The NOνA Experiment and the Future of Neutrino Oscillations

Università di Roma "La Sapienza"
24 January 2006

Gary Feldman

What are Neutrinos?

- **Three of the 12 fundamental building blocks of nature:**

Quarks		Leptons	
d	u	e	ν_e
s	c	μ	ν_μ
b	t	τ	ν_τ

Why are Neutrinos Particularly Interesting?

- **Masses are anomalously low**
  - **From CMB data $m_\nu < 0.2$ eV/$c^2 \cong 0.0000004\ m_e$**
  - **A Window on the the GUT Scale? (seesaw mechanism)**
- **Only fundamental fermion which can be its own antiparticle (Majorana particle)**
- **Could be responsible for the matter/antimatter asymmetry of the universe (leptogenesis)**

Seesaw Mechanism

- **Right-handed neutrinos have no weak interactions and thus are not confined to the weak mass scale. Postulate both a GUT-scale right-handed Marjorana neutrino N_R and both Majorana and Dirac mass terms in the Lagrangian:**

$$\mathcal{L} = \tfrac{1}{2} M_{ij} \overline{N}_{R_i} N_{R_j} + \lambda_{ij} \begin{pmatrix} \nu_L, & e_L \end{pmatrix}_i \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} N_{R_j} + \text{h.c.}$$

Dropping the flavor index, this results in a mass matrix

$$\begin{pmatrix} 0 & m_| \\ m_| & M \end{pmatrix}, \quad \textit{where } m_| = \lambda\langle\phi\rangle,$$

a "normal" fermionic mass.

Seesaw Mechanism

Diagonalizing the mass matrix to obtain the physical masses yields,

$$m_N \approx M \quad \text{and} \quad m_\nu = \frac{m_l^2}{M}.$$

This is the seesaw mechanism.

Leptogenesis

- To explain how our matter-dominated universe arose from a matter-antimatter symmetric big bang, we need (Sakharov conditions)
  - Lepton and baryon number violation
  - CP violation (Standard Model quark CP violation not sufficient)
  - Thermal non-equilibrium
- Majorana neutrinos can provide these conditions.

Leptogenesis

- CP-violating decays of *N*'s in the big bang era provides a source of lepton-number violation.
  - Example: $N \rightarrow h\nu \neq \overline{N} \rightarrow h\overline{\nu}$

- GUT-level (B - L)-conserving interactions convert the lepton-number asymmetry to a baryon asymmetry.

Neutrino Oscillations

- Neutrino oscillations occur because the weak eigenstates and not identical to the mass eigenstates.
- Neutrinos are always produced and detected in weak eigenstates, but they propagate in mass eigenstates.
- To the extent that the masses of the mass eigenstates are different, the phase relations generated by the propagation ($e^{-iEt/\hbar}$) change, producing the oscillation.

Mixing Matrix

- **The relationship between the weak eigenstates and the mass eigenstates is given by a unitary rotation matrix:**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mixing Matrix

- **The mixing matrix can be specified by 3 angles and one complex phase:**

$$|\nu_l\rangle = U|\nu_n\rangle, \quad \text{where} \quad (c_{ij} \equiv \cos\theta_{ij}, \quad s_{ij} \equiv \sin\theta_{ij})$$

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

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

Vacuum Oscillations

- When a 2 x 2 oscillation is sufficient, in vacuum,

$$i\hbar \frac{d}{dt}\begin{pmatrix} \nu_e \\ \nu_x \end{pmatrix} = H \begin{pmatrix} \nu_e \\ \nu_x \end{pmatrix}, \quad H = \begin{pmatrix} \frac{\Delta m^2}{4E}\cos 2\theta & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & -\frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix}$$

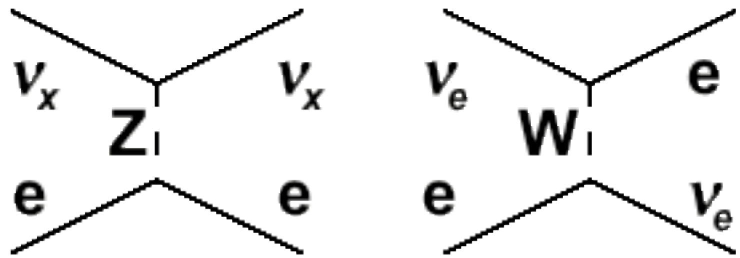
$$P(\nu_e \to \nu_x) = \sin^2 2\theta \sin^2\left(\frac{1.27\,\Delta m^2 L}{E}\right)$$

$$\Delta m_{ij}^2 \equiv (m_i^2 - m_j^2) \text{ is in } (\text{eV}/c^2)^2,$$

L is in km, and E is in GeV

Matter Oscillations

- **Matter effects: In matter ν_e's interact differently than ν_x's.**



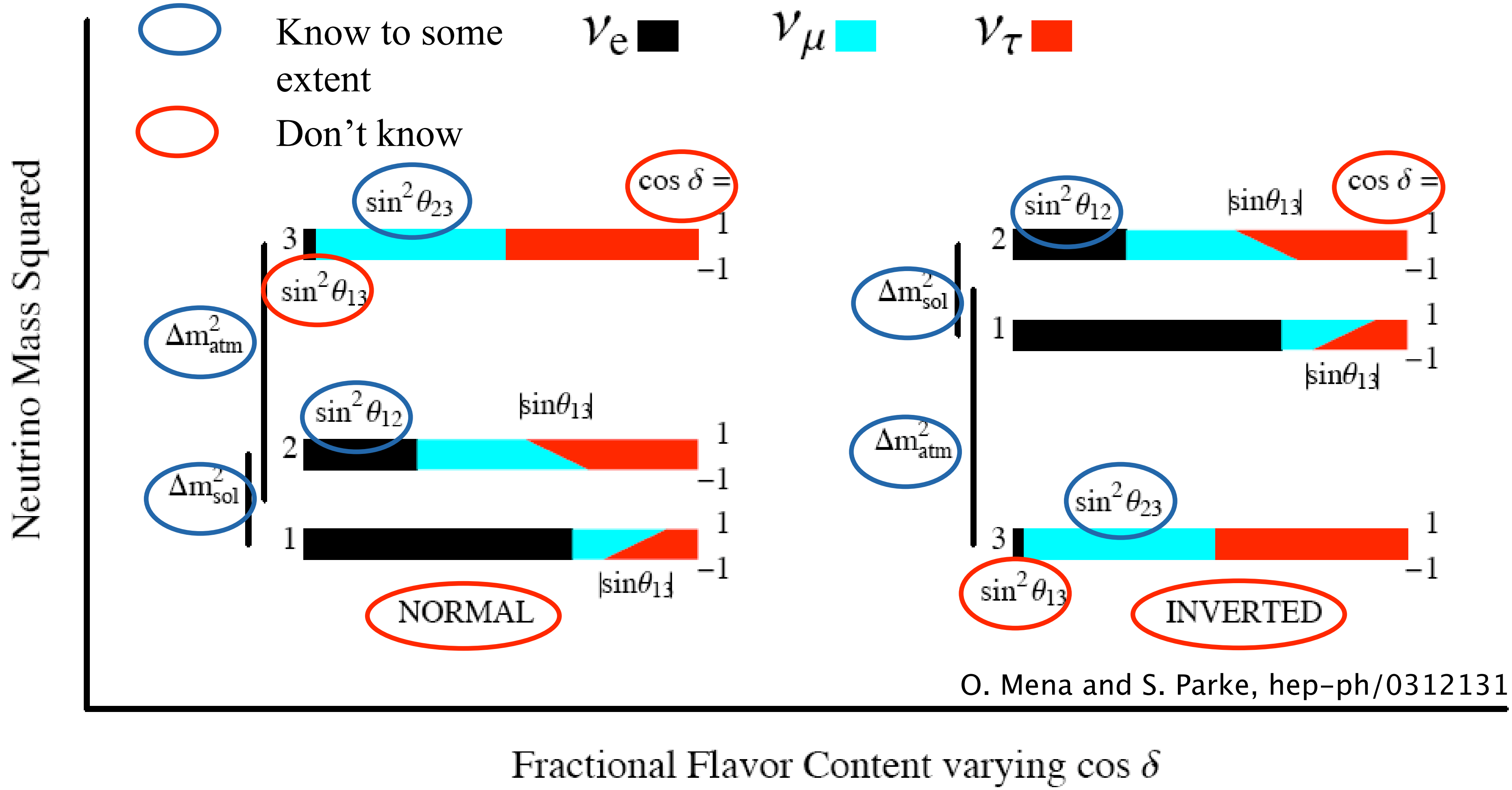
$$H = \begin{pmatrix} \frac{\Delta m^2}{4E}\cos 2\theta - \sqrt{2}G_F\rho_e & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & -\frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix}$$

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{(\cos 2\theta - \sqrt{2}G_F\rho_e E / \Delta m^2)^2 + \sin^2 2\theta}$$

What Have We Learned?

- We have learned a great deal over the past decade.
- From observing neutrinos from the sun and reactors, we have learned that $\nu_e \to \nu_\mu$ and $\nu_e \to \nu_\tau$ with $L/E \approx$ 15 000 km/GeV, with a large but not maximal mixing angle.
- From observing neutrinos produced in the atmosphere by cosmic rays, we have learned that $\nu_\mu \to \nu_\tau$ with $L/E \approx$ 500 km/GeV and θ consistent with being maximal.

What We Know and What We Don't Know



One Anomaly

- A Los Alamos experiment with stopped pions (LSND) has reported evidence for oscillations of $\bar{\nu}_\mu \to \bar{\nu}_e$ with $\Delta m^2 > 0.1\,(\mathrm{eV})^2$.
- Such an oscillation requires a sterile neutrino since three active neutrinos admit only two independent Δm^2s.
- Such a neutrino would be only very marginally consistent with solar and atmospheric data.
- This effect is being checked currently by MiniBooNE, a Fermilab experiment.
- A confirmation would be exciting and require rethinking some of our plans.

1st Generation Long Baseline Experiments

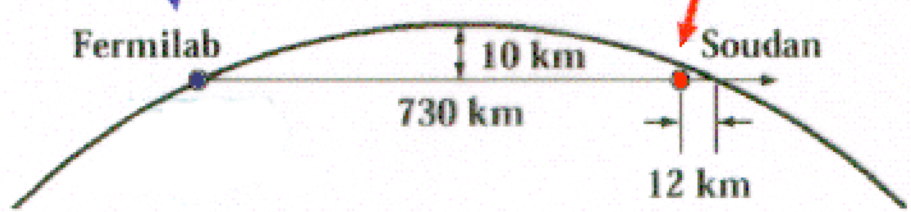
- **We are now starting the first generation of long baseline accelerator experiments**
  - **K2K: Low statistics experiment in Japan now completed.**
  - **CNGS: Gran Sasso program will start this year.**
  - **MINOS: Fermilab experiment started last year. Will report first results in a few months.**
- **First generation goals:**
  - **Verify dominant $\nu_\mu \rightarrow \nu_\tau$ oscillations**
  - **Precise measurement of dominant Δm_{23}^2 and $\sin^2 2\theta_{23}$**
  - **Search for subdominant $\nu_\mu \rightarrow \nu_e (\sin^2 2\theta_{13})$ and $\nu_\mu \rightarrow \nu_s$ oscillations**

MINOS Layout
(Main Injector Neutrino Oscillation Search)

Two detector oscillation experiment using Fermilab 120-GeV Main Injector beam

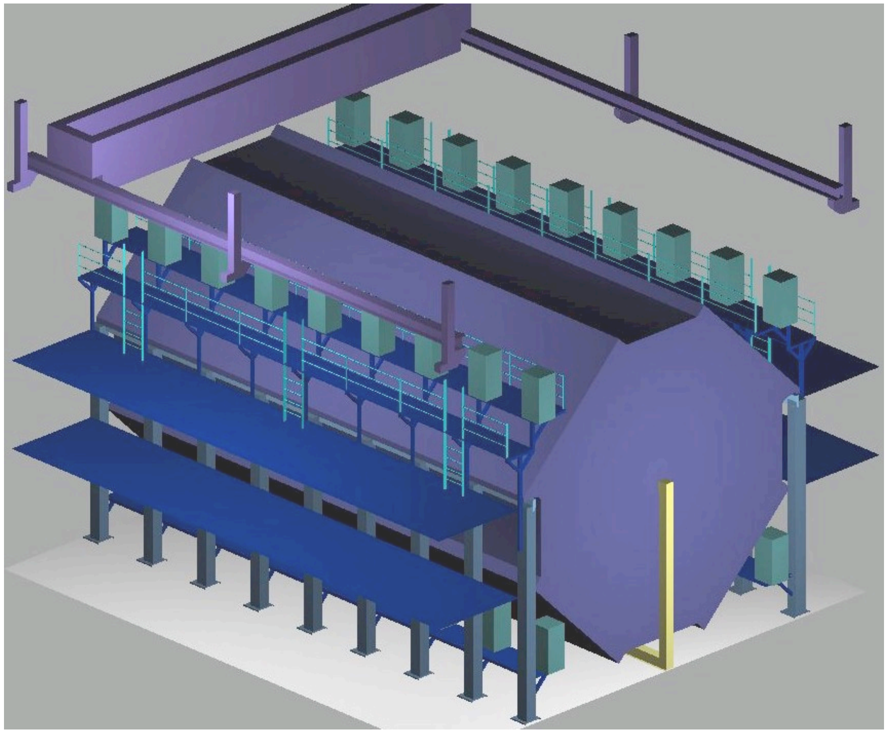
Near detector 980 T at 1 km

Far detector 5400 T at 730 km



MINOS Far Detector

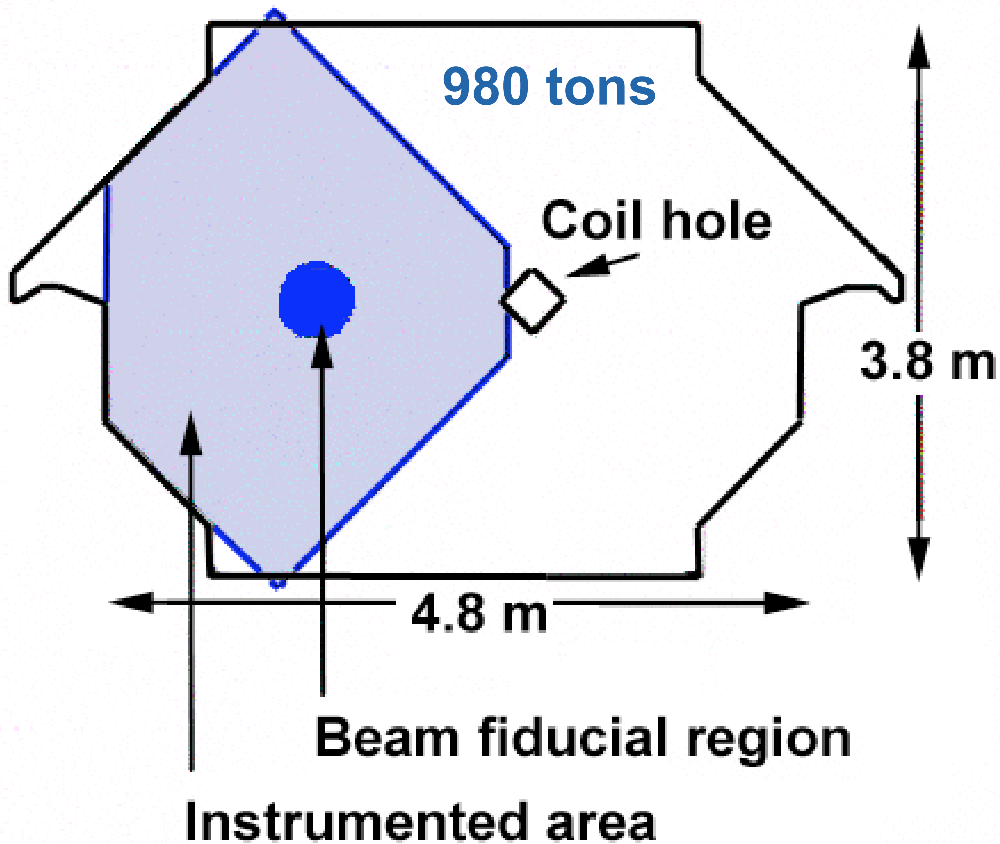
- 8m octagonal tracking calorimeter
- 484 layers of 2.54 cm Fe plates
- 4.1 cm-wide scintillator strips with WLS fiber readout, read out from both ends
- 8 fibers summed on each PMT pixel; 16 pixels/PMT
- 25,800 m^2 of active detector planes
- Toroidal magnetic field <B> = 1.3 T
- Total mass 5.4 kT



MINOS Far Detector

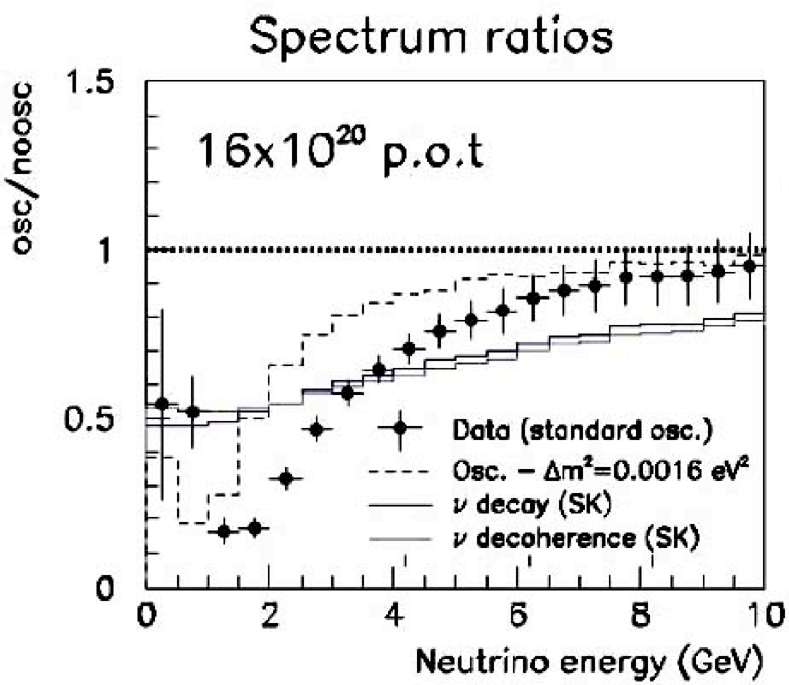
MINOS Near Detector

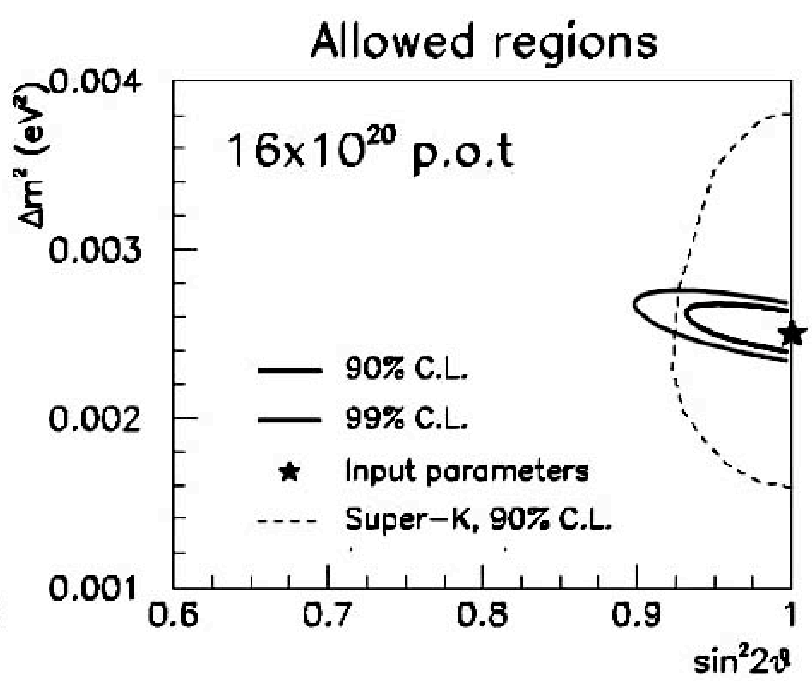
- 280 “squashed octagon” plates
- Same plate thickness, scintillator thickness and width as far detector
- Target/calorimeter section: 120 planes
  - 4/5 partial area instrumented
  - 1/5 full area instrumented
- Muon spectrometer section: 160 planes
  - 4/5 uninstrumented
  - 1/5 full area instrumented



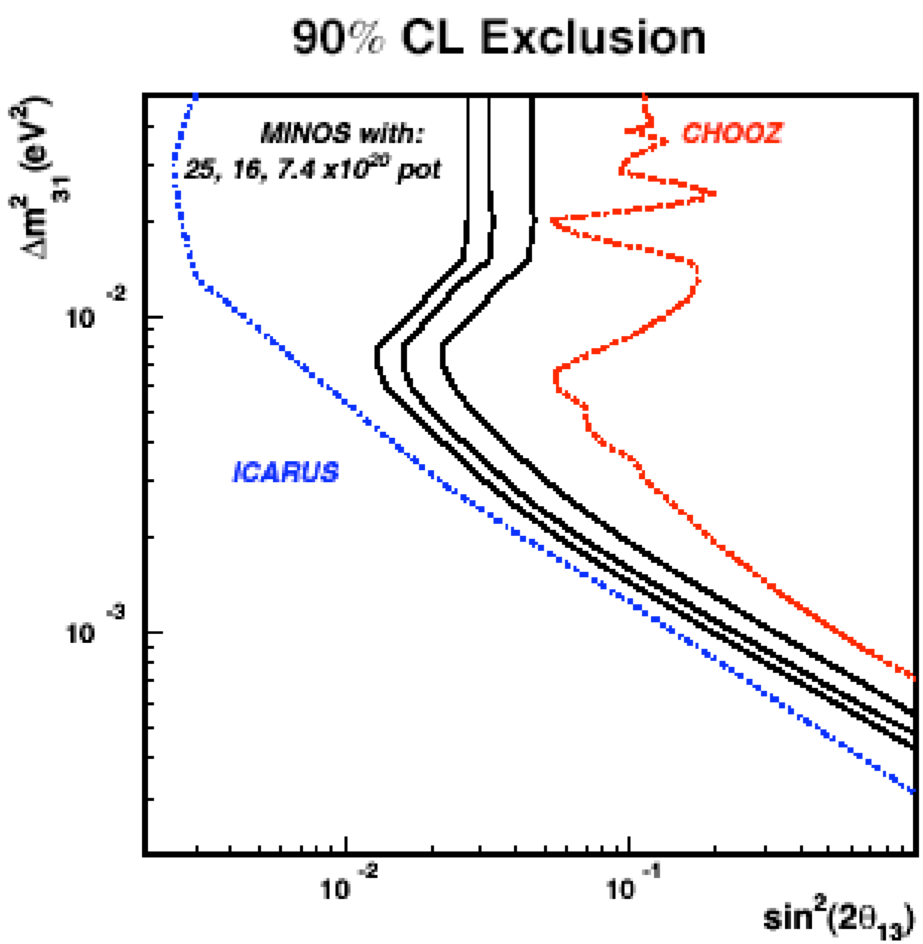
MINOS Near Detector
(Under Construction)

MINOS Sensitivity
5 year run





MINOS Sensitivity to $\nu_\mu \rightarrow \nu_e$ at 90% CL



2nd Generation Experiments

- The 2nd generation experiments will concentrate on $\nu_\mu \rightarrow \nu_e$ oscillations, which are needed for the measurements of
  - $\sin^2(2\theta_{13})$
  - $\text{sign}(\Delta m_{32}^2)$
  - δ
- T2K: 295 km baseline, Tokai to SuperKamiokande
- NOνA: 810 km baseline, Fermilab to Ash River, MN

The T2K Experiment (Tokai to Kamiokande)

Phase 1
- 0.77 MW into
- 50 kT SuperK
- (full intensity in 2012)

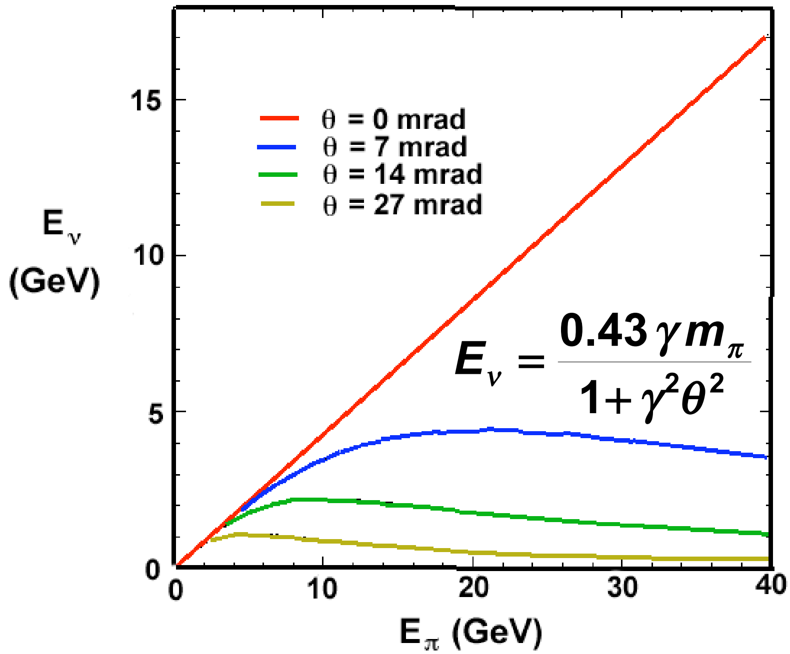
Phase 2
- 4 MW into
- 1 MT HyperK

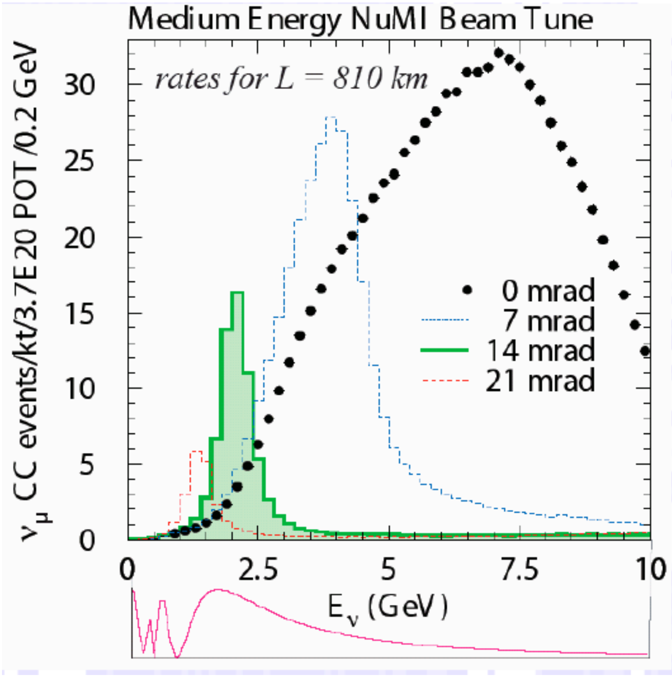
The NOνA Experiment
(NuMI Off-Axis ν_e Appearance Experiment)

- NOνA is an approved Fermilab experiment optimized for measuring ν_e appearance with the goal of improving MINOS's $\nu_\mu \to \nu_e$ measurement by approximately an order of magnitude.
- The NOνA far detector will be
  - a 30 kT "totally active" liquid scintillator detector
  - located 15 mrad (12 km) off the NuMI beamline axis near Ash River, MN, 810 km from Fermilab
- The uniqueness of NOνA is the long baseline, which is necessary for determining the mass ordering of the neutrino states.

Off-Axis Rationale

- Both Phase 2 experiments, NOνA and T2K are sited off the neutrino beam axis. This yields a narrow band beam:
  - More flux and less background (ν_e's from *K* decay and higher-energy NC events)



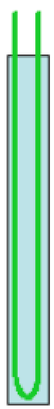


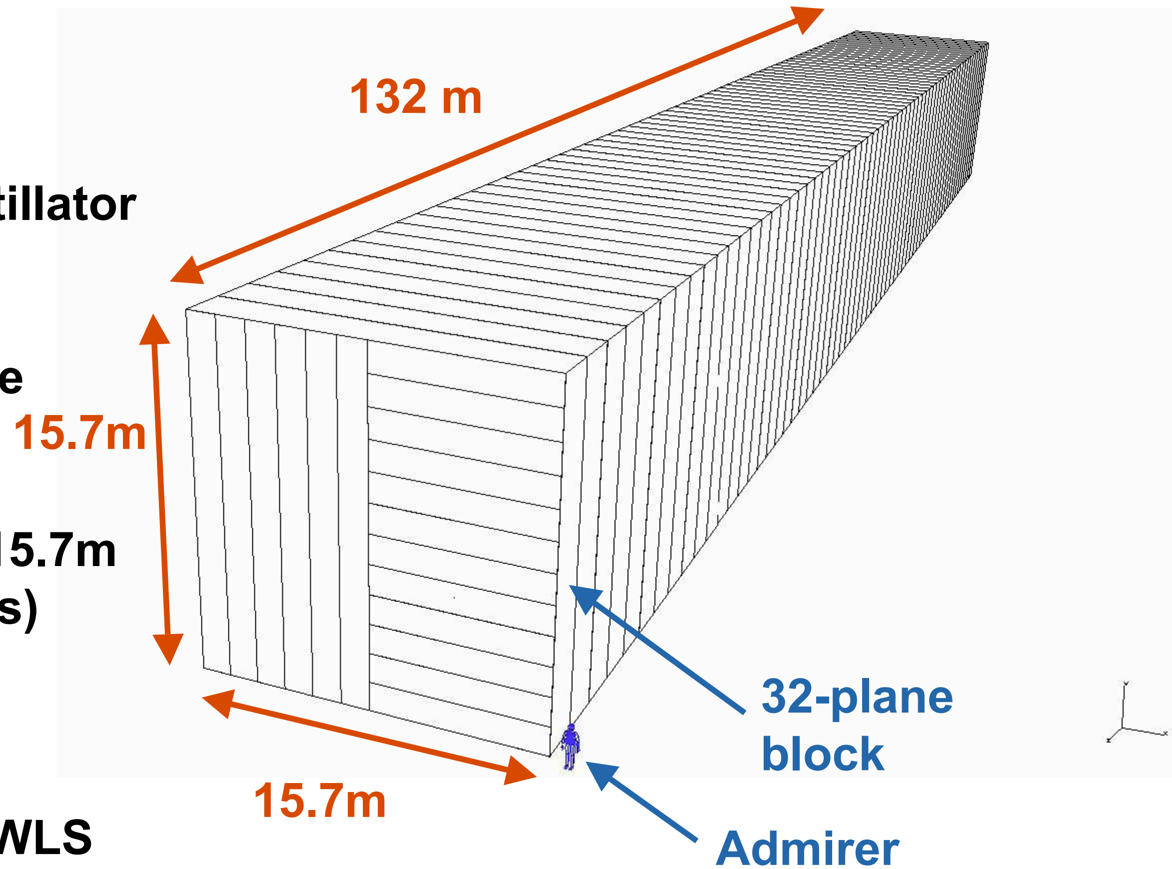
NOνA Site


Beam
Ash River
Soudan
International Falls
Fort Frances
Voyageurs Natl. Park
Kabetogama
Ontario
Minnesota
Crane Lake
Orr
Tower
Virginia
Eveleth
Chisholm
Hibbing
Atikokan
©2003 MapQuest.com, Inc.

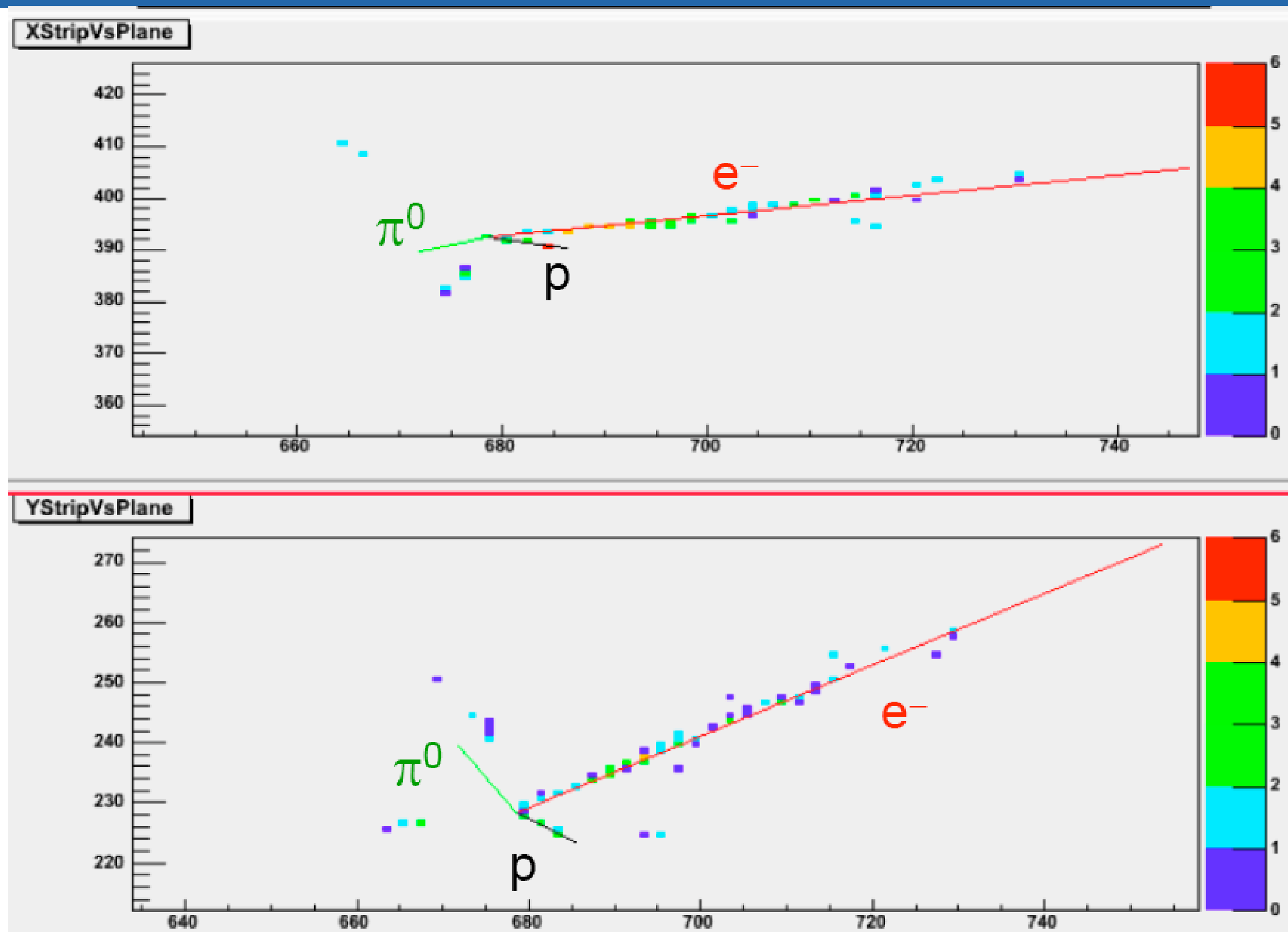
NOνA Far Detector

“Totally Active”
30 kT:
  24 kT liquid scintillator
  6 kT PVC
32 cells/extrusion
12 extrusions/plane
1984 planes
Cell dimensions:
  3.9 cm x 6 cm x 15.7m
  (0.15 X_0 thickness)
Extrusion walls:
  3 mm outer
  2 mm inner
U-shaped 0.8 mm WLS fiber into APD

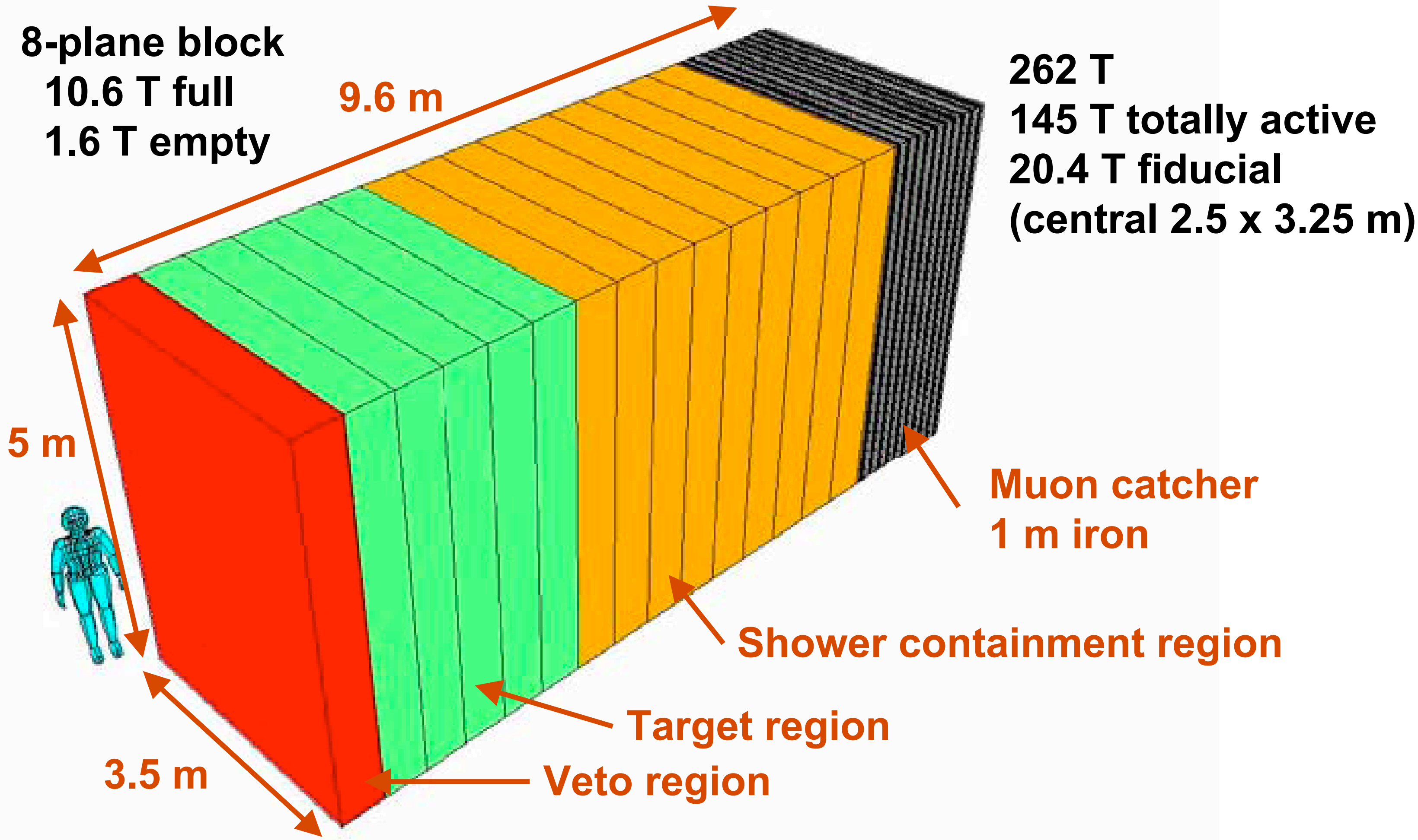




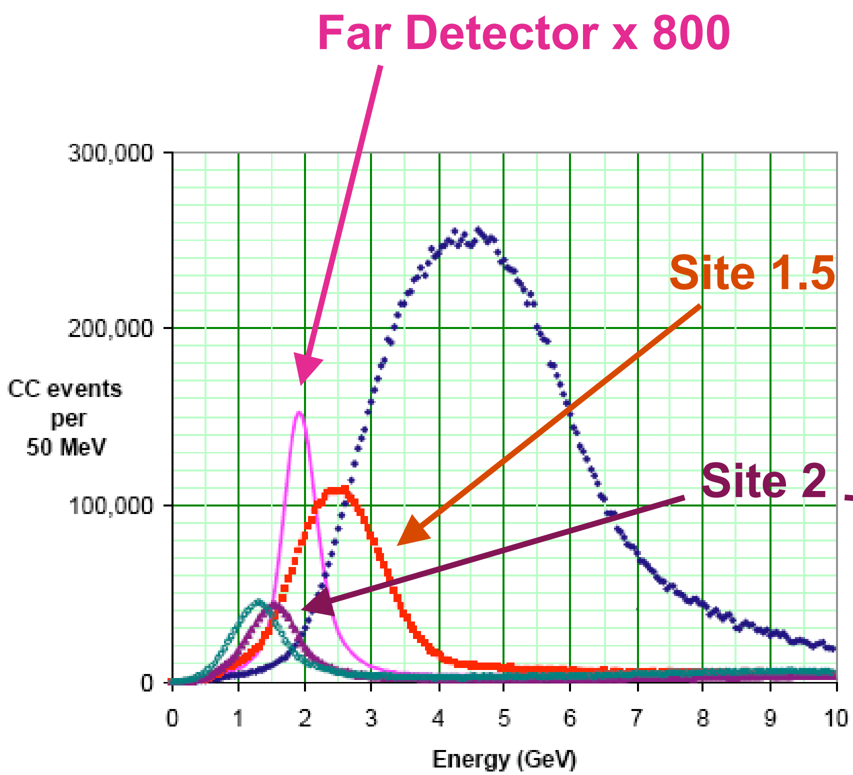
1.65 GeV $\nu_e N \rightarrow e p \pi^0$



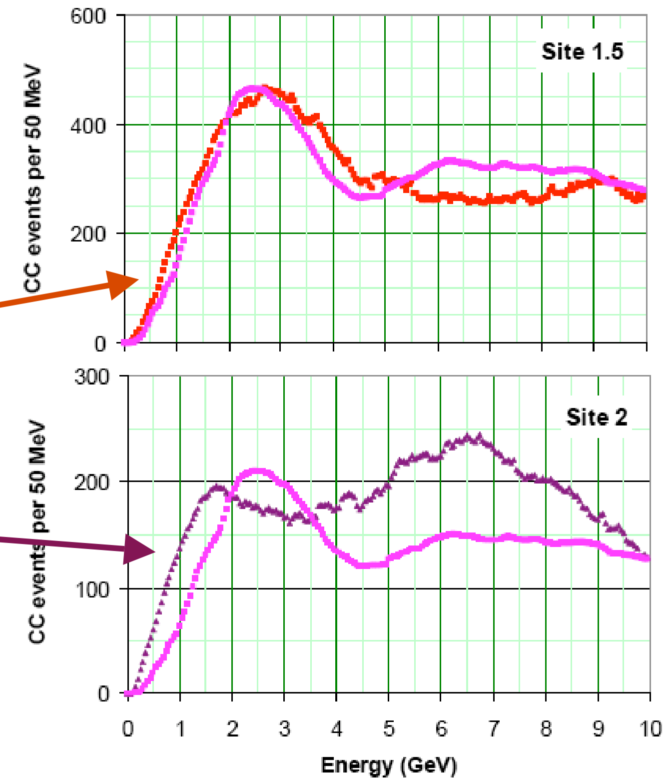
NOνA Near Detector



Near Detector in the Access Tunnel



ν_μ CC events



ν_e CC events

Proton Intensity (1)

- NOνA will run after the Tevatron terminates operation. Thus, parts of the accelerator complex now devoted to antiproton production and storage will be available for the neutrino program.
- Presently, we must load Booster batches at 15/sec into the Main Injector and then ramp the Main Injector.
- Idea for increased proton intensity is to get Booster batches while the Main Injector is ramping.

Proton Intensity (2)

- Assumption of our proposal: Slip-stack 11 Booster batches into the Recycler and inject them into the Main Injector. This gives 0.7 MW, of which we assumed 0.625 MW for the NOνA program. Graphs (without Proton Driver) will be based on this.
- New idea: (Dave McGinnis) Momentum stack 4 Booster batches into the Accumulator, and then boxcar stack 6 Accumulator batches into the Recycler (24 Booster batches in all). Somewhat reduced Booster intensity gives 1.1 MW.
- Could be ready in FY 2011 at a cost of about $15M.

Proton Intensity (3)

- Fermilab strategy:
  - If ILC looks affordable, move to host the ILC and do "cheap" upgrades to the proton intensity.
  - If ILC will be delayed, move toward a Proton Driver (i.e., a new Booster).
- We assume that the Proton Driver will allow 2.4 MW.
- If no Proton Driver, then upgrade to 1.1 MW, add mass (perhaps liquid argon detector), and run longer to achieve the equivalent of the Proton Driver intensity.

Improvement over MINOS

- How does NOνA get an order of magnitude improvement over MINOS for $\nu_\mu \rightarrow \nu_e$ oscillations?
  - Off-axis advantages (more flux, less background)
  - 5.5 times the mass
  - Twice the beam intensity initially, more later
  - Greater sensitivity to ν_e events: 0.15 X0 longitudinal segmentation compared to 1.5 X0 in MINOS

$P(\nu_\mu \rightarrow \nu_e)$ (in Vacuum)

- $P(\nu_\mu \rightarrow \nu_e) = P_1 + P_2 + P_3 + P_4$
  - $P_1 = \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(1.27\ \Delta m_{13}^2\ L/E)$ "Atmospheric"
  - $P_2 = \cos^2(\theta_{23}) \sin^2(2\theta_{12}) \sin^2(1.27\ \Delta m_{12}^2\ L/E)$ "Solar"
  - $P_3 = \mp J \sin(\delta) \sin(1.27\ \Delta m_{13}^2\ L/E)$
  - $P_4 = J \cos(\delta) \cos(1.27\ \Delta m_{13}^2\ L/E)$

  } Atmospheric-solar interference

  where $J = \cos(\theta_{13}) \sin(2\theta_{12}) \sin(2\theta_{13}) \sin(2\theta_{23})$ x

  $\sin(1.27\ \Delta m_{13}^2\ L/E) \sin(1.27\ \Delta m_{12}^2\ L/E)$

$P(\nu_\mu \rightarrow \nu_e)$ (in Matter)

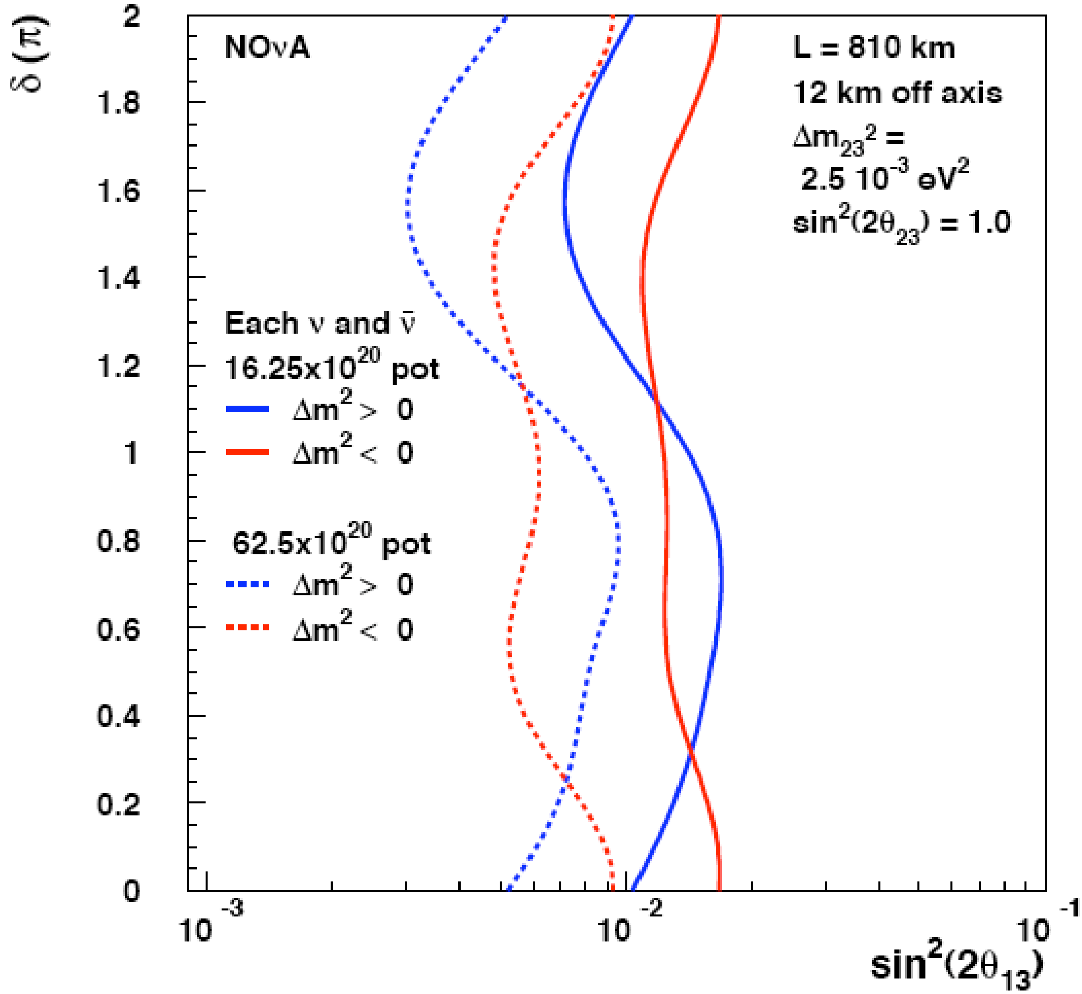
- In matter at oscillation maximum, P_1 will be approximately multiplied by $(1 \pm 2E/E_R)$ and P_3 and P_4 will be approximately multiplied by $(1 \pm E/E_R)$, where the top sign is for neutrinos with normal mass hierarchy and antineutrinos with inverted mass hierarchy.

$$E_R = \frac{\Delta m^2_{13}}{2\sqrt{2}G_F\rho_e} \approx 11\,\text{GeV for the earth's crust.}$$

About a ±30% effect for NuMI, but only a ±11% effect for T2K.

However, the effect is reduced for energies above the oscillation maximum and increased for energies below.

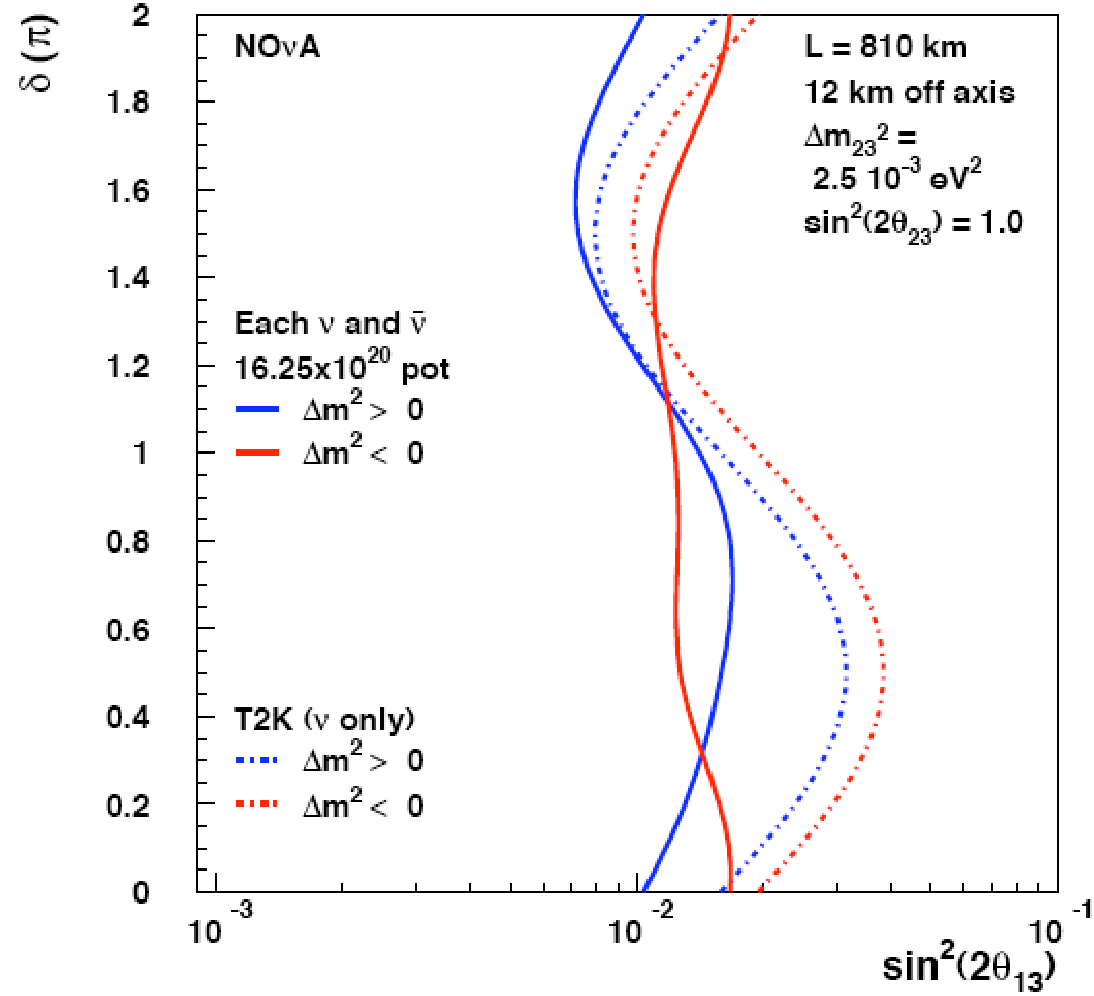
3 σ Sensitivity to $\theta_{13} \neq 0$
Comparison with Proton Driver



2.5 yr each

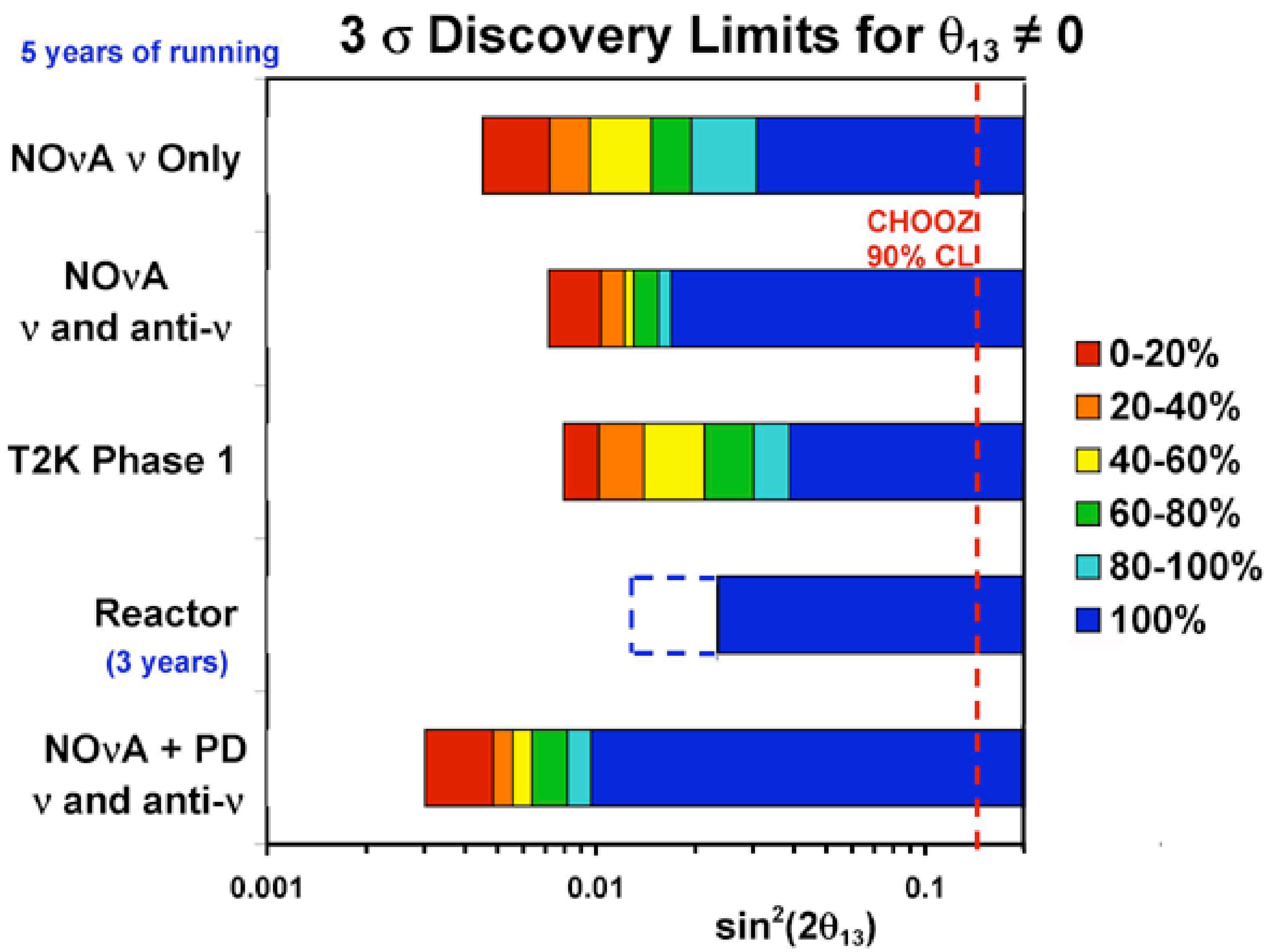
ν and $\bar{\nu}$ run

3 σ Sensitivity to $\theta_{13} \neq 0$



2.5 yr each ν and $\bar{\nu}$ run

3 σ Sensitivity to $\theta_{13} \neq 0$



Importance of the Mass Ordering

- Window on very high energy scales: grand unified theories favor the normal mass ordering, but other approaches favor the inverted ordering.
- If we establish the inverted ordering, then the next generation of neutrinoless double beta decay experiment can decide whether the neutrino is its own antiparticle. However, if the normal ordering is established, a negative result from these experiments will be inconclusive.

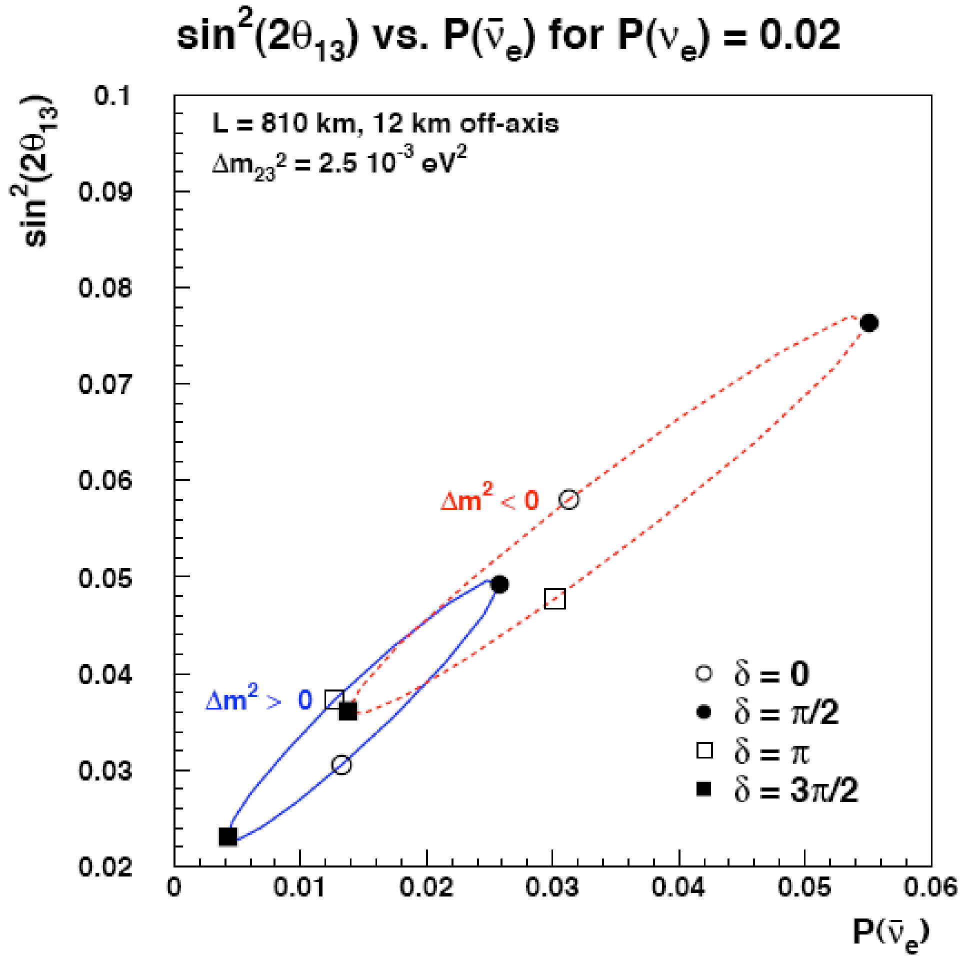
Importance of the Mass Ordering

- **To measure CP violation, we need to resolve the mass ordering, since it contributes an apparent CP violation that we must correct for.**
  - **CP violation in neutrinos may be connected to the mystery of why the universe is composed of matter.**

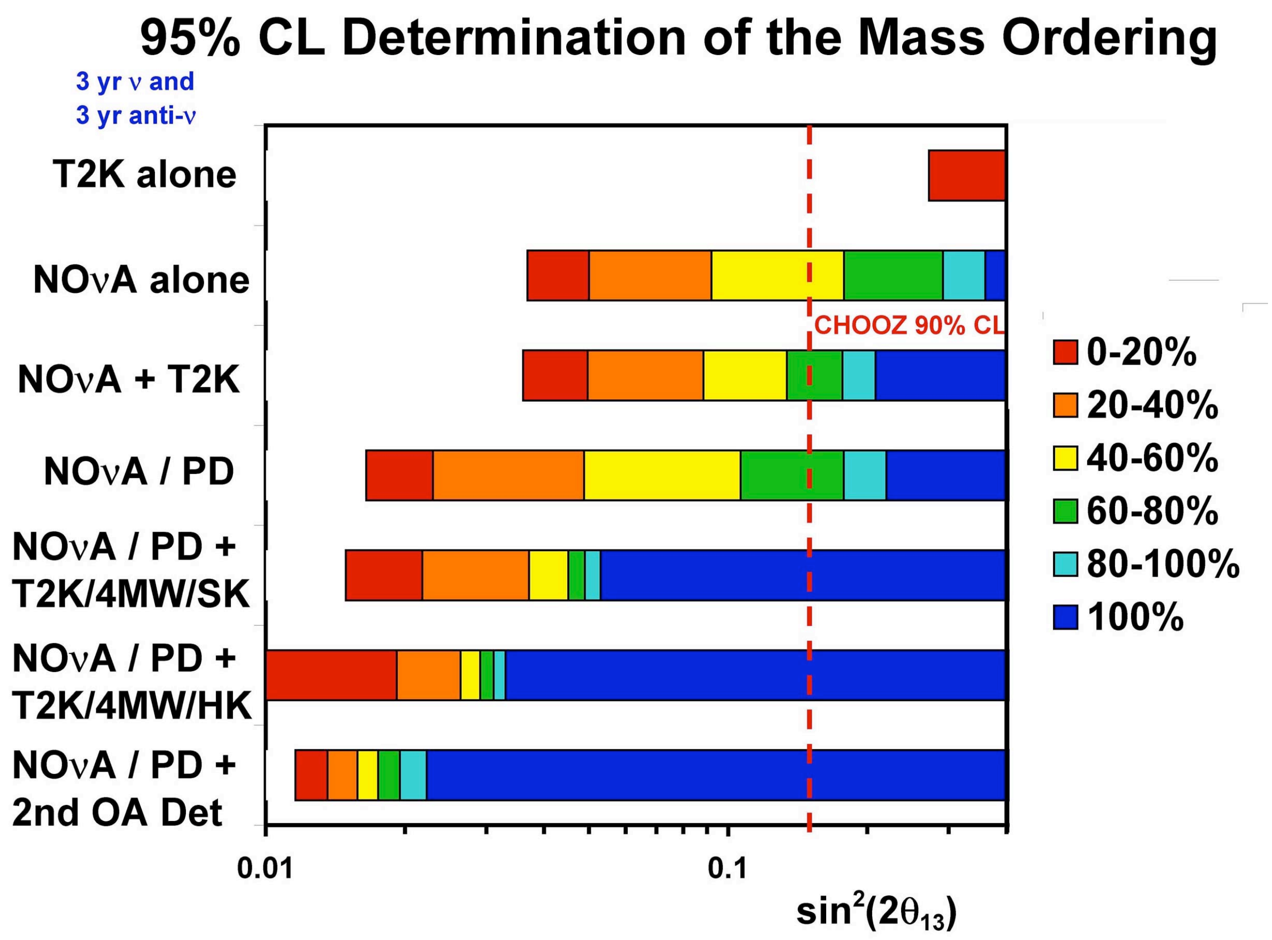
Matter Effect

- The mass ordering can only be determined by observing the matter effect, which is caused by a quantum mechanically coherent interaction of ν_es interacting with the electrons in matter.
- For a given oscillation phase (the oscillation maximum, for example), the effect is proportional to the distance the neutrino has traveled times the electron density of the matter.
- Therefore, it can only be observed by long baseline experiments.

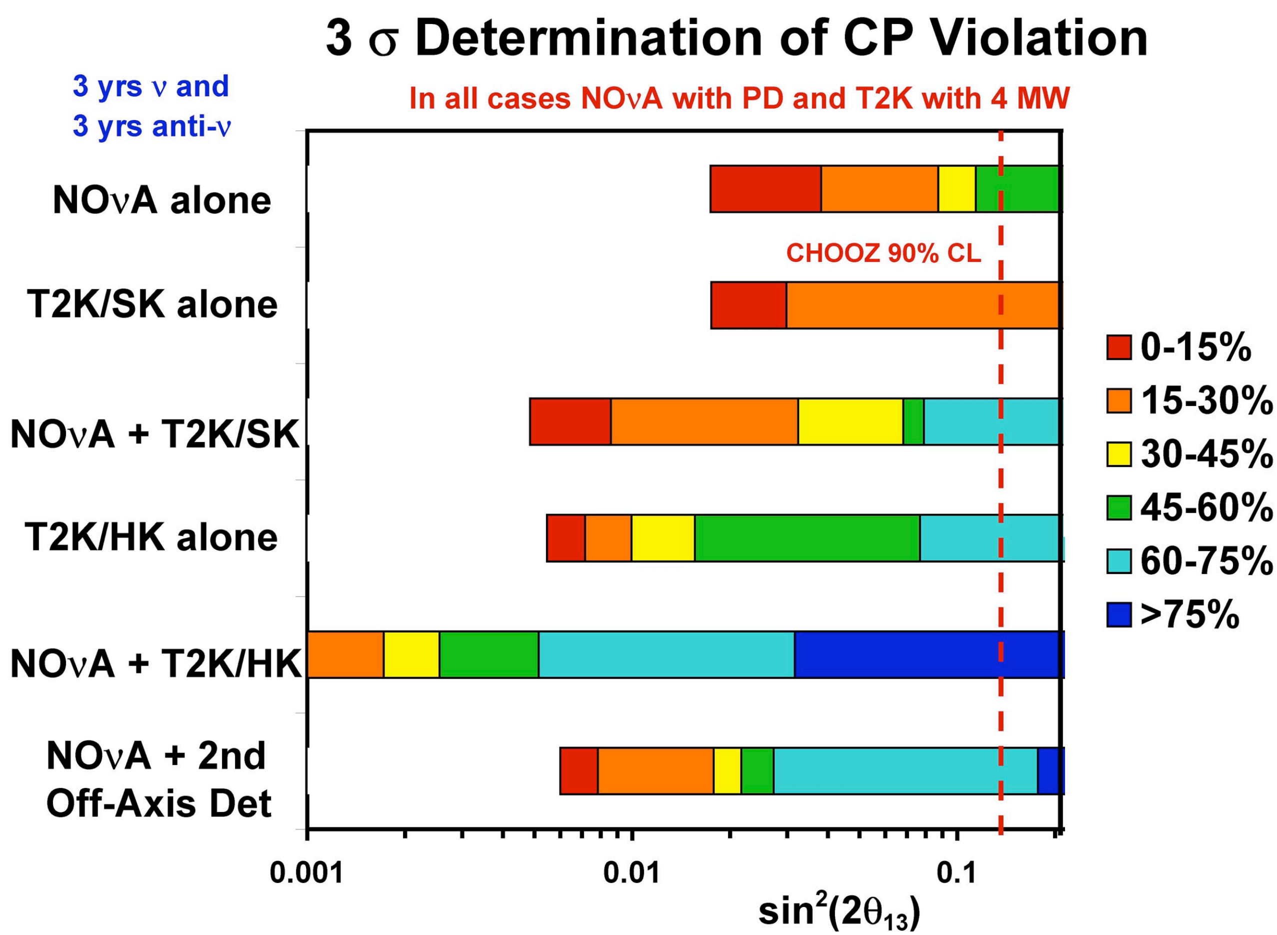
Ambiguity between Mass Ordering and CP Phase



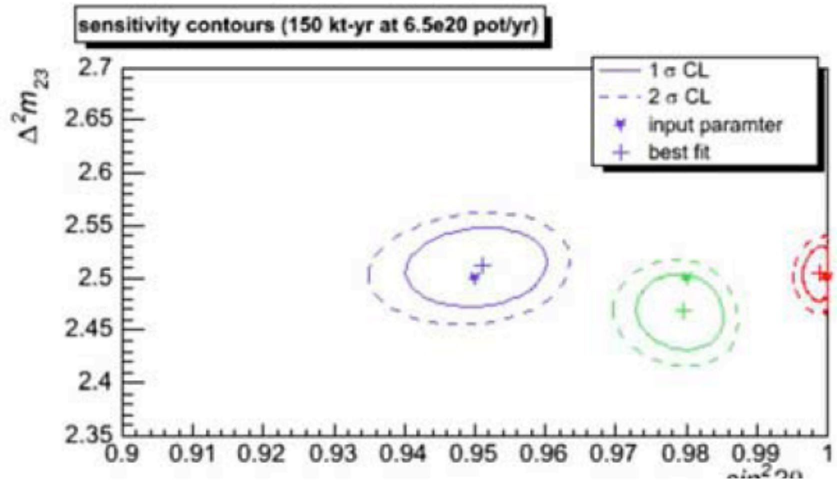
95% CL Resolution of the Mass Ordering: Summary



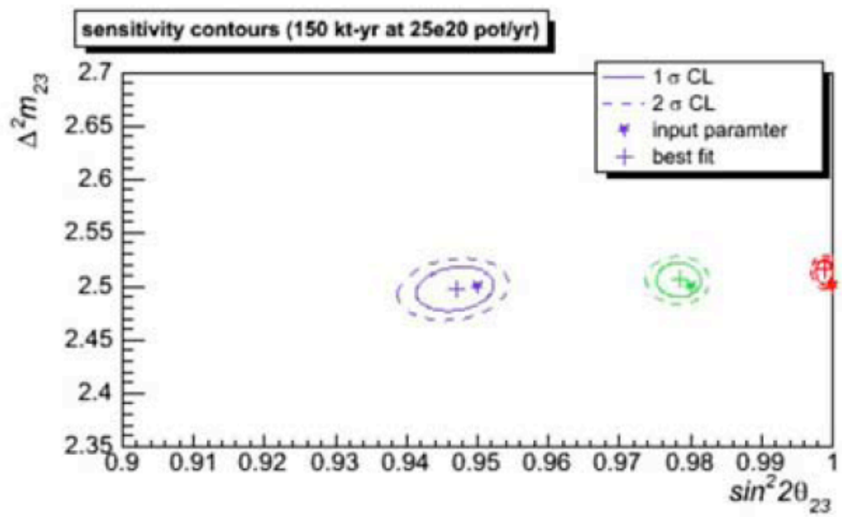
3 σ Determination of CP Violation



Measurement of Δm_{32}^2 and $\sin^2(2\theta_{23})$



5-year ν run



5-year ν run
with Proton Driver

Schedule

- Aiming for a FY2008 project start.
- Can get FY2007 Preliminary Engineering Design and Long Lead Item funding ($12M?)
- Now completing the Conceptual Design Report for review in February.
- Technical Design Report due for review in July.
- Start of data taking October 2010
- Completion of the Far Detector July 2011

Conclusions

- The Fermilab/NuMI/NOνA program provides a flexible, step-by-step approach to studying all of the parameters of neutrino oscillations
  - A long baseline approach is crucial in the context of the world program.
  - NOνA is the first stage of a flexible program where each stage can be planned according to what has been learned in previous stages.
  - The NOνA physics reach is comparable to or greater than other experiments being contemplated for the next few years.
  - Even without a Proton Driver, the NOνA/NOνA II program should be able to attain equivalent sensitivity.