# Neutrino Experiments at Fermilab

- Physics Motivation
- Fermilab/NuMI neutrino beam(s)
- Experimental Program
  - MINOS
  - Off-axis experiment
  - ‘Other’ experiments
- Synergy of Neutrino Experiments and Opportunities for Collaborative efforts

# 11 Greatest Unanswered Questions of Physics

- What is dark matter ?
- What is dark energy ?
- How were the elements from iron to uranium made?
- **Do neutrinos have mass ?**
- …
- Are protons unstable ?
- What is gravity ?
- Are there additional dimensions ?
- How did the Universe begin ?

Discover
February 2002

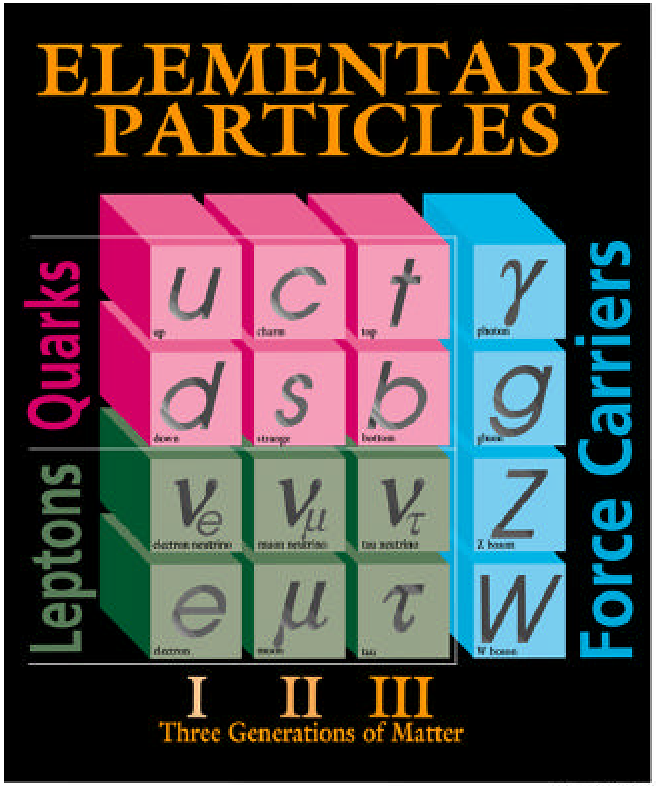
# Mass Generation: Central Problem in Particle Physics (II)

Version 2 (circa 2000)

1. Particles are massless
2. Higgs Peter (Pan?) comes and dispenses mass
3. Others get from their share (0.05 eV – 175 GeV)

Mass generation mechanism = payroll scheme with for workers with salaries ranging from <$0.00005 to $175,000,000. Bizarre ! Why such a colossal disparity ??

Perhaps, if we knew the salary pattern of the lowest paid workers we can get some insight into the underlying rules ➔ need to measure masses of the order of 0.01 eV and less



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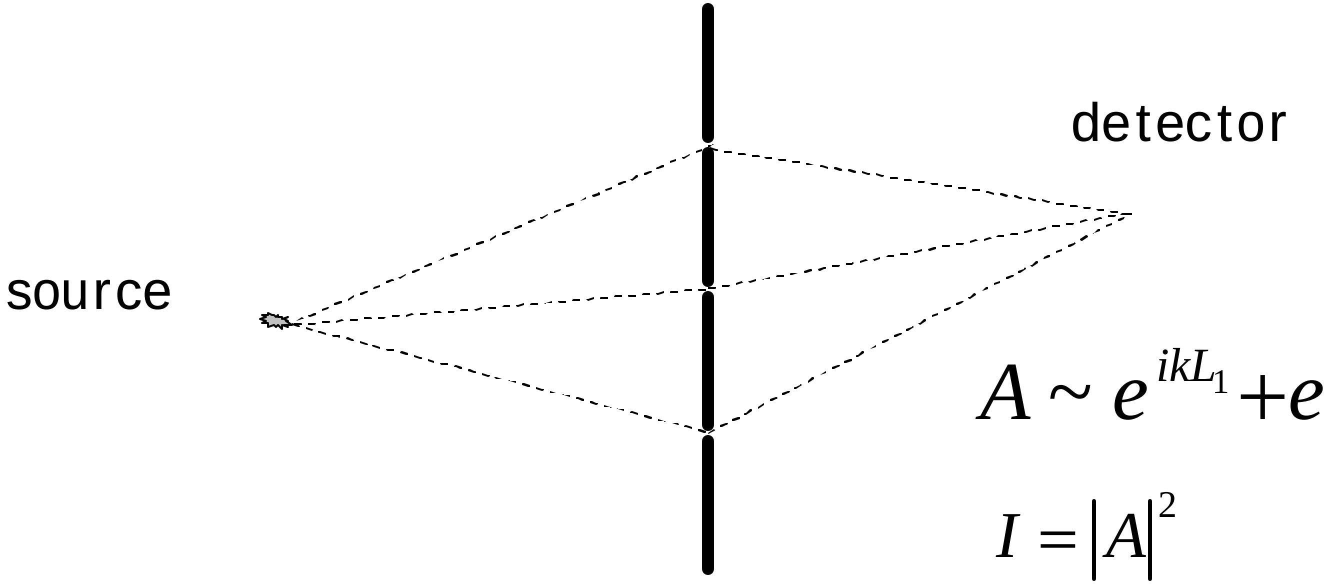
# Interferometry: a technique for precise measurement of mass differences

Three slit interference experiment



$$A \sim e^{ikL_1} + e^{ikL_2} + e^{ikL_3}$$

$$I = |A|^2$$

I(x) – interference pattern is a result of phase differences due to <u>optical path differences</u> (optics) or due to <u>different masses</u> of the neutrino components (neutrino oscillations).

Analogous to $K^0_S$-$K^0_L$ mass difference measurement.

# 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)

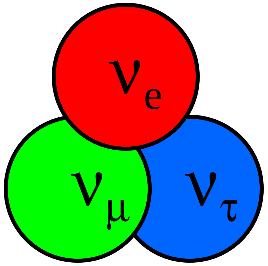
Electron neutrinos disappear (Homestake, SAGE, GNO, SuperK, SNO)

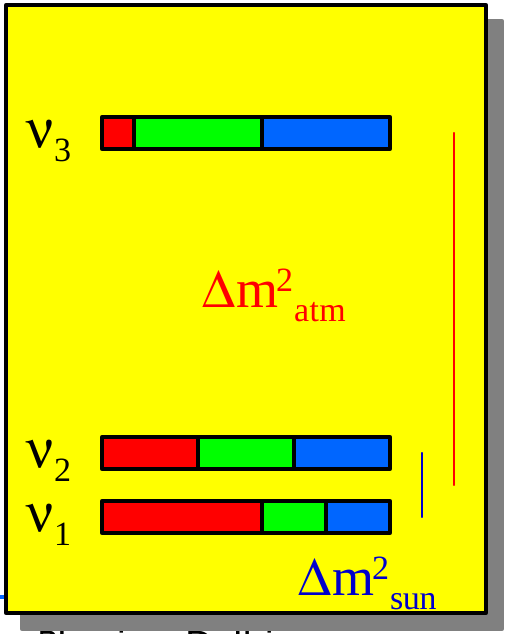
Electron antineutrinos disappear (KamLand)

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

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

$$\begin{bmatrix} n_e & n_m & n_t \end{bmatrix} = \begin{pmatrix} U^*_{e1} & U^*_{e2} & U^*_{e3} \\ U^*_{m1} & U^*_{m2} & U^*_{m3} \\ U^*_{t1} & U^*_{t2} & U^*_{t3} \end{pmatrix} \begin{bmatrix} n_1 \\ n_2 \\ n_3 \end{bmatrix}$$





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

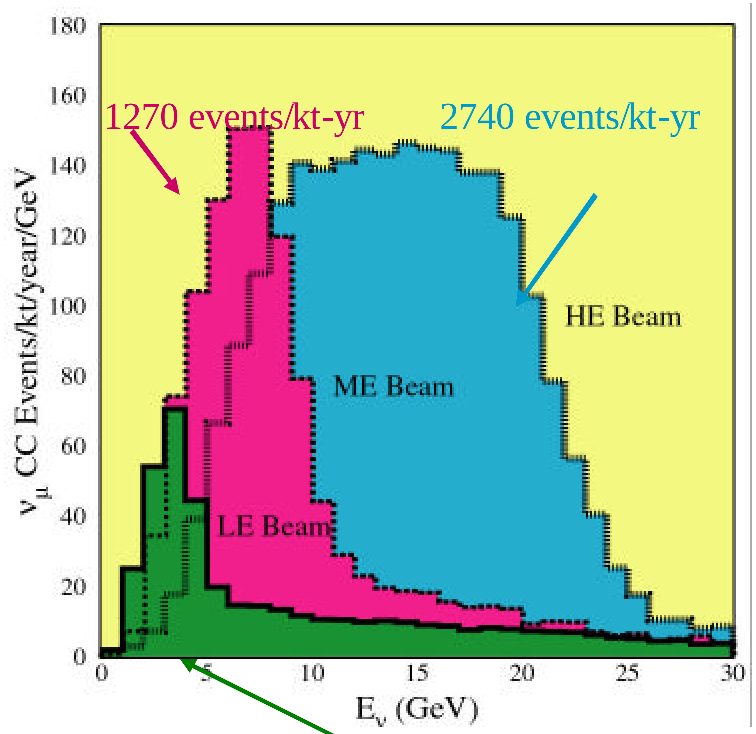
# What do we know/want to know better (I)

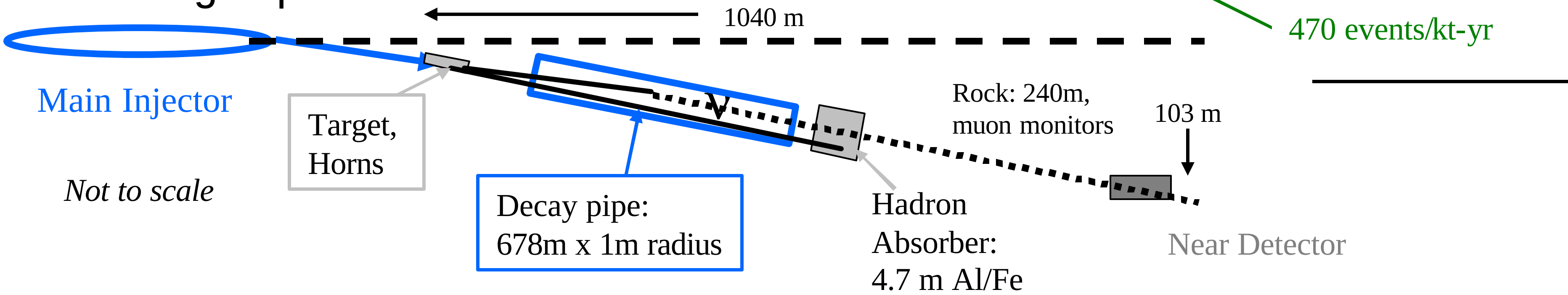
- There are two mass scales:
  - $\Delta m^2_{12} \sim 7\text{x}10^{-5}$ eV$^2$
  - $\Delta m^2_{23} \sim 1.5\text{-}3\text{x}10^{-3}$ eV$^2$
- Two mixing angles are large:
  - $\theta_{12} \sim 35^o$
  - $\theta_{23} \sim 90^o$ ($\sin^2 2\theta_{23} > 0.9$)
- Third mixing angle is not very large $\sin^2 2\theta_{13} < 0.1$
- 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 $\Delta m^2_{23}$?
- Is $\theta_{23} = 90^o$ ? Full mixing ➔New symmetry?
- What is the value of $\theta_{13?}$
- 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:
  - $4\times10^{13}$ protons/pulse design
  - $2.5\times10^{13}$ p/p expected at startup
- Hadrons focused with 2 horns
  - Flexible: select beam energy spectrum by adjusting horn and target positions




1040 m

Main Injector

Not to scale

Target,
Horns

Decay pipe:
678m x 1m radius

ν

Rock: 240m,
muon monitors

103 m

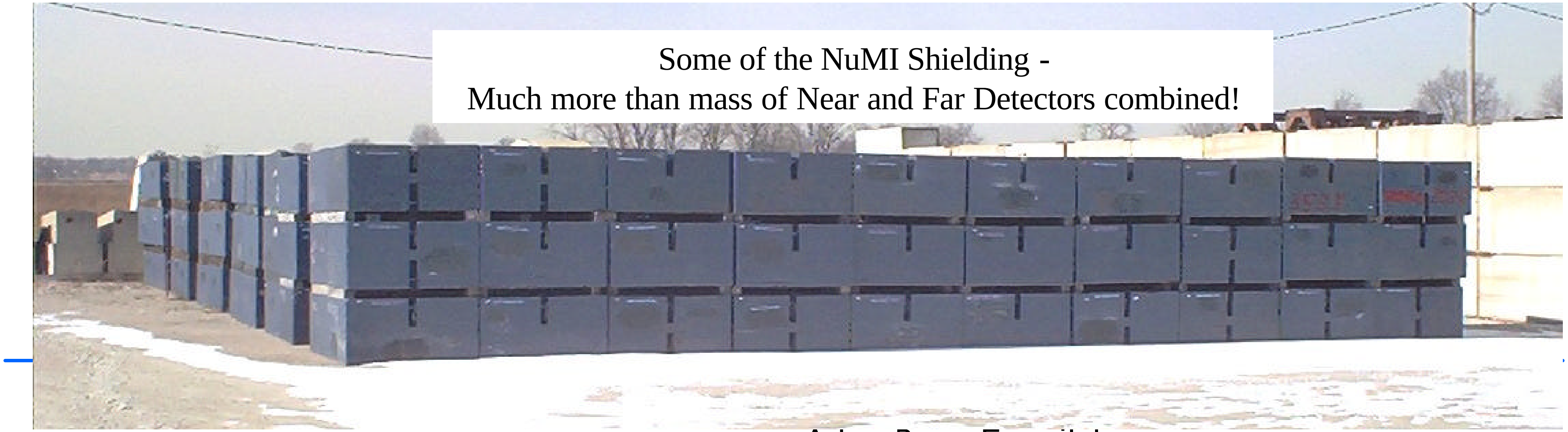
Hadron
Absorber:
4.7 m Al/Fe

Near Detector

# NuMI Beam Status

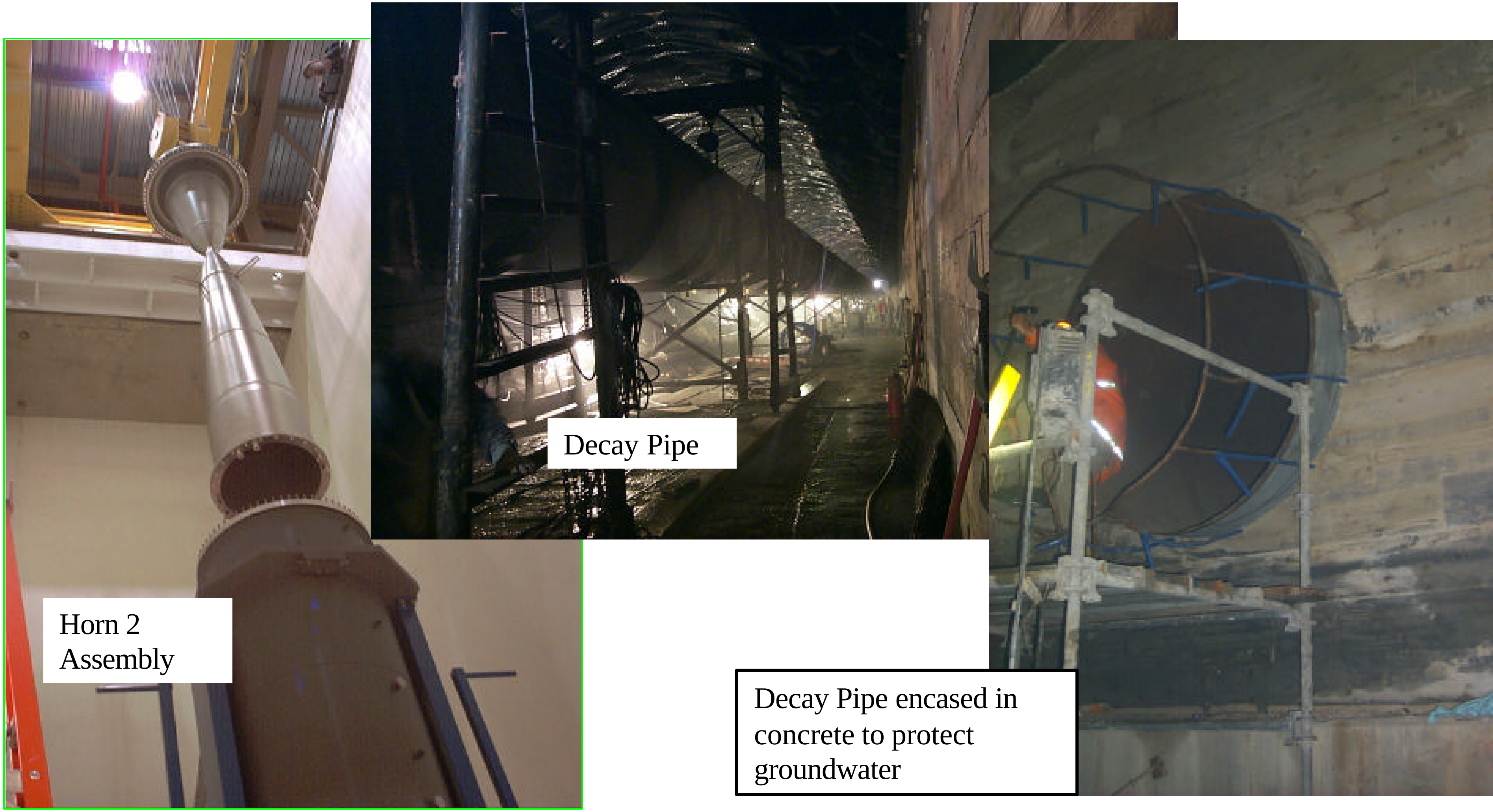
- Excavation of underground complex complete
- Decay Pipe installed
- Tunnel/Hall Outfitting in progress
- Target has been fabricated
- Horns have been assembled
- Project will be complete/ commissioning starts Dec. 2004

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

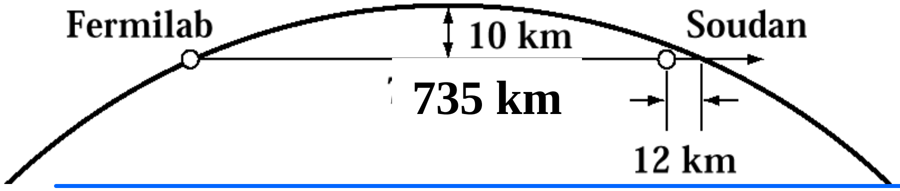
Decay Pipe

Decay Pipe encased in concrete to protect groundwater

# MINOS

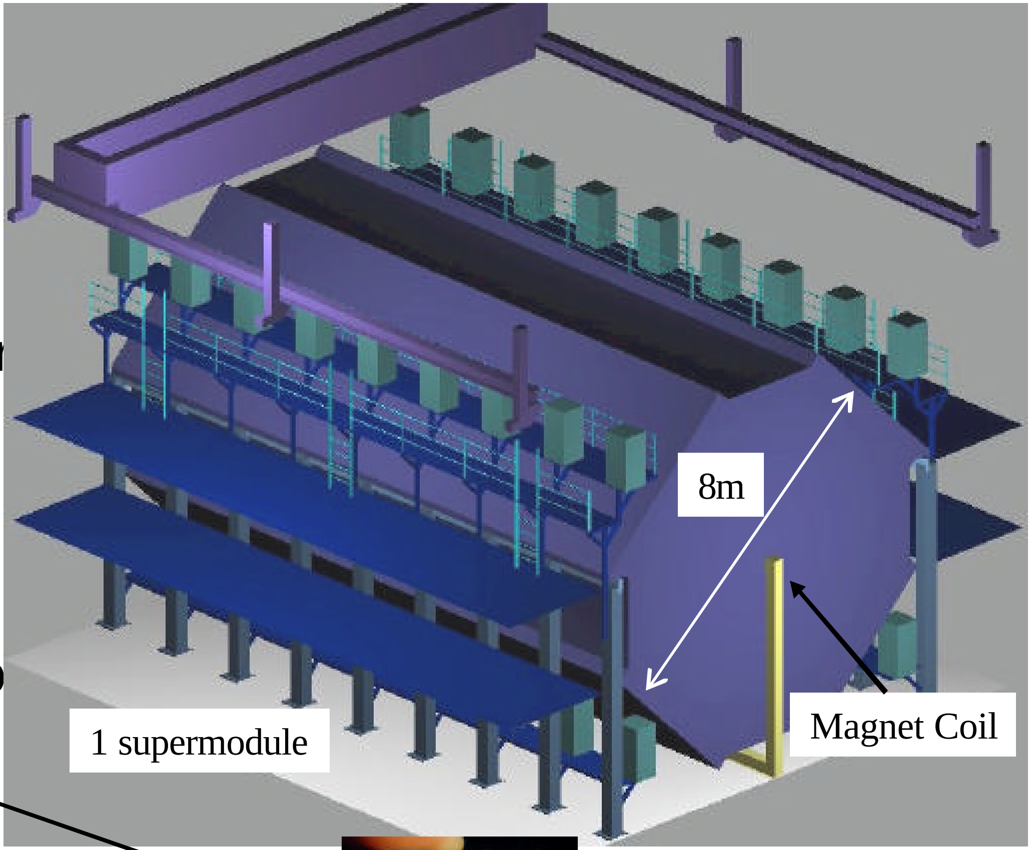
Main Injector Neutrino Oscillation Search

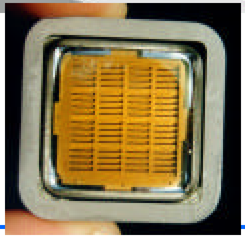
- Precision $\Delta m_{23}^2$ and $\sin^2(2\theta_{23})$ measurement in $\nu_\mu$ disappearance
- 2 detectors, functionally identical, separated by 735km baseline
  - Near Detector: 1kt detector at Fermilab
  - Far Detector: 5.4kt detector at Soudan



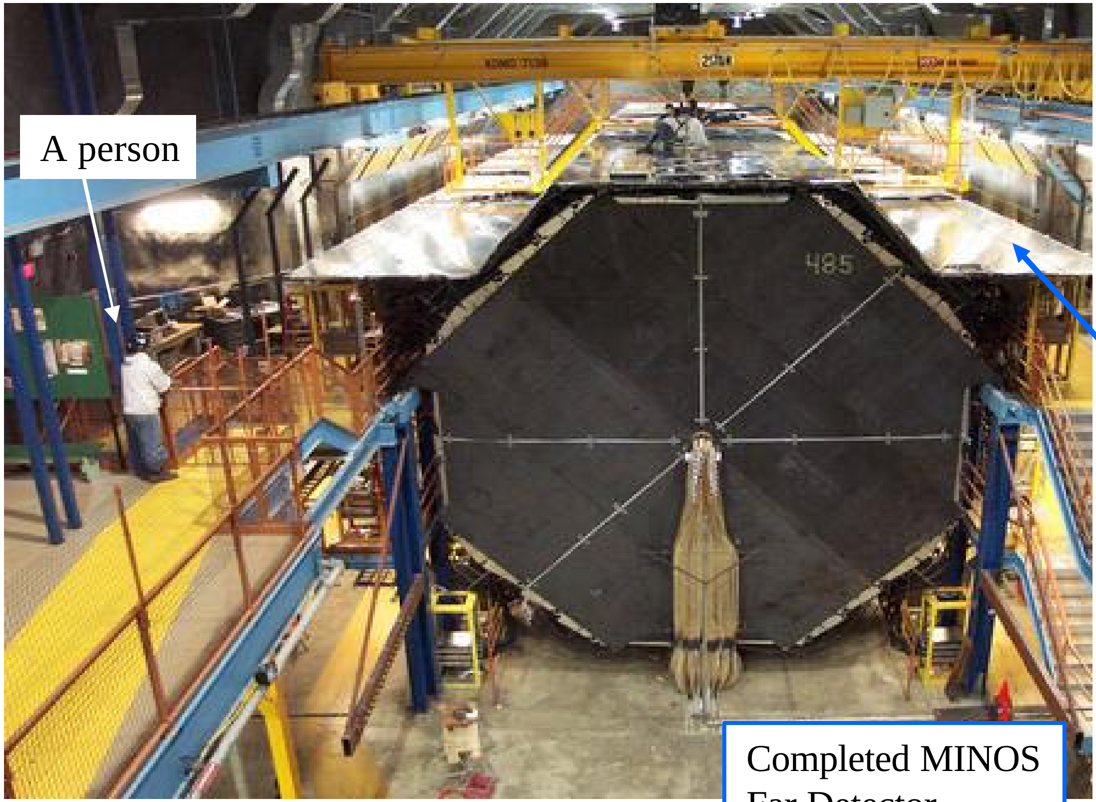
# Far Detector

- 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

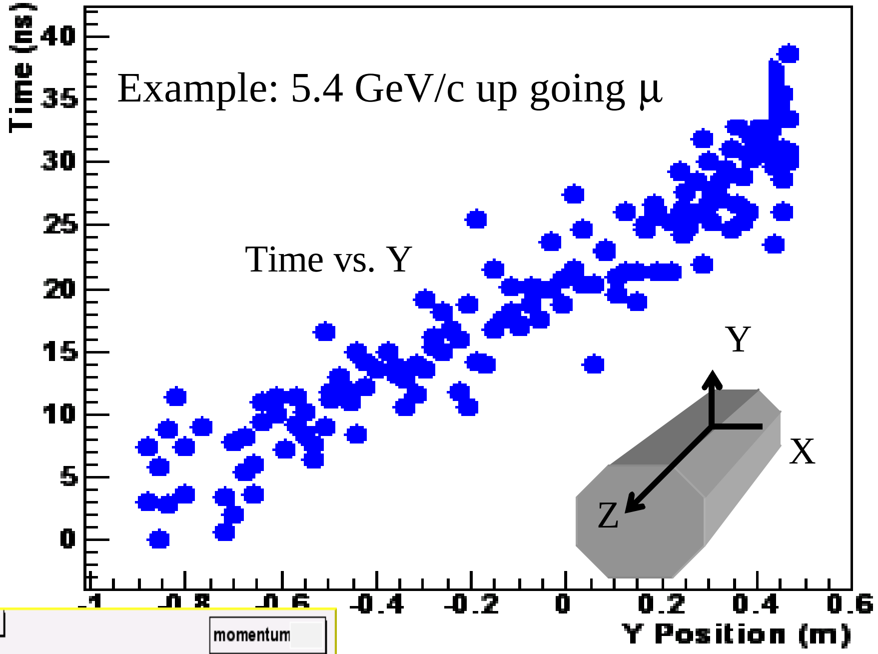


Completed MINOS Far Detector

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

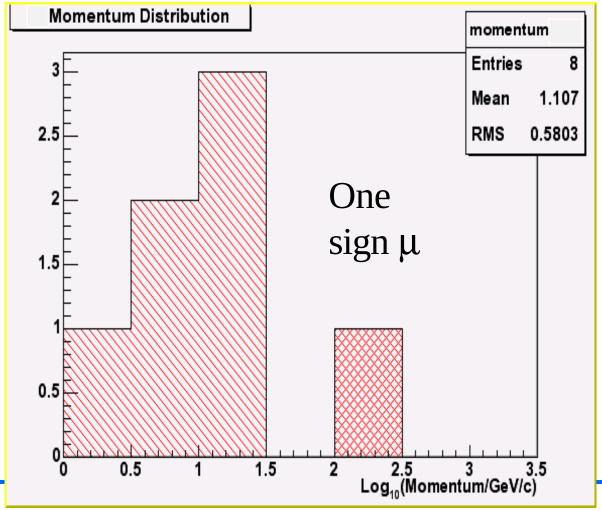
# Far Detector Data

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

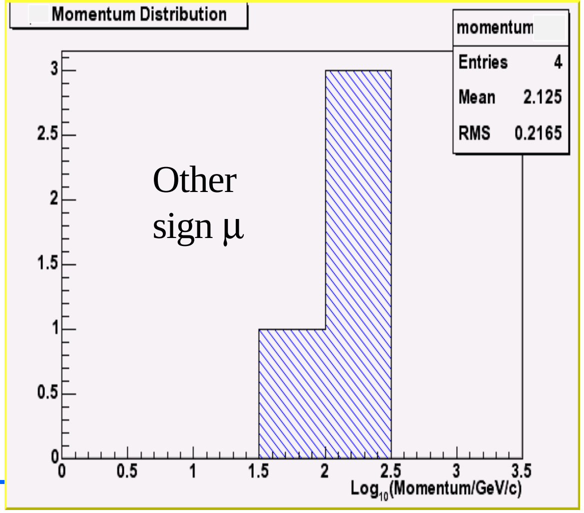


Example: 5.4 GeV/c up going μ

Time vs. Y



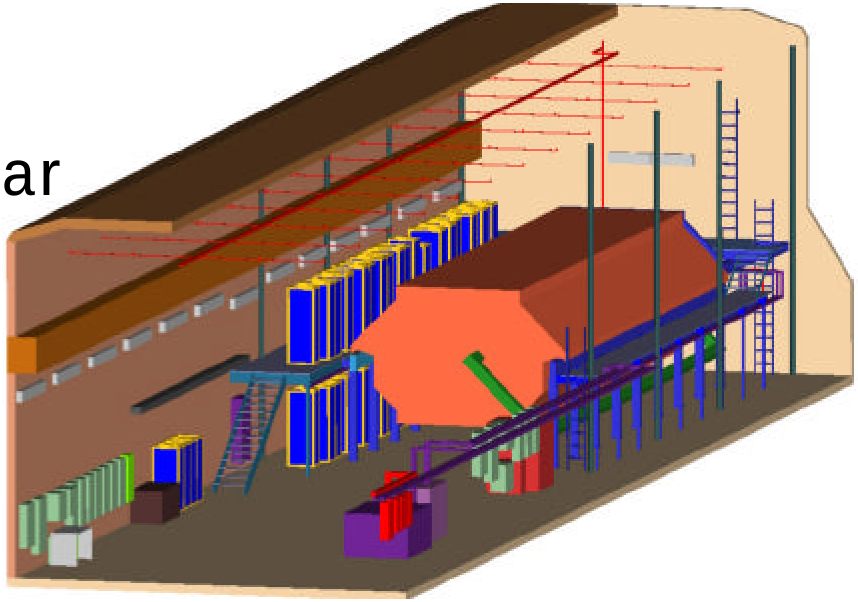
One sign μ



Other sign μ

MINOS PRELIMINARY UPGOING MUON DATA

# Near Detector

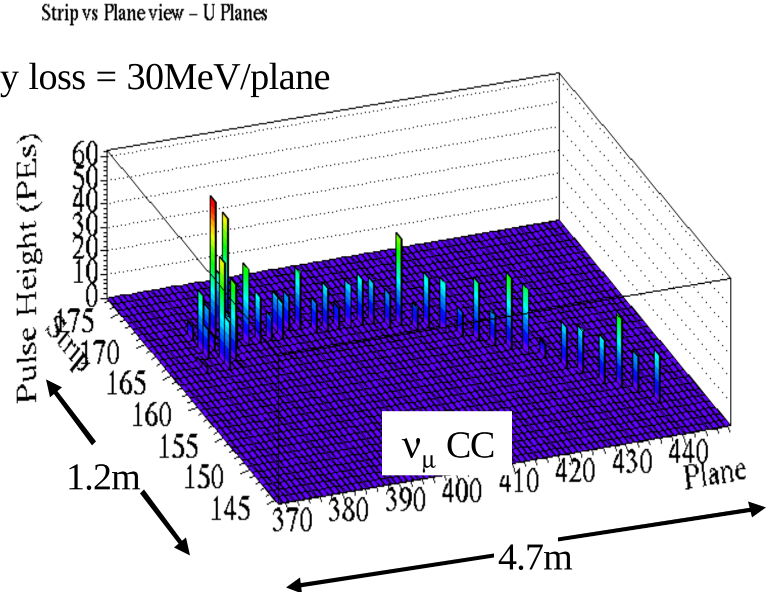


- Same sampling/structure as far detector
- 980 t
- High rate (10μs spill)
  - HE beam: 20 interactions/m/spill
  - LE beam: 3.2 interactions/m/spill
  - High speed electronics
  - 4x multiplexing in spectrometer only
- All Planes have been assembled in a surface building

# MINOS ν Event Topologies

- $\nu_\mu$ identified by μ in Charged Current interactions

MIP energy loss = 30MeV/plane

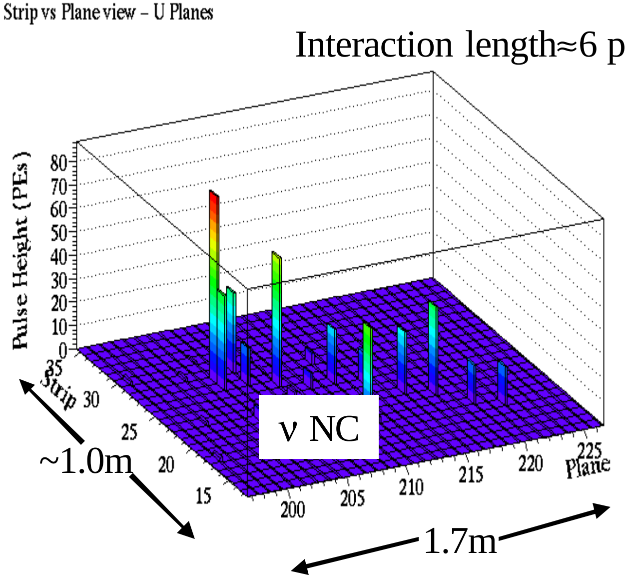


$\nu_\mu$ CC

1.2m

4.7m

Interaction length≈6 planes

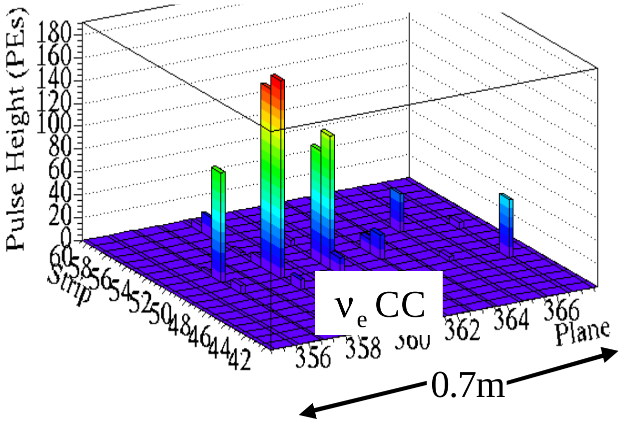


ν NC

~1.0m

1.7m

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

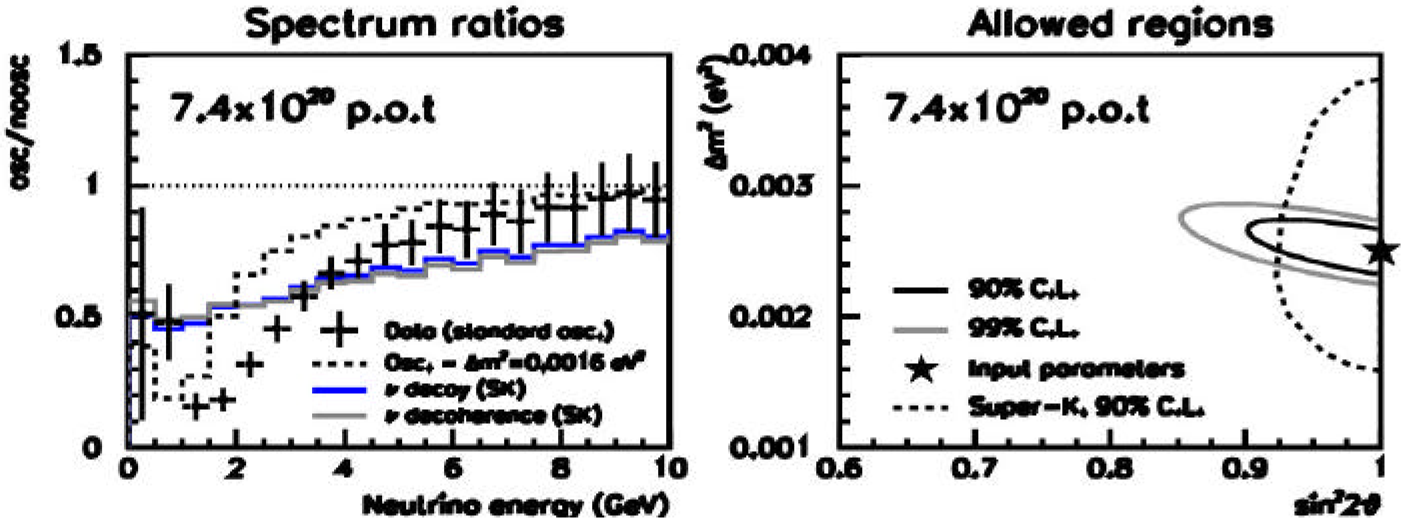


$\nu_e$ CC

0.7m

1 plane ≈ 1.4 $X_0$

# Oscillation measurements



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

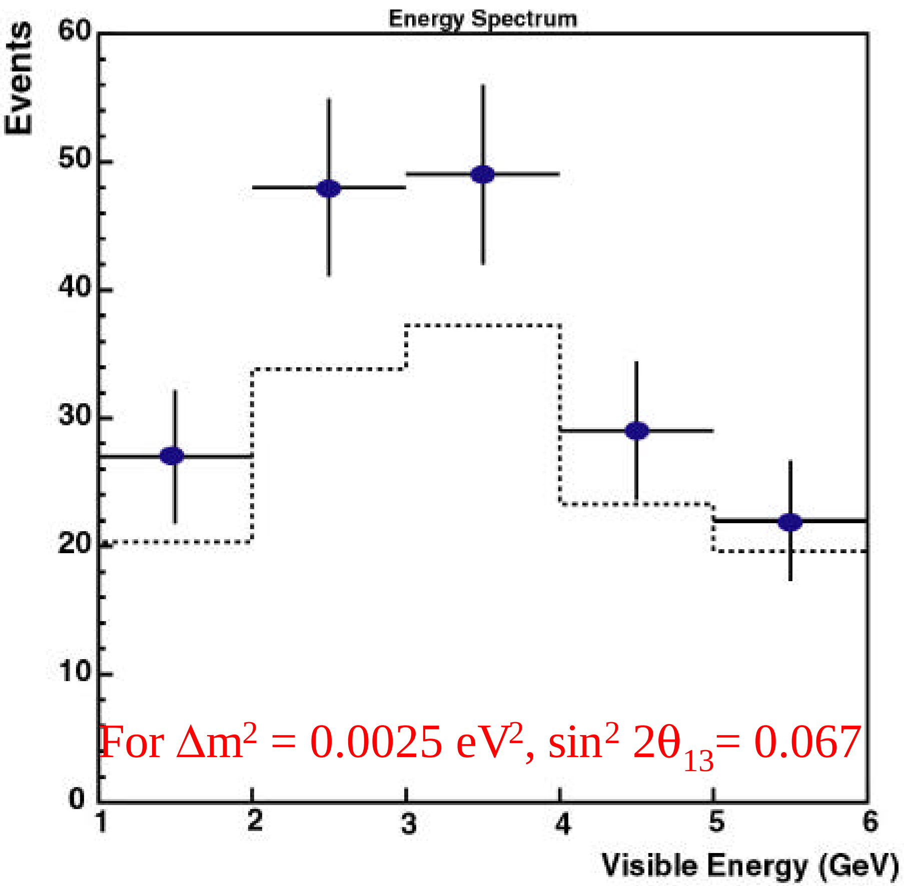
$$P = 1 - \sin^2 2J_{23} \sin^2 \frac{1.27\Delta m^2 L}{E_n}$$

Does the disappearance follow this functional form?

Neutrinos <u>and</u> antineutrinos?

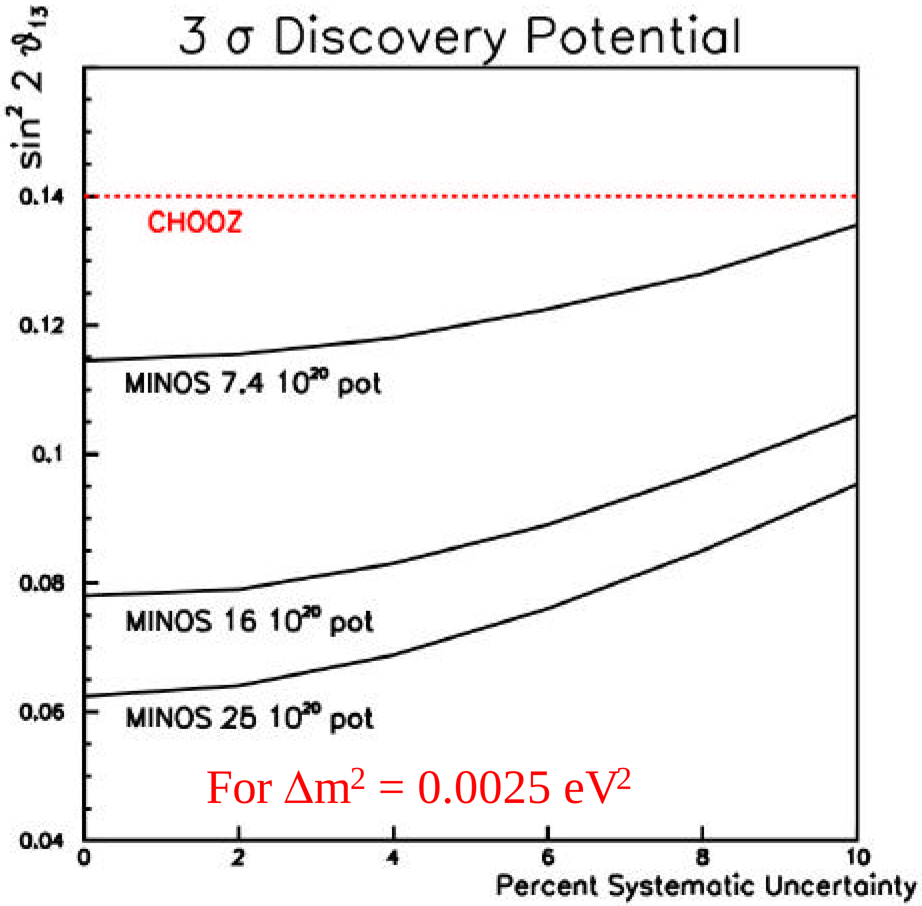
- Dip depth ←→ oscillation amplitude ($\sin^2 2\theta_{23}$)
- Dip position ←→ $\Delta m^2_{23}$ ($\pi/2 = 1.27 \times \Delta m^2_{23} \times L/E_{dip}$)

# Electron Neutrino Appearance



For $\Delta m^2 = 0.0025\ \mathrm{eV}^2$, $\sin^2 2\theta_{13} = 0.067$

Observed number of $\nu_e$ CC candidates with and without oscillations. $25\times10^{20}$ protons on target.



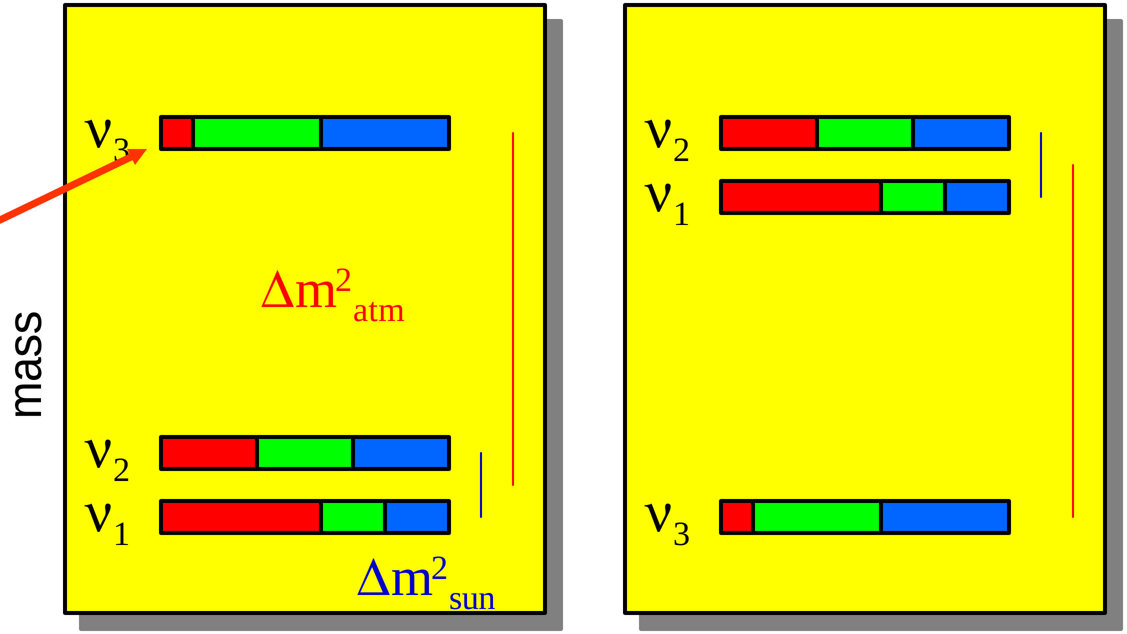
For $\Delta m^2 = 0.0025\ \mathrm{eV}^2$

3 σ discovery potential versus systematic uncertainty on the background.

# What do we want to know (II)

1. Neutrino mass pattern:

This ? Or that?



“Normal” mass hierarchy “Inverted” mass hierarchy

2. Electron component of $\nu_3$ ($\sin^2 2\theta_{13}$)

$$\begin{bmatrix} n_e & n_m & n_t \end{bmatrix} = \begin{pmatrix} B & B & s \\ B & B & B \\ B & B & B \end{pmatrix} \begin{bmatrix} n_1 \\ n_2 \\ n_3 \end{bmatrix}$$

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

$$\boldsymbol{P}(n_m \rightarrow n_e) = \boldsymbol{P}_1 + \boldsymbol{P}_2 + \boldsymbol{P}_3 + \boldsymbol{P}_4$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2}{2E_n};$$

$$A = \sqrt{2} G_F n_e;$$

$$B_{\pm} = \left| A \pm \Delta_{13} \right|;$$

$$J = \cos q_{13} \sin 2q_{12} \sin 2q_{13} \sin 2q_{23}$$

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

Oscillation at the 'atmospheric' frequency

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

Oscillation at the 'solar' frequency

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

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

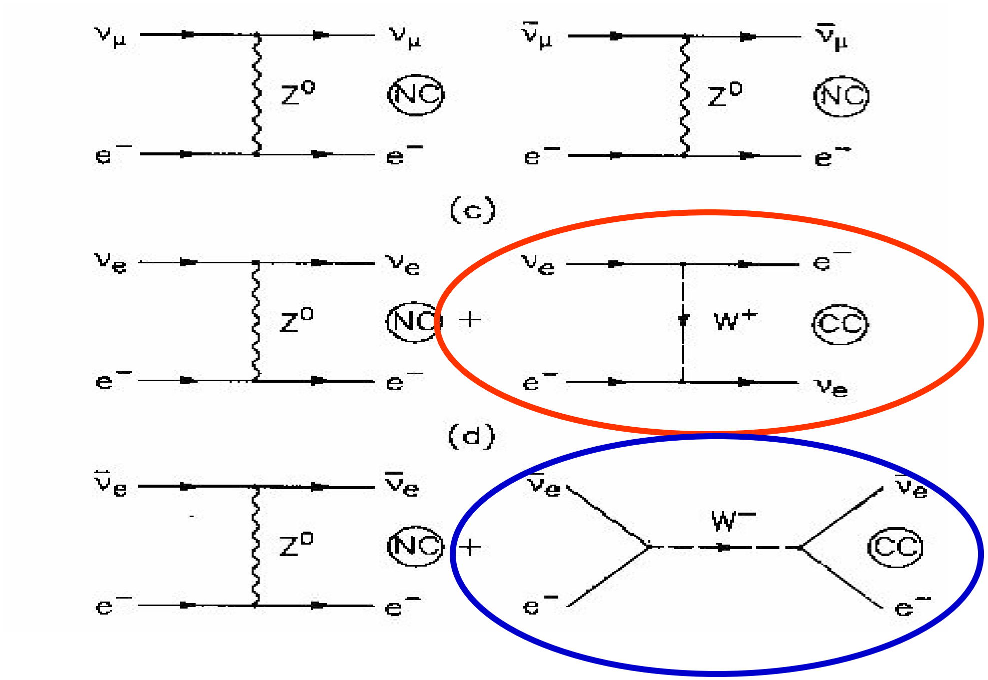
Interference of these two amplitudes ➔ CP violation

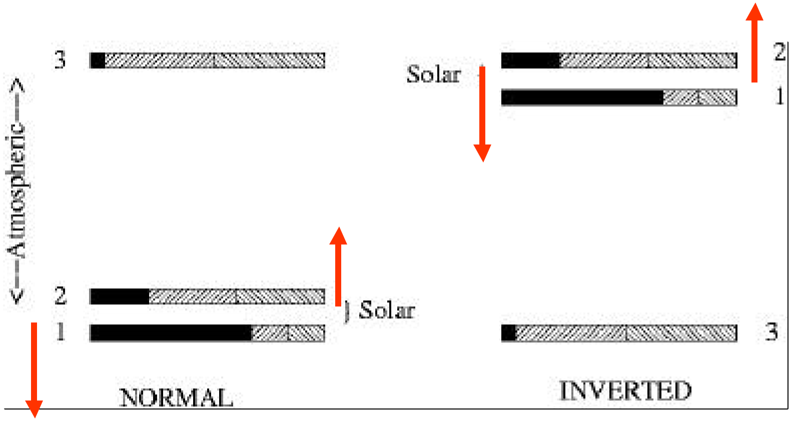
$$P = f\left(\sin^2 2q_{13}, d, \mathrm{sgn}(\Delta m_{13}^2), \Delta m_{12}^2, \Delta m_{13}^2, \sin^2 2q_{12}, \sin^2 2q_{23}, L, E\right)$$

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

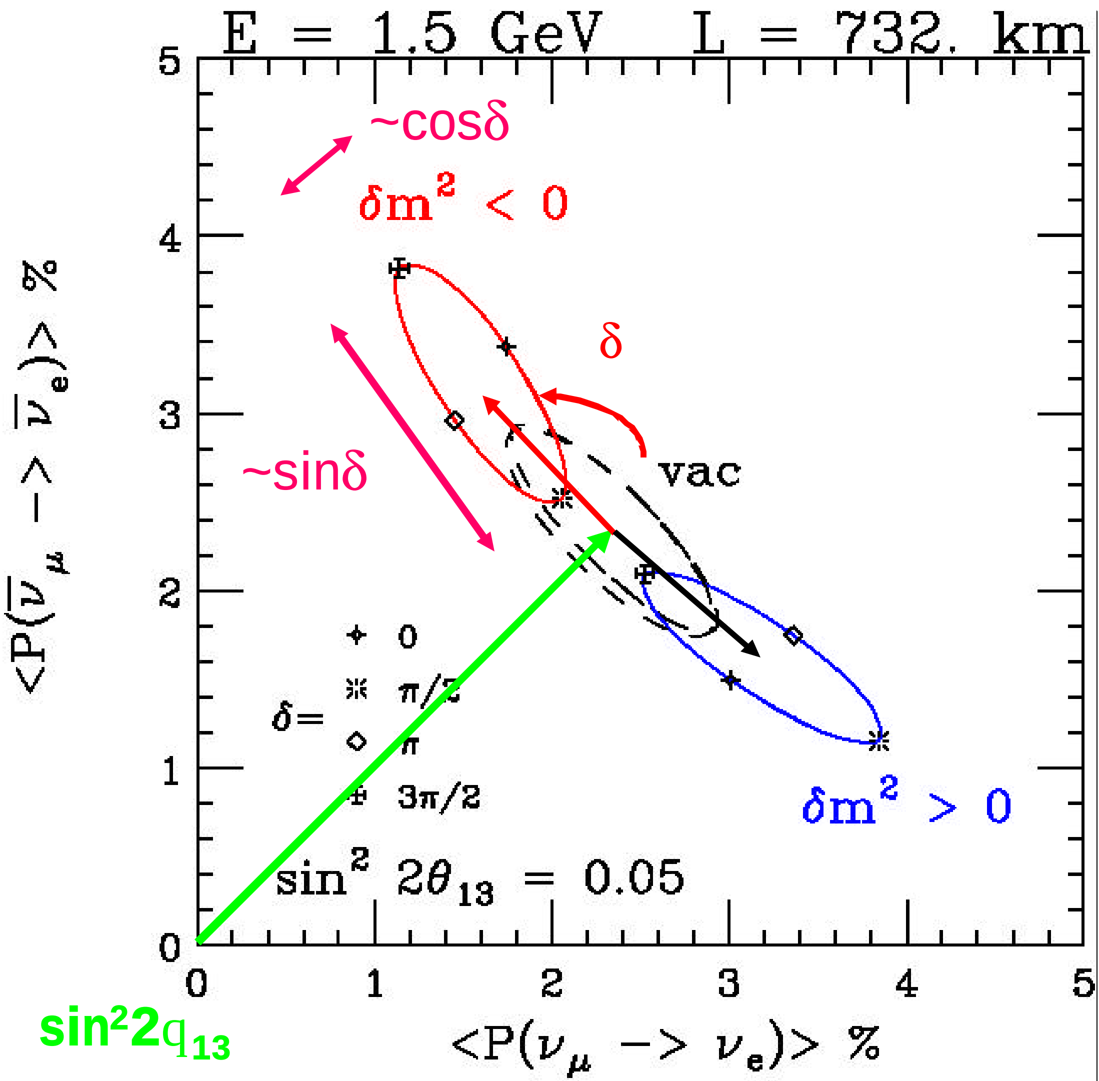




- Matter effects reduce mass of $\nu_e$ and increase mass of $\overline{\nu}_e$
- Matter effects increase $\Delta m^2_{23}$ for normal hierarchy and reduce $\Delta m^2_{23}$ for inverted hierarchy for neutrinos, opposite for antineutrinos

- 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



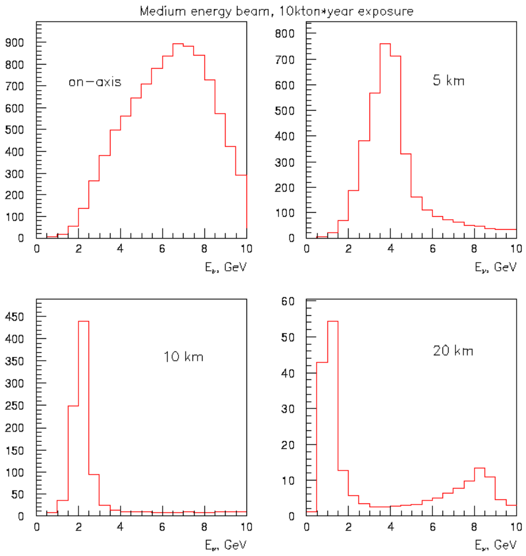
Minakata and Nunokawa, hep-ph/0108085

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)

# 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 $\tau$ 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 0.5x$10^{-5}$
  - 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 (Now)

# NuMI Off-axis Experiment

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

  - Liquid scintillator or
  - Glass RPC

Electron ID efficiency ~ 30% while keeping NC background below intrinsic $\nu_e$ 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
- $3\sigma$ evidence if $\sin^2 2\theta_{13}$ factor 10 below the CHOOZ limit (normal hierarchy, $\delta=0$), or
- Factor 20 improvement of the limit

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- ➢ Factor 20 improvement of the limit

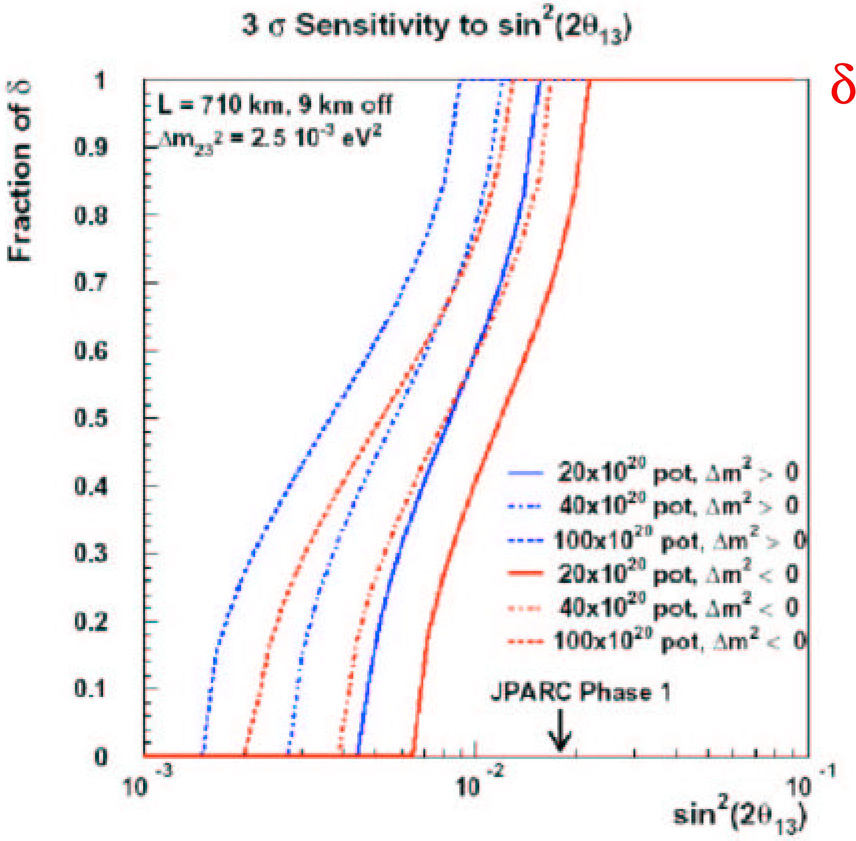
# Observations

1. One of the considered detector designs similar to the INO detector concepts (great minds think alike?) ➔ mutual benefits from the common R&D program (underway):
   - Understanding of glass RPC chambers
   - Design of large area chambers
   - Development of economical techniques for large scale chamber production
   - Development of signal readout techniques
   - Development of hybrid readout VME board (prototype just delivered)
   - Development of ASIC chip for a large scale experiment
2. Detector cost a major element of the final selection decision ←→ cheap detector with costs dominated by manpower ←→possibility for a major impact on the final experiment design

# 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 $\delta$
- Figure of Merit: 3 $\sigma$ discovery limit as a function of the fracion of the possible range of $\delta$'s



$\delta=3\pi/2$

$\delta=\pi/2$

# Observations(2)

Physics reach of the off-axis experiment is determined by a product: (detector mass) x (delivered proton intensity)

NuMI beam intensity is likely to be below the expected/possible level due to various ‘complications’

- ➢ Can be remedied, but help needed

The program of CP violation studies will require a new proton source (a.k.a. superbeam)

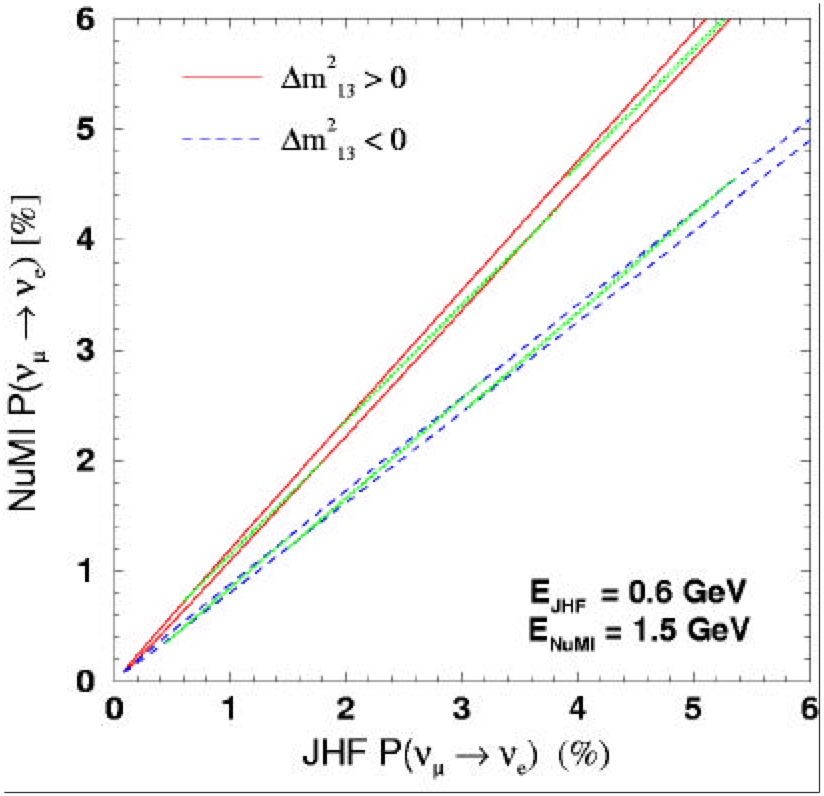
- ➢ An external help/collaboration would be a huge step towards making it possible

(see talk by Doug Michael)

# NuMI and JPARC experiments in numbers (Phase I)

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

# Determination of mass hierarchy: complementarity of JPARC and NuMI



Combination of different baselines NuMI + JPARC:

- Oscillation probabilities differ because of difference of the matter effects.
- Sign of the matter effect depends on the neutrino mass hierarchy.

Minakata, Nunokawa, Parke

# Observations (3)

Studies of neutrino oscillations are likely to be a world-wide program of complementary program involving several complementary experiments (NuMI, JPARC, LNGS, INO, reactors,…)

Future precise experiments will run into a <u>common</u> brick wall: systematic errors related to our poor (very poor, indeed) understanding of neutrino physics at low energies

NuMI beam and the near MINOS hall provide a unique opportunity of new, precise experiments: 1000 events/year per one kg of a detector (or 1,000,000 event per ton)

- ‘engineering’ measurements for the oscillation studies
- Rich program of physics in its own right
- Several proposals/ideas under discussions (MINERVA,…)
- An interesting area for a collaborative effort

# 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: $\nu_\mu$ disappearance
  - Will demonstrate oscillatory energy dependence
  - Precision measurements of $\Delta m^2$, $\sin^2(2\theta)$ (10%)
- $\nu_e$ appearance
  - Improved bounds on $|U_{e3}|^2$
- Physics starting April 2005

Experiment is in a fairly advanced stage, but a lot of opportunities for a new interested parties to make a significant contributions still exist.

# 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 CHOOZ 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/LNGS/INO/others).
- 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.
- **There are many opportunities for collaborative efforts. In fact we need a lot of external help to fully exploit a physics potential of the NuMI beam.**

- **IT IS FUN TIME FOR NEUTRINO PHYSICS. LET'S SHARE THE FUN.**