NuMI Overview:
Physics On and Off Axis

- NuMI Construction & Installation Status
- MINOS Near & Far Detector Status
- MIPP
- NuMI Beam Options
  - Moving target
  - ν-bar
  - Off-Axis Beam Possibilities
- Summary

Neutrino Oscillations: What we know now

Muon neutrinos disappear at Δm^2 of few 10^{-3} eV^2 (SuperK, K2K,Soudan II, Macro)

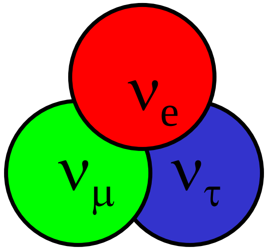
Electron neutrinos disappear at Δm^2 of several 10^{-5} eV^2 (Homestake, SAGE, GNO, SuperK, SNO)

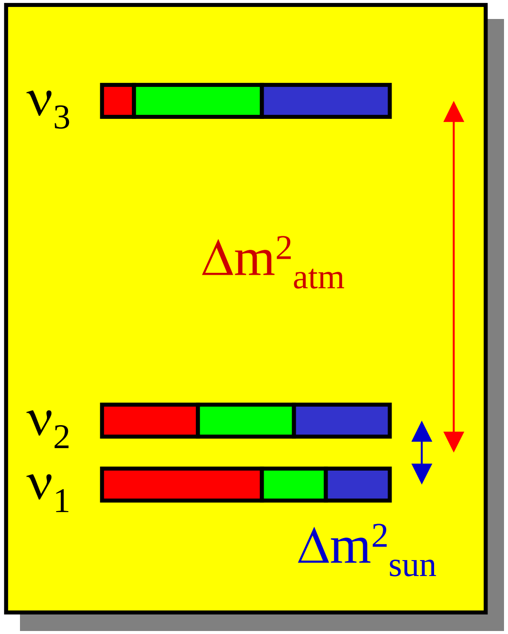
Electron antineutrinos also disappear , more likely at several 10^{-5} eV^2 (KamLand)

Electron neutrinos convert into other active neutrinos (SNO)

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

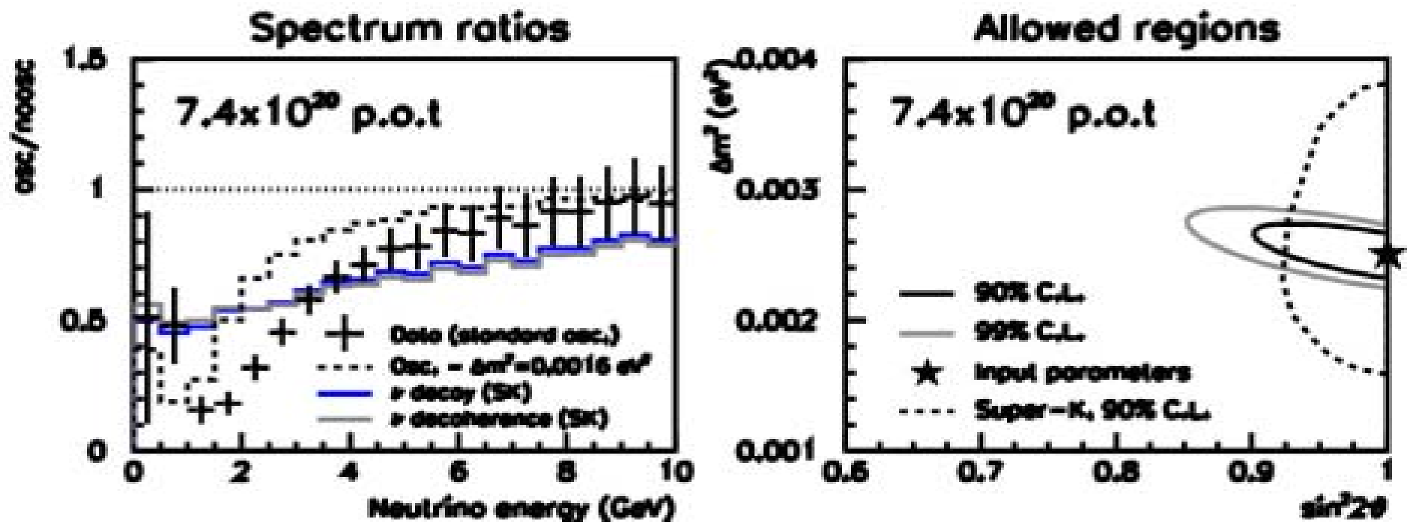
$$\begin{bmatrix} \nu_e & \nu_\mu & \nu_\tau \end{bmatrix} = \begin{pmatrix} U^*_{e1} & U^*_{e2} & U^*_{e3} \\ U^*_{\mu 1} & U^*_{\mu 2} & U^*_{\mu 3} \\ U^*_{\tau 1} & U^*_{\tau 2} & U^*_{\tau 3} \end{pmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$





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

ν_μ Disappearance at MINOS



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 and antineutrinos?

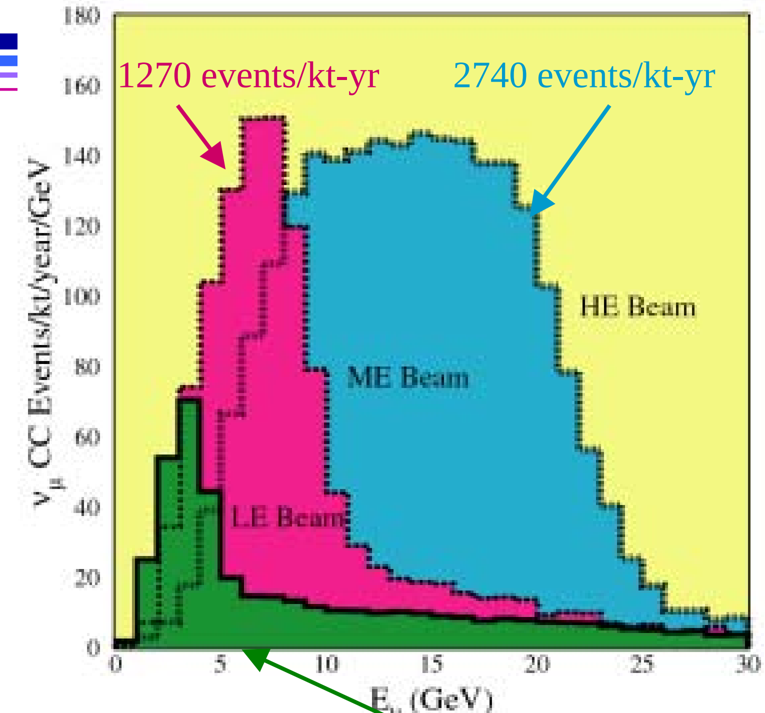
- Dip depth ←→ oscillation amplitude ($\sin^2 2\theta_{23}$)
- Shape of disappearance probability ←→ Δm^2_{23} ($\pi/2 = 1.27 \text{x} \Delta m^2_{23} \text{x} L/E_{dip}$)

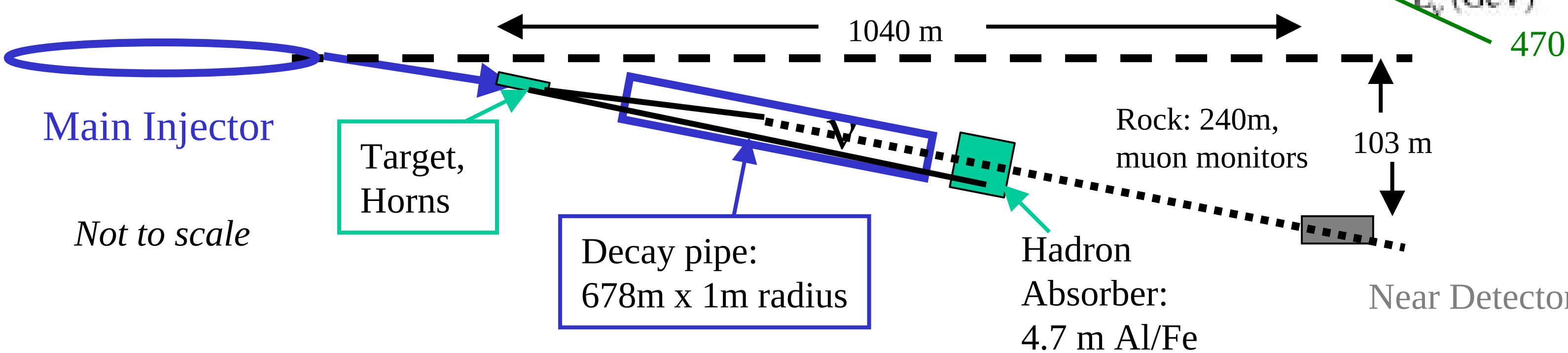
MINOS Physics

- Demonstrate oscillatory behavior
  - Precise measurement of CC energy distribution between near & far detectors (2-4% sys. uncertainty in E_ν per GeV bin)
  - "Standard" or non-standard oscillations?
- Precise measurement of oscillation parameters
  - Δm^2_{23} at ~ 10%
  - How close to 1.0 is $\sin^2 2\theta_{23}$? (Can test to ~5% level)
    - Are we looking at a new fundamental symmetry?
- Improved determination of flavor participation
  - # of CC ν_μ events far/near (for ν_μ -> ν_x at about ~2%)
  - # of CC ν_e events far/near (for ν_μ -> ν_e down to about 2%)
  - # of NC events far/near (for ν_μ -> ν_s down to about 10%)
- Direct measurement of atmospheric ν_μ vs $\bar{\nu}_\mu$ disappearance
  - CPT Violation

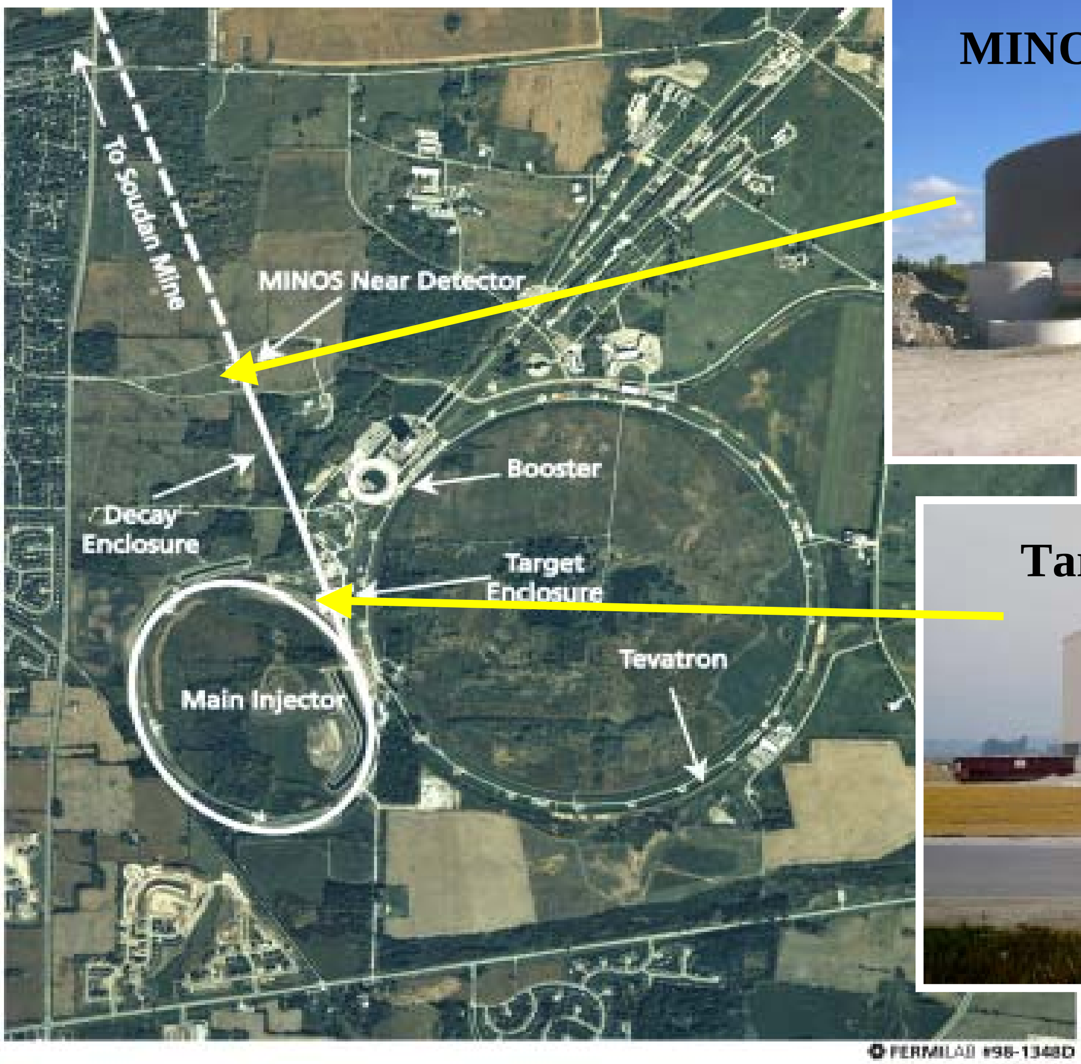
NuMI Beam

- 120 GeV Protons from Fermilab Main Injector
- 10μs pulse, every 1.9s
- Proton Intensity:
  - « $4x10^{13}$ protons/pulse design
  - « $2.5x10^{13}$ p/p expected at startup
- Hadrons focused with 2 horns
  - « Select beam energy spectrum by adjusting relative horn and target positions





NuMI Beamline Overview



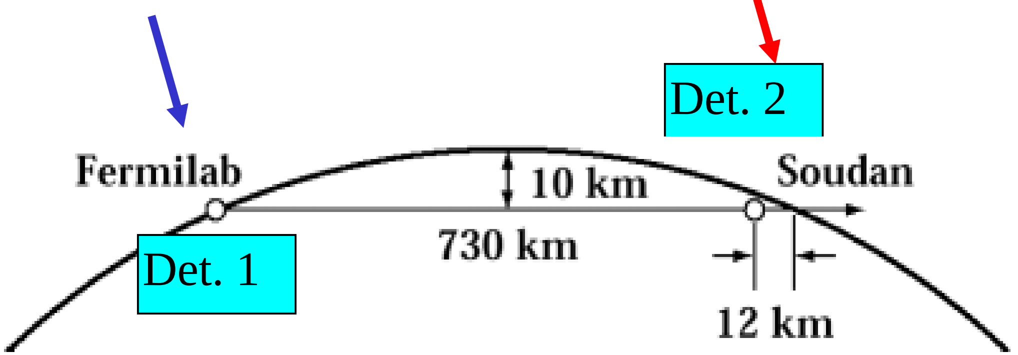
MINOS Experiment

Construct Facilities and Equipment for a Two Detector Neutrino Oscillation Experiment with Variable Energy Neutrino Beam (Start 2005)

Obtain firm evidence for oscillations and measure oscillation parameters, Δm^2, $\sin^2 2\theta$. Probe for $\nu_\mu \rightarrow \nu_e$ appearance.

Far Detector: 5400 tons

Near Detector: 980 tons



NuMI Project Status

NuMI Beam(Beam commissioning planned for January 2005)**:**

- Design status -> “complete”, Beamline ~70% complete overall for all systems
- Testing done on: horns, remote clamp, transmission line, horn power supply
- Prototype piles/stacking of: T-blocks, target pile, hot cell
- Accelerator and extraction beam studies for NuMI, proton intensity working group
- Beam commissioning planned for January 2005

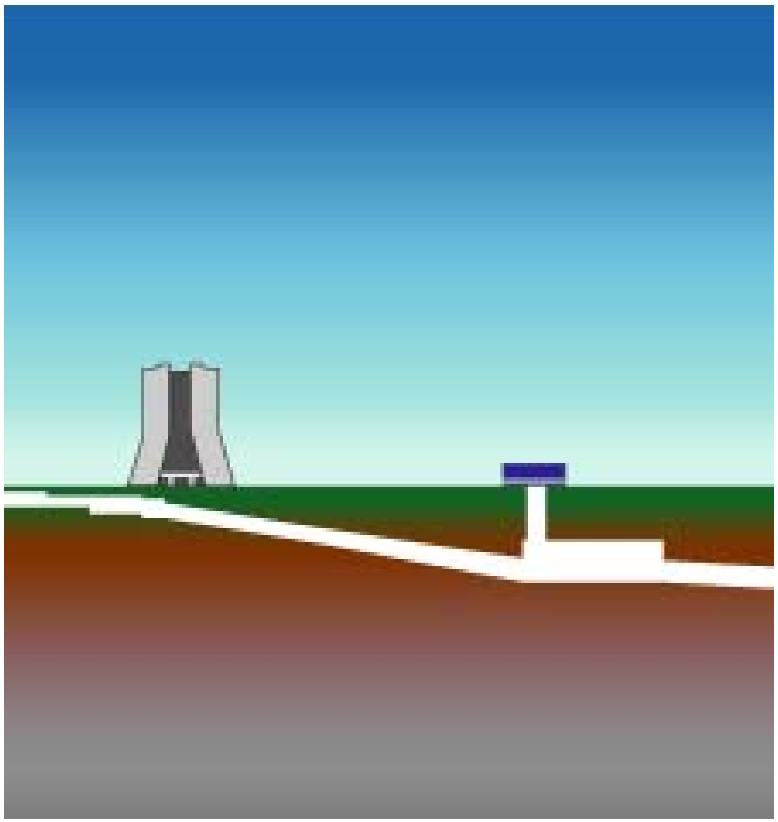
Near Detector

- Near Detector planes surface assembly complete
- DAQ racks being assembled
- Installation starts Feb. 2004
- Calibration Detector run complete at CERN PS
  - **EM & Hadron response & event topology**
  - **Near/Far readout comparison**

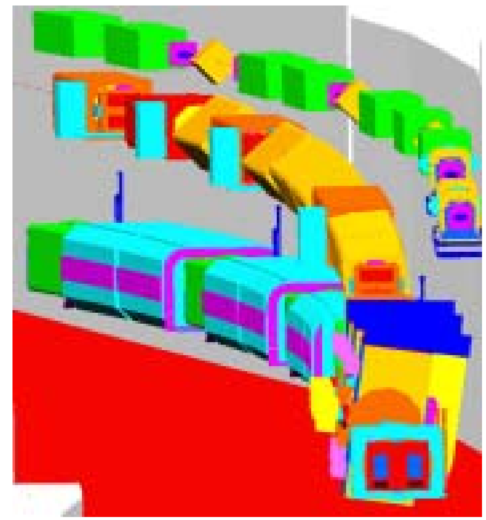
Far Detector – Finished August 2003!!!

- Taking atmospheric neutrino data as we speak

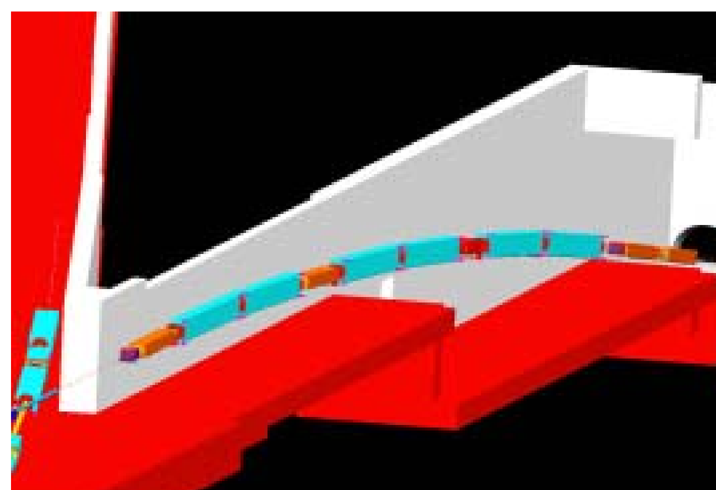
Adding a new Beamline to Fermilab



From Main Injector to Extraction to Stub to Target

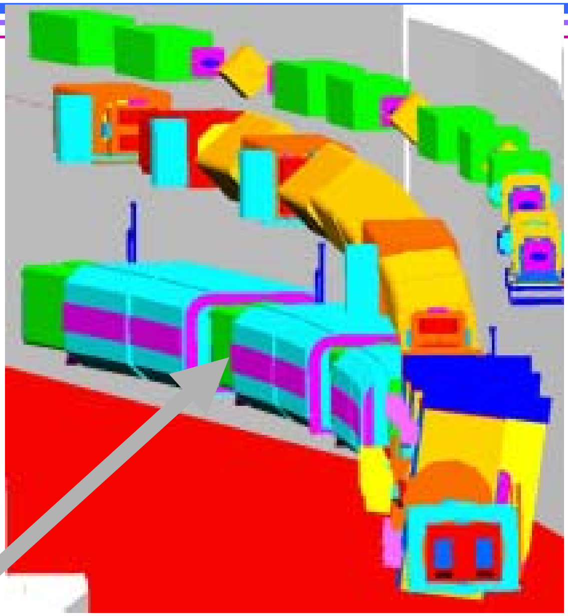


MI ring on bottom, Recycler on top, NuMI in the middle
(fit between two accelerators)



NuMI Stub and beyond…

NuMI Primary Beam Installation: Upstream Extraction Region



Lambertsons being baked out

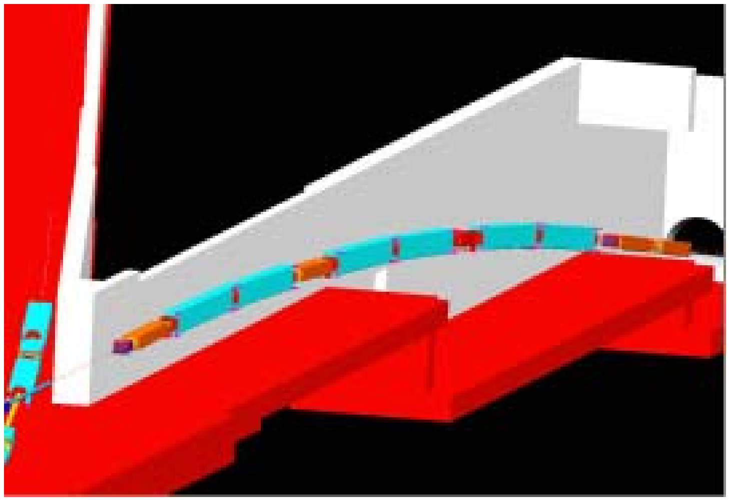
MI ring on bottom, Recycler on top, NuMI in the middle (fit between two accelerators)

Extraction region

NuMI

MINOS

NuMI Primary Beam Installation: Downstream Region



From NuMI Stub…

to carrier tunnel (lined section)

..to Peter's Porch

NuMI Primary Beam: Pre Target Hall Region

Downstream end of carrier tunnel, at Beneficial Occupancy

Pre Target at Beneficial Occupancy

(installation of magnets/instrumentation underway now in both these places)

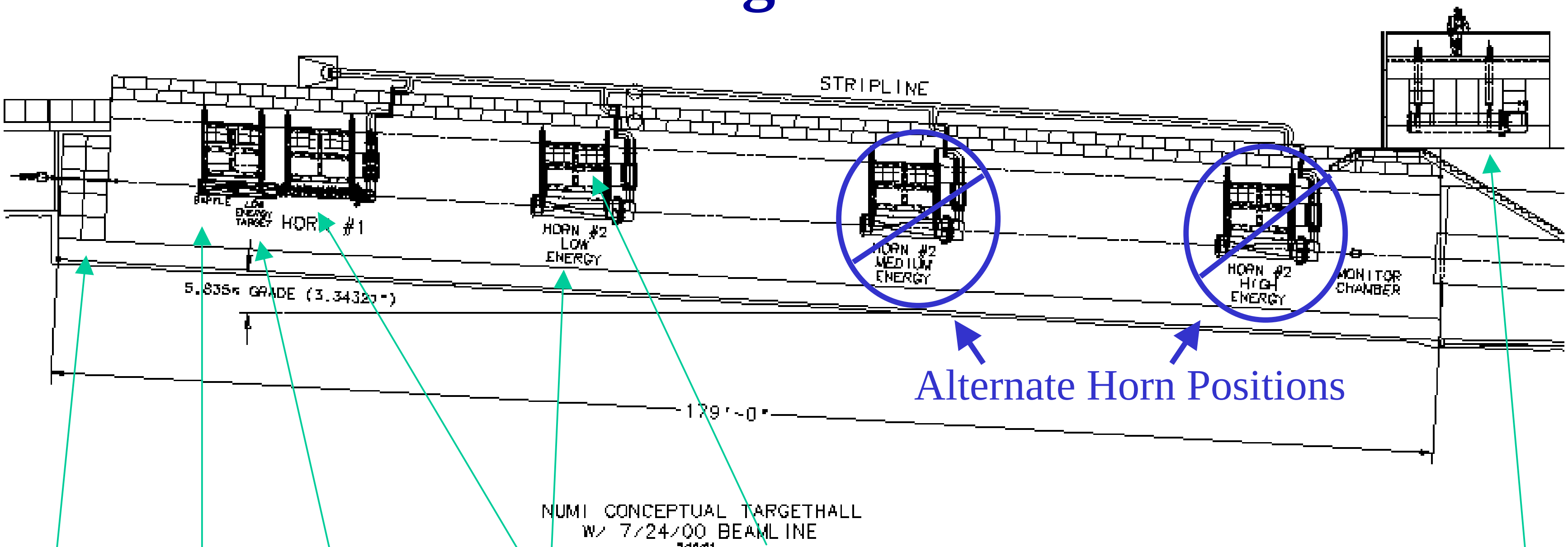
NuMI Project: Target Hall & Support Rooms

- Horn Power Supply Room, penetration for transmission line to Target Hall horns

- Installation of rails in the Target Hall pit

- Radioactive Water Room (RAW) and piping through penetration to Target Hall

Neutrino Beam Production Devices and Target Pile



Beamline Component Positioning Modules

Two Types of Magnetic Focusing Horns

Pion Production Target (plus readout of target, vacuum pump)

Baffle to protect horn from beam accidents

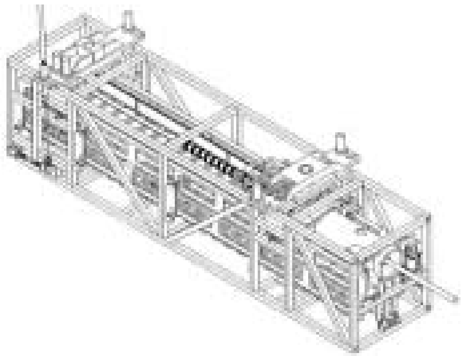
Target Hall Radiation Shielding

Hot (Radioactive) Component Workcell and Hot Handling Procedures/Tooling

Shield Pile Recirculating Air Cooling System

Target Hall in pictures

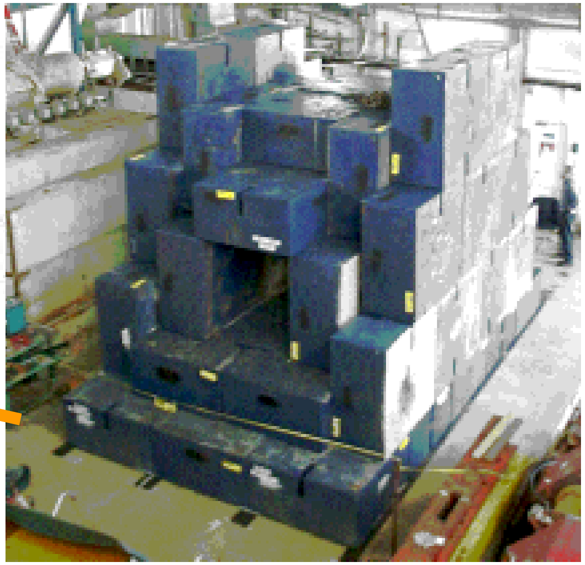
(plus recirculating air cooling, target, hot work cell, etc)



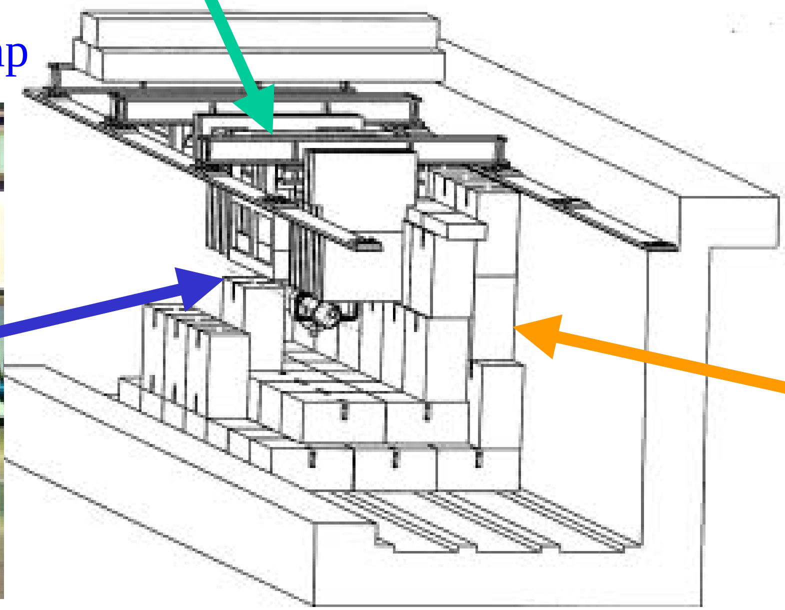
Target with motion system

1 of three 27 ton support modules

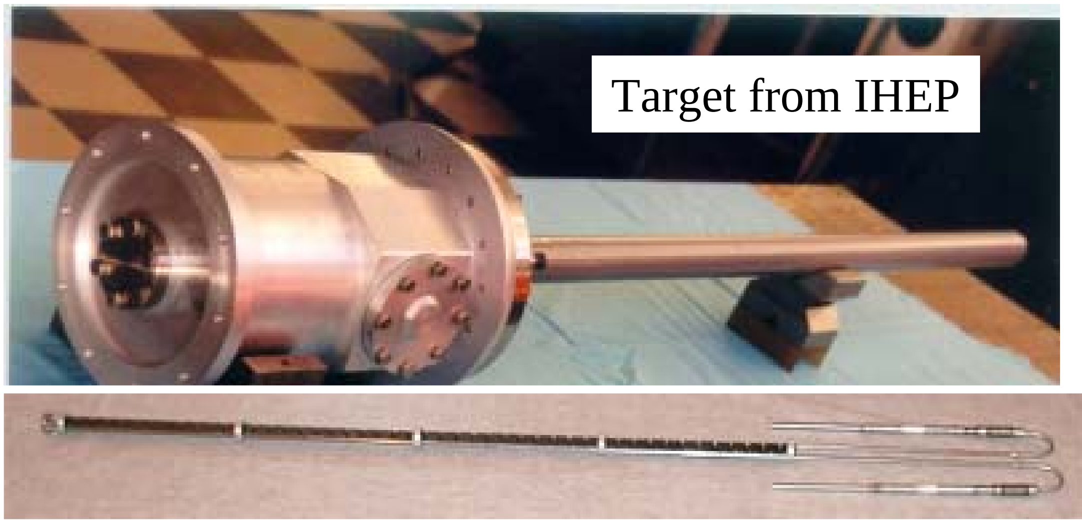
(10% of) Shielding Blocks



Horn 1, stripline, clamp



Neutrino Beam Devices

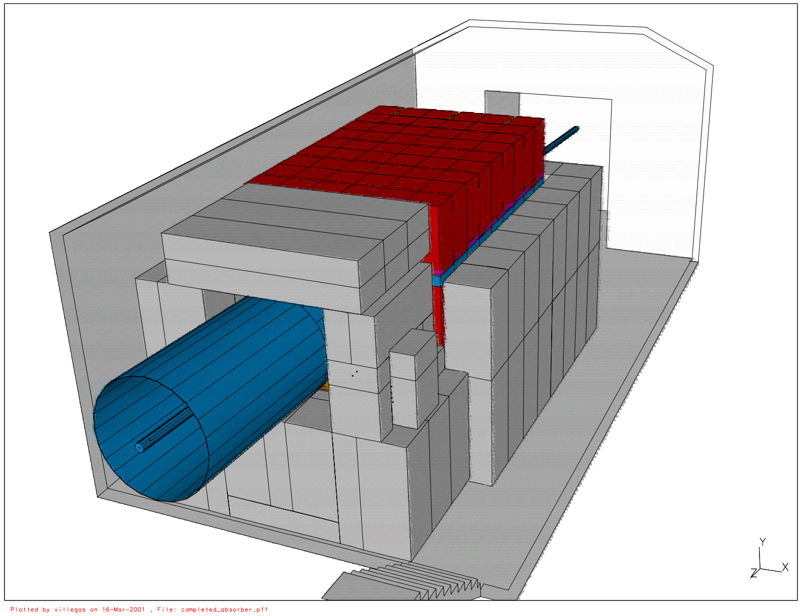


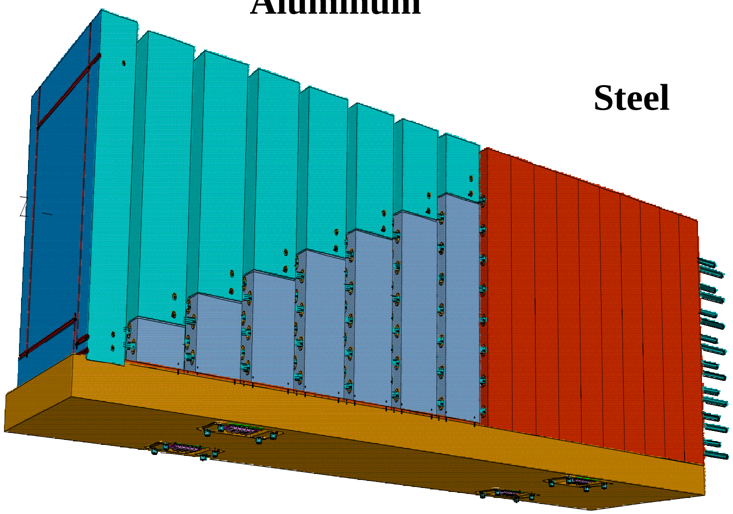
NuMI Secondary Beam : Decay Region Then & Now

- Decay tunnel before shielding pour: 11/22/02
- Decay tunnel now (concrete shielding, electrical, fire): 10/20/03

675m long, 2m diameter

Hadron Absorber





Absorber Cavern / Shield

Absorber Core

Presentation 15 March - J. Hylen

Decay Region & Hadron Absorber

- Decay region power deposition
  - 63 kW in 1 cm thick steel decay pipe
  - 52 kW in shielding concrete
  - Peak deposition in the steel is ~360 W/m (~ 50 m from target hall)
  - Drops to 20 W/m (at ~610 m)
  - Heat is removed by twelve copper water-cooling pipes, limiting decay pipe temperature to ~ 50 deg C

- Absorber core
  - 8 modules of aluminum with dual water-cooling paths
    - 30.5 x 129.5 x 129.5 cm^3 each
    - 8 kW peak power in one module (normal beam conditions)
  - Followed by 10 plates of steel, each 23.2 cm thick.

- Total power in Absorber region: 60 kW

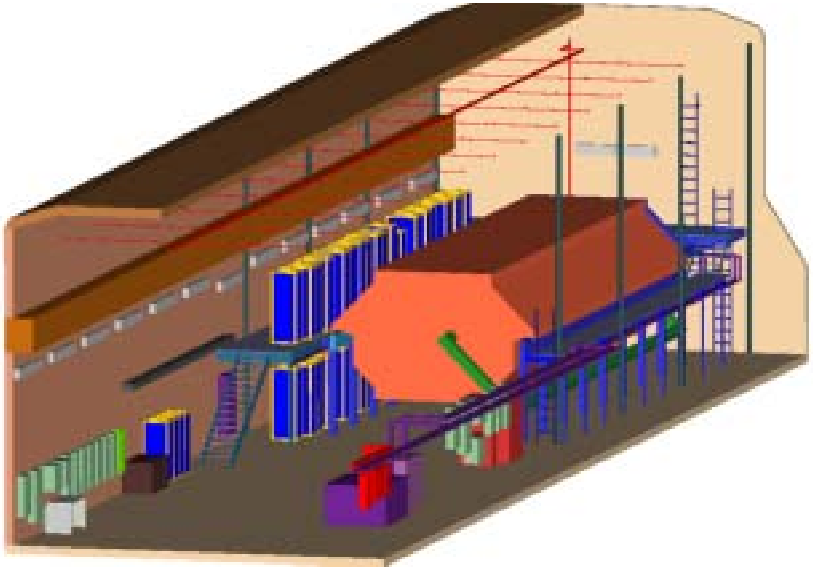
  (nearly entire 400 kW beam power in accident condition)

MINOS HALL: Then and Now

- MINOS Hall as delivered by S. A. Healy (drip ceiling over the detector): 11/22/02
- MINOS Hall now: 10/30/03
  - Steel near detector support structure
  - Crane installed
- Beneficial Occupancy of MINOS Hall: 1/31/04

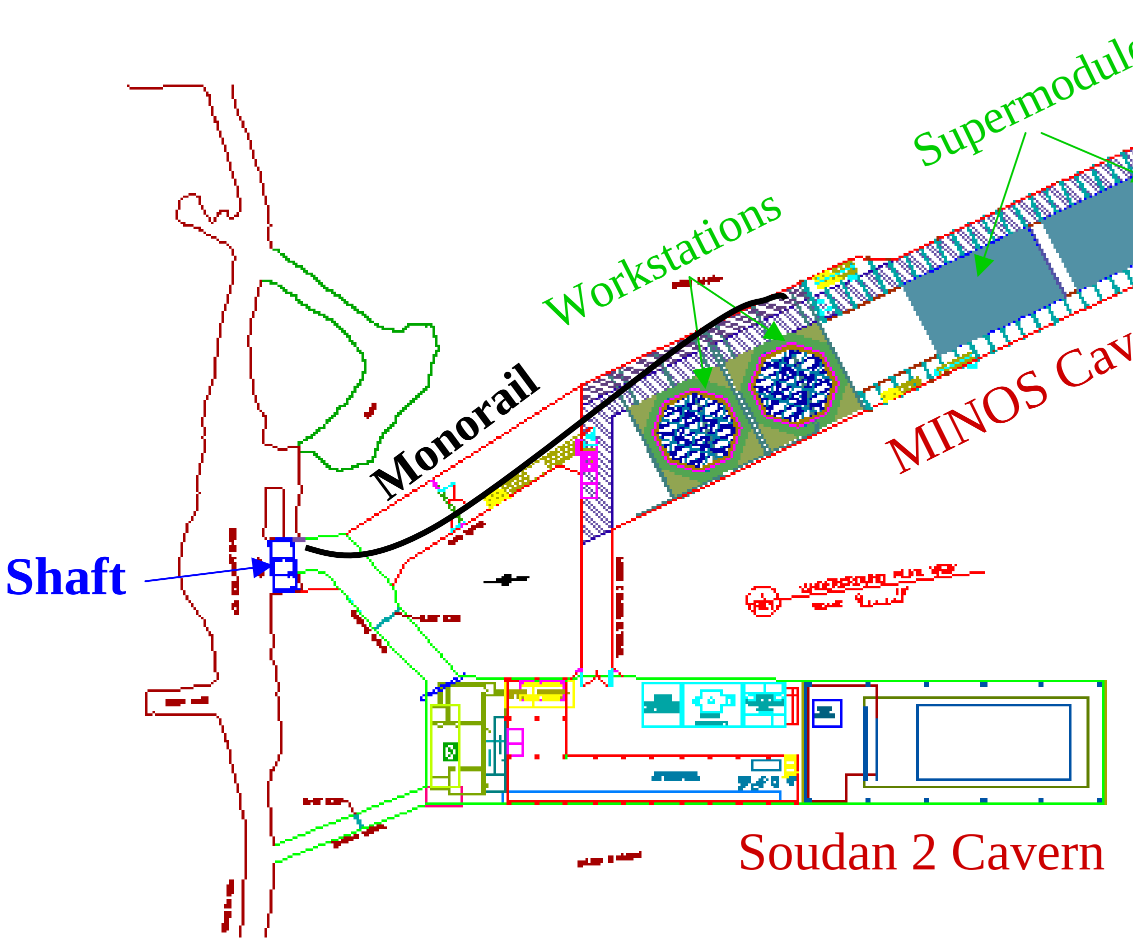
MINOS Near Detector

- **3.8 x 4.8m** “octagonal” steel & scintillator tracking calorimeter
- Same basic construction, sampling and response as the far detector.
- No multiplexing in the main part of the detector due to small size and high rates.
  - Hamamatsu M64 PMT
  - Faster Electronics (QIE)
- **282 planes of steel**
- **153 planes of scintillator**



Near Detector Construction/Assembly at New Muon Lab

Far Detector Cavern Layout, Soudan Underground Laboratory



MINOS Far Detector

- 8m octagonal steel & scintillator tracking calorimeter
  - Sampling every 2.54 cm
  - 4cm wide strips of scintillator
  - 2 sections, 15m each
  - 5.4 kton total mass
  - 55%/√E for hadrons
  - 23%/√E for electrons
- Magnetized Iron (B~1.5T)
- 486 planes of steel & scintillator
  - 26,000 m^2
  - 95,000 scintillator strips

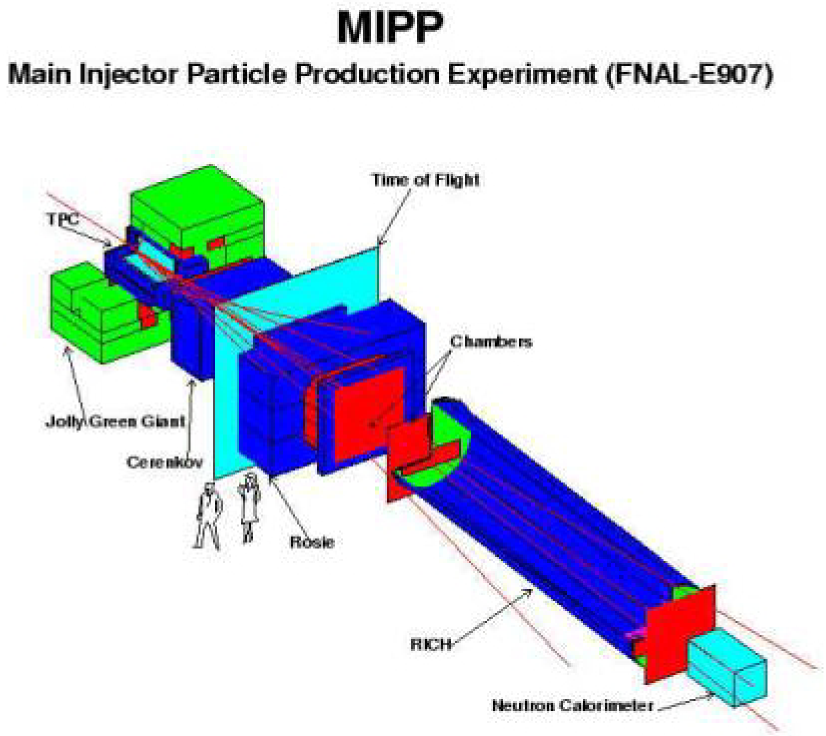
MINOS Far Detector:

Done, magnetized since July!

NuMI/MINOS Schedule

- Project far detector complete and operational.
- Upstream MI65 Beneficial Occupancy 10/20/03.
  - Upstream beamline installation in progress.
- Downstream MINOS Beneficial Occupancy 1/31/04.
- Upstream installation/pre-commissioning of Beamline complete: December 2004.
- Downstream installation of Hadron Absorber, beam monitors & near detector complete: December 2004.
- Near detector complete and tested late 2004.
- Beam/commissioning Dec 2004/January 2005.

MIPP: Measure Hadron Production



MIPP will start to run at FNAL in late 2003

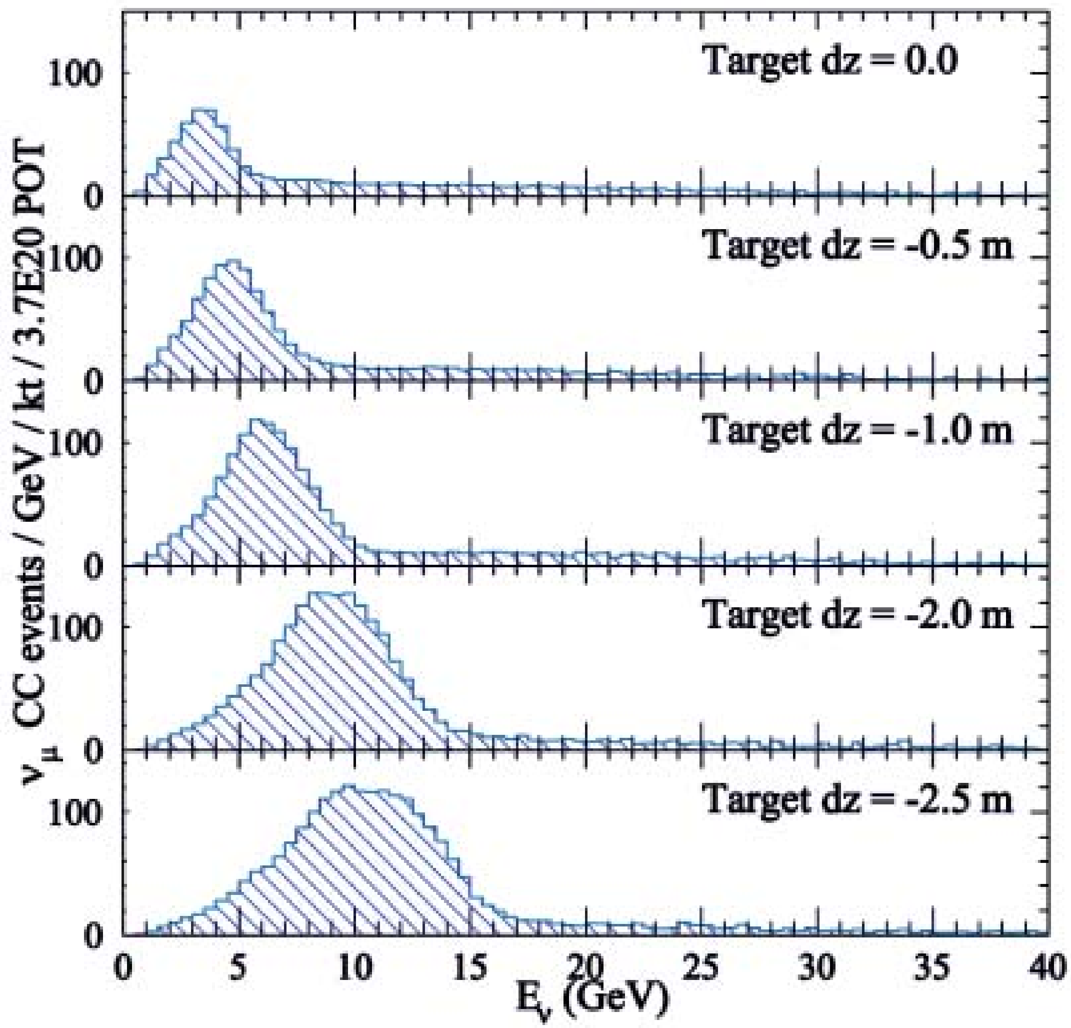
- Measure 120 GeV proton-carbon -> π, K, …
- Good precision, ~ 2%
- NOT single arm spectrometer
  - *get all P_t, P*
  - *acceptance correction easier*
- Use actual NuMI target

With NuMI precision horns and above MIPP hadron production measurements, will make very good prediction of ν flux in near detector

- *have already measured excellent magnetic field quality in horn 1*

With well understood near detector, and above flux predictions, will measure neutrino cross sections to a few %

NuMI: Tuning Neutrino Spectra by Horn/Target Reconfiguration



- Carbon target can move up to 2.5m on beam axis along with water, vacuum & electric lines
- Provides variable neutrino beam energy with real time control
- Can also move second horn, although much more difficult (need to build items ahead of time, restack blocks in hall, etc.)

NuMI Running: ν-bar Beam

Antineutrinos are crucial to understanding:

- Mass hierarchy (electron neutrino/antineutrino appearance)
- CP violation (electron neutrino/antineutrino appearance)
- CPT violation (muon neutrino/antineutrino disappearance)

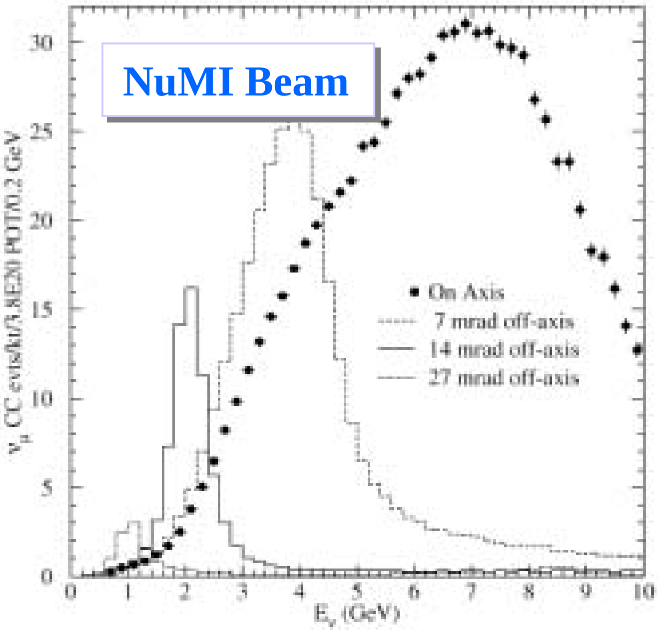
Common wisdom: antineutrinos are 'expensive': cross section ratio is ½ at high energies, 1/3 at NuMI energies.

NuMI ME beam: $\sigma(\pi^+)\sim1.15\sigma(\pi^-)$ (charge conservation!) so flux in antineutrino running is near flux in neutrino running

NuMI Running (electron neutrino appearance strategy, off axis):

- Start the experiment with neutrinos (move target around to better define signal)
- Run in that mode until either:
  - A definite signal is seen, or
  - Potential sensitivity with ν-bar could be significantly higher (x2?) than with ν's
- Switch to antineutrinos and run in that mode until either:
  - A definite signal is seen
  - Potential sensitivity improvement from additional running would be better with neutrinos

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



- Beam energy defined by the off-axis detector position (works in Low or Medium Energy Beam setting!)
- Narrow energy range (minimize all backgrounds)
- Simultaneous operation (with MINOS &/or other detectors)
- ~ 15mrad has narrowest energy spread 0.5% ν_e contamination
- Matter effects can differentiate mass hierarchies
- Baselines 700 – 900 km are possible

figure courtesy M.Messier

Off Axis Detector

- To see matter effects, want long baseline, but at right angle (~15mrad, ~800 km)
- Reasonable sites exist, we are investigating further

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

  - « Liquid scintillator or
  - « Glass RPC (resistive plate chamber)

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

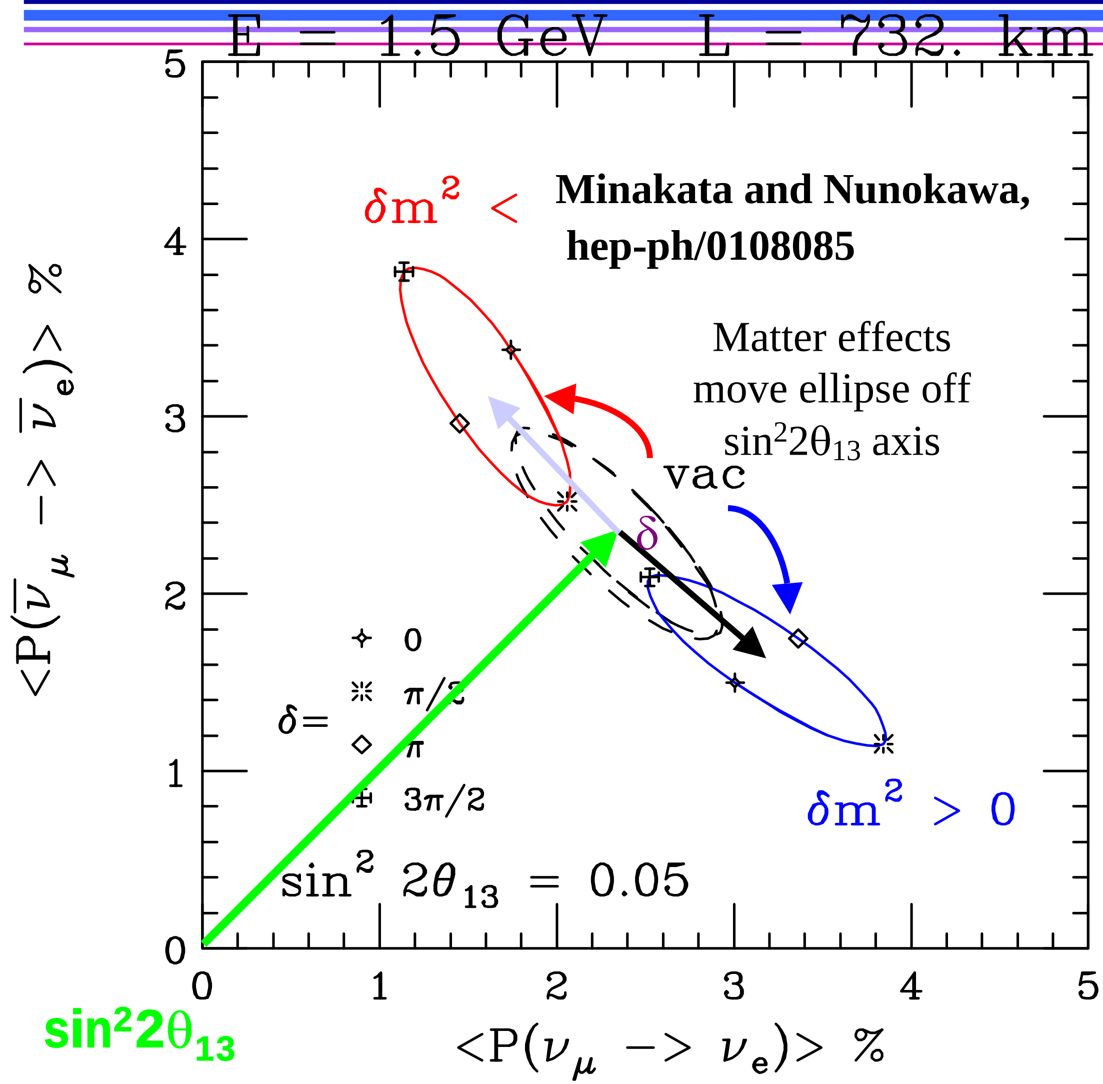
✓ Well known and understood detector technologies

✓ Primary challenge: (cheaply) engineer & construct 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, $\delta=0$), or
- Factor 20 improvement of the limit

From Probabilities to Mixing Angles



Observables are:

- P (neutrino appearance)
- $\overline{P}$ (antineutrino appearance)

$\sin^2 2\theta_{13}$: oscillations (0.05 assumed, green)

δ: CP violation, phase around ellipse

δm^2: matter effects (red & blue ellipses)

$\sin\delta$: length of ellipse

$\cos\delta$: width of ellipse

Matter effects and CP violation effects are of the same order as the main oscillation

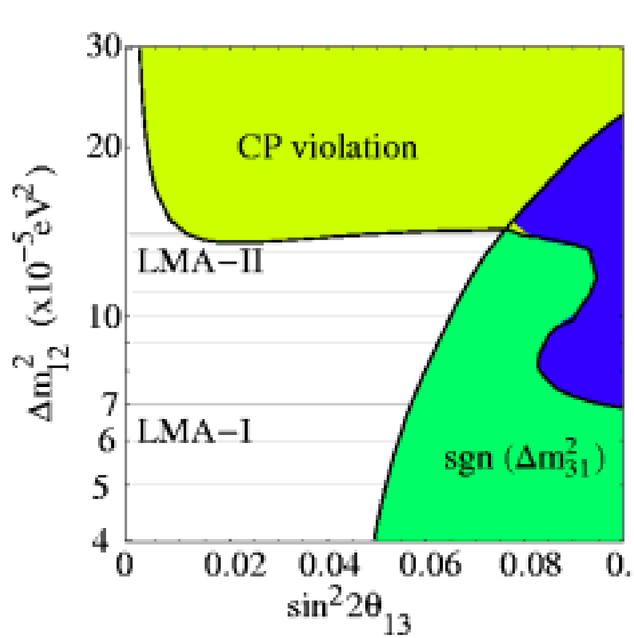
Comparison of NuMI-Off Axis and J-PARC to Super-K

(assumes $\sin^2 2\theta_{13}$=0.1)	NuMI Off-axis 50 kton, 85% eff, 5 years, 4×10^{20} pot/y (0.4MW)		J-PARC to SK Phase I, 5 years (0.8MW)	
	all	After cuts	all	After cuts
ν_μ CC (no osc)	28348	6.8	10714	1.8
Neutral Current	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
Figure Of Merit (signal/sqrt(bckg))		41		26

- NuMI off-axis makes up for lower proton power, and longer baseline with higher neutrino energy, longer decay pipe, and more fiducial mass.

But having two is much better than having twice as much of either experiment!

Huber, Lindner, Winter
Nucl. Phys. **B**654,2003



Status of NuMI: On & Off Axis

MINOS:

- Design is flexible to permit variations, upgrades
- Installation underway, commissioning end of 2004, physics starting April 2005.
- MINOS:
  - ✓ ν_μ disappearance: demonstrate oscillatory energy dependence, Precision measurements of Δm^2, $\sin^2(2\theta)$ (10%)
  - ✓ ν_e appearance
  - ✓ Improved bounds on $|U_{e3}|^2$

Off Axis (optimistic):

- NuMI off-axis experiment has complementary capabilities to JHF
- Off-axis collaboration: Letter of Intent 2002, done
- Proposal in preparation (November 2003)
- ~2 years for approval, funding starts 2006
- ~2 years to build, data taking starts 2008/2009