Atmospheric Neutrinos at MINOS

Caius Howcroft, Caltech.
FNAL JETP Seminar, 19/Aug/2005

Overview:

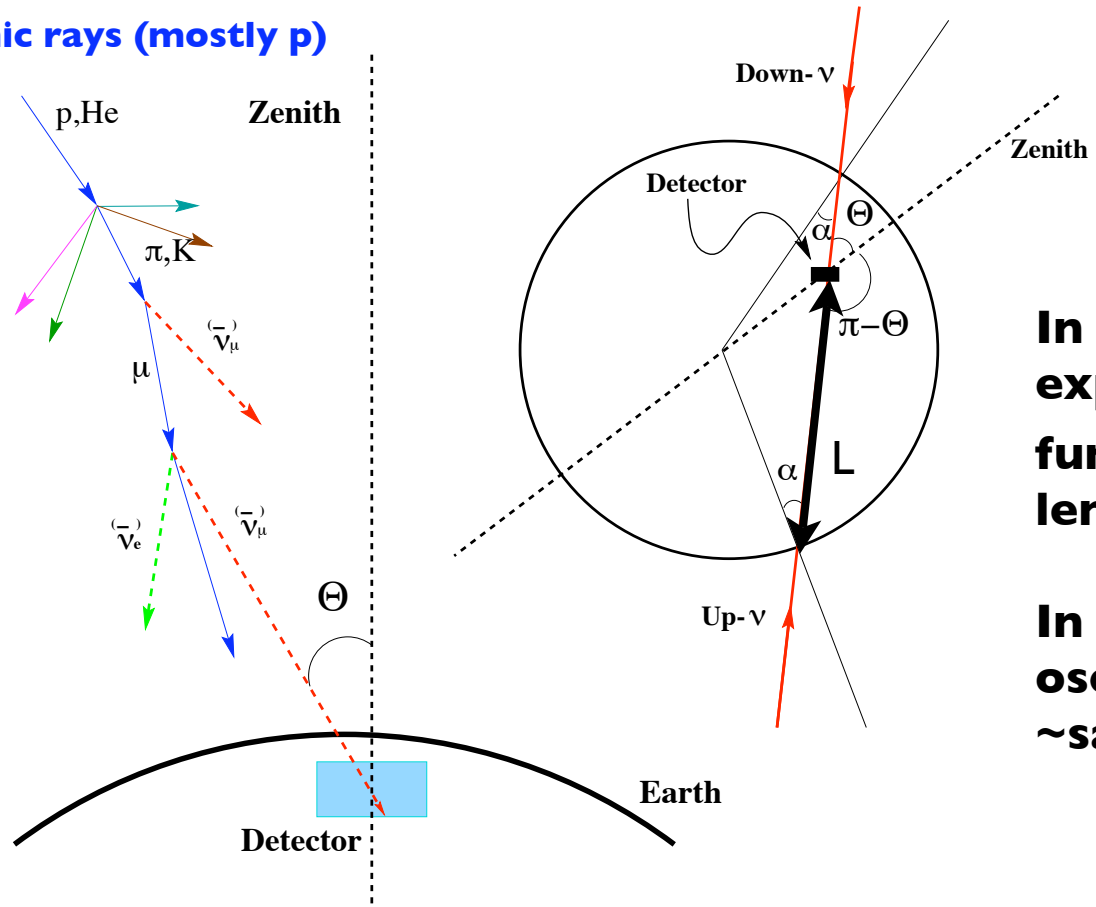
i. Atmospheric Neutrinos
ii. MINOS overview and goals
iii. Types of atmospheric neutrino analyses at MINOS
iv. ν induced μ analysis
v. Contained vertex analysis

The MINOS Collaboration

Argonne • Athens • Benedictine• Brookhaven • Caltech • Cambridge • Campinas • Dubna • Fermilab • College de France • Harvard • Illinois Inst. of Technology • Indiana • ITEP-Moscow • Lebedev • Livermore • Minnesota-Twin Cities • Minnesota-Duluth • Oxford • Pittsburgh • Protvino • Rutherford • Sao Paulo • South Carolina • Stanford • Sussex • Texas A&M • Texas-Austin • Tufts • University College London • Western Washington • William&Mary • Wisconsin

Atmospheric Neutrinos

cosmic rays (mostly p)



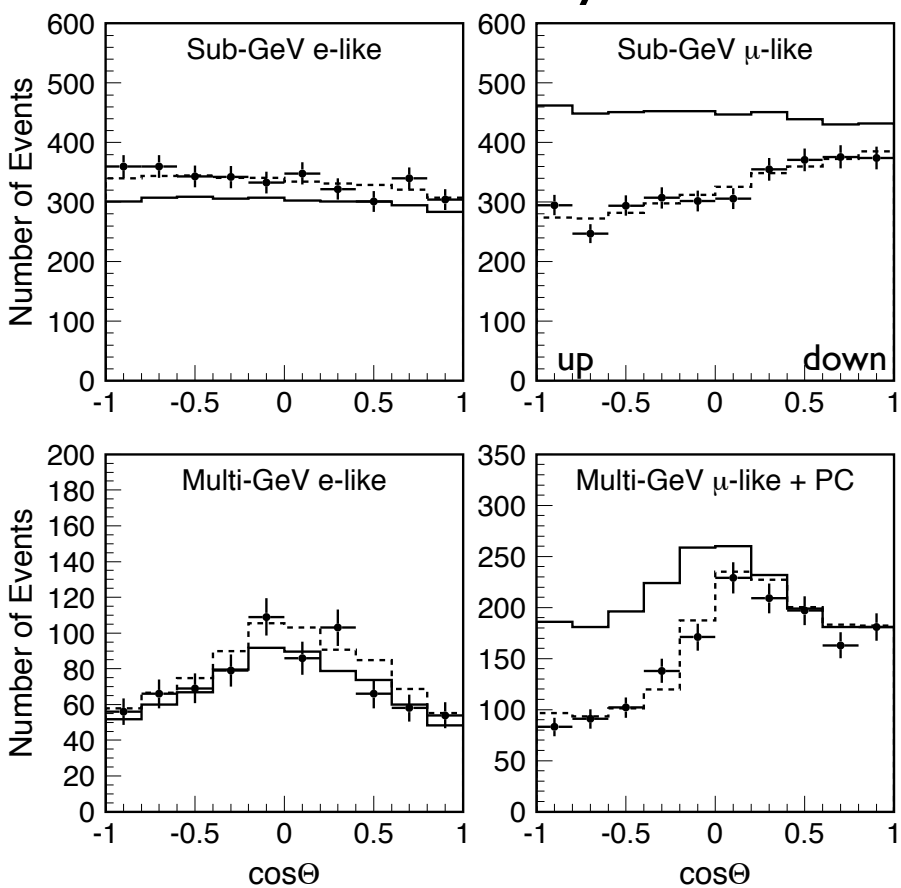
$$p + N \rightarrow \pi^{\pm} + X$$
$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu_{\mu}})$$
$$\mu^{\pm} \rightarrow e^{\pm} + \nu_{e}(\bar{\nu_{e}}) + \nu_{\mu}(\bar{\nu_{\mu}}).$$

In general, atmospheric neutrino experiments study the ν_μ flux as a function of zenith angle (or path length L) and neutrino energy.

In the absence of neutrino oscillations, would expect flux to be ~same in all directions.

Atmospheric ν Experiments

- First hint of atmospheric neutrino oscillations from IMB then Kamiokande
- Currently most constraining measurement of oscillation parameters from Super-Kamiokande
- Confirmed by Soudan 2 and MACRO



$\nu_\mu \leftrightarrow \nu_\tau$ OSCILLATIONS

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta \sin^2(\Delta m^2_{23} L/4E)$$

Current SK best fit:

$\sin^2 2\theta = 1.0$, $\Delta m^2_{23} = 0.0024$ eV^2

Principle MINOS Physics Goals

- Demonstrate the oscillation behaviour using an accelerator based experiment.
  Provide very high statistics discrimination against other models for $\nu\mu$ disappearance , e.g. decoherence, neutrino decay, ...?
- Measure Δm^2_{23}
  to better than 10%

- Search for sub dominate νe appearance
  θ_{13} 3σ discovery limit is factor 2 improvement on CHOOZ current limit.
- Observe charge separated atmospheric neutrinos
  This talk!

MINOS Basic Idea

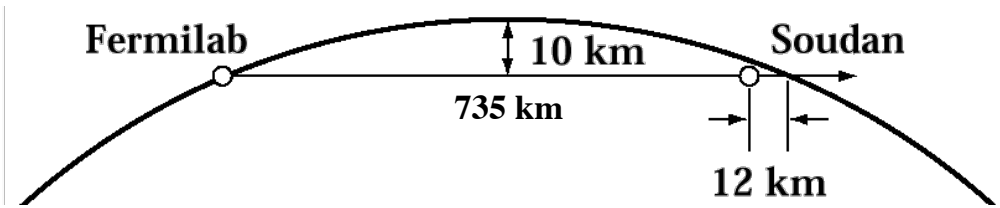
ν_μ beam:

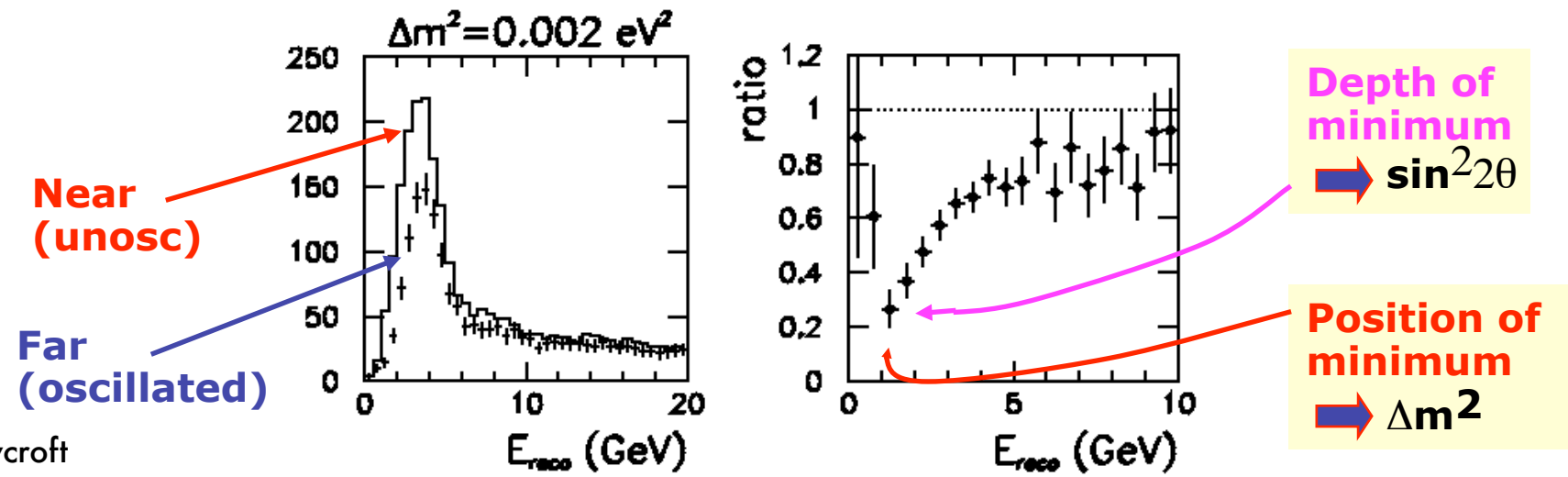
120 GeV protons from FNAL Main Injector

2 detectors:

`Near' detector, FNAL, IL: unoscillated spectrum

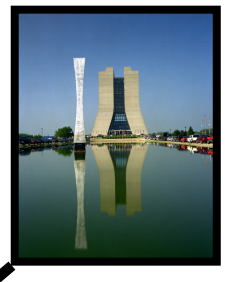
`Far' detector Soudan , MN (735km away): measure oscillated neutrino energy spectrum

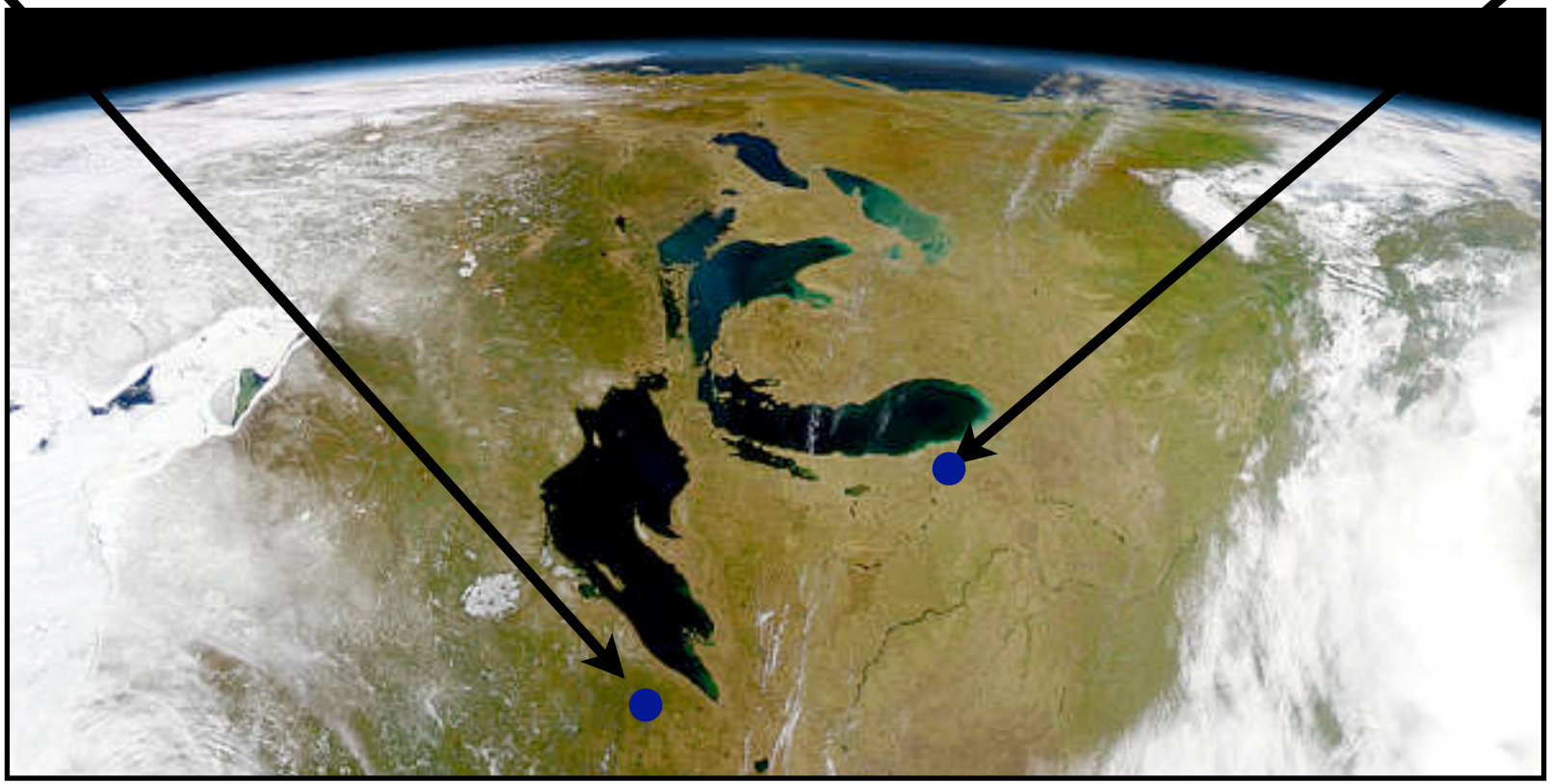




Soudan, Mn
`Far' detector

FNAL, IL
Beam Production
& `Near' detector



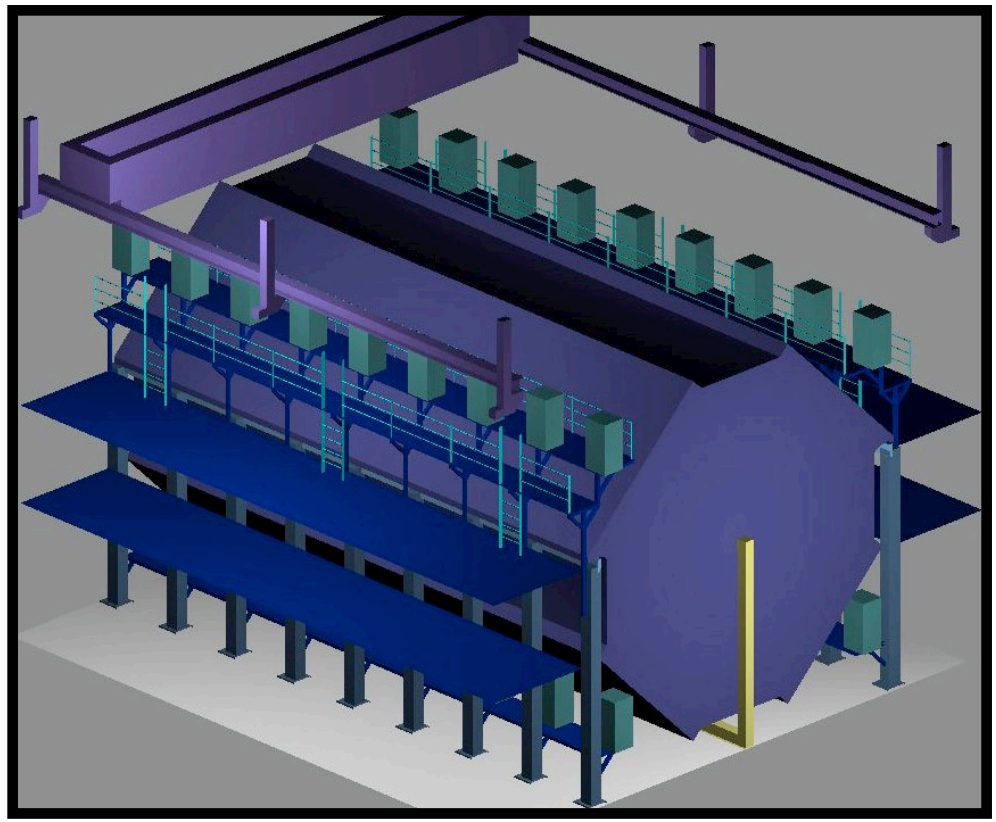


MINOS Far Detector Site

- Located in former iron mine in northern Mn, USA.
- Also the home of Soudan1&2 (ret.) and CDMS II.
- MINOS is 2341 ft. (2070 mwe) below the surface.

The Far Detector

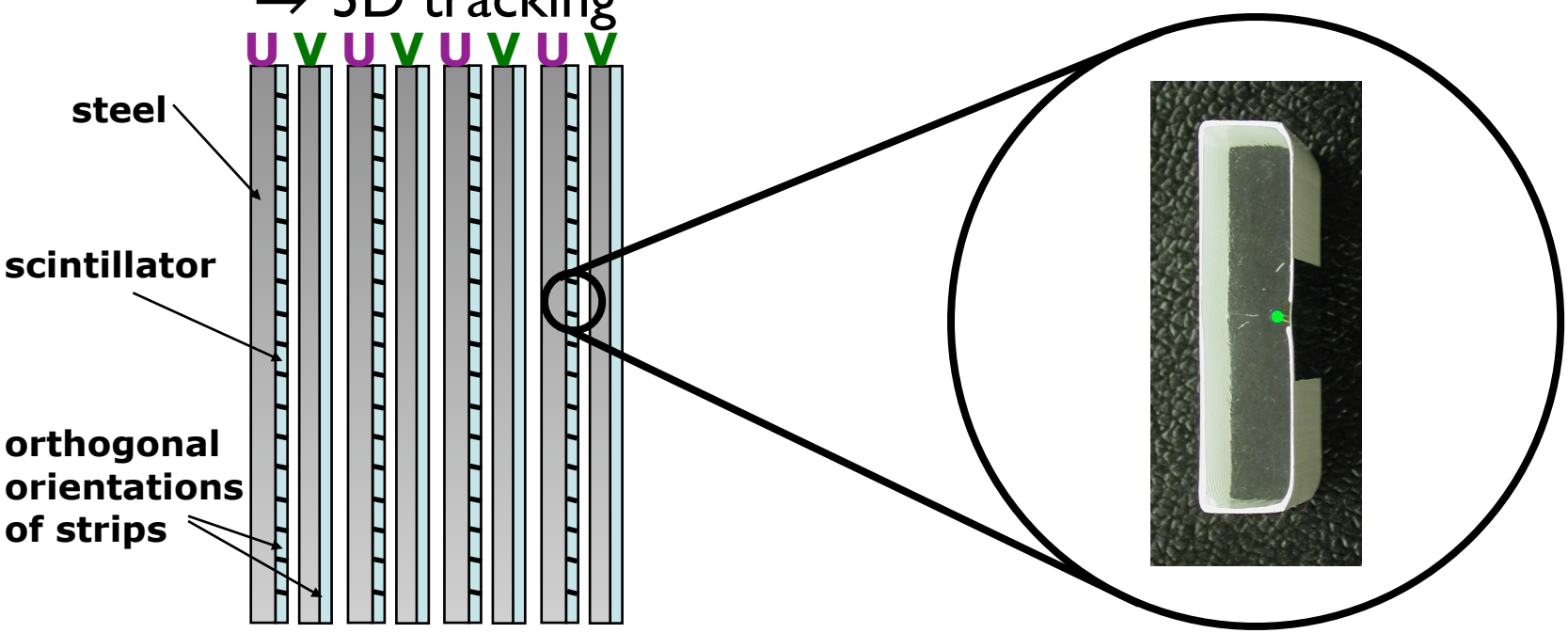
- 8m octagonal steel scintillator tracking calorimeter.
- Divided into two 15m sections (supermodules)
- Each supermodule has a 1.5T toroidal magnetic field
- 5.4 kton total mass
- Hadronic energy resolution ~55%/√E
- Muon momentum resolution ~7% (range), ~20% (curve)
- Active Veto shield to tag cosmic ray muons.
- Completed in Aug 2003.



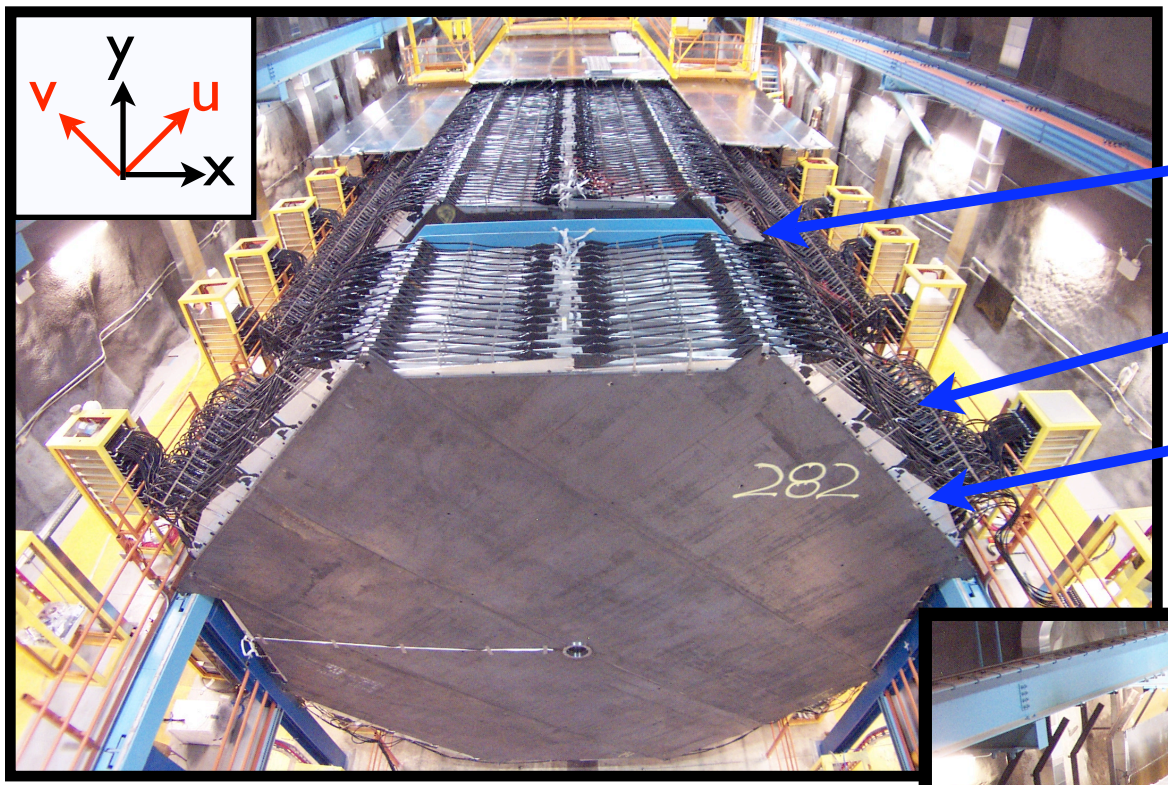
A single supermodule

Detector Readout

- Steel-Scintillator sandwich, each layer (or plane) consists of a 2.54 cm steel +1 cm scintillator
- Each scintillator plane divided into 192 x 4.1cm wide strips
- Scintillation light collected by WLS fibres glued into each strip and read out by multi-pixel PMTs
- Alternate planes have orthogonal strip orientations, U and V ⇒ 3D tracking



The Far Detector



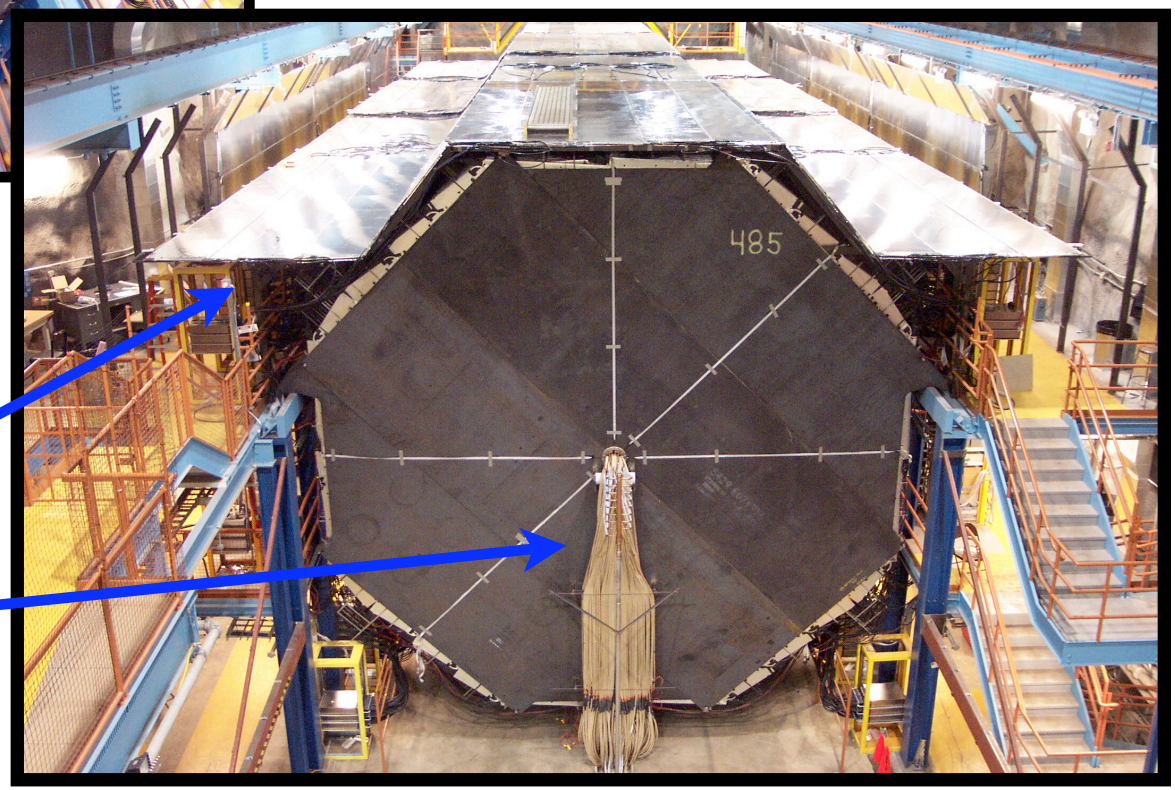
During construction.

Supermodule boundary

Optical readout

Scintillator

Completed

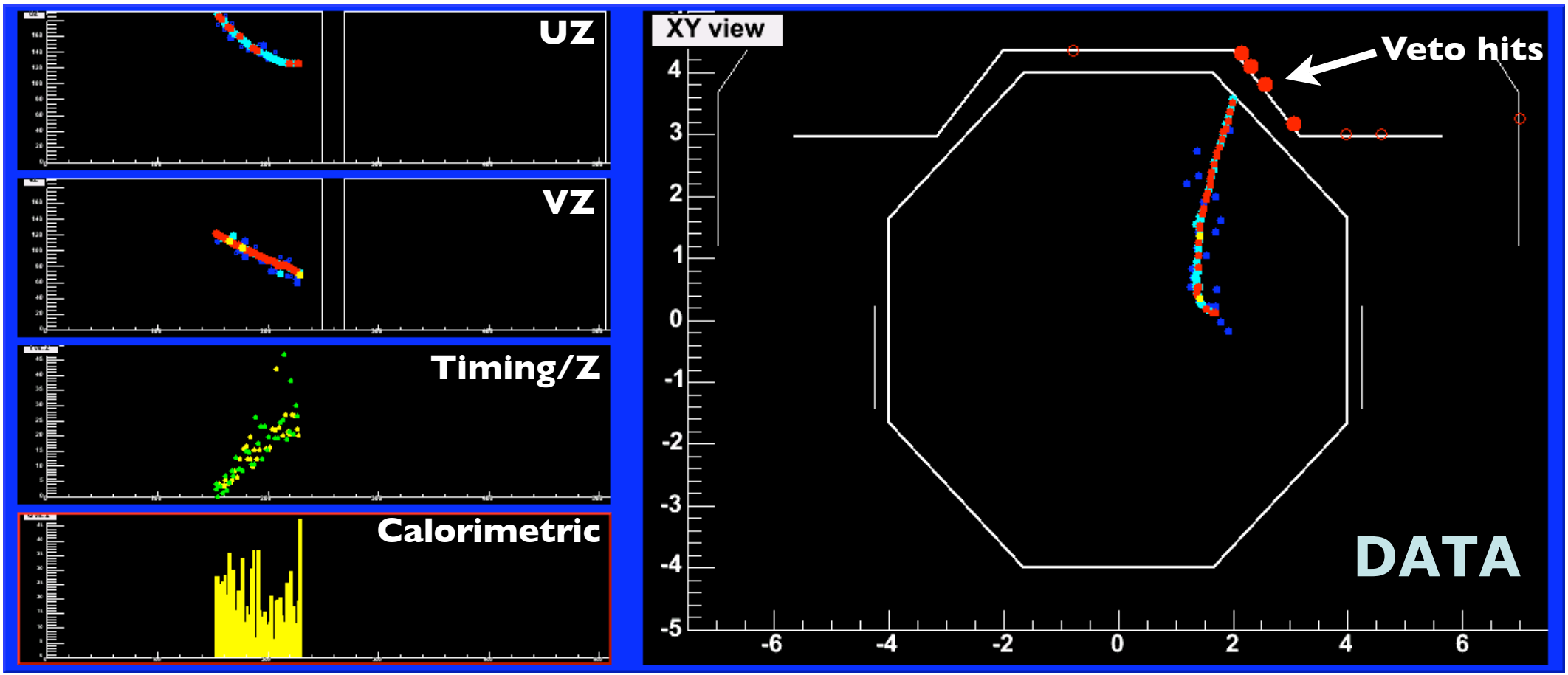


Veto shield

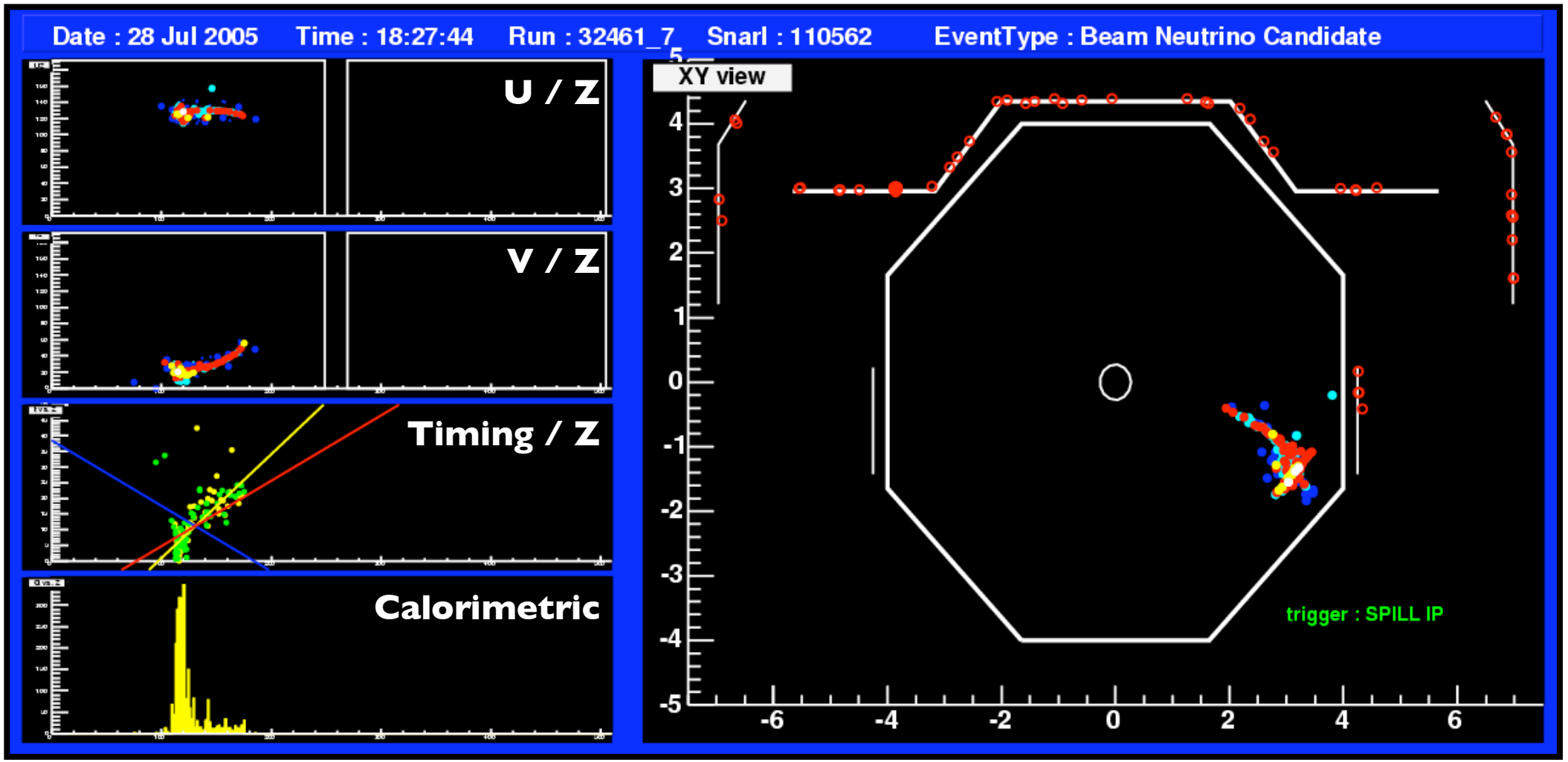
Coil

Event Information

- Two Views (UZ and VZ) are combined to give 3D tracks and showers.
- Event timing information
- Calorimeteric information
- Event charge and muon momentum from curvature of tracks in B-field.
- Active veto shield tags incoming particles.

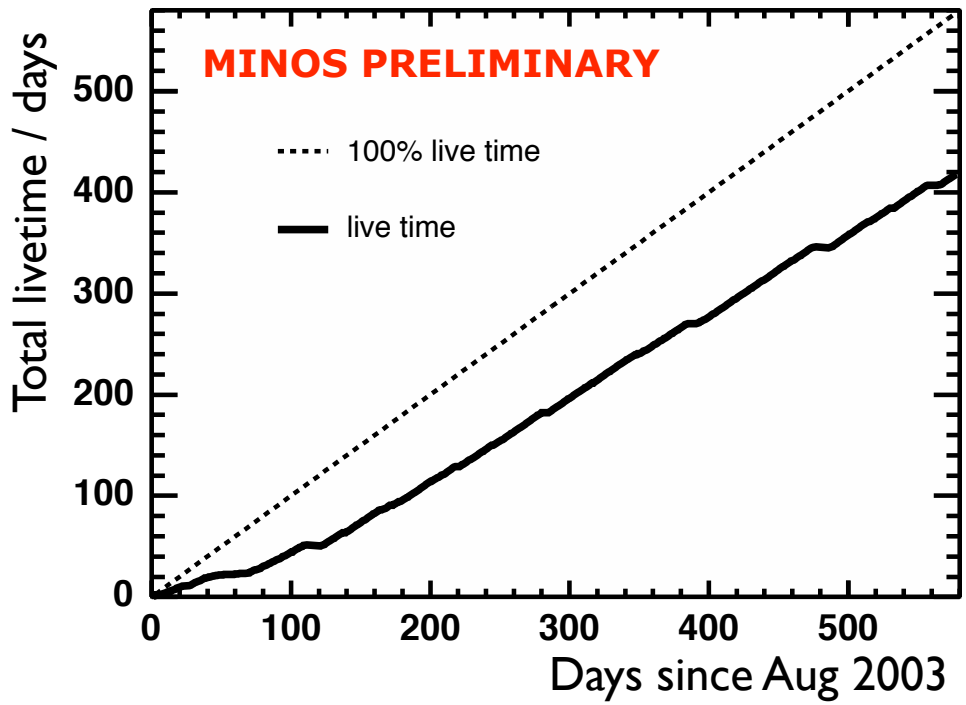


FarDet Beam Data Event



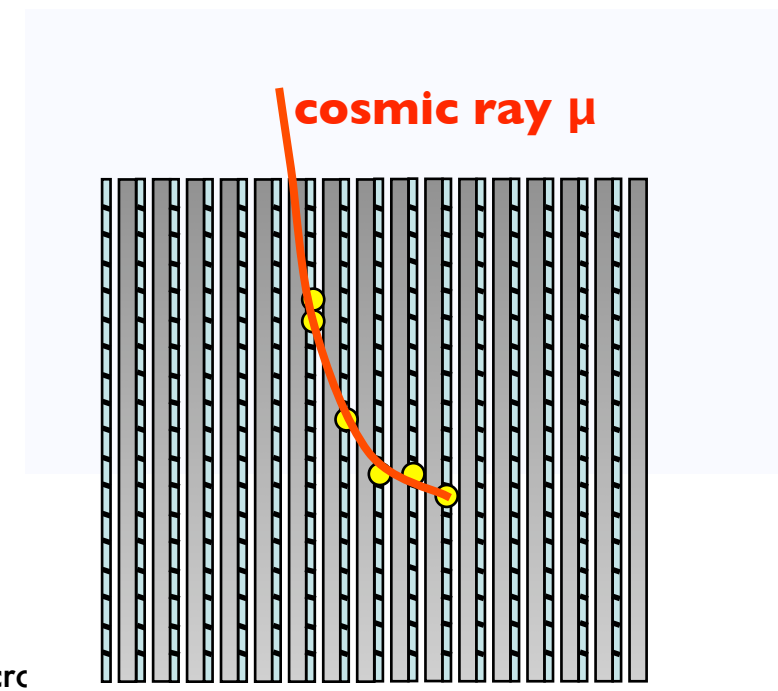
Atmospheric Data

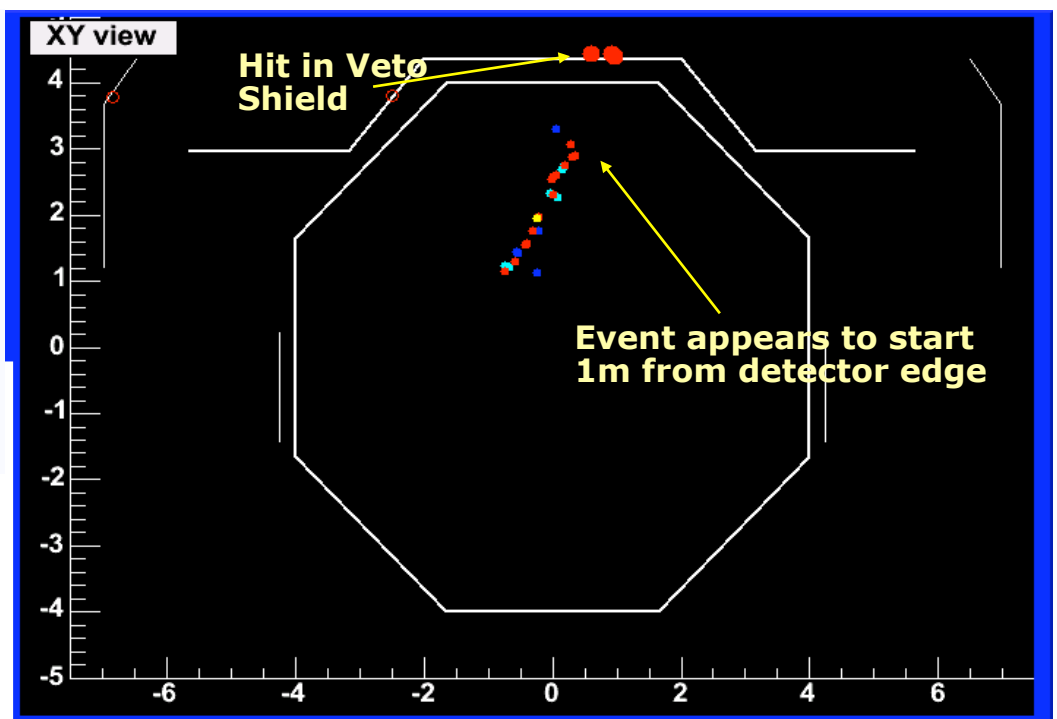
- Since completion in August 2003 the Far Det has been taking cosmics data.
- Beam switched on 1st March 2005 at which point the Far Detector had collected 420 days of physics quality data, excellent for a detector still in commissioning stage.
- Total of 6.18 kton-years of data suitable for atmospheric neutrino studies, c.f. Soudan 2's 7.36 kton-years.
- Will still take cosmics data during beam running.



Atmos ν Pros and Cons

- **MINOS Far Detector has a lot going for it:**
  - Deep (2070 mwe), giving 100,000:1 reduction in cosmic muon rate.
  - Magnetic field giving information about:
    - **muon charge ⇒ ν $\bar{\nu}$ separation**
    - **muon momentum, even for muons that leave the detector ⇒ neutrino energy for all events**
- **The challenge,**
  - 80% of the detector surface is uninstrumented.

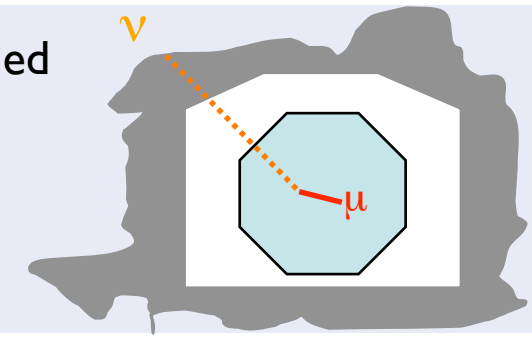


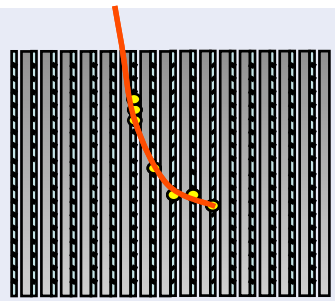


Event Classes & Backgrounds

Fully Contained

FC



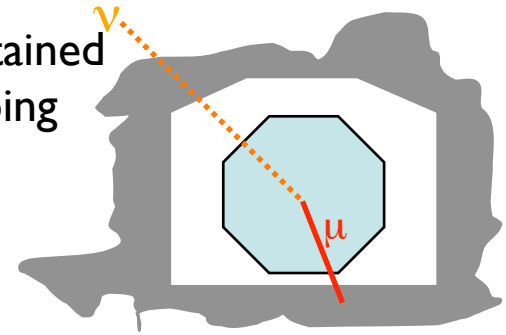


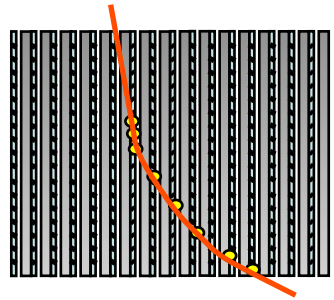
Sneaky Stopping Cosmic Muons

Cut: Containment, topology, veto

Partially Contained Downward-going

PCDN





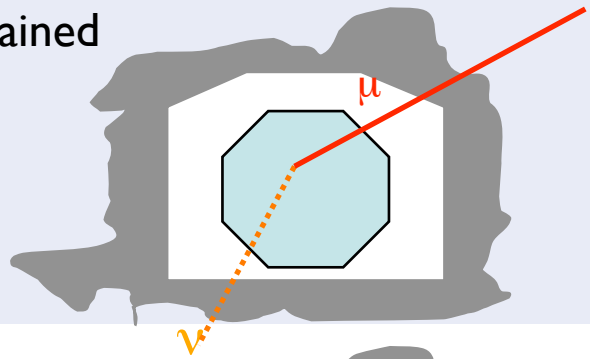
Sneaky Thru-going Cosmic Muons

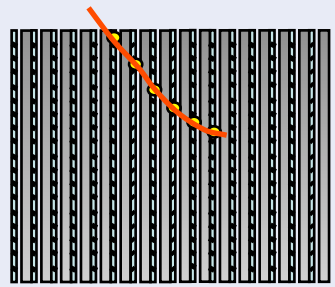
Cut: Containment, topology, Veto

Contained Vertex

Partially Contained upward-going

PCUP



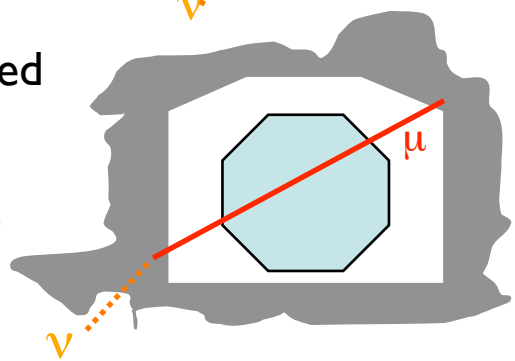


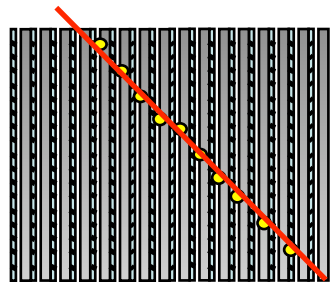
Stopping Cosmic Muons (Reco Direction Wrong)

Cut: containment timing

neutrino induced rock muon

νinducedμ



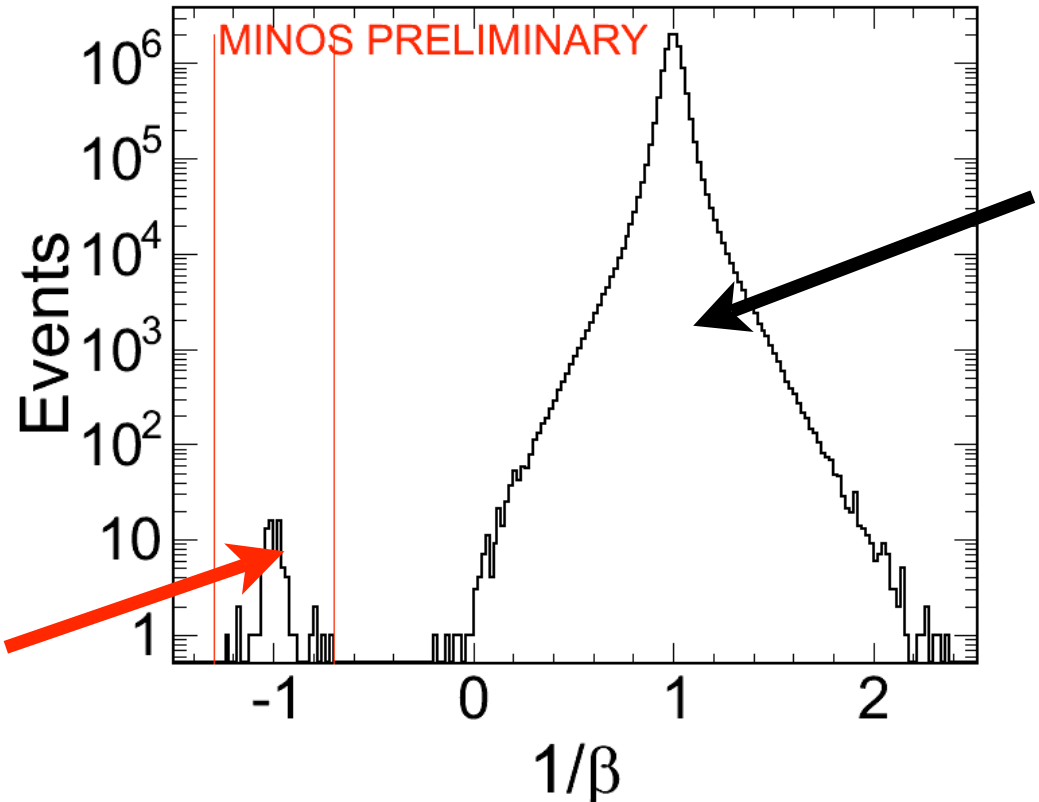


Thru-going Cosmic Muons (Reco Direction wrong)

Cut: timing

Neutrino Induced Muons

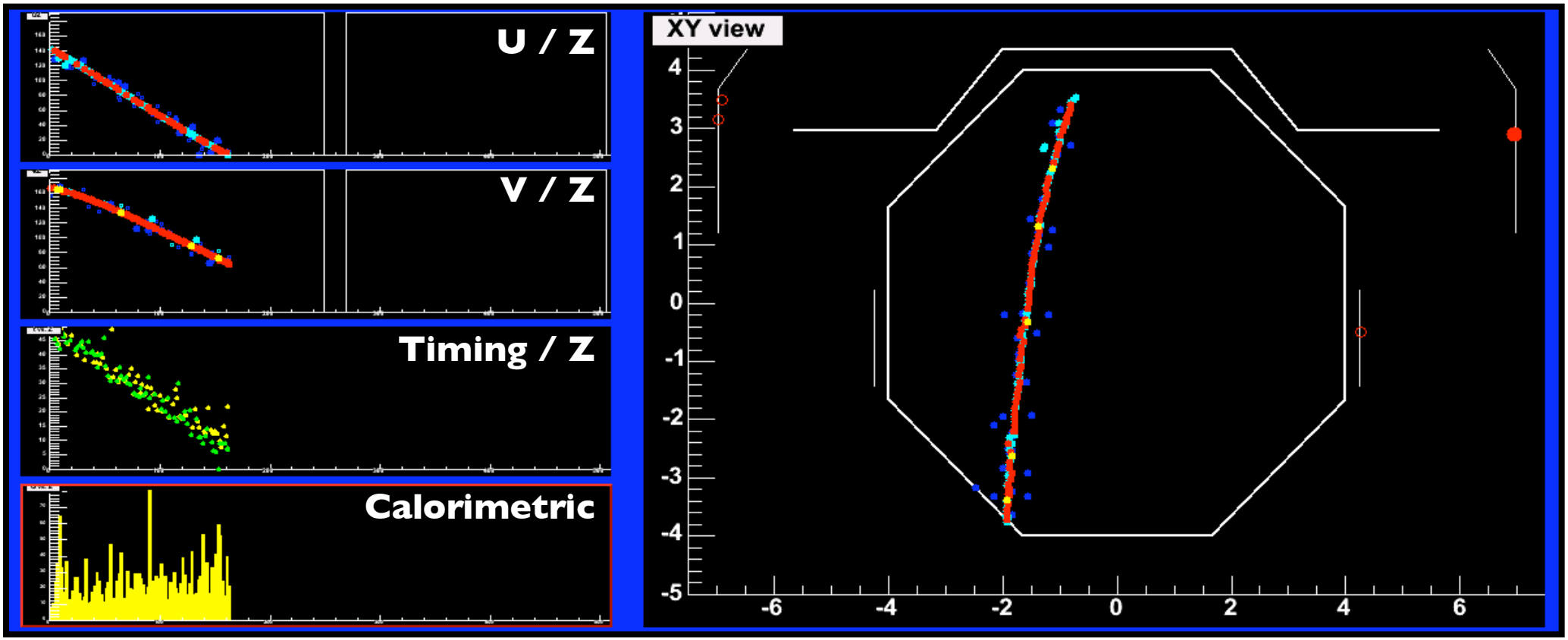
- Look for events coming from below the horizon. The flat overburden at Soudan means can also look for events slightly above horizon.
- Event selection is based on event timing, timing resolution 2.4ns per channel. Require 20 planes and 2m tracks, look at event timing 1/β (c/v).



Downward going cosmic ray muons

Candidate upward going events

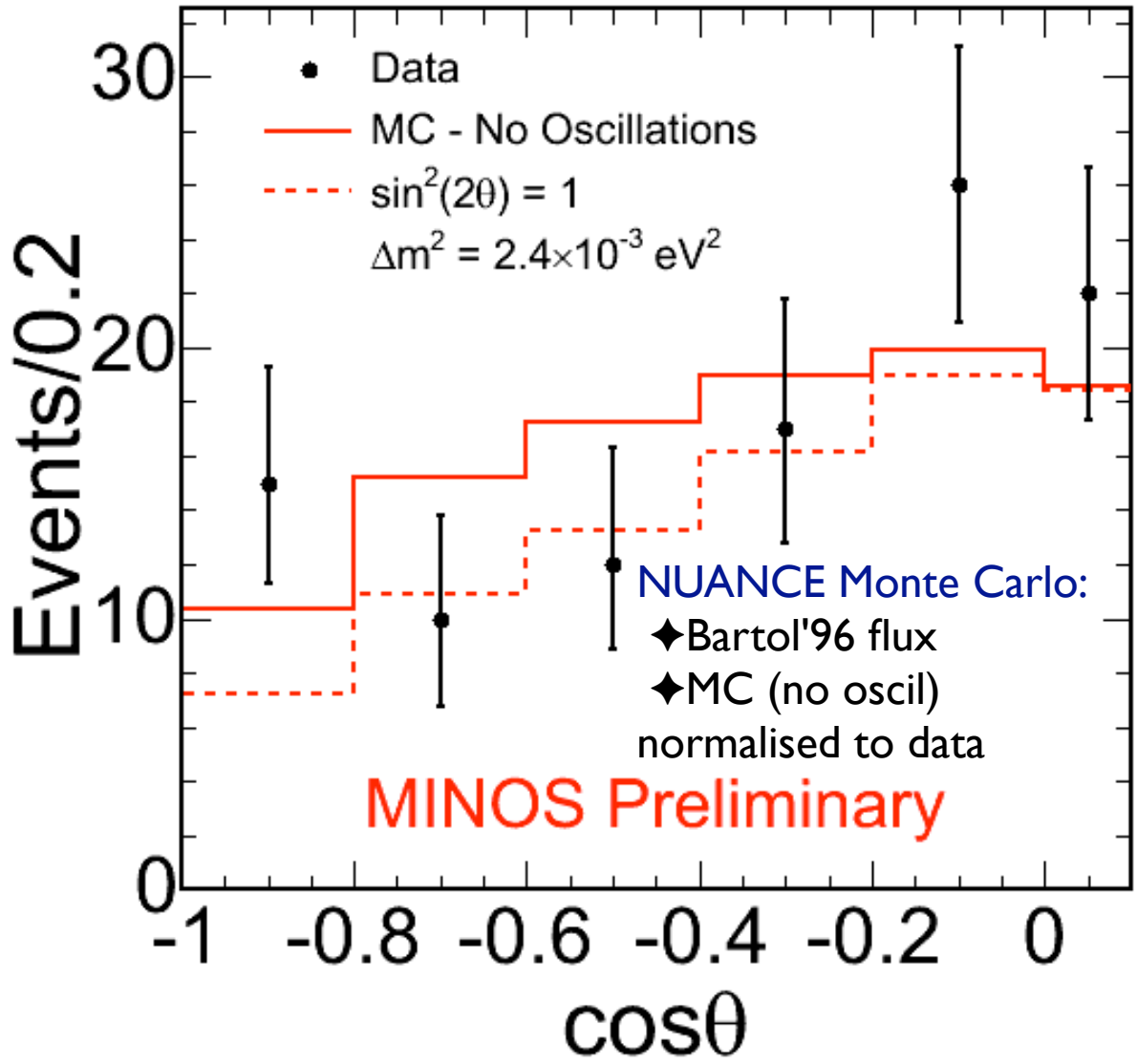
Example Event



- Timing clearly identifies this as an upward going event.
- Curvature of track in magnetic field identifies this event as a μ^+.

Neutrino Induced Muon Results

- Select 91 events.
- Currently not enough statistics to make statement about oscillation parameters based on neutrino induced muons alone.
- This analysis is a work in progress.



Contained Vertex Analysis

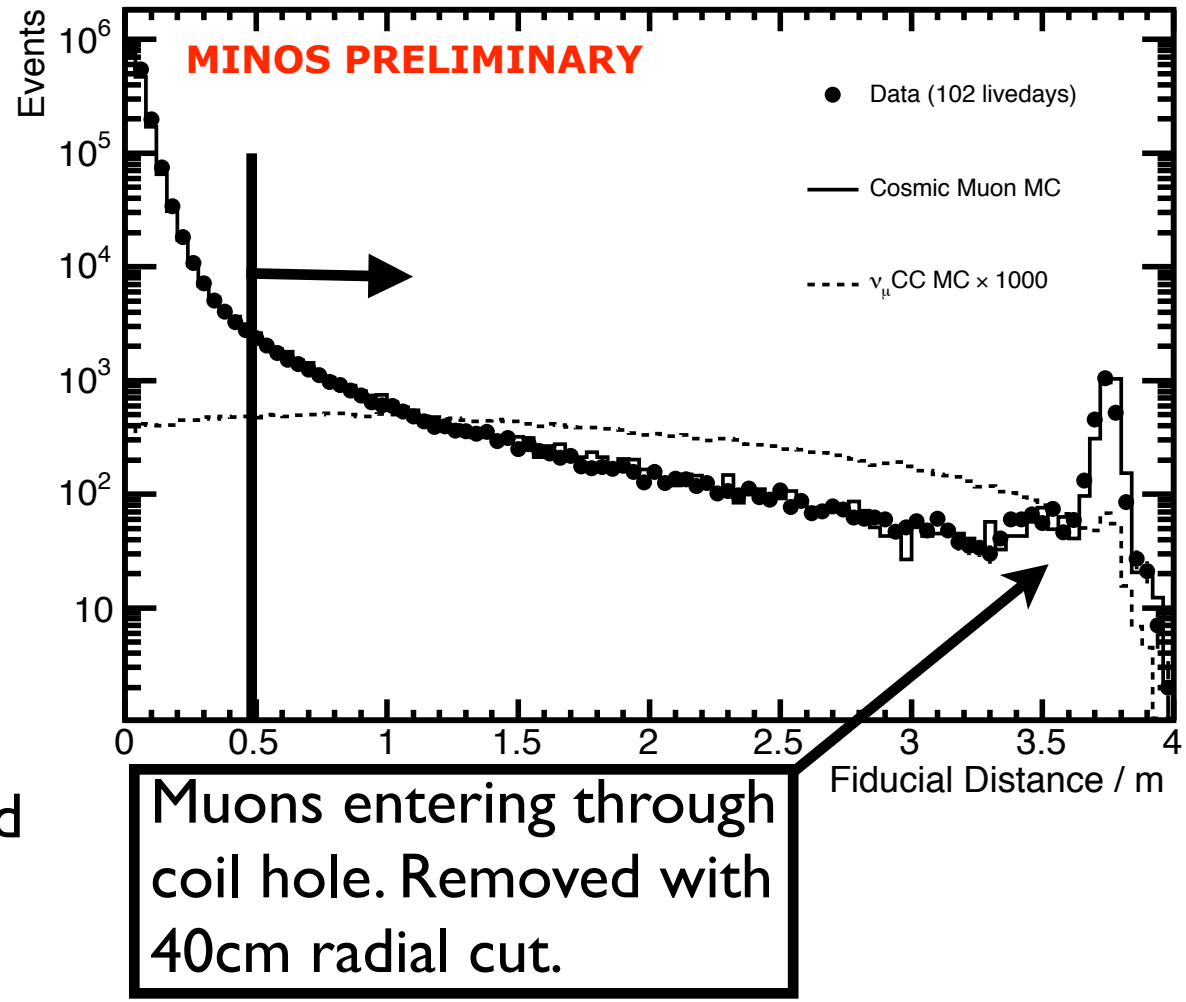
- The contained vertex analysis is concerned with the FC, PCDN and PCUP events classes.
- FC and PCDN share backgrounds (sneaky cosmic ray muons) ⇒ Use same event selection
- PCUP very different
  - Major background due to incorrect track direction reco.
  - Unable to use the veto shield
- Use signal and cosmic ray muon MC (Barr '04 flux) to develop a cuts based selection.
- Present results based on 6.18 kton-years of data. Results to be submitted any day.

FC PC-Down Selection

- FC and PC-Down have same background: sneaky cosmic muons. Therefore, use same cuts.
- Rejection factor of 1 in 10^7 required to achieve a signal to background ratio of 10:1.
- Use cuts based on containment and event topology to reduce signal:background to ~1:1, then apply veto shield (~97% efficient).
- Use independently measured veto shield efficiency to measure remaining background in sample.

FC/PCDN:Containment

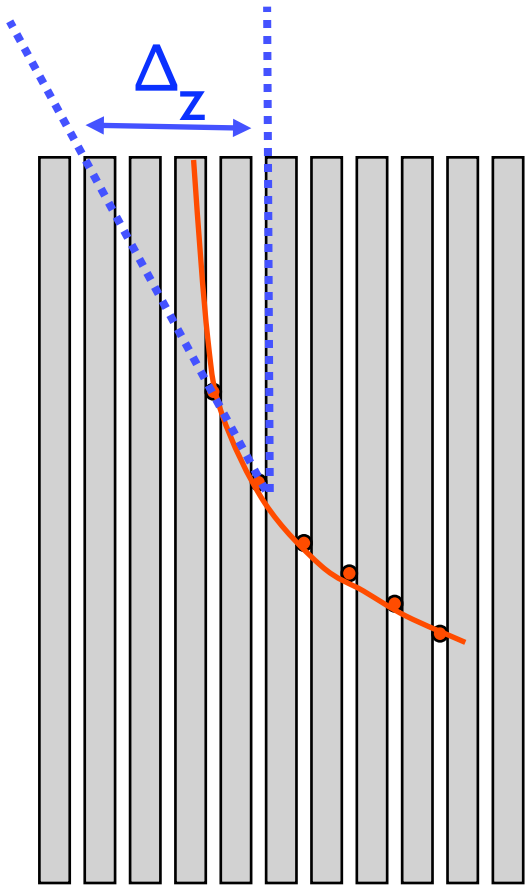
- Define a fiducial volume:
  - 0.5m from detector edge
  - 5 planes from each supermodule end
- Cuts:
  - FC - require both ends be 'contained'
  - PCDN - require upper end 'contained' and lower end non-contained.

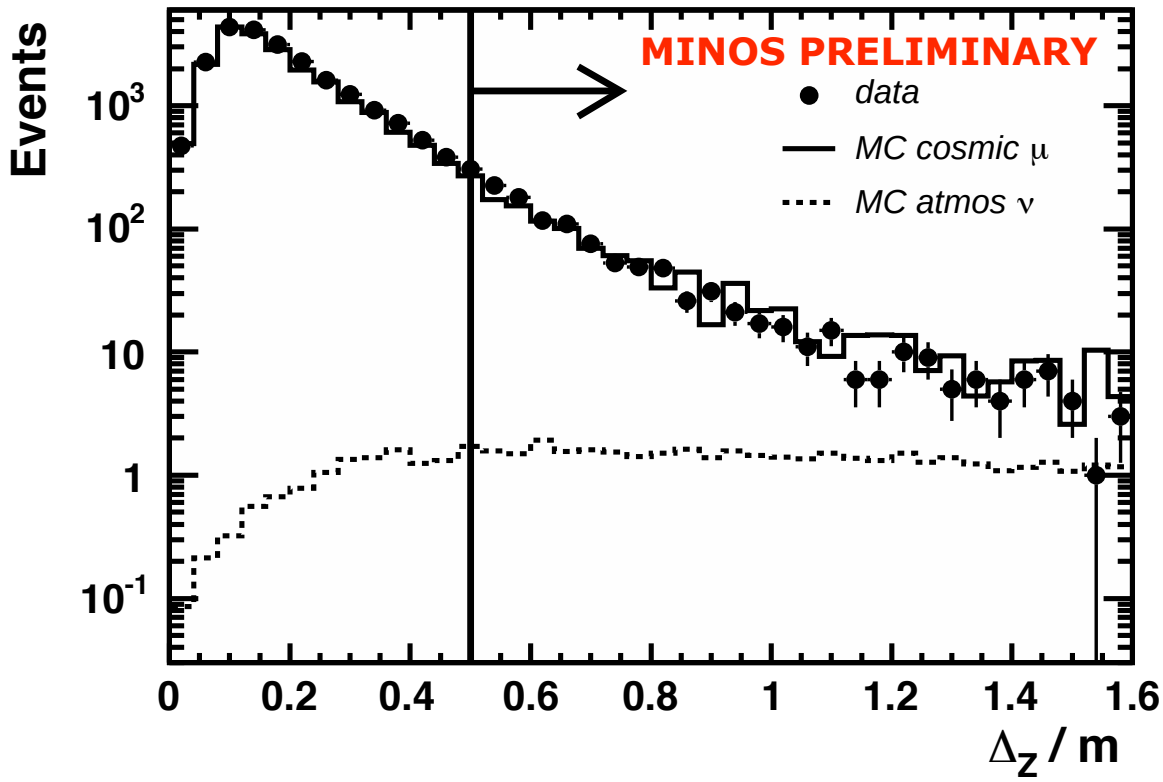


Signal:Cosmic ~ 1:300

FC/PCDN Topology Cut

- Background dominated by steep cosmic ray muons entering between the planes, "sneakers".



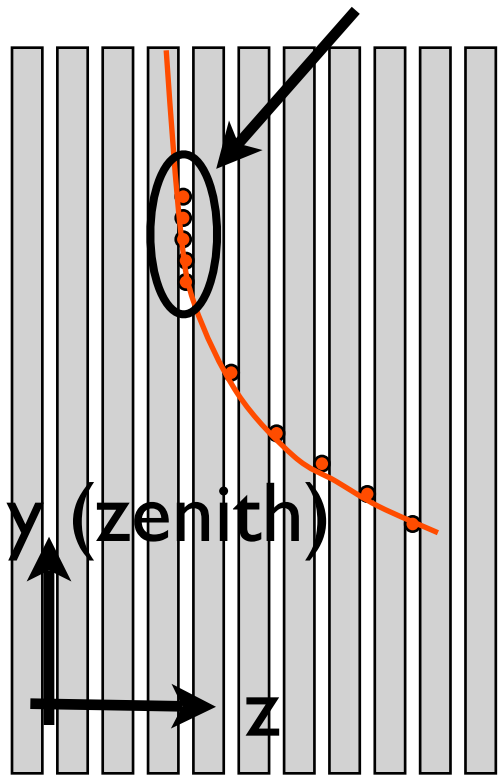


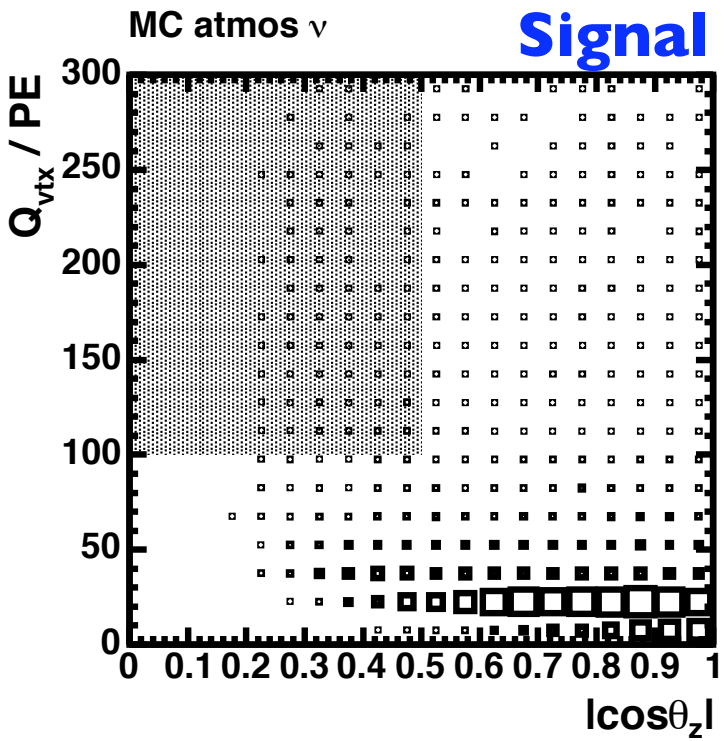
Signal:Cosmic ~ 1:15

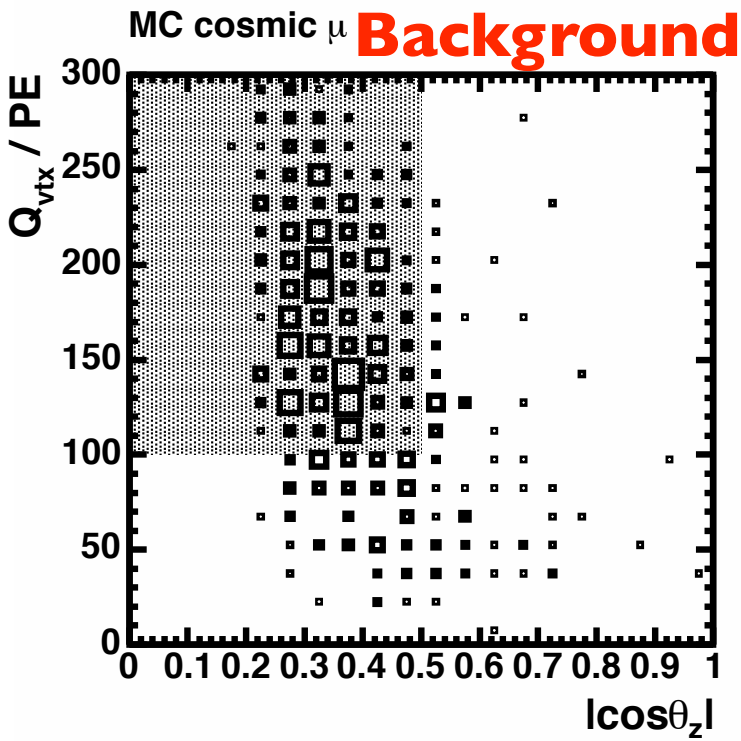
FC/PCDN Topology cut

- Remaining background is steep, highly curving cosmic ray muons

Deposit lots of energy in first couple of planes (Q_{vtx})



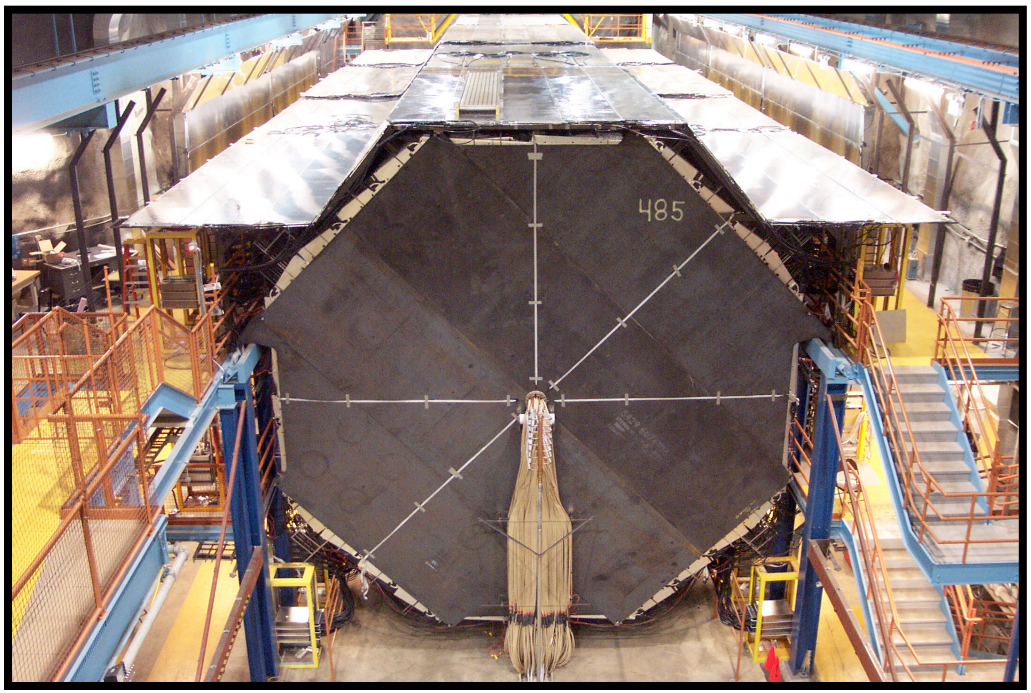


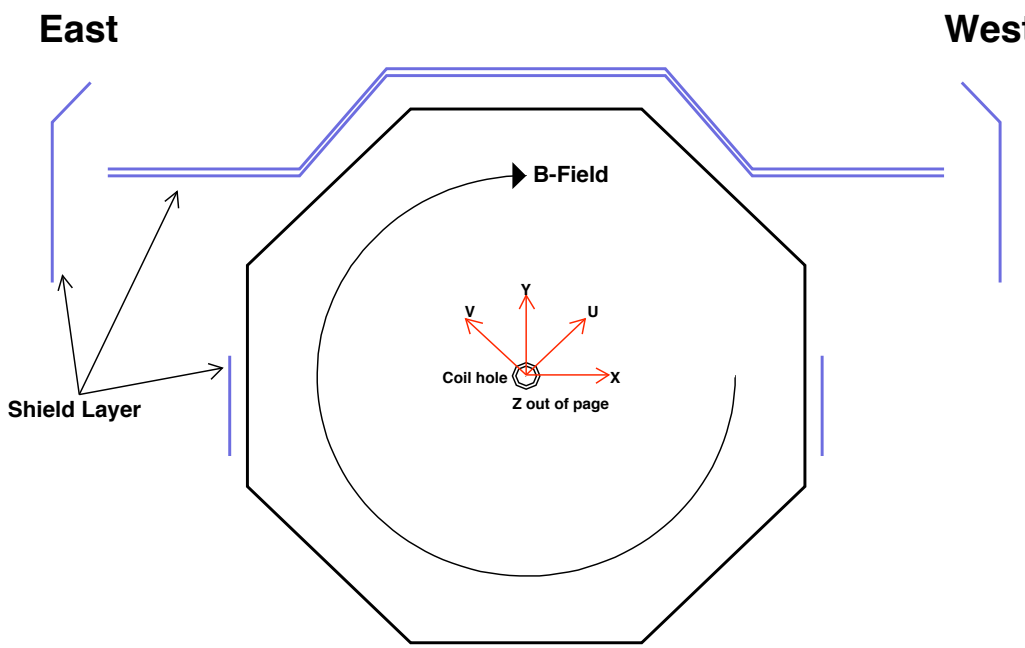


Signal:Cosmic ~ 1:1.5

The Veto Shield

- Same scintillator strips used in detector, but parallel to Z axis. 4 sections (2 per supermodule) each 8 meters long.
- Event is 'vetoed' if energy is deposited in the shield within 100ns of the event.
- Measure cosmic ray muon rejection efficiency using stopping muons: **97.1±0.1(*sys*) %**
- Signal rejection inefficiency **2.5±0.2(*sys*)%**





Applying the Veto Shield

- Applying veto shield:

	Data	Total MC (no oscillations)	Total MC (Δm^2=0.0024eV^2)
Total	94	110±11	87±9
PCDN	25	20±2	19±2
FC	69	90±9	68±7

MC predictions include all backgrounds

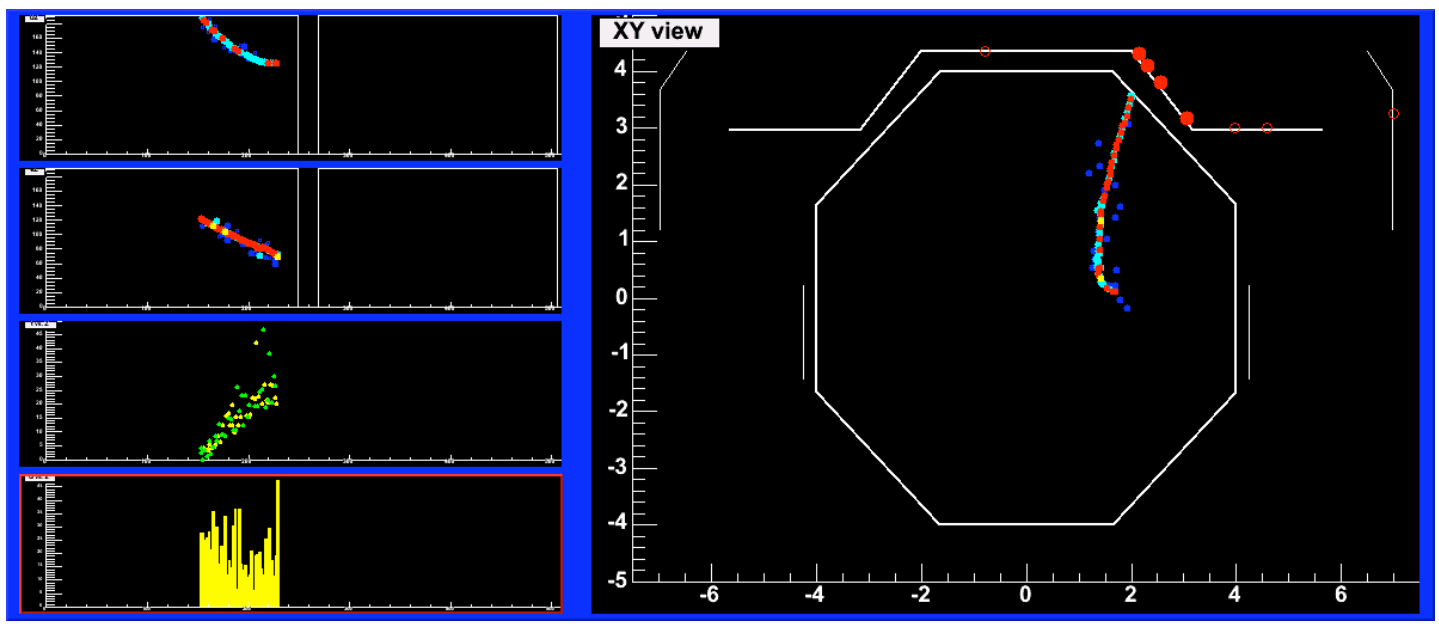
- Know veto shield efficiency and number of vetoed events, therefore can estimate cosmic ray muon background in selected sample.

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

Partially Contained Up (PCUP)

- Very different backgrounds to FC/PCDN. Stopping cosmic ray muons with incorrect direction from timing, therefore timing cuts do the work here.

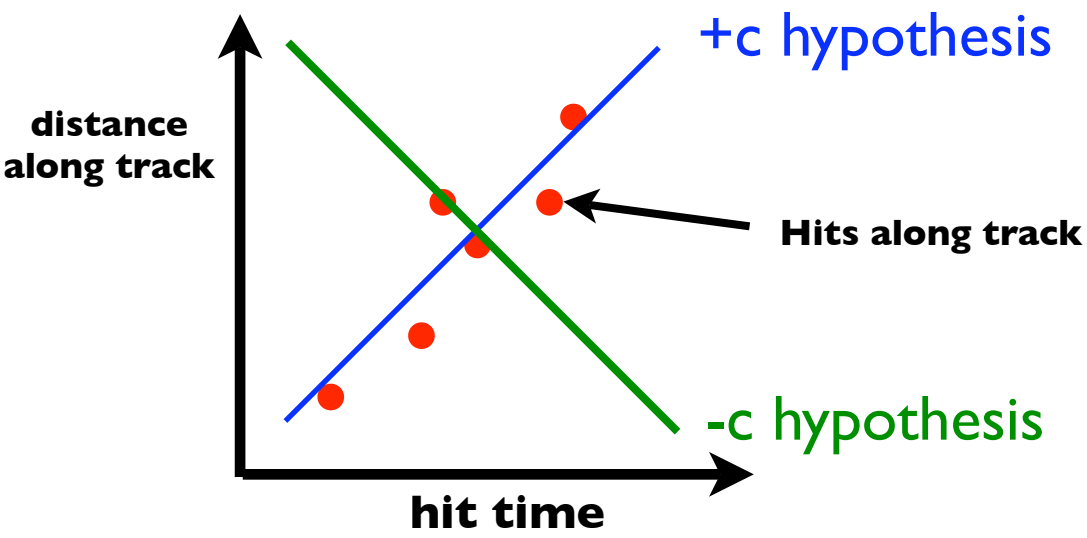
Stopping cosmic ray muon

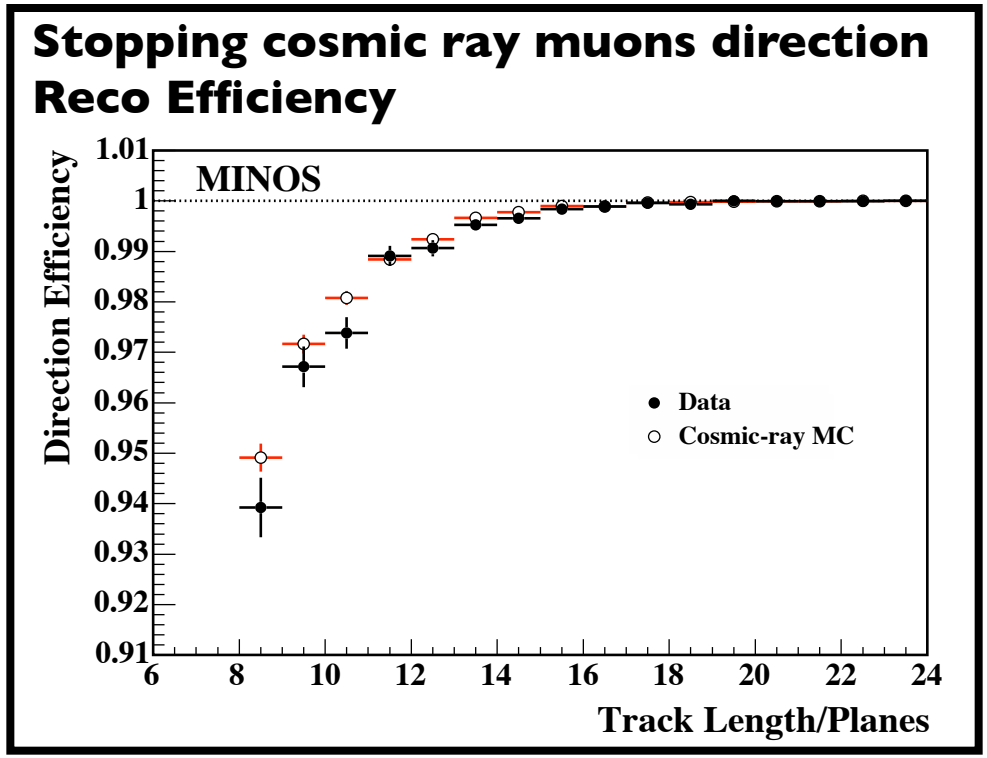


Signal:BG ~ 1:15

PCUP:Timing

- Direction of track is determined from timing of hits along its length. Single hit resolution 2.4 ns.
- The RMS of the hits times about the track is calculated for the two hypotheses of +c or -c. The hypothesis with smallest RMS is selected as track direction.

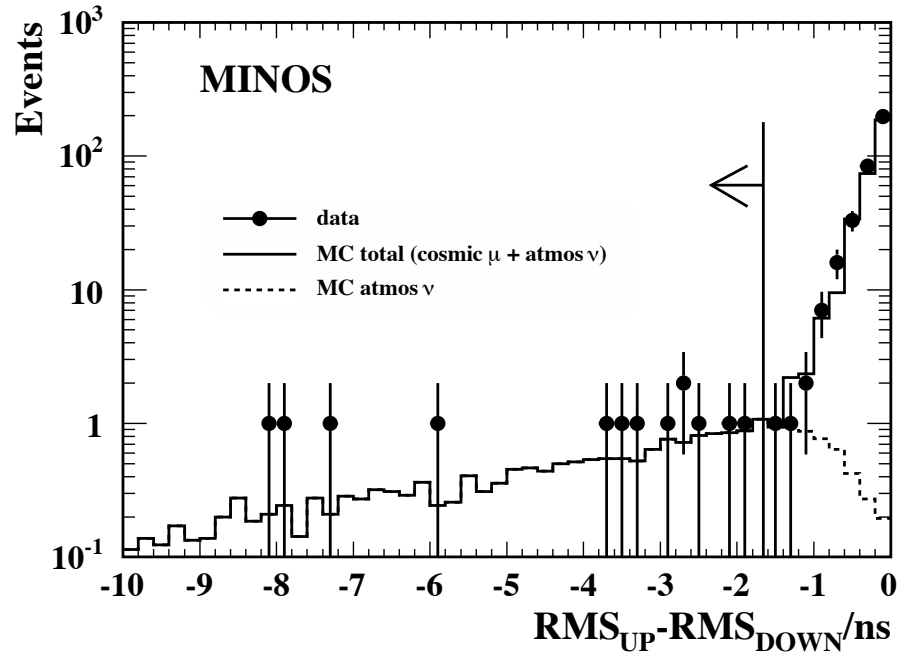




Excellent (~1%)data/MC agreement

PCUP:Timing

- Use difference in RMS to select events with unambiguous direction



- Remaining background is estimated from high statistics Monte Carlo studies <0.36 (68% c.f.).

	Data	Total MC (no oscillations)	Total MC ($0.0024eV^2$)
Events	13	17.6±1.8	9.8±1.0

Event Summary

	Data	MC $\overline{\nu}_\mu/\nu_\mu$CC no oscillations	MC $\overline{\nu}_\mu/\nu_\mu$CC 0.0024 eV^2	Cosmic Muon MC	Other Backgrounds
Total	107	127.1±12.7	96.2±9.5	4.9±0.7	5.1±0.35

Barr'04 flux scaled by Soudan2 measurement

ν_τCC, Rock muons ,ν_eCC, Neutral Current, Neutrons

★ Using Soudan 2's ν_e data to normalise has two advantages:

a) Soudan 2 is iron, like MINOS

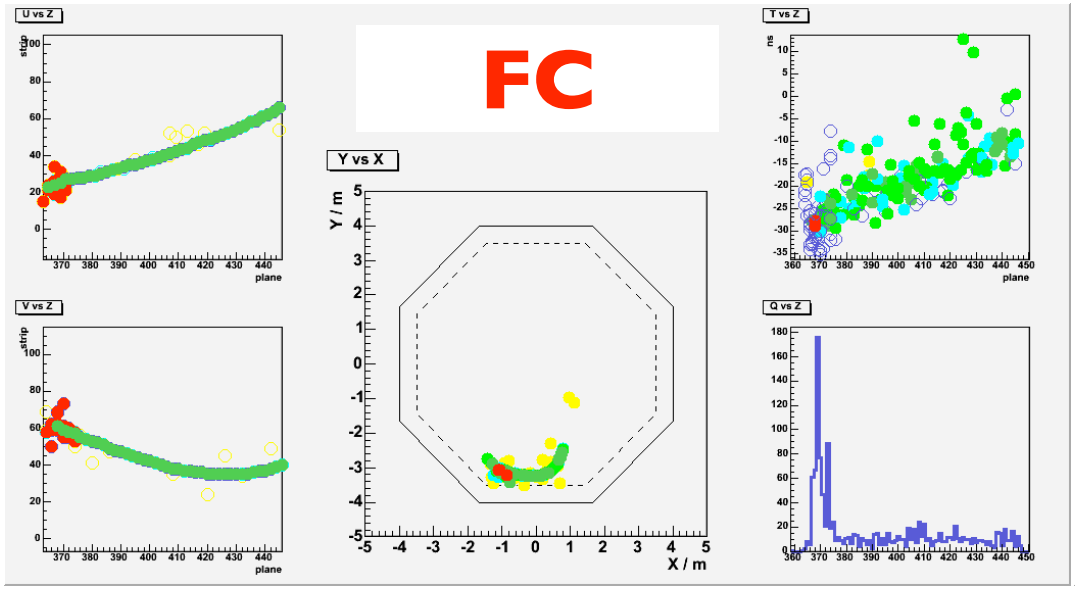
b) It is located in the same place

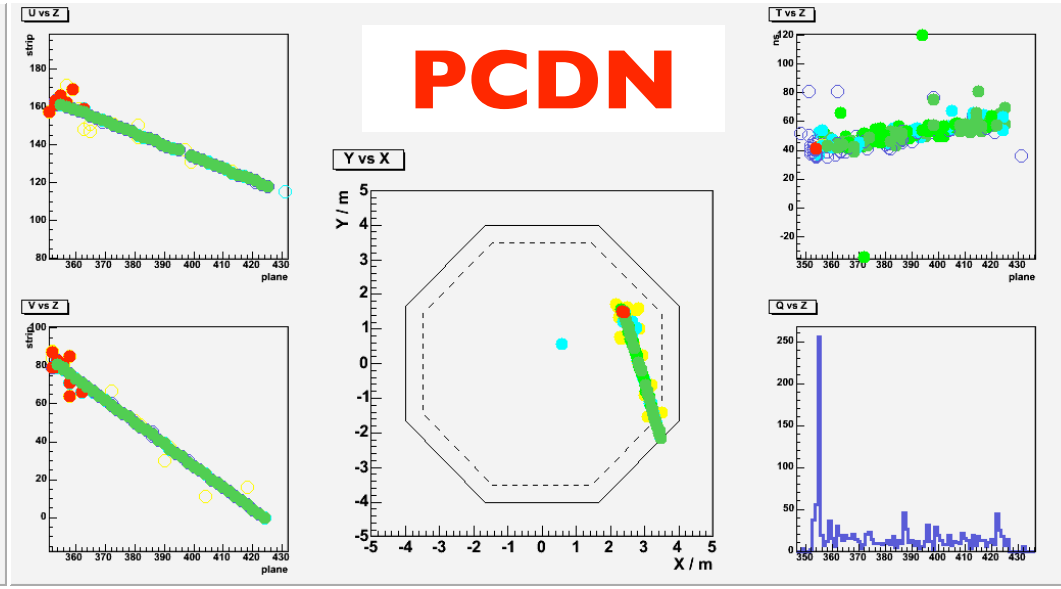
★ Recent analysis of Soudan 2 data suggests that Barr'04 should be scaled by 0.88±0.07(stat).

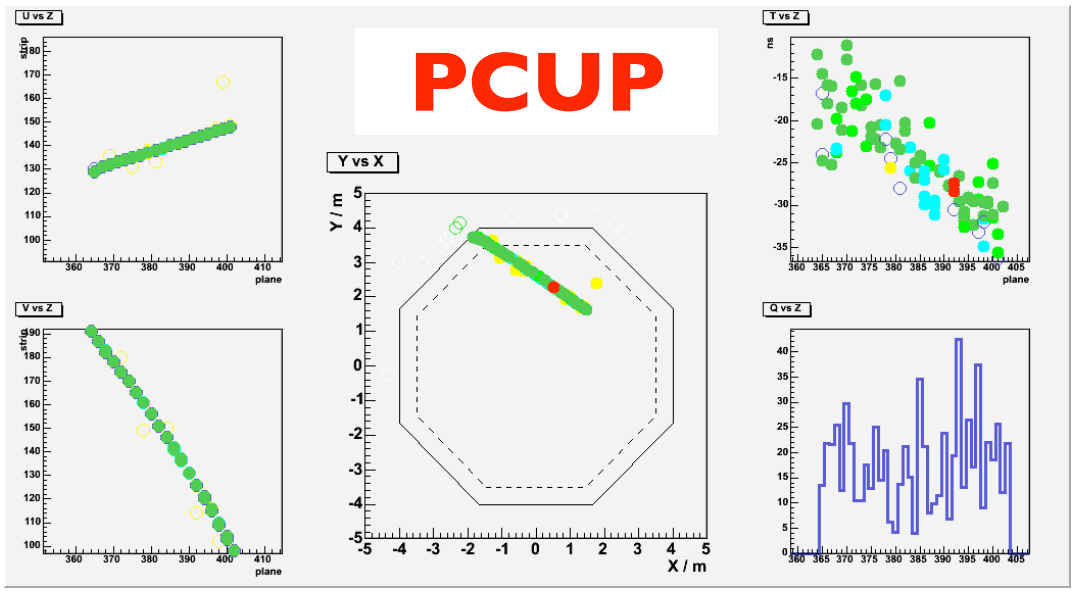
★ An additional 5% systematic uncertainty due to different energy thresholds and 2.5% due to different points in the solar cycle.

★ Total 10% systematic uncertainty is used for neutrino flux.

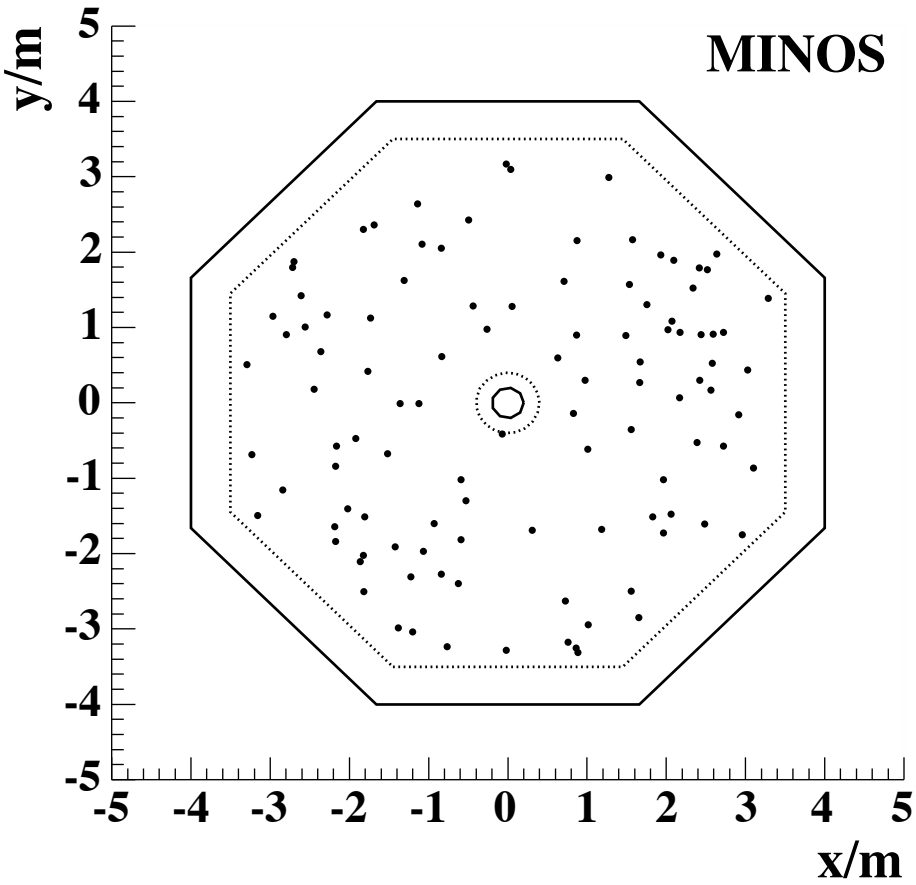
Example Events

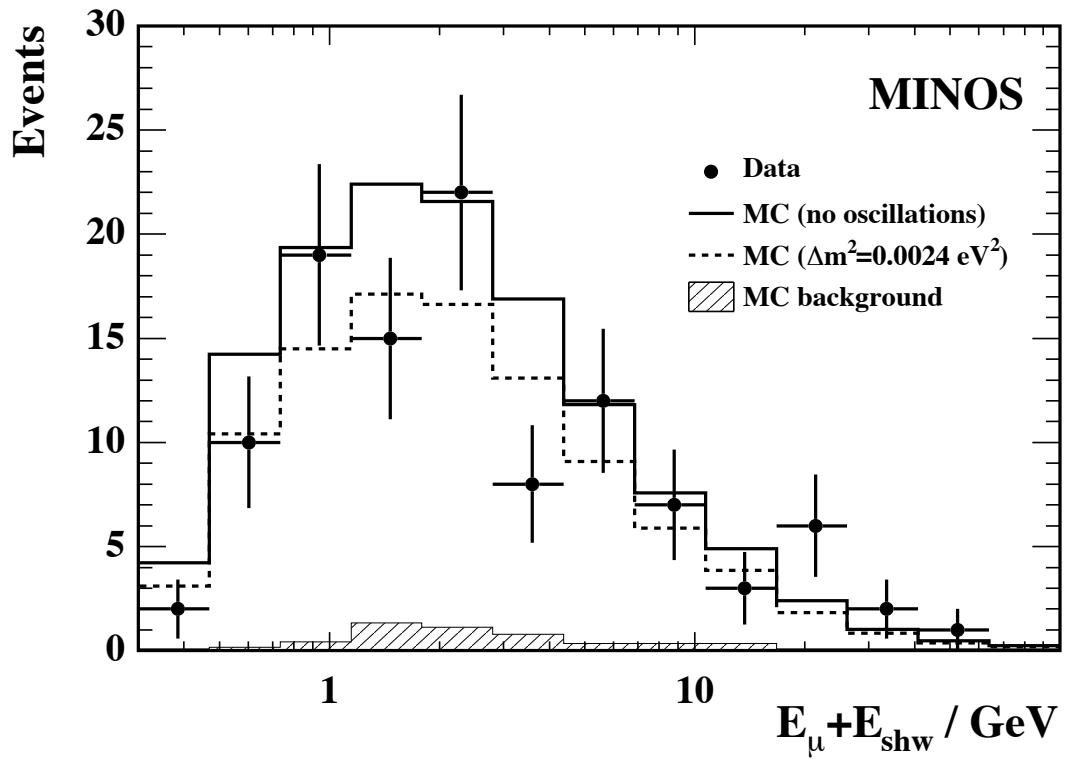






Event Distributions

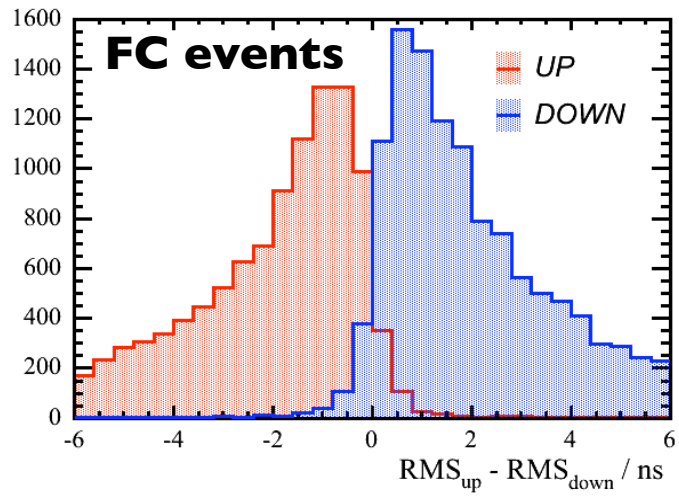




Event Direction

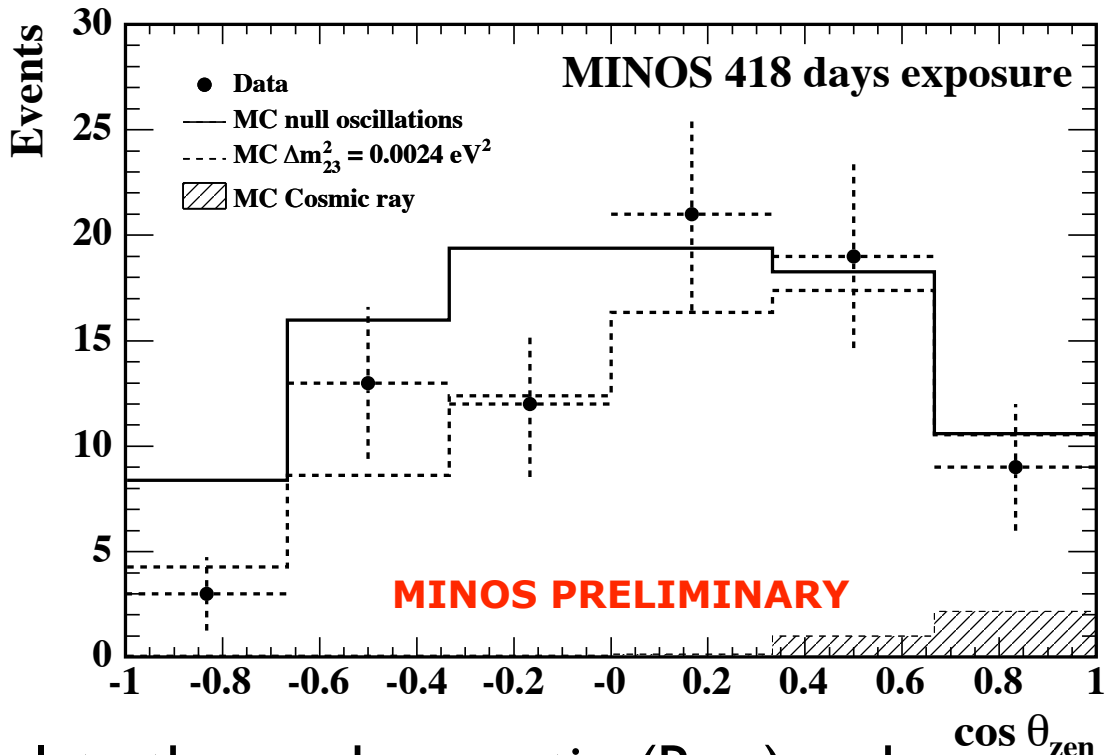
- Define a 'high resolution' sample of FC events, by applying similar timing cuts to PCUP.
- Place events that fail into a 'low resolution' sample. These events have ambiguous direction.

Correct Track Direction
Before Cut = 96.0 %
After Cut = 99.9 %



	Data	Total MC (no oscillations)	Total MC (Δm^2=0.0024eV^2)
Good timing	77	90.3±9.0	68.3±6.8
Low res	30	36.9±3.7	27.9±2.8
Total	107	127.1±12.7	96.2±9.5

Up/Down Ratio



- Calculate the up-down ratio (R_{obs}) and compare it to MC expectation in the absence of oscillations (R_{MC}).
- Only used events that have unambiguous direction from timing, 77 out of 107 events.

$$R^{data}_{up/down} / R^{MC}_{up/down} = 0.62 \pm 0.14(stat.) \pm 0.02(sys.)$$

Oscillation Analysis

- MINOS Far Det is unique: can measure $E=E_{\mu}+E_{had}$ for both FC and PC events.
- Not all events carry the same amount of information about oscillation parameters:
  - All 107 events can be used for normalisation
  - 77 events have good direction from timing, contain information about up/down ratio.
  - These 77 events have very different L/E resolutions, resolution is degraded for:
    - **Events near the horizon (large $dL/d\theta$)**
    - **Low Energy/High y (opening angle)** $y = 1 - E\mu/E\nu$
    - **PC events with large error on p_{μ}.**
- Event-by-event resolution in L/E ($\sigma_{L/E}$) calculated.
- Bin data in terms of L/E and $\sigma_{L/E.}$

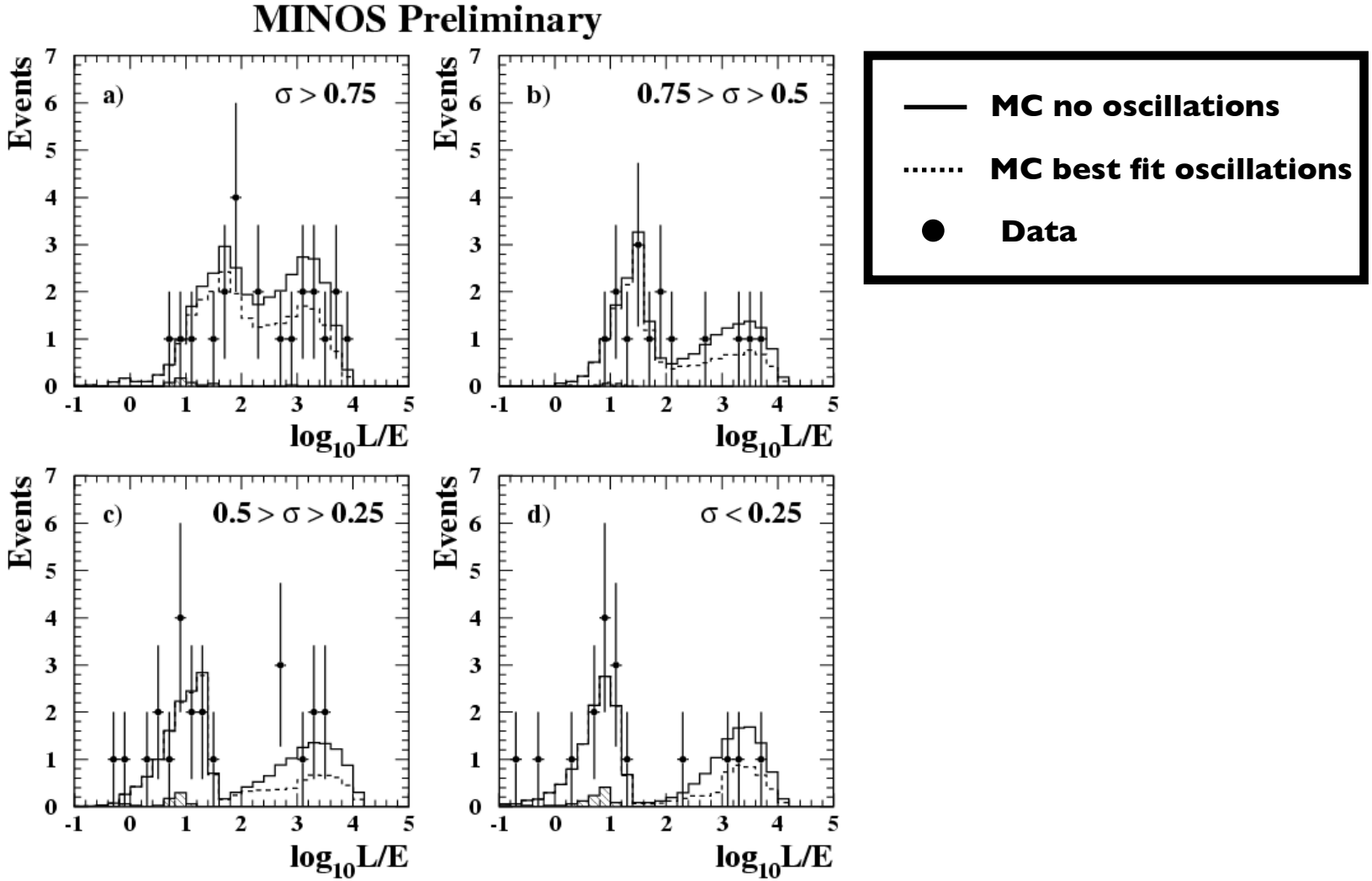
L/E distributions

- For each event determine the measured L/E

  L = measured muon direction

  E = total reconstructed energy

- Fit in 10 bins of σ and bins 0.2 wide in $\log_{10}$(L/E).



Likelihood

- Out of the 107 selected events:
  - 77 have good direction (direction from timing unambiguous)
  - 67 have well measured p_μ, either from range or curvature fit.
- Fit independently:
  - Normalisation (all 107 events)
  - Up-down ratio binned in resolution (77 events)
  - Upward and downward going L/E shapes (67 events)

$$-\ln \mathcal{L} = (\mu - N \ln \mu)$$

Normalisation

$$- \sum_k (N_u^k \ln P_u^k + N_d^k \ln P_d^k)$$

Up-Down ratio summed over bins of σ

$$- \sum_{i_u} \ln f_u^k([L/E]_{i_u})$$

$$- \sum_{i_d} \ln f_d^k([L/E]_{i_d})$$

Separate shapes of upward and downward going events

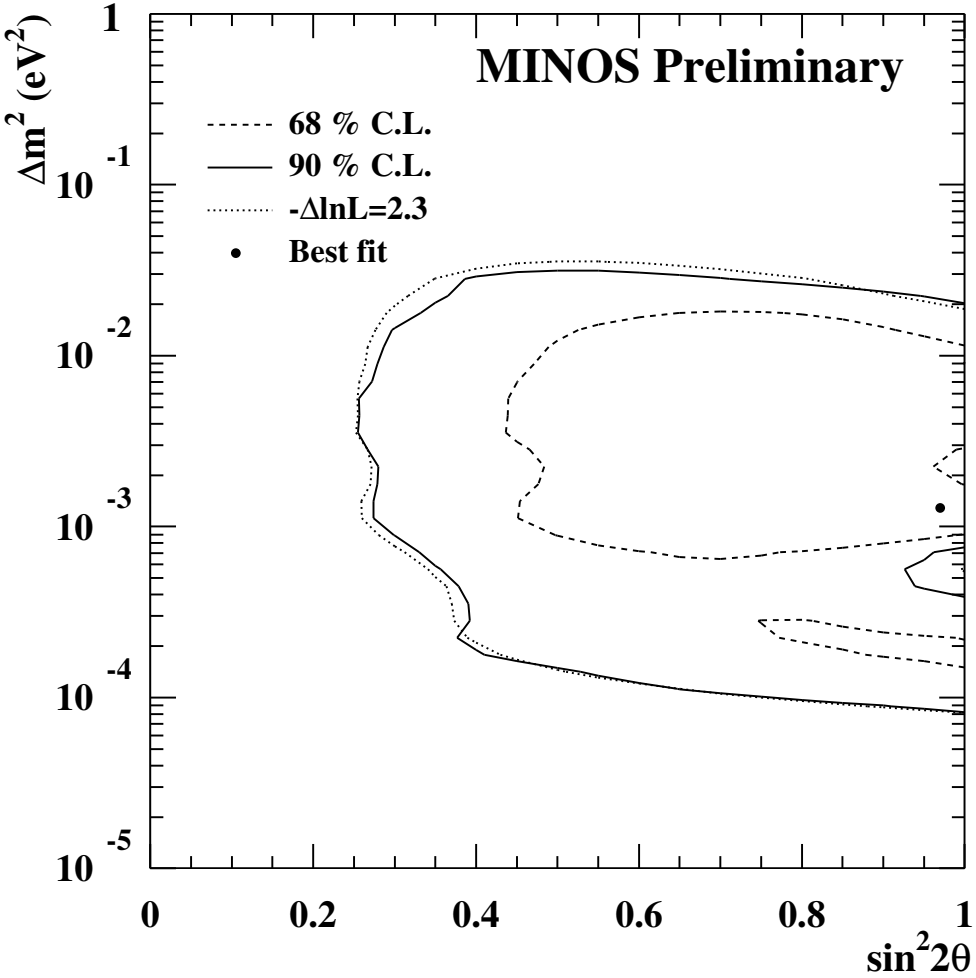
$$+ \sum_j \frac{\alpha_j^2}{2\sigma_{\alpha_j}^2}$$

Penalty function for systematic errors, treated as nuisance parameters. Likelihood min wrt to these at each point in parameter space.

Systematic Uncertainties

- Systematic Uncertainties included in the fit:
  - 10% normalisation uncertainty
  - 3% up down ratio (from selection uncertainties)
  - Uncertainties in flux spectrum shape to cover the differences in different neutrino flux models
  - Neutrino x-sections: allow the QE contribution to vary by ±20%.
  - 3% momentum scale
  - 5% hadronic scale

Fit Results



90% C.L. obtained by:

a) Feldman and Cousins approach

b) -lnL = 2.3

Best fit point

$$\sin^2 2\theta = 0.90,\ \Delta m^2_{23} = 0.0013\,\mathrm{eV}^2$$

Consistent with a wide range of oscillation parameters including SK and K2K.

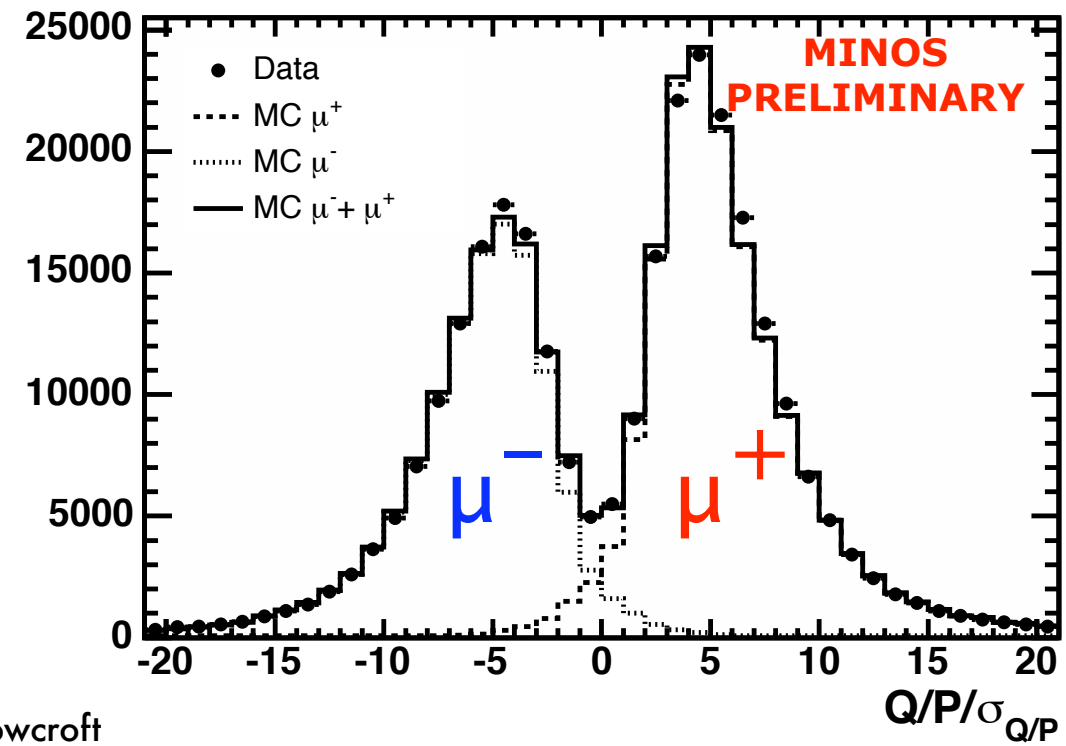
Null oscillation hypothesis disfavoured at 98% confidence.

Quality of the fit is good. For 10000 simulated experiments with (Δm^2_{23}=0.0024 eV^2, $\sin^2 2\theta$ =1.0) 84% experiments min -lnL exceeded that of the data.

MINOS Charge Separation

- Ability to separate charge depends on:
  - muon momentum
  - track length
  - **vxB**
- Measure charge from curvature of track in magnetic field, giving Q/P. Error in fit ($\sigma_{Q/P}$) is also estimated.
- To get clean charge separation require that $|Q/P|/\sigma_{Q/P} > 2.0$

Stopping cosmic ray muons

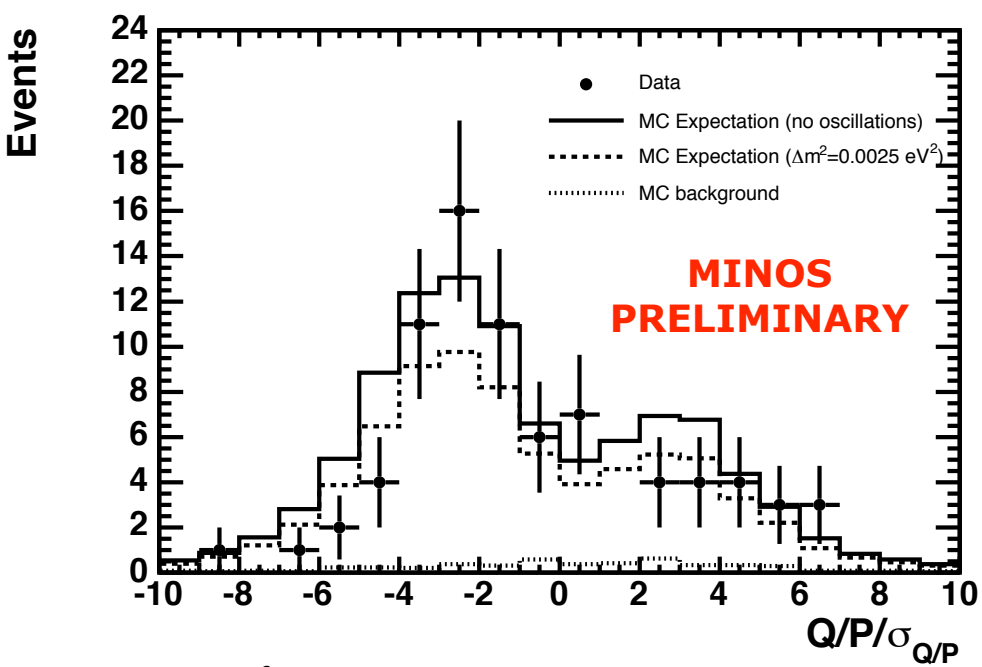


Excellent data/MC agreement

Charge of Selected Events

- Only use events where direction from timing is unambiguous.
- Require $|Q/P|/\sigma_{Q/P} > 2.0$, gives a charge purity (from MC) of 98.7%
- Observe 34 ν_μ and 18 $\bar{\nu}_\mu$ events, measured $\bar{\nu}_\mu$ fraction (R^{data}) 0.35, expected ν_μ fraction (R^{mc}) 0.36.

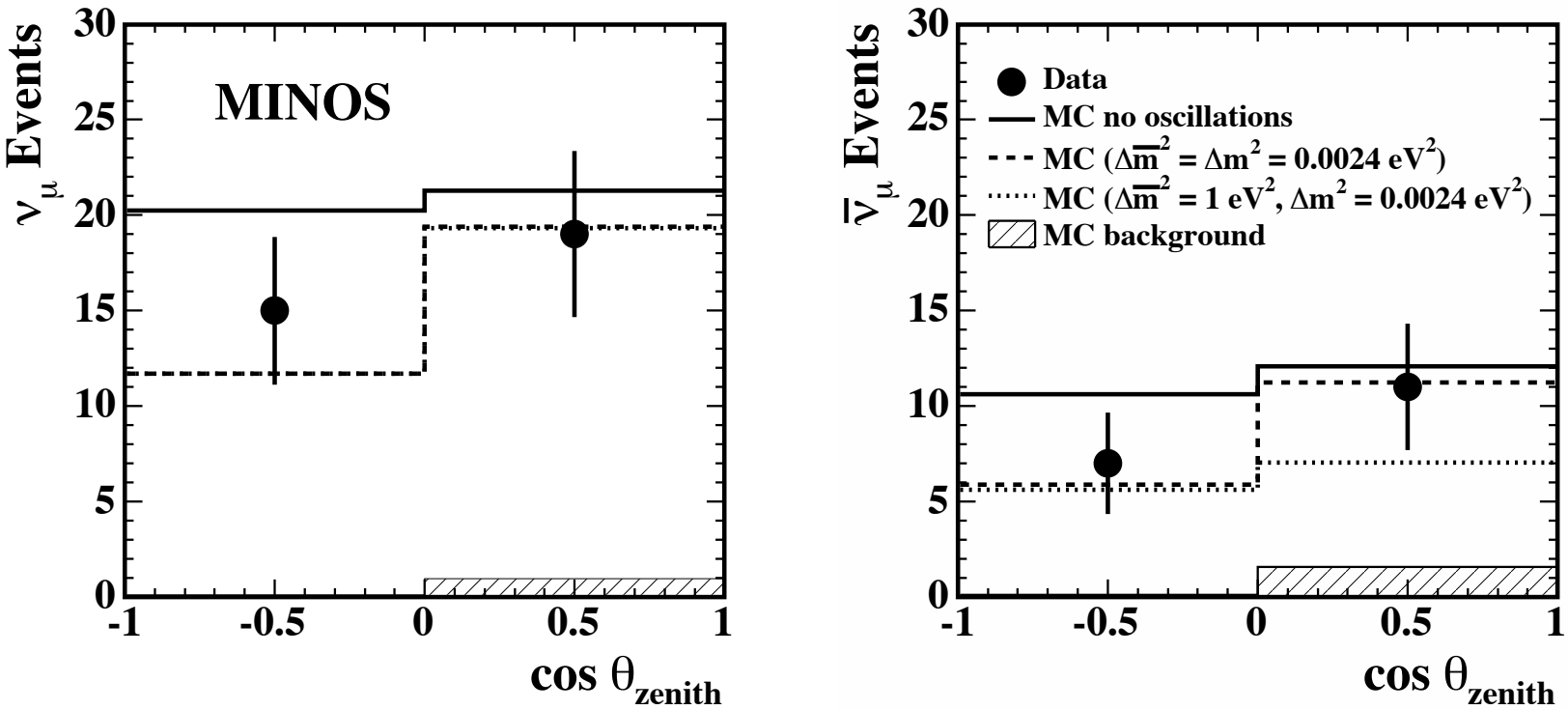
$$R^{data}_{\bar{\nu}_\mu/(\bar{\nu}_\mu+\nu_\mu)} / R^{MC}_{\bar{\nu}_\mu/(\bar{\nu}_\mu+\nu_\mu)} = 0.98 \pm 0.19(stat.) \pm 0.06(sys.)$$



	Data	Total MC (no osc)	Total MC ($0.0024eV^2$)
ν_μ	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

Barr '04 flux/ NEUGEN 3

Q Separated Up-Down



- The data are consistent with the same oscillation parameters for neutrinos and anti-neutrinos however...
- statistics too low to exclude large values of Δm^2_{23} for anti-neutrinos.

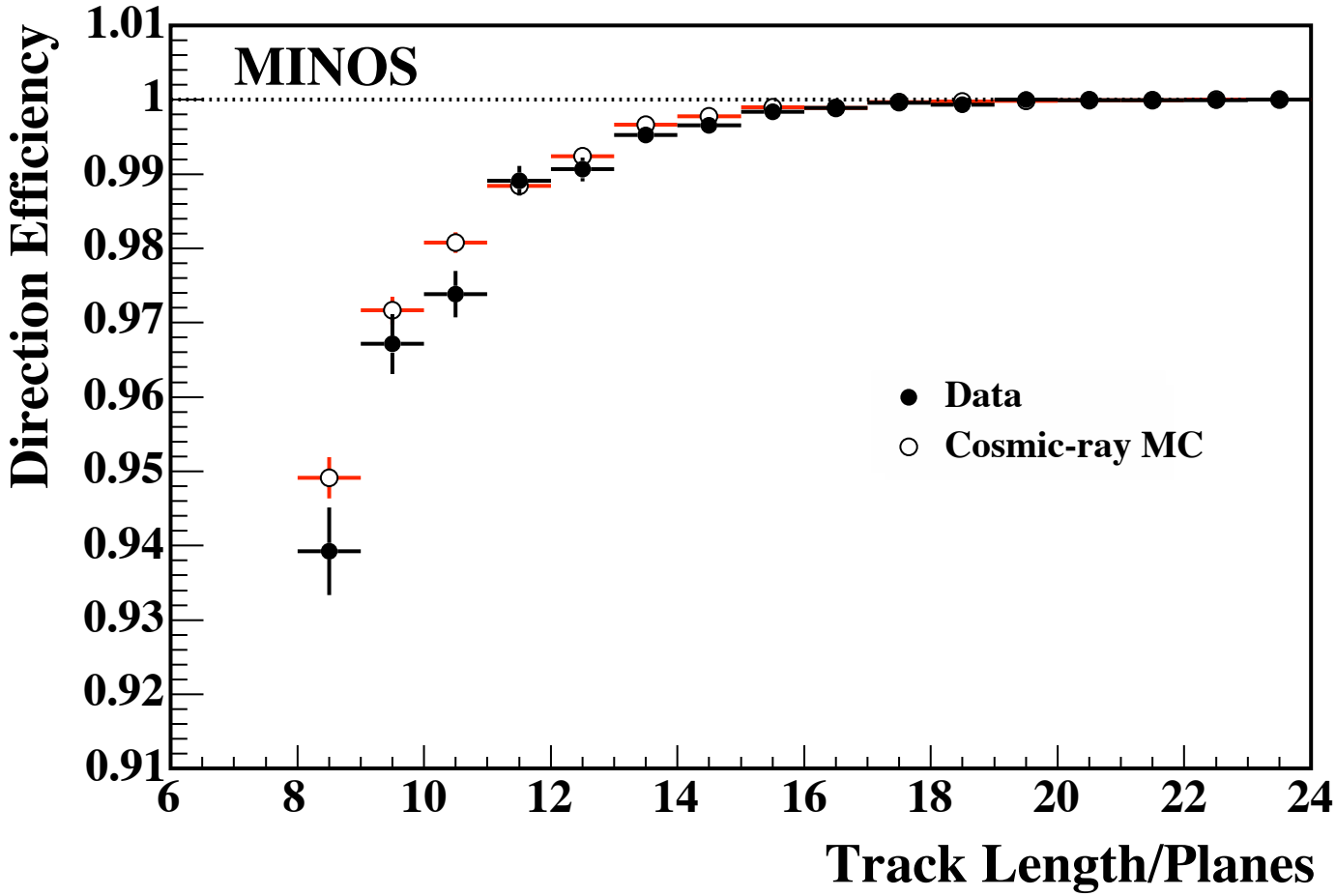
Summary

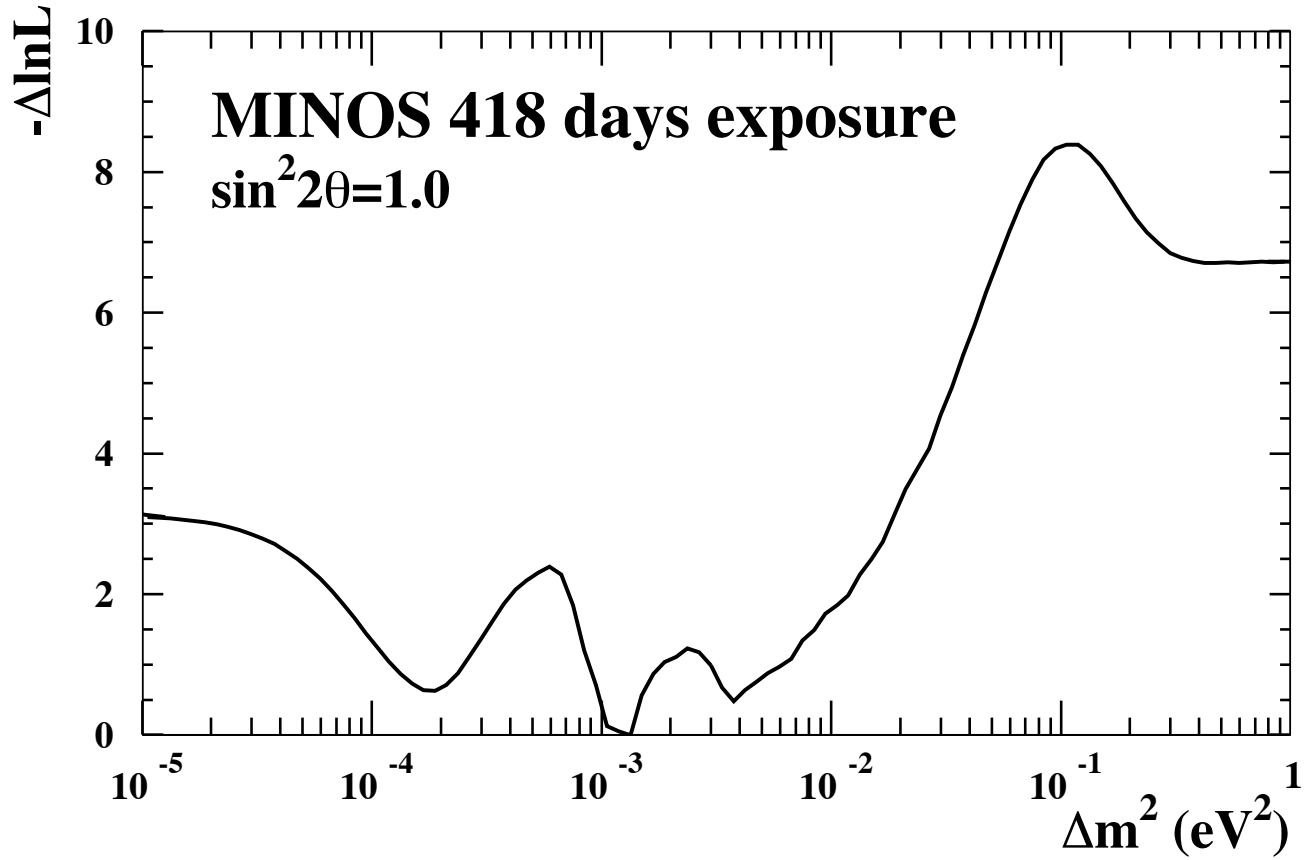
- MINOS has collected 6.18 kton-years of cosmic data before beam switch on in March 2005.
- Have observed a total of 198 atmospheric neutrino events, 107 contained vertex and 91 upward-going muons.
- Contained event up-down ratio excludes no oscillations to 2.6σ, $R^{data}_{up/down}/R^{MC}_{up/down} = 0.62 \pm 0.14(stat.) \pm 0.02(sys.)$
- Contained events can be charge identified with 98% purity.
- $R^{data}_{\bar{\nu}_\mu/(\bar{\nu}_\mu+\nu_\mu)}/R^{MC}_{\bar{\nu}_\mu/(\bar{\nu}_\mu+\nu_\mu)} = 0.98 \pm 0.19(stat.) \pm 0.06(sys.)$
- Not enough statistics yet to make any statement about charge separated oscillation parameters.

Acknowledgements: A. Blake, J. Chapman, B. Rebel and M. Thomson

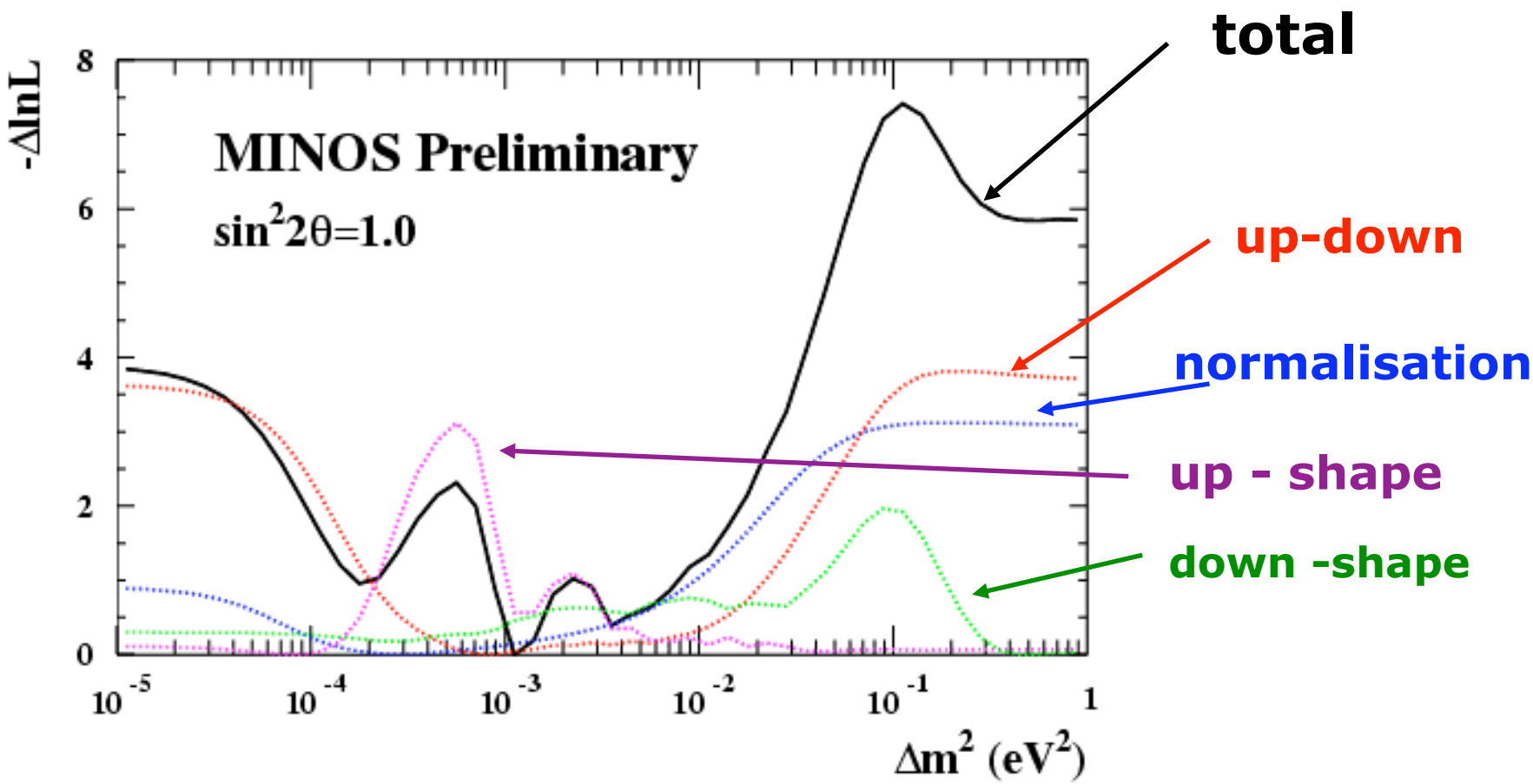
Backup slides

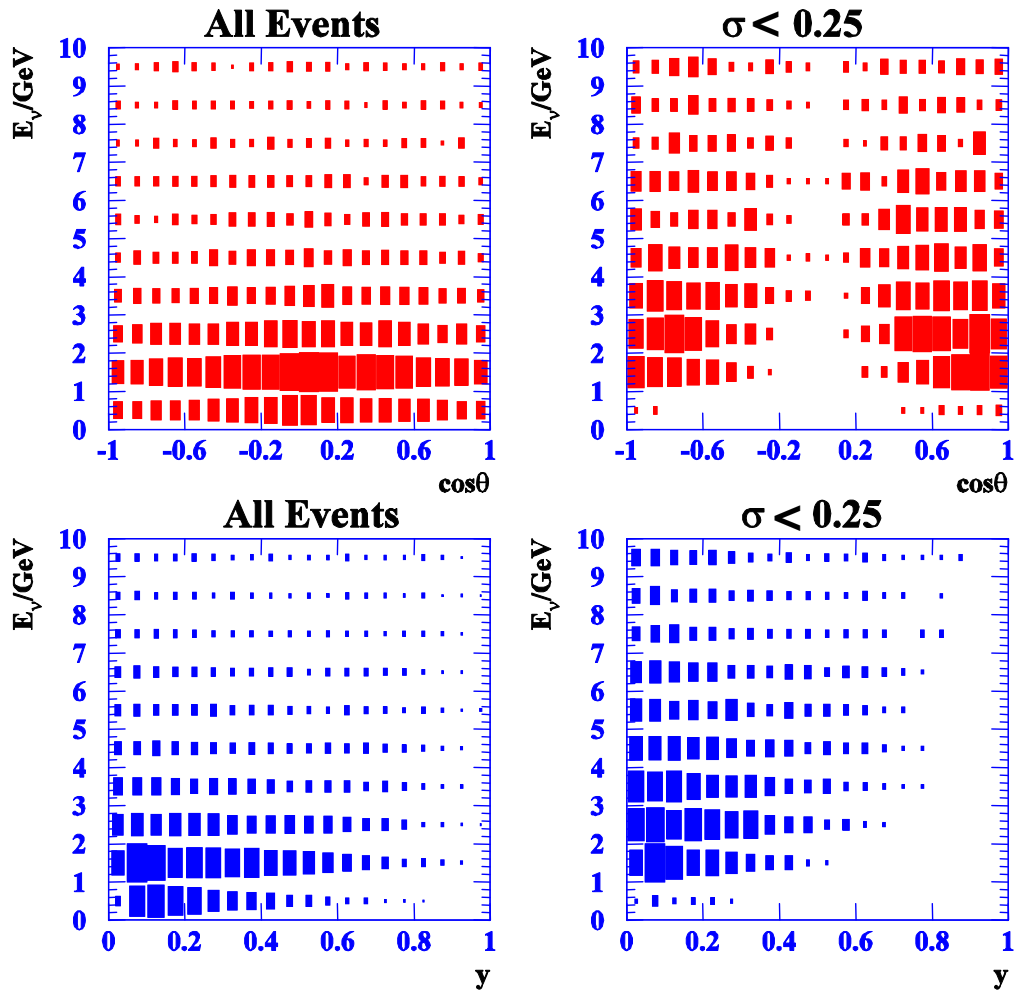
Timing simulation




MINOS 418 days exposure
sin²2θ=1.0
-ΔlnL
10
8
6
4
2
0
10 -5
10 -4
10 -3
10 -2
10 -1
1
Δm² (eV²)

Fit breakdown




All Events
σ < 0.25
All Events
σ < 0.25
E_ν/GeV
cosθ
y