Neutrino Oscillation Studies with the Fermilab NuMI beam

- Physics Motivation
- NuMI neutrino beam
- MINOS experiment:
  - Detectors
  - Physics goals
  - Expected performance
- Off-axis Beam(s)
  - Backgrounds and Detector Issues
  - Sensitivity of NuMI Off-axis Experiments

Episode I: Before the "New Era"

Theory:

- Neutrino mass differences 1-100 eV^2
- Neutrino mixing matrix similar to quarks (small or very small mixing angles)

WRONG!!

Experiment:

- No evidence for neutrino oscillations in accelerator (BEBC, CDHS, CHARM, CCFR) or reactor (Bugey, Gosgen) experiments
- Confusing 'solar neutrino problem'

New Era started by **"SuperK revolution":**

- Neutrinos have mass, mass differences are very small
- Neutrino mixing angles are very large

Neutrino Physics after the SuperK Revolution

Muon neutrinos disappear (SuperK, K2K,Soudan II, Macro)

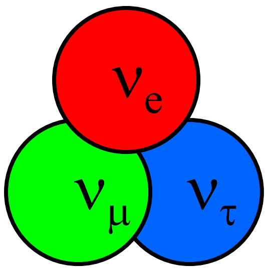
Electron neutrinos disappear (Homestake, SAGE, GNO, SuperK, SNO)

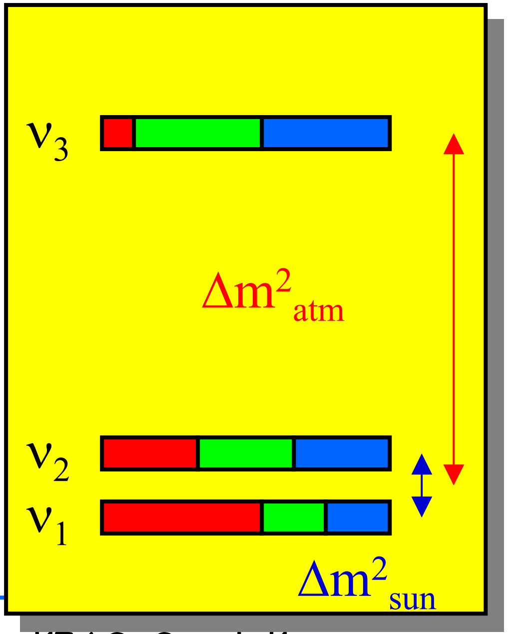
Electron antineutrinos disappear (KamLand)

Electron neutrinos convert into 'other' types of neutrinos (SNO + SuperK)

- Neutrinos have non-zero mass (*****)
- Weak neutrino eigenstates are coherent mixtures of mass eigenstates (****)

$$\begin{bmatrix} \nu_e & \nu_\mu & \nu_\tau \end{bmatrix} = \begin{pmatrix} U^*_{e1} & U^*_{e2} & U^*_{e3} \\ U^*_{\mu 1} & U^*_{\mu 2} & U^*_{\mu 3} \\ U^*_{\tau 1} & U^*_{\tau 2} & U^*_{\tau 3} \end{pmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$





- Magnitude of mixing matrix elements defines composition of electron/muon/tau neutrinos
- Mass differences determine the oscillation length

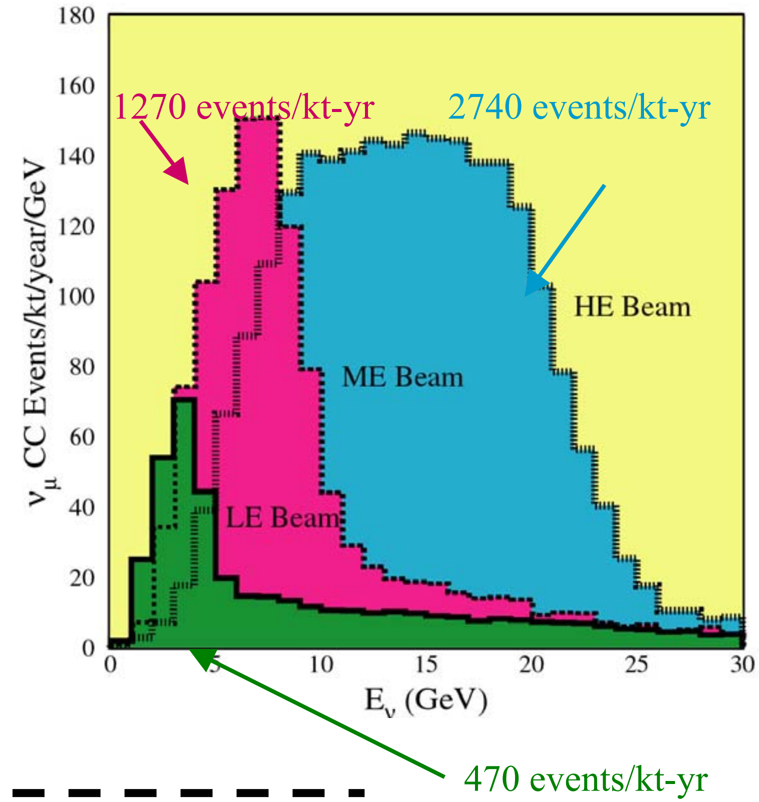
What do we know/want to know better (I)

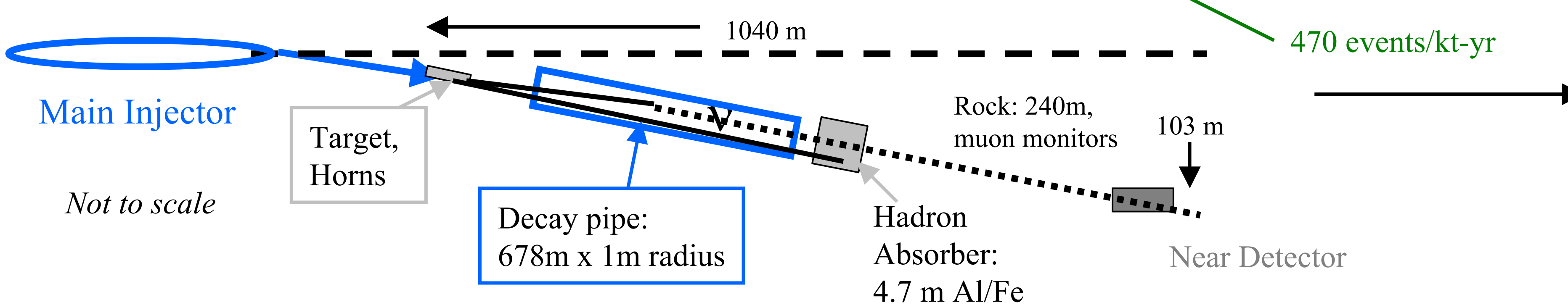
- There are two mass scales:
  - $\Delta m^2_{12} \sim 7\times10^{-5}$ eV^2
  - $\Delta m^2_{23} \sim 1.5\text{-}3\times10^{-3}$ eV^2
- Two mixing angles are large:
  - $\theta_{12} \sim 35^o$
  - $\theta_{23} \sim 90^o$ ($\sin^2 2\theta_{23} > 0.9$)
- Third mixing angle is not very large $\sin^2 2\theta_{13} < 0.1$
- Physics of neutrino mixing is similar to quark mixing, yet the pattern is completely different

- Is the disappearance of muon neutrinos indeed due to neutrino oscillations (see the characteristic oscillation pattern)
- Do other possible mechanisms contribute (decays, extra dimensions,..)?
- What is the precise value of Δm^2_{23}?
- Is $\theta_{23} = 90^o$? Full mixing → New symmetry?
- What is the value of θ_{13}?
- Do neutrinos and antineutrinos oscillate the same way? (CPT!)

A Tool: NuMI Beam

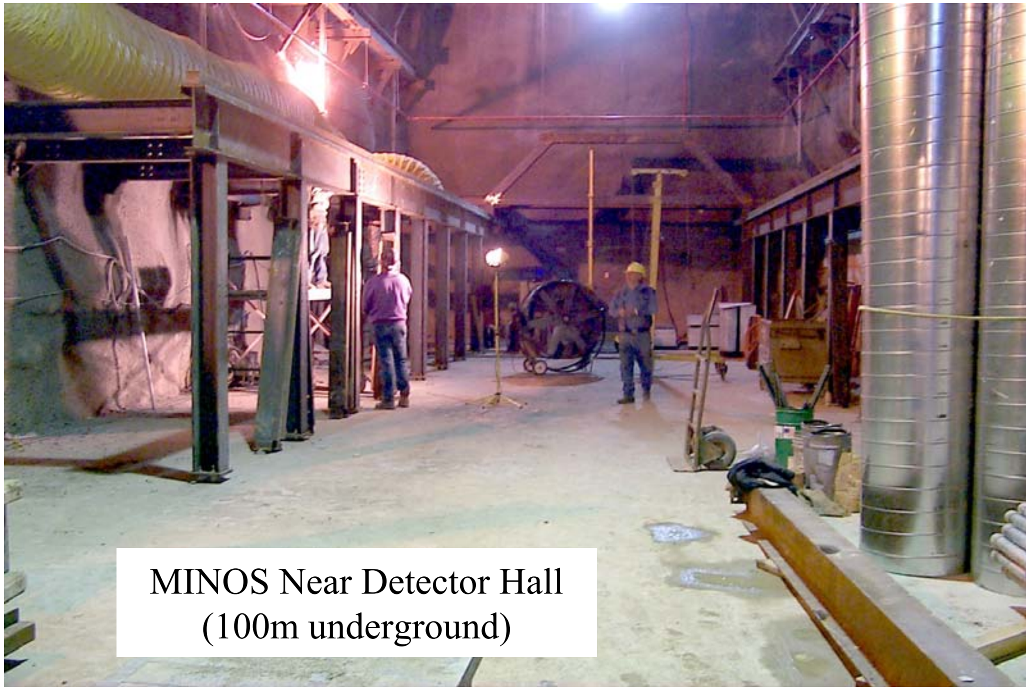
- 120 GeV Protons from Fermilab Main Injector
- 10μs pulse, every 1.9s
- Proton Intensity:
  - 4×10^{13} protons/pulse design
  - 2.5×10^{13} p/p expected at startup
- Hadrons focused with 2 horns
  - Select beam energy spectrum by adjusting horn and target positions



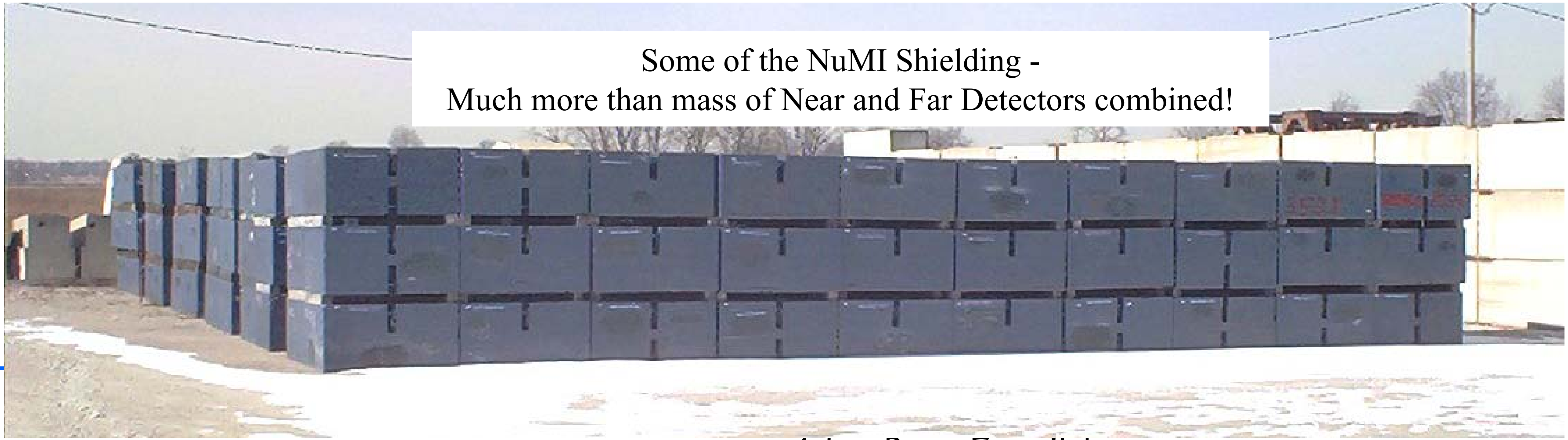


NuMI Beam Status

- Excavation of underground complex complete
- Decay Pipe installed
- Tunnel/Hall Outfitting in progress
- Target has been fabricated
- Horns have been assembled
- Project will be complete/ commissioning starts Dec. 2004

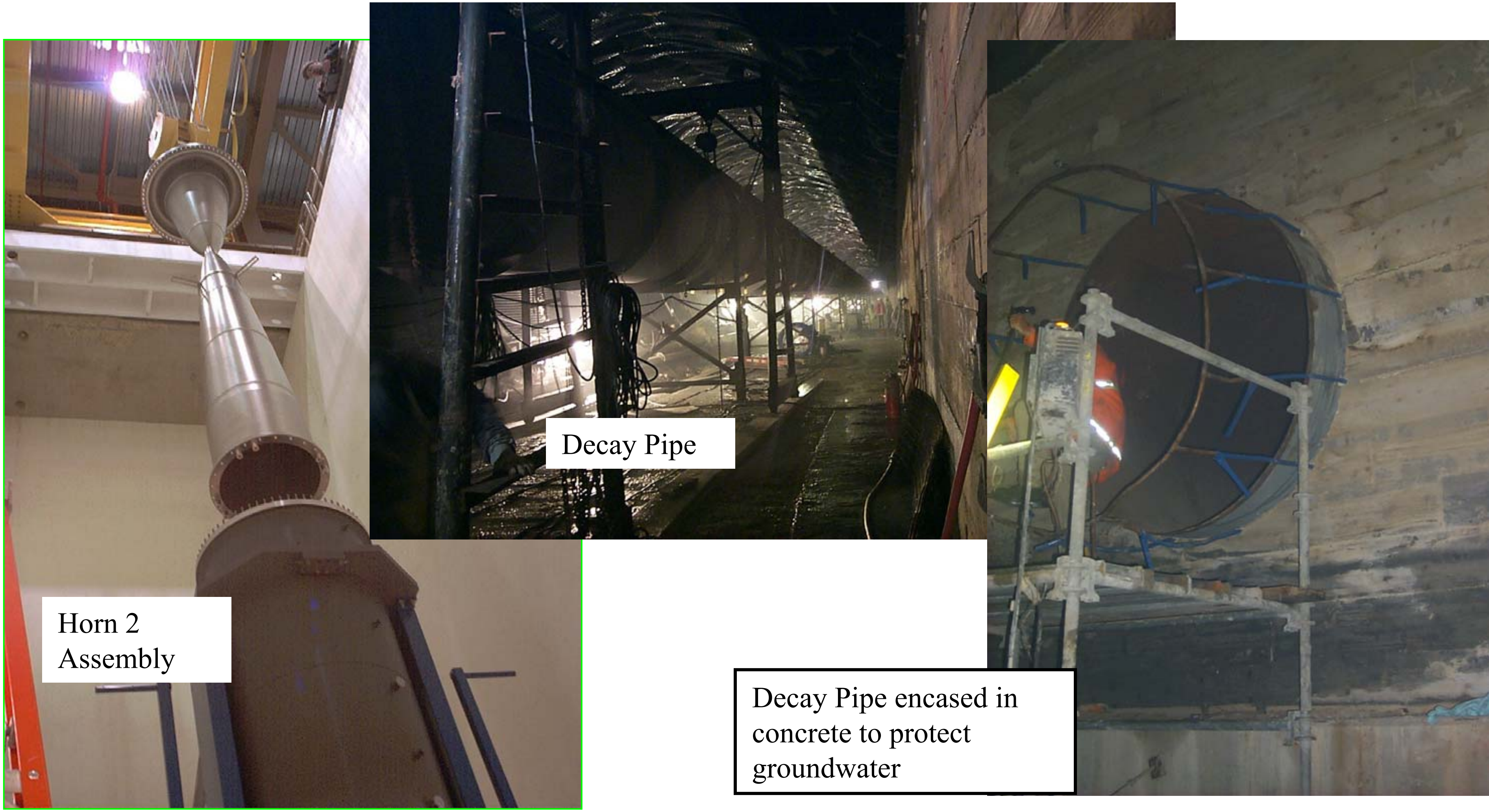


MINOS Near Detector Hall
(100m underground)



Some of the NuMI Shielding -
Much more than mass of Near and Far Detectors combined!

NuMI Beam Status



Horn 2 Assembly

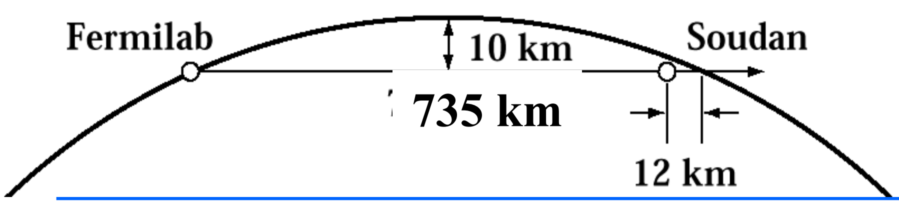
Decay Pipe

Decay Pipe encased in concrete to protect groundwater

MINOS

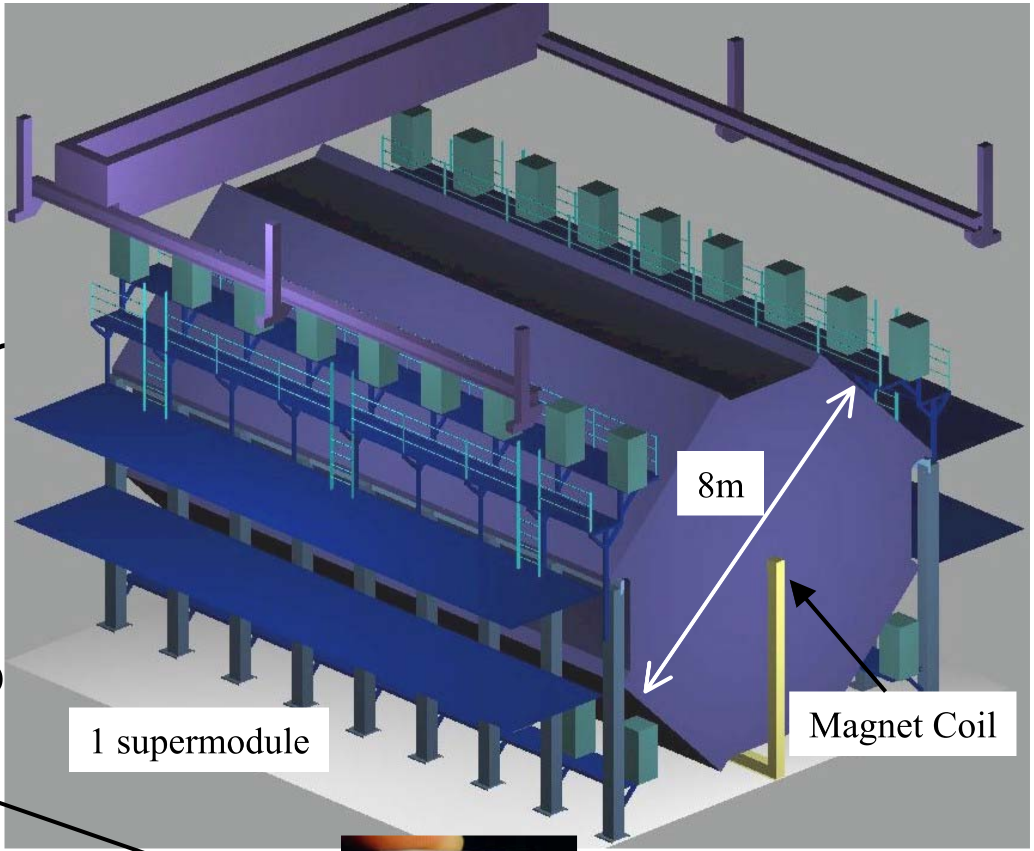
Main Injector Neutrino Oscillation Search

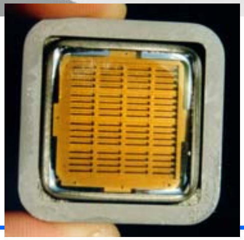
- Precision Δm_{23}^2 and $\sin^2(2\theta_{23})$ measurement in ν_μ disappearance
- 2 detectors, functionally identical, separated by 735km baseline
  - Near Detector: 1kt detector at Fermilab
  - Far Detector: 5.4kt detector at Soudan



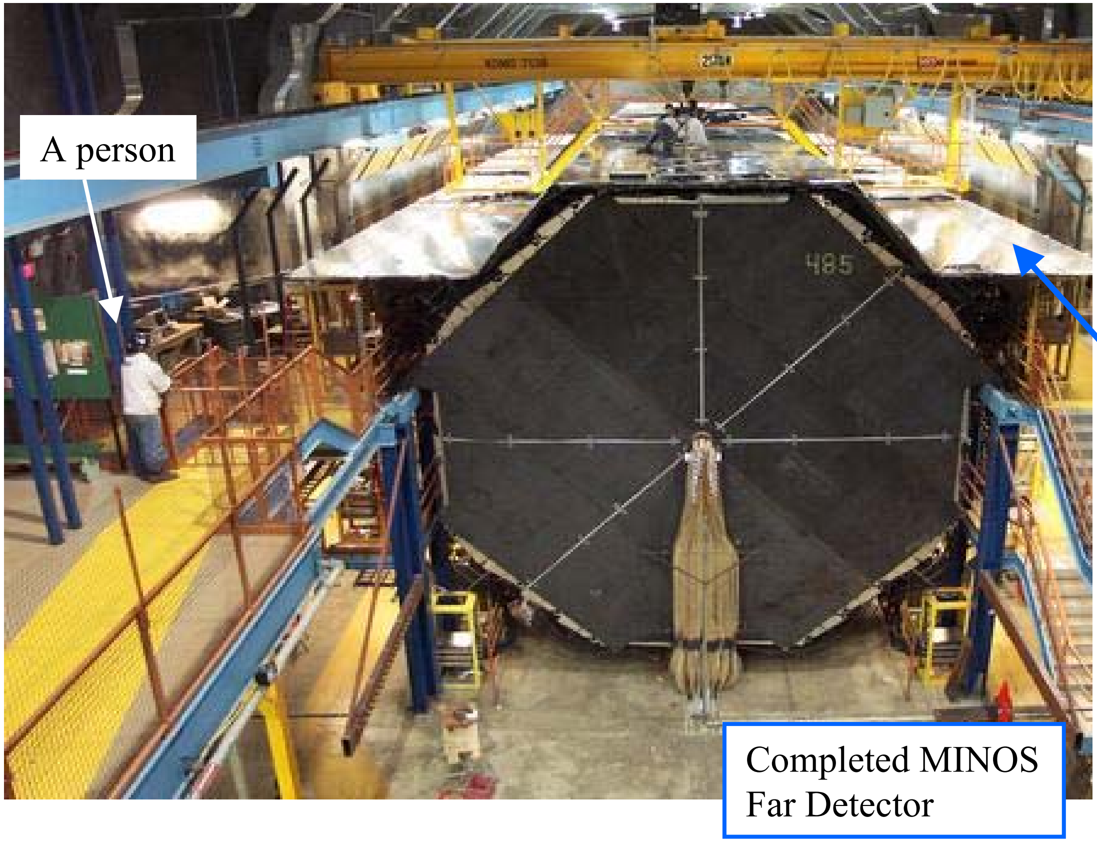
Far Detector

- 5.4kt total
  - 484 planes in two ~14.5m long "super modules"
  - Each plane 8m octagon
  - 2.54cm Fe, 1cm Scintillator
  - ~1.5T Magnetic field
- Readout
  - 2 ended readout
  - 8x optical multiplexing into M16 multi-anode PMTs
  - ~92k strips, 23k channels
- Overburden
  - 710 m (2090 mwe)





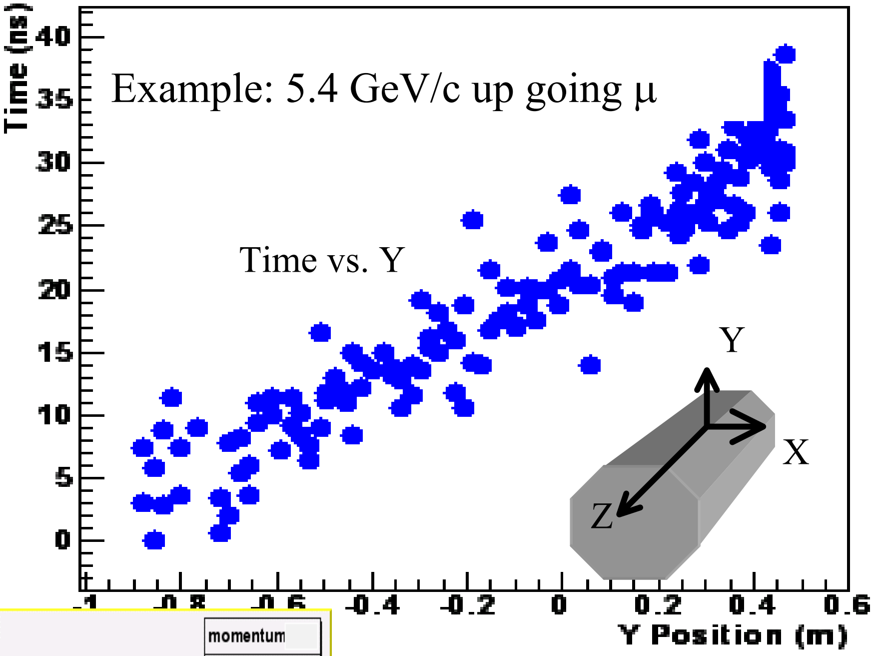
Far Detector Status

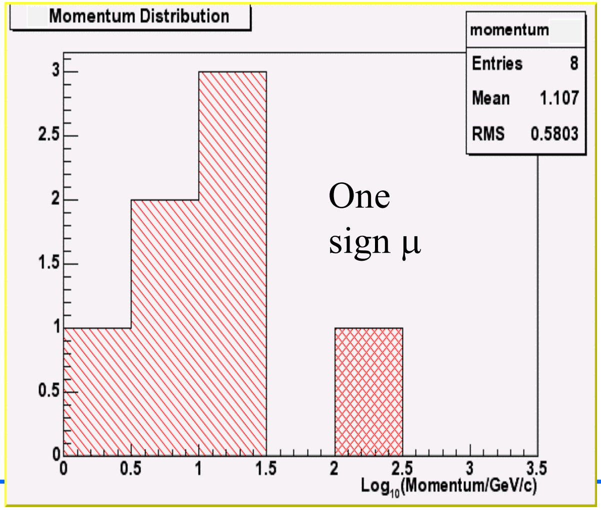


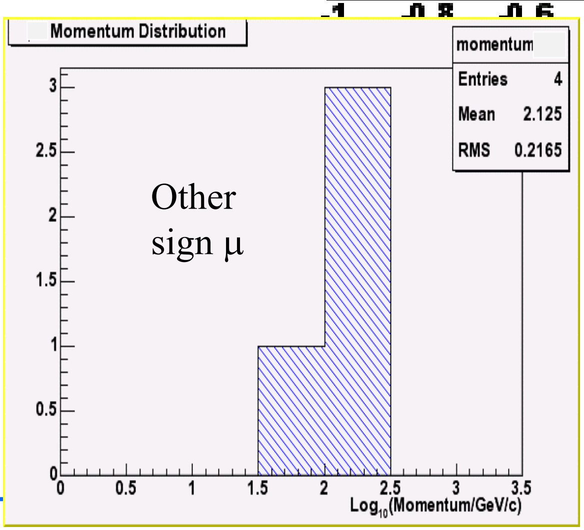
- Far Detector construction completed!
  - 1st supermodule operational since 7/02
- Veto Shield
  - Build from same scintillator used in detector
  - Help ID Atmospheric neutrino interactions

Far Detector Data

- Up Going Muons: ν interactions below detector
  - Use timing to select up going muons
- Magnetic Field
  - Distinguish μ^-, μ^+



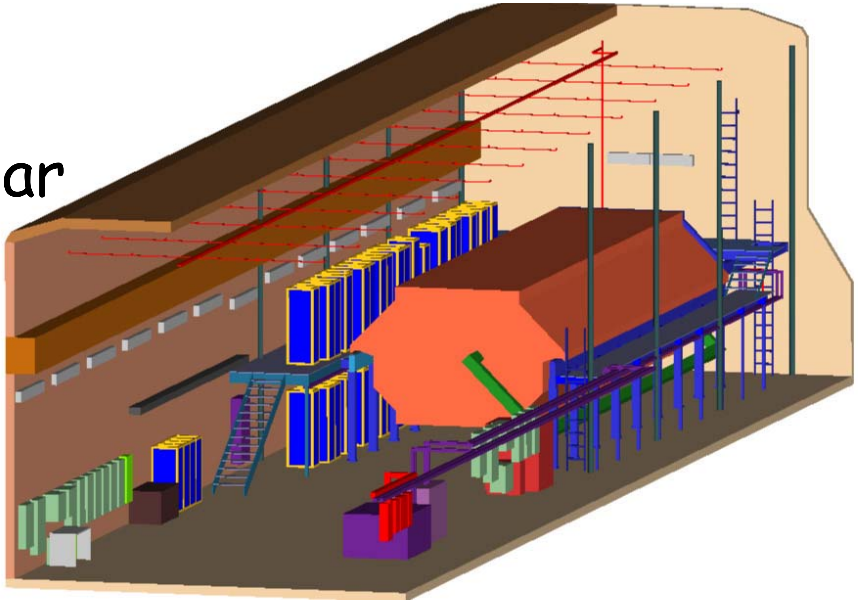


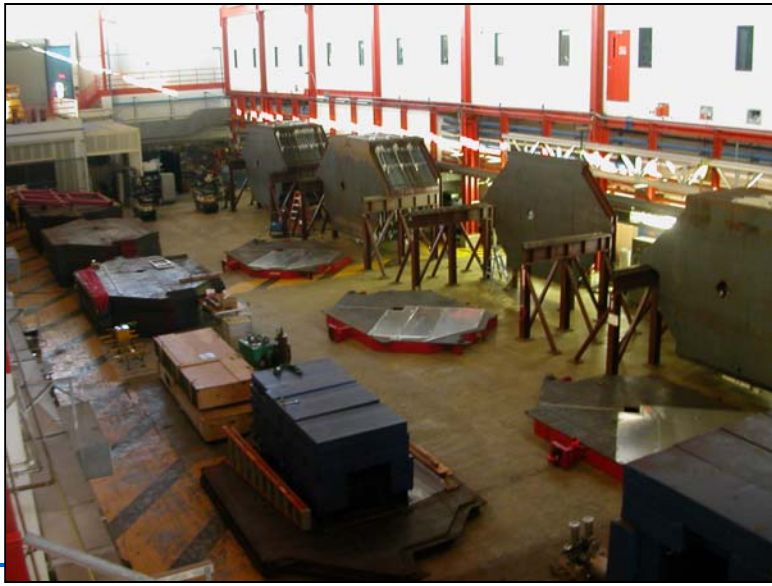


MINOS PRELIMINARY UPGOING MUON DATA

Near Detector

- Same sampling/structure as far detector
- 980 t
- High rate (10μs spill)
  - HE beam: 20 interactions/m/spill
  - LE beam: 3.2 interactions/m/spill
  - High speed electronics
  - 4x multiplexing in spectrometer only
- All Planes have been assembled in a surface building

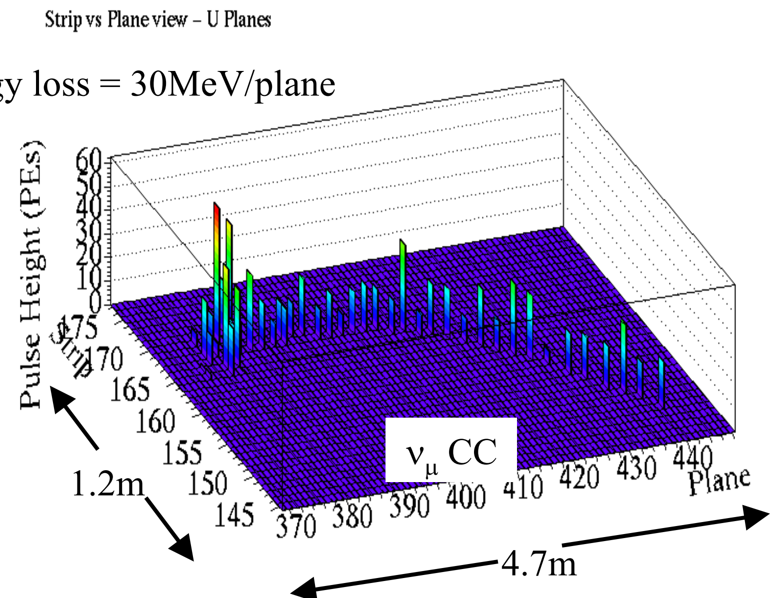




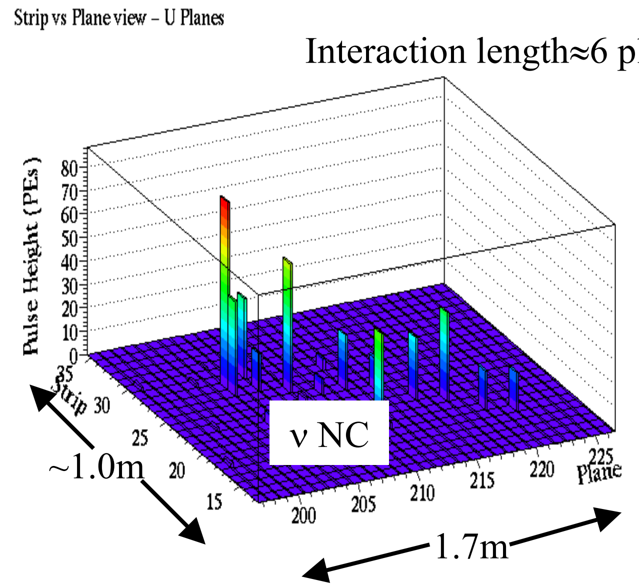
MINOS ν Event Topologies

- ν_μ identified by μ in Charged Current interactions

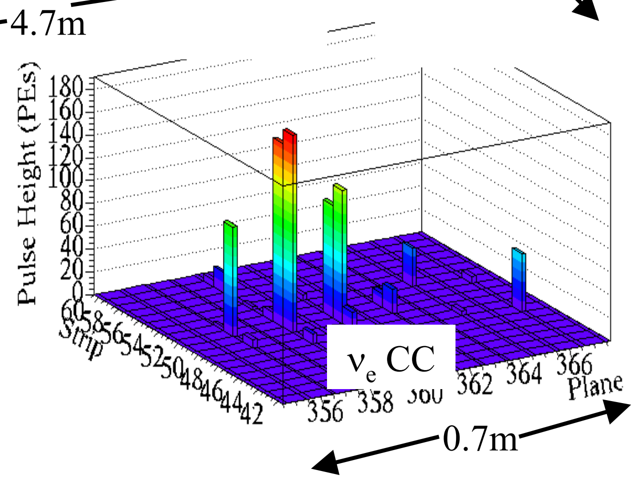
MIP energy loss = 30MeV/plane



Interaction length≈6 planes

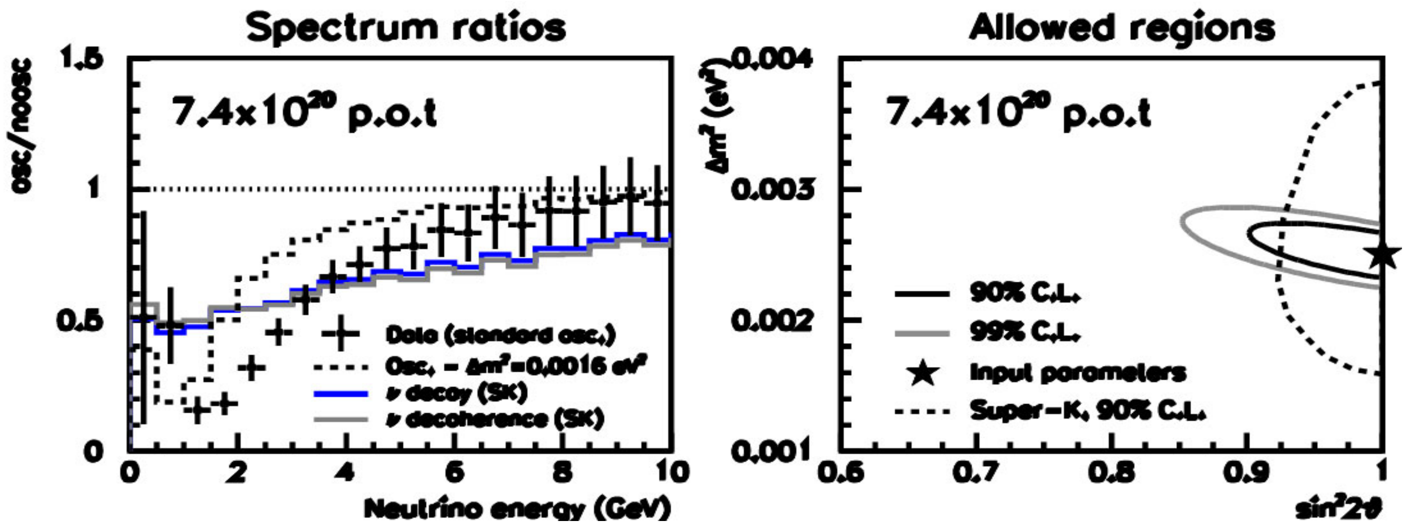


Example Monte Carlo events
Pulse height vs. Strip & plane
4-5 GeV neutrinos



1 plane ≈ 1.4 X_0

Oscillation measurements



Comparison of the observed spectrum of ν_μ charged current events with the expected one provides a direct measure of the survival probability as a function of neutrino energy

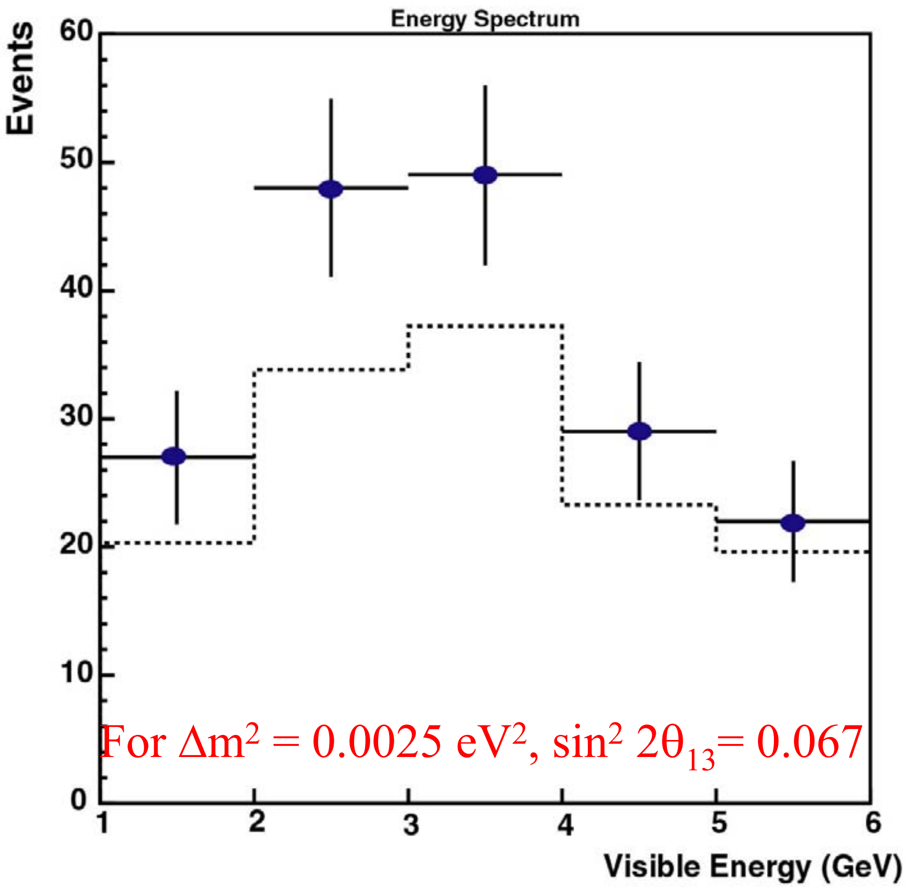
$$P = 1 - \sin^2 2\vartheta_{23} \sin^2 \frac{1.27\Delta m^2 L}{E_\nu}$$

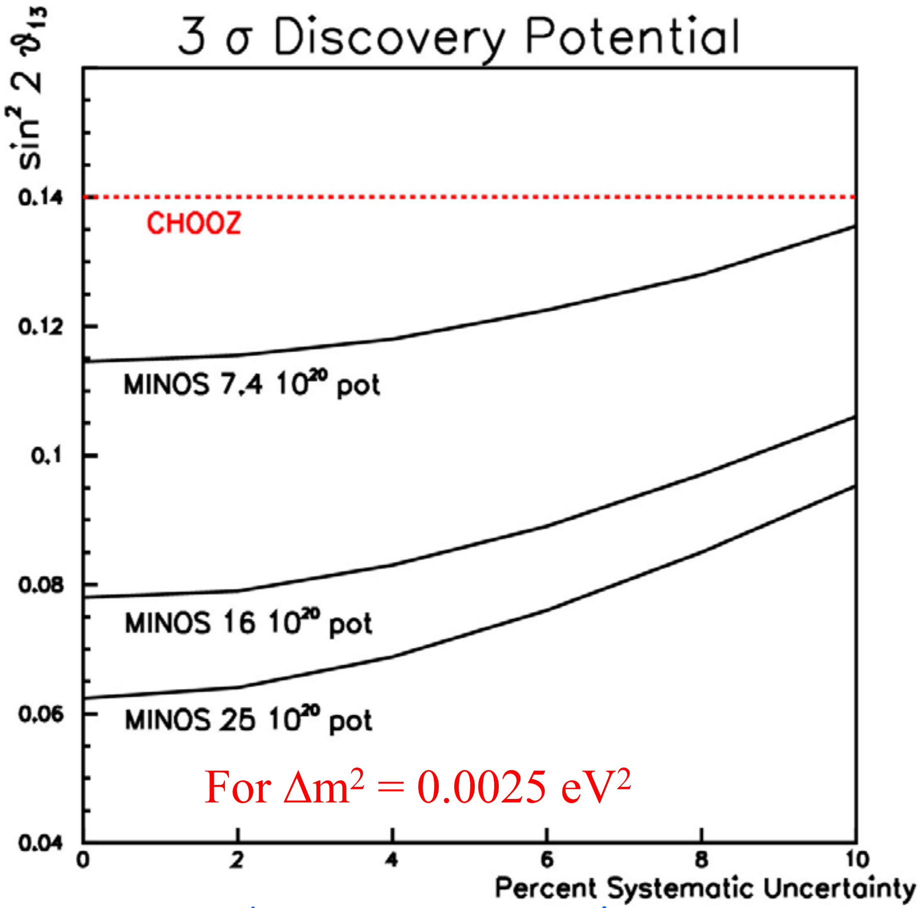
Does the disappearance follow this functional form?

Neutrinos <u>and</u> antineutrinos?

- Dip depth ←→ oscillation amplitude ($\sin^2 2\theta_{23}$)
- Dip position ←→ Δm^2_{23} ($\pi/2 = 1.27 \times \Delta m^2_{23} \times L/E_{dip}$)

Electron Neutrino Appearance





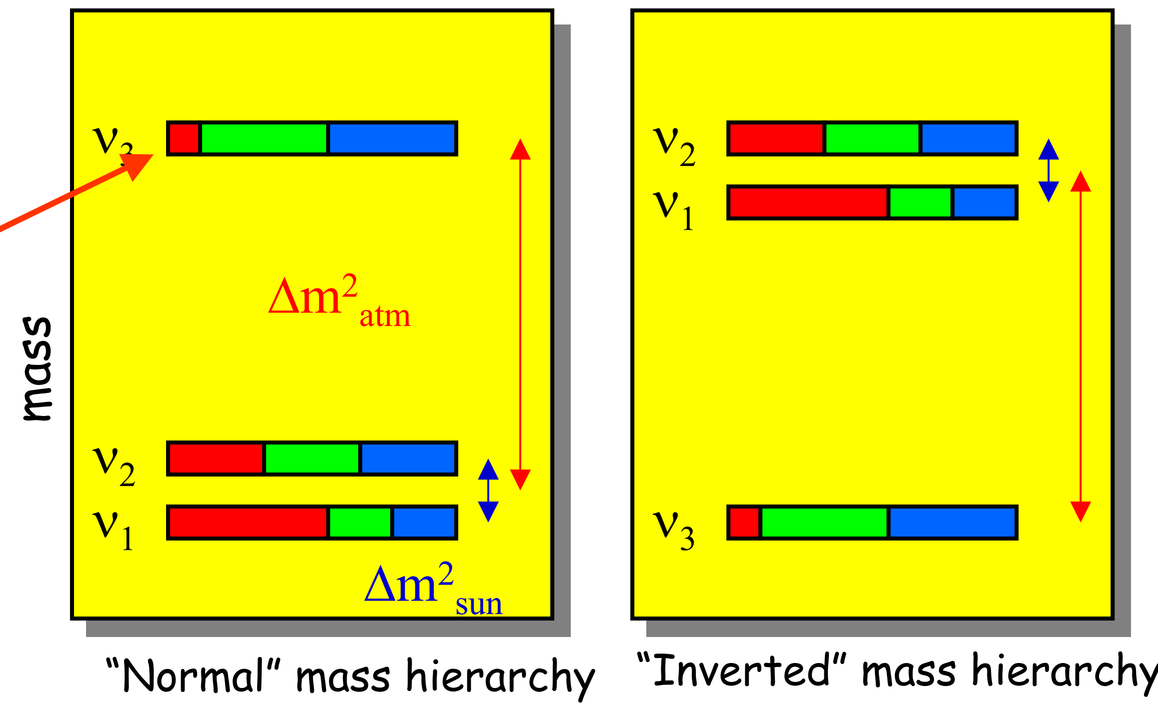
Observed number of ν_e CC candidates with and without oscillations. 25×10^{20} protons on target.

3 σ discovery potential versus systematic uncertainty on the background.

What do we want to know (II)

1. Neutrino mass pattern:

This ? Or that?



2. Electron component of ν_3 ($\sin^2 2\theta_{13}$)

$$\begin{bmatrix} \nu_e & \nu_\mu & \nu_\tau \end{bmatrix} = \begin{pmatrix} B & B & s \\ B & B & B \\ B & B & B \end{pmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

3. Complex phase of s(?) ←→ CP violation in a neutrino sector ←→ (?) baryon number of the universe

The key: $\nu_\mu \Rightarrow \nu_e$ oscillation experiment

$$P(\nu_\mu \to \nu_e) = P_1 + P_2 + P_3 + P_4$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2}{2E_\nu};$$
$$A = \sqrt{2}G_F n_e;$$
$$B_\pm = |A \pm \Delta_{13}|;$$
$$J = \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

$$P_1 = \sin^2\theta_{23}\sin^2\theta_{13}\left(\frac{\Delta_{13}}{B_\pm}\right)^2\sin^2\frac{B_\pm L}{2}$$

Oscillation at the 'atmospheric' frequency

$$P_2 = \cos^2\theta_{23}\sin^2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2\sin^2\frac{AL}{2}$$

Oscillation at the 'solar' frequency

$$P_3 = J\cos\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\cos\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

$$P_4 = J\sin\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\sin\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

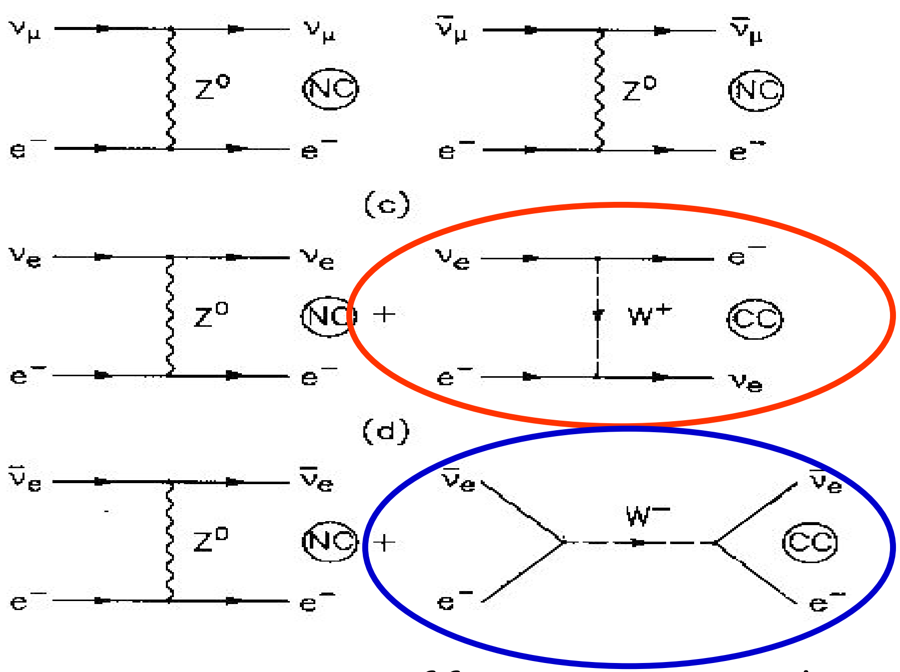
Interference of these two amplitudes ➔ CP violation

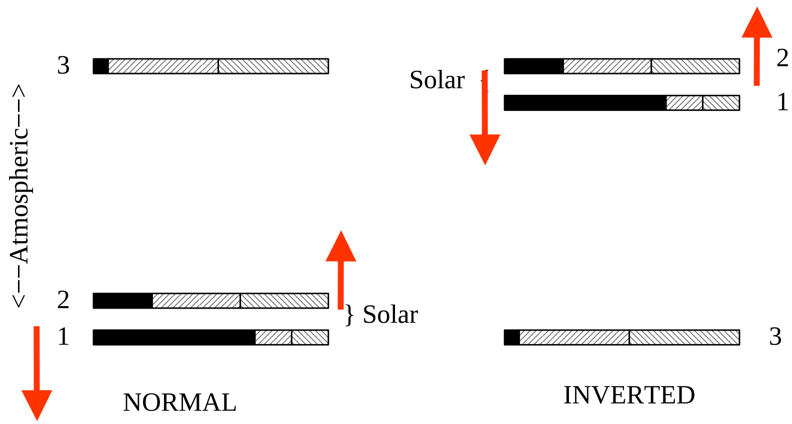
$$P = f(\sin^2 2\theta_{13}, \delta, \mathrm{sgn}(\Delta m_{13}^2), \Delta m_{12}^2, \Delta m_{13}^2, \sin^2 2\theta_{12}, \sin^2 2\theta_{23}, L, E)$$

3 unknowns, 2 parameters under control L, E, neutrino/antineutrino

Need several independent measurements to learn about underlying physics parameters

Matter Effects in Neutrino Propagation

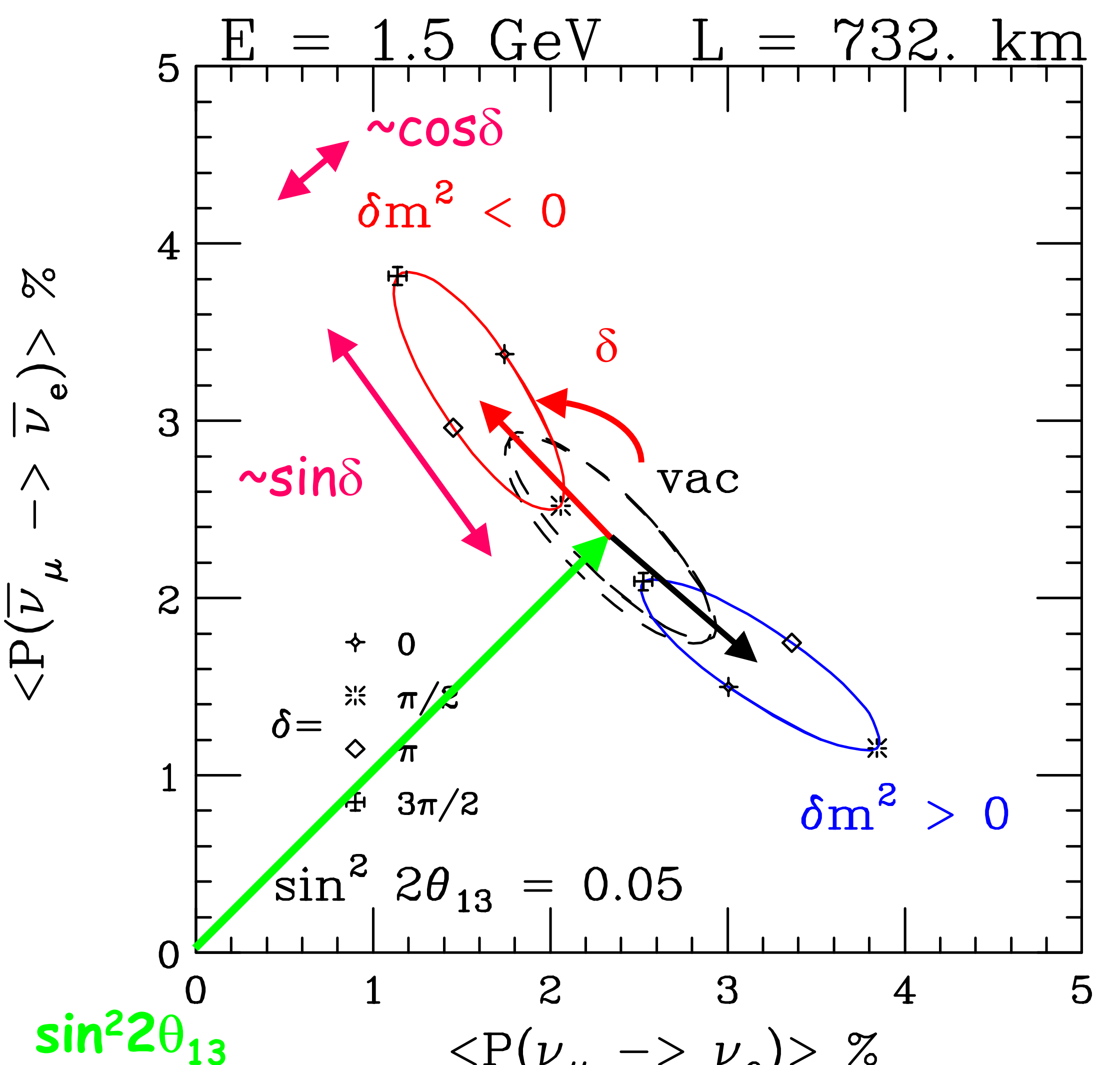




- Matter effects reduce mass of ν_e and increase mass of $\overline{\nu}_e$
- Matter effects increase Δm^2_{23} for normal hierarchy and reduce Δm^2_{23} for inverted hierarchy for neutrinos, opposite for antineutrinos

- Neutrinos move in an effective potential ➔ shift of energy levels(masses), common to all neutrinos
- Electron neutrinos/antineutrinos have additional (CC) interactions ←→ addition mass shifts

Anatomy of Bi-probability ellipses

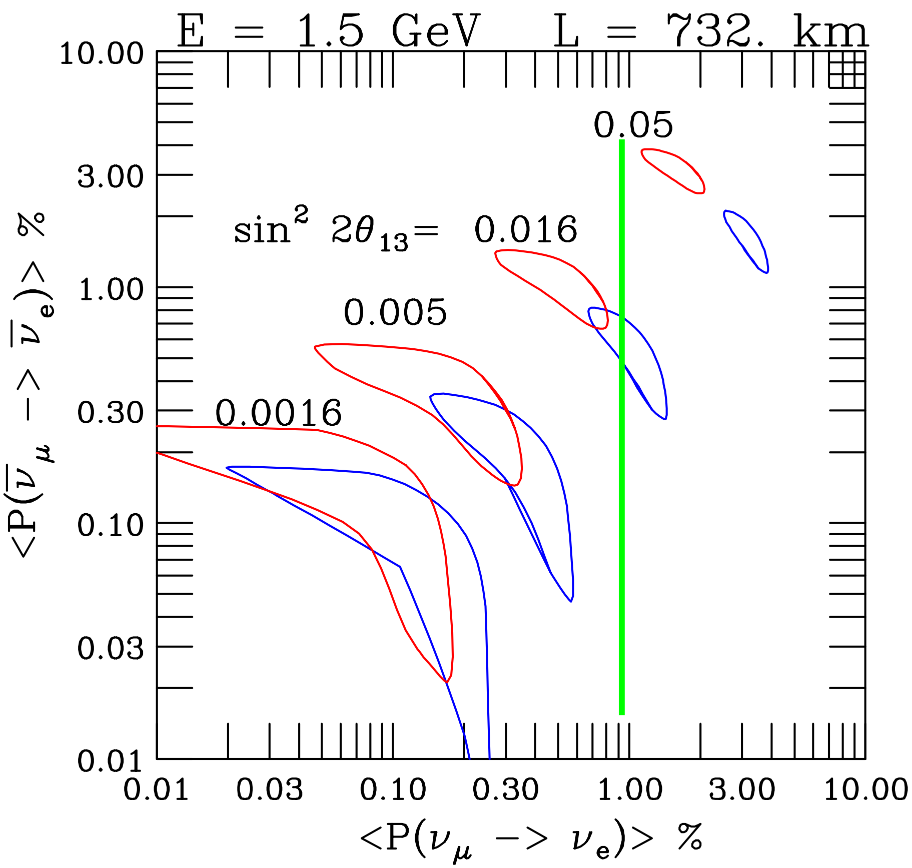


Minakata and Nunokawa, hep-ph/0108085

Observables are:
- P (neutrino appearance)
- P (antineutrino appearance)

Matter effects and CP violation effects are of the same order as the main oscillation (for a NuMI baseline)

Varying the mixing angle..



- Parameter correlation: even very precise determination of P_ν leads to a large allowed range of $\sin^2 2\theta_{23}$ ➔ **antineutrino beam** is more important than improved statistics

- *CP violation effects (size of the ellipse) ~ $\sin 2\theta_{13}$, overall probability ~ $\sin^2 2\theta_{13}$ ➔relative effect very large*

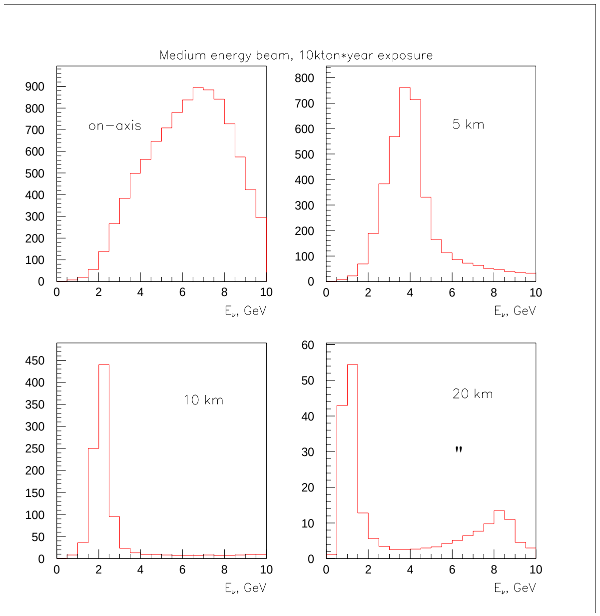
Recipe for an ν_e Appearance Experiment

- Large neutrino flux in a signal region
- Reduce background (neutral currents, intrinsic ν_e)
- Efficient detector with good rejection against NC background
- Large detector

Lucky coincidences:

- distance to Soudan = 735 km, Δm^2=0.02-0.03 eV^2
- $$\frac{1.27\Delta m^2 L}{E} = \frac{\pi}{2} \quad \Rightarrow \quad E = \frac{2.54\Delta m^2 L}{\pi} \approx 1.5 - 2.2\ GeV$$ => 'large' cross section
- Below the τ threshold! (BR(τ->e)=17%)

Off-axis NuMI Beams: Unavoidable By-product of the MINOS Experiment



- Beam energy defined by the detector position (off-axis, Beavis et al)
- Narrow energy range (minimize NC-induced background)
- Simultaneous operation (with MINOS and/or other detectors)
- ~ 2 GeV energy :
  - Below τ threshold
  - Relatively high rates per proton, especially for antineutrinos
- Matter effects to amplify to differentiate mass hierarchies
- Baselines 700 – 1000 km

NuMI Challenge: “have” beam, need a new detector

- Surface (or light overburden)
  - High rate of cosmic μ’s
  - Cosmic-induced neutrons
- But:
  - Duty cycle 0.5×10^{-5}
  - Known direction
  - Observed energy > 1 GeV

Principal focus: electron neutrinos identification

- Good sampling (in terms of radiation/Moliere length)

Large mass:

- maximize mass/radiation length
- cheap

Off-axis collaboration: Letter of Intent 2002,

Proposal in preparation (October 2003)

NuMI Off-axis Experiment

Low Z imaging calorimeter: particle board ~30% of radiation length thick

- Liquid scintillator or
- Glass RPC

Electron ID efficiency ~ 40% while keeping NC background below intrinsic ν_e level

Well known and understood detector technologies

Primarily the engineering challenge of (cheaply) constructing a very massive detector

How massive??

50 kton detector, 5 years run =>

- 10% measurement if $\sin^2 2\theta_{13}$ at the CHOOZ limit, or
- 3σ evidence if $\sin^2 2\theta_{13}$ factor 10 below the CHOOZ limit (normal hierarchy, δ=0), or
- Factor 20 improvement of the limit

Backgrounds Summary

- ν_e component of the beam
  - Constrained by ν_μ interactions observed in the near MINOS detector (π)
  - Constrained by pion production data (MIPP)
- NC events passing the final analysis cuts (π^0?)
  - Constrained by neutrino data from K2K/NuMI near detector
  - Constrained by the measurement of EM 'objects' as a function of E_{had} in the dedicated near detector
- Cosmics
  - Cosmic muon induced 'stuff' overlapped with the beam-induced neutrino event
  - (undetected) cosmic muon induced which mimics the 2 GeV electron neutrino interaction in the direction from Fermilab within 10 μsec beam gate

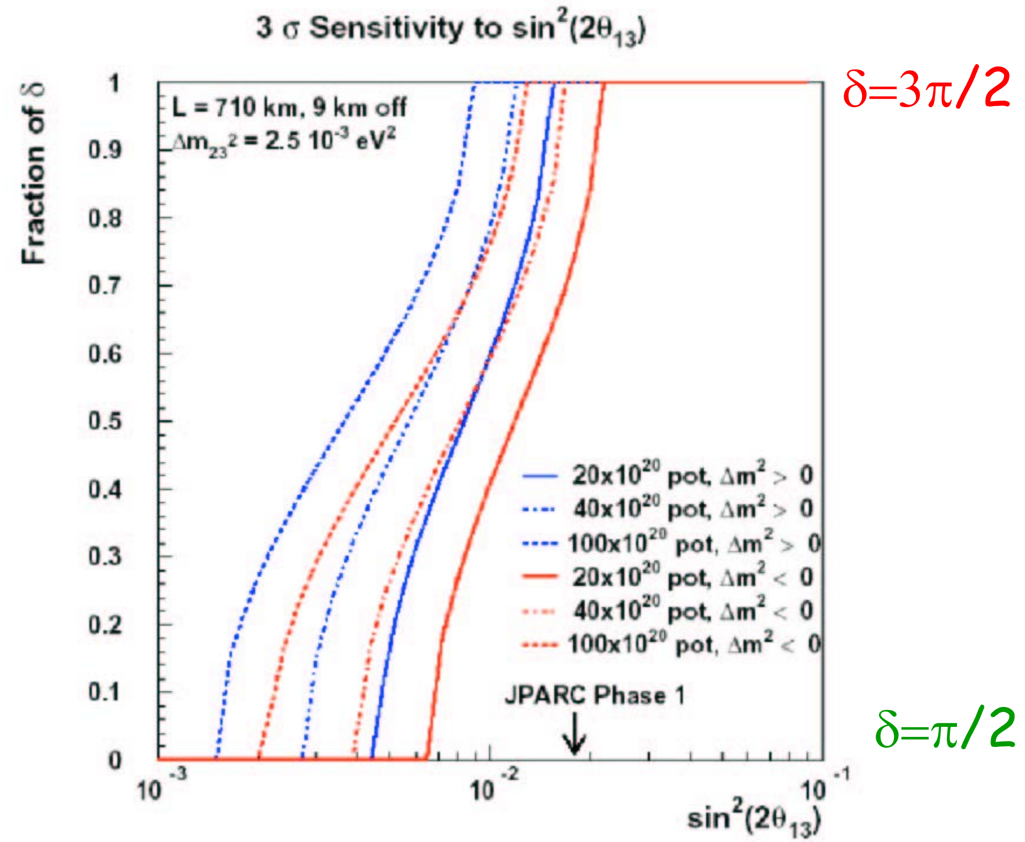
• Expected to be very small

• Measured in a dedicated setup (under construction)

NuMI Off-axis sensitivity?

FAQ: What is the smallest $\sin^2 2\theta_{13}$ one can detect?

- It depends on the exposure (proton beam intensity, eventual proton driver…)
- It depends on unknown physics parameters:
  - Mass hierarchy. Matter effect can amplify or attenuate the signal.
  - CP violating angle δ
- Figure of Merit: 3 σ discovery limit as a function of the fracion of the possible range of δ's



Two phase program

Phase I (~ $150M, running 2009 - 2014)

- 50 kton (fiducial) detector with ε~35-40%
- 4×10^{20} protons per year
- 1.5 years neutrino (6000 ν_μ CC, 70-80% 'oscillated')
- 5 years antineutrino (6500 ν_μ CC, 70-80% 'oscillated')

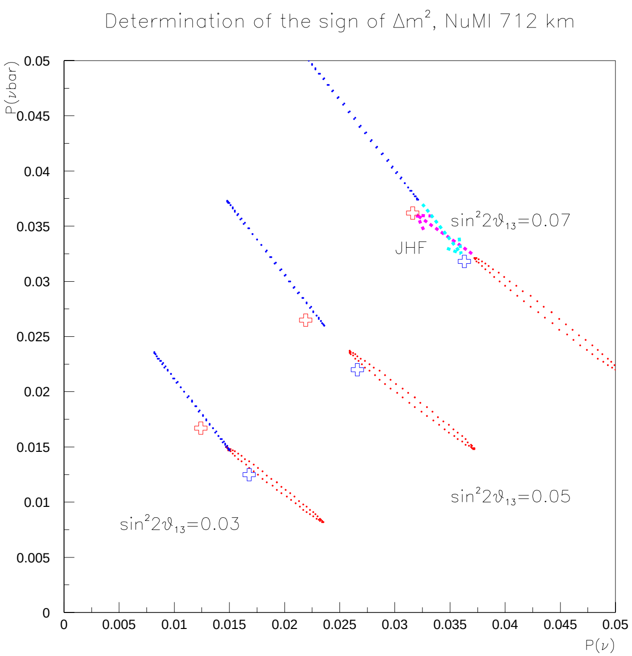
Phase II (running 2014-2020)

- 200 kton (fiducial) detector with ε~35-40%
- 20×10^{20} protons per year (new proton source?)
- 1.5 years neutrino (120000 ν_μ CC, 70-80% 'oscillated')
- 5 years antineutrino (130000 ν_μ CC, 70-80% 'oscillated')

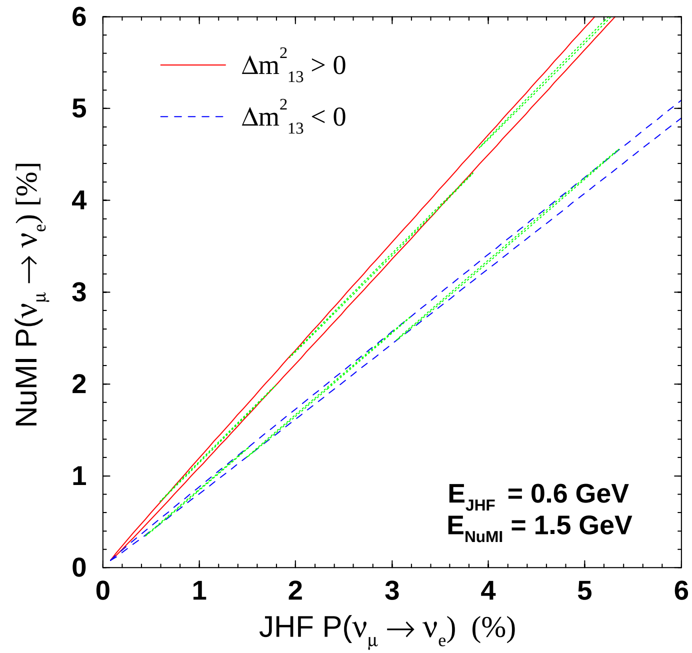
NuMI and JPARC experiments in numbers (Phase I)

	NuMI Off-axis 50 kton, 85% eff, 5 years, 4×10^{20} pot/y		JHF to SK Phase I, 5 years	
	all	After cuts	all	After cuts
ν_μ CC (no osc)	28348	6.8	10714	1.8
NC	8650	19.4	4080	9.3
Beam ν_e	604	31.2	292	11
Signal (Δm^2_{23}=2.8/3 x 10^{-3}, NuMI/JHF)	867.3	307.9	302	123
FOM (signal/$\sqrt{}$bckg)		40.7		26.2

Determination of mass hierarchy: complementarity of JPARC and NuMI



Combination of different baselines: NuMI + JPARC extends the range of hierarchy discrimination to much lower angles mixing angles. P(NuMI) - P(JPARC) measures the mass shift due to matter effects



Mass hierarchy determination with NuMI alone: reach depends on δ

Minakata,Nunokawa, Parke

Conclusions I (NuMI/MINOS)

- NuMI beam construction nearing completion. First operation expected end of 2004.
- MINOS:
  - Far detector operational
  - Near detector 'constructed', will be installed in 2004,
- MINOS: ν_μ disappearance
  - Will demonstrate oscillatory energy dependence
  - Precision measurements of Δm^2, $\sin^2(2\theta)$ (10%)
- ν_e appearance
  - Improved bounds on $|U_{e3}|^2$
- Physics starting April 2005

Conclusions II (Off-axis)

- NuMI Off-axis beam offers a very powerful tool to study nue appearance
- Phase I detector will establish the existence of the effct (or improve the CHHOZ limit by a factor of ~20). With some luck it may establish the mass hierarchy, or even detect CP violation
- Phase II detector + proton driver may be able to establish/measure parameters of CP violation in a neutrino sector, or improve the limit by another factor of 10..

Conclusions III(General)

- Neutrino Physics is an exciting field for many years to come
- Most likely several experiments with different running conditions will be required to unravel the underlying physics. Healthy complementary program is shaping up (JPARC).
- Fermilab/NuMI beam is uniquely matched to this physics in terms of beam intensity, flexibility, beam energy, and potential source-to-detector distances that could be available.
- Important element of the HEP program in the US for the next 20 years.