Observations of Separated Atmospheric ν_μ and $\overline{\nu}_\mu$ Events in the MINOS Detector

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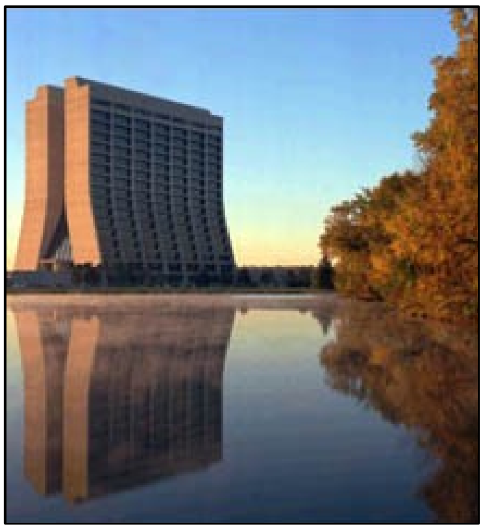
The MINOS Experiment

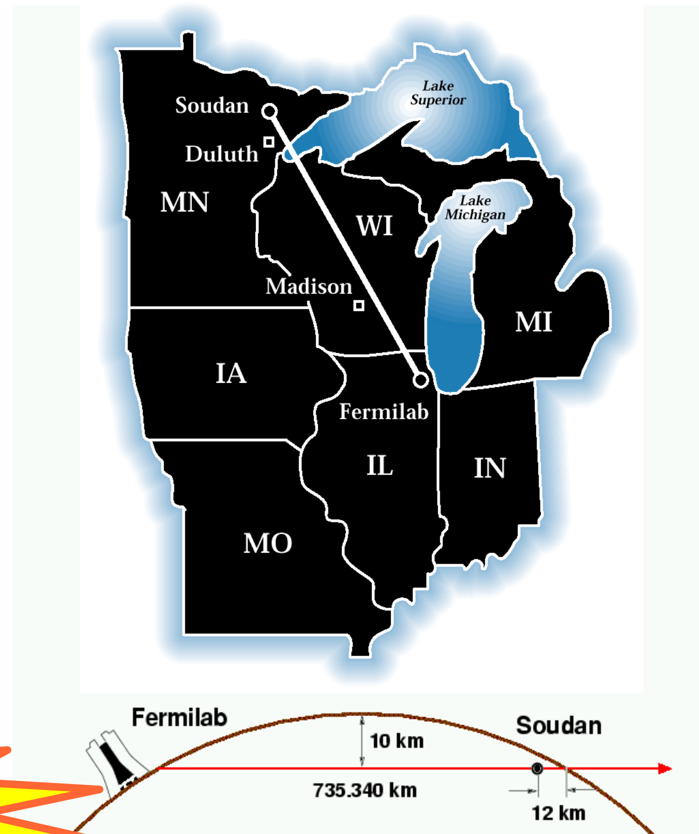
Main Injector Neutrino Oscillation Search

Fermilab, IL



Near Detector

Taking Data!



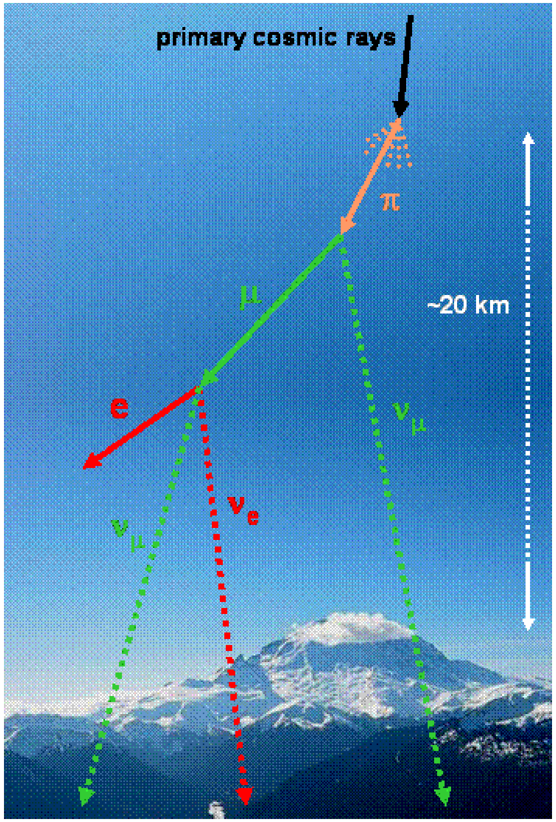
Neutrino Beam
Running Since March 2005

Soudan Mine, MN

Far Detector

Taking Data!

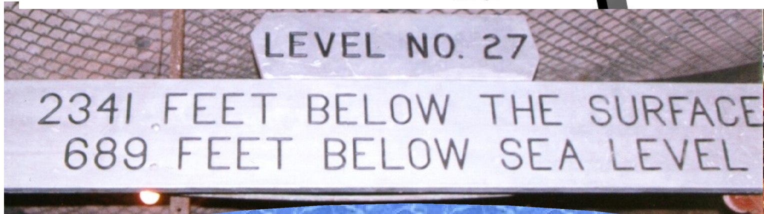
Atmospheric Neutrino Oscillations



- **Cosmic rays (mainly p, He) hitting the upper atmosphere produce νs:**
  - **Flux ~ 1 cm^{-2} sr^{-1} s^{-1}**
  - **E_ν ~ 1 GeV**
  - **$N(\nu_\mu)/N(\nu_e)$ ~ 2 (in the absence of oscillations)**
- **Many experiments have measured up/down asymmetry in atmospheric ν_μ flux.**

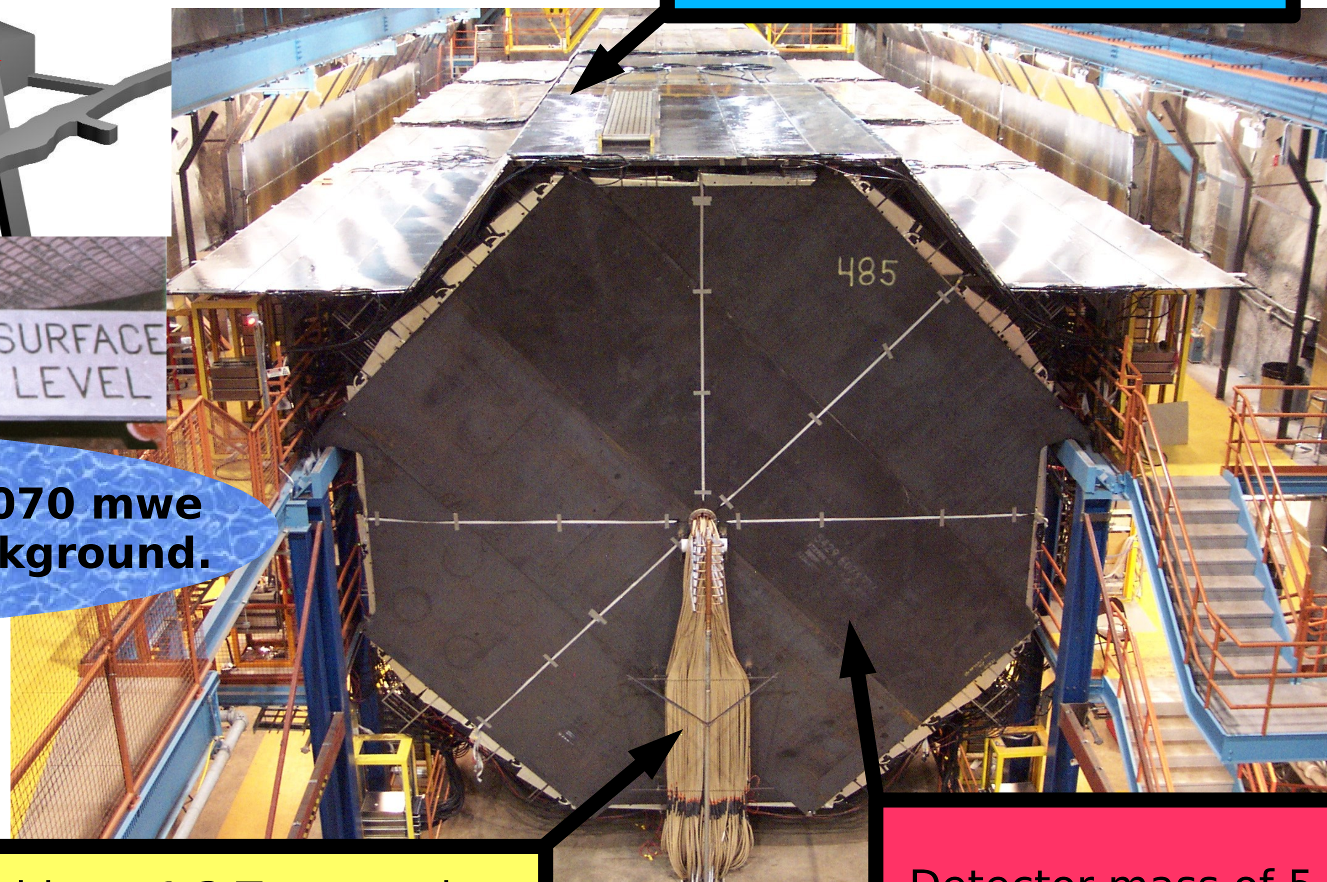
  ⇒ Compelling evidence for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations.
- **MINOS magnetic field can distinguish μ^- from μ^+, and thus ν_μ from $\overline{\nu_\mu}$**
- **MINOS detectors measure E_ν (= E_μ + E_{had})**
- **Using the NuMI beamline, MINOS will be able to make a precise measurement (~10%) of Δm^2_{23}**
- **The MINOS Far Detector can also be used to study atmospheric neutrinos directly.**

MINOS Far Detector



Rock overburden of ~2070 mwe reduces cosmic ray background.

Veto shield gives improved tagging of cosmic muons.

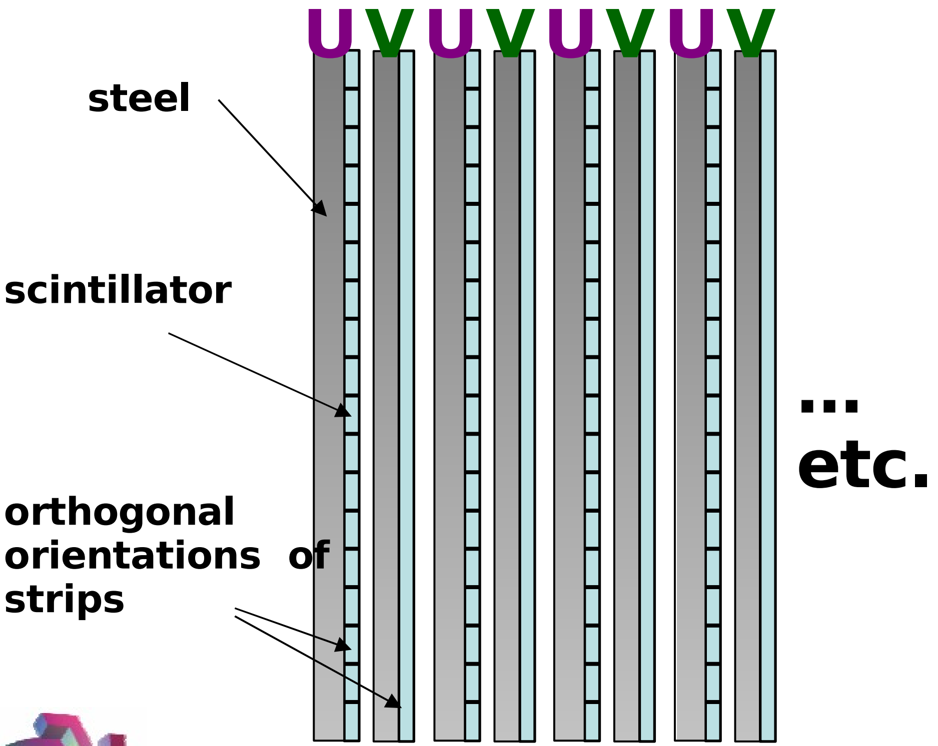


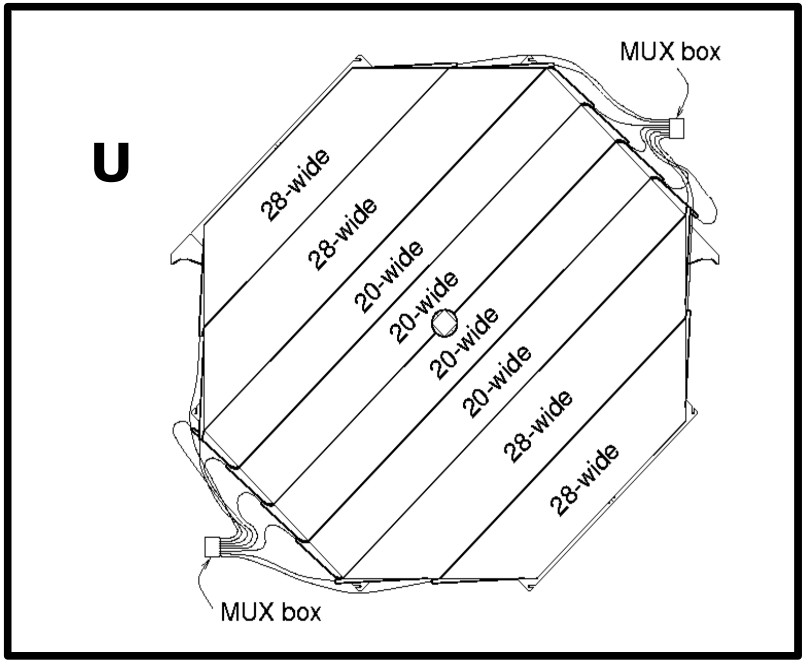
Coil provides a 1.3 T magnetic field allowing charge separation.

Detector mass of 5.4 kt gives a good event rate.

Far Detector Elements

- **MINOS detector : SAMPLING CALORIMETER**
- **Steel-Scintillator sandwich (484 scintillator planes)**
- **Each plane consists of a 2.54 cm steel +1 cm scintillator**
- **Each scintillator plane divided into 192 x 4cm wide strips**
- **Alternate planes have orthogonal strip orientations U and V**
- **Octagonal Geometry**



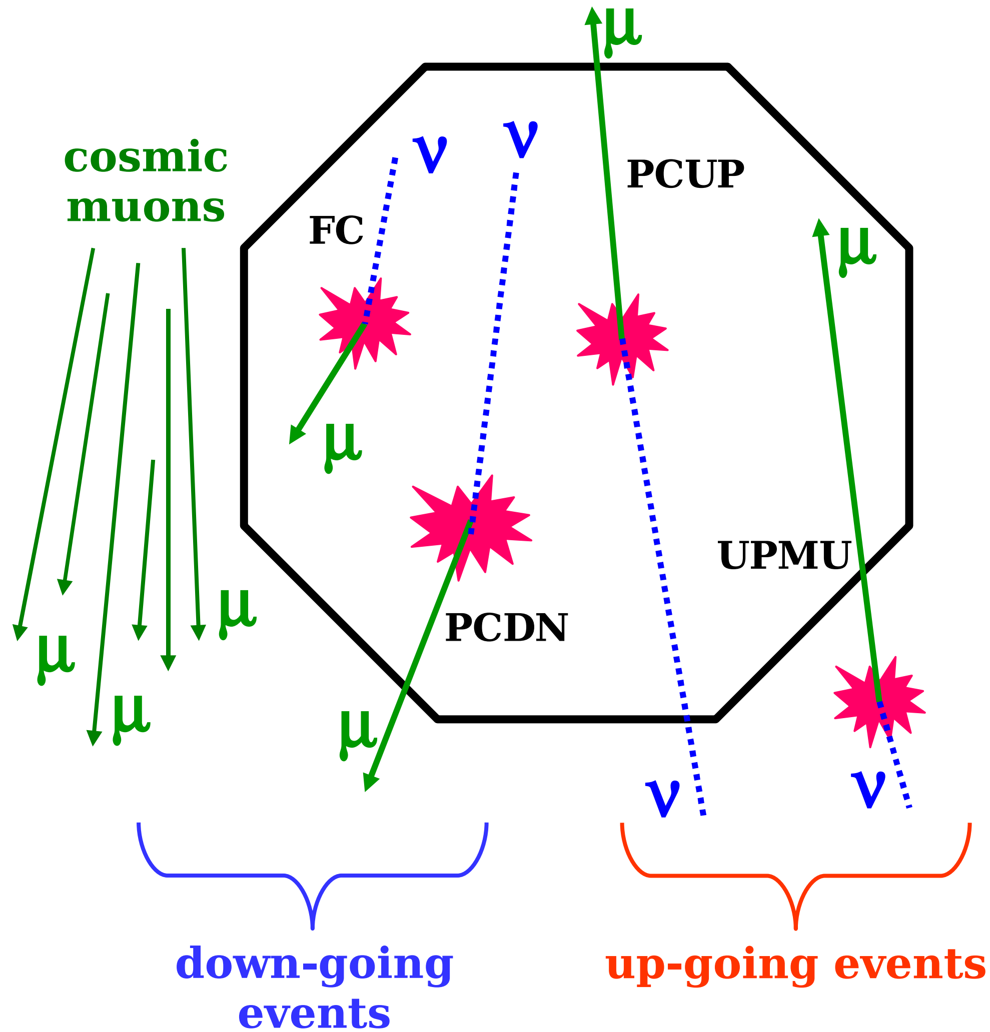


Atmospheric ν in MINOS Far Detector

- **Events can be classified as Fully Contained, Partially Contained or un-contained.**
- **Different event classes suffer different backgrounds:**

FC
PC DN
} **Main background – cosmic muons that appear contained.**

PC UP
UP MU
} **Main background – cosmic muons that appear up-going.**



Recent MINOS analysis (published in Phys. Rev. D) considered contained vertex events only.

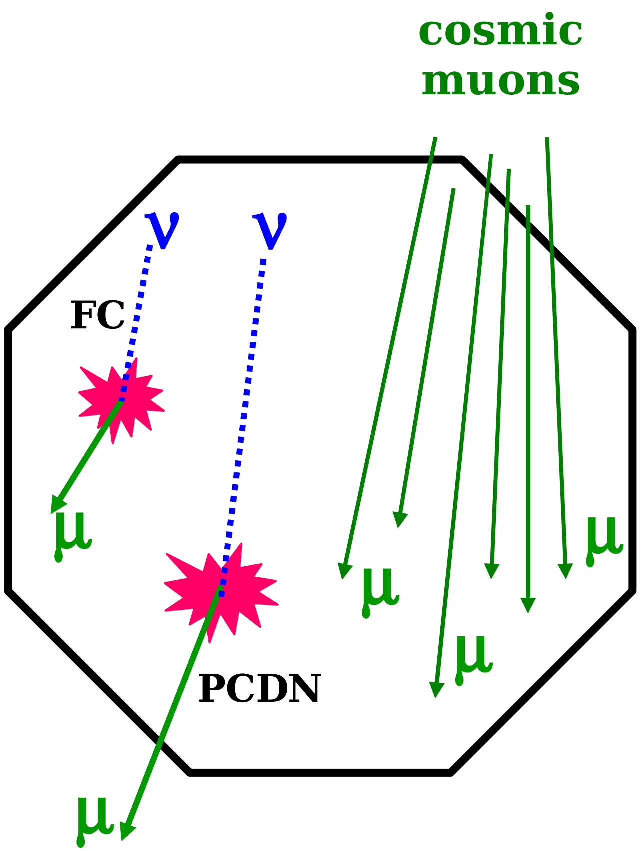
FC and PCDN Events (1)

Targets

Signal : Noise (cosmics) ~ 1 : 100,000
Require rejection factor ~ 1 : 10,000,000....
⇒ Cuts have to work very hard!
Extremely sensitive to reconstruction errors.
⇒ Need high quality reconstruction.

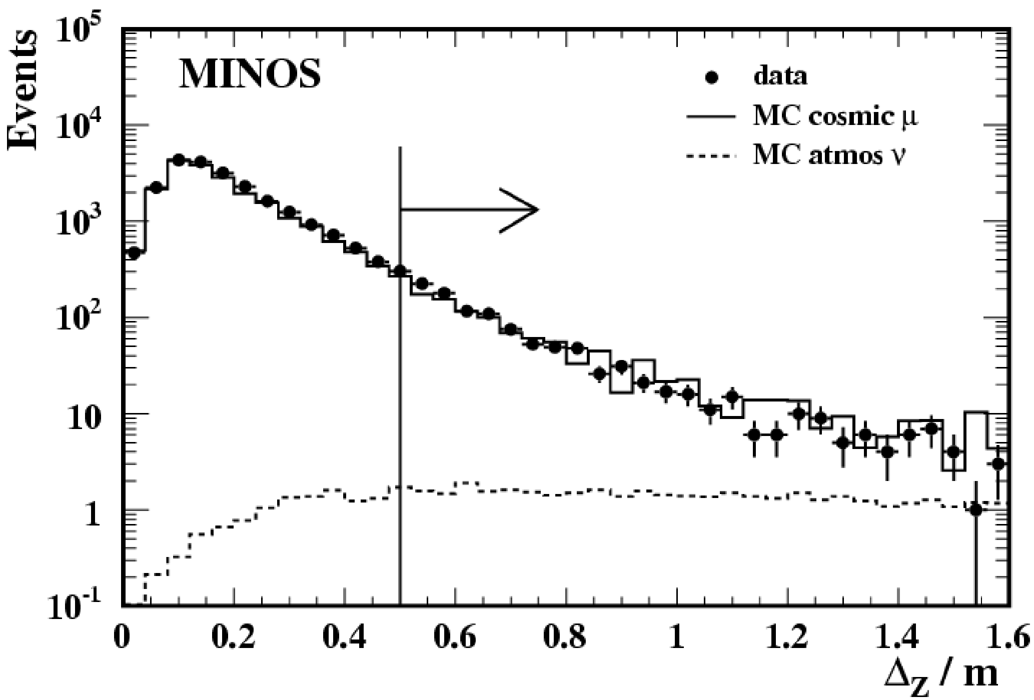
Analysis Cuts

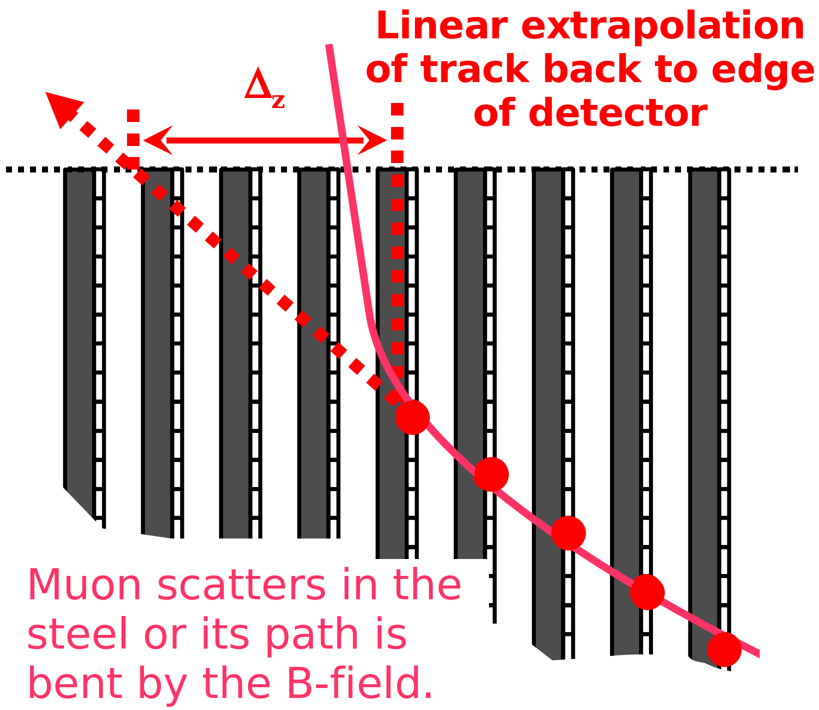
- **Fiducial Volume:**
  little activity within 50cm of detector edge
- **Reconstructed muon track**
  track which crosses 8 planes
- **Cosmic muon rejection 'Δ_z cut'**
  removes events which sneak into fid. vol. between planes.
- **Topology Cut**
  'turn-over' events
- **Veto Shield**
  no`in-time' Veto shield hit



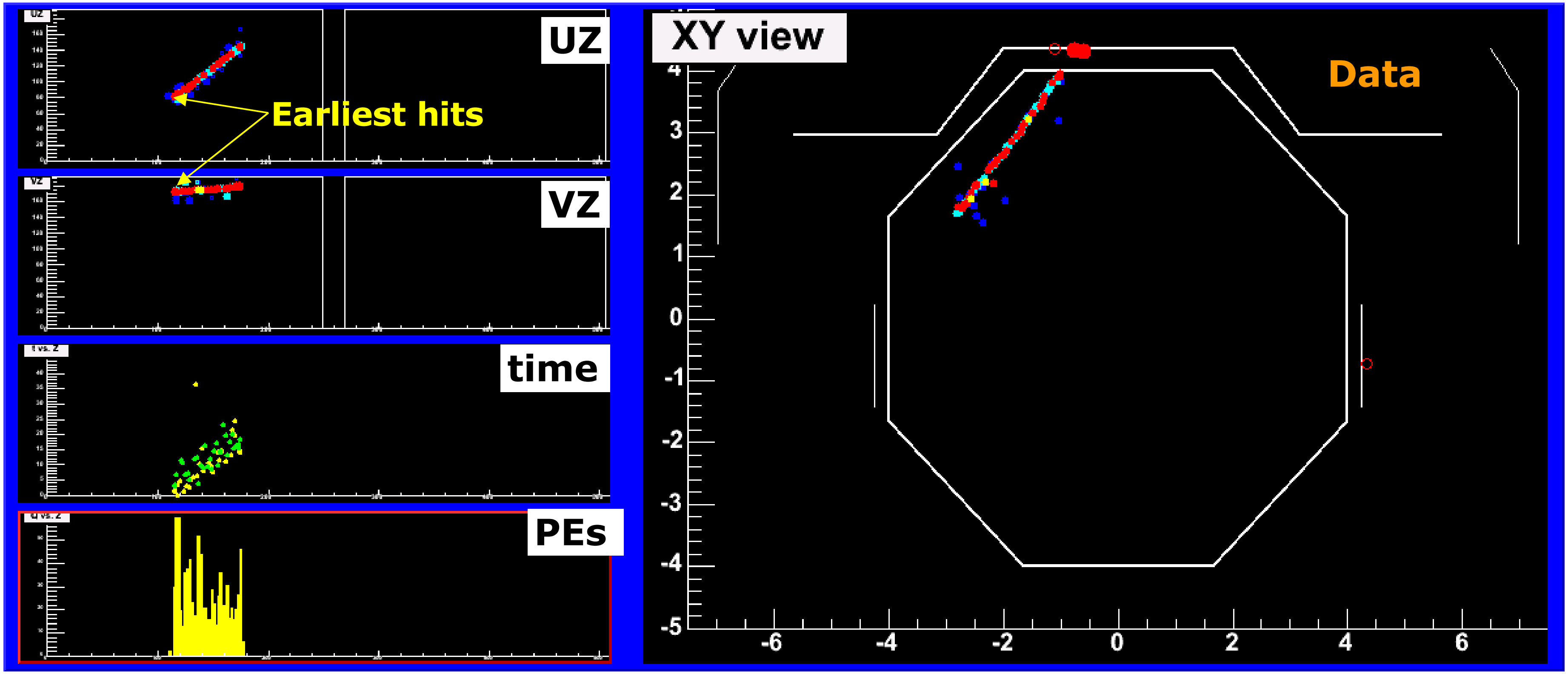
FC and PCDN Events (2)

The Δ_z cut removes events which sneak into the fiducial volume between planes (ie without leaving hits in the outer part of the detector).





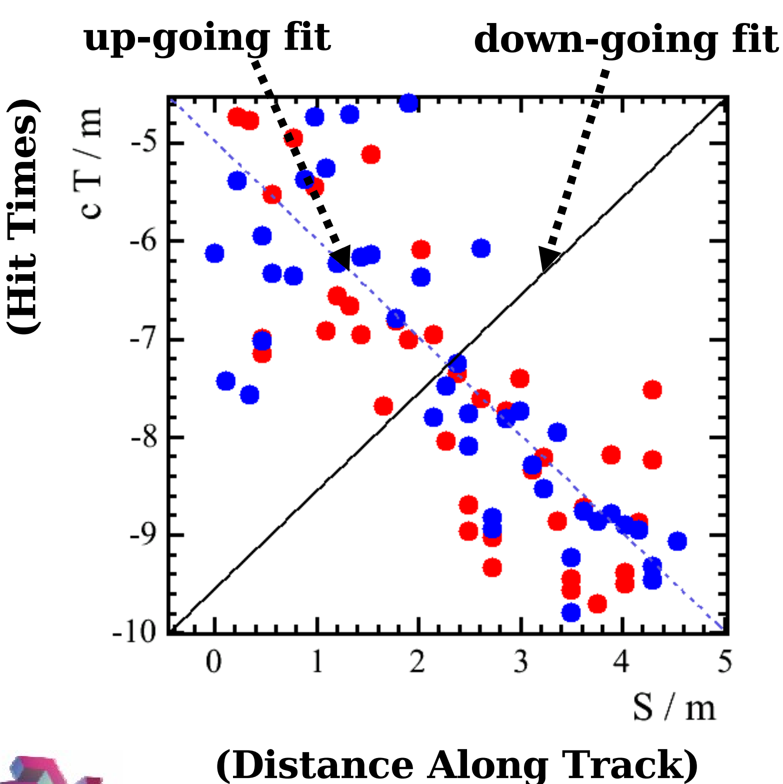
PCUP Events (1)

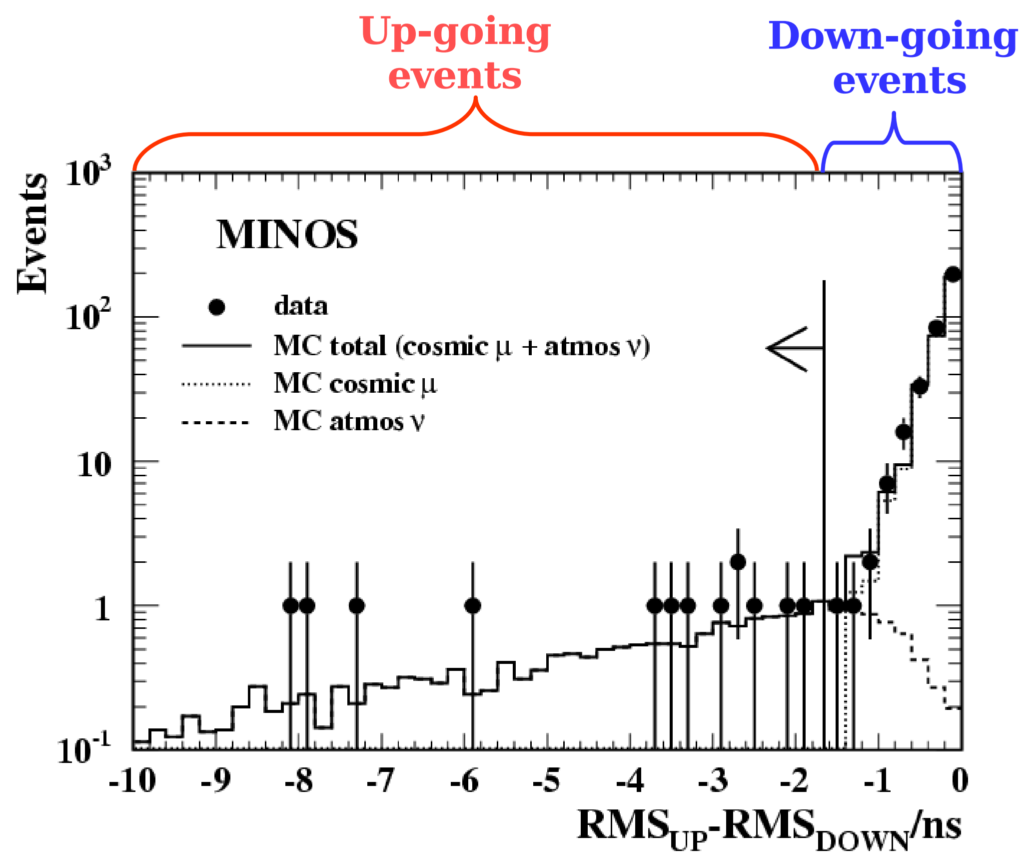


- To distinguish PCUP events from stopping muons we rely on timing information.
- Recorded hit times calibrated using cosmic ray muons.
- Achieved single hit timing resolution of 2.3 ns.

PCUP Events (2)

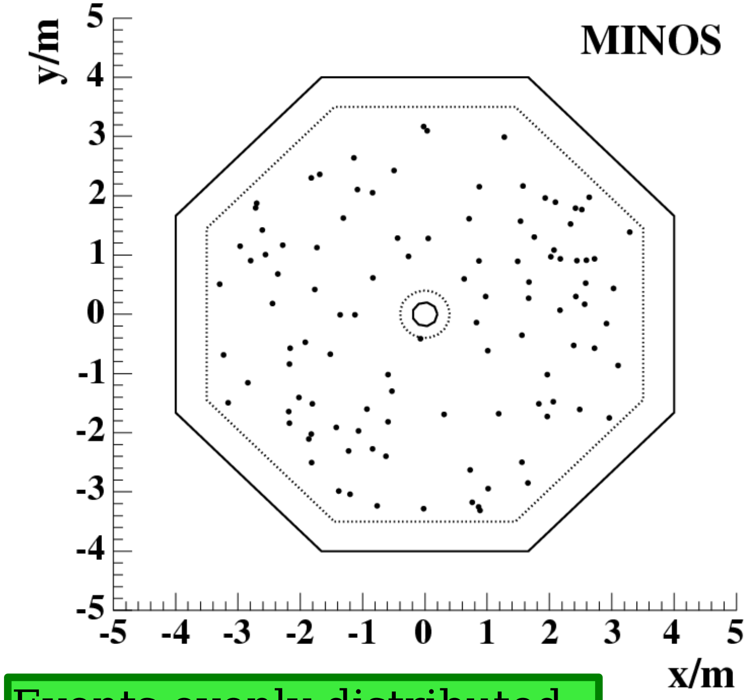
- Consider distance *versus* time for track.
- Apply fits to hypotheses $\beta = \pm 1$. (One will correspond to an up-going muon the other to a down-going muon.)
- Calculate RMS about each fit.
- EG for an up-going muon.



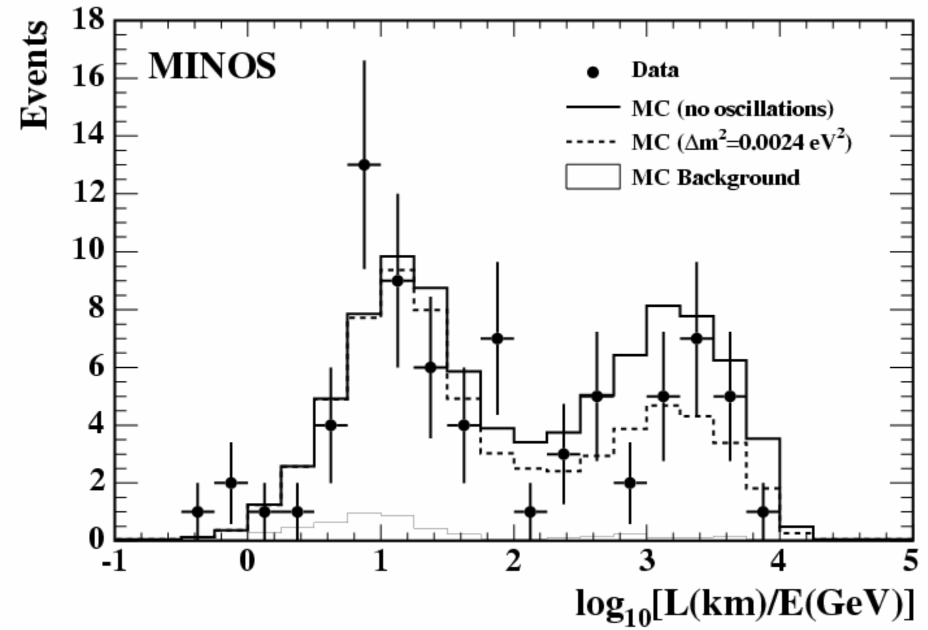


Atmospheric ν Oscillations?

(Based on an exposure of 418 days.)



Events evenly distributed throughout the detector.



Observe: 107 events
Expect: 125 ± 13 (no osc)
96 ± 10 (Δm^2=0.0024 eV^2)

Extended Maximum Likelihood analysis of observed L/E distributions:
⇒ no oscillations hypothesis excluded at the 98% confidence level.

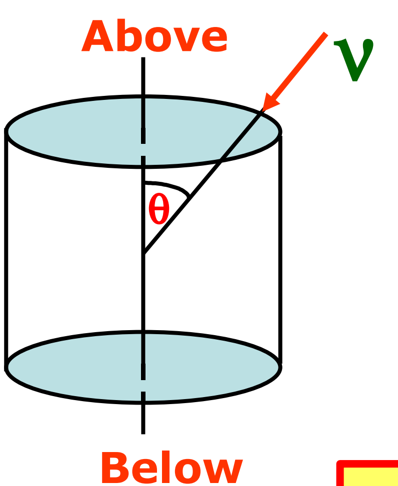
Charge Separation Results

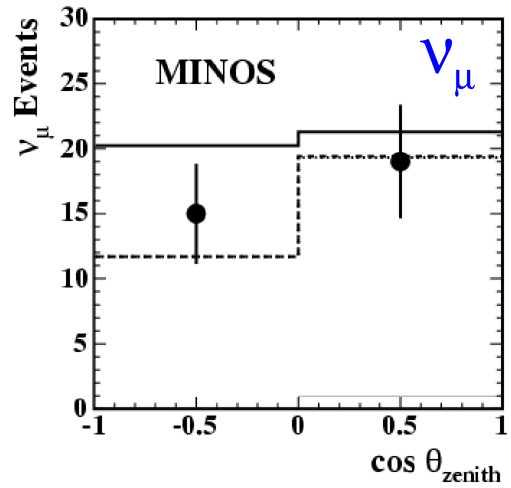
Of the 107 events observed:

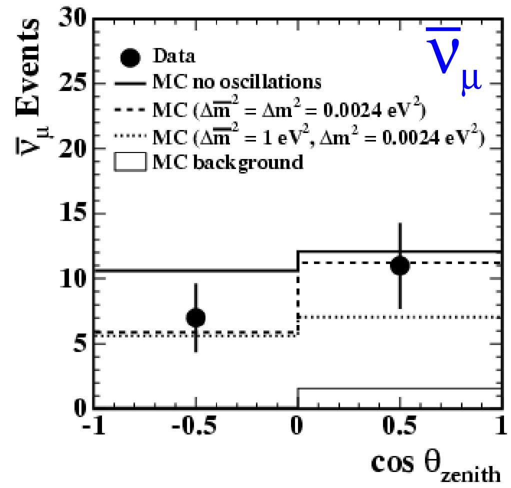
- 34 clear ν_μ candidate events
- 18 clear $\bar{\nu}_\mu$ candidate events

MC ratio assumes ν_μ and $\bar{\nu}_\mu$ oscillate in the same way

$$R^{data}_{\nu_\mu/\bar{\nu}_\mu} / R^{MC}_{\nu_\mu/\bar{\nu}_\mu} = 0.96^{+0.38}_{-0.27}(stat.) \pm 0.15(sys.)$$







Higher statistics will allow us to make a more definitive statement on this.

Summary

- First results from MINOS! (hep-ex/0512036)
- First direct observation of separate ν_μ and $\bar{\nu}_\mu$ events!
- To within errors, ν_μ and $\bar{\nu}_\mu$ appear to oscillate in the same way.
- Have ~ x2 atmospheric exposure on disc (will have ~x5 by the end of the experiment) + Working on a more efficient event selection.
- No oscillation hypothesis excluded at 98% confidence level from analysis of L/E distribution.
- Results from the beam-line just announced!

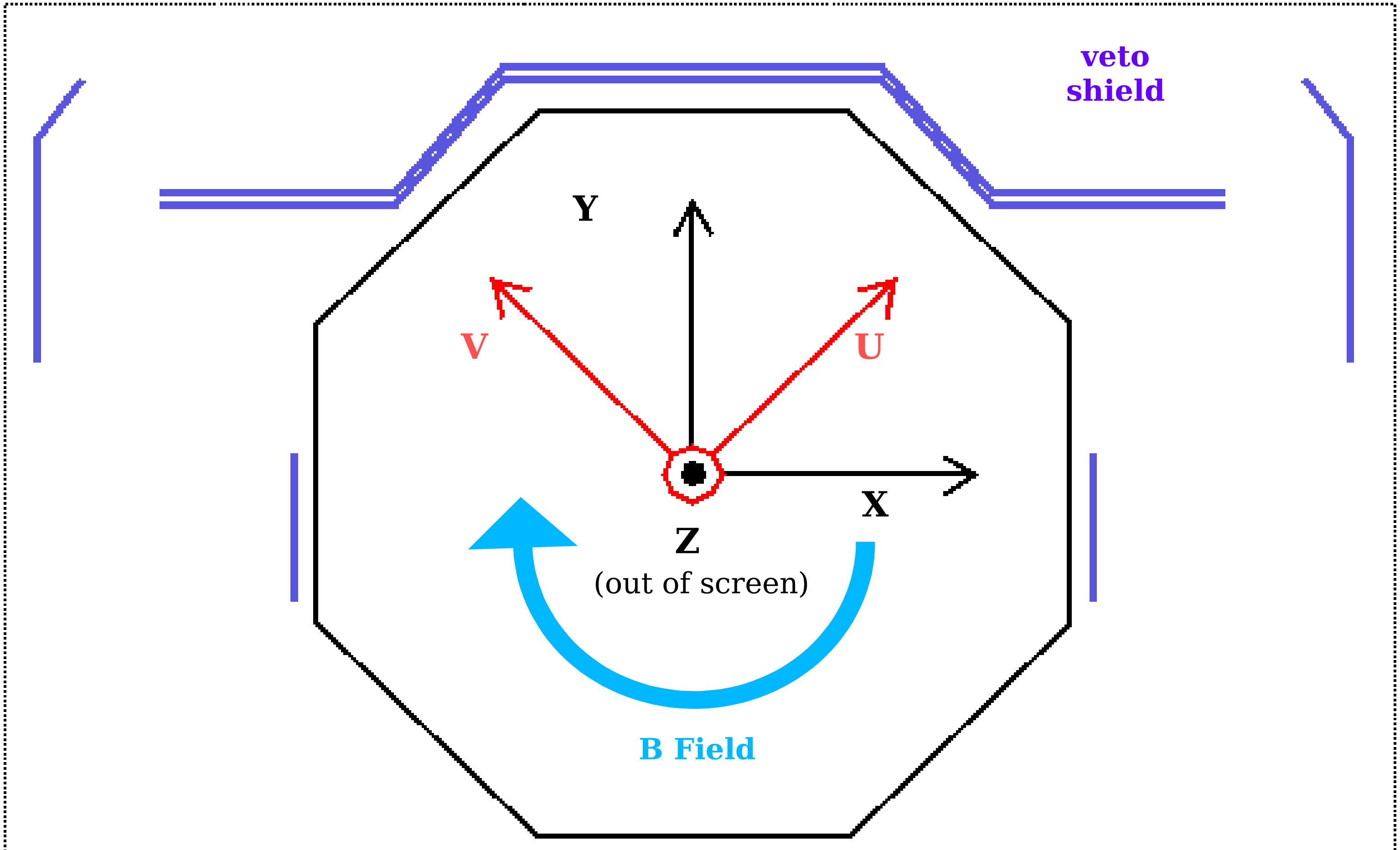
Backup Slides

Results

(Based on an exposure of 418 days.)

Selection	Data	Expectation (no oscillations)					
		Cosmic μ	ν_μ CC	ν_e CC	NC	Rock ν	ν_τ CC
FC	69	3.9±0.4	81.2±8.5	2.5±0.3	2.0±0.2	0.3±0.1	-
PC Down	25	0.6±0.2	18.5±1.9	0.1	-	0.1	-
PC Up	13	< 0.36	17.4±1.8	-	-	0.1	-
Total	107	4.4±0.5	117.1±12.2	2.6±0.3	2.0±0.2	0.5±0.1	-
		Expectation (Δm^2 = 0.0024 eV^2)					
FC	69	3.9±0.4	58.4±6.1	2.5±0.3	2.0±0.2	0.2	0.7±0.1
PC Down	25	0.6±0.2	17.5±1.8	0.1	-	0.1	-
PC Up	13	< 0.36	9.2±1.0	-	-	0.1	0.5±0.1
Total	107	4.4±0.5	85.1±8.9	2.6±0.3	2.0±0.2	0.4±0.1	1.2±0.1

Far Detector Coordinate System

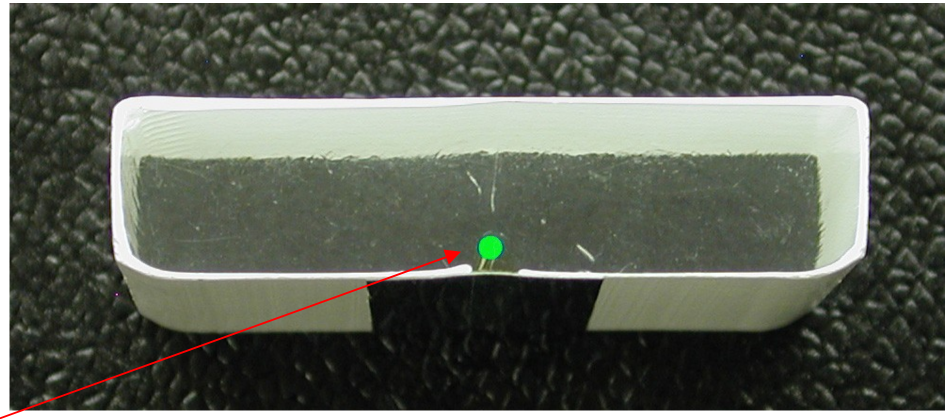


(viewed towards Fermilab.)

Basic Technology

★ **MAIN FEATURES:**

★ **Extruded scintillator strips**
★ **Wavelength-shifting fibres**
+ clear fibre optical readout
★ **Multi-anode PMT readout**
M16 in Far
M64 in Near
★ **8-fold optical multiplexing in Far Detector**



WLS fibre glued into groove