

**M**ain  
**I**njector  
**N**eutrino  
**O**scillation  
**S**tudy

# Progress & Prospects

Robert Hatcher  
Fermilab Computing Division

Argonne Trends in Neutrino Physics – May 2003



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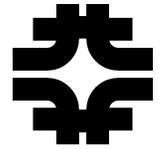
# Outline



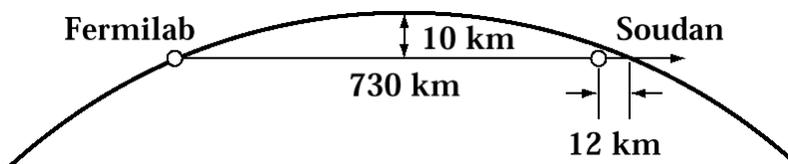
- Overview
- Construction Status
  - NuMI Beamline
  - Near Detector
  - Far Detector
- Current Work
  - Atmospheric  $\nu$
  - Calibration
- Beam Physics Potential



# MINOS Experiment



- NuMI beam using FNAL Main Injector
- Near detector at Fermilab
- Far detector in Soudan Mine, Minnesota

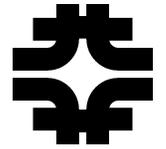


MINOS Collaboration: ~175 physicists, 32 institutions  
US, UK, Russia, Greece, France, Brazil





# MINOS Physics



- NuMI Beam

- measurement of the oscillation parameters  $\Delta m^2$ ,  $\sin^2(2\theta)$  in the region suggested by the atmos.  $\nu$  expts: SuperK, MACRO, Soudan2

- demonstration of the oscillatory behaviour

- measurement of sub-dominant oscillation modes:

$$\nu_{\mu} \rightarrow \nu_e, \nu_{\mu} \rightarrow \nu_{sterile}$$

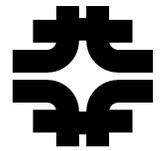
- Atmospheric

- measurement of  $\nu$  vs. anti- $\nu$  oscillations using magnetized far detector – CPT test

- contained vertex events, upward-going muon



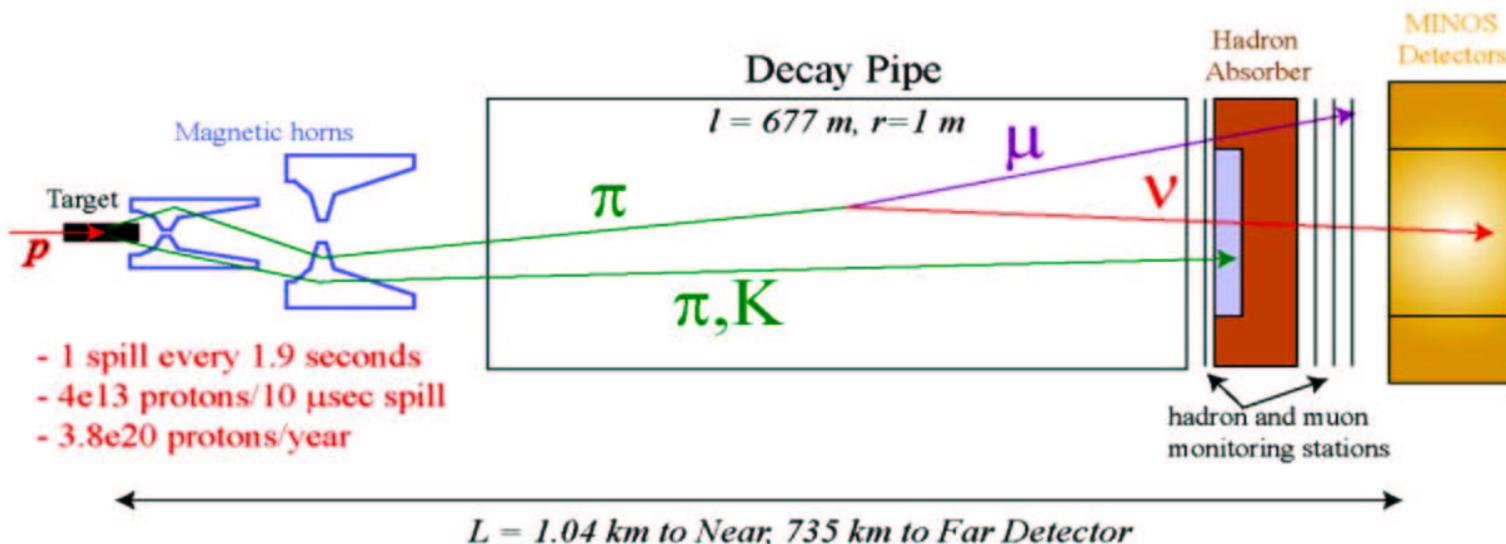
# Making Neutrinos



120 GeV/c protons strike graphite target

Magnetic horns focus charged mesons (pions and kaons)

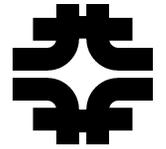
Pions and kaons decay giving neutrinos



Neutrino energy spectrum can be modified by moving the target and/or second horn relative to the first. Designed three standard configurations: Low, Medium and High Energy, but not discrete fixed positions.



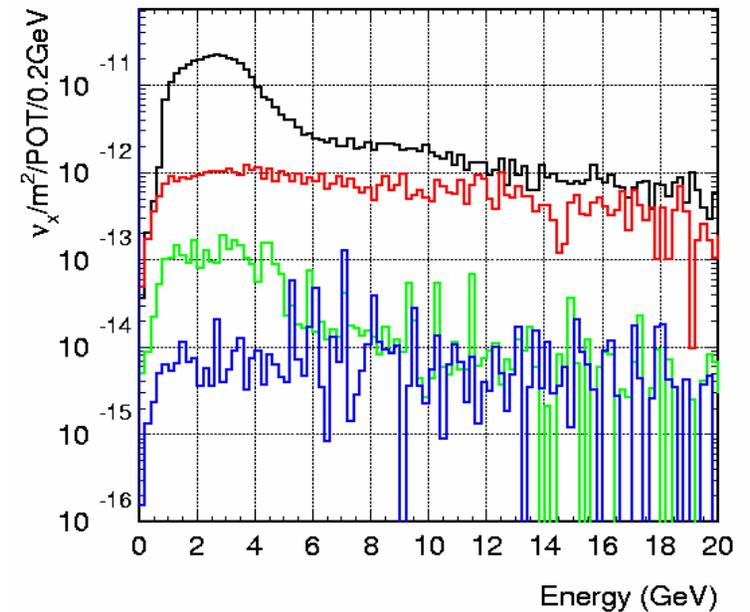
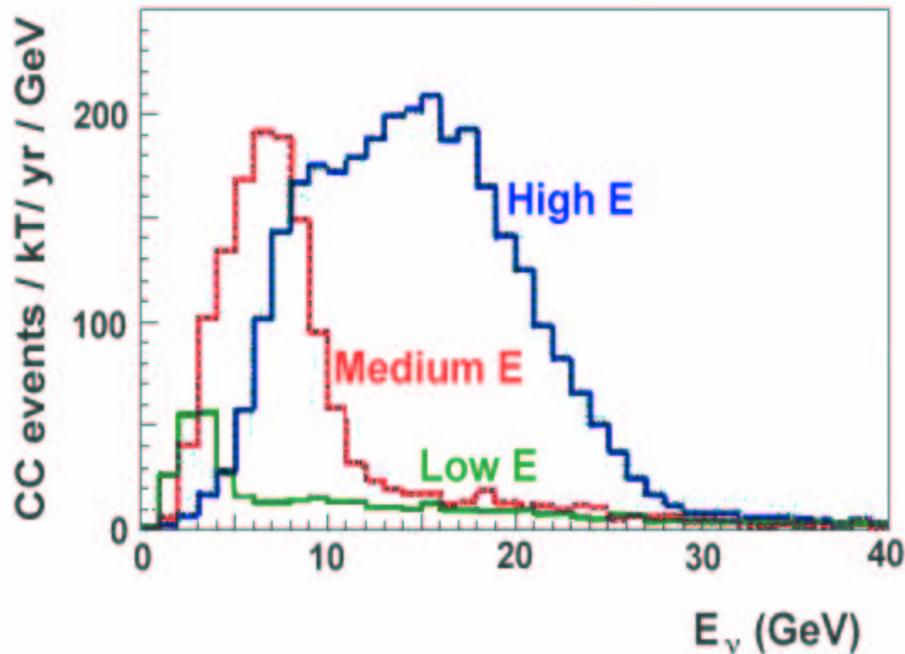
# Neutrino Beam



	LE	ME	HE
NearDet evts/spill		39	114

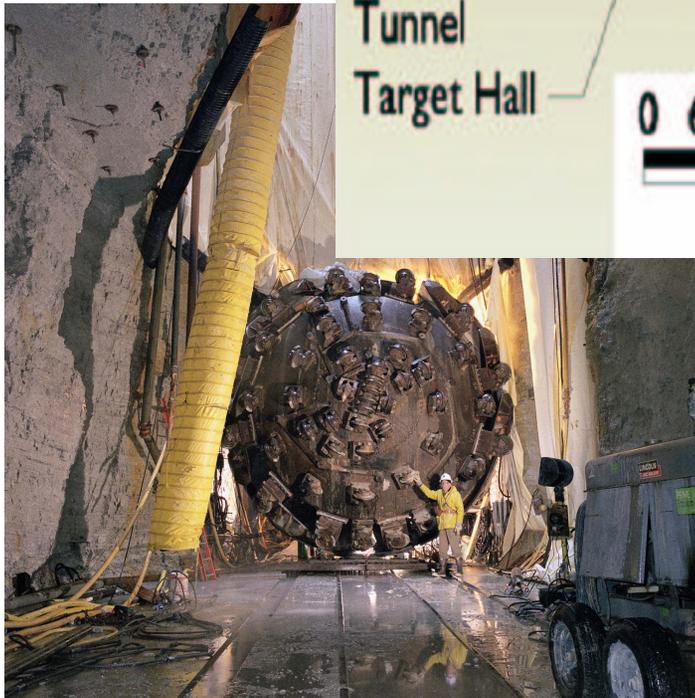
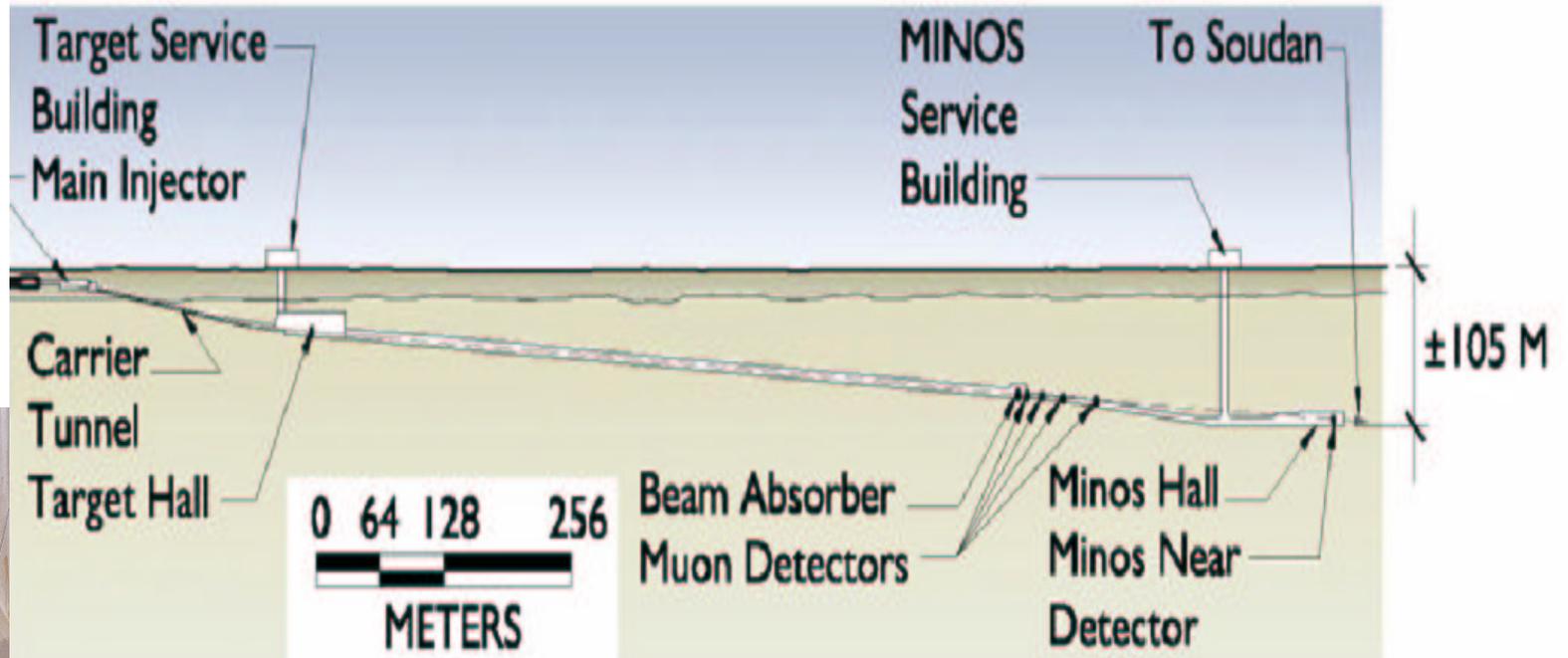
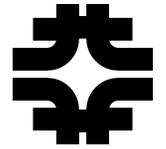
Far  $\nu_\mu$  CC evts/kt/yr

214	2.5-4x10 <sup>20</sup> protons on target/year
1270	single turn extraction (8.4 $\mu$ s)
2740	





# NuMI Beamline Schedule

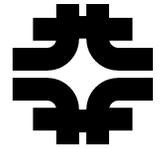


Tunnelling: a nightmare ... but it's now done

- Carrier Tunnel – June '03
- Target Hall, Surface Bldg – Oct '03
- MINOS Hall – Dec '03



# NuMI Construction



Beam Carrier Tunnel



MINOS Near Hall



Horn 1

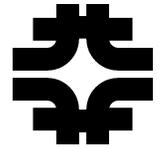


Horn 2 Assembly

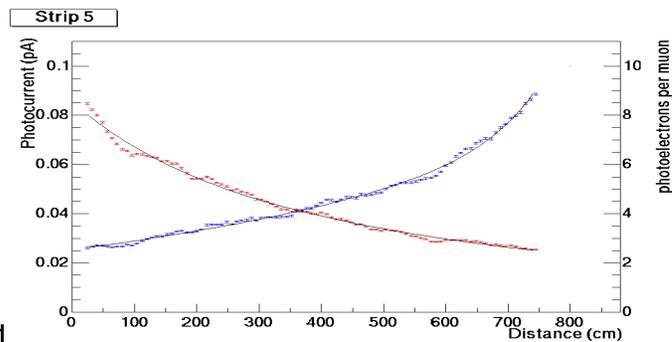
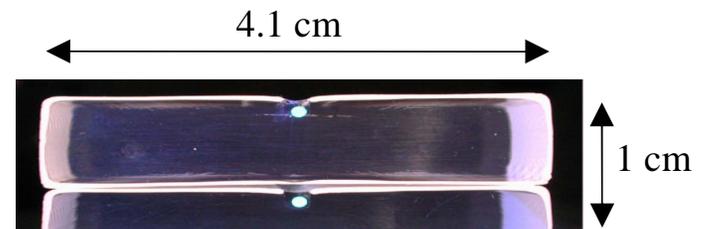
Robert Hatcher - MINOS



# Common Features of Detectors



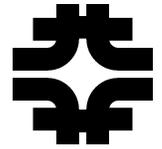
- iron/scintillator sampling calorimeter
- 2.54cm thick steel absorbers
- toroidal B-field of  $\sim 1.3\text{T}$
- 1cm x 4cm scint strips, coextruded w/ reflective cover ( $\text{TiO}_2$ )
- Kuraray 1.2 mm WLS fiber
- Hamamatsu Multi-anode PMTs: M16 (FarDet), M64 (NearDet)
- planes alternate strip orientation



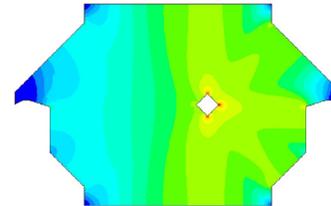
Robert



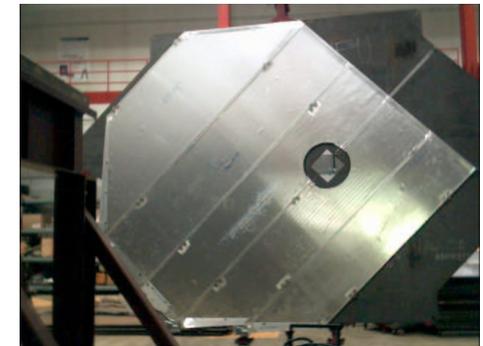
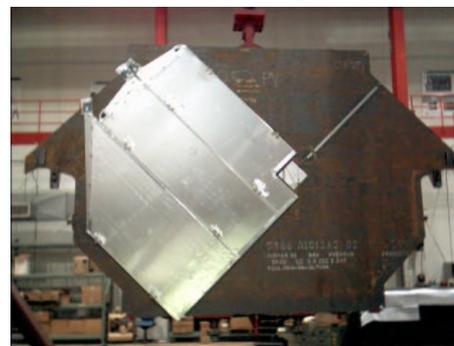
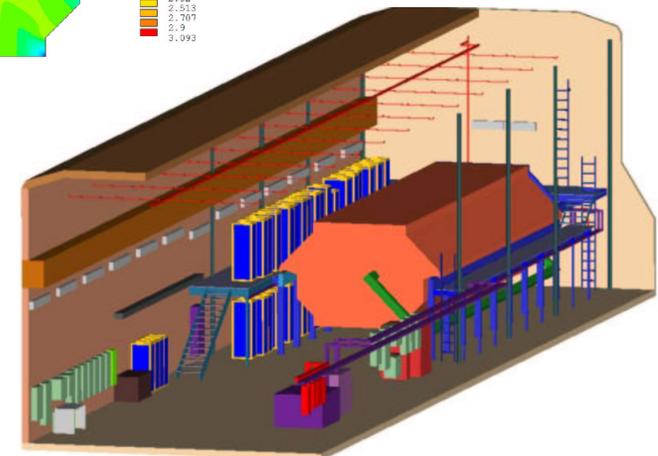
# Near Detector



- “squashed” octagon 4.8m x 3.8m
- 1 kT mass, single B field coil
- 120 planes (veto+target+shower)
  - 1:4 full vs. partial coverage
- 160 steel planes spectrometer
  - 4 of 5 uninstrumented (full)
- single-ended readout, reflector
- 220 Hamamatsu M64 PMTs
- QIE-based front-end electronics
  - 53 MHz digitization
  - 1:4 channels electrically connected in spectrometer

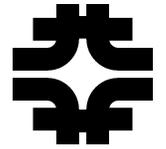


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ANSYS 5.5.15P
JUN 14 2000
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NODAL SOLUTION
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SUB =1
TIME=1
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SMX =3.093
.778E-05
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.28668
.590015
.778351
.964697
1.16
1.353
1.547
1.74
1.933
2.127
2.32
2.513
2.707
2.9
3.093
```





# NearDet Construction Status



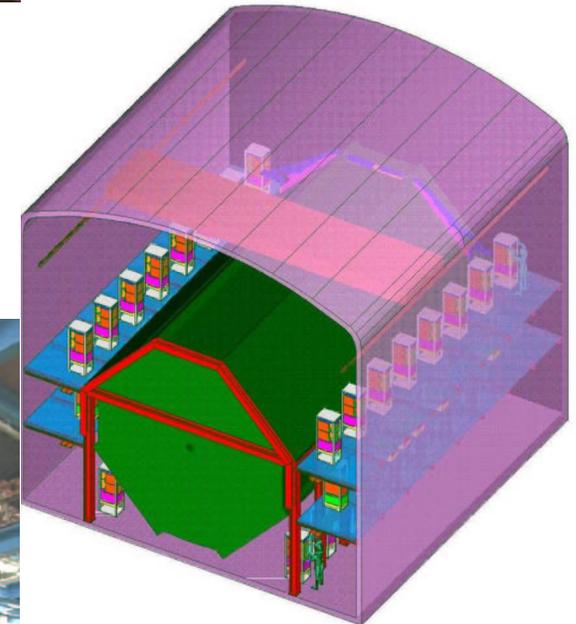
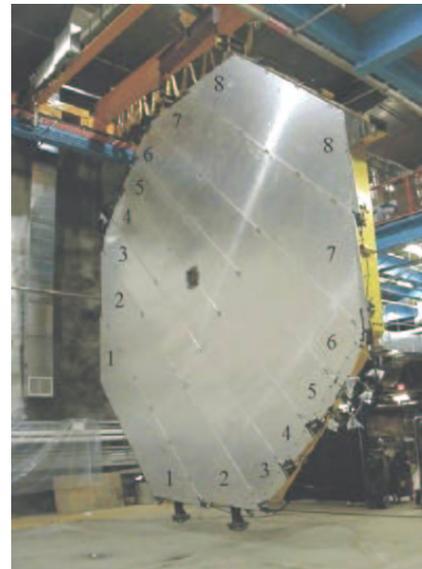
- All scintillator planes have been assembled (on the surface) and are stored in the New Muon Lab awaiting installation
- Installation will start with the beneficial occupancy of the NuMI MINOS Hall, scheduled for Dec '03
- Installation is scheduled to finish in Oct '04





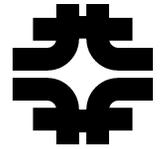
# Far Detector

- 8m octagon
- 2 independently magnetized SuperModules (each 15m long)
- total of 5.4 kT
- 484 scintillator planes, each with 192 strips (92,928 total)
- 1452 Hamamatsu M16 PMTs
- 8-fold optical summing onto pixels (“multiplexing”), readout both ends
- Viking “VA” front end electronics

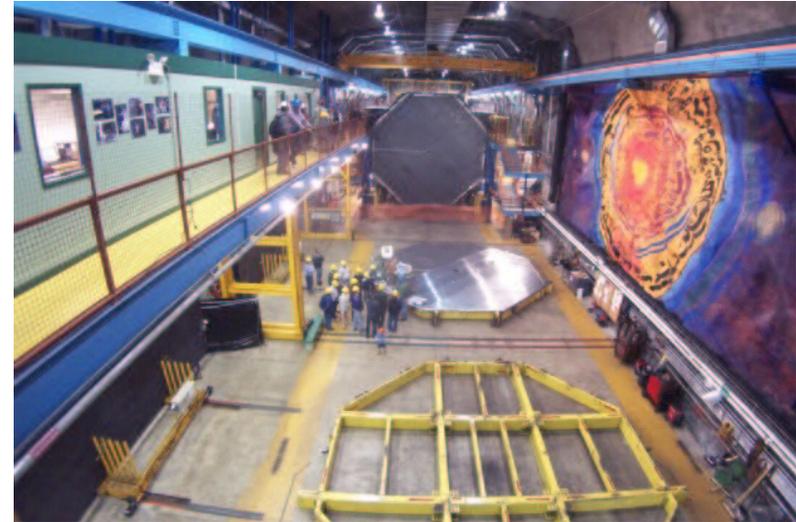




# FarDet Construction Status



- Installation started Aug '01
- SM1 completed July '02
  - B field turned on Aug '02
  - Collecting cosmic/atmos  $v$  data, ~70% uptime – total exposure ~1.5 kton\*years
- Currently 474 of 486 planes
- Installation of planes to be complete ~ end of May



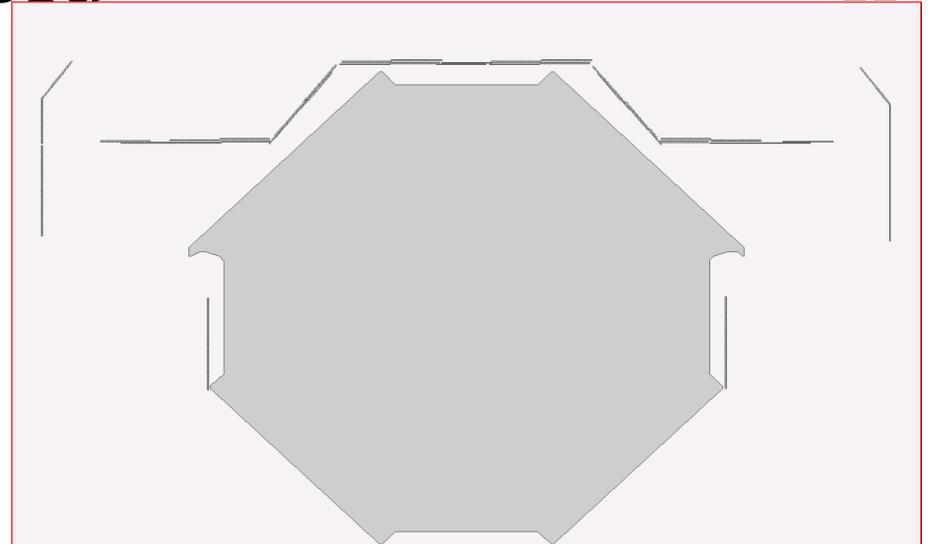


# FarDet Veto Shield



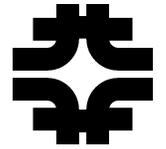
## Detector is not hermetic

- Collected data showed that cosmic ray  $\mu$  produce a significant bkgd to atmospheric  $\nu$  events
  - upward muons very clean
  - background  $\sim$  signal for contained vertex events
- Veto shield installation
  - Built from same components
  - construction started in fall 2002
    - currently 3 of 4 sections in z are installed
    - SM1 completely covered
    - data taking and analysis of performance is underway





# Calibration Detector

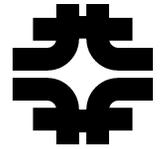


- same basic geometry ... just smaller
- 60 planes, 1m x 1m (24 strips)
- no magnetic field
- exposed to CERN test beam of  $\mu$ ,  $\pi$ , e, p beams 0.5 – 10 GeV
  - hadron, EM energy response
  - event topology
  - VA (Far) vs. QIE (Near) readout electronics comparison





# Atmospheric Neutrinos

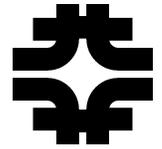


- MINOS is the first magnetized underground detector
- Able to distinguish  $\nu_{\mu}$  CC events from NC and  $\nu_e$  events
- Measurement of momentum and charge of  $\mu$  possible in  $\sim 0.5 - 100$  GeV range
- Expected statistics accumulated by the end of 2007:

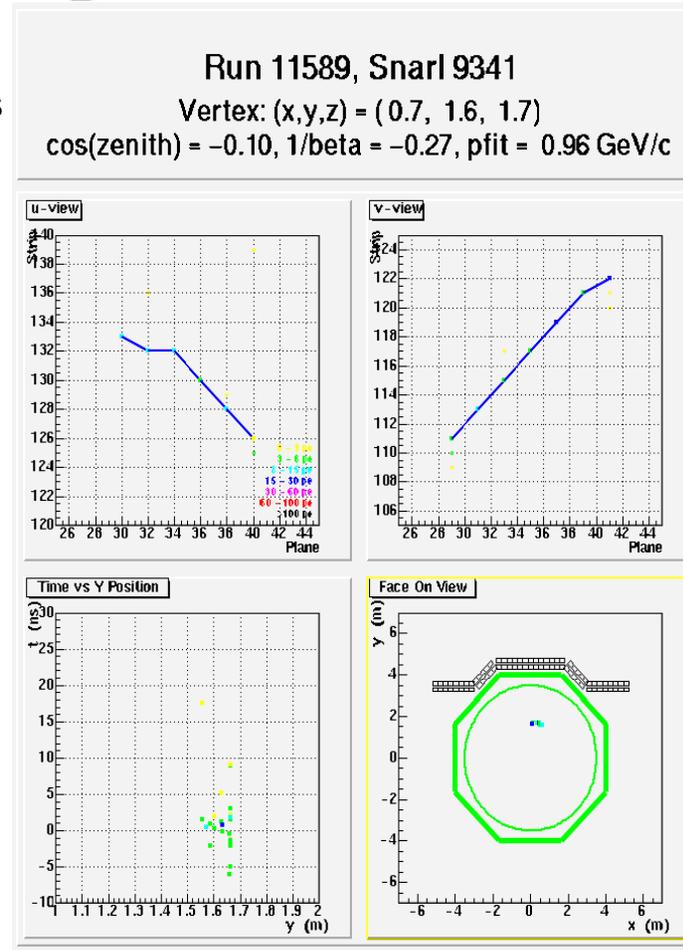
	neutrino	anti-neutrino
reconstructed contained vertex with muon	620	400
reconstructed upgoing muon	280	120



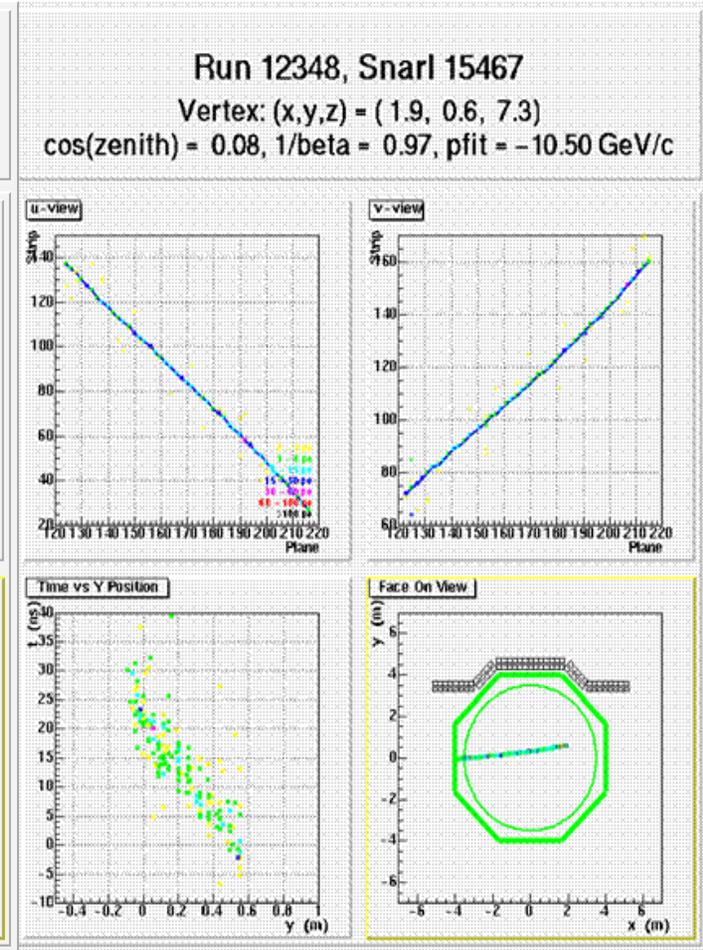
# Atmospheric Neutrinos



- Examples of event candidates
- Reconstruction software is still under (very) active development



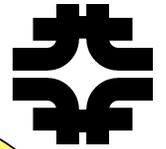
Fully Contained Candidate



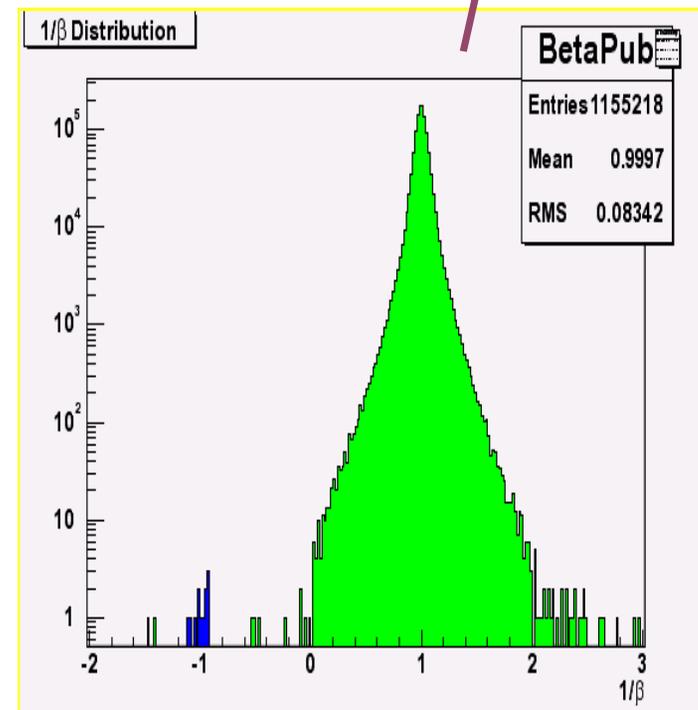
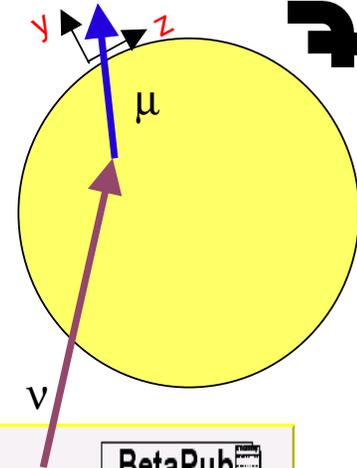
Partially Contained Candidate



# Upward Going Muons

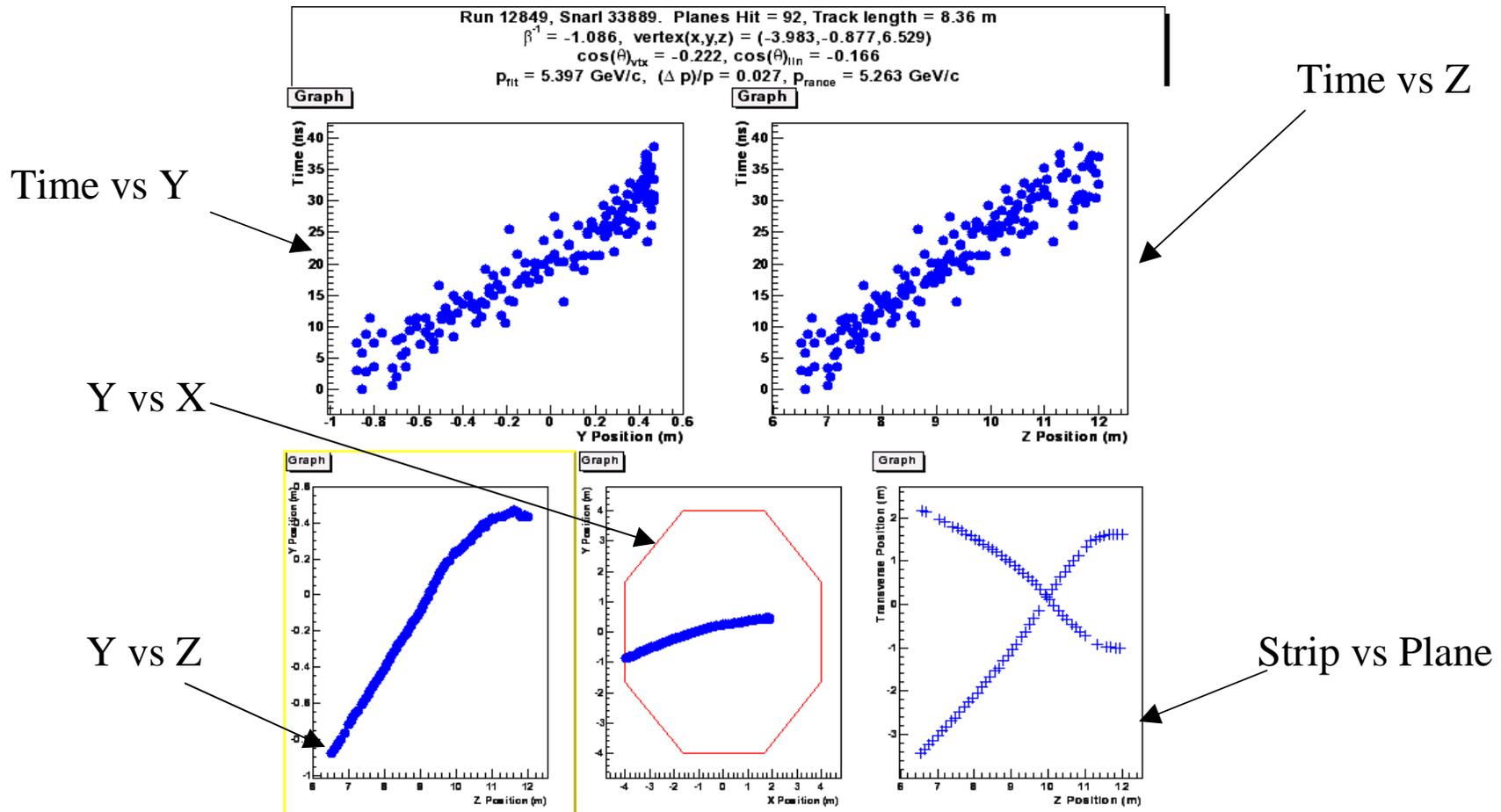
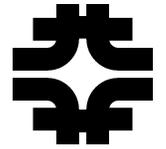


- use timing and direction cos at the vertex to identify upward going muons
- negative  $1/\beta$  ( $=c/v$ ) indicates upward going, peak at -1 is clearly seen
- require minimum path length of 20 planes and 2m
- tight distribution indicates good timing; resolution of  $\sim 2.4\text{ns}$  dominated by 8ns decay of Y11 flour in WLS fiber
- identify both stopping and throughgoing muon





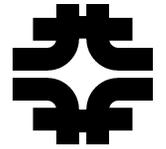
# Example Upward Going Muon





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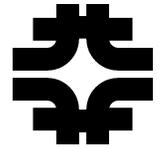
# Timing & Position Resolutions



- Position along a strip can be inferred from
  - orthogonal view
  - difference in time from signal on each end
- Timing
  - allows determination of  $\mu$  track direction
  - resolution dominated by 8ns decay time of Y11 fluor in WLS fiber
  - can be used to evaluate reconstruction errors
    - due to misplacement when resolving effects of optical summing (“muxing”)



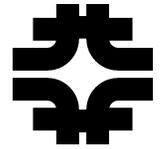
# Charge Resolution



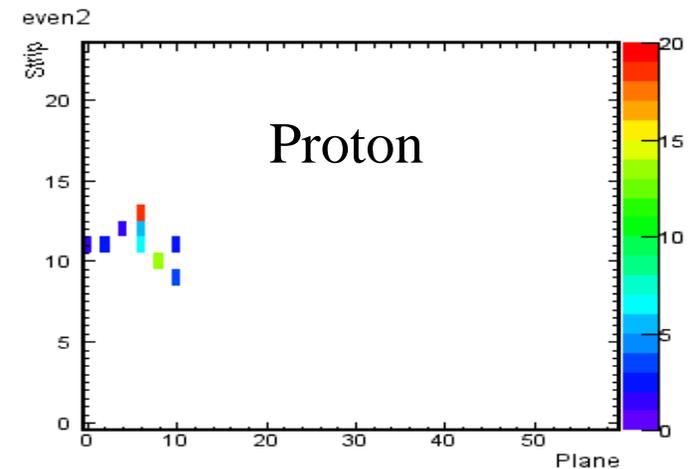
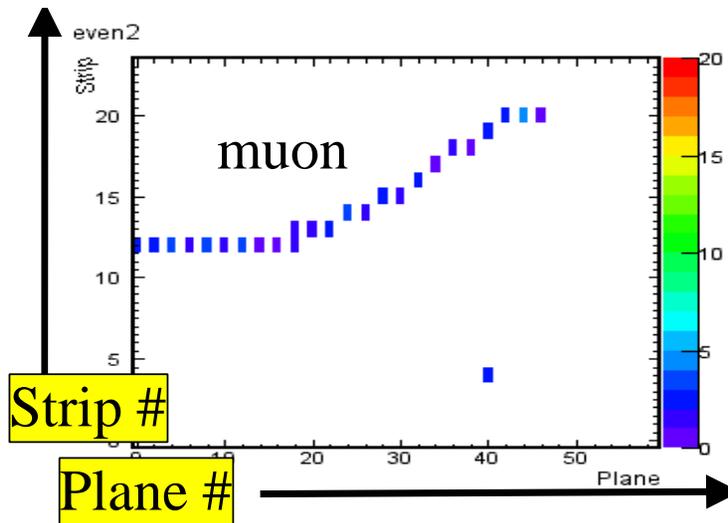
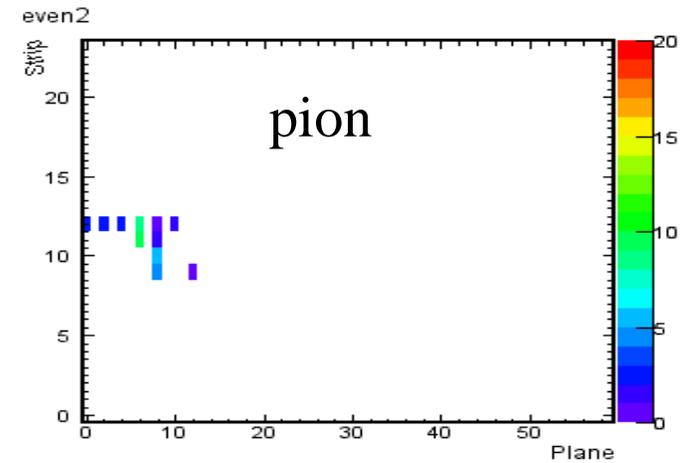
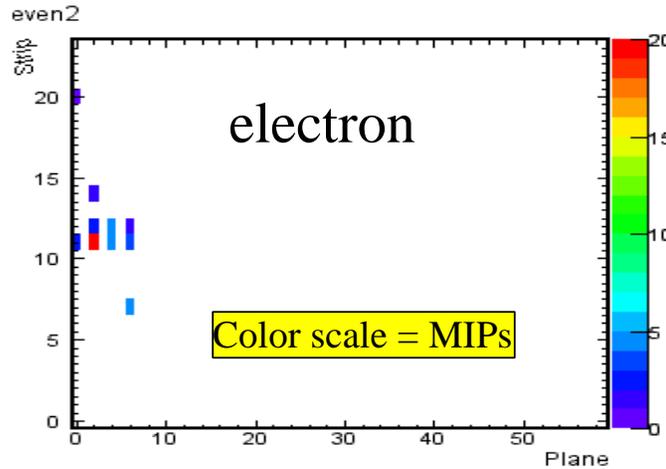
- Differentiating between up/down going and  $\mu^+/\mu^-$  depends on track length, # of planes hit, energy of  $\mu$
- Good determination for  $E_\mu \leq 100$  GeV
- Flat overburden of Soudan should reduce cosmic ray background near horizon; favorable for observing  $\nu$  induced  $\mu$  for  $\cos\theta = -1.0$  to  $\sim 0.1$
- Expect  $\sim 450$  upgoing events in 5 year exposure
  - +/- ratio of  $\sim 1:2$  (i.e.  $150 \mu^+$ ,  $300 \mu^-$ )



# CalDet: Event Topology

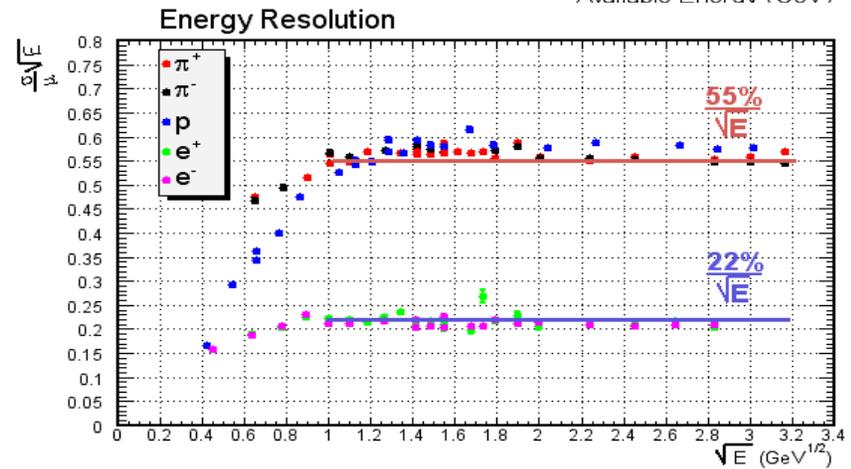
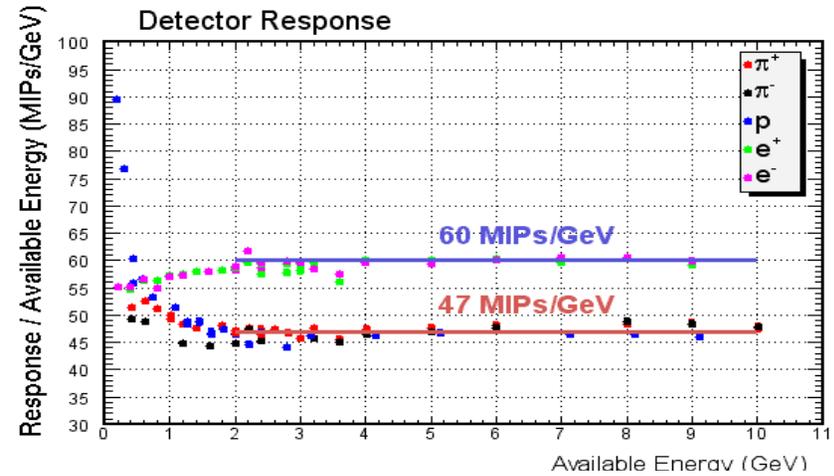
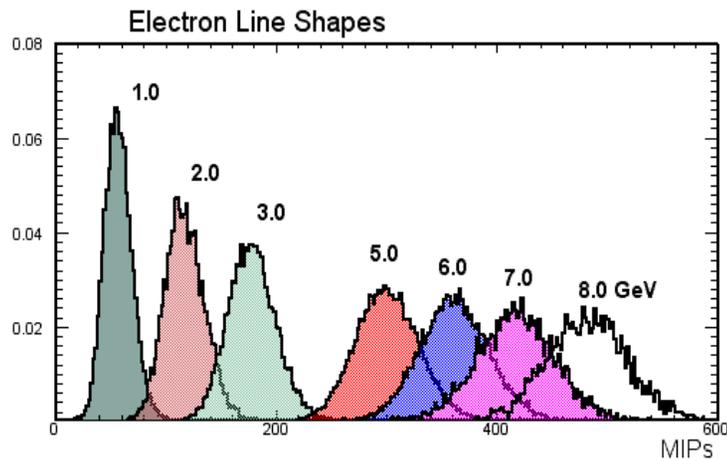
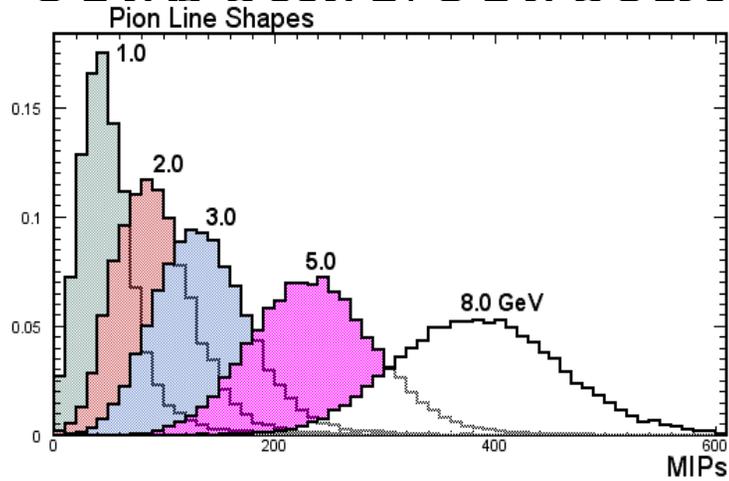
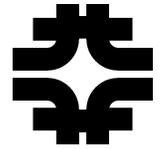


- Exposures
  - Sept '01
  - June '02
  - Sept '02
- Planned
  - Sept '02



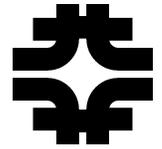


# CalDet: detector response/resolution

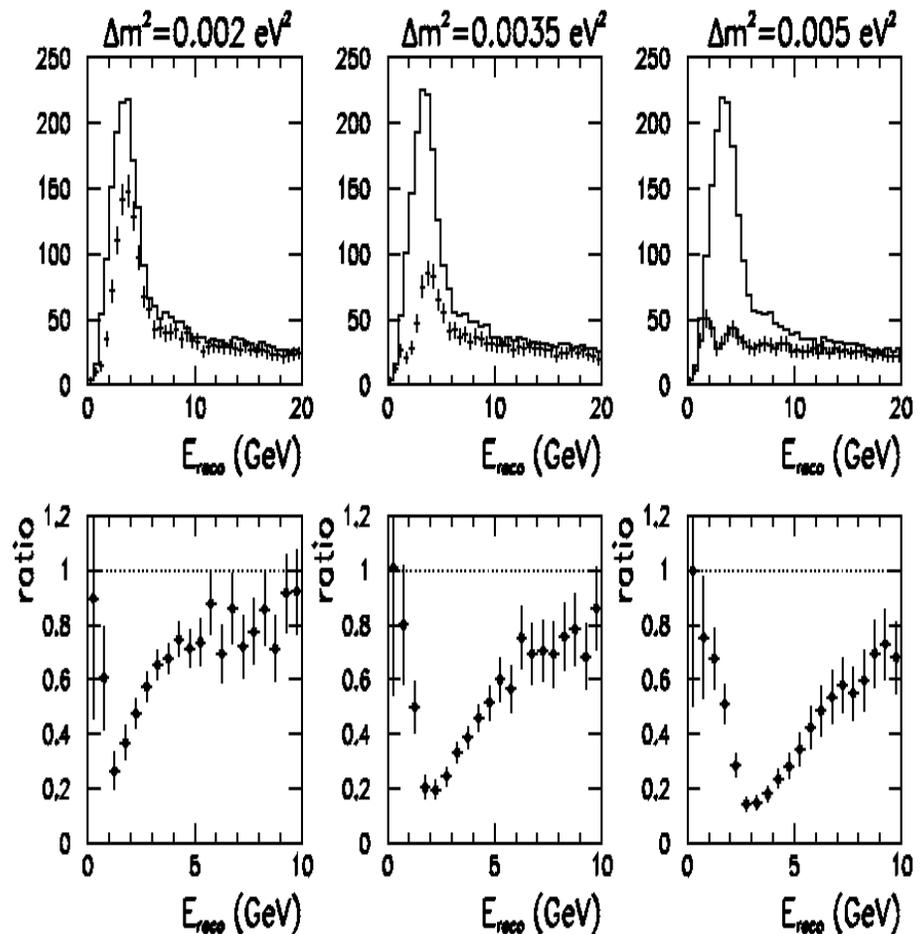




# Neutrinos Near $\rightarrow$ Far



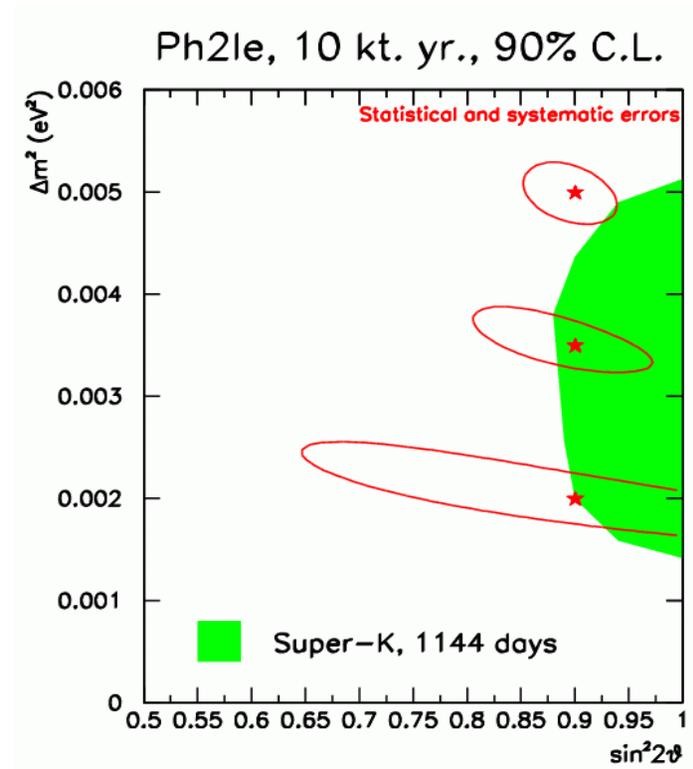
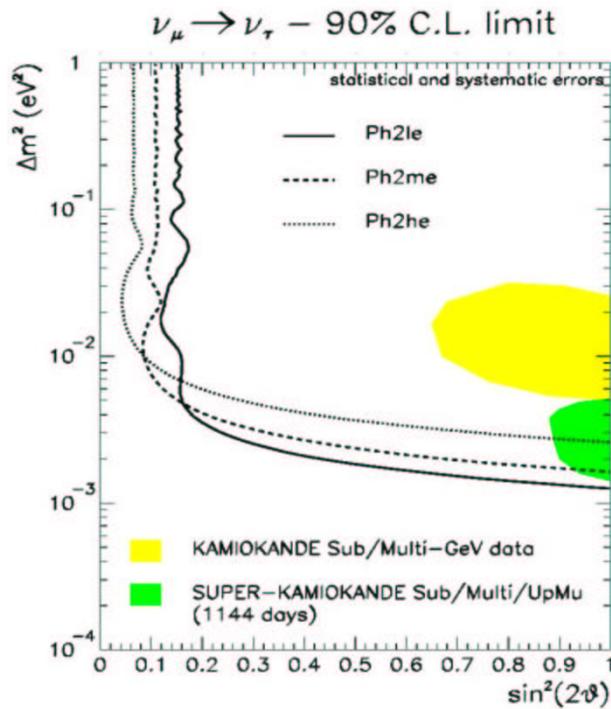
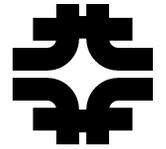
- Oscillation parameters determined by observing a change in the measured far spectrum relative to that predicted by extrapolating the measured near spectrum.
- Near  $\rightarrow$  Far extrapolation correction adds to the systematics; designed to give  $\sim 2\%$  near/far relative calibration, 5% absolute
- Observing shape change can differentiate between oscillations and exotic alternatives (decay, alternative dimensions, etc.)



“blessed” plots are  $\sim 2$  yrs old and are based on 2 yrs of running w/  $3.8 \times 10^{20}$  POT/yr.

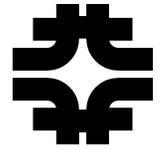


# $\nu_\mu$ Disappearance Measurement

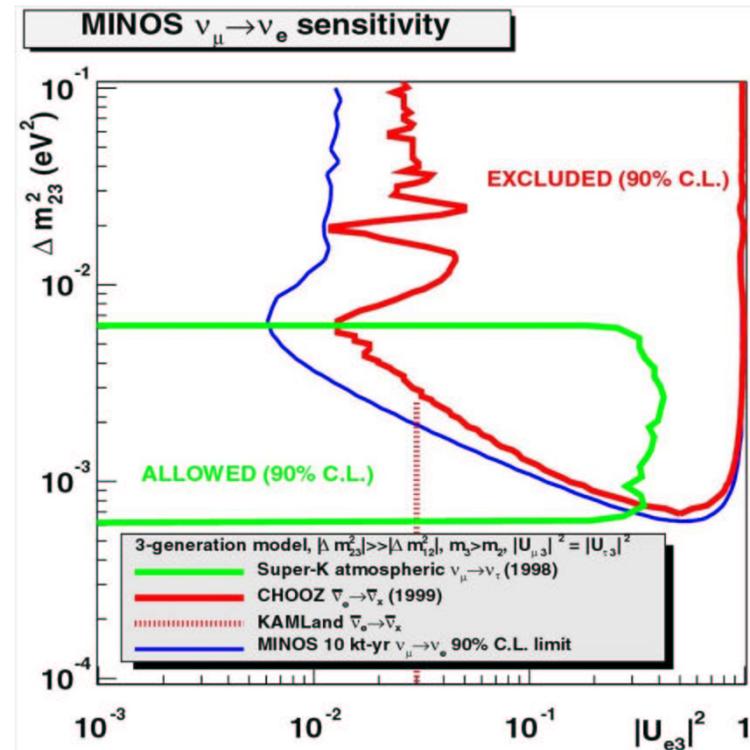




# Electron Appearance: $U_{e3}^2$



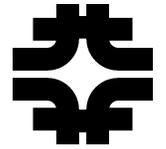
- Improvement of the current limits on the sub-dominant oscillation mode  $\nu_\mu \rightarrow \nu_e$  by the analysis of  $\nu_e$  CC events
- Sensitivity is limited by statistical fluctuations in the NC  $\pi^0$  background in FarDet
  - large contribution from high energy tail of spectrum
  - additional contribution from intrinsic  $\nu_e$  from K, $\mu$  decay
- For any reasonable exposure we are limited by statistics not systematics





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# Conclusions



- Far Detector is almost complete including veto shield
- NuMI construction work is on schedule and expected to be finished Dec 2003
- Near Detector planes are assembled and ready for installation in the detector hall Dec 2003
- Cosmic/atmospheric  $\nu$  data taking with magnetized SM1 is ongoing, SM2 will be magnetized soon after completion
- Lots of work on calibration, reconstruction software, and analysis is underway
- First protons on target expected in December 2004