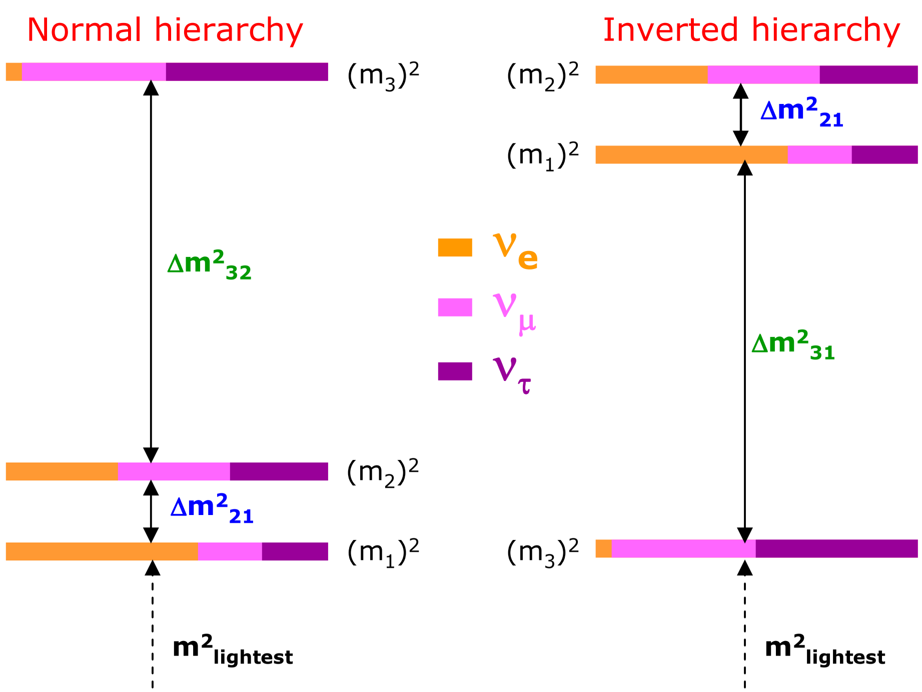
Overview of the Fermilab Neutrino Program

Steve Brice
PPD Neutrino Department

Mixing Matrix and Masses

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



3σ Ranges

Δm^2_{21} : $(7.0 - 9.1) \times 10^{-5}$ eV²
$TAN^2\theta_{12}$: 0.34 – 0.62

Δm^2_{32} : $(1.9 - 2.98) \times 10^{-3}$ eV²
$TAN^2\theta_{23}$: 0.49 – 2.2

$SIN^2\theta_{13} \leq 0.045$
δ unknown
Hierarchy unknown

$m_{lightest} < 2.2$ eV
Dirac or Majorana unknown

[updated from Gonzalez-Garcia PASI 2006]

Open Questions in Neutrino Physics

- General
  - **Is the picture more complex?** → **MiniBooNE, MicroBooNE**
  - **What are the cross-sections?** → **MiniBooNE, SciBooNE, MINERνA, MicroBooNE**
- 12 Sector
- 23 Sector
  - **Is θ_{23} maximal?** → **MINOS, NOνA**
- 13 Sector
  - **What is the value of θ_{13}?** → **NOνA, LBNE**
  - **How are the mass eigenstates ordered?** → **NOνA, LBNE**
  - **Is CP violated?** → **LBNE**
- Mass
  - **What are the neutrino masses?**
  - **Are neutrinos their own anti-particles?**

  → No plans to address at FNAL

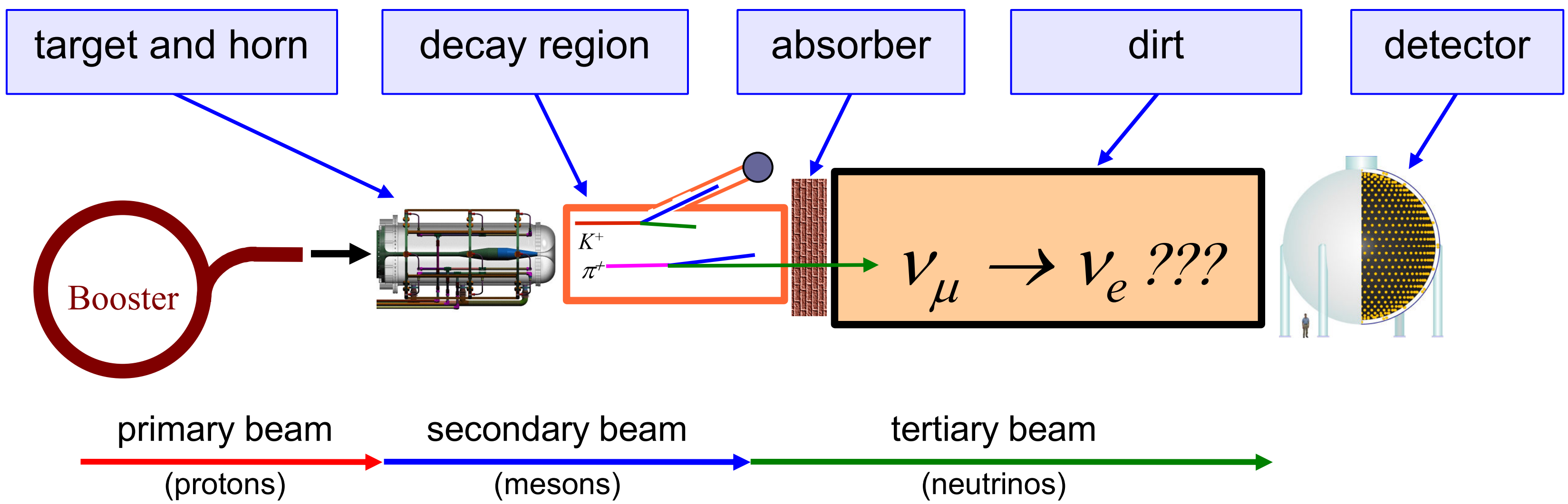
FNAL Neutrino Program

- 8 GeV protons from the Booster
  - Neutrinos from Booster Neutrino Beam (BNB) to…
    - **MiniBooNE (running)**
    - **SciBooNE (completed in 2008)**
    - MicroBooNE (approved, design phase)
- 120 GeV protons from the Main Injector
  - Neutrinos from NuMI to…
    - **MINOS (running)**
    - ArgoNeut (being installed)
    - MINERvA (under construction)
    - NOvA (passed CD2, CD3a, awaiting funding)
  - Neutrinos from a new beamline to…
    - LBNE (pre CD0)

MiniBooNE

Keep L/E same as LSND
while changing systematics, energy & event signature

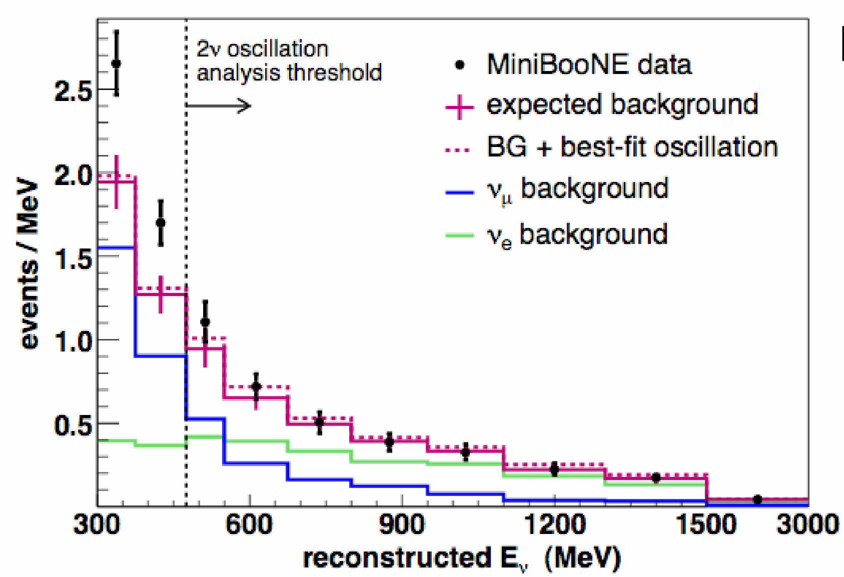
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \, \sin^2(1.27 \Delta m^2 L/E)$$



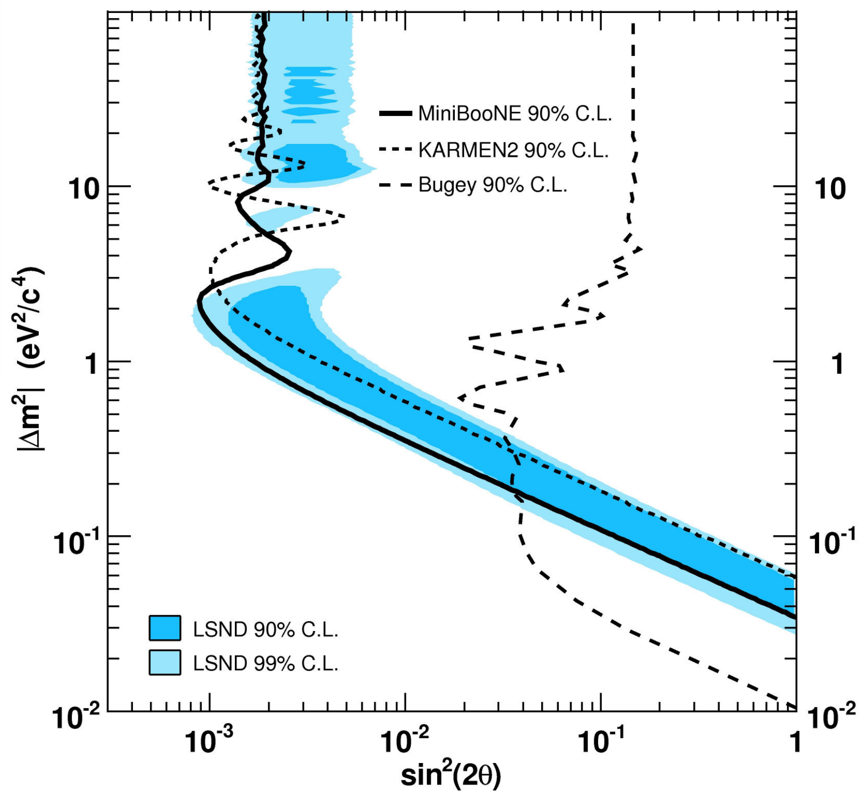
Order of magnitude
higher energy (~500 MeV)
than LSND (~30 MeV)

Order of magnitude
longer baseline (~500 m)
than LSND (~30 m)

Main MiniBooNE Result



No ν_e excess in oscillation signal region but 96 ± 17 ± 20 events above background, for 300<EnQE<475MeV



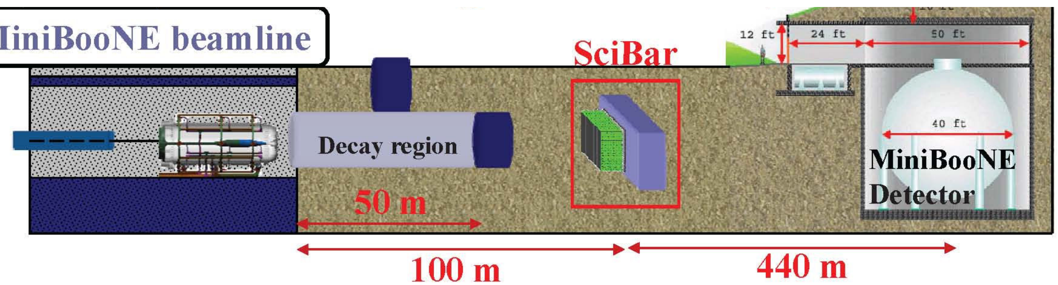
Two independent analyses show no evidence for $\nu_\mu \rightarrow \nu_e$ appearance-only oscillations.

MiniBooNE Status

- Taken ~6.6 x 10^{20} POT in neutrino mode
  - Making suite of cross-section measurements
  - Searching for various neutrino oscillations
  - Found interesting excess of low energy ν_e candidates
  - Publications coming out
- Taken ~4.5 x 10^{20} POT in anti-neutrino mode
  - Making suite of cross-section measurements
  - Searching for anti-neutrino appearance and disappearance
  - No evidence of a low energy ν_e candidate excess
  - Request to PAC for 10.0 x 10^{20} POT with further running

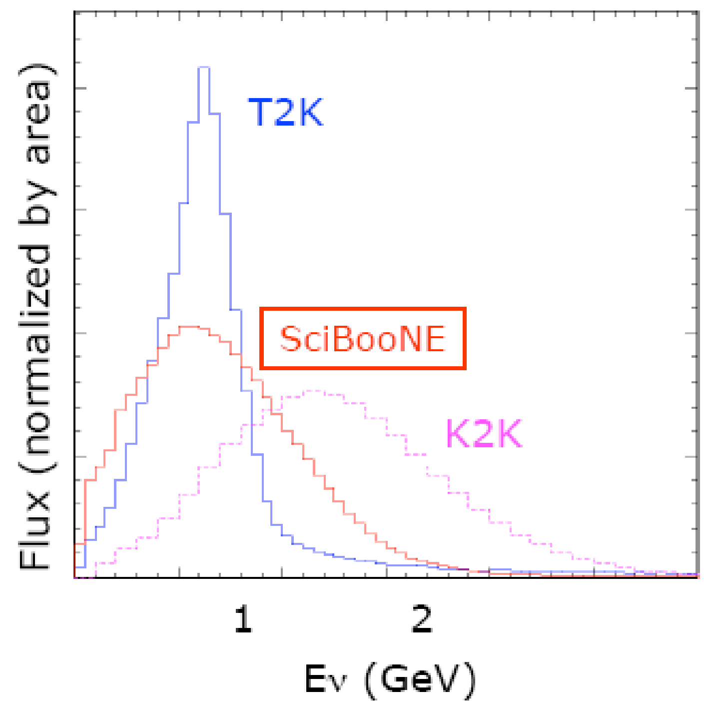
SciBooNE

Idea: Put well developed K2K SciBar detector into the well understood FNAL Booster Neutrino Beamline



- Precision measurement of xsecs for T2K
- BNB beam well matched to T2K beam
- Low cost (<$1M)

SciBooNE Timeline
- 2005, Summer - Collaboration formed
- 2005, Dec - Proposal
- 2006, Jul - Detectors move to FNAL
- 2006, Sep - Groundbreaking
- 2006, Nov - EC Assembly
- 2007, Feb - SciBar Assembly
- 2007, Mar - MRD Assembly
- 2007, Mar - Cosmic Ray Data
- 2007, Apr - Detector Installation
- 2007, May – Commissioning
- 2007, Jun - Neutrino Data Run
- 2008, Aug – Run Ends

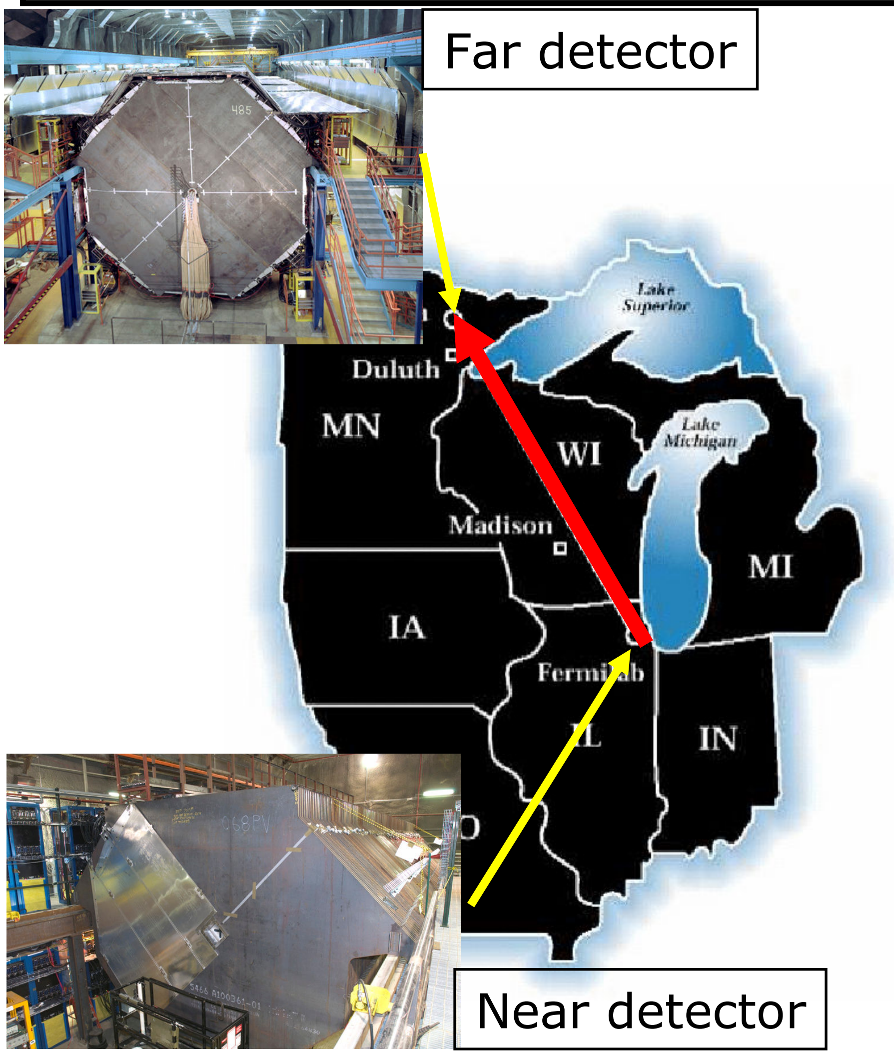


SciBooNE Outlook

- First Result
  - No evidence for CC coherent pion production found
  - Confirms K2K result, sets stronger limit
  - σCoh/σCC < 0.67x10-2 (90% CL) at 1.1 GeV
  - Also have small higher energy sample
  - σCoh/σCC < 1.36x10-2 (90% CL) at 2.2 GeV

- Outlook
- 11 current PhD students
- Up to 8 new results in the next year
- Shooting for NuInt09 workshop in most cases
- Will maintain strong presence at Fermilab until spring 2009
- Maintain analysis center at Fermilab for several more years

MINOS

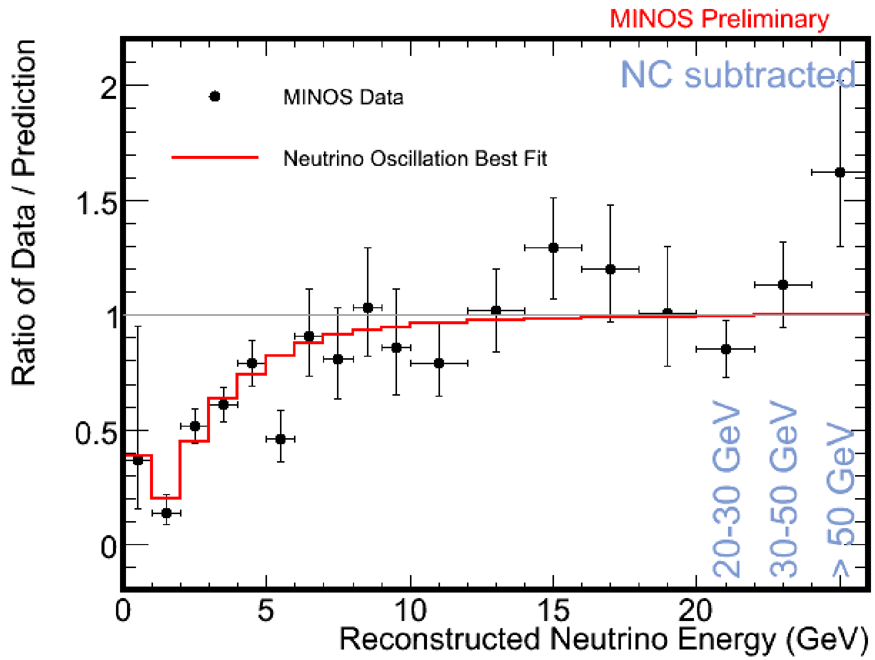


Far Detector:
Soudan, Minnesota, 735 km from target
5.4 kton mass
484 steel/scintillator planes, 8x8x30 m^3

Near Detector:
Fermilab, 1km from target
1 kton mass
282 steel planes
153 scintillator planes, 3.8x4.8x15 m^3

Main MINOS Result

2.50 POT analyzed ≈ 2x statistics of 2006 result
Also improved modeling, reconstruction, and PID

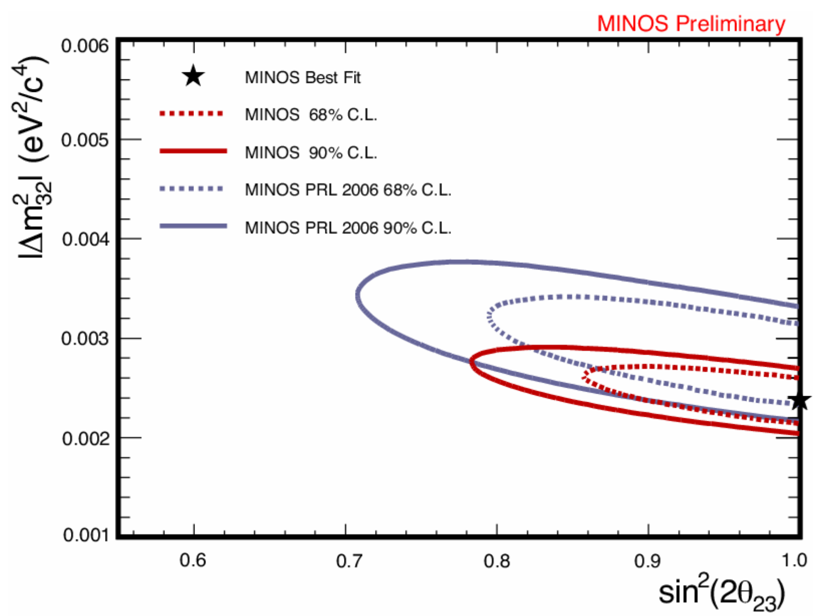


$$\Delta m^2_{23} = 2.38^{+0.20}_{-0.16} \times 10^{-3}\ \text{eV}^2$$

$$\sin^2 2\Theta_{23} = 1.00_{-0.08}$$

$$\frac{\chi^2}{N_{DoF}} = \frac{41.2}{32}$$

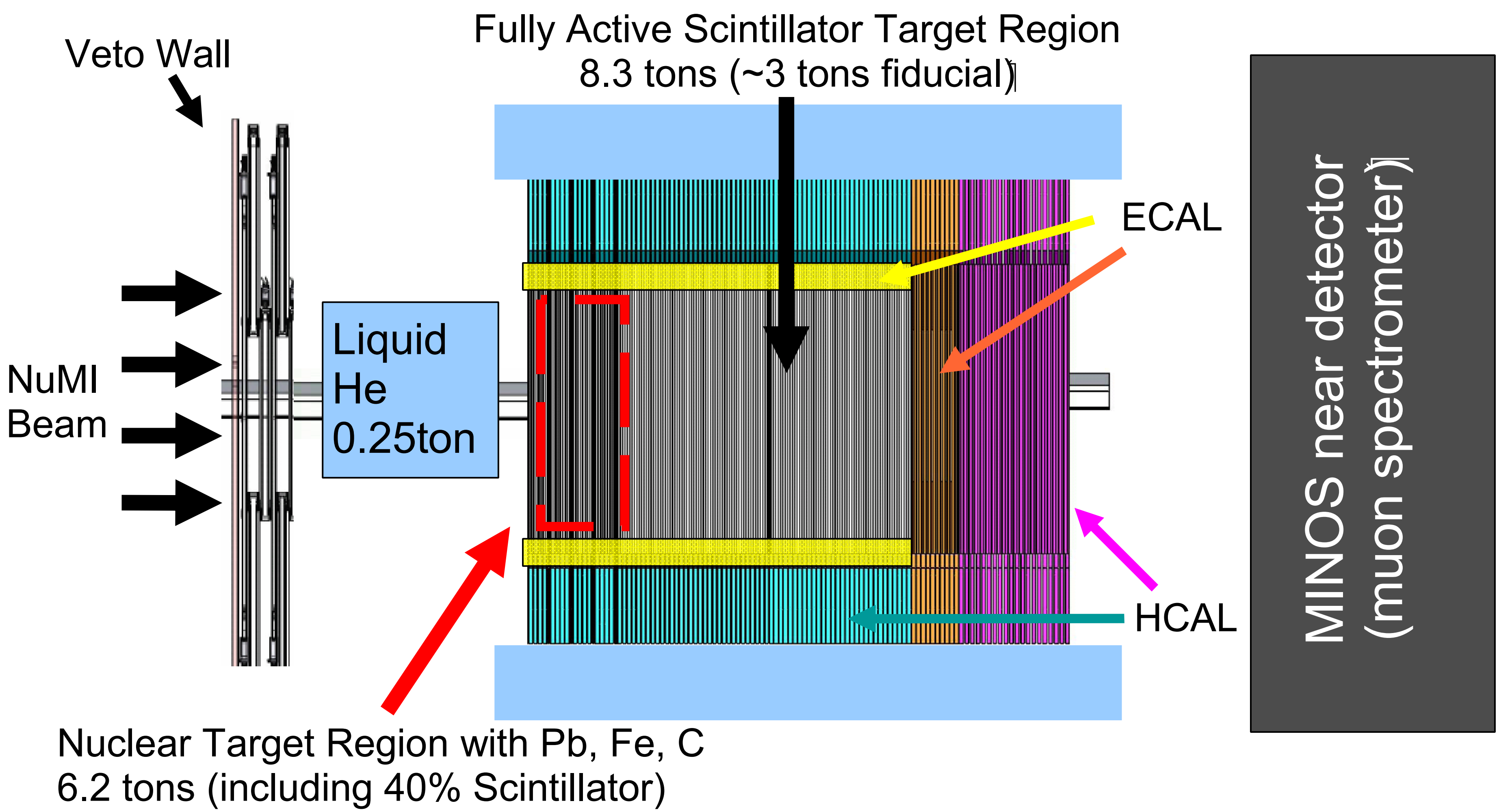
Comparison of new and old MINOS results



MINOS Near Term Outlook

- Expect data set of 7×10^{20} POT by summer 2009.
  - This doubles the currently published CC sample.
- Electron neutrino appearance
  - First result with 3.25×10^{20} POT two weeks ago
  - Analysis of doubled dataset to follow
- Neutral currents
  - Extended analysis of 3.25×10^{20} POT by early 2009
  - Analysis of doubled dataset by end 2009
- Muon Antineutrino disappearance
  - 3.2×10^{20} POT exposure result nearly completed. Expect results early 2009.
  - Using 6% intrinsic beam antineutrinos
- Total cross-section from Near Detector
  - Low model dependence flux determination
  - Expect end of 2008
- Request to switch to anti-neutrino running after the 2009 shutdown

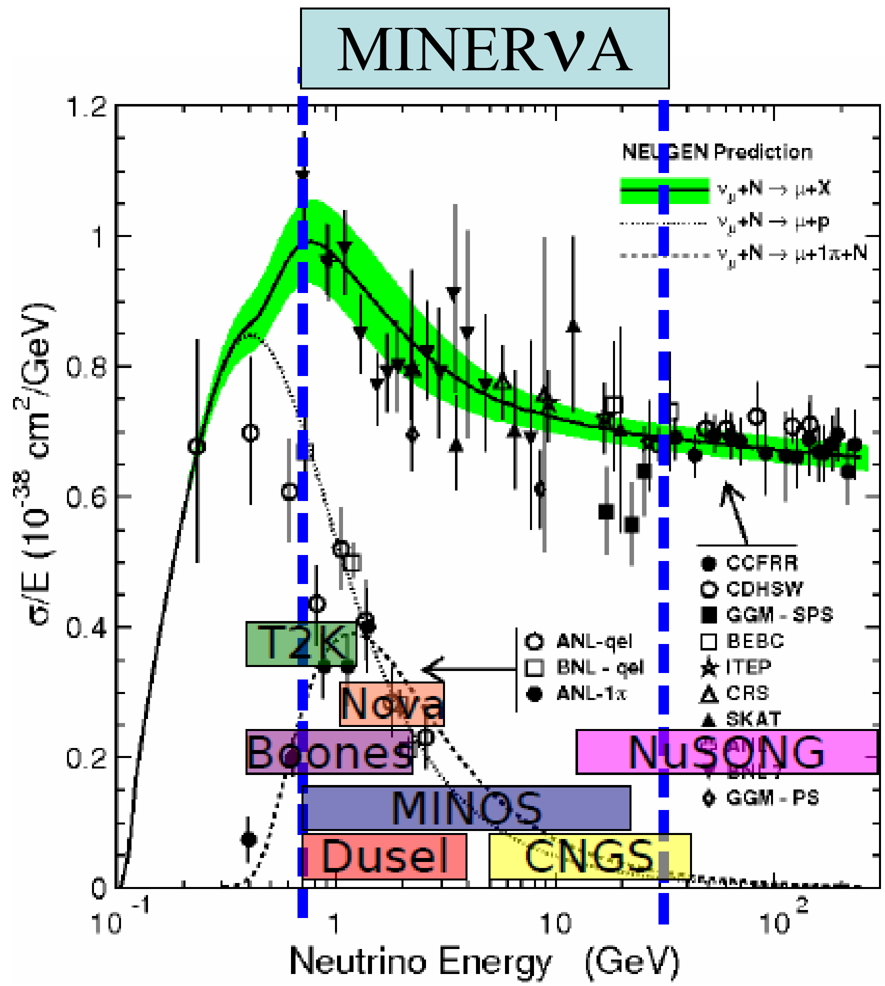
MINERνA


Veto Wall
NuMI Beam
Liquid He 0.25ton
Fully Active Scintillator Target Region
8.3 tons (~3 tons fiducial)
ECAL
HCAL
MINOS near detector
(muon spectrometer)
Nuclear Target Region with Pb, Fe, C
6.2 tons (including 40% Scintillator)

MINERνA Physics Program

- **Quasi-elastic scattering**
- **Resonance Production - 1pi**
- **Resonance/transition Region – npi resonance to DIS**
- **Deep-Inelastic Scattering**
- **Coherent Pion Production**
- **Strange & Charm Particle Production**
- **s_T , Structure Functions and PDFs**
  - **s(x) and c(x)**
  - **High-x parton distribution functions**
- **Nuclear Effects**

- **Generalized Parton Distributions**



MINERνA Proposed Schedule

- Continue construction and commissioning, with cosmics, of the Tracking Prototype at WideBand Hall.
- If successful, install in NuMI beam early in CY2009 to check response to neutrino beam.

- Continue commissioning of tertiary test beam through end CY2008.
- Install and commission test beam detector as well as test beam physics runs in CY2009.

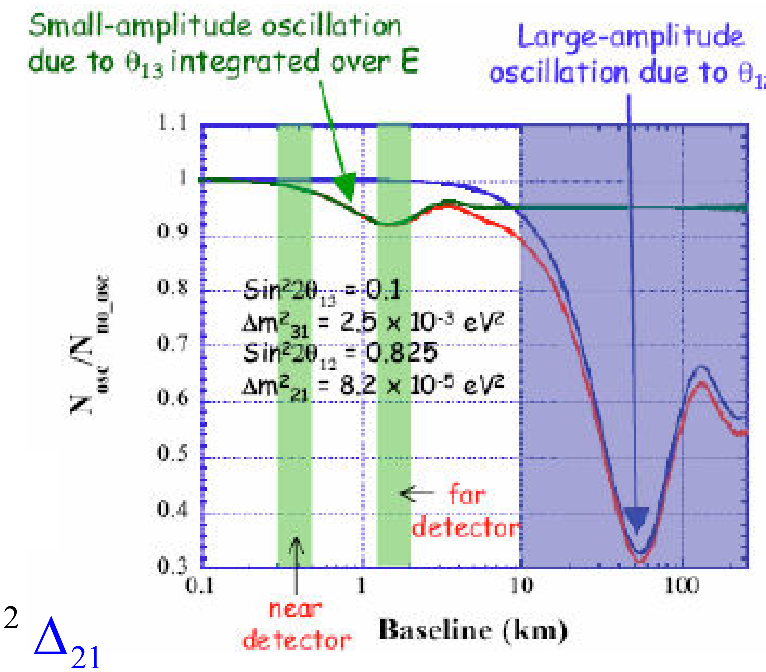
- Complete construction of full MINERnA detector and install in stages throughout CY2009, partial commissioning as we install.
- Begin commissioning of full detector toward end of CY2009.

- **Begin physics data taking end-CY2009/beginning-CY2010.**

How to Measure the 13 Sector

Probed by measuring the disappearance of reactor produced electron anti-neutrinos.

Need to work at an L/E matched to the atmospheric Δm^2
(C.F. Kamland measurement at solar Δm^2)



$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21}$$
$$- \sin^2 2\theta_{13} (\cos^2 \theta_{12} \sin^2 \Delta_{31} + \sin^2 \theta_{12} \sin^2 \Delta_{32})$$

$\Delta_{ij} \equiv 1.27 \Delta m^2_{ij} L / E$
L(km), E(MeV), m(10^{-3}eV)

How to Measure the 13 Sector (cont)

Also probed by measuring electron neutrino appearance from accelerator produced muon neutrinos

Need to have an L and E such that interference between solar and atmospheric scales can bee seen

$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)^2}\Delta_{31}{}^2$$

$$+\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}{}^2$$

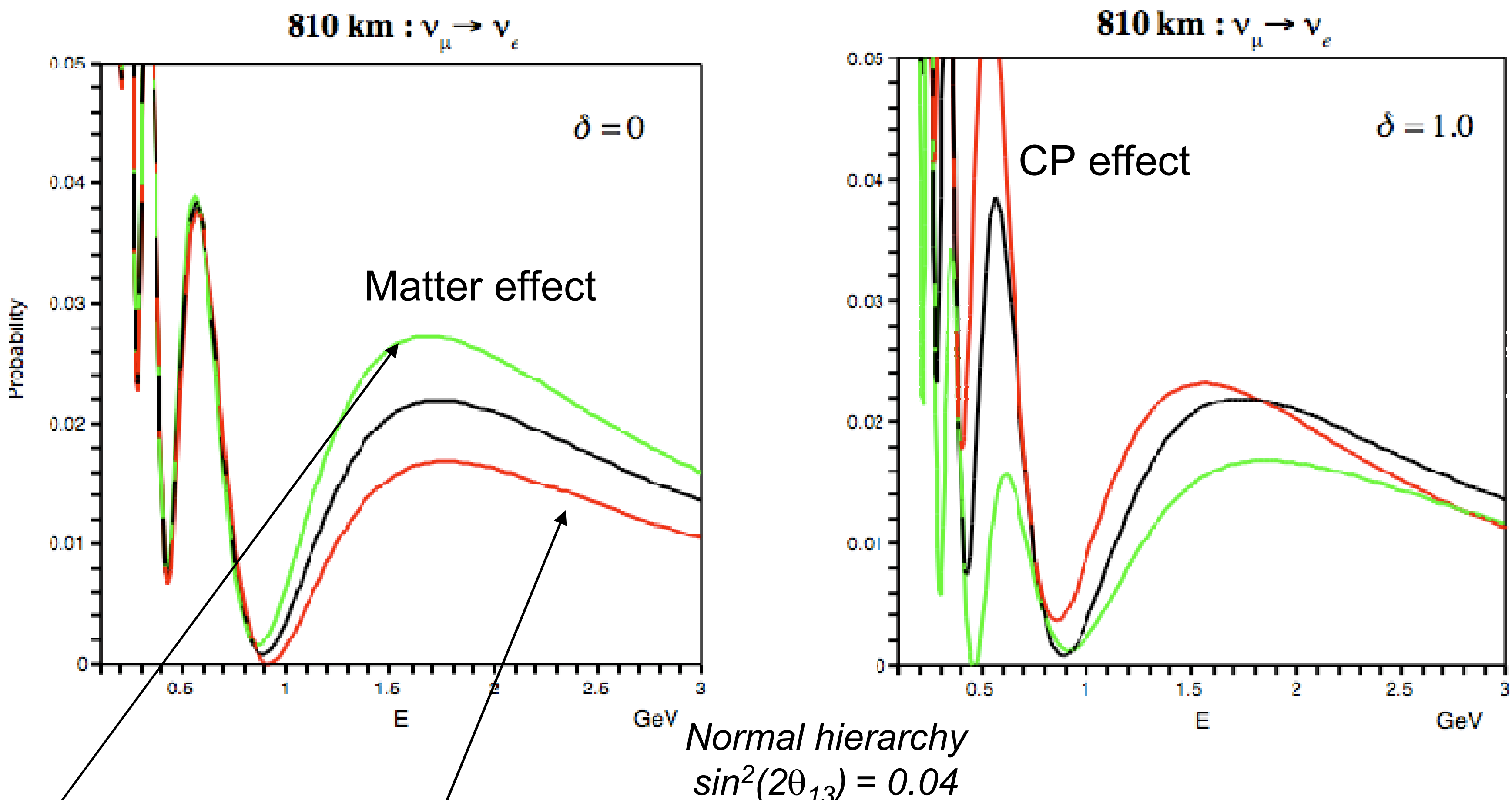
$$+\cos\delta\sin 2\theta_{23}\sin 2\theta_{12}\sin 2\theta_{13}\cos\Delta_{32}\left(\frac{\sin(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)}\Delta_{31}\right)\left(\frac{\sin(aL)}{(aL)}\Delta_{21}\right)$$

$$+\sin\delta\sin 2\theta_{23}\sin 2\theta_{12}\sin 2\theta_{13}\sin\Delta_{32}\left(\frac{\sin(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)}\Delta_{31}\right)\left(\frac{\sin(aL)}{(aL)}\Delta_{21}\right)$$

$P(\bar{\nu}_\mu \to \bar{\nu}_e):\quad \sin\delta \to -\sin\delta,\quad a \to -a$ $\qquad \Delta_{ij} \equiv 1.27\Delta m^2{}_{ij}L/E$

Matter effect $a \equiv G_F N_e/\sqrt{2} \approx (4000\text{ km})^{-1}$ $\qquad$ L(km), E(GeV), m(eV)

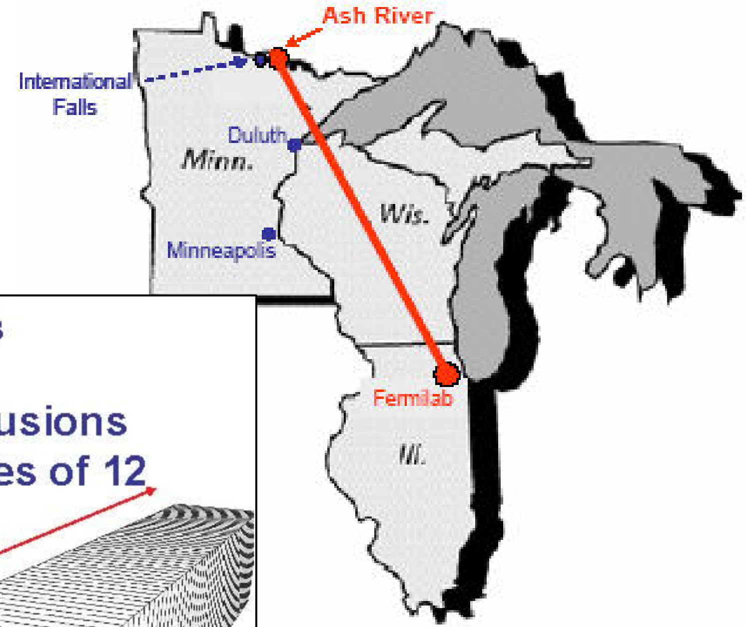
Matter Effects and CP

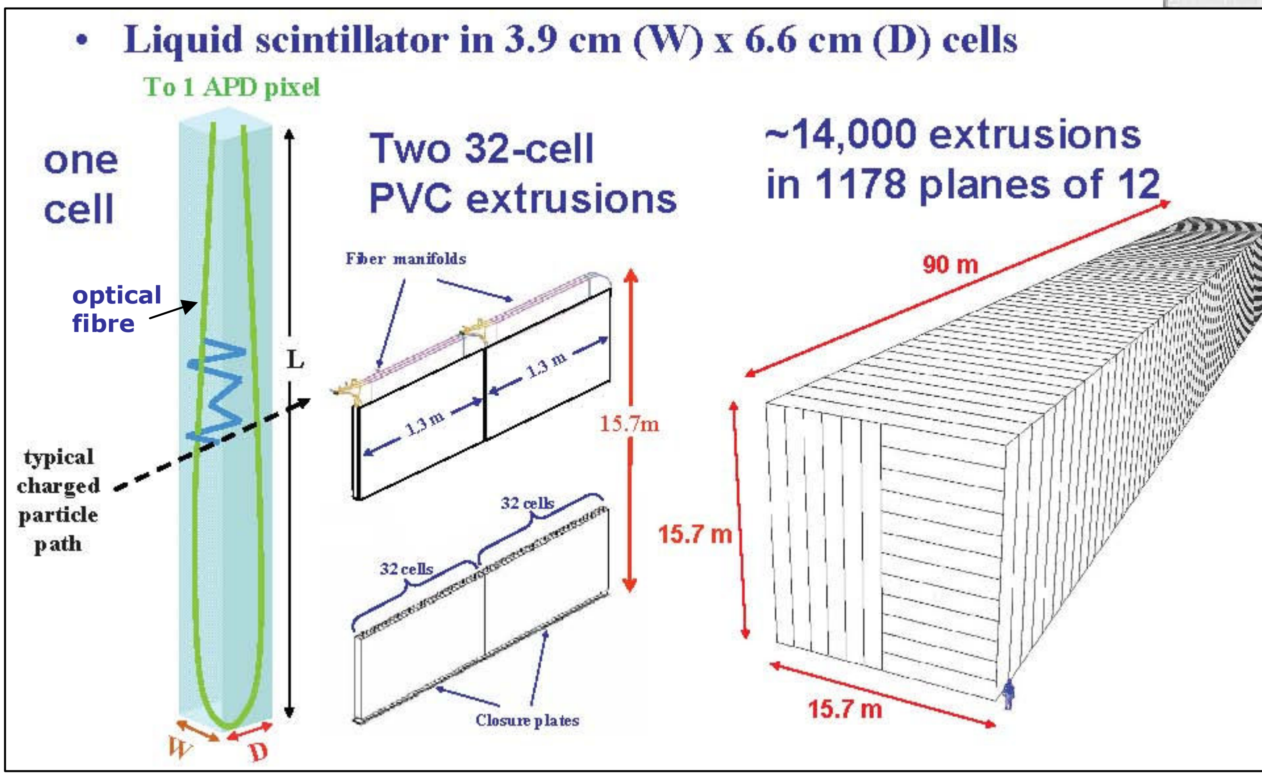


ν's and and anti-ν's can be used to distinguish ambiguities

NOνA

Far detector:
18 kton, fully active segmented detector
12 km off NuMI beamline axis
810 km baseline

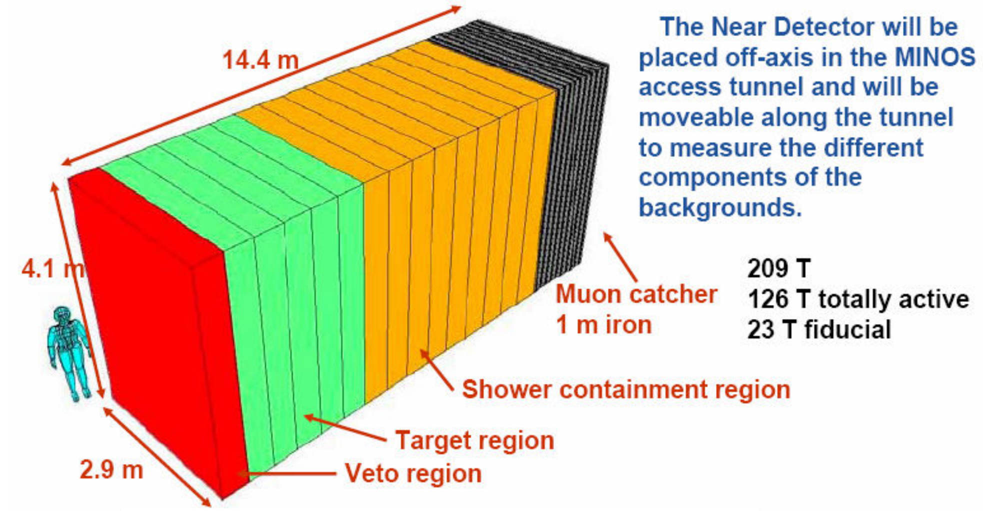


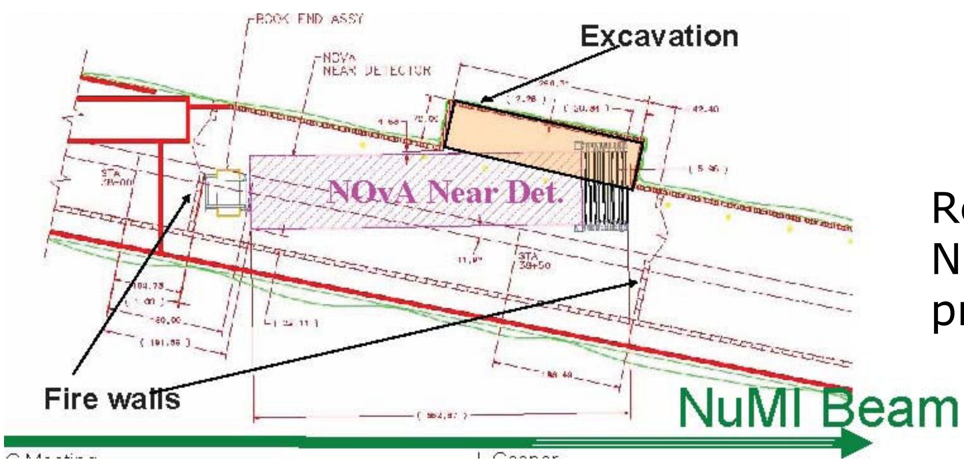


NOνA Near Detector

186 liquid scintillator planes in target
10 in muon ranger, 1m steel

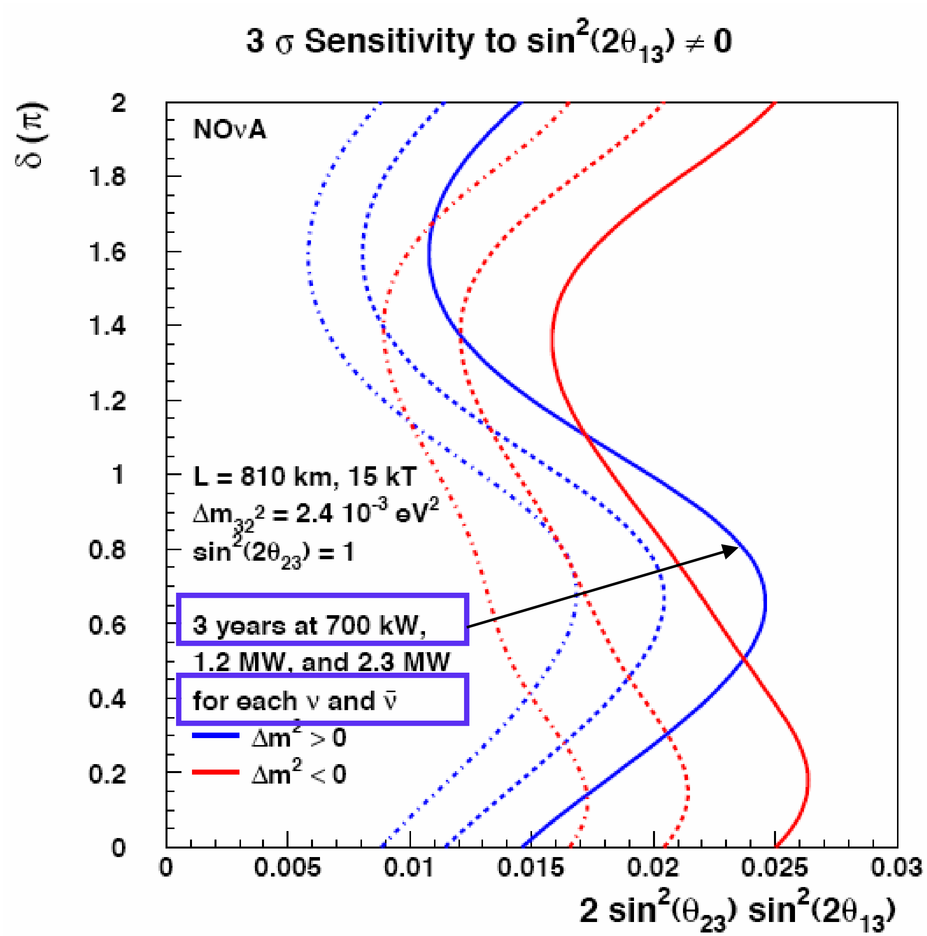
Same cell size as far detector
Readout from one side per plane
with APDs plus faster electronics
than far detector



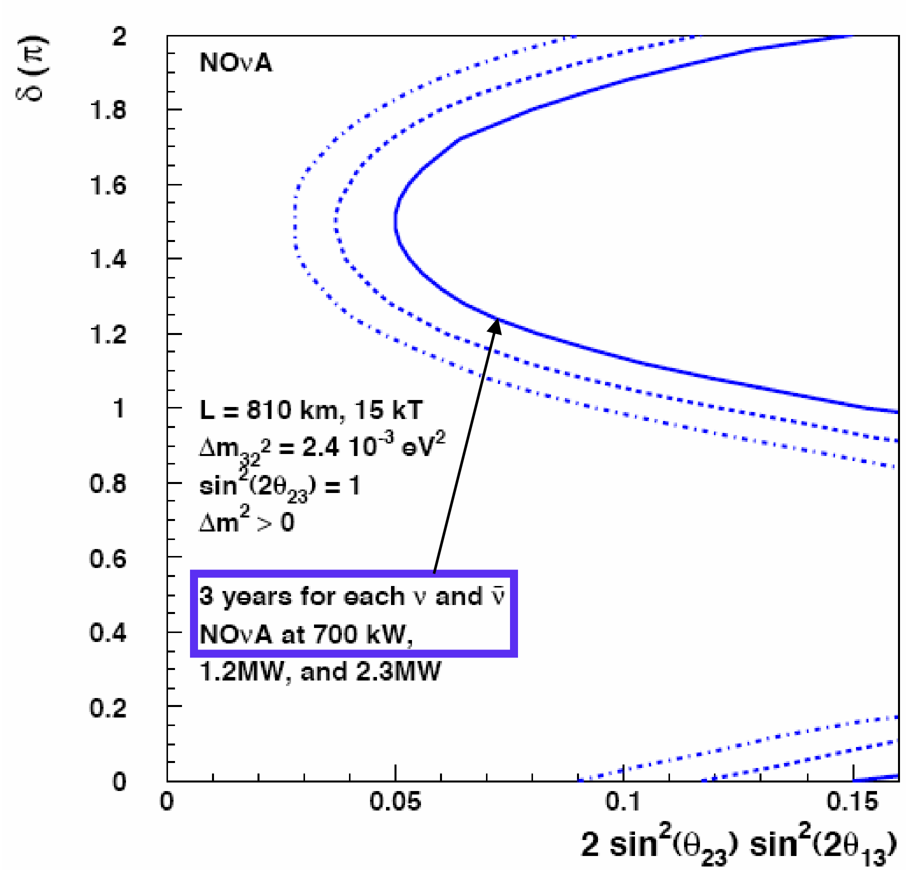


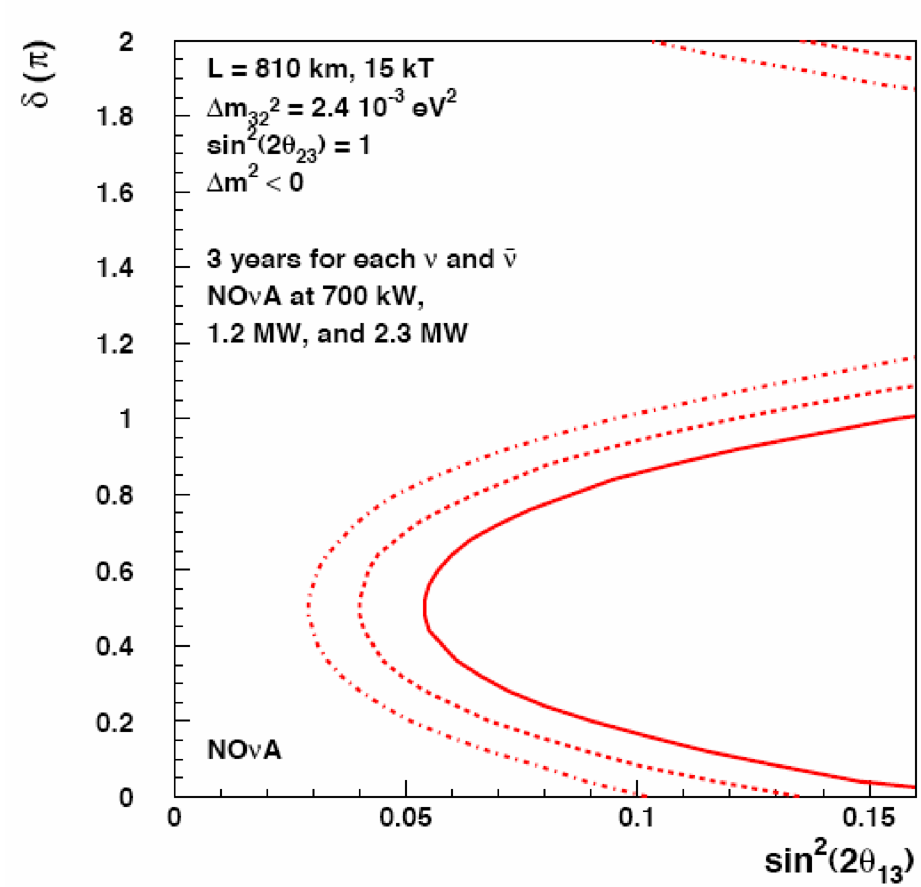
Requires some additional excavation in NuMI tunnel in order for detector to be at proper 14 mrad angle

NOνA θ_{13} Sensitivity



NOνA Mass Hierarchy Sensitivity





NOνA Schedule

Apr 30 2008	Passed Repeat CD-2/3a Review
May 29 2008	Re-recommended by P5 under Scenario B or better
July 1 2008	Supplemental bill restores $9.5 M NOνA funding
Sep 15 2008	CD-2 Granted
Oct 24 2008	CD-3a Granted: $17.3 M for long-lead items:
	$8.9 M for far site prep - road and excavation
	$6.2 M for ANU tooling, parts, and instrumentation
	$2.1 M for scintillator wave-shifters (single source)

Best estimate of schedule:

- Apr 2009 — Start of Construction (assumes FY09 funding final before March 6)
- Jun 2011 — Far Detector Building Beneficial Occupancy
- Aug 2012 — 1st 2.5 kT of the Far Detector Online
- Jan 2014 — Full Far Detector Online

Neutrino Program Evolution

- Numerous studies over the past several years have laid out options for further exploring the neutrino sector
- In particular, searching for CP violation
- i.e. BNL-FNAL US long baseline neutrino experiment study (March 2006-June 2007) explored
  - Beam options
  - NuMI , new Wide Band Beam at a longer baseline
  - On and off axis detector locations
  - Detector technology options
    - Water cerenkov, liquid argon
- These studies make sense in the context of a non-zero determination of θ_{13}

General Conclusions

- Future experiments using <u>conventional</u>* neutrino beams can be designed to have 3-5σ discovery potential for measuring **CP violation and the neutrino mass hierarchy** for values of $\sin^2 2\theta_{13}$ as low as ~ 0.01
- These sensitivities are reached assuming :
  - –a **proton source** at the Megawatt level (or decades of running time)
  - –a **neutrino beam** optimized to the oscillation probability (covering the 1st and 2nd oscillation maximum)
  - –an **experiment baseline > 1000 km** (to improve the sensitivity to determine the mass hierarchy)
  - –a **Detector** with effective mass (mass*efficiency) **> 100kT**

- If nature has made θ_{13} very small we may need to consider a non-conventional neutrino source, i.e. **neutrino factory**

from P5 report

The Intensity Frontier

The accelerator-based neutrino program

- Measurements of the mass and other properties of neutrinos are fundamental to understanding physics beyond the Standard Model and have profound consequences for understanding the evolution of the universe. The US can build on the unique capabilities and infrastructure at Fermilab, together with the proposed DUSEL, the Deep Underground Science and Engineering Laboratory proposed for the Homestake Mine, to develop a world-leading program in neutrino science. Such a program will require a multi-megawatt proton source at Fermilab.

- The panel recommends a world-class neutrino program as a core component of the US program, with the long-term vision of a large detector in the proposed DUSEL laboratory and a high-intensity neutrino source at Fermilab.

from P5 report

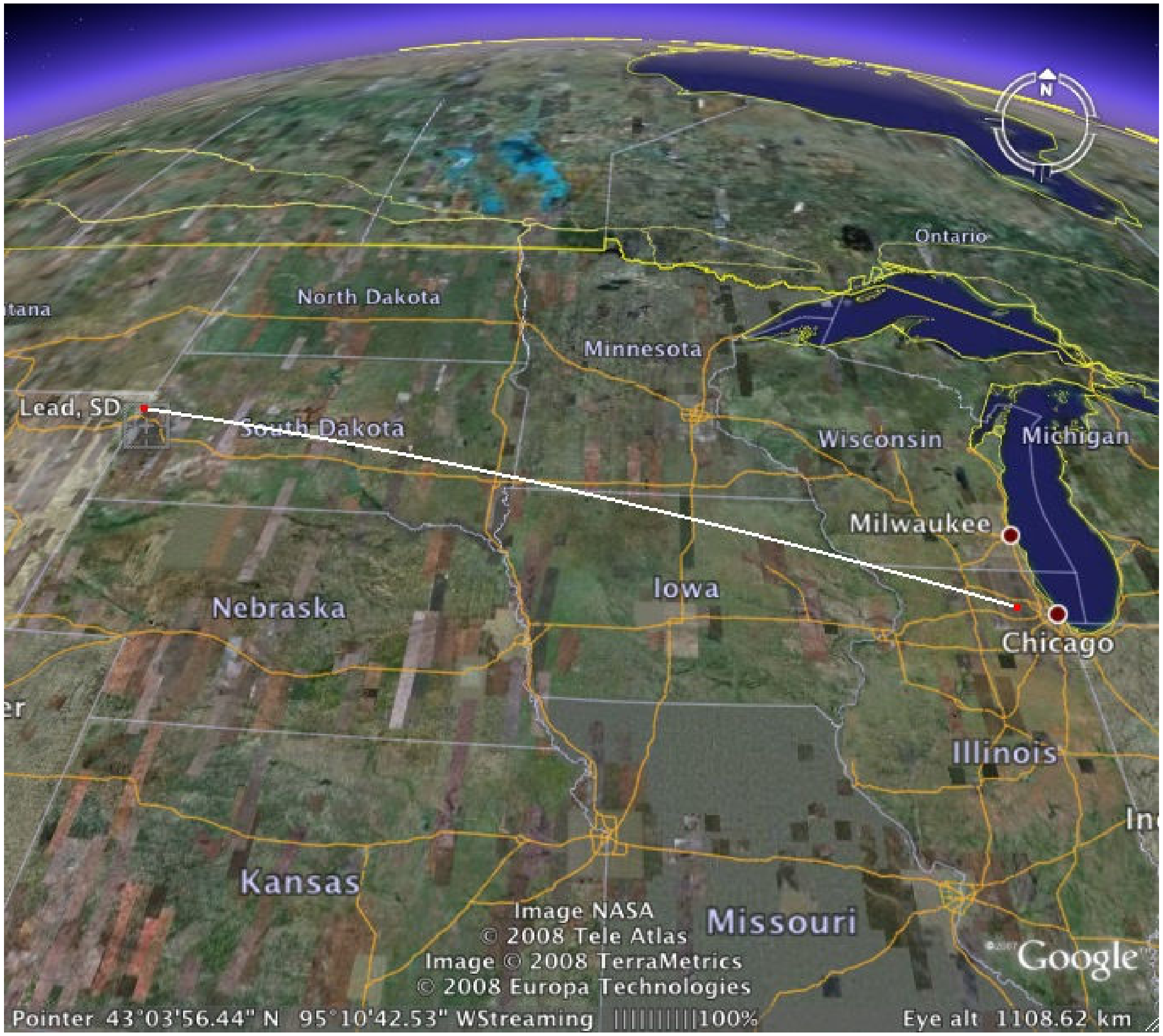
Neutrino Program (cont)

- The panel recommends proceeding now with an R&D program to design a multi-megawatt proton source at Fermilab and a neutrino beamline to DUSEL and recommends carrying out R&D on the technology for a large detector at DUSEL.

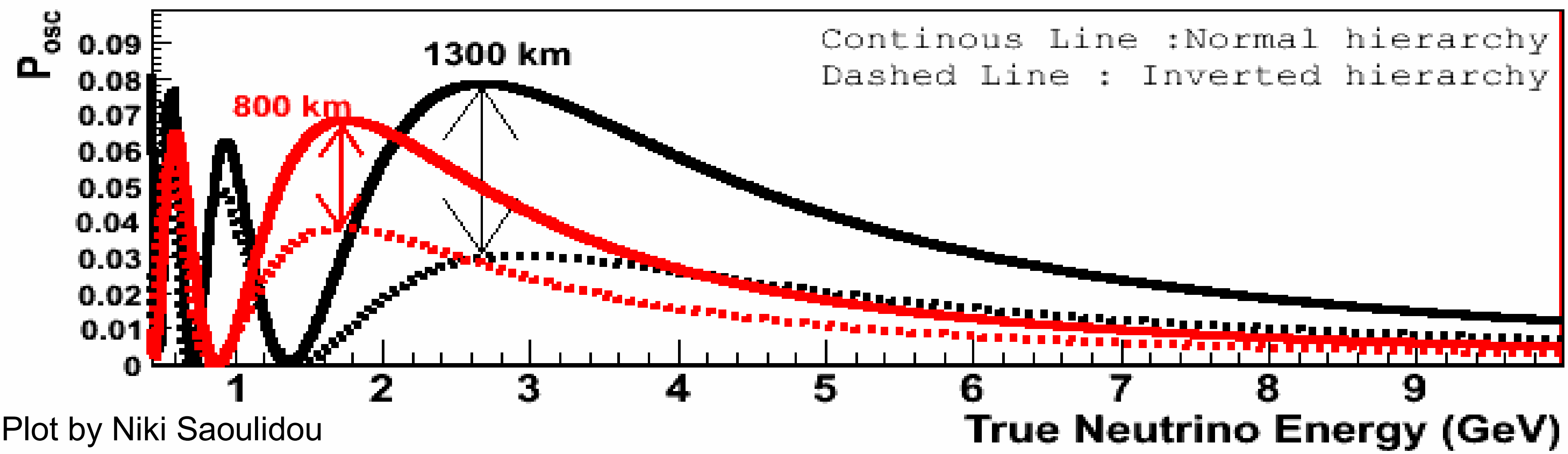
- Construction of these facilities could start within the period considered by this report.

- A neutrino program with a multi-megawatt proton source would be a stepping stone toward a future neutrino source, such as a neutrino factory based on a muon storage ring, if the science eventually requires a more powerful neutrino source. This in turn could position the US program to develop a muon collider as a long-term means to return to the energy frontier in the US

Fermilab to Homestake DUSEL (1290km)



Advantage of the Longer Baseline



Plot by Niki Saoulidou

- Oscillation maxima are moved to higher energy
- Matter effects are significantly larger

Neutrino Beam Requirements*

- **The maximal possible neutrino fluxes to encompass at least the 1st and 2nd oscillation nodes, which occur at 2.4 and 0.8 GeV respectively**

- **Since neutrino cross-sections scale with energy, larger fluxes at lower energies are desirable to achieve the physics sensitivities using effects at the 2nd oscillation node**

- **To detect $\nu_\mu \rightarrow \nu_e$ at the far detector, it is critical to minimize the neutral-current contamination at lower energy, therefore minimizing the flux of neutrinos with energies greater than 5 GeV where there is little sensitivity to the oscillation parameters is highly desirable**

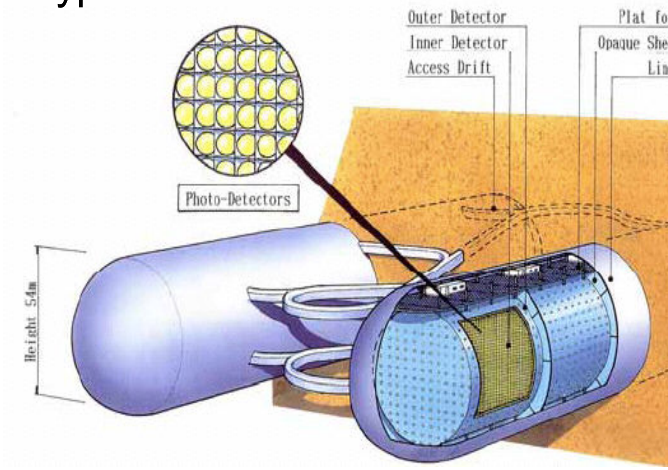
- **The irreducible background to $\nu_\mu \rightarrow \nu_e$ appearance signal comes from beam generated ν_e events, therefore, a high purity νμ beam with as low as possible νe contamination is required**

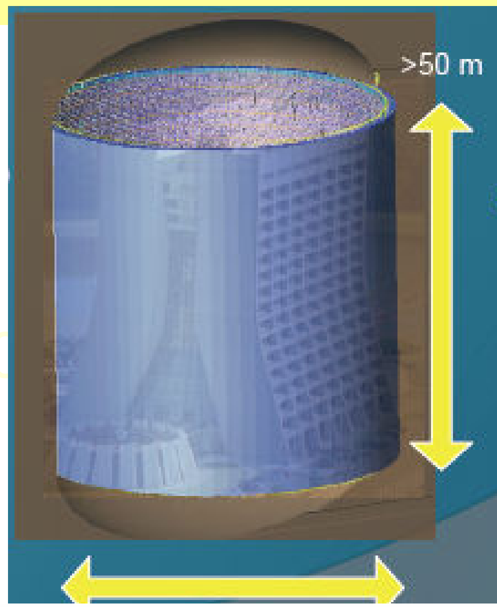
**From "Simulation of a Wide-Band Low-Energy Neutrino Beam for Very Long Baseline Neutrino Oscillation Experiments", Bishai, Heim, Lewis, Marino, Viren, Yumiceva*

Worldwide Concepts for a Large Detector

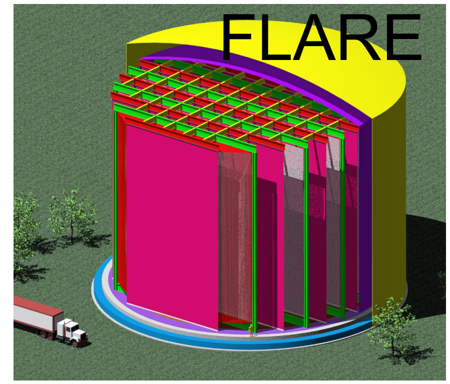
Water Cerenkov
Liquid Argon
Liquid Scintillator

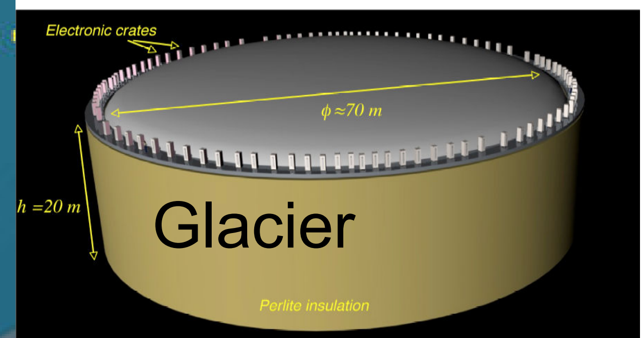
Hyper-Kamiokande



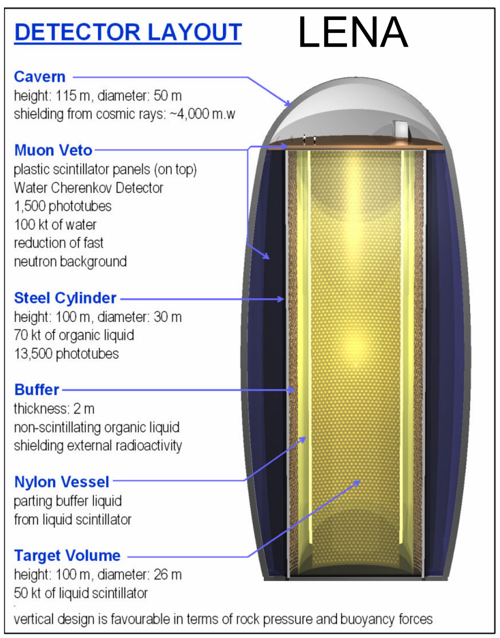


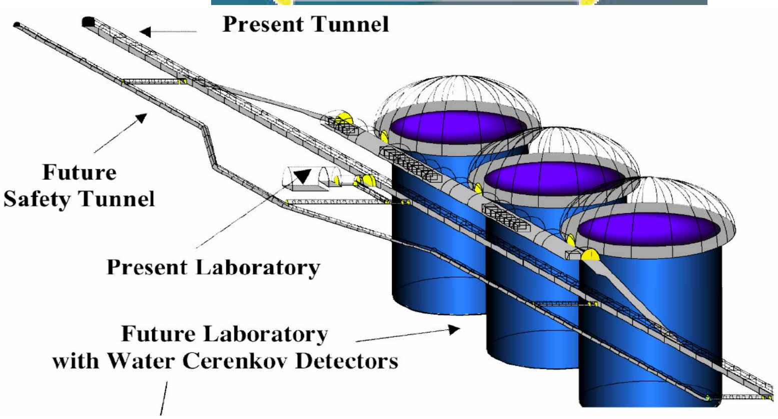
FLARE

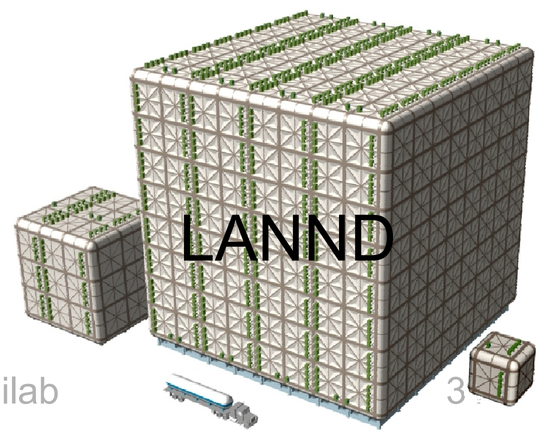




LENA

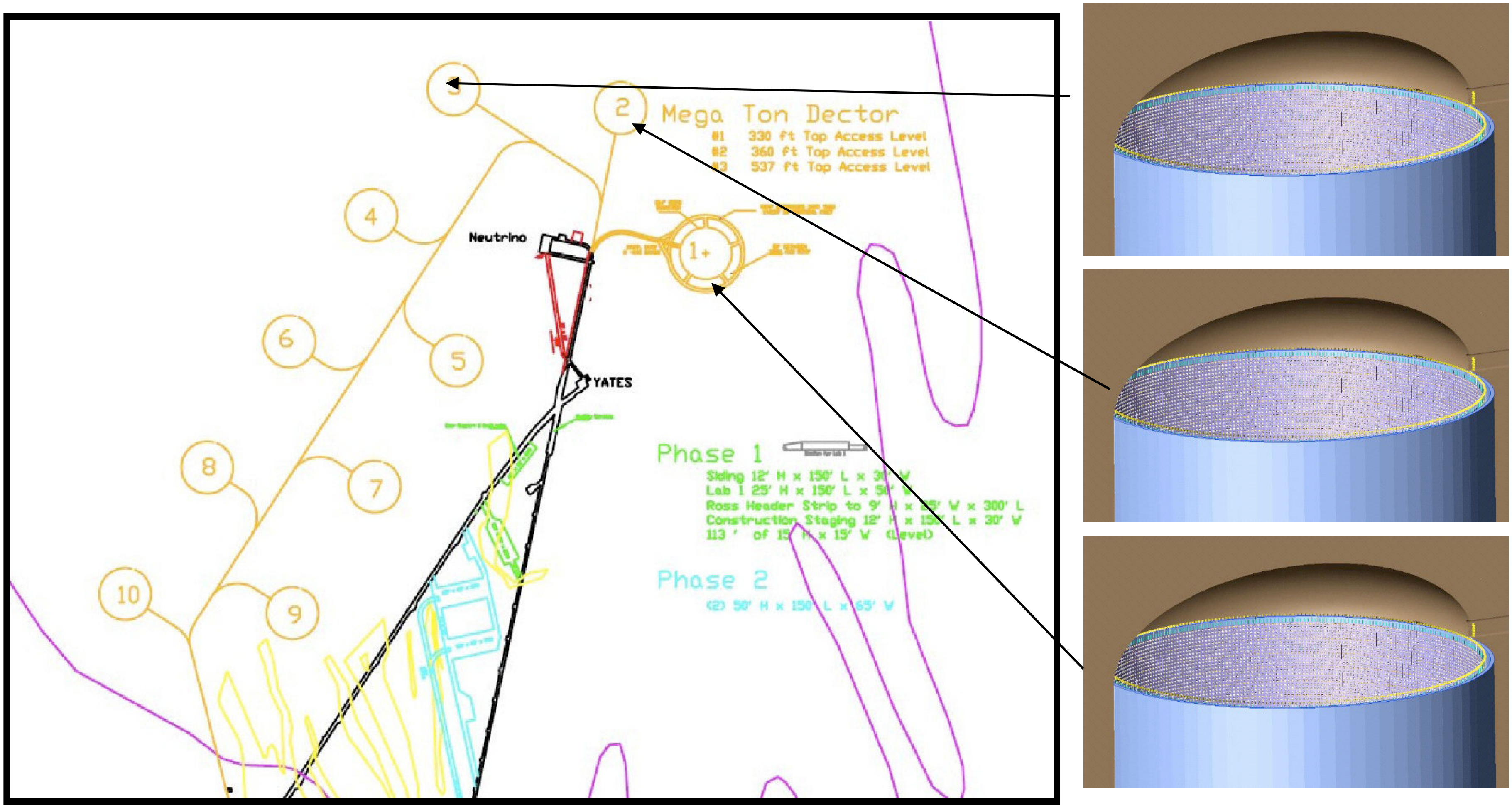






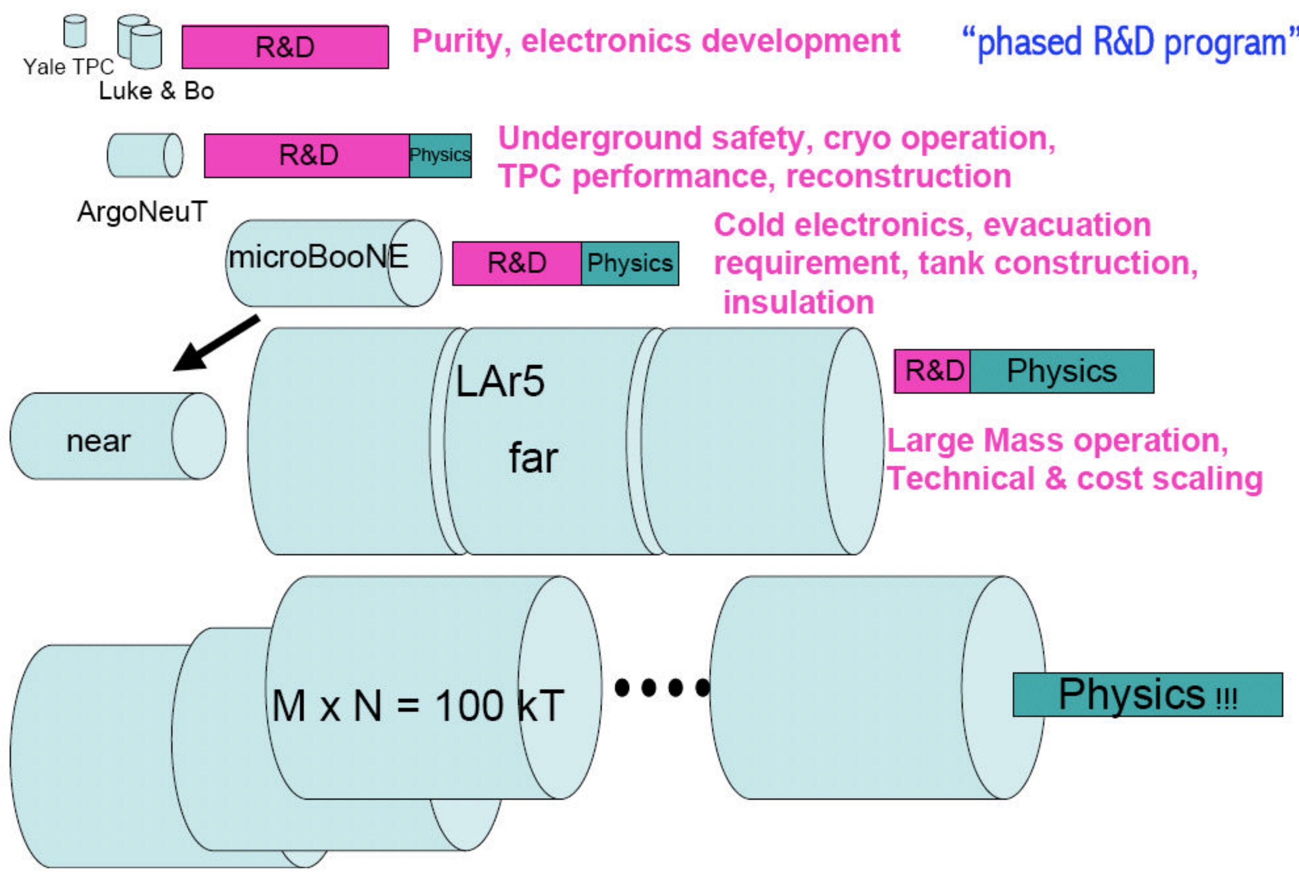
milab

WC-100 x 3 @ Homestake DUSEL



25% PMT coverage □ 60,000 10 inch PMT's per module

Liquid Argon Phased Program



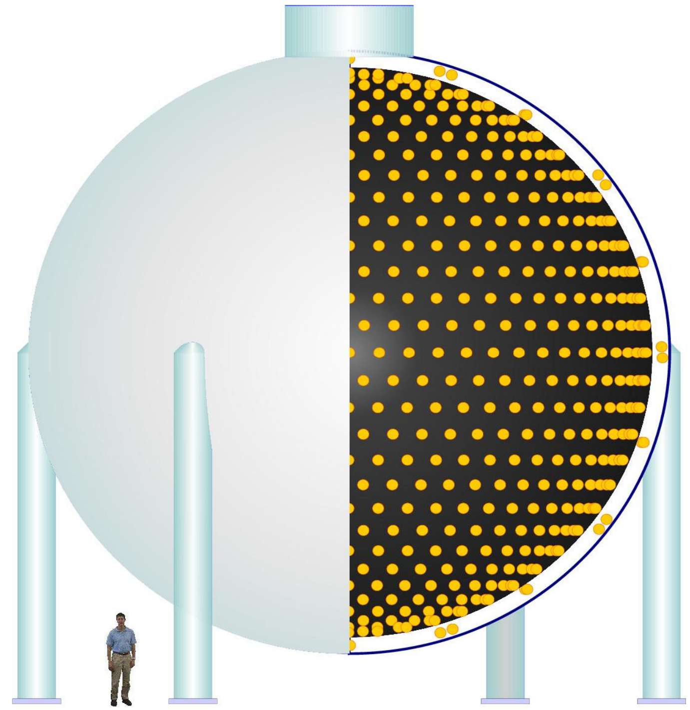
LBNE Collaboration Organisation

- Several workshops/meetings
  - April 24 at Leed South Dakota
  - June 20 at FNAL
  - August 14 at FNAL
  - October 14-15 at BNL
  - February 26-28 at UC Davis
- Temporary Executive Committee formed
- Formed an Institutional Board of “interested groups”
- WC and LAr groups submitted Proposals for the NSF S4 solicitation
- Working Towards DOE CD-0

Summary

- The last decade has been revolutionary in neutrino physics
- The next decade promises an even more rapid development of our understanding
- The masses and mixings are giving us hints of physics well beyond the Standard Model
- Fermilab has a vibrant current, near term, and far term program at the heart of this global effort

Cross-Sections with MiniBooNE



By almost 2 orders of magnitude MiniBooNE has the largest ~1 GeV neutrino data set ever taken.

A range of Cross-Section measurements are planned:-

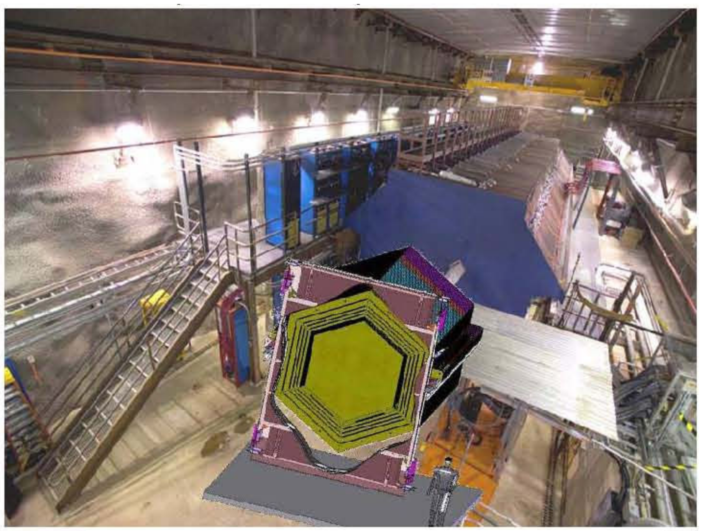
- CC Quasi-elastic (M_A, osc signal channel)
- NC elastic (compare to CC QE)
- CC π^+ (disapp. osc. bkgd, coh. prod.)
- NC π^0 (osc bkgd., coh. prod.)
- CC π^0 (compare to NC channel)

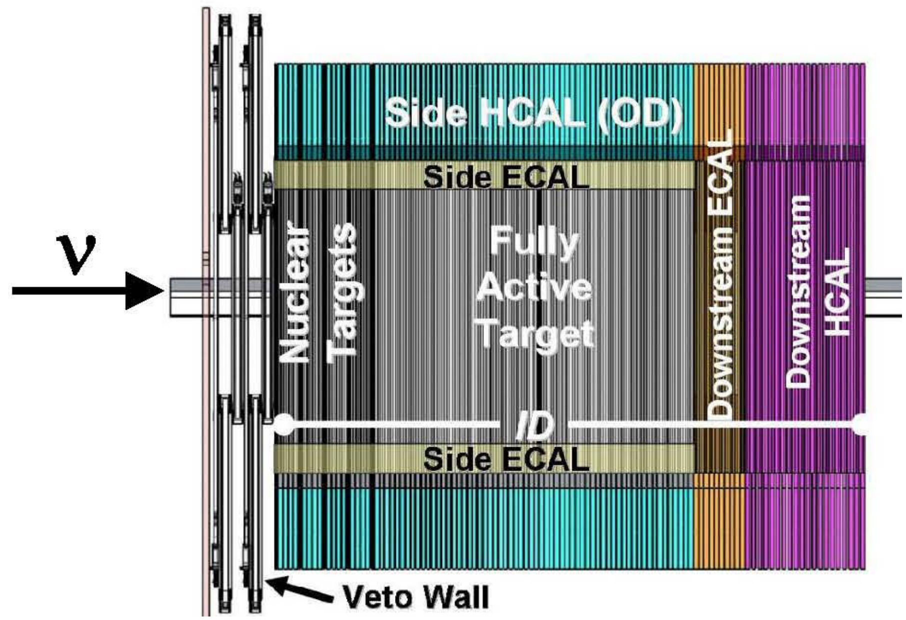
First CCQE paper completed (arXiv:0706.0926 [hep-ex])

Cross-Sections are also being published by the K2K collaboration

Cross-Sections with MINERνA

High granularity detector in NuMI beamline
Large physics program including xsec measurements at a few GeV

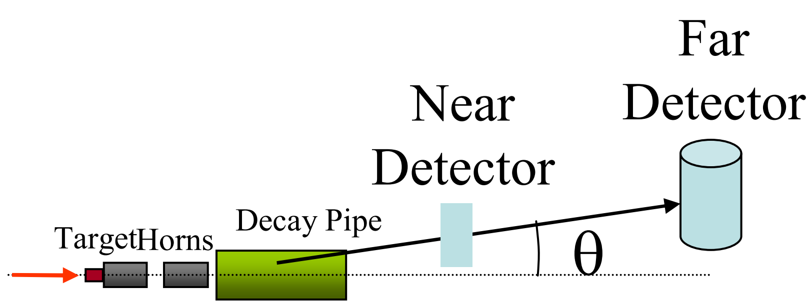


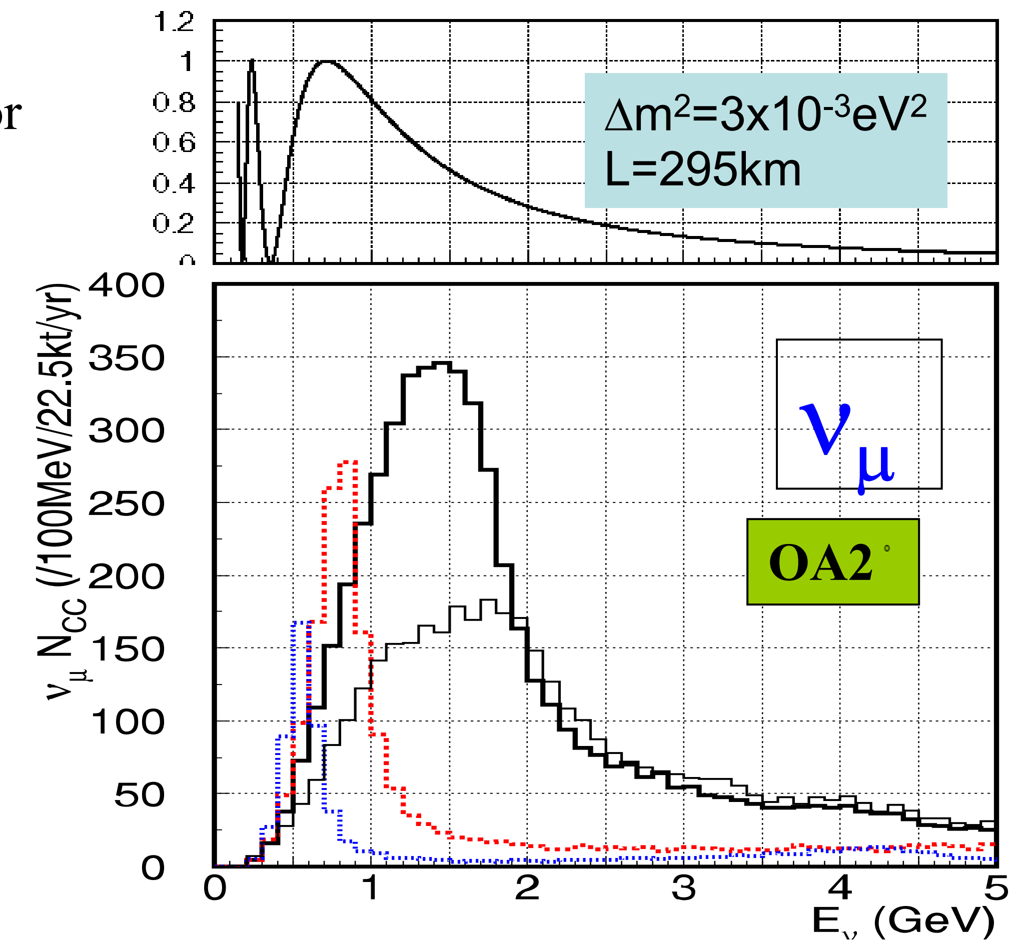


"Chewy center (active target), with a crunchy shell of muon, hadron, and EM absorbers"

The νSNS experiment is planning to measure cross-sections of 10-50 MeV neutrinos produced by stopped pions and muons at SNS. Necessary input to supernova calculations

Off Axis Beams





- Increases flux on osc. max.
- Reduces high-E tail, and thus NC backgrounds
- Reduces ν_e contamination from K and μ decay