MINOS/NuMI Update

Hai Zheng
California Institute of Technology
for MINOS Collaboration

QUARKS
St. Petersburg, Russia
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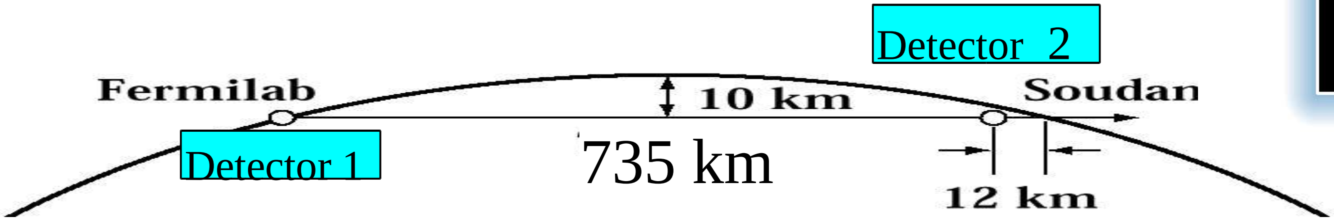
- **Introduction to MINOS/NuMI**
    - **Physics goals of MINOS**
    - **NuMI beamline**
    - **MINOS detectors**
- **Beam data analysis**
    - **Oscillation result from 0.93 x 10^{20} POT**
- **Summary**

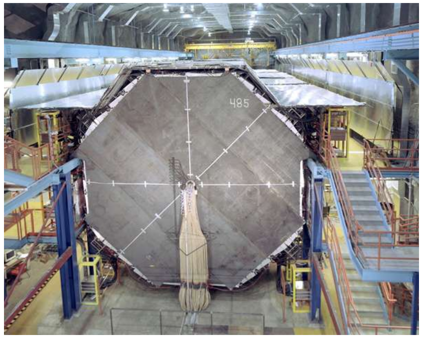
Introduction

- MINOS is an accelerator-based Long-Baseline neutrino experiment to study ν_μ oscillation with high statistics
- ν's are generated at Fermilab from 120 GeV protons and delivered by the NuMI beamline



Near Detector
980 Tons
measure the beam energy spectrum
Fermilab, IL

Far Detector
5.4 kTons
measure the oscillation
Soudan, MN



Both detectors have magnetic fields:

first large underground ν detectors to identify μ- and μ+ separately

MINOS Physics goals

ν_μ disappearance :

- Confirm ν oscillations
- Measurement of $\sin^2(2\theta_{23})$ & Δm^2_{23} :
  - $P_{oscillation} = 1 - \sin^2(2\theta_{23})\sin^2(1.27\Delta m^2_{23}\ L/E)$
  - **Goal: 1 σ precision 3-5%**

Search for ν_e appearance:

Might be able to observe ν_e appearance

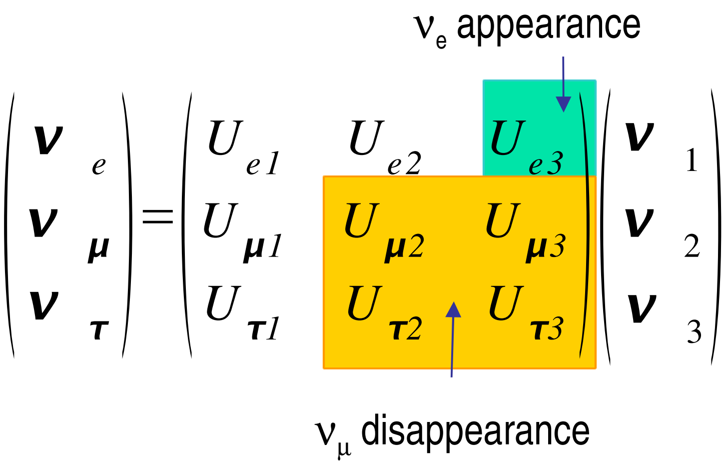
$P(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2(1.27\Delta m^2\ L/E)$

Search for/rule out exotic phenomena

- Sterile neutrinos
- Neutrino decay

Atmospheric ν measurements and capable of first direct observation of separated atmospheric ν and $\bar{\nu}$ oscillations

First MINOS paper: Phys. Rev. D73:0720002 (2006)



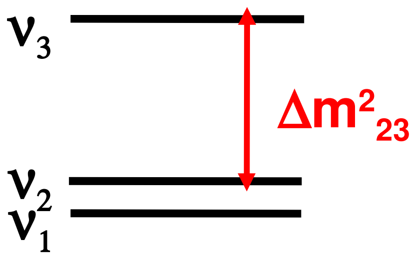
ν_e appearance

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

ν_μ disappearance

$$\sin^2 2\theta = 4U^2_{\mu 3}(1 - U^2_{\mu 3})$$

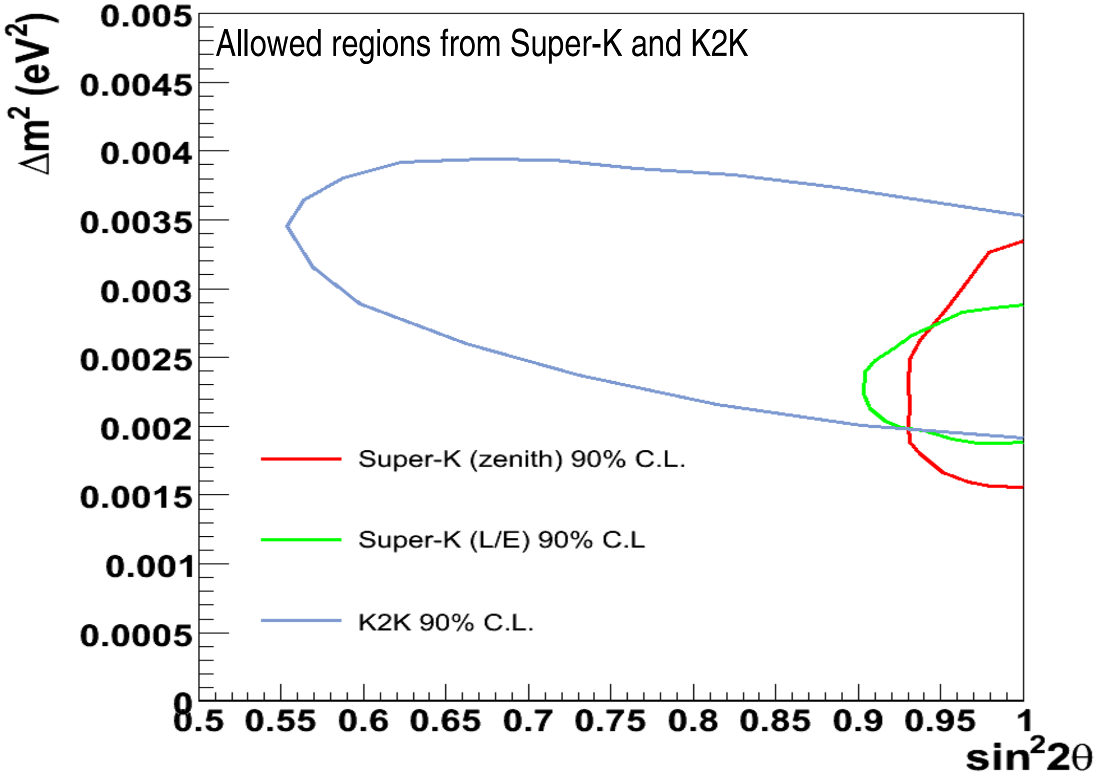
$$\Delta m^2_{23} >> \Delta m^2_{12}$$



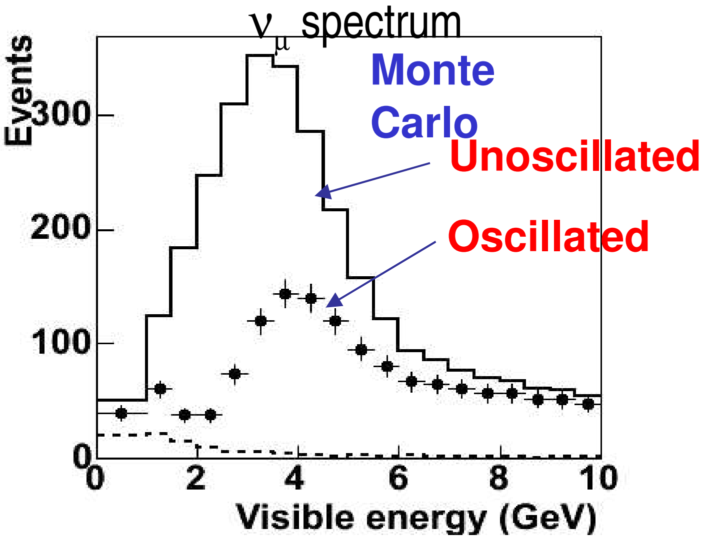
Oscillation Measurement

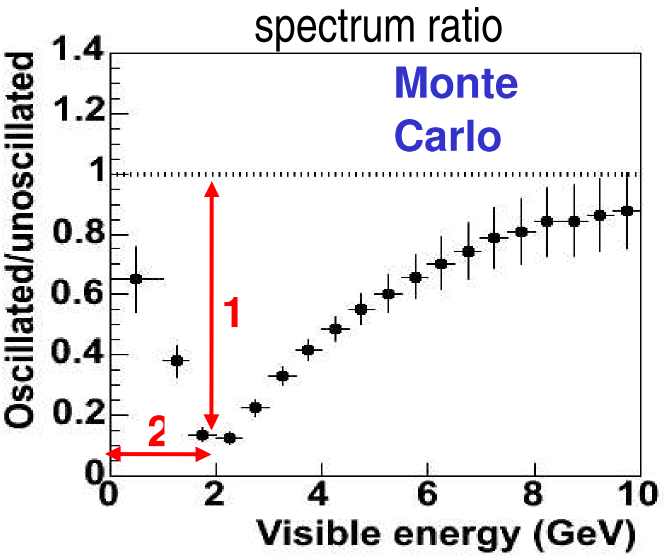
Look for a deficit of ν_μ events at FD

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \underset{1}{\boxed{\sin^2 2\theta}} \sin^2(1.267 \underset{2}{\boxed{\Delta m^2}} L/E)$$



Current best measurements of Δm^2_{23} and $\sin^2 2\theta_{23}$ are provided by Super-Kamiokande (atmospheric neutrino analysis) and K2K (9×10^{19} pot)





NuMI – MINOS @ Fermilab

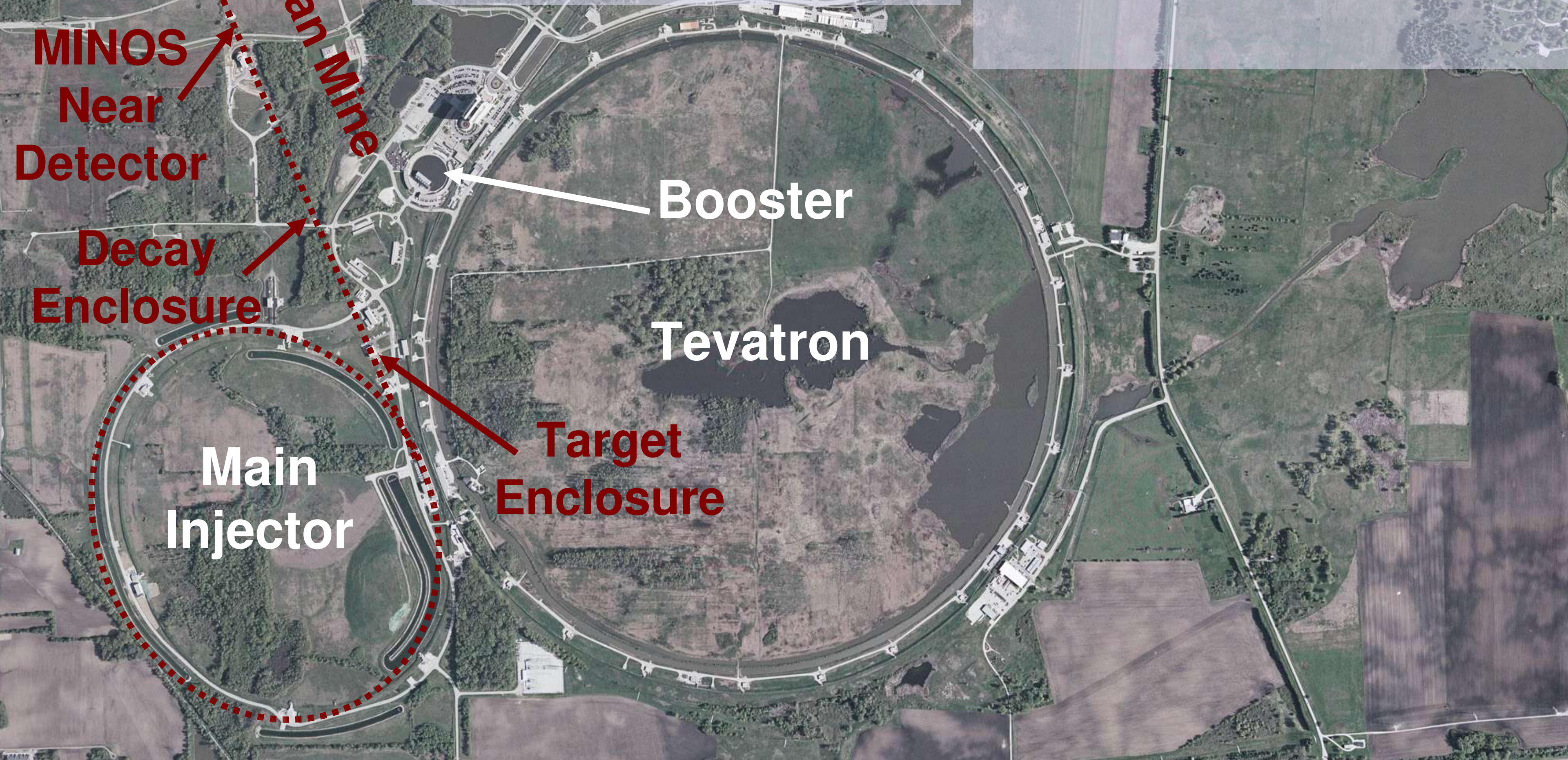
Main Injector (MI)

goal for this year

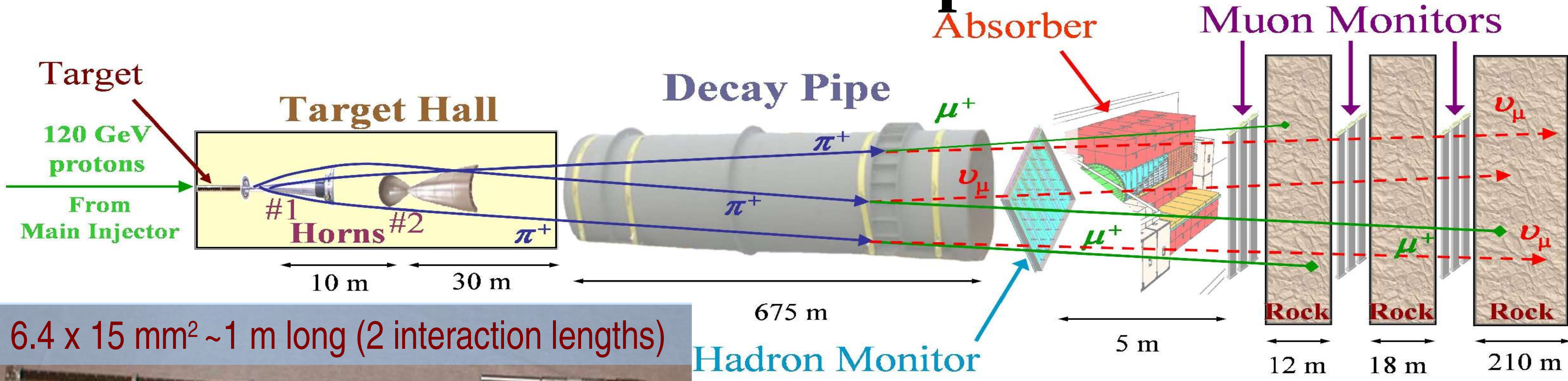
accelerate 2.5 x 10^{13} protons
every 1.9 sec to 120 GeV
~10 μsec spill, 0.4 MW

NuMI Beamline

To transport protons to the target & generate the ν beam
Designed for up to 4 x 10^{13} protons/pulse

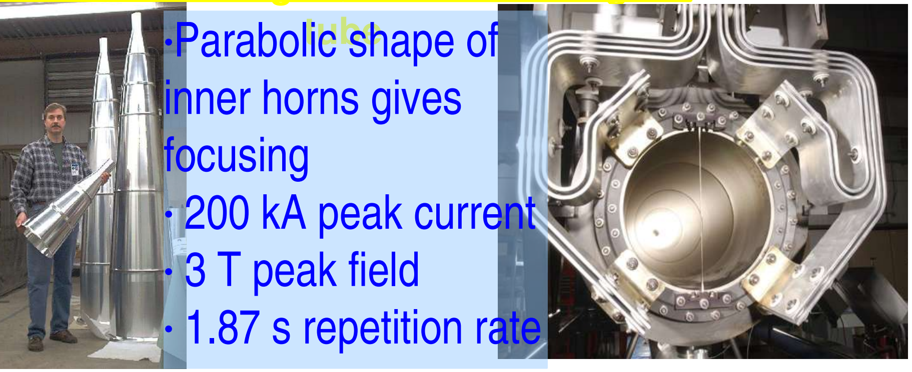


NuMI Beamline Components

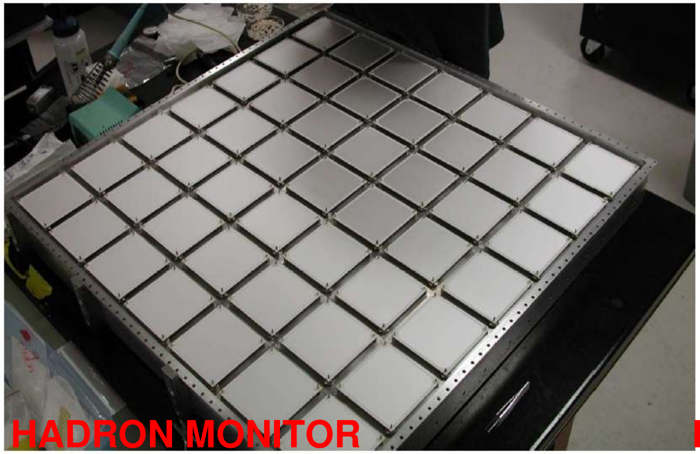


6.4 x 15 mm² ~1 m long (2 interaction lengths)

Graphite target w/ water cooling tube



- Parabolic shape of inner horns gives focusing
- 200 kA peak current
- 3 T peak field
- 1.87 s repetition rate

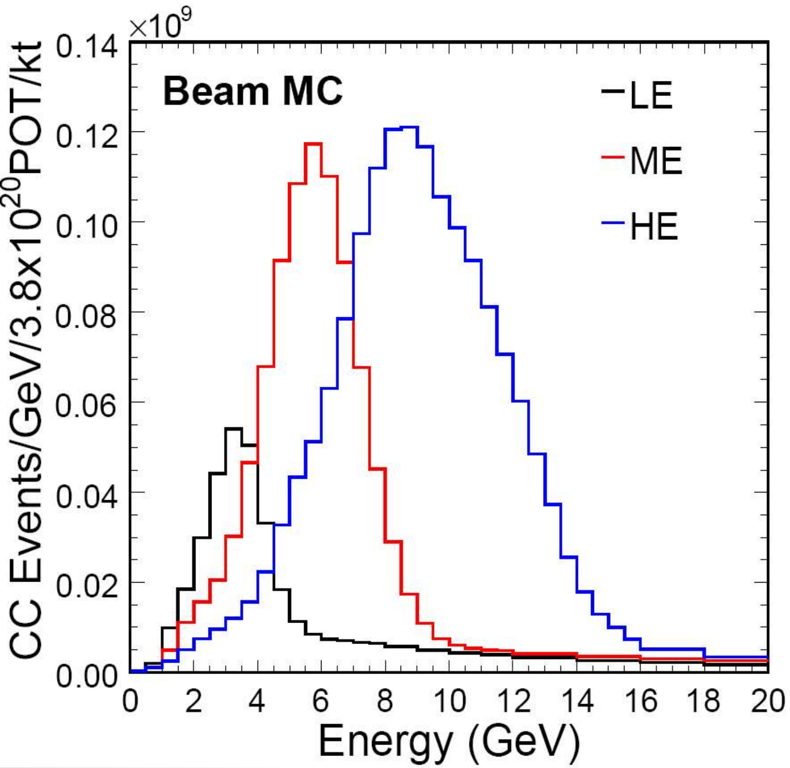


HADRON MONITOR

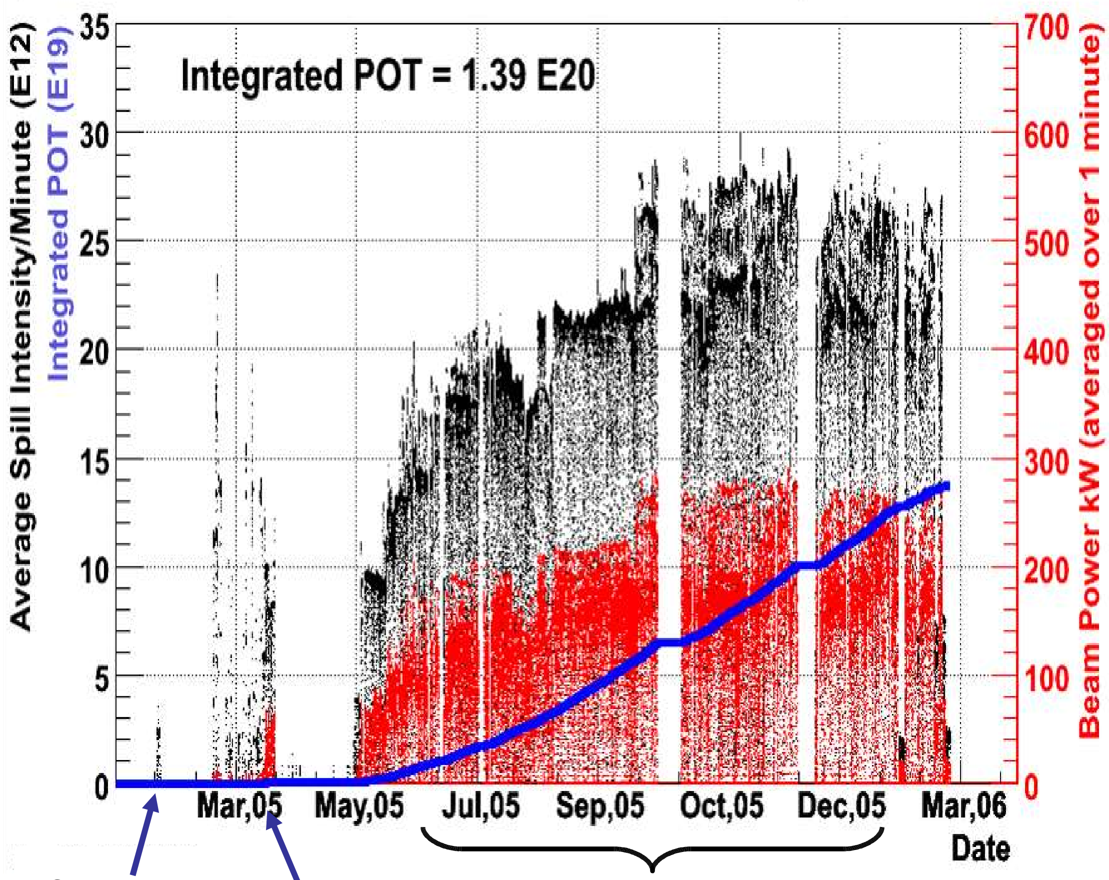
MUON MONITOR

- Aimed downwards at 58 mrad toward the Soudan mine
- Protons hit segmented graphite target & charged hadron beam is focused with two magnetic horns
- 675m long steel vacuum decay pipe
- Hadron monitor and hadron absorber downstream of decay pipe
- 200m rock upstream of Near Detector for muon absorption & muon monitors

NuMI ν Beam Running



Beam	Target z position (cm)	FD Events (no osc) / 1e20 pot
LE-10	-10	390
pME	-100	970
pHE	-250	1340



Observation of neutrinos in Near Detector

Start of LE running

Dataset used for the oscillation analysis

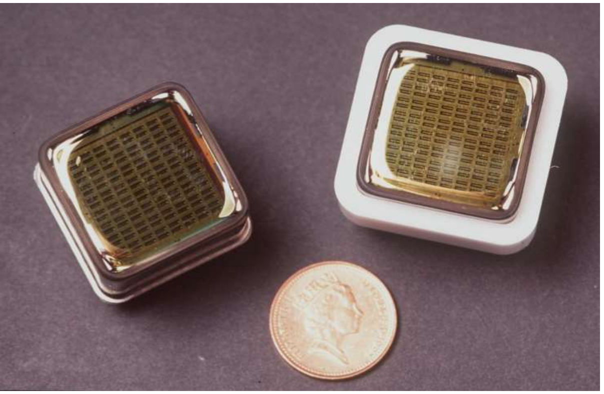
- **Currently running in the LE-10 configuration**
- Beam composition (events in low energy configuration): **98.5% $\nu_\mu+\bar{\nu}_\mu$ (6.5% $\bar{\nu}_\mu$), 1.5% $\nu_e+\bar{\nu}_e$**
- Data in five different beam configurations were taken for commissioning and systematics studies

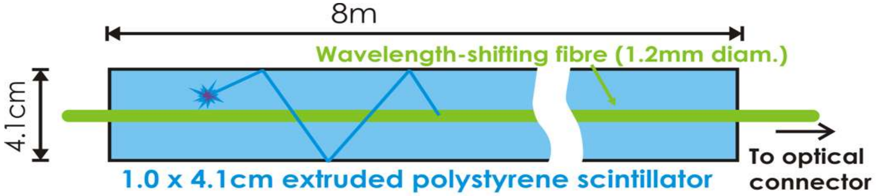
Detector Technology

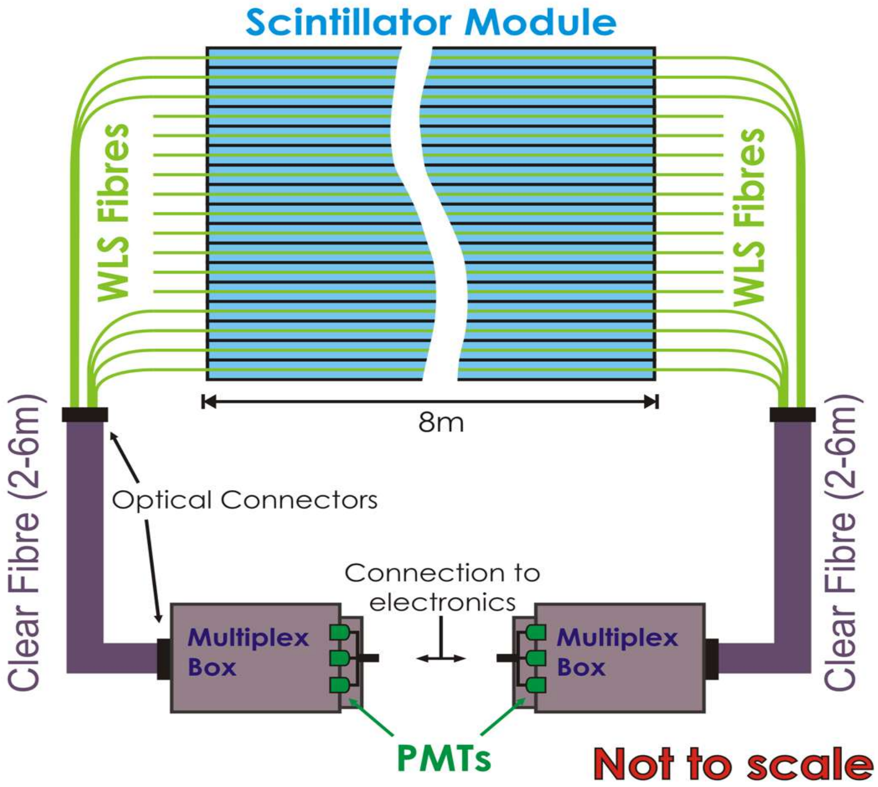
Scintillator Module

- Iron/scintillator sampling calorimeters
  - –2.54 cm thick steel absorber
  - –1 cm thick, 4.1 cm wide polystyrene strips with TiO_2 coating
- Kuraray WaveLength Shifting (WLS) fibers (1.2mm) collect light, clear fibers transfer light

- Multi-anode Hamamatsu PMT
  - –Far Det. M16 16-channel PMT(8 fibers/pixel)
  - –Near Det. M64 (4 fibers/pixel in spectrometer)

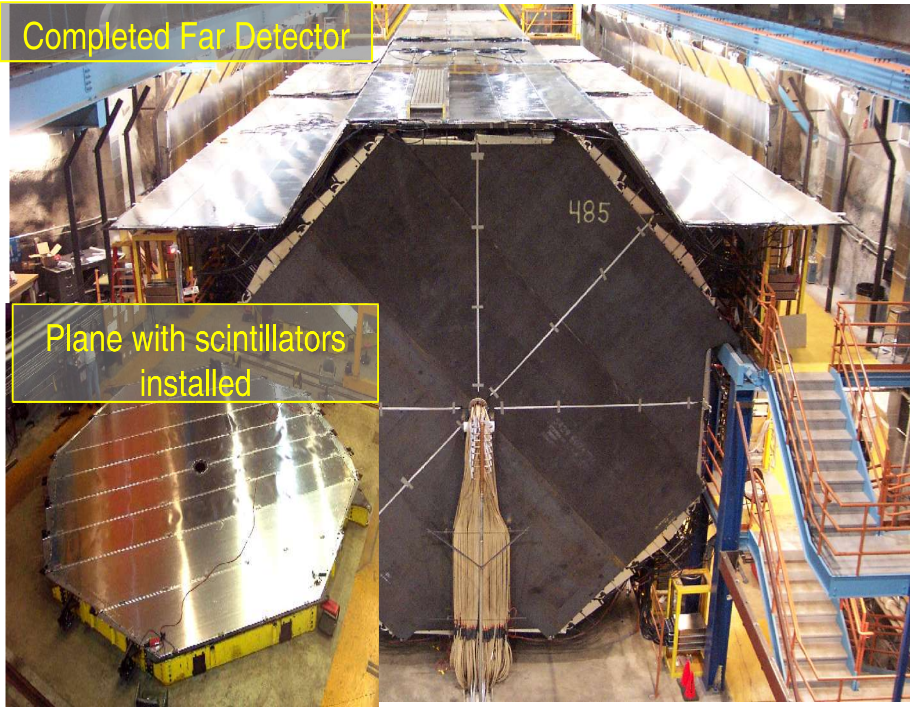






readout system:
Far Det. from both ends of fibers
Near Det. from one end of fibers

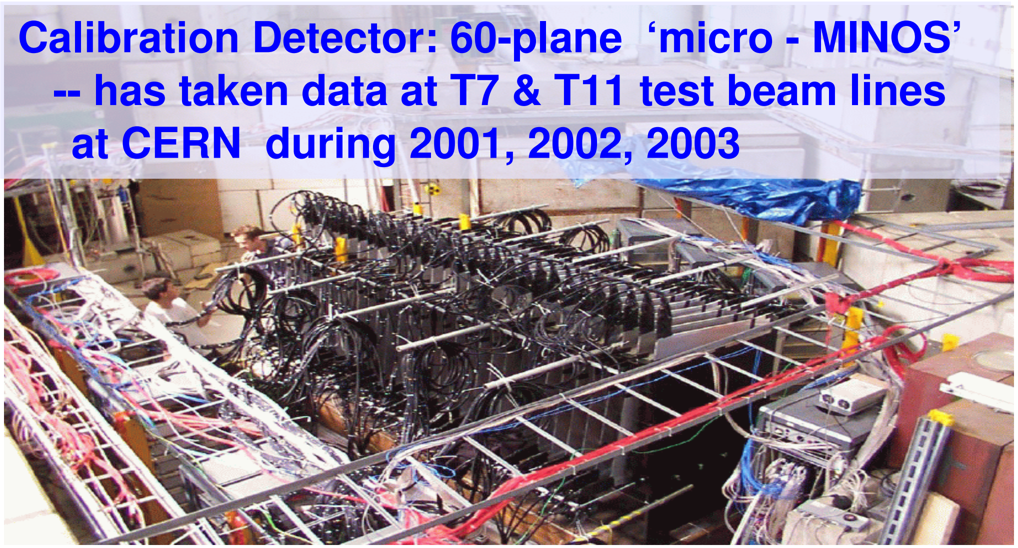
MINOS Detectors



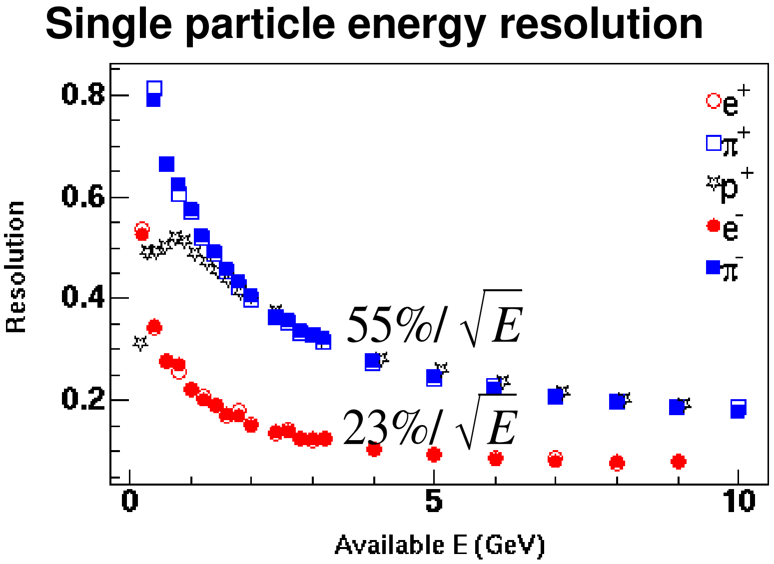
8m octagonal tracking Calorimeter
486 planes (5.4 kTon total)
2 super modules(SM) : 15 m long each
Toroidal B-field: 1.3 T at r = 2m
Installation fully completed in July 2003

282 single steel planes 980 Tons
Calorimeter (120 planes) is partially instrumented except for 1/5 of planes with full coverage
Spectrometer (162 planes) has only every 5th plane instrumented
Plane assembly was completed in August 2004

MINOS Calibration System

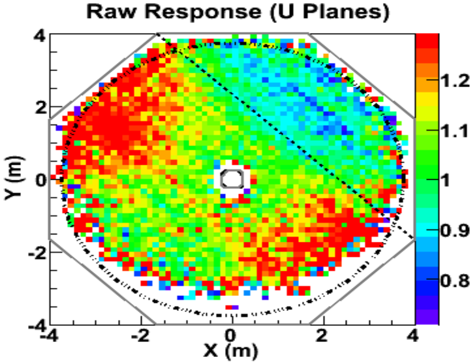


Calibration Detector: 60-plane ‘micro - MINOS’ -- has taken data at T7 & T11 test beam lines at CERN during 2001, 2002, 2003

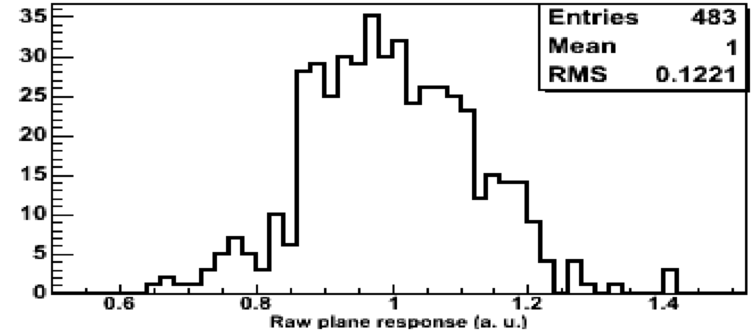


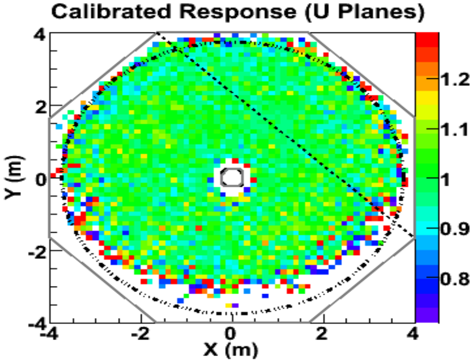
Single particle energy resolution

- Calibration of ND and FD response using:
  - Light Injection system (PMT gain)
  - Cosmic ray muons (strip to strip and detector to detector)
  - Calibration detector (overall energy scale)
- Energy scale calibration:
  - 1.9% absolute error in ND
  - 3.5% absolute error in FD
  - 3% relative

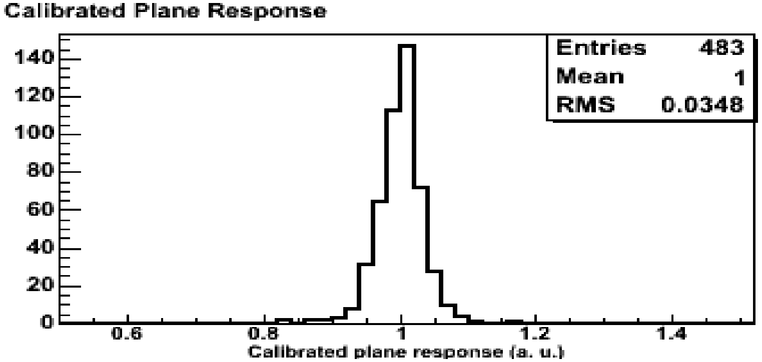


Raw Response (U Planes)





Calibrated Response (U Planes)

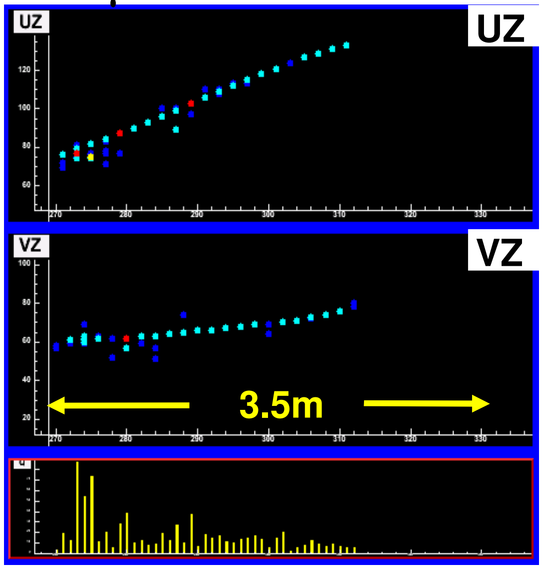


Calibrated Plane Response

Event Topologies

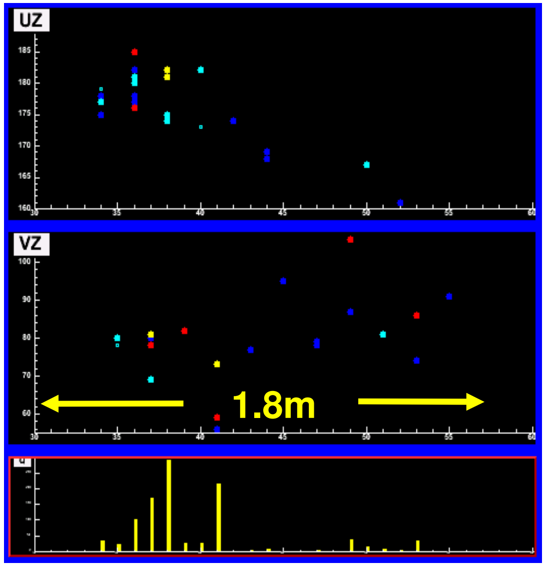
Monte Carlo

ν_μ CC Event



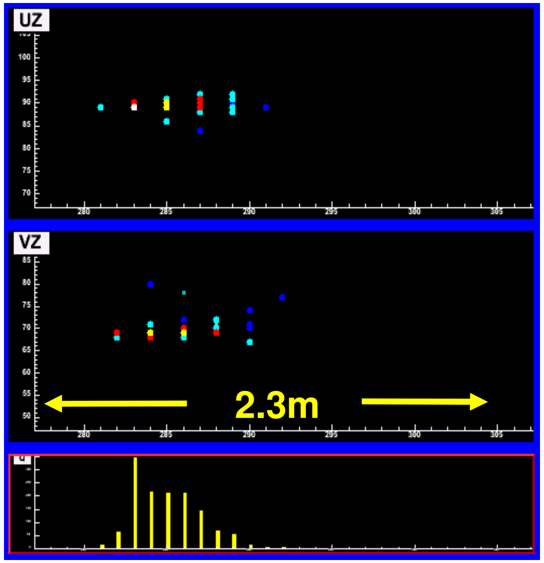
Long μ track + hadronic activity at vertex

NC Event



Short event, often diffuse

ν_e CC Event



Short, with typical EM shower profile

$$E_\nu = E_{shower}+P_\mu$$

55%/√E 6% range, 10% curvature

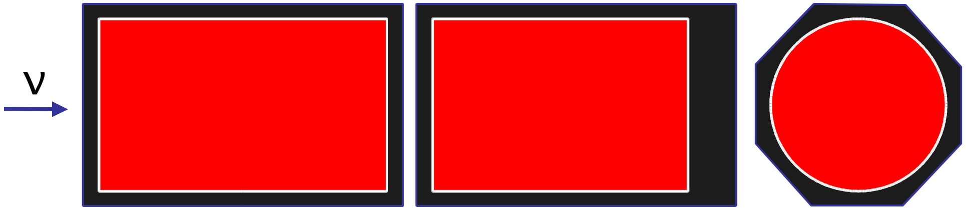
Event Selection Cuts

ν_μ CC-like events:

- Event must contain at least one good reconstructed track
- Reconstructed track vertex within fiducial volume of detector

Near Detector:
1 m < z < 5 m (from detector front),
R < 1 m from beam centre

Far Detector:
z > 50 cm from front face,
z > 2 m from rear face,
R < 3.7 m from detector centre



- Fitted track should have negative charge (rejects $\overline{\nu}_\mu$)
- Separation of CC from NC events:
  cut on likelihood-based Particle ID parameter

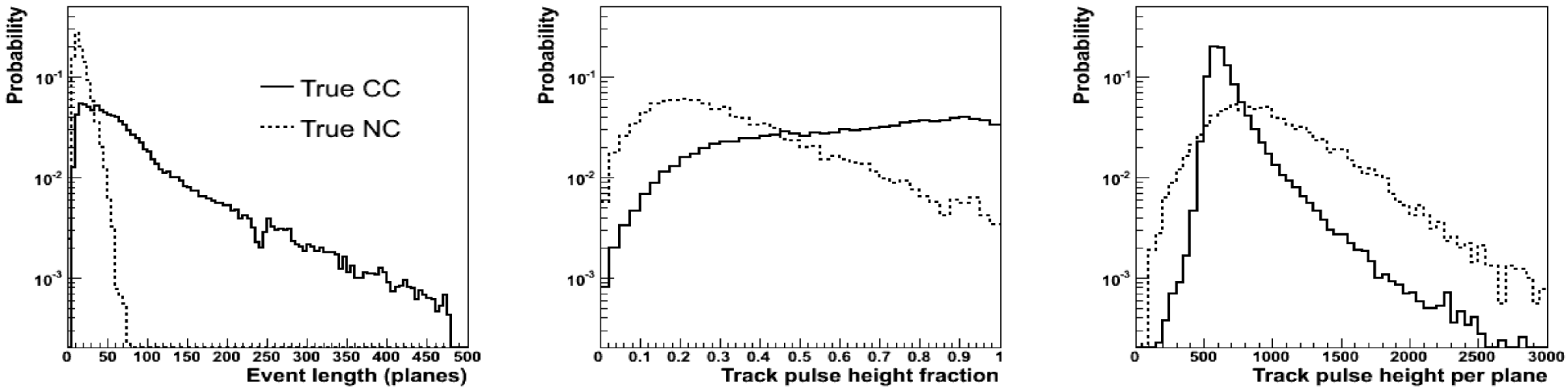
Selecting CC Events

- Events selected by likelihood-based procedure, with three input PDFs:
  - Event length, fraction of event pulse height in the recoed track, average track pulse height/plane
- P_μ (P_{NC}) as the product of the three CC (NC) PDFs and Particle ID (PID) parameter:

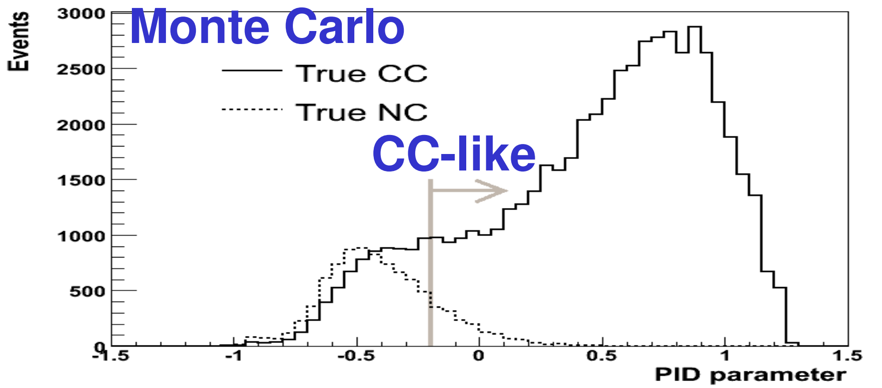
$$PID = -\left(\sqrt{-\log(P_\mu)} - \sqrt{-\log(P_{NC})}\right)$$

- CC-like events: PD > -0.2 in the FD (> 0.1 in the ND)

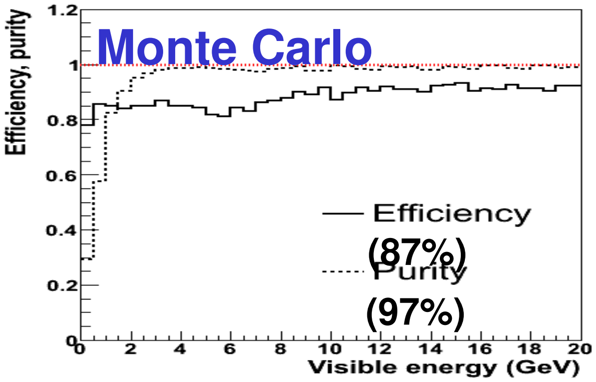
Input variables for PDF-based event selection



PDF PID parameter distribution for true CC and NC events



CC selection efficiencies and purities



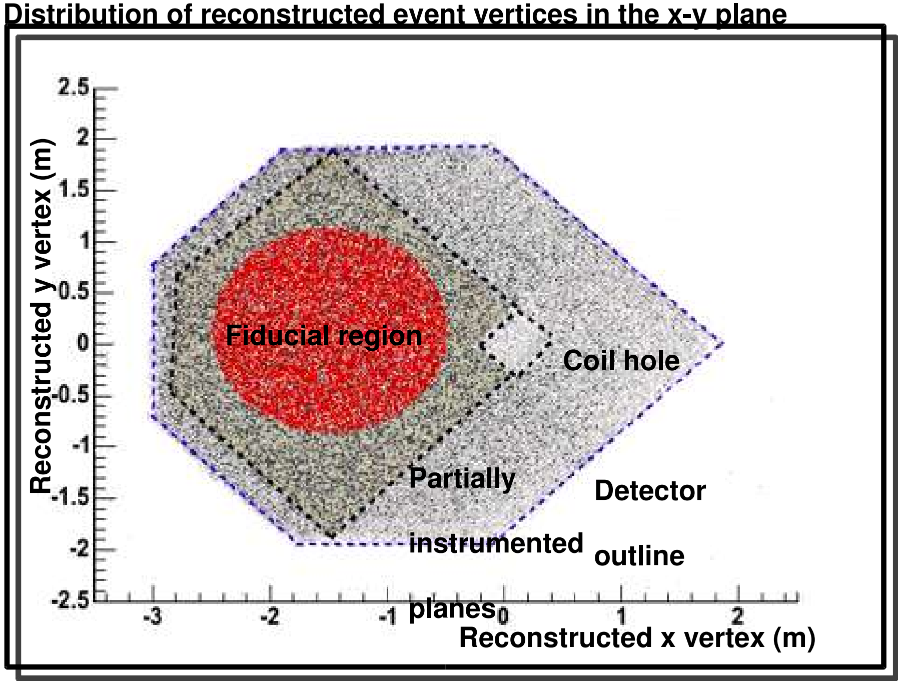
Near Detector Distributions

- Very large event rates in the Near Detector (~10^7 events in the fiducial volume for 10^{20} POT)

→ High-statistics dataset:

  - Understand performance of Near Detector
  - Check level of agreement between data and Monte Carlo

Distribution of reconstructed event vertices in the x-y plane



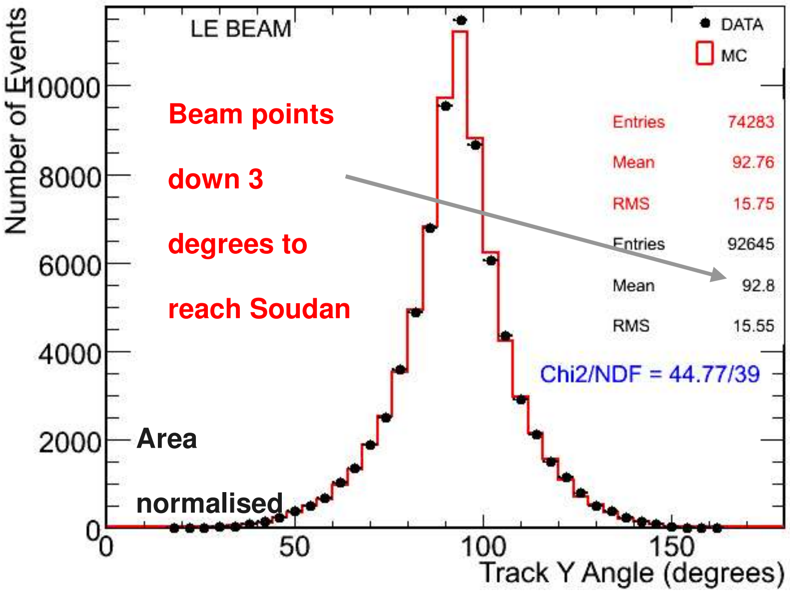
Fiducial region

Coil hole

Partially instrumented planes

Detector outline

Reconstructed track angle with respect to vertical



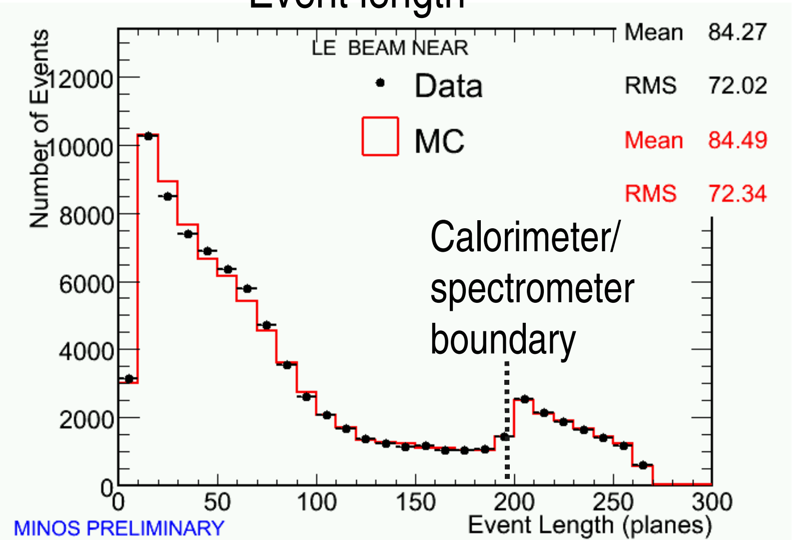
Beam points down 3 degrees to reach Soudan

Area normalised

Particle ID Variables and PID Parameter

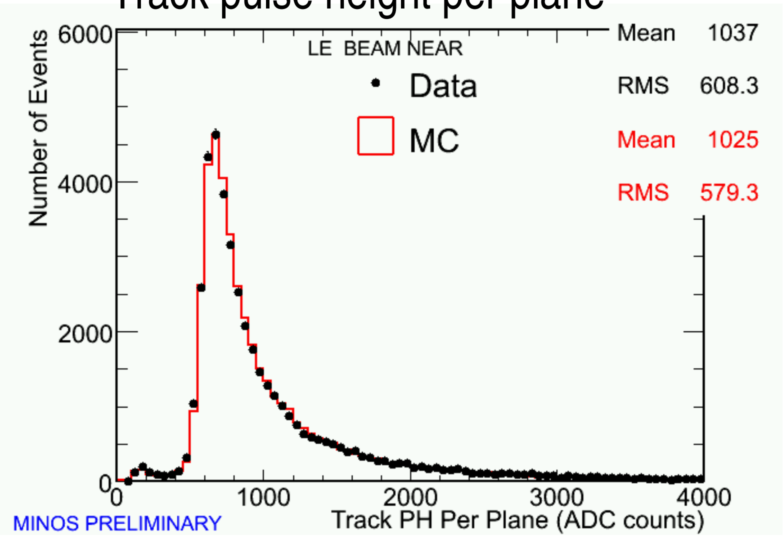
LE-10 beam

Event length

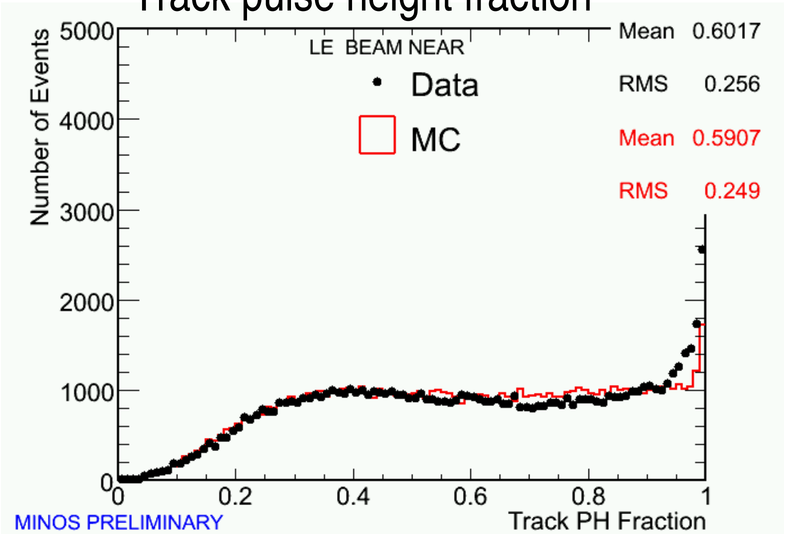


Calorimeter/ spectrometer boundary

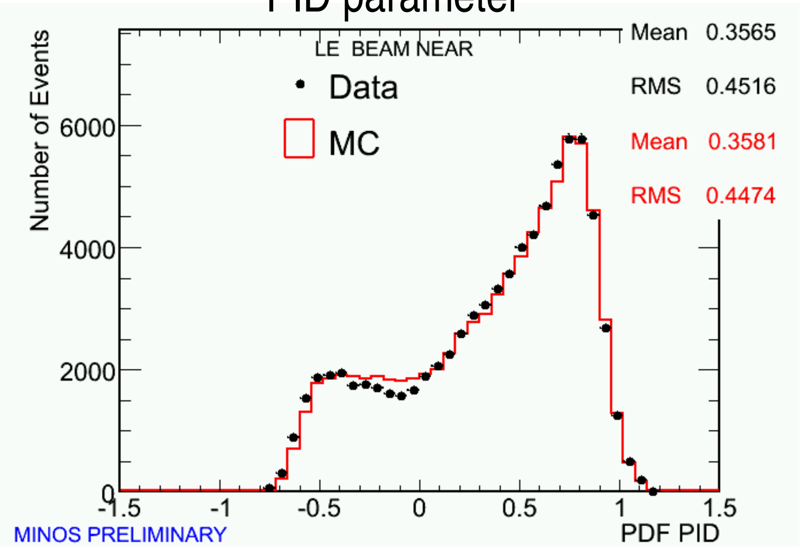
Track pulse height per plane



Track pulse height fraction



PID parameter



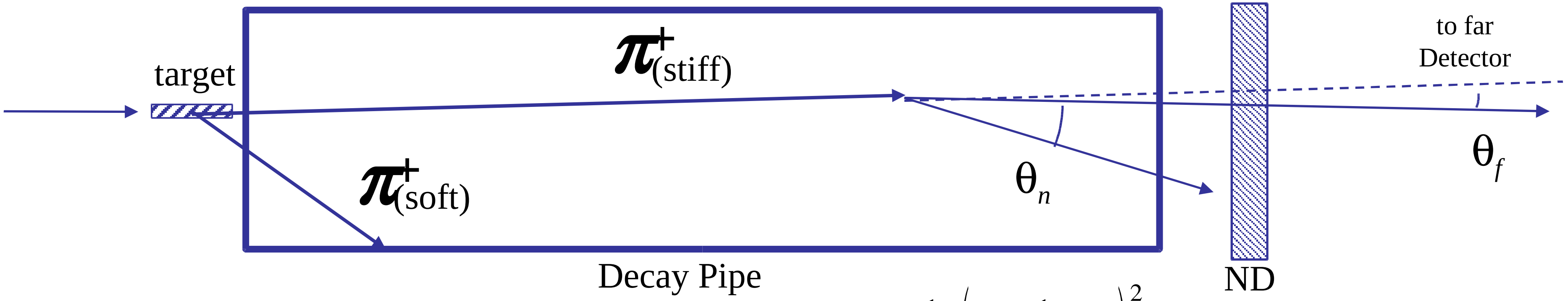
Far Detector Beam Analysis

- Oscillation analysis performed using data taken in the LE-10 configuration from 20 May to 6 Dec 2005
  - Total integrated POT: 0.93 × 10^{20}
  - POT-weighted FD live time: 98.9%

- Blind analysis: FD box opening on March 4th, 2006
  - Unknown fraction of Far Detector events hidden (based on event length and total energy deposition)
  - “Open” set examined to confirm that there are no problems with FD data
  - Oscillation analyses pre-defined and validated on MC
  - When satisfied that FD data and analysis methods are OK: “open the box” and perform final analysis on total sample
  - No re-tuning of cuts allowed after box opening

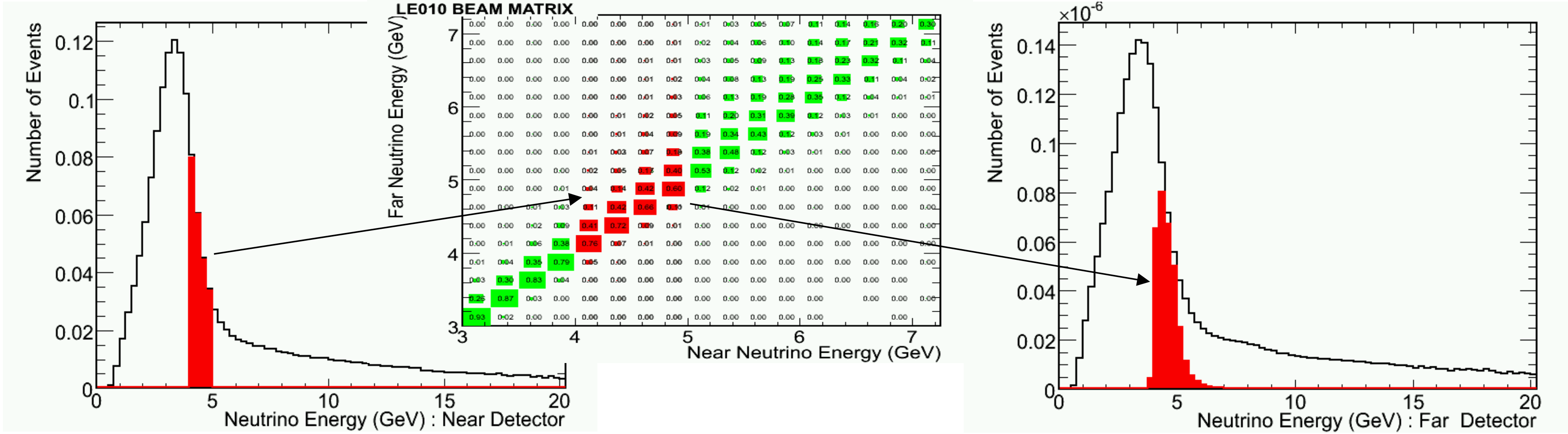
Predicting the Un-Oscillated FD Spectrum

- Directly use the Near Detector data to perform extrapolation between Near and Far
- Use Monte Carlo to provide necessary corrections due to energy smearing and acceptance
- Use our knowledge of pion decay kinematics and the geometry of our beamline to predict the FD energy spectrum from the measured ND spectrum

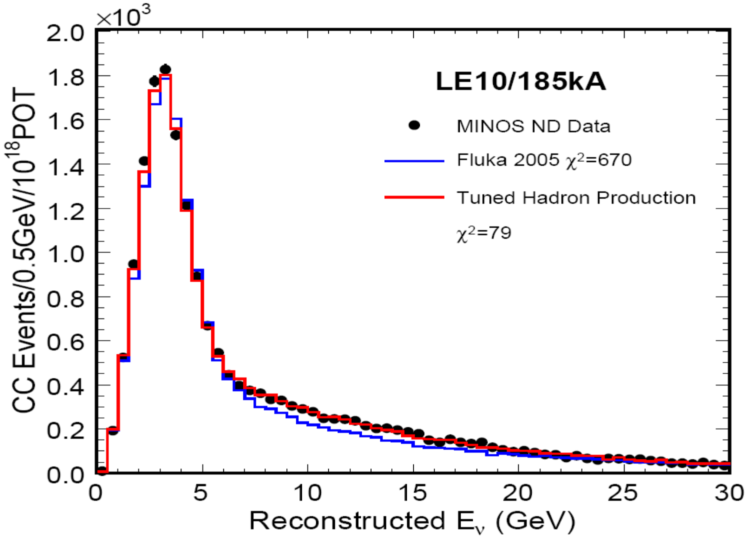


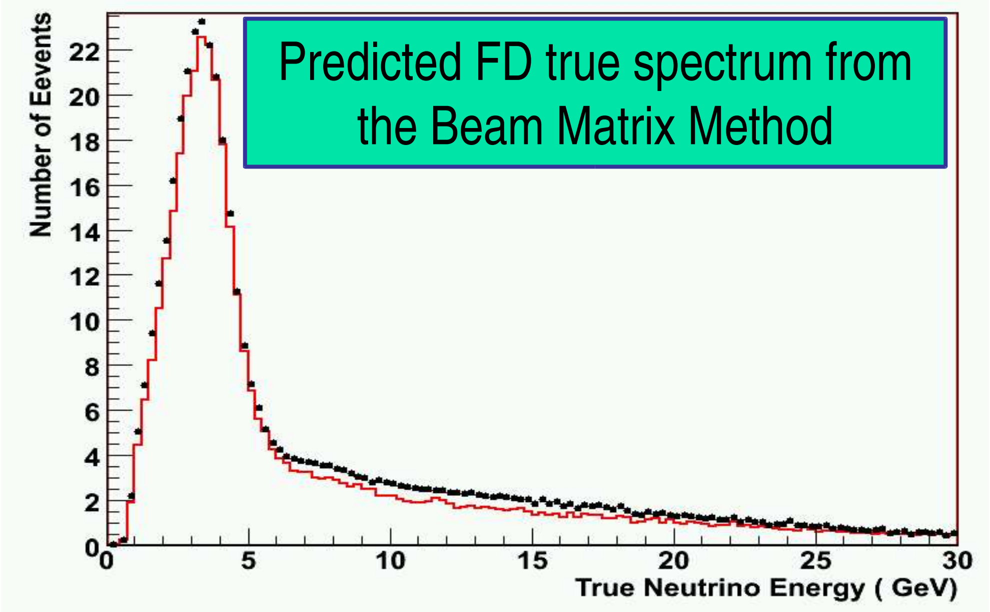
- Known as the Beam Matrix Method

$$Flux \propto \frac{1}{L^2}\left(\frac{1}{1+\gamma^2\theta^2}\right)^2 \qquad E_\nu = \frac{0.43\,E_\pi}{1+\gamma^2\theta^2}$$



Predicted True FD Spectrum

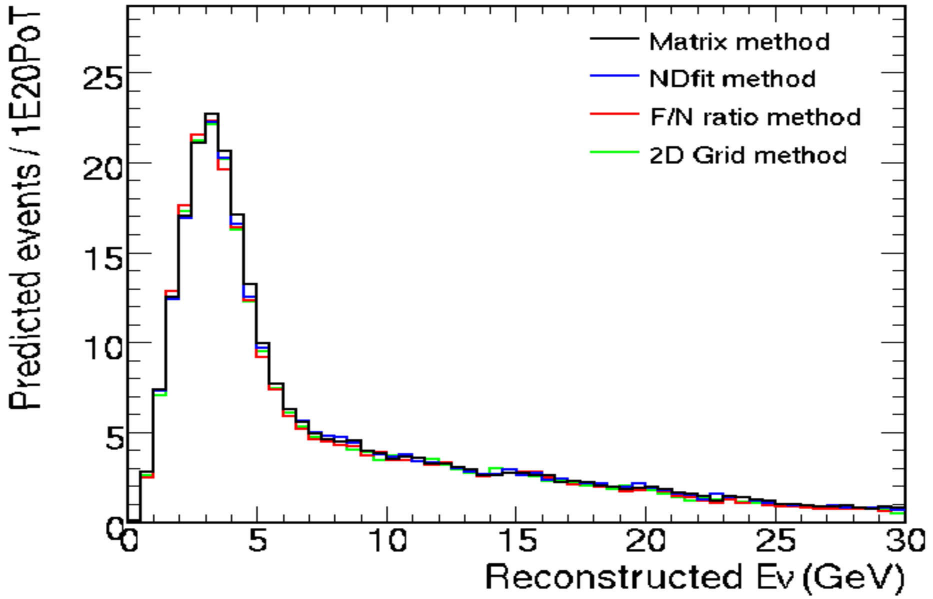




Predicted FD true spectrum from the Beam Matrix Method

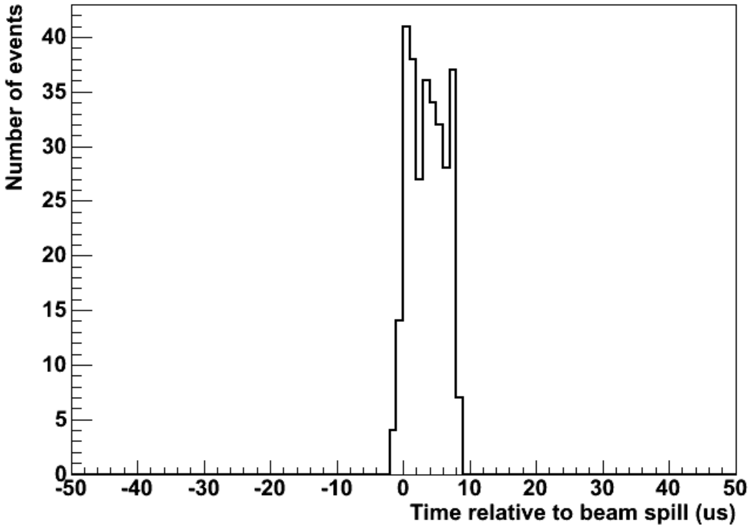
- Higher than nominal FD MC in high-energy tail as expected, given that the ND spectrum is also higher than the nominal MC in this region
- Three other methods to derive FD spectrum from ND data:
  - Extrapolation using Far/Near ratio from MC
  - Fitting to ND data → derive systematic parameters → reweight FD MC
    - Two independent methods: "NDfit" and "2d Grid Fit"
- Above methods have quite different sensitivities to systematic errors
  - Comparing results from all four provides good check of robustness of oscillation measurement

Predicted FD unoscillated spectra

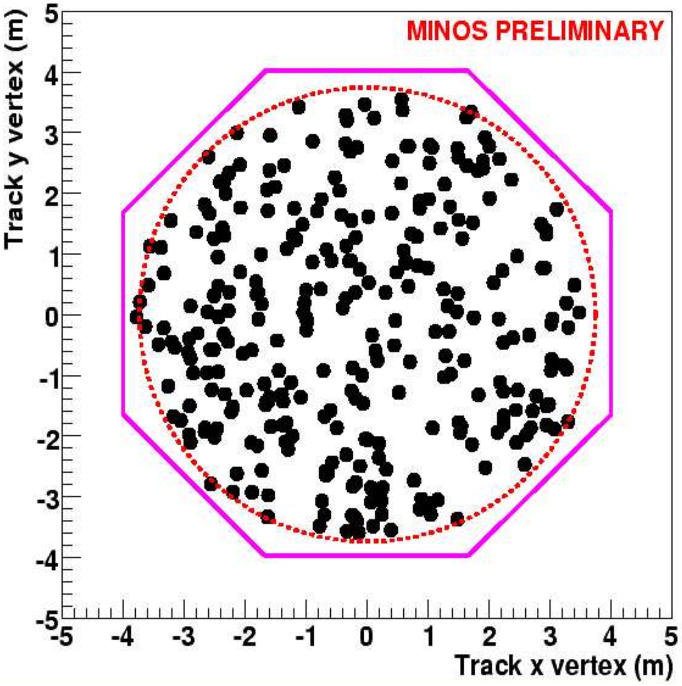


FD Beam Events

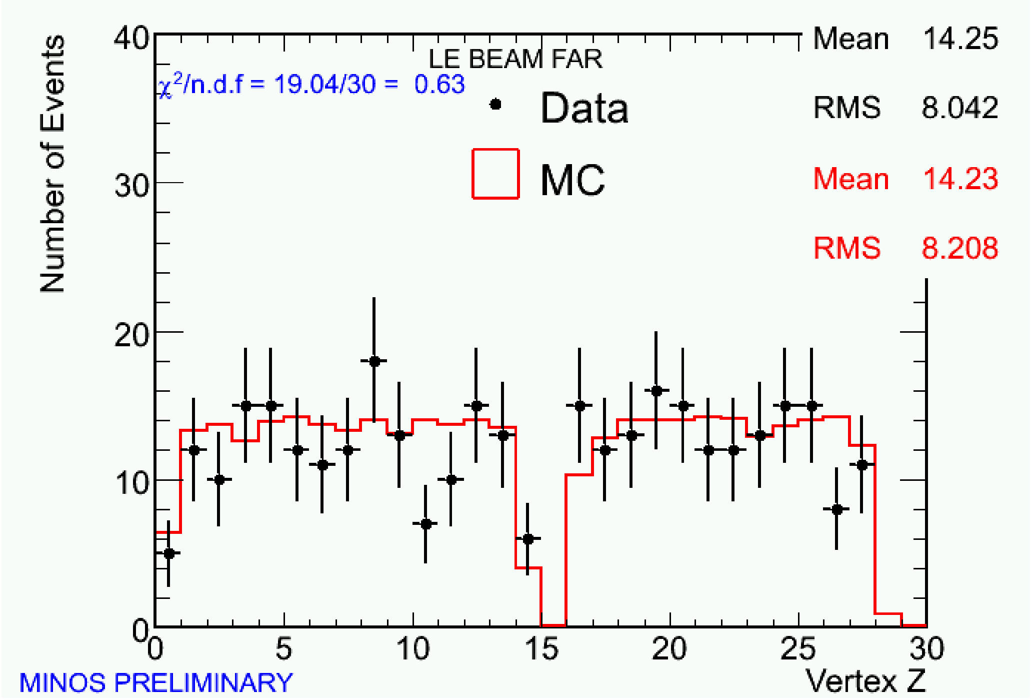
- Neutrino events are selected within 100 μs around beam spills, using GPS time stamp
- Far Detector neutrino events easily separated from cosmic muons (0.5 Hz). Estimated using “fake” triggers taken in anti-coincidence with beam spills (upper limit on background in open sample is 1.7 events at 90% C.L.)



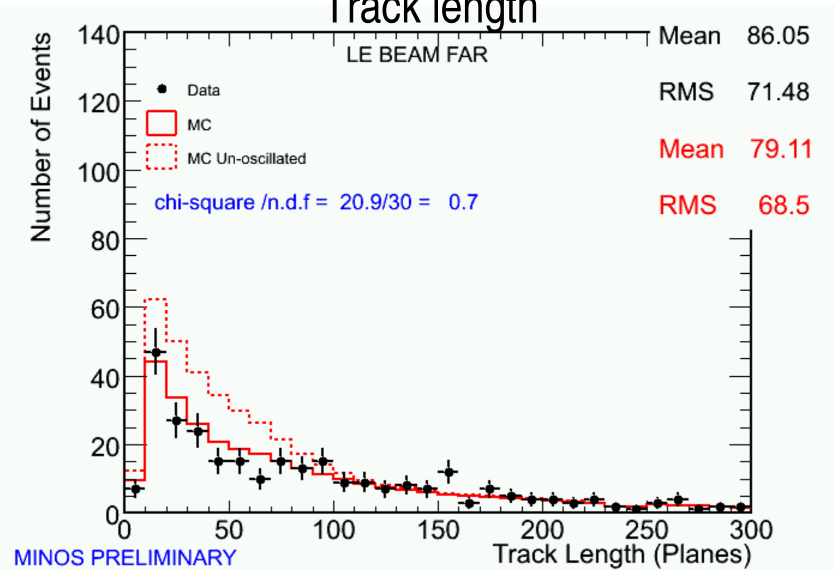
Reconstructed track vertices of neutrino candidates



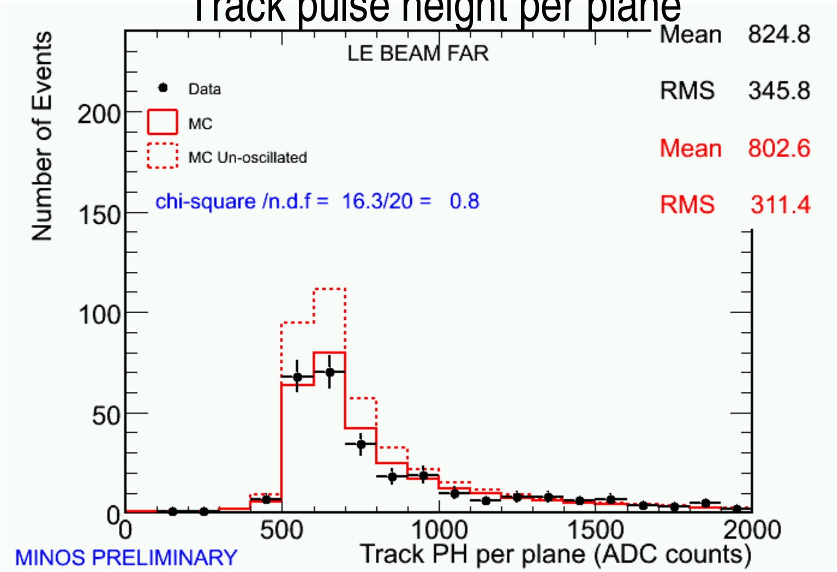
Box-opened



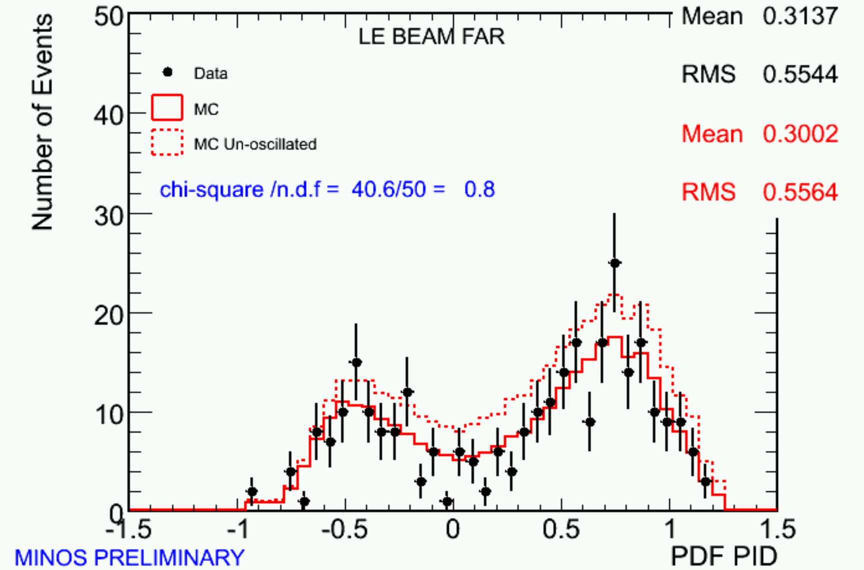
Track Quantities and PID Parameter



Track length



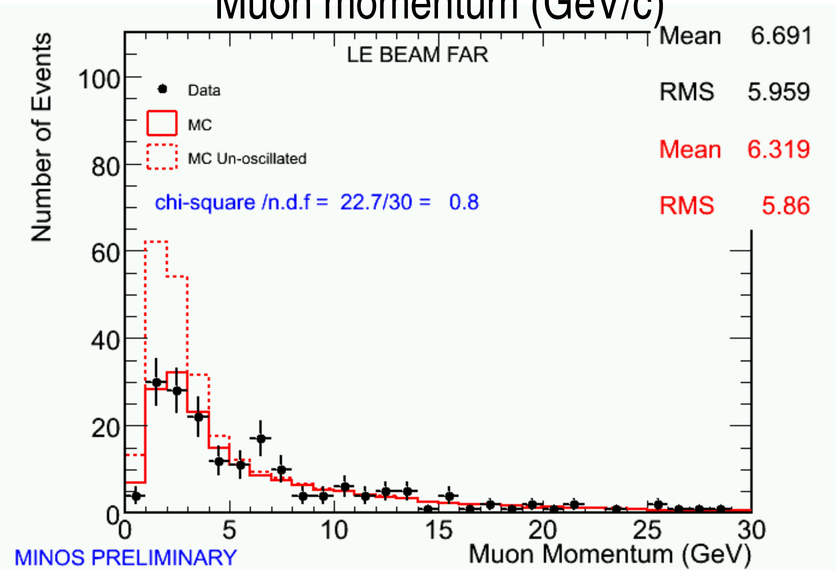
Track pulse height per plane



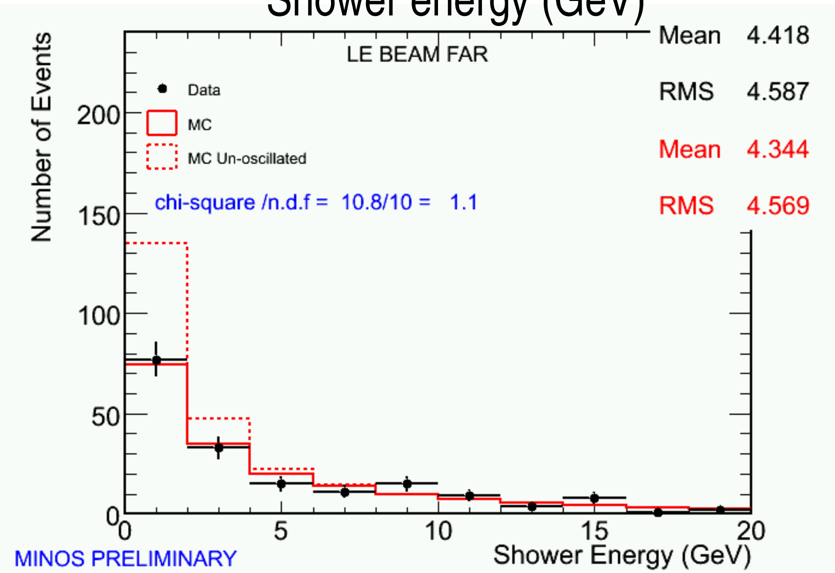
Particle identification parameter

Physics Distributions

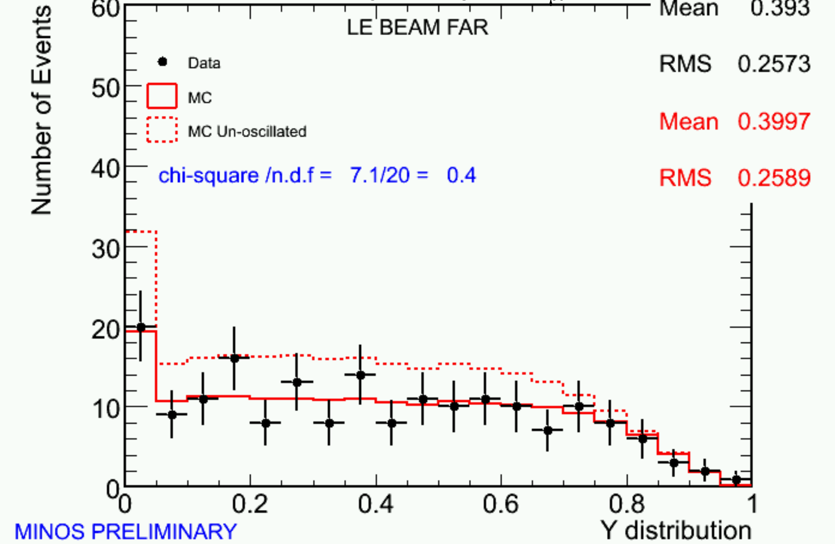
Muon momentum (GeV/c)



Shower energy (GeV)



$y = E_{shw}/(E_{shw}+P_{\mu})$

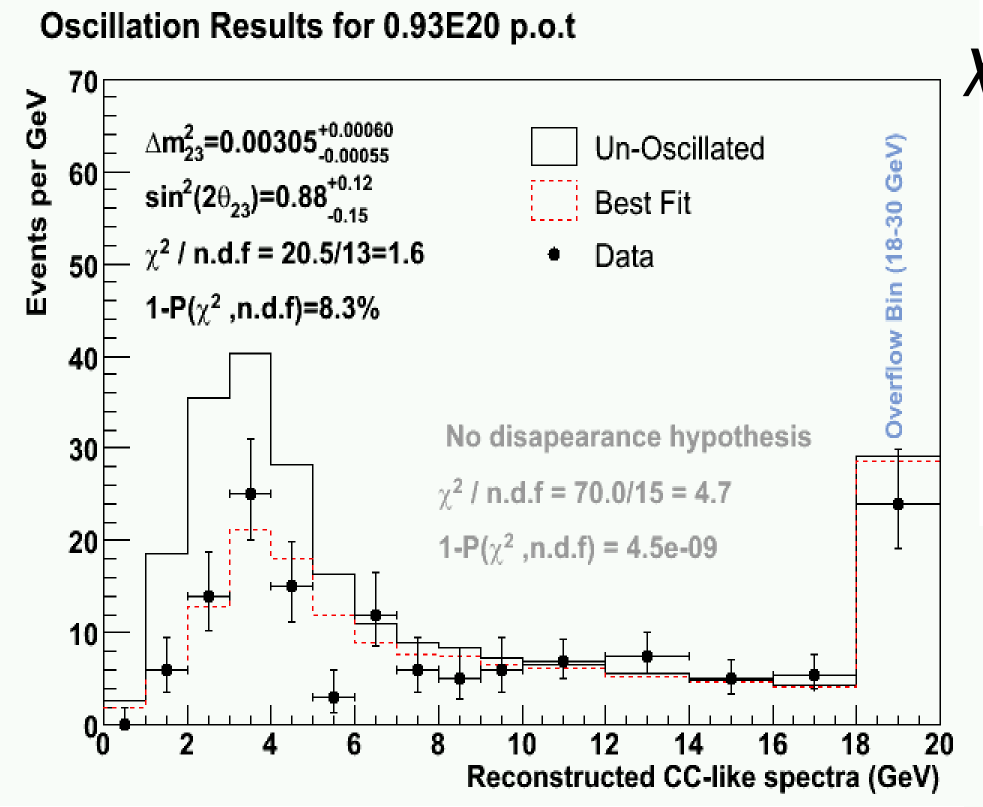


Numbers of Events

Data sample	**observed**	**expected**	**ratio**	**significance**
ν_μ only (<30 GeV)	166	249±14	0.67	4.0σ
ν_μ only (<10 GeV)	92	177±11	0.52	5.0σ

- 33% deficit of events between 0 and 30 GeV with respect to no-oscillation expectation.
- **Rate-only significance: 5 standard deviations**

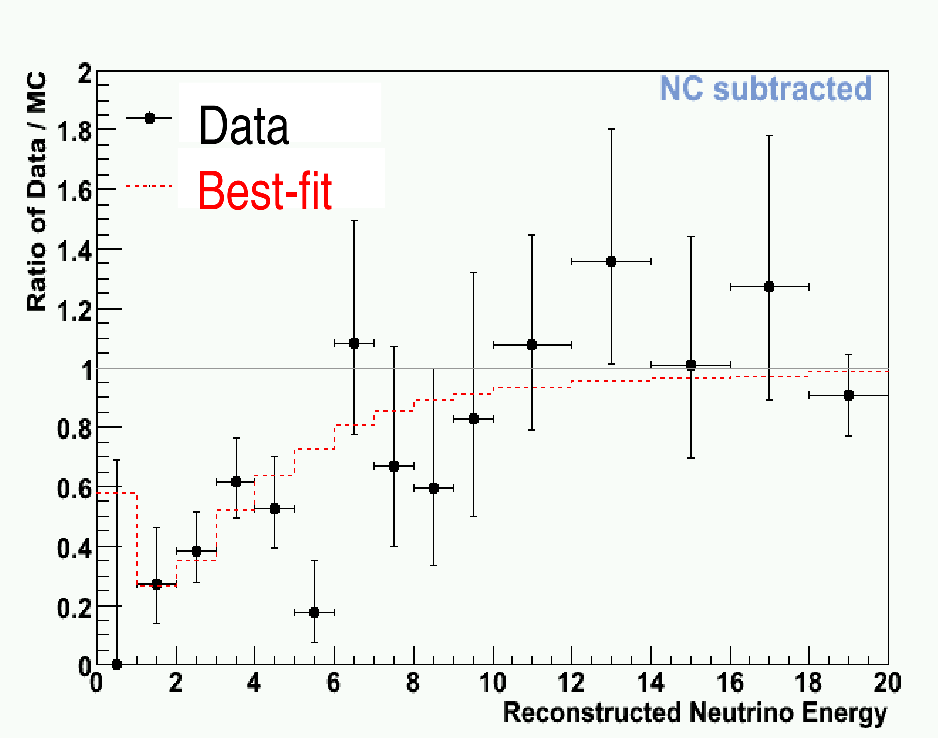
Best-Fit



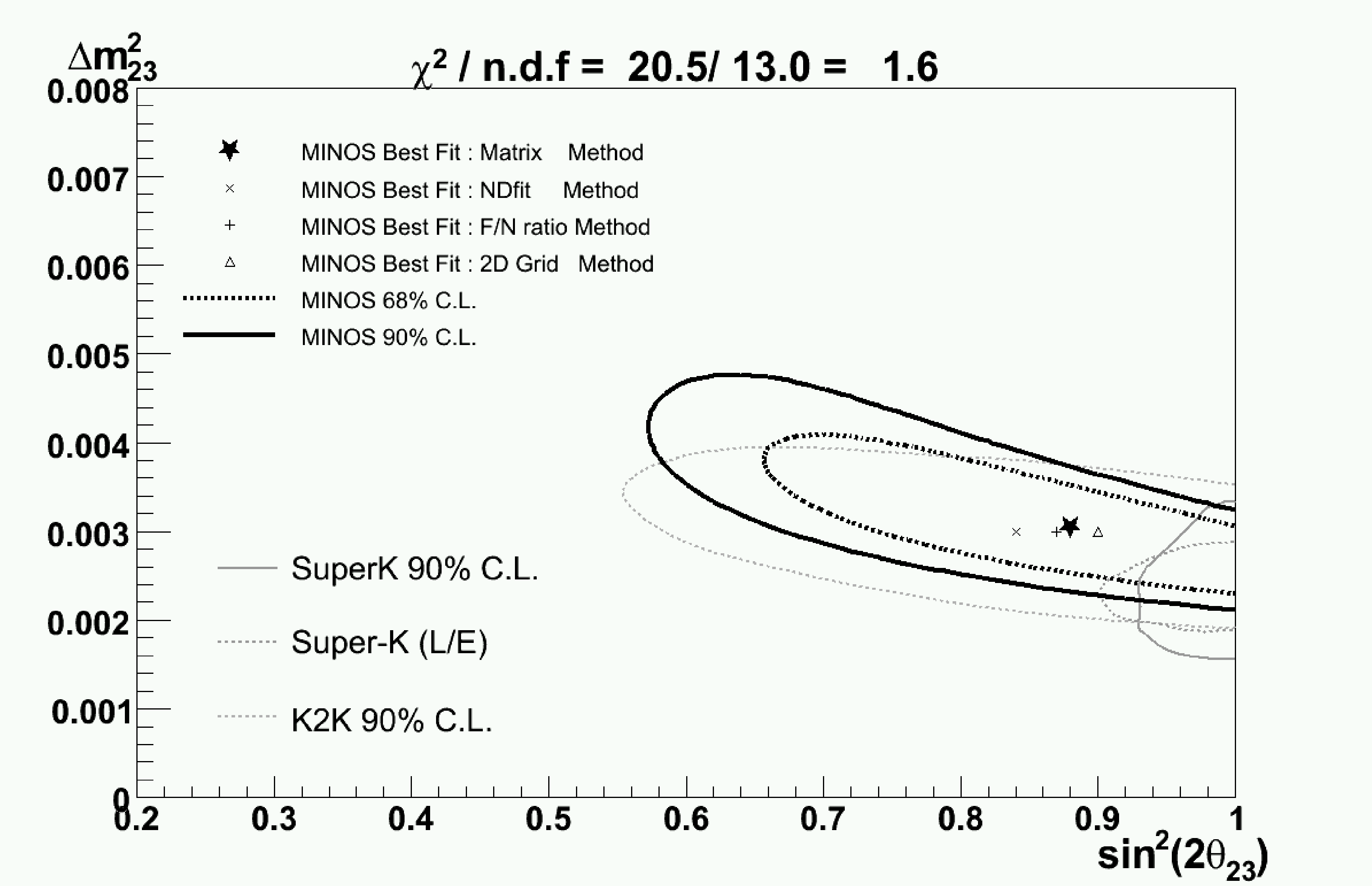
$$\chi^2(\Delta m^2, \sin^2 2\theta) = \sum_{i=1}^{nbins} 2(e_i - o_i) + 2 o_i \ln(o_i / e_i)$$

o_i = observed

e_i = expected



Allowed Regions



Systematic Errors

Systematic shifts in the fitted parameters computed with
MC “fake data” samples for $\Delta m^2 = 0.003$ eV^2, $\sin^2 2\theta = 0.9$:

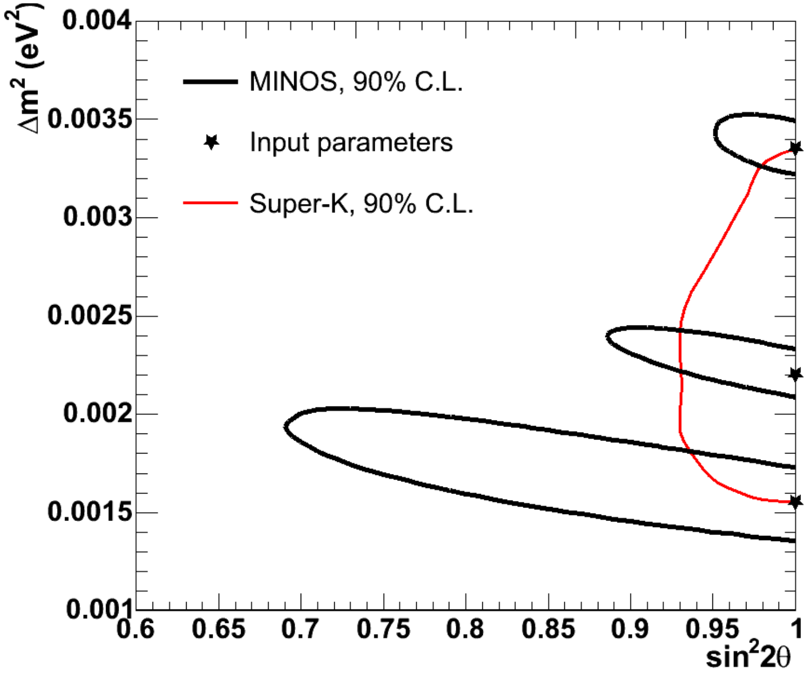
Uncertainty	**Δm^2 shift (eV^2)**	**$\mathrm{Sin}^2 2\theta$ shift**
Normalisation +/- 4%	0.63e-4	0.025
Muon energy scale +/- 2%	0.14e-4	0.020
Relative Shower energy scale +/- 3%	0.27e-4	0.020
NC contamination +/- 30%	0.77e-4	0.035
CC cross-section uncertainties	0.50e-4	0.016
Beam uncertainty	0.13e-4	0.012
Intranuclear re-scattering	0.27e-4	0.030
Total (sum in quadrature)	**1.19e-4**	**0.063**
Statistical error (data)	**6.4e-4**	**0.15**

Accumulating beam ν data at both detectors !!!

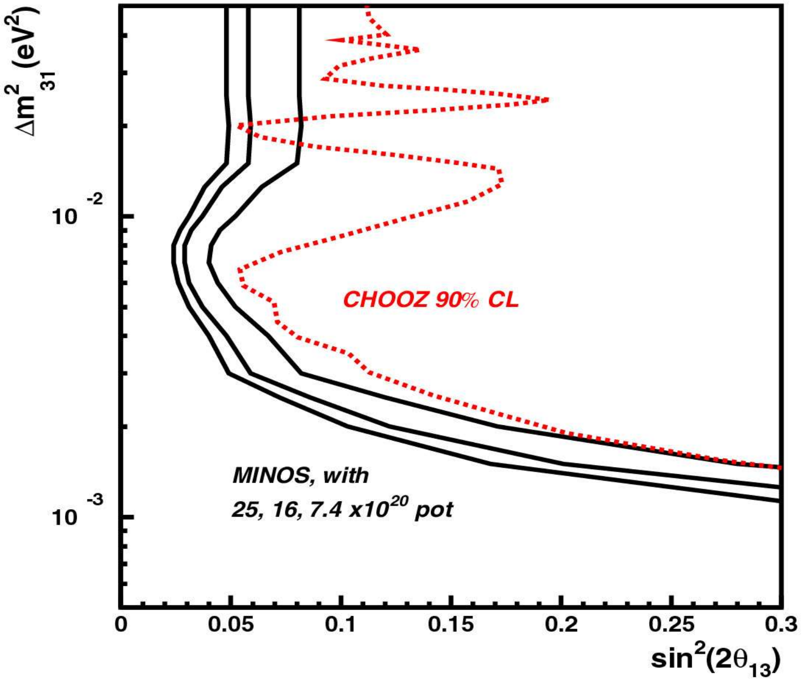
Projected Sensitivity

Improve this measurement:

Sensitivity at 16 *10^{20} POT



Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations



- Study neutrino/anti-neutrino oscillations
- Search for/rule out exotic phenomena:
  - Sterile neutrinos, neutrino decay

detection of ν_e at Δm^2_{atm}

→ ***evidence for non-zero θ_{13}***

Can improve 90% CL by a factor of ~2 with higher proton intensity

Summary and Conclusions

- MINOS has performed a preliminary oscillation analysis of 0.93 x 10^{20} protons on target
- No disappearance disfavoured at 5σ (rate-only) consistent with ν oscillation results, with parameters:

$$\Delta m^2_{23} = 3.05^{+0.60}_{-0.55}(stat) \pm 0.12(syst) \times 10^{-3}\, eV^2$$

$$\sin^2 2\theta_{23} = 0.88^{+0.12}_{-0.15}(stat) \pm 0.06(syst)$$

- Measurement is statistically limited; systematics under control
- Significant improvements expected with more data, stay tuned for update in summer conferences
  - Total exposure to date: 1.4 x 10^{20} POT