The MINOS Experiment

- The NuMI beamline
- The MINOS Detectors
- Some first data!
- Physics Measurements
- Atmospheric ν vs $\overline{\nu}$.
- Summary

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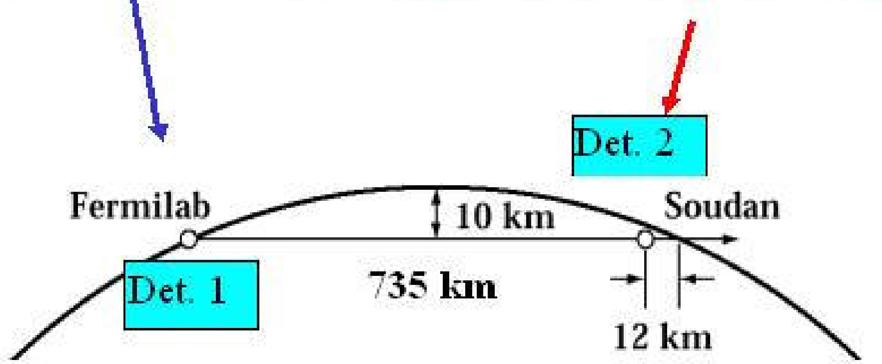
The MINOS Experiment

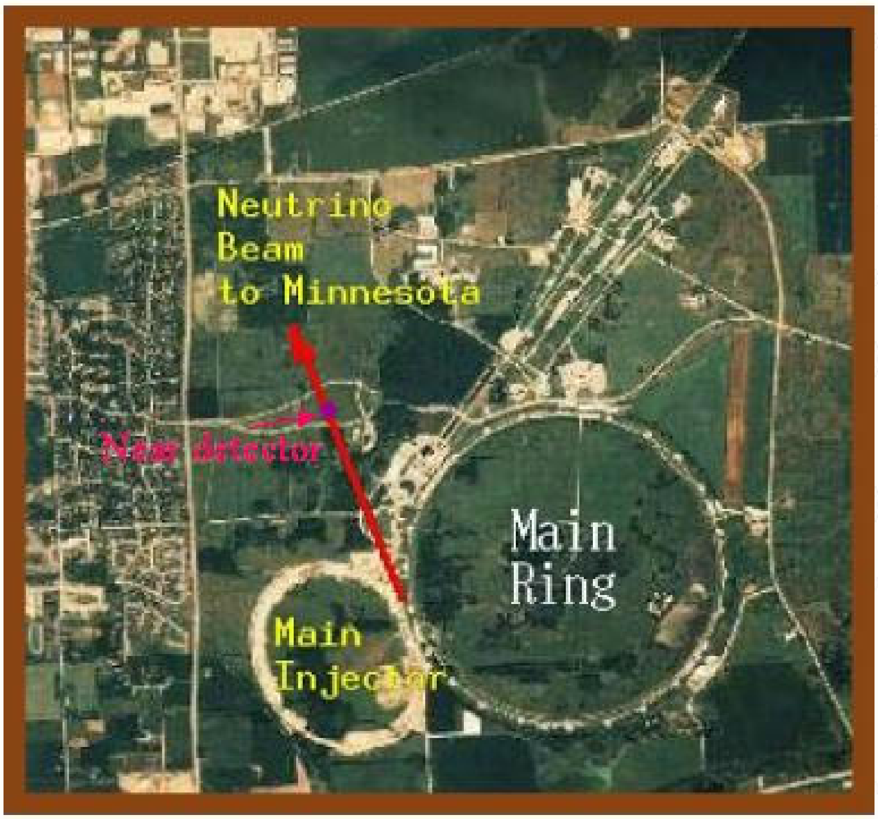
- Precision measurements of:
  - Energy distribution of oscillations
  - Measurement of oscillation parameters
  - Participation of neutrino flavors
- Direct measurement of ν vs $\overline{\nu}$ oscillation
  - Magnetized far detector: atm. ν's.
  - Likely eventual measurement with beam

Near Detector: 980 tons

Far Detector: 5400 tons



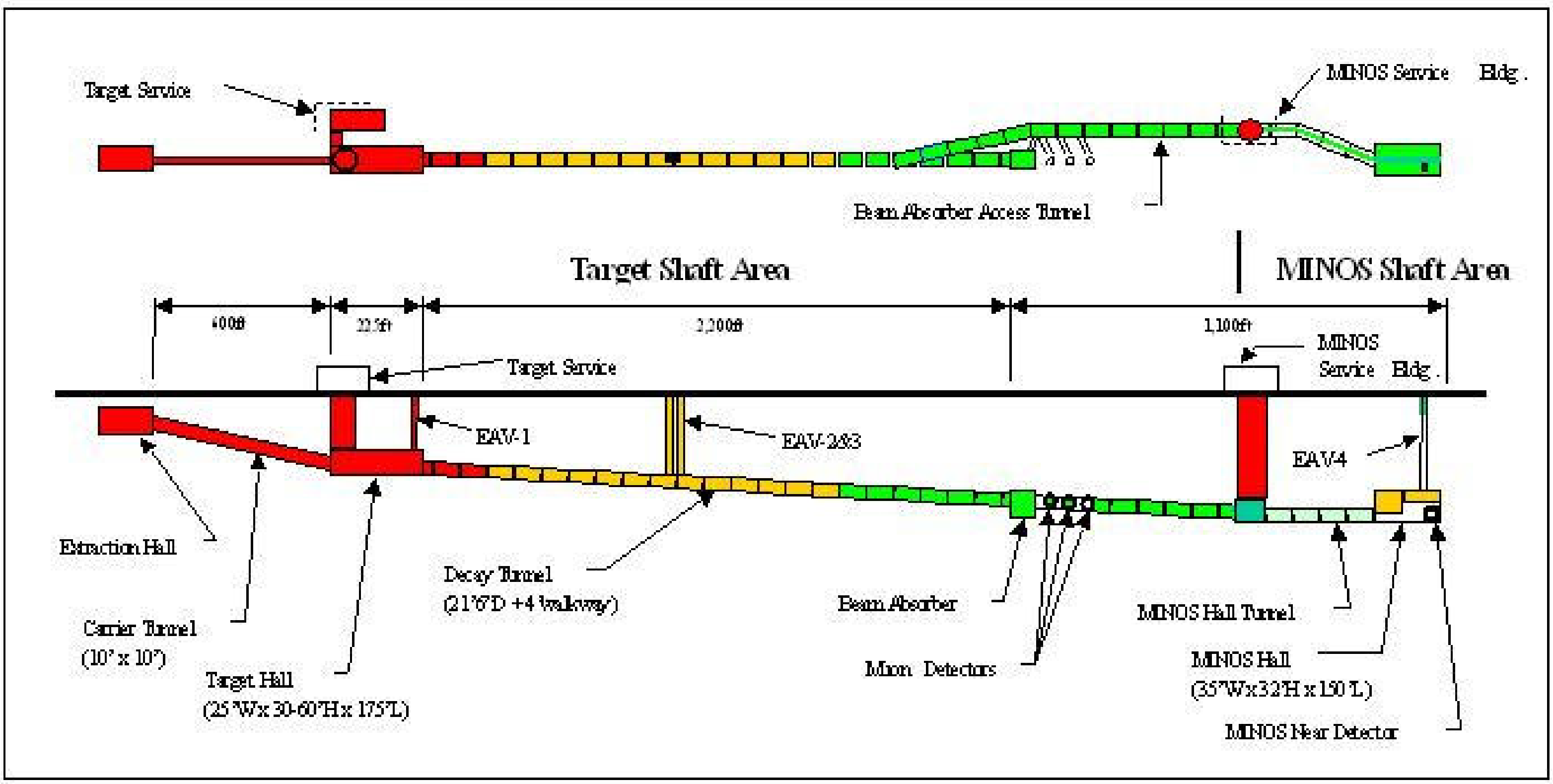
Neutrinos at the Main Injector (NuMI)



- 120 GeV protons
- 1.9 second cycle time
- 4×10^{13} protons/pulse
- 0.4 MW!
- Single turn extraction (10μs)
- 4×10^{20} protons/year
- 700 m x 2 m diameter decay pipe for neutrino beam.
- 200 m rock absorber.
- Near detector complex.

Status of NuMI Beamline Construction

- The excavation of the NuMI beamline halls and tunnels is ~complete.
- Outfitting and installation of beamline components will take about two years.
- First protons on target expected in December 2004.



The NuMI Decay Tunnel

The Decay Pipe

- Installation of the decay pipe is underway.
- Pipe is installed, welded, and concrete shielding is poured into place around it.
- Work is proceeding on schedule and should be complete this fall.

The first section of decay pipe is hoisted into place.

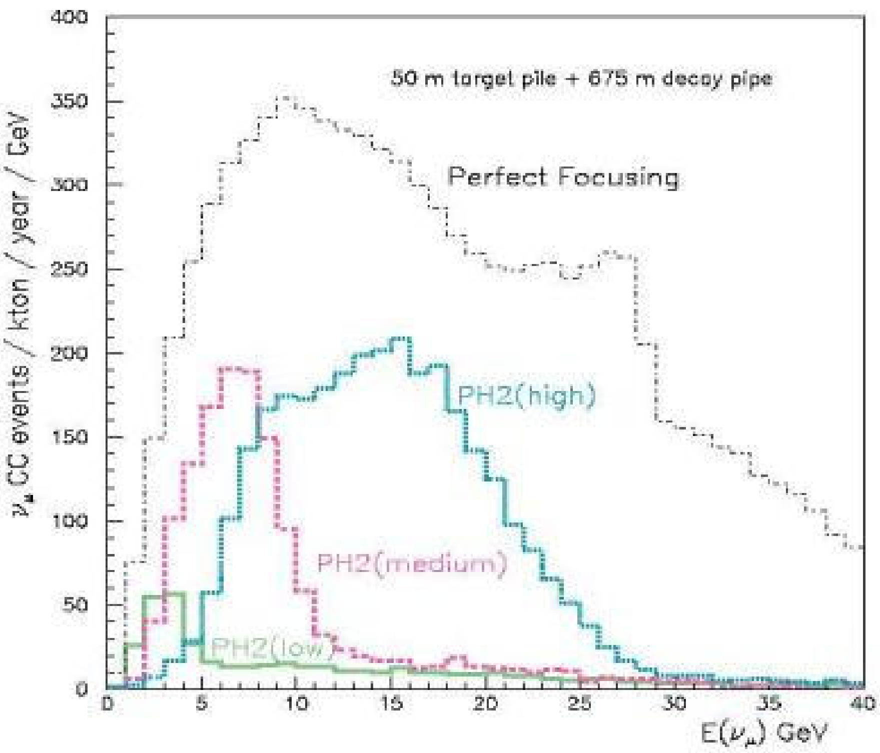
Fabrication and Testing of Horns

Horn 2 inner conductors.

- The prototype upstream horn has been tested for 8 million pulses (80% of a NuMI year) with no problems.
- Both the final upstream horn and the downstream horn are now in fabrication.
- Target design is complete and fabrication is beginning.

Prototype horn 1 in test stand

The NuMI Neutrino Energy Spectra



ν_μ CC Events/kt/year

Low	Medium	High
470	1270	2740

ν_μ CC Events/MINOS/2 year

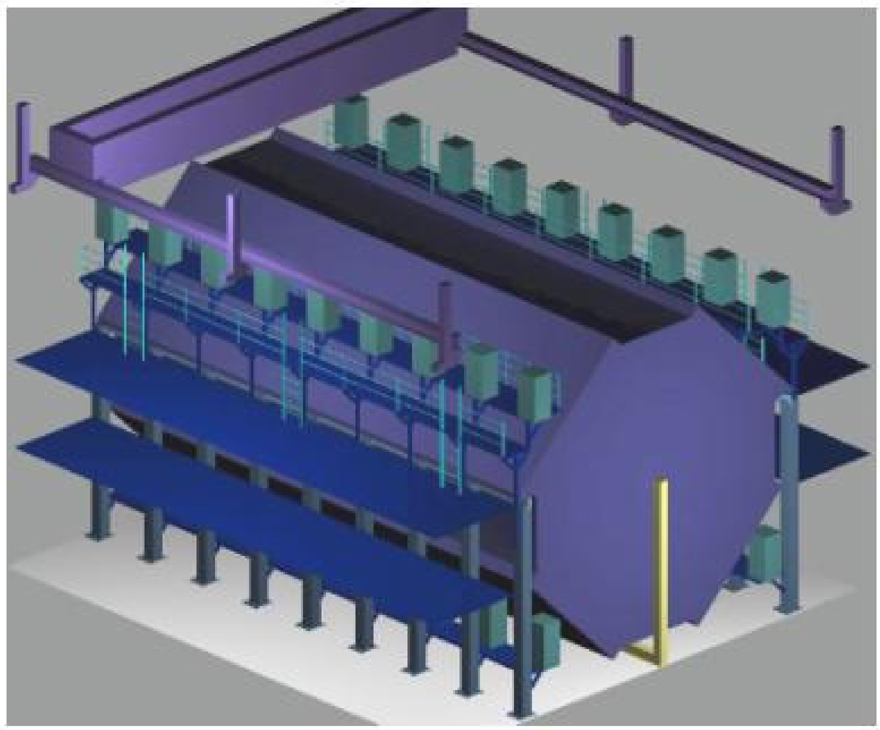
Low	Medium	High
5080	13800	29600

$4\text{x}10^{20}$ protons on target/year
$4\text{x}10^{13}$ protons/1.9 seconds

By moving the horns and target, different energy spectra are available using the NuMI beamline. The energy can be tuned depending on the specific oscillation parameters expected/observed.

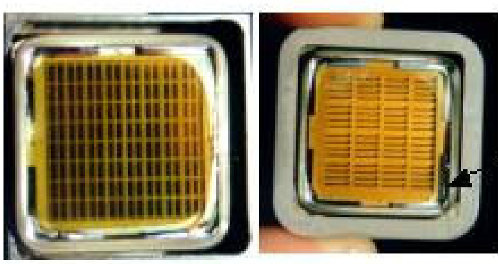
The MINOS Far Detector

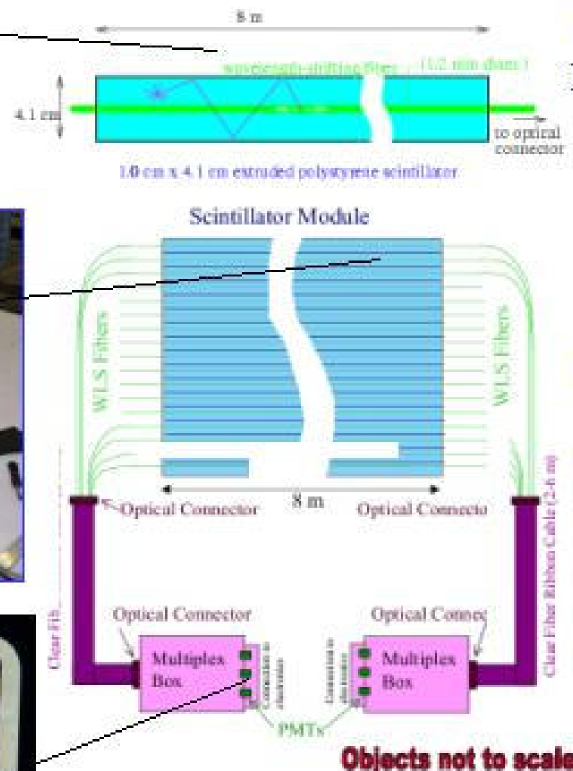
- 8m octagonal steel & scintillator tracking calorimeter
  - Sampling every 2.54 cm
  - 4cm wide strips of scintillator
  - 2 sections, 15m each
  - 5.4 kton total mass
  - 55%/√E for hadrons
  - 23%/√E for electrons
- Magnetized Iron (B~1.5T)
- 484 planes of scintillator
  - 26,000 m^2



One Supermodule of the Far Detector…
Almost a "snapshot" of how the detector looks now!

Detector Technology

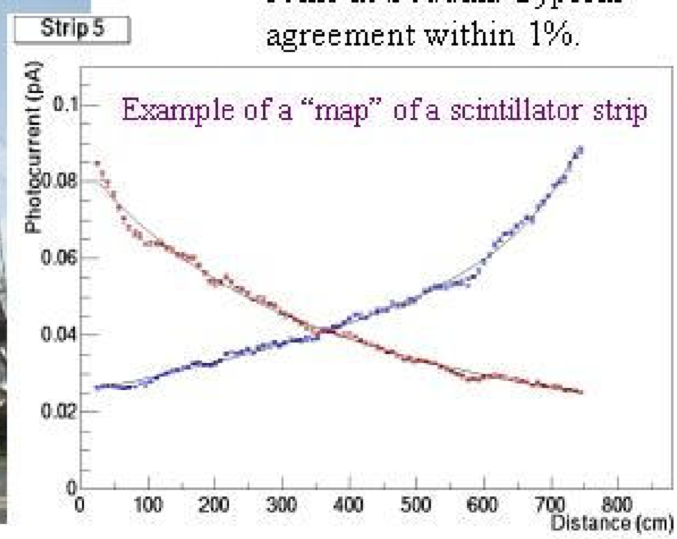




- Scintillator strips are extruded polystyrene (Itasca Plastic)
  - PPO (1%) and POPOP (0.03%) fluors
  - Co-extruded TiO_2 reflective coating
  - Fiber groove
- Kuraray 1.2mm WLS Fibers
  - (Y-11 175ppm)
- PMTs:
  - Far Detector: Hamamatsu R6000-M16 multi-anode PMTs (16 channels), 8 fibers/pixel.
  - Near Detector: "M64", one fiber per pixel.
- Viking "VA"-based front-end electronics.

Assembly and Testing at Soudan

- Scintillator system components are assembled at universities and shipped to Soudan.
- Steel and components are sent down the shaft.
- Scintillator modules are mapped at the factories and some at Soudan. Typical agreement within 1%.

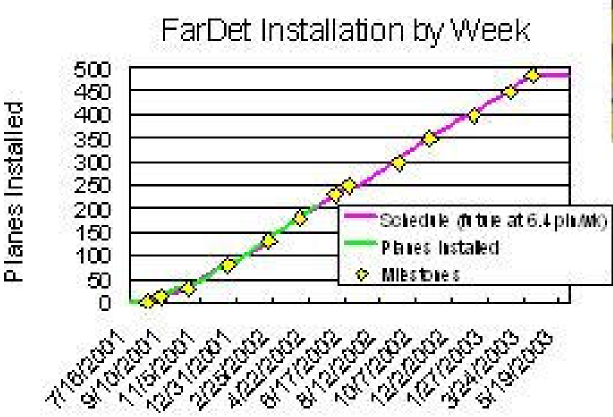


Plane Assembly

Steel Welded and modules placed.

Plane lifted to vertical

Crane carries plane down the hall for installation



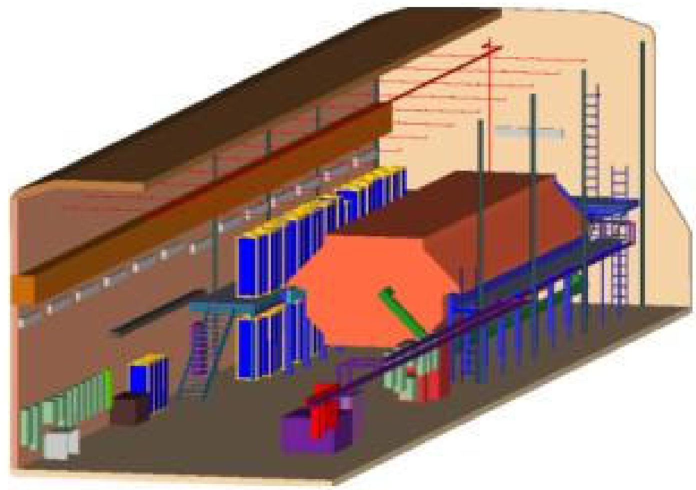
6-8 Planes per week

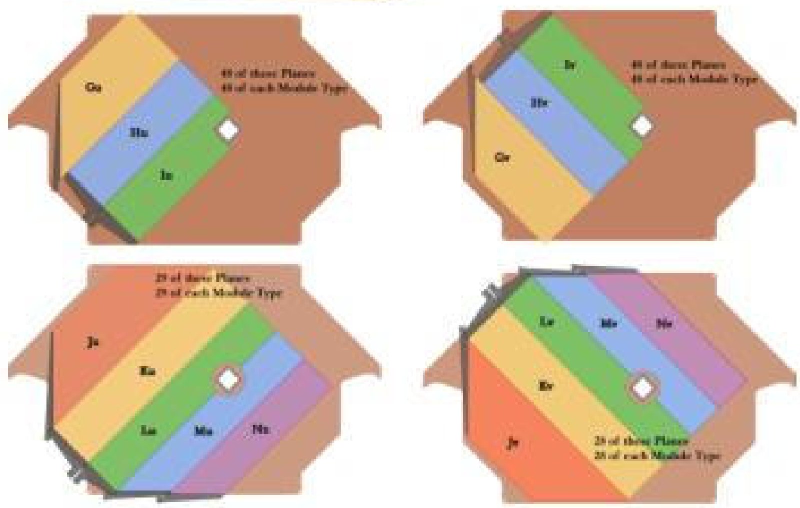
Status of MINOS Construction

- The far detector is almost half built.
- The coil will be installed in the first supermodule in June and energized in July.
- The full detector will be complete by June 2003.
- Cosmic Ray data are being collected for calibration and commissioning.

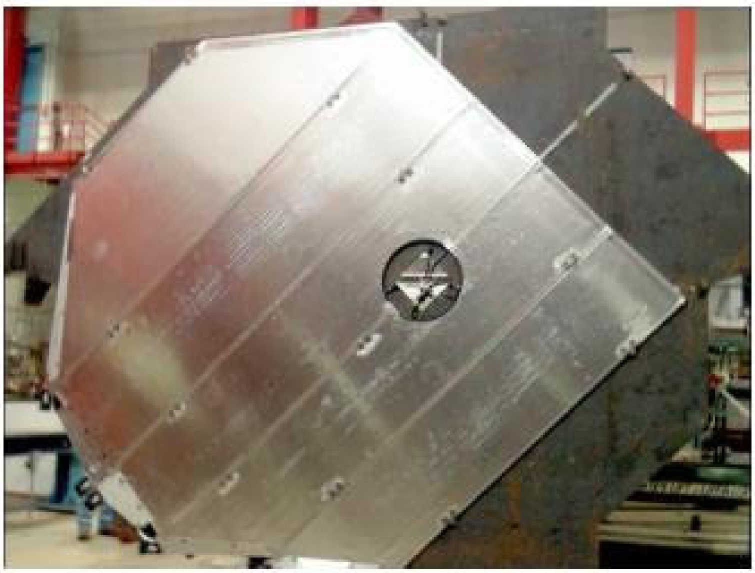
The Near Detector

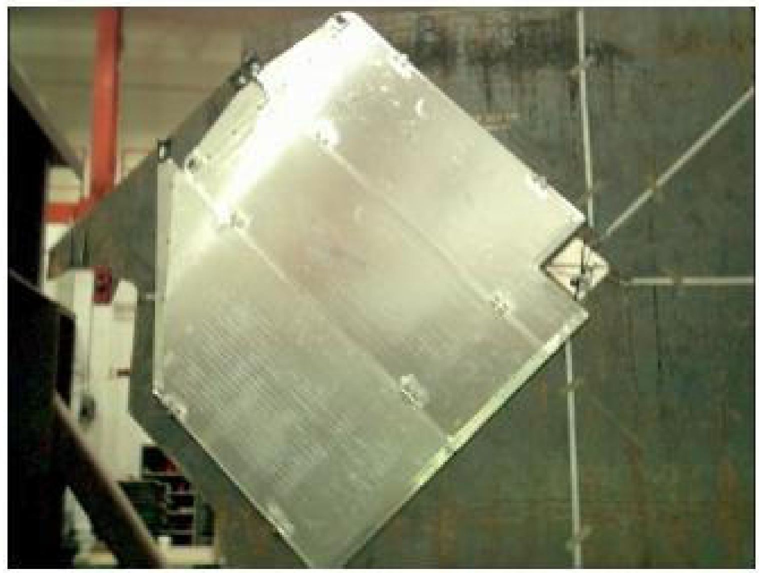
- **3.8 x 4.8m** "octagonal" steel & scintillator tracking calorimeter
- Same basic construction, sampling and response as the far detector.
- No multiplexing in the main part of the detector due to small size and high rates.
  - Hamamatsu M64 PMT
  - Faster Electronics (QIE)
- **282 planes of steel**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





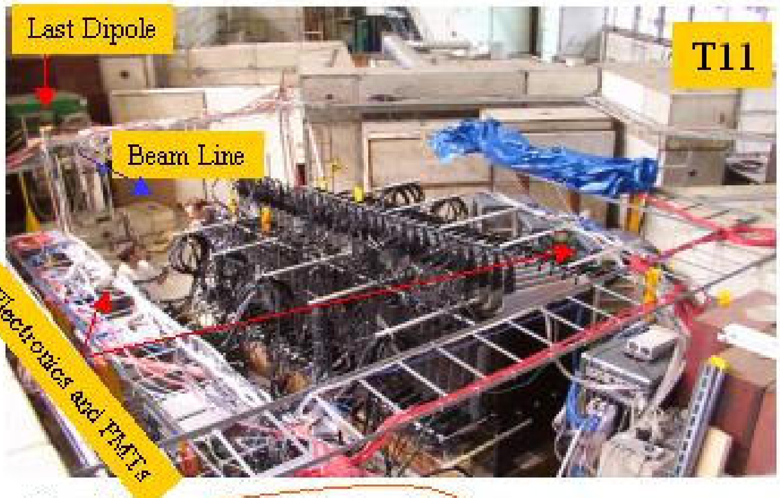
Near Detector Assembly

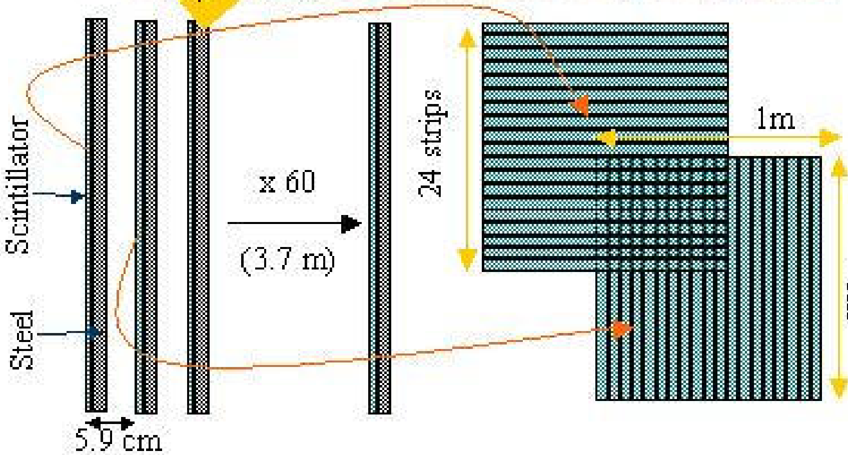




- Assembly of near detector planes is now underway on the surface at Fermilab.
- All planes will be assembled on the surface and then transferred (one at a time) underground once the hall is ready. This will allow the ND to be commissioned in time for beam turn-on.

The MINOS Calibration Detector

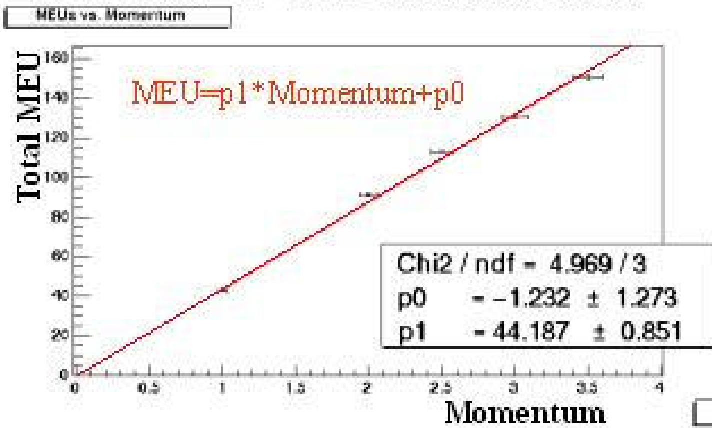




- **A mini-version of the MINOS near and far detectors**
  - 1m x 1m x 3.7 m
  - 60 planes x 24 strips/plane
  - Readout technologies of both the near and far detectors
- **Being exposed to electron, pion, proton and muon beams from 0.5-10 GeV/c momentum at the CERN PS.**
  - First data in 2001 up to 3.5 GeV using far detector readout.
  - Data in 2002 up to 10 GeV and to compare near and far electronics.
  - Additional running in 2003 with full near readout system.
- **Physics Goals:**
  - EM and Hadron energy response
  - EM and Hadron event topology
  - Near/Far readout comparison

Electron Response Results from Caldet

Total MEU vs. Beam Momentum

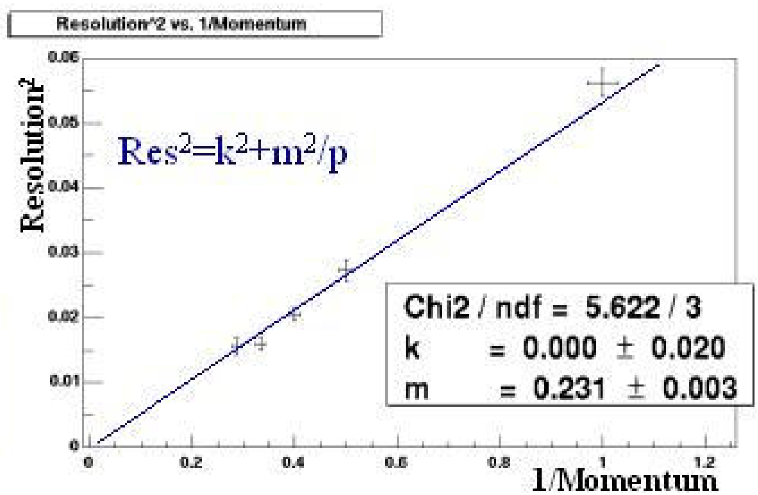


Preliminary

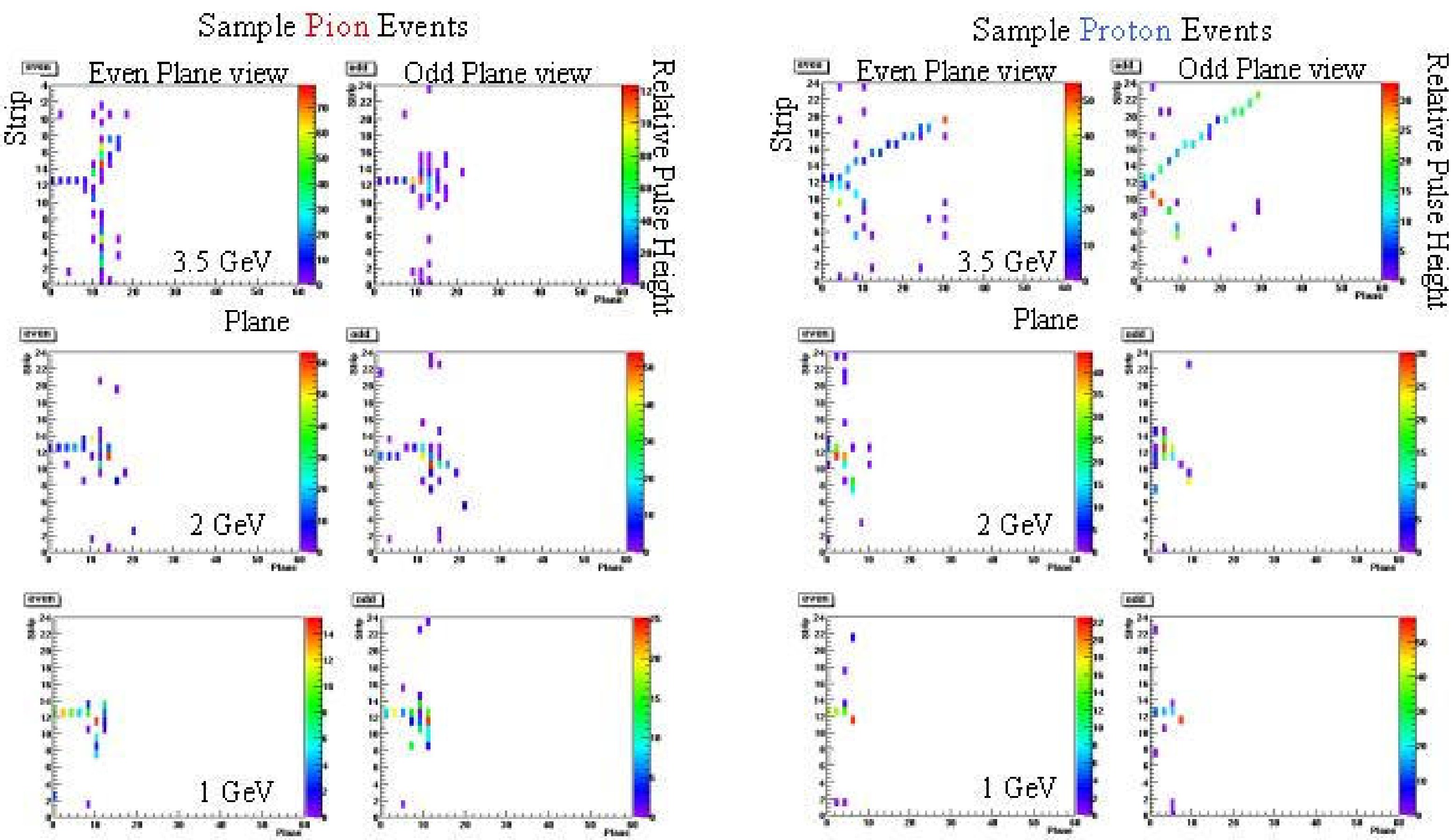
"MEU"= Muon Energy Unit. It is the average detector response resulting from a ~2 GeV/c muon crossing perpendicularly through a plane of scintillator, corrected for gain-variation and local light output.
It is the fundamental "calibration unit" for MINOS.

Expected resolution, 23%/√E
constant term <5%

Resolution^2 vs. 1/Beam Momentum



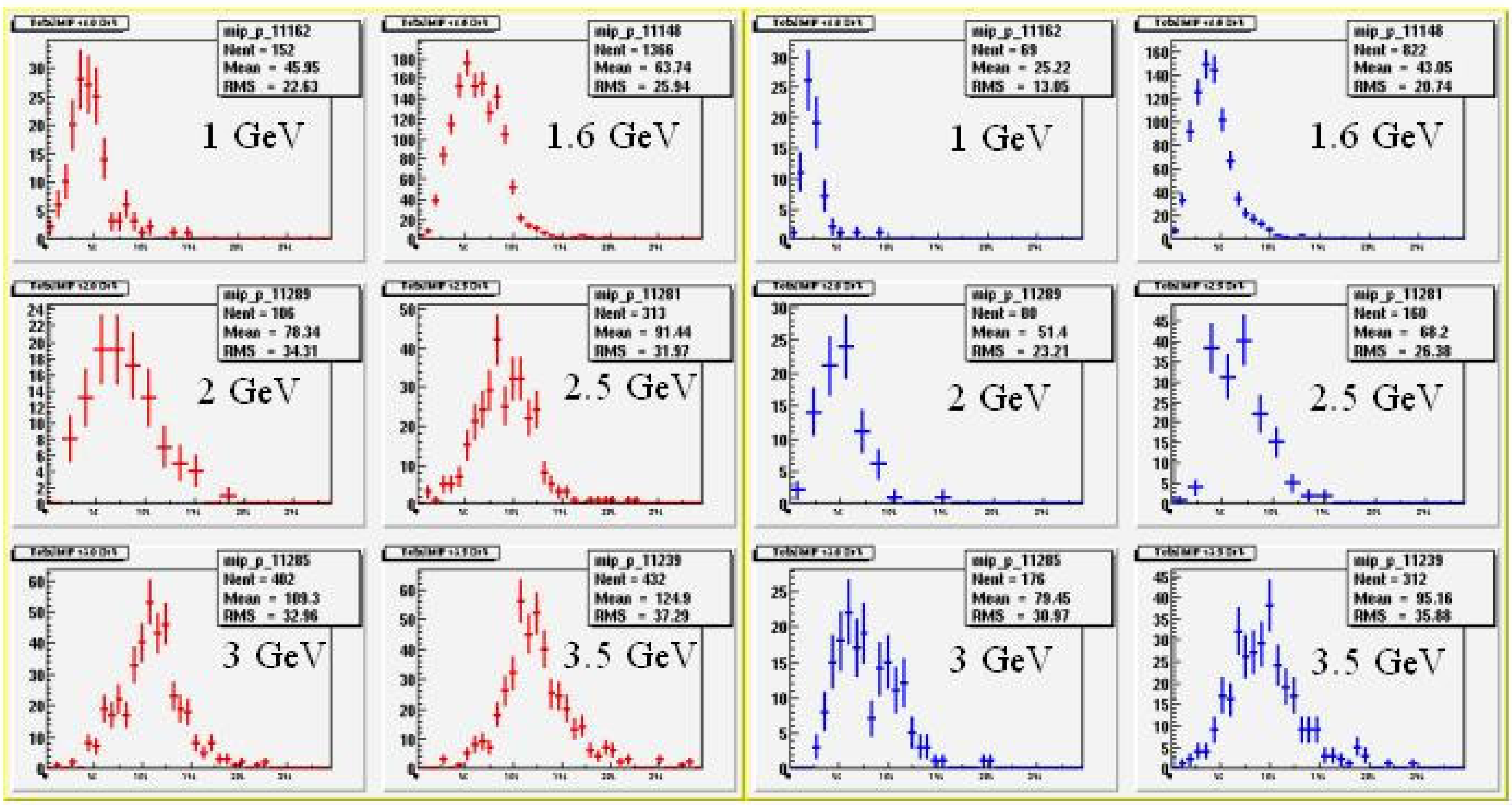
Hadron Topology Measurements in Caldet



Hadron Response Results from Caldet

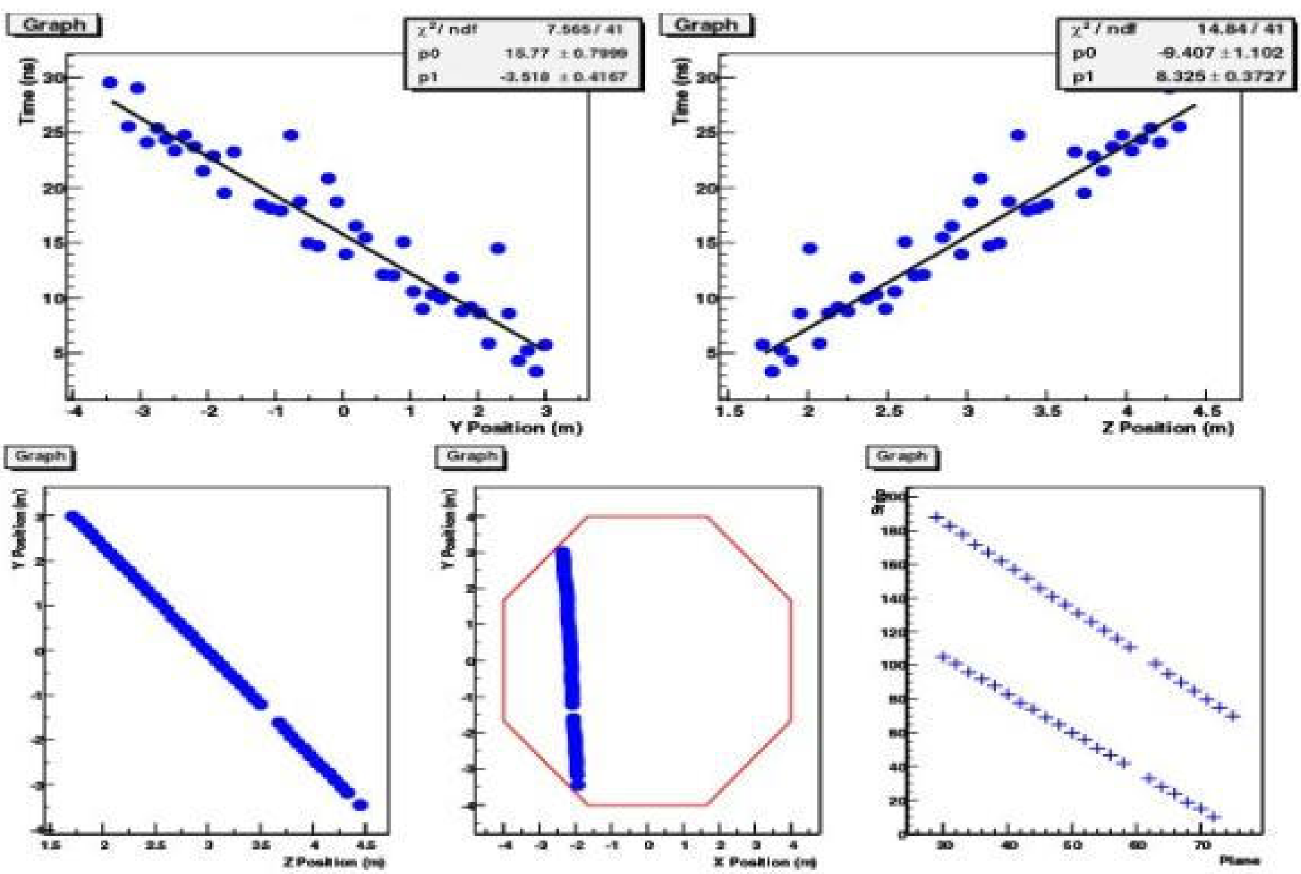
Pion MEU distributions

Proton MEU Distributions



Cosmic Ray Muon in the Far Detector

- Downgoing Cosmic Ray Muon
- Current rate of CR muons ~ 2 Hz
- Magnetic field not yet on (curvature measurable up to ~70 GeV)



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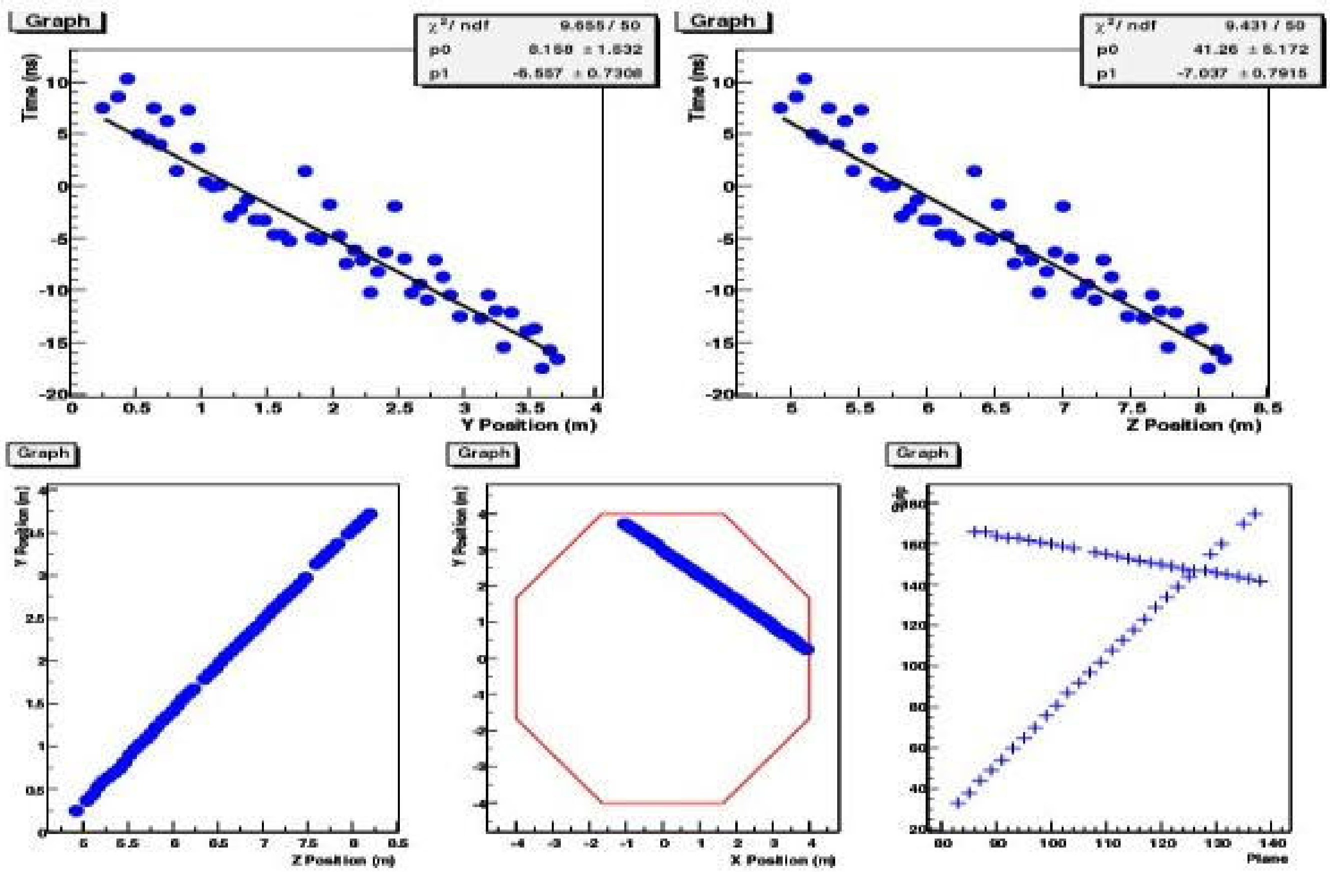
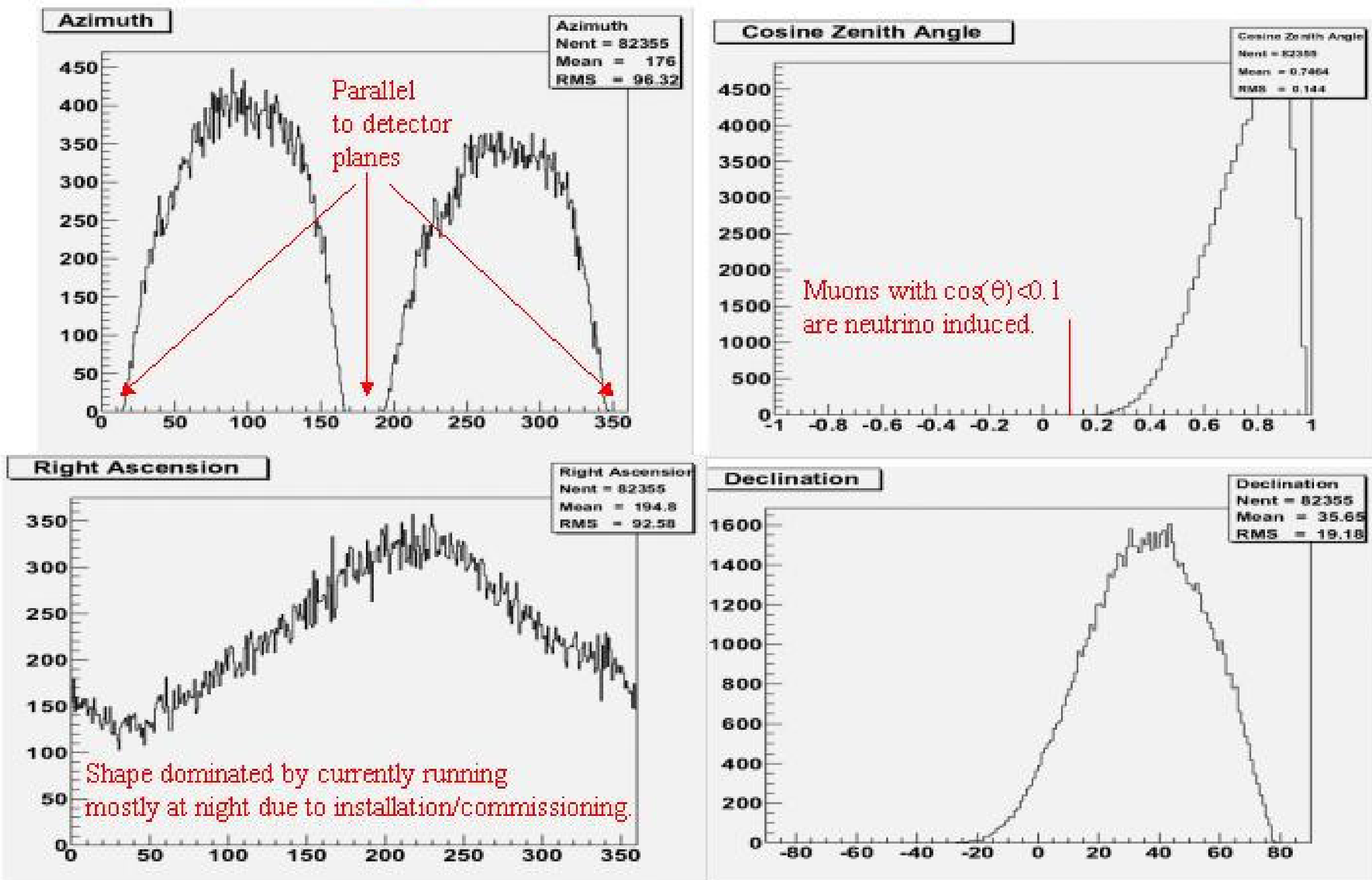
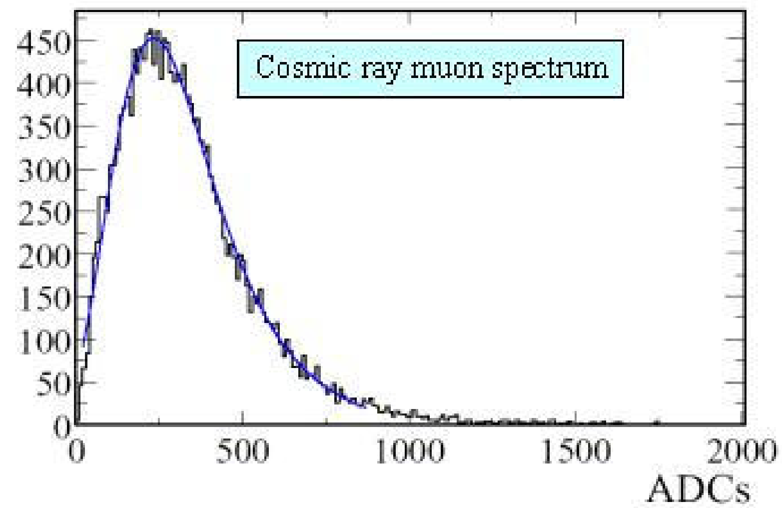


Cosmic Ray Muons in the Far Detector

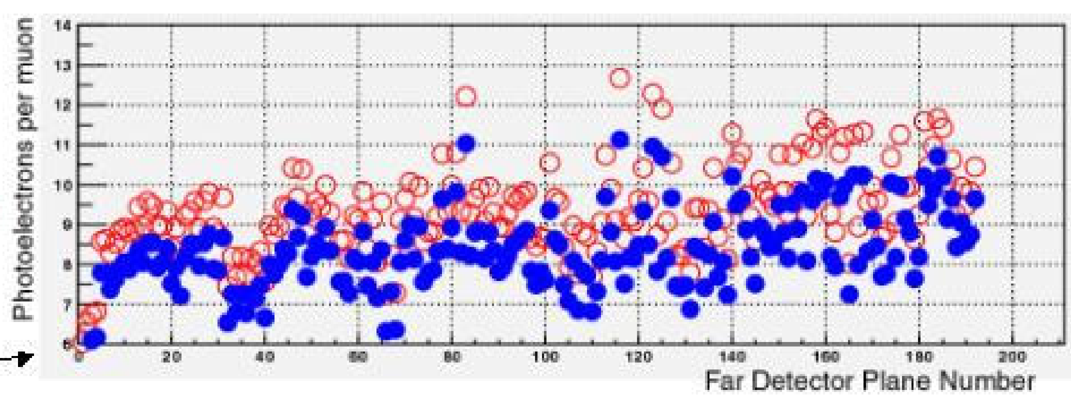


Calibrating With Cosmic Rays

- Cosmic ray muons are used to measure the light output of the scintillator system in all detectors.
- The cosmic-ray muons are used to intercalibrate the three detectors.
- "Clean" muons (no showers) are selected for light calibration and for each muon the light output is corrected for the pathlength to the equivalent light for 1 cm pathlength.
- PMT gains are corrected using light injection data.
- On average ~ 8.5 pe's/cm.



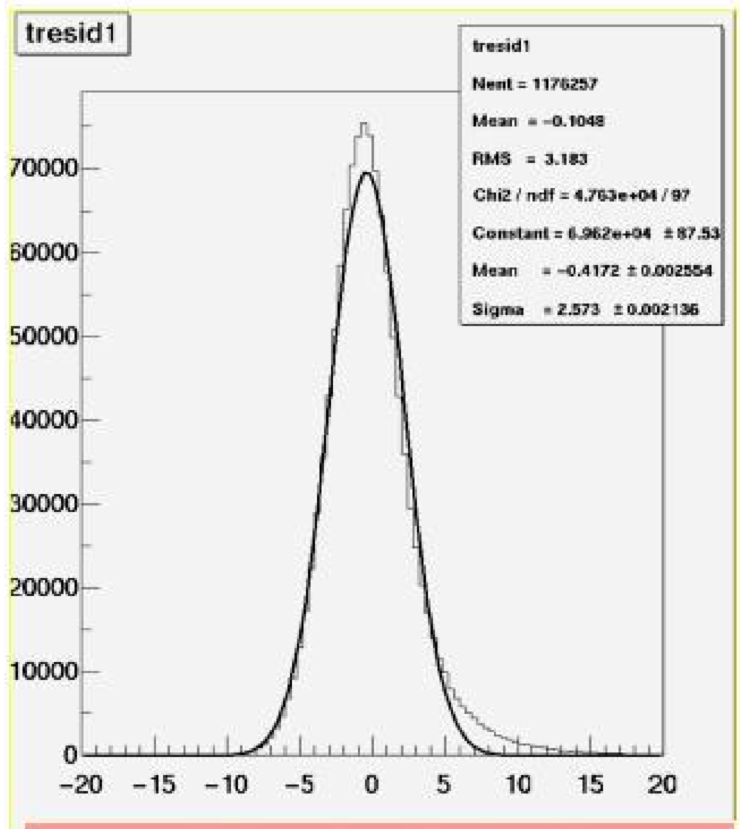
Note: suppressed zero!



Average light output for all detector planes.

Time Resolution in the Far Detector

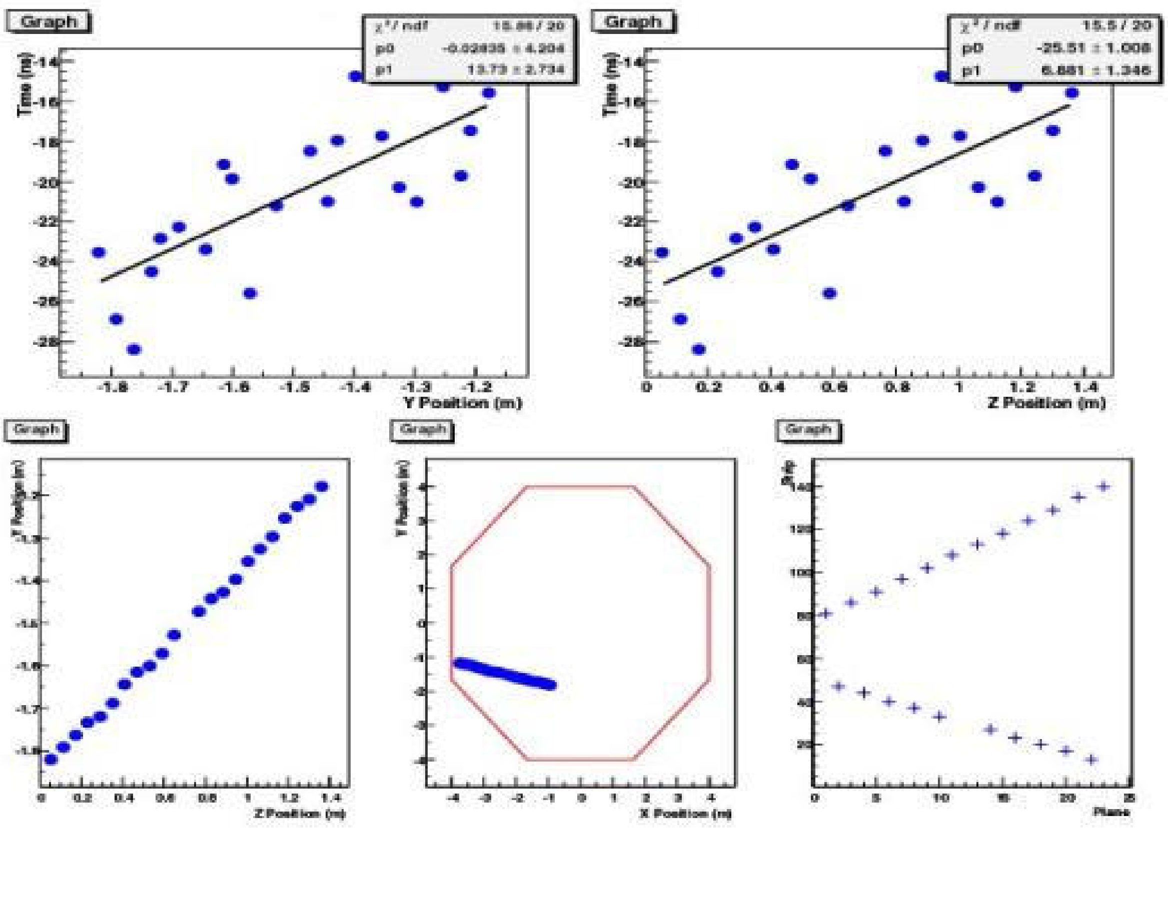
- The time resolution of the MINOS scintillator system is determined primarily by the decay time of the Y11 fluor in the WLS fiber ~ 8 ns.
- The time resolution for each scintillator strip is expected to be ~2.5 ns based on the photoelectron statistics for muons.
- Current measurement of resolution using downgoing muons in the far detector is σ=2.6 ns/plane.
- The direction of muons can be determined with ~ 10 planes for contained vertex events.
- To distinguish upgoing from downgoing through-going muons ~ 20 planes are needed.



Distribution of measured time residuals for muons Passing through all strips in the far detector. The Time resolution of 2.6 ns is calculated from this data.

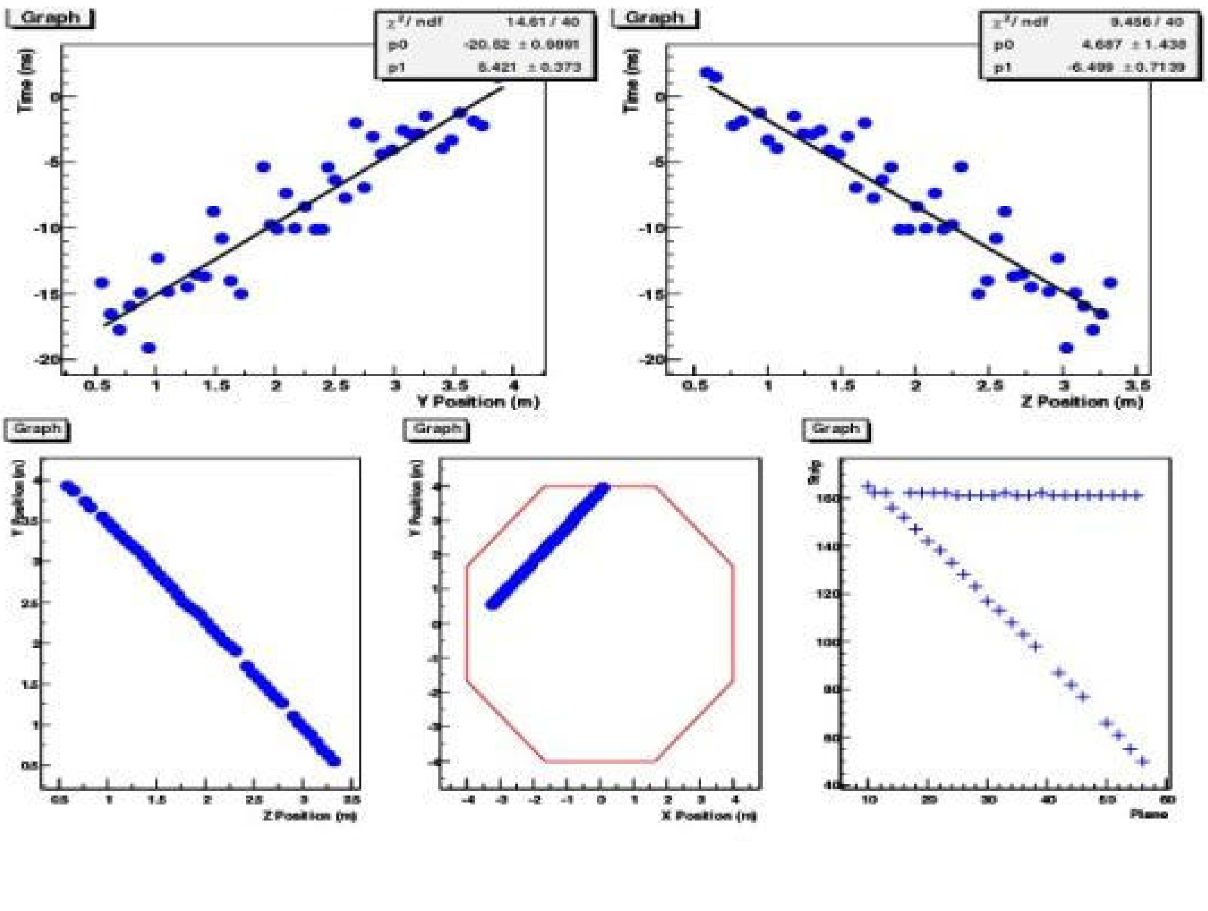
The First MINOS Neutrino Event!

- The first neutrino-induced event has recently been observed!
- Upgoing muon passing through about 3.5 m of the detector. ($p_{\mu} > 1.9$ GeV/c)
- Magnetic field not on yet so no measurement of the momentum.

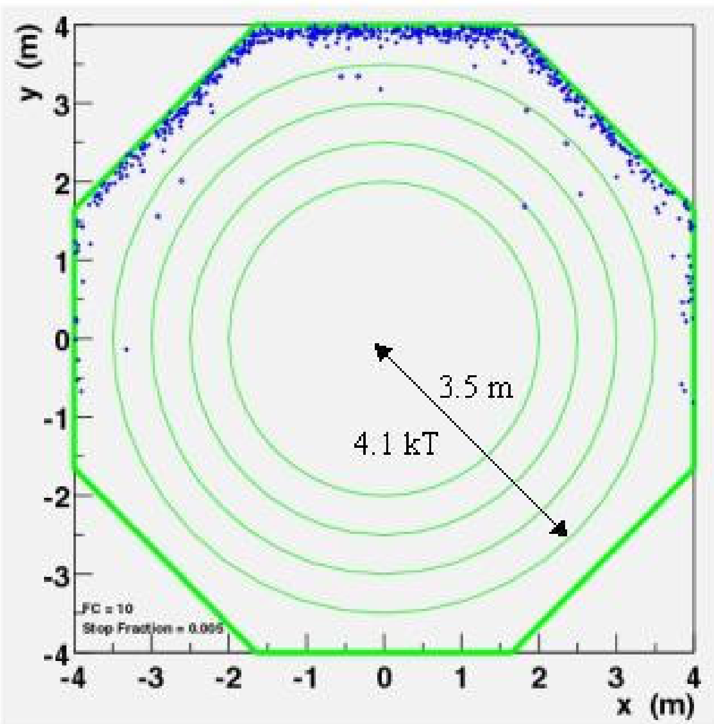


And the Second!

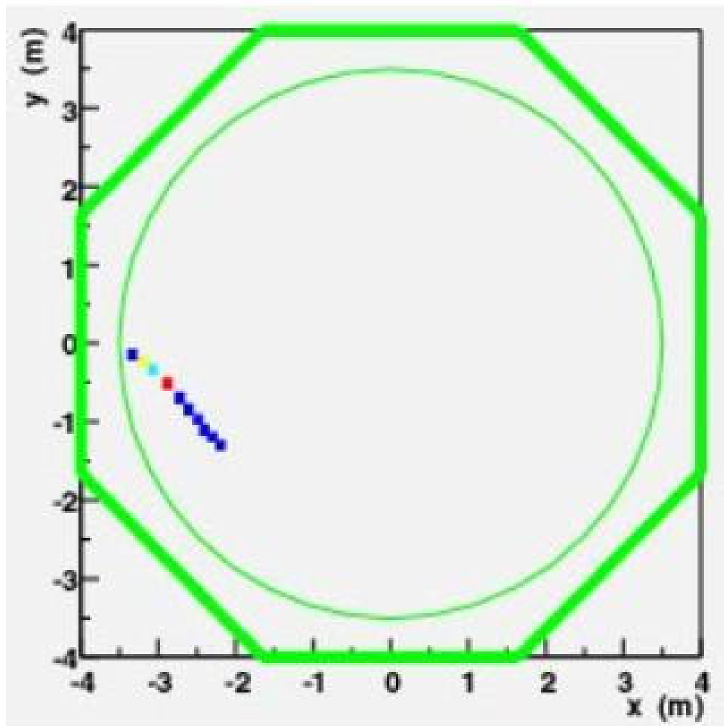
- The second neutrino-induced event has recently been observed.
- Upgoing muon passing through about 5.6 m of the detector. (p_{μ} > 3.0 GeV/c)
- Magnetic field not on yet so no measurement of the momentum.
- Contained vertex event?



On the Road to Contained Events



Reconstructed "vertices" for cosmic ray events which have a track that ends inside the detector. Most are clearly downgoing stopping muons. A few mis-reconstruct for known reasons (hardware and software commissioning) which will be fixed soon.



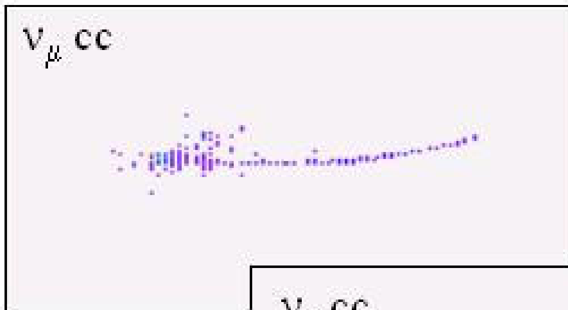
Example of one downgoing stopping muon which appears to have a vertex just inside the nominal fiducial volume of the detector. This was due to tracking software which is not yet completely commissioned.

MINOS Physics Goals (by 2007)

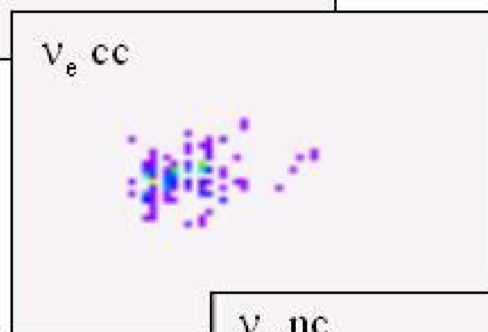
- Demonstrate Oscillation Behavior
  - Precise measurement of CC energy distribution between near and far detector (2-4% sys. uncertainty in E_ν per 2 GeV bin).
  - "Standard" or non-standard oscillations?
    - Can we see clear "oscillatory" behavior from the first osc. max?
    - Are there features in the energy spectrum not well described by a standard oscillation?
- Precise Measurement of Oscillation Parameters
- Precise Determination of Flavor Participation
  - Number of CC ν_μ events far/near ~2%: Probability for $\nu_\mu - \nu_x$ oscillation.
  - Number of CC ν_e events far/near: Sensitive to $\nu_\mu - \nu_e$ oscillation down to about 2%.
  - Number of NC events far/near: probability for $\nu_\mu - \nu_{sterile}$ oscillation down to about 5%.
  - ν_μ's which disappear but don't appear as ν_e or disappear to $\nu_{sterile}$ **must** be ν_τ!
- Direct Measurement of Atmospheric ν vs $\overline{\nu}$.

Topology of Neutrino Events

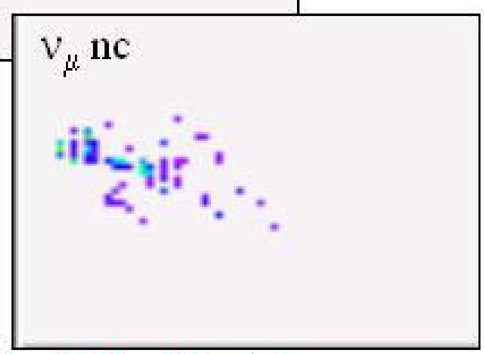
Identified by a relatively long track in an event. At very low energies, there can be some BG from NC π^-.



Identified by lack of a long track and a relatively concentrated EM shower in the core. Main BG comes from NC π^0 events From higher energy ν's.

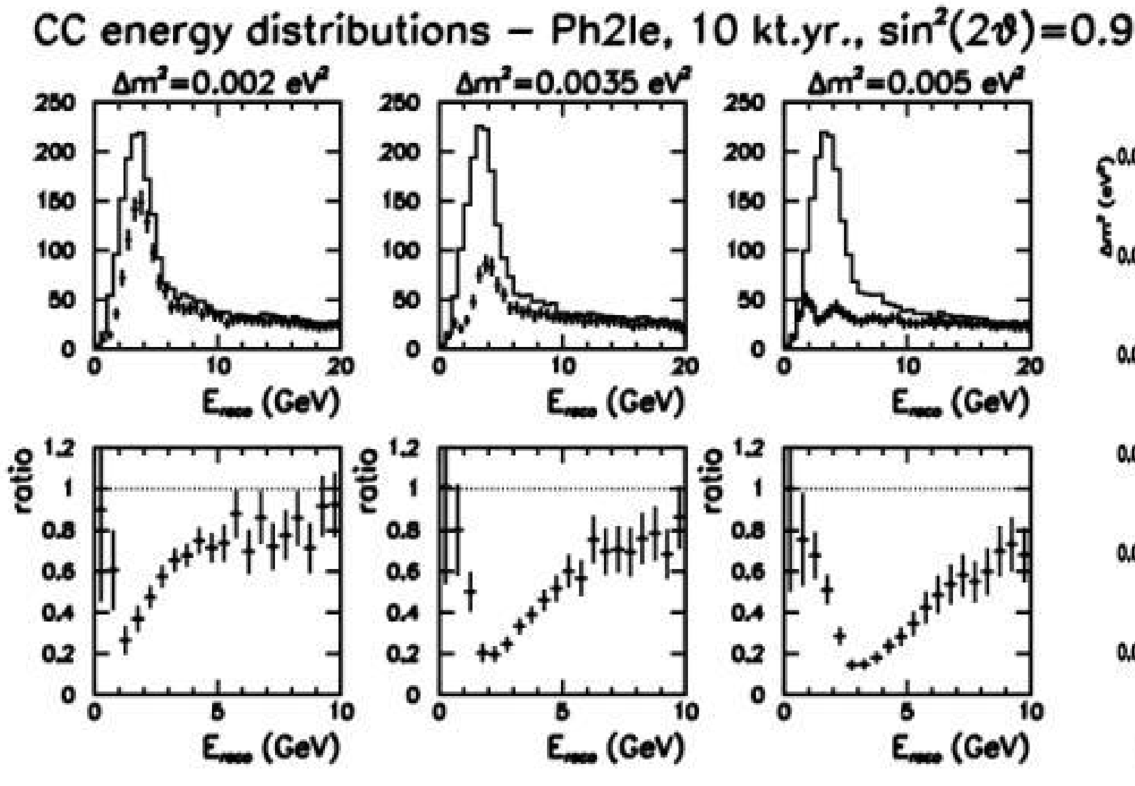


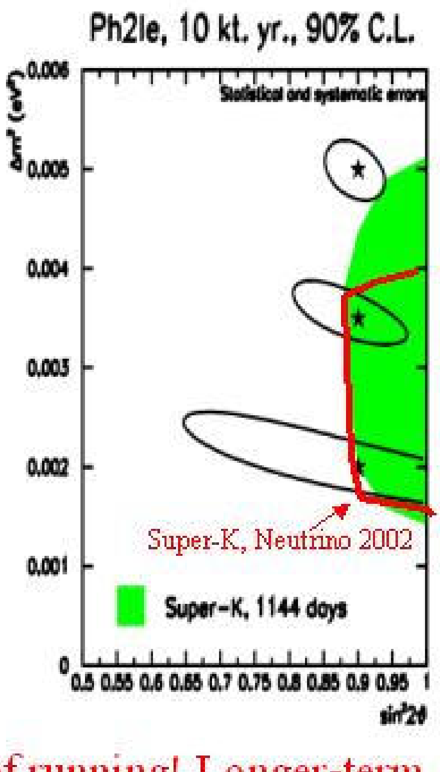
Identified by lack of a long track and lack of strong EM core. Some high y CC events are BG.



The Near Detector provides the ability to make statistical identification of events with high precision.

Measurement of Oscillations in MINOS



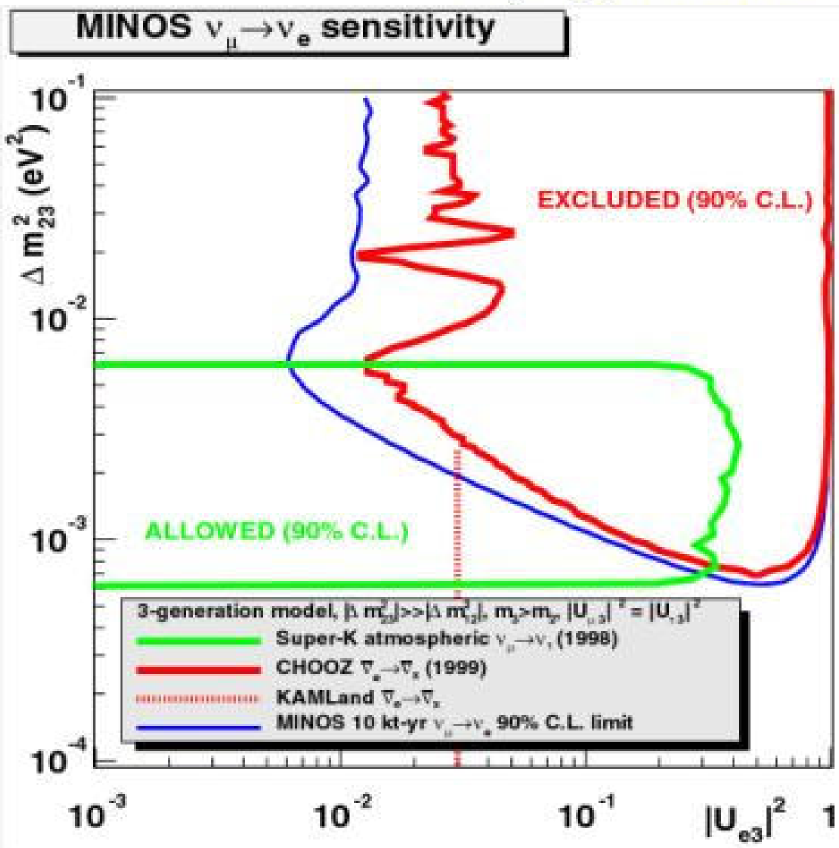


Note: MINOS beam results are presented for only 2 years of running! Longer-term running is certainly possible, even probable. Results are statistics limited.

Appearance of Electrons

10 kT Years of data

ν_e Appearance



- Sensitivity is determined by statistical fluctuation of the NC π^0 BG in the far detector.
- Limit on U_{e3}^2 will scale like 1/sqrt(N) and is not limited by systematics for any realistic exposure.
- Limit can be further improved by removing high-energy tail from the NuMI beam and increased proton flux in later years.
- Ultimate MINOS limits ~1/3 as shown here assuming extended running.

Atmospheric Neutrino Measurements

- MINOS is the first large underground detector which has a magnetic field.
  - Measure charge/momentum of muons from ~0.5-70 GeV/c momentum.
  - Events with the neutrino interaction in the detector but where the muon exits still have complete E_ν measurement: L/E measurements.
- Event direction reconstructed using timing and topology.
- Able to identify CC ν_μ and $\bar{\nu}_\mu$ events from NC and CC ν_e events over a very broad energy range as long as p_μ > ~1 GeV/c.
- We can directly compare whether atmospheric ν_μ and $\bar{\nu}_\mu$ oscillate in the same way.
- Expected sensitivity is being calculated. Statistics for 24 kT years (end of 2007) are:

Number of Events in 24 kT years	Neutrino	Anti-Neutrino
Reconstructed Contained Vertex with muon	620	400
Reconstructed Upgoing Muon	280	120

Conclusions

- The MINOS Detectors together with the NuMI beam will permit a next step in precision measurements of "atmospheric" neutrino oscillations:
  - Precise energy distribution… Showing the oscillation signature (?)
  - Precise measurement of Δm^2
  - Precise determination of participation of different neutrino flavors
  - Extend sensitivity for small $\nu_\mu - \nu_e$ mixing
  - Measurement of anti-neutrino mixing for atmospheric neutrinos
- Construction of the MINOS far detector is ~half complete and cosmic ray data is being accumulated with installed planes.
- Construction of the NuMI beamline is well underway. The tunnel excavation is complete. Remaining construction work on schedule.
- Data acquisition for cosmic rays and atmospheric neutrinos underway!
- First protons on target scheduled for December 2004.
- Count on more than two years of beam data from MINOS!