Experiments at the

Neutrinos at the Main Injector:

MINOS
MINERνA
NOνA

Sacha E. Kopp,

University of Texas – Austin

ν Mixing Paradigm

- If you believe in flavor mixing, there must be a 3×3 unitary transformation to mass states:

$\sin\theta_{solar} < 0.62$
(Smirnov, hep/0309299)

Is this ***non-zero???***
Large enough to measure
$\not{CP}$ in $\nu_\mu \rightarrow \nu_e$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$c_{ij} \equiv \cos\theta_{ij} \quad s_{ij} \equiv \sin\theta_{ij}$$

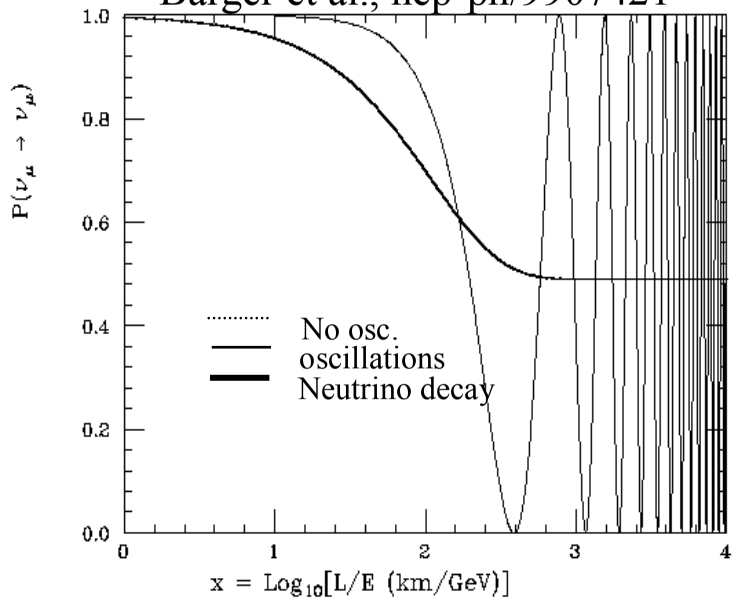
Is the mixing angle
truly ***maximal???***

- In the quarks, mixing matrix has phase $\delta \neq 0$ responsible for $\not{CP}$.

Who Says It's Oscillations, Anyway?

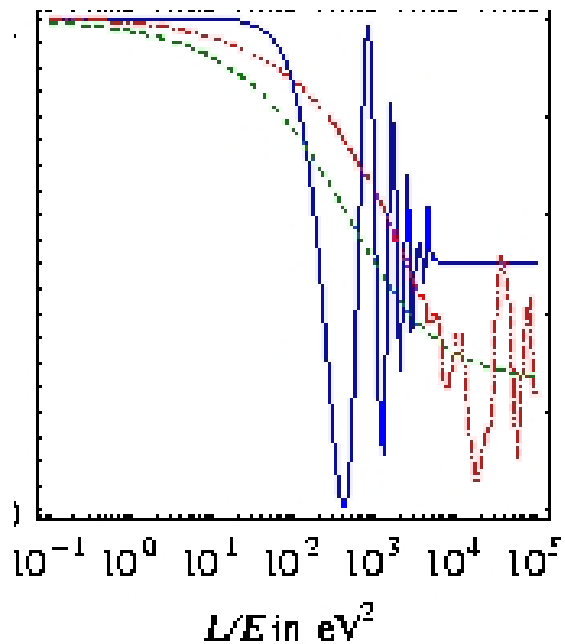
"Neutrinos actually decay to lighter states"

Barger et al., hep-ph/9907421



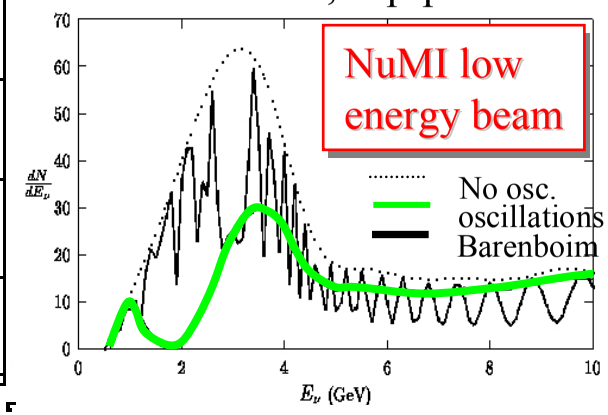
"Neutrinos propagating in Extra Dimensions"

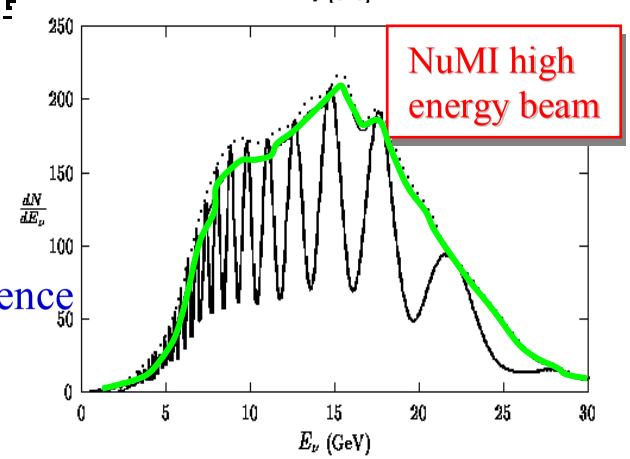
Barbieri et al., hep-ph/9907421



"SuperK effect is combination of Δm^2(solar) and Δm^2(LSND)"

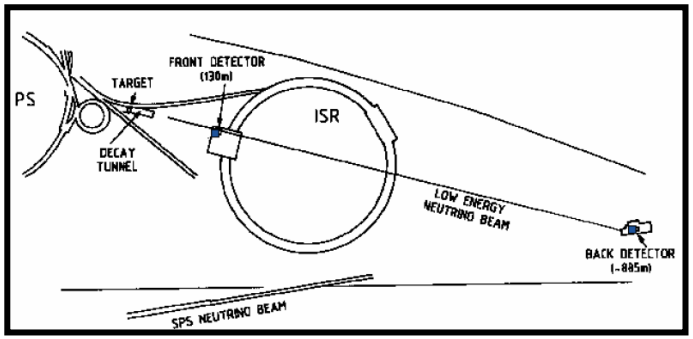
Barenboim et al., hep-ph/0009247





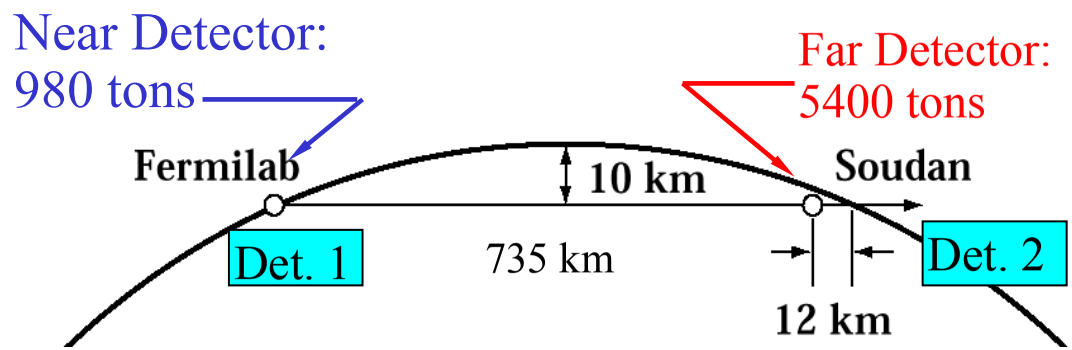
- Many alternatives proposed to interpret Super-K data
- All of these models modify expected L/E_ν shape.
- Other models will surely come along in coming years?
- MINOS can unambiguously demonstrate oscillatory energy dependence of ν disappearance

Idea dates back to CERN, FNAL mid-1980's



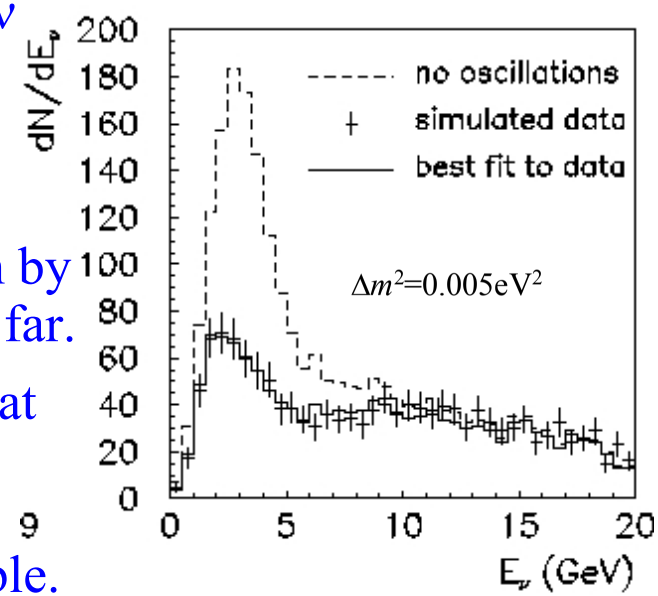
Two Detector ν Experiment

On an extreme size scale!



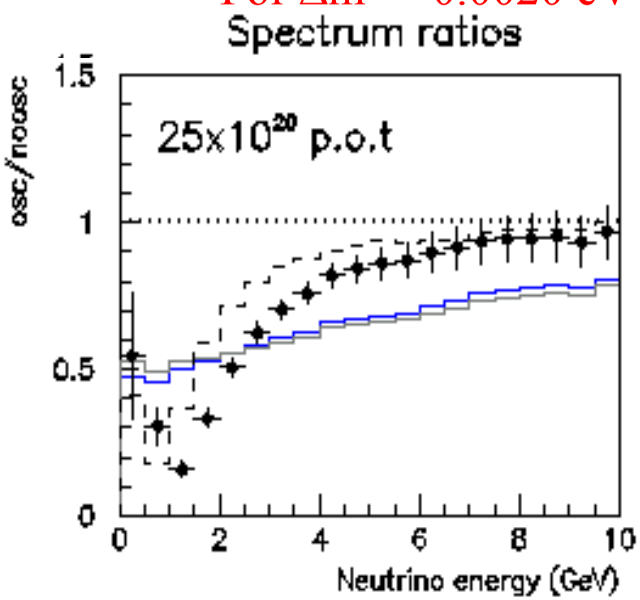
- Near detector predicts ν energy spectrum at far detector (in absence of oscillations)
- Multiply near spectrum by scaling factor to predict far.

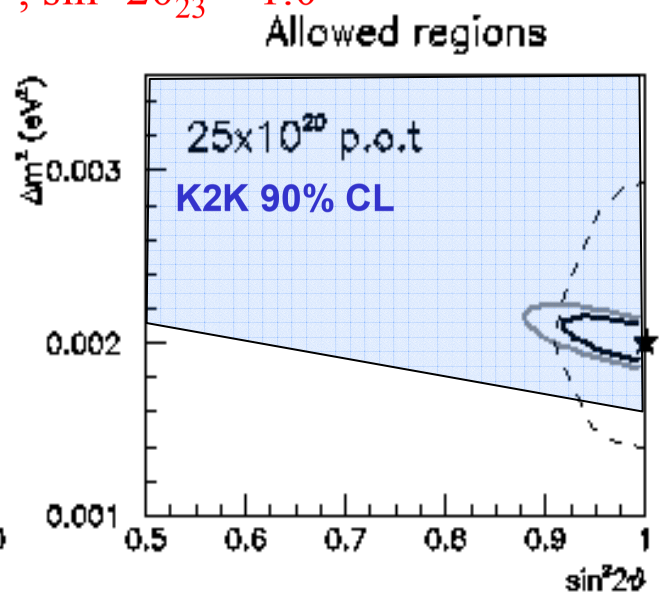
Must believe that beam at two detectors is
(1) the same, or
(2) difference calculable.



Measurement of ν_μ Disappearance in MINOS

For $\Delta m^2 = 0.0020\ eV^2$, $\sin^2 2\theta_{23} = 1.0$



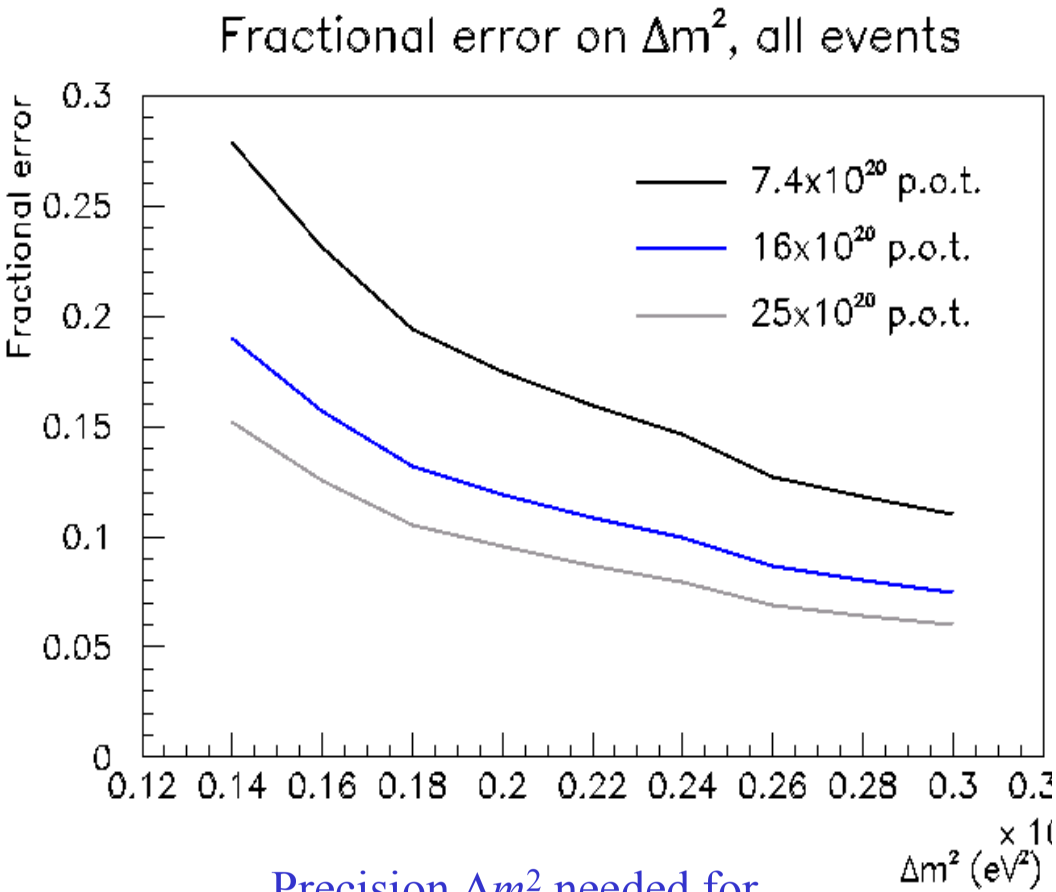


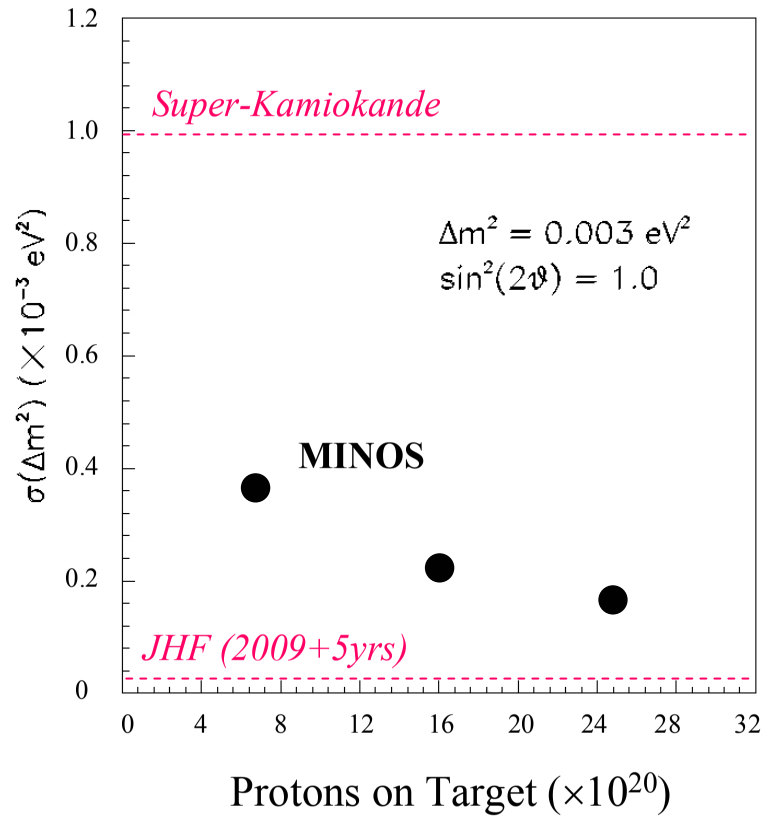
Oscillated/unoscillated ratio of number of ν_μ CC events in far detector *vs* $E_{observed}$

90% and 99% CL allowed oscillation parameter space for the Super-K best fit point.

Figures from MINOS 5yr plan submitted to Fermilab PAC 2003

Precision on Measurement of Δm_{23}^2





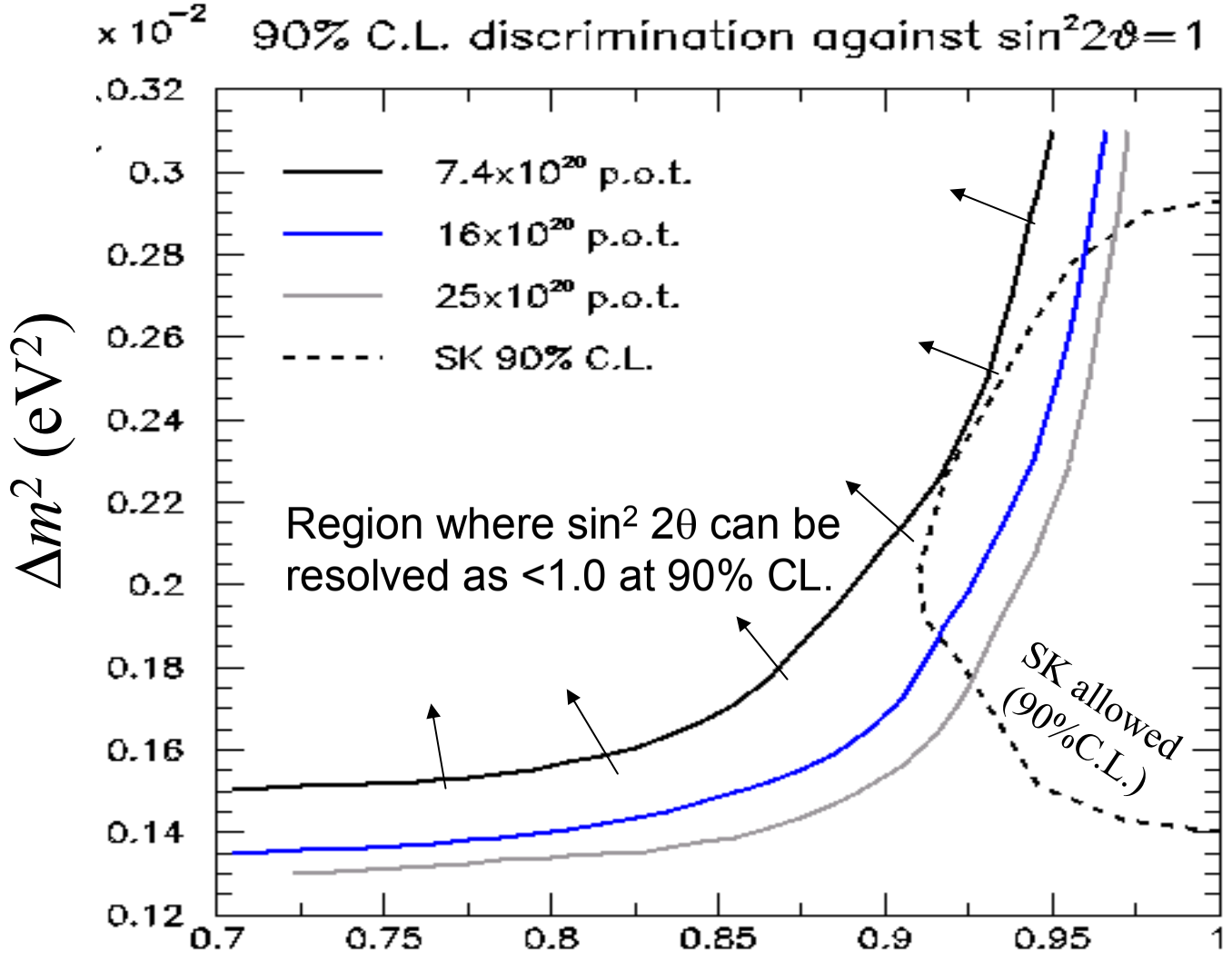
Precision Δm^2 needed for

reactor $\nu_e \rightarrow \nu_e$,

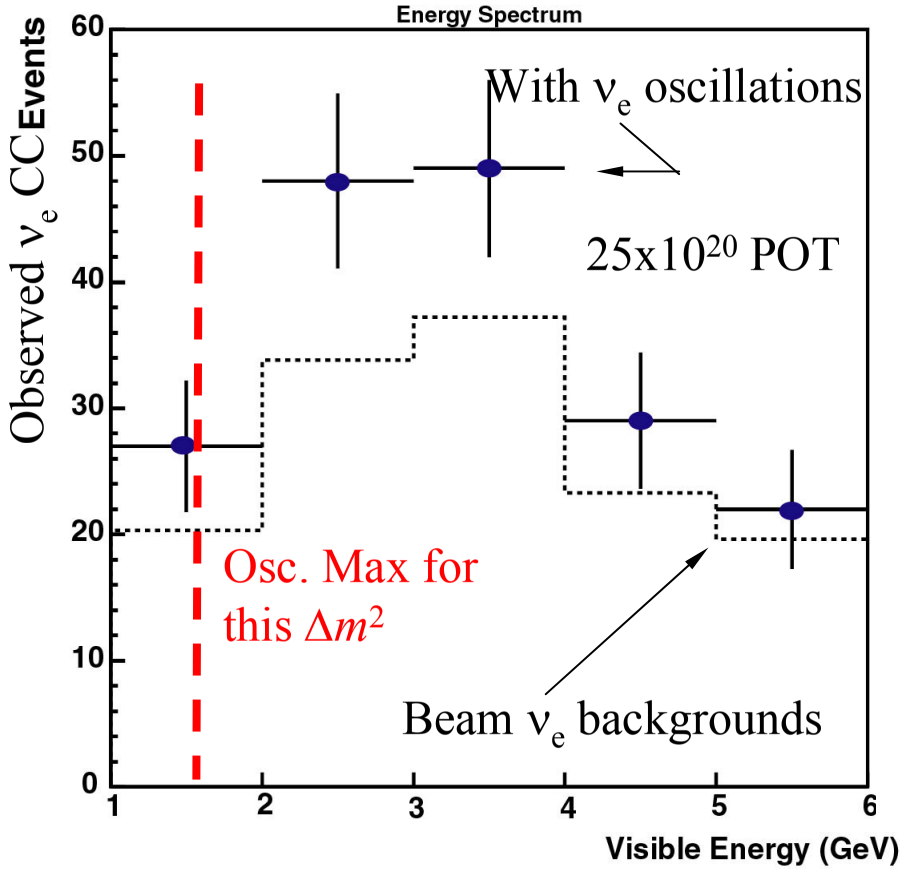
accelerator off-axis beams (JHF, NOνA)

At these low expected Δm^2's, MINOS requires *statistics*

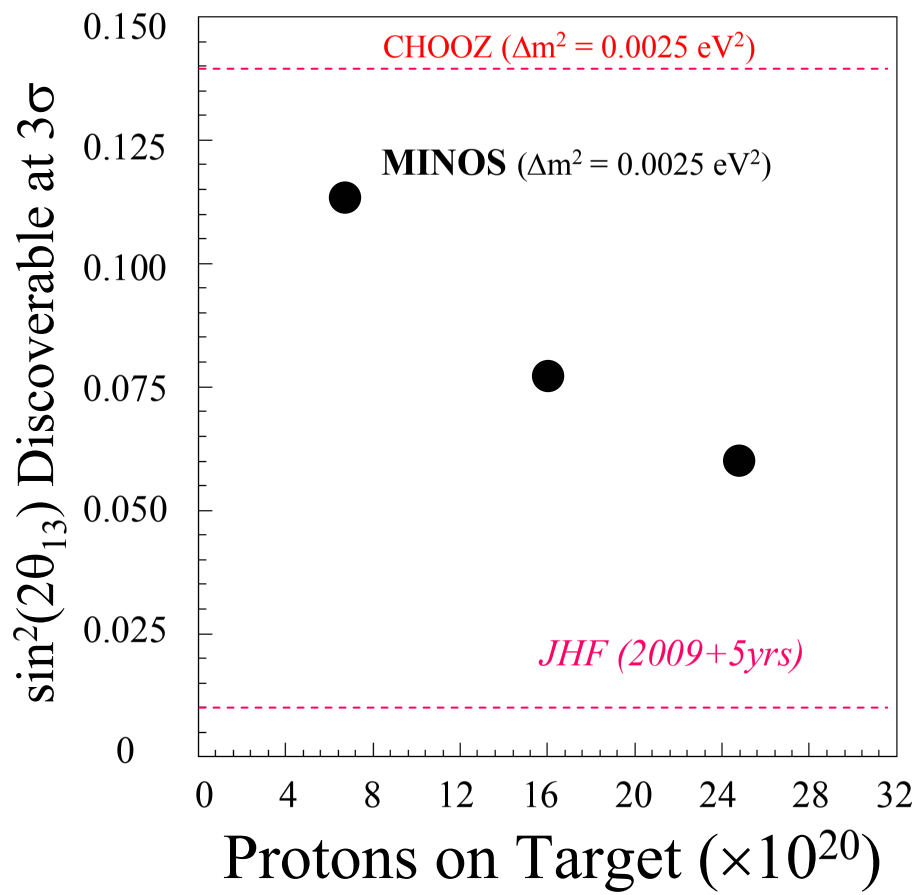
Resolve Non-Maximal Mixing?



Search for $\nu_\mu \rightarrow \nu_e$ Appearance



Or 3σ Discovery!!



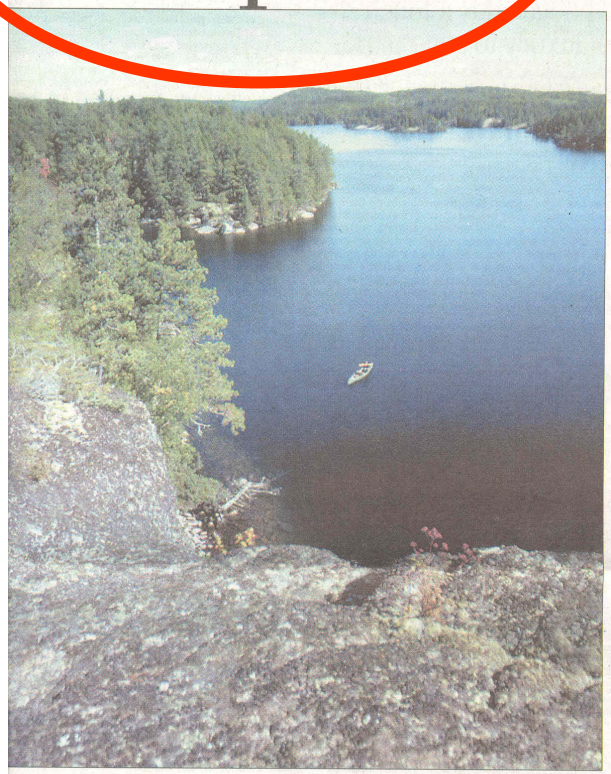
For $\Delta m^2 = 0.0025$ eV^2, $\sin^2 2\theta_{13} = 0.067$

Raison d'Être for a Northern Minnesota Experiment!

Bound to impress

Canoes glide through Minnesota's vast unspoiled trove of lakes and wilderness

By Beth Gauper
SAINT PAUL PIONEER PRESS



ELY, MINN. CHAMBER OF COMMERCE PHOTOS

You can canoe all day without seeing another person in the Boundary Waters Canoe Area Wilderness, which has more than 1,500 miles of water trails. The area is the largest wilderness preserve east of the Rocky Mountains.

Along Minnesota's northern border with Canada, more than 200,000 people a year find an increasingly rare commodity — absolute wilderness.

The million-acre Boundary Waters Canoe Area Wilderness is barely changed since voyageurs used its chain of lakes and rivers to push deep into the continent's interior. Today, the foot trails over which they carried canoes and 180-pound packs are used by vacationers, who wind their way from lake to lake in search of the perfect combination of woods, water and solitude.

As they paddle along the glassy waters of more than 1,000 lakes, they may see moose, lynx, otters and beaver, who have rebounded from near-extinction at the hands of trappers. In the evening, at nearly 2,200 campsites, they listen for the trill of loons and the howl of wolves, whose numbers also have rebounded.

To people who consider the Midwest flyover land, the BWCA Wilderness puts Minnesota on the map. National Geographic Traveler listed it as one of 50 Places of a Lifetime/The World's Greatest Destinations, along with the Grand Canyon and Big Sur. In the book "1,000 Places to See Before You Die," it's the only Minnesota entry.

Whenever I travel outside the Midwest, people I meet always scan their brains for whatever they know about Minnesota, then ask, "Have you been to the Boundary Waters?"

Last August, I finally took a week and went. And I was surprised. The

See **CANOE**, back page

Rangers, outfitters help you dip your toe in the waters

The easiest way for a beginner to go to the Boundary Waters is with a group or a friend who has good gear to share — lightweight tent, stove and water filter, in addition to the lightweight sleeping bag, Therma-

Along Minnesota's northern border with Canada, more than 200,000 people a year find an increasingly rare commodity — absolute wilderness.

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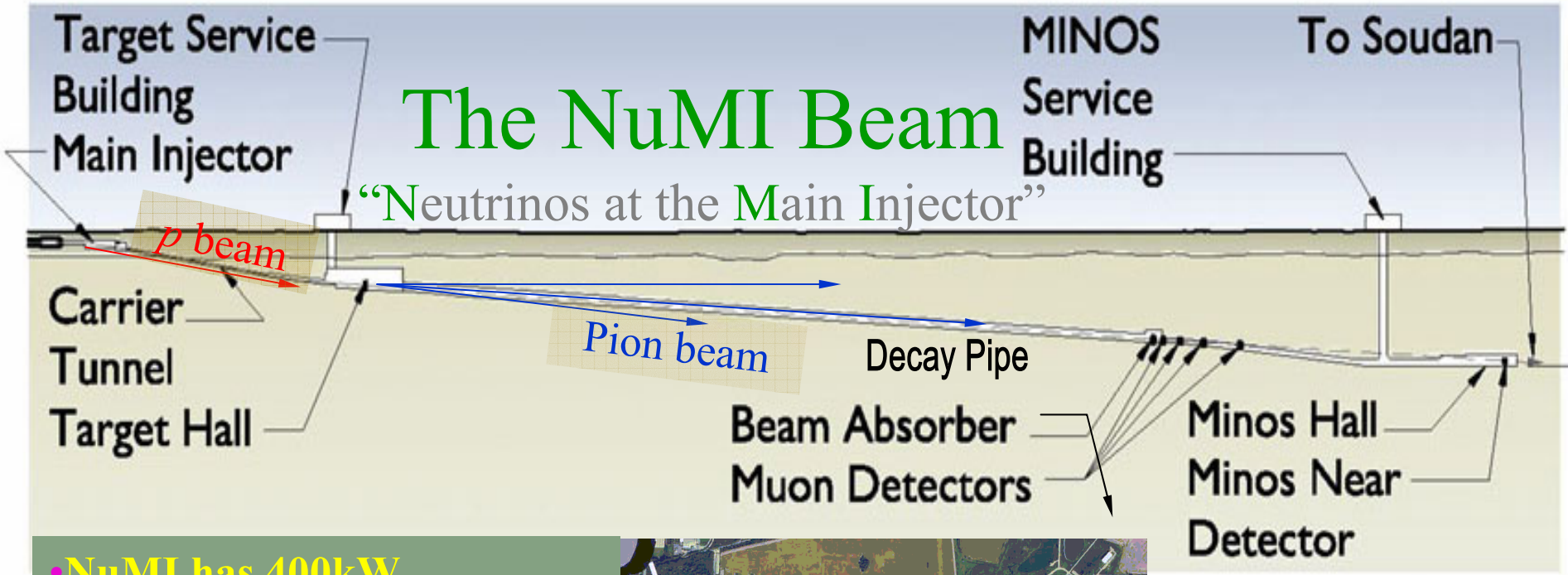
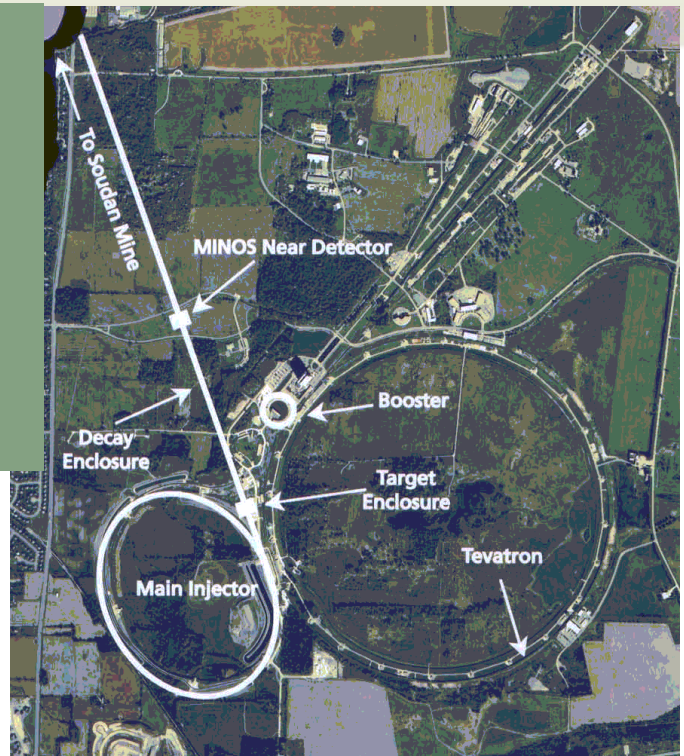
Austin *American-Statesman* Newspaper, Sunday, April 18, 2004

The NuMI Beam

"Neutrinos at the Main Injector"



- **NuMI has 400kW primary proton beam**
  - **120 GeV**
  - **8.67 μsec spill**
  - **1.9 sec rep rate**
  - **5 Booster batches (2.5×10^{13} prot/spill)**

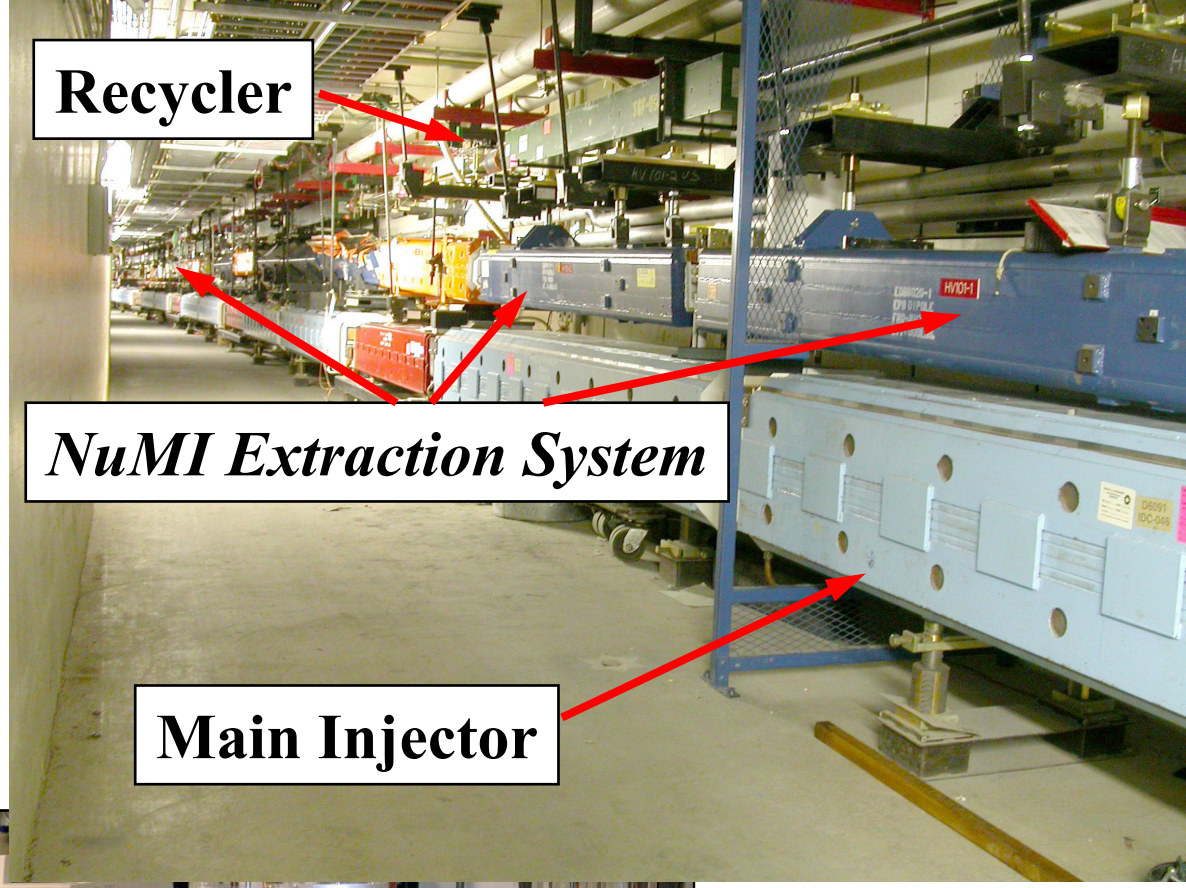


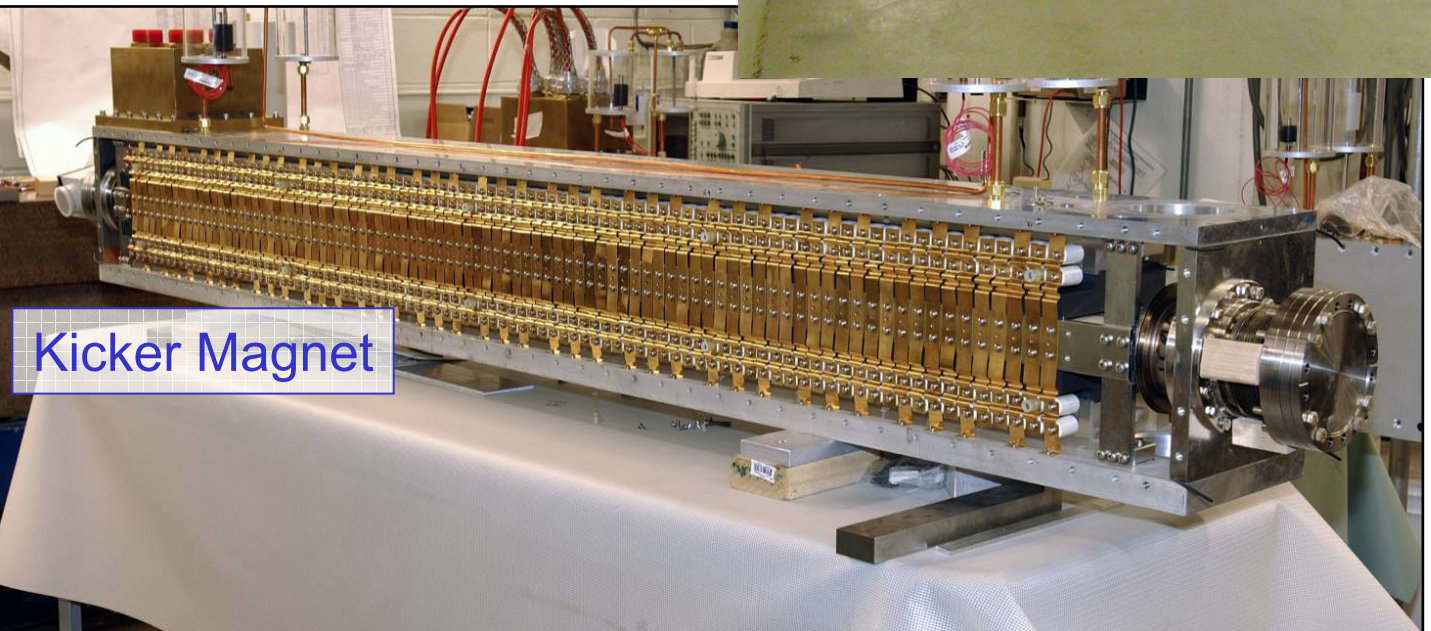
Protons for MINOS

- The lab has understood and educated us on the difficulties associated with the promised 4×10^{20} protons/year
- The MINOS collaboration has committed significant resources to accelerator improvement
  - Booster Cogging – UTexas/Austin
  - Booster RF Upgrade – UTexas/Austin, Caltech, Tufts, Indiana
  - MI BPM's – Caltech
  - Barrier RF + Slip Stacking – Stanford, Caltech
  - MI Beam Permit – South Carolina
  - MI Dampers – Stanford, U.Coll.London
- The lab has begun to commit study time to MI multibatch running
- MINOS and the lab must work toward
  - Fast turn-on to 2.5×10^{20} protons/year (begin Dec. '04!)
  - (Modest?) upgrades toward $(4\text{-}6) \times 10^{20}$ protons/year

NuMI in Main Injector Tunnel

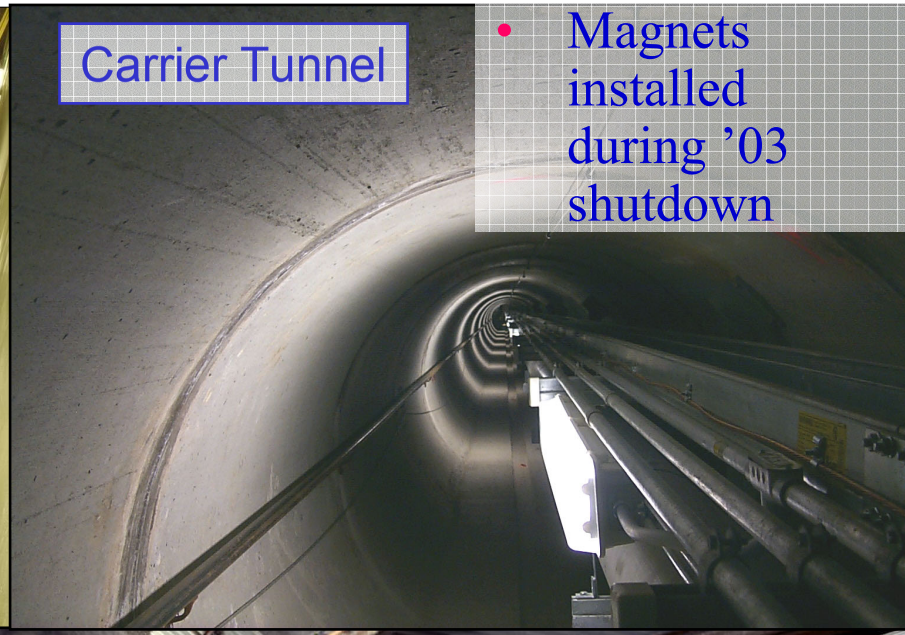
- Lambertsons installed ’03
- Kicker to be installed Fall ’04



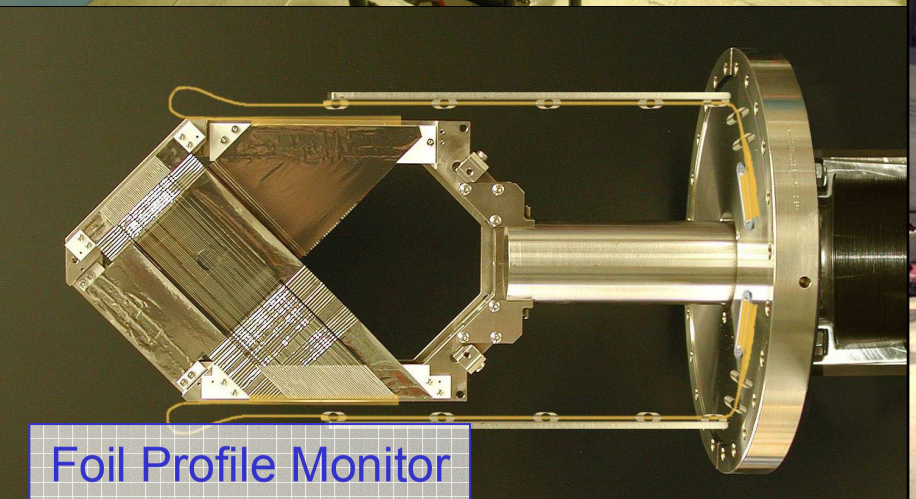


- Magnetic shielding (Recycler) installed Feb.’04

Extracted Proton Beam Line

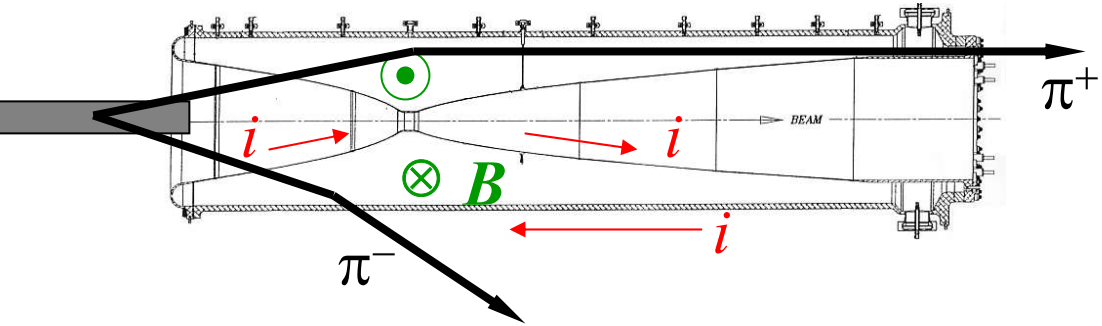


- Magnets installed during ’03 shutdown



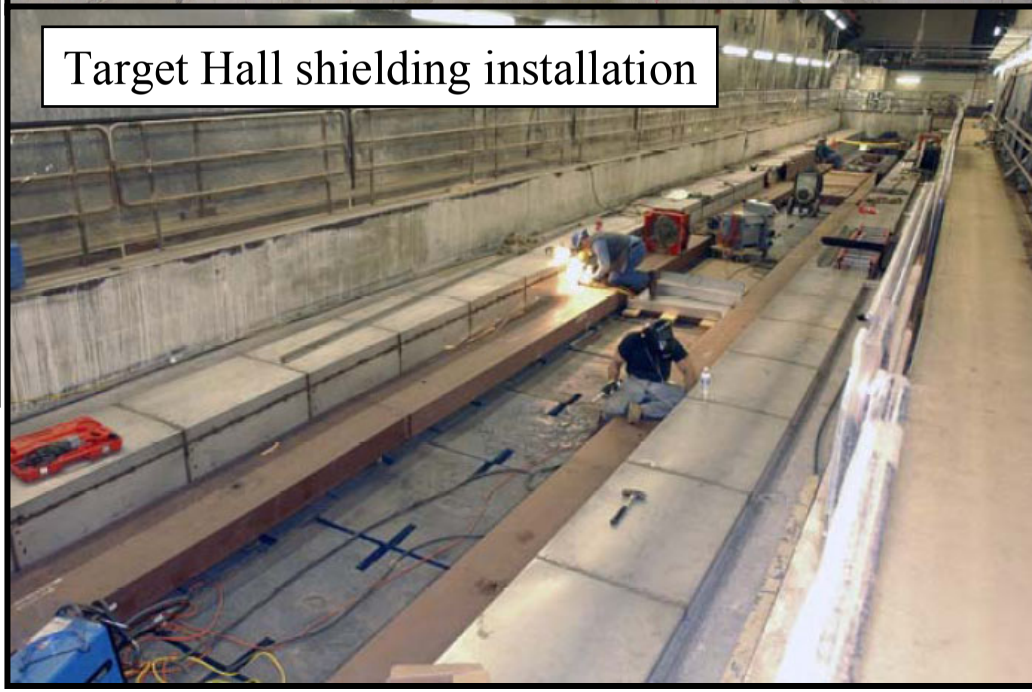
The "Magnetic Horns"

- Toroidal Magnet $B \sim 1/r$
- p_T kick of $\Delta p_T \propto \int B d\ell \propto r \propto p_\pi \propto E_\nu$

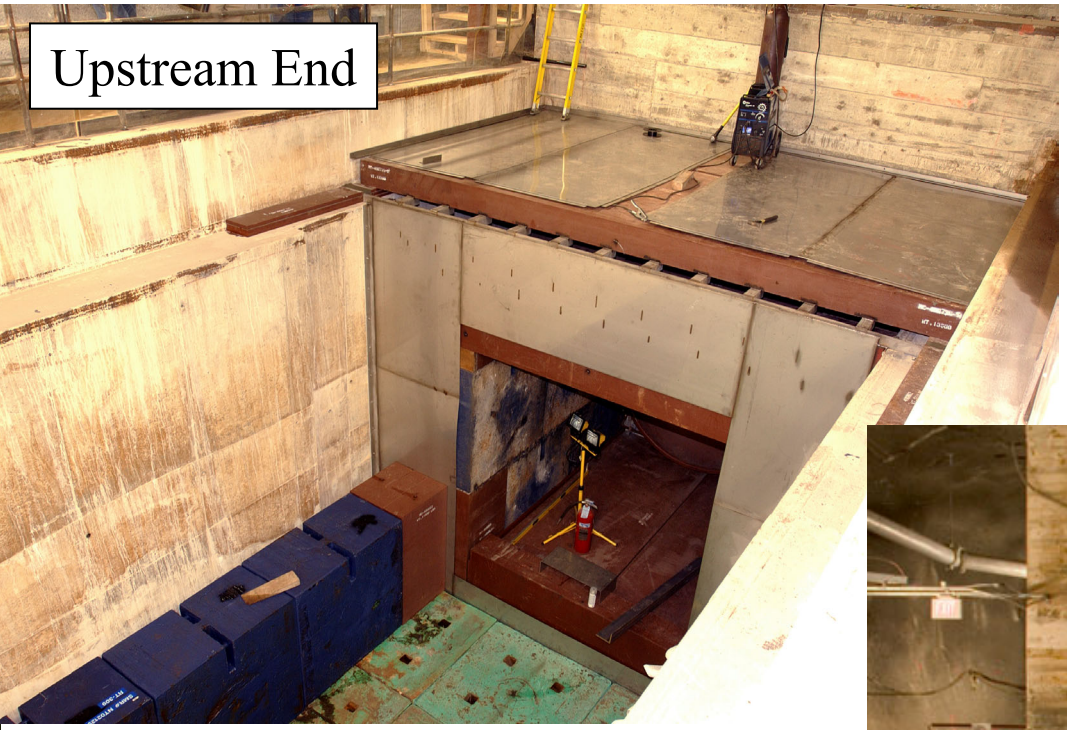


Progress on Target Hall

Horn Pulsed Power Supply Installed



Meson Decay Tunnel



March 2004

- Steel decay pipe installed, encased in 6-8 ft. of concrete.
- Decay Pipe evacuated to 1.5Torr (May 2004).
- Water cooling system for decay pipe operational.

μMonitors to Study ν Beam

Bypass Tunnel

Hadron Monitor

p

Decay Pipe

π^+

Absorber

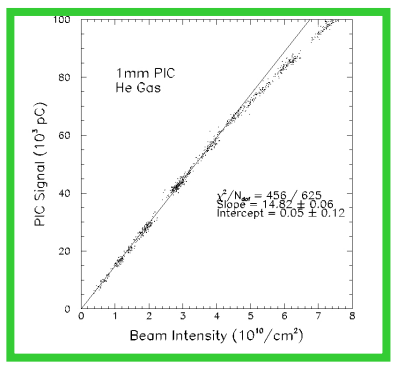
Muon Monitors

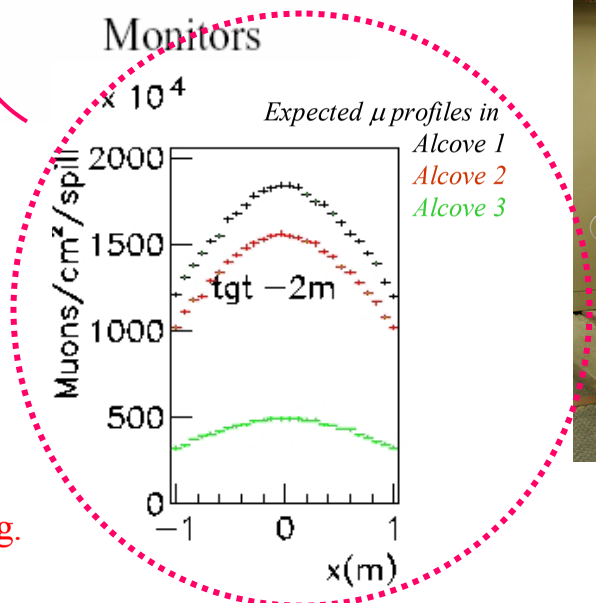
μ^+

ν_μ

0 10 20 30 40 feet

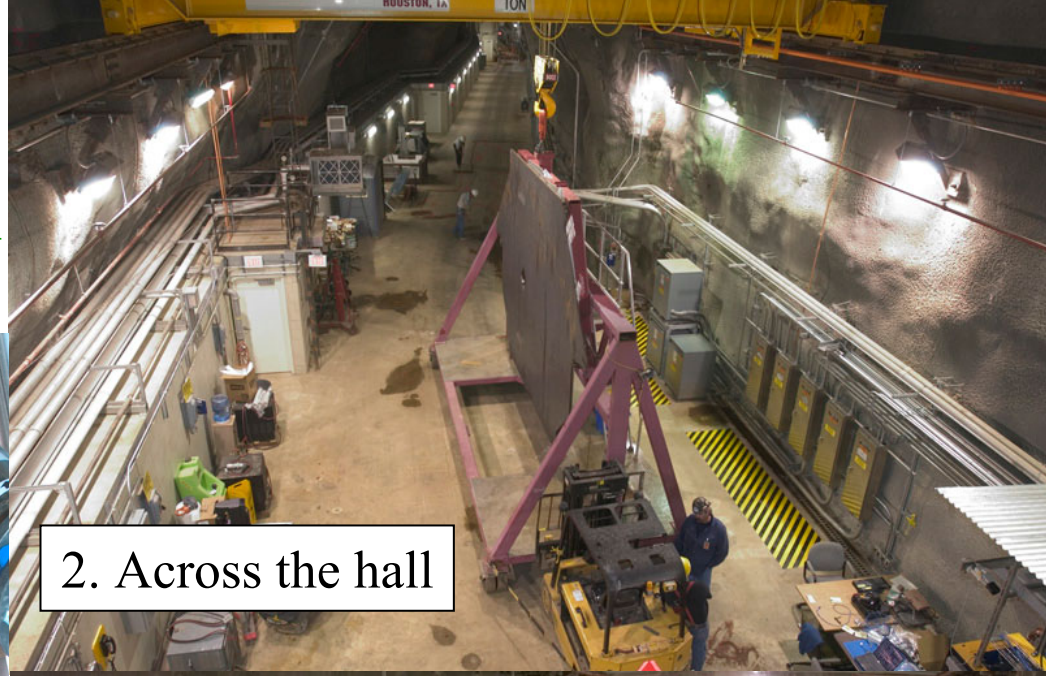
Beam Tests





Sacha Kopp, FNAL Users' Mtg.
June 2-3, 2004

MINOS Near Detector Construction



MINOS Far Detector

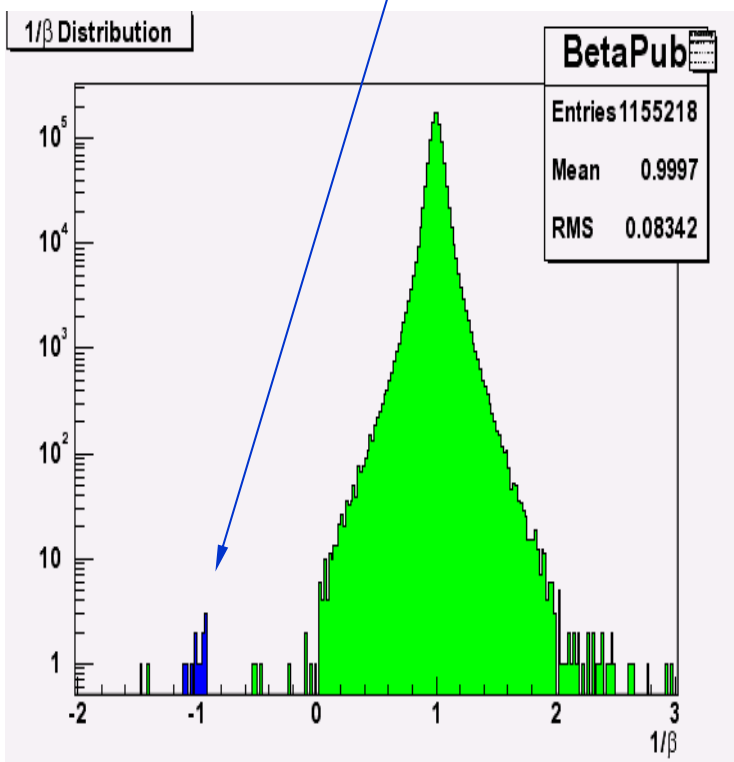
magnetized Fe-scintillator calorimeter

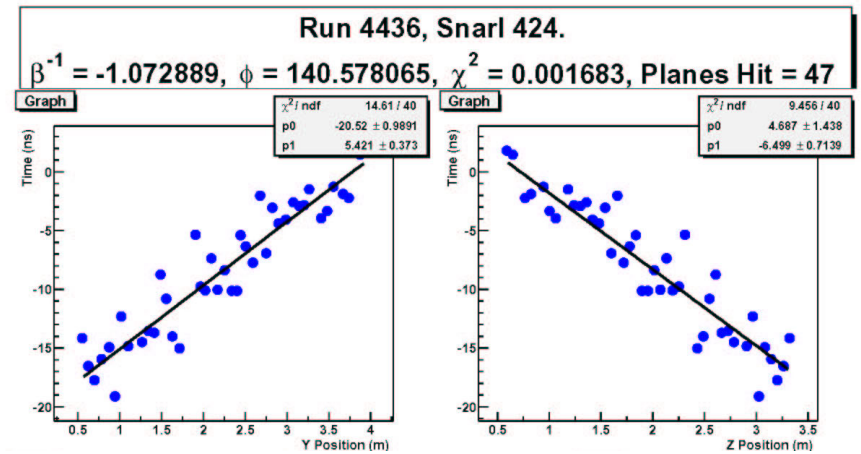
segmented scint for *X*, *Y* tracking

485 planes, 8m diam, 5400 tons

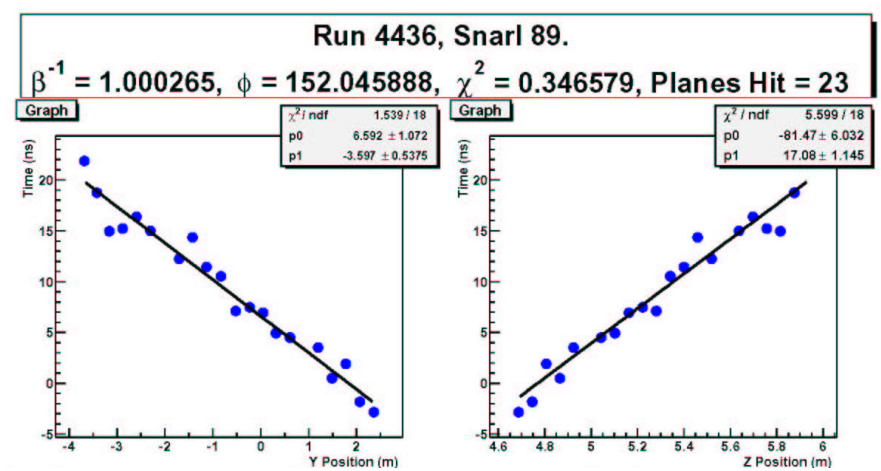
MINOS Cosmic μ's

Now have ~ 40 up μ's





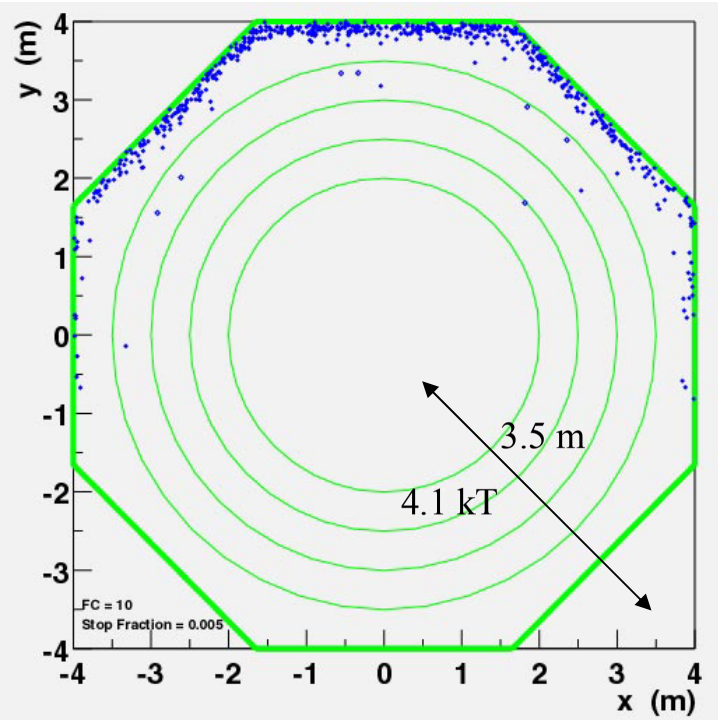
Upward candidate



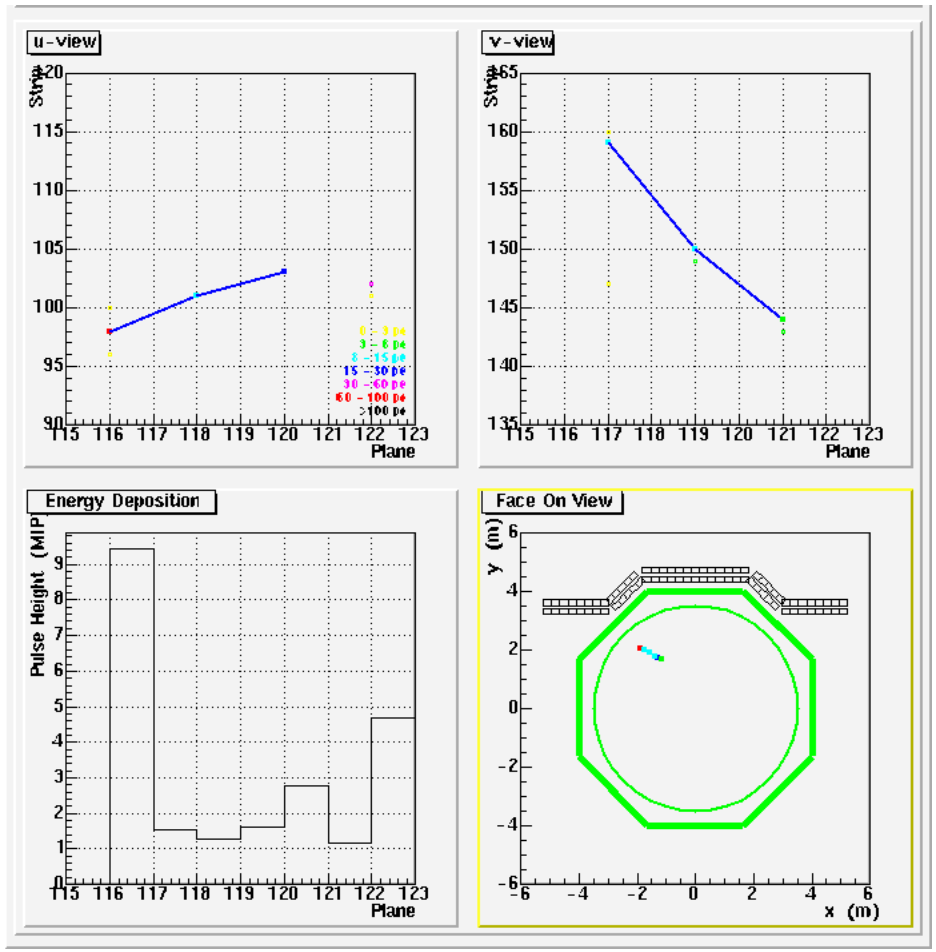
Downward candidate

MINOS cosmic ν's:

finding a ν-dle in a stack of steel…

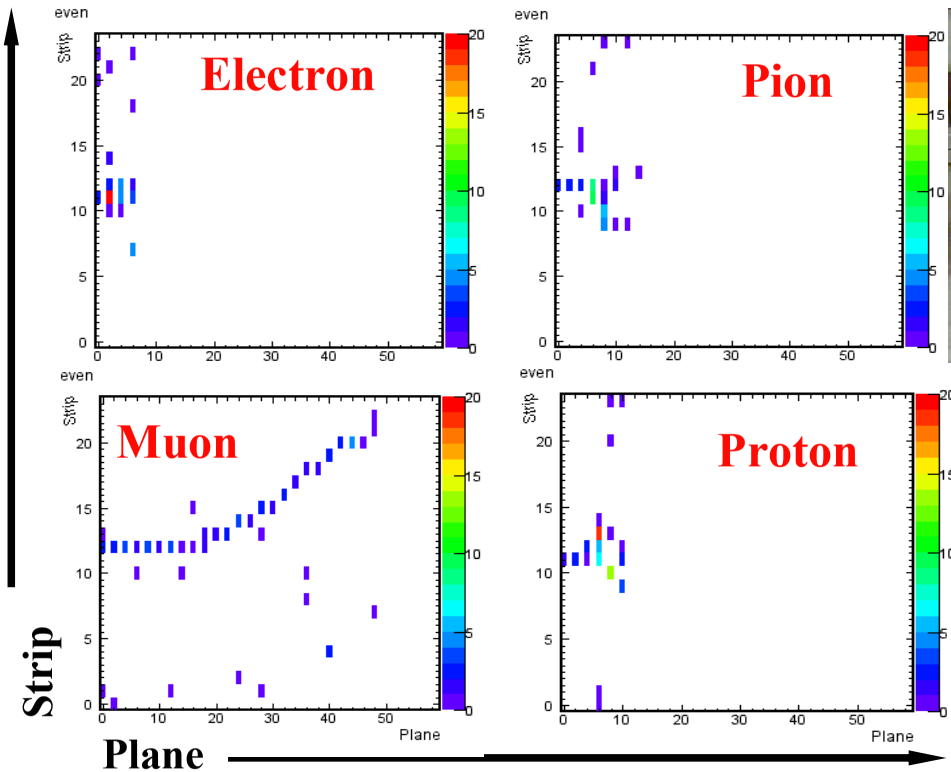


Reconstructed "vertices" for cosmic ray events which have a track that ends inside the detector. Most are clearly downgoing stopping muons.



Contained ν candidate

MINOS Calibration Detector



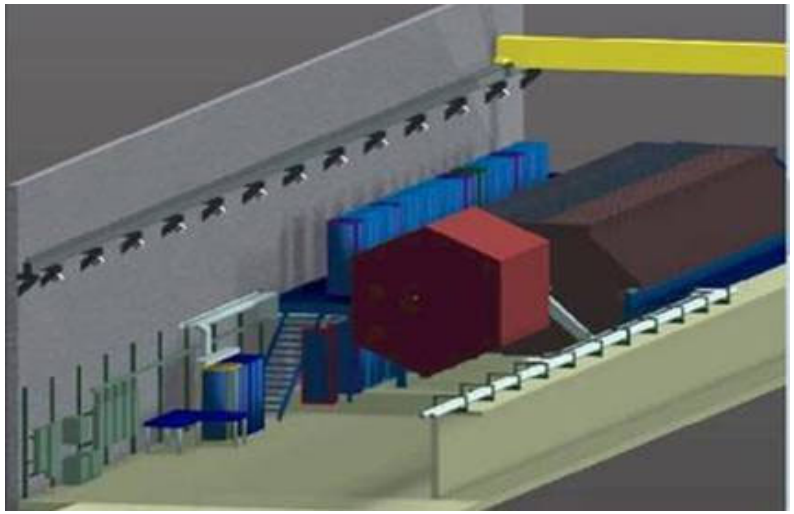
- Measure particle responses in Fe/scint
- Compare near, far electronics to 2%
- Test of electronics, calibrations
- Ran at CERN 2-10 GeV *e*, μ, π, *p* beams 2001-2003

MINOS Schedule

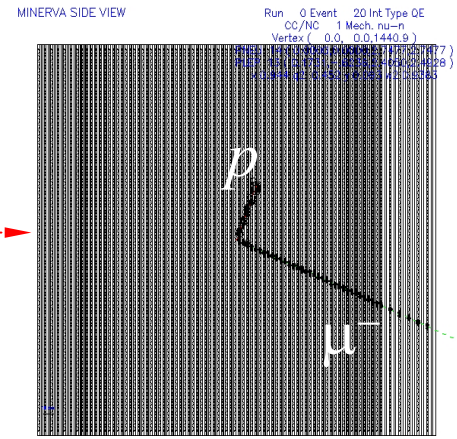
- Far Detector completed in 2003
- NuMI Tunnel
  - Excavation complete in 2002
  - Outfitting (electrical, air, water, *etc*) complete in fall 2003 and March 2004 (two phases)
- Primary beamline and target hall installation
  - Begun in fall 2003
  - Finish in November 2004
- Near detector installation to finish early fall '04
- **READY FOR BEAM November, 2004**

MINErVA:

Main Injector Neutrino Experiment for *V-A*



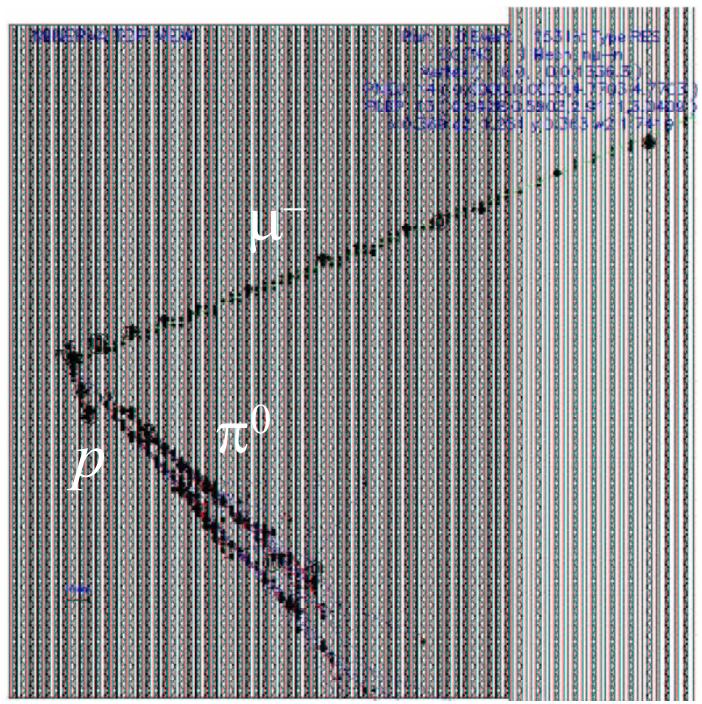
- Stage I approval for ν scattering experiment in near hall.
- Fine-grained scintillating bar detector with fiber readout *à la* MINOS
- Already unusual nuclear effects inferred from MiniBooNE, K2K data.



$\nu_\mu + n \rightarrow \mu^- + p$

$\nu_\mu + n \rightarrow \mu^- + \Delta^+$

$\Delta^+ \rightarrow p\pi^0$



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June 2-3, 2004

Figures courtesy K.McFarland

Impact of ν Cross Section Measurements

- Future osc. exp'ts rely on paucity of bubble chamber data.

World results of ν_μ CC scattering

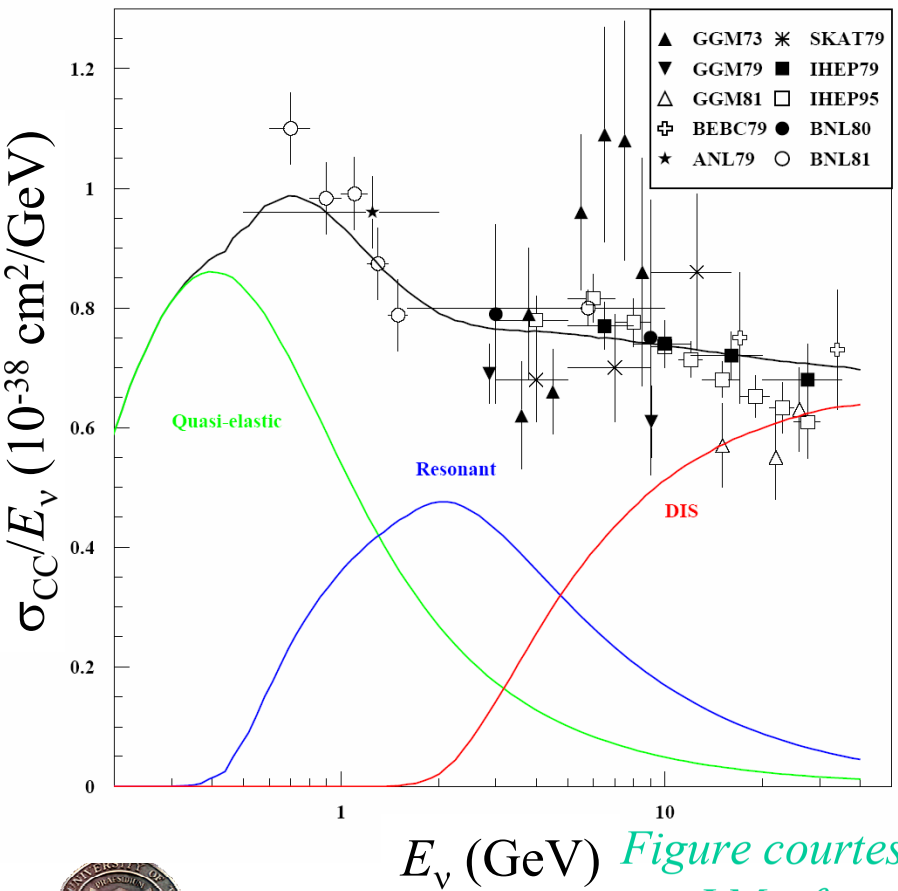


Figure courtesy J.Morfin

- Understand xsec's for
  - Quasi-elastics
  - $\nu_\mu n \rightarrow p\pi^0\mu^-$ and $\nu_\mu N \rightarrow \nu_\mu X\pi^0$
  - Resonant states

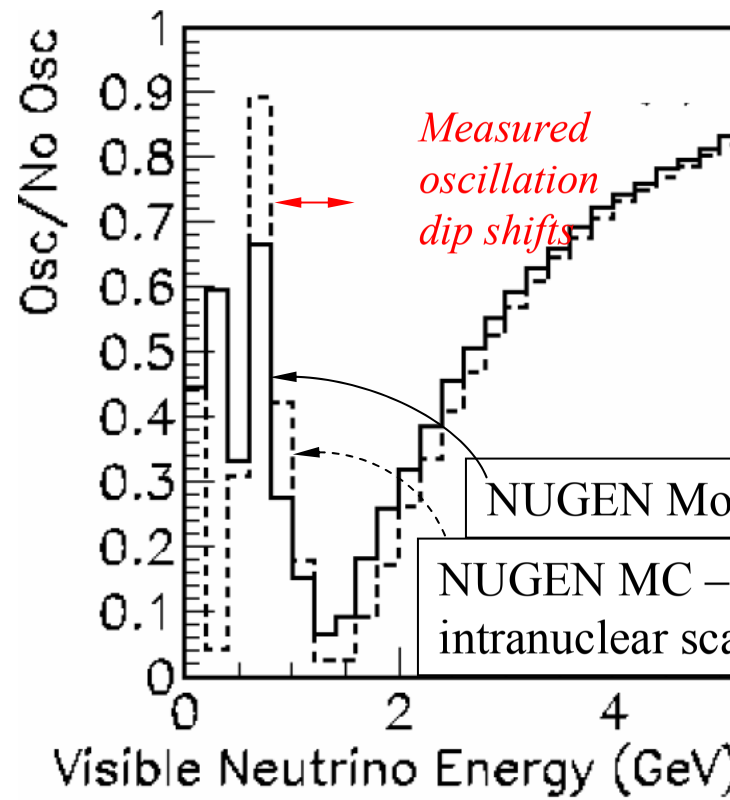
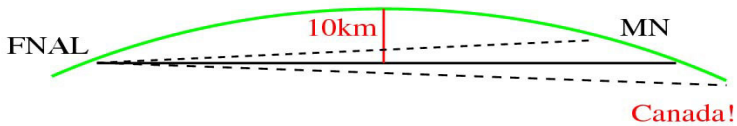


Figure courtesy D.Harris

Off-Axis Beam from NuMI



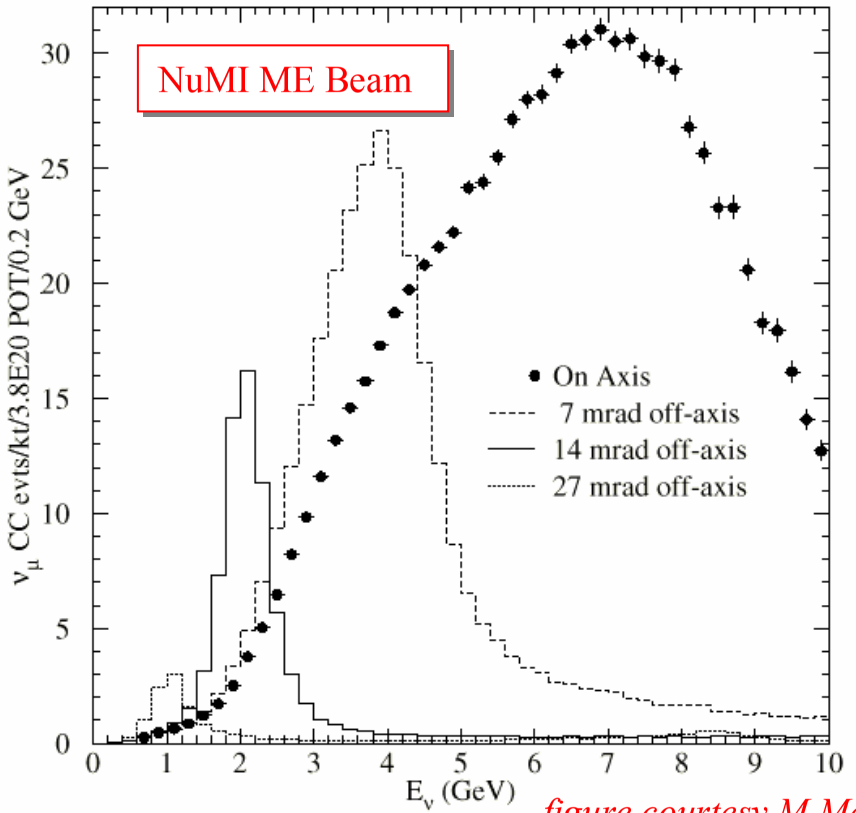
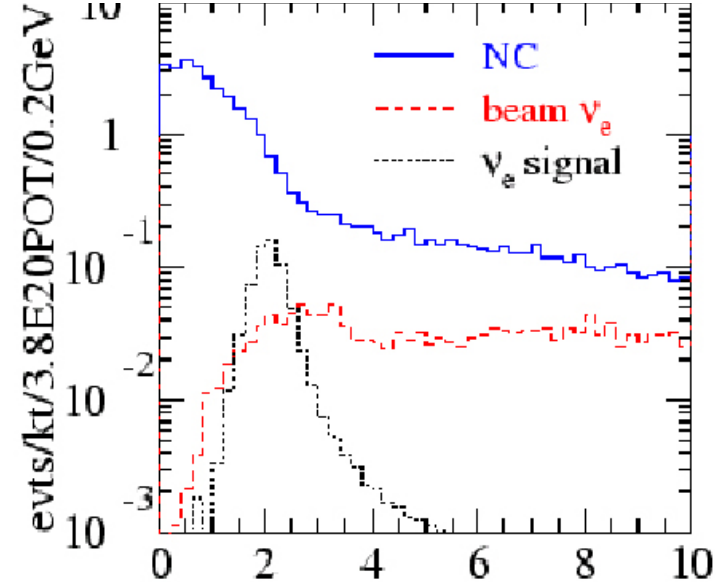


figure courtesy M.Messier

- NuMI facility will spray neutrinos all over the U.S./Canadian border
- Of virtue if you want to…
  - ❖Create a 'narrow-band' beam energy spectrum
  - ❖Deliberately force neutrinos to propagate through greater earth distance

ν_e Appearance in Off-Axis ν_μ Beam

- $P(\nu_\mu \rightarrow \nu_e)$ $\sin^2 2\theta_{13} < 0.18$ at $\Delta m^2 = 2\times10^2$ eV^2 (CHOOZ)
- Narrow beam reduces backgrounds from other (NC) neutrino reactions



$\Delta m^2 = 3.0 \times 10^{-3}$ eV^2 $\sin^2 2\theta_{13} = 0.1$

NuMI Off-Axis,
5yrs @ 4E20 POT/yr
712 km baseline

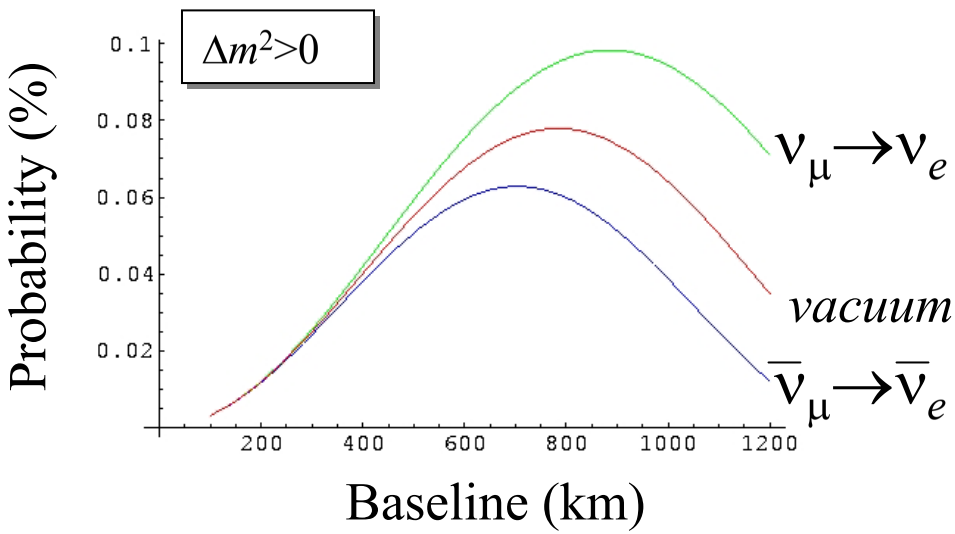
	ν_μ CC	NC	Beam ν_e	Signal ν_e
all	10714	4080	292	302
after cuts	1.8	9.3	11	123

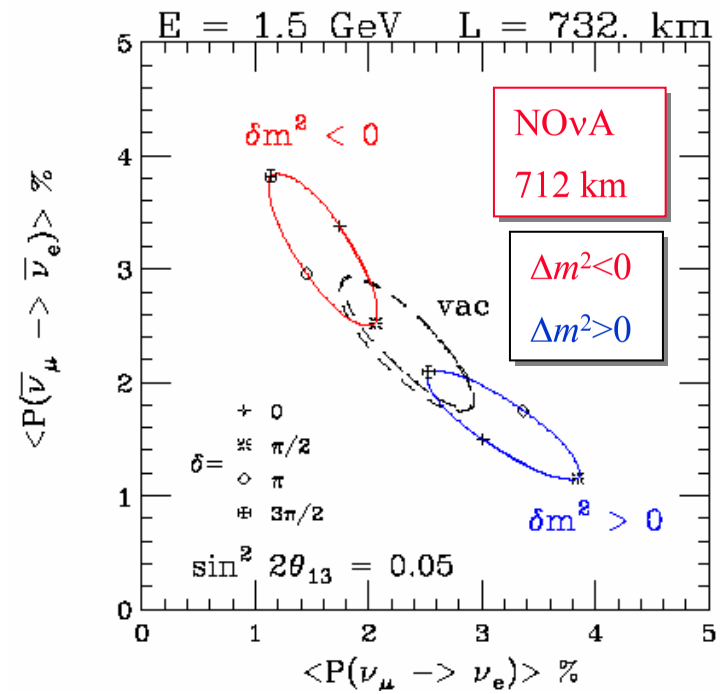
JHF Phase I,
5yrs @ 0.77MW
295 km baseline

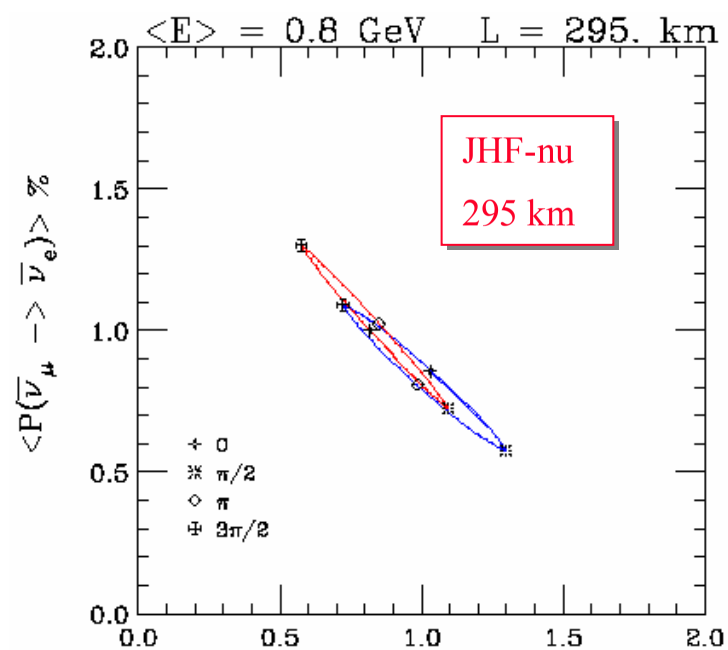
	ν_μ CC	NC	Beam ν_e	Signal ν_e
all	12104	5696	295.4	293
after cuts		10.2	10.2	85.5

- For NuMI, assume a 20kt detector, 85% fid.vol, low-Z calorimeter
- NuMI makes up for lower proton power, longer baseline because of higher neutrino, pion, cross sections.

~~CP~~ in Neutrinos?







- Possible to measure different rates $P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ due to…
  - CP violation
  - Neutrinos propagating through matter
- P929 (NOνA) to consider construction of off-axis experiment
- Antineutrino running requires proton intensity upgrade.

figures courtesy S.Parke

Summary

- Rich program of physics ahead
  - Decisive results on osc. *vs* other new physics
  - Precise measurement of oscillation parameters
  - Possibility to observe rare osc. phenomena
  - CP violation
  - Mass Heirarchy

The light at the end of the tunnel

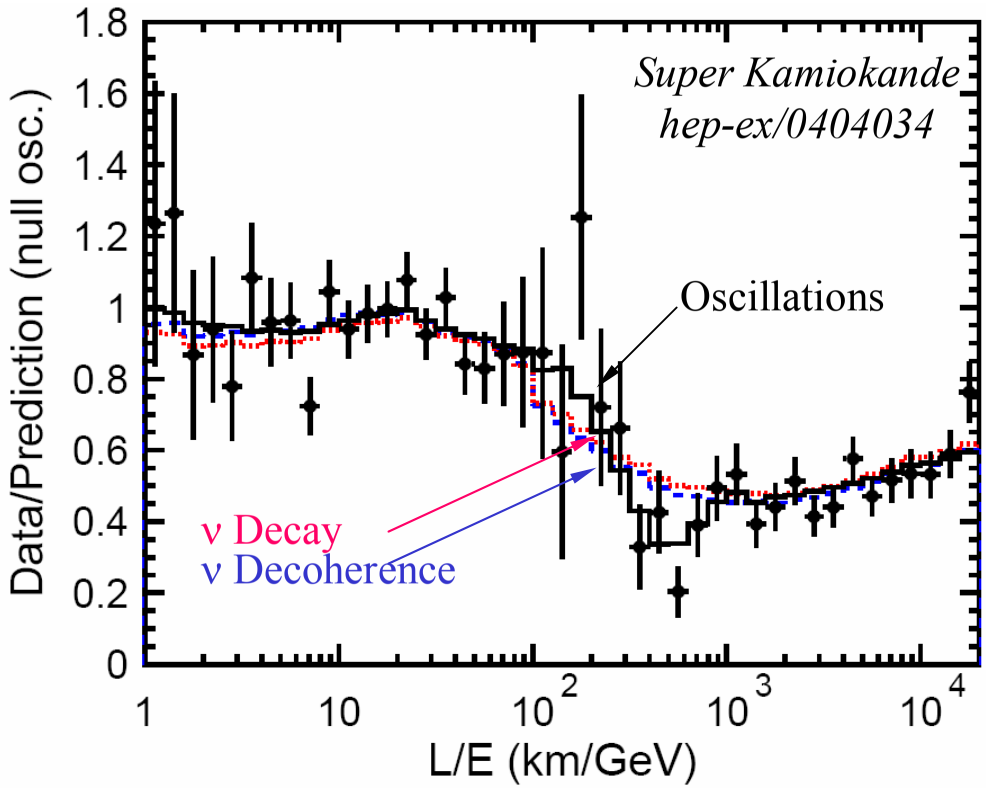
- NuMI is substantial investment in US HEP program
  - Design is flexible to permit variations, upgrades
  - Adjustable neutrino beam energy
  - Large target hall cavern to permit new focusing elements
  - Conservative design parameters permit intensity upgrades
- NuMI is ready for beam November ’04

Extra Slides

Role of NuMI/MINOS – I

Within 3-ν mixing 'orthodoxy', there are several key questions that the MINOS experiment could hope to address:

- Are there sub-dominant oscillation modes at this Δm^2?
- Precision measurement of $\Delta m_{23}{}^2$?
  - It's a fundamental parameter
  - Precision impacts precision on $\sin^2 2\theta_{13}$ achievable at reactor disappearance experiment
  - Its central value important in layout of long baseline $\nu_\mu \rightarrow \nu_e$.
- Is $\nu_\mu \rightarrow \nu_\tau$ mixing maximal?
  - We are told ν mixing just analogous to quarks, but…
  - Quark CKM matrix is largely diagonal
  - "Revolution of 1998" (*cf. A.Y.Smirnov)* SK showed large mixing
  - If mixing matrices are 'analogous', ought their values to be as well?

Role of NuMI/MINOS – II

- Most of community thinks that $\nu_\mu \rightarrow \nu_\tau$ looks like a pretty good explanation of the atmospheric ν depletion *vs* zenith angle, but one must be open to other possibilities given
  - The 3 Δm^2 problem
  - Naturalness of a $\nu_{sterile}$ that appears in GUT models
  - Due skepticism of jumping to conclusions in hard experiments
- Such considerations have spawned array of more sophisticated (busier) but quite serious theoretical scenarios
- MINOS can unambiguously demonstrate oscillatory energy dependence of ν disappearance