Accelerator-Based Neutrino Programs

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What are Neutrinos?

- Three of the 12 fundamental building blocks (fermions) 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/$c^2 \cong m_e$/2,500,000**
  - **This ratio is 7 times the difference between the electron and the top quark**
  - **A window on the the scale of grand unification? (seesaw mechanism)**

  $\Rightarrow$ **Understanding mass ordering of neutrinos will be a key priority**

Why are Neutrinos Particularly Interesting?

- Neutrinos are the only fundamental building blocks which can be their own antiparticles (Majorana particles)
  - Can only be decided from measurements of neutrinoless double β decay
  - However, understanding the mass ordering is crucial to the interpretation of these experiments

Why are Neutrinos Particularly Interesting?

- Neutrinos could be responsible for the matter/antimatter asymmetry of the universe (leptogenesis)
  - Requires CP violation in the lepton sector

  $\Rightarrow$ Understanding whether neutrinos exhibit CP violation will be a key priority (although not the same CP violation as required for leptogenesis)

This Is Not Quite Correct!

- Three of the 12 fundamental building blocks (fermions) of nature:

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

This Is Better

- Three of the 12 fundamental building blocks (fermions) of nature:

Quarks		Leptons	
d	*u*	e	ν_1
s	*c*	μ	ν_2
b	*t*	τ	ν_3

$\nu_e = a_{e1}\nu_1 + a_{e2}\nu_2 + a_{e3}\nu_3$, where

$a_{e3} = \sin(\theta_{13})e^{-i\delta}$

Neutrino Oscillations

- Neutrinos are always produced and detected in flavor states (ν_e, ν_μ, ν_τ).
- If the flavor states are not identical to the mass states, and if the mass states have different masses, then quantum mechanics requires that flavor states will morph into one another to at least some extent over time (=distance).
  - This is a macroscopic quantum mechanical effect, which can extend over the size of the earth.

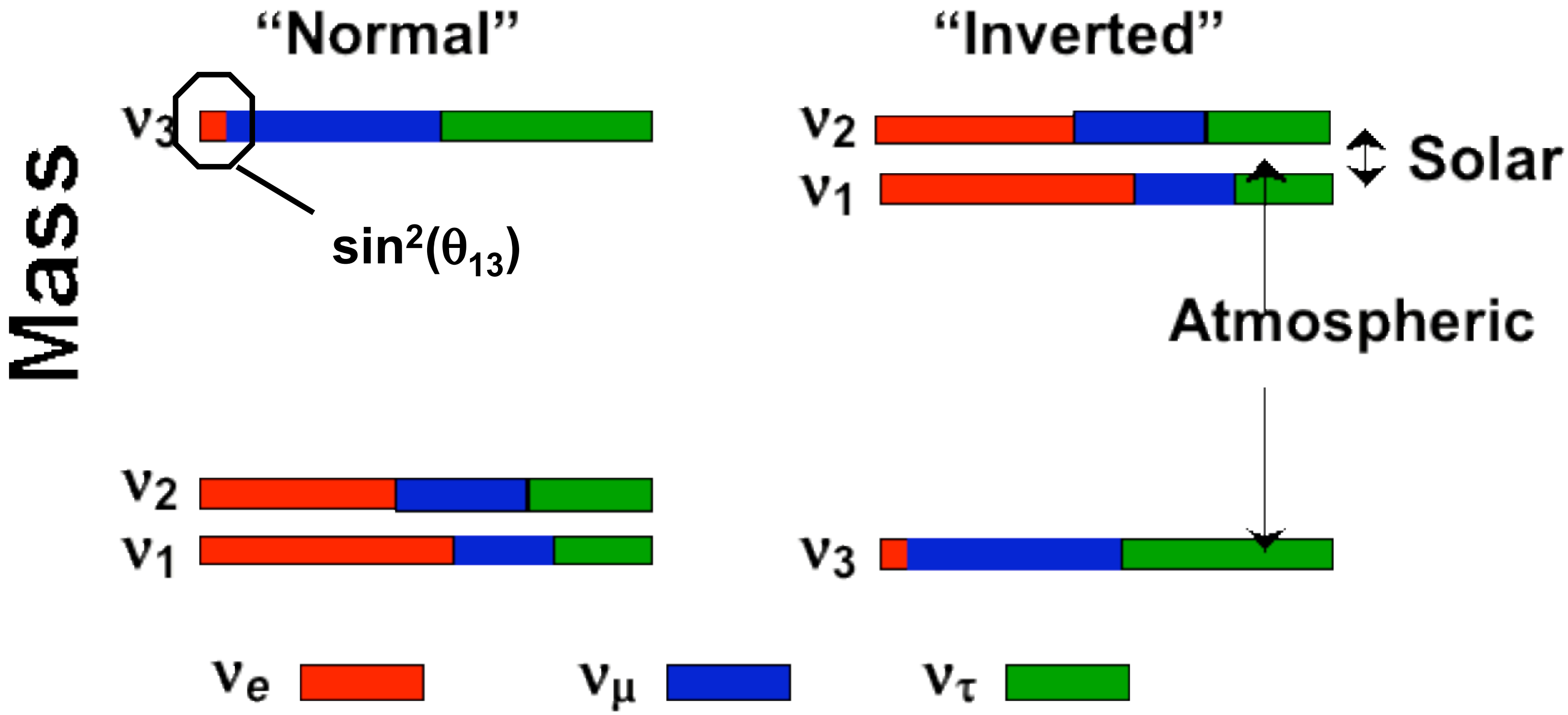
Neutrino Oscillations

- Oscillation distance (L_O) ≡ distance of maximal oscillation $\propto E_\nu / (m_i^2 - m_j^2)$
- Experiments have found two L_O's (for E_ν = 1 GeV):
  - Solar: ν_e's from the sun oscillate into ν_μ's and ν_τ's with L_O = 15,000 km.
  - Atmospheric: ν_μ's produced in cosmic ray interactions with the earth's atmosphere oscillate into ν_τ's with L_O = 500 km.

Sterile Neutrinos?

- An unconfirmed Los Alamos experiment reported evidence for $\bar{\nu}_\mu$ to $\bar{\nu}_e$ oscillations with $L_O \sim 1$ km.
- This L_O is inconsistent with the other mass scales if there are only three neutrinos, but we know there are only three "active" neutrinos. Thus, this would imply the existence of a "sterile" neutrino.
- Being studied by the Fermilab MiniBooNE experiment in ν_μ to ν_e oscillations, and results will be reported by the end of the year.
- If confirmed, this would be something completely new and would call for additional short and long baseline experiments and a rethinking of present plans.

What Do We Know?



Goals of the Future Program

- The atmospheric L_O is the appropriate one for accelerator experiments, and fortunately it is the one we need to answer the key questions.
- We will want to improve the measurements we have, do subsidiary experiments to measure needed ν cross sections (MINERνA), and search for the unexpected.
- I will concentrate on the measurement of the basic three unknown parameters: θ_{13} ($\nu_\mu \rightarrow \nu_e$), the mass ordering, and δ (CP violation). For long baseline experiments, all three of these parameters lead to the same order effects.

Mass Ordering

- The mass ordering can only be determined by ν_e's traversing the earth. (ν_e's have a coherent interaction with the earth's electrons that is different from that of ν_μ's and ν_τ's.)
- There is an enhancement for neutrinos with the normal mass ordering and antineutrinos with the inverted mass ordering, and a suppression for the other cases. (Faux CP violation)
- At the oscillation maximum, the effect is linear with distance and is ± 30% for Fermilab's NuMI beamline.

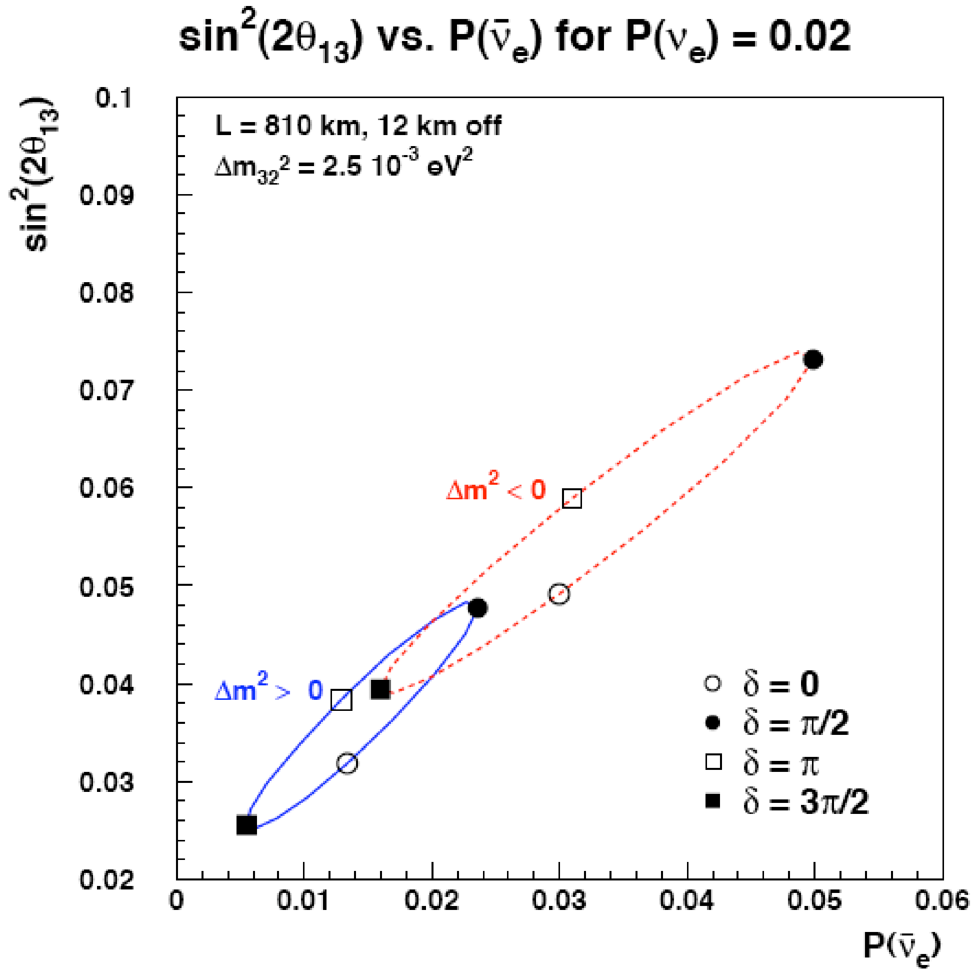
Importance of the Mass Ordering

- 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.
- To measure CP violation, we need to resolve the mass ordering, since it contributes an apparent CP violation that we must correct for.

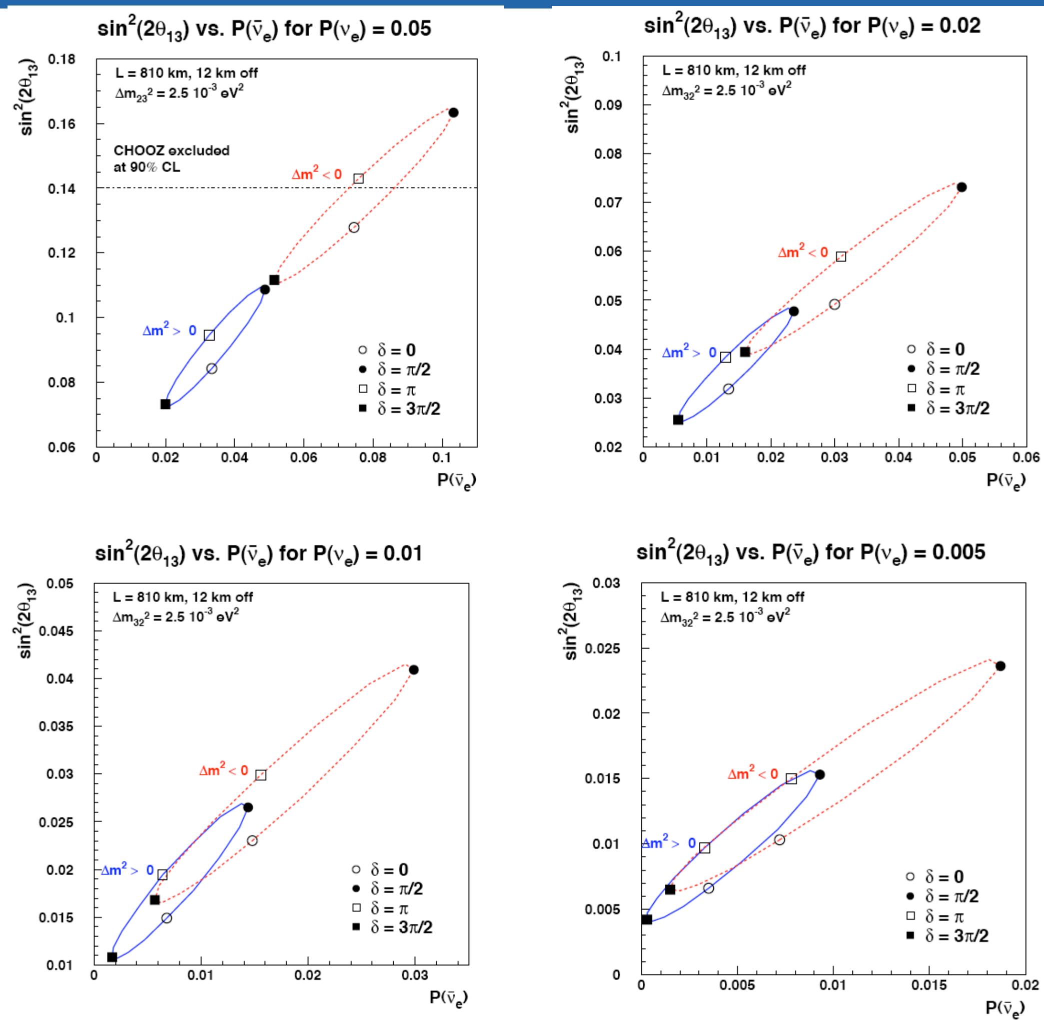
CP Violation

- Occurs as a quantum mechanical interference effect between the solar and atmospheric oscillations.
- Proportional to θ_{13} while the atmospheric oscillation is proportional to θ_{13}^2.

Parameters Consistent with a 2% $\nu_\mu \rightarrow \nu_e$ Oscillation



Parameters Consistent with Other Oscillation Probabilities

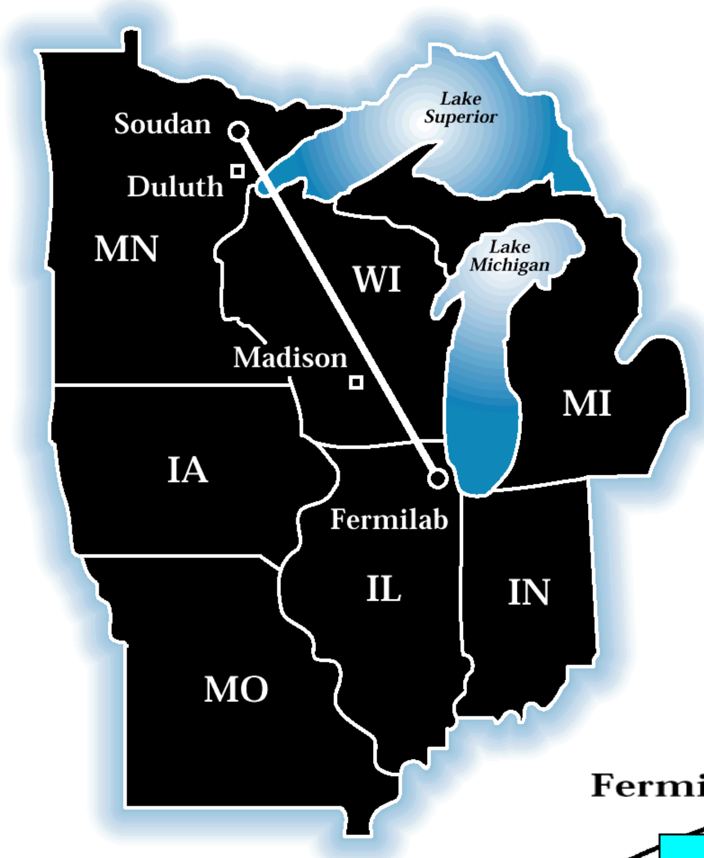


Accelerator Experiments

Phase	US	Japan	Europe
1 Now	MiniBooNE MINOS (735 km)	K2K (low statistics, completed) (250 km)	CNGS (τ appearance) (730 km)
2 Next 5 yrs	NOνA (810 km)	T2K (295 km)	
3 After that	NOνA w/PD 2nd OA NuMI Detector Very long baseline	T2K w/4MW HyperK	SPL β Beam (130 km)
		ν Factory	

MINOS Layout

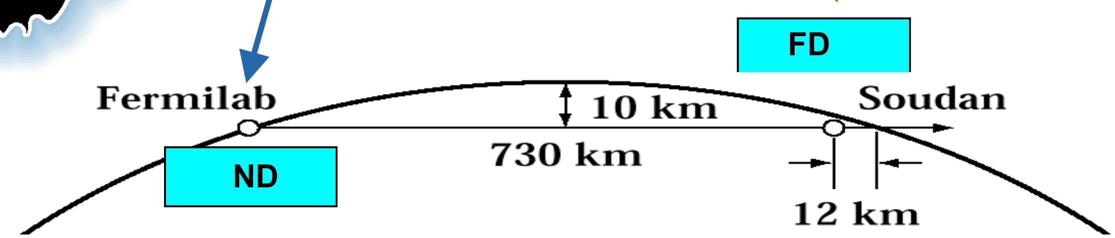
(Main Injector Neutrino Oscillation Search)



Far Detector

5400 T

Near Detector
980 T



MINOS Far Detector

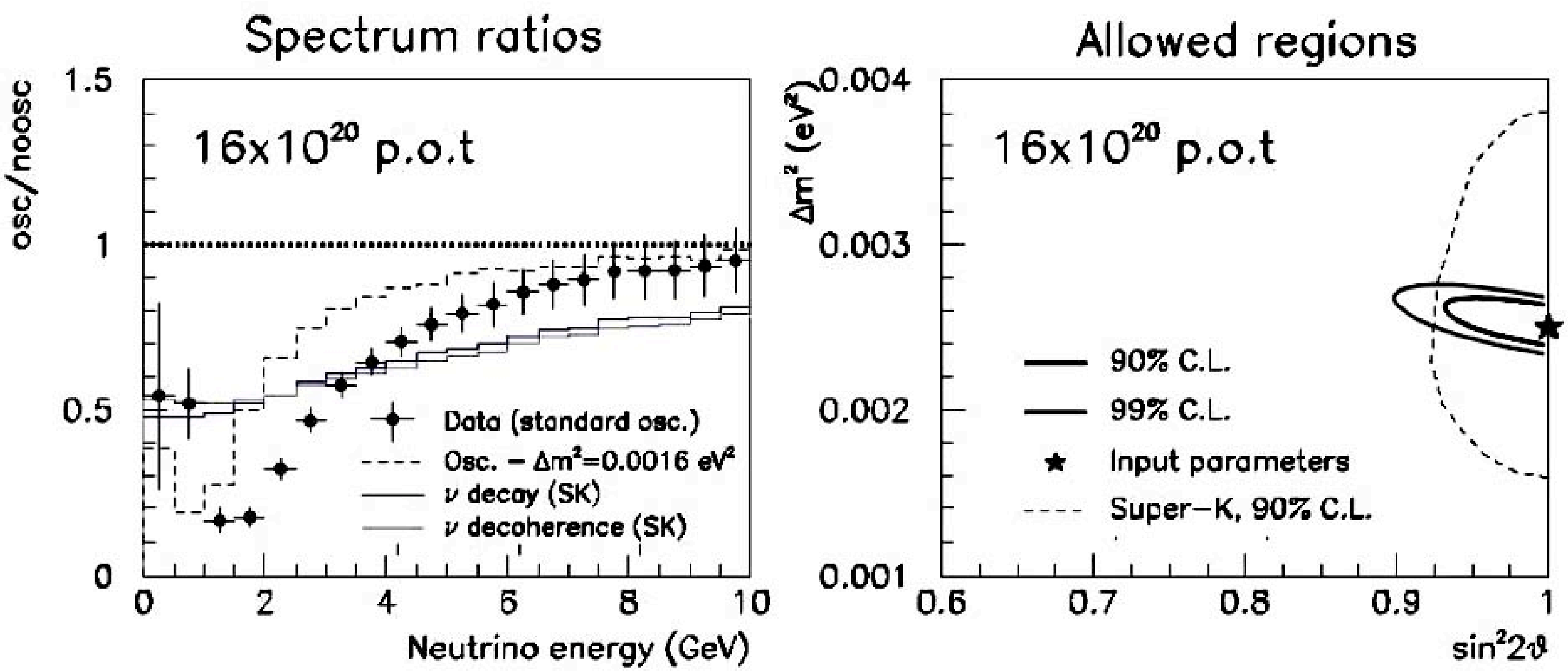
- 8m octagonal tracking calorimeter
- 484 layers of 1 in Fe plates
- 4.1 cm-wide scintillator strips with WLS fiber readout, read out from both ends
- 8 fibers summed on each PMT pixel; 16 pixels/PMT
- 25,800 m^2 (6.4 acres) of active detector planes
- Toroidal magnetic field <B> = 1.3 T
- Total mass 5.4 kT

Major MINOS Physics Goals

- Verify dominant $\nu_\mu \rightarrow \nu_\tau$ oscillations
  - See the characteristic oscillation energy dependence
  - Set a limit on sterile neutrino contributions
  - Study unconventional explanations: neutrino decay, extra dimensions, etc.
- Precise measurement of the atmospheric mass difference Δm_{23}^2: ~10%
- Search for $\nu_\mu \rightarrow \nu_e$ oscillations: 3 σ discovery about a factor of 2 below the CHOOZ limit.

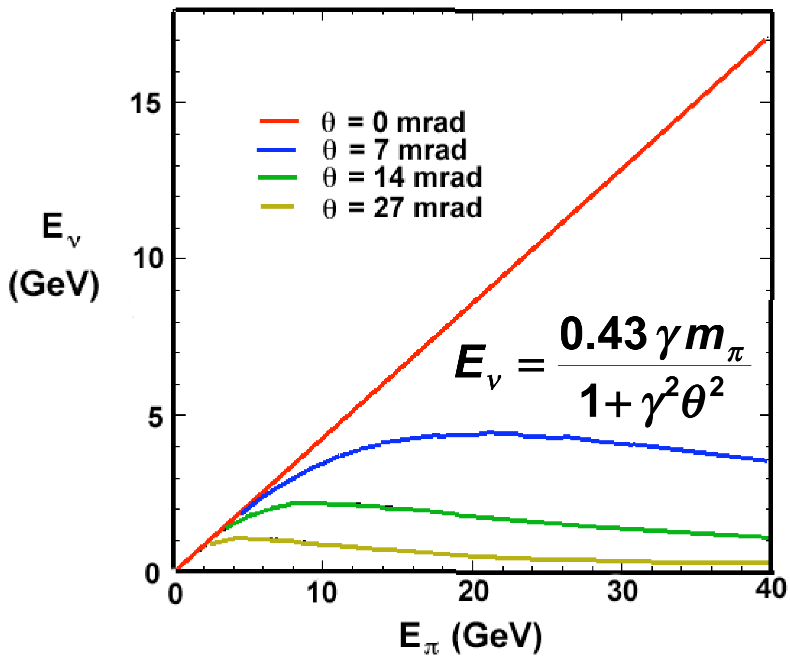
Expected MINOS Sensitivity

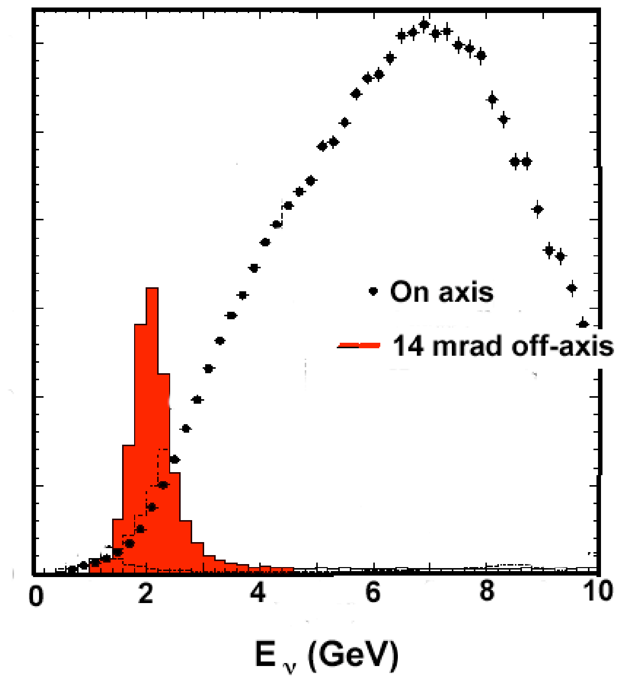
~5 years of ν running



Off-Axis Rationale

- **Both Phase 2 experiments, NOνA and T2K are sited off the neutrino beam axis. This yields a narrow band beam:**





Advantages of the Off-Axis Beam

- More ν flux at the oscillation maximum
- Less background
  - ν_e's from *K* decay at the "wrong energy"
  - Higher-energy neutral current background disappears

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

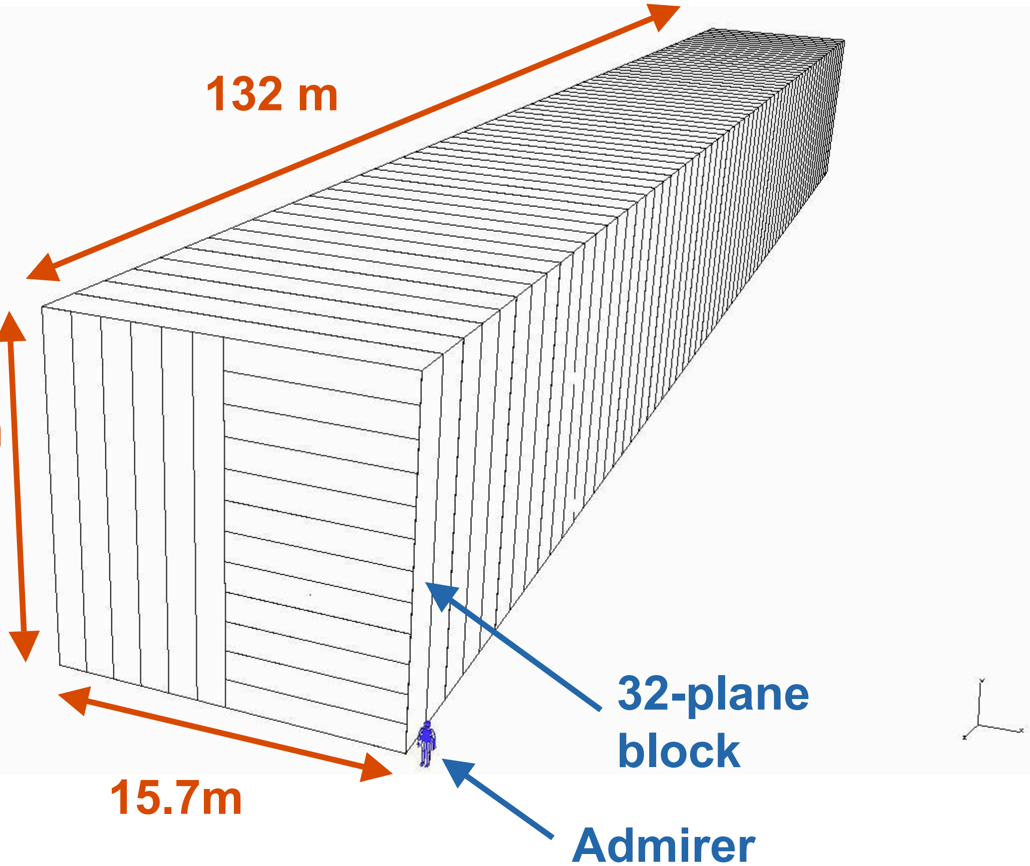
The NOνA Experiment

(NuMI Off-Axis ν_e Appearance Experiment)

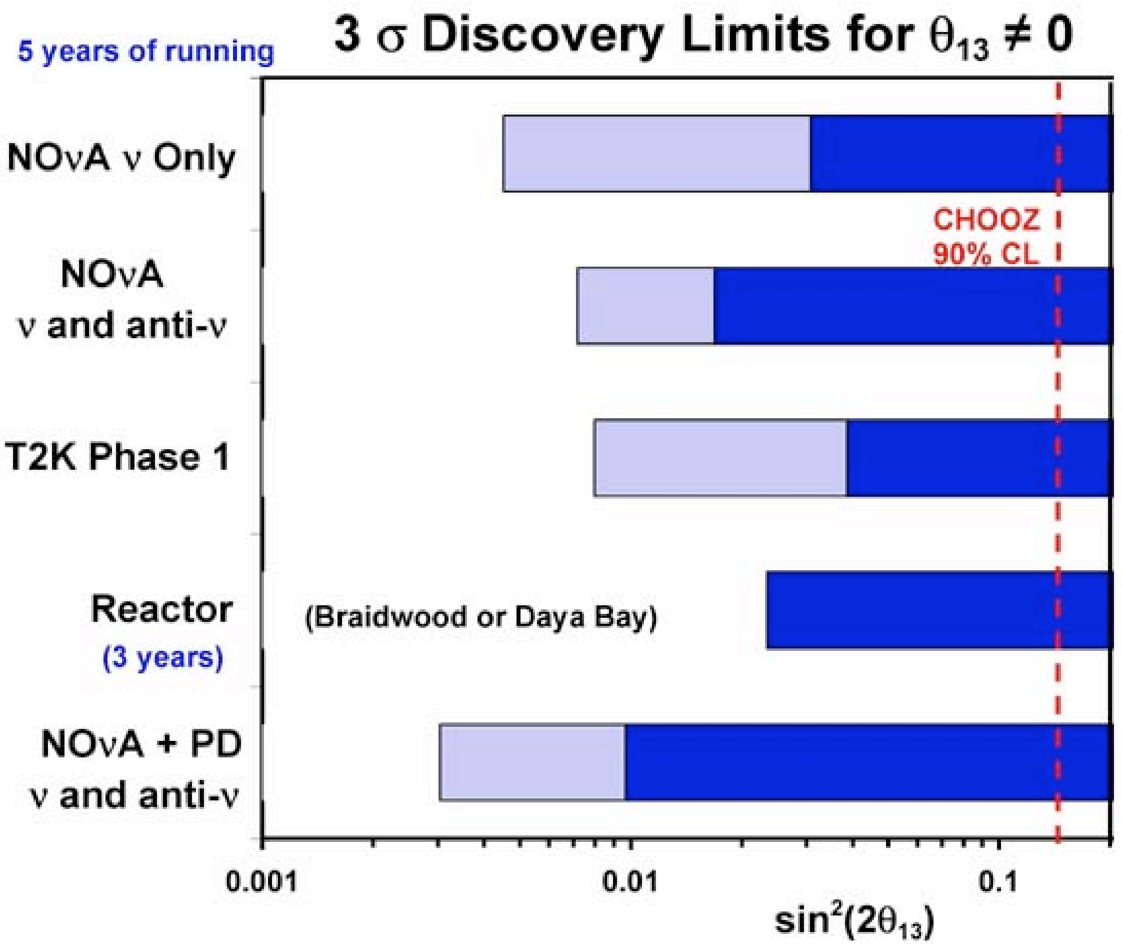
- Goal: ~ An order of magnitude more sensitivity to $\nu_\mu \rightarrow \nu_e$ oscillations than MINOS
  - Off-axis advantages
  - 5 x the mass
  - 10 x better longitudinal segmentation (1.5 X_0 to 0.15 X_0)
- Site: Ash River, MN, 810 km from Fermilab, along the road furthest north in US on the NuMI beamline

NOνA Far Detector

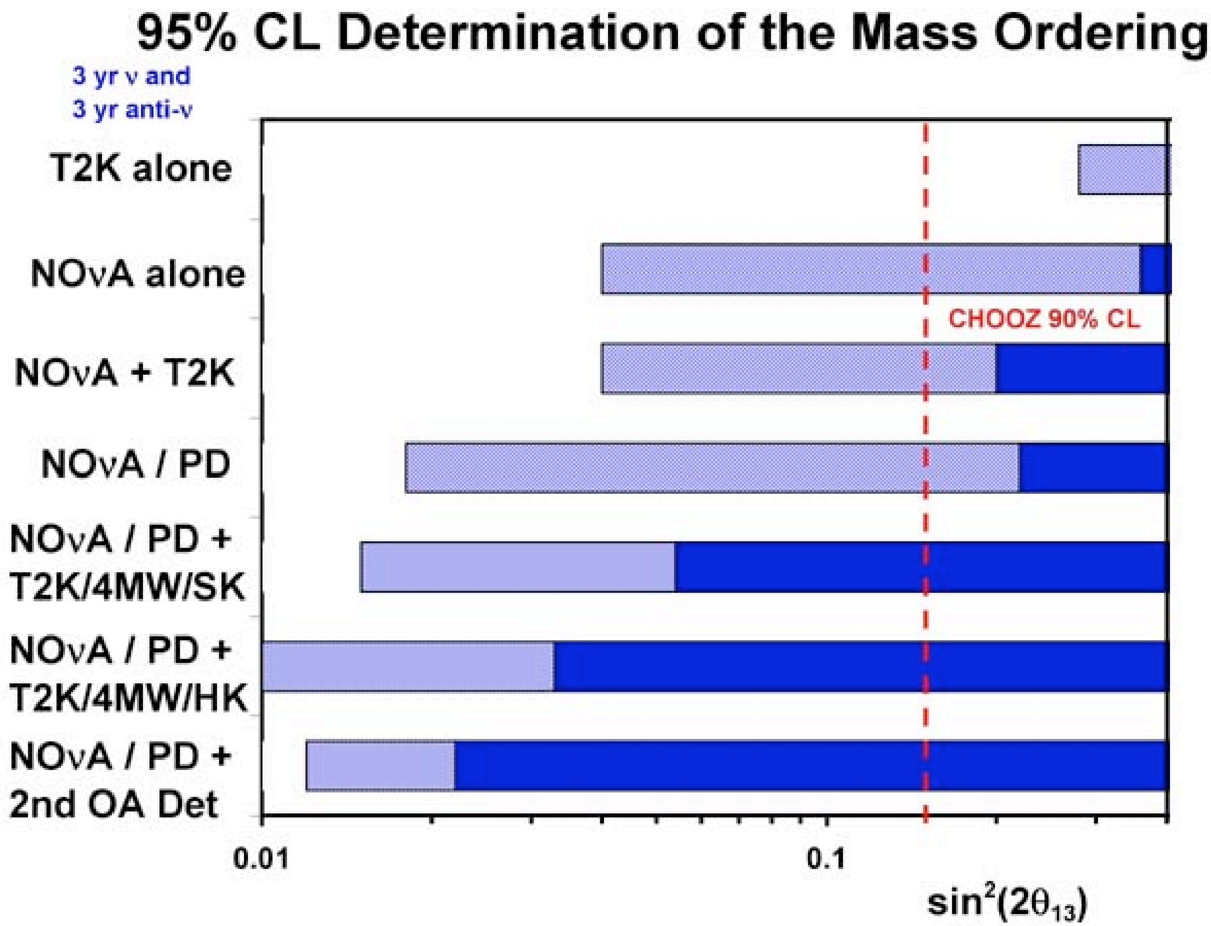
"Totally Active"
30 kT:
  24 kT liquid scintillator
  6 kT PVC
32 cells/extrusion
12 extrusions/plane
1984 planes
Cell dimensions:
  3.9 cm x 6 cm x 15.7m
Extrusion walls:
  3 mm outer
  2 mm inner
U-shaped 0.8 mm WLS fiber into APD



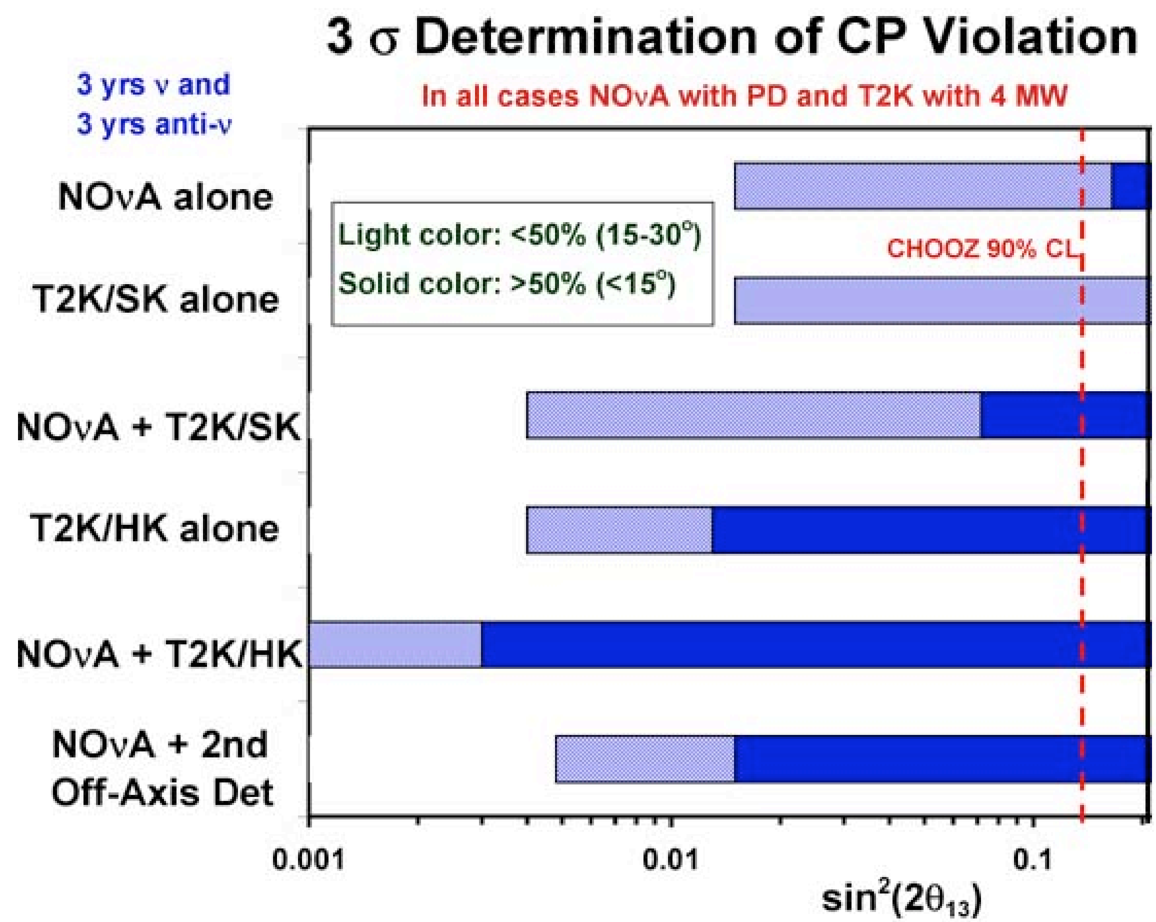
3 σ Sensitivity to $\theta_{13}\neq 0$



95% CL Determination of the Mass Ordering



3 σ Determination of CP Violation



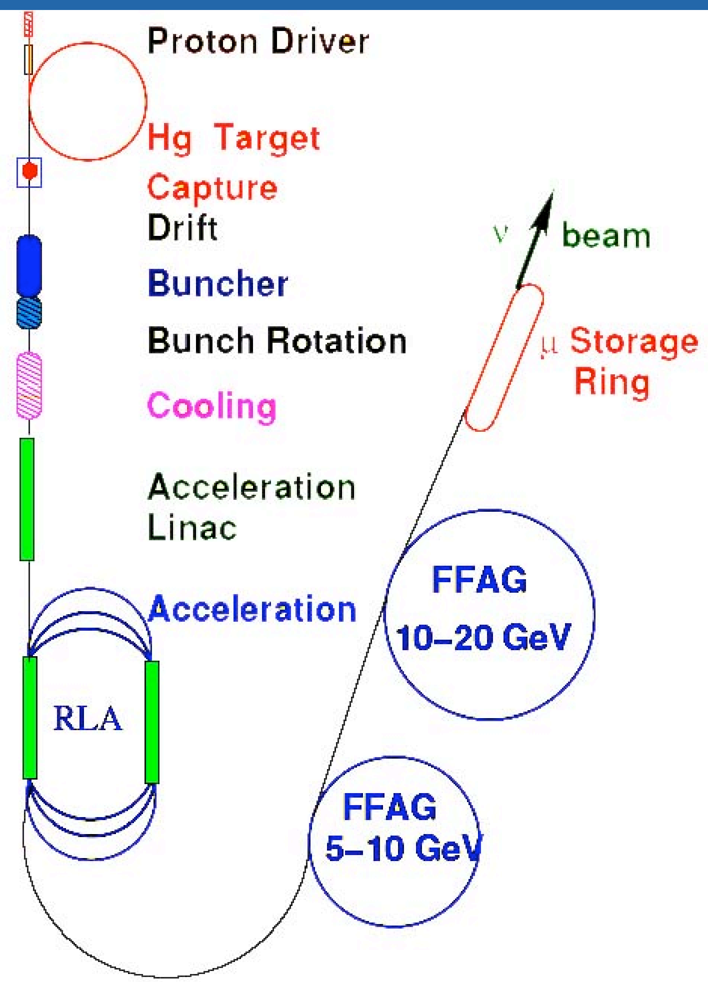
What If $\sin^2(2\theta_{13}) < 0.01\text{-}0.02$?

- Experiments on the NuMI beamline can address almost all of the parameter space available to conventional neutrino beams.
- What if $\sin^2(2\theta_{13}) < 0.01\text{-}0.02$?
- A "neutrino factory" utilizing one of the world's intense proton sources (proton drivers) could be built.

Neutrino Factories

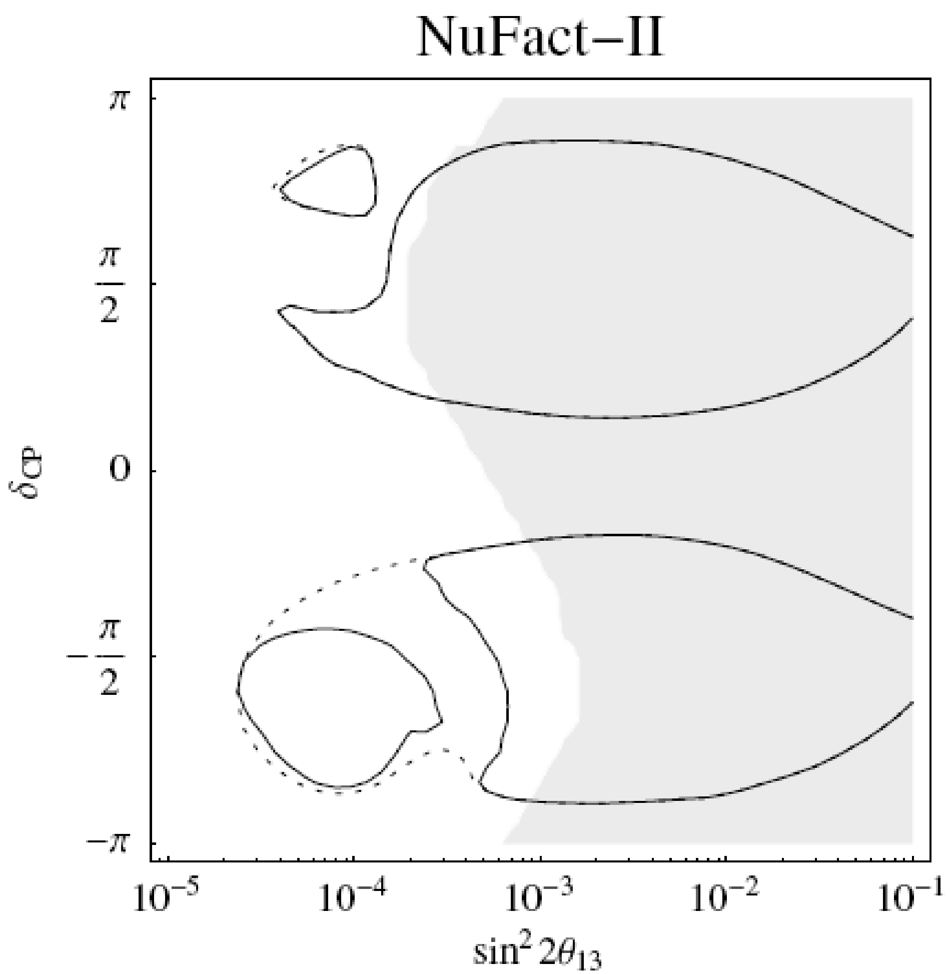
- The idea is simple (but the execution is not): Store muons in a ring with long straight sections and observe neutrinos from the muon decays.
- If μ^+ stored, then $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$.
- Normal CC give only μ^+ and e^-.
  - $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations give e^+.
  - $\nu_e \rightarrow \nu_\mu$ oscillations give μ^-.
- Easy to detect the sign of a muon, so the essentially background-free signature is a "wrong sign" muon

Neutrino Factory Layout



Active international R&D effort including 2 R&D experiments:
- **MICE: muon cooling experiment at RAL**
- **Target experiments at CERN**

Neutrino Factory
2 σ Sensitivity to CP Violation



From Huber, Linder, and Winter, hep-ph/0204352 v2

Conclusion

- 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 greater than other experiments being contemplated for the next few years.
  - The full range of the NOνA/NuMI program is comparable to that of other conventional approaches.
  - A new proton driver at Fermilab will serve both the conventional program and a neutrino factory, if needed.