Calibration in the MINOS Detectors

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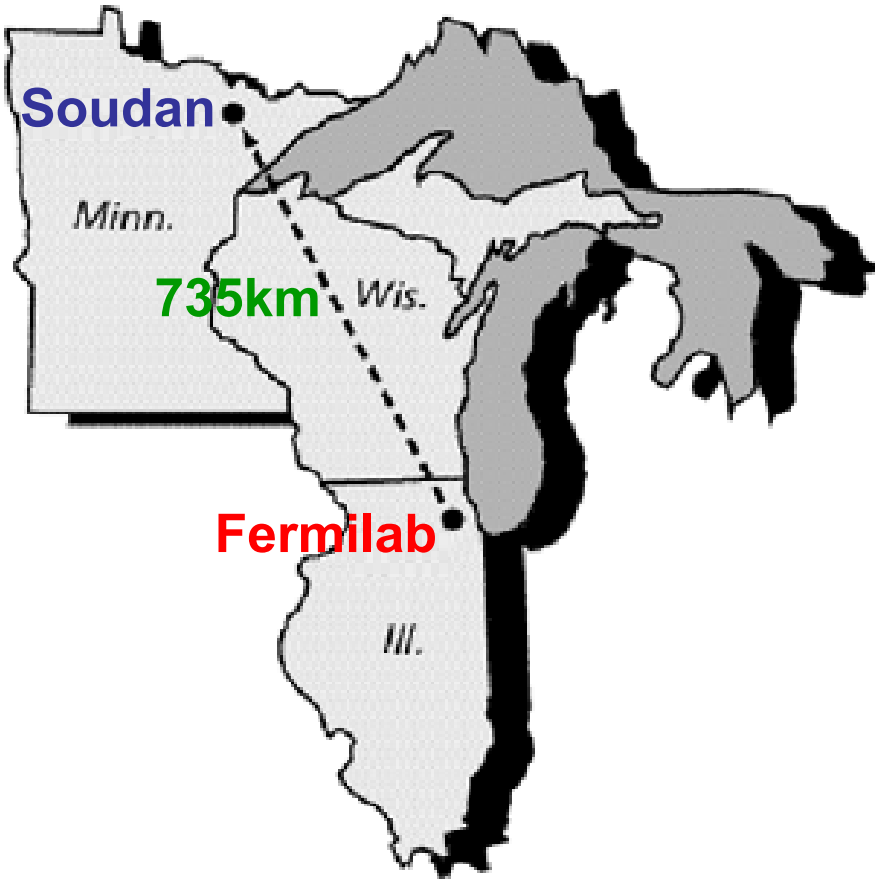
Introduction

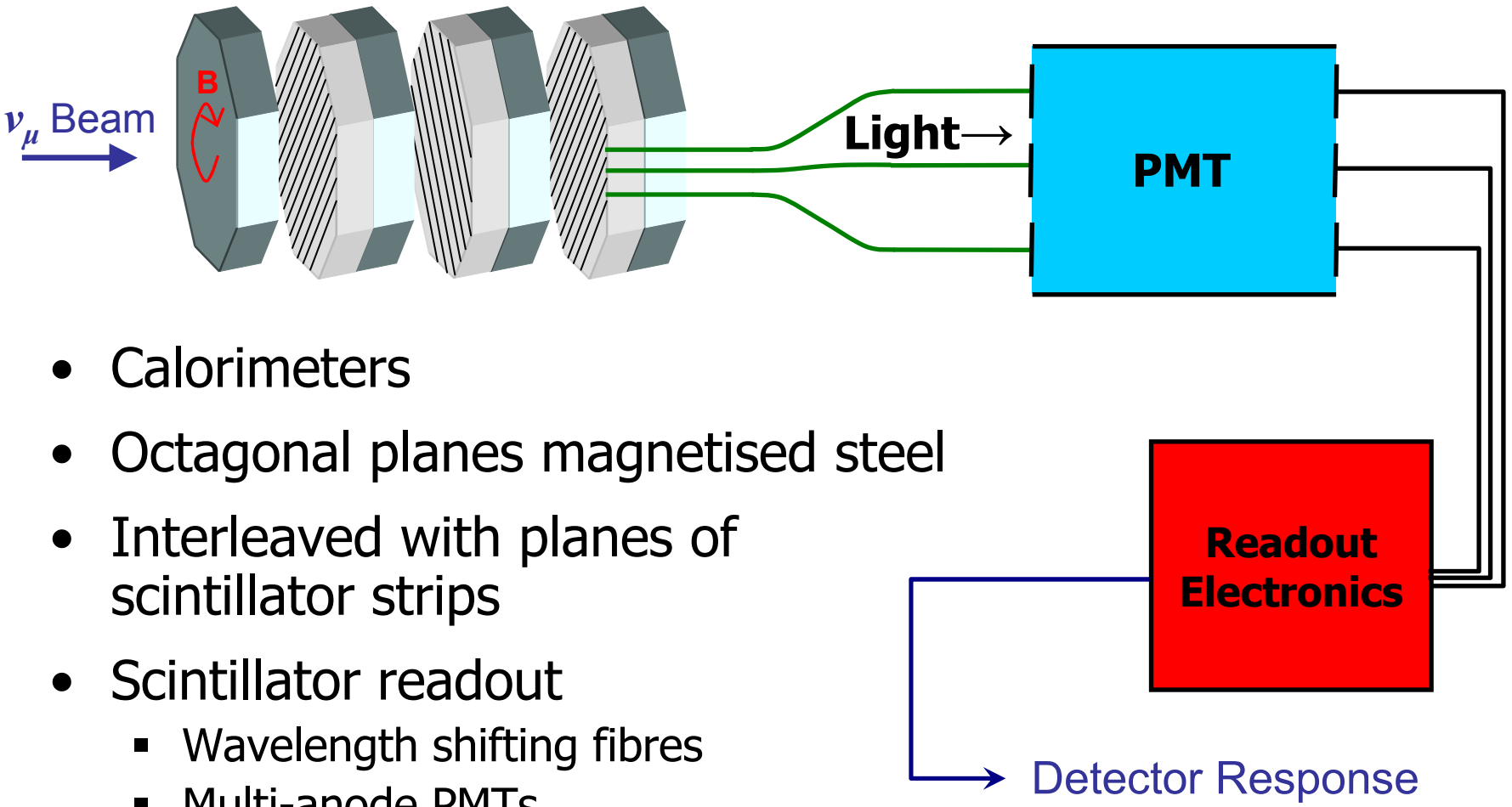
- Calorimetric energy measurements in MINOS detectors
- Measuring calorimetric energy resolution
- Calibrating temporal drifts in detector response
- Calibrating spatial variance in response
- Obtaining absolute energy scale

The MINOS Experiment



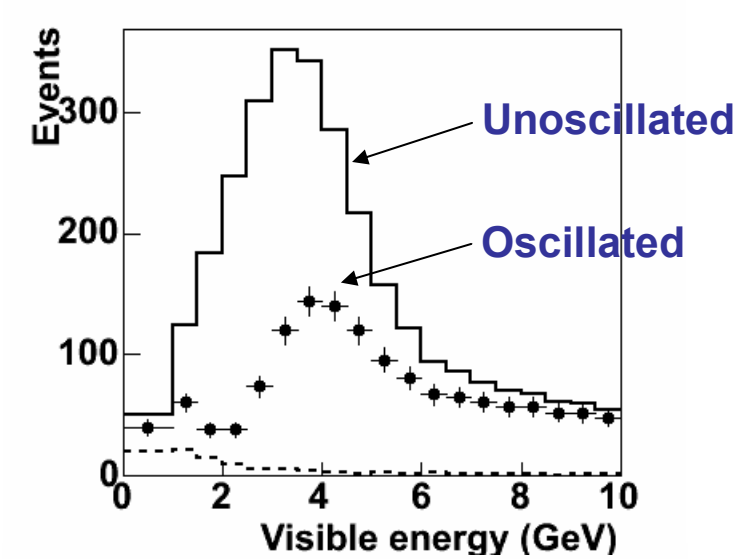
- Long-baseline neutrino oscillation search
- ν_μ beam at Fermilab
- Near Detector at Fermilab
  - ν_μ energy spectrum before oscillations
- Far Detector 735 km away
  - Soudan mine
  - Oscillated ν_μ energy spectrum

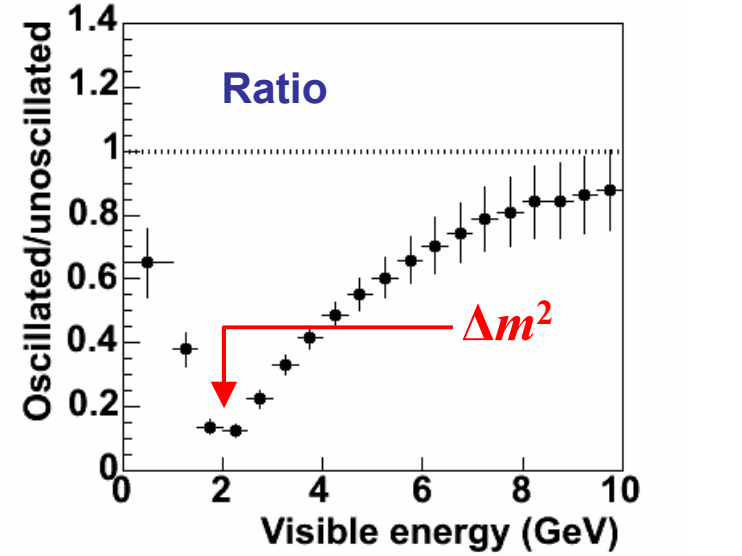
The MINOS Detectors



- Calorimeters
- Octagonal planes magnetised steel
- Interleaved with planes of scintillator strips
- Scintillator readout
  - Wavelength shifting fibres
  - Multi-anode PMTs

Measuring Neutrino Oscillations

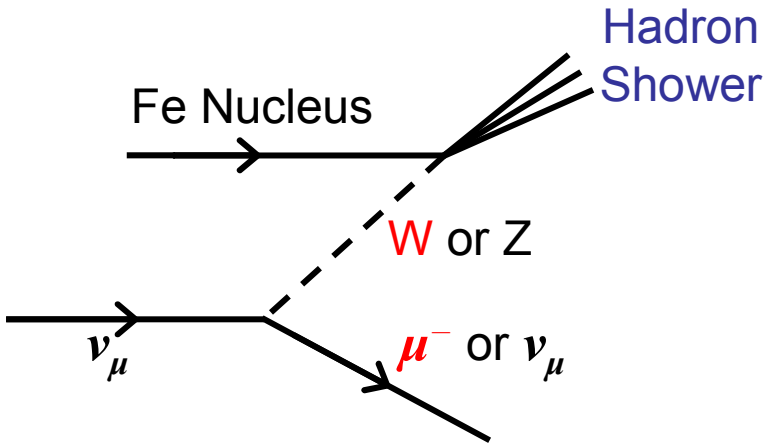


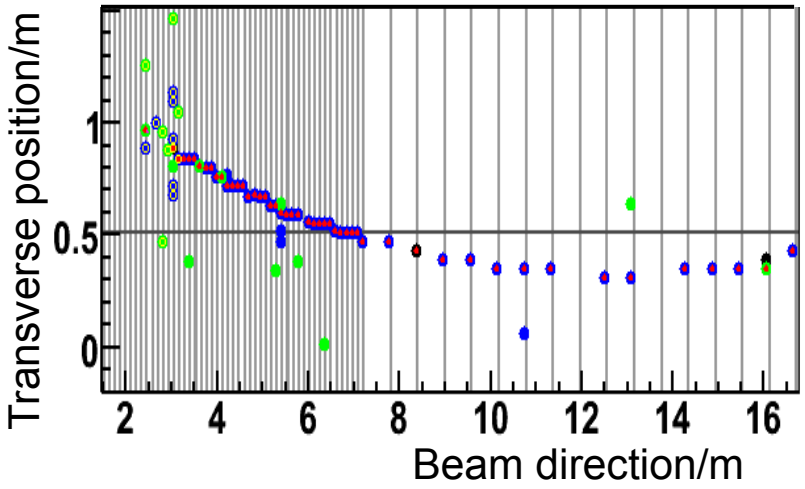


- Measuring Δm^2 of neutrino eigenstates
- Measure oscillated and unoscillated neutrino spectra
- Position of dip (in energy) tells us Δm^2
- Require accurate measurement of neutrino energy

Measuring Neutrino Energy

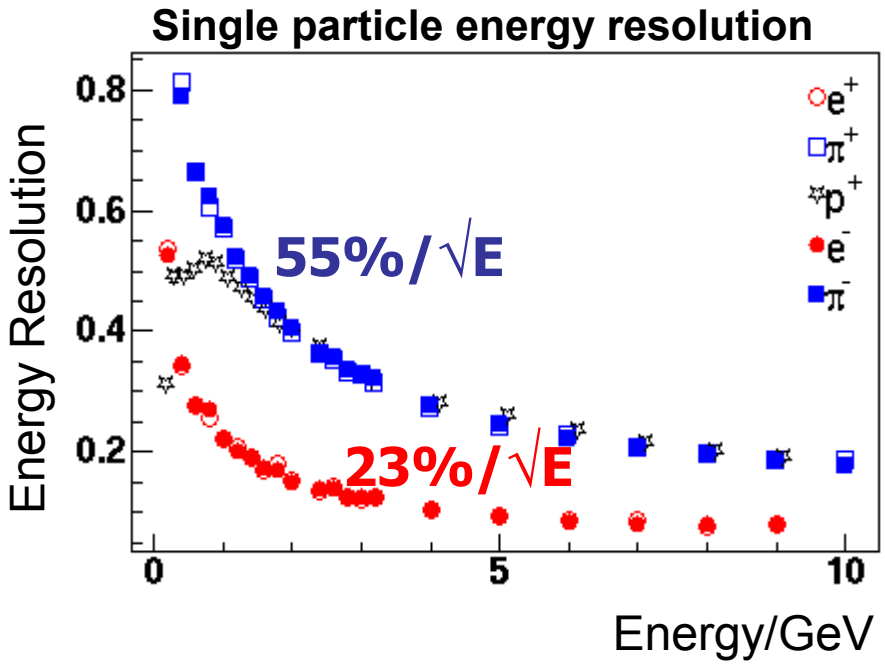
- Neutrino interacts through CC or NC
- Produces hadron shower and muon (in CC case)
- $E_\nu = E_\mu + E_{\text{shower}}$
- Accurate ν_μ energy measurement requires
  - Accurate μ energy
  - Accurate hadronic shower energy
- Muon energy from range or curvature in B-field
  - Resolution 6% from range, 12% from curvature
- Hadronic energy from calorimetry
- MINOS detectors have no source of known-energy particles
  - Makes calibration difficult





Calibration Detector

- 60-plane detector built at CERN
- Same steel-scintillator structure and readout electronics as other MINOS detectors
- Fired beams of known-energy muons, electrons, pions, protons through it
- Relate hadronic and electromagnetic energy response to muon response
- Measure of detector resolution for hadrons and electrons

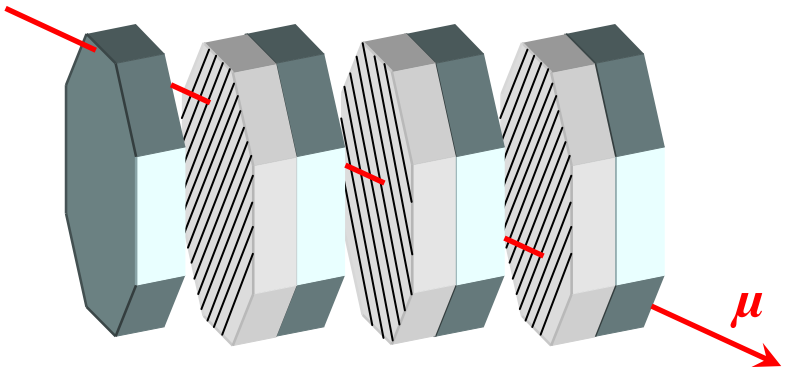


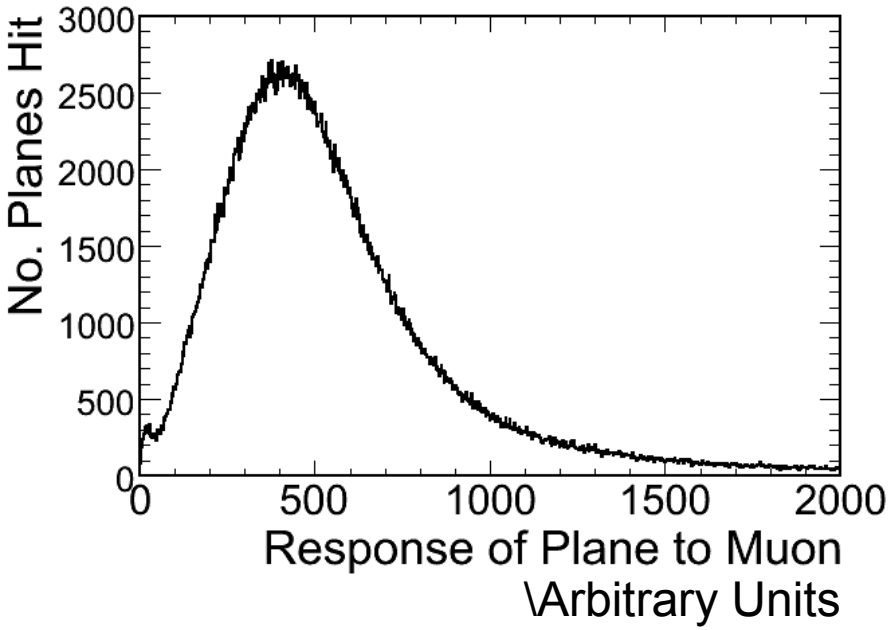
Temporal Drift of Detector Response

- Scintillator response decays with time
- PMT response changes with time
- Scintillator & PMT responses temperature dependent
- Hardware swaps in electronics alter detector response

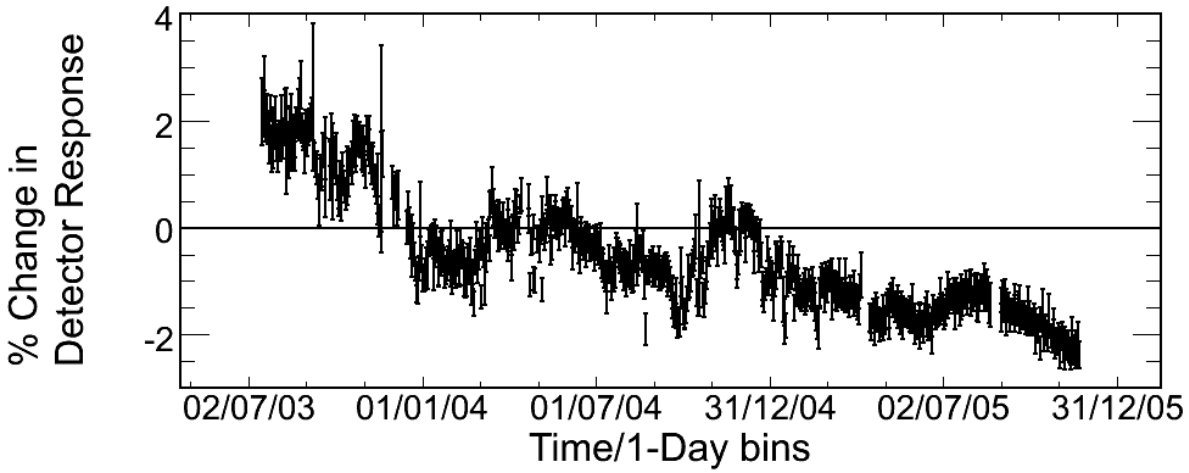
Drift Calibration

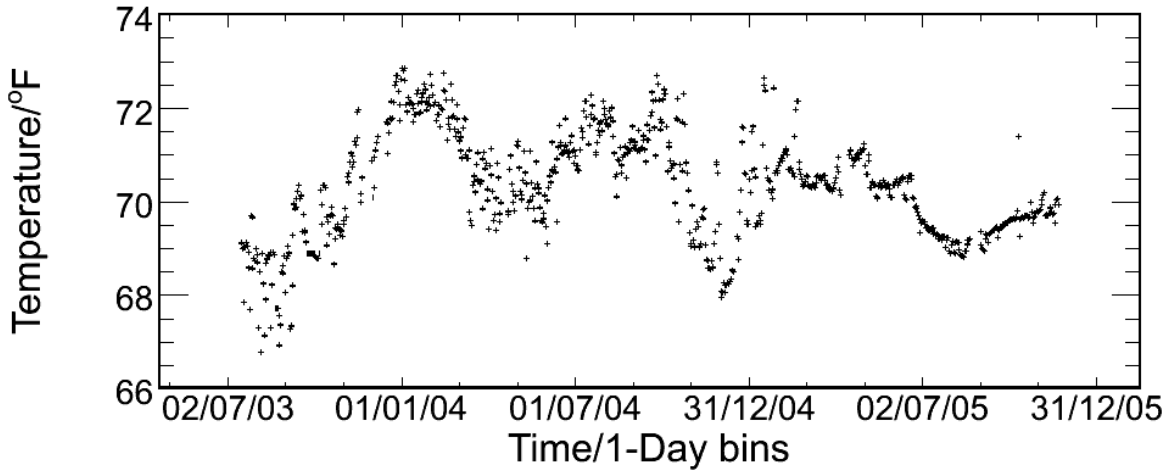
- Use through-going cosmic muons
- Record energy deposited per plane
- Path-length correction
  - Muons not perpendicular to planes
- Take median energy deposited per plane over 1 day
  - Median removes high-energy fluctuations
  - e.g. muon bremsstrahlung
- Tracks drift of entire detector response
  - Precision of 1 day





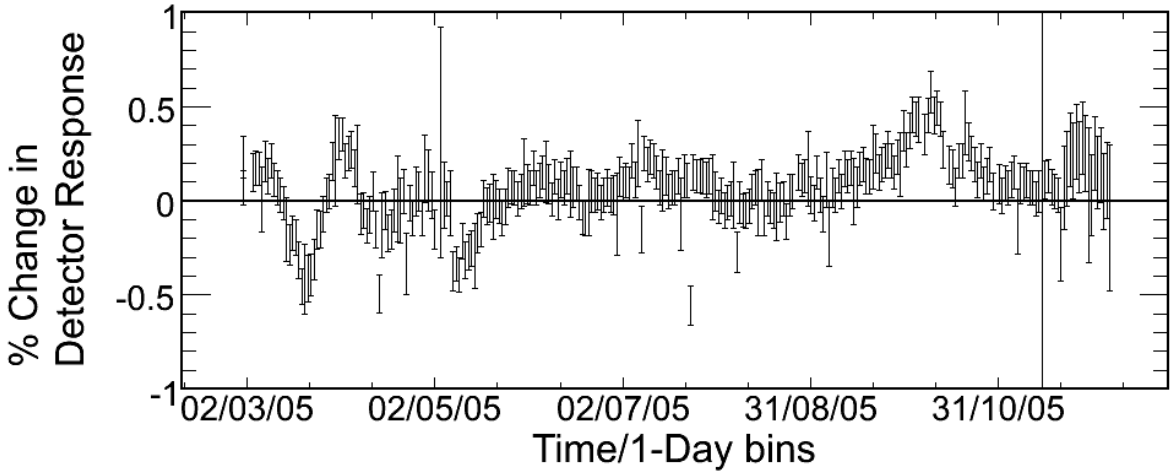
Drift Calibration Results

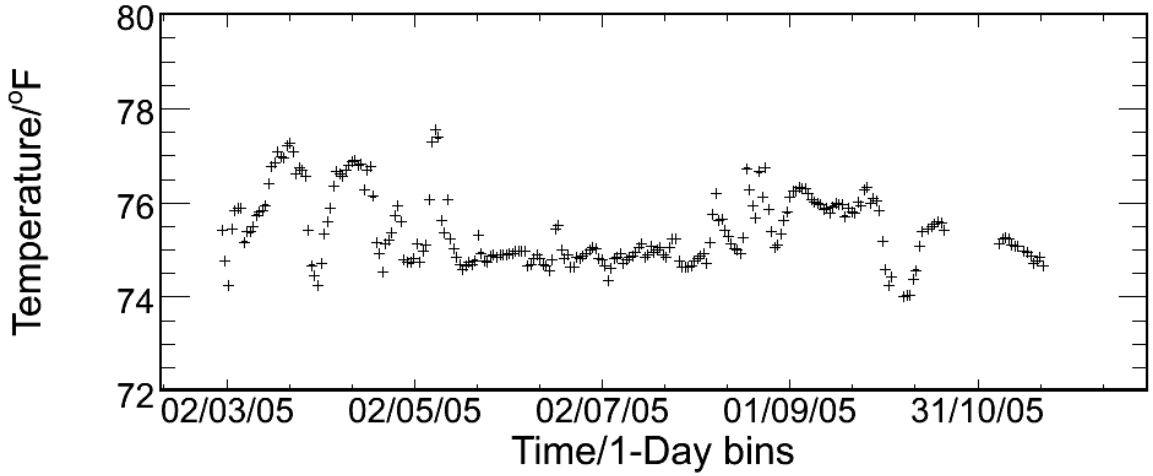




- Far Detector
- ~17,800 muons per day
- ~4% decay in response over 2.5 years
- ~1% response change per °C

Drift Calibration Results

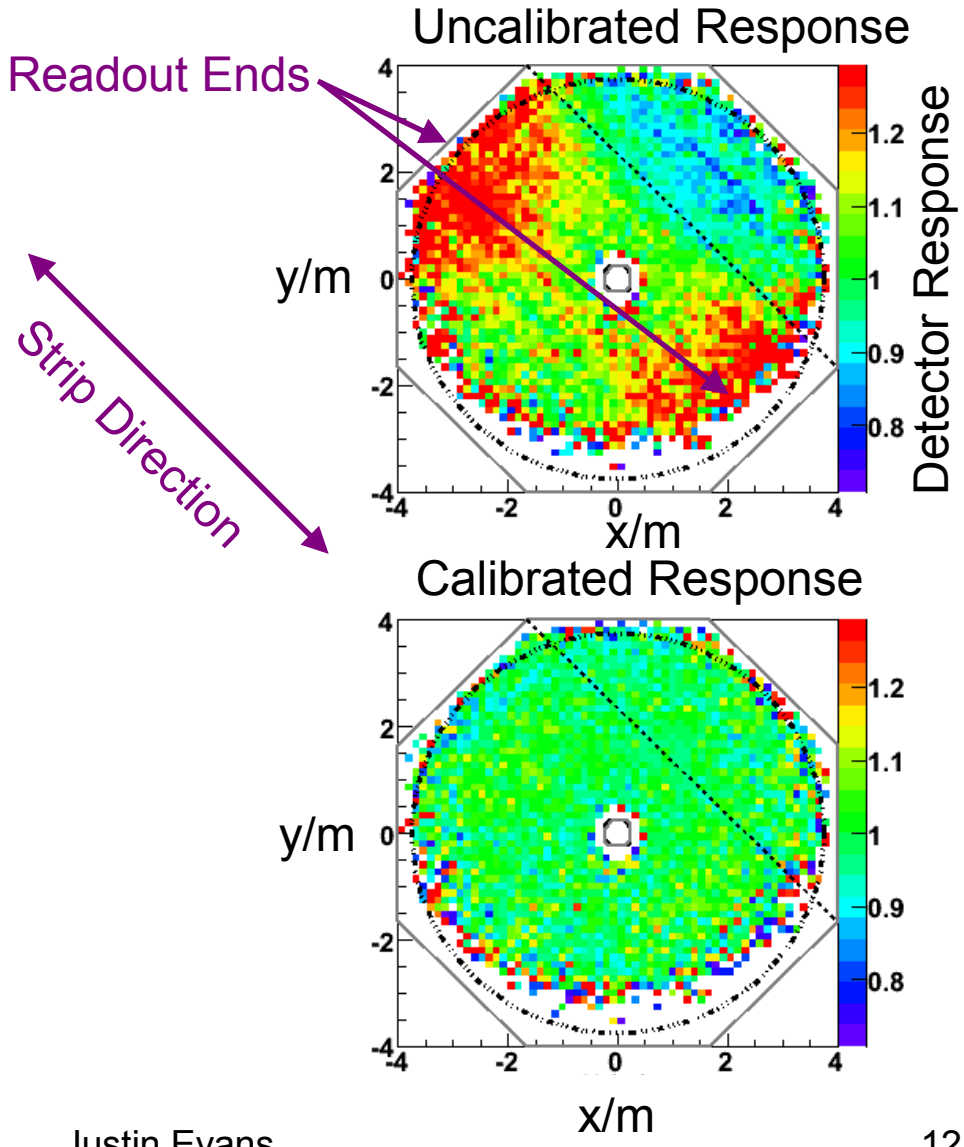




- Near Detector
- ~260,000 muons per day
- No definite decay in response over 10 months
- ~1% response change per °C

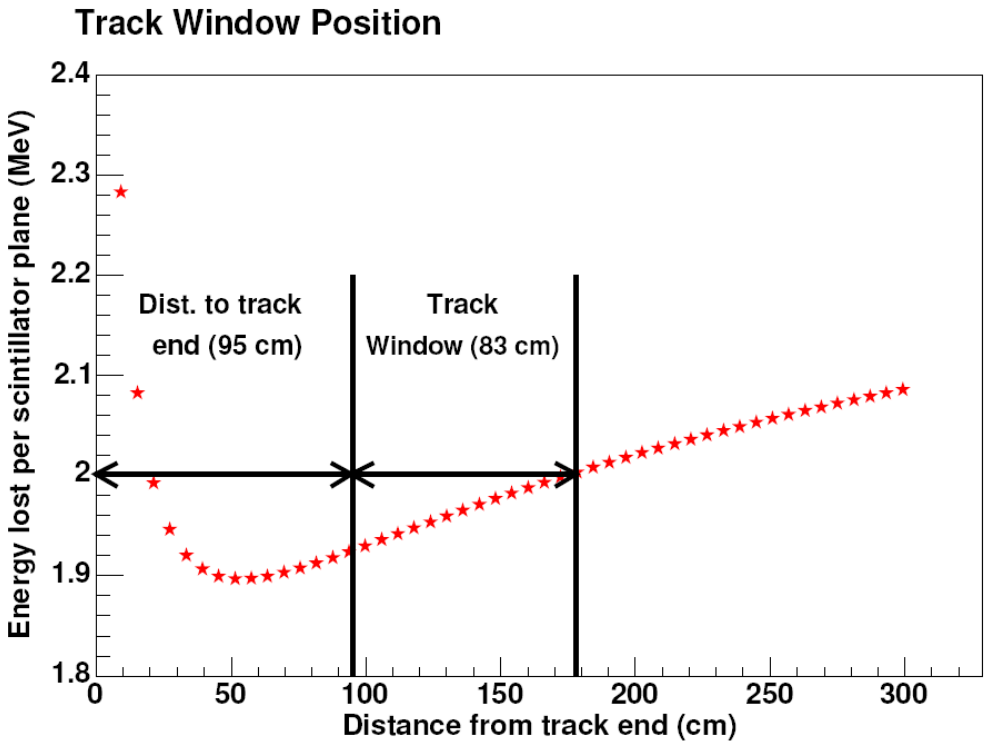
Spatial Response Calibration

- Different scintillator strips give different responses
- Different readout fibres give different responses
- Hits nearer readout end of strip give higher response
- Shine light onto fibres on test-stand to measure attenuation
- Use position of cosmic muon hits to calibrate strips in detector



Absolute Energy Scale

Use stopping cosmic muons to relate detector response to GeV



- Muons deposit energy per plane
  - Bethe-Bloch formula
- Select tracks to be entering and stopping in detector
- Path-length correction
  - muons not perpendicular to planes
- Count back 95 cm from track end
- Over next 83 cm, energy deposited changes by only 4%
- Gives a measure of muon energy response
- Gives an absolute energy scale

Conclusion

- Measured calorimetric energy resolution
  - Calibration detector
- Measured drifts in detector responses over time
  - Cosmic muons
- Measured spatial variance of detector response
  - Cosmic muons
- Measured absolute energy scale
  - Stopping cosmic muons

- Final absolute energy uncertainties
  - Far Detector: 3.5%
  - Near Detector: 2%
  - Detector to detector: 3%