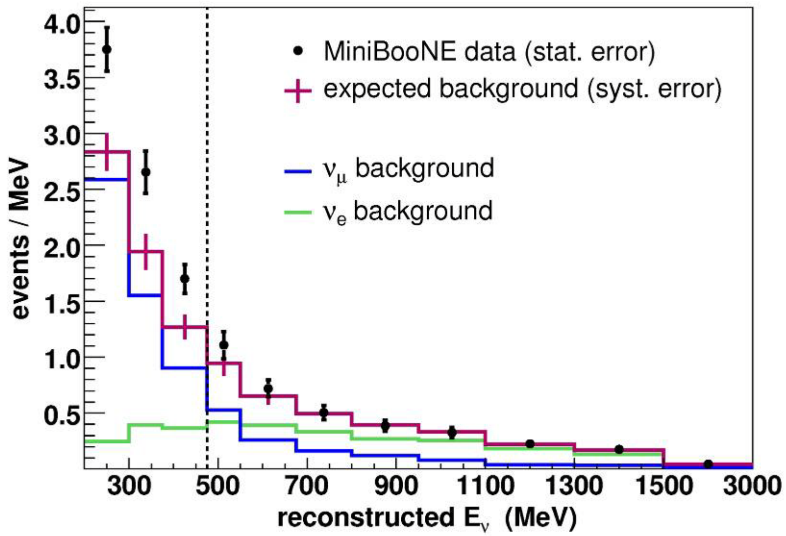

Ref: M. Soderberg, FNAL All Experimenter’s Meeting 10/26

# MicroBooNE

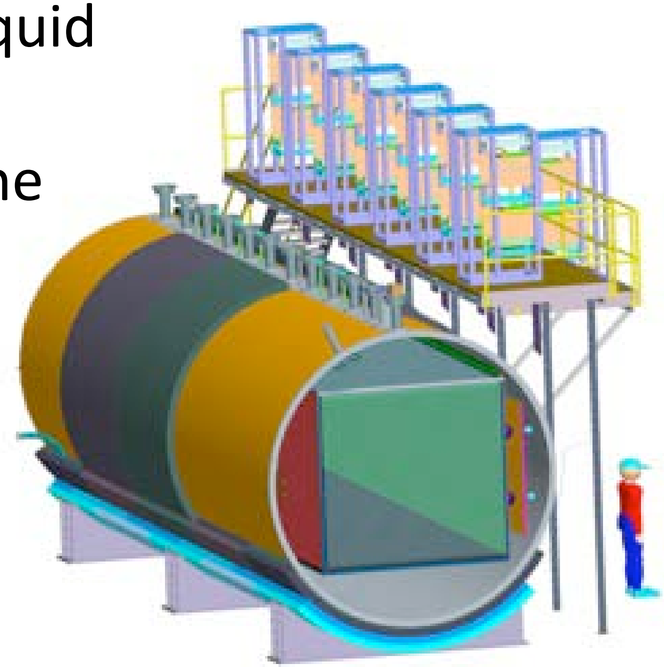



B.Fleming, Fermilab PAC 3/2008

- Booster Neutrino Beamline: Energy spectrum overlaps with T2K




170 tons Liquid Argon,
1km baseline

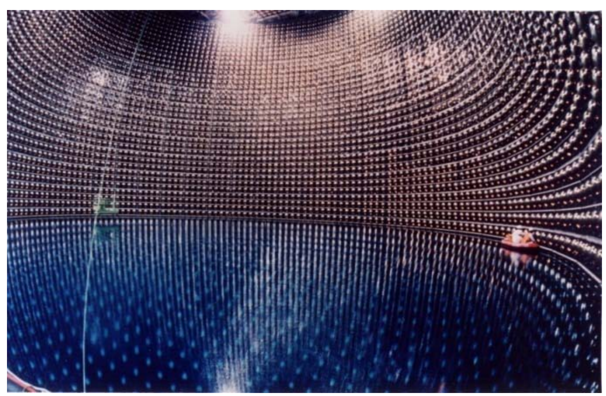


- Excess of low energy events seen at MiniBooNE:
  what are the implications for T2K?
- Put scalable Liquid Argon detector technology in Booster ν Beamline

http://www-microboone.fnal.gov

# Long Baseline Neutrino Experiment @FNAL

- Upgraded Proton Source: Project X
- New beamline pointing from Fermilab to Homestake, SD 1290km
- Investigating two detector options:
  - Water Cerenkov (à la SuperK)
  - Liquid Argon TPC

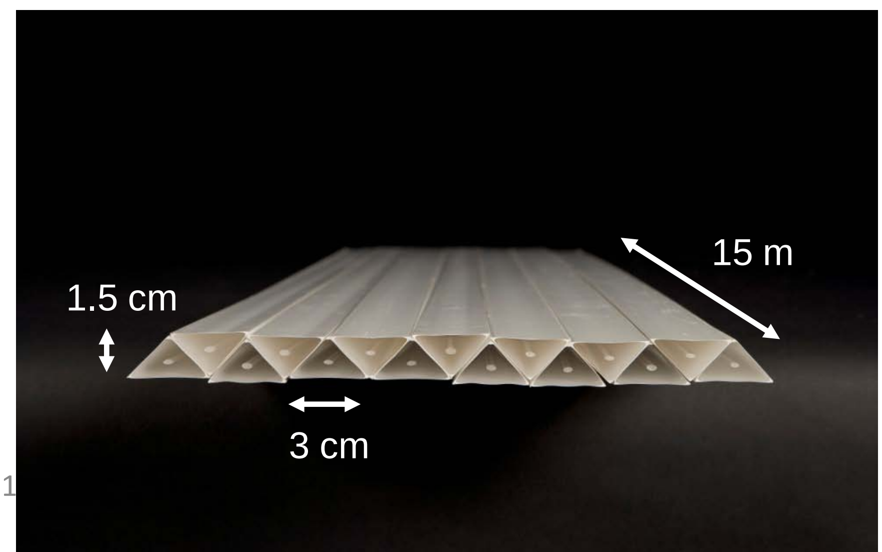


Proof of principle:
50kton Super-Kamiokande

Cryostat containing
100ktons LNG

# What will we want to learn from Neutrino Factory?

- CP-violation studies:
  - Realizing that we may get to a low energy neutrino factory may be best way to see CP-violation
  - Copy MINERvA detector construction and huge magnetic volumes to begin thinking of new neutrino factory detectors (A. Bross, NuFact'09)




- Mass Hierarchy and precision $\Theta_{13}$ measurement
  - Use "magic Baseline" of 7000km where matter effects are largest, CP-violation is smallest
  - (Agarwalla, Choubey,Raychaudhuri Nucl.Phys.B771:1-27,2007)

# Conclusions

- The neutrino community is very busy these days
  - Precision measurements of oscillations
  - Precision interaction measurements
  - Keeping Neutrino Factory Designers on their toes…
- Experiments of all different sizes and stages
  - Mature experiments getting the most from the data
  - New Experiments just coming online right now
  - Experiments deep into construction
  - Experiments on our wish list, working their ways through design and approval
- Thank you to Chris for your guidance: yesterday, today, and tomorrow