Status and first atmospheric neutrino results from MINOS

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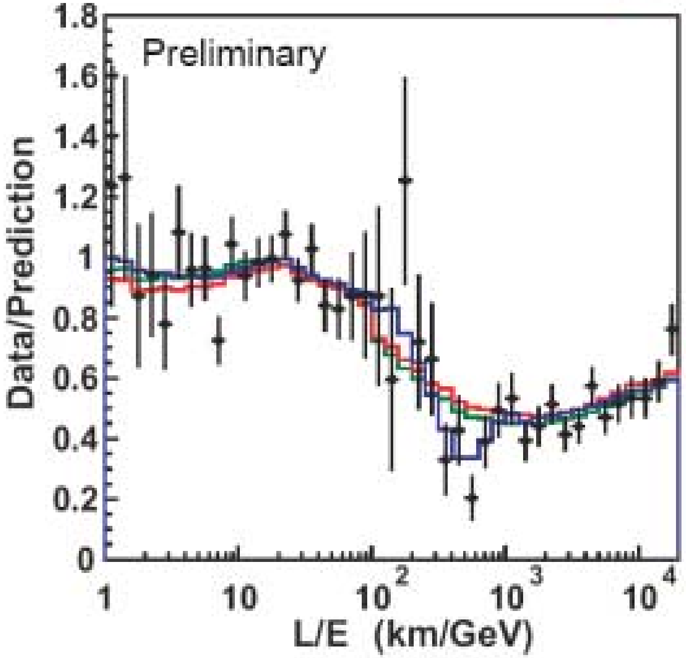
Preview

- Introduction
  - Reason for this experiment
- Detector and Project Description and Status
  - Far Detector is taking data (atmospheric ν)
  - Near Detector assembly has begun
- Data Analysis : Present
  - Detector Calibration has been demonstrated
  - Atmospheric neutrino measurements
- Data Analysis : Future
  - 5-10% measure of parameters
  - Important search for ν_μ to ν_e
- Whats next for neutrino physics?

Introduction

Tests for neutrino decay & decoherence

—	Oscillation	χ^2_{min}=37.8/40 d.o.f
—	Decay	χ^2_{min}=49.2/40 d.o.f → $\Delta\chi^2$=11.4
—	Decoherence	χ^2_{min}=52.4/40 d.o.f → $\Delta\chi^2$=14.6



3.4 σ to ν decay

3.8 σ to ν decoherence

First dip observed in data cannot be explained by alternative hypotheses

Introduction

- The neutrino mixing matrix looks like this:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- The matrix is Unitary

  $\nu e, \nu \mu, \nu \tau$ are the weak eigenstates

- ν_1, ν_2, ν_3 are the mass eigenstates

Introduction

- Super-K claim data suggests $\nu_\mu \; \nu_\tau$ only

$$P(\nu_\mu \to \nu_\tau) = U_{\mu1}^2 U_{\tau1}^2 + U_{\mu2}^2 U_{\tau2}^2 + U_{\mu3}^2 U_{\tau3}^2$$
$$+U_{\mu1}U_{\tau1}^* U_{\mu2}^* U_{\tau2} K\left(\frac{\Delta m_{12}^2}{E}\right)$$
$$+U_{\mu2}U_{\tau2}^* U_{\mu3}^* U_{\tau3} K'\left(\frac{\Delta m_{23}^2}{E}\right)$$
$$+U_{\mu3}U_{\tau3}^* U_{\mu1}^* U_{\tau1} K''\left(\frac{\Delta m_{31}^2}{E}\right)$$

- Approximation that $\nu_e \; \nu_1$ not involved

$$\mathrm{P}(\nu_\mu \to \nu_\tau) = \mathrm{U}_{\mu2}U_{\tau2}^* U_{\mu3}^* U_{\tau3} K'\left(\frac{\Delta m_{23}^2}{E}\right)$$

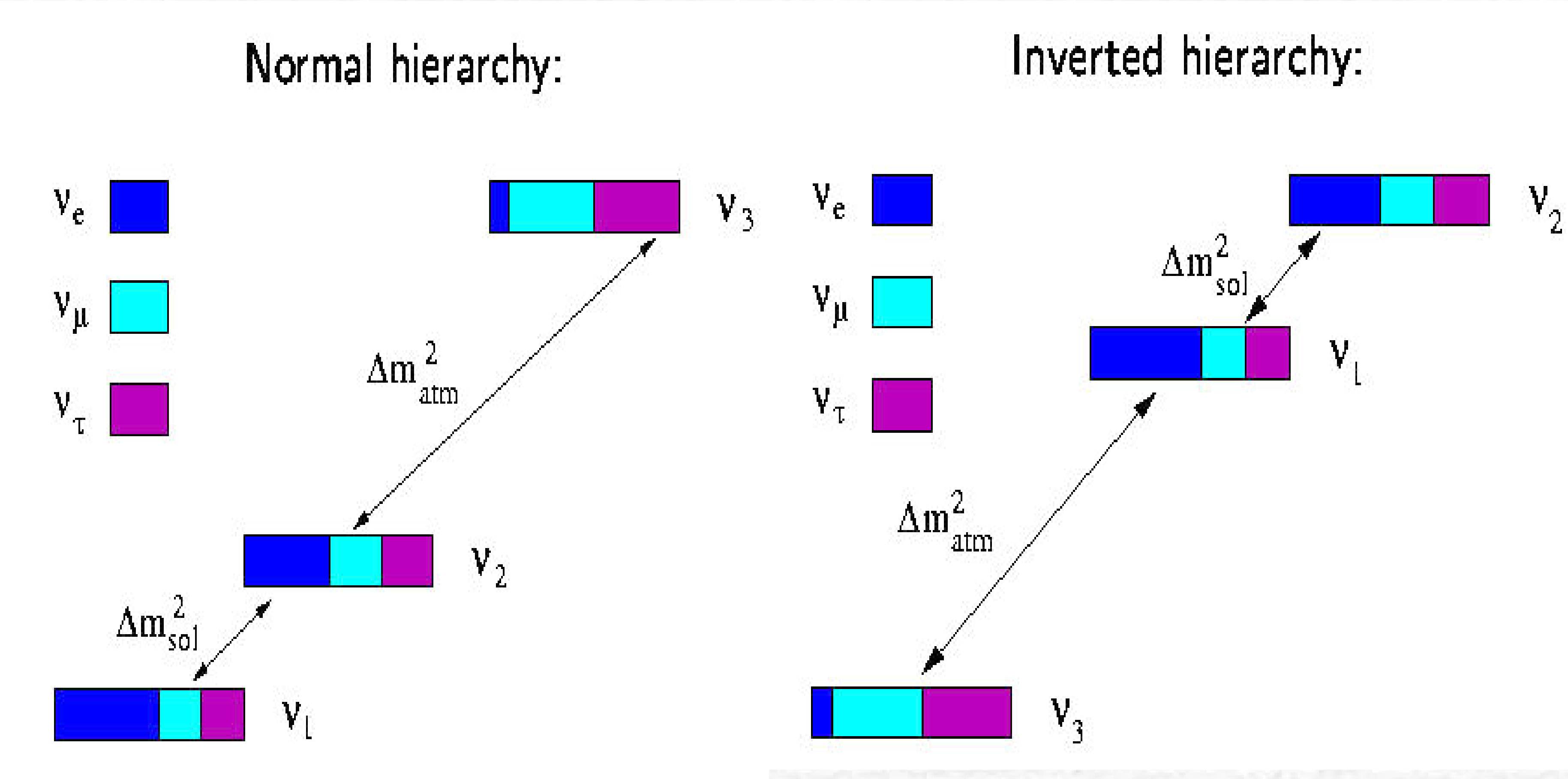
Introduction

- Leading to the familiar (v.simplified) equation

$$P(\nu_\mu \rightarrow \nu_\tau) = \mathrm{Sin}^2 2\theta \ \mathrm{Sin}^2(1.27 \Delta m^2_{23} \frac{\mathrm{L}}{\mathrm{E}})$$

- Super-K gives measure of $\Delta m^2 = 3\mathrm{x}10^{-3}\mathrm{eV}^2$
- $\mathrm{Sin}^2 2\theta \sim 1$
- Combination SNO/Kamland gives measure of $\Delta m^2 = 5\mathrm{x}10^{-5}\mathrm{eV}^2$, $\mathrm{Tan}^2\theta_{12}$ large

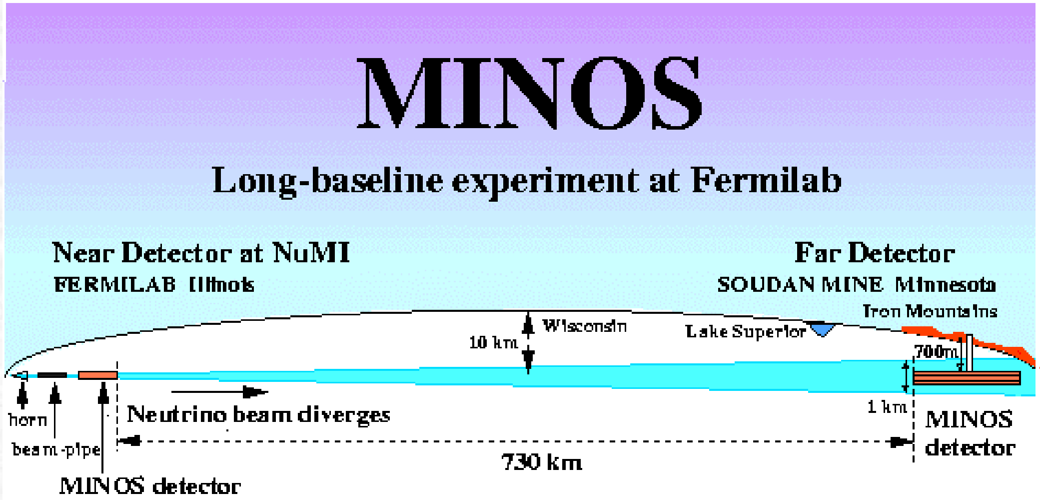
Introduction

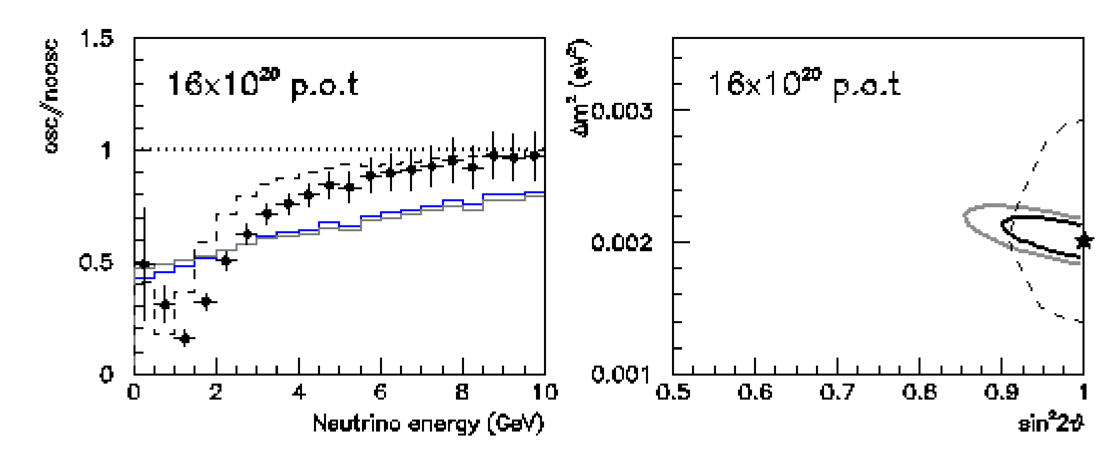


- MINOS will measure ν_μ ν_τ and limit ν_e content and *presumably* Δm_{23}^2

The NuMI/MINOS Project Description and Status

Introduction



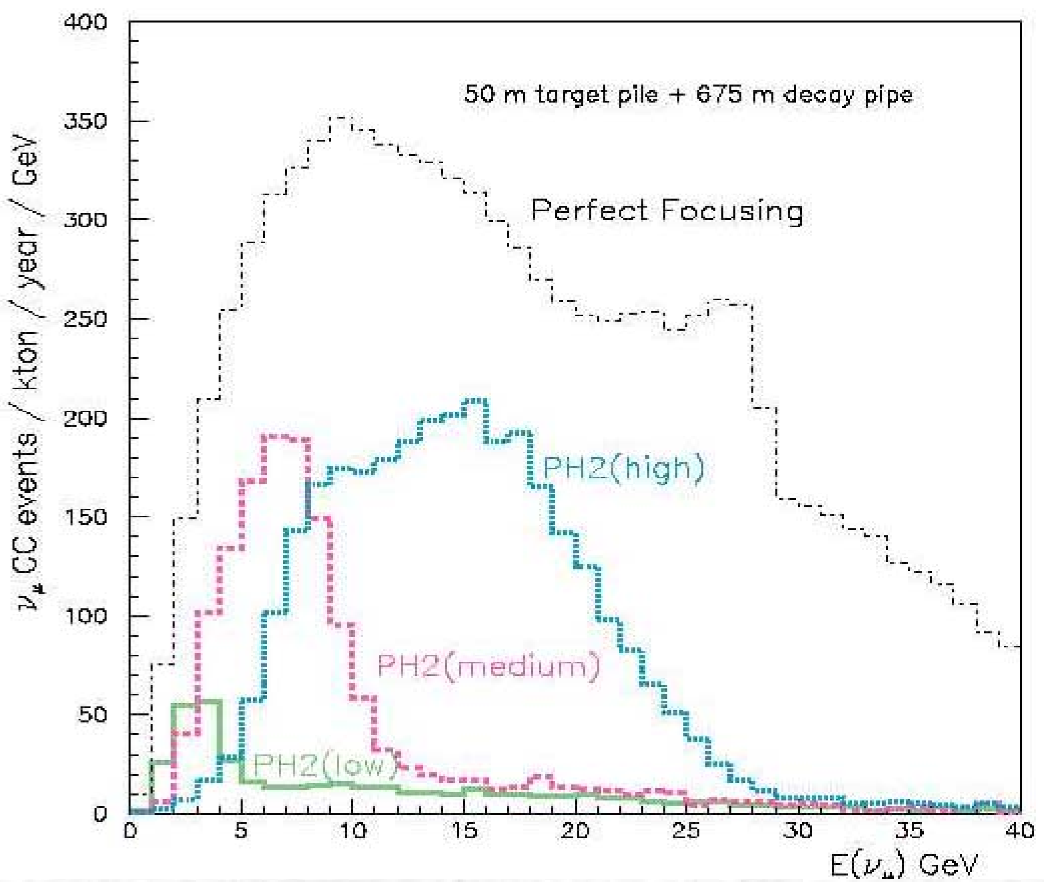


- MINOS comprises
  - US Universities 45%
  - US Labs 29%
  - UK Institutions 16%
  - Non US/UK 10%

Introduction

- NuMI beam comes off the main injector
- Protons impinge on carbon pencil target producing pions
- Pions are made parallel with double horn arrangement
- Allows beam energy to be selected
- We will start with low energy beam <E>=3GeV

Introduction



By moving the horns and target, different energy spectra are available using the NuMI beamline. The energy can be tuned depending on the specific oscillation parameters expected/observed.

Introduction

12/07/05 Construction Site Visit

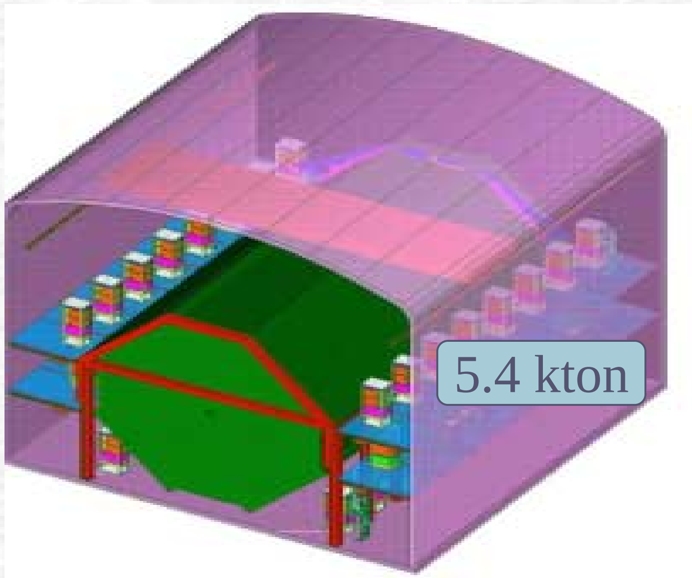
Steel installed in the Target Pit 4510

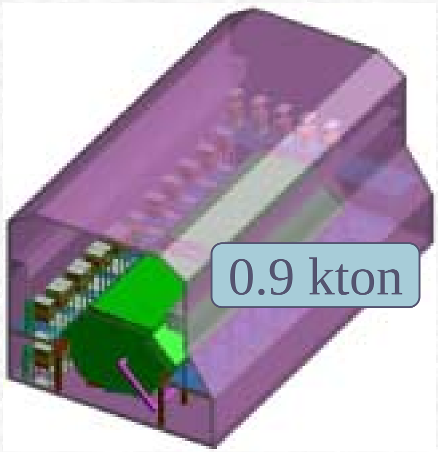
Magnet mover 4519

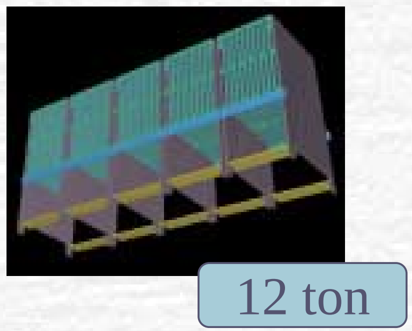
Target pit with installed steel in center of photo 4507

MINOS Detektoren

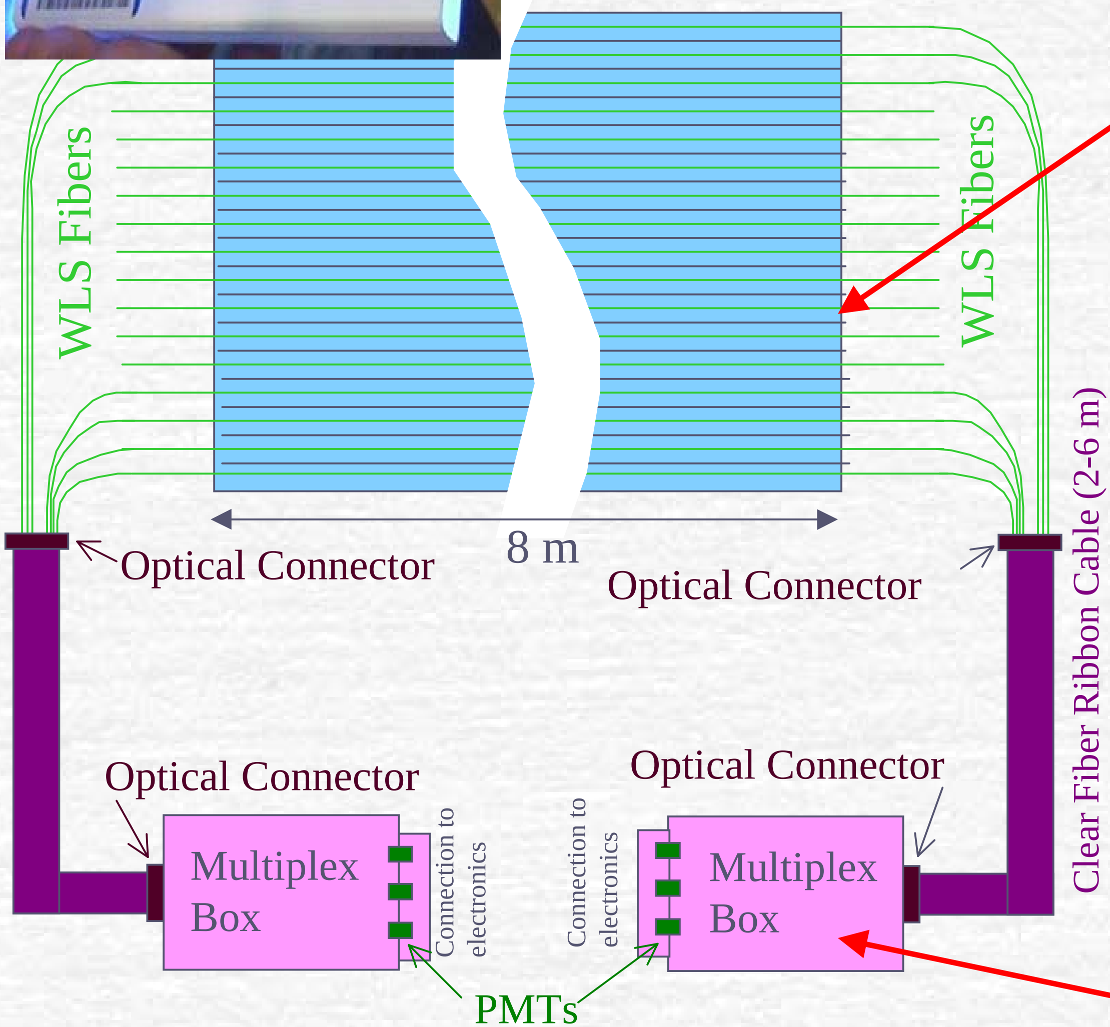
- Es gibt 3 MINOS Detectors
  - Nah Detektor @ FNAL (ND)
  - Fern Detektor @ Soudan (FD)
  - Kalibrations Detektor @ CERN (CalDet)







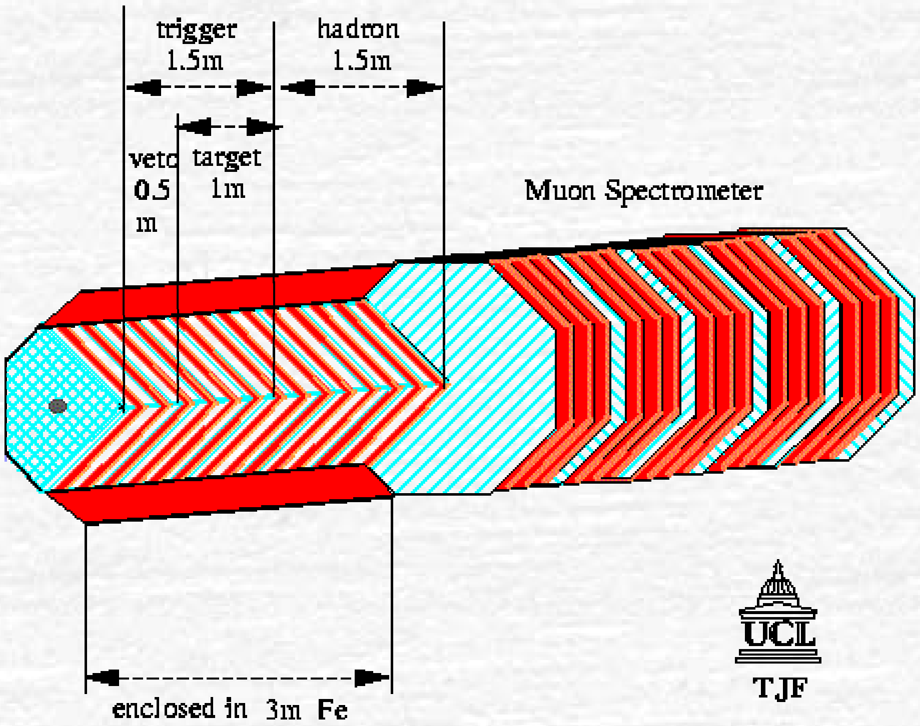
MINOS Detectors



Objects not to scale

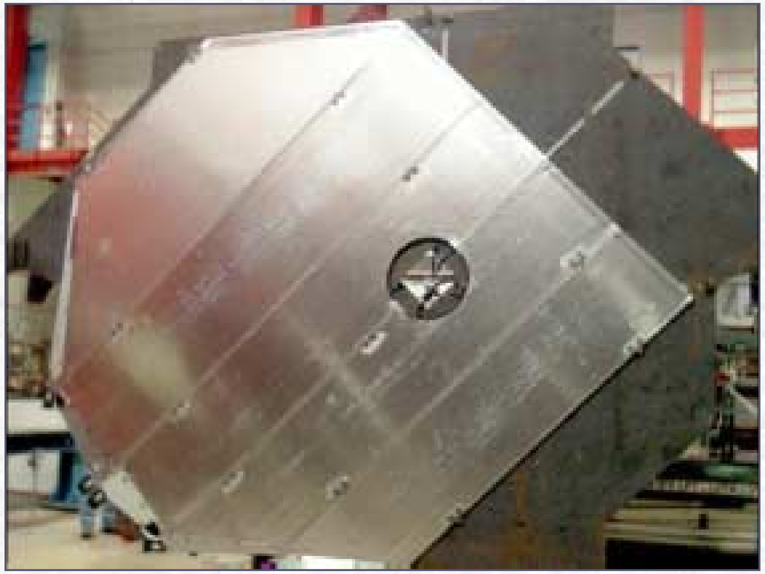
MINOS Far Detector

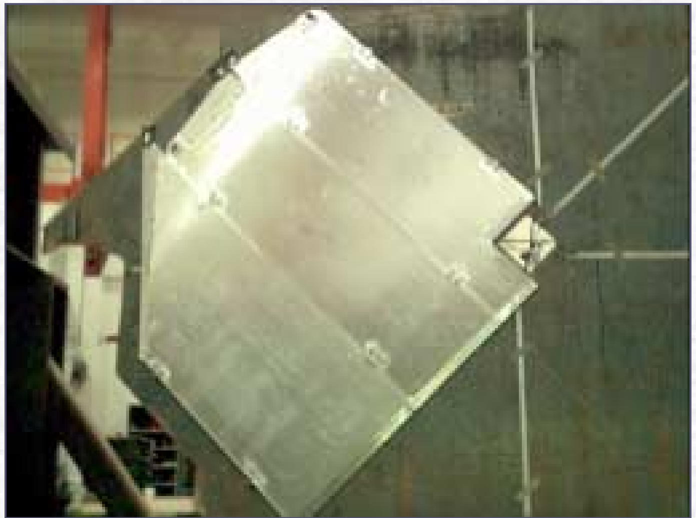
MINOS Near Detector



- 200 planes (14m long)
- measures ν_e (~5x10^{-3})
- Near Det offset wrt beam
- Use to measure energy spectrum and predict that in FD
- Rate in ND is high: ***~100 events per spill!***
- Electronics different from FD
- Spectrometer section

MINOS Near Detector





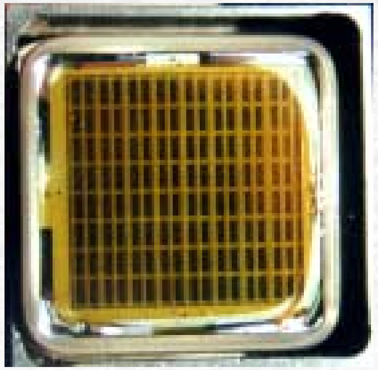
MINOS Near Detector

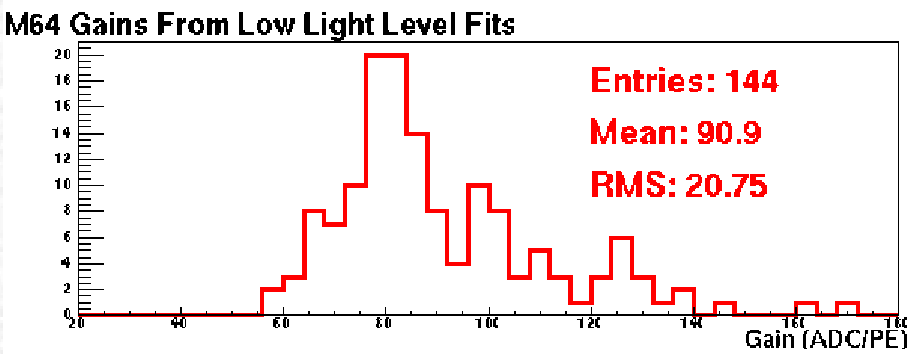
First Near Detector Plane (Installed 3/31/04)

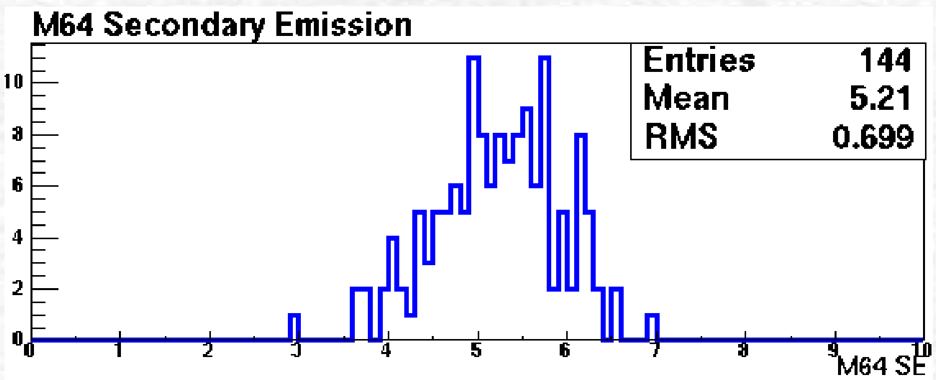
Beam Turns on end 2004

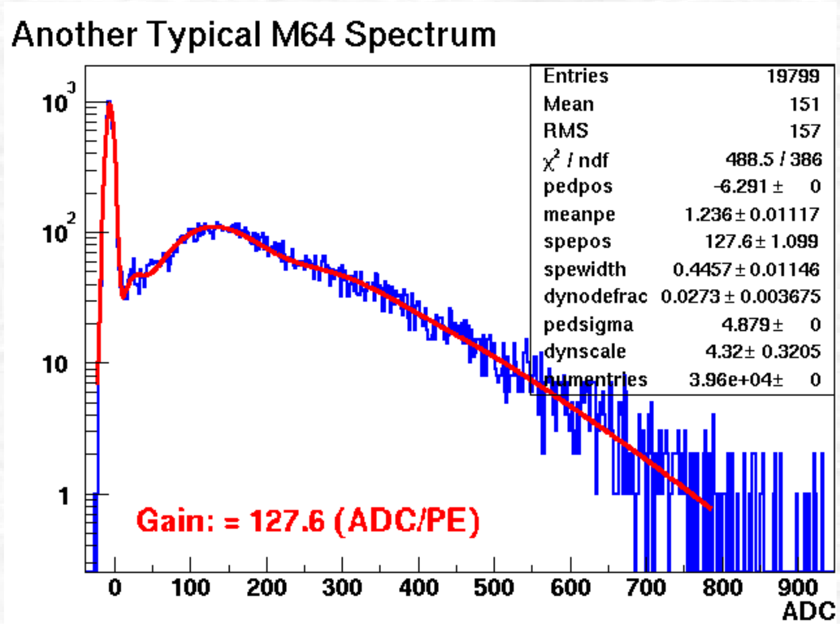
MINOS Detectors

- Modules read out with Hamamatsu M16 and M64 PMTs









Calibration Detector

- Ca
  - – CERN
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  - – s
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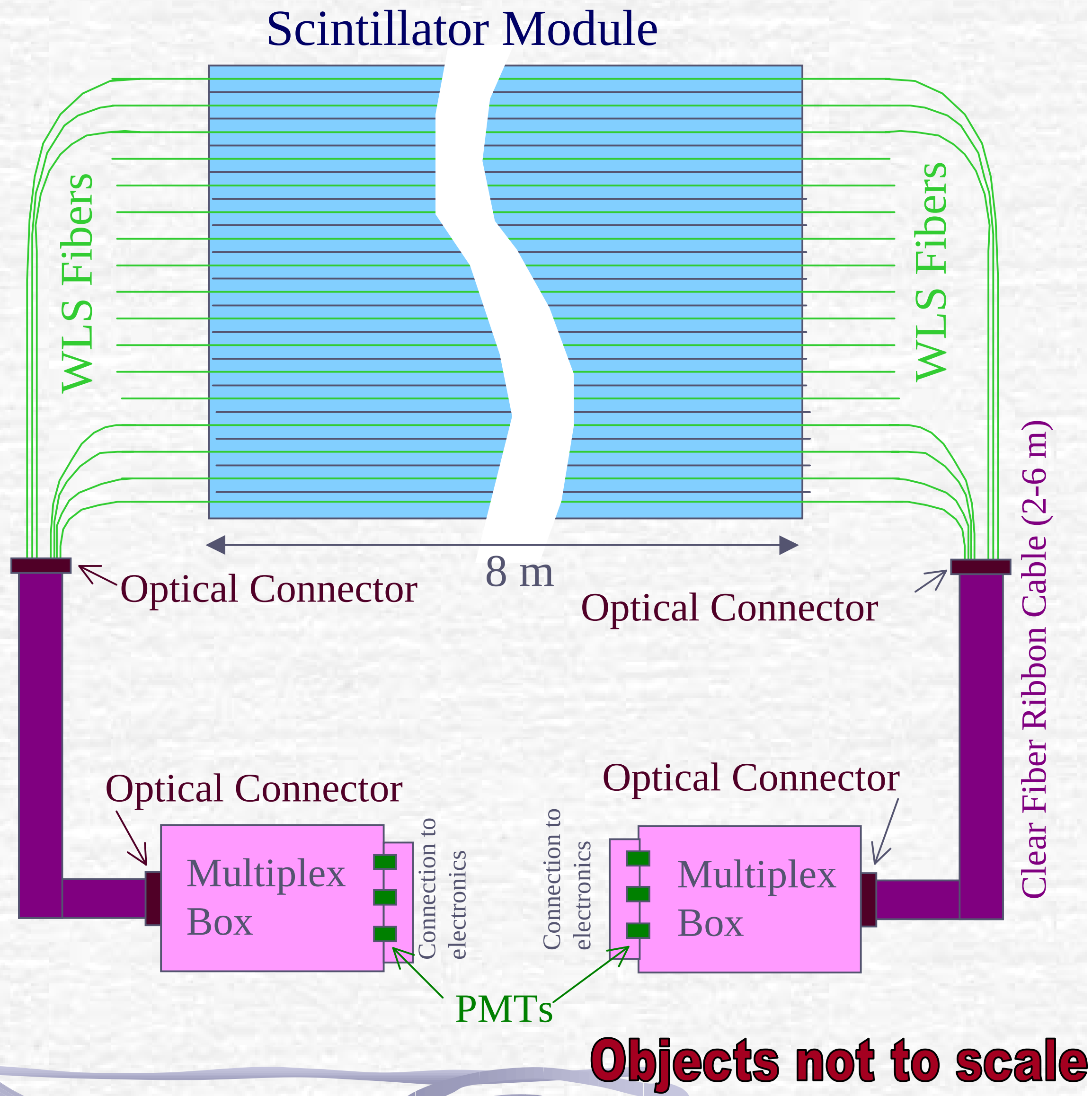
  - –

Calibration Detector

- CalDet has been used to verify performance of sub-systems
  - Light Injection system
  - Calibration chain
  - System Stability
  - PMT response
  - ND vs FD electronics
  - ……
  - Input for pattern recognition algorithms

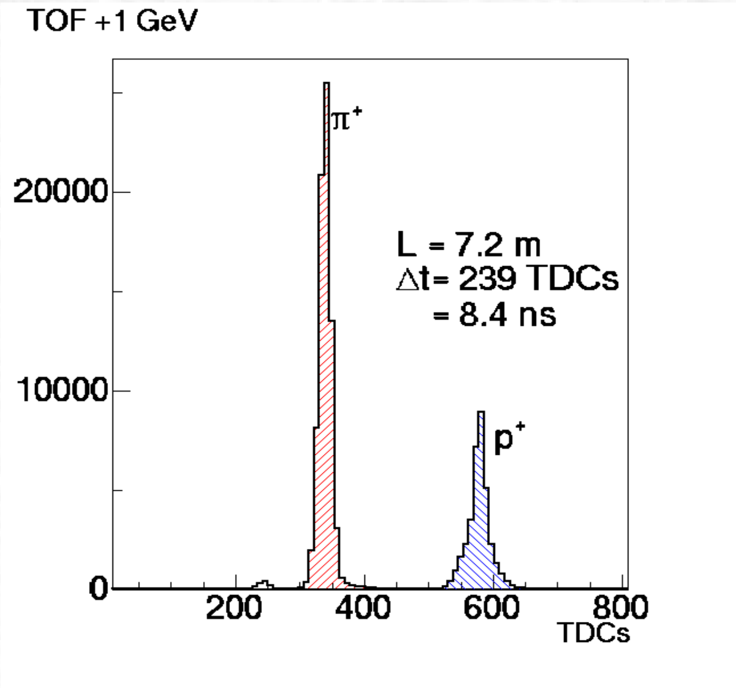
Calibration Detector

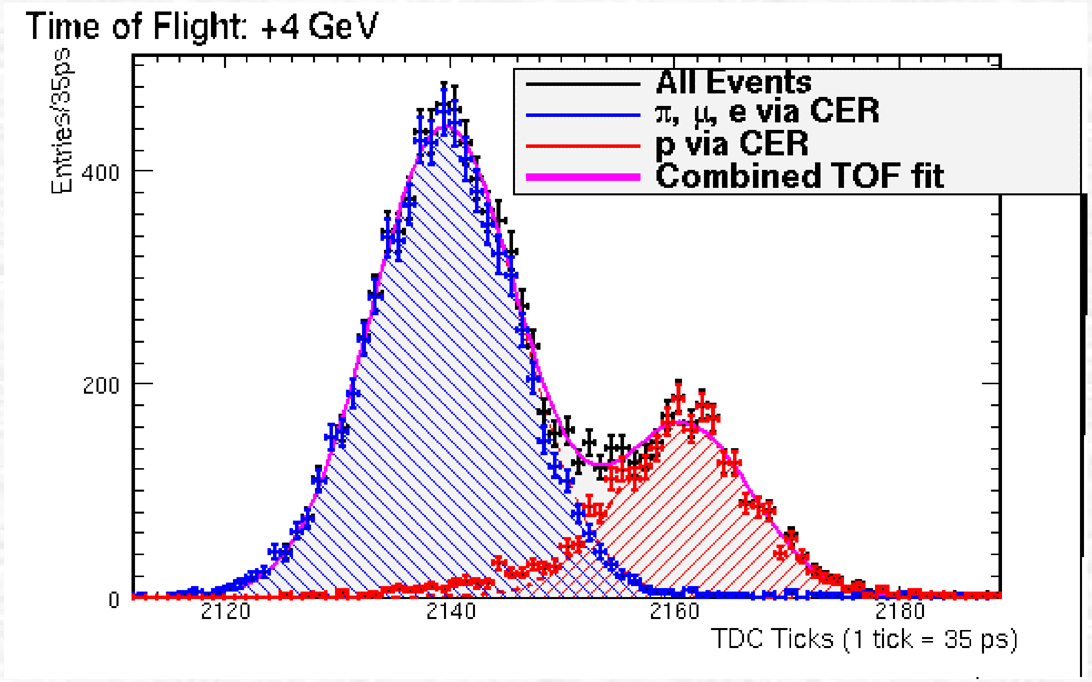
- One small difference
- One side 4m green WLS fibre
- Apes a bigger detector



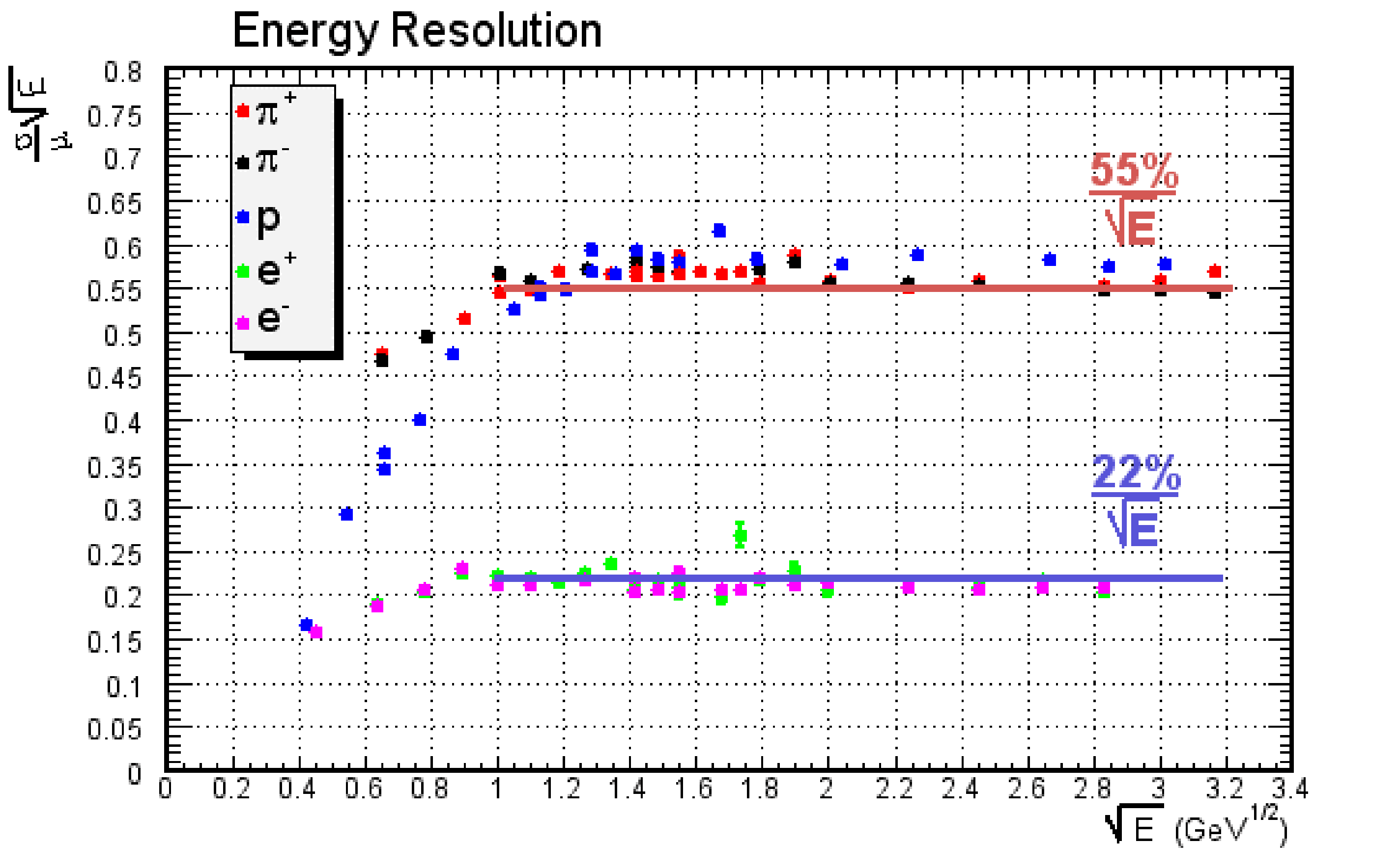
CalDet Physics Analysis

- CalDet data measures calorimetric response to pions and protons separately using TOF and Cerenkov systems
- ToF separates π,p up to 3.5GeV, Cerenkov up to 10 GeV
- Electron anti-ID with good efficiency: ~no e > 6GeV
- Discrepancy between Geant 3 and 4 for π,p

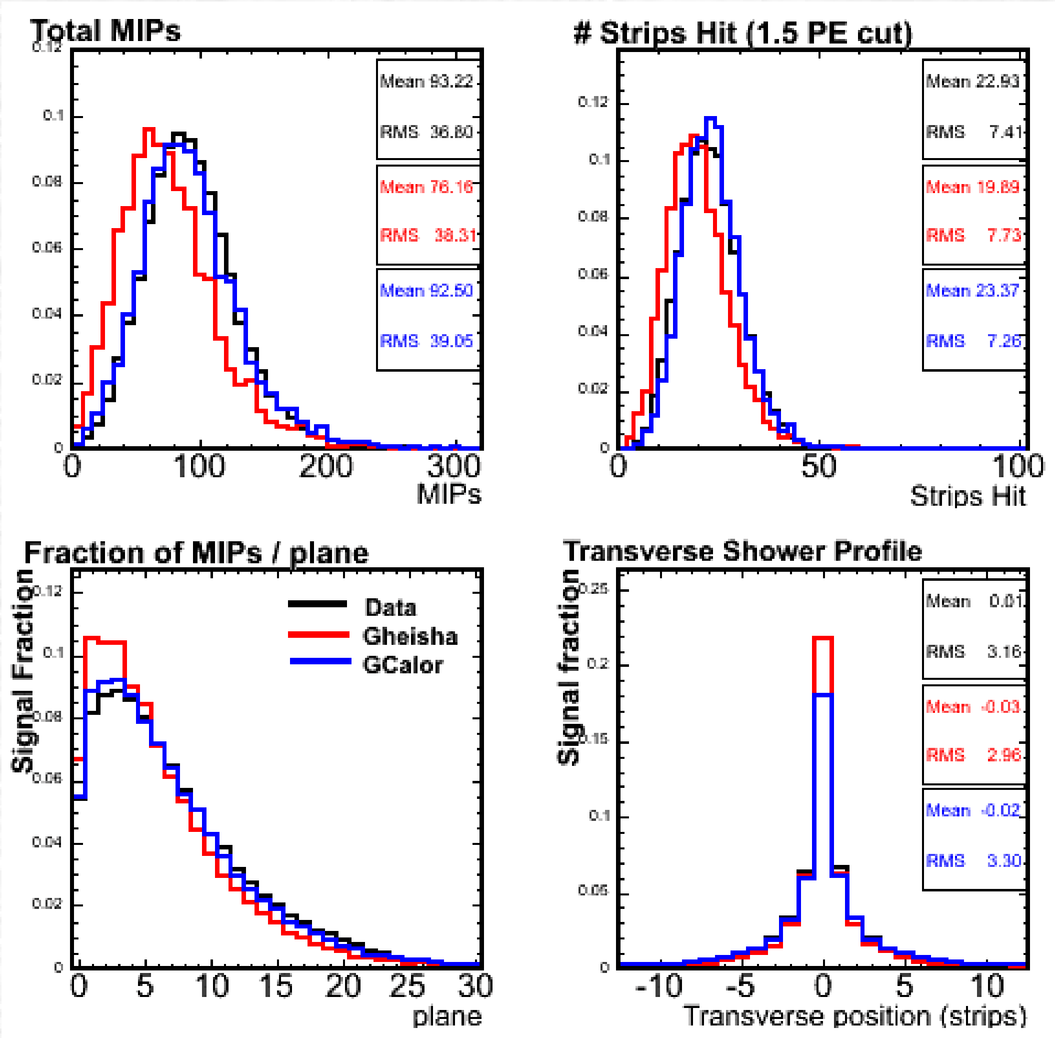




CalDet Data Analysis



CalDet Data Analysis



- Example of how CalDet data will be used in the future:
  - CalDet data show clear preference for GCALor hadronic shower modelling over GEANT-3
  - Understood because GCALOR has more detailed data, GEISHA an extrapolation

Detector Calibration

Data Analysis

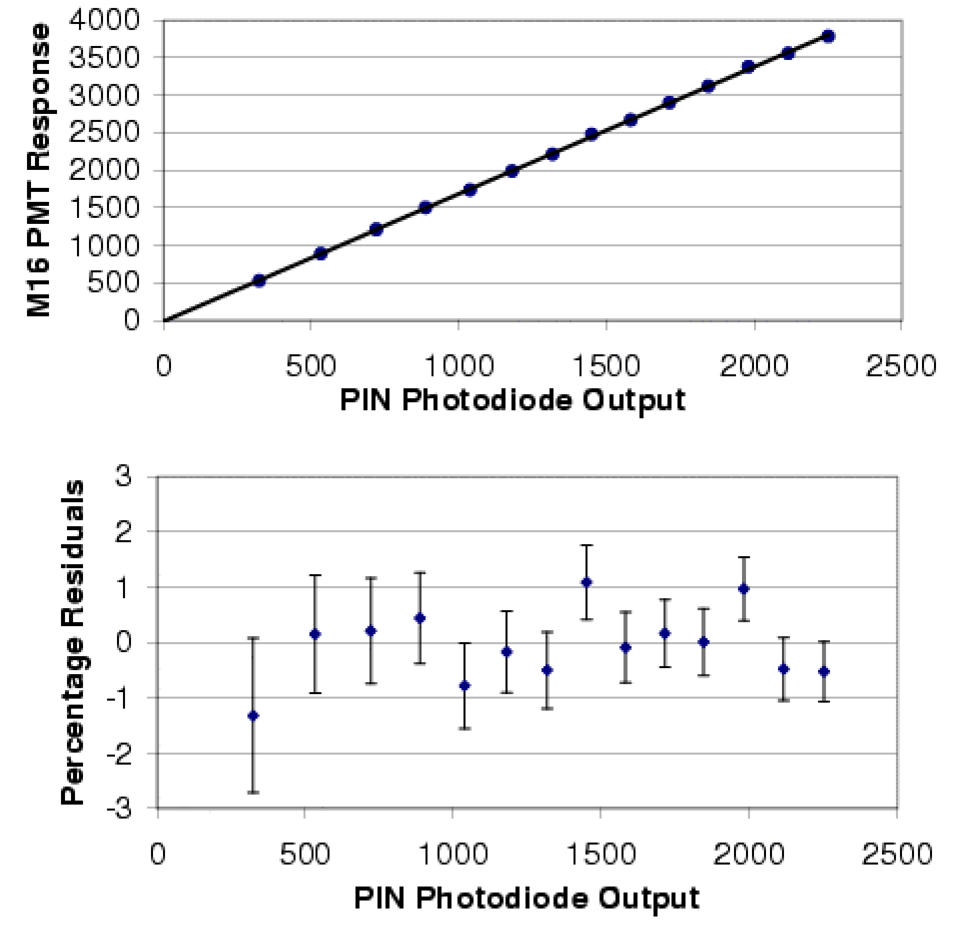
- Exploitation has already begun:
  - Calibration of the Detectors
    - Paramount to measuring the oscillation parameters
    - How do you know you have the same energy scale in both detectors?
    - Simple arguments demand 5% absolute, 2% relative
    - Non-trivial job, needs muons, LI system and CalDet data
  - Atmospheric Neutrinos
    - MINOS has unique capabilities in this arena
    - First measurement of sign selected oscillation will come from MINOS

Calibration

- Need first to calibrate Calibration Detector!
- Light Injection system used to take out PMT gain
- Strip to strip variations normalised using cosmic rays
- Final energy scale (Muon Energy Units, or MIPs) determined by beam muons of given energy
- Idea is to select similar muons (e.g. stopping cosmics) in the FD and ND
- Finally, CalDet provides MIP to GeV conversion

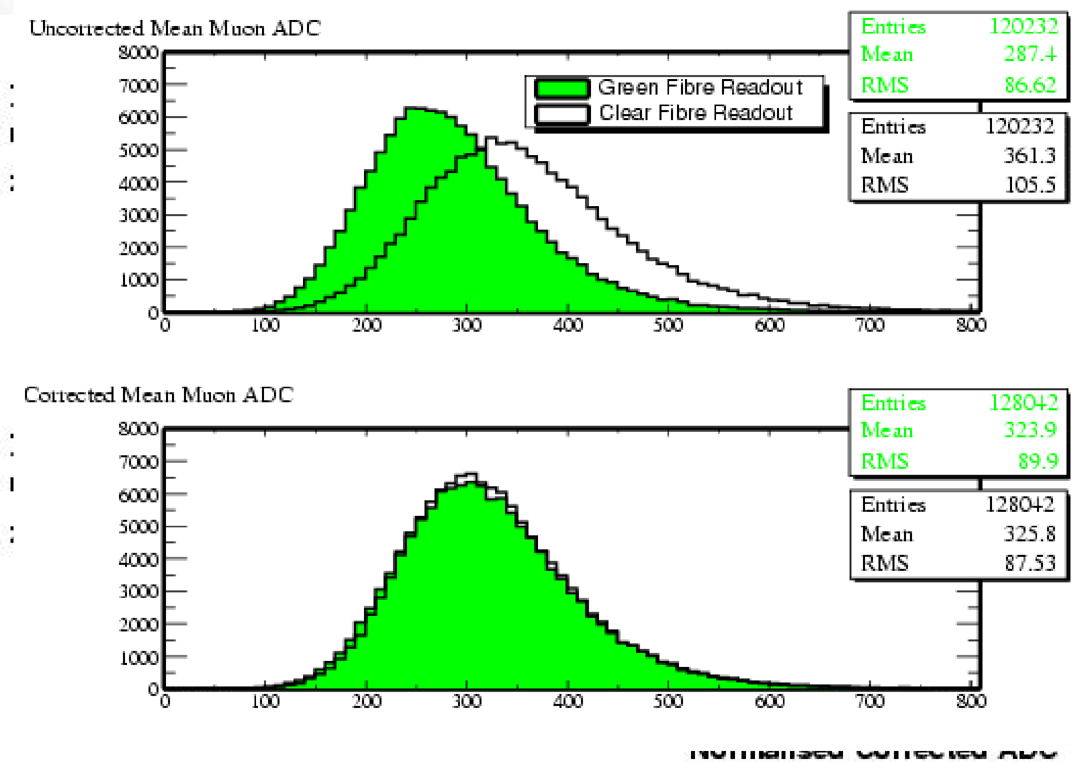
Calibration

- Light Injection System
  - Injects light of known and variable intensity into the PMTs via the WLS fibres
  - Hardware has been delivered to Far Detector, Near Detector and Calibration Detector
  - Demonstrated to work (at 1% level), invaluable debugging tool



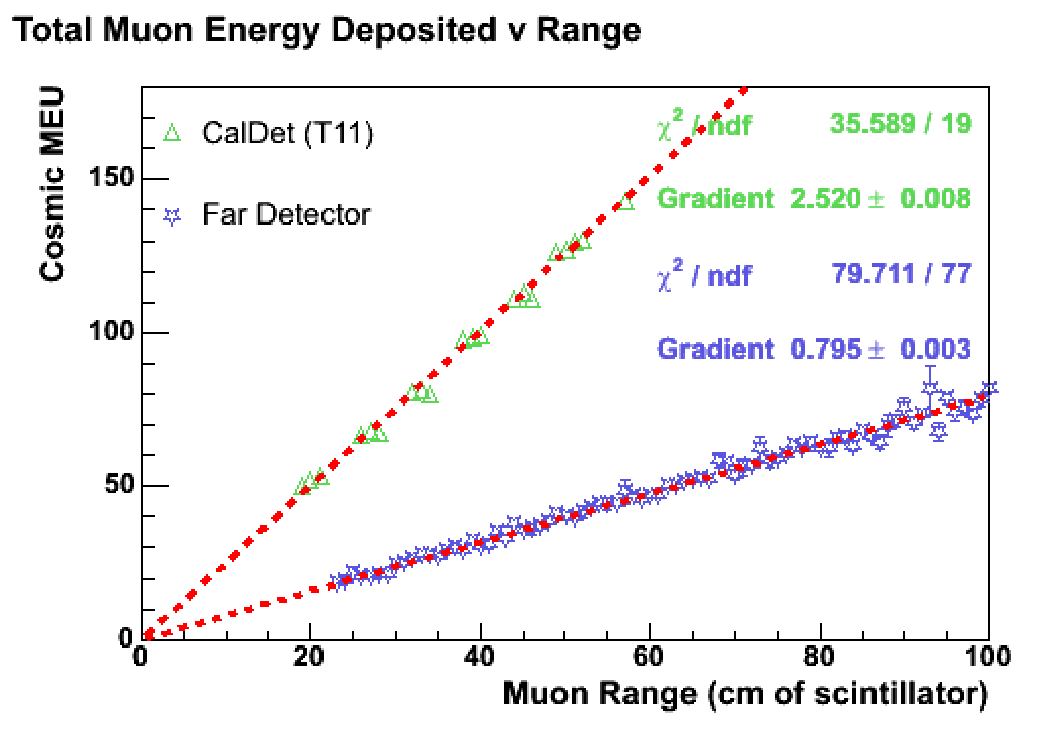
Calibration

- PMT Gains taken out to 1% with LI
- Cosmic ray muons taken in special runs
- Muon Energy Unit (MEU) universal unit (different in all detectors due to different energy distribution)
- Green side and clear side give markedly different light output
- Great to demonstrate calibration is working



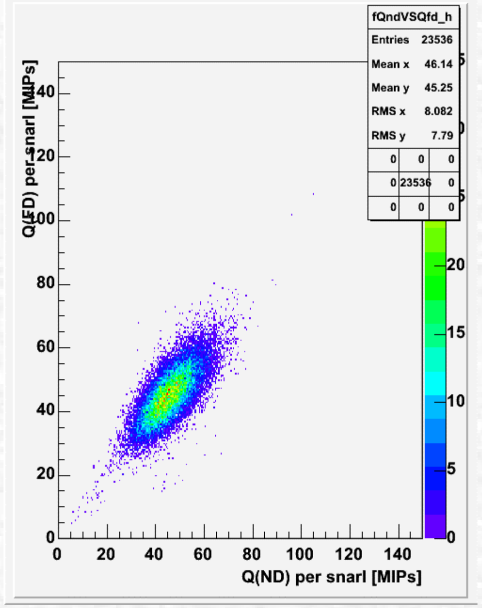
Cross Detector Calibration

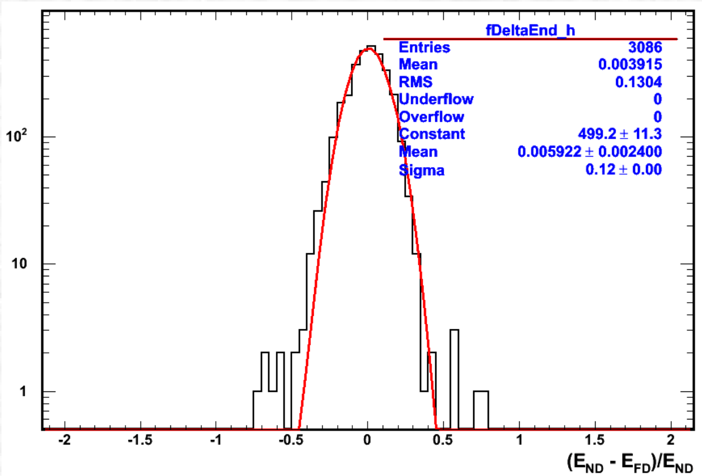
- Using stopping muons, plot muon range vs total energy deposited in detector
- Two different slopes due to difference between stopping μ energy scale, and cosmic energy scale
- Find the scale between strip-to-strip calibration across all detectors
- CalDet gives you GeV!



ND FD Comparison

- ND and FD have different electronics, readout
- Viking FD, QIE ND
- Cannot afford ANY unknown systematic differences
- Comparison at CalDet of ND and FD readout on same events was invaluable to measure differences
- Less than 1% observable difference



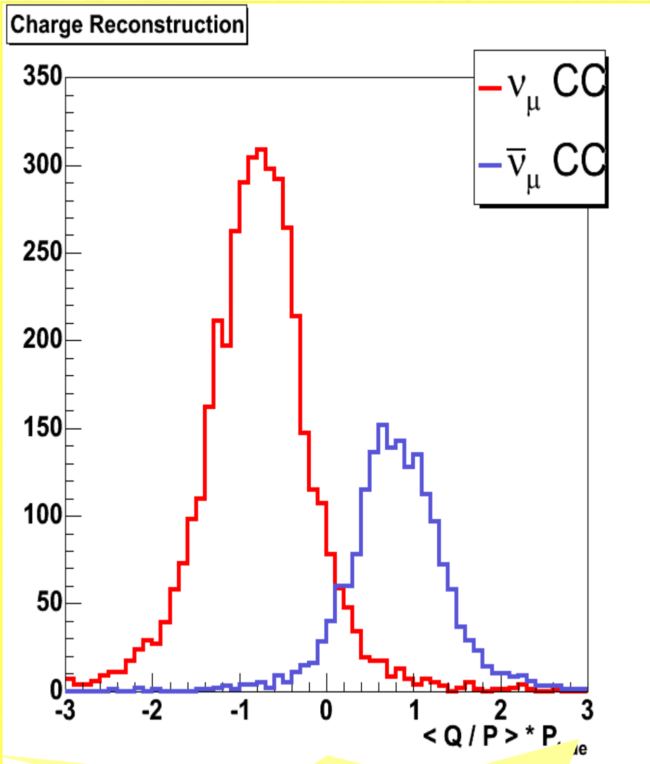


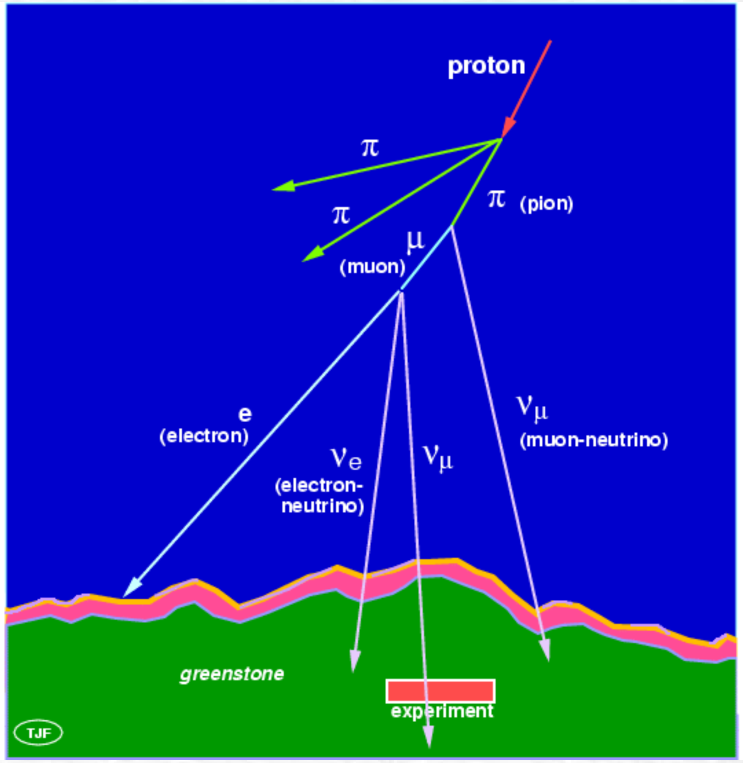
Atmospheric Neutrinos

This is very very preliminary

Atmospheric Neutrino Analysis

- MINOS now in a unique position to discriminate μ^+ from μ^- atmospheric neutrino events (B=1.5T)

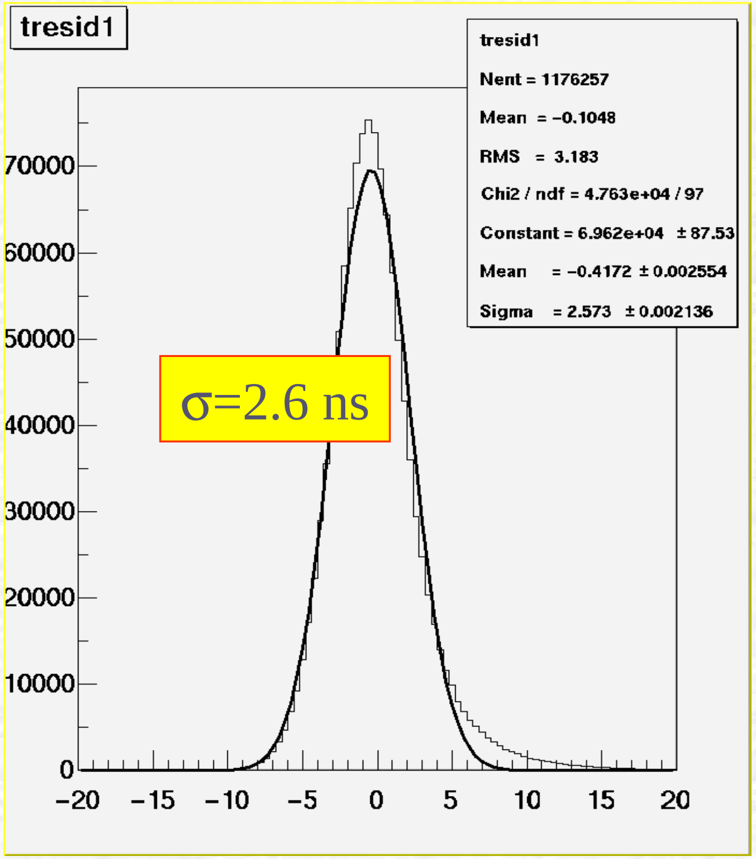




> 90% charge separation

MINOS Far Detector:Status

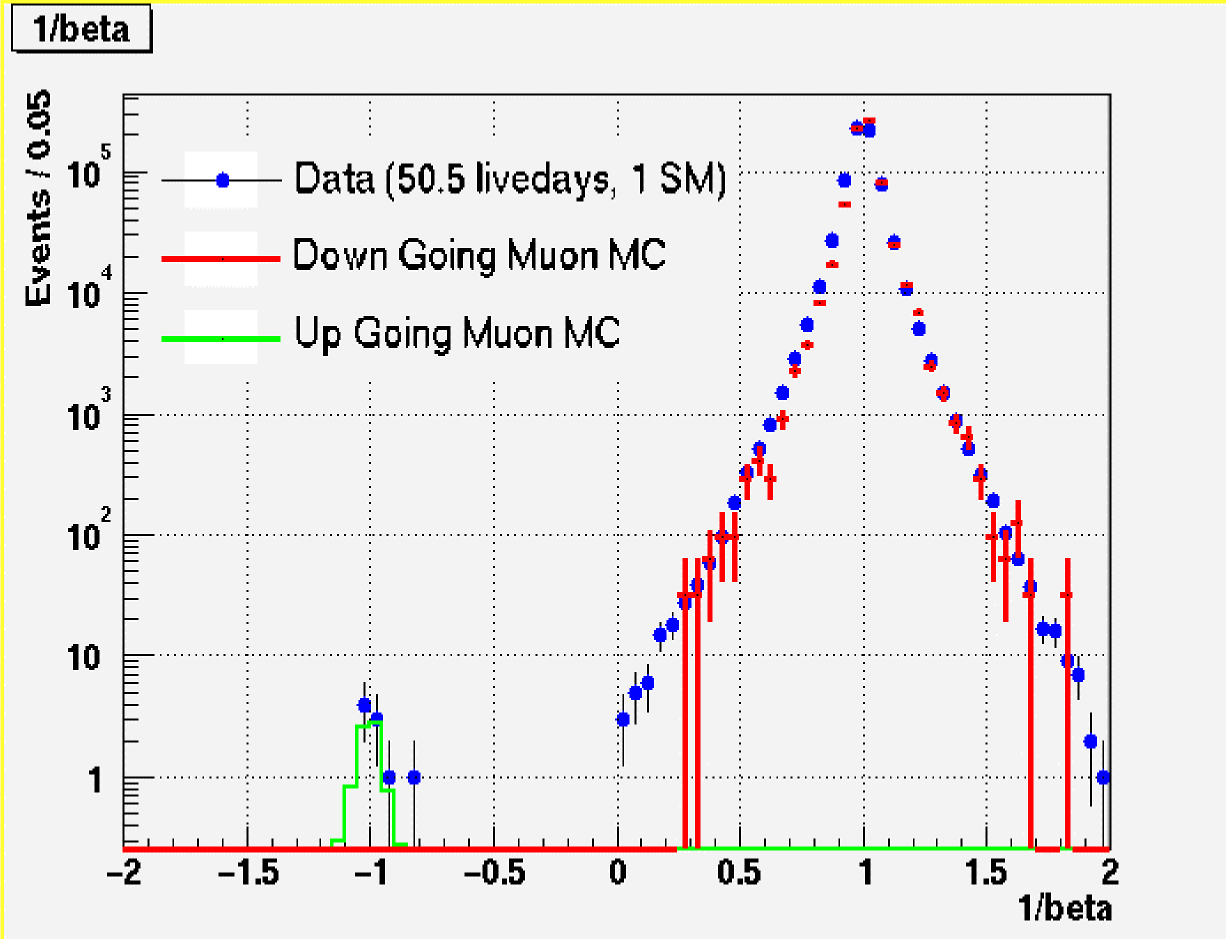
- FD is taking data with field on
- Measure charge and momentum from 0.5-70GeV/c : measure Eν for all events, for L/E
- Use timing and topology for event direction
- Distinguish ν from anti-ν for pμ>1GeV



Number of events in 24 kT years	Neutrino	Antineutrino
Reconstructed contained vertex with muon	620	400
Reconstructed upgoing muon	280	120

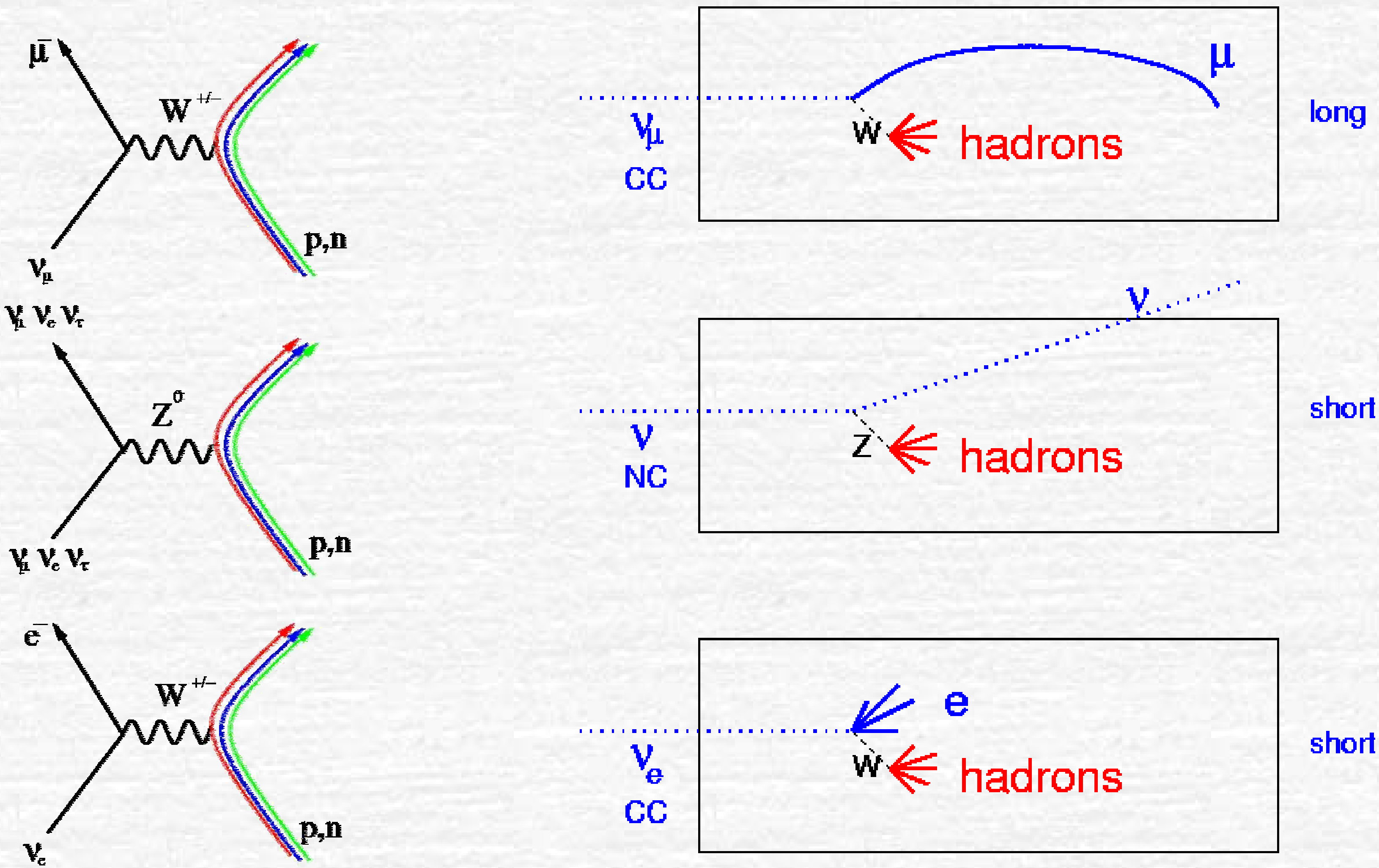
Upward going muons

- Atmospheric neutrino MC fits the data very well
- This was developed on MACRO

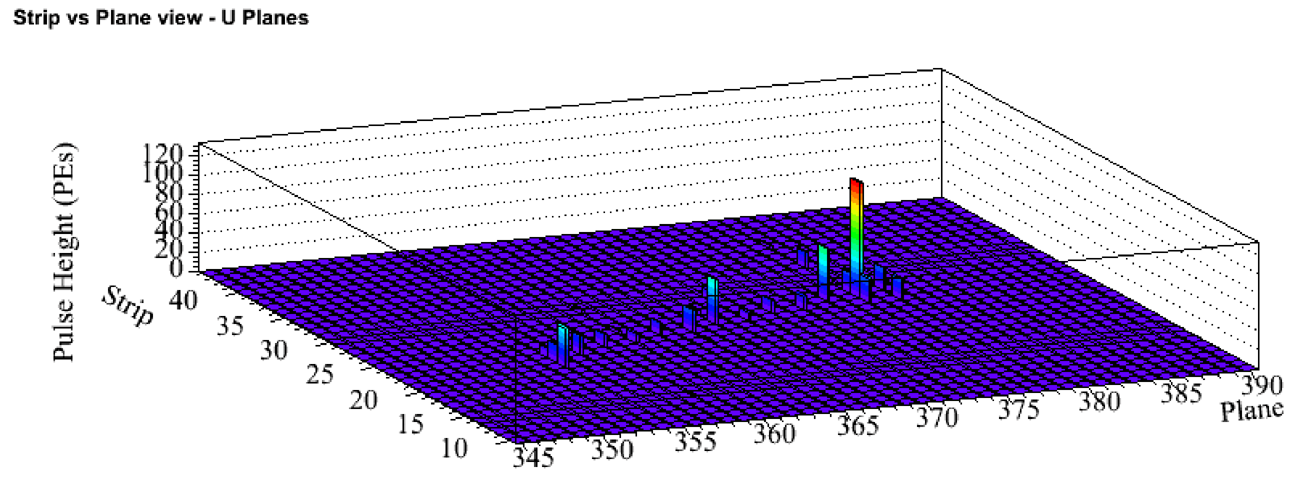


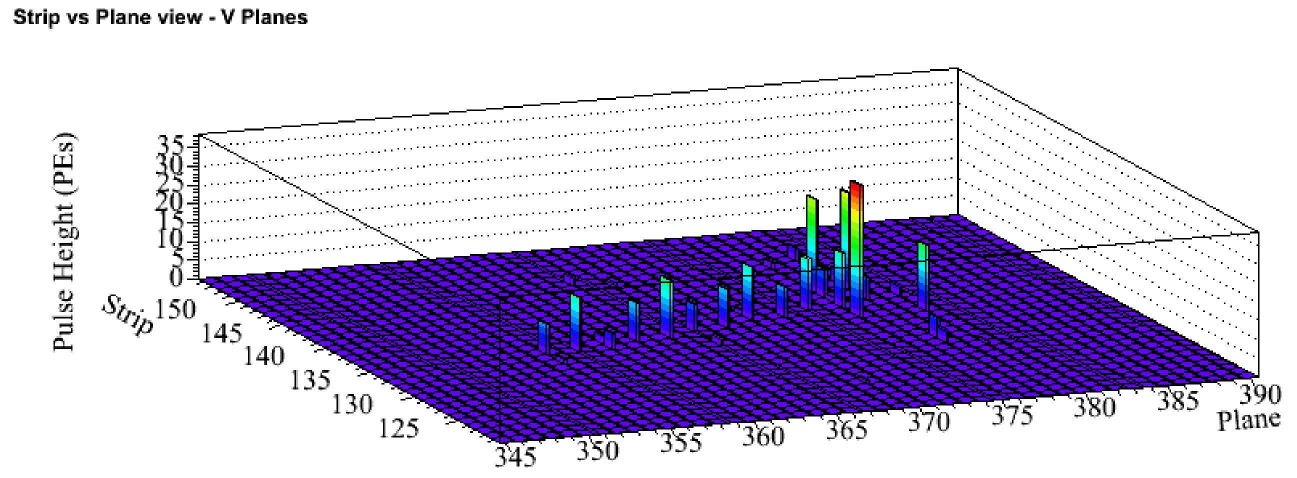
Physics with beam neutrinos

MINOS Physics Measurements



ν_μ events


Strip vs Plane view - U Planes
Pulse Height (PEs)
Strip
Plane
120 100 80 60 40 20 0
40 35 30 25 20 15 10
345 350 355 360 365 370 375 380 385 390

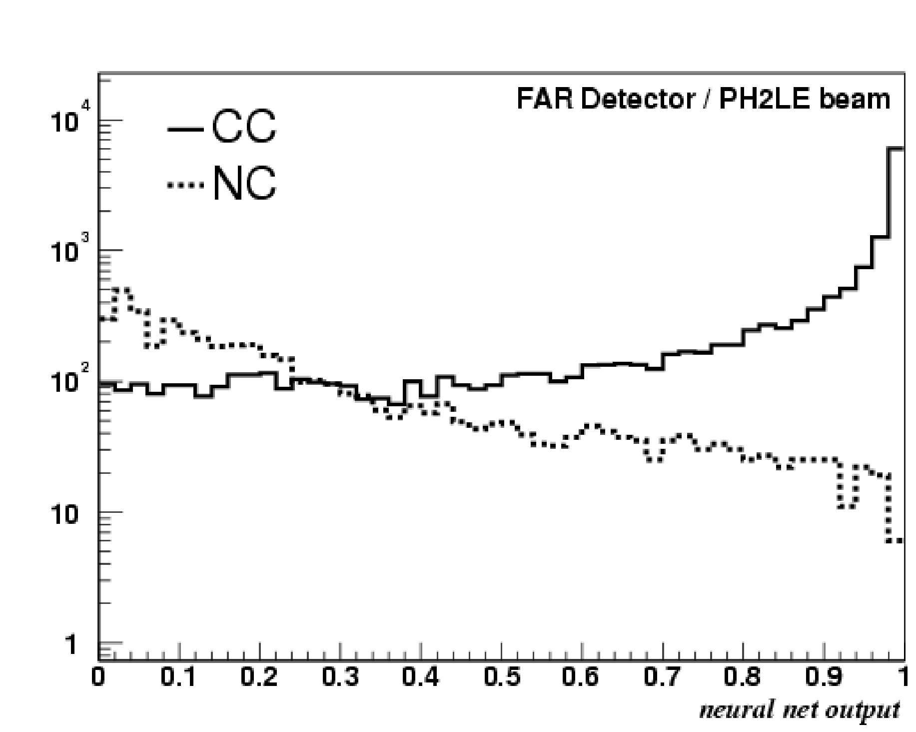

Strip vs Plane view - V Planes
Pulse Height (PEs)
Strip
Plane
35 30 25 20 15 10 5 0
150 145 140 135 130 125
345 350 355 360 365 370 375 380 385 390

Near Detector Measurements

- Near Detector provides the unoscillated ‘control sample’ of neutrinos to compare with Far Detector
- 200Kevents/Ton year unprecedented low energy neutrino sample for traditional neutrino physics
- Ambitious plan to collect and evaluate world’s neutrino scattering data and provide tools for accessing database
- Initiated by MINOS, now a collaboration including Durham/PDG

Neutral Current ID

- NC events : background for some, denominator for others
- Positive ID of NC events : algorithms being developed.
- ANNs being studied for resolution of CC and NC events
- Triggering another challenge: work underway to turn off threshold during beam spill
- Increase efficiency for NC event detection

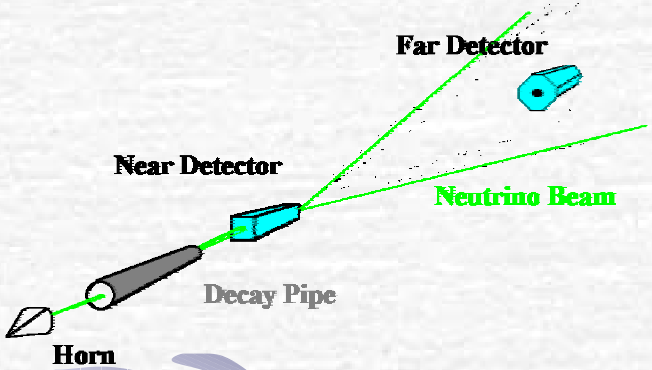


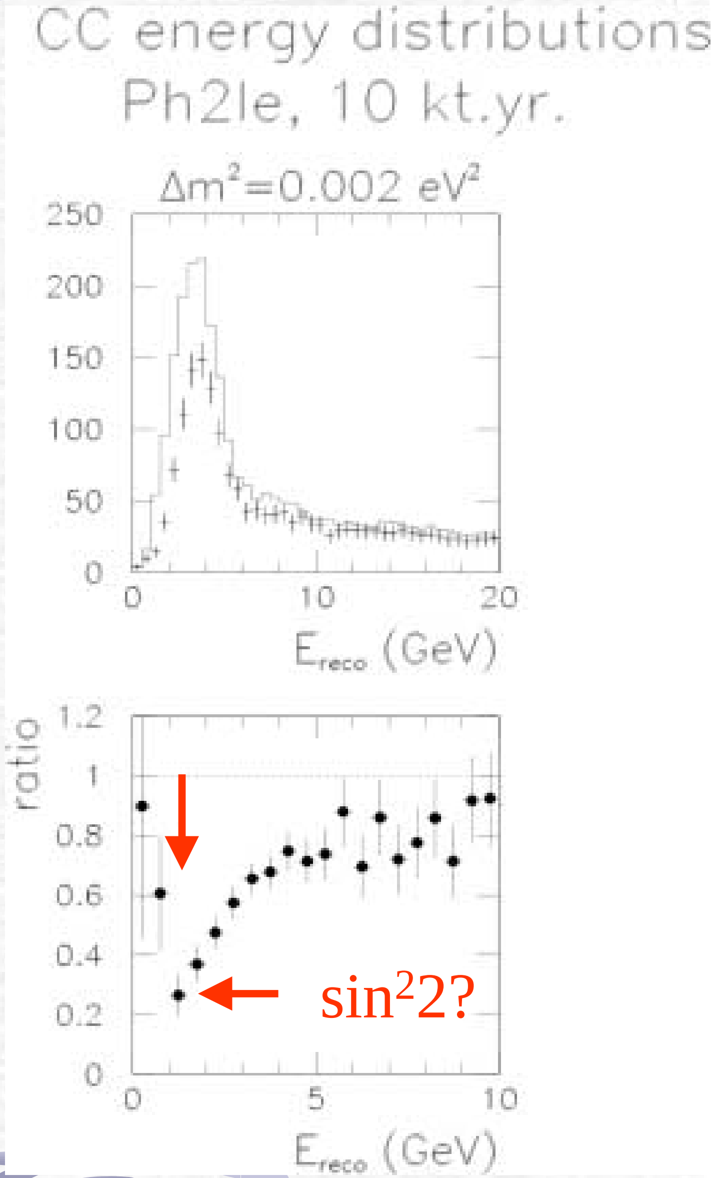
MINOS Physics Measurements

- $E\nu = E\mu + Eh$

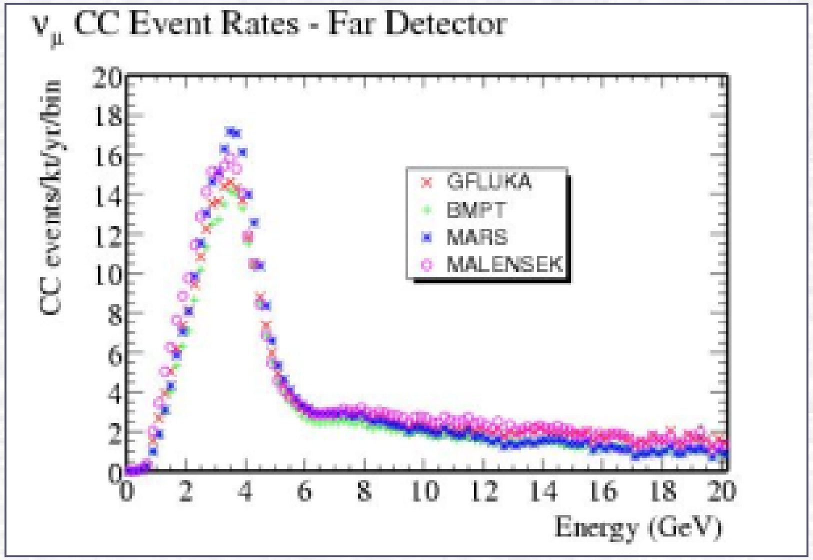
  $\Delta p\mu/p\mu$ = 6%–20%

  $\Delta E\mu/E\mu$ = 55%
- Comparison of ND and FD spectra give measurement of Δm^2 and $\sin^2 2\theta$
- One little problem is that ND and FD beam ain't the same: Heavily relies on MC for the FD spectrum prediction

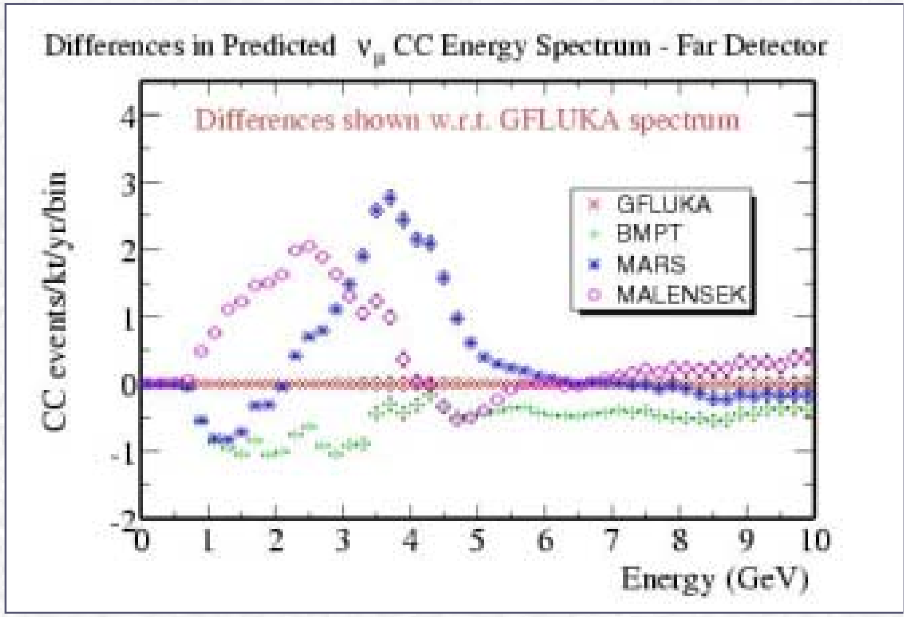




Muon charged current analysis



- Main uncertainty comes from pion beam divergence
- Secondary hadron production models



- E907 (MIP) will measure similar target and similar beam
- BUT, if not, what can we do?

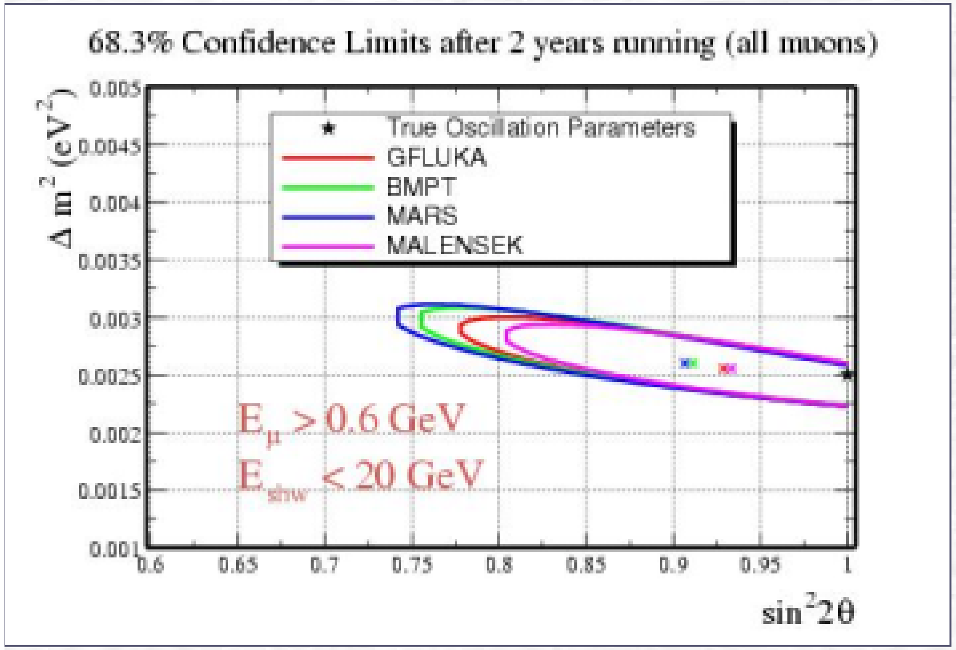
Muon charged current analysis

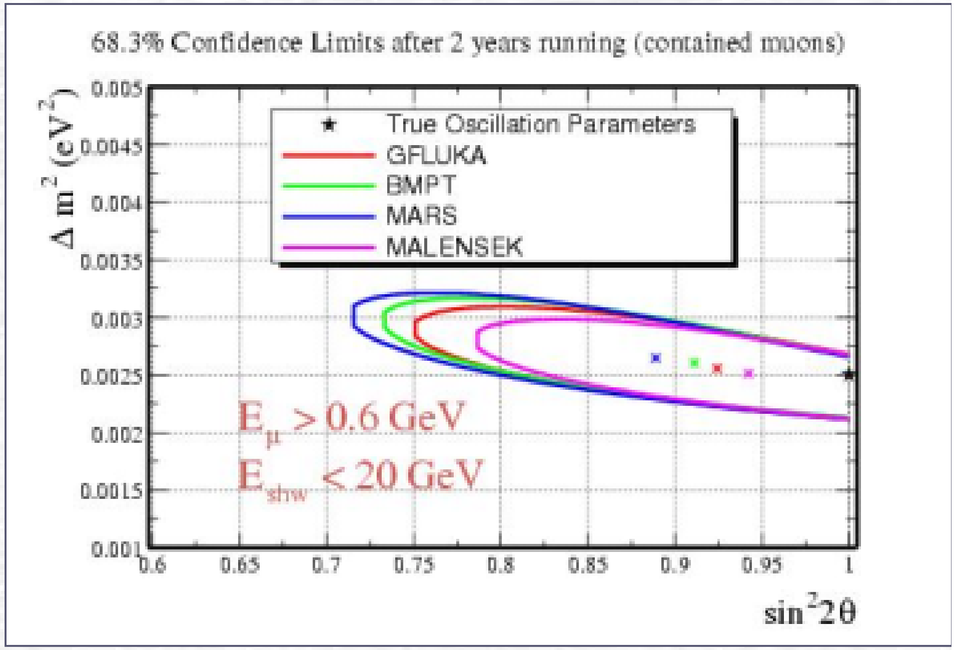
- Using muons alone (quasi elastic events) good parameter measurement is possible
- Different models make 5% difference (maximum)

▪Using all muons: measure Δm^2 to ~20% , $\sin^2 2\theta$ to ~18%

▪Contained muons: measure Δm^2 to ~22% , $\sin^2 2\theta$ to ~20%

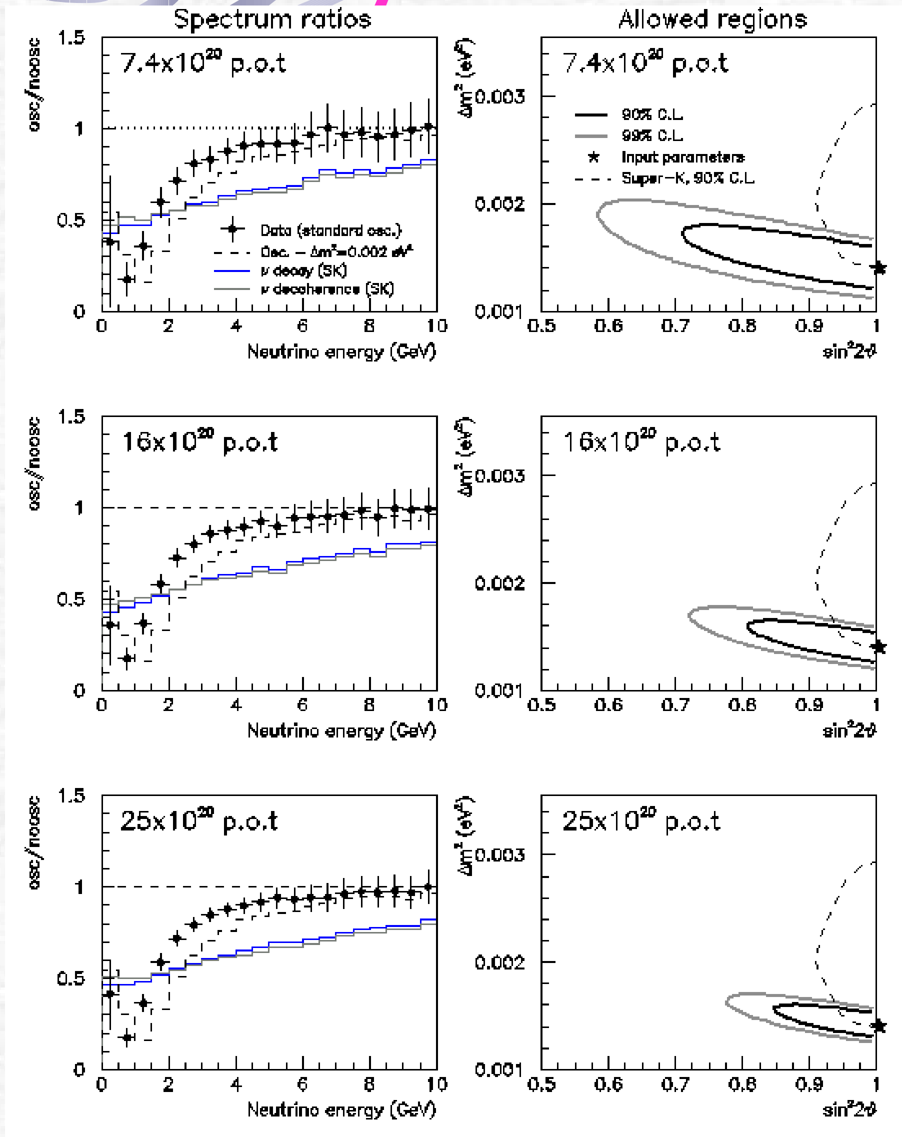
("worst case" errors from models)





Proton Intensity

- Proton Intensity is THE issue for ultimate success of MINOS
- Not part of MINOS project, but collaboration was asked to help
- PI improvement project now real

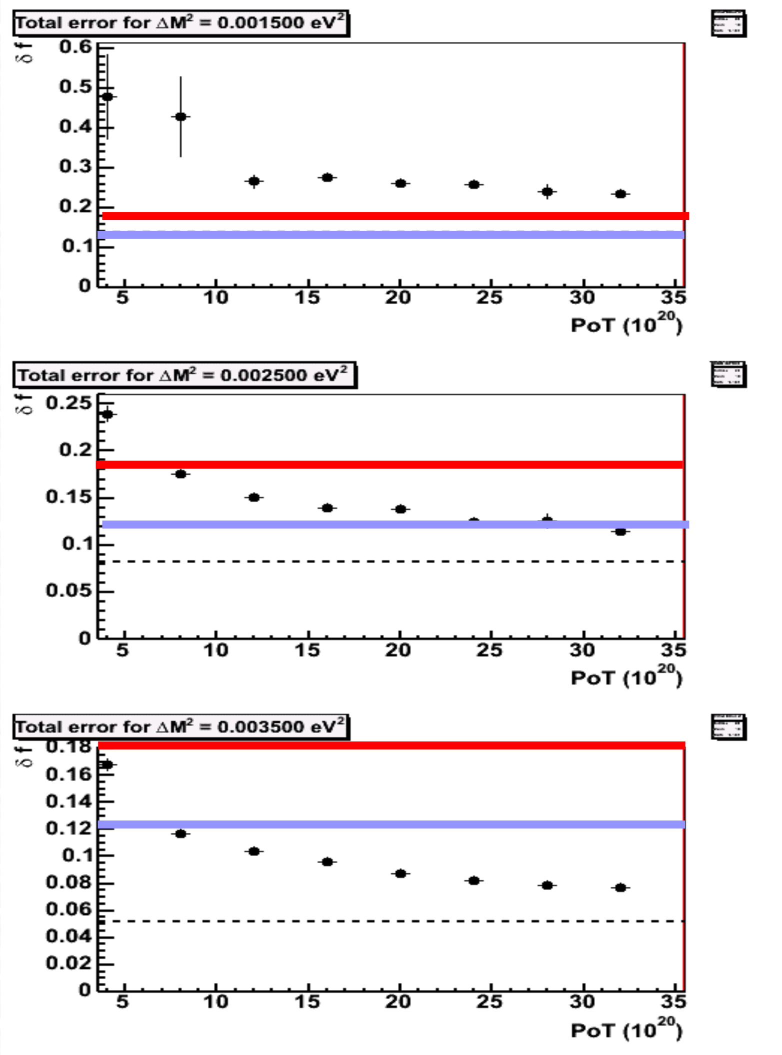


Proton Intensity

- Proton Intensity Project is real at FNAL
- ~$20M to be spent over the next 'years'
- Three places to improve:
  - Reduce losses in the booster : max p batch is 5 10e12
  - Store more protons in the Main Injector
    - Barrier Stacking : progress but cycle time too slow
    - Slip Stacking : 2 4e12 slipped to 1 8e12
  - Improve MI ramp time
    - Any slipping will increase MI cycle time
    - Useful for new proton driver no matter what

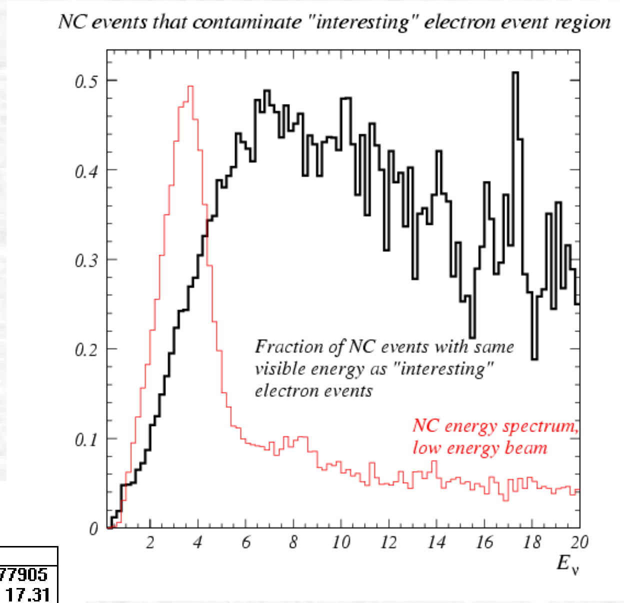
NC Physics Measurements

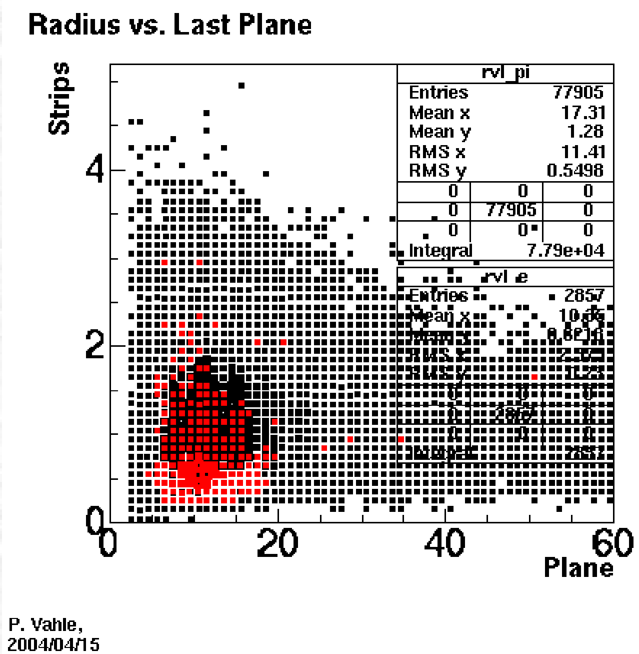
- NC events not expected to exhibit a deficit in FD because they are independent of neutrino flavour.
- Actually, this is not true in a model with Sterile neutrinos
- Plot shows results relative to Super-K



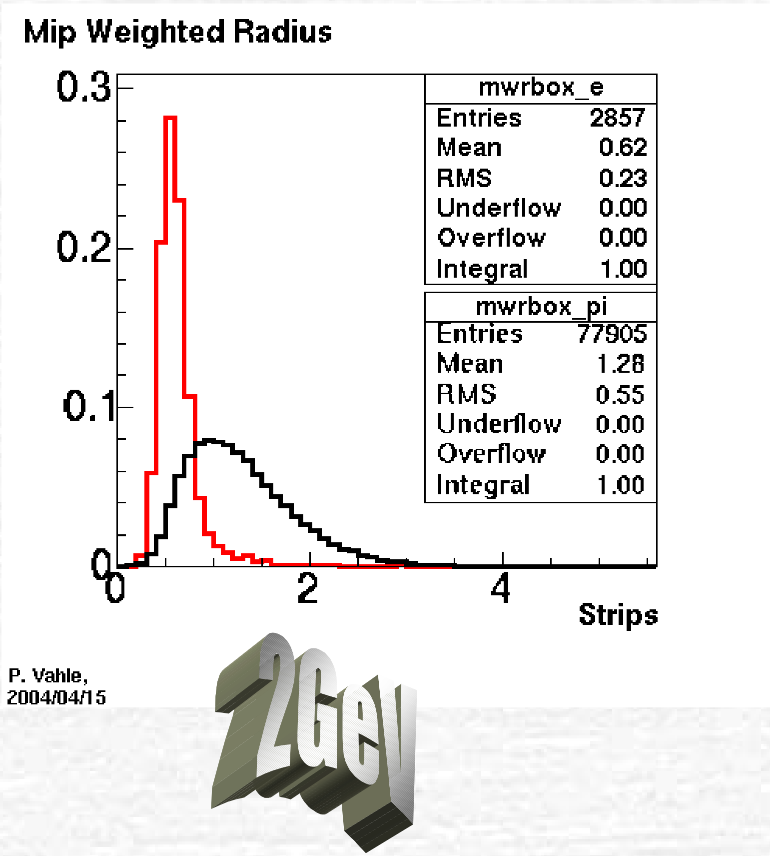
Electron Charged Current Analysis

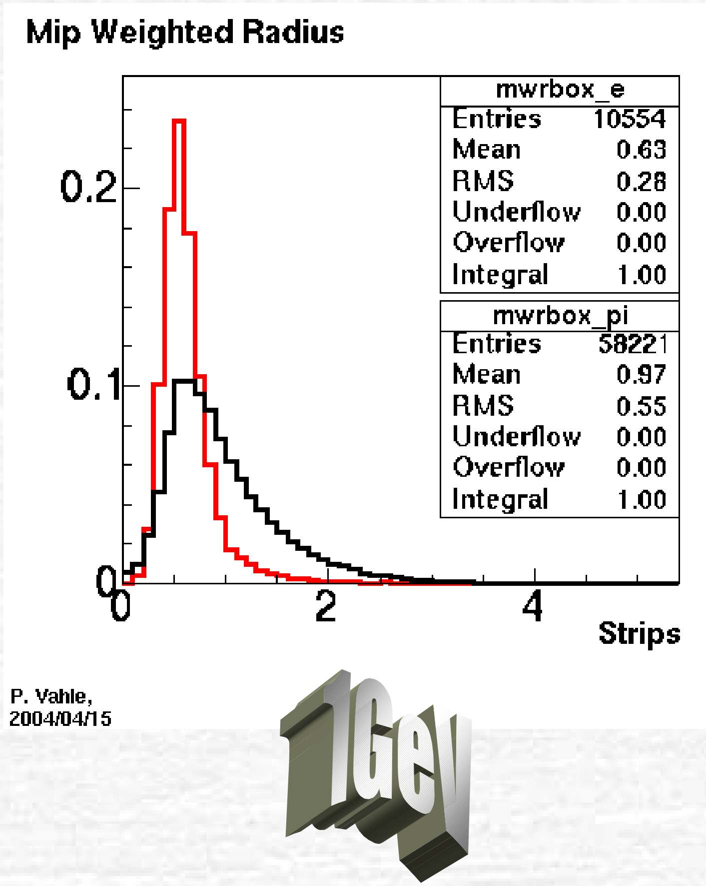
- Although MINOS not optimised for ν_e ID, we do have some sensitivity
- We should be able to improve on Chooz by a factor of a few
- CalDet data will be used to study NC/ν_e separation





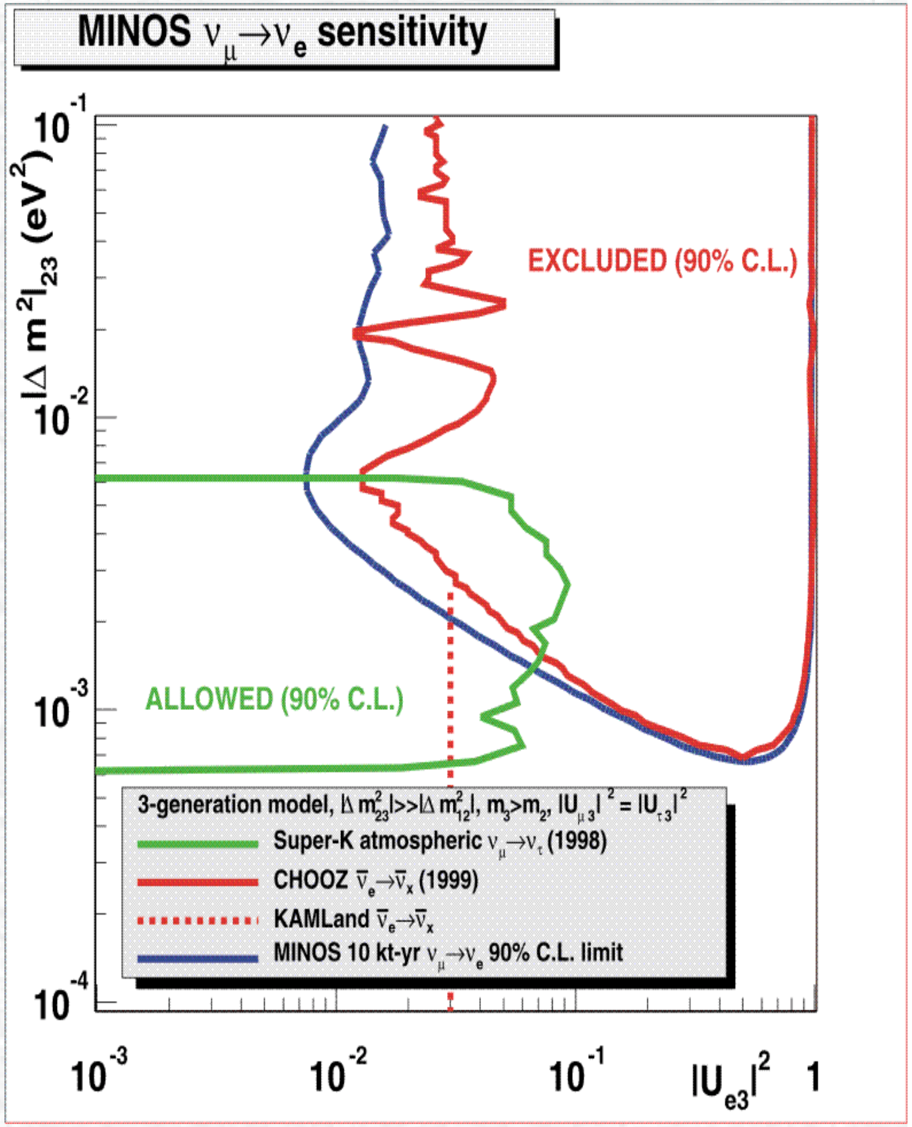
Electron charged current analysis





Physics Measurements

- Sensitivity is determined by statistical fluctuation of the NC π^0 BG in the far detector.
- Limit on U_{e3}^2 will scale like 1/sqrt(N) and is not limited by systematics for any realistic exposure.
- Limit can be further improved by removing high-energy tail from the NuMI beam and increased proton flux in later years.
- Ultimate MINOS limits ~3X better than here with 5 years



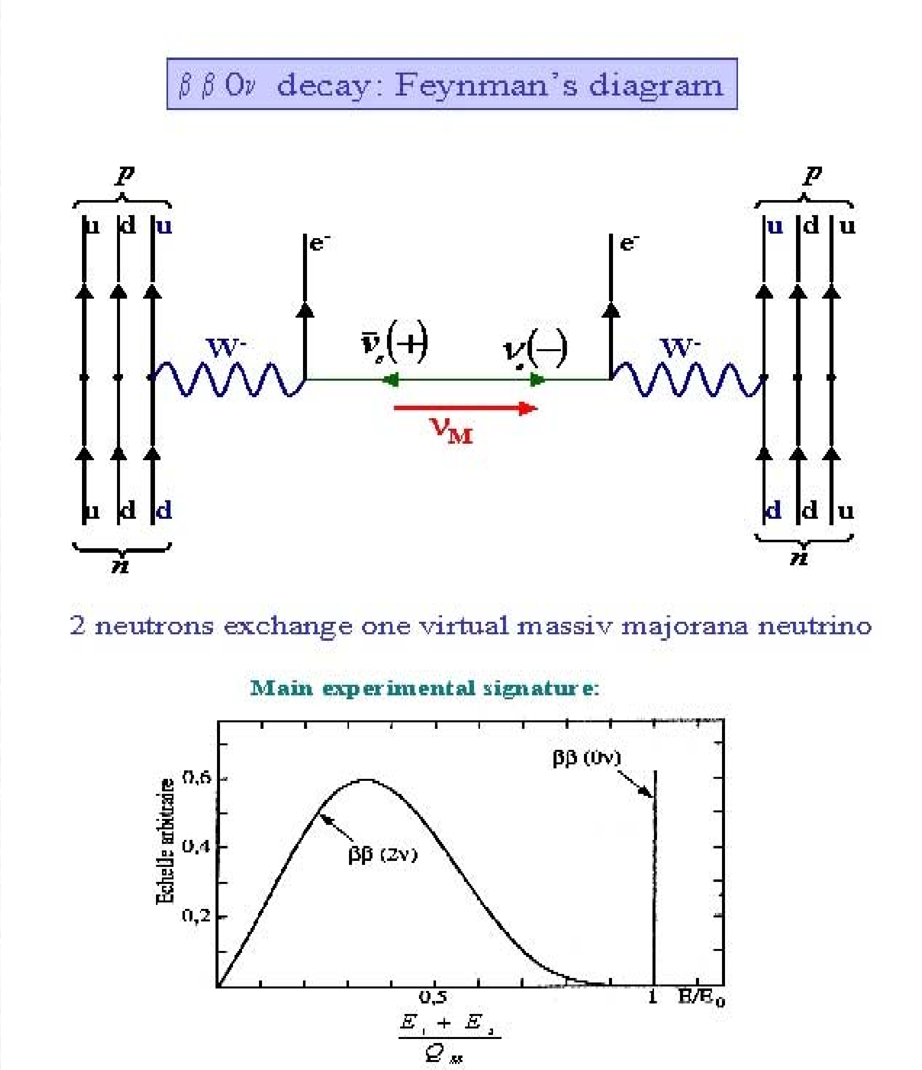
Recent Developments

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & s_{13} \\ -c_{23}s_{12}e^{i\delta} - c_{12}s_{13}s_{23} & c_{12}c_{23}e^{i\delta} - s_{12}s_{13}s_{23} & c_{13}s_{23} \\ s_{23}s_{12}e^{i\delta} - c_{12}c_{23}s_{13} & -c_{12}s_{23}e^{i\delta} - c_{23}s_{12}s_{13} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Major future effort will try to pin down U_{e3} (θ_{13})
- If its big enough, look for CP violation
- Efforts (to be) proposed in Japan,Off-axis NuMI, BNL, GranSasso (from Frascati), Frejus (from CERN) …..
- Manpower for all these???

Recent Developments

- The fundamental type of neutrino will not be measured by long baseline experiments
- Neutrinos could be Majorana particles (particle=antiparticle) because they are neutral
- Plans for new, bigger Double Beta Decay experiments are being developed
- Should push limits on Majorana mass down to 0.01-0.05eV :
- Maybe its been found already?



Future Plans

- NuMI beam will turn on late 2004
- MINOS will take atmospheric neutrino data until beam start end of 2004
- First measurement of +/- upward going muons with magnetic field of MINOS
- ~10-20% measurement of mixing parameters within 2 years of turn on (by end 2006)
- The next few years will undoubtedly be an exciting time for neutrino physics!