First MINOS Results from the NuMI Beam

Masaki Ishitsuka, Indiana University
For the MINOS Collaboration

KEK Seminar
April 17th, 2006

Overview of the talk

- Introduction to the MINOS experiment
  - MINOS Physics Goals
  - The NuMI facility and the MINOS detectors

- Near detector data
  - Near detector distributions and comparison with Monte Carlo
  - Beam measurements by the near detector data

- Far detector analysis
  - Selecting Beam neutrino candidates in the Far detector
  - Near-Far extrapolation of the neutrino flux
  - **Oscillation Analysis with 0.93e20 pot**

Neutrino oscillation

Weak eigenstates
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$
Mass eigenstates

Mixing parameters

- 3 mass states (2 mass differences)
  - Δm_{12}^2 : solar+reactor
  - $\boxed{\Delta m_{23}^2}$: Atm-ν, long baseline ← **MINOS**
- 3 mixing angles & 1 CPV phase

$c_{ij}=\cos\theta_{ij}$ $s_{ij}=\sin\theta_{ij}$

$$U_{PMNS} = \overset{\text{Atm-}\nu\text{, LBL} \leftarrow \textbf{MINOS}}{\boxed{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}} \underbrace{\begin{pmatrix}c_{13} & 0 & s_{13}e^{i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{-i\delta} & 0 & c_{13}\end{pmatrix}}_{\text{LBL \& reactor}} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{Solar+reactor}}$$

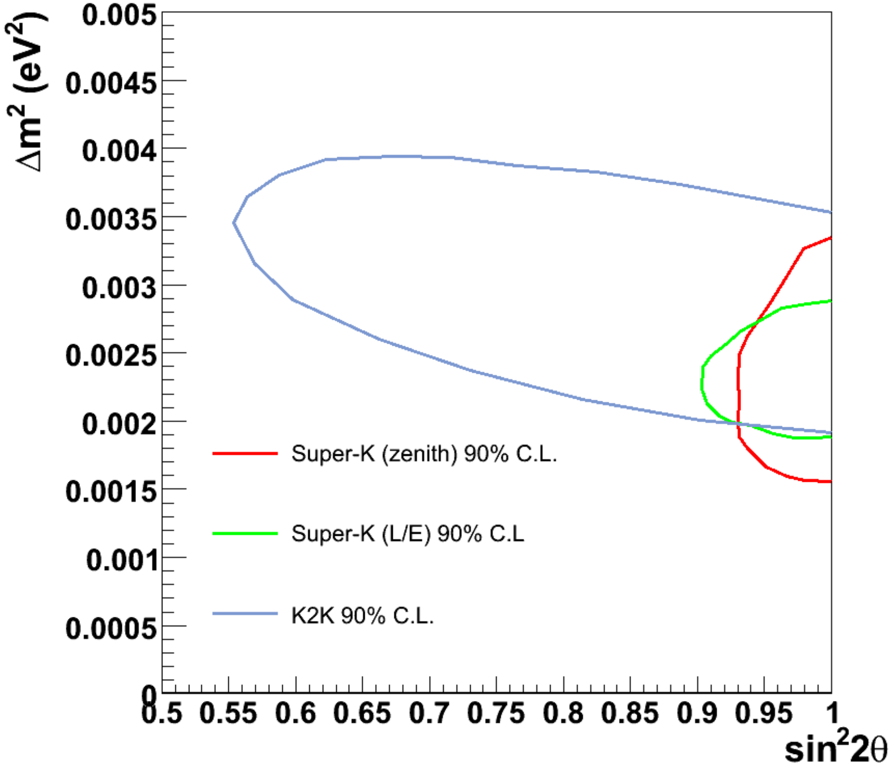
Current knowledge of the 2-3 sector of the MNS mixing matrix

- Current measurements of Δm^2_{23} and $\sin^2 2\theta_{23}$ from Super-Kamiokande and K2K ($9\text{x}10^{19}$ pot)
  - $\sin^2 2\theta > 0.9$
  - $1.9 < \Delta m^2 < 3.0 \times 10^{-3}$ eV^2

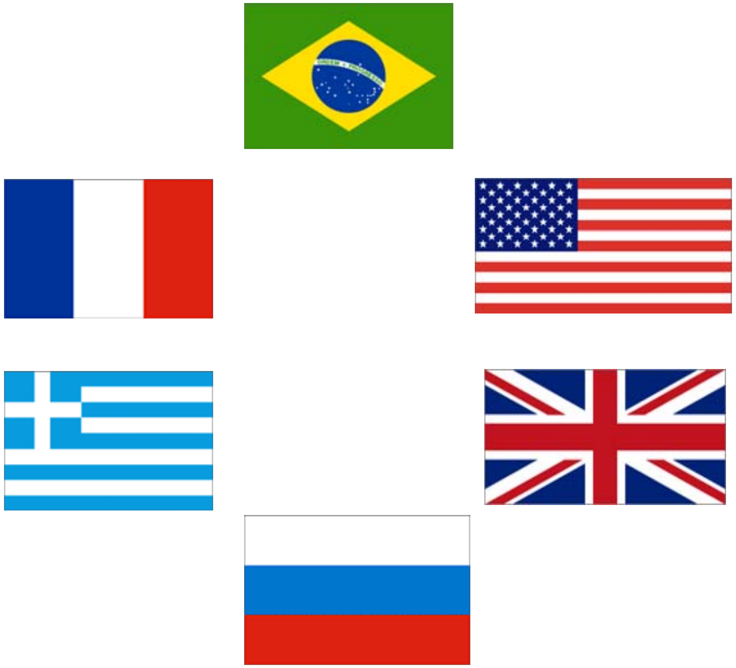
  at 90%CL from SK L/E analysis

- The MINOS first result for $9.3\text{x}10^{19}$ pot provide a competitive measurement of the mixing parameters

Allowed regions from Super-K and K2K



The MINOS Collaboration



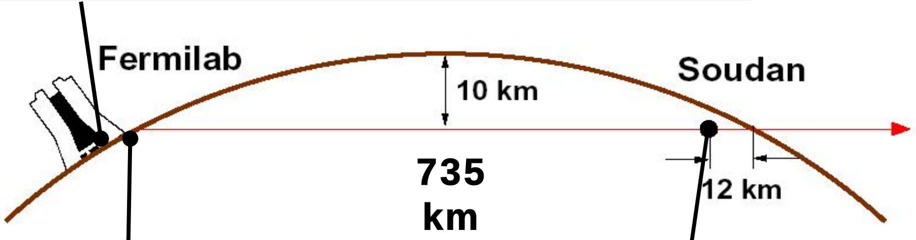
175 scientists
32 institutions
6 countries

Argonne • Athens • Benedictine • Brookhaven • Caltech • Cambridge • Campinas • Fermilab
College de France • Harvard • IIT • 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 • UCL • Western Washington • William & Mary • Wisconsin

The Concept of MINOS

MINOS (Main Injector Neutrino Oscillation Search)
is a long-baseline neutrino oscillation experiment:

High intensity muon neutrino beam produced from Main Injector 120GeV proton beam at Fermilab



Near detector at Fermilab measure the **un-oscillated** energy spectrum

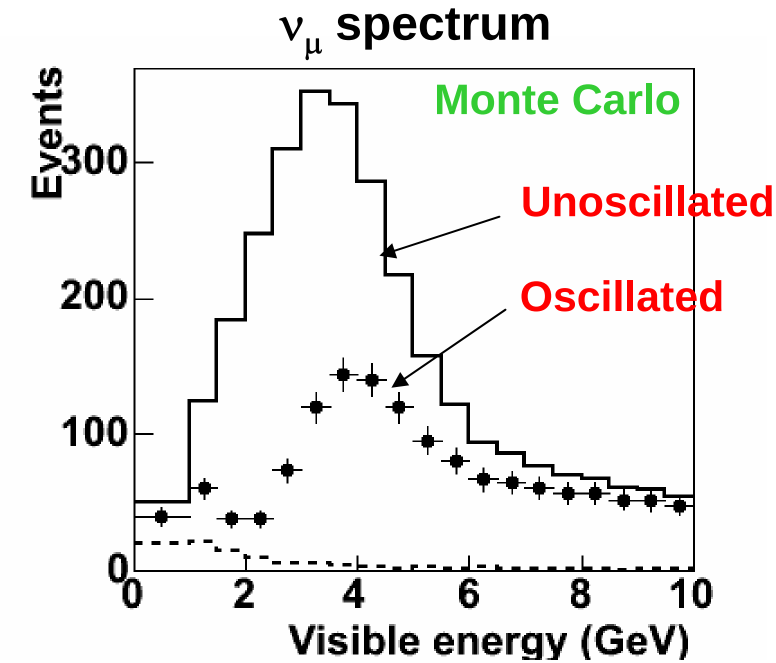
Search for evidence for **oscillations** at **Far detector** deep underground in the Soudan Mine, Minnesota

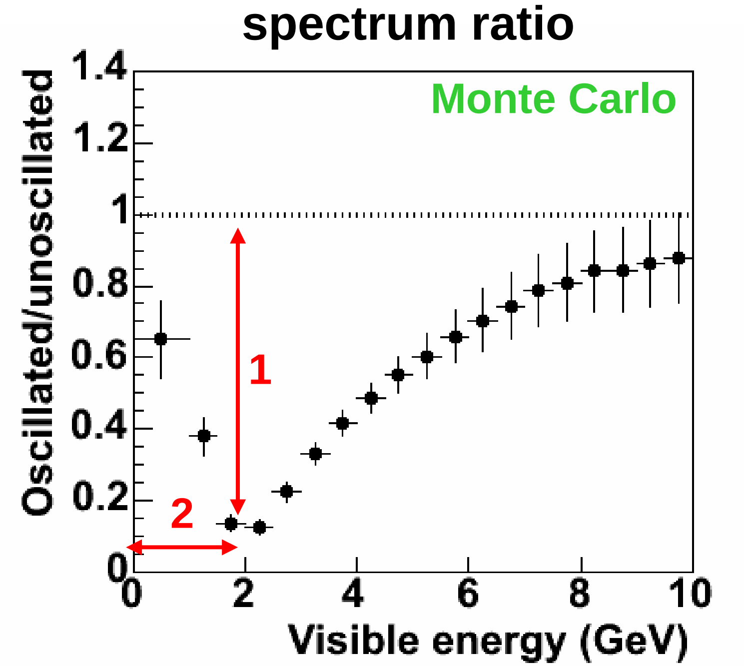
Example of ν_μ disappearance measurement

Survival probability of muon neutrinos:

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

1 2





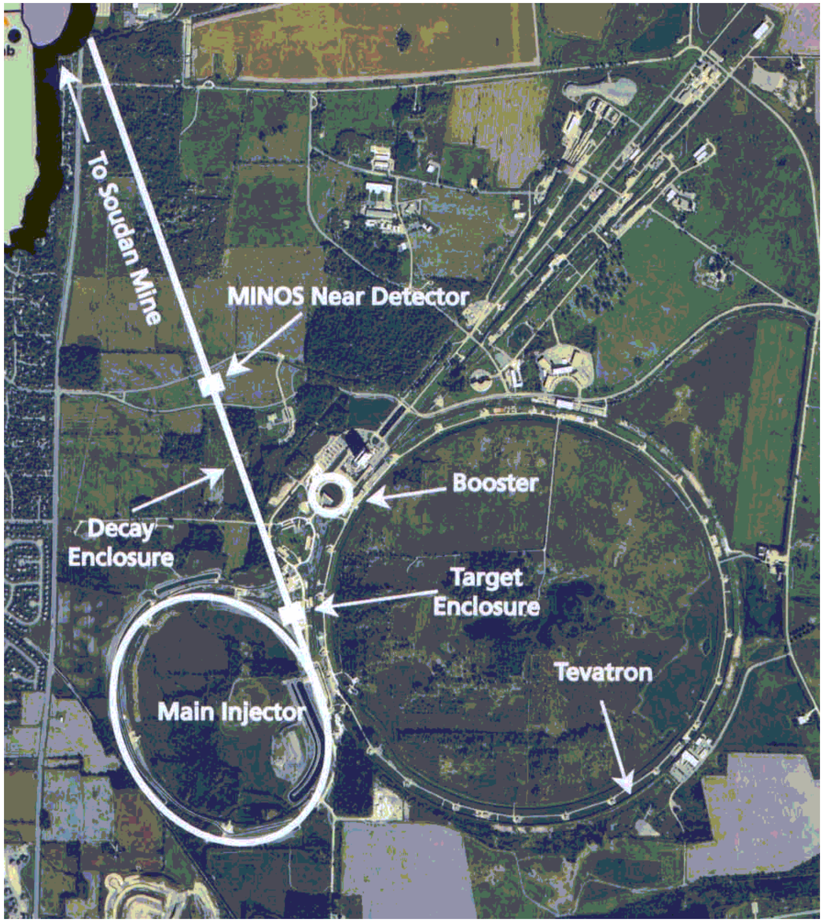
MINOS Physics Goals

•Demonstrate of $\nu_\mu \rightarrow \nu_\tau$ oscillation behavior

•Precise (<10%) measurement of oscillation parameters: Δm^2 and $\sin^2 2\theta$.

- Search for/rule out exotic phenomena:
    - Sterile neutrinos
    - Neutrino decay
- Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations
- Use magnetized MINOS Far detector to study neutrino and anti-neutrino oscillations
    - Test of CPT violation
- Atmospheric neutrino oscillations in the MINOS far detector:
    - First MINOS paper: **hep-ex/0512036, to be published In Phys. Rev. D**

The NUMI facility

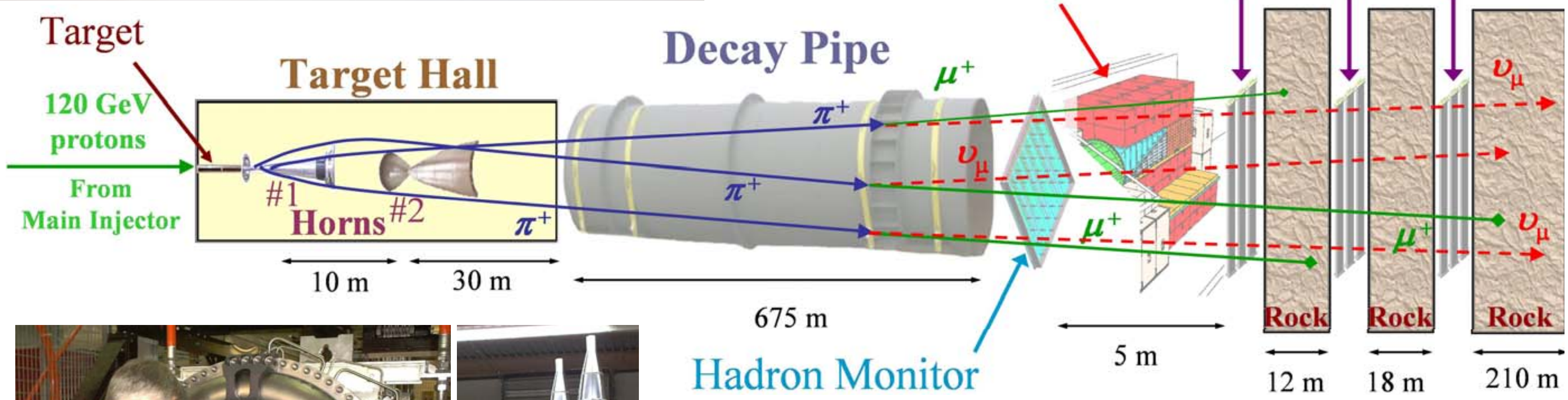


Design parameters:

- 120 GeV protons from the Main Injector
- Main Injector can accept up to 6 Booster batches/cycle,
- Either 5 or 6 batches for NuMI
- 1.9 second cycle time
- $4x10^{13}$ protons/pulse
- 0.4 MW
- Single turn extraction (10μs)

Producing the neutrino beam

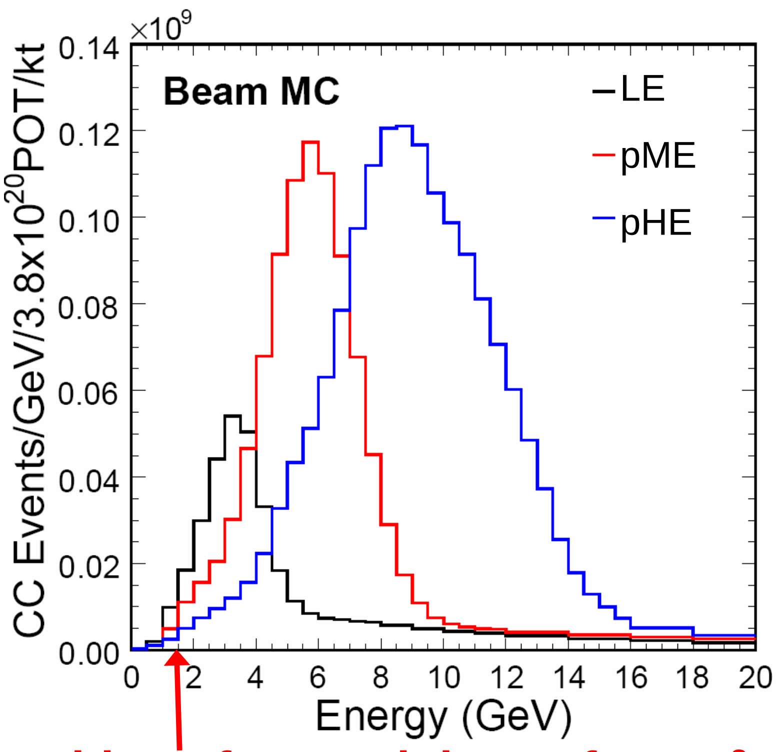
47 segments of graphite of 20 mm length and
6.4×15 mm2 cross section (total length 95.4 cm)



- Two parabolic focussing horns (3.0 Tesla peak field)
- Moveable target relative to horn 1 – continuously variable neutrino spectrum

The NuMI neutrino beam

- **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% $\nu_e+\bar{\nu}_e$**
- We have already accumulated ~1.5e18 pot in pME and pHE early in the run for commissioning and systematics studies



Position of osc. minimum for $\Delta m^2=0.0025\ eV^2$

Expected no of events (no osc.) in Far Detector

Beam	Target z position (cm)	FD Events per 1e20 pot
LE-10	-10	390
pME	-100	970
pHE	-250	1340

Events in fiducial volume

The MINOS Detectors

Far Detector

Near Detector

5.4 kton mass, 8×8×30m	1 kton mass 3.8×4.8×15m
484 steel/scintillator planes	282 steel and 153 scintillator planes
(x 8 multiplexing)	(x 4 multiplexing after plane 120)
VA electronics	Fast QIE electronics

B ~1.2T

Multi-pixel (M16,M64) PMTs

GPS time-stamping to synch FD data to ND/Beam

Continuous *untriggered* readout of whole detector (only during spill for the ND)

Interspersed light injection (LI) for calibration

Spill times from FNAL to FD trigger farm

Detector Technology

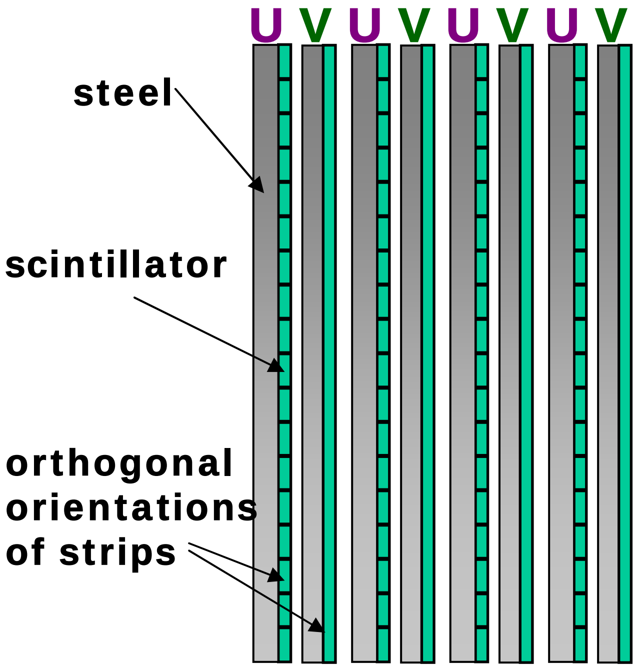
Near and Far Detectors: Identical target components and detection technology

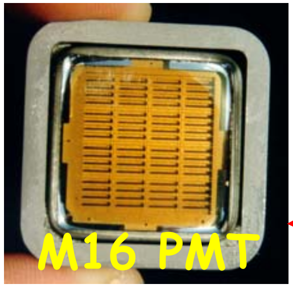
2.54 cm thick magnetized steel plates

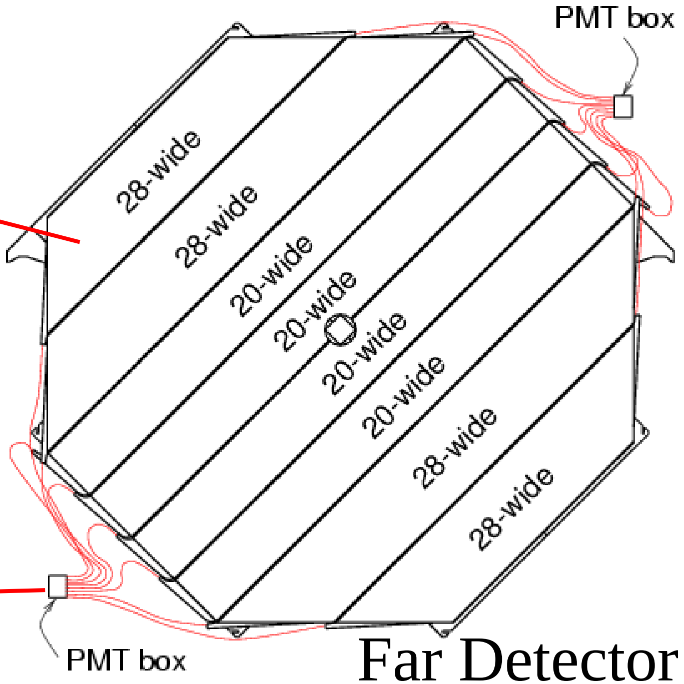
4.1x1cm co-extruded scintillator strips (MINOS-developed technology)

orthogonal orientation on alternate planes – U,V

optical fibre readout to multi-anode PMTs

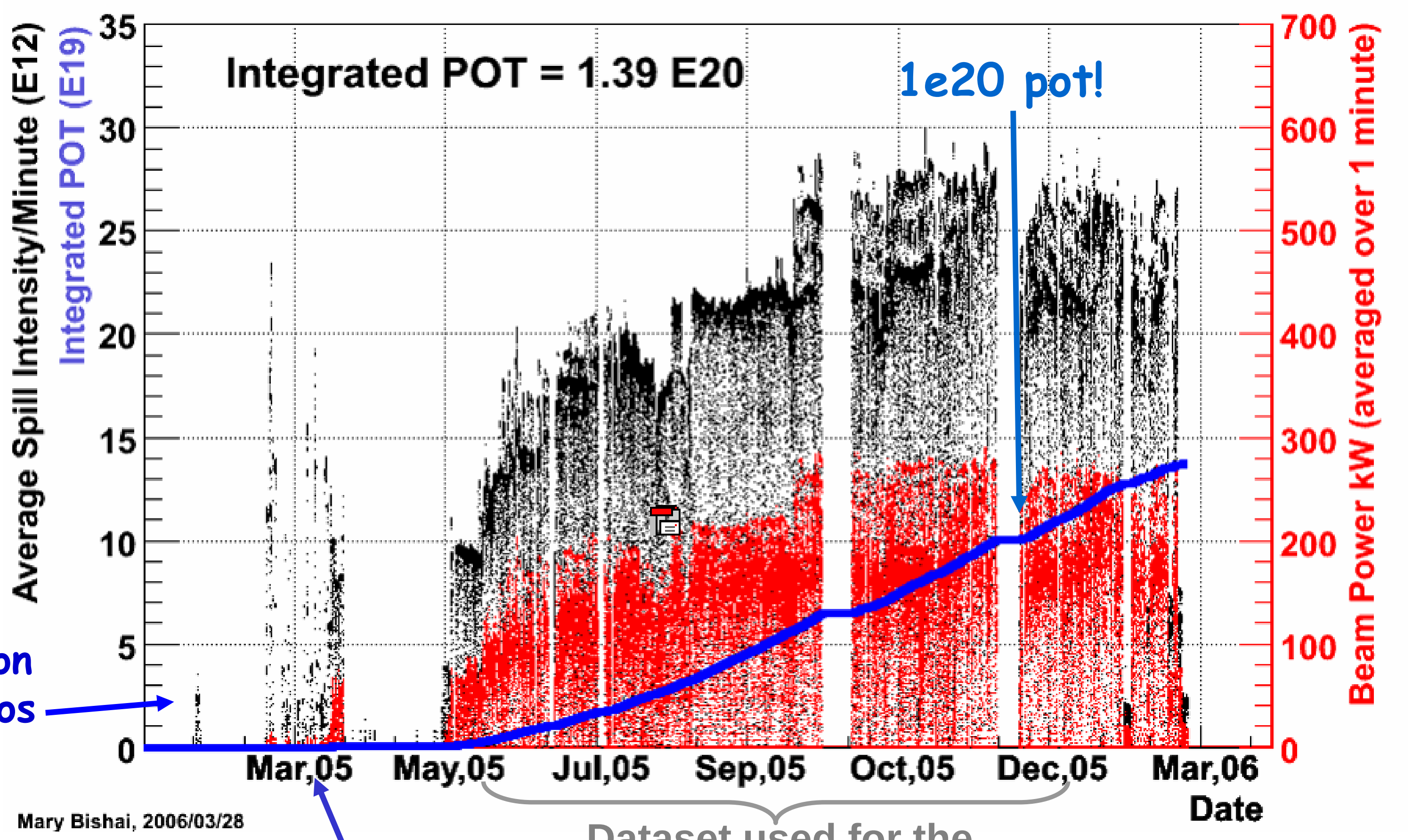






Far Detector

First Year of MINOS running



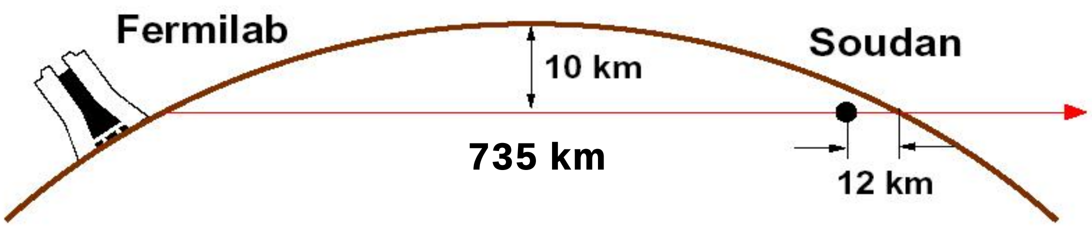
Observation of neutrinos in Near Detector!

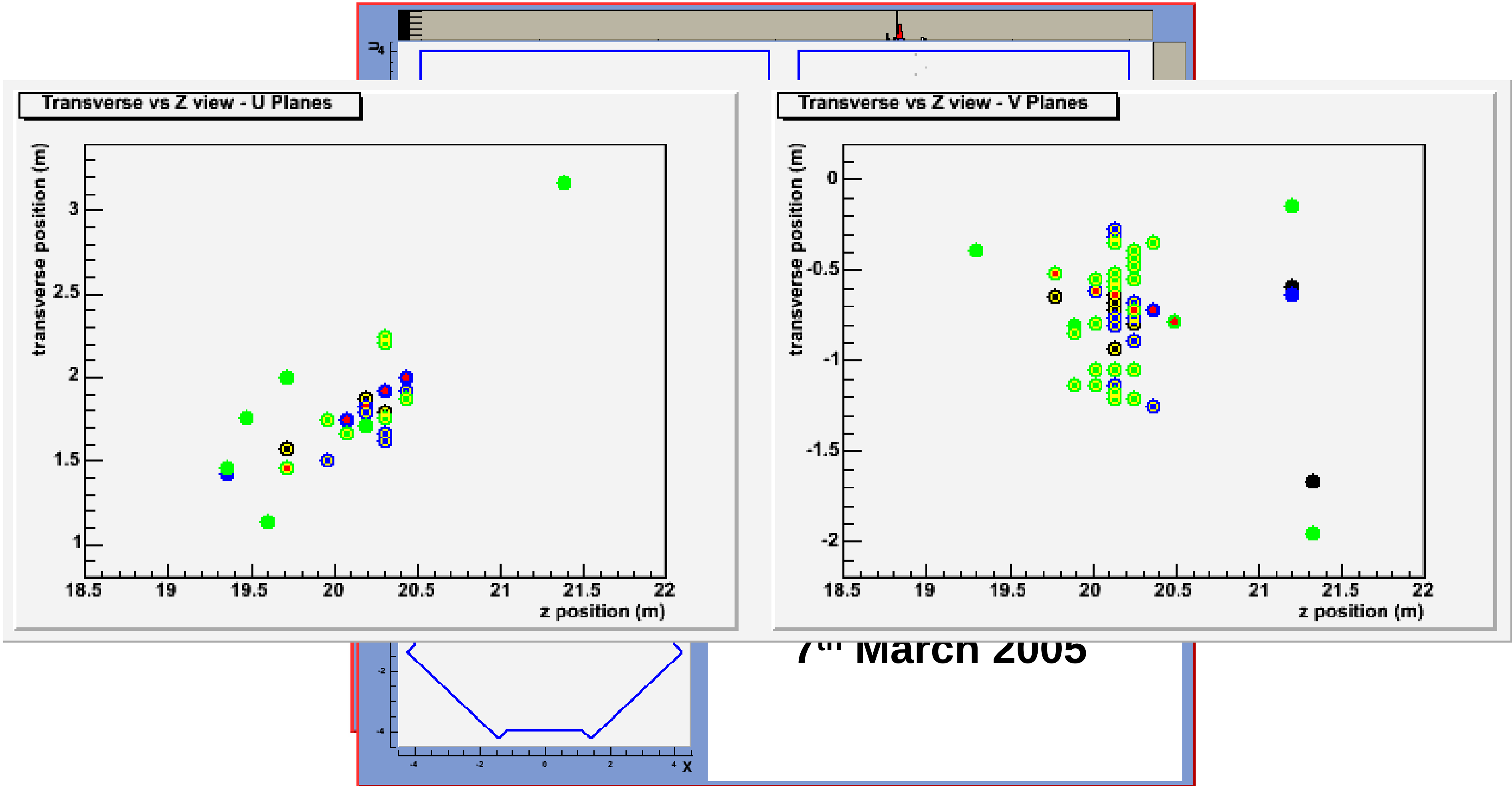
Start of LE running

Dataset used for the oscillation analysis

2.3E13 ppp averaged for Oct. 15 to Jan 31 (2.2 s cycle)

First ND & FD beam neutrinos observed



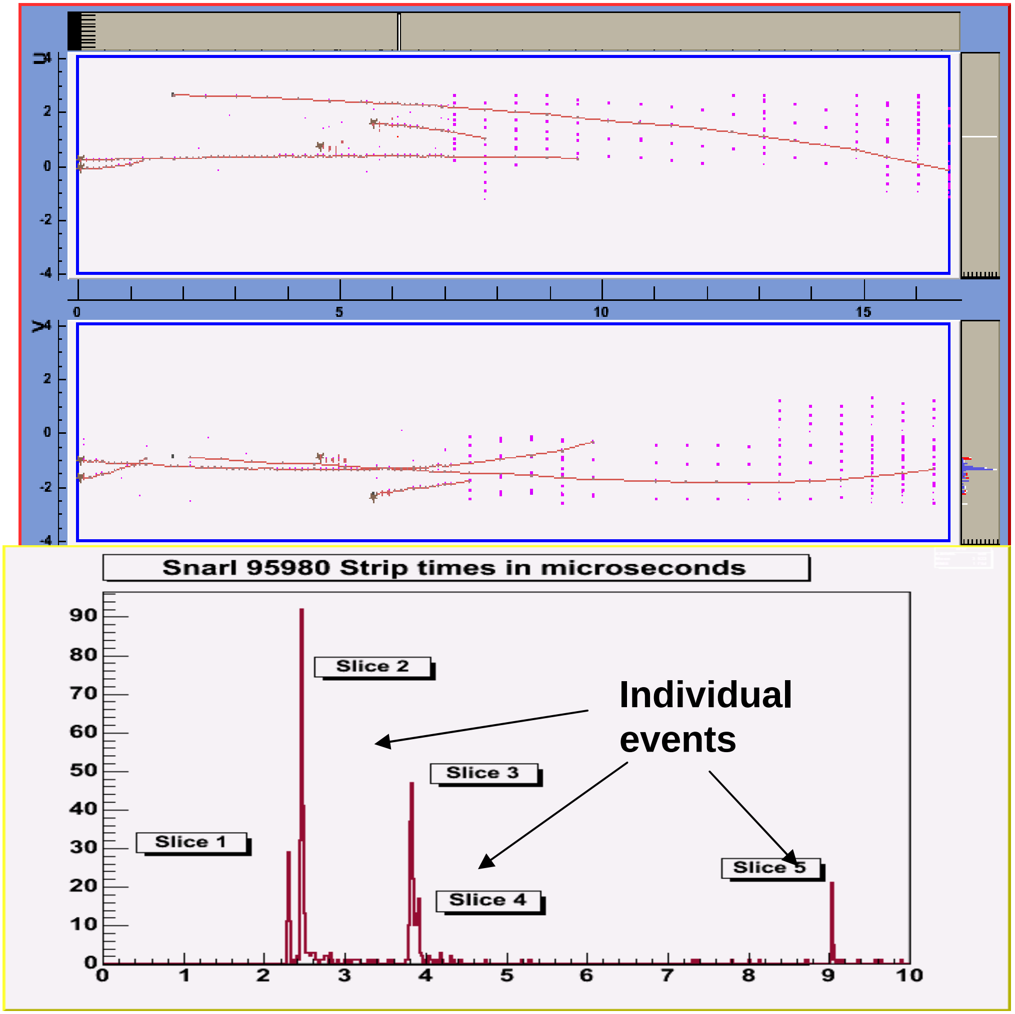


7th March 2005

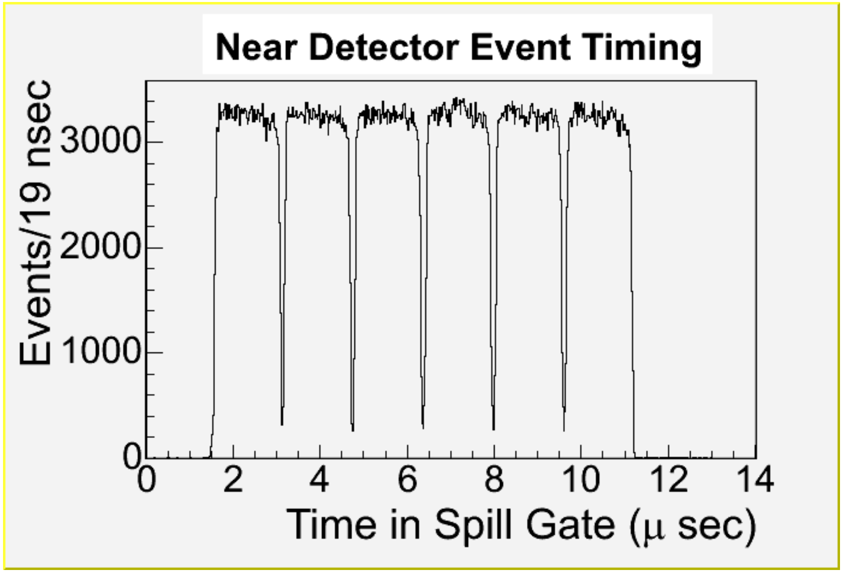
Near detector events

- Intense neutrino beam makes multiple neutrino interactions per spill in the near detector
- Events are separated by topology and timing

One near detector spill



Time (us)

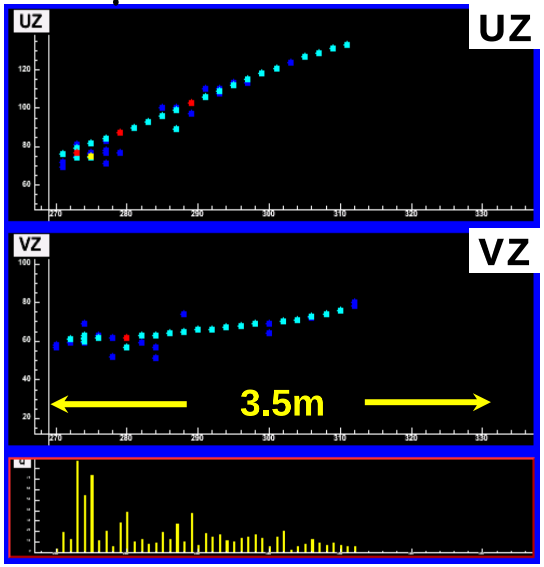


Batch structure clearly seen!

Event topologies

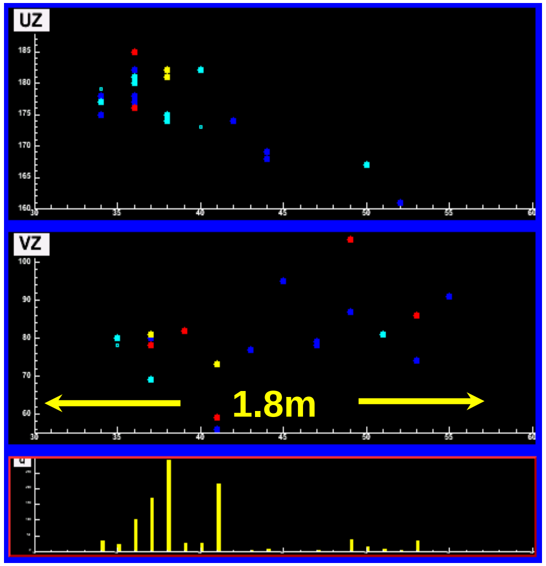
Monte Carlo

ν_μ CC Event



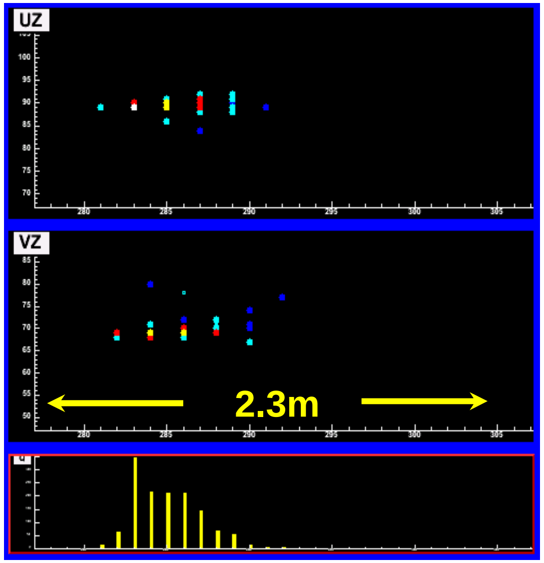
long μ track+ hadronic activity at vertex

NC Event



short event, often diffuse

ν_e CC Event



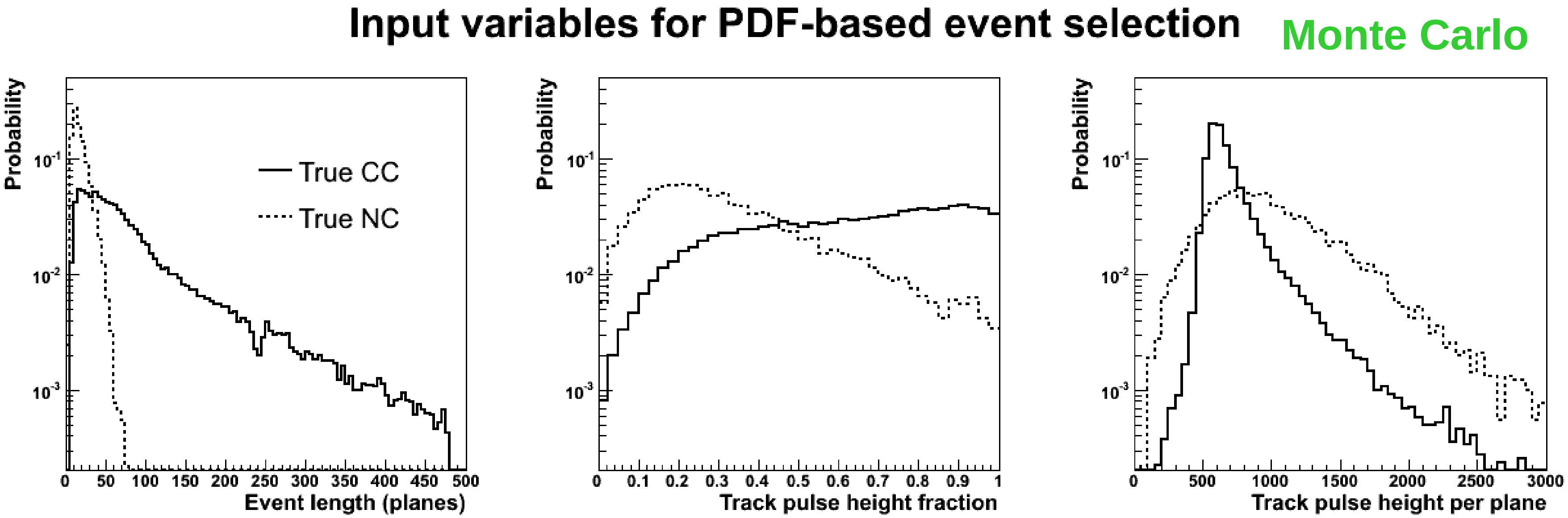
short, with typical EM shower profile

Sensitive to
$\nu_\mu - \nu_\tau$ oscillation

$$E_\nu = \underset{\substack{\uparrow \\ 55\%/\sqrt{E}}}{E_{\text{shower}}} + \underset{\substack{\uparrow \\ 6\%\text{ range, }10\%\text{ curvature}}}{P_\mu}$$

Selecting CC events

CC events are selected using a likelihood-based procedure



Input variables for PDF-based event selection

Monte Carlo

- **Event length in planes** (*related to muon momentum*)
- **Fraction of event pulse height in the reconstructed track** (*related to the inelasticity of CC events*)
- **Average track pulse height per plane** (*related to dE/dX of the reconstructed track*)

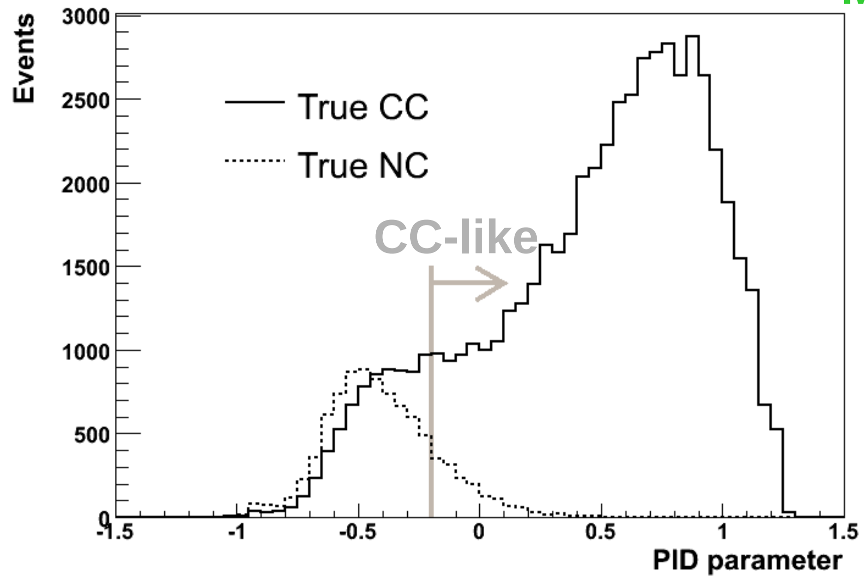
CC selection efficiencies

- The Particle ID (PID) parameter is defined as:

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

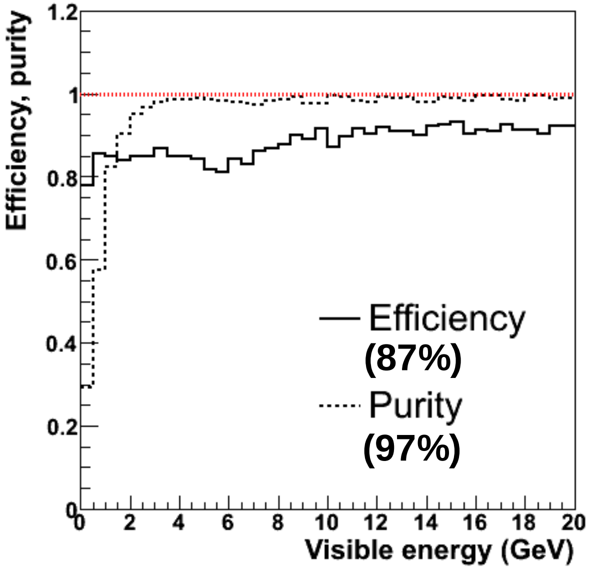
- CC-like events are defined by the cut PID>-0.2 in the FD (>-0.1 in the ND)
  - NC contamination is limited to the lowest visible energy bins (below 1.5 GeV)
  - Selection efficiency is quite flat as a function of visible energy

PDF PID parameter distribution for true CC and NC events



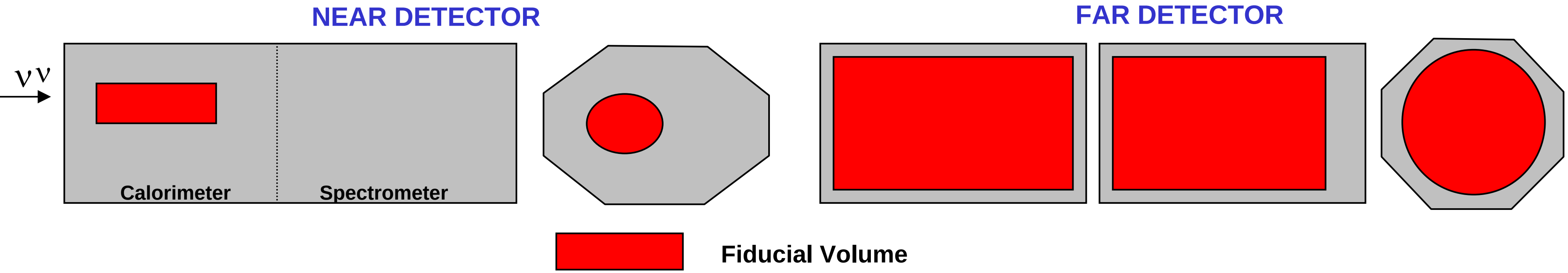
Monte Carlo

CC selection efficiencies and purities



Event selection cuts – Near and Far

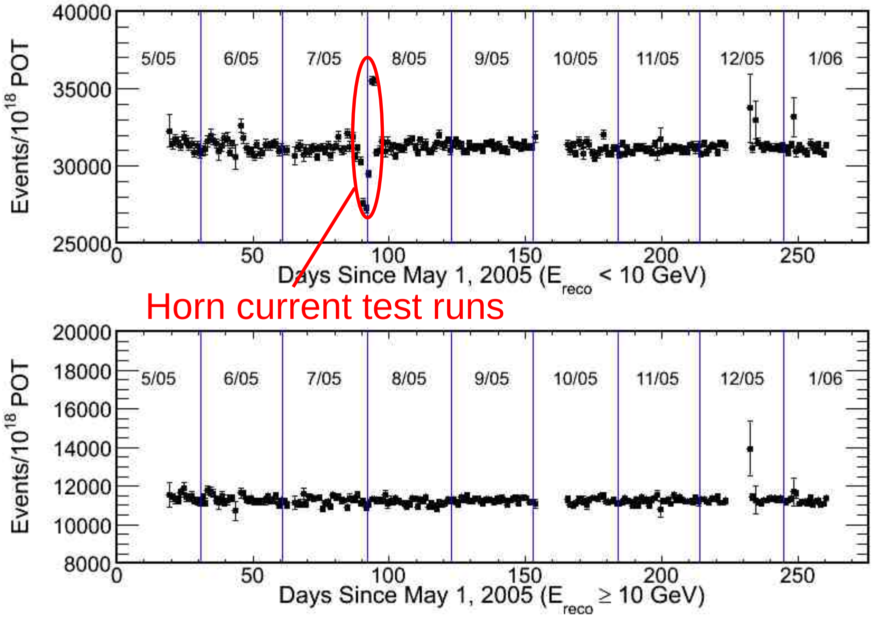
1. Event must contain at least one good reconstructed track
2. The reconstructed track vertex should be within the fiducial volume of the detector:
   - NEAR: $1m < z < 5m$ (z measured from the front face of the detector), R< 1m from beam centre.
   - FAR: z>50cm from front face, z>2m from rear face, R< 3.7m from centre of detector.



3. The fitted track should have negative charge (selects ν_μ)
4. Cut on likelihood-based Particle ID parameter which is used to separate CC and NC events.

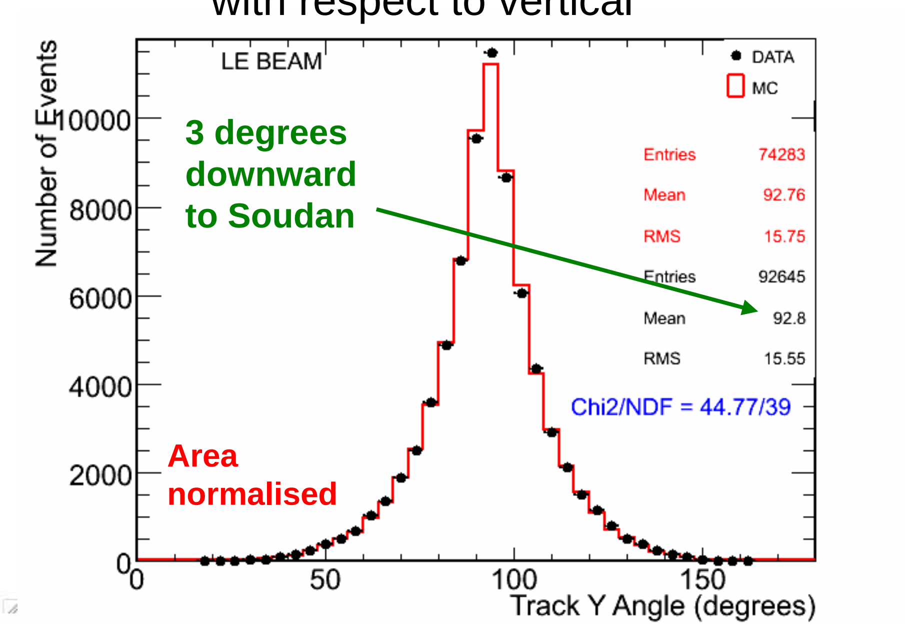
Near Detector data distributions

Near detector event raye – LE-10



Horn current test runs

Reconstructed track angle with respect to vertical

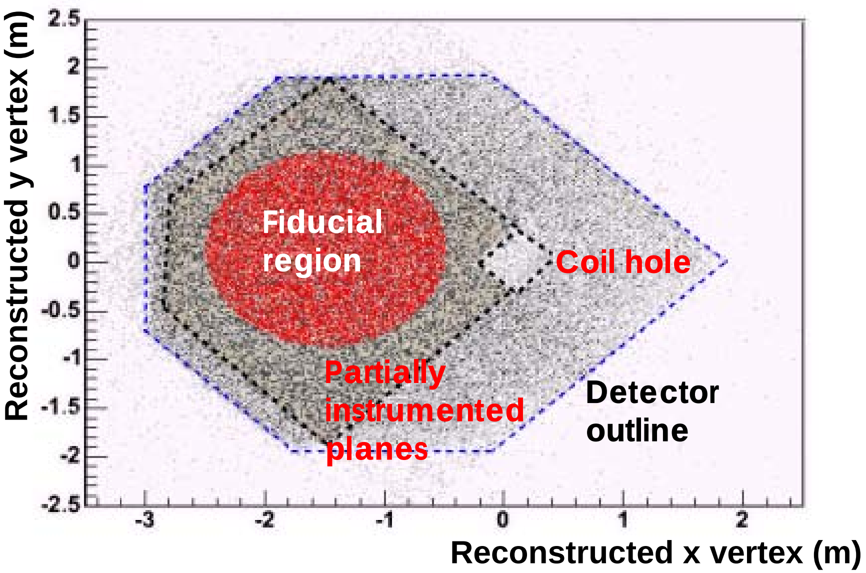


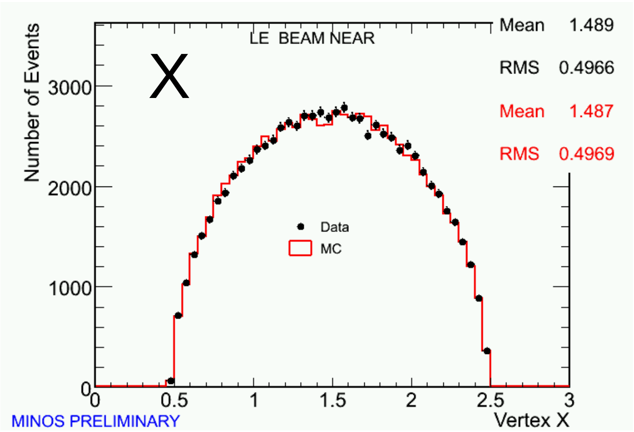
3 degrees downward to Soudan

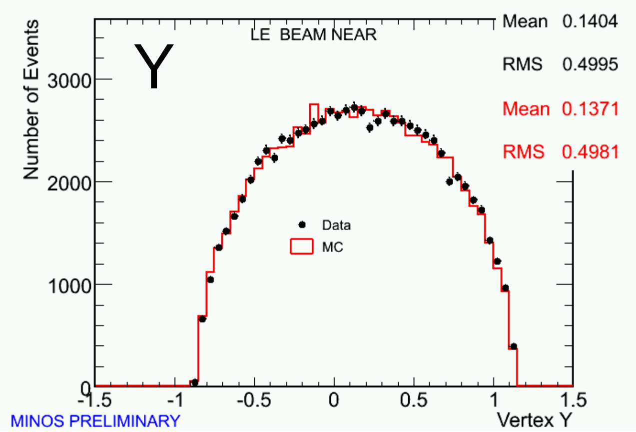
Area normalised

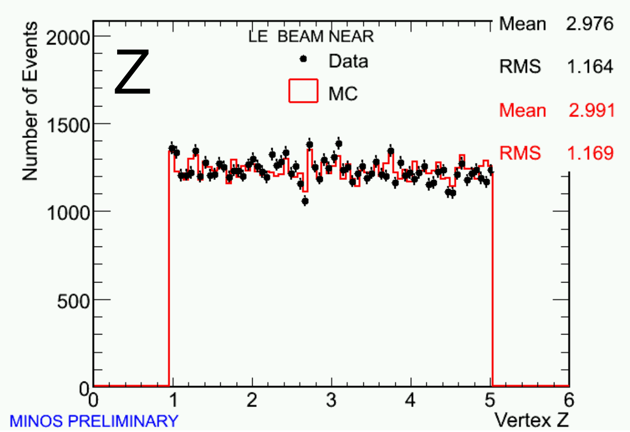
Near detector event vertices – LE-10 beam

Distribution of reconstructed event vertices in the x-y plane



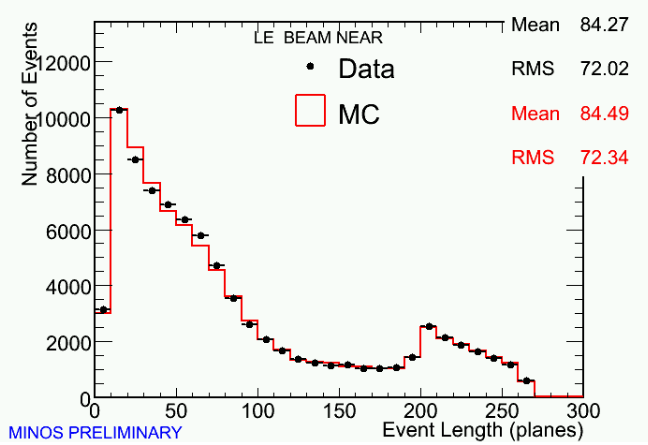




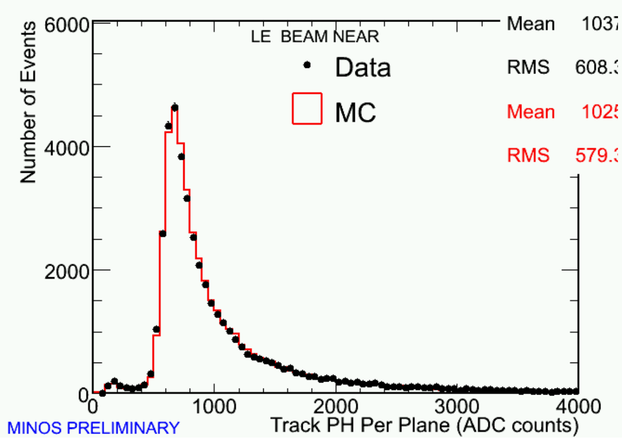


Particle Identification – LE-10 Beam

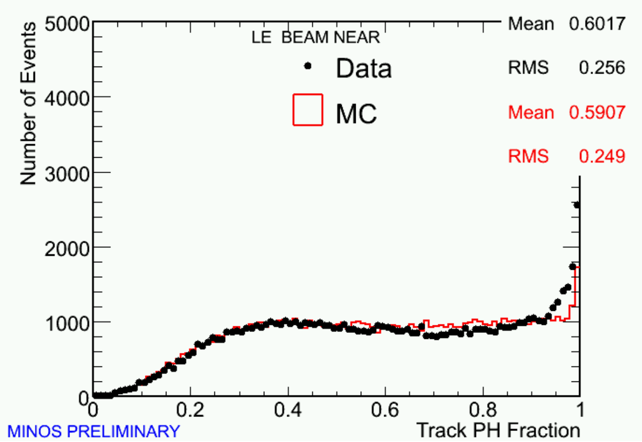
Event length



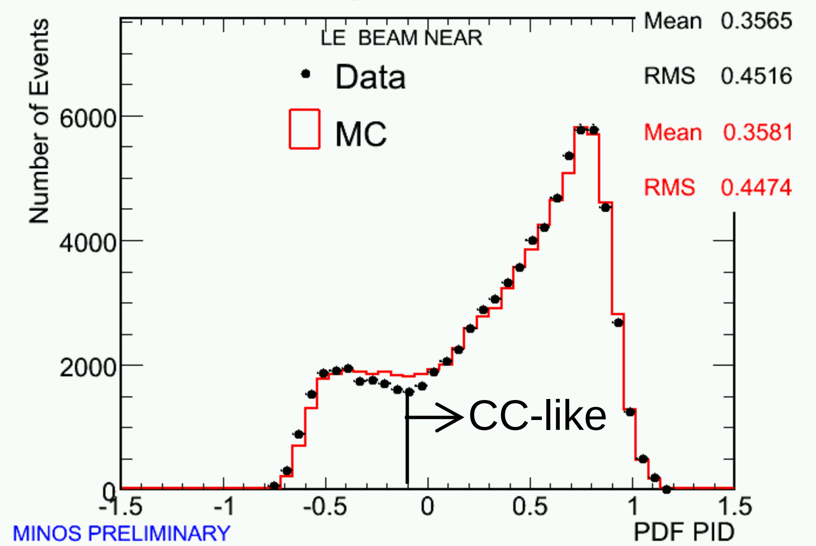
Track PH per plane



Track PH fraction

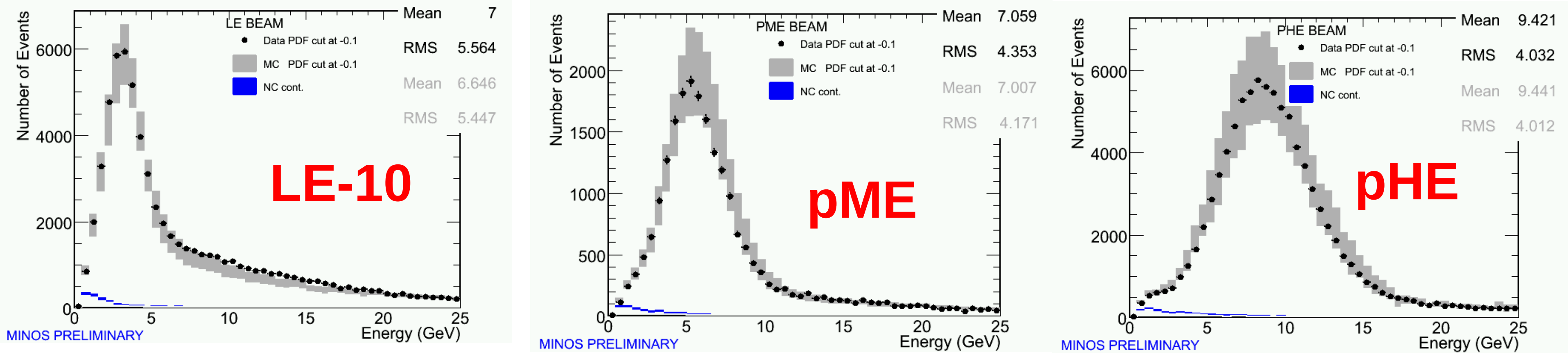


PID parameter

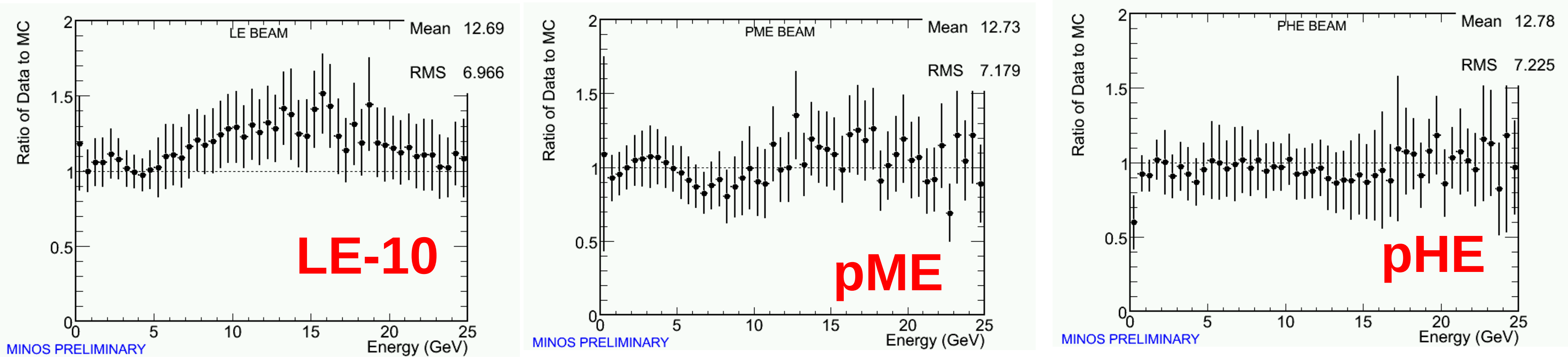


Energy spectra & ratios in ND (CC-like events)

Reconstructed Neutrino Energy



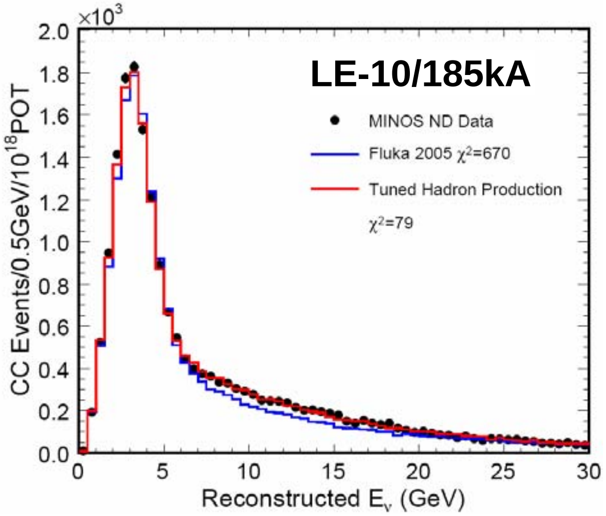
Ratios of Data/MC

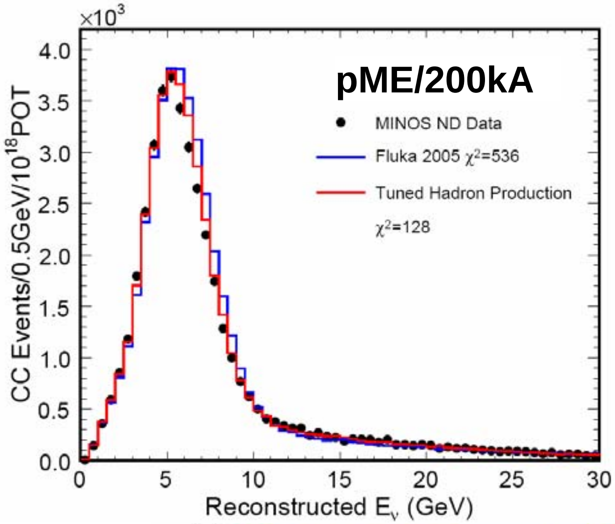


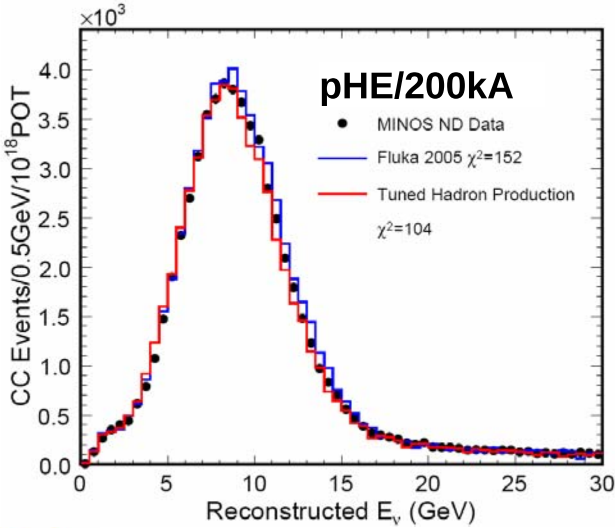
Error envelope shown on the plots includes uncertainties due to cross-section modelling, beam modelling and calibration uncertainties.

Hadron production tuning

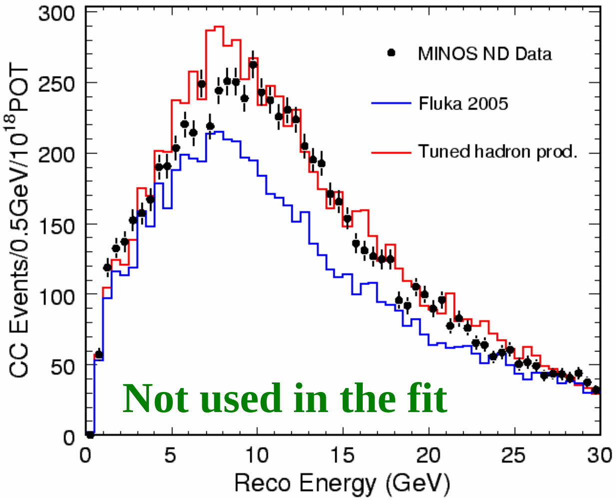
Agreement between data and Fluka05 Beam MC is within the systematic errors
→ Further improvement by hadron production tuning as a funtion of x_F and p_T



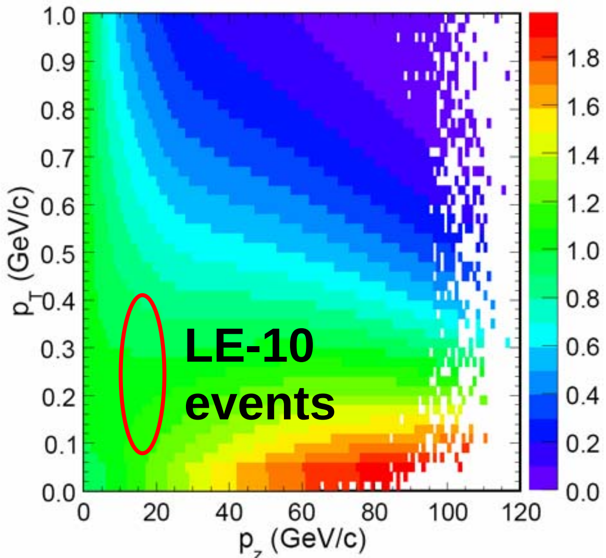




LE-10/Horns off



Not used in the fit

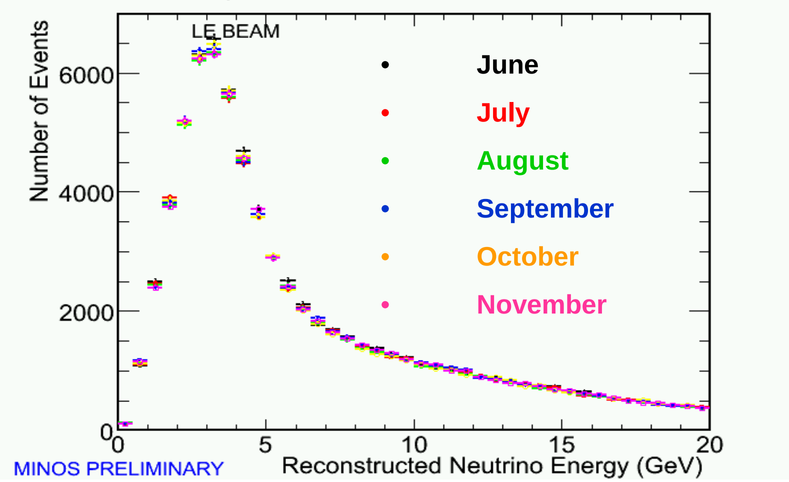


LE-10 events

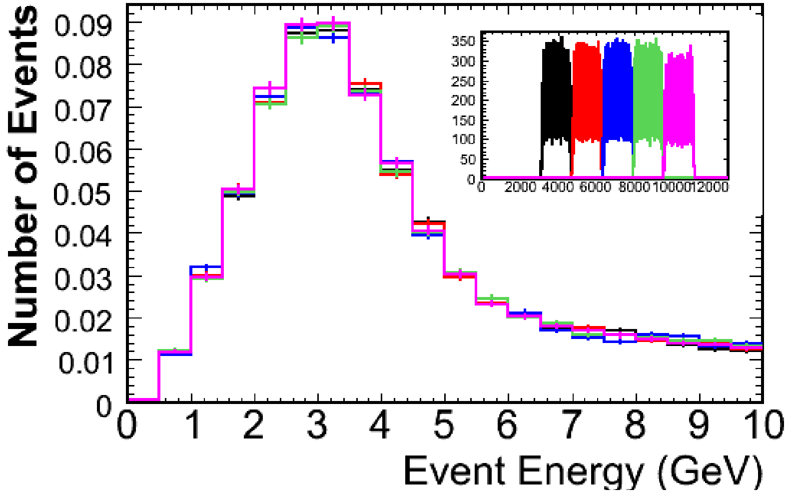
Weights applied as a function of hadronic x_F and p_T.

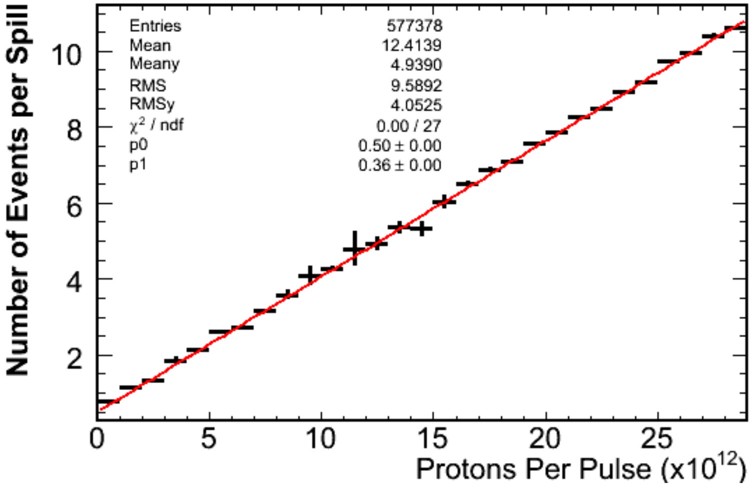
Stability of the energy spectrum & reconstruction

Energy spectrum by Month



Data **Energy spectrum by batch**

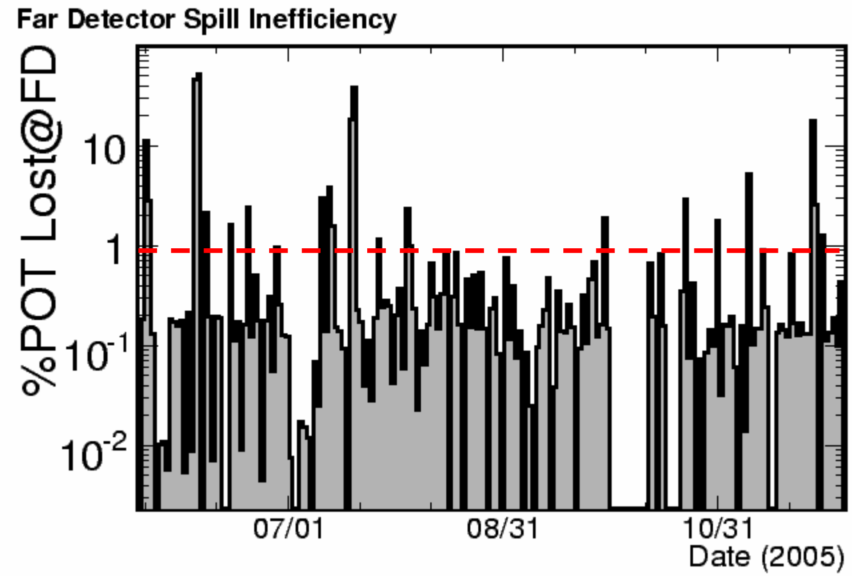




- Reconstructed energy distributions agree to within statistical uncertainties (~1-3%) – beam is stable for long period
- There is no significant intensity-dependent biases in event reconstruction

Far Detector Beam Analysis

- Oscillation analysis performed using data taken in the LE-10 configuration from May 20th 2005 – December 6th 2005
  - **Total integrated POT: 0.93e20**
  - Excluded periods of “bad data” – coil and HV trips, periods without accurate GPS timestamps. The effect of these cuts are small (~0.7% of our total POT)
  - The POT-weighted livetime of the Far detector for this time period is 98.9%



Performing a blind analysis

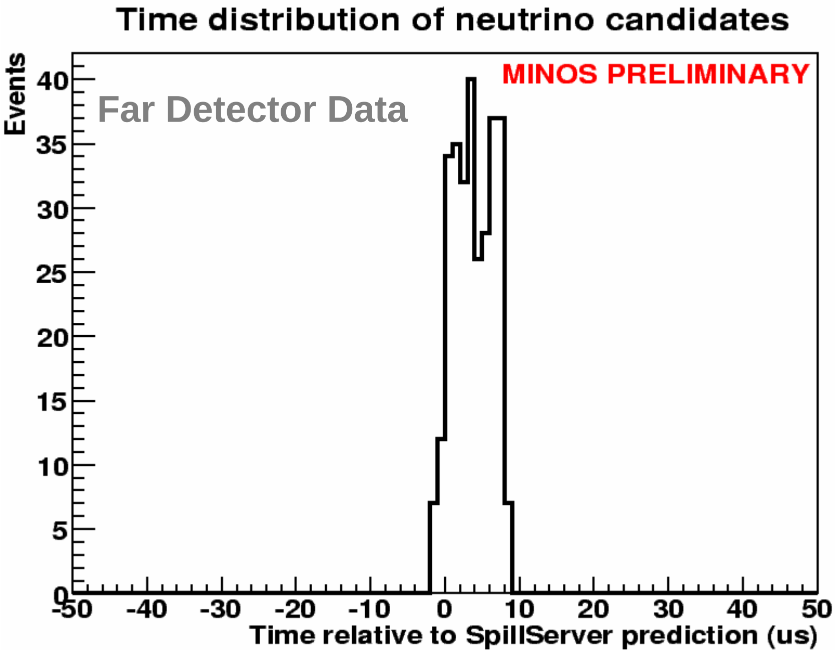
- The MINOS collaboration decided to pursue a "blind" analysis policy for the first accelerator neutrino results
  - **The blinding procedure hides an unknown fraction of our events based on their length and total energy deposition**.
- Unknown fraction Far Detector Data was "open" - used them to perform extensive data quality checks.

- Remaining fraction was "hidden". Final analyses were performed on total sample once Box was opened**.** Box opening criteria were:
  - **Checks on open sample should indicate no problems with the FD beam dataset (missing events, reconstruction problems etc.)**
  - **Oscillation analysis (cuts and fitting procedures) should be pre-defined and validated on MC. No re-tuning of cuts allowed after box opening**

Selecting beam induced events

- Time stamping of the neutrino events is provided by two GPS units (located at Near and Far detector sites).
  - FD Spill Trigger reads out 100us of activity around beam spills
- Far detector neutrino events have very distinctive topology and are easily separated from cosmic muons (0.5 Hz)

Time difference of neutrino interactions from beam spill

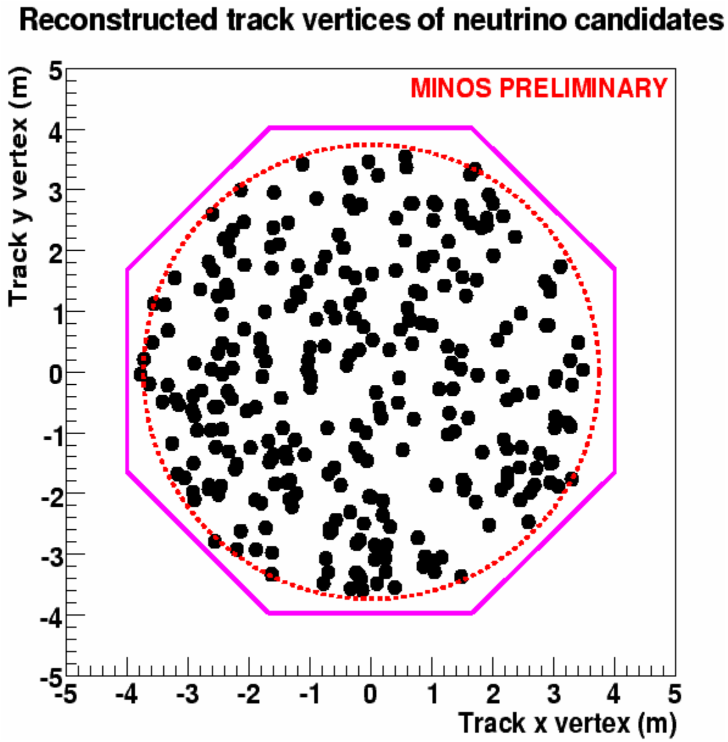


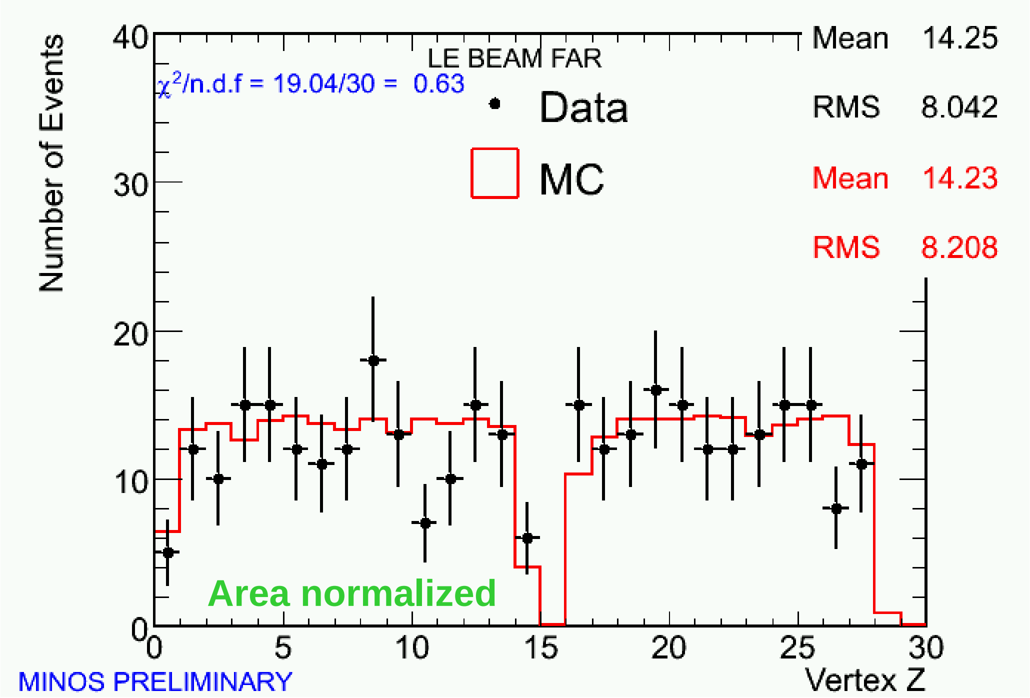
Backgrounds were estimated by applying selection algorithm on “fake” triggers taken in anti-coincidence with beam spills.

In 2.6 million “fake” triggers, 0 events survived the selection cuts (upper limit on background is 1.7 events at 90% C.L.)

Vertex distributions of FD events

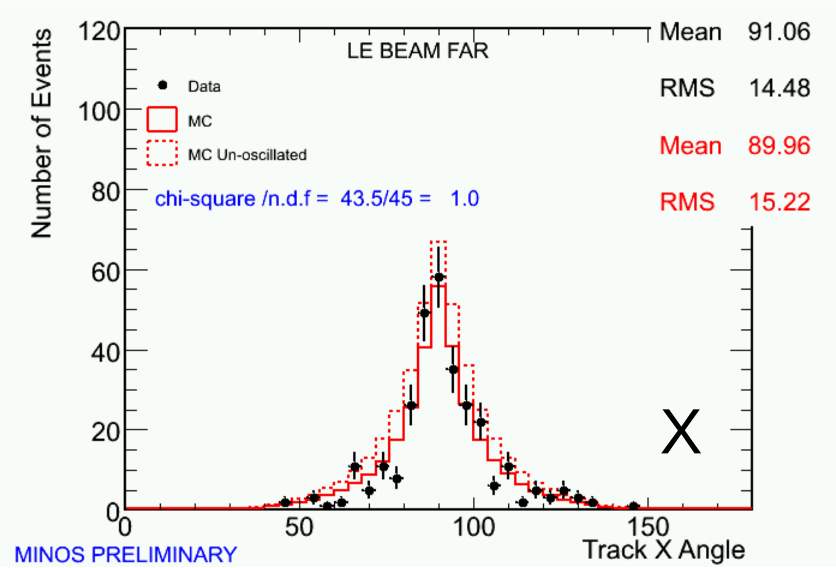
Full dataset

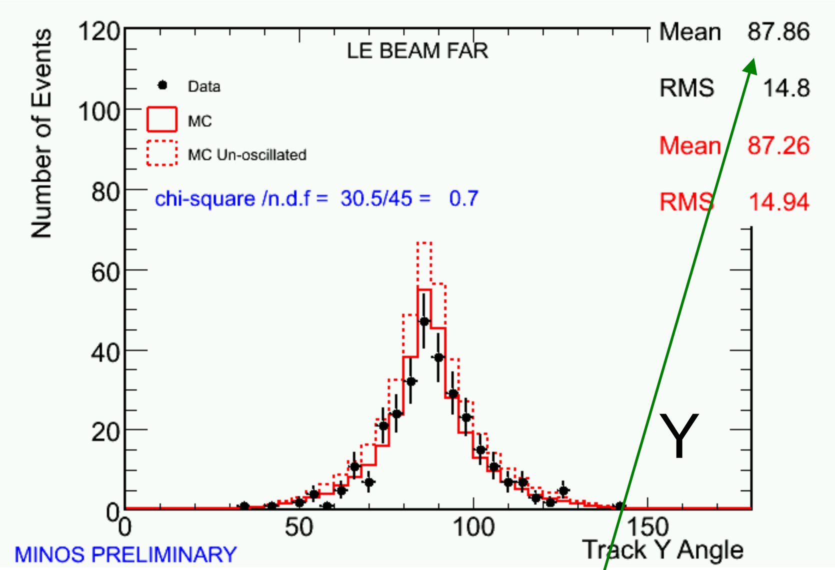




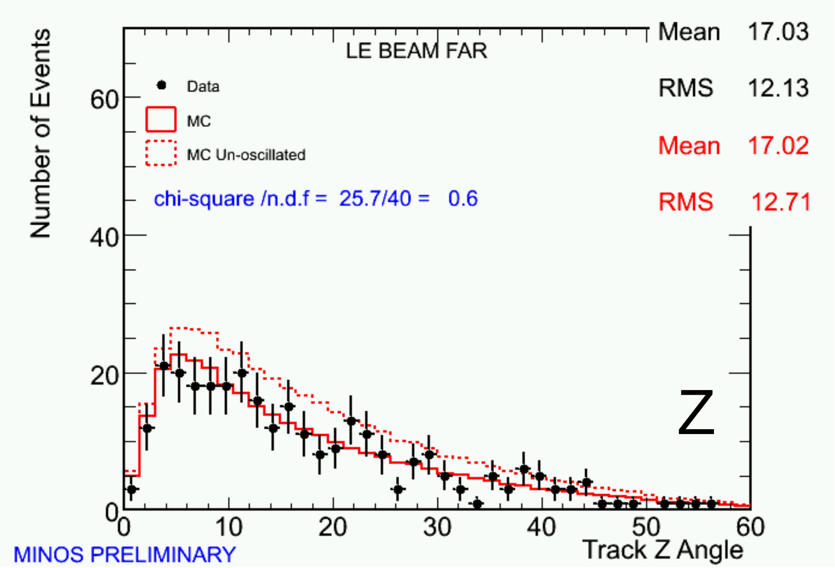
- 296 events are selected with a track
- Vertex of selected events are uniformly distributed consistent – no evidence of background contaminations

Track angles



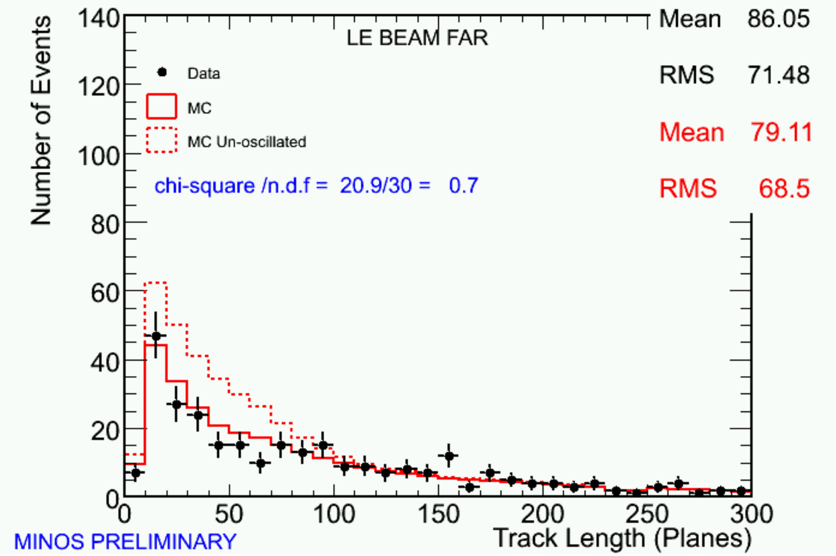


3 degrees upward at Soudan

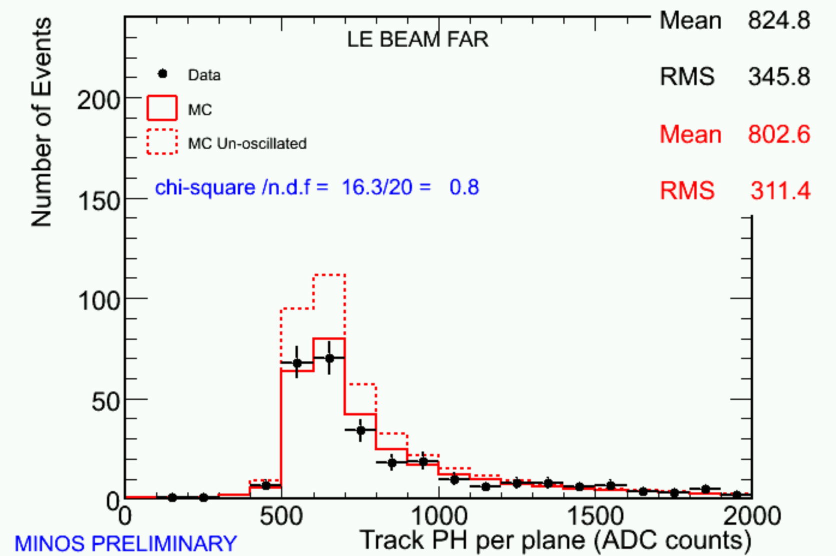


Track quantities & PID parameter

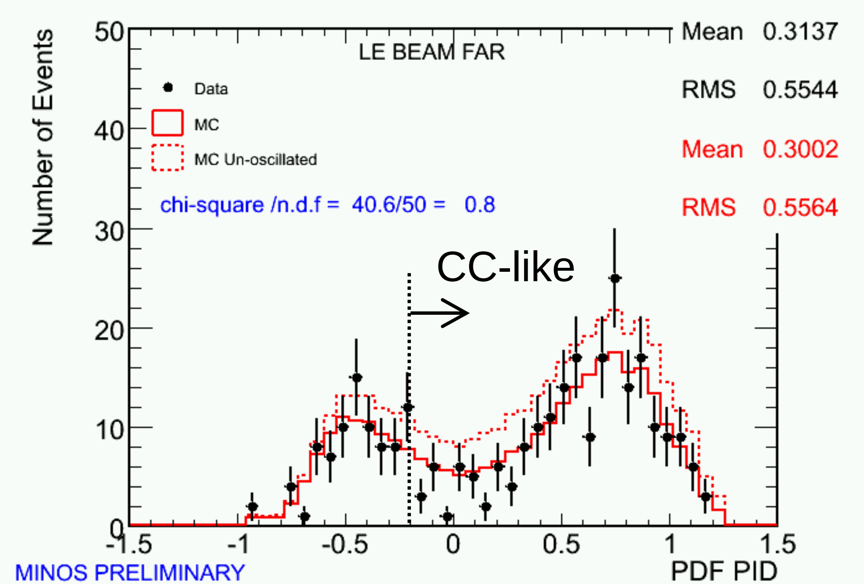
Track Length



Track Pulse Height per Plane



PID Parameter

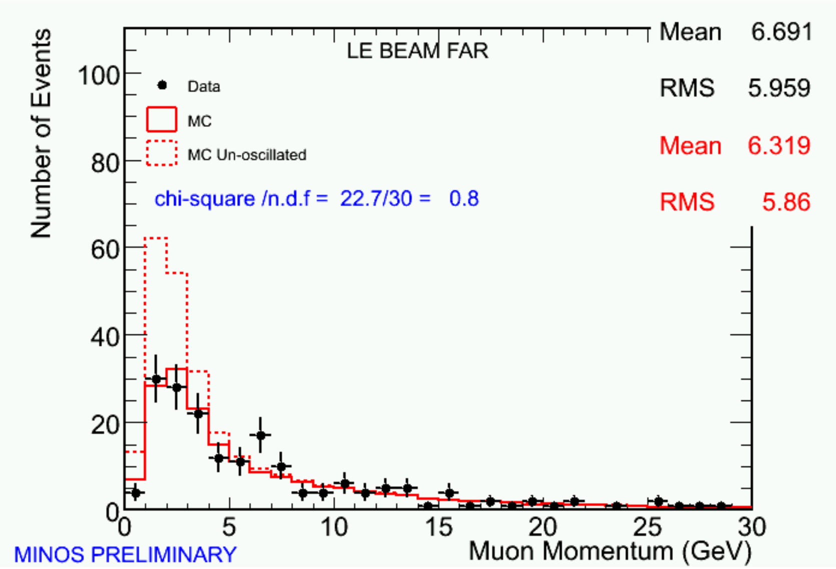


FD data selection procedure

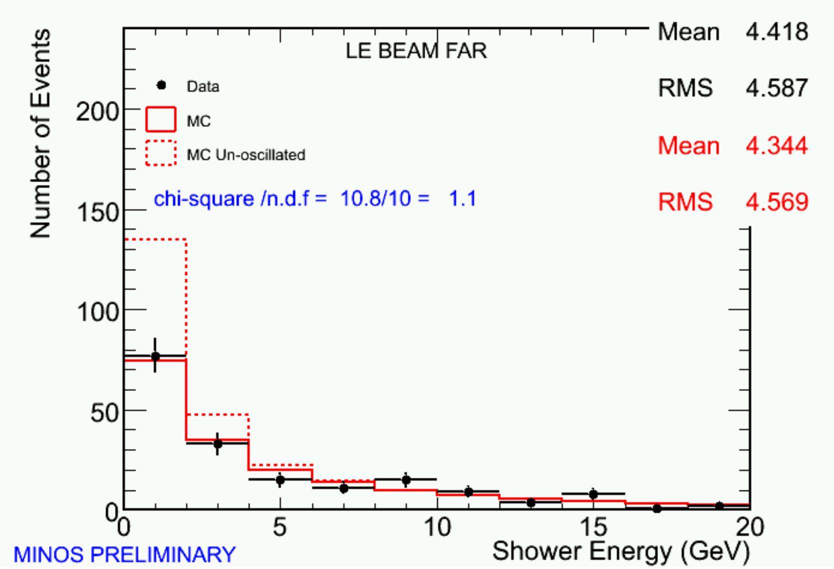
Cut	Events	efficiency
All events in fiducial vol	331	-
Events with a track	296	89.1%
Track quality cuts	281	95.3%
PID cut (CC-like)	204	72.9%
Track charge sign cut (negative muons only)	186	91.2%
Reconstructed energy < 30 GeV	166	89.2%

Physics distributions

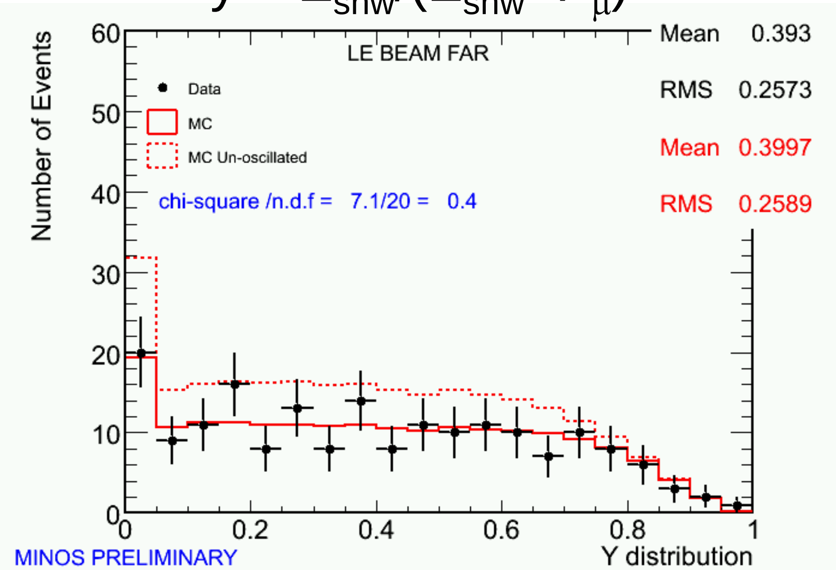
Muon Momentum



Shower Energy

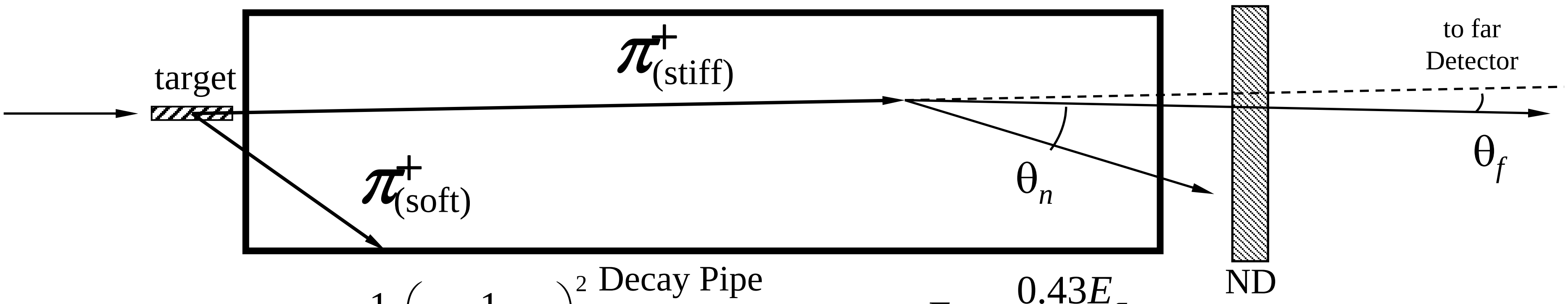


$y = E_{shw}/(E_{shw}+P_{\mu})$



Near to Far extrapolation: “Beam Matrix” method

- Directly use the Near detector data to perform the extrapolation between Near and Far, using our Monte Carlo to provide necessary corrections due to energy smearing and acceptance.
- Predict the Far detector energy distribution from the measured Near detector distribution using pion decay kinematics and the geometry of beamline.



$$Flux \propto \frac{1}{L^2}\left(\frac{1}{1+\gamma^2\theta^2}\right)^2$$

$$E_\nu = \frac{0.43E_\pi}{1+\gamma^2\theta^2}$$

Procedure of predicting the FD spectrum

A)

$$E^{\text{Reconstructed}}_{\mathit{Near}\ \text{CC-like}} \Rightarrow E^{\mathit{True}}_{\mathit{Near}\ \text{CC}}$$

Correction for purity, Reconstructed =>True, Correction for efficiency

B)

$$E^{\mathit{True}}_{\mathit{Near}\ \text{CC}} \Rightarrow E^{\mathit{True}}_{\mathit{Far}\ \text{CC}}$$

BEAM MATRIX

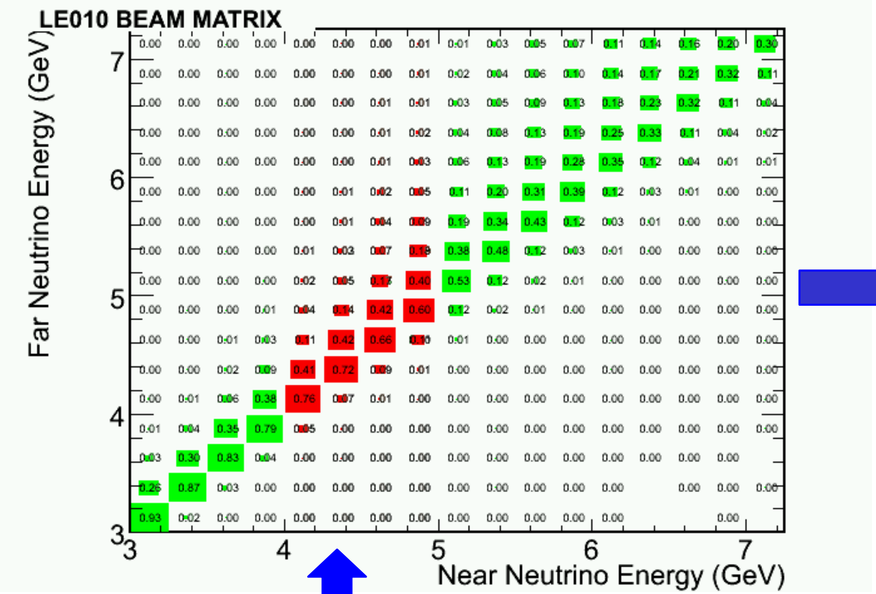
C)

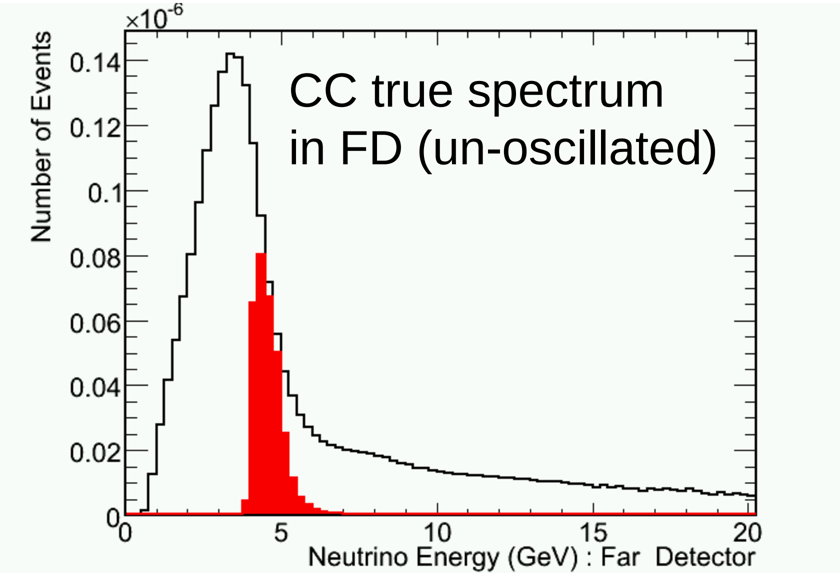
$$E^{\mathit{True}}_{\mathit{Far}\ \text{CC}} \Rightarrow E^{\text{Reconstructed}}_{\mathit{Far}\ \text{CC-like}}$$

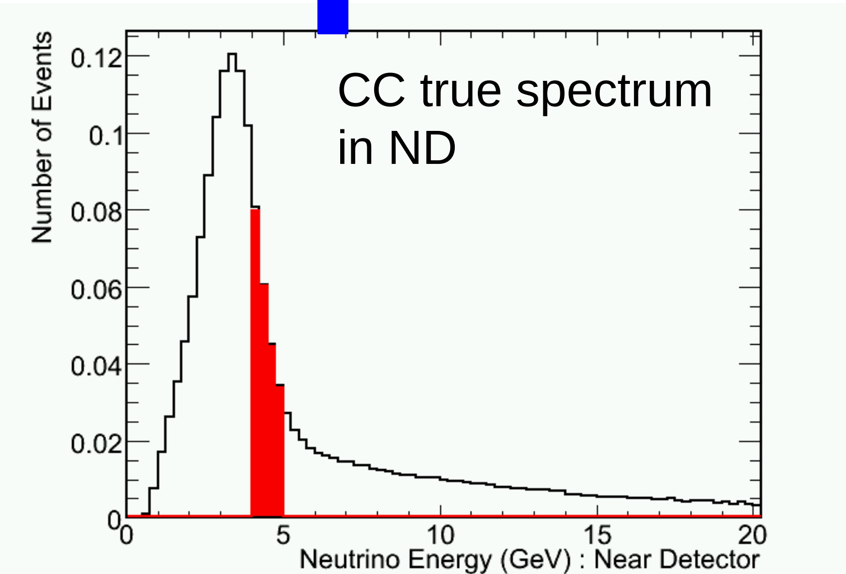
i) Oscillation, True => Reconstructed, Correction for efficiency to obtain CC oscillated spectrum

ii) Unoscillated True => Reconstructed, Use purity to obtain NC background

“Beam Matrix” : Near to Far extrapolation







Beam Matrix

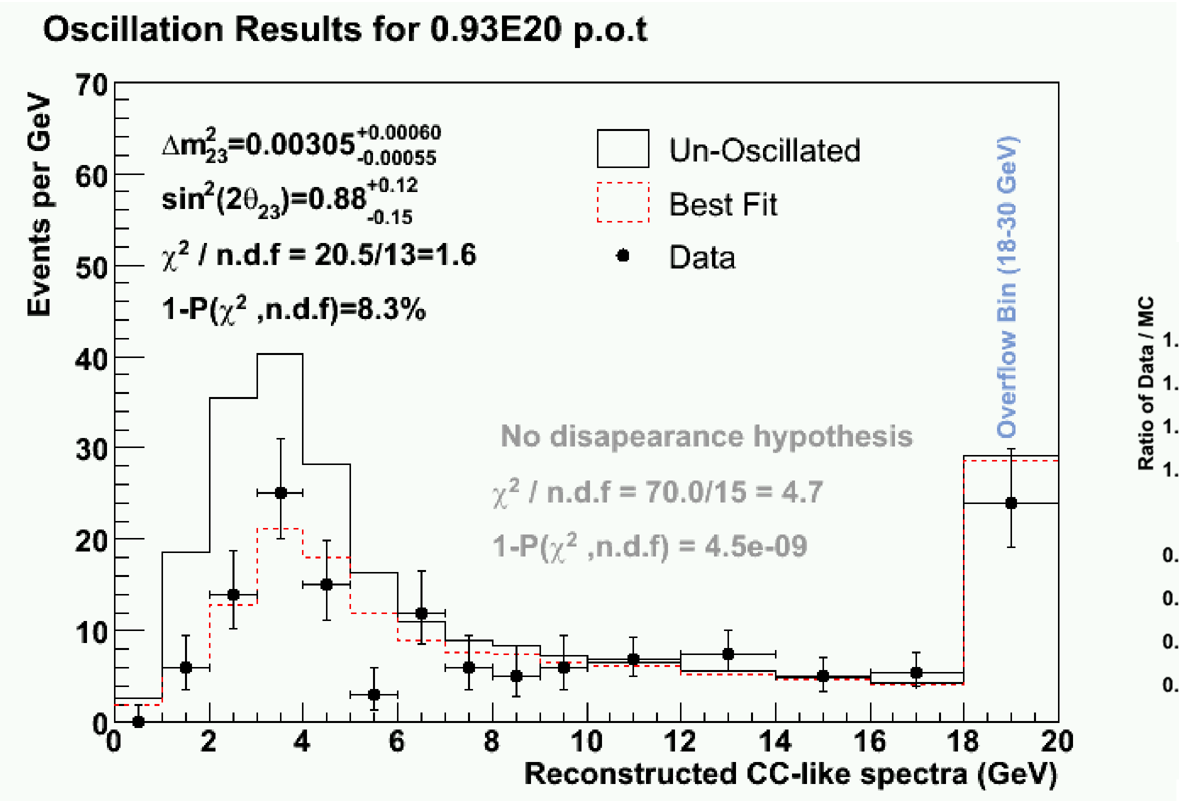
provides relations between the FD and ND spectrum determined by pion 2-body decay kinematics and geometry of beamline

Numbers of observed and expected events

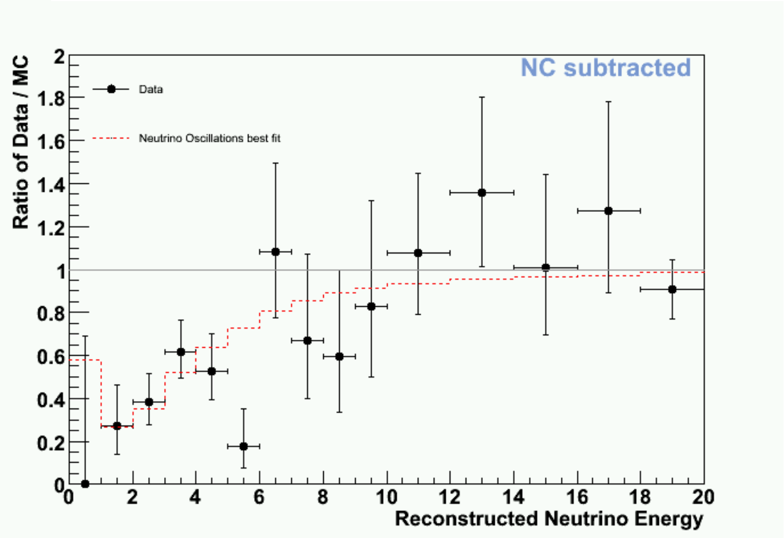
Data sample	observed	expected	ratio	significance
All CC-like events ($\nu_\mu+\bar{\nu}_\mu$)	204	298±15	0.69	4.1σ
ν_μ only (<30 GeV)	166	249±14	0.67	4.0σ
ν_μ only (<10 GeV)	92	177±11	0.52	5.0σ

- We observe a 33% deficit of events between 0 and 30 GeV with respect to the no oscillation expectation.
  - Numbers are consistent for $\nu_\mu+\bar{\nu}_\mu$ sample and for the ν_μ-only sample
- **The statistical significance of the deficit of muon neurinos is 5 standard deviations (< 10 GeV).**

Observed spectrum and the best-fit



Ratio of Data/MC

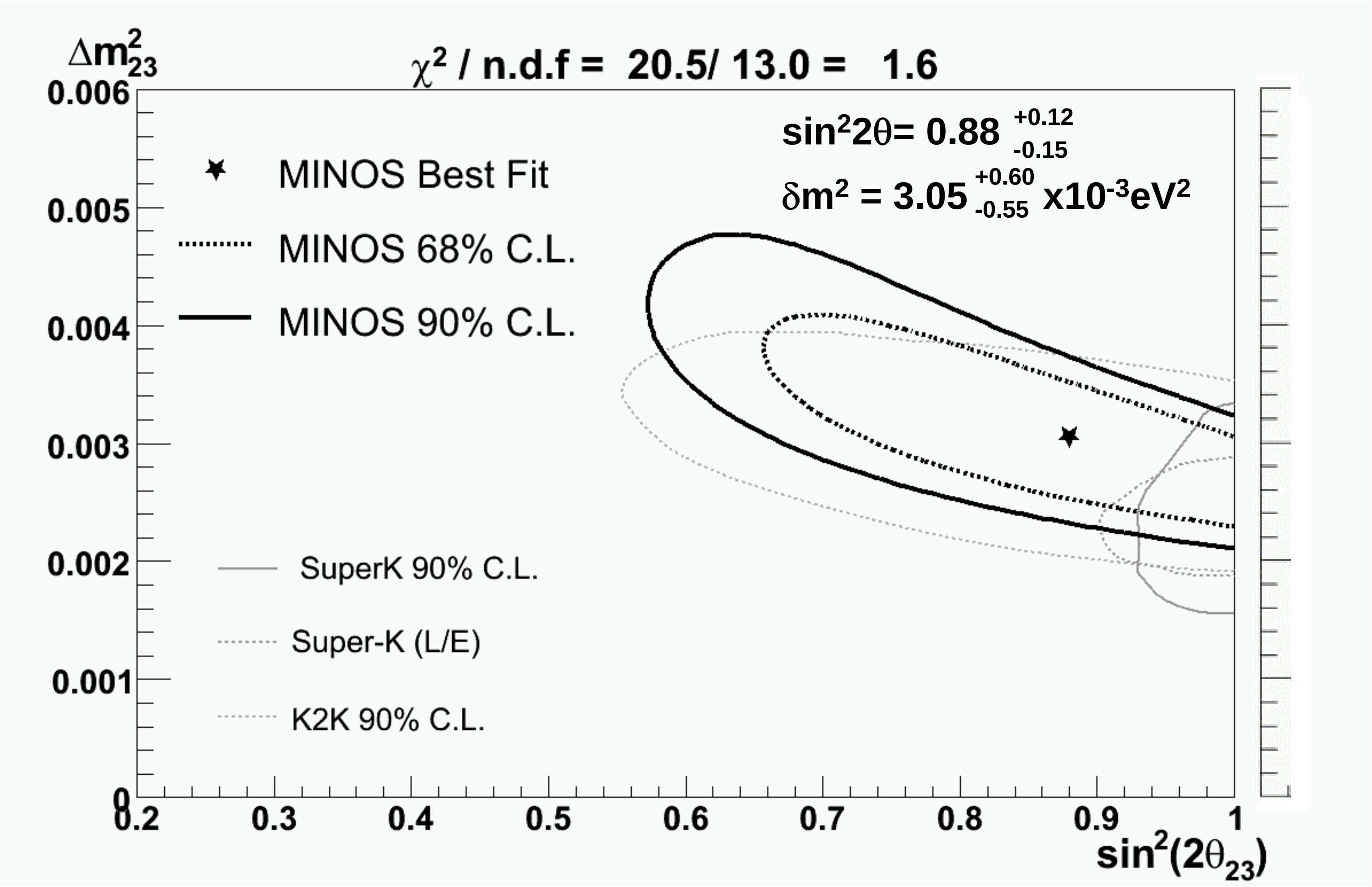


$$\chi^2(\Delta m^2, \sin^2 2\theta) = \sum_{i=1}^{nbins} 2(e_i - o_i) + 2o_i \ln(o_i / e_i)$$

o_i : observed # events

e_i : expected # events

Allowed regions



Systematic errors

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

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**

Alternative methods for predicting the FD spectrum

Three alternative ND to FD extrapolation methods:

F/N ratio :

Extrapolation using the Far/Near spectrum ratio from MC

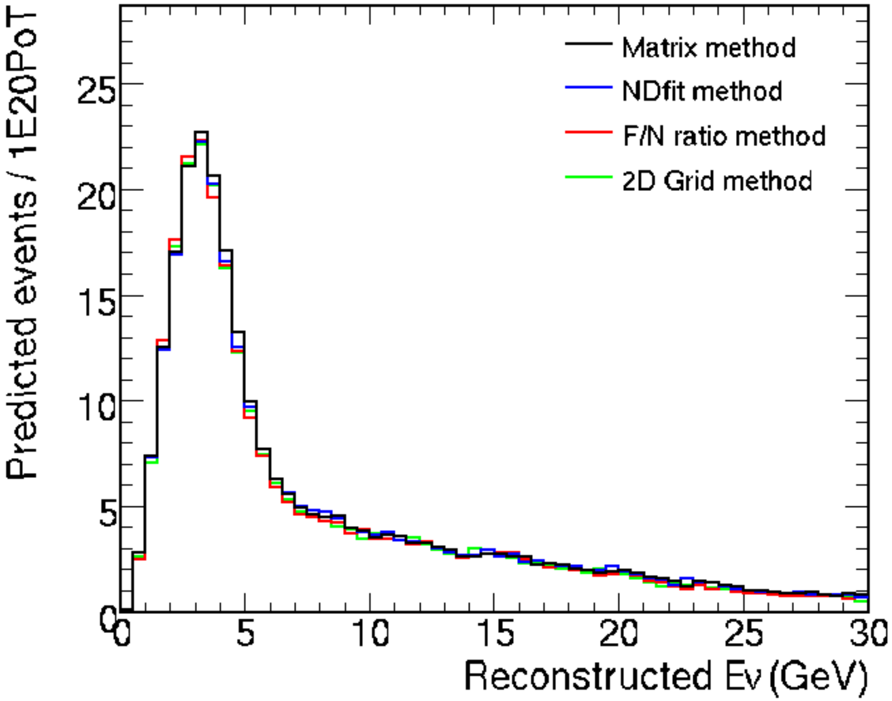
ND fit :

Reweight the FD MC using systematic parameters obtained by the ND fit

2D Grid fit :

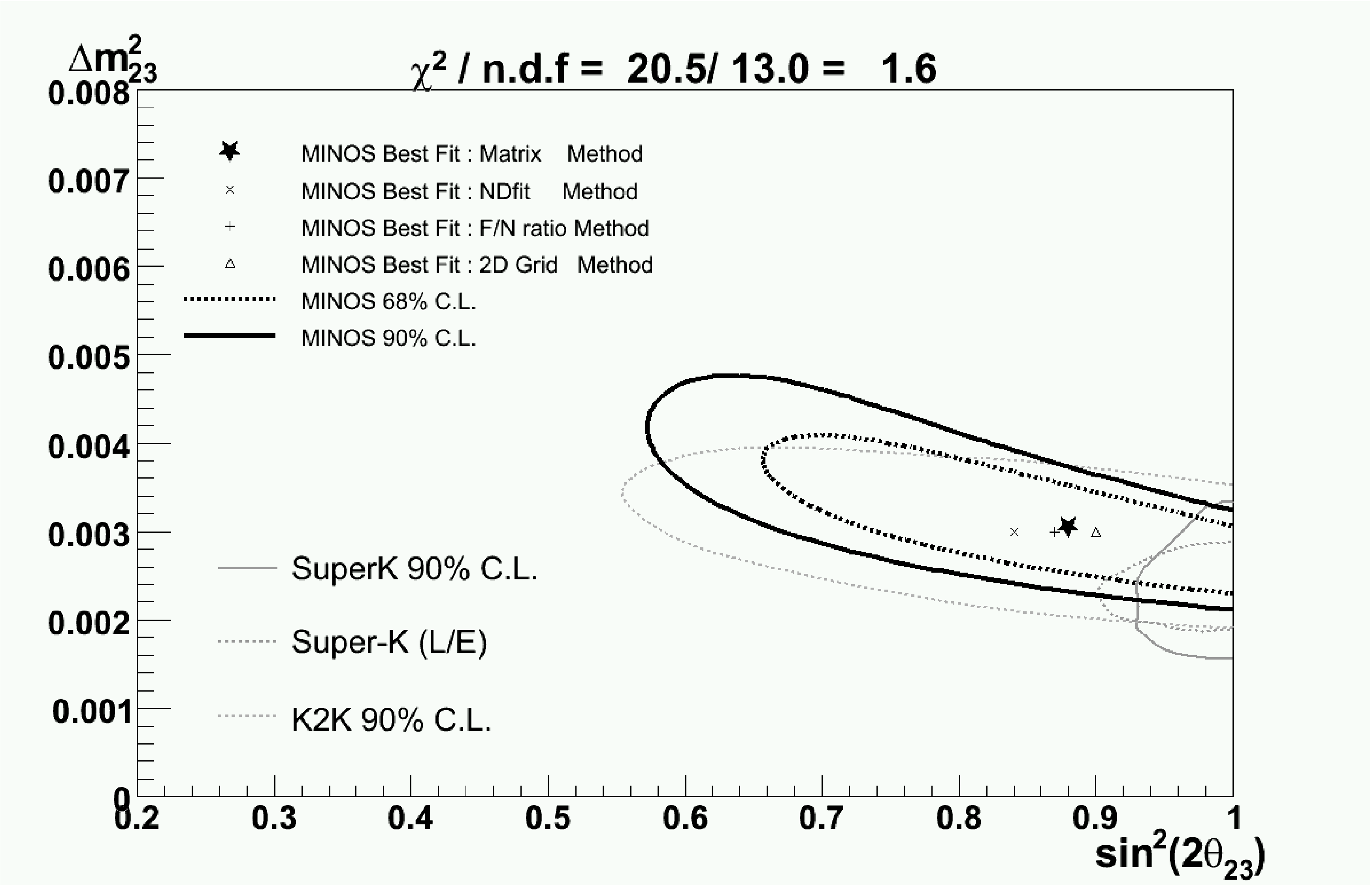
Reweight the FD MC using E_ν x y correction matrix and systematic parameters obtained by the ND fit

Predicted FD unoscillated spectra



Results obtained with all four methods are compared to check the robustness of our oscillation measurement

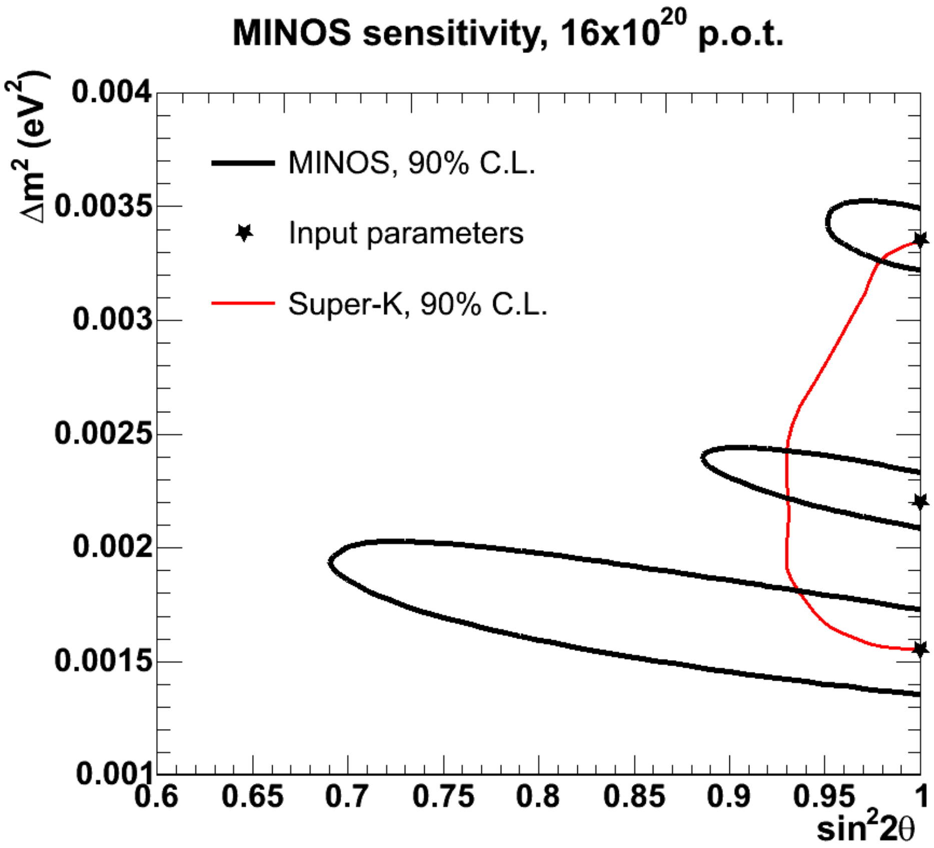
Allowed regions and the best-fit from 4 different methods



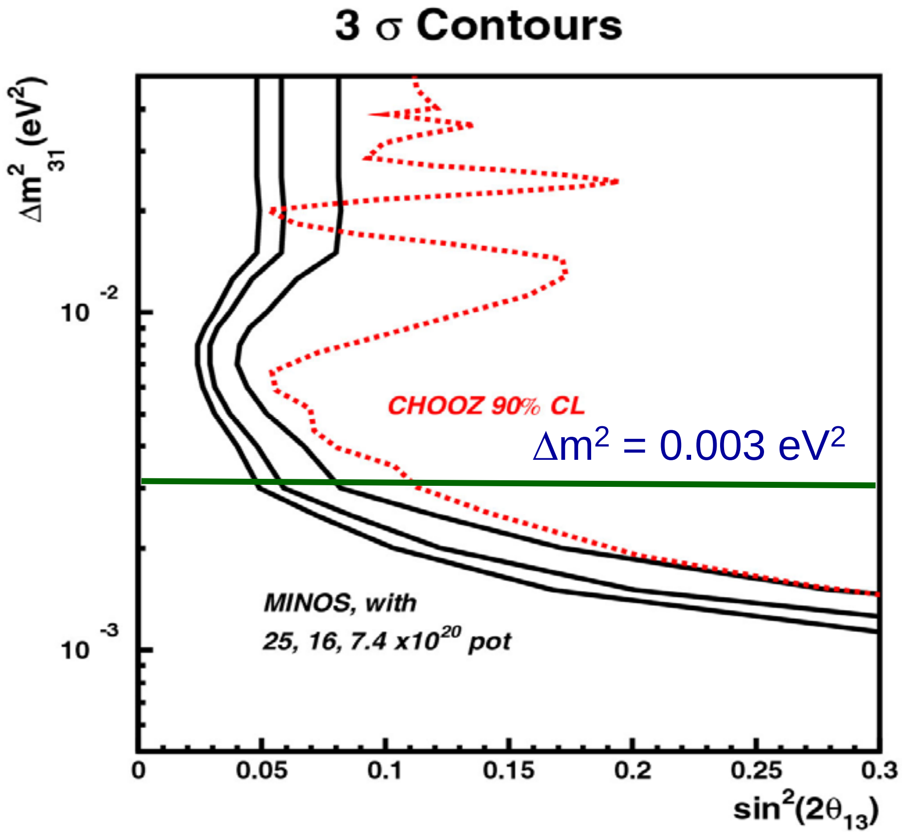
- **The results of the four different extrapolation methods are in excellent agreement with each other.**

Projected sensitivity of MINOS

ν_μ disappearance



$\nu_\mu \to \nu_e$



- With increased statistics, we should be able to make a very precise measurement of Δm^2_{23} and also search for sub-dominant $\nu_\mu \to \nu_e$ oscillations well-below the current exclusion limit
- We have reasonable chance of making first measurement of non-zero θ_{13}.

Summary and Conclusions

- The first accelerator neutrino oscillation results from a 0.93×10^{20} pot exposure of the MINOS far detector was presented in this talk.
- **Deficit of ν_μ events (< 10GeV) disfavours no oscillation at 5 σ.**
- **FD spectrum distortion is consistent with ν_μ disappearance with the following parameters:**

$$\boxed{\begin{aligned}\Delta m^2{}_{23} &= 3.05^{+0.60}_{-0.55}(stat) \pm 0.12(syst) \times 10^{-3} eV^2 \\ \sin^2 2\theta_{23} &= 0.88^{+0.12}_{-0.15}(stat) \pm 0.06(syst)\end{aligned}}$$

- The systematic uncertainties on this measurement are well under control and we should be able to make significant improvements in precision with a larger dataset.
  - Our total exposure to date is 1.4e20 pot.