



# **Atmospheric Neutrino Results from the MINOS Experiment**

**Pedro Ochoa  
California Institute of Technology**

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# Atmospheric Neutrinos



- **The 5.4kT MINOS Far detector is unique:**

- 2070 mwe deep.
- It is magnetized, which allows us to separate  $\nu$  and  $\bar{\nu}$  events.
- Can measure muon energy and hadronic shower energy for all contained vertex events.



- **The Far detector has been taking data since August 2003:**

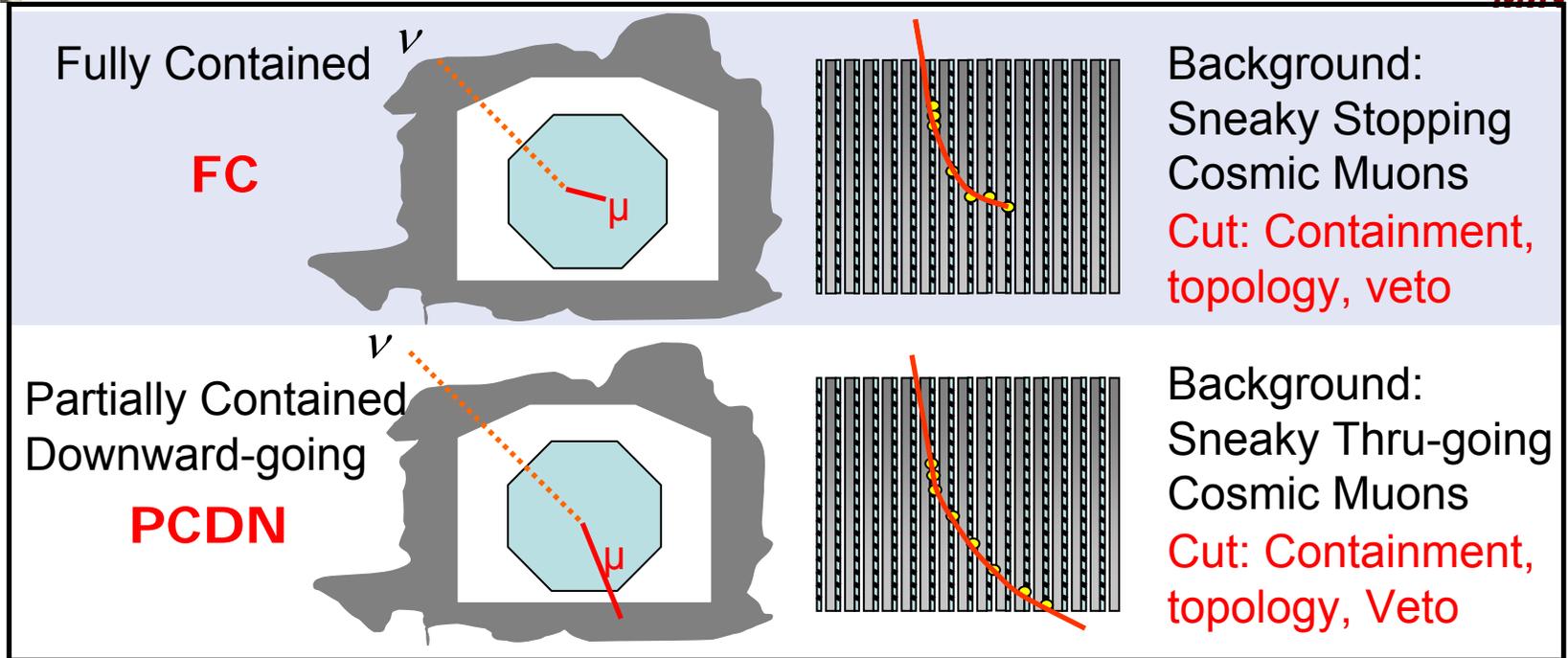
- 418 days of atmospheric neutrino data (6.18 kton-years) were collected. This data has been analyzed and the results published (Phys. Rev. D73 (2006) 072002, hep-ex/0512036).

- **This work constitutes the first direct observation of atmospheric neutrino interactions separately for  $\nu_{\mu}$  and  $\bar{\nu}_{\mu}$ .**

- **Atmospheric data taking continues during beam running.**



# Contained vertex: FC and PCDN



- FC and PCDN share the same backgrounds → same cuts.
- Use signal and cosmic ray muon MC (Bartol 3D flux) to develop a cuts based selection.
- Active veto shield used to measure remaining background in sample.

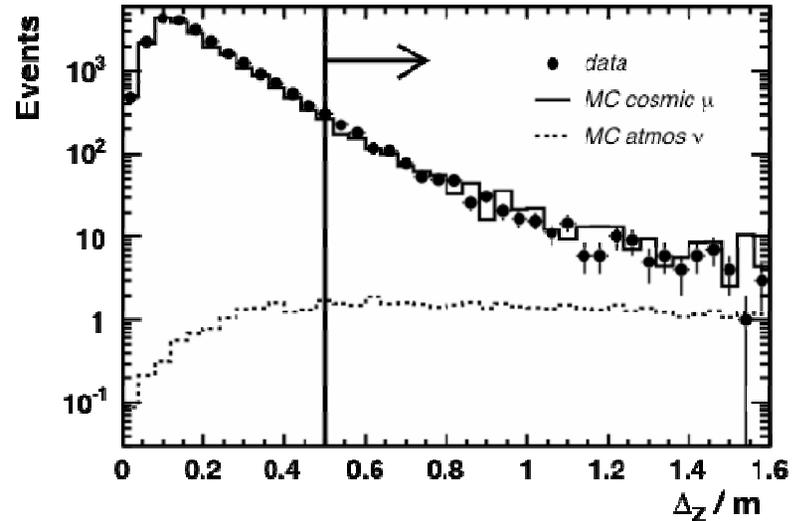
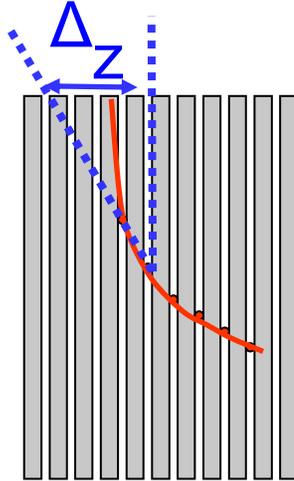


# Contained vertex: FC and PCDN

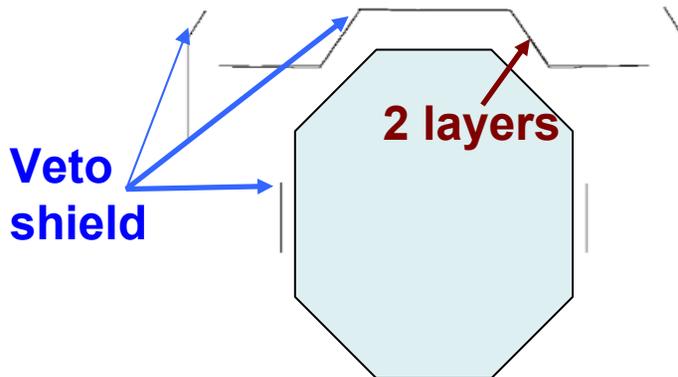


MINOS

Apply a set of cuts based on topology of the event, especially around the upper vertex:



Use cuts based on topology to reduce signal to background to ~1:1, then apply veto shield (97% efficient):



- After veto shield, kept 25 PCDN and 69 FC
- From efficiency and # of vetoed events get

	Measured Cosmic Muon BG	MC Cosmic Muon BG
Events	4.4±0.4(stat)±0.3(sys)	4.9±0.7(sys)



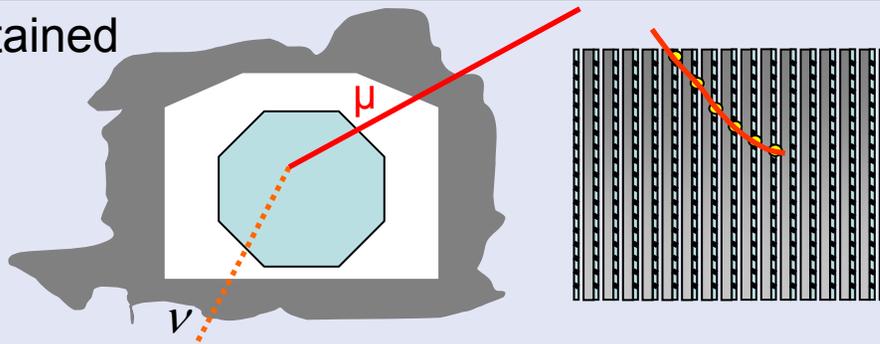
# Contained vertex: PCUP



MINOS

Partially Contained  
upward-going

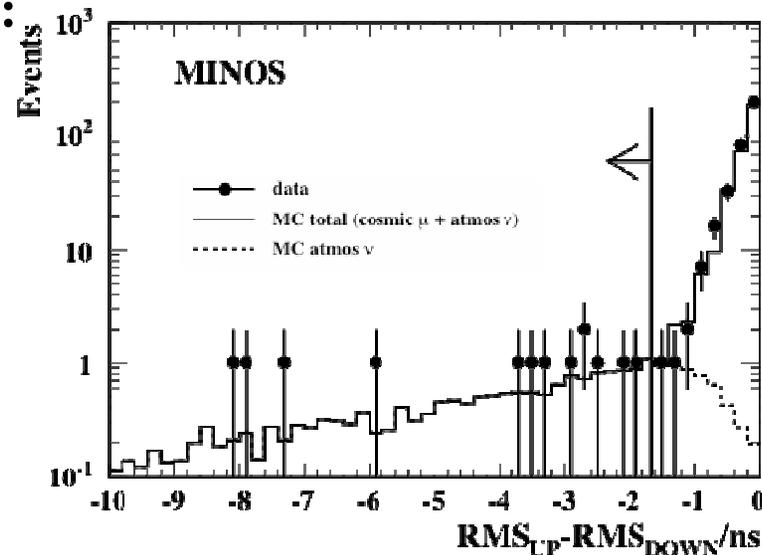
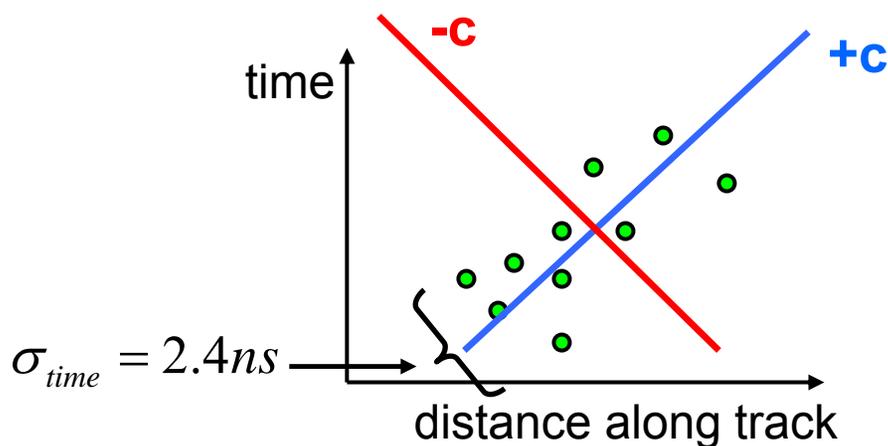
PCUP



Background: Stopping  
Cosmic Muons  
(Reco Direction  
Wrong)

Cut: containment  
timing

- Cut on direction from timing: Calculate RMS about **up** and **down** hypothesis, take smallest RMS as direction:



- Kept 13 PCUP events. The total MC expected (no osc.) is  $17 \pm 2$  (sys). Remaining background  $< 0.36$  (68% c.f.)

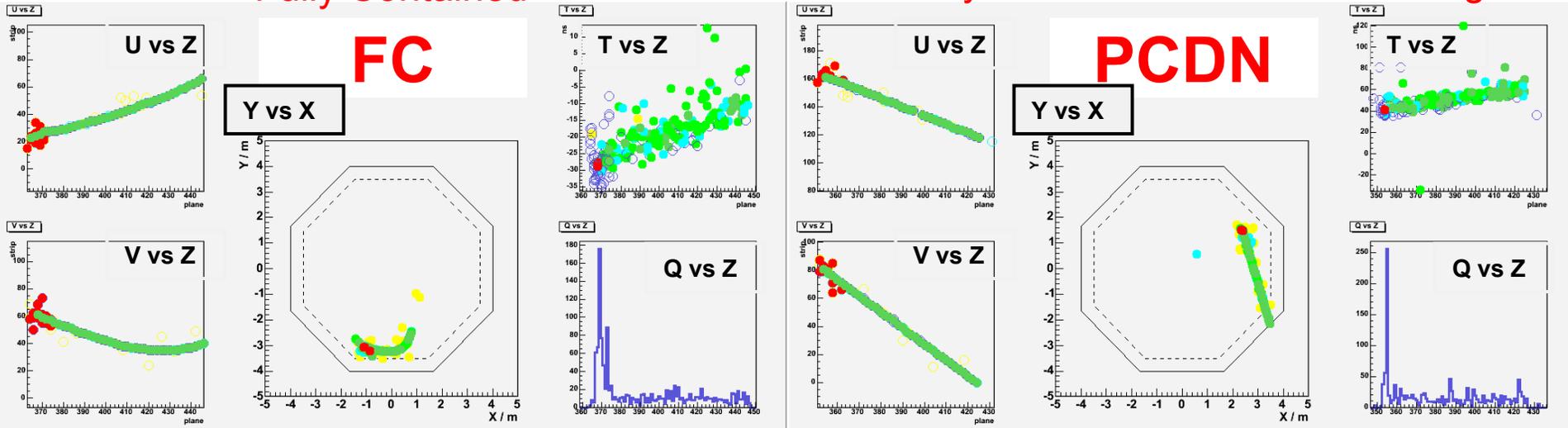


# Contained Vertex Event Examples

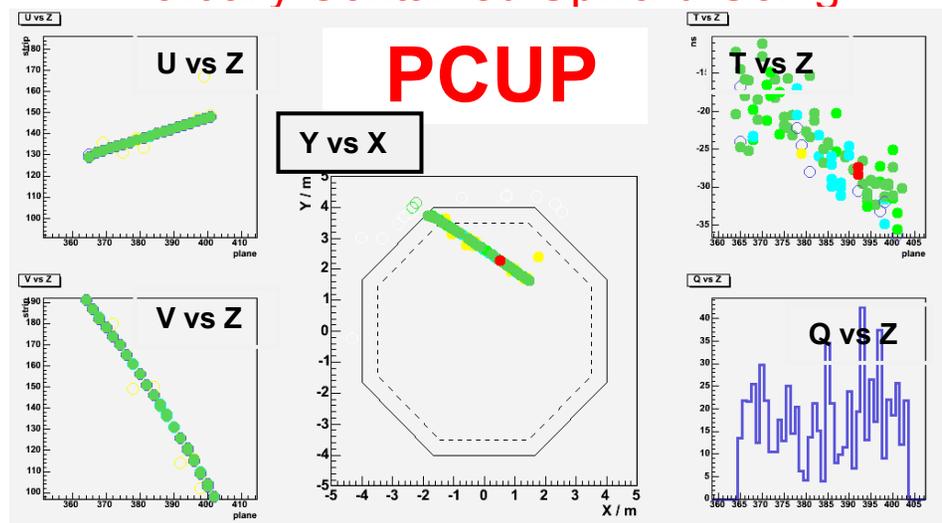


Fully Contained

Partially Contained Downward Going



Partially Contained Upward Going





# Event Selection



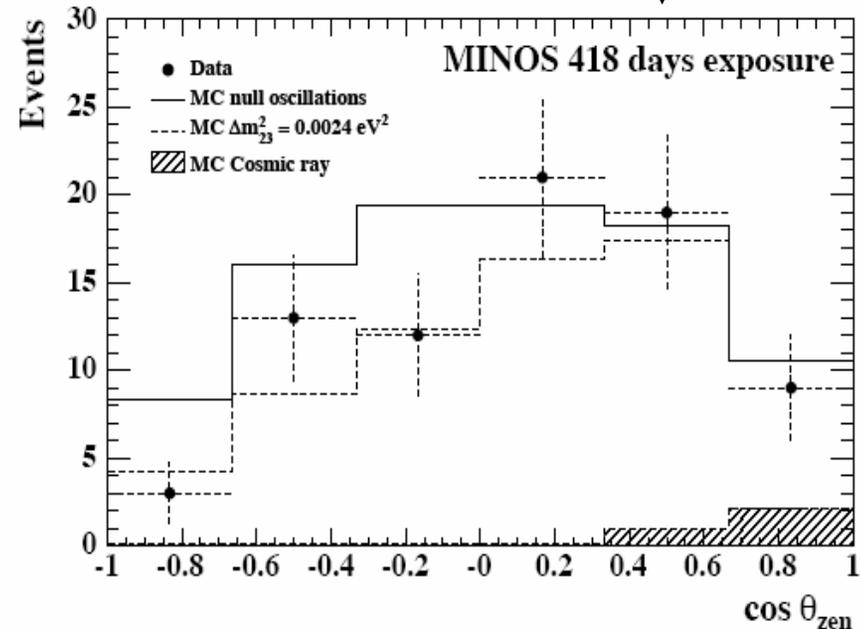
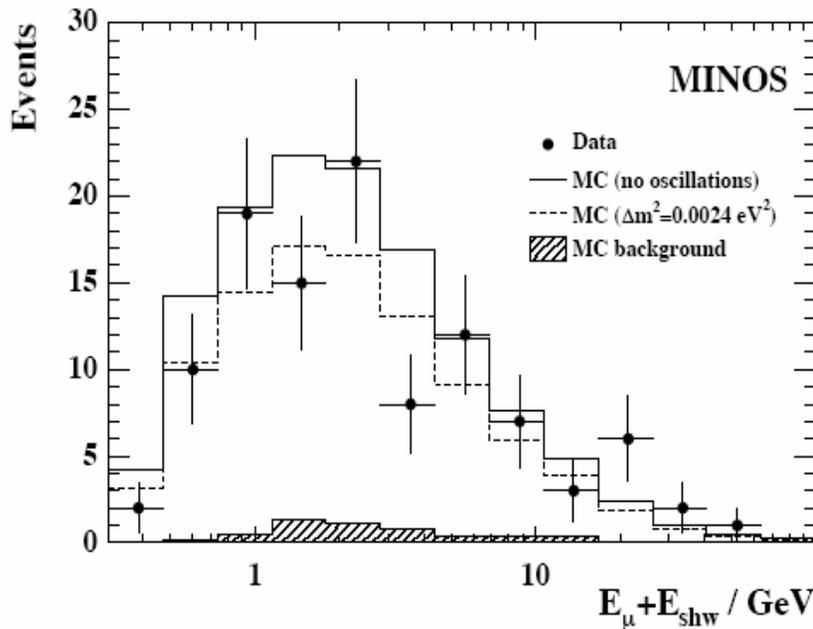
- From the 6.18kton-years of data extracted a total of 107 events

	Data	MC $\nu_\mu/\nu_\mu^{CC}$ no oscillations	MC $\nu_\mu/\nu_\mu^{CC}$ $0.0024 \text{ eV}^2$	Cosmic Muons	Other Backgrounds
Total	107	$127.1 \pm 12.7$	$96.2 \pm 9.5$	$4.9 \pm 0.7$	$5.1 \pm 0.35$

Bartol 3D flux scaled by  
Soudan 2  $\nu_e$  measurement

$\nu_\tau^{CC}$ , Rock muons  
 $\nu_e^{CC}$ , Neutral  
Current, Neutrons

- Of these, 77 carry good neutrino direction information.



Up/down ratio:  $R_{up/down}^{data} / R_{up/down}^{MC(no\_osc)} = 0.62 \pm 0.14(stat.) \pm 0.02(sys.)$

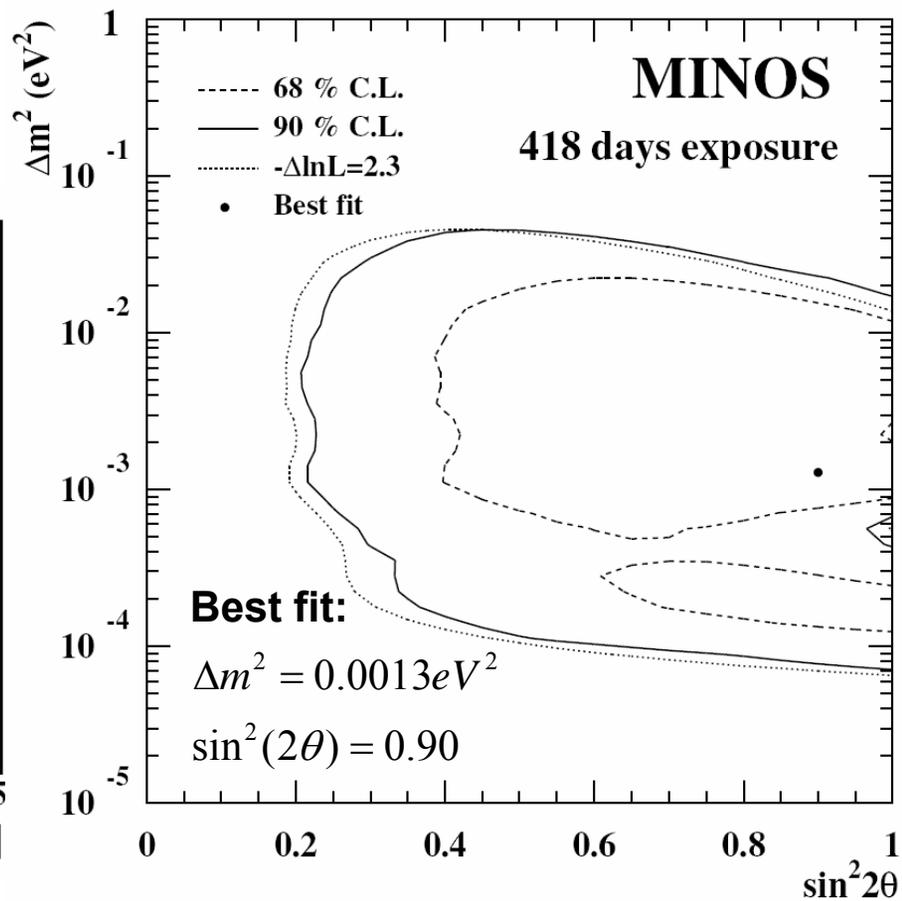
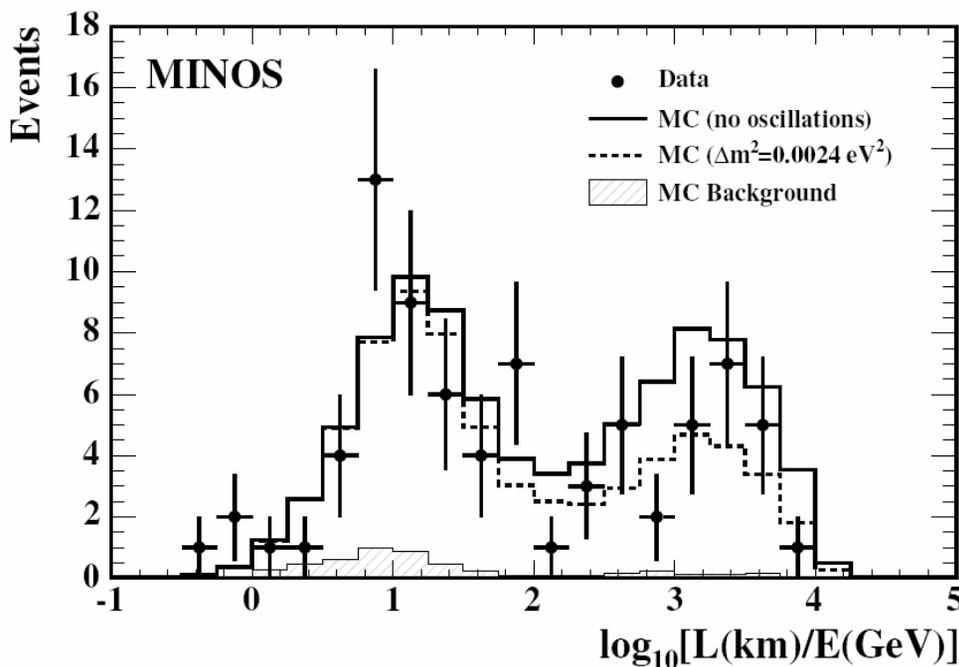
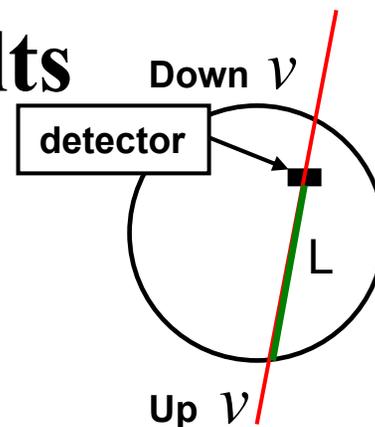
→ 2.6 $\sigma$  from no oscillations !



# Atmospheric Results



- For each event measured L/E
- Maximum likelihood analysis:
  - result consistent with SK/K2K/Soudan2/MACRO.
  - no oscillations excluded with 98% confidence.





# Charge Separation

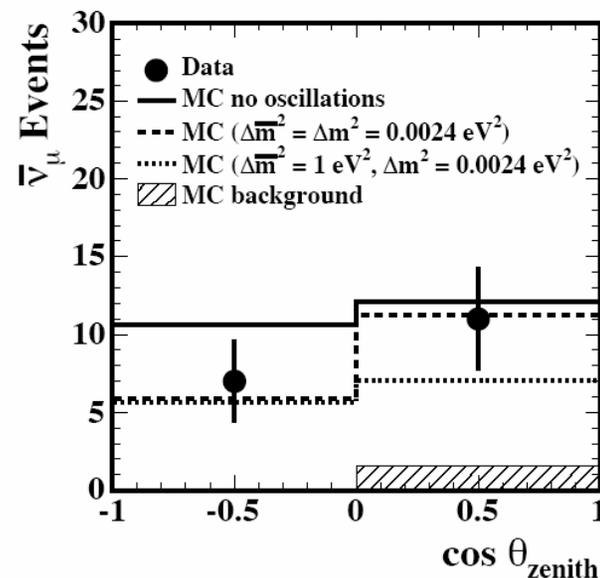
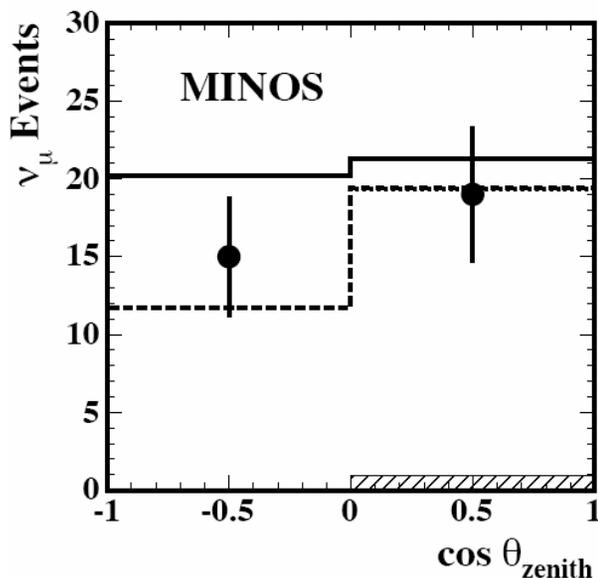


- The curvature of the muon in the magnetic field allows us to separate  $\nu$  and  $\bar{\nu}$ .
- So far 34  $\nu$ 's and 18  $\bar{\nu}$ 's have been identified with 99% purity.

	Data	Total MC (no osc)	Total MC (0.0024eV <sup>2</sup> )
$\nu_\mu$	34	42±4	31±3
$\bar{\nu}_\mu$	18	23±2	17±2
$\nu_\mu/\bar{\nu}_\mu$ ?	25	26±3	20±3
Low res	30	37±4	28±3

- $R_{\bar{\nu}_\mu/(\bar{\nu}_\mu+\nu_\mu)}^{data} / R_{\bar{\nu}_\mu/(\bar{\nu}_\mu+\nu_\mu)}^{MC} = 0.98 \pm 0.19(stat.) \pm 0.06(sys.)$

- Data consistent with same  $\nu$  vs  $\bar{\nu}$  oscillations (no CPT violation)
- Statistics too low to exclude large values of  $\Delta m_{23}^2$  for  $\bar{\nu}$





# Summary



## Atmospheric neutrino results:

- **Current atmospheric results exclude no-oscillations at 98% confidence and are consistent with Super-K/K2K/Soudan-2/MACRO.**
- **Results provide a measurement of the charge ratio for atmospheric neutrinos. Data so far consistent with same oscillation parameters for  $\nu$  and anti- $\nu$ , but statistics are low.**
- **Atmospheric data taking continues during beam running.**

## In addition:

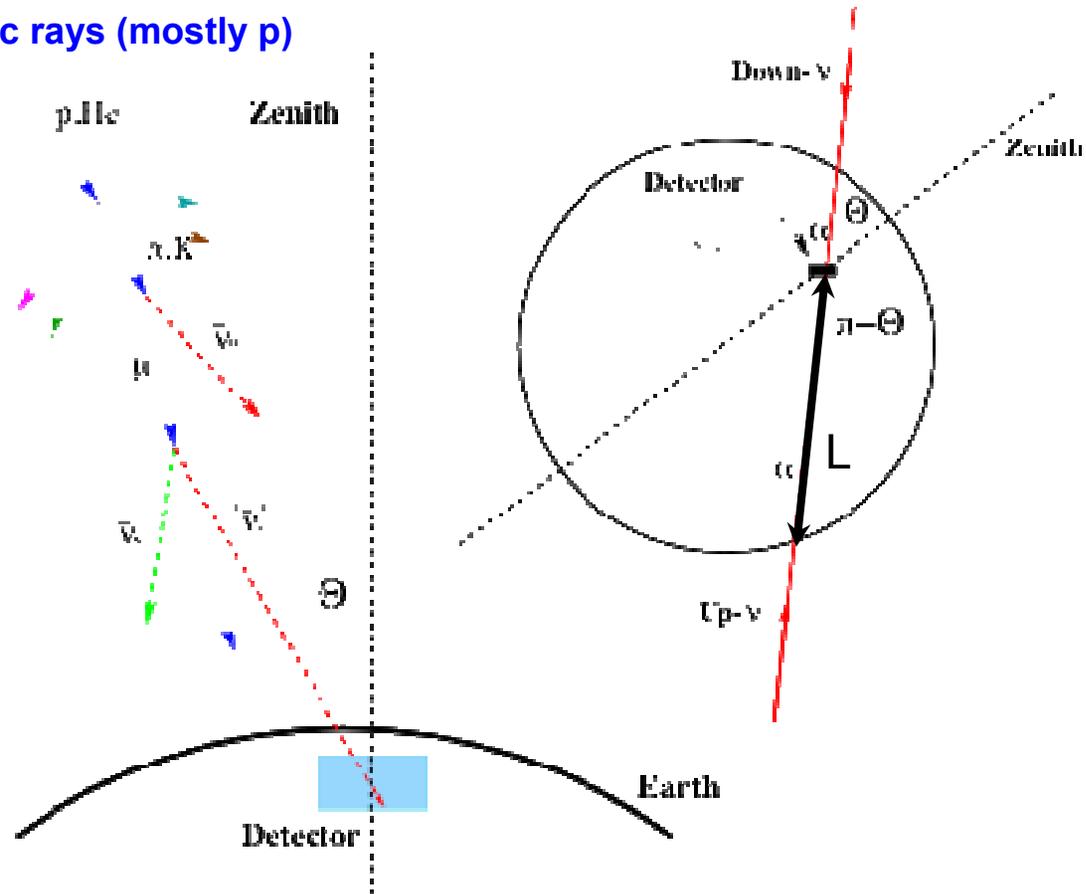
- **A publication on neutrino induced muons is in the works.**

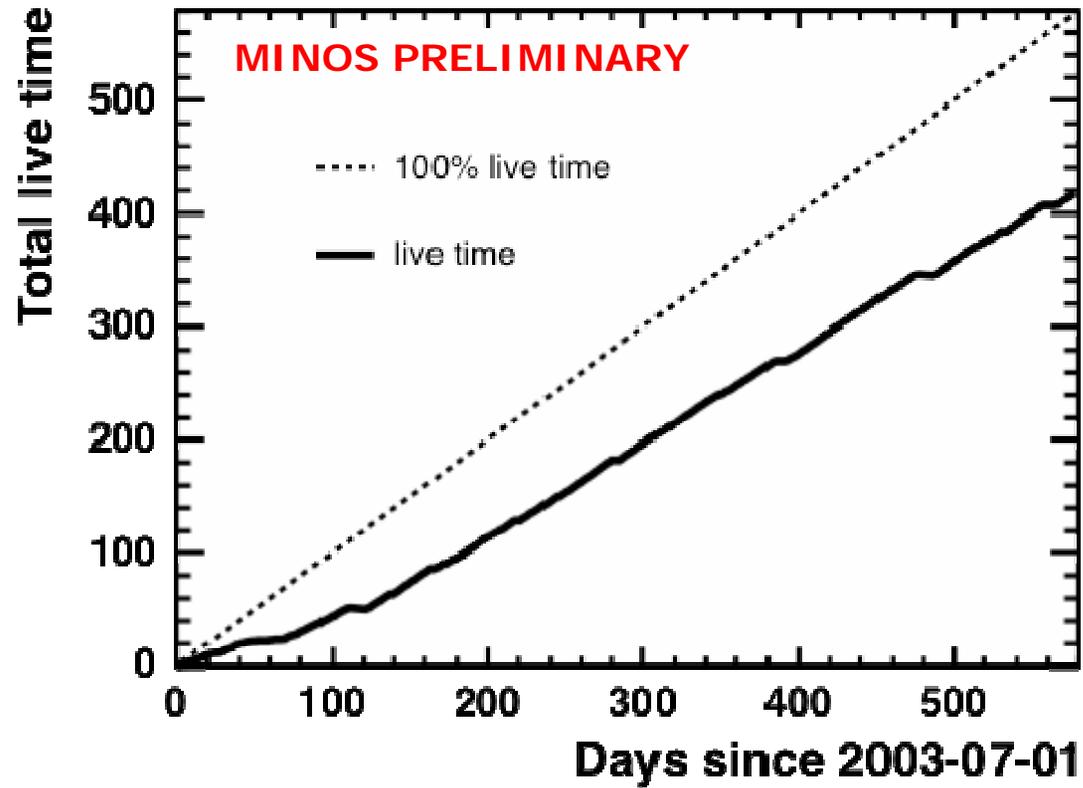


# Backup slides



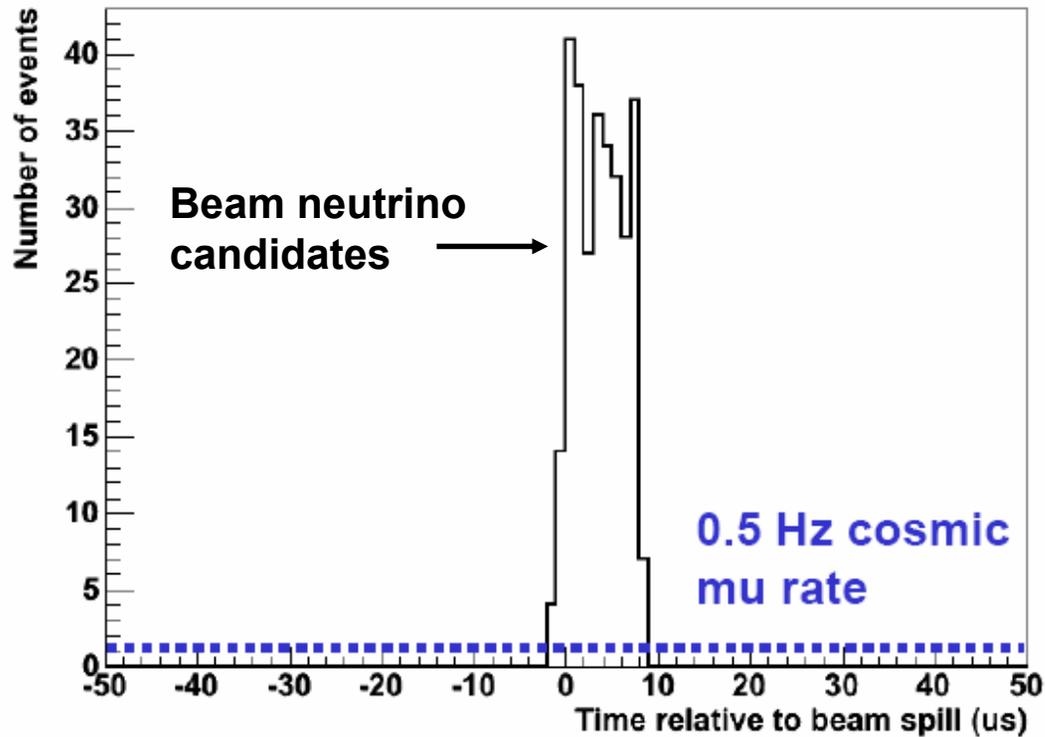
cosmic rays (mostly p)

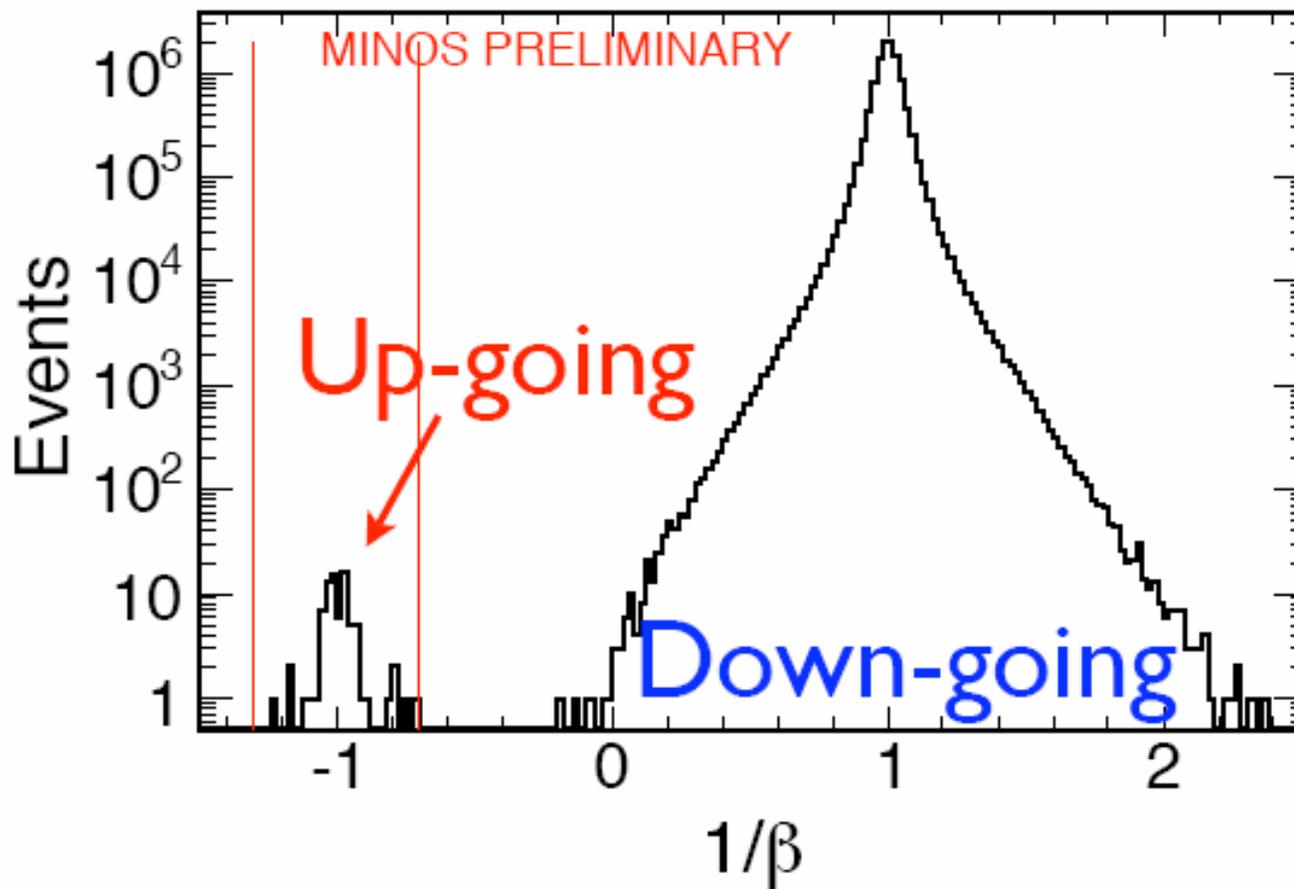






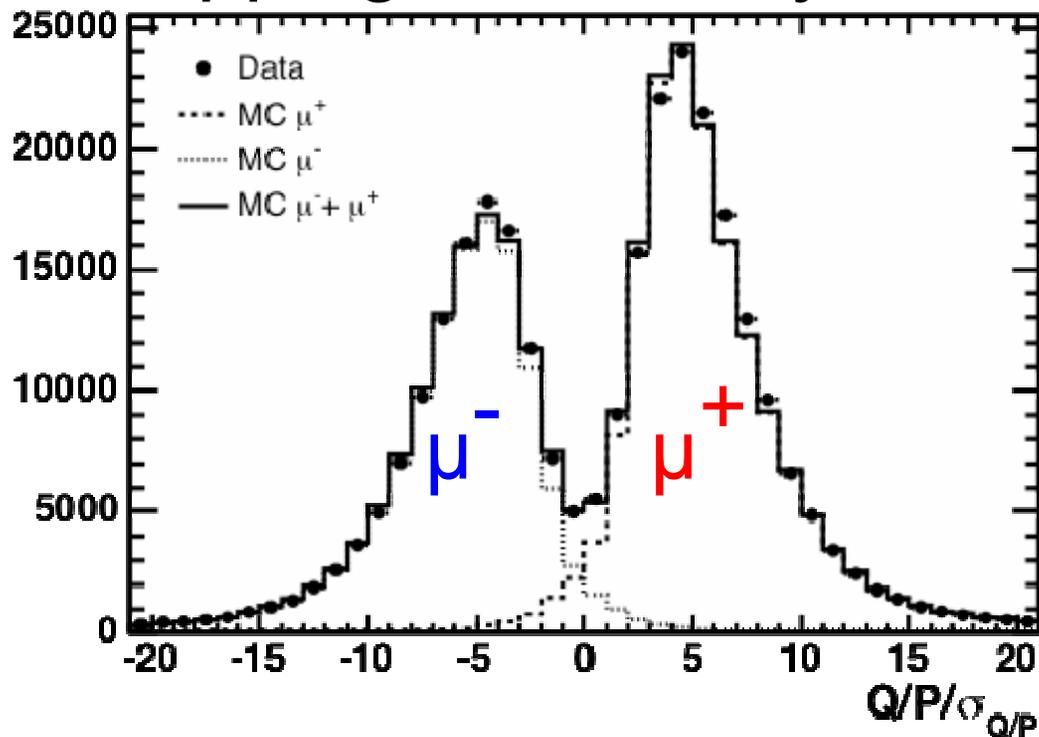
## Time difference of neutrino interactions from beam spill







# Stopping cosmic ray muons





# Upward Going Muon

