Atmospheric Neutrinos in MINOS

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RAL

- Atmospheric neutrinos are being detected in the far detector NOW. What do we have to do to find and analyse them?
- Analyses have shown that potentially MINOS has similar sensitivity to current Super-K data
- PLUS we have a magnetic field which no previous detector has had.
    - Separate neutrinos and anti-neutrinos,
        - check lepton universality
        - check alternatives to oscillations
        - check matter effects???
        - check flux calculations
        - measure momenta of exiting muons to increase acceptance and resolution
        - measure muon direction by slowing in the field

What are we looking for?

- Fully contained events, no track or major part of a shower exits the detector.
    - Muon energy measured by range
    - Hadron and electron shower by calorimetry (in Soudan 2 we measured individual tracks)
    - Full reconstruction of L/E
    - Electron neutrino events difficult to resolve from neutral current and low energy muon events
- Partially contained events, the muon exits the detector (if a significant part of the hadron/electron shower exits the event flavour cannot be identified and/or the energy measured).
    - Muon energy measured in the field - our major advantage over Super-K. There must be sufficient length to make a reasonable measurement
    - Full L/E reconstruction
- Upward muons (from neutrino interactions below the detector)
    - No good measurement of total energy, muon energy measured by range or magnetic field
    - Need to separate by stopping, timing or slowing in the field from downward cosmic muons

How do we find them?

•~100 atmospheric neutrino interactions/kton/year ie ~1.5/day in MINOS

•~1 Hz of cosmic ray muons, i.e 86400/day. 100% duty cycle, no timing help. Need to reject cosmic muons at ~10^6:1

•Muons interact in the detector, lots of them produce electron showers, some interact hadronically.

•How did Soudan 2 do it ?

- •~96% of cosmic muons pass through the detector. Need excellent muon reconstruction, close to 100%, to ensure that the muon has both entered and exited the detector. MINOS has the complication of the field which means tracks are not straight lines. Probably going to have to have strict vertical cuts. Problem with muons which never enter the scintilllator. Problems with demultiplexing.

- •Soudan 2 had a veto shield with ~95% efficiency to flag both ends of a through going muon. MINOS reconstruction has to be that much better.

- •~4% of muons stop in the detector (3500/day), almost all travelling downwards, major background to upward partially contained neutrino events. Need to determine track direction by time of flight, slowing, coulomb scattering and vertex activity.

Non-muon background

•Neutrons and gammas which are produced by muons that miss the detector, mostly passing through the rock. They can enter the detector and interact deep inside.

•Mostly flagged in Soudan 2 by hits in the veto shield. The amount of background remaining determined by fits to the depth distribution. Neutron interaction length ~40cm. Background negligible at high energies ~1 GeV

•Noise background. It will be there at some level. Zens and snakes in Soudan 2 parlance. Usually easily recognisable by eye, less easily by program. Probably only a problem at low event energies.

•Soudan 2 completed the job by scanning. ~10:1 junk to good events in the scanning. Could reduce the junk more but at the expense of good event efficiency.

•Major scan reduction categories;

- •mis-reconstructed events, often hits missing from the end of slow highly coulomb scattering tracks
- •events with muons entering via the cracks between modules
- •noise events

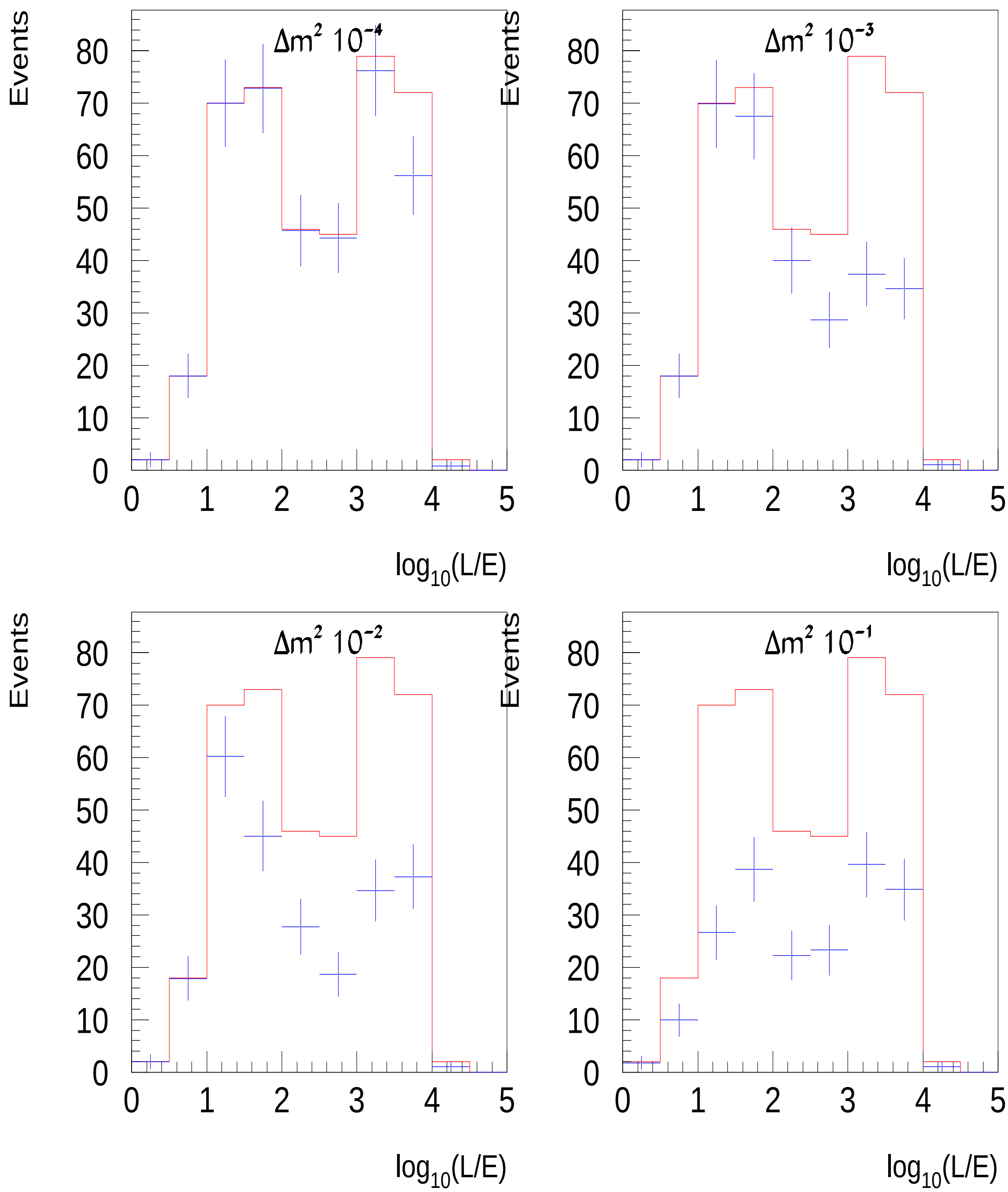
Analysis

- Very difficult to separate electron events (David Petyt's analysis)
    - ~2:1 initial muon production
    - neutral current background
    - short muon background
- BUT muons are what we are interested in and we can get a pure sample of them.
- BUT we become more dependent on flux calculations. In Soudan 2 we normalise the flux to the unoscillated electron events.

High energy μ event selection

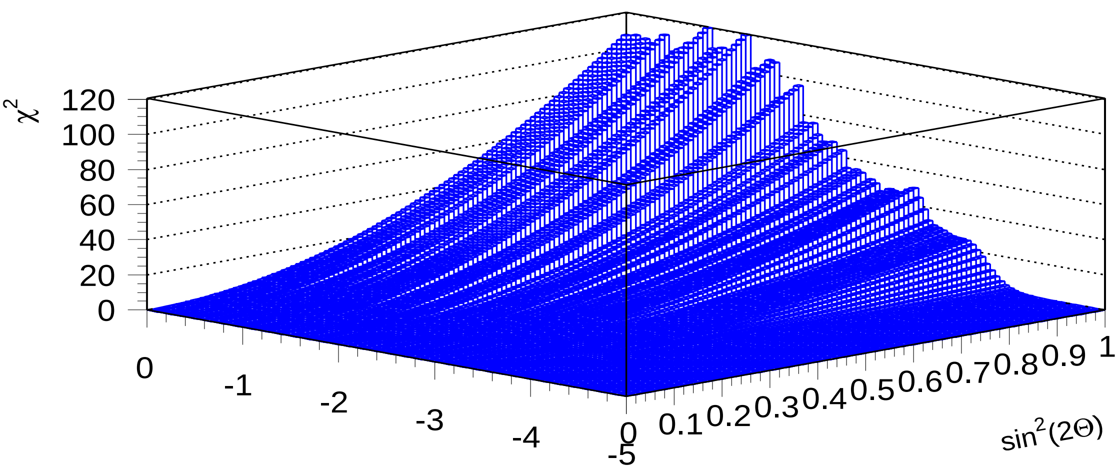
- We select high energy events by requiring;
  - A μ track >1GeV by range
  - Pulse height > 100 photo-electrons
  - Require 3m length for uncontained μ to allow momentum measurement
- Direction of muon determined by
  - change of curvature in field while slowing
  - vertex activity
  - timing
- 407 events remain from an 18 kton year MC sample, a four year run.
- Practically pure sample of ν_μ cc events
- Practically 100% correct direction determination
- μ energy resolution ~ 10% from combination of range and curvature measurements

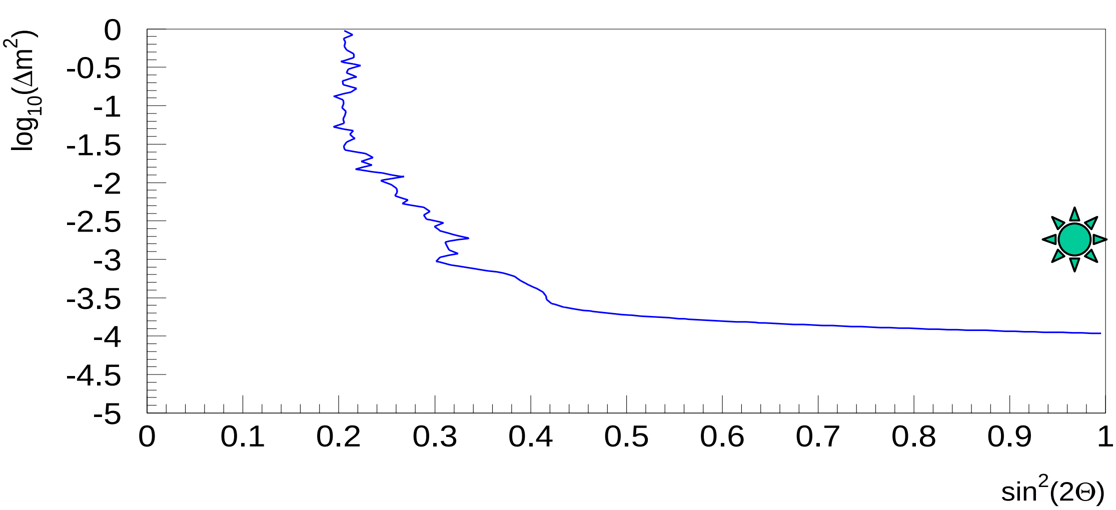
L/E distributions



MINOS sensitivity region

χ^2 difference between the oscillated and unoscillated distributions calculated on a grid of points and the 90% confidence contour plotted





Normalisation assumed known

Super-K best fit

Parameter measurement sensitivity

$\Delta m^2=10^{-3}$,$\sin^2(2\theta)=1.0$

Fixed normalisation